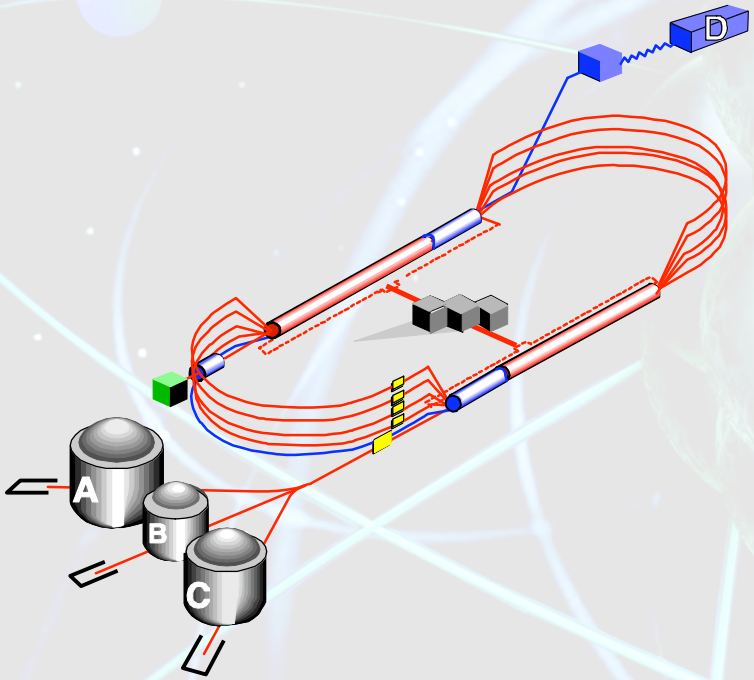
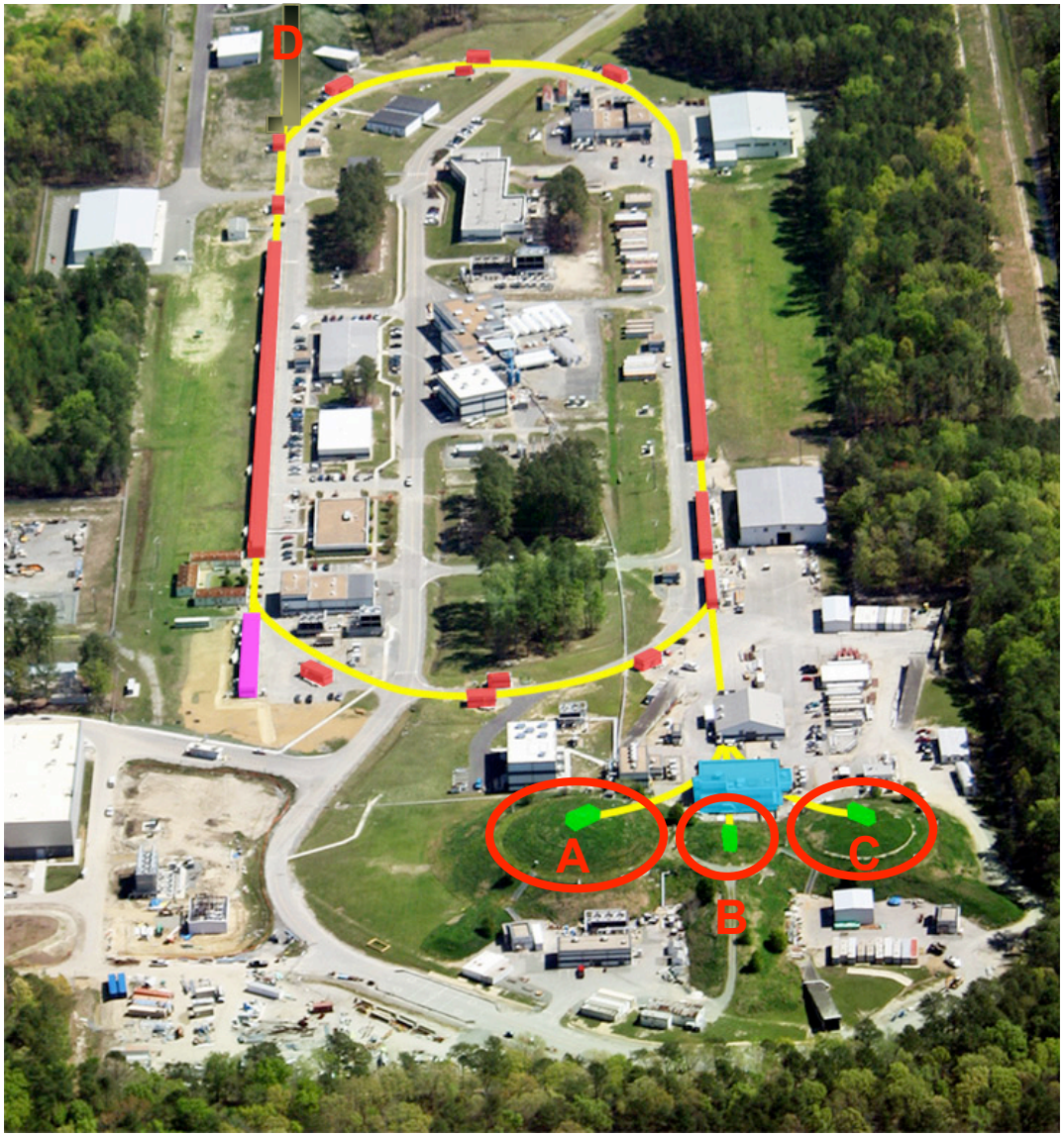
# Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab




Thia Keppel

DIS 2013

# JLab accelerator CEBAF - until recently

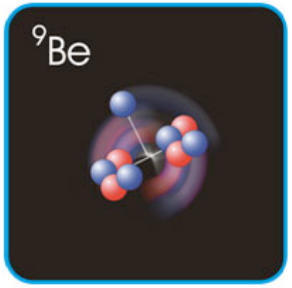



Continuous Electron Beam

- Energy 0.4 – 6.0 GeV
- 200 μA, polarization 85%
- Simultaneous delivery 3 halls
- ~1995 - 2012, lots of physics!

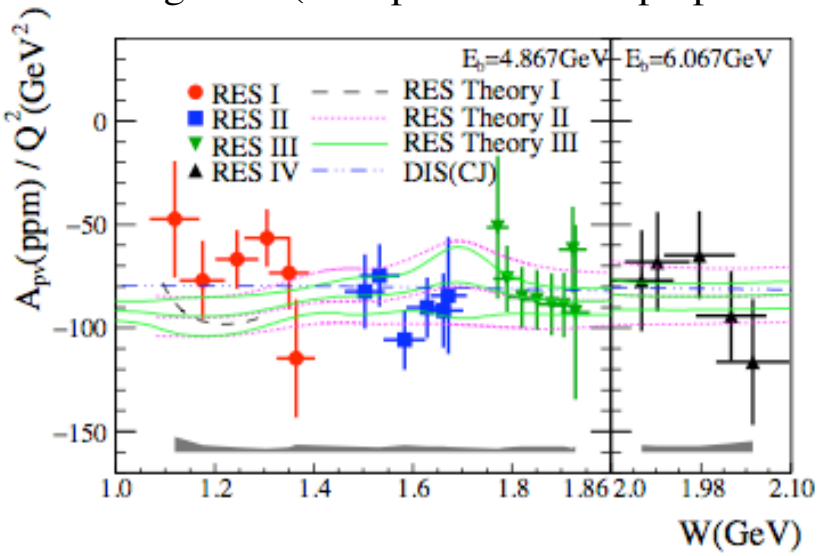
# *DIS Physics at 6 GeV*

- Quark-Hadron Duality and the onset of parton physics@JLab
- Separated ($F_2$, $F_1$, $F_L$) p, d and nuclear structure functions
  - used by CTEQ-JLab for pdf extraction including large x
  - Neutron tagging (BoNuS) towards $F_2^n/F_2^p$
- Separated ($g_1$, $g_2$) p, d, $^3$He spin-dependent structure functions
  - JAM collaboration underway for polarized pdfs
- Onset of Semi-Inclusive DIS: large z, cross sections, ratios
  - towards flavor decomposition and transverse momentum dependence
- Nuclear structure functions: EMC effect in light nuclei
  - towards the microscopic origin/understanding of the EMC effect



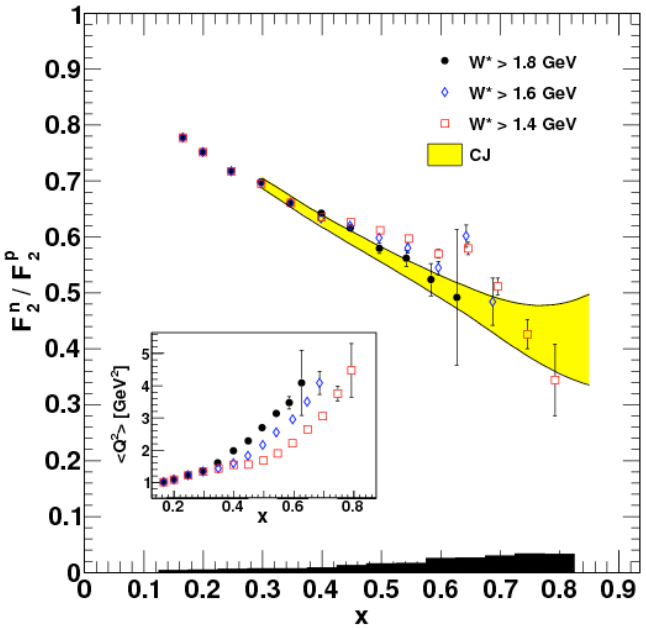
# Some recent work at 6 GeV large x….

D. Wang et al. (final publication in preparation)

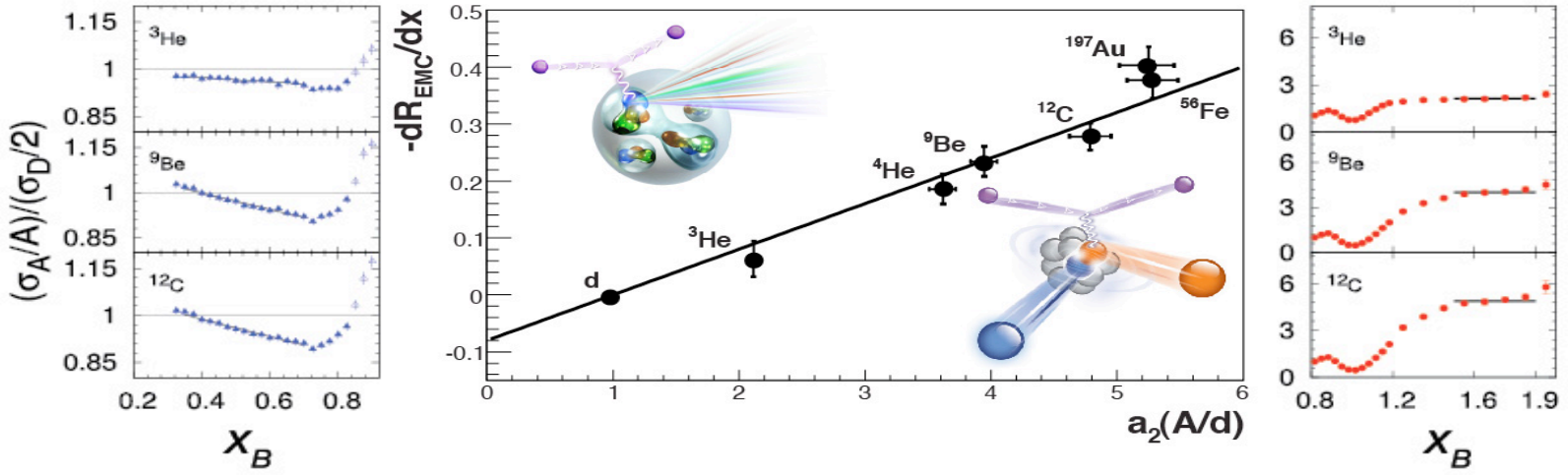



N.K. Baillie, et al, PRL 108, 199902 (2012)

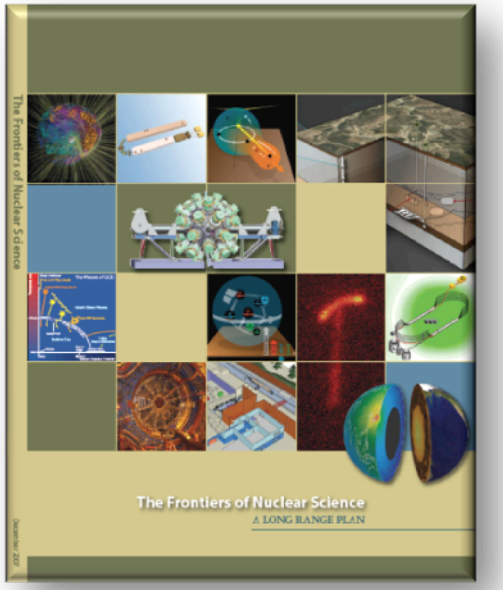
*See Wednesday afternoon SF session!*




L.B. Weinstein, et al, Phys.Rev.Lett. 106 (2011) 052301

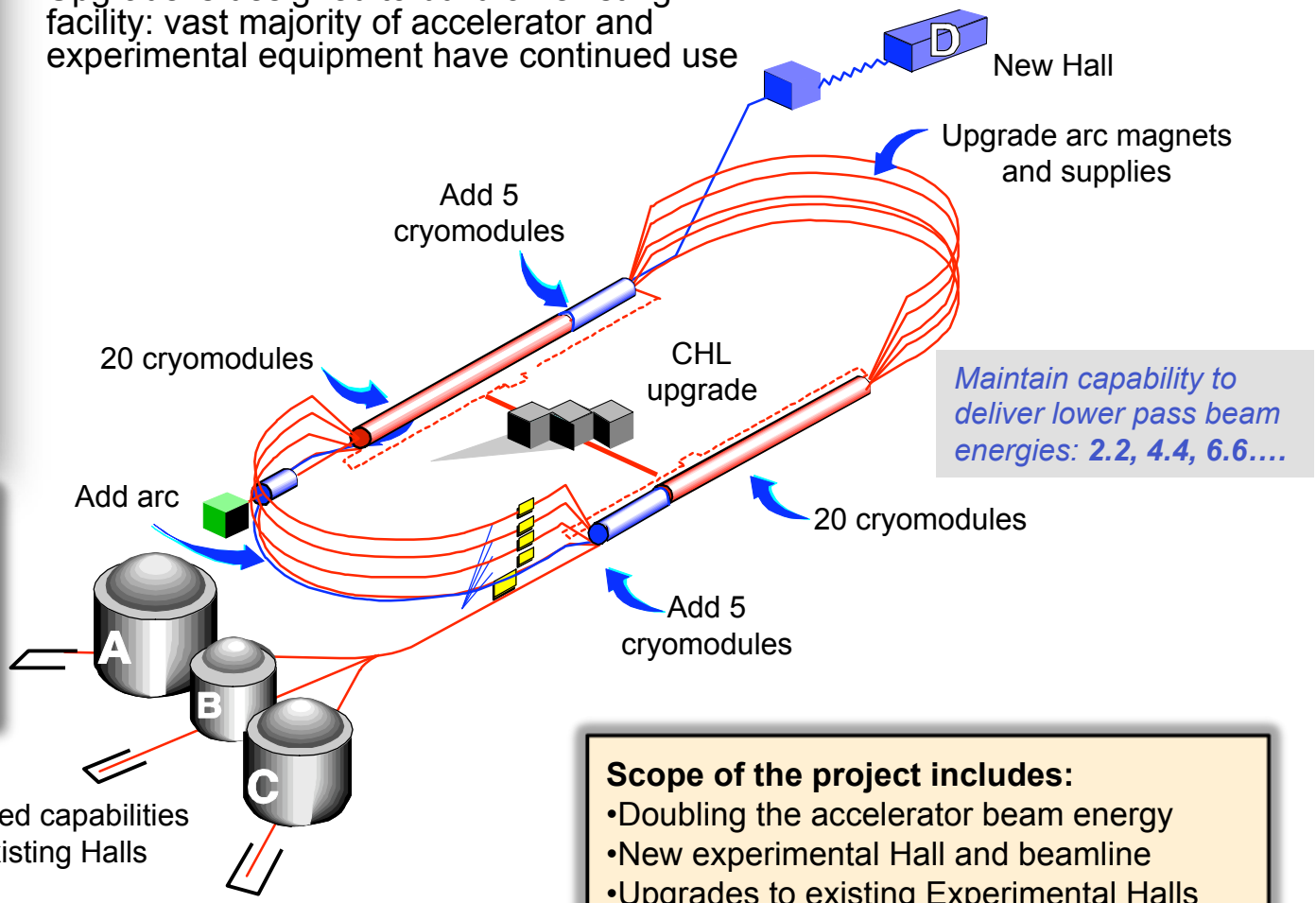


# 12 GeV Upgrade Project




The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use

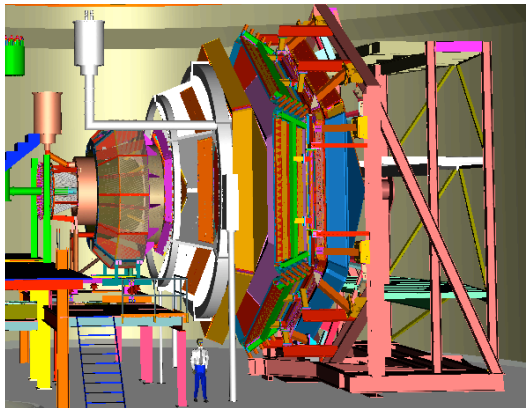


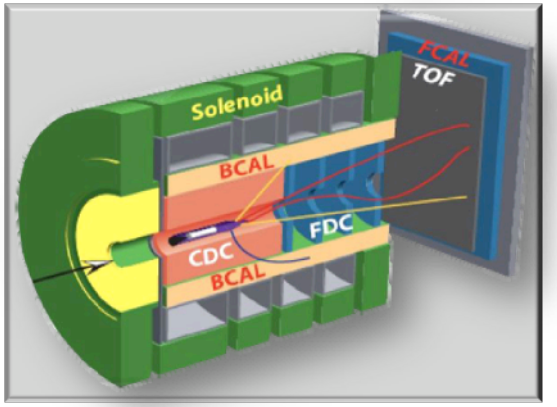

*Maintain capability to deliver lower pass beam energies:* ***2.2, 4.4, 6.6….***

**Scope of the project includes:**
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

# 12 GeV Upgrade Physics Instrumentation

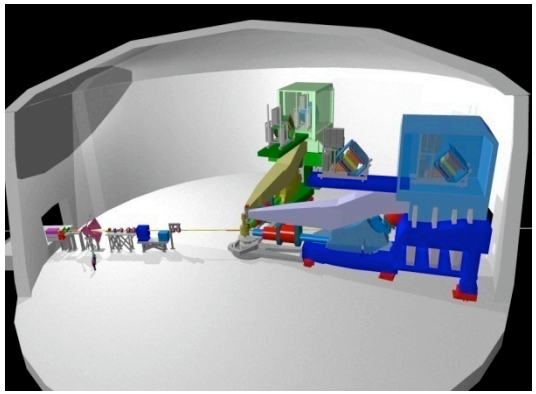
***GLUEx (Hall D):*** **exploring origin of confinement by studying hybrid mesons**

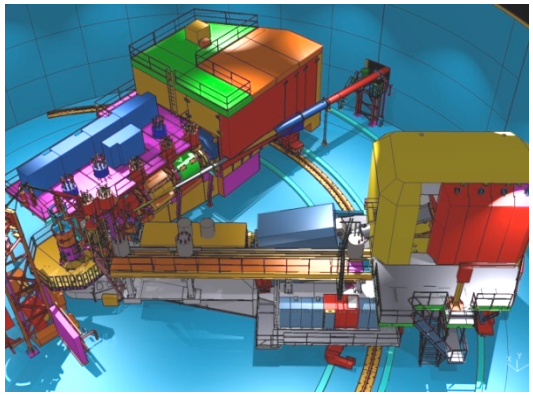





***CLAS12 (Hall B):*** **understanding nucleon structure via generalized parton distributions**

***SHMS (Hall C):*** **precision determination of valence quark properties in nucleons and nuclei**



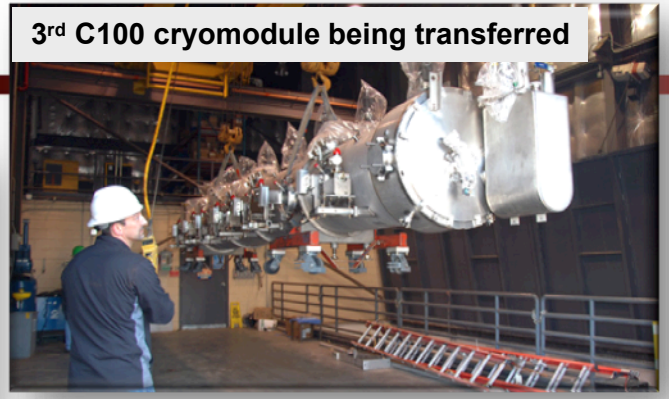


***Hall A:*** **nucleon form factors, *& future new precision electroweak experiments, SM tests***

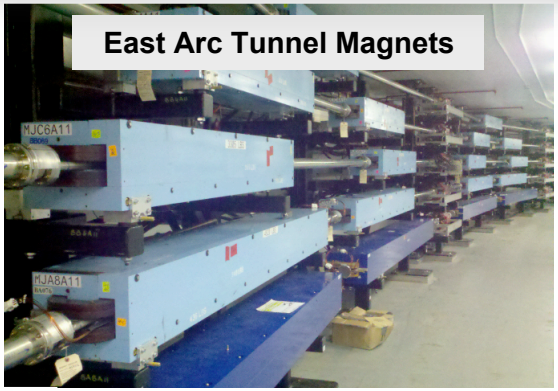
# 12 GeV Project Status

Hall D Interior

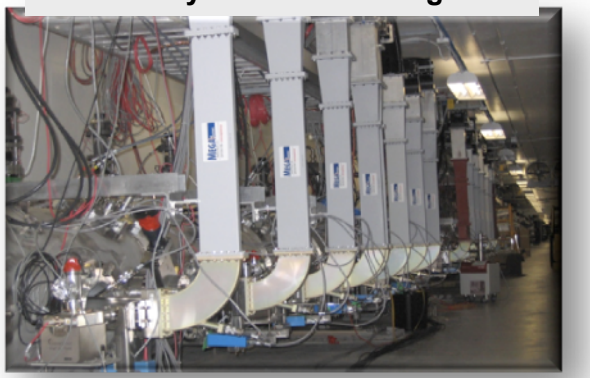

3rd C100 cryomodule being transferred




East Arc Tunnel Magnets



12 GeV Cryomodules/Waveguides

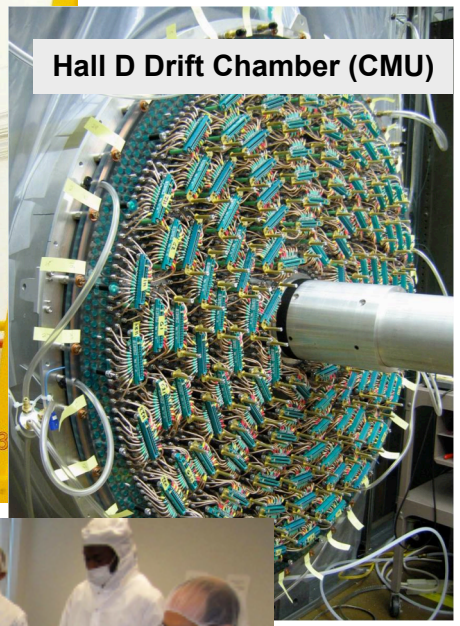


- Project 75% Complete, 88% Obligated
  - Civil (92%) ; Accelerator (88%) ; Physics Equip (~60%)
- We expect to be running beam to Hall A in February 2014 and Hall D later in the year
- Large user involvement in 12-GeV detector construction
- 7+ years approved, Halls have prepared initial schedule

# Example Construction Activities


Hall B Drift Chamber (ODU, Idaho State, Jlab)

Hall D Forward Calorimeter (Indiana)



Hall D Drift Chamber (CMU)

Hall A SBS Spectrometer Magnet

Hall C Wire Chambers (Hampton U)

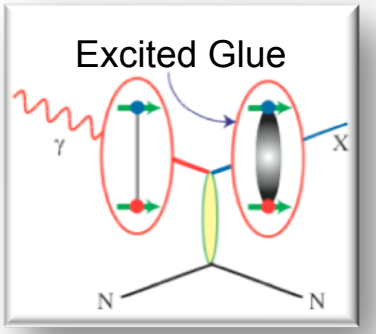
# 12 GeV Approved Experiments by Physics Topic

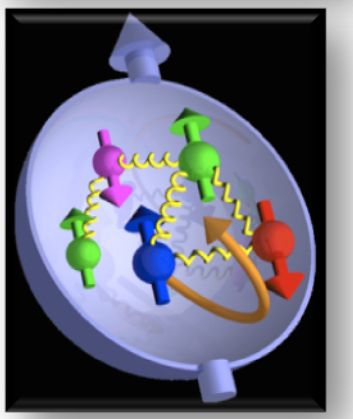
| Topic | Hall A | Hall B | Hall C | Hall D | Total |
|---|---|---|---|---|---|
| The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy) | | 1 | | 1 | 2 |
| The transverse structure of the hadrons (Elastic and transition Form Factors) | 4 | 3 | 2 | | 9 |
| The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions) | 2 | 2 | 5 | | 9 |
| The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions) | 5 | 10 | 3 | | 18 |
| Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, F N-N correlations, hypernuclear spectroscopy, few-body experiments) | 3 | 2 | 6 | | 11 |
| Low-energy tests of the Standard Model and Fundamental Symmetries | 2 | | | 1 | 3 |
| **Total** | **16** | **18** | **16** | **2** | **52** |

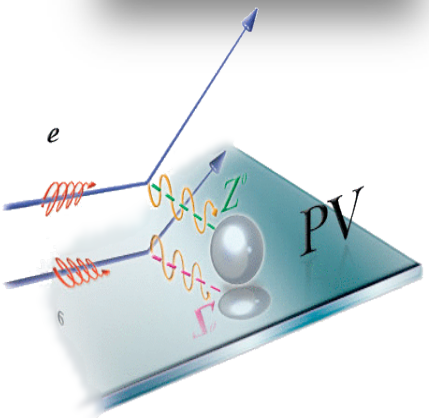
**More than 7 years of approved experiments**

# Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons?
- Where is the missing spin in the nucleon? What is the role of orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation of short-range nuclear structure and parton dynamics?
- Can we discover evidence for physics beyond the standard model of particle physics?



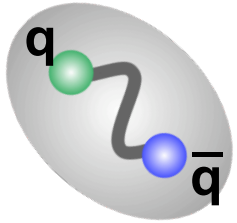



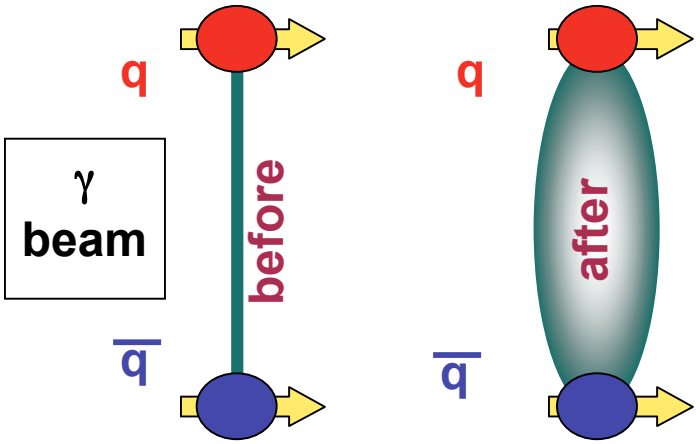


# Gluonic Excitations and the mechanism for confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

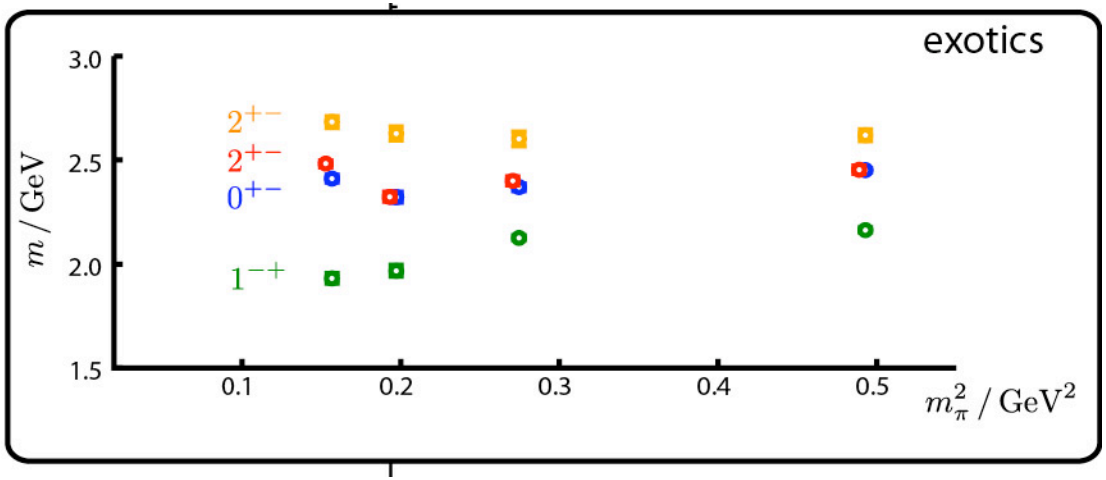
With the upgraded CEBAF, a linearly polarized photon beam, and the GlueX detector, Jefferson Lab will be uniquely poised to:
- discover these states,
- map out their spectrum, and
- measure their properties



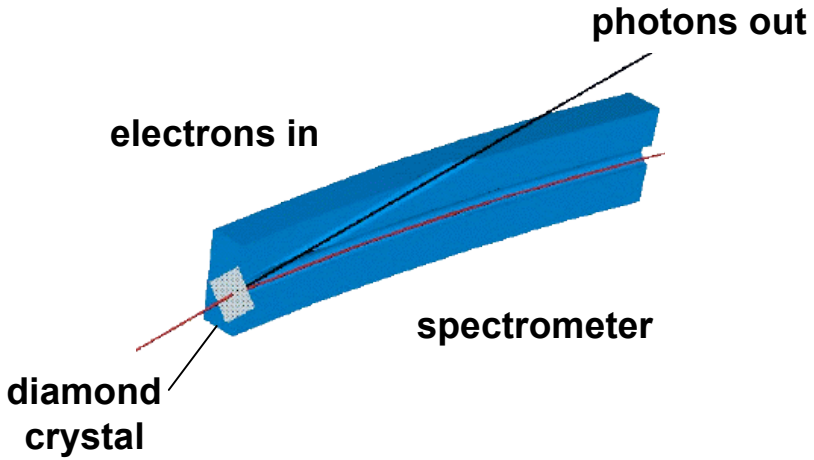

Dudek et al.

***States with Exotic Quantum Numbers***

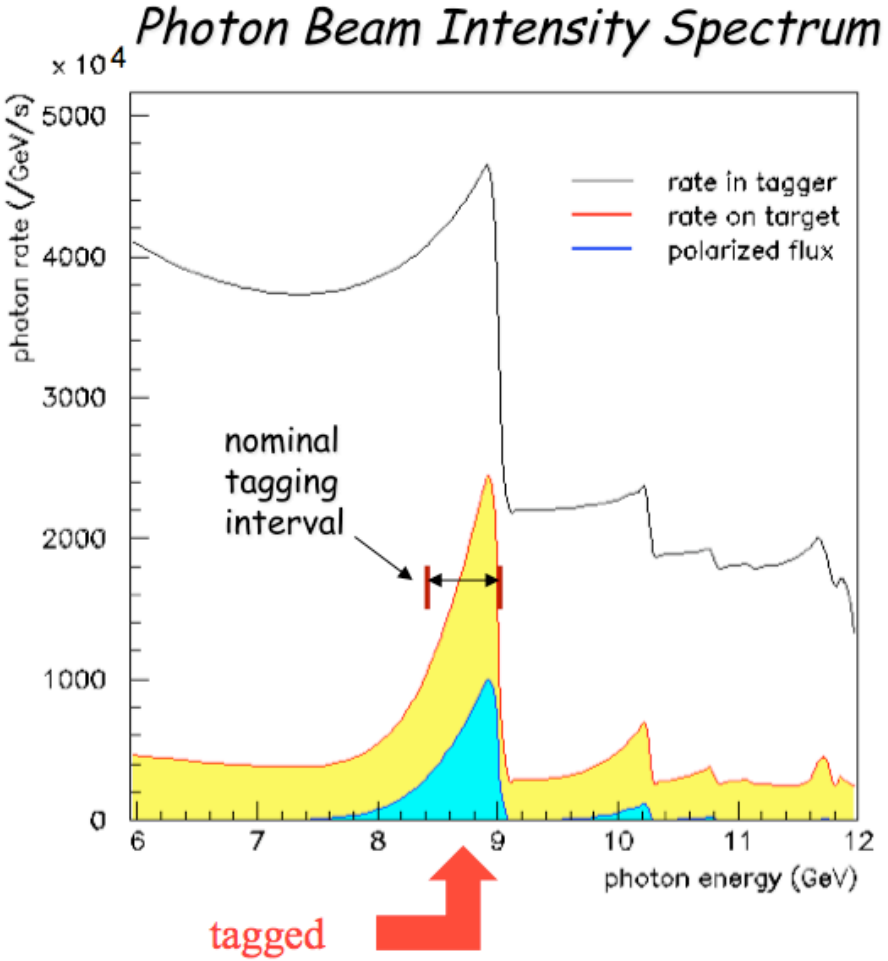


# Hall D Strategy: Coherent Bremsstrahlung

- Use 8-9 GeV polarized photons (12 GeV electron beam)
- Use hermetic detector with large acceptance
- Perform amplitude analysis




**This technique provides requisite energy, flux and polarization**
*(gain of 10,000 versus existing photo-production data)*



# Sample Amplitude Analysis with GlueX

$$\gamma p \rightarrow \pi^+\pi^+\pi^-n$$

generated waves

$a_1(1260) \rightarrow \rho\pi \quad (\mathrm{S-wave})$

$a_2(1320) \rightarrow \rho\pi \quad (\mathrm{D-wave})$

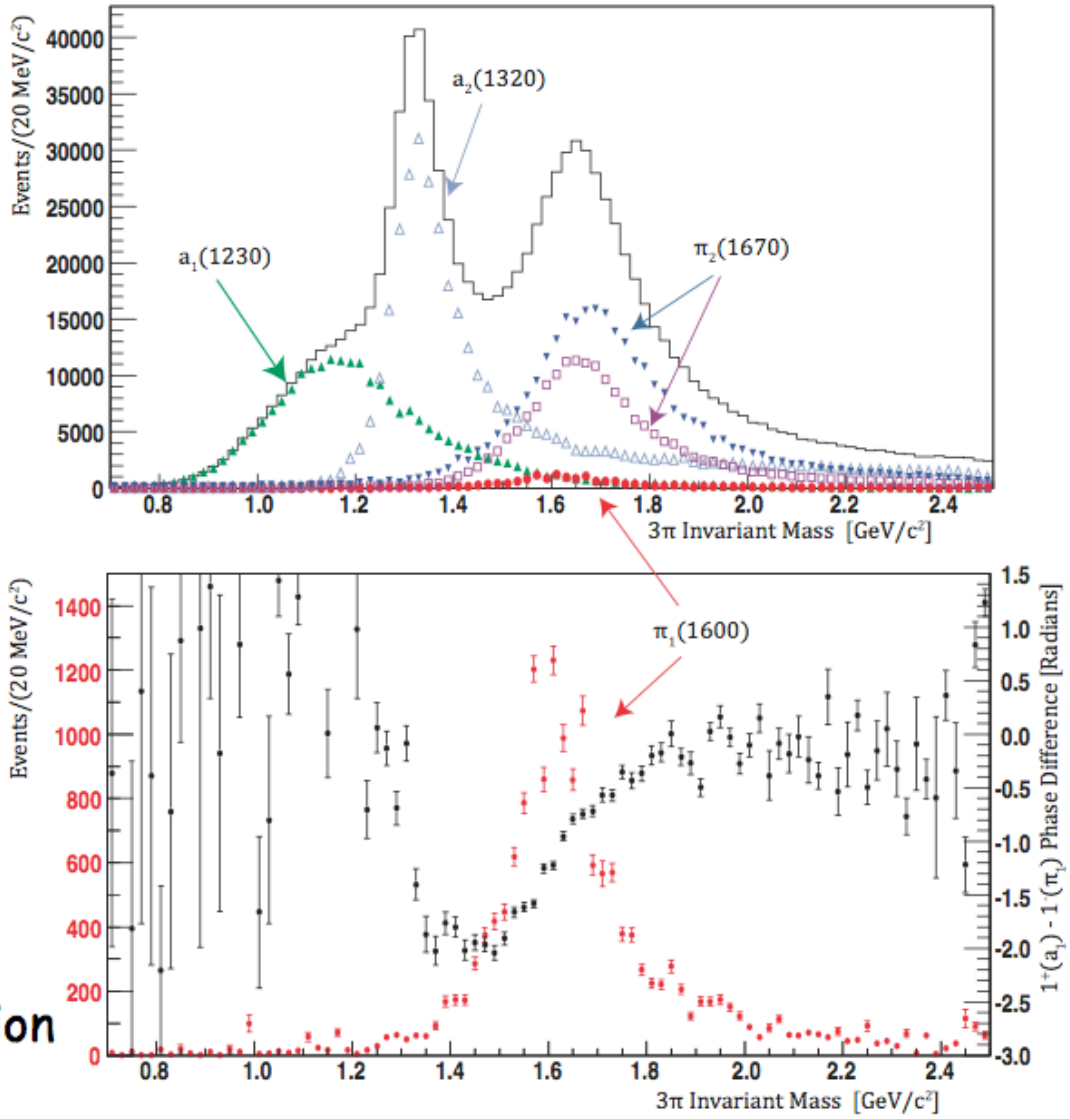
$\pi_1(1600) \rightarrow \rho\pi \quad (\mathrm{P-wave})$

$\pi_2(1670) \rightarrow f_2\pi \quad (\mathrm{S-wave})$

$\pi_2(1670) \rightarrow \rho\pi \quad (\mathrm{P-wave})$

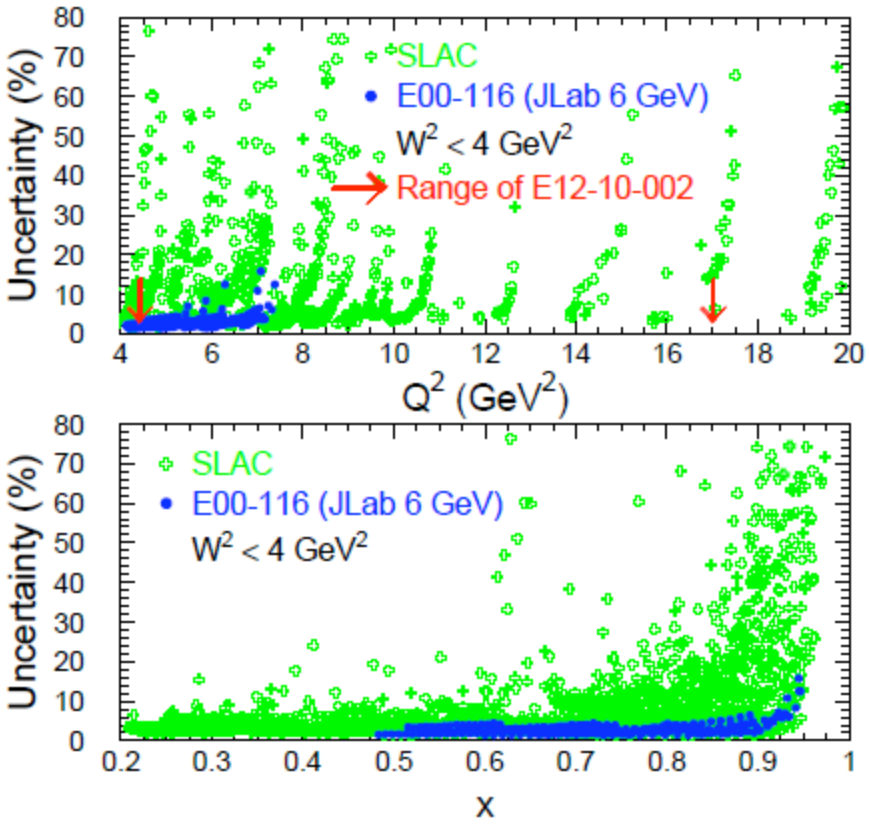
$1^{-+}$ exotic wave generated with 1.6% relative strength

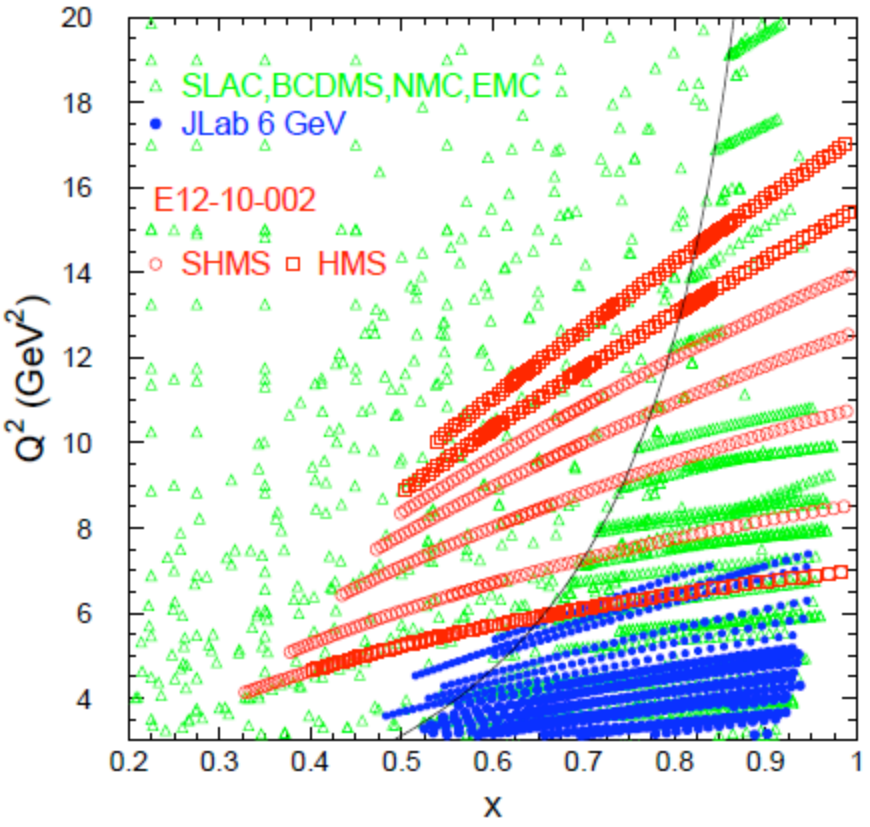
Corresponds to 3.5 hours GlueX data, full detector simulation and reconstruction



# $F_2^p$ & $F_2^d$ Structure Functions at High-x

One of envisioned commissioning experiments aims to reduce uncertainties in $F_2^p$ and $F_2^d$ structure functions accessible within 12-GeV phase space



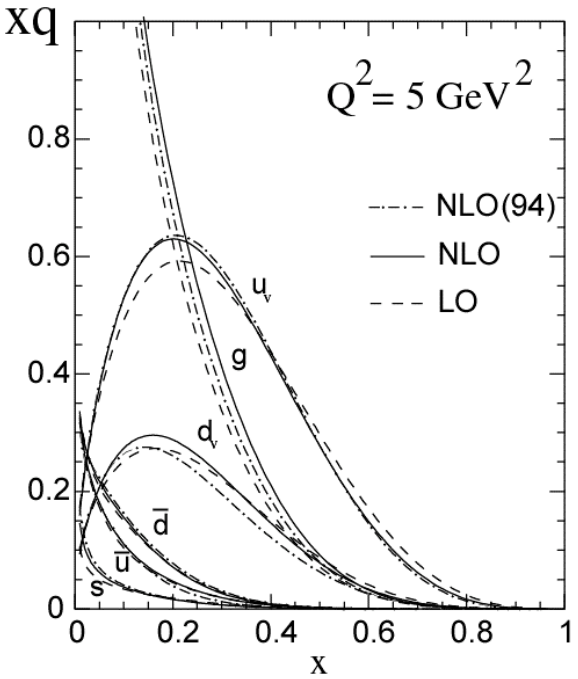




Goal @ 12 GeV: similar precision as E00-116 (@ 6 GeV)

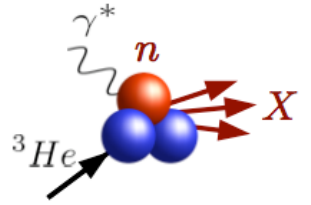
# Measuring High-x Structure Functions - unpolarized

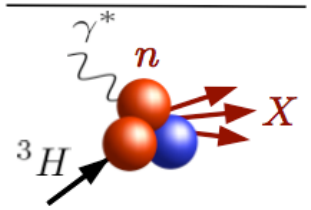
*REQUIRES:*

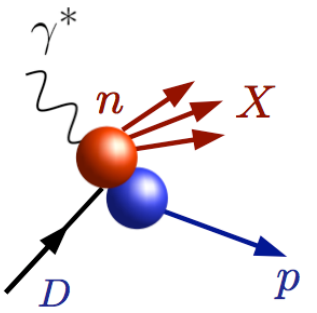
- High electron current
- Reduction of nuclear uncertaintie
- PDF efforts - CJ (Accardi talk!)
- Also see my talk tomorrow



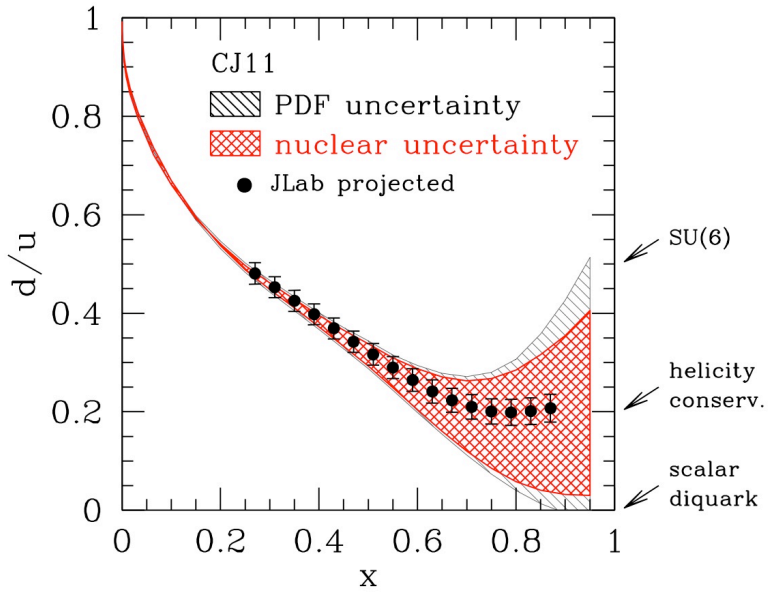

**12 GeV will access the regime (x > 0.3), where valence quarks dominate**

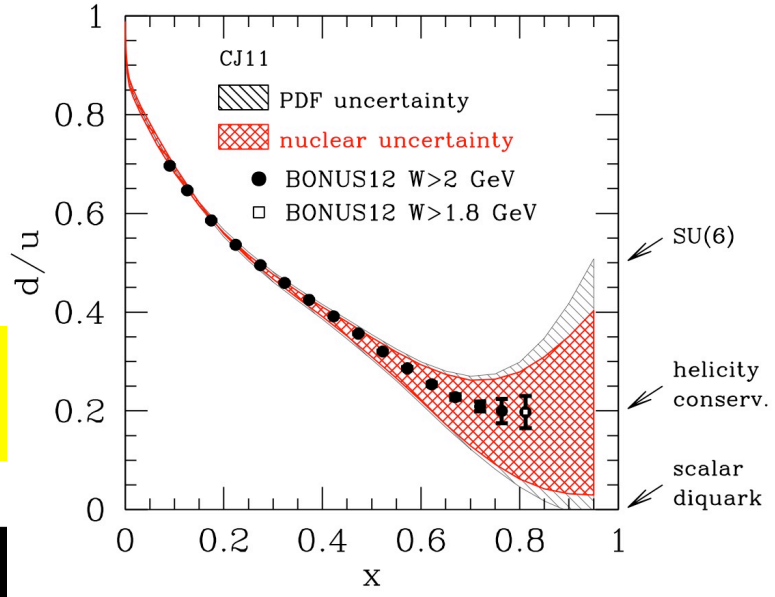



Also PVDIS on p!



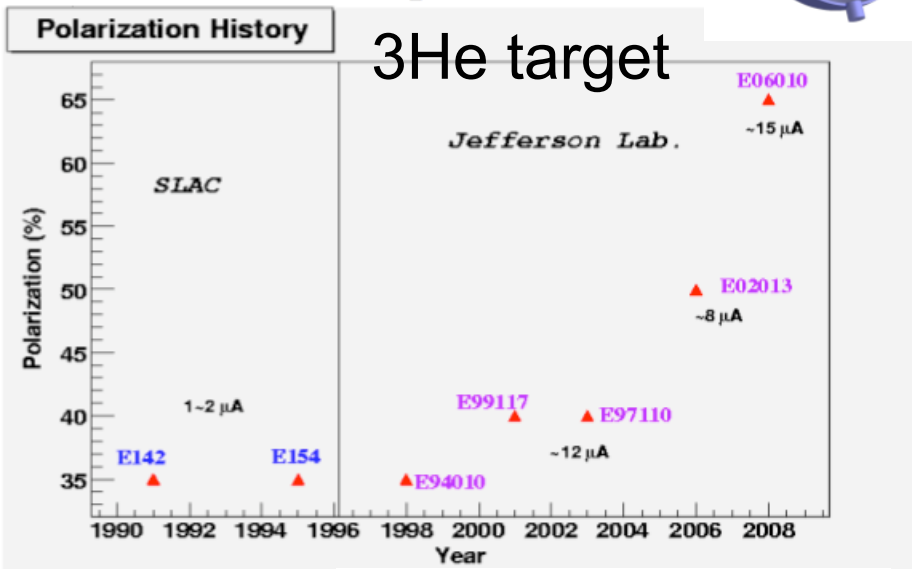



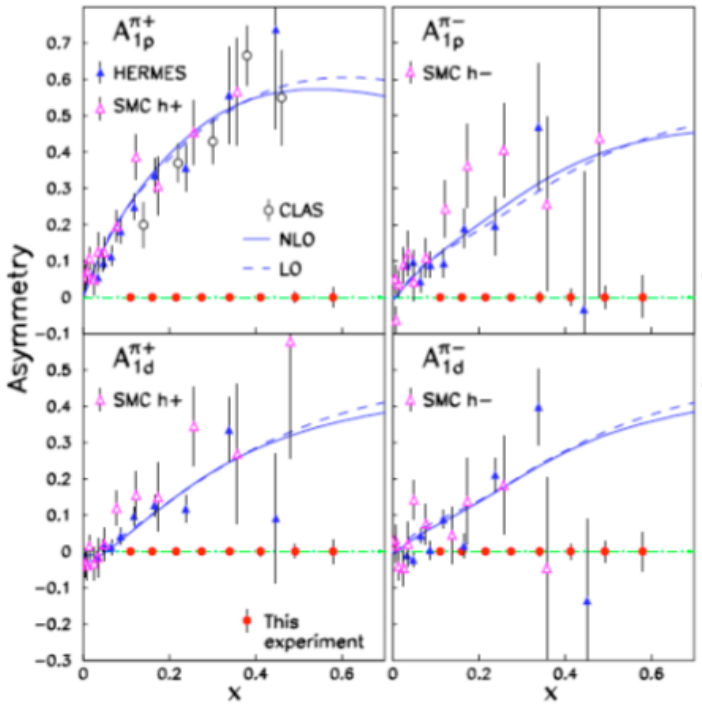
# Measuring High-x Structure Functions - polarized

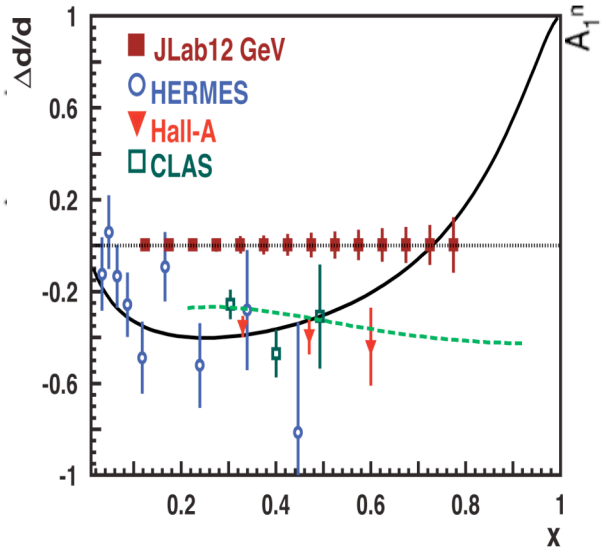
REQUIRES:

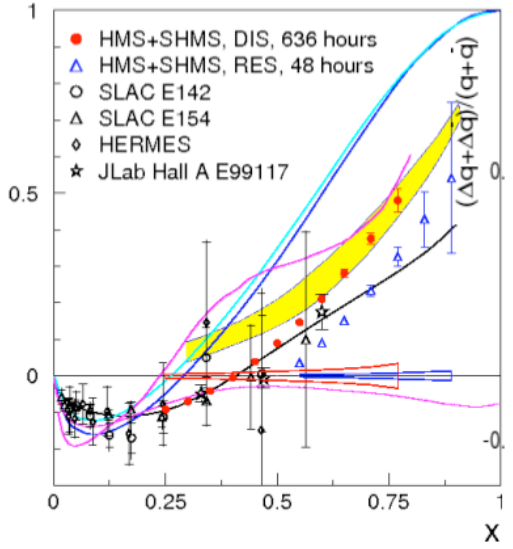
- High beam, target polarization
- High electron current
- Large solid angle spectrometers
- PDF efforts - JAM (see Accardi talk!)

3He target

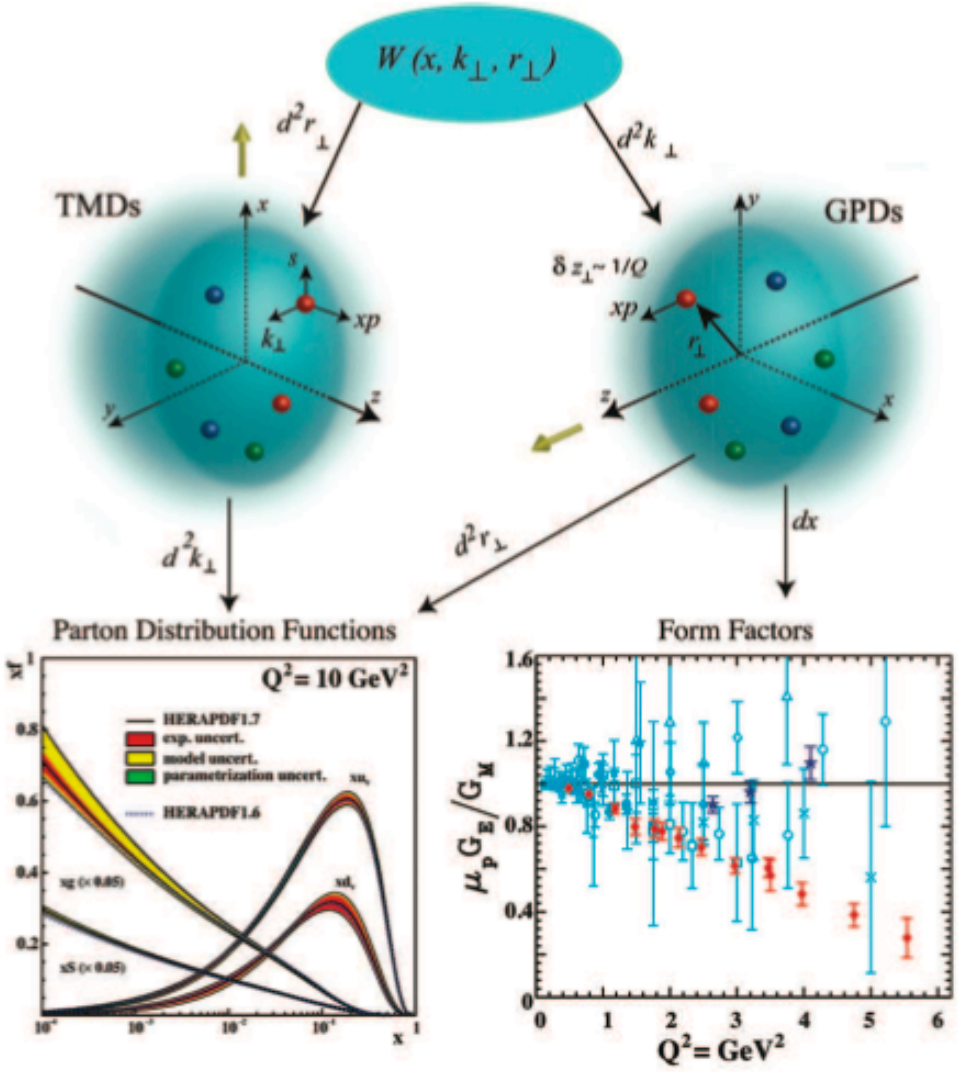


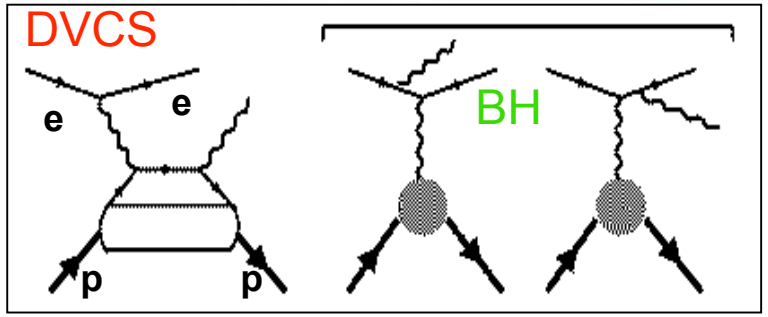
# Unified View of Nucleon Structure




- Spin crisis - static picture of the nucleon with s-state quarks may not account for complexity of parton dynamics… Δg? orbital angular momentum?
- Wigner Distributions in QCD: yield a unified description of a nucleon in terms of the position and momenta of its constituents.
- The uncertainty principle precludes knowing position and momentum simultaneously -> project Generalized Parton Distributions (GPDs) and Transverse-Momentum-Dependent Distributions (TMDs)

# Towards the 3D Structure of the Proton - GPDs

Simplest process: **e + p → e' + p + γ (DVCS)**

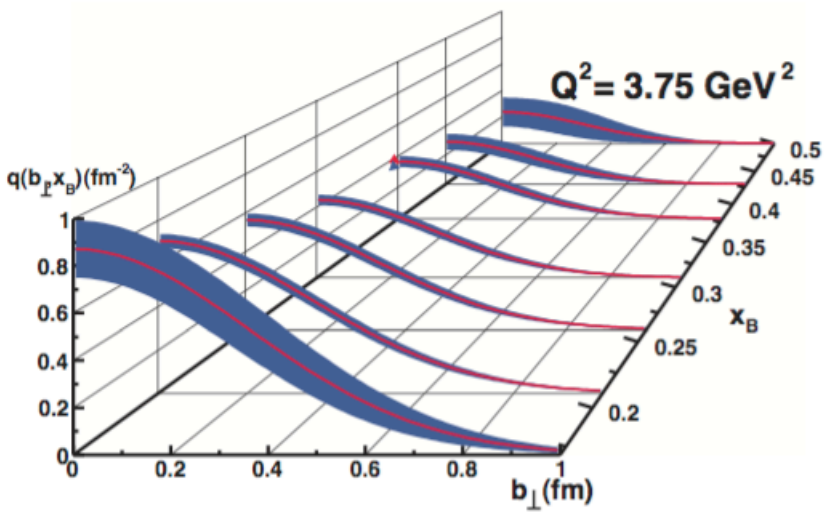



- Polarized beam, unpolarized target: $H(\xi,t)$
- Unpolarized beam, long. polarized target: $\widetilde{H}(\xi,t)$
- Unpolarized beam, transv. polarized target: $E(\xi,t)$

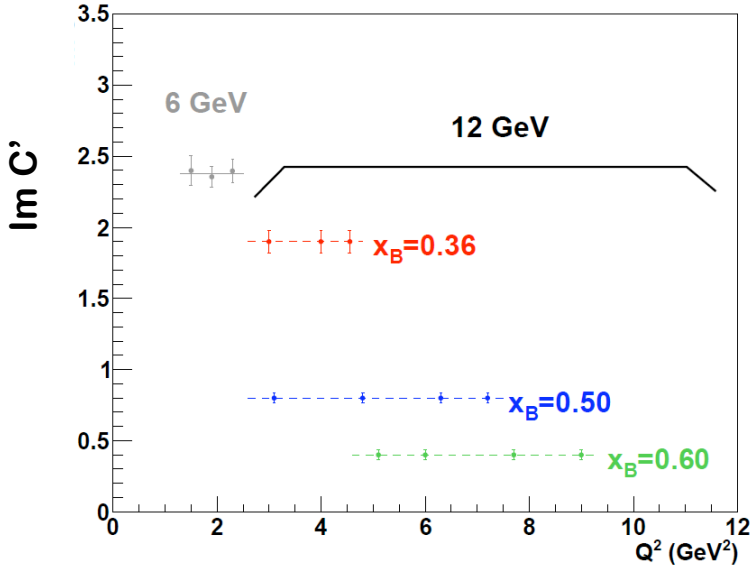
Hall B beam-spin asymmetry data show potential for imaging studies from analysis in x, $Q^2$ and t

Hall A data for Compton form factor (over *limited* $Q^2$ range) agree with hard-scattering

*12 GeV projections: transverse spatial maps*

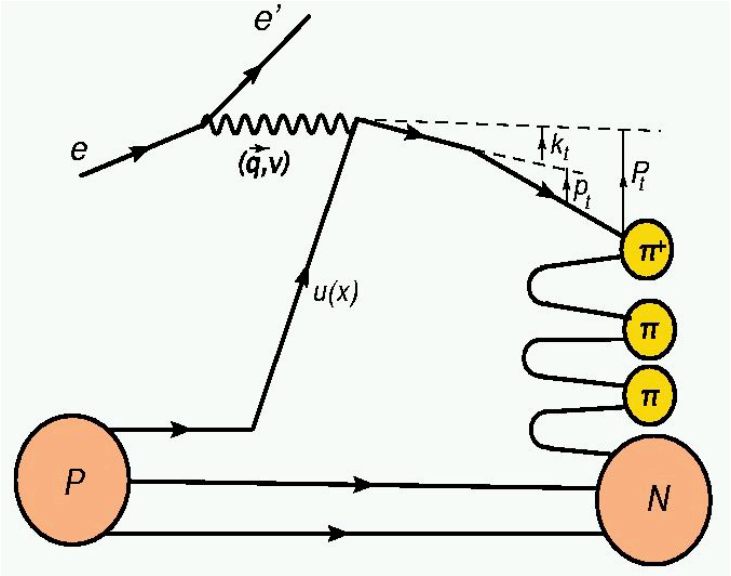



*12 GeV projections: confirm formalism*



# The road to orbital motion

## SIDIS – $k_T$ Dependence

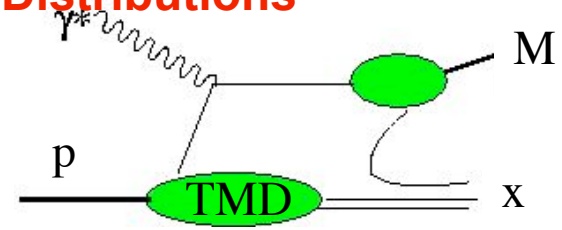



Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

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

**Linked to framework of Transverse Momentum Dependent Parton Distributions**

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



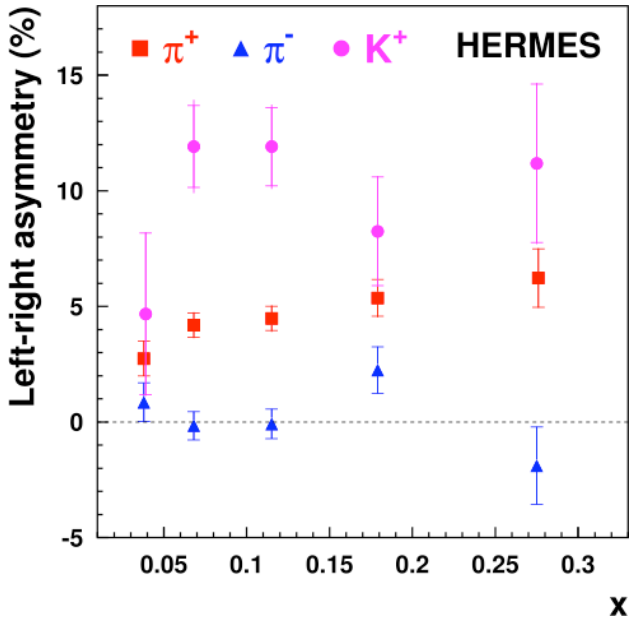

$$TMD^u(x,k_T)$$

$$f_1, g_1, f_{1T}^{\perp}, g_{1T}$$

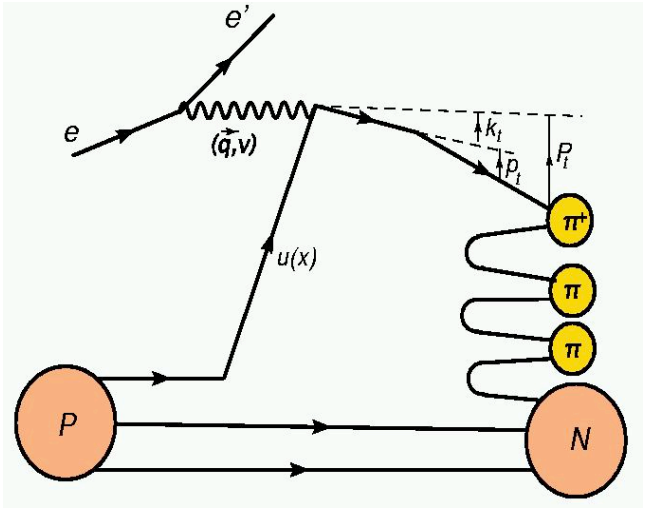
$$h_1, h_{1T}^{\perp}, h_{1L}^{\perp}, h_1^{\perp}$$

# The road to orbital motion

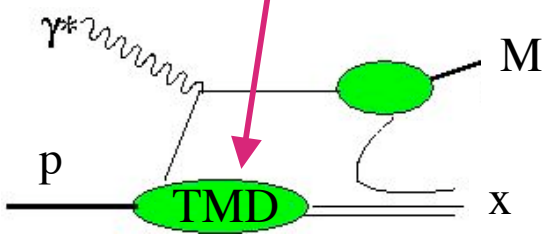
A surprise of *transverse-spin* experiments




The difference between the $\pi^+$, $\pi^-$, and $K^+$ asymmetries reveals that quarks and anti-quarks of different flavor are **orbiting in different ways** within the proton.




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




$$\mathrm{TMD}^u(x,k_T)$$

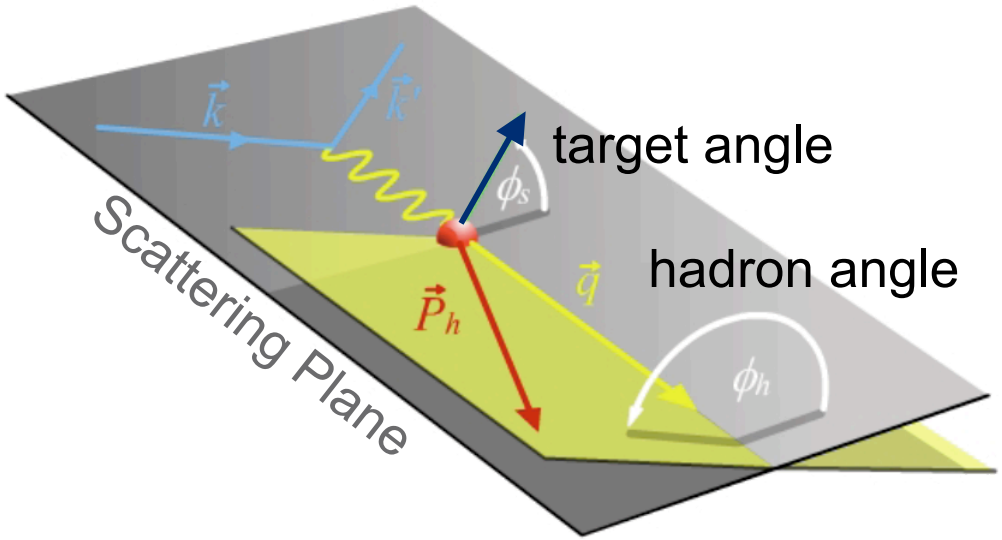
$$f_1, g_1, f_{1T}^{\perp}, g_{1T}$$

$$h_1, h_{1T}^{\perp}, h_{1L}^{\perp}, h_1^{\perp}$$

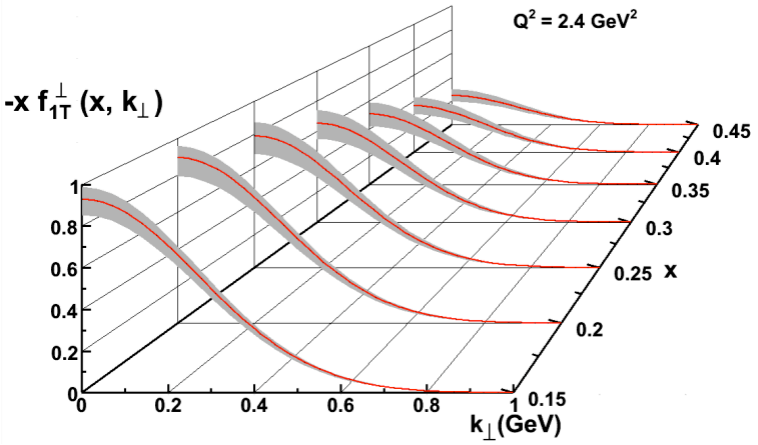
Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

# SIDIS Electroproduction of Pions

- Separate Sivers and Collins effects




- Previous data from HERMES,COMPASS
- New landscape of TMD distributions
- Access to orbital angular momentum

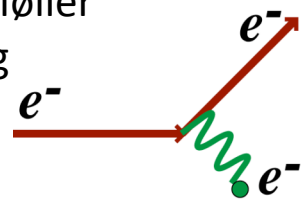



- **Sivers** angle, effect in distribution function: ($\phi_h$-$\phi_s$)
- **Collins** angle, effect in fragmentation function: ($\phi_h$+$\phi_s$)

# MOLLER at 11GeV JLab

*Example electroweak measurement*

11 GeV Møller scattering

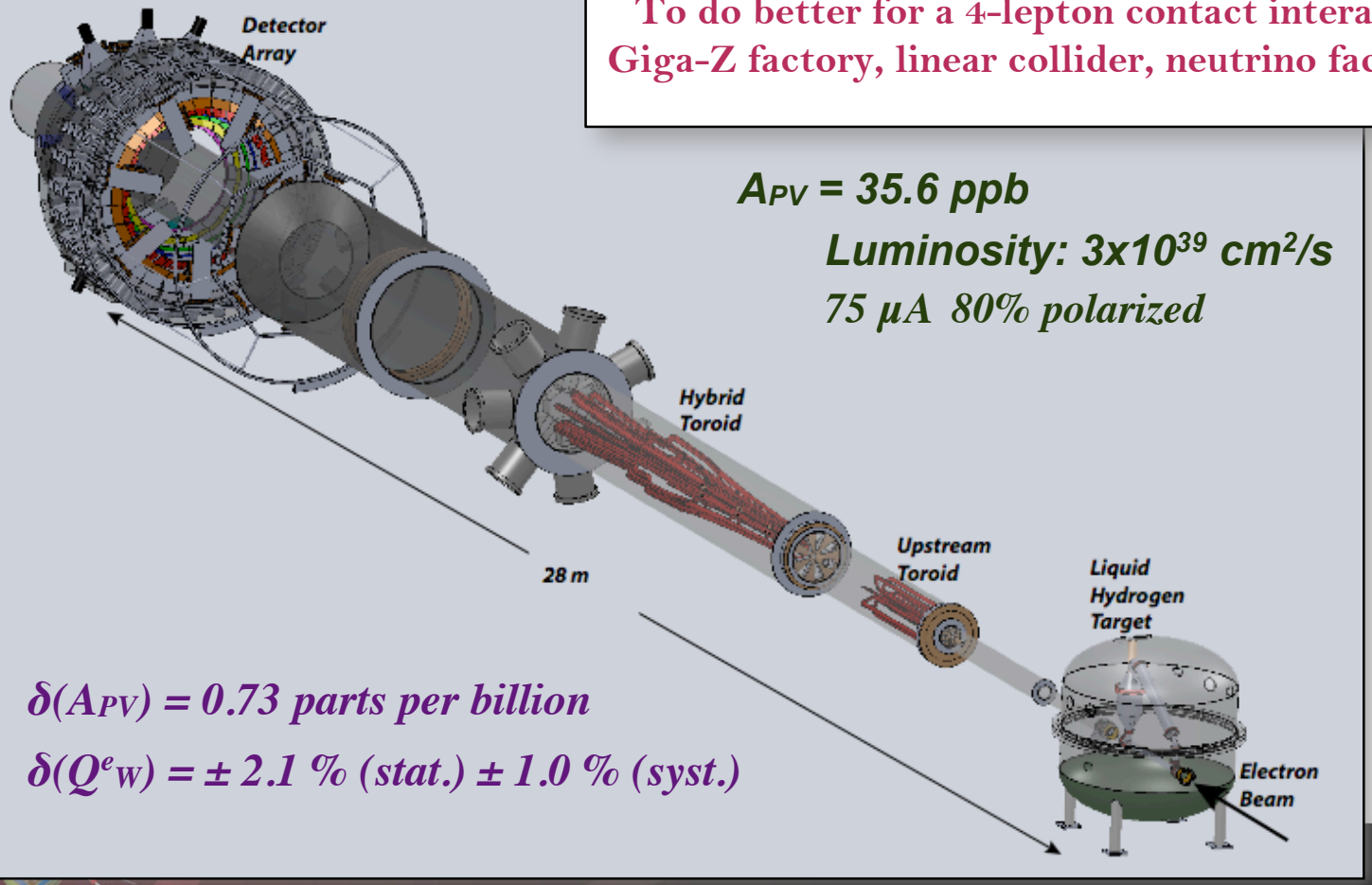



$\delta(\sin^2\theta_W) = \pm 0.00026\ (stat.) \pm 0.00012\ (syst.)$ ⇨ ~ 0.1%

Matches best collider (Z-pole) measurements!

***best contact interaction reach for leptons at low OR high energy***

To do better for a 4-lepton contact interaction would require:
Giga-Z factory, linear collider, neutrino factory or muon collider




$A_{PV}$ = 35.6 ppb

Luminosity: $3\times10^{39}$ cm$^2$/s

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.0\ \%\ (syst.)$

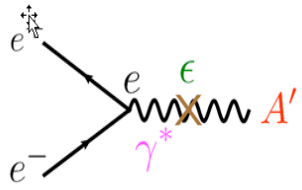
$$\frac{\Lambda}{g} = 7.5\ \text{TeV}$$

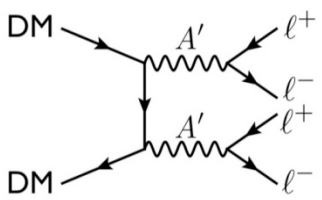
SUSY, heavy Z', doubly-charged scalars, electron compositeness, light Z' (dark photon)…

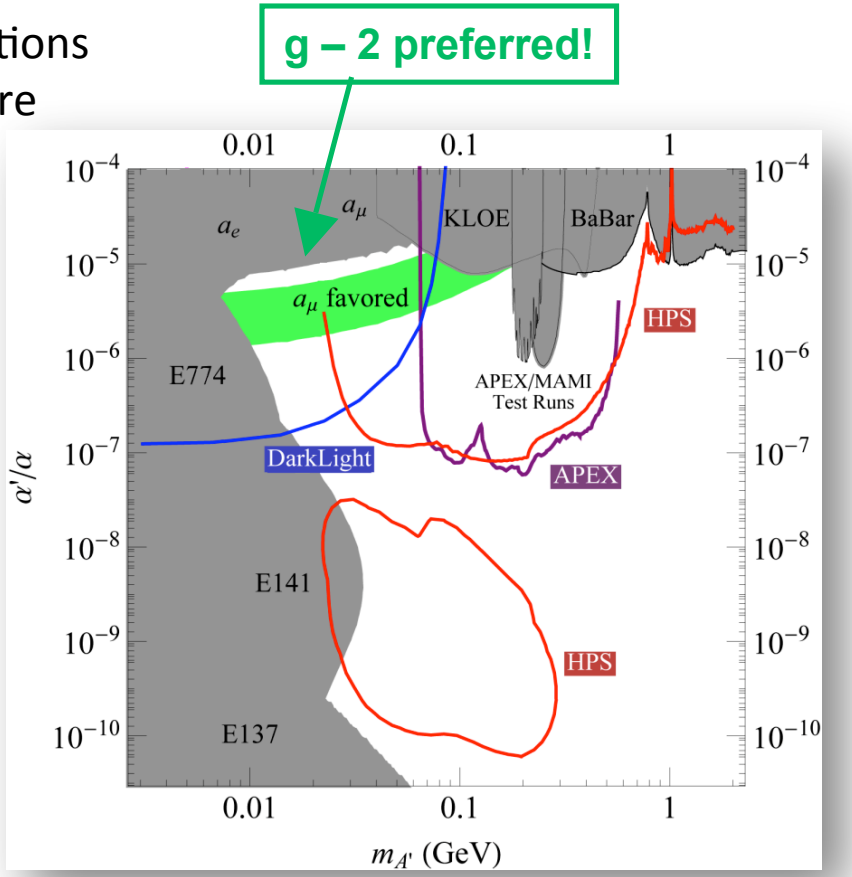
# Search for A' at Jefferson Lab

**The Heavy Photon (A') is** a massive vector gauge boson which kinetically mixes with the SM $\gamma$, inducing a weak coupling $\varepsilon e$ to electric charge. $\alpha'/\alpha \equiv \varepsilon^2$

**Heavy photons** may evidence Dark Matter annihilations to HE $e^+/e^-$ or explain the muon g-2 anomaly, and are expected in BSM theories.




- **3 Jefferson Lab proposals:**
  - APEX test run (Hall A) – published
  - HPS test run (Hall B) – completed
  - DarkLight test run (FEL) – completed

**S. Abrahamyan *et al.*, PRL 107, 191804 (2011)**

# 12 GeV JLab – The Potential

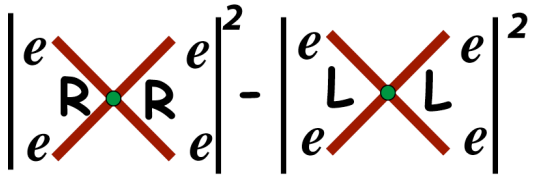
- Opportunity to discover and study new exotic mesons to elucidate the mechanism of confinement.
- Open a new landscape of nucleon tomography, with potential to identify the missing angular momentum.
- Address long-standing mystery of nucleon valence structure at large x, improve knowledge of parton distribution functions in this regime,
- Provide stringent new tests of the standard model and extensions, complementing the information obtained at LHC.

# Project Summary

- The project is 75% complete and 88% obligated as of March 2013.
- **We expect to start commissioning the 12 GeV accelerator in November, and running beam to Hall A in February 2014**
- **First three experiments: DVCS, GMp, d(x)/u(x)**
- Next PAC: June 2013

# Møller Parity-Violating Experiment: New Physics Reach

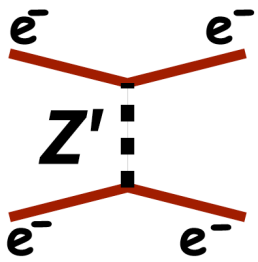
*(example of large installation experiment with 11 GeV beam energy)*

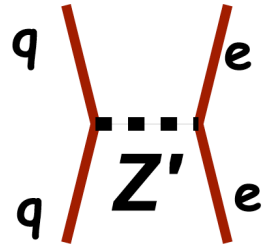



**JLab Møller**

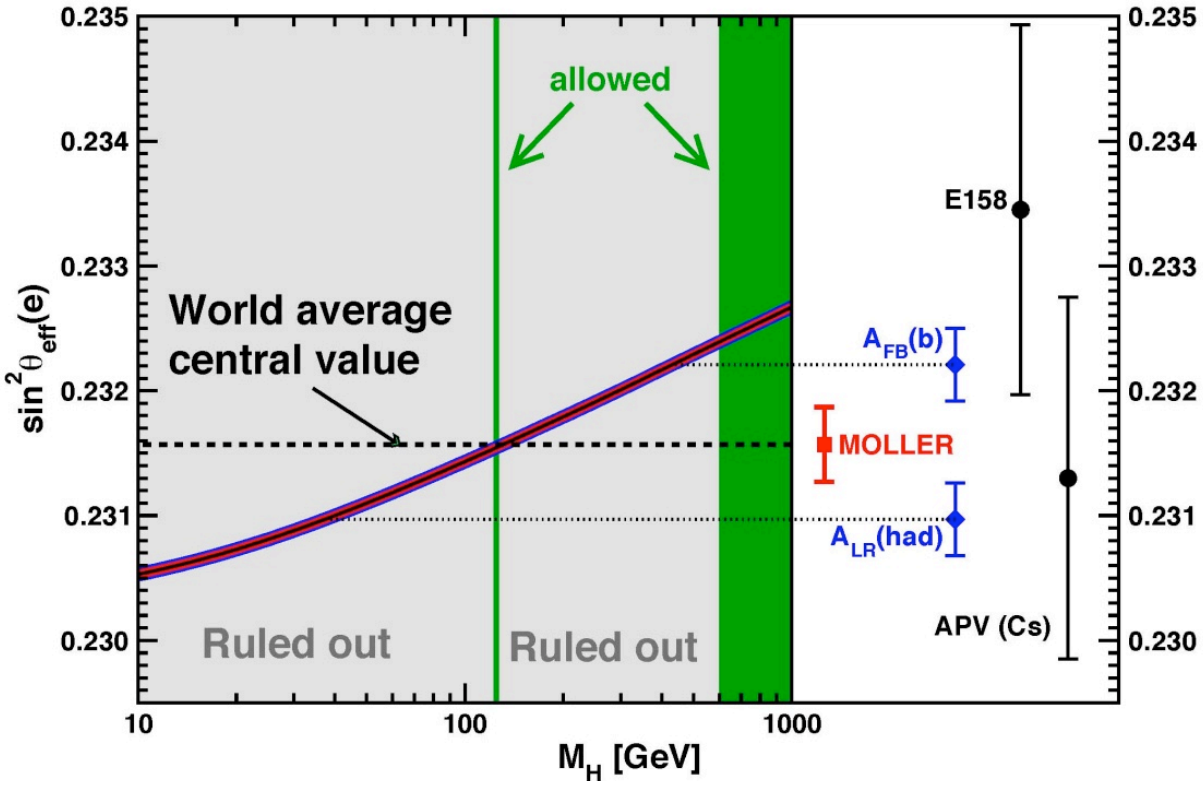
$\Lambda_{ee}$ ~ 25 TeV

*New Contact Interactions*




LHC




Not "just another measurement" of $\sin^2(\Theta_w)$

- $A_{FB}$(b) measures the product of e- and b-Z couplings
- $A_{LR}$(had) measures purely the e-Z couplings
- Proposed $A_{PV}$(b) measures purely the e-Z couplings at a different energy scale