The Super Bigbite Program for Hall A at Jefferson Lab

Seamus Riordan
Stony Brook University
`seamus.riordan@stonybrook.edu`

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Outline

- Nucleon Form Factors at High Q^2
- The Super Bigbite Project
- Outlook

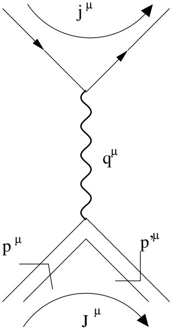
Elastic Scattering

What does electron elastic scattering tell us?

For electron scattering from spin-0 particle, Born approx.:

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \times |F(Q^2)|^2$$

pointlike × structure



- Differential cross section factorizes into point-like and structure part
- Structure part is just function dependent on 4-momentum transfer, $Q^2 = 2EE'(1 - \cos\theta)$
- Non-relativistically, is just the Fourier-transform

Sachs Form Factors and Rosenbluth

Sachs Form Factors

$$\begin{aligned} G_E &= F_1 - \kappa\tau F_2 & \qquad F_1 &= \text{Dirac}, \chi - \text{nonflip} \\ G_M &= F_1 + \kappa F_2 & \qquad F_2 &= \text{Pauli}, \chi - \text{flip} \end{aligned}$$

Rosenbluth Formula

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right], \tau = \frac{Q^2}{4M^2}$$

Difficulties

- G_E becomes highly suppressed at higher Q^2
- Neutron is uncharged, G_E relatively very small
- Free neutrons decay in $\sim 15\ \mathrm{min.}$ Needs to be bound in a nucleus

G_E/G_M through Spin Observables

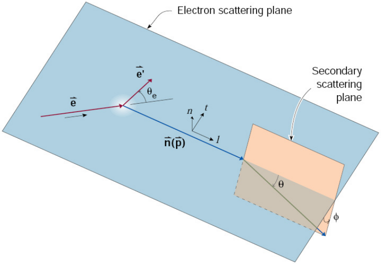
- Akhiezer and Rekalo (1968) - Polarization offers access to G_E/G_M
- Typically have fewer systematic contributions from radiative effects and nuclear structure

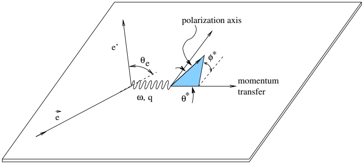
Polarization Transfer, $\vec{e}N, e'\vec{N}'$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan\theta_e/2}{2M}$$

Polarized Beam/Target $\vec{e}\vec{N}, e'N'$

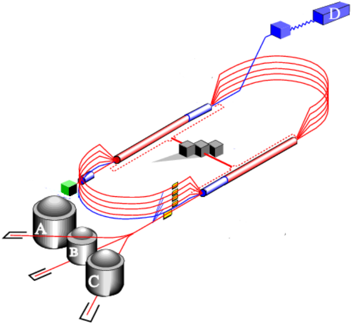
$$A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$





Jefferson Lab

Continuous **E**lectron **B**eam **A**ccelerator **F**acility
at Jefferson Lab, Newport News, VA
“World’s most powerful microscope”



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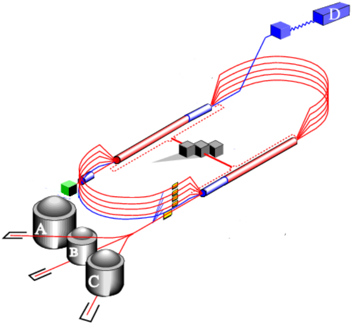
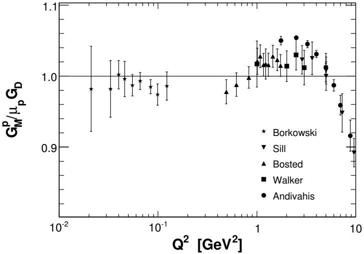


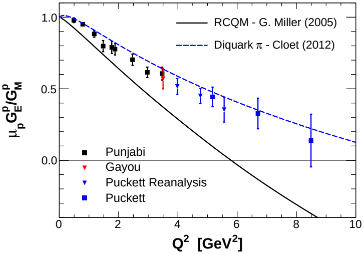
- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- E up to 11 GeV ($\lambda \sim r_p/50$)
- $I_{\mathrm{max}} = 200\ \mu\mathrm{A}$
- $P_e = \sim 90\%$
- Ideal for studying insides of nucleons and nuclei!

Proton Results

- G_M^p generally follow dipole - exponential distribution

$$G_D = \frac{1}{\left(1 + Q^2/(0.71\ \mathrm{GeV}^2)\right)^2}$$



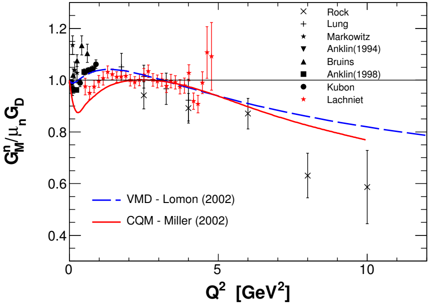


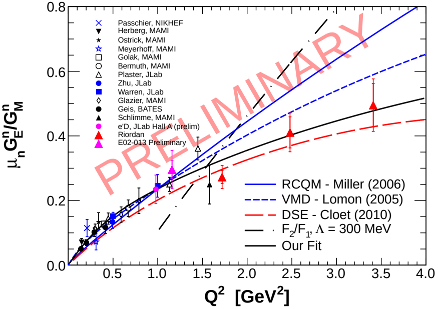
- JLab, Jones *et al.*, G_E^p different from G_M^n using polarization
- Charles Perdrisat 2017 Bonner Prize
- Textbooks still will show you $G_E^p/G_M^p \sim$ const
  - Hard two-photon exchange systematic errors in extraction?
  - OLYMPUS most recent results to test this (Kohl talk Thurs)

Neutron Form Factors

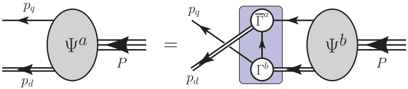
Challenges:

- Neutron studies require nuclear corrections
- G_E^n is small
- Q^2 coverage typically factor 2 smaller than proton





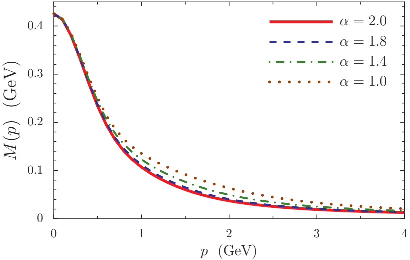
DSE - Mapping Out Quark Mass Generation

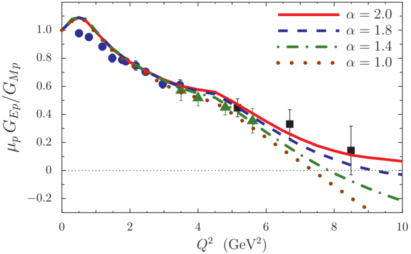


Cloet *et al.*

Phys. Rev. Lett. 111, 101803 (2013)

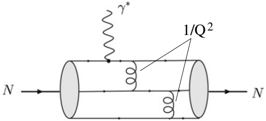
- DSE approach describes dressed quarks, naturally includes diquarks
- Higher precision at higher Q^2 sensitive to dressed quark mass
- Symbolic zero crossing for G_E^p is sensitive





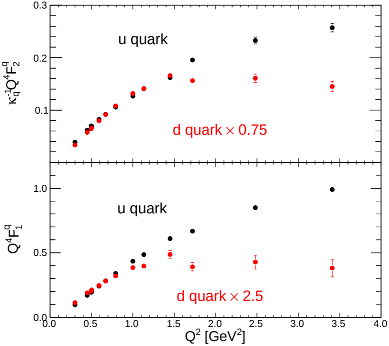
Quark Flavor Decomposition

$$Q^4 F^{u,d}_{1,2}$$



$$F^p_{1,2} = \frac{2}{3}F^u_{1,2} - \frac{1}{3}F^d_{1,2}$$

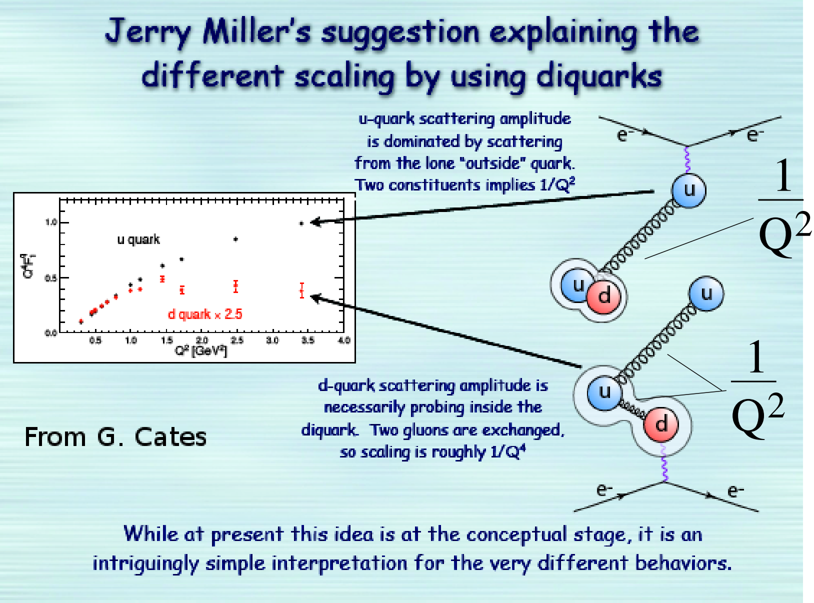
$$F^n_{1,2} = -\frac{1}{3}F^u_{1,2} + \frac{2}{3}F^d_{1,2}$$



G.D. Cates *et al.*, PRL 106, 252003 (2011)

- High Q^2 for G_E^n data allows for quark decomposition
- Same flavor quarks show similar scaling behavior in F_2, F_1
- Not shown in proton or neutron data
- F_2/F_1 ratio different from $1/Q^2$ prediction

Scaling Interpretation



Jerry Miller's suggestion explaining the different scaling by using diquarks

u-quark scattering amplitude is dominated by scattering from the lone "outside" quark. Two constituents implies $1/Q^2$

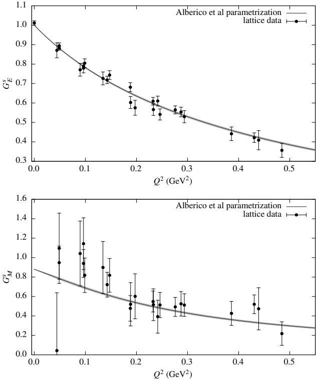
d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons are exchanged, so scaling is roughly $1/Q^4$

From G. Cates

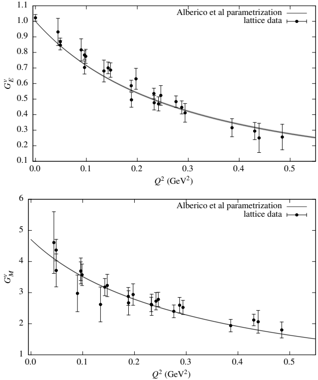
While at present this idea is at the conceptual stage, it is an intriguingly simple interpretation for the very different behaviors.

Lattice Calculations

Isoscalar G_E, G_M



Isovector G_E, G_M

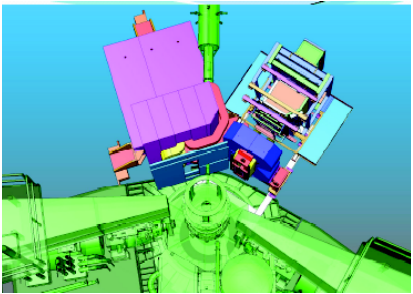


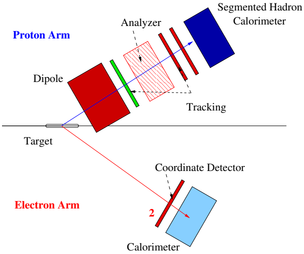
- $m_\pi = 149\ \mathrm{MeV}$, Q^2 to 0.5 GeV^2
- Calculations are now reaching into the low few GeV^2 range
- Low Q^2 results are becoming more precise but cannot give radius results but have uncertainties on the order of proton

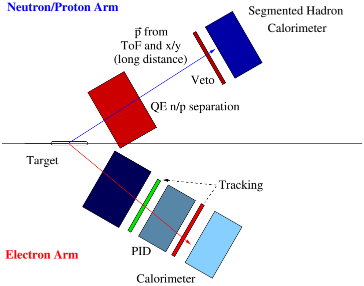
SBS Experimental Program

Overview

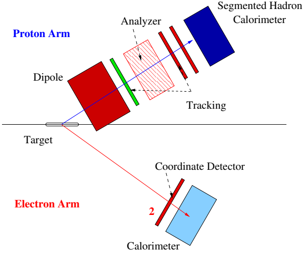
- Super Bigbite program measures three nucleon elastic form factors to high Q^2, SIDIS on $^3\overrightarrow{\mathrm{He}}$, (Cond. Appv. TDIS)
- Form factors → \$5M DOE Project
- Total 184 days of running approved (+ 27 cond.)
- Earliest start date Spring 2019





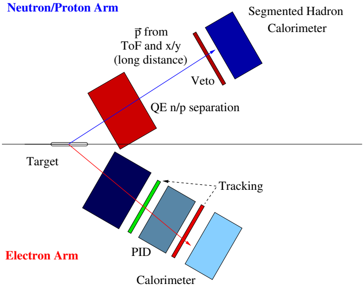


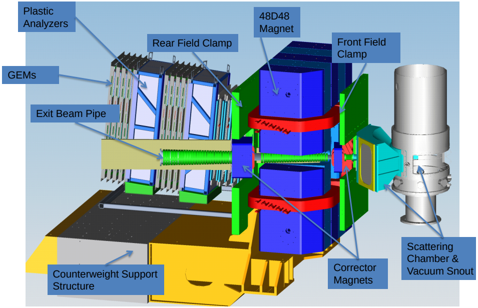
Super Bigbite Program - FFs to High Q^2

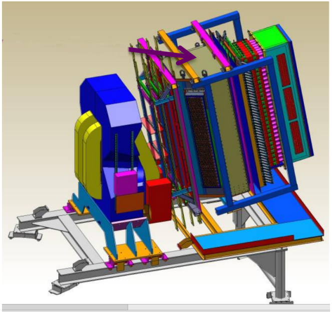


- G_E^p/G_M^p to 12 GeV^2, E12-07-109: Cisbani, Jones, Khandaker, Liyanage, Pentchev, Perdrisat, Punjabi, Wojtsekhowski

- G_E^n/G_M^n to 10 GeV^2, E12-09-016: Cates, Riordan, Wojtsekhowski
- G_M^n to 13.5 GeV^2, E12-09-019: Gilman, Quinn, Wojtsekhowski







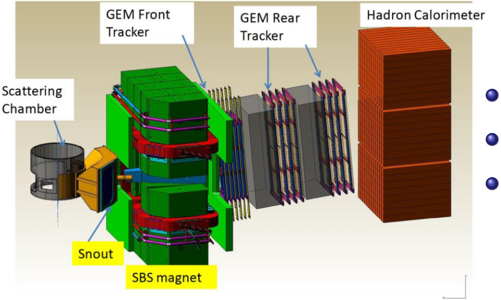
- Several major new systems -
  Experiments have different combinations

Event rate	up to $\sim$5 kHz
Several sets of GEM trackers	$\sim$100k strips (up to $\sim$ 20% occ.)
Hadronic Calorimeter	288 FADC ch
Electromagnetic Calorimeter	1700 ADC ch
Scint. Coord. Det	2k TDC ch
Gas Cherenkov	550 TDC ch
Scintillator Timing Plane	360 TDC/ADC ch

- Reuse of existing Bigbite EM calorimetery ($\sim$200 PMTs), HERMES RICH ($\sim$2k PMTs)

G_E^p

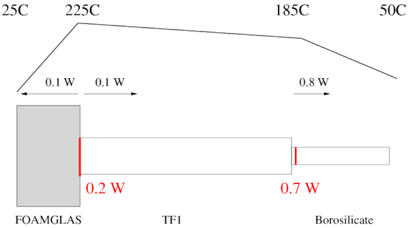
- Recoil polarimetry through two CH_2 analyzers
- e^- detected in electromagnetic calorimeter with coordinate detector
- Q^2 up to 12 GeV^2

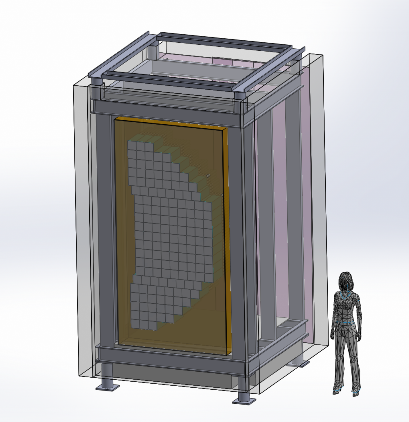


- 75 μA on 40 cm target
- θ_h down to 17°
- Background rates up to 150 kHz/cm^2

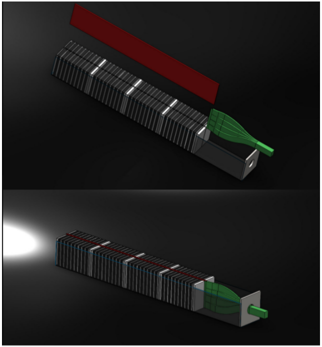
G_E^p - ECal

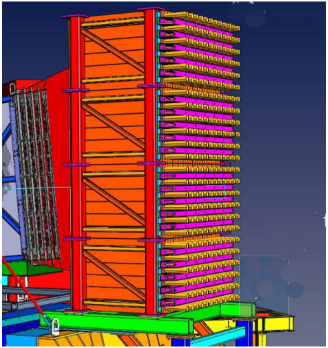
- ECal absorbs 0.5 kRad/hour for $Q^2 = 12$ GeV^2 (no magnetic elements)
- Thermal annealing with $\sim 200^\circ$C temperature provides method for optical transparancy
- Full construction by NCCU





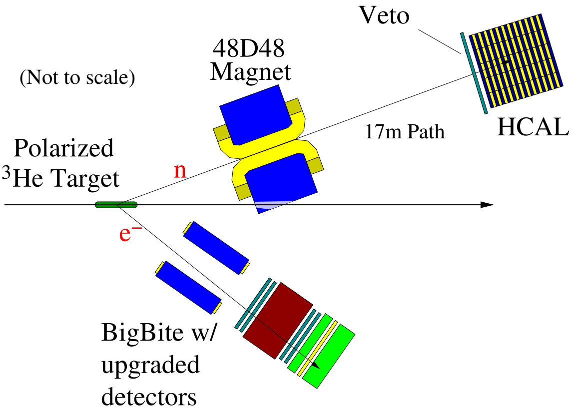
HCAL-J Design





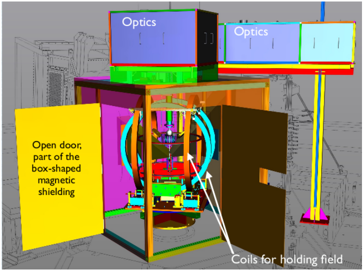
- Hadronic calorimeter provides 30% energy resolution and $\sim$700 ps ToF resolution
- 288 modules, 3.6×1.8 m for acceptance matching at 17 m
- $> 95\%$ recoil proton and neutron detection efficiency with virtual total suppression of all low energy backgrounds < 1 GeV

High Q^2 G_E^n Experimental Layout

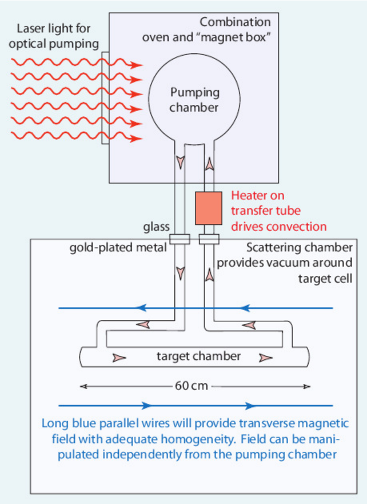


- Upgraded Bigbite detector stack for higher rates, better PID
- Hadron calorimeter at 17 m, need 0.5 ns ToF
- 48D48 deflects protons
- New addition of Cherenkov and GEMs for π^- rejection and high rate tracking

Polarized ^{3}He Target

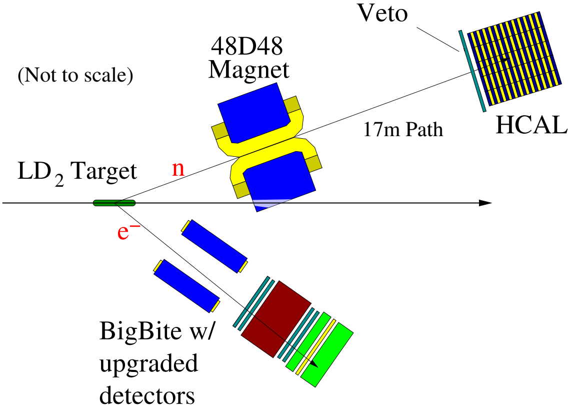


- Upgraded $^3\mathrm{He}$ cell allows for $I = 8 \to 60\ \mu\mathrm{A}$, $l = 40 \to 55\ \mathrm{cm}$
- Convection and metal cell ends allow for higher sustained $\vec{P}$ ($\sim 60\%$)
- Bench testing underway

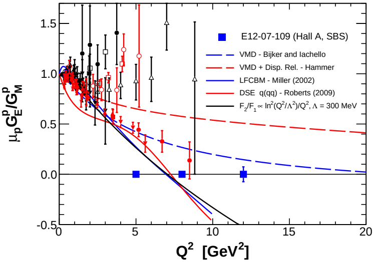


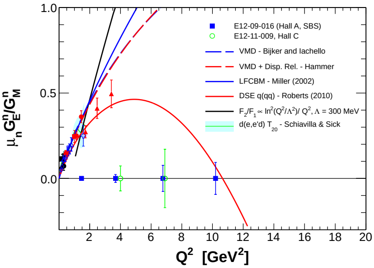
G_M^n Setup

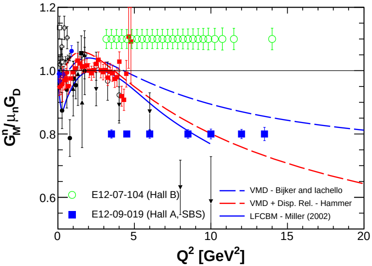
- Relative QE deuterium σ_n/σ_p gives G_M^n/G_M^p
- 7 Q^2 points ranging from 3.5 GeV^2 to 13.5 GeV^2
- Setup similar to G_E^n with LD_2 target



SBS FF reach with 12 GeV CEBAF



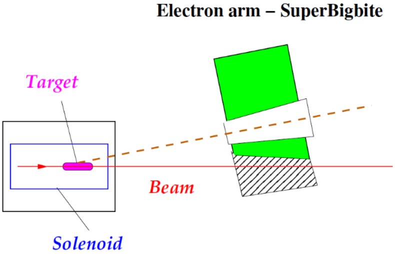


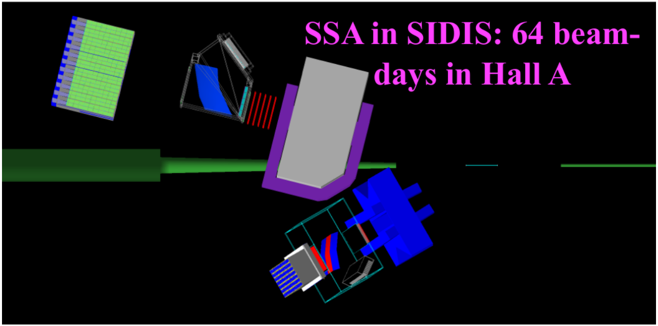


- All four up to same Q^2 range $\sim 10\ \mathrm{GeV}^2$
- Flavor decomposition into new several GeV^2 range possible

SIDIS and TDIS

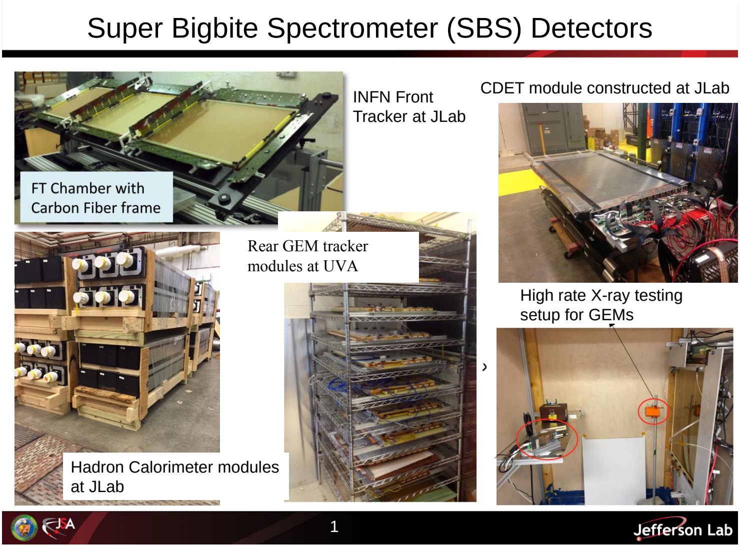
- 64 day $^3\overrightarrow{\mathrm{He}}$ SIDIS measurement for $\pi^\pm$ and $\mathrm{K}^\pm$
- 27 day TDIS C1 approved with CLAS large angle calorimeter and GEM rTPC on LH_2 and LD_2





Detector Assembly

Detectors and infrastructure finalizing construction



Super Bigbite Spectrometer (SBS) Detectors

FT Chamber with Carbon Fiber frame

INFN Front Tracker at JLab

CDET module constructed at JLab

Rear GEM tracker modules at UVA

High rate X-ray testing setup for GEMs

Hadron Calorimeter modules at JLab

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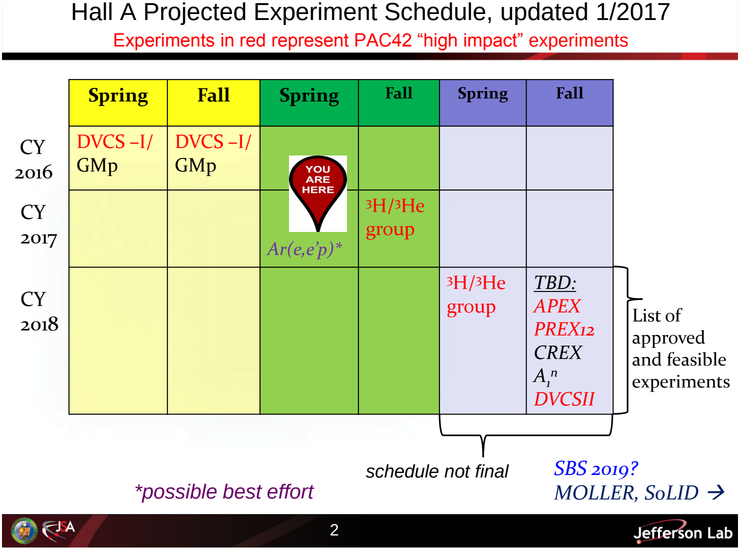
Jefferson Lab

Projected Schedule



Hall A Projected Experiment Schedule, updated 1/2017

Experiments in red represent PAC42 “high impact” experiments

	Spring	Fall	Spring	Fall	Spring	Fall
CY 2016	DVCS –I/ GMp	DVCS –I/ GMp				
CY 2017			Ar(e,e’p)*	^{3}H/^{3}He group		
CY 2018					^{3}H/^{3}He group	*TBD:* *APEX* *PREX12* *CREX* A_1^n *DVCSII*

List of approved and feasible experiments

schedule not final

*possible best effort

SBS 2019?
MOLLER, SoLID →

via Thia Keppel

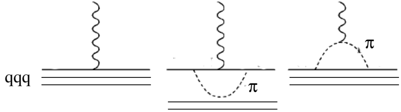
Summary

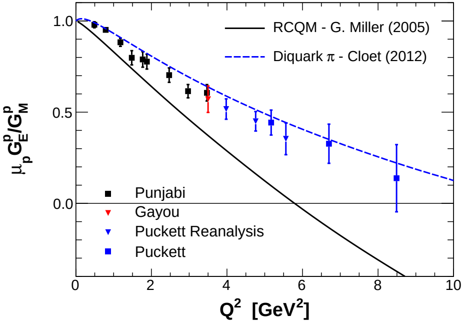
- By studying the EM properties of the nucleon, we can gain insight into the underlying mechanisms, helping refine theory and gain intuition
- Protons and neutrons together give flavor separation which provides excellent opportunities for model comparison
- Upcoming programs in high Q^2 form factors with SBS will provide information on underlying quark dynamics

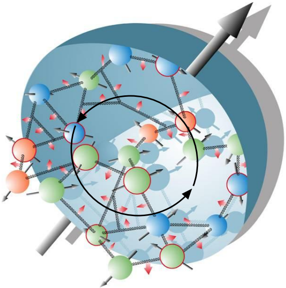
BACKUP

Constituent Quark Light-Front Cloudy Bag Model

- Construct model of 3 massive quarks or quark/diquark, include pion cloud:



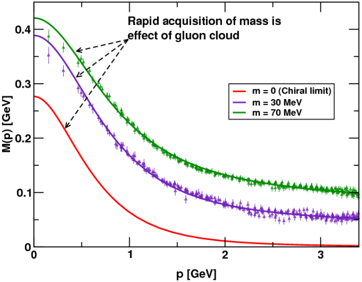


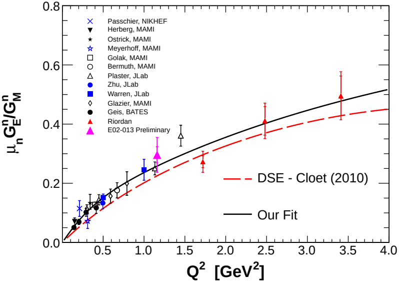


- G_E^p suppression at higher Q^2 due to inclusion of quark orbital angular momentum
- Know only 1/3 of the spin of the proton is carried by the quark *spins*, reproduced with di-quark DOF

DSE/Fadeev q(qq) Calculations

- Model based on QCD's Dyson-Schwinger equations to describe dressed quark propagator
- Fadeev amplitudes describe three-quark states
- Few free parameters tuned to reproduce nucleon properties such as masses





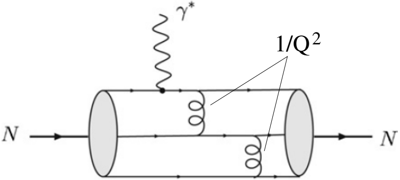
- Bhagwat et. al. arXiv:nucl-th/0610080
- Cloët et. al. arXiv:nucl-th/0804.3118

pQCD

- Can treat with pQCD for large Q^2
- Log order calculations for F_1, F_2 by Belitsky *et al.* (including hadron helicity non-conservation through quark OAM) makes prediction that as $Q^2 \to \infty$

$$\frac{Q^2}{\log^2(Q^2/\Lambda^2)} \frac{F_2}{F_1} = \mathrm{const.}$$

Λ parameter related to size of the nucleon



- Published proton data scaling starts at fairly low Q^2
- Neutron scaling should also occur if this is pQCD

pQCD

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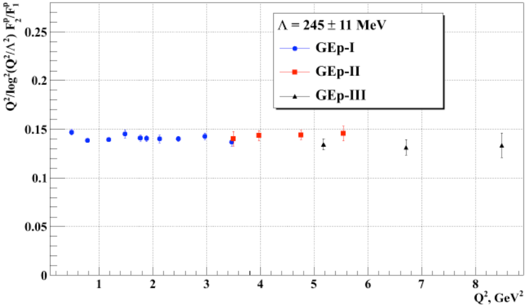
Λ parameter related to size of the nucleon



- Published proton data scaling starts at fairly low Q^2
- Neutron scaling should also occur if this is pQCD

pQCD

- Can treat with pQCD for large Q^2
- Log order calculations for F_1, F_2 by Belitsky *et al.* (including hadron helicity non-conservation through quark OAM) makes prediction that as $Q^2 \to \infty$

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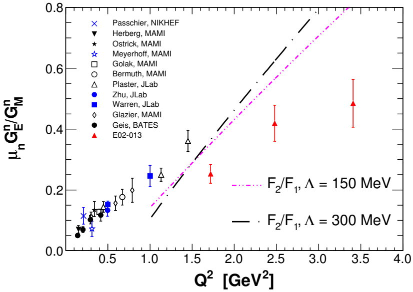

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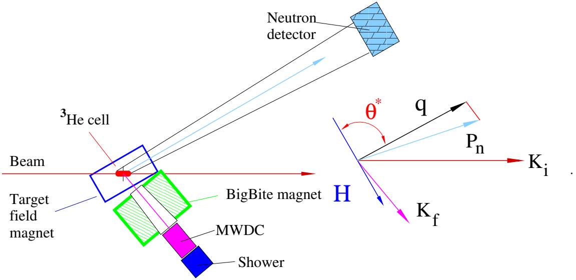
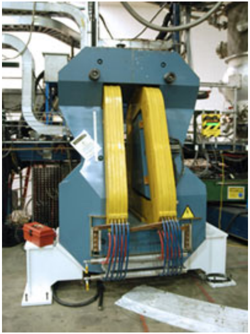
High Q^2 G_E^n

E02-013 - Highest Q^2 G_E^n through QE scattering

- Polarized $^3\mathrm{He}$ target acts as effective free neutron source
- Two arms to measure coincidence e' and n, allow for cuts on $p_{\mathrm{miss},\perp}$ to suppress FSI

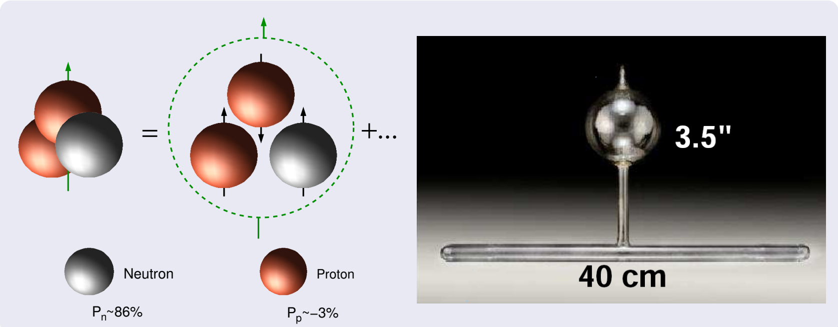




- BigBite - large acceptance spectrometer, reconstructs $\vec{e'}$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID

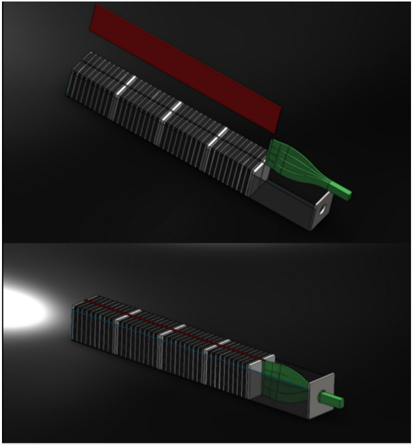
Polarized ^{3}He Target

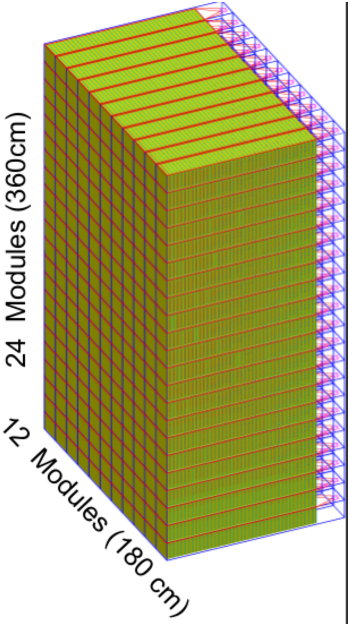
- ^{3}He is spin $1/2$, 3 body calculations describe polarization as



- 86% only for inclusive case
- D-wave state contributes $\sim 10\%$ to w.f. - sensitive to missing momentum range

HCAL-J Design



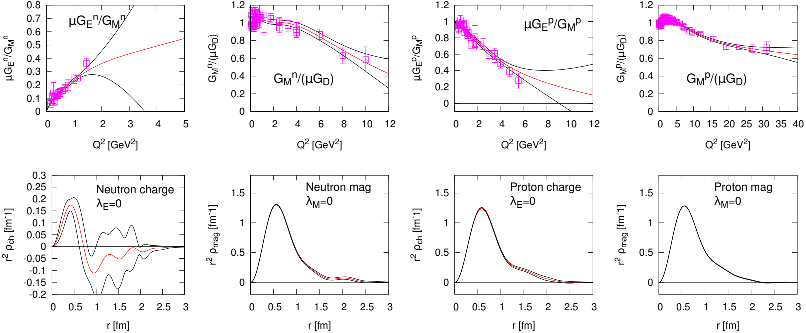


(Mostly) Model-Independent Fits

- Update based on Kelly, PRC 66, 065203 (2002)
- Form to account for relativistic distortions:

$$\begin{aligned} \tilde{\rho}_{\rm ch}(k) &= (1+\tau)^{\lambda_E}\, G_E(Q^2) \qquad \tau = Q^2/(4M_p) \\ \mu\tilde{\rho}_{\rm mag}(k) &= (1+\tau)^{\lambda_M}\, G_M(Q^2) \qquad k^2 = Q^2/(1+\tau) \end{aligned}$$

- Use Fourier-Bessel expansion with general scaling constraints



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