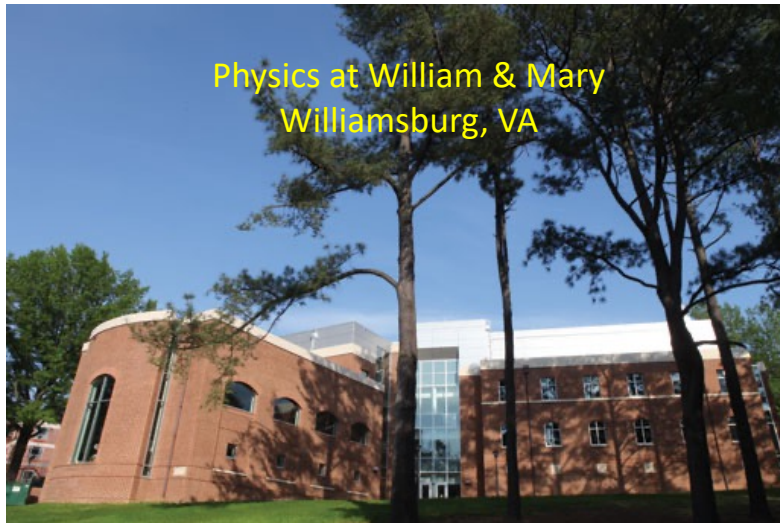


New Results on the Polarized and Unpolarized Structure of the Neutron from Jefferson Lab

Todd Averett, William & Mary



Jefferson Lab

Collaborations:

- A1n/d2n
- SuperBigBite (SBS)
- Polarized ^3He

Averett Research Group:

- Students: Derek Holmberg, Jack Jackson, Ben Spaude
- Postdoc: Eric Fuchey



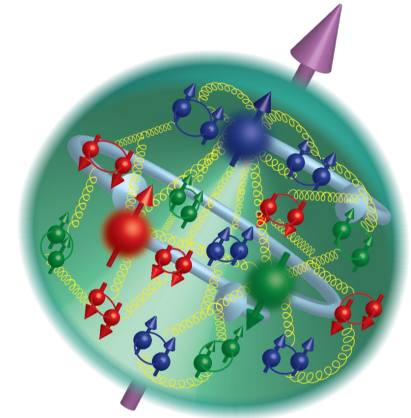


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- e^- - n scattering motivation, Jefferson Lab – nucleon structure studies
- Sachs Form Factors (FFs) from elastic scattering
 - Motivation
 - Experimental Setup
 - Polarized ^3He Target
 - Neutron Results
- Spin Structure Functions from deep-elastic scattering (DIS)
 - Motivation
 - Experimental Setup
 - Neutron Results

GOAL: Understanding the structure of the neutron in terms of its constituents

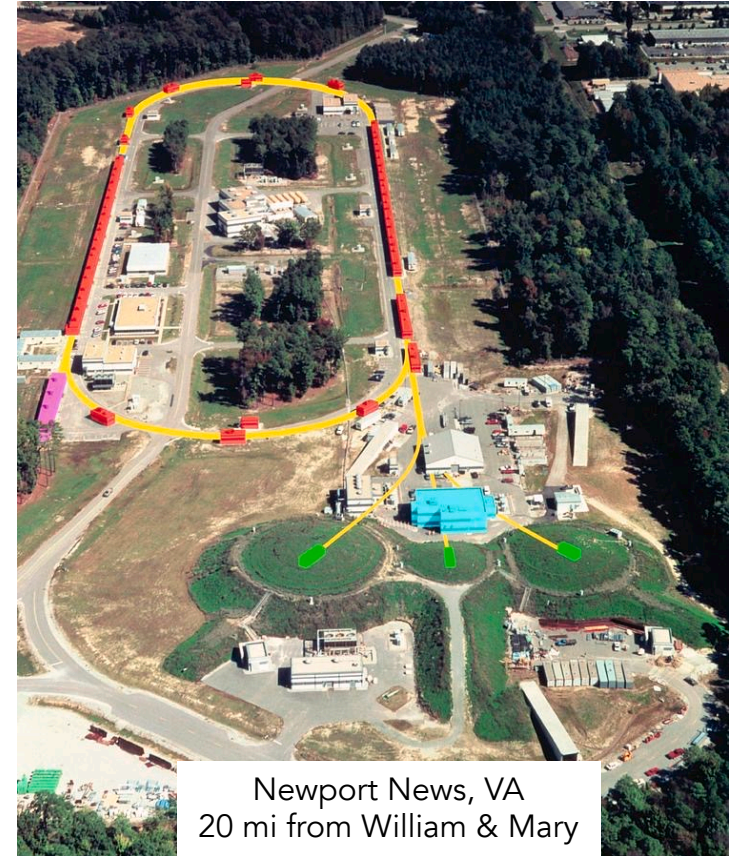
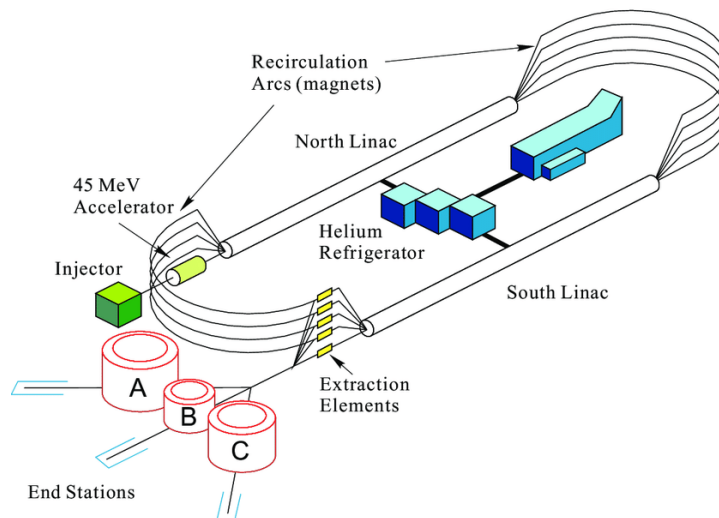
- **The players:**
 - valence quarks, $q\bar{q}$ pairs, gluons
- **The measurements:**
 - Form Factors and Structure Functions
 - Large Q^2 - scaling, pQCD
 - Large x_{Bj} – valence quark regime



Questions we can study via elastic and DIS e - n scattering

- Where do quarks physically reside?
- What are the charge and magnetization distributions?
- What contributes to spin = $\frac{1}{2}$; quark spin distribution?
- What are the roles of $q\bar{q}$ pairs and strange quarks?
- Appearance of QCD as Q^2 decreases – higher twist effects

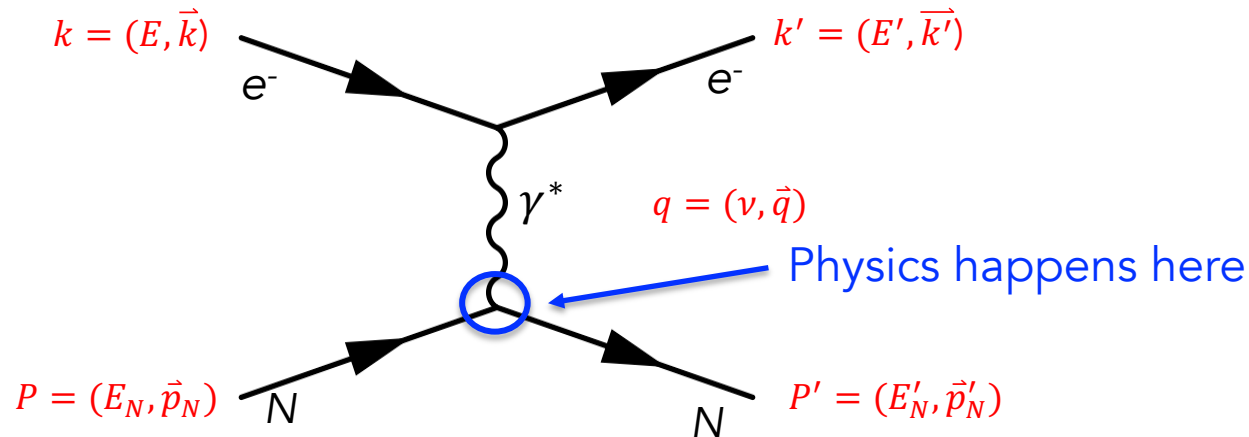
- Electron beam → EM scalpel, no strong interaction
 - Current up to 100 μA CW
 - Polarization $\sim 85\%$
 - Energy 1-12 GeV
 - Beam diameter $\sim 200\ \mu\text{m}$
- 4 experimental halls
 - Hall A – high resolution spectrometers
 - custom large acceptance detectors
 - Hall B – $\phi=2\pi$ spectrometer → multi-particle
 - Hall C – High momentum spectrometers
 - Hall D (not shown) – $e^- \rightarrow \gamma$: meson spectroscopy



Newport News, VA
20 mi from William & Mary

Elastic e^- - n Scattering

Measure in the lab frame: $E, E', \theta_e, \theta_N$



Kinematic variables

- $Q^2 \equiv -q^2 = 2EE'(1 - \cos \theta)$
- $\nu = E - E'$
- $W^2 = M^2 + 2M\nu - Q^2$
- $x = \frac{Q^2}{2M\nu}$
- $(-)$ four-momentum transfer²
- virtual photon energy
- invariant mass of γ^* -N system
- fraction of nucleon momentum of struck quark

Rosenbluth formula

$$\left(\frac{d\sigma}{d\Omega}\right)_{eN} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left\{ G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right\}, \quad \tau = \frac{Q^2}{4M^2}$$

- Dominated by G_M for the neutron, enhanced by τ
- $$\epsilon = \left(1 + 2(1 + \tau) \tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$$

$G_E(Q^2)$ = Electric form factor

$G_M(Q^2)$ = Magnetic form factor

- Depend only on Q^2

- “Parameterize our ignorance of the structure of the nucleon” – H & M

- At $Q^2 = 0$ require

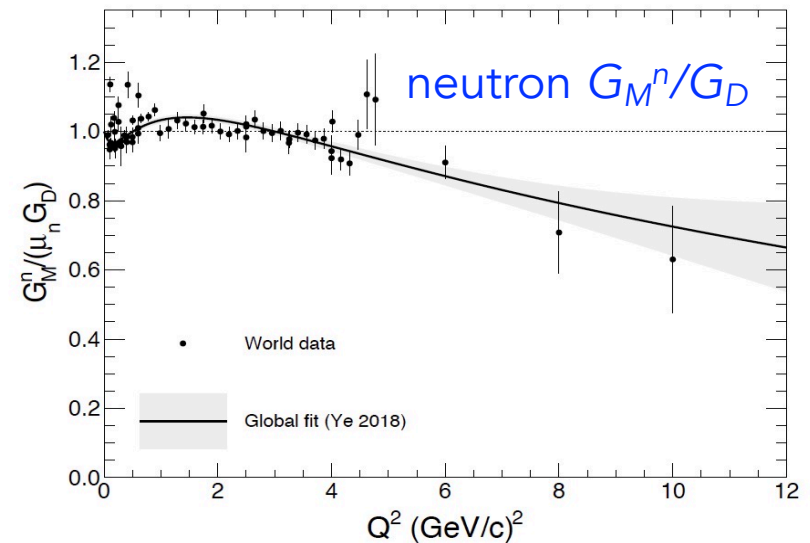
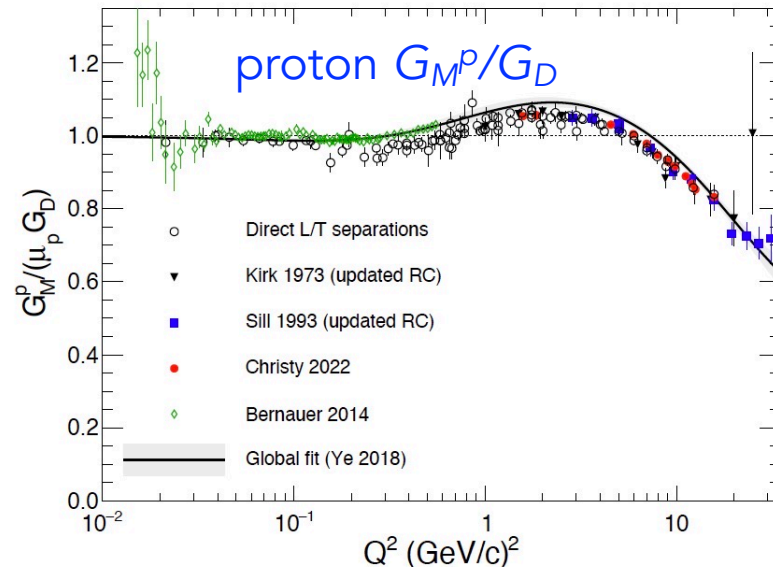
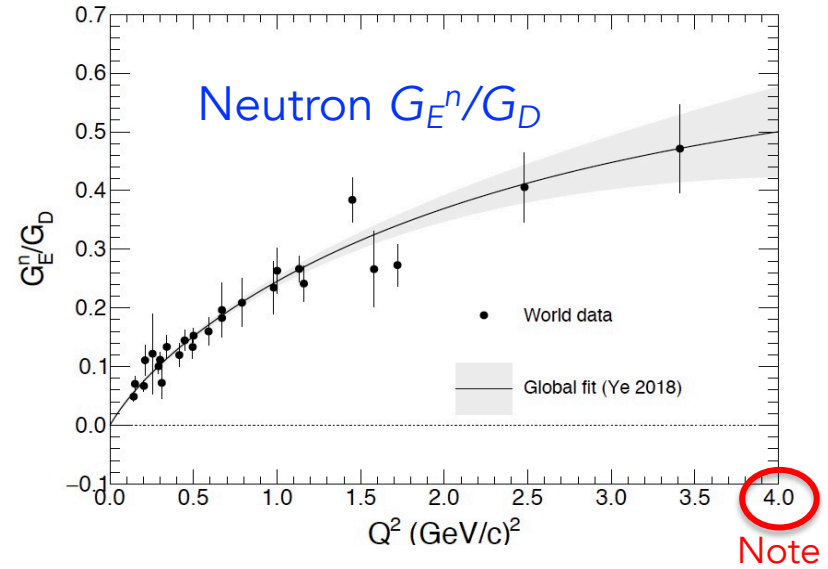
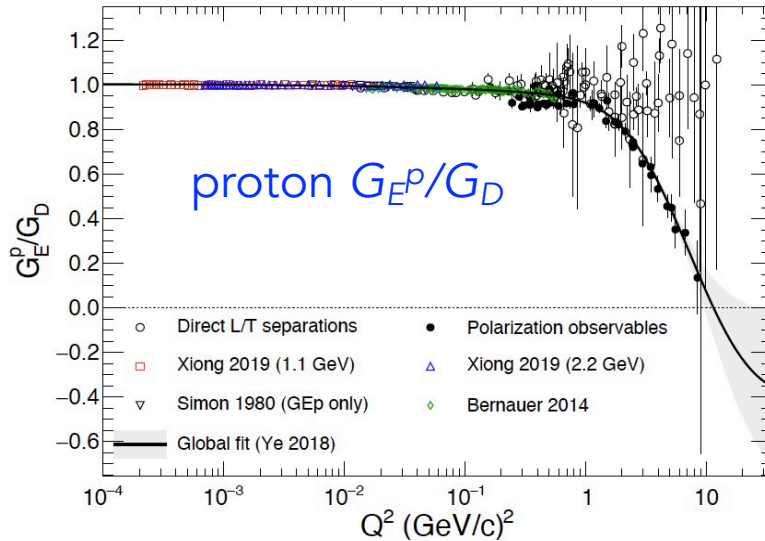
- Charges

$$G_E^p(0) = 1, \quad G_E^n(0) = 0$$

- Magnetic moments

$$G_M^p(0) = \mu_p, \quad G_M^n(0) = \mu_n$$

- Sachs form factors ~ not too different from dipole FF at lower Q^2 (except G_E^n)
- Lots of nucleon dynamics entering at large Q^2



- What do these form factors tell us?

Charge radius $\langle r^2 \rangle = -6 \frac{dG_E(Q^2)}{Q^2} \Big|_{Q^2=0}$

$$\langle r_p^2 \rangle = 0.707 \text{ fm}^2 \quad \langle r_n^2 \rangle \sim -0.11 \text{ fm}^2$$

-
- In the neutron case, it is the highly complicated dynamics of the strong force between quarks and gluons, the fermionic nature of quarks and spin-orbit correlations that leads to an asymmetric distribution of u- and d-quarks in it, thus resulting in a negative value. *Nature Commun.* 12, 1759 (2021)
 - This occurs because its internal quark structure features positively charged up quarks concentrated near the center and negatively charged down quarks residing more toward the outer region. *Google AI Overview*
-

Charge and Magnetization distributions obtained by Fourier transform

$$\rho(\vec{r}) = \int_0^\infty e^{-i\vec{q}\cdot\vec{r}} G_E(\vec{q}) d^3\vec{q}$$

$$M(\vec{r}) = \int_0^\infty e^{-i\vec{q}\cdot\vec{r}} G_M(\vec{q}) d^3\vec{q}$$

- Treating recoil relativistically makes these *frame-dependent*

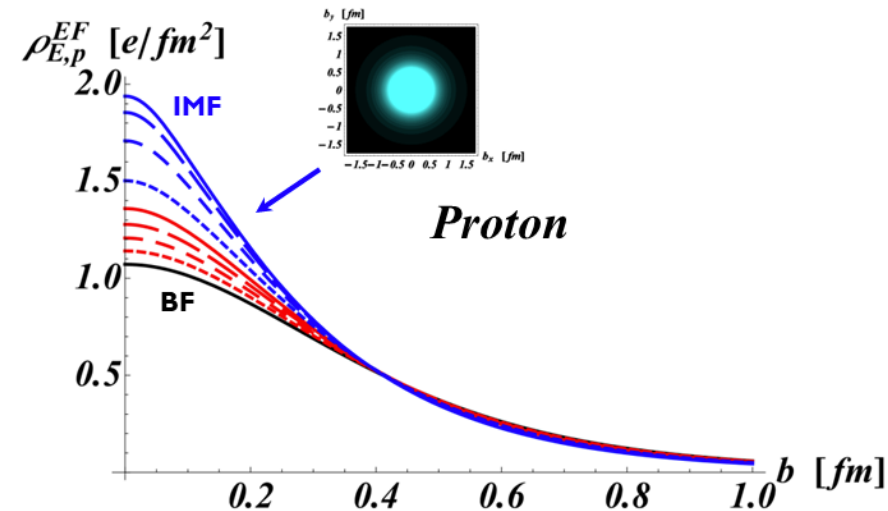
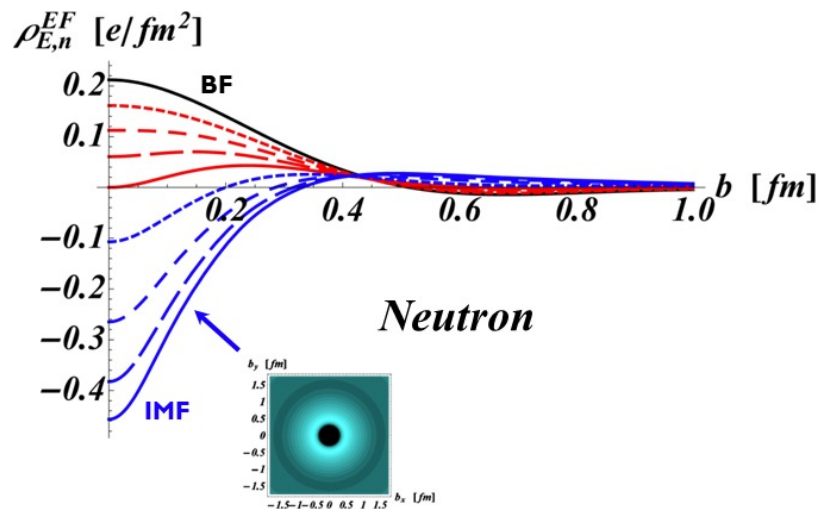
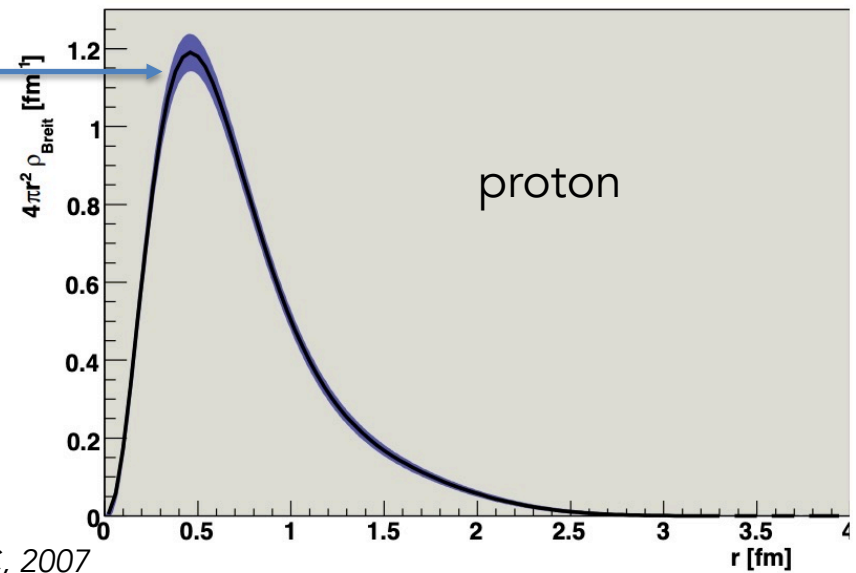
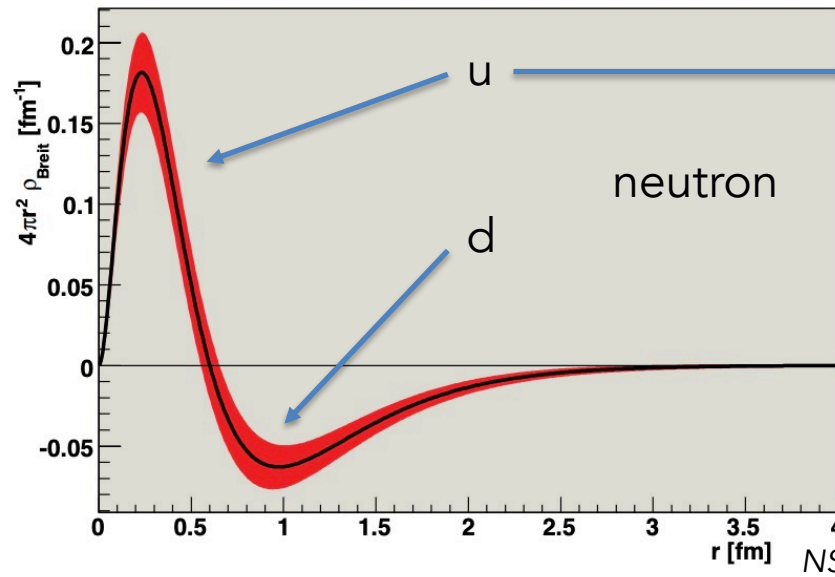
Charge distribution



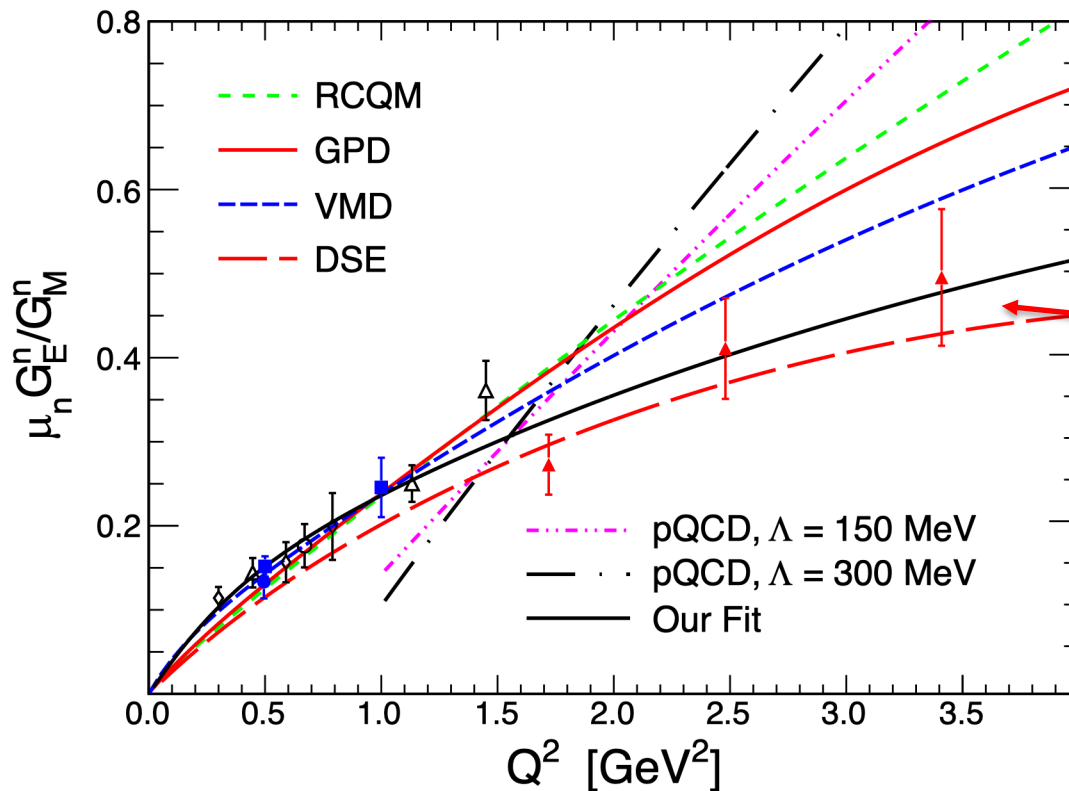
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Breit Frame



What does G_E^n tell us?



Riordan et al., Phys.Rev.Lett. 105 262302 (2010)

➤ Measured to $Q^2 \sim 3.5 \text{ GeV}^2$

➤ Data at higher Q^2 needed to constrain theory

Red triangles: First JLab measurement using polarized ^3He

If charge and magnetization densities have the same spatial distribution:

$$\frac{\mu_p G_E^n(Q^2)}{G_M^n(Q^2)} = 1$$

➤ Except G_E^n , all form factors behave like the dipole form factor G_D for $Q^2 < 1 \text{ GeV}^2$

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

Re-write Sachs FFs in terms of Dirac and Pauli FFs, F_1 and F_2

$$F_1 = \frac{G_E + \tau G_M}{1 + \tau}$$

$$F_2 = \frac{G_M - G_E}{1 + \tau}$$

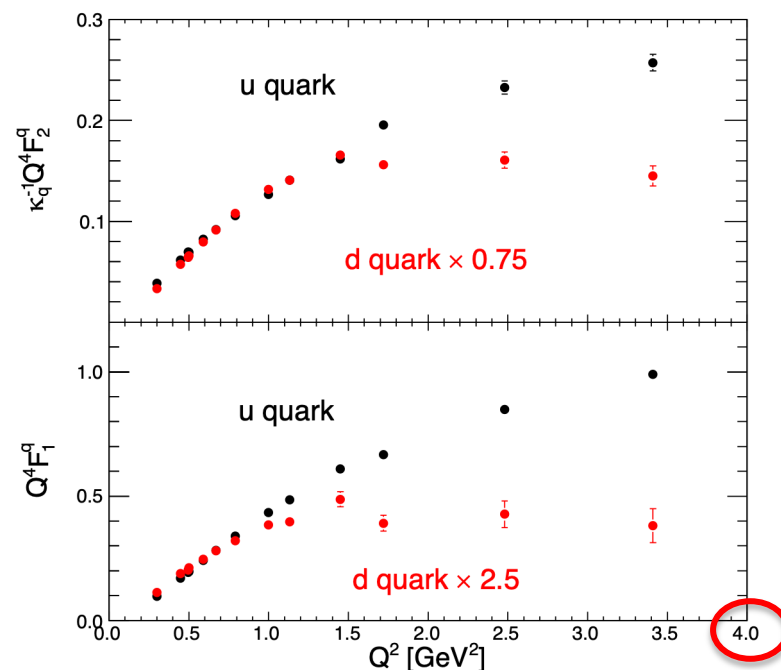
- Using both proton and neutron Sachs EM FFs, and assuming charge symmetry, we can do a flavor decomposition to extract the u and d contributions

$$F_{1(2)}^p = \frac{2}{3}F_{1(2)}^u - \frac{1}{3}F_{1(2)}^d$$

$$F_{1(2)}^n = \frac{2}{3}F_{1(2)}^d - \frac{1}{3}F_{1(2)}^u$$

- Simple expectation

$$Q^4 F_{1(2)} = \text{constant}$$

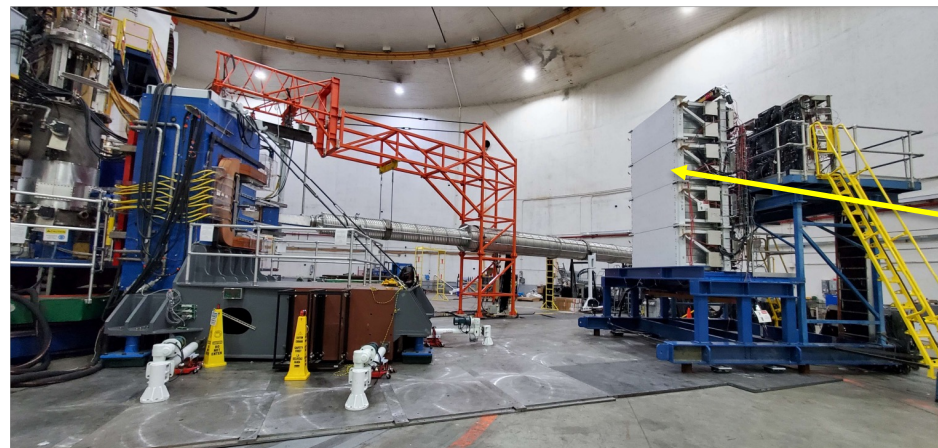
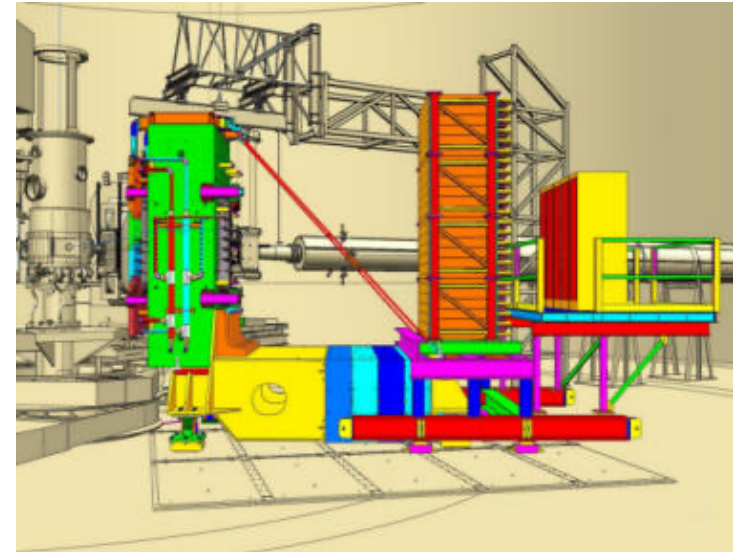
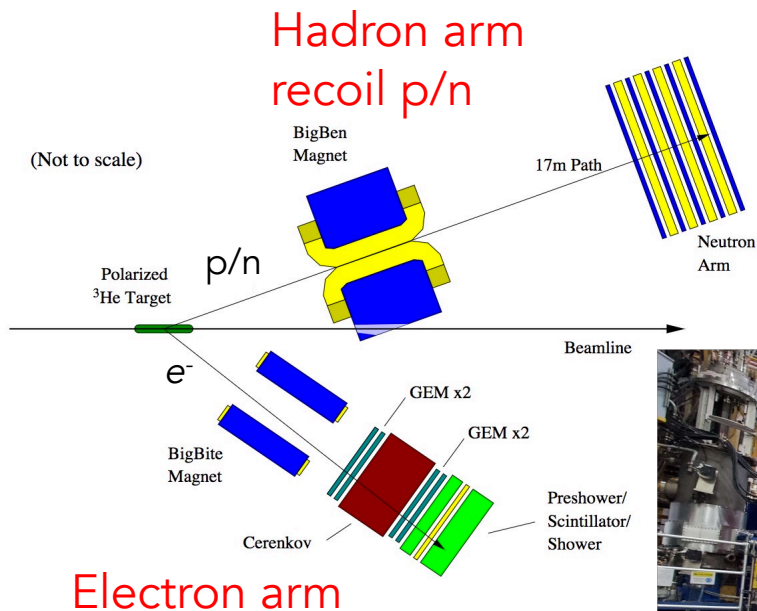


Note: maximum Q^2 limited by G_E^n

Neutron Magnetic Form Factor Measurement at Large Q^2

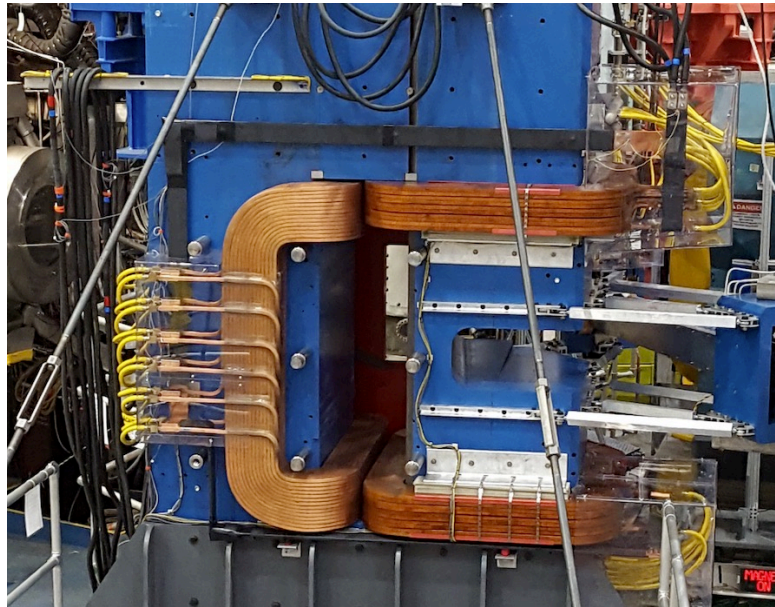
➤ G_M^n using LD_2

- Small cross sections require spectrometers with large angular and momentum acceptance & high luminosity
- SBS = Super Big Bite Spectrometer system
- Neutron from LD_2 and polarized ^3He targets



HCAL-
Hadron
calorimeter
for (p/n)
detection

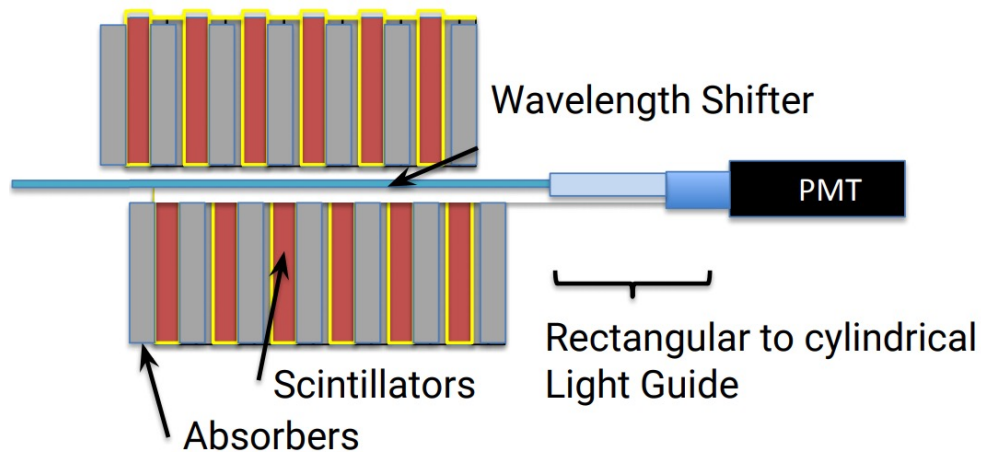
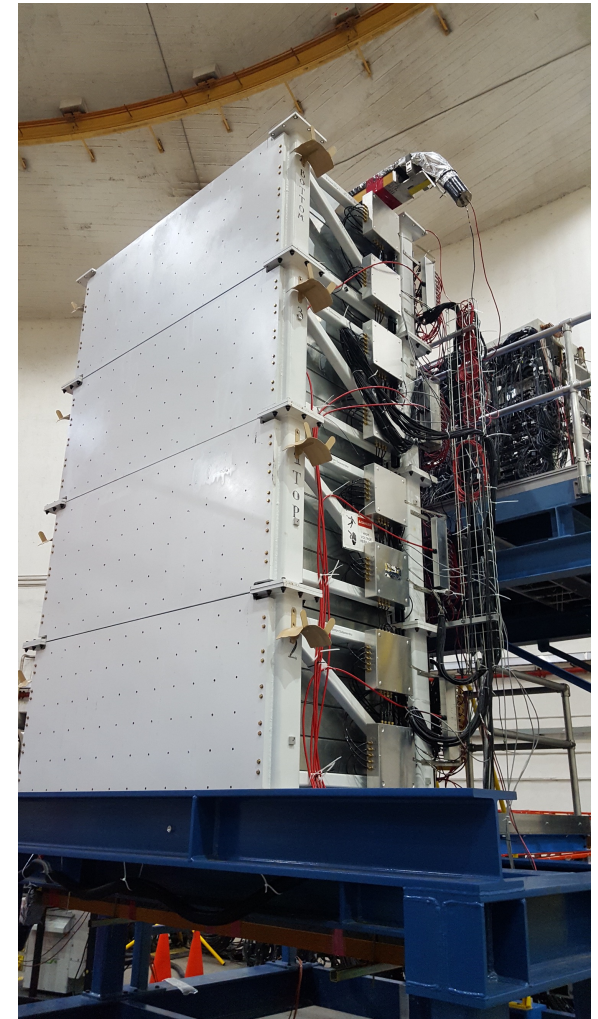
Hadron Calorimeter



SBS magnet
for p/n
separation



Hadron
Calorimeter

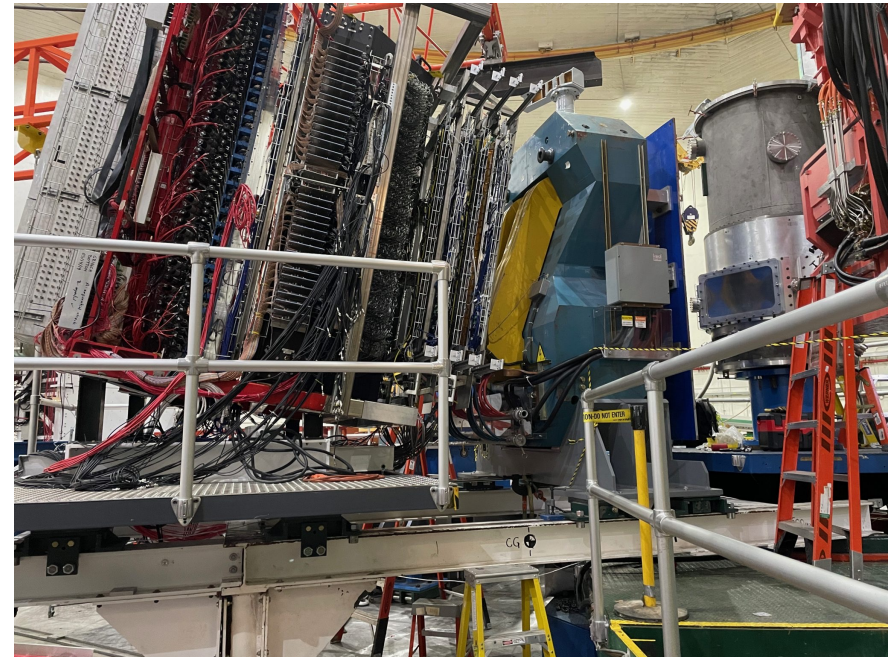
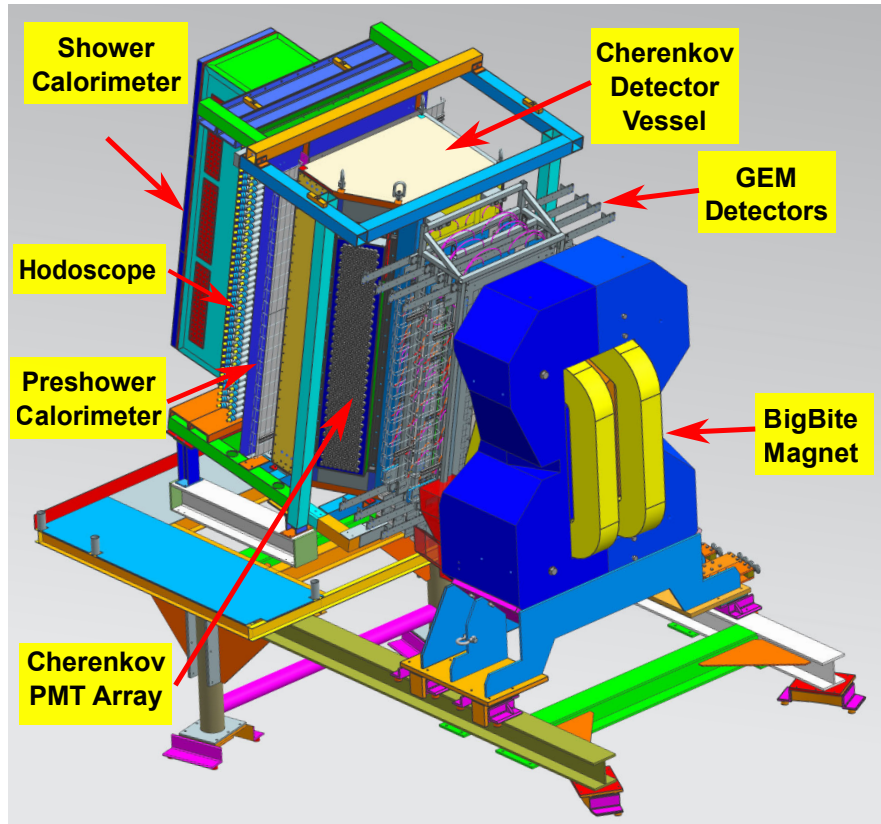


SBS BigBite Electron Spectrometer

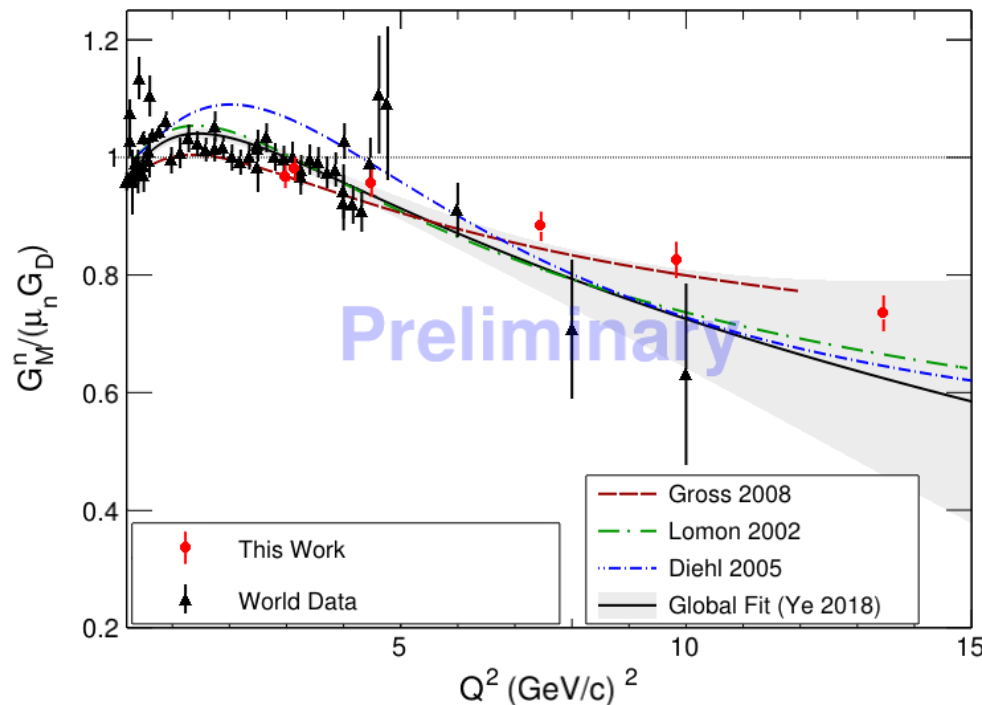


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- With the SBS spectrometer and a 15cm LD₂ target we measured $G_M^n(Q^2)$ to $Q^2 = 13.5 \text{ GeV}^2$
- Draft publication complete
- We also measured Rosenbluth Separation – not shown, to search for two-photon exchange in e-n scattering



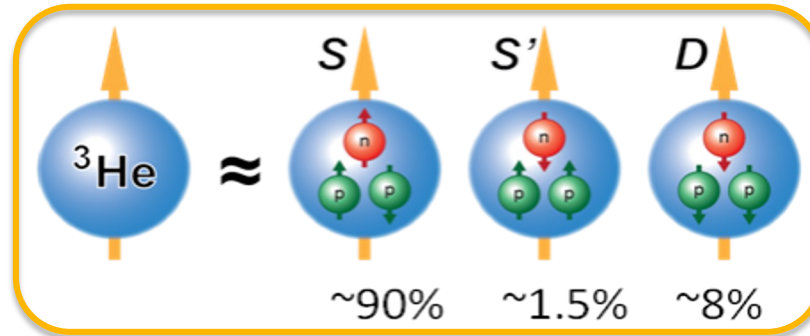
- Improved statistics; larger Q^2
- Needed for nucleon flavor decompositions
- This will move global fit above theory predictions

Plot courtesy of Eric Fuchey

Neutron Electric Form Factor Measurement at Large Q^2

- G_E^n using polarized ^3He

Measuring $G_E^n(Q^2)$ using a Polarized ^3He Target



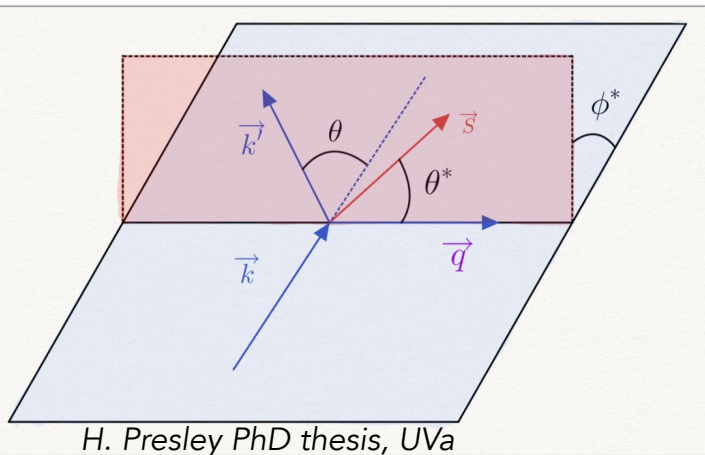
Fix the target polarization direction and measure the asymmetry

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

where + & - are the beam helicities

- Use double polarization technique to isolate relatively small G_E^n

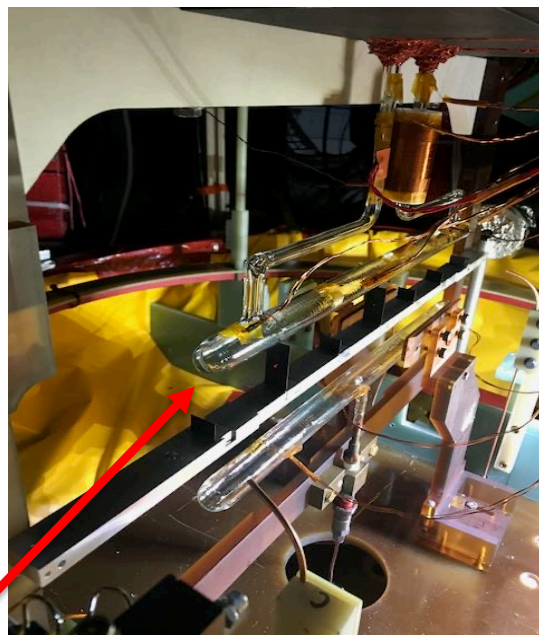
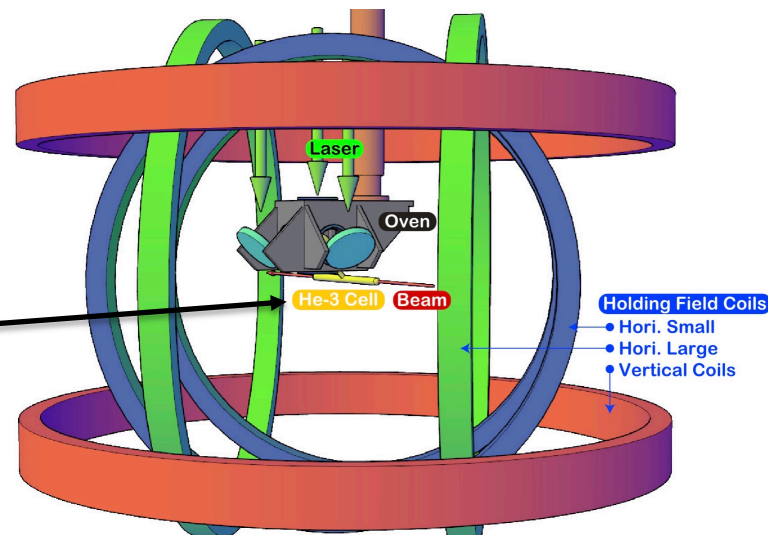
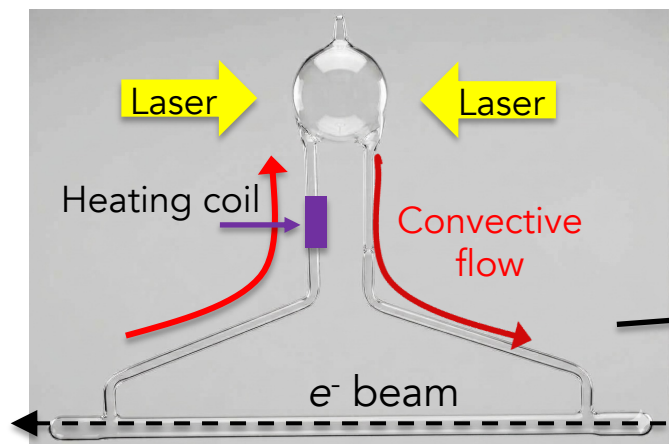
$$A = -\frac{G_E^n}{G_M^n} \frac{2\sqrt{\tau(1+\tau)} \tan \frac{\theta}{2} \sin \theta^* \cos \phi^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + (\tau + 2\tau(1+\tau) \tan^2 \frac{\theta}{2})} - \frac{2\tau \sqrt{1+\tau + (1+\tau)^2 \tan^2 \frac{\theta}{2}} \tan \frac{\theta}{2} \cos \theta^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + (\tau + 2\tau(1+\tau) \tan^2 \frac{\theta}{2})}$$



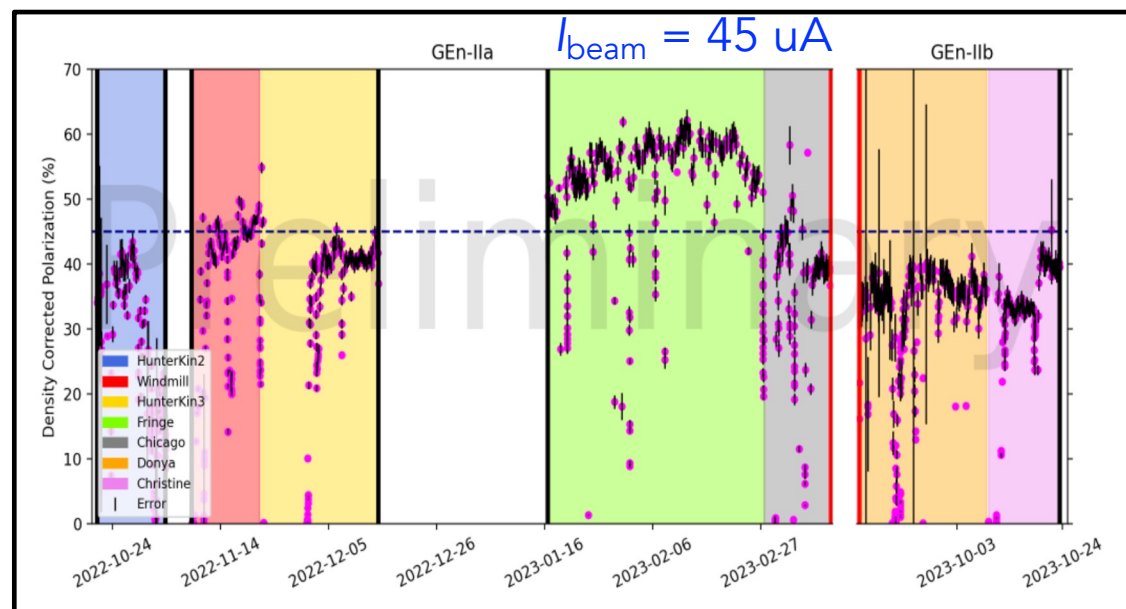
- θ is the electron scattering angle
- θ^* is the angle between the ^3He polarization vector $\vec{S}$ and photon 3-momentum, $\vec{q}$
- ϕ^* is the angle between the electron scattering and the $(\vec{S}, \vec{q})$ planes.
- Set $\vec{S}$ perpendicular to $\vec{q}$ ($\theta^* = \frac{\pi}{2}$) and $\phi^* = 0$
- Only the FF *ratio* contributes to the asymmetry:

$$A = -\left(\frac{G_E^n}{G_M^n}\right) \frac{2\sqrt{\tau(1+\tau)} \tan \frac{\theta}{2}}{\left(\frac{G_E^n}{G_M^n}\right)^2 + (\tau + 2\tau(1+\tau) \tan^2 \frac{\theta}{2})}$$

^3He convection cell



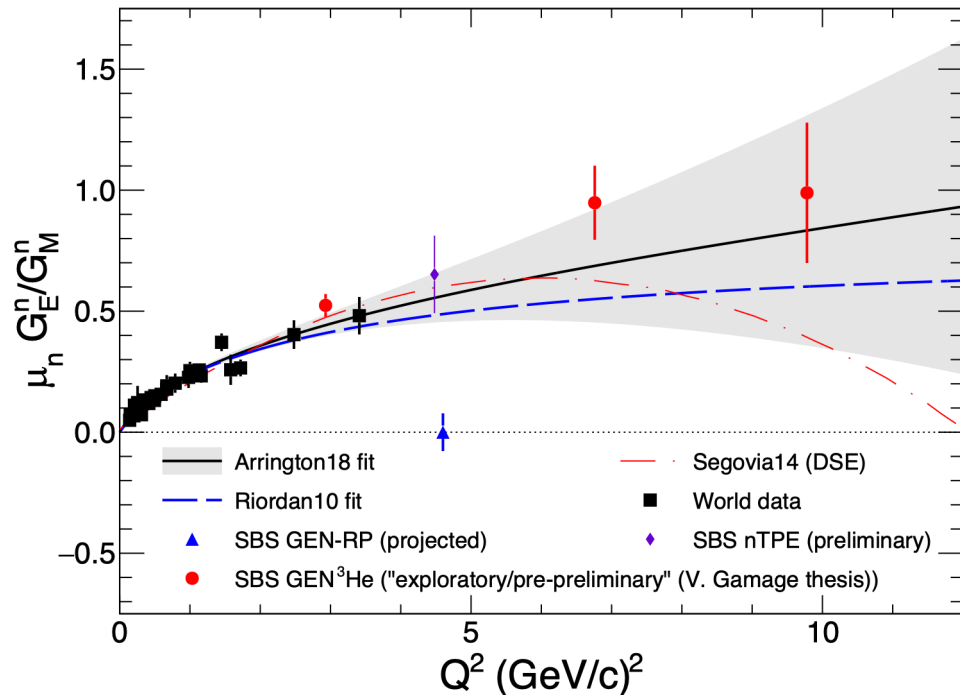
Target cell in beamline



Preliminary Results for G_E^n from SBS



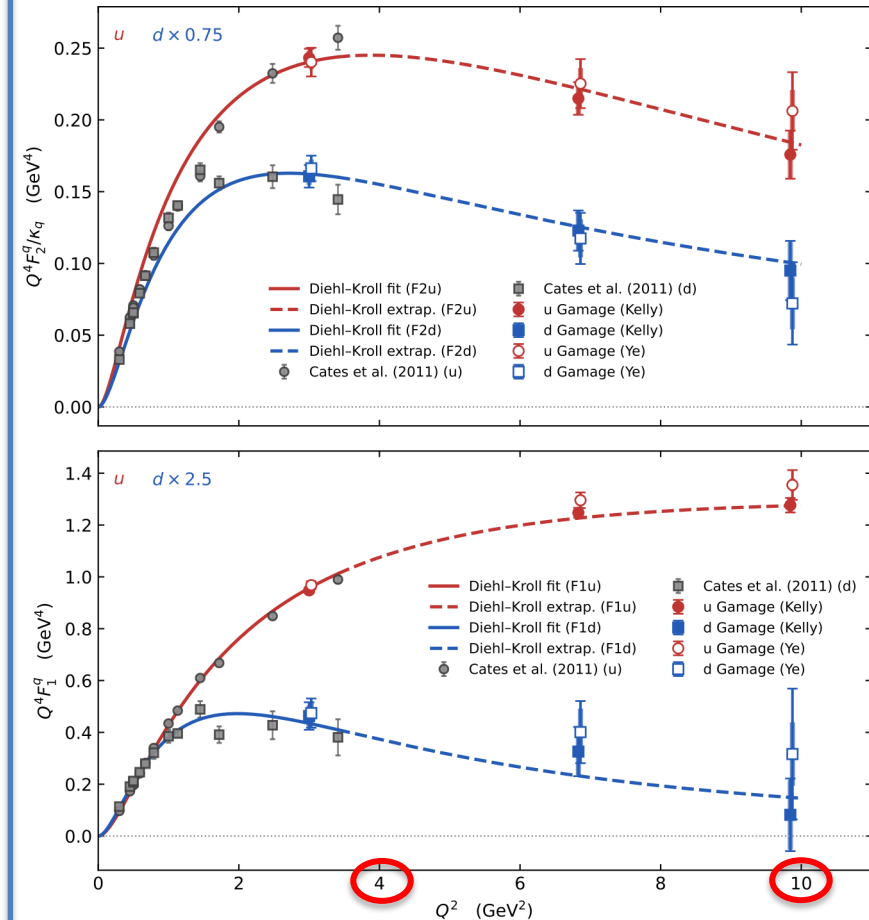
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- Additional statistics expected as we better understand inelastic backgrounds and improve Monte Carlo
- Also note we have results for nTPE using Rosenbluth separation
- Result for FF using recoil polarization from SBS

GEN-II Gamage: nucleon flavor separation

New result for flavor decomposition



Plots courtesy of V. Gamage

Spin Structure Functions from Polarized Deep-inelastic Scattering

$${}^3\text{He}(e,e')X$$

→ Two unpolarized structure functions

$$F_1(\nu, Q^2), F_2(\nu, Q^2)$$

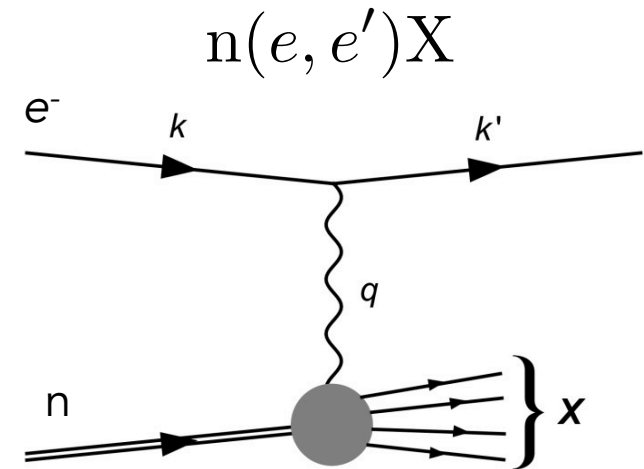
→ Two polarized structure functions

$$g_1(\nu, Q^2), g_2(\nu, Q^2)$$

→ At large Q^2 , scaling limit

$$F_{1(2)}(\nu, Q^2) \rightarrow F_{1(2)}(x)$$

$$g_{1(2)}(\nu, Q^2) \rightarrow g_{1(2)}(x)$$



➤ Unpolarized:
$$\frac{d\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left(\frac{E'}{E} \right) \left\{ \frac{F_2(x)}{\nu} + \frac{2}{M} F_1(x) \tan^2 \left(\frac{\theta}{2} \right) \right\}$$

➤ Longitudinally polarized beam and target

$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} = 4M\nu \tan^2 \frac{\theta}{2} \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \{ (E + E' \cos \theta) g_1(x) - 2Mx g_2(x) \}$$

Parton Model Interpretation

$$F_2(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 (q_i(x) + \bar{q}_i(x)),$$

$q_i(x)$ = probability to find a quark with flavor i and momentum fraction x

$$g_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 (\Delta q_i(x) + \Delta \bar{q}_i(x)),$$

$$\Delta q_i(x) = q_i^\uparrow(x) - q_i^\downarrow(x)$$

$q_i^\uparrow(x)$ = probability to find a quark with flavor i and momentum fraction x parallel to the nucleon spin

- We can also write an expression for the virtual photon – neutron asymmetry

$$A_1(x) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \sim \frac{g_1(x)}{F_1(x)}$$

- Wide variety of model predictions
- Expect mainly valence quark physics at large x

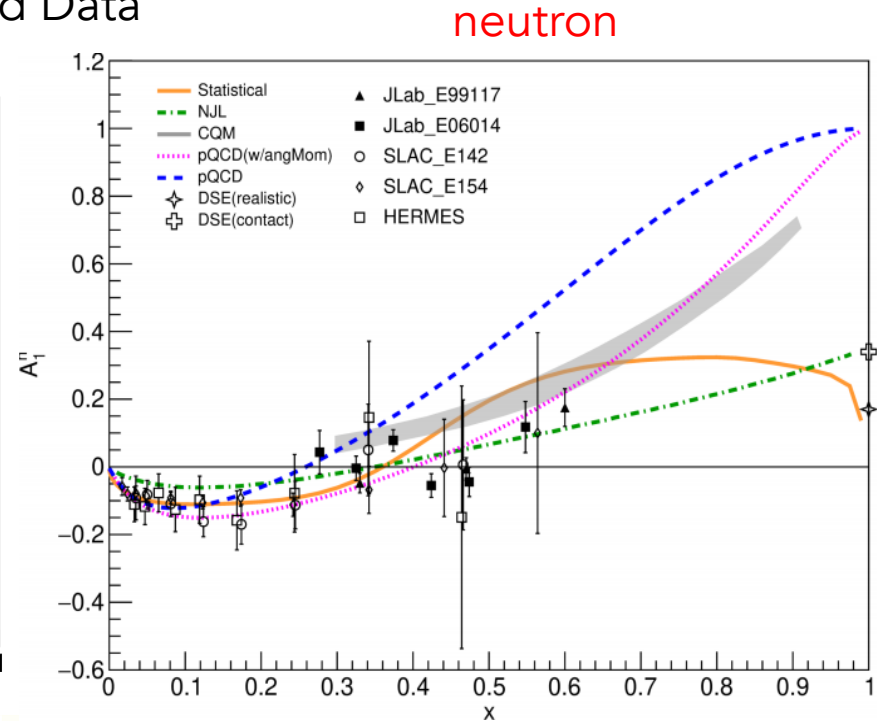
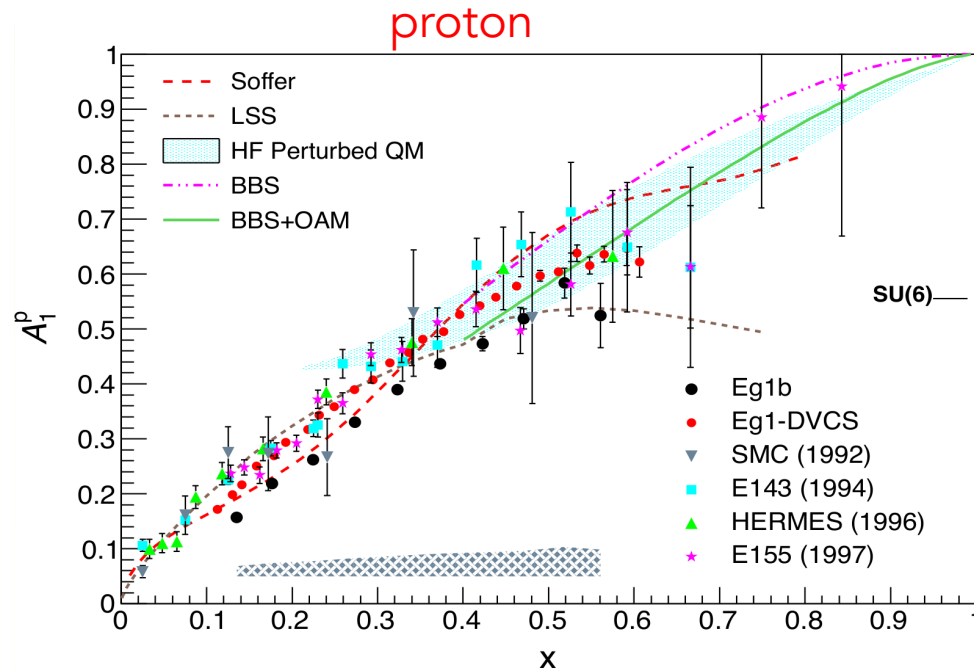
Simple parton model example:

$$A_1^n(x) = \frac{\left(\frac{2}{3}\right)^2 \Delta d(x) + \left(\frac{-1}{3}\right)^2 \Delta u(x)}{\left(\frac{2}{3}\right)^2 d(x) + \left(\frac{-1}{3}\right)^2 u(x)}$$

$A_1(x)$ -- a clean handle on valence quarks



Prior World Data



D. Parno et al. Phys.Rev.Lett. 113 (2014) 2, 022002, [1404.4003](#)

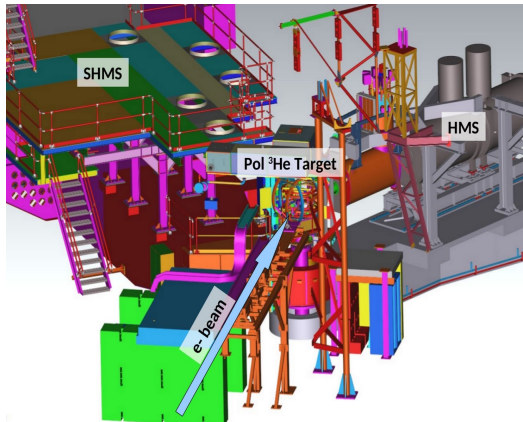
Simple parton model predictions as $x \rightarrow 1$:

Model	$\Delta u/u$	$\Delta d/d$	A_1^p	A_1^n	d/u
SU(6)	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{5}{9}$	0	$\frac{1}{2}$
Broken SU(6), scalar diquark	1	$-\frac{1}{3}$	1	1	0
QCD Counting Rules	1	1	1	1	$\frac{1}{5}$

➤ proton OK

➤ Neutron data needed at large x

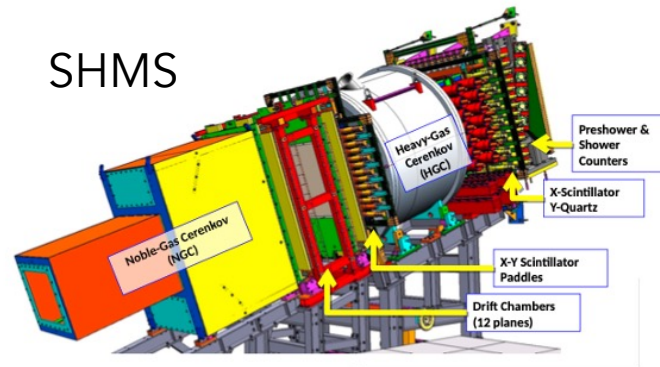
Hall C Setup



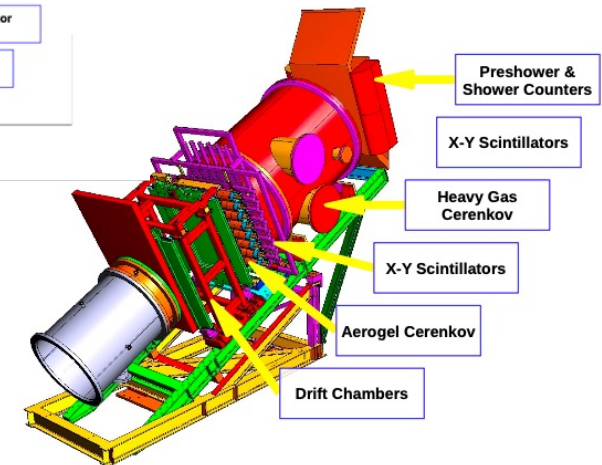
- $E_e = 10.4 \text{ GeV}$
- $I_{\text{beam}} = 30 \text{ uA}$
- $\theta = 30^\circ$
- $E' = 2.6 - 3.5 \text{ GeV}$
- $P_e \sim 85\%$
- $P_{\text{targ}} > 50\%$

2 Independent Electron Spectrometers

SHMS

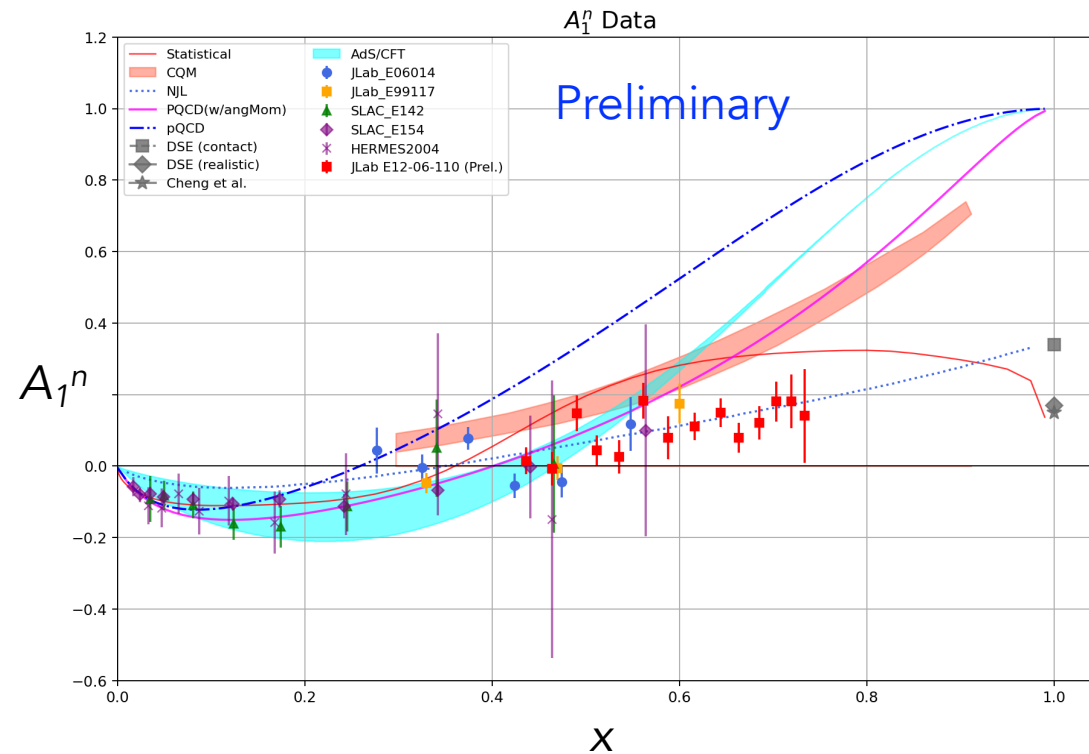


HMS



	SHMS	HMS
Central Momentum Range	2 to 11 GeV	0.4 to 7.4 GeV
Momentum Acceptance	-10% to 22%	-8% to 8%
Scattering Angle Range	5.5° to 40°	10.5° to 90°
Solid Angle Acceptance	$> 4 \text{ msr}$	8.1 msr
Horizontal Angle Resolution	$\sim 0.03^\circ$ to $\sim 0.07^\circ$	$\sim 0.05^\circ$
Vertical Angle Resolution	$\sim 0.02^\circ$ to $\sim 0.06^\circ$	$\sim 0.06^\circ$

Table from M. Cardona thesis, Temple Univ. 2022



DIS

$W > 2 \text{ GeV}, Q^2 > 1 \text{ GeV}^2, x_{\text{max}} = 0.7$

Theoretical predictions as $x \rightarrow 1$

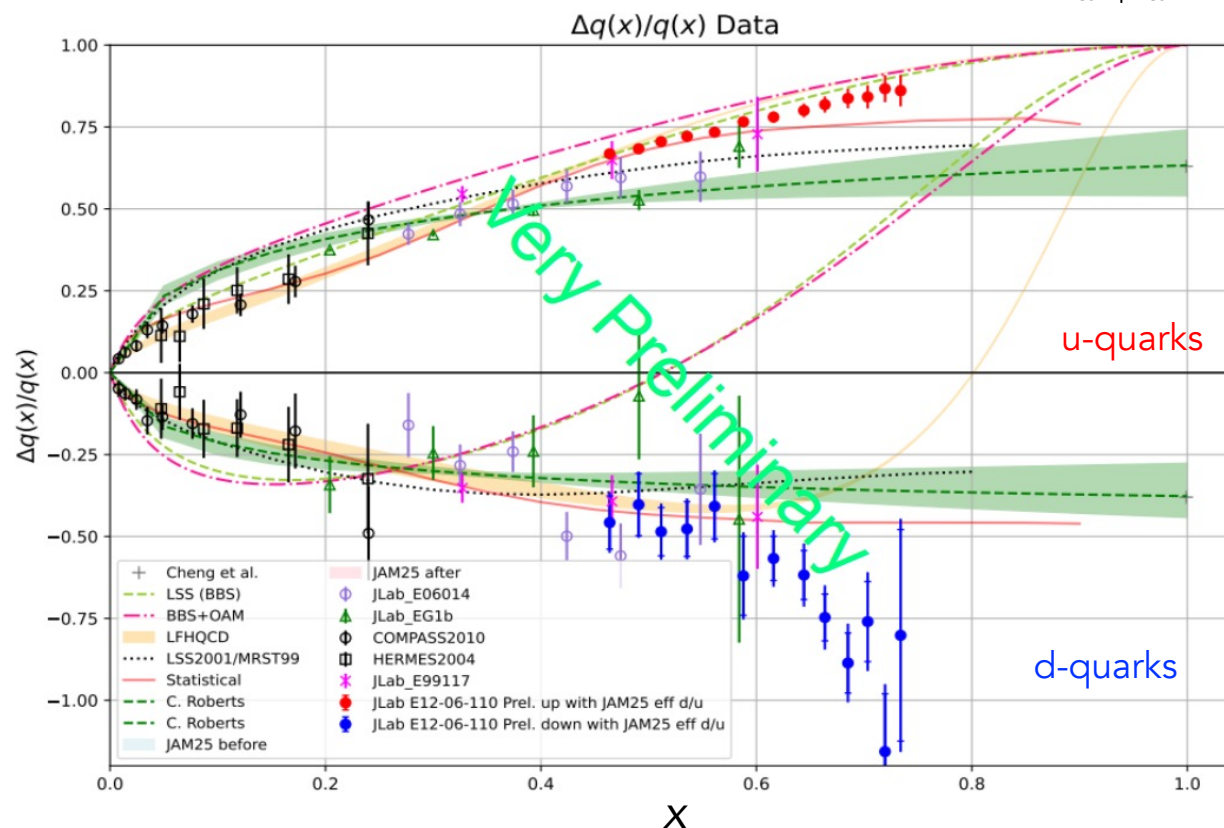
Model	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
di-quark	$\frac{1}{4}$	0	0	1	0	1	1
RCQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1
HLFQCD	0.28	0.035	0.035	1	1	1	1
LPC*				0.68	-0.50	-0.02	0.58
DSE-1	0.49	0.28	-0.11	0.65	-0.26	0.17	0.59
DSE-2	0.41	0.18	-0.07	0.88	-0.33	0.34	0.88
CSM	0.45	0.23	-0.14	0.63	-0.38	0.15	0.58
NJL	0.43	0.2	-0.06	0.8	-0.25	0.35	0.77

* the LPC predictions are made at $x = 0.8$

- First clearly observed zero crossing
- Best agreement with Nambu-Jona-Lasinio (NJL) EFT model: constituent quarks and contact interaction, no gluons
- Poor agreement with pQCD models
- Data also obtained in the resonance region

- Assume p/n charge symmetry, naive QPM

- Use $F_1^{(p,n)}(x)$ and $g_1^{(p,n)}(x)$ to extract: $\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}}$ $\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}}$



- Note: d-quark distribution remains negative

- **Higher-twist effects** are non-perturbative corrections to deep inelastic scattering (DIS) and hard-scattering processes that scale as powers of $1/Q^2$ (such as $1/Q^2$ or $1/Q^4$) arising from quark-quark, quark-gluon, and multi-parton interactions inside the nucleon rather than independent single-quark impulse approximations.
- **Leading-twist contribution** describes the interaction of a virtual photon with a single, quasi-free quark

$$\text{Observable} \sim C_2(x) + \frac{C_4(x)}{Q^2} + \frac{C_6(x)}{Q^4} + \dots$$

Leading twist = 2
twist = 3
twist = 4

- Operator Product Expansion
- $C_i(x)$ are non-pQCD coefficients

- $g_2(x)$ is one of the cleanest observables to quantify higher-twist effects

- Leading twist contribution to can be calculated from $g_1(x)$

$$g_2^{WW}(x) = -g_1^n(x) + \int_x^1 \frac{g_1(y)}{y} dy$$

Wandzura-Wilczek relation gives leading twist contribution

$$\bar{g}_2(x) = g_2(x) - g_2^{WW}(x)$$

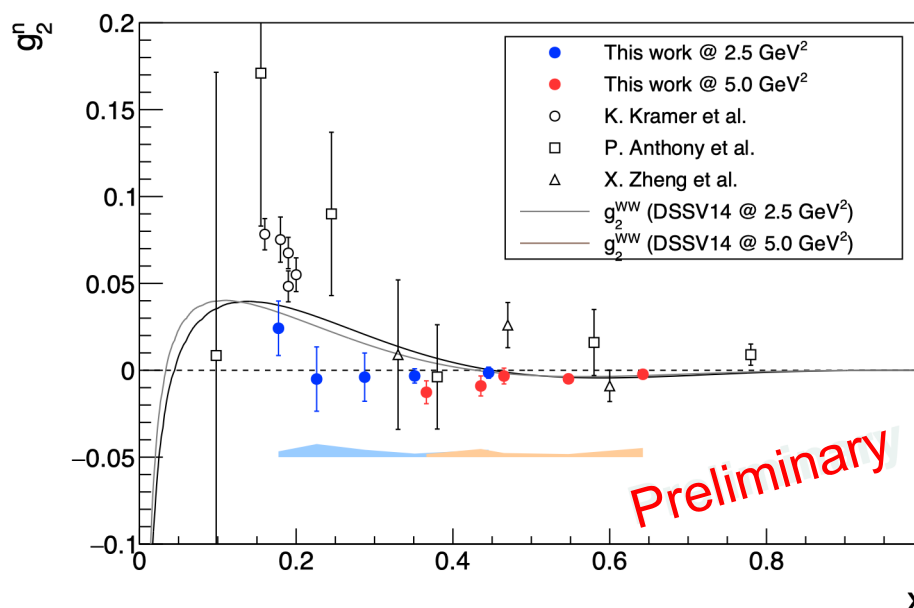
Deviation from $g_2^{WW} \rightarrow$ Higher twist contributions

- Twist-3 matrix element can be cleanly calculated in LQCD

$$d_2(Q^2) = \int_0^1 x^2 [3g_2(x, Q^2) - 2g_1(x, Q^2)] dx$$

- Good agreement for proton; neutron not yet clear
- Stay tuned for these results

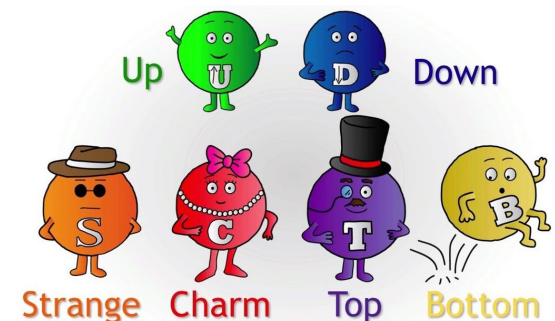
New results for g_2^n at constant Q^2



See also: Z.-E. Meziani *et al.*, Phys.Lett.B613:148-153,2005

- New questions and answers from precise neutron measurements
 - Elastic scattering from $LD_2 \rightarrow G_M^n(Q^2)$ up to $Q^2 = 13.5 \text{ GeV}^2$
 - Elastic scattering from polarized $^3\text{He} \rightarrow G_E^n(Q^2)$ up to $Q^2 = 10 \text{ GeV}^2$
 - Combine these results with proton to get flavor decomposition
- DIS from polarized ^3He :
 - $A_1^n(x)$ up to $x = 0.7 \rightarrow$ Testing wide variety of models
 - pQCD models not working in the valence quark region at large Q^2
 - $\frac{\Delta d}{d}$ remains negative
 - $g_2^n(x)$ at fixed $Q^2 = 3.0$ and 5.0 GeV^2
 - Search for higher-twist contributions
 - Extract twist-3 matrix element, compare to robust LQCD results

Thank you for your attention

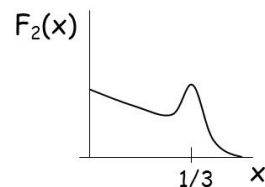
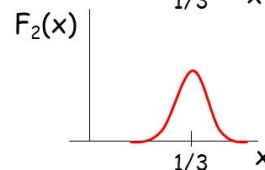
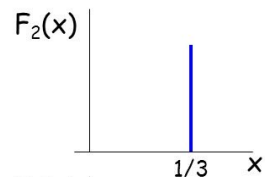
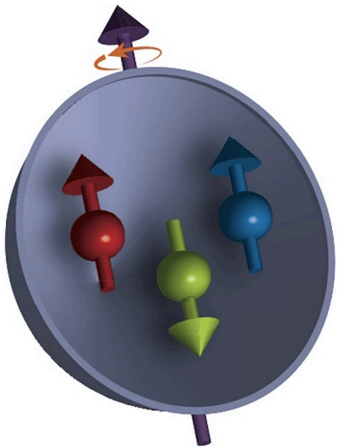


Random Backup Slides

1969, J.D. Bjorken predicts when $Q^2, \nu \rightarrow \infty$ and Q^2/ν finite, the cross section becomes the incoherent sum of elastic scattering from point-like, charged, spin-1/2, non-interacting quarks. Scattering becomes a function of only one variable describing the kinematics of the struck quark!!

- $x = \frac{Q^2}{2M\nu}$; the fraction of the nucleon's momentum carried by the struck quark
- Bjorken Scaling: $W_1(Q^2, \nu), W_2(Q^2, \nu) \rightarrow F_1(x), F_2(x)$

Expect $F_2(x) = \frac{1}{3}$ for a nucleon consisting of only 3 non-interacting valence quarks



QuickTime™ and a decompressor are needed to see this picture.

Three quarks with 1/3 of total proton momentum each.

$$Q^2 \rightarrow \infty$$

Three quarks with some momentum smearing.

$$\text{moderate } Q^2$$

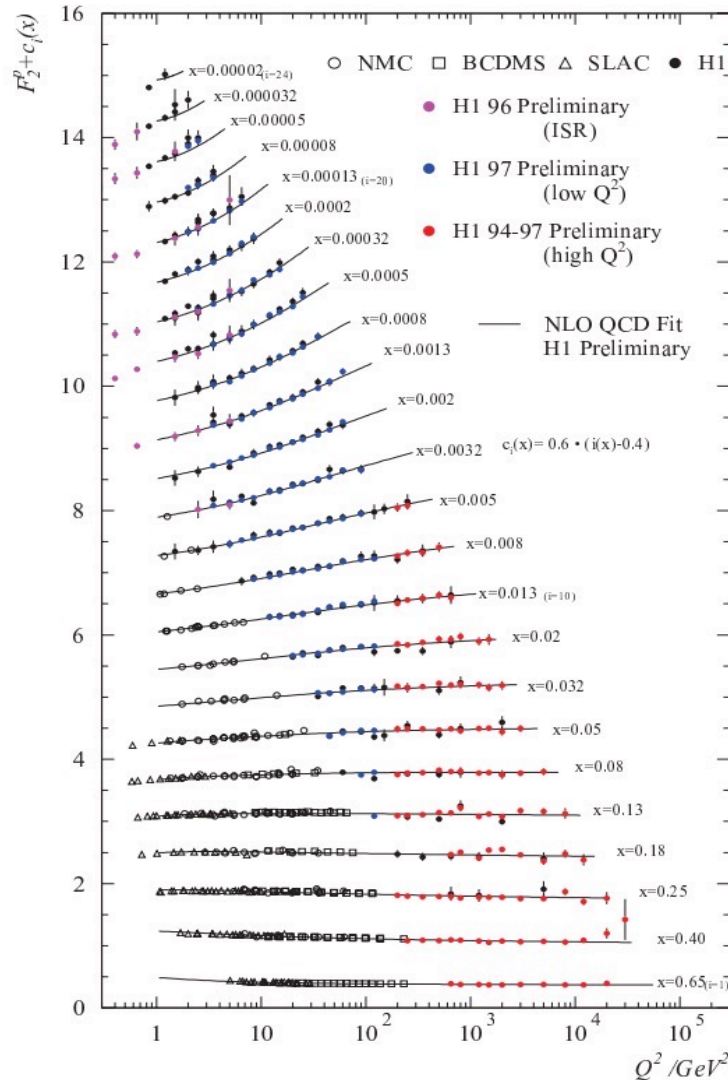
The three quarks radiate partons at low x .

$$\text{low } Q^2$$

Kendall, Taylor, Friedmann
Nobel Prize 1990

....The answer depends on the Q^2 !

Scaling



Scaling predictions

$$F_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 (q_i(x) + \bar{q}_i(x))$$

- e_i = quark charge
- $q_i(x)$ = momentum distribution

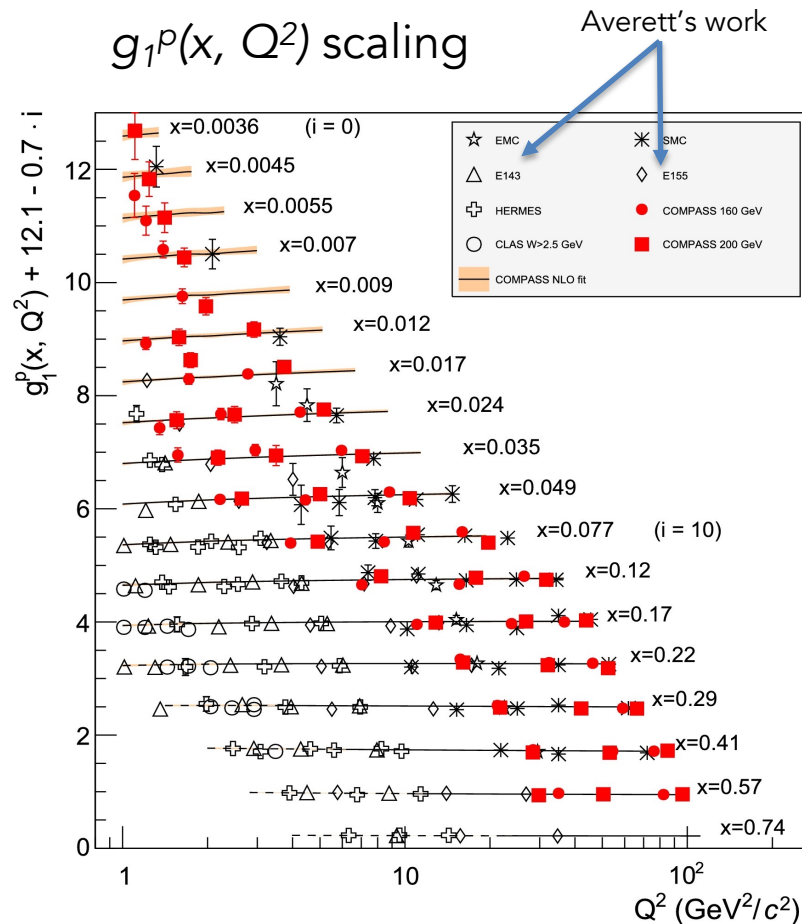
Total contribution to nucleon momentum from i^{th} quark flavor.

$$q_i = \int_0^1 q_i(x) dx$$

What about nucleon spin distributions?



$$\left(\frac{d\sigma}{d\Omega dE'} \right)^{\uparrow\downarrow} \propto g_1, g_2 \quad \text{Two spin-dependent structure functions, } g_1(\nu, Q^2), g_2(\nu, Q^2)$$



$$g_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 (\Delta q_i(x) + \Delta \bar{q}_i(x)),$$

$$\Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

Contribution to nucleon spin from i^{th} quark flavor:

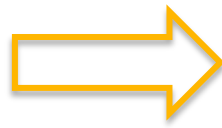
$$\Delta q_i = \int_0^1 \Delta q_i(x) dx$$

$\Delta\Sigma$ = Total quark contribution to nucleon spin

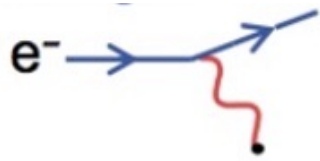
$$\Delta\Sigma = \underbrace{\Delta u + \Delta d + \Delta s}_{\text{valence + sea quarks}} + \underbrace{\Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s}}_{\text{sea quarks}}$$

de Broglie
Wavelength

$$\lambda = \frac{h}{p}$$

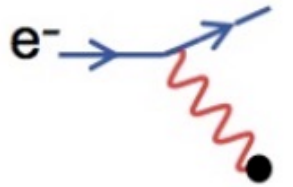


Studying the internal structure
of the nucleon (N) requires a
probe with energy $\sim 1\text{-}12\text{ GeV}$



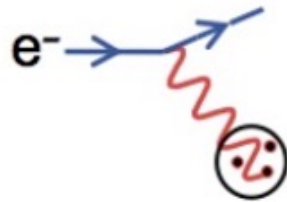
➤ Very low energy: nucleon = point-like

$$\lambda \gg r_N$$



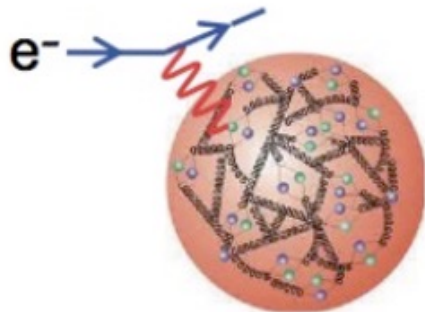
➤ Low energy: featureless nucleon with finite size

$$\lambda \sim r_N$$



➤ High energy: quark structure, resonances

$$\lambda < r_N$$

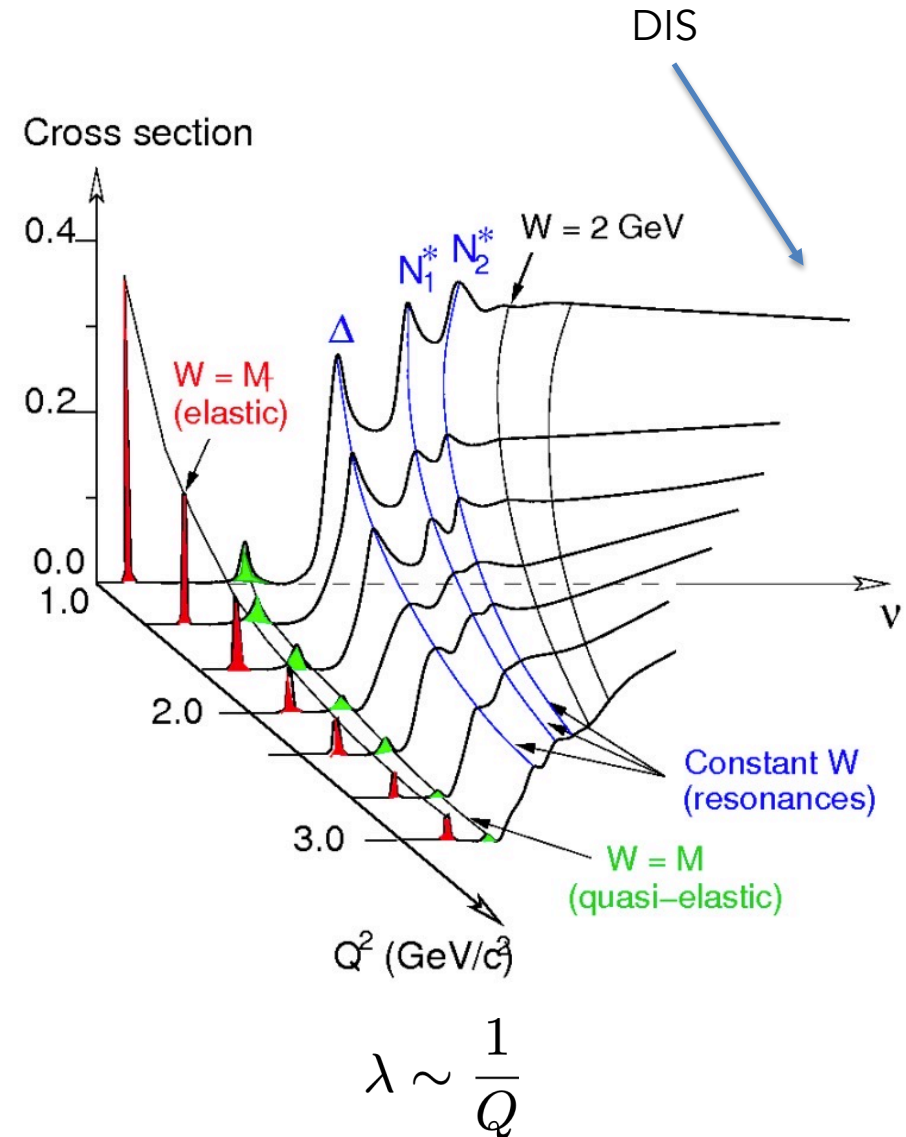


➤ Very high energy: quarks, $q\bar{q}$ pairs, gluons

$$\lambda \ll r_N$$

nucleon radius $r_N \sim 1\text{ fm}$

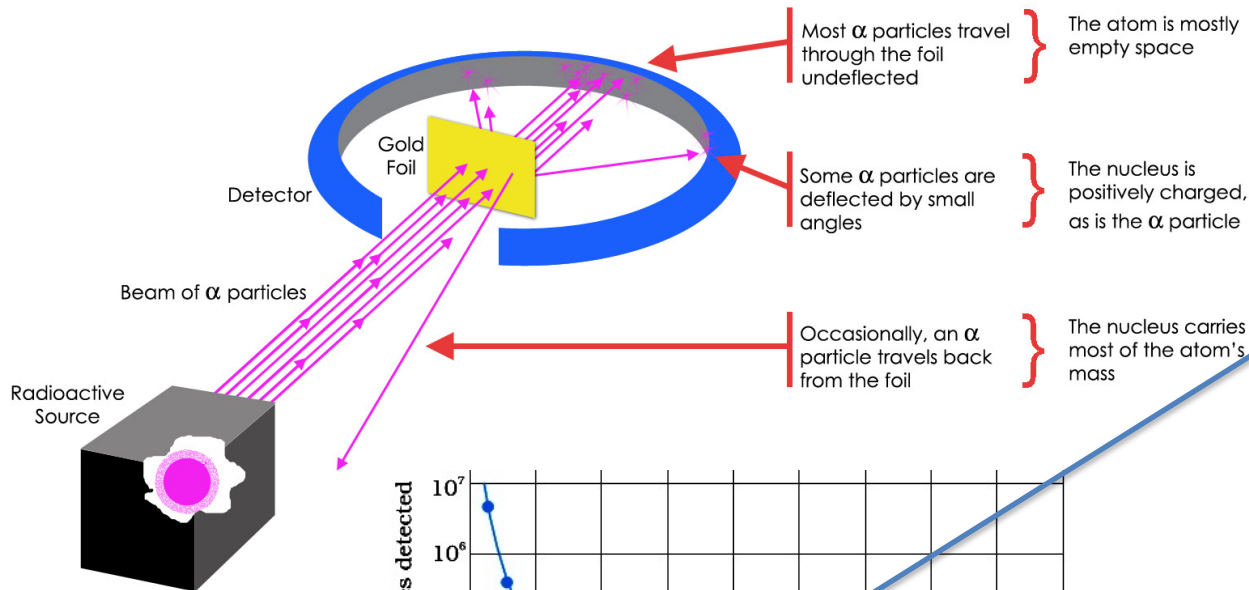
- Elastic scattering = free nucleon
 - Quasi-elastic = nucleon in a nucleus
 - Inelastic = nucleon resonances, $W < 2$ GeV
 - Deep-inelastic (DIS) = partons
-
- Proton = uud
 - Neutron = ddu
 - $\Delta^{++} = uuu$
 - DIS = $W > 2$ GeV



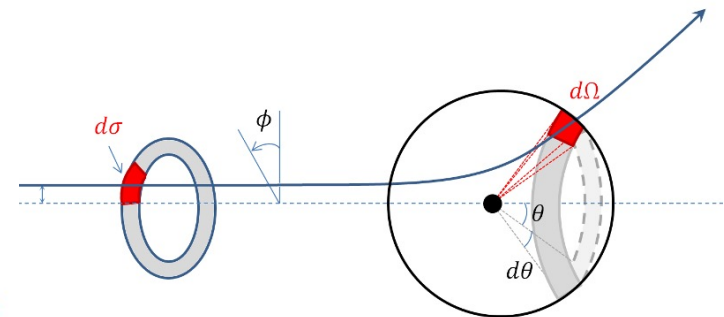
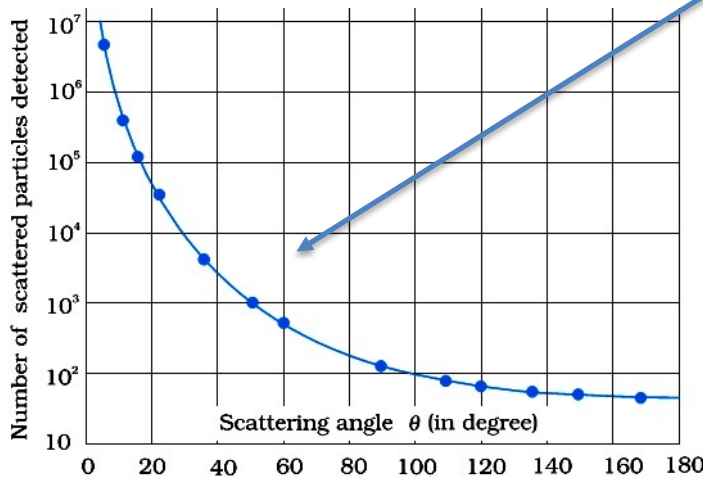
Coulomb scattering from a point-like charge

Not included: magnetic contribution, relativity, spin, Au recoil

Rutherford's Gold Foil Experiment

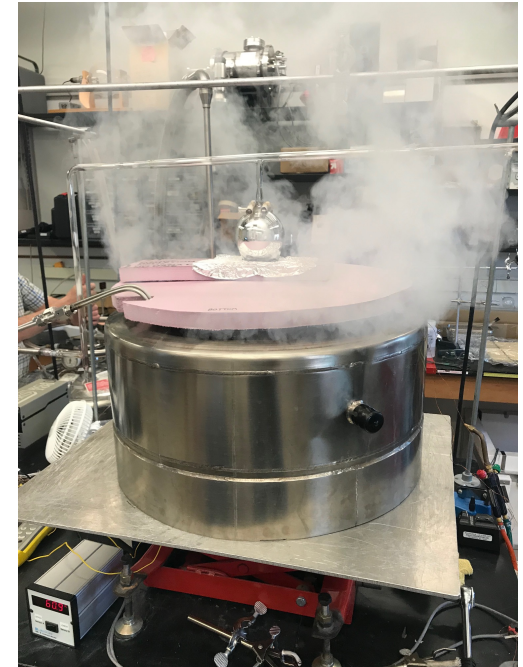
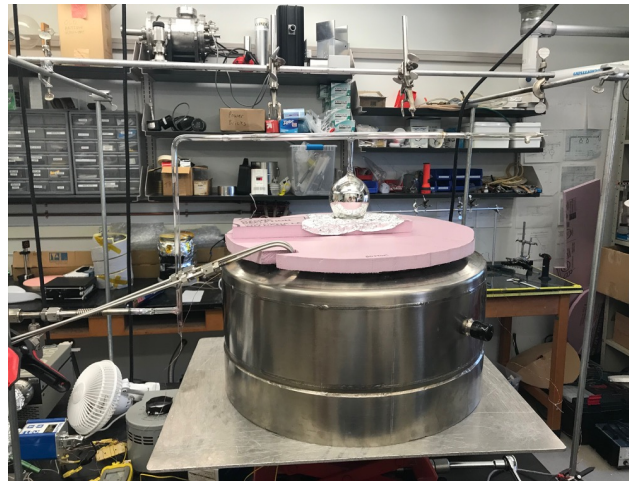
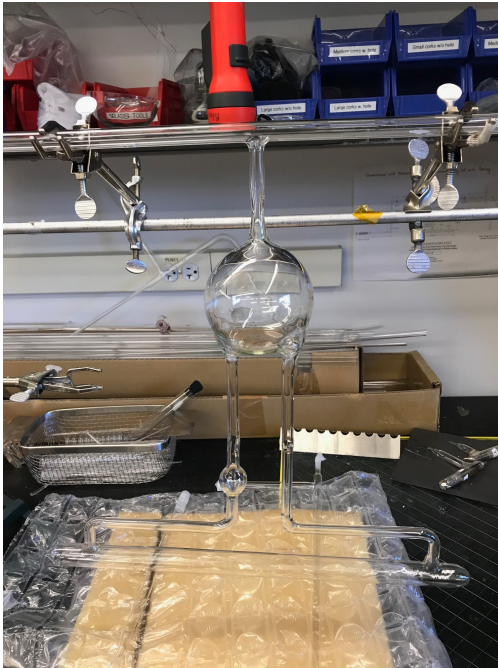


$$\frac{d\sigma}{d\Omega} = \frac{Z^2 \alpha^2}{4E^2} \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$



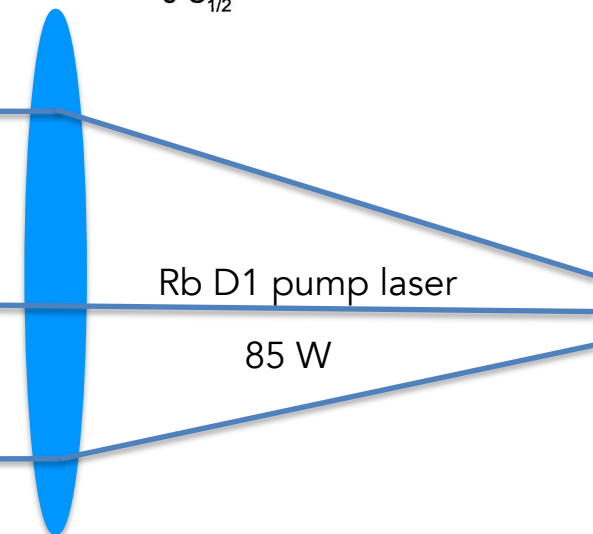
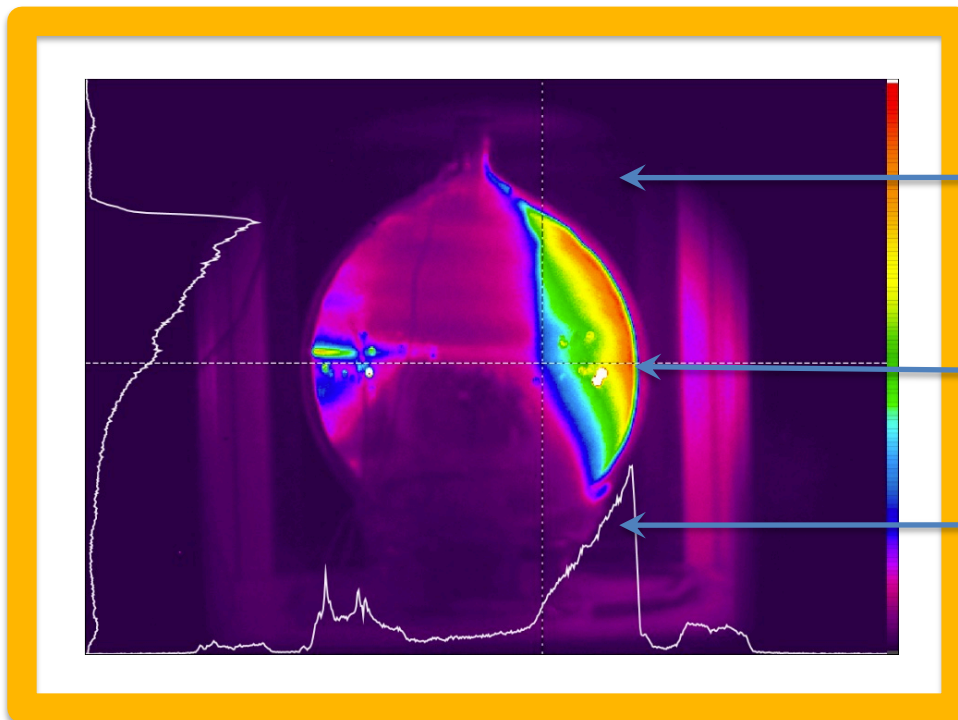
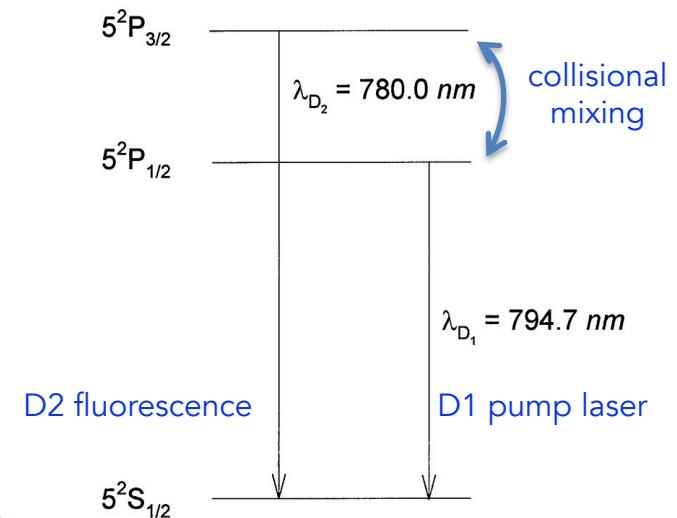
Target cell filling at W&M

- Cells constructed at Princeton by Mike Souza
- Attach to vacuum system
- Pump and bake cell to 10^{-9} Torr
- Fill with ^3He at ~ 10 atm
- Cool down with liquid ^4He
- Cell pull-off with hand torch





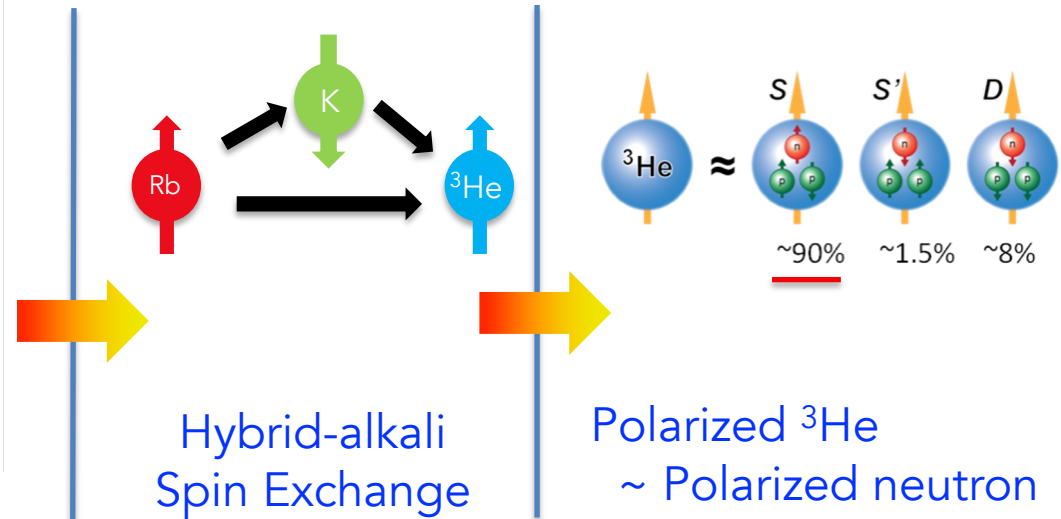
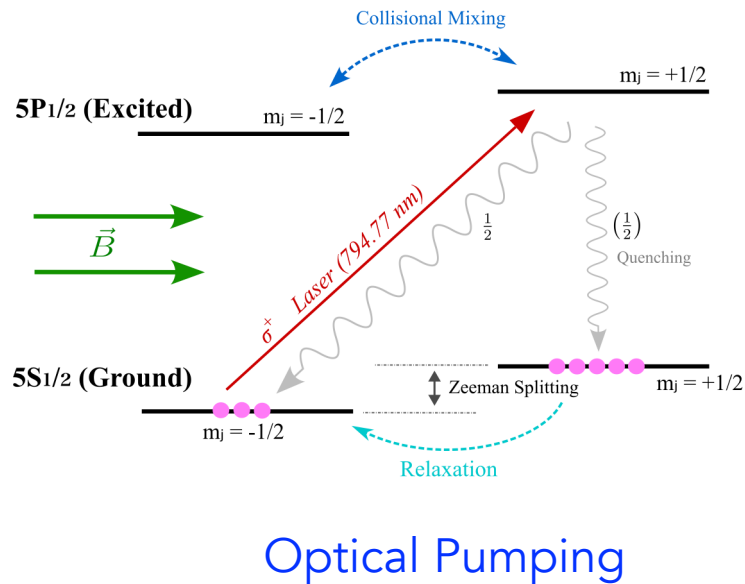
- New undergraduate project (Lauren Vannell)
- Study the characteristics of optical pumping by monitoring D2 fluorescence.
- Variables: laser intensity, spot size, circular polarization, incident angle, alkali density...



How to polarize ^3He ?



- Sealed aluminosilicate glass cell with 8 atm ^3He gas, trace Rb, K, N_2
- Principle: Optical Pumping of Rb followed by Spin Exchange with K atoms and ^3He nuclei $\rightarrow$ SEOP

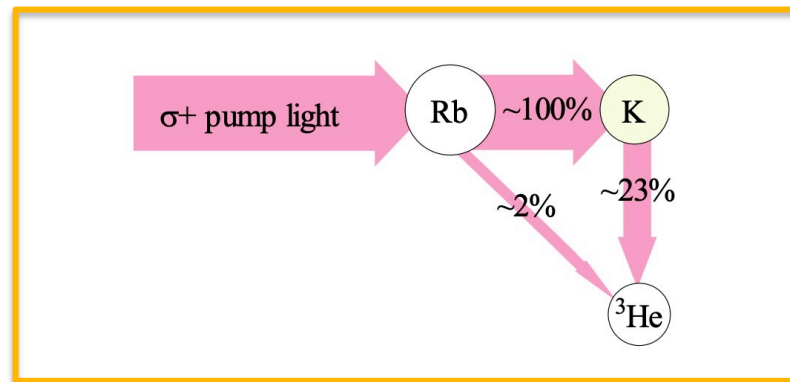
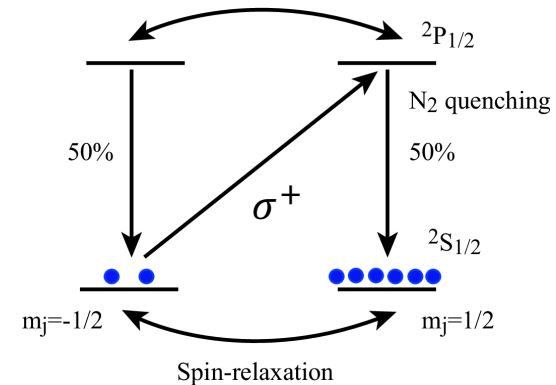


The polarization process - SEOP



WILLIAM & MARY
CHARTERED 1693

- Place cell in $B \sim 25$ G field
- Optically pump Rb D1 transition I upper chamber
- Spin exchange to K
- Rb, K spin-exchange with ^3He nuclei
- Convection to circulate gas



$$P(t) = \langle P_A \rangle \left[1 - e^{-\left(\frac{\gamma_{SE}}{\gamma_{SE} + \Gamma} \right)} \right]$$

γ_{SE} = alkali - ^3He spin exchange rate

Γ = all ^3He spin relaxation mechanisms

- Require $\gamma_{SE} \gg \Gamma$