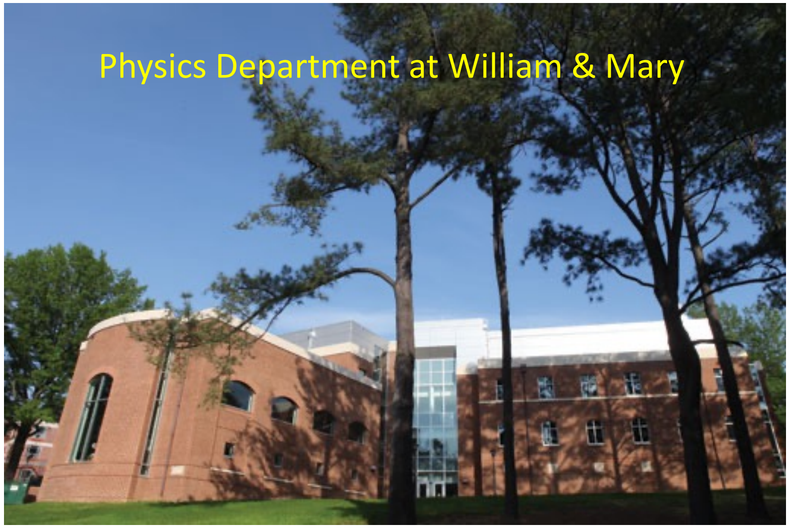
Exploring the Parton Structure of the Nucleon through Precision Electron Scattering Experiments at Jefferson Lab

Todd Averett, William & Mary



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- Postdoc: *Eric Fuchey*
- Undergraduates: *A. Swartz, C. Cassidy*

Research Supported by DOE Grant DE-FG02-96ER41003

Outline

- Overview and Motivation
- Nucleon charge and magnetization from elastic e-N scattering
- Quark structure using deep-inelastic scattering
- Hardware: Polarized ^{3}He at William & Mary
- Hardware: Particle detectors
- *Quantum Enhanced Tracker (QET) project

Nucleon Structure Studies

GOAL: Understanding the structure of the nucleon in terms of its constituent parton

- **The players:** 3 valence quarks, $q\bar{q}$ pairs, gluons
- Quarks are spin ½, electrically charged, color charged, interact via the strong nuclear force
- Gluons are spin 1, electrically neutral, color charged, self-interacting, strong force mediator

proton/neutron properties

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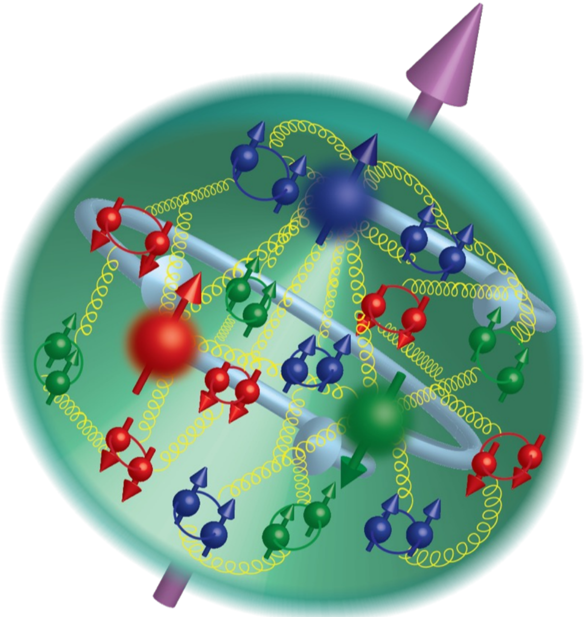
Mass ~ 1 GeV
Spin = ½
Charge = 0/1 (n/p)
Radius ~ 1 fm
Mag. moment (μ_N)= 2.79/ -1.91 (p/n)

Dirac moment = 1/0 (p/n) $\mu = \frac{e\hbar}{2m}$

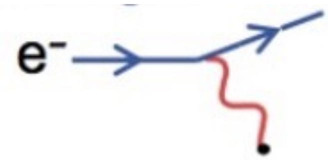
Motivation-How to make a nucleon?

- Where do quarks physically reside?
- What is the charge distribution inside the nucleon?
- How does the nucleon get its mass when the bare quark mass is ~ *2-5* MeV
- What is the spatial spin distribution?
- What contributes to spin = ½ ?
  - Quark and gluon spin?
  - Quark and gluon angular momentum?
- What is the role of $q\bar{q}$ pairs? gluons?
- Why contributes to the magnetic moments?

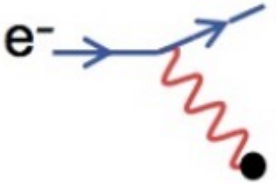


e-*N* scattering – a quark microscope

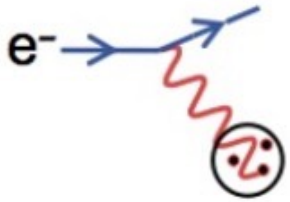
de Broglie Wavelength $\lambda = \frac{h}{p}$ ⇨ Studying the internal structure of the nucleon (N) requires a probe with energy ~1-12 GeV



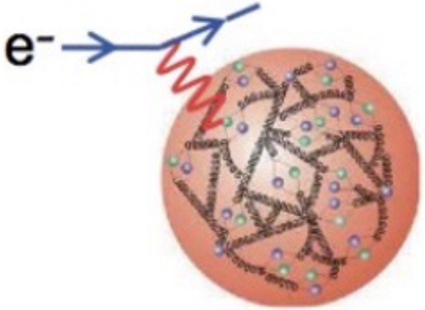
- Very low energy: nucleon = point-like $\lambda \gg r_N$



- 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 $\lambda \ll r_N$

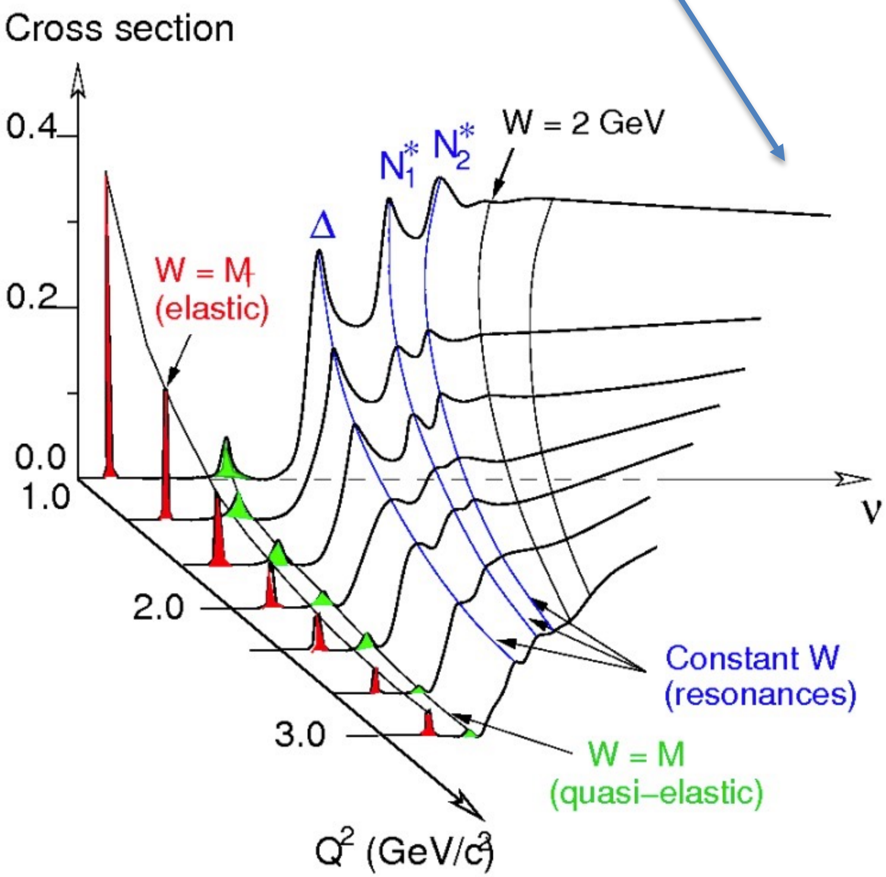
nucleon radius r_N ~ 1 fm

e-N Cross Section

- Elastic scattering = free nucleon
- Quasi-elastic = nucleon in a nucleus
- Inelastic = nucleon resonances, *W*<2 GeV
- Deep-inelastic (DIS) = partons

  - Proton = uud
  - Neutron = ddu
  - Δ^{++} = uuu
  - DIS = W >2 GeV

DIS

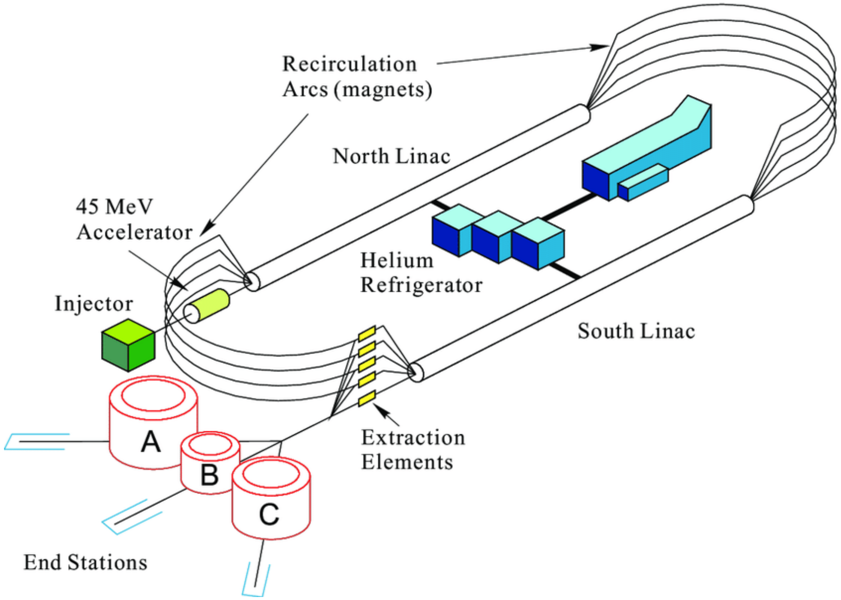


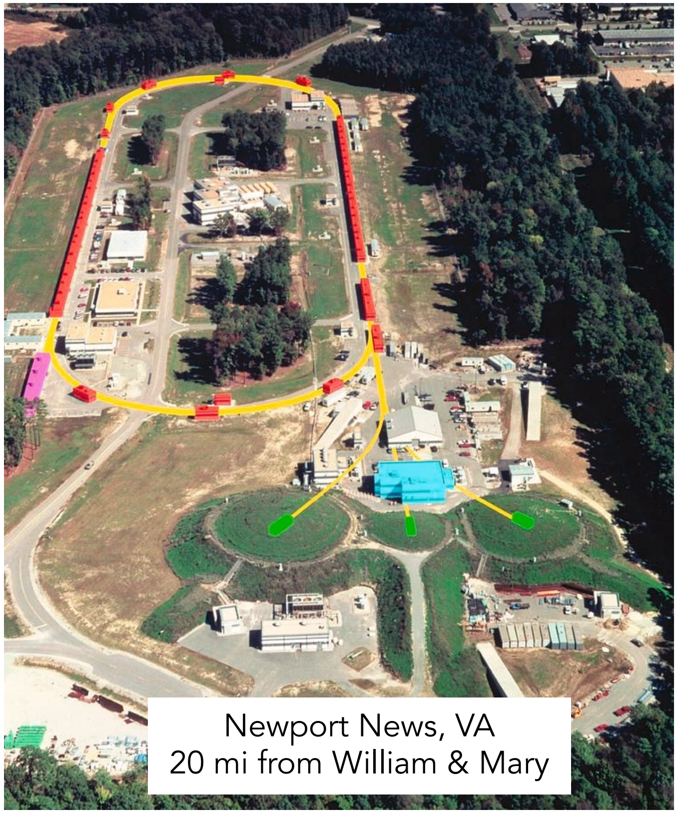
$$\lambda \sim \frac{1}{Q}$$

Thomas Jefferson National Accelerator Facility (DOE)

- Electron beam → EM scalpel, no strong interaction
  - Current up to 80 μA CW
  - Polarization ~ 85%
  - Energy 1-12 GeV
  - Diameter ~ 200 μm

- 4 experimental halls
  - Hall A – high resolution, large acceptance
  - Hall B – 4π spectrometer → multi-particle
  - Hall C – High momentum
  - Hall D -- *e-* → *γ*: meson spectroscopy





Newport News, VA
20 mi from William & Mary

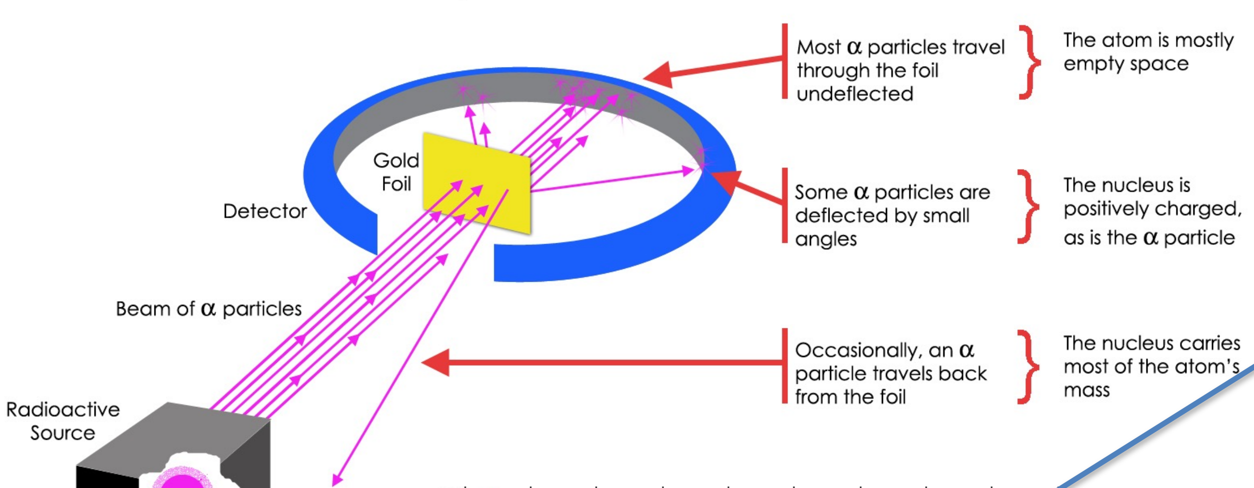
- My primary research at Jlab:
  Neutron structure studies using polarized electron scattering from polarized ^{3}He (n) targets

Introduction to Scattering: Rutherford

Coulomb scattering from a point-like charge

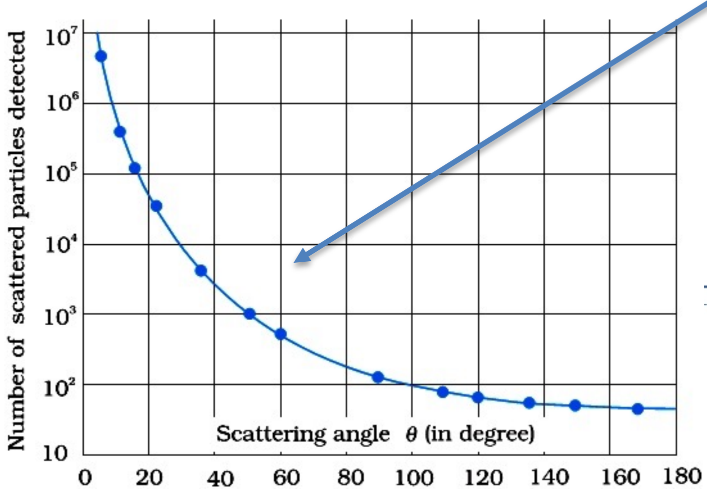
Not included: magnetic contribution, relativity, spin, Au recoil

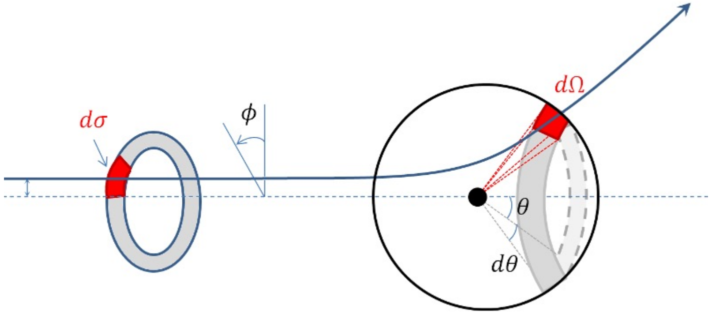
Rutherford's Gold Foil Experiment



Observation	Interpretation
Most α particles travel through the foil undeflected	The atom is mostly empty space
Some α particles are deflected by small angles	The nucleus is positively charged, as is the α particle
Occasionally, an α particle travels back from the foil	The nucleus carries most of the atom's mass

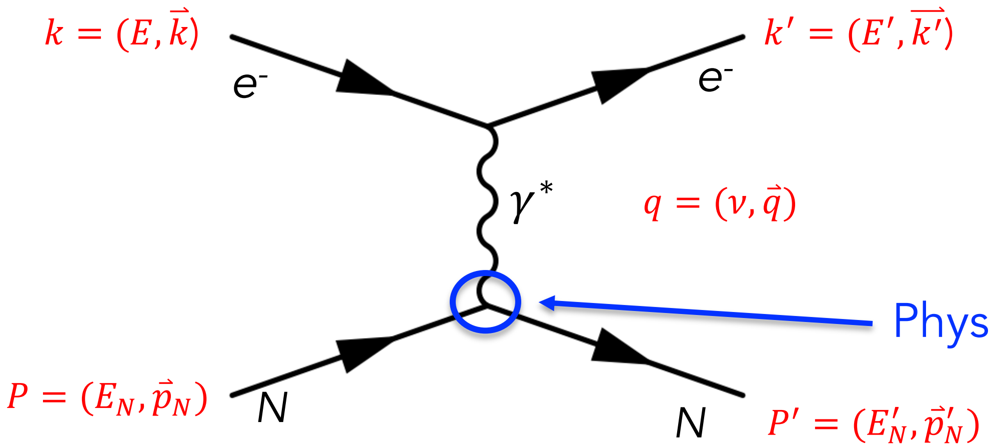
$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2}{4E^2}\frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$





Quantum Description

- Mott scattering = point-like scattering + relativistic + electron spin



Physics happens here

Measure in lab frame: E, E', θ_{scat}

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth} \cos^2\left(\frac{\theta}{2}\right)$$

Kinematic variables

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

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e-*N* Elastic Scattering Cross Sections

Rosenbluth formula

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

$$\epsilon = \left(1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$$ γ^* polarization

---

$G_E(Q^2) =$ 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*

- <u>At Q^2 = 0 we expect</u>

- Charge

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

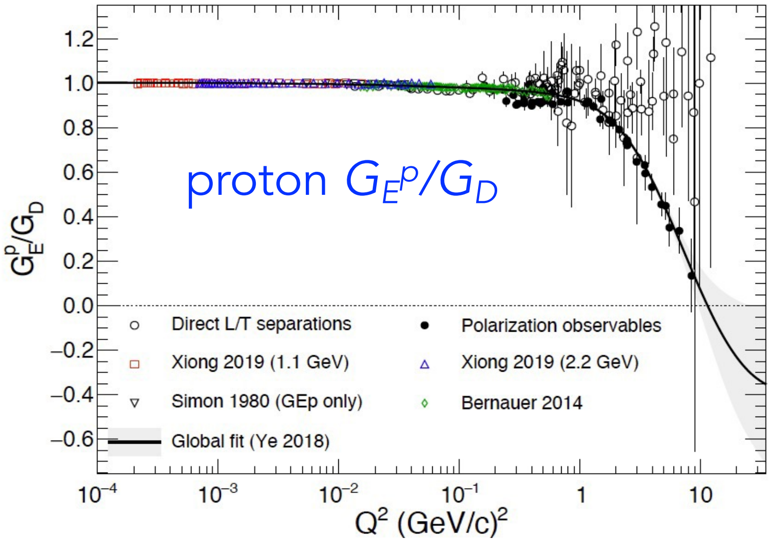
- Magnetic moment

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

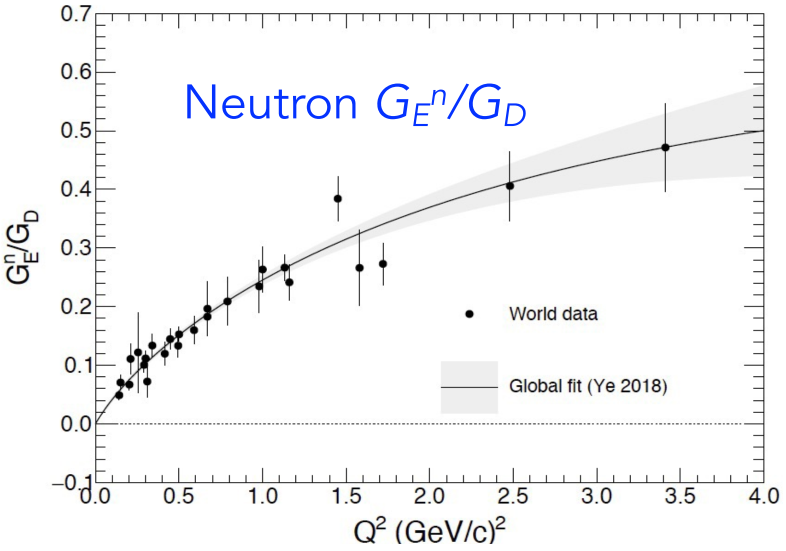
- But cannot measure at $Q^2 = 0$
- Fit data to get intercept

World Form Factor Data versus Dipole FF

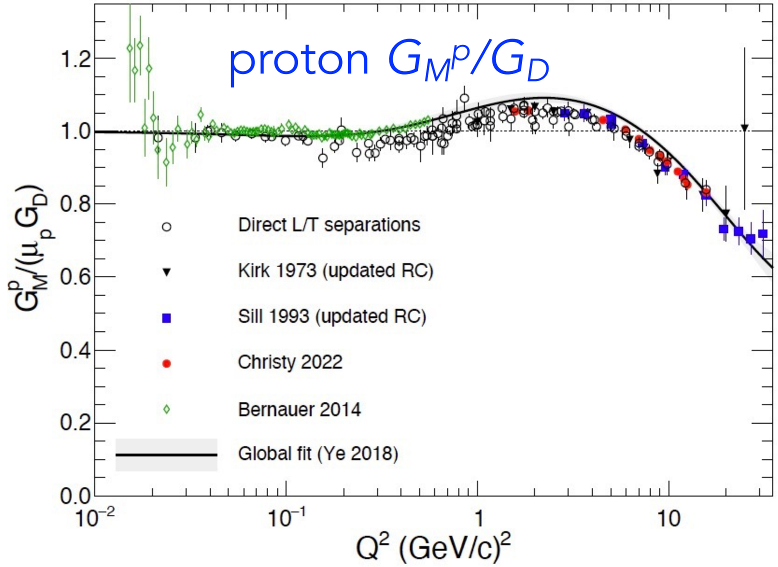
- Sachs form factors ~ not too different from dipole FF at lower Q^2 (ex. G_E^n)
- Lots of nucleon dynamics entering at large Q^2



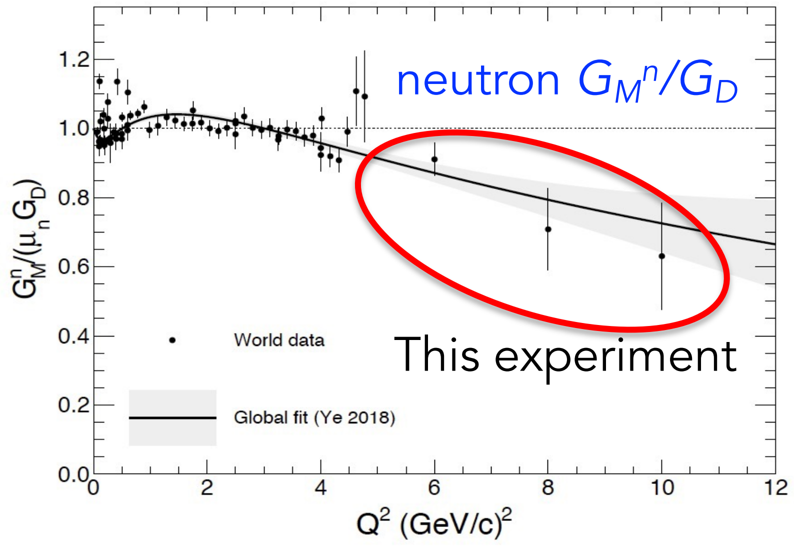
proton G_E^p/G_D



Neutron G_E^n/G_D



proton G_M^p/G_D



neutron G_M^n/G_D

This experiment

Plots from "50 years of QCD", 729 pages! hep-ph>arXiv:2212.11107

Form factor interpretation

- What do these form factors tell us?

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

$$\langle r_p^2 \rangle \simeq 0.717 \pm 0.014 \text{ fm}^2 \qquad \langle r_n^2 \rangle \simeq -0.11 \pm 0.008 \text{ fm}^2$$

- Proton-- ~agreement between e-N and atomic measurements

- In the neutron case, it is the 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) arXiv:2105.00571

Charge distribution

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

Magnetization distribution

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

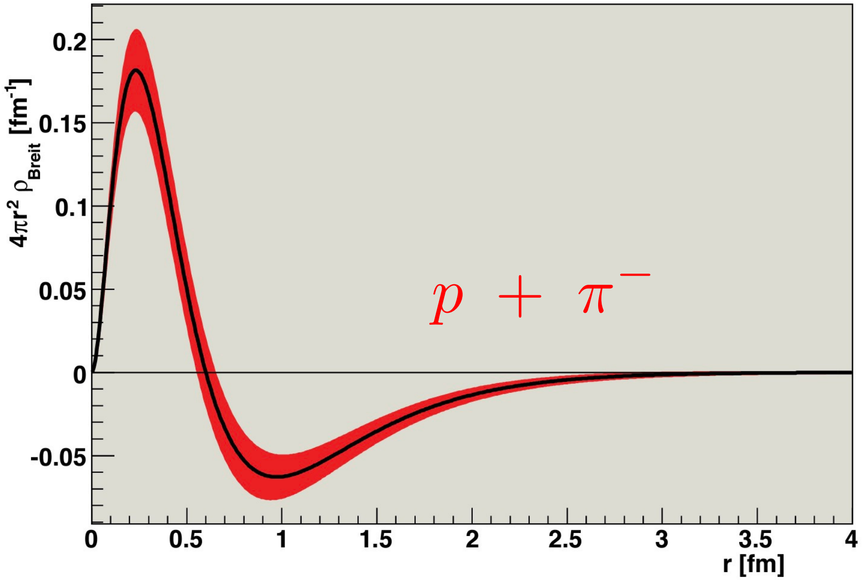
- Experimentally these limits cannot be reached

Neutron Charge Distribution

What is the charge distribution within the nucleon? → Frame dependent 👿

- Non-relativistic: Fourier transform of lab frame spatial distributions
- With relativistic corrections: No probabilistic interpretation, $|p_f| \neq |p_i|$
- **Breit Frame**: $\vec{p_i} = -\vec{p_f}$ → probabilistic interpretation but…model-dependent boost corrections

$4\pi r^2 \rho(r)$ **Breit Frame** neutron



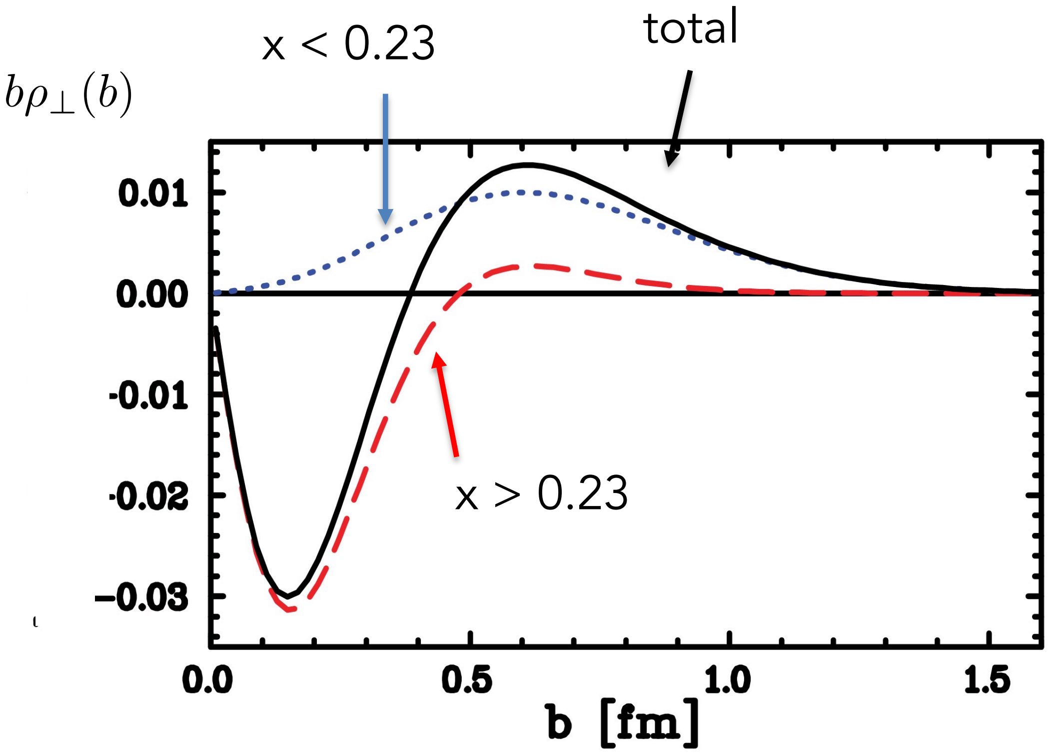
NSAC 2007 Report, "recent achievement"

→ *The charge distribution of the neutron was mapped precisely and with high resolution. The measurements confirmed that the neutron has a positively charged core and a negatively charged pion cloud.*

Neutron Charge Distribution in IMF (2008)

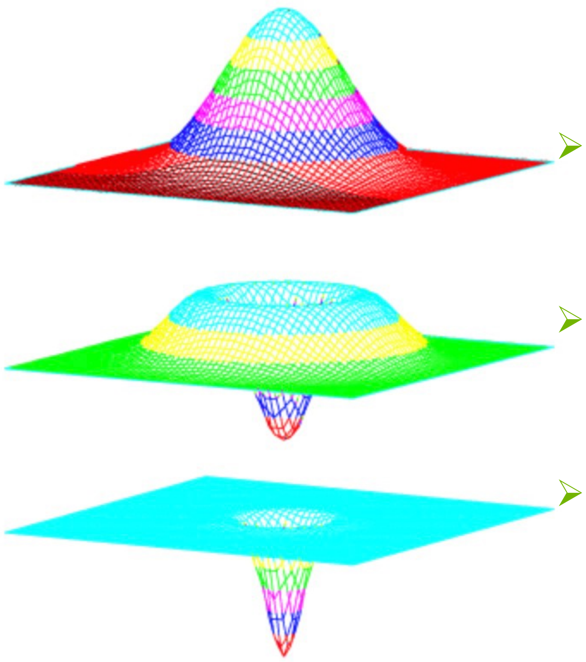
- **IMF - Infinite Momentum Frame**: Model-independent interpretation
- No recoil correction needed

Transverse charge density vs. *b* *found to have negative core…hmmmm…*



Miller, Arrington PRC 78, 032201 (R) (2008)

Transverse charge distribution



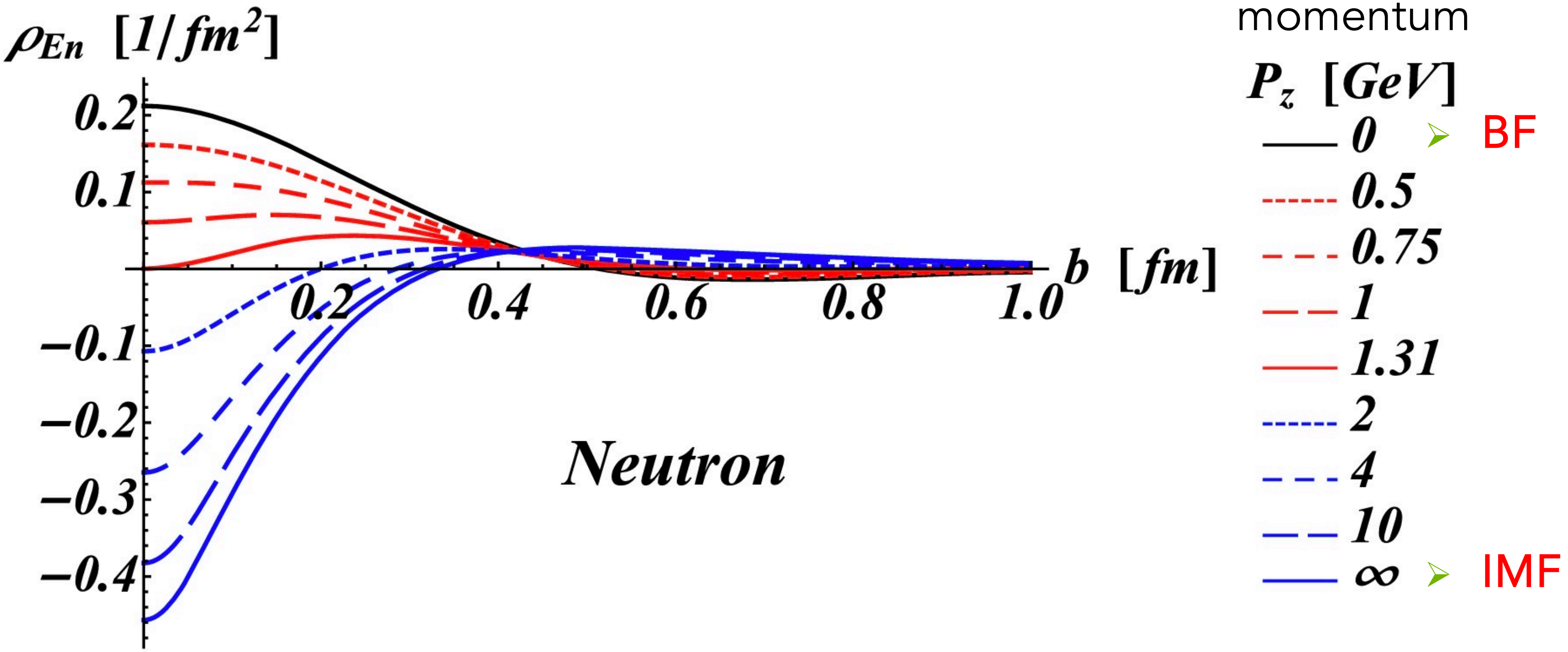
- Low x
- Med x
- High x

John Arrington, ANL

Phase Space Interpretation (2020)

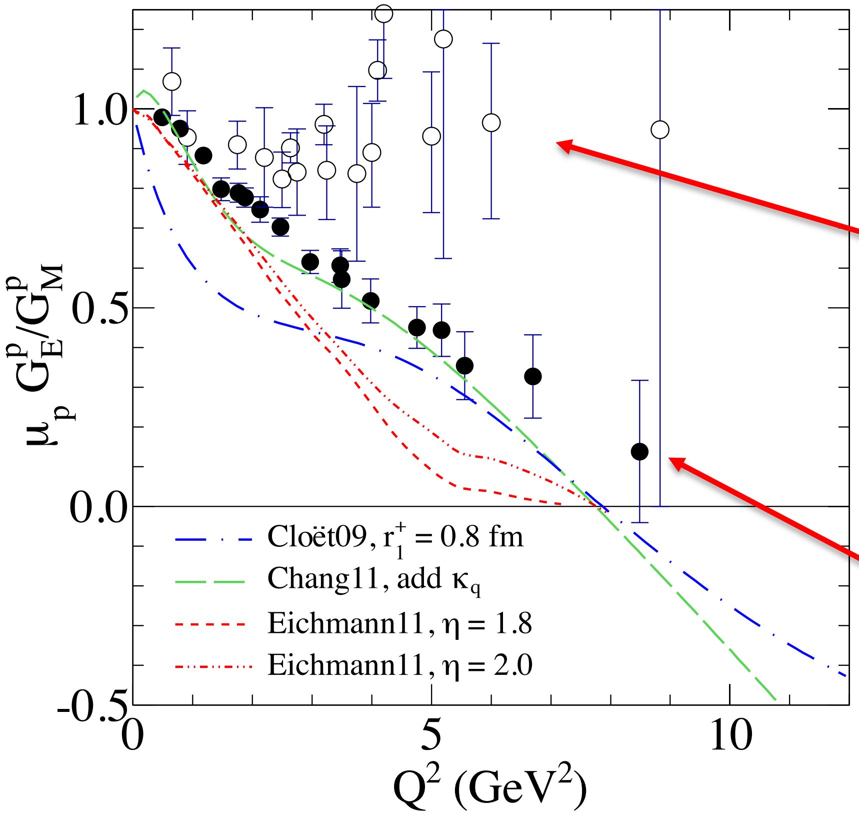
Appearance (disappearance) of negative neutron core in IMF (BF) is due to contribution from magnetization as nucleon momentum increases. Interpreted as the frame-dependence of the direction of the nucleon polarization.

P_z = average longitudinal momentum



C. Lorce, PRL 125, 232002 (2020)

World data for proton $G_E(Q^2)$



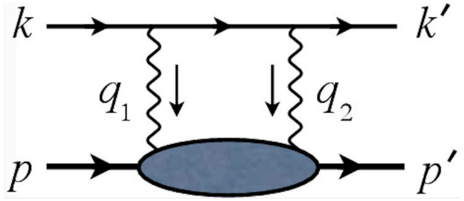
- Cannot keep decreasing with Q^2
- Data needed at higher Q^2 - *Stay Tuned*

A.J.R Puckett, et al.,
Phys.Rev.Lett. 104 (2010) 242301

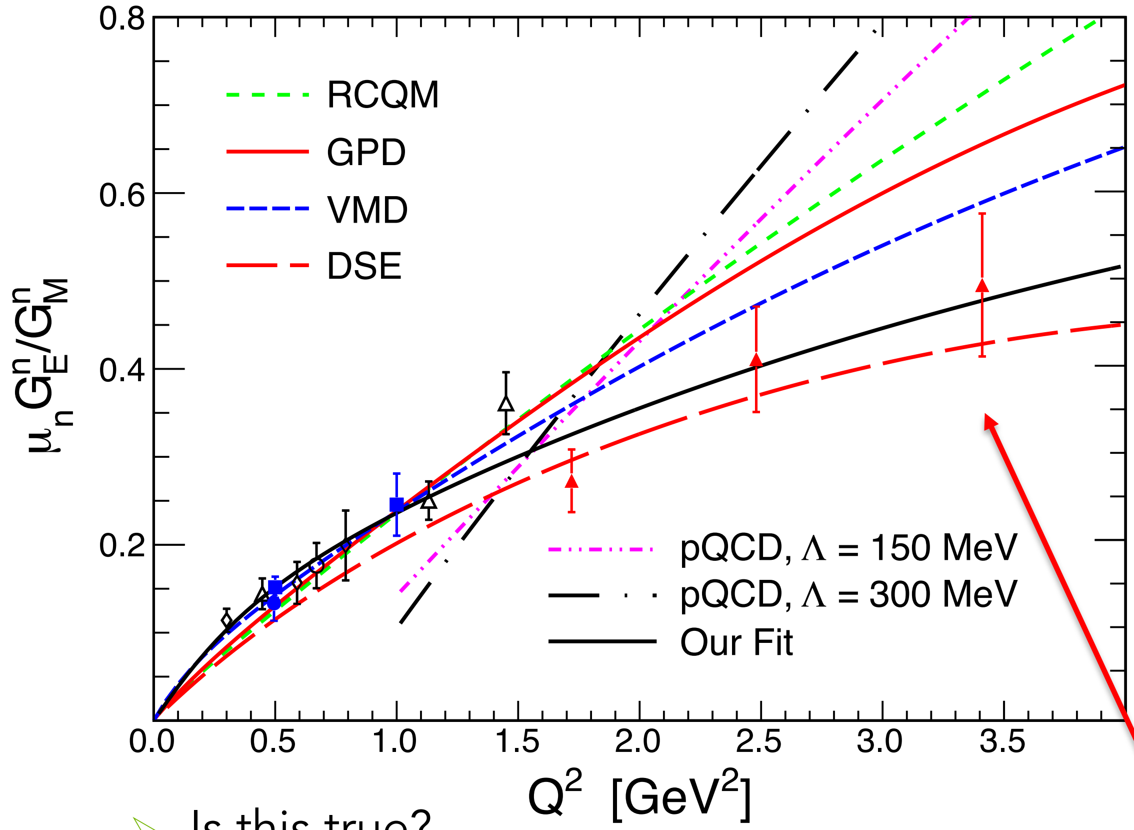
If charge and magnetization have the same spatial distribution:

expect →
$$\frac{\mu_p G_E^p(Q^2)}{G_M^p(Q^2)} = 1$$

- proton measured to 8 GeV^2 at JLab
- completely unexpected decrease
- 2-γ exchange was ignored.
  JLab precision



World data for neutron $G_E(Q^2)$



- Measured to Q^2 ~ 3.5 GeV^2
- Not converging at all
- Hard to do Fourier transform with data to only 3.5 GeV^2
- Theory all over the place
- Data at higher Q^2 needed

- Is this true?

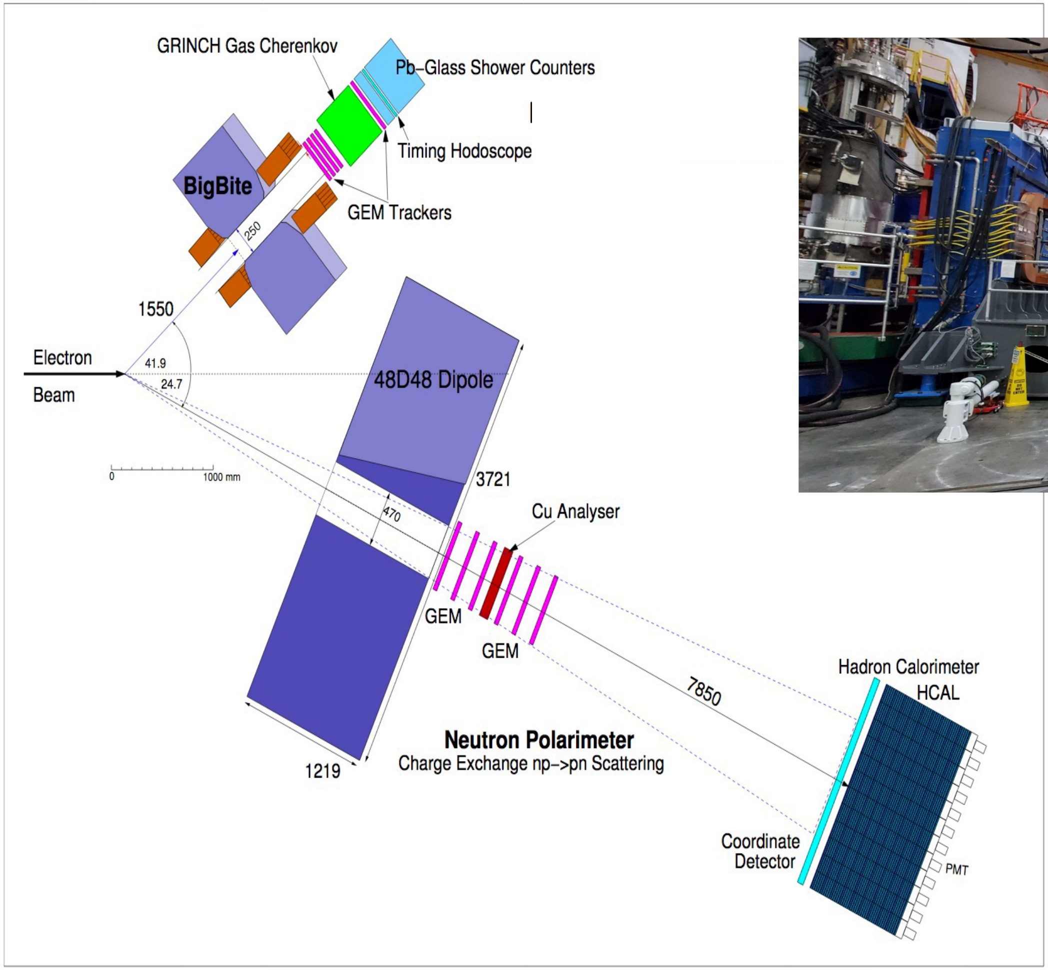
Again, if charge and magnetization have the same spatial distribution:

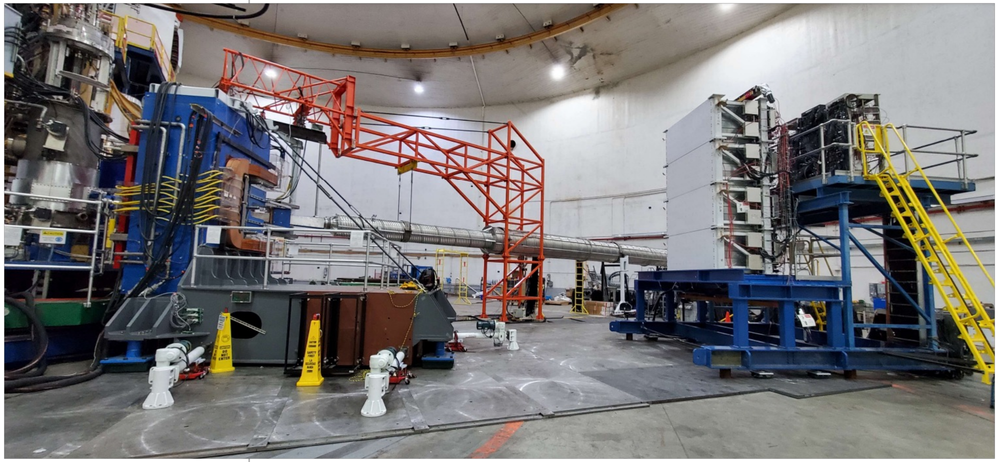
expect →
$$\frac{\mu_p G_E^n(Q^2)}{G_M^n(Q^2)} = 1$$

Red triangles: *S. Riordan, …, T. Averett*
Phys.Rev.Lett. 105 (2010) 262302

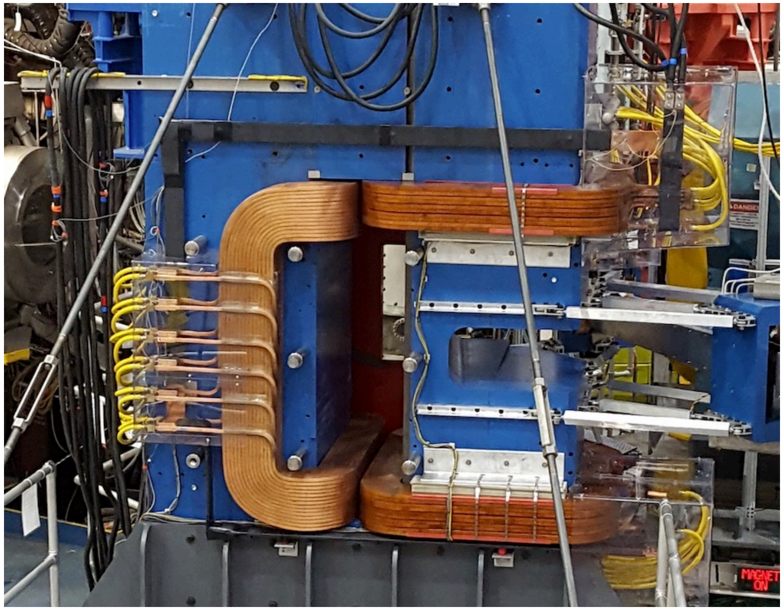
SBS spectrometer system

- Small cross sections require spectrometers with large angular and momentum acceptance
- SBS = Super Big Bite Spectrometer system (SBS): electron spectrometer (BigBite) and hadron calorimeter (HCAL)



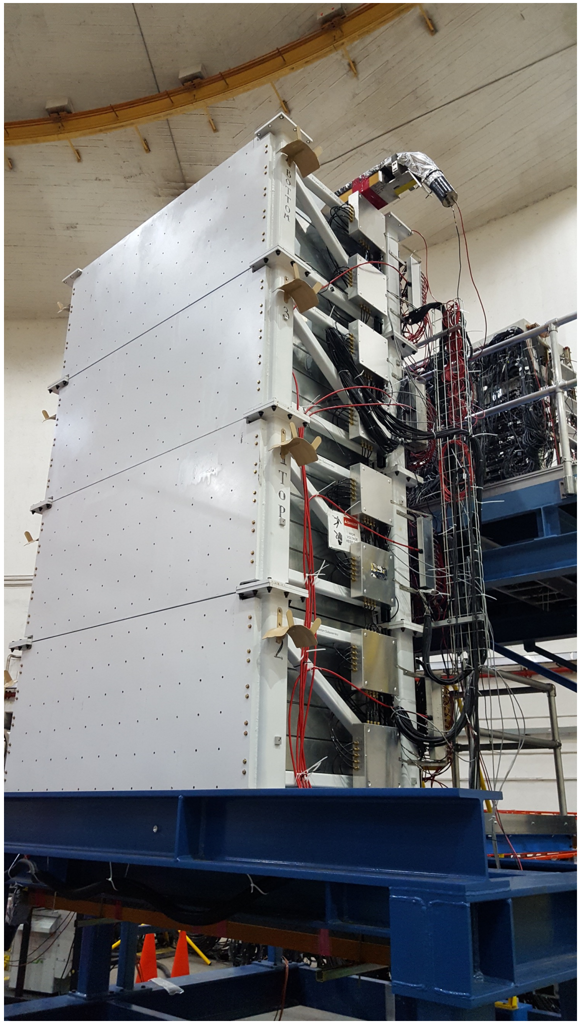


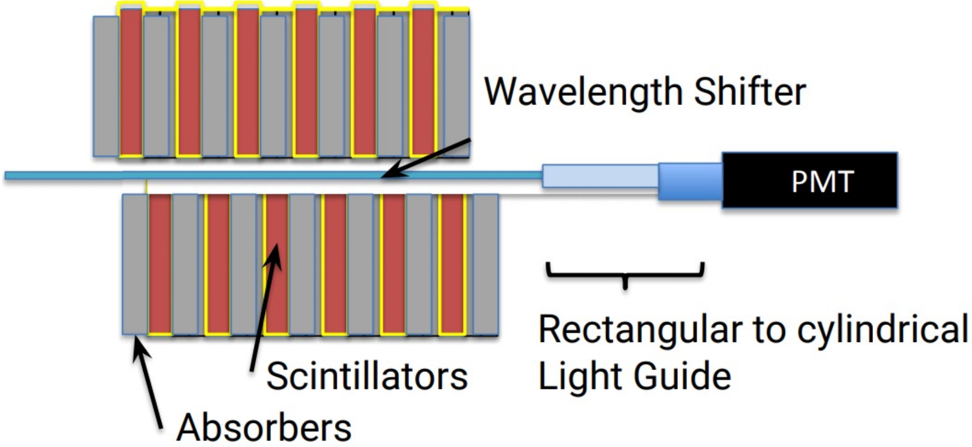
Hadron calorimeter



Sweeper magnet for p/n separation

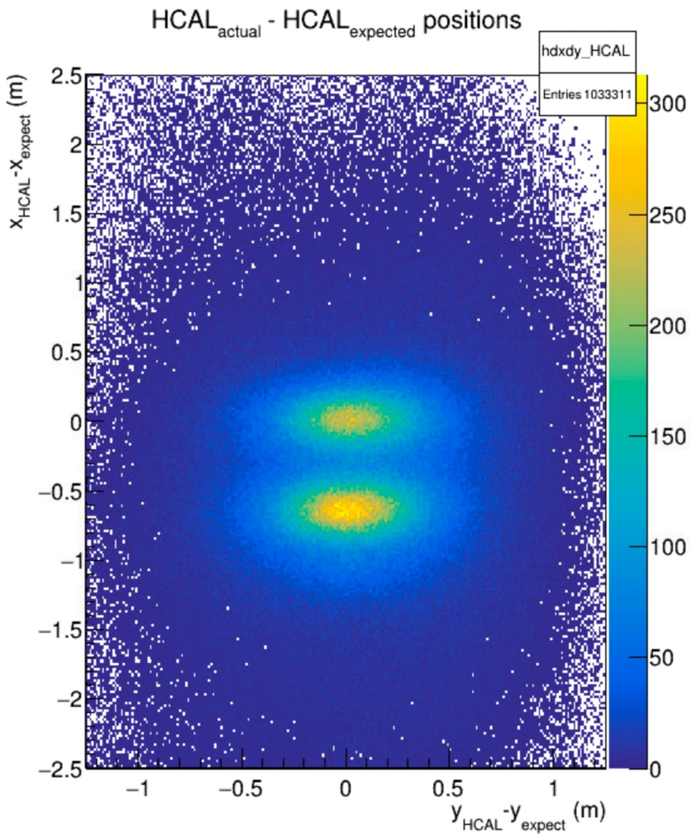
Hadron Calorimeter as currently installed

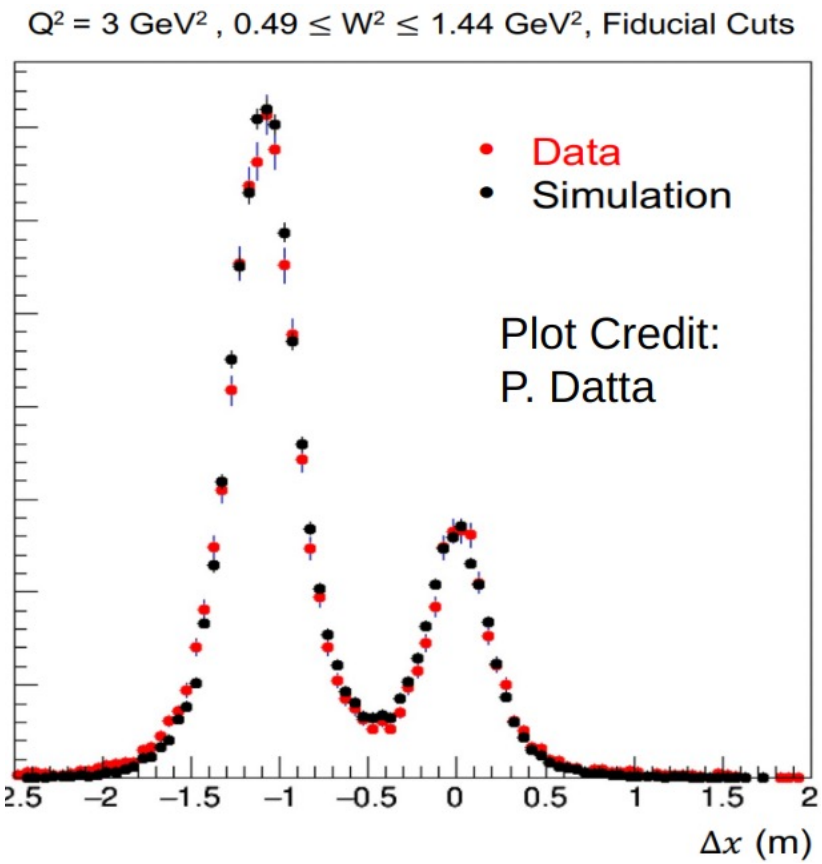




HCAL p/n events

- Protons are down-bended

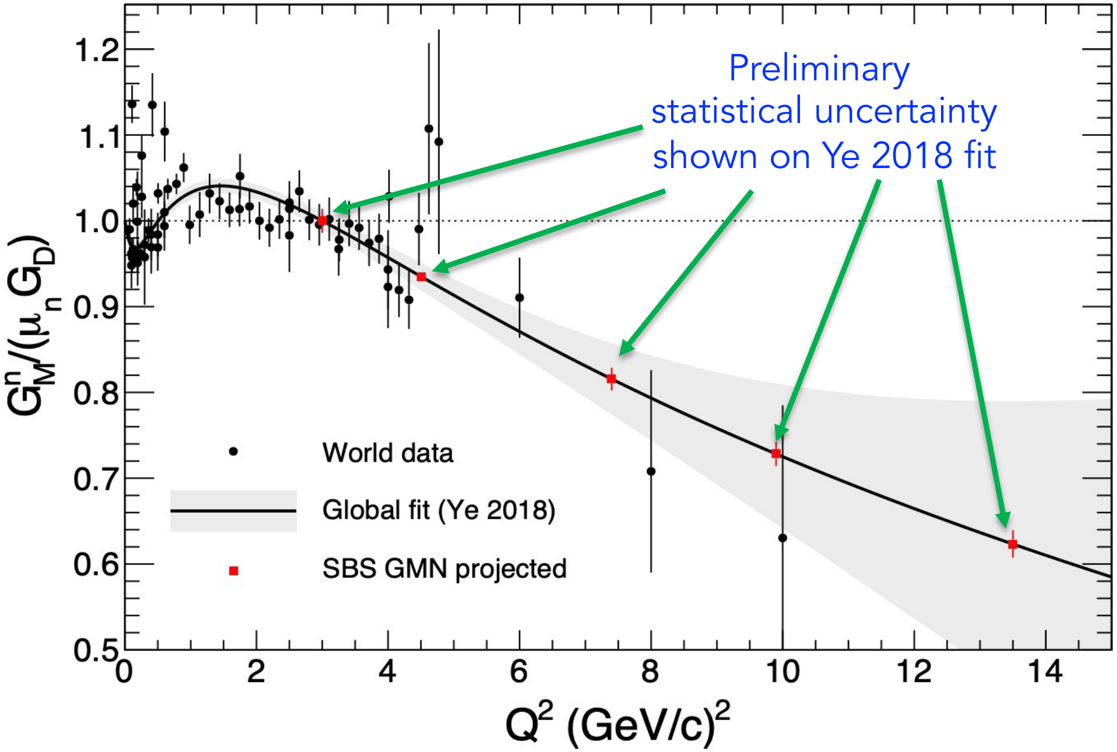




HCAL proton efficiency ~95%
Time resolution - currently 2 ns but expect 1 ns after additional calibration
Energy resolution ~30%

G_M^n Preliminary Statistical Uncertainties

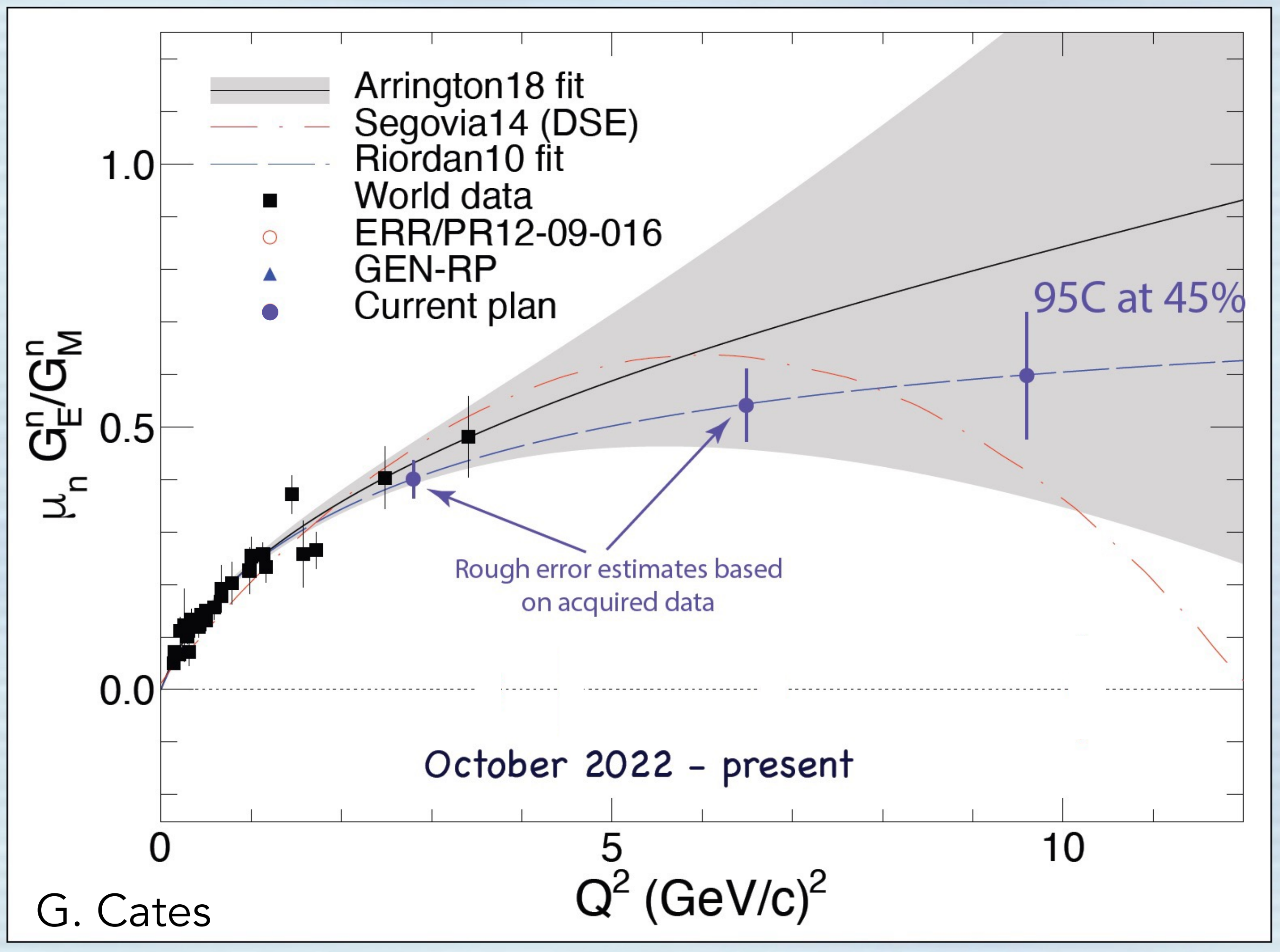
- Completed Feb. 2022
- Data analysis now on pass 2
- First results ~ Summer 2023
- Systematics ~ 3%



World data for $G_M^n/\mu_n G_D$ with **projected SBS accuracy** ***based on completed data taking 2021-2022***

Where are we? CURRENT STATUS

- First run complete $Q^2 = 2.9, 6.6$ + <u>some</u> 9.7 GeV^2
- Second run in progress at $Q^2 = 9.7$ GeV^2



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e-*N* Deep-inelastic Scattering Formalism

- Nucleon with extended structure

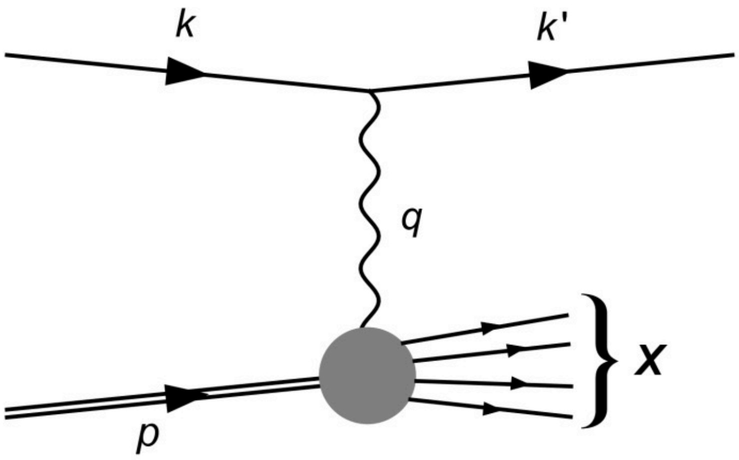
→ two unpolarized structure functions

$$W_1(\nu, Q^2),\ W_2(\nu, Q^2)$$

→ two polarized structure functions

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

$$N(e, e')X$$



$$\frac{d\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{E'}{E}\right) \left\{ W_2(\nu, Q^2) + 2W_1(\nu, Q^2) \tan^2\left(\frac{\theta}{2}\right) \right\}$$

$$\left(\frac{d\sigma}{d\Omega dE'}\right)^{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega dE'}\right)^{\uparrow\downarrow} \propto g_1(\nu, Q^2), g_2(\nu, Q^2)$$

- Add g1 terms

Parton Model and Bjorken Scaling

- Bjorken scaling: At large Q^2, ν with $x = \frac{Q^2}{2M\nu}$ finite, the scattering becomes the sum of incoherent elastic scattering from free quarks.
- x is the momentum fraction of the struck quark

$$W_1(\nu, Q^2),\ W_2(\nu, Q^2) \rightarrow \quad F_1(x),\ F_2(x)$$

$$g_1(\nu, Q^2),\ g_2(\nu, Q^2) \rightarrow \quad g_1(x),\ g_2(x)$$

Parton Model Interpretation

$$F_2(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 \left(q_i(x) + \overline{q_i}(x)\right),$$

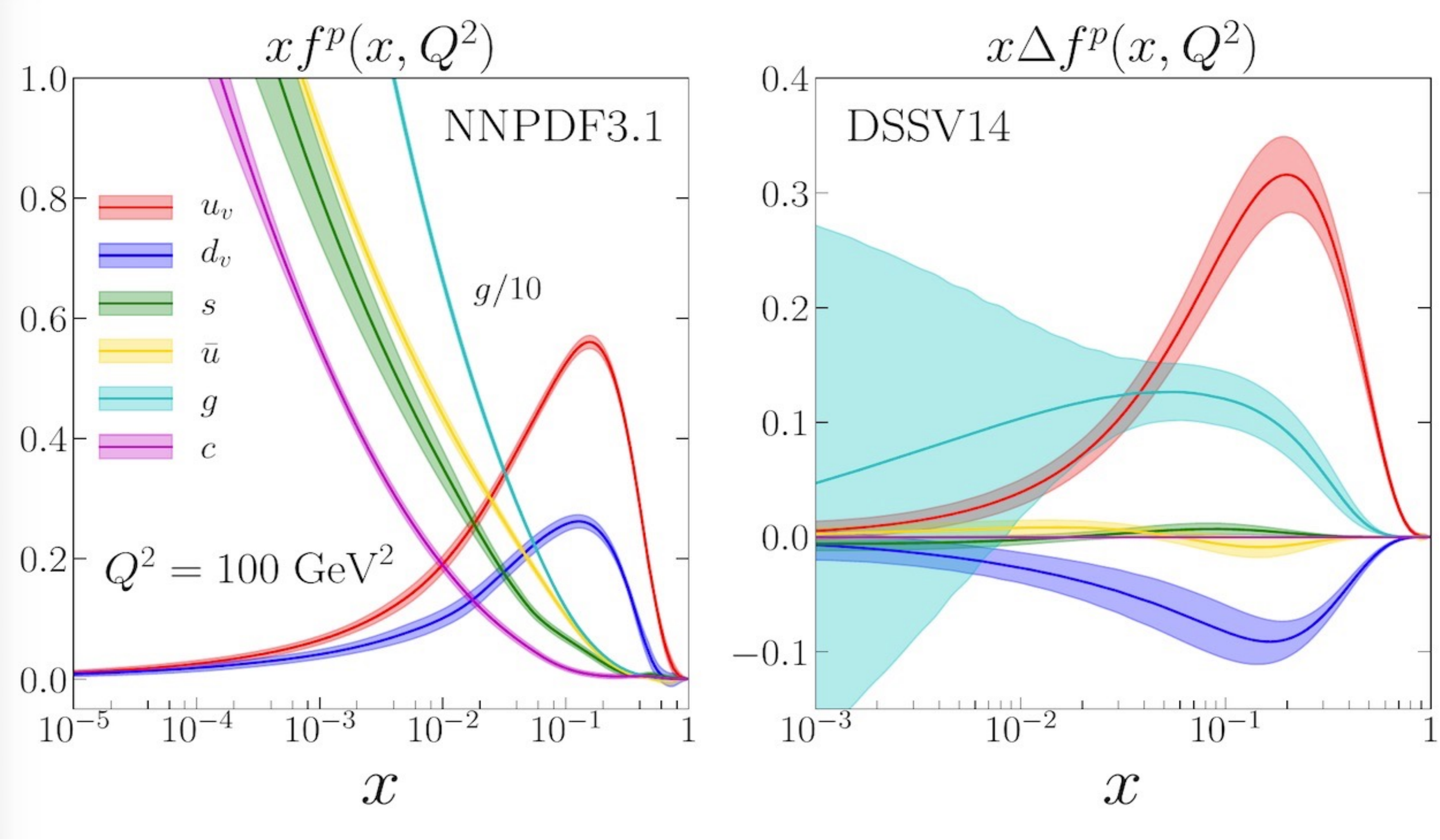
$q_i(x)$ = probability to find a quark with flavor *i* and momentum fraction *x*

$$g_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 \left(\Delta q_i(x) + \Delta\overline{q_i}(x)\right),$$

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

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

Unpolarized and polarized parton distribution functions



Where does the nucleon get its spin?

Quark contribution to nucleon spin

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

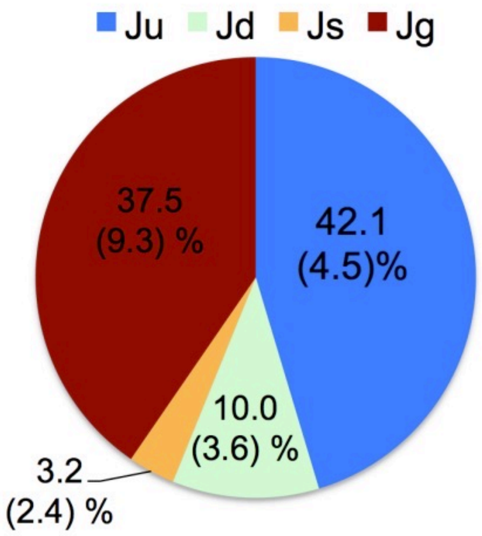
- EMC (1988) finds $\Delta\Sigma = 4 - 24\%$ 'Spin Crisis'
- Averett's thesis experiment, SLAC E143, re-measured with higher precision using polarized proton and deuteron targets → Crisis confirmed!
- Current status: $\Delta\Sigma \sim 15 - 35\%$ $\Delta s = -0.1 \pm 0.04$

S. Bass, Rev.Mod.Phys.77:1257–1302,2005

Ji Sum Rule $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

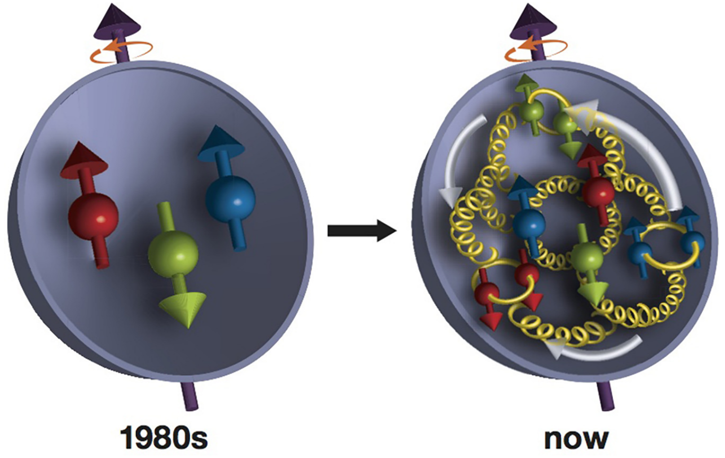
$\frac{1}{2}$ *= quark spin + quark angular momentum + gluon contribution*

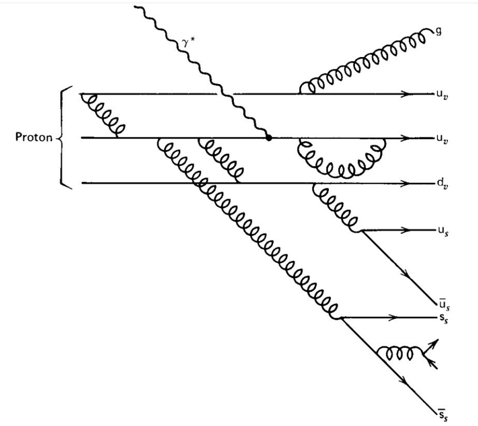
Lattice QCD calculation



X. Ji, F. Yuan, Y. Zhao, arXiv:2009.01291v1

So the nucleon is not so simple…





- QCD is not analytically solvable. Asymptotically free → non-perturbative
- BUT <u>valence</u> quarks dominate behavior as $x \to 1$; the only place theorists can make absolute predictions
- For access to the valence quarks, we measure the virtual photon asymmetry

$$A_1(x) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{g_1(x)}{F_1(x)}$$

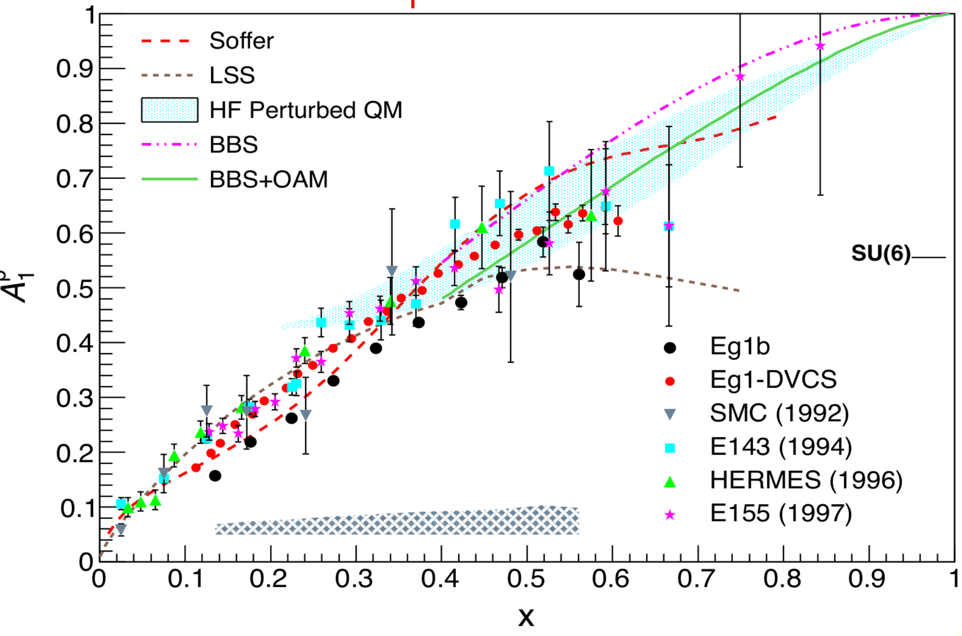
Scaling model

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

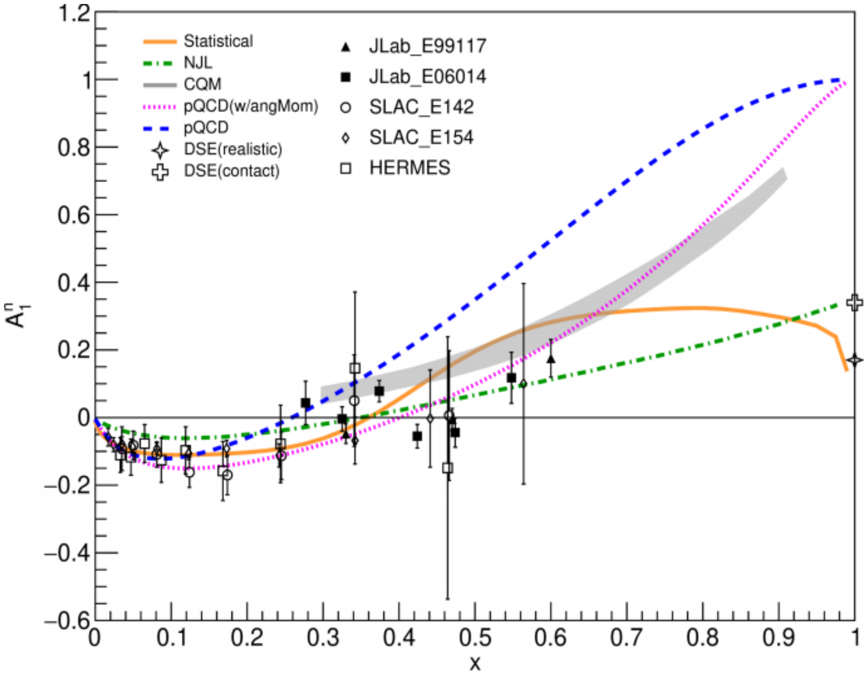
X. Zheng, UVa

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

proton



neutron



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

Both data sets support pQCD calculations (pink)

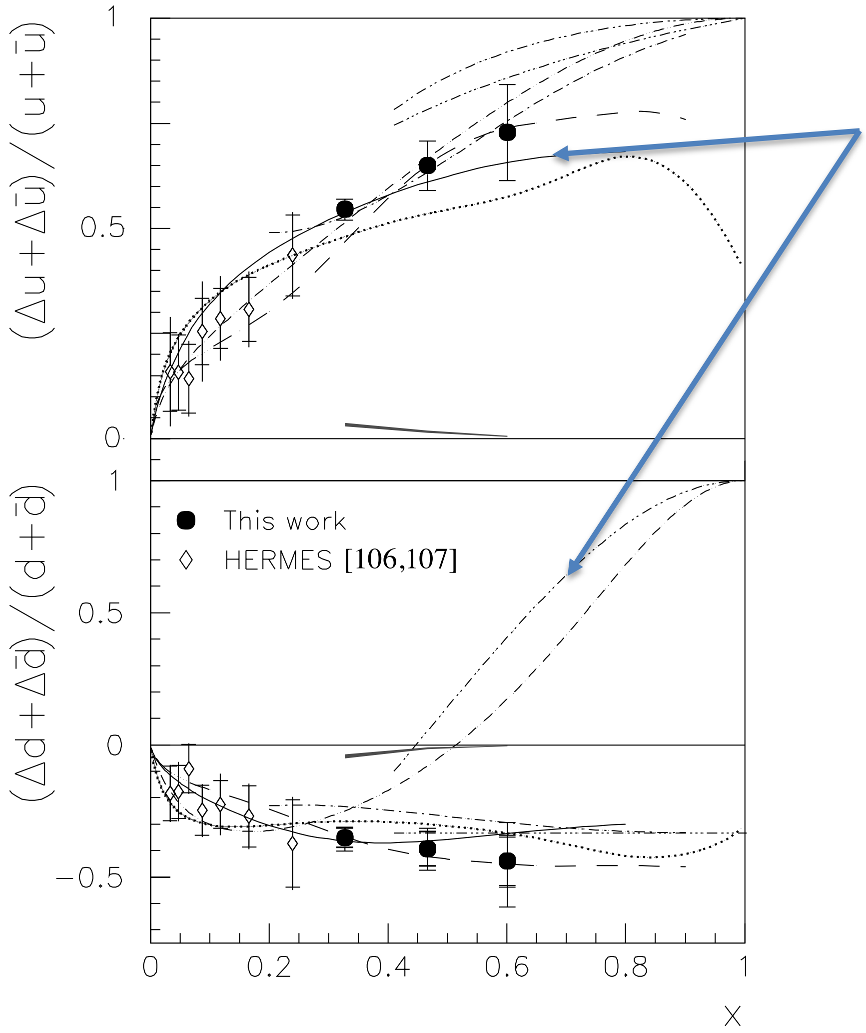
Simple parton model predictions:

- proton OK; neutron???
- Data needed at large x

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	$\frac{1}{5}$

S. Bass, Rev.Mod.Phys.77:1257-1302,2005

PDFs extracted by combining $A_1^p(x)$ and $A_1^n(x)$

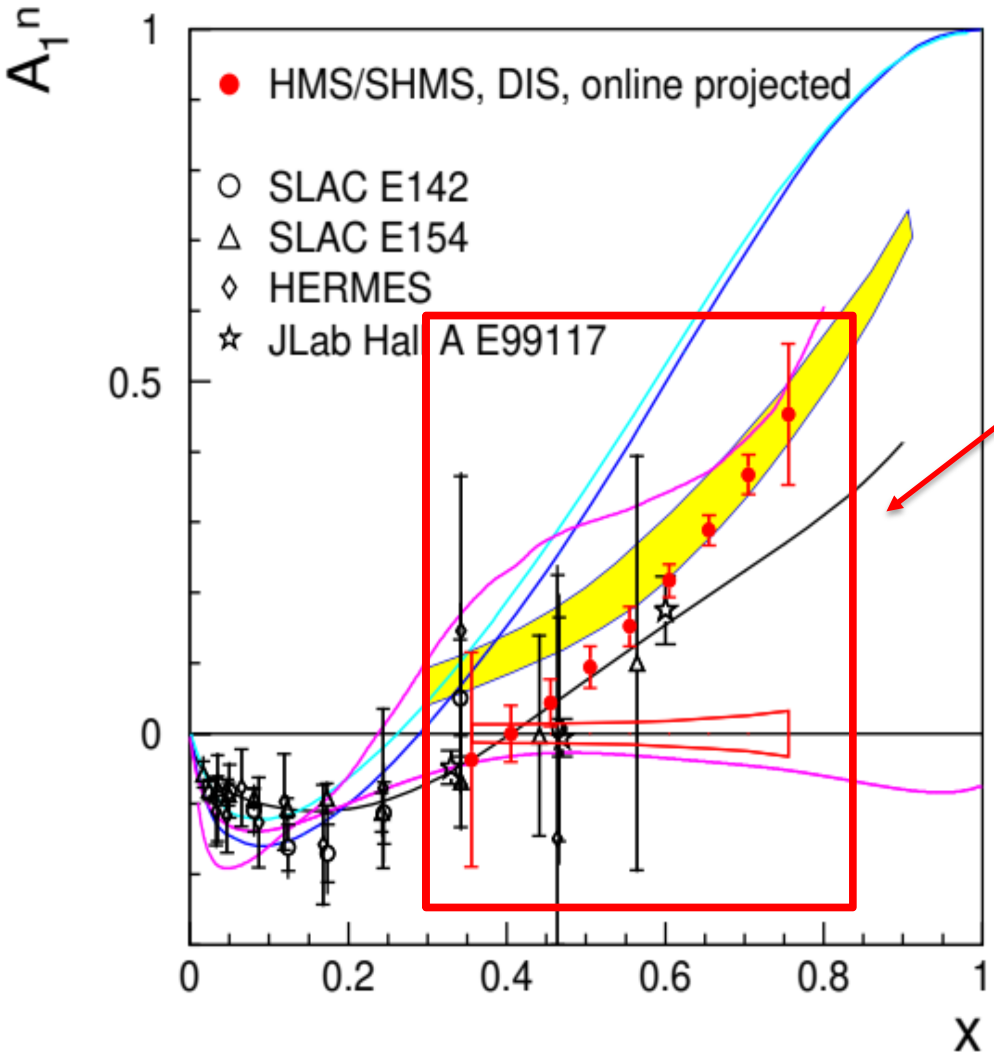


- pQCD with HHC works well for up quarks; not for down??
- Evidence of orbital angular momentum?
- Need more data at large x

X. Zheng,… T. Averett,
Phys.Rev.C 70 (2004) 065207

Latest Measurement of A_1^n – Reaching Higher x

- Measured up to x ~ 0.75 in the DIS region



- New measurement using state-of-the-art hyperpolarized ^{3}He target
- "Flagship" experiment for Jlab 12 GeV upgrade

W&M PhD student Junhao Chen

Actual data coverage; arb. values

Now for the fun part!

How do we make polarize neutrons?
What is hyperpolarized ^{3}He?
Why is it so darn cool?

Outline

- Overview and Motivation
- Nucleon charge and magnetization from elastic e-N scattering
- Quark structure using deep-inelastic scattering
- Hardware: Polarized ^{3}He at William & Mary
- Hardware: Particle detectors
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Hyperpolarized ^{3}He

Requirements for a polarized neutron target for DIS at high Q^2

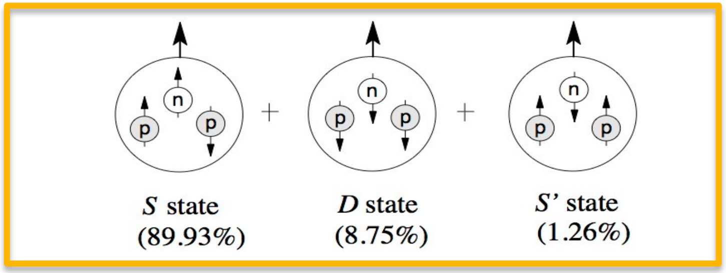
Small cross section measurements require lots of statistics
→ high beam current

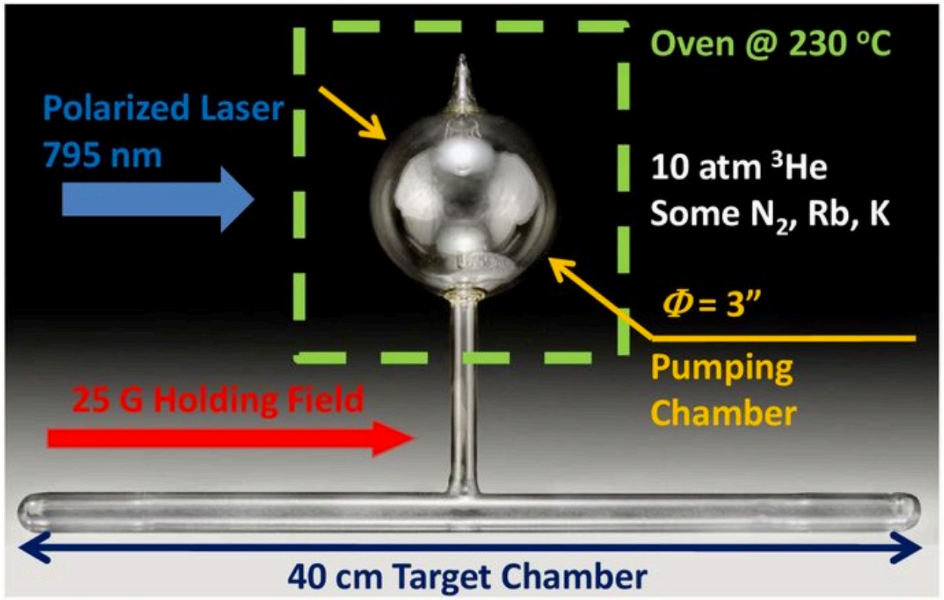
1. High density gas ~ 10 atm
2. Extended target length 40-60 cm
3. Minimum dilution → 120 um windows
4. High polarization in-beam → convection

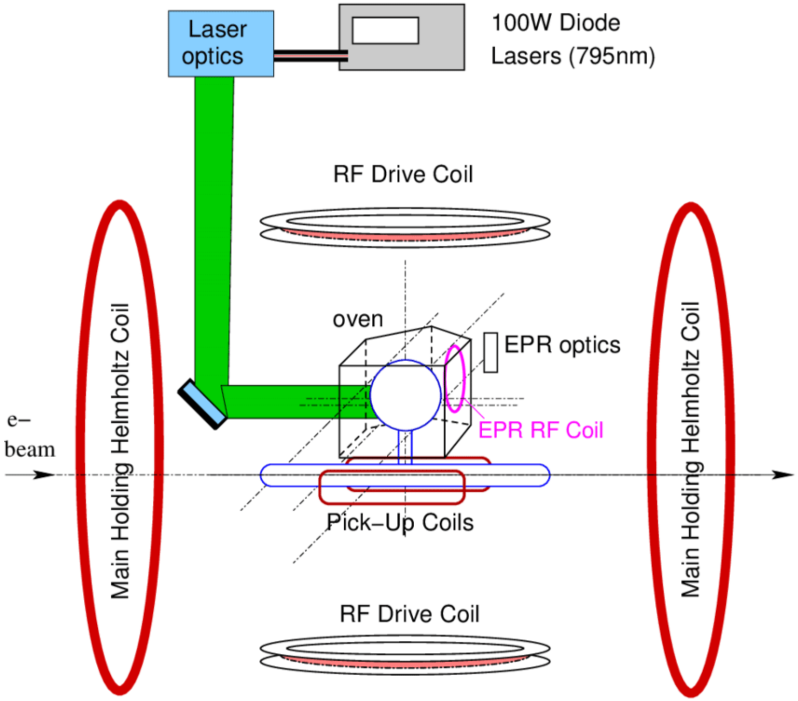
Most recent target cell design

Hyperpolarized ^{3}He Targets

- Options: ^{2}H or ^{3}He, with nuclear corrections
- My expertise is in polarized ^{3}He targets
- Ground state wavefunction:

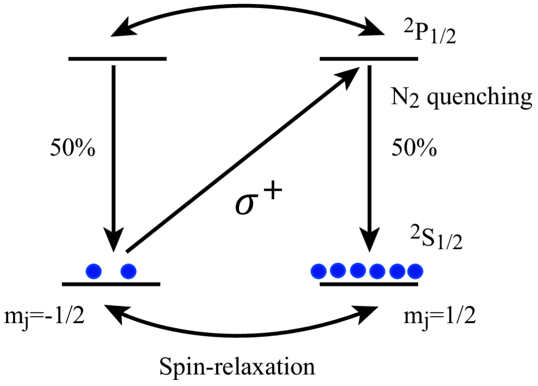


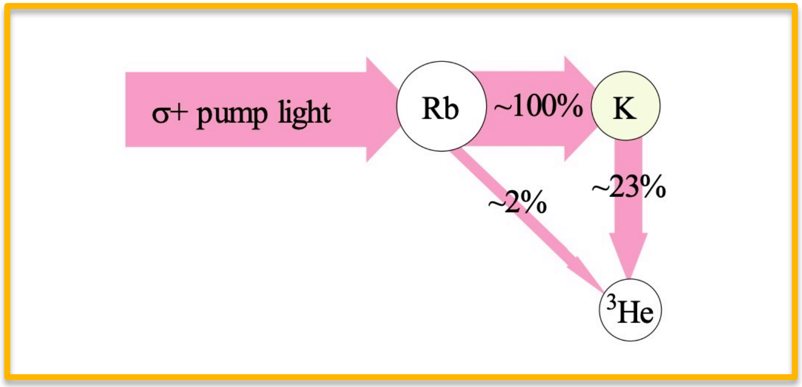




The polarization process - SEOP

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





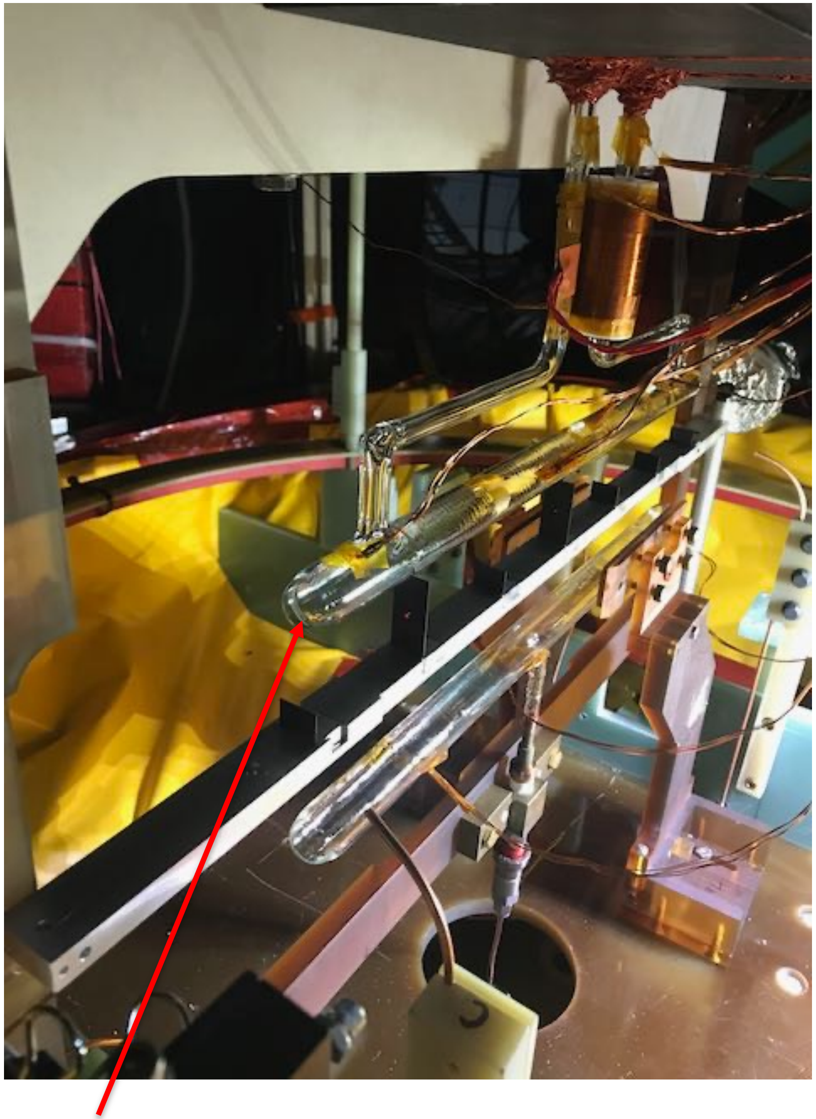
$$P(t) = \langle P_A \rangle \left[1 - e^{-\left(\frac{\gamma_{SE}}{\gamma_{SE}+\Gamma}\right)}\right]$$

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

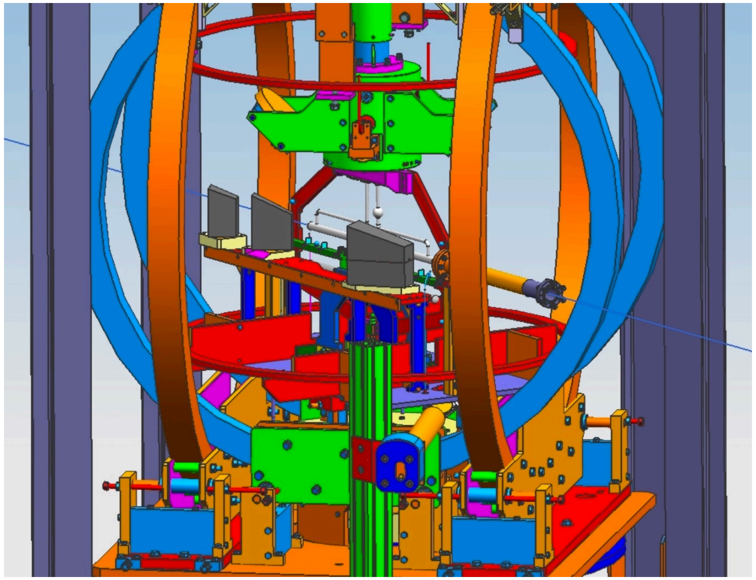
Γ = all ^{3}He spin relaxation mechanisms

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

Current target system at Jefferson Lab

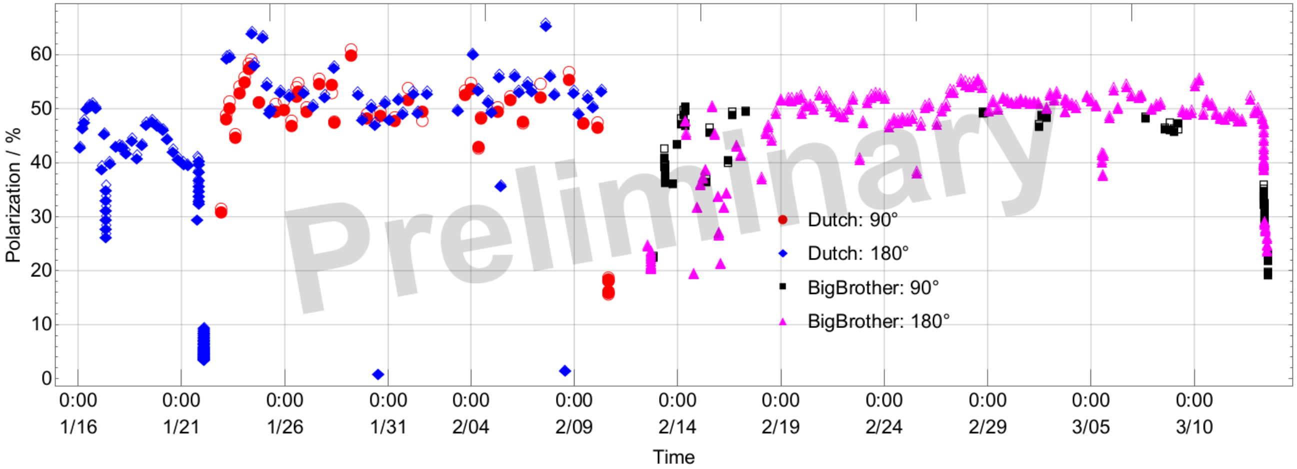


Target cell in beamline



2021 Target Performance

Most recent experiment w/ 30 uA beam current
Polarization vs. time

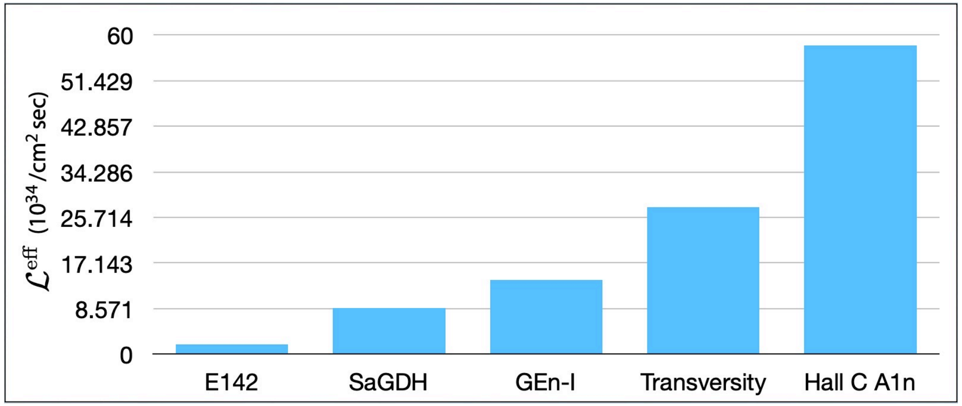


50% in-beam polarization using convection cell design

Collaborators: T. Averett, W&M, G. Cates, UVa, J.P. Chen, JLab

W&M PhD student Junhao Chen

Effective luminosity vs. time (1993-present)



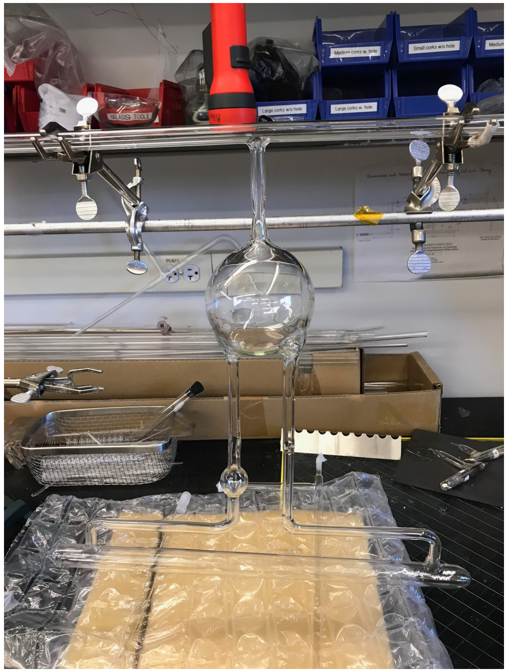
Factor of 10 improvement

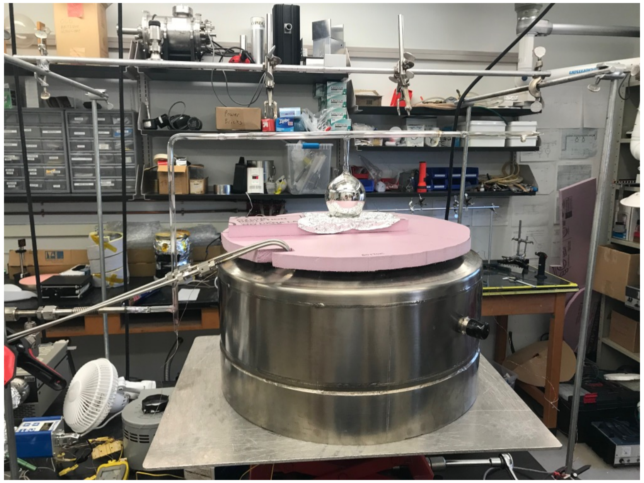
- Hybrid alkali
- Line-narrowed lasers

Development of high-performance alkali-hybrid polarized ^{3}He targets for electron scattering,
J. Singh…, T. Averett
Phys.Rev.C 91 (2015) 5, 055205

Target cell filling at W&M

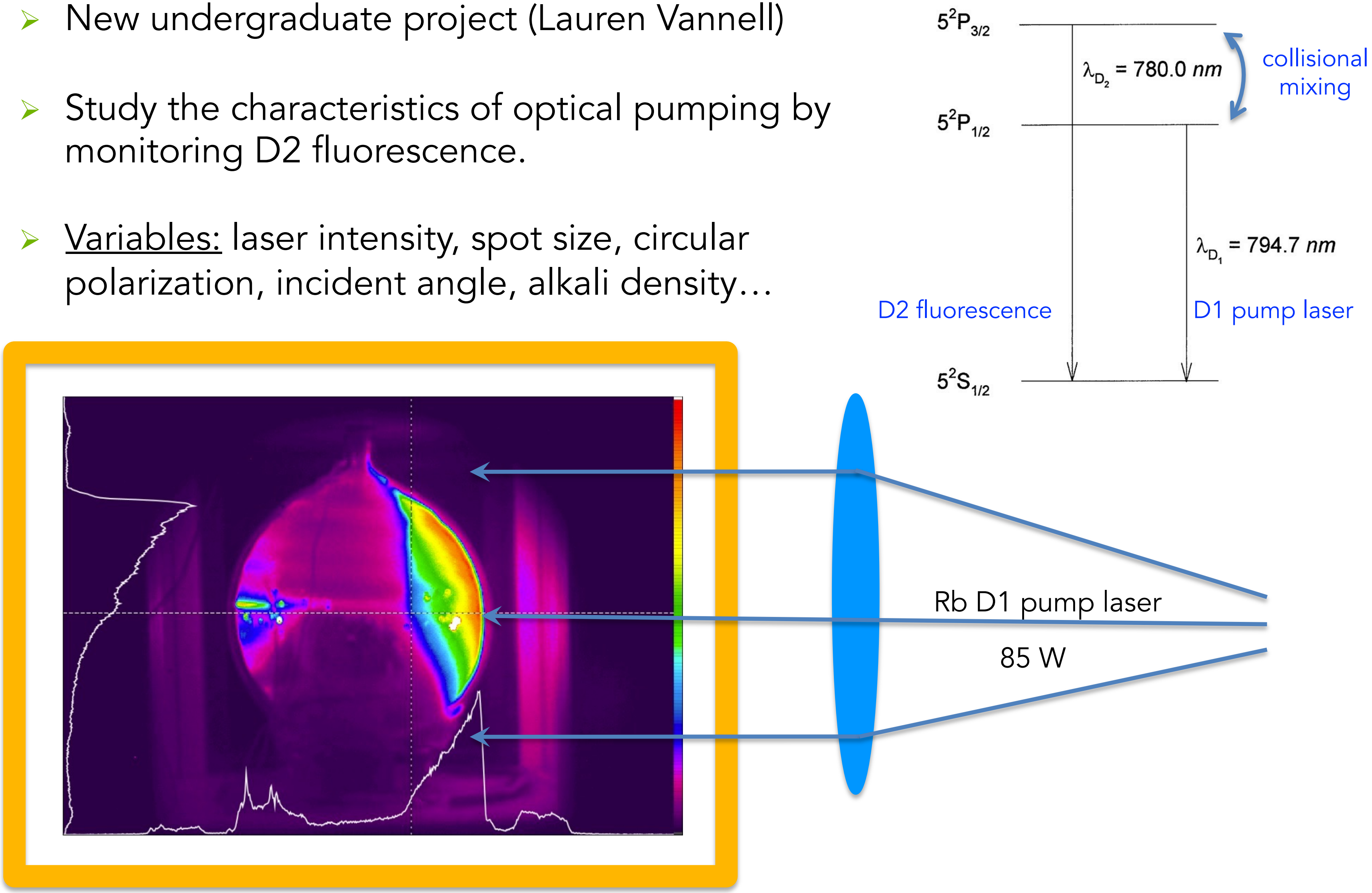
- Cells constructed at Princeton by Mike Souza
- Attach to vacuum system
- Pump and bake cell to 10^{-9} Torr
- Fill with ^{3}He at ~ 10 atm
- Cool down with liquid ^{4}He
- Cell pull-off with hand torch





Side project: Optimizing optical pumping efficiency

- 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…



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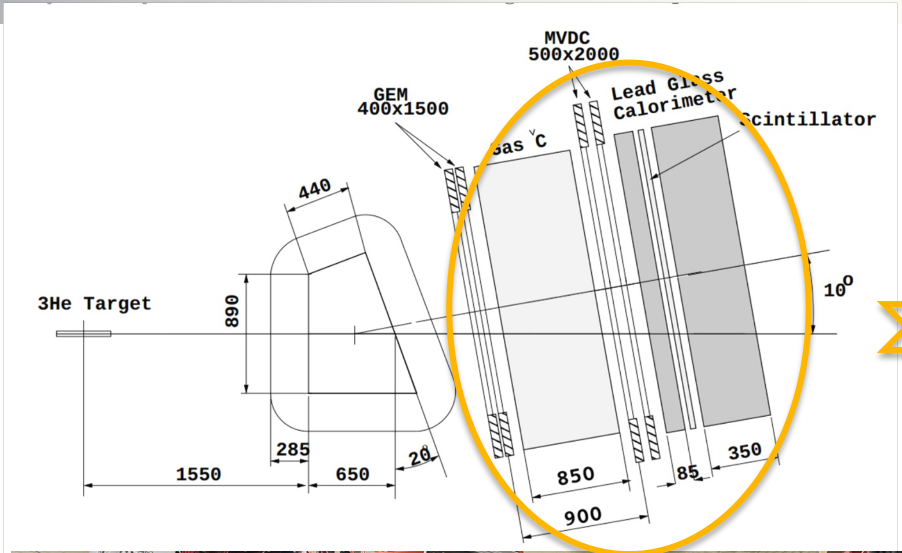
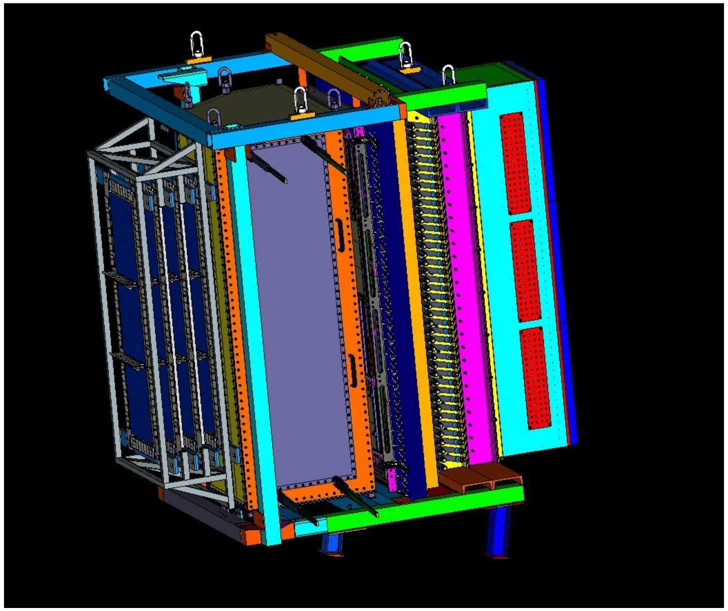
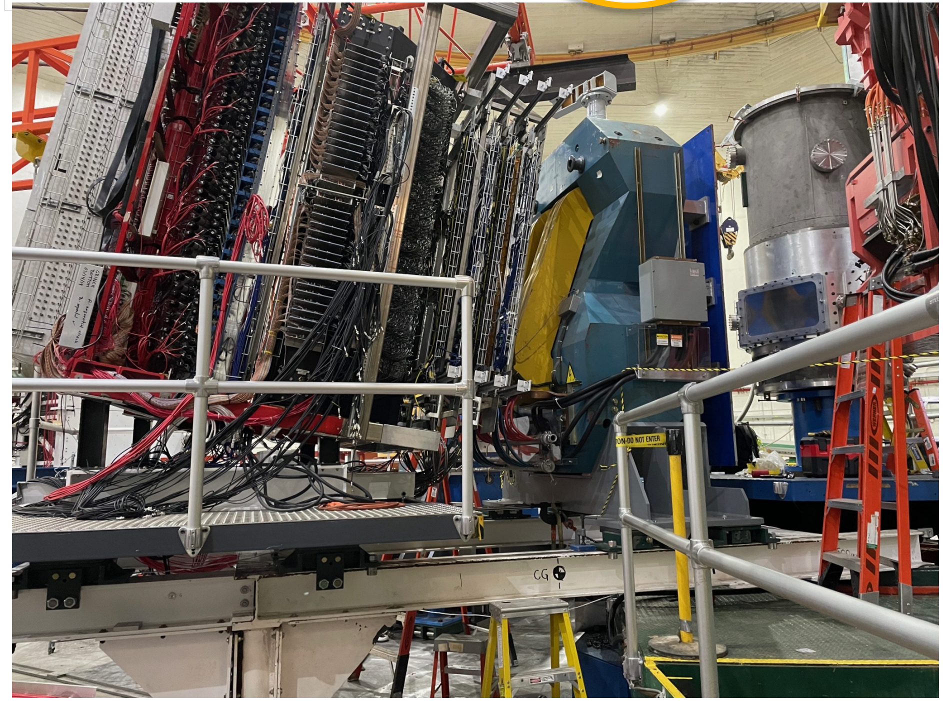
SBS BigBite Electron Spectrometer



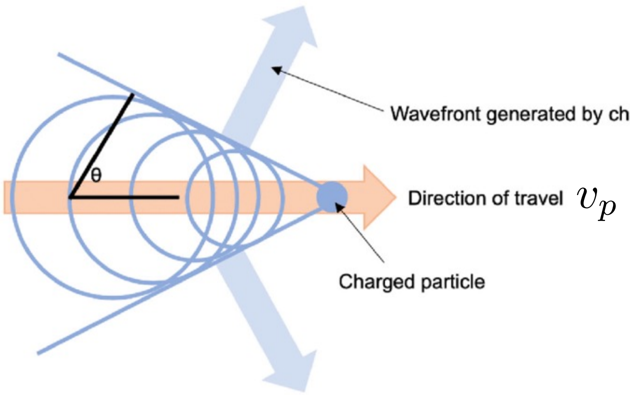




- Large angular acceptance
- Large momentum acceptance
- GEM trackers → momentum
- GRINCH Cherenkov → PID
- Scintillator hodoscope → timing
- Pb-glass EM calorimeter → *E′*
- Fast electronics

Electron ID -- Gas Cherenkov Detector

- Efficient electron identification is essential for *e-N* scattering experiments
- Largest background is from π^-
- The most efficient is a gas Cherenkov detector

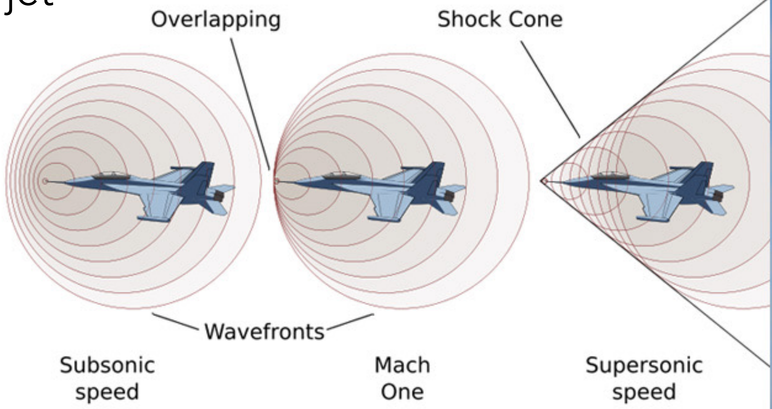


- For a particle with speed v_p, in gas with index of refraction, *n*, the condition for producing Cherenkov radiation is

$$v_p > \frac{c}{n}$$

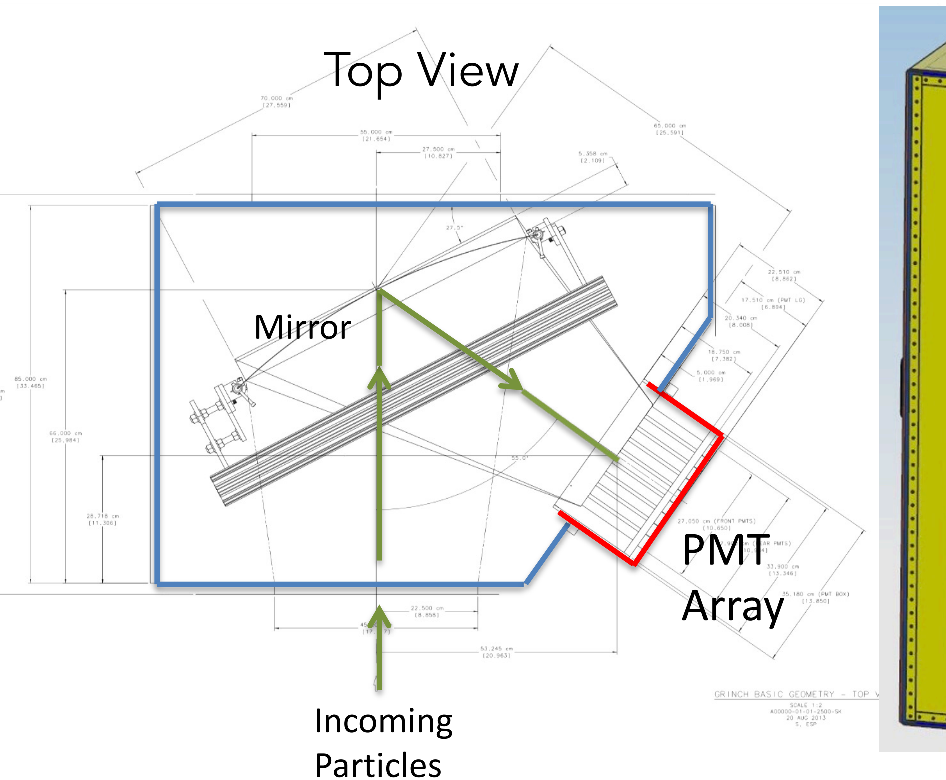
- choose *n* so that $v_e > \frac{c}{n}$ and $v_\pi < \frac{c}{n}$

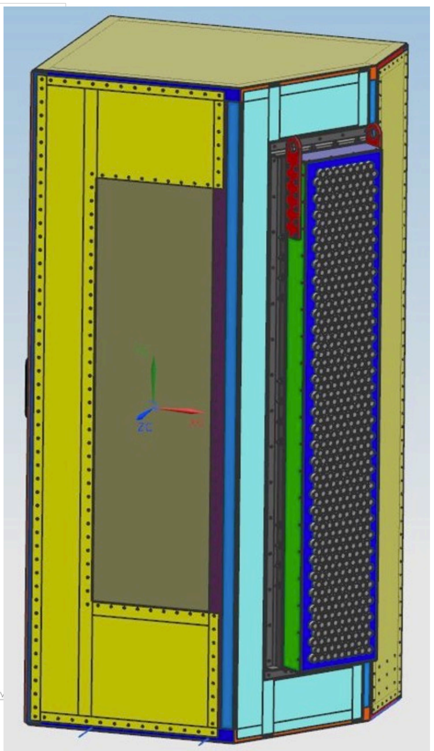
Similar to a supersonic jet



The W&M GRINCH

- GRINCH: Gas RINg imaging CHerenkov detector
- Designed, built and installed by W&M
- C_4F_8 heavy gas gives a pion threshold of ~2.3 GeV
- ~70 cm path length, 4 mirrors, 510 PMTs
- Custom, high speed electronics (JLab)
- Commissioned in early 2022,
  Maria Satnik, W&M PhD student

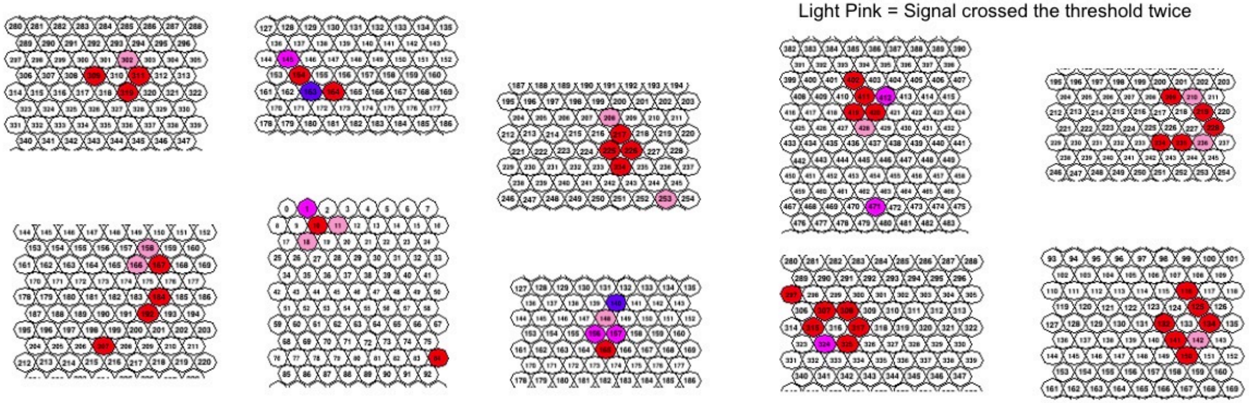




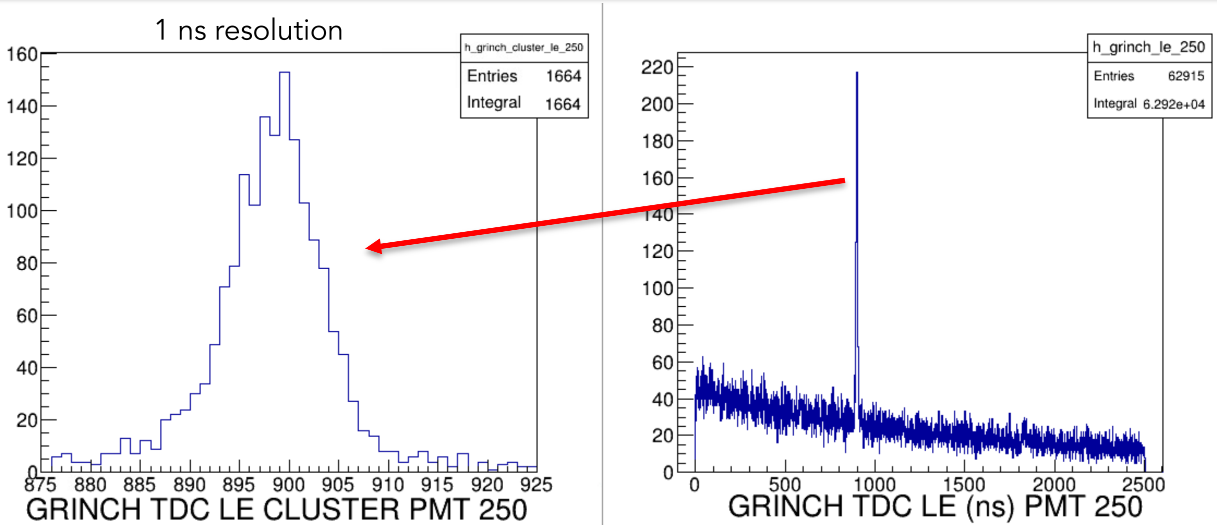
Early GRINCH results, Jan.– Feb. 2022

GRINCH Cluster Finding Examples

Color is related to TDC multiplicity:
Red = Signal crossed the threshold once
Light Pink = Signal crossed the threshold twice



Cluster Size = 3 Cluster Size = 4 Cluster Size = 5 Cluster Size = 6 Cluster Size = 7



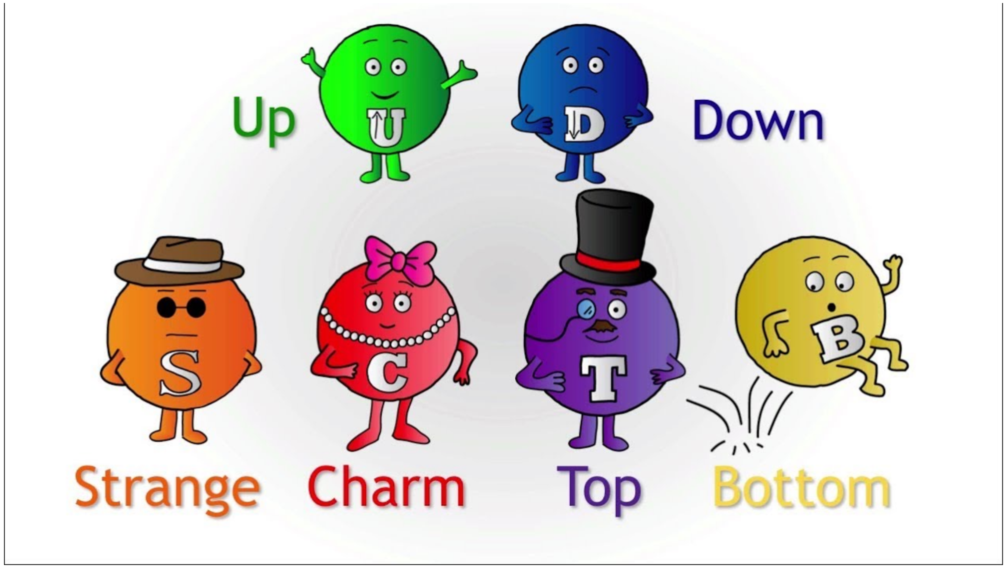
Timing spectrum for PMT 250

Plots by Maria Satnik

THE END

So that's what I do when I'm not teaching!
Thanks for your attention

Questions?



* Anyone interested in Quantum Enhanced Tracking with Rydberg Atoms??

Outline

- Overview and Motivation
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- Hardware: Polarized ^{3}He at William & Mary
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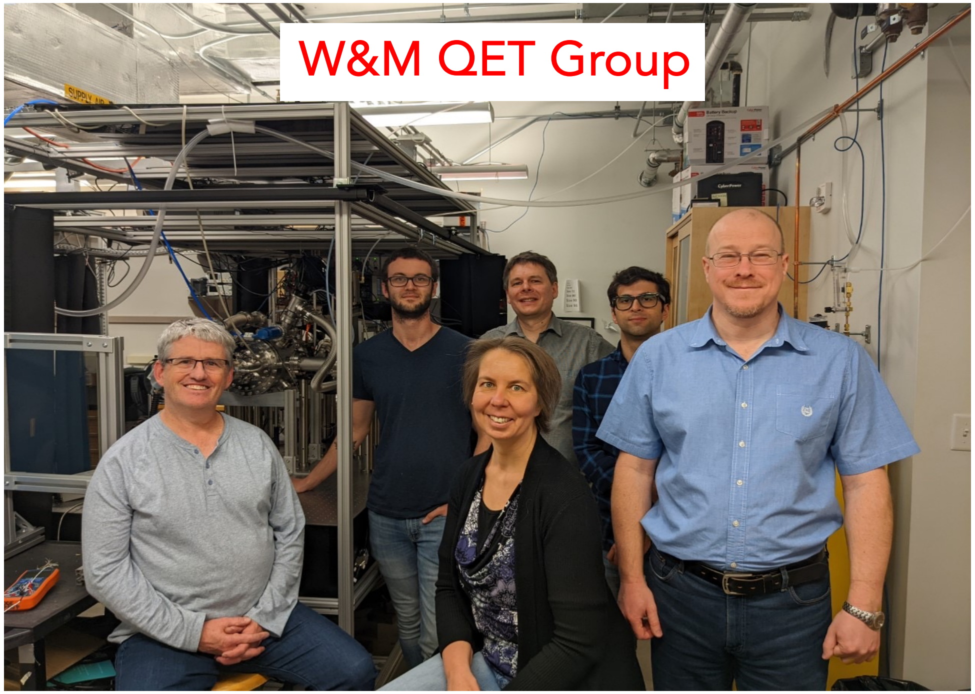
QET Research Group



- **W&M Faculty:** T. Averett (DOE PI)
  - AMO: S. Aubin, E. Mikhailov, I. Novikova

- **W&M Grad. Students:** N. DeStefano
  - Rob behary

- **Jefferson Lab Staff:** A. Camsonne (DAQ), G. Park (Beamline), S. Zhang (LDRD PI) (Electron Source)

Funding: (Jefferson) Laboratory Directed R&D and DOE QIS Grant

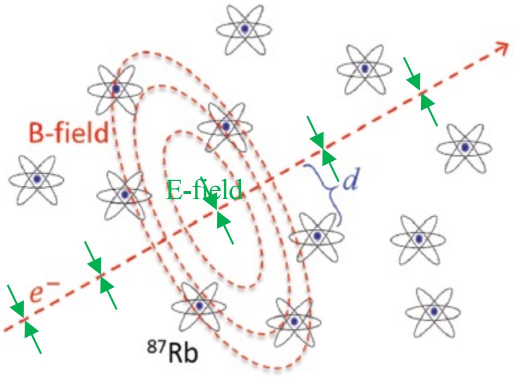
Quantum Enhanced Tracking – QET R&D

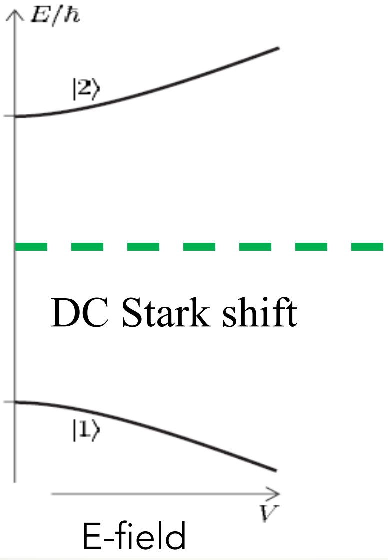
- Use Rydberg atoms to detect passing charged particles

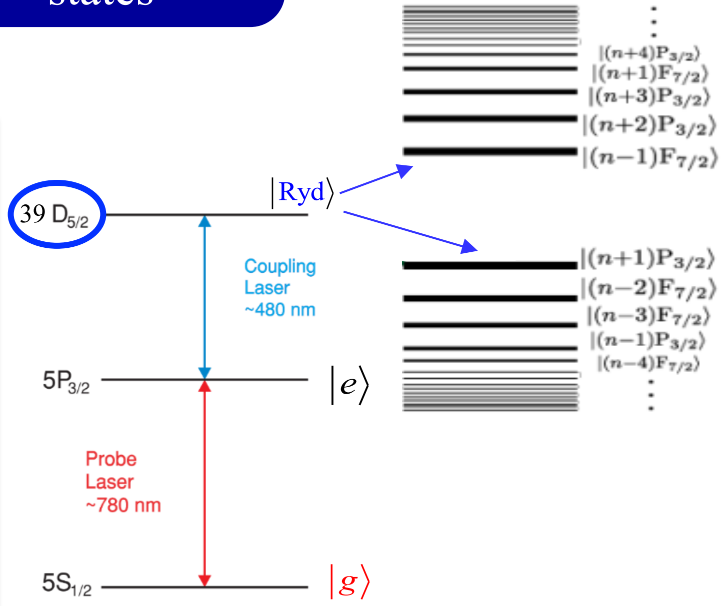
Moving charged particles produce electric & magnetic fields

Stark/ Zeeman effect perturbs energy state of atoms, changing the atomic quantum state

Charge particles are detected by monitoring Rydberg atom states

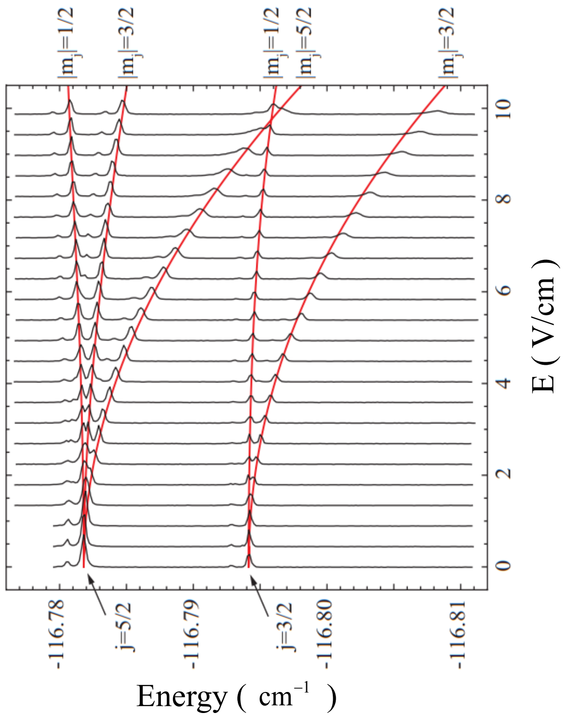




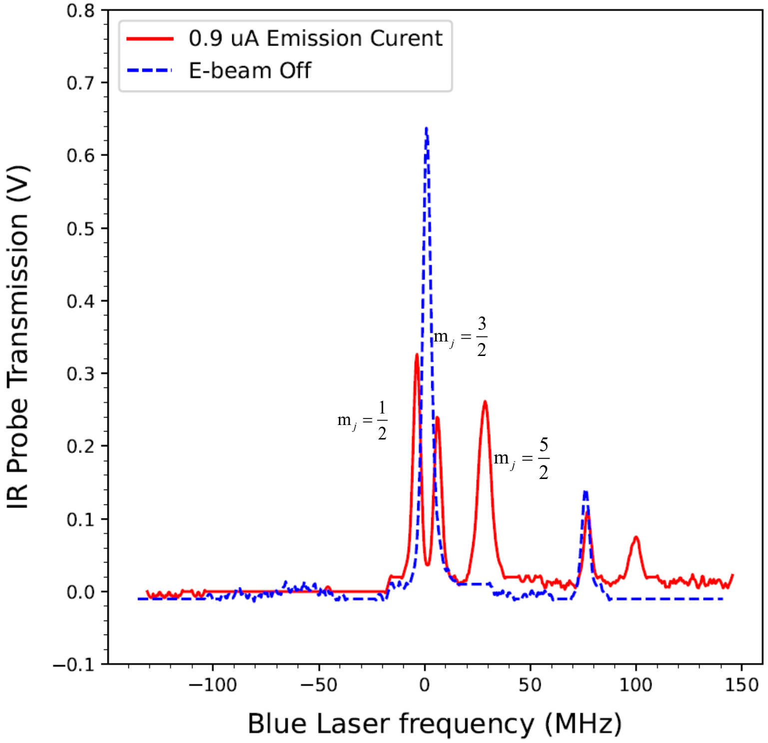


e-beam sensitivity measurement through DC Stark effect

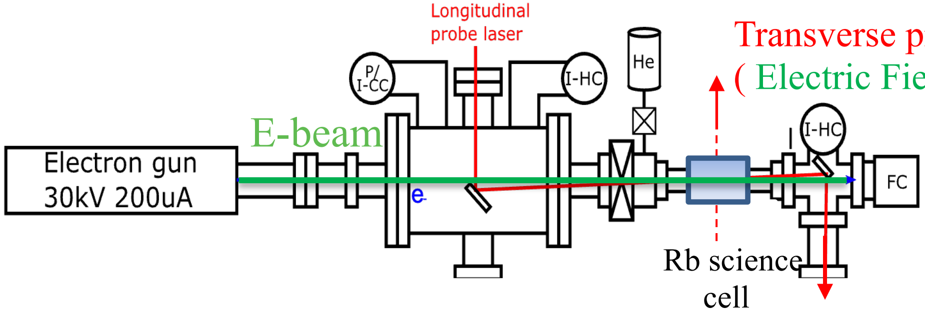
D. Fahey, et. al, Opt. Express 19, 17002-17012 (2011)



Measured spectra

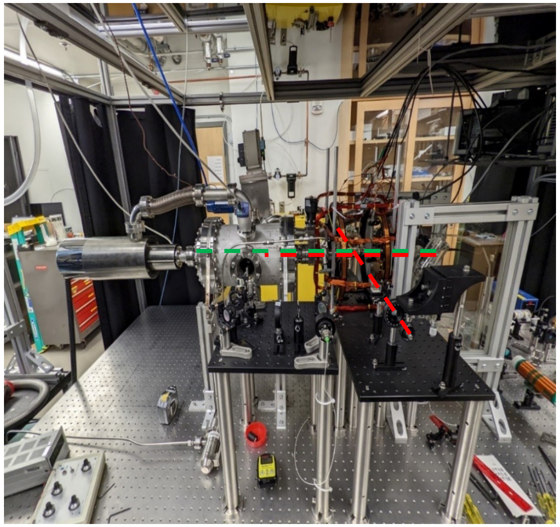


W&M QET experiment

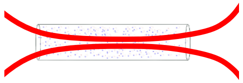


Transverse probe beam
(Electric Field & Magnetic Field)

Longitudinal probe beam
(Magnetic Field)

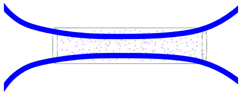


E-beam Focus 2

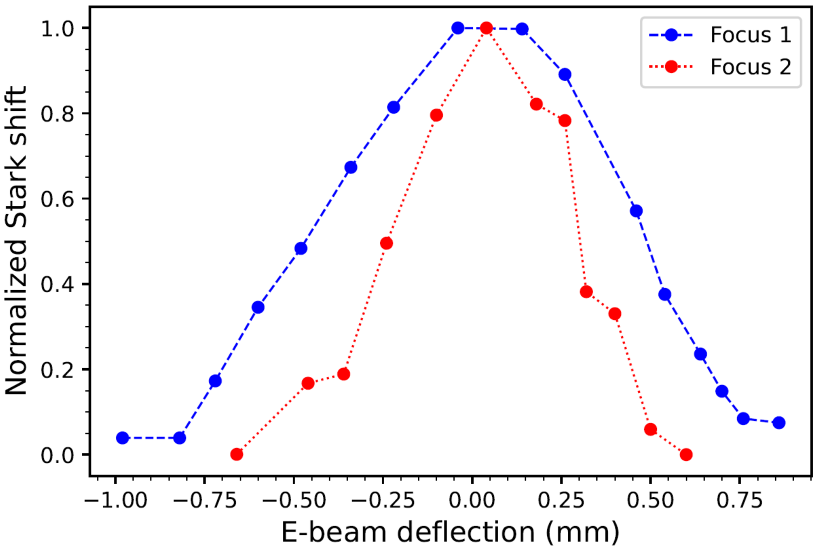


- Tight focus

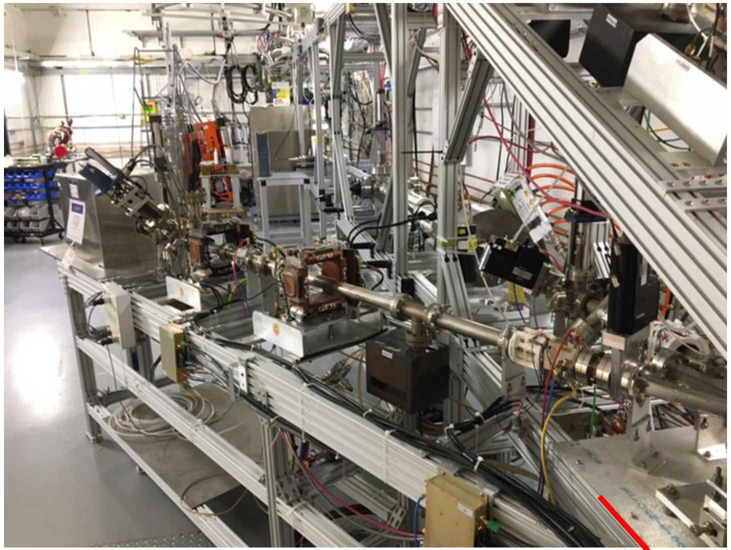
E-beam Focus 1



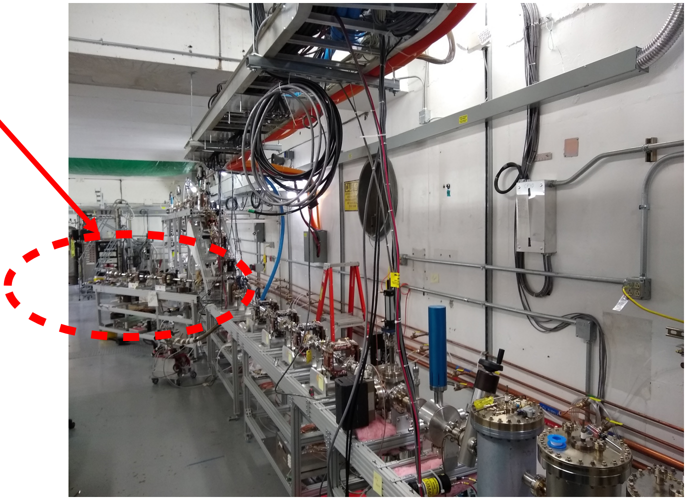
- Wider focus



Plan for implementation of QET at Jefferson Lab



- We are building a QET system to test at Jefferson Lab
- UITF (Upgraded Injector Test Facility) provides a 9 MeV electron beam
- Rydberg opto-mechanics and vacuum hardware are being acquired
- System built using ConFlat vacuum parts compatible with JLab beam line.
- Intended use: 2D beam tracking

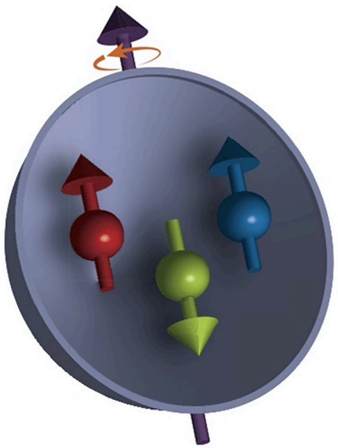


Discovery of quarks using electron DIS

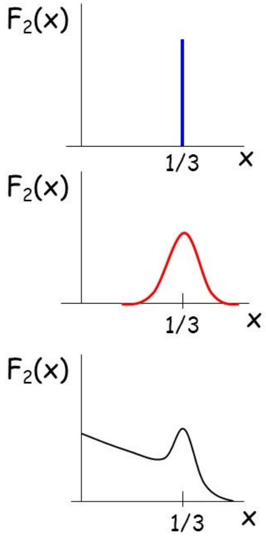
1969, J.D. Bjorken predicts when $Q^2, \nu \to \infty$ and Q^2/ν finite, the cross section becomes the incoherent sum of elastic scattering from point-like, charged, spin-1/2, non-interacting quarks.
Scattering becomes a function of only one variable describing the kinematics of the struck quark!!

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

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



Kendall, Taylor, Friedmann
Nobel Prize 1990



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

Three quarks with 1/3 of total proton momentum each. $Q^2 \to \infty$

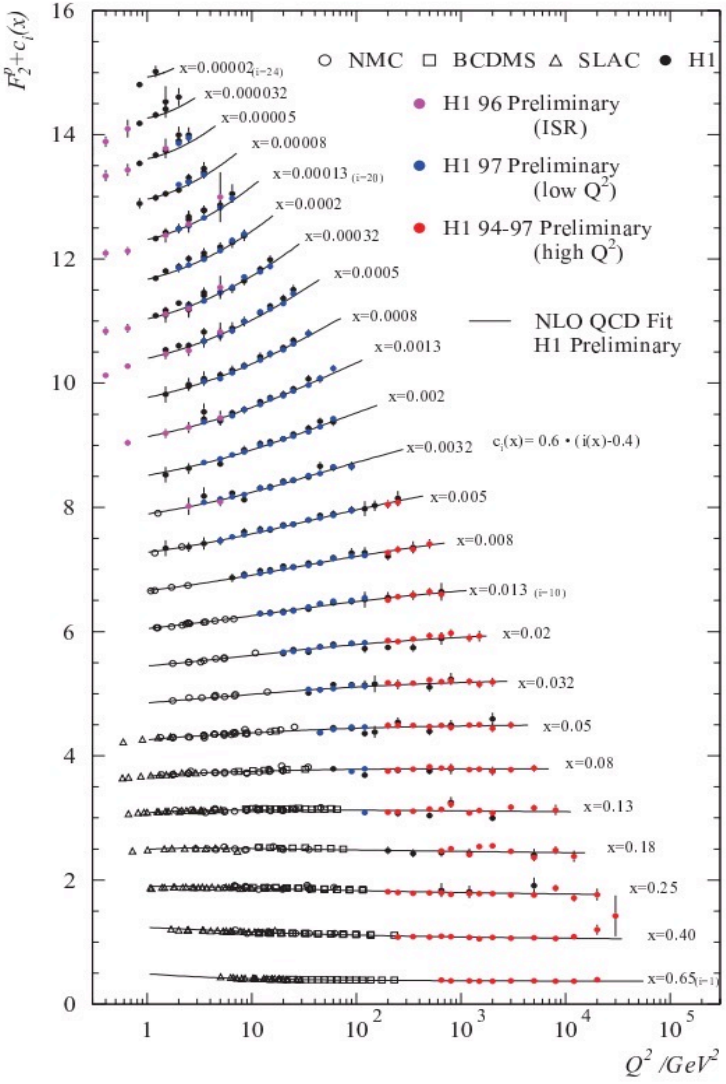
Three quarks with some momentum smearing. moderate Q^2

The three quarks radiate partons at low x. low Q^2

….The answer depends on the Q^2!

Quark momentum distributions

Scaling



Scaling predictions

$$F_1(x) = \frac{1}{2} \sum_{i=u,d,s} e_i^2 \left(q_i(x) + \overline{q_i}(x)\right)$$

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

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

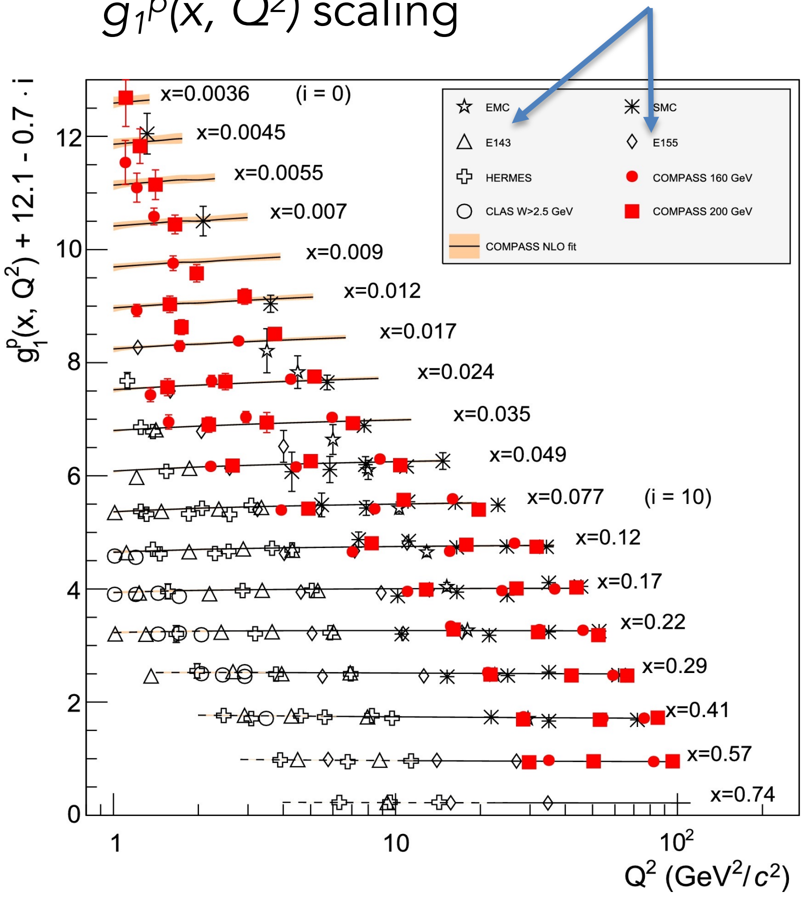
$$q_i = \int_0^1 q_i(x)dx$$

What about nucleon spin distributions?

$$\left(\frac{d\sigma}{d\Omega dE'}\right)^{\uparrow-\downarrow} \propto g_1, g_2$$

- Two spin-dependent structure functions, $g_1(\nu, Q^2), g_2(\nu, Q^2)$

$g_1{}^p(x, Q^2)$ scaling



Averett's work

$$g_1(x) = \frac{1}{2}\sum_{i=u,d,s} e_i^2 \left(\Delta q_i(x) + \Delta\overline{q_i}(x)\right),$$

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

- 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

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