SBS Overview and Status

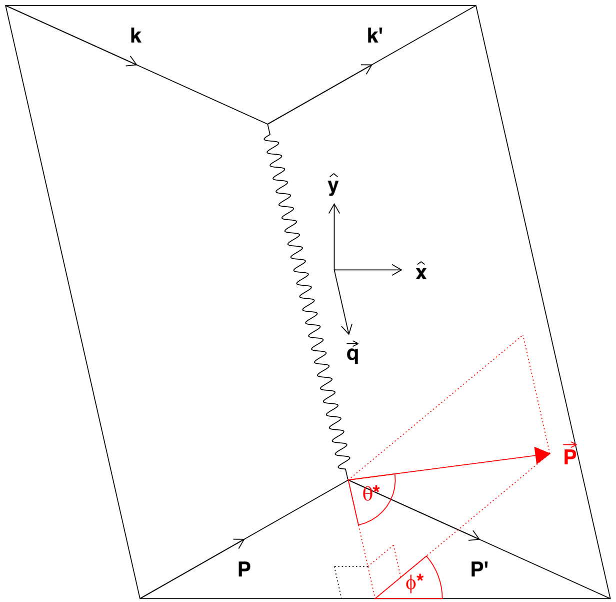
Andrew Puckett
University of Connecticut
January 22, 2021
Hall A Winter Meeting

UCONN

Acknowledgements

- This work is supported by the US Department of Energy Office of Science, Office of Nuclear Physics, Award ID DE-SC0021200
- Additional support from Jefferson Lab and the University of Connecticut
- SBS and Hall A Collaborations
- The Hall A CC for organizing this meeting

Motivation—Nucleon electromagnetic Form Factors at high Q^2



$\vec{\mathbf{P}} \equiv$ Target polarization

Feynman diagram and coordinate system for elastic eN scattering in one-photon-exchange approximation

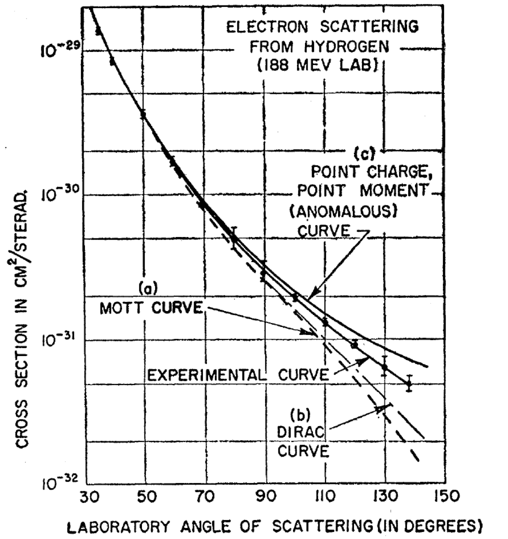


FIG. 24. Electron scattering from the proton at an incident energy of 188 Mev. The experimental points lie below the point-charge point-moment curve of Rosenbluth, indicating finite size effects.

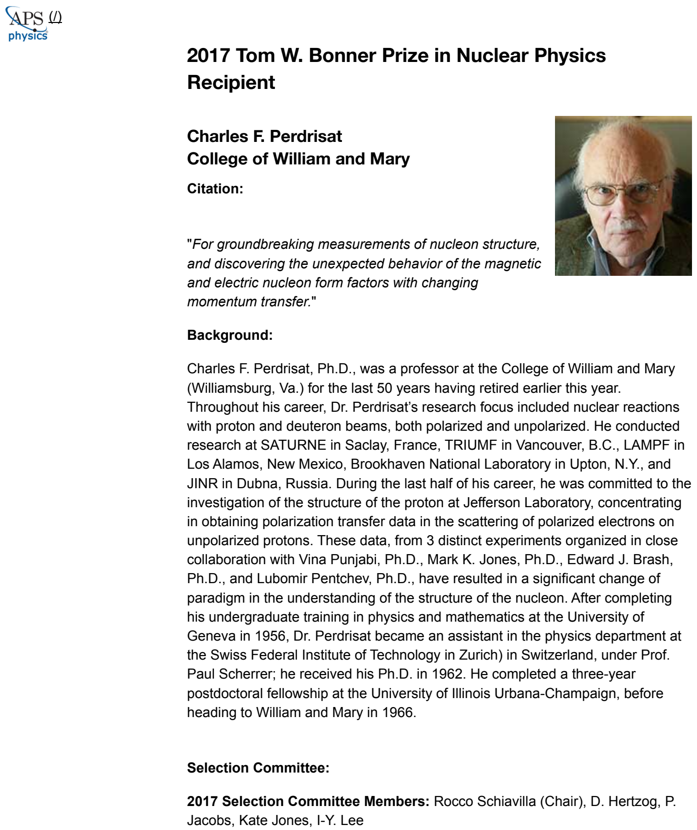
R. Hofstadter, Rev. Mod. Phys., 28, 214 (1956)

Nobel Prize in Physics 1961

Elastic eN scattering observables in terms of FFs (one photon exchange approximation):

$$
\begin{aligned}
\text{Sachs Form Factors: } G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\
G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \\
\epsilon &\equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1} \\
\tau &\equiv \frac{Q^2}{4M^2} \\
r &\equiv \frac{G_E}{G_M} \\
\text{Reduced cross section: } \sigma_R &= \frac{\epsilon(1+\tau)\frac{d\sigma}{d\Omega_e}}{\left(\frac{d\sigma}{d\Omega_e}\right)_{Mott}} = \epsilon G_E^2 + \tau G_M^2 \\
\text{Beam-target asymmetry: } A_{eN} &= P_{beam}P_{target}\left[A_t \sin\theta^* \cos\phi^* + A_\ell \cos\theta^*\right] \\
A_t &= -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2} \\
A_\ell &= -\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2} \\
\text{Polarization transfer: } P_t &= A_t \\
P_\ell &= -A_\ell \\
\frac{G_E}{G_M} &= -\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\frac{P_t}{P_\ell}
\end{aligned}
$$

Highlights of Nucleon FFs from the 6 GeV era @CEBAF: G_E^p/G_M^p, G_E^n/G_M^n, flavor decomposition, and diquarks


APS physics

2017 Tom W. Bonner Prize in Nuclear Physics Recipient

Charles F. Perdrisat
College of William and Mary

Citation:

"For groundbreaking measurements of nucleon structure, and discovering the unexpected behavior of the magnetic and electric nucleon form factors with changing momentum transfer."

Background:

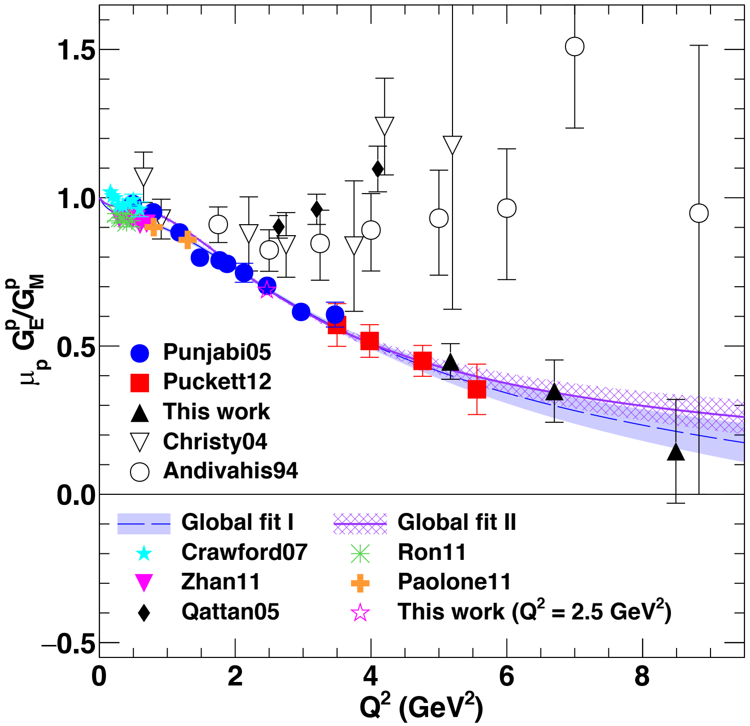
Charles F. Perdrisat, Ph.D., was a professor at the College of William and Mary (Williamsburg, Va.) for the last 50 years having retired earlier this year. Throughout his career, Dr. Perdrisat's research focus included nuclear reactions with proton and deuteron beams, both polarized and unpolarized. He conducted research at SATURNE in Saclay, France, TRIUMF in Vancouver, B.C., LAMPF in Los Alamos, New Mexico, Brookhaven National Laboratory in Upton, N.Y., and JINR in Dubna, Russia. During the last half of his career, he was committed to the investigation of the structure of the proton at Jefferson Laboratory, concentrating in obtaining polarization transfer data in the scattering of polarized electrons on unpolarized protons. These data, from 3 distinct experiments organized in close collaboration with Vina Punjabi, Ph.D., Mark K. Jones, Ph.D., Edward J. Brash, Ph.D., and Lubomir Pentchev, Ph.D., have resulted in a significant change of paradigm in the understanding of the structure of the nucleon. After completing his undergraduate training in physics and mathematics at the University of Geneva in 1956, Dr. Perdrisat became an assistant in the physics department at the Swiss Federal Institute of Technology in Zurich) in Switzerland, under Prof. Paul Scherrer; he received his Ph.D. in 1962. He completed a three-year postdoctoral fellowship at the University of Illinois Urbana-Champaign, before heading to William and Mary in 1966.

Selection Committee:

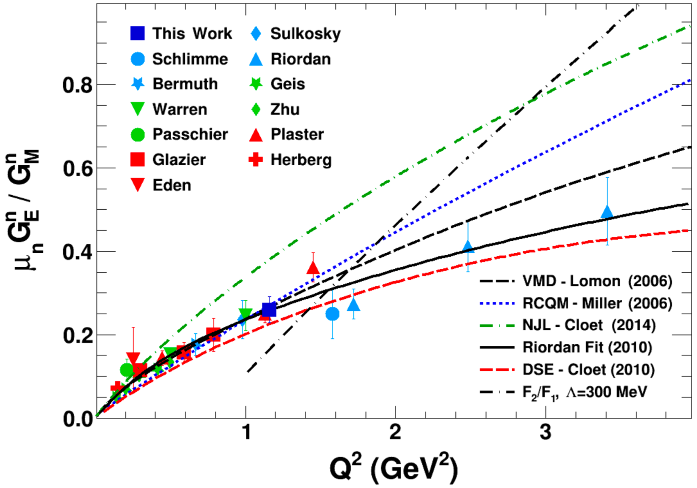
2017 Selection Committee Members: Rocco Schiavilla (Chair), D. Hertzog, P. Jacobs, Kate Jones, I-Y. Lee

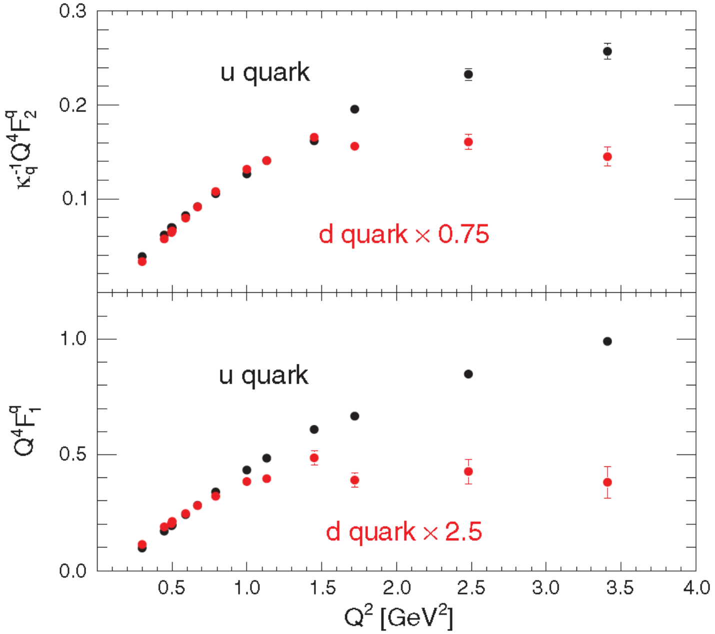
JLab polarization data for proton FF ratio among most-cited results from JLab:

- Jones *et al.,* PRL 84, 1398 (2000): 900+ citations
- Gayou *et al.,* PRL 88, 092301 (2002): 800+ citations



- Above: Summary of Jlab polarization transfer data for G_E^p/G_M^p from Puckett *et al.,* **PRC 96**, 055203 (2017)
- Top right: G_E^n/G_M^n from Obrecht *et al.,* (in preparation) and Riordan *et al.*, **PRL 105**, 262302 (2010)
- Bottom right: Flavor decomposition of nucleon EMFF from Cates *et al.,* **PRL 106,** 252003 (2011)





ECT* diquarks workshop, Trento, Sept. 23-27, 2019

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Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/ppnp

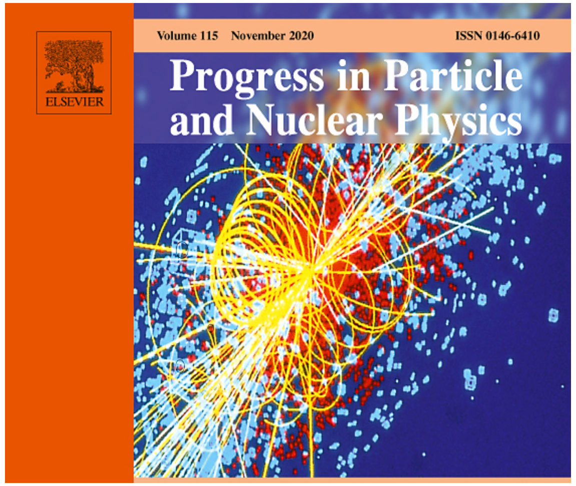
Review

Diquark correlations in hadron physics: Origin, impact and evidence

Check for updates

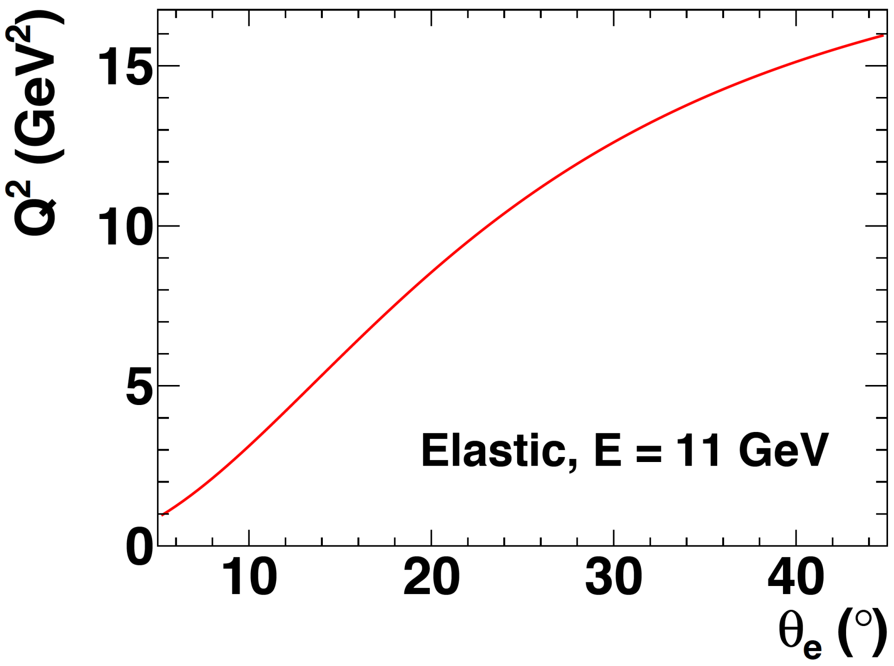
M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6,7], E. Cisbani [8], M. Ding [9], G. Eichmann [10,11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15,12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18,19,*], P. Rossi [12,20], G. Salmé [21], E. Santopinto [22], J. Segovia [23,19], S.N. Syritsyn [24,25], M. Takizawa [26,27,28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Wojtsekhowski [12]

[1] *Joint Institute for Nuclear Research, Dubna, 141980, Russia*



- High-Q^2 form factors are among the most sensitive experimental signatures of diquark correlations, now thought to play an important role in hadron structure; 2019 workshop brought together theorists and experimentalists at ECT* in Trento, Italy
- PPNP article now published as PPNP 116, 103835 (2021: https://www.sciencedirect.com/science/article/abs/pii/S014664102030082X

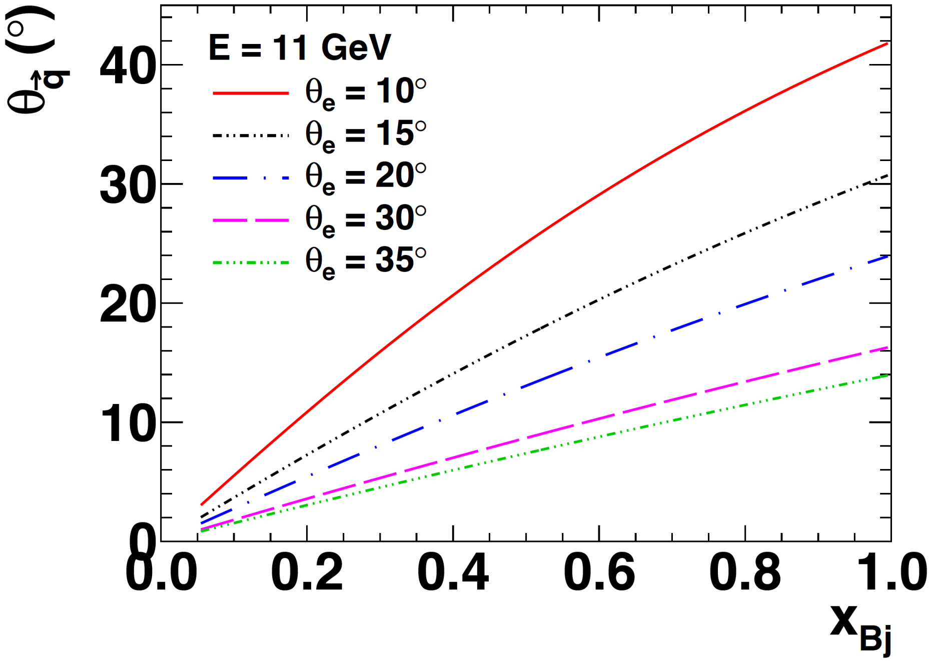
Toward high-Q^2: Fixed-target Electron Scattering Kinematics @11 GeV



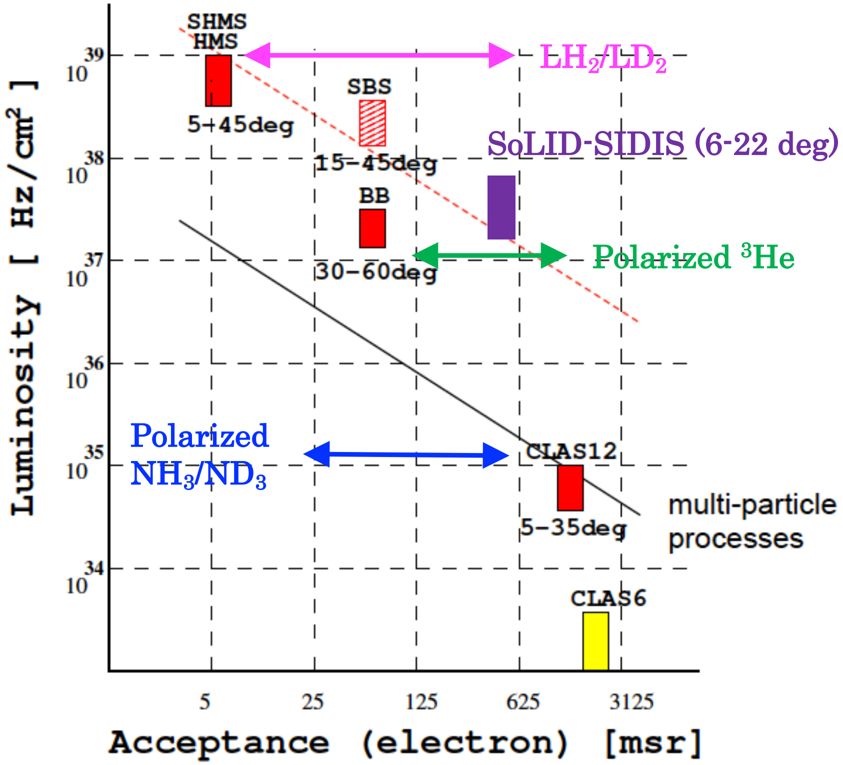
- Particles associated with the partonic (or other) degree of freedom that absorbed the virtual photon are found predominantly near the direction of the momentum transfer **q**
- ***Partonic interpretation of electron scattering data is accessible at large Q^2 → particles of interest are located at forward angles and high momentum***

- Measurements of high-Q^2 elastic FFs, SIDIS, DVCS, etc involve coincidence N(e,e'X) (electroproduction) reactions, where X =
  - N' (elastic or quasi-elastic)
  - h (SIDIS or DVMP)
  - γ (DVCS)
- Virtual photon angle decreases as "inelasticity" and Q^2 increase:

$$Q^2 = 2M\nu x_{Bj}$$



JLab detector landscape



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).
=========================
The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments SBS was found to be the best match to the physics.

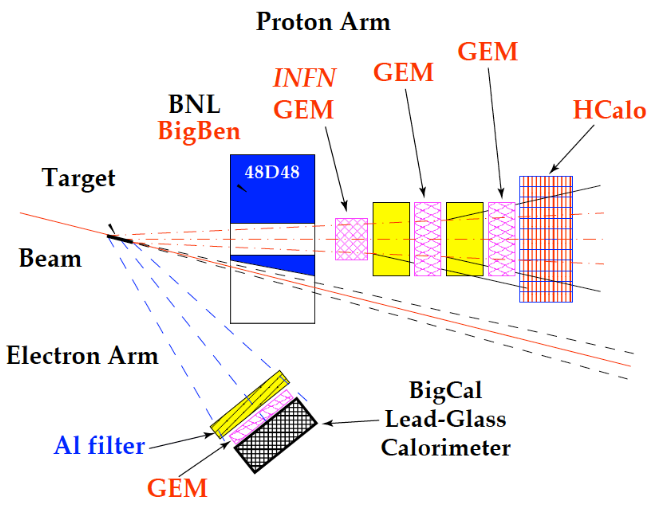
GEM allows a spectrometer with open geometry (->large acceptance) at high L.

11/16/15 Super Bigbite Spectrometer Review slide 9

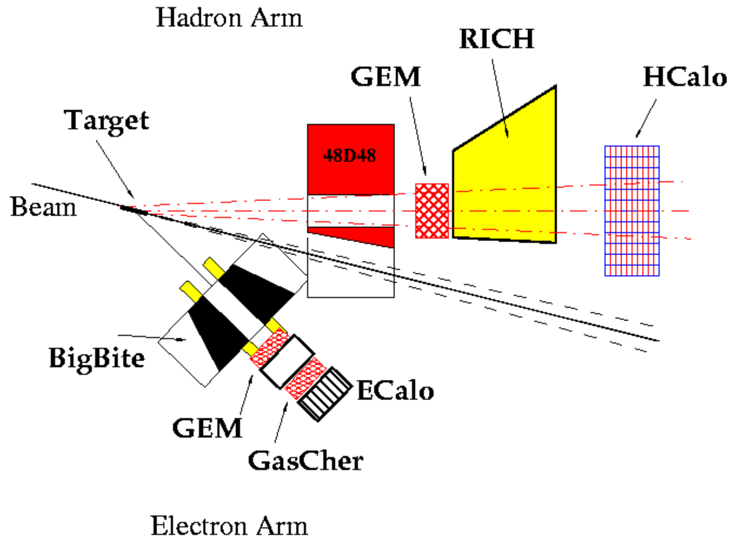
- Complementary equipment/capabilities of Halls A, B, C allow optimal matching of (Luminosity x Acceptance) of the detectors to the luminosity capabilities of the targets, including state-of-the-art polarized target technology.

The Super BigBite Spectrometer in Hall A

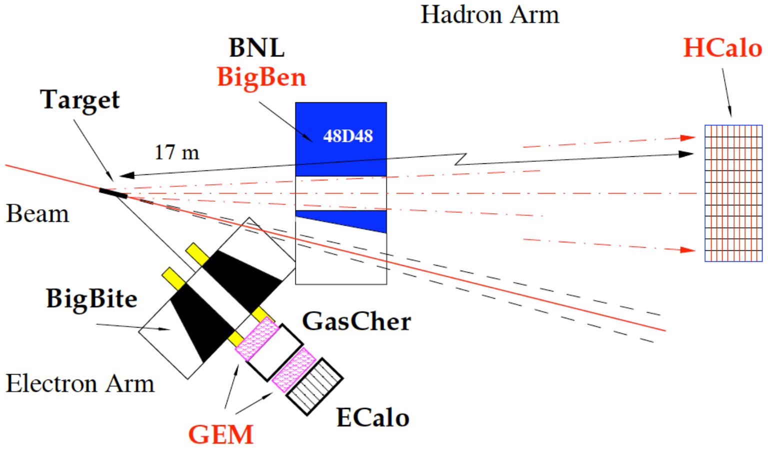
Proton form factors ratio, GEp(5) (E12-07-109)



SIDIS transverse single-spin asymmetry experiment: E12-09-018

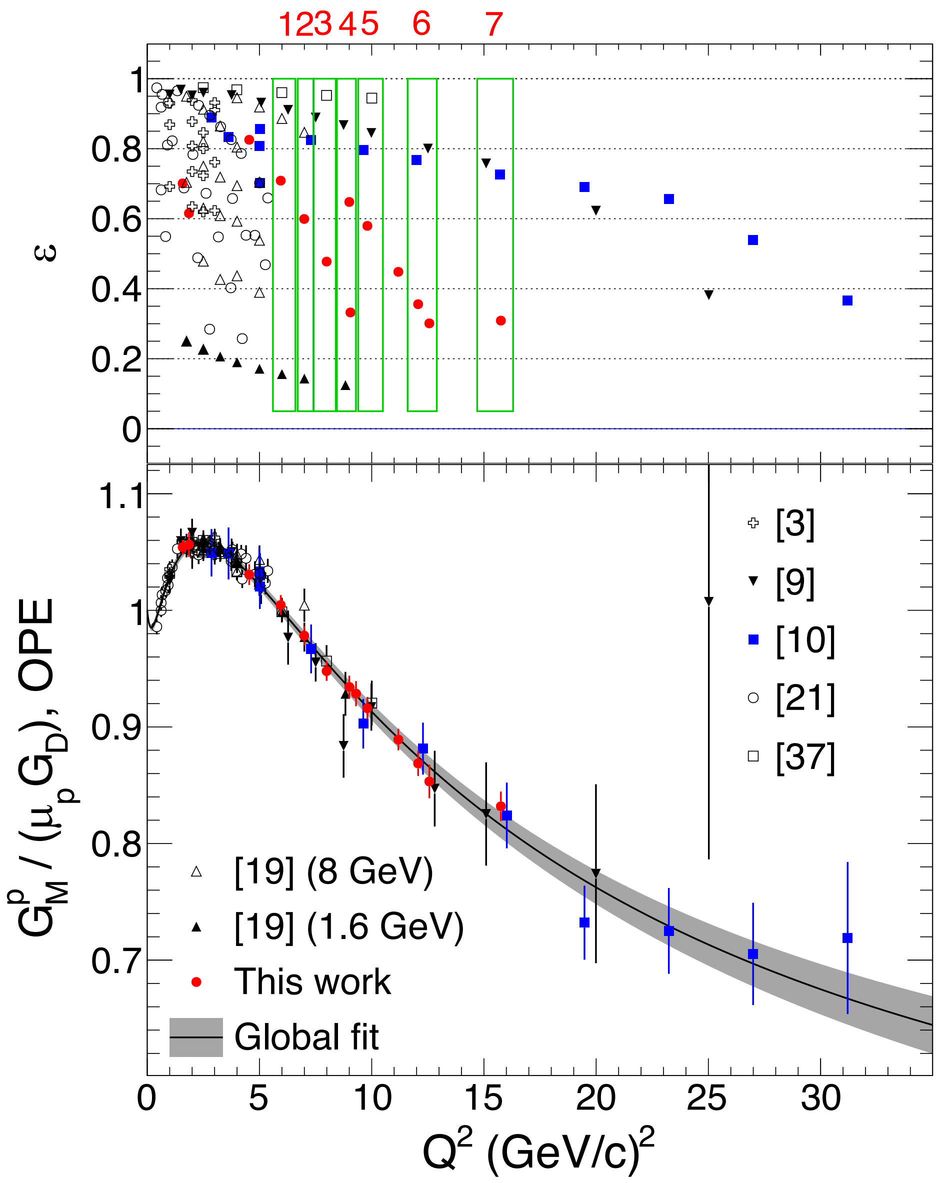


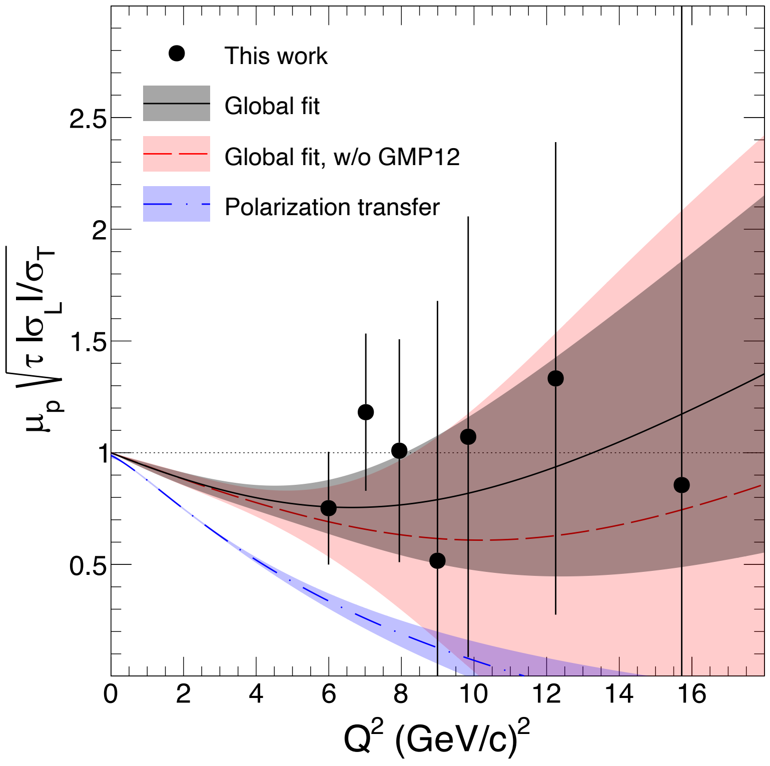
Neutron form factors, E12–09–016 and E12–09–019

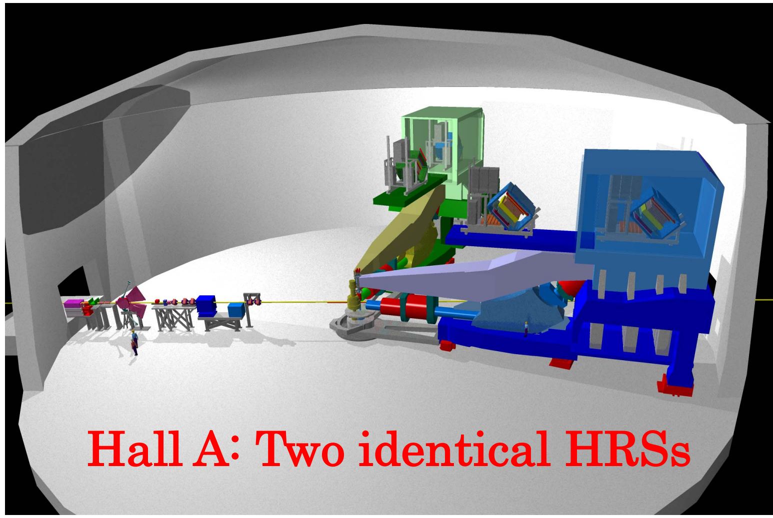


- What is SBS? → (up to) $\int BdL \approx 2.5\, T \cdot m$ dipole magnet with vertical bend, a cut in the yoke for passage of the beam pipe to reach forward scattering angles, and a flexible/modular configuration of detectors.
- Designed to operate at luminosities up to 10^{39} cm^{-2} s^{-1} with large momentum bite, moderate solid angle
- Five fully approved "large" experiments plus two fully approved "small" experiments, focused on high-Q^2 nucleon form factors, transverse SSAs in SIDIS
- Conditionally approved future program of "tagged DIS"
- ***Large solid-angle + high luminosity @ forward angles = most interesting physics!***

Hall A G_M^p experiment: New precise elastic *ep* cross sections up to $Q^2 \approx 16\ GeV^2$







- Above: new L/T separation results including Hall A data
- Left: new G_M^p data and (Q^2, ϵ) coverage; groupings of data for new L/T separations
- Submission to PRL expected ~Q1 of 2021
- See Eric Christy's talk from yesterday for more detail!

- Precision elastic *ep* cross section measurements in Hall A carried out in fall 2016 up to $Q^2 \approx 16$ GeV^2
- Significantly improved precision for $Q^2 \geq 6$ GeV^2
- ϵ coverage of new data allows new L/T separations out to ~16 GeV^2
- Significant tension between L/T separations and polarization discrepancy now firmly established to higher Q^2

Overview of SBS Program—Actual and Potential

Fully Approved:

- E12-07-109 (GEP): 45 PAC days, A- rate, "High Impact"
- E12-09-019 (GMN): 25 PAC days, B+ rate
- E12-09-016 (GEN): 50 PAC days, A- rate
- E12-09-018 (SIDIS): 64 PAC days, A- rate
- E12-17-004 (GEN-RP): 5 PAC days, A- rate
- E12-20-010 (nTPE): 2 PAC days, A- rate
- E12-20-008 (WAPP): 2 PAC days, B+ rate

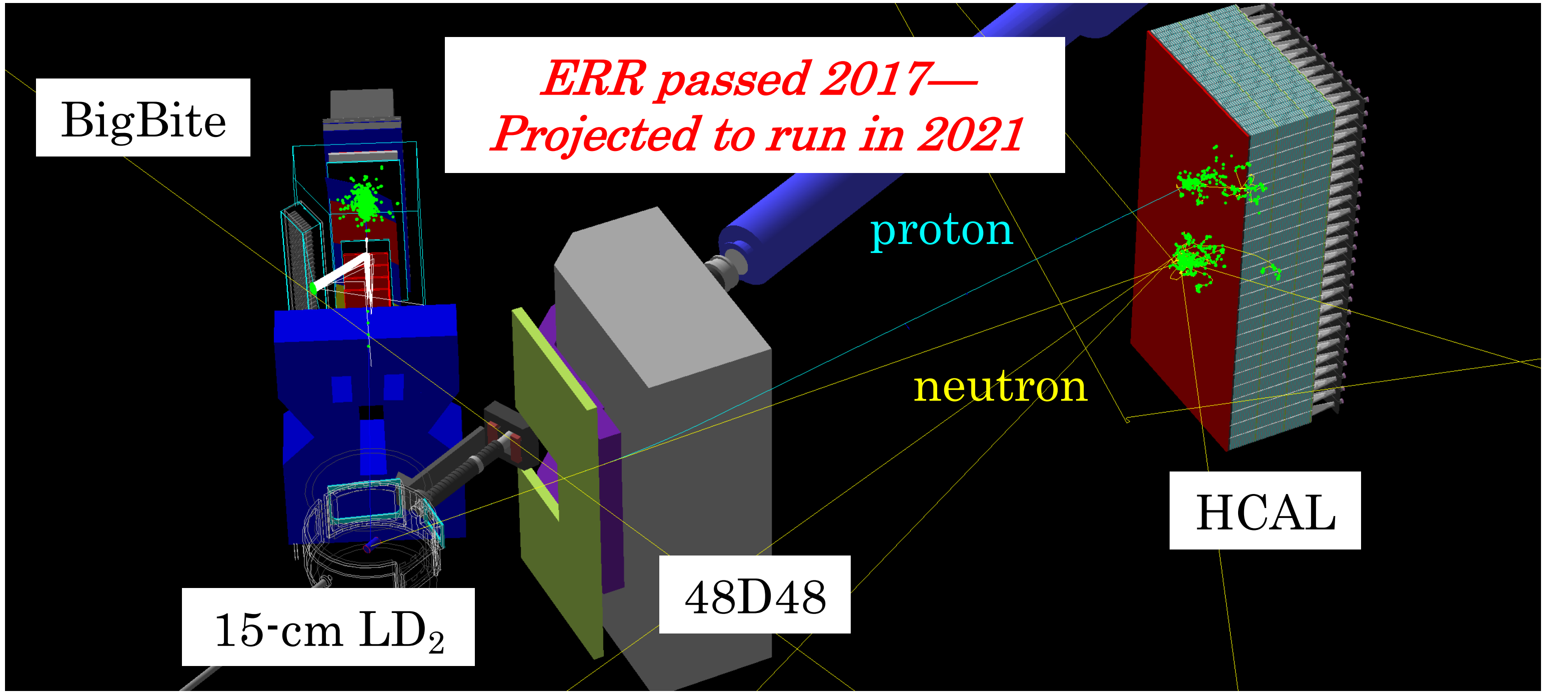
Conditionally Approved:

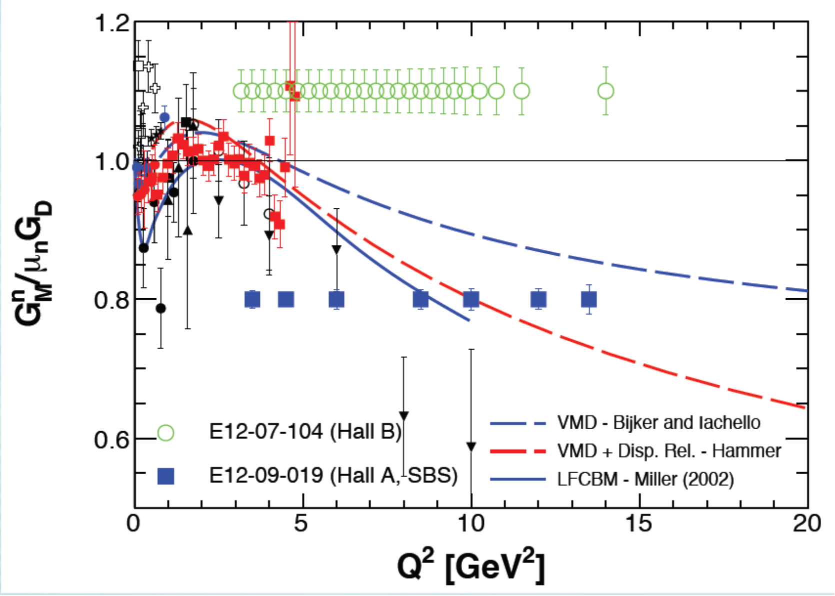
- C12-15-006 (TDIS): 27 PAC days, A- rate; "C1" approval status
  - "Run-group" add-on of kaon structure measurement also C1 approved

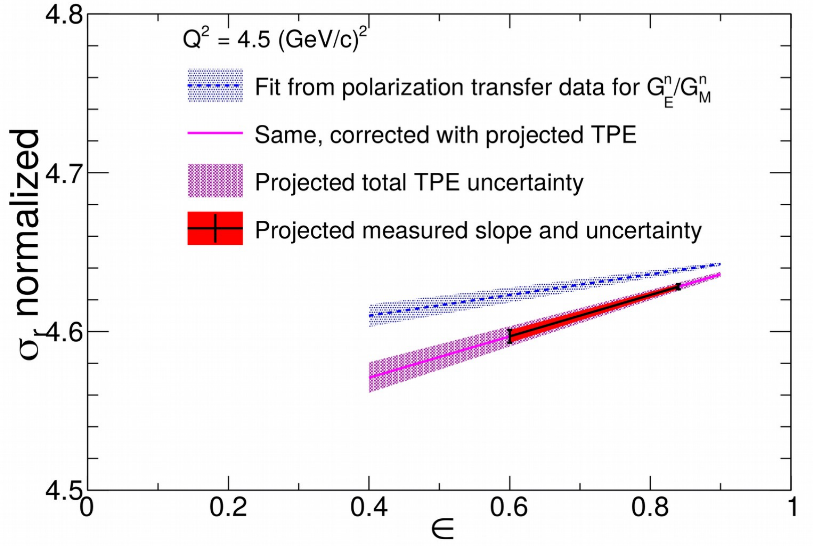
Potential future physics using SBS:

- A_1^n: formerly an approved BigBite experiment (2006), withdrawn at jeopardy (2019) due to imminent Hall C run, new proposal with BB+SBS likely (pending Hall C results)
- J/ψ photoproduction polarization observables/LHCb pentaquark physics: LOI submitted 2017
- e^+p elastic scattering polarization transfer—part of science program for positron beam at CEBAF in LOI and now white paper available in arxiv: https://arxiv.org/abs/2007.15081
- More DIS/SIDIS/TMD physics:
  - Longitudinally polarized SIDIS on ^{3}He and spin-flavor decomposition (deferred PR12-14-008)
  - Transversely polarized DIS/SIDIS on proton: g_2^p, Collins, Sivers, etc.
- Polarization observables and xsec in exclusive ϕ production
- Strange FFs at high Q^2 (not really an "SBS" proposal *per se*, but re-using some SBS components)
- Higher-Q^2 EMFFs/higher-x physics w/future CEBAF energy upgrade?

E12-09-019: Neutron magnetic form factor G_M^n to $Q^2 = 13.5$ GeV²

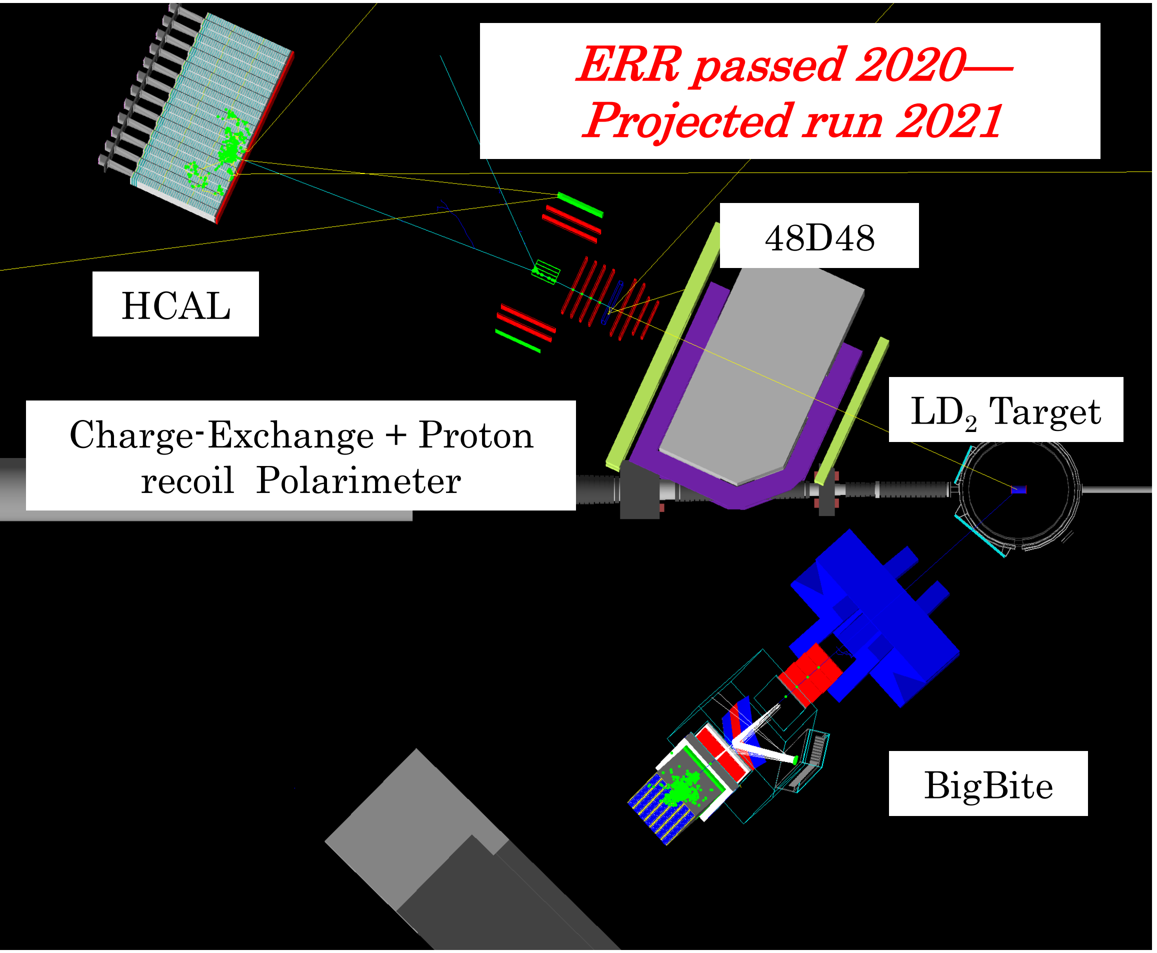


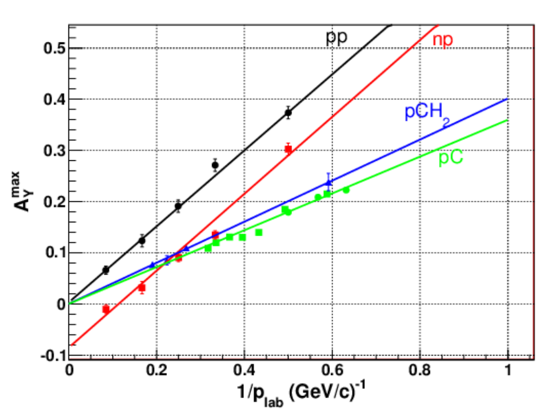


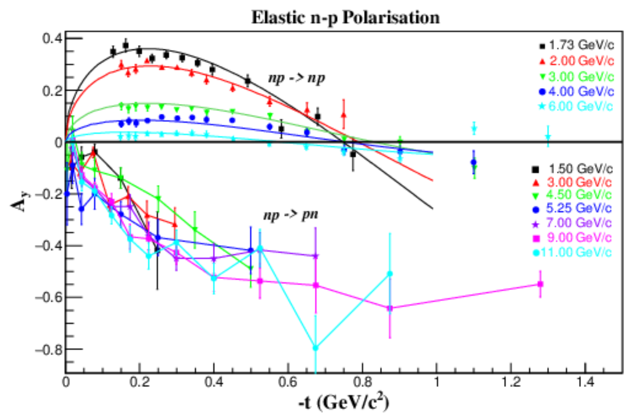


- E12-09-019 will measure neutron magnetic form factor G_M^n to 13.5 GeV² using the "ratio" method on deuterium.
- E12-20-010, a recently approved "add-on" measurement, will determine the Rosenbluth slope in elastic *en* scattering for the first time at $Q^2 = 4.5\ GeV^2$
  - **See Eric Fuchey's talk later in this session**
- Uses hadron calorimeter for efficient nucleon detection; magnetic deflection for charge ID
- BigBite detects electron, defines $\vec{q}$ vector, vertex for selection of quasi-elastic

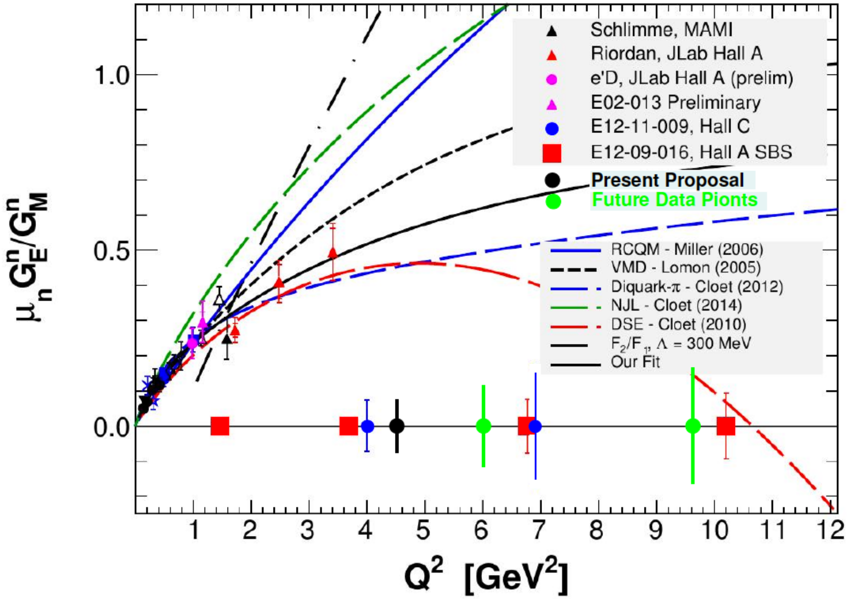
E12-17-004: G_E^n/G_M^n to 4.5 GeV^2 via charge-exchange recoil polarimetry





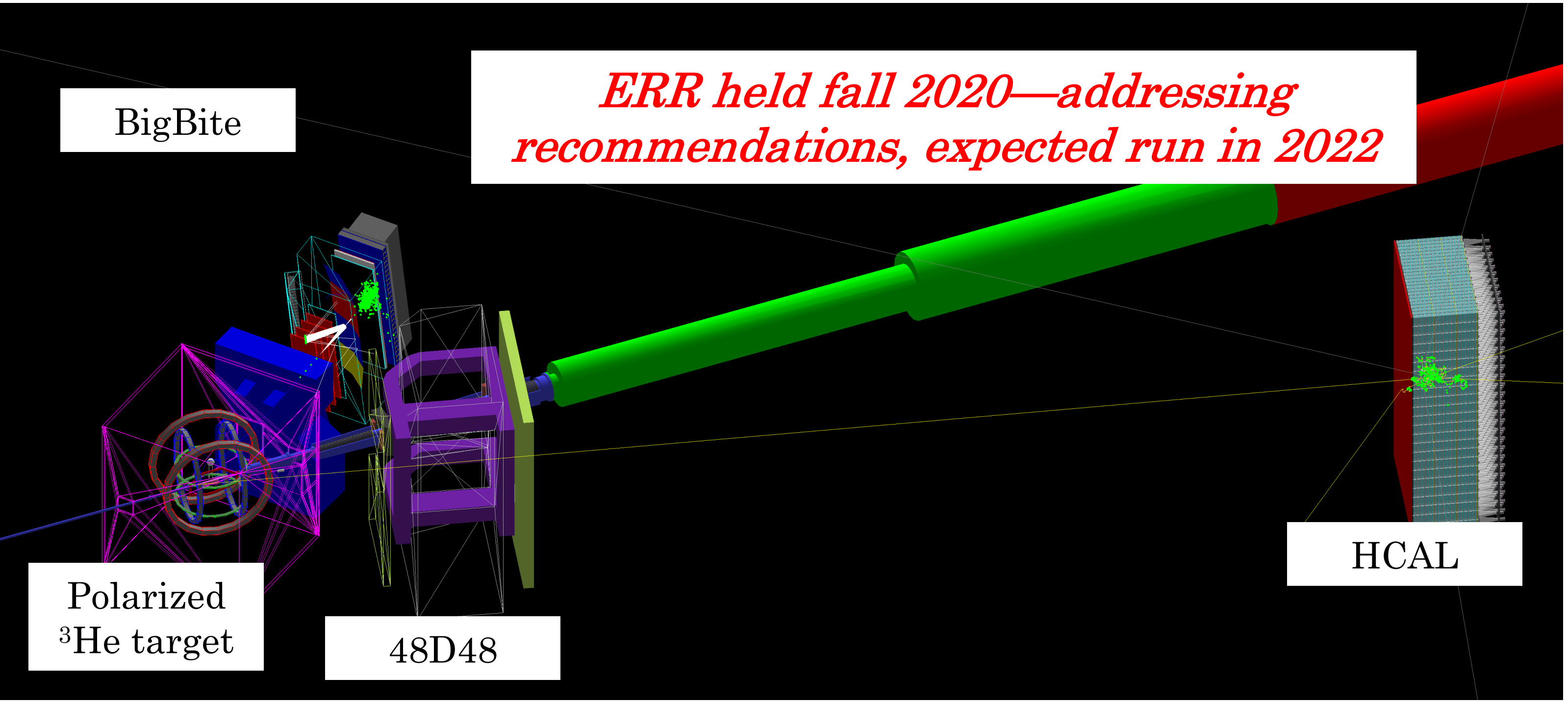


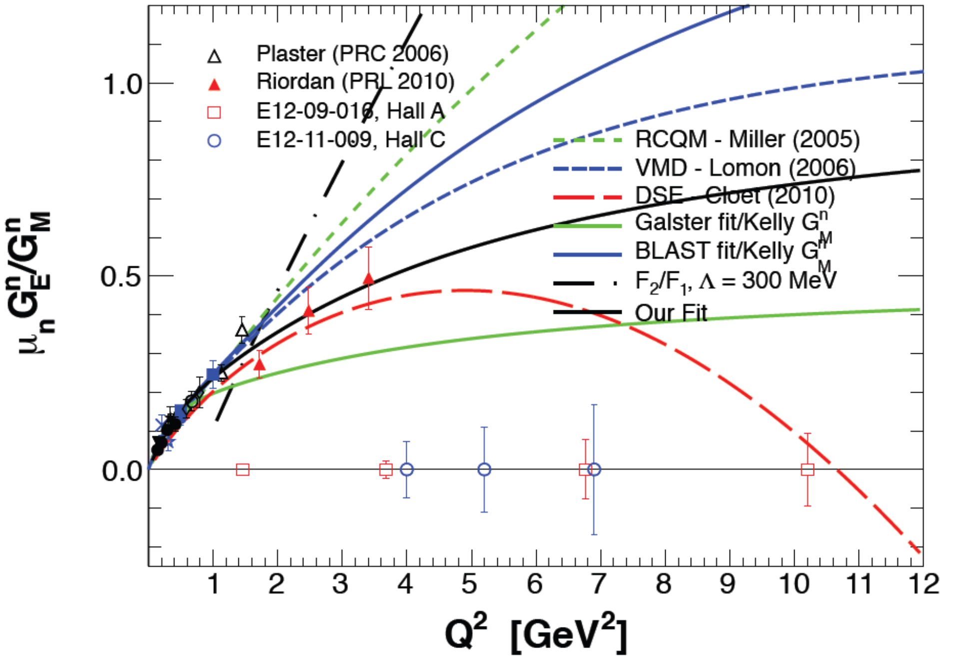
Analyzing powers for np, pp, pA scattering vs. initial momentum (left) and vs. transferred momentum (right)



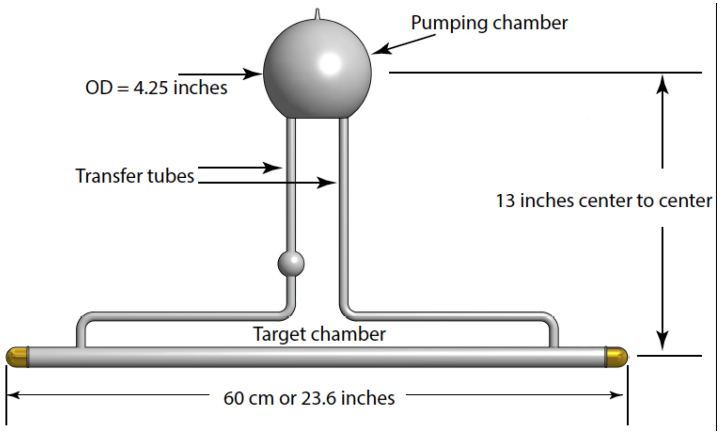
- E12-17-004 layout (above) and projected results (right):
  - First use of charge-exchange polarimetry in a FF experiment
- E12-20-008 approved as add-on to measure K_{LL} for $\gamma n \rightarrow \pi^- p$
  - See Arun Tadepalli talk later in this session!

E12-09-016: G_E^n / G_M^n to 10 GeV^2 using polarized ^{3}He(e,e'n)pp

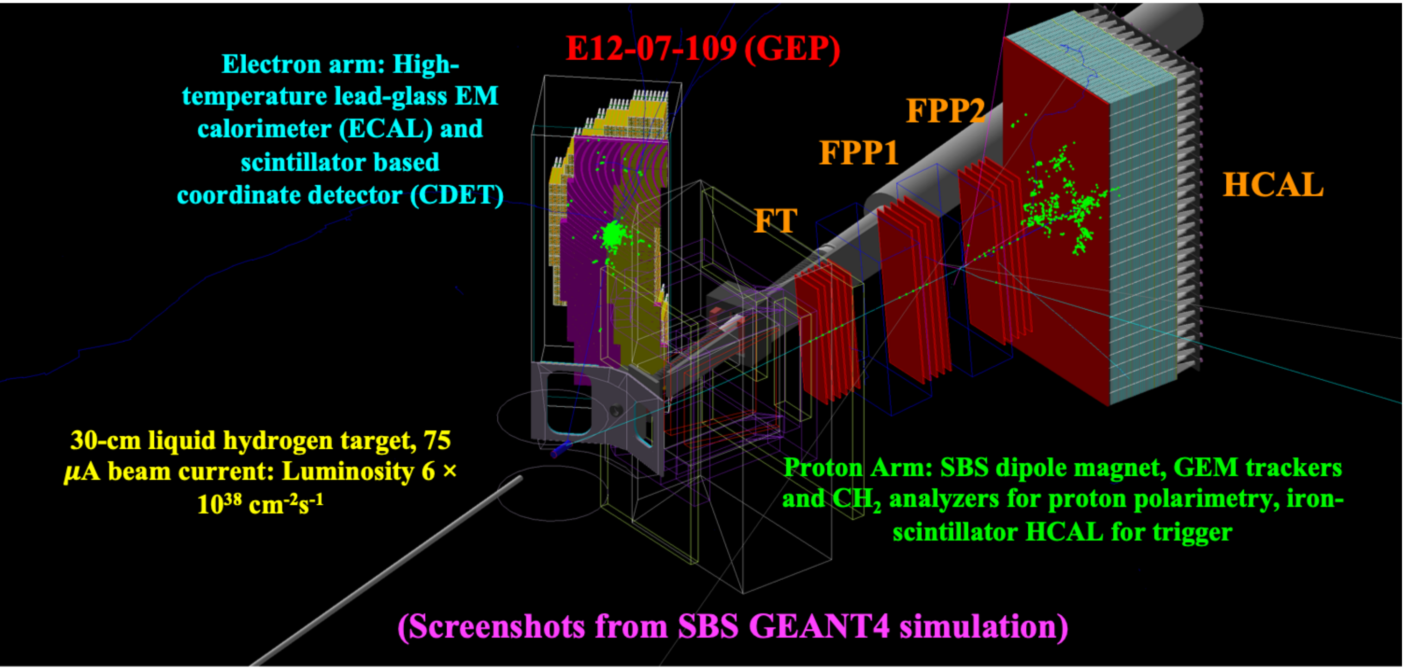




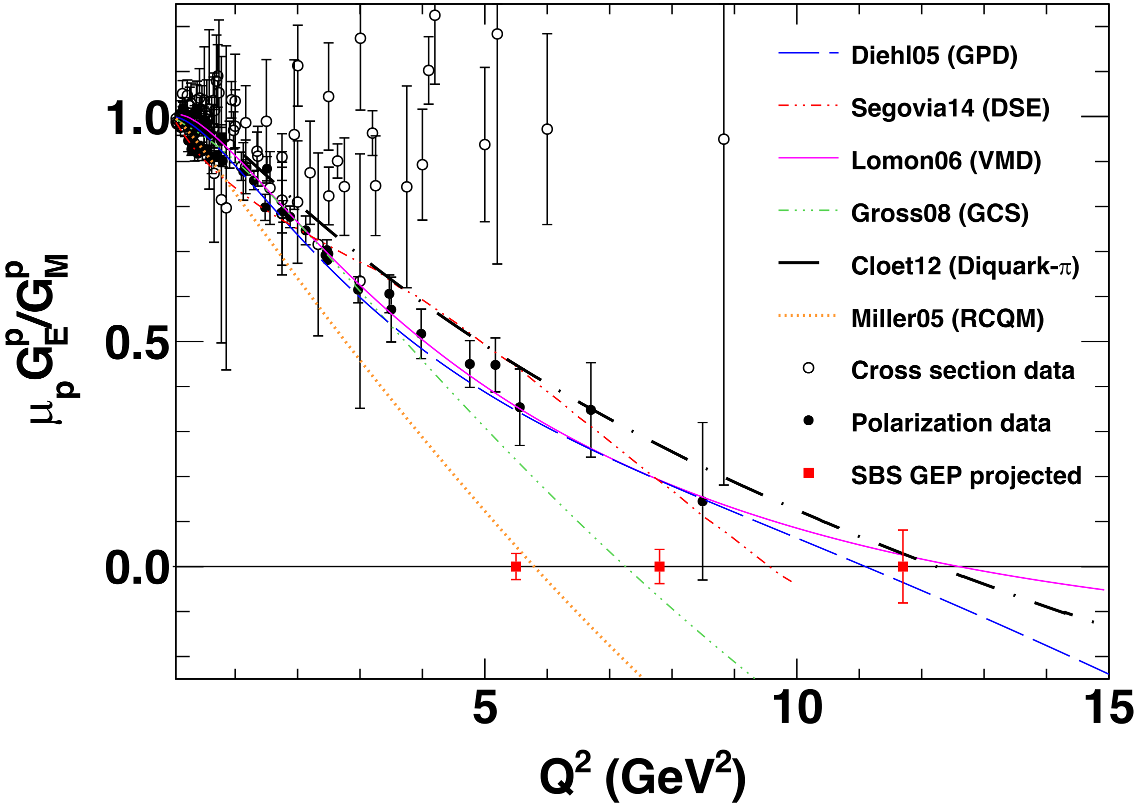
- E12-09-016 will measure the neutron electric form factor to 10 GeV^2 using the beam-target double-spin asymmetry method on polarized ^{3}He
- Same detector configuration as GMN (E12-09-019)
- High-luminosity polarized ^{3}He target with convection-driven circulation of polarized gas.
- Measurement to 10 GeV^2 has enormous discrimination power among theoretical models—will severely test DSE calculations, virtually alone in predicting a turnover and zero crossing of G_E^n



E12-07-109: G_E^p/G_M^p to 12 GeV^2 via polarization transfer

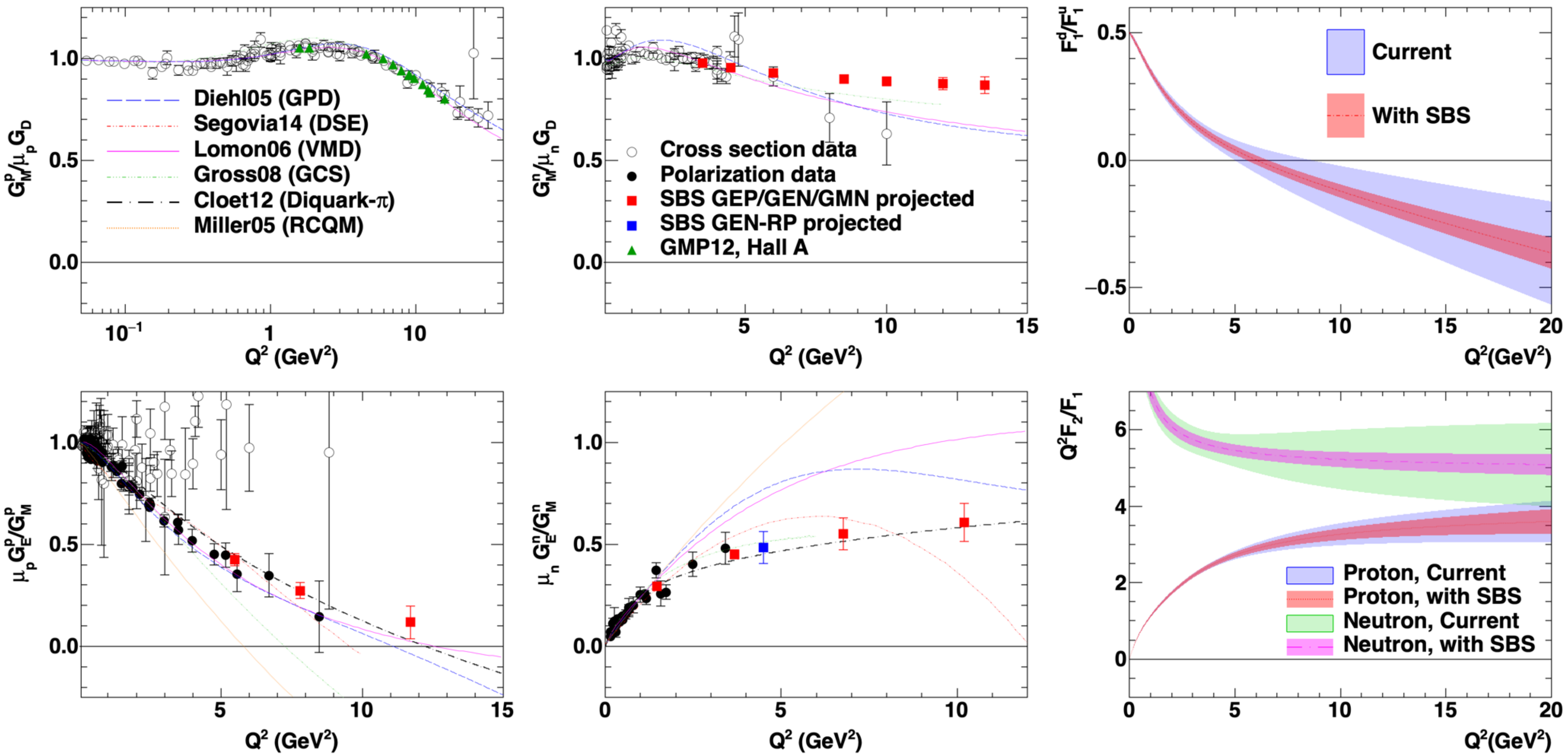


- Original motivation for SBS concept—first approved 2007
- Designated "High Impact Experiment" by JLab PAC41
- Jeopardy proposal reapproved by PAC47 in 2019
- Currently projected to run in ~2023
- Novel high-temperature lead-glass calorimeter detects scattered electron with scintillator-based coordinate detector—triggering, aid tracking in front GEMs, and rejection of inelastics
- GEM-based trackers with CH_2 analyzers for proton polarimetry
- HCAL for trigger and preferential section of nuclear scattering events with high analyzing power



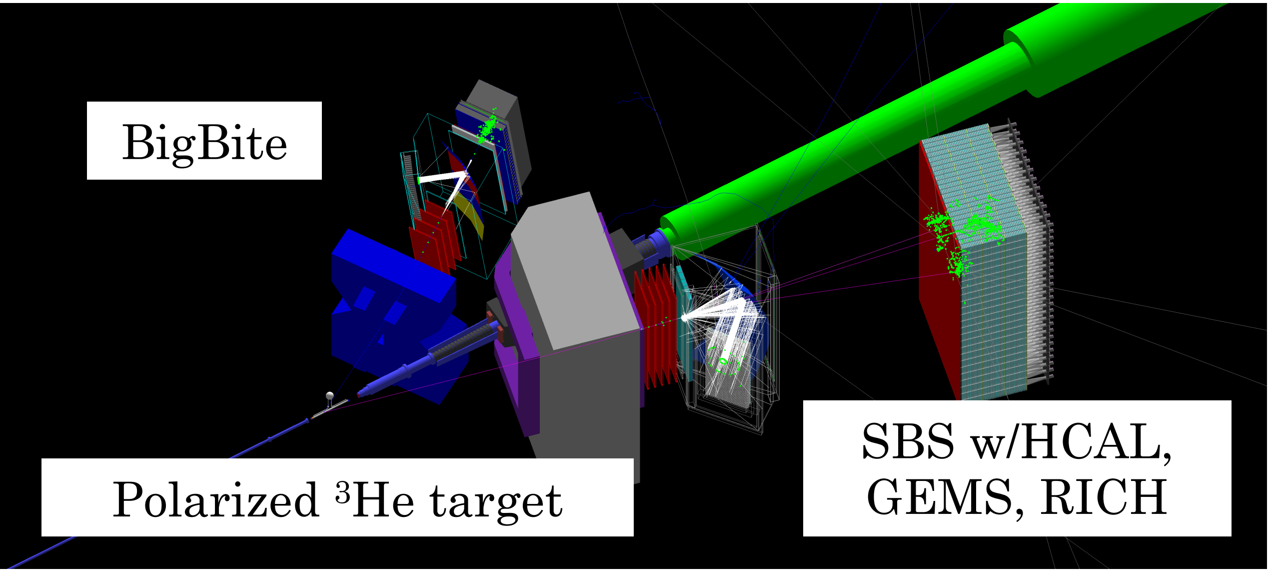
Projected SBS statistical precision for $\mu_p G_E^p/G_M^p$ compared to existing data and selected theoretical models

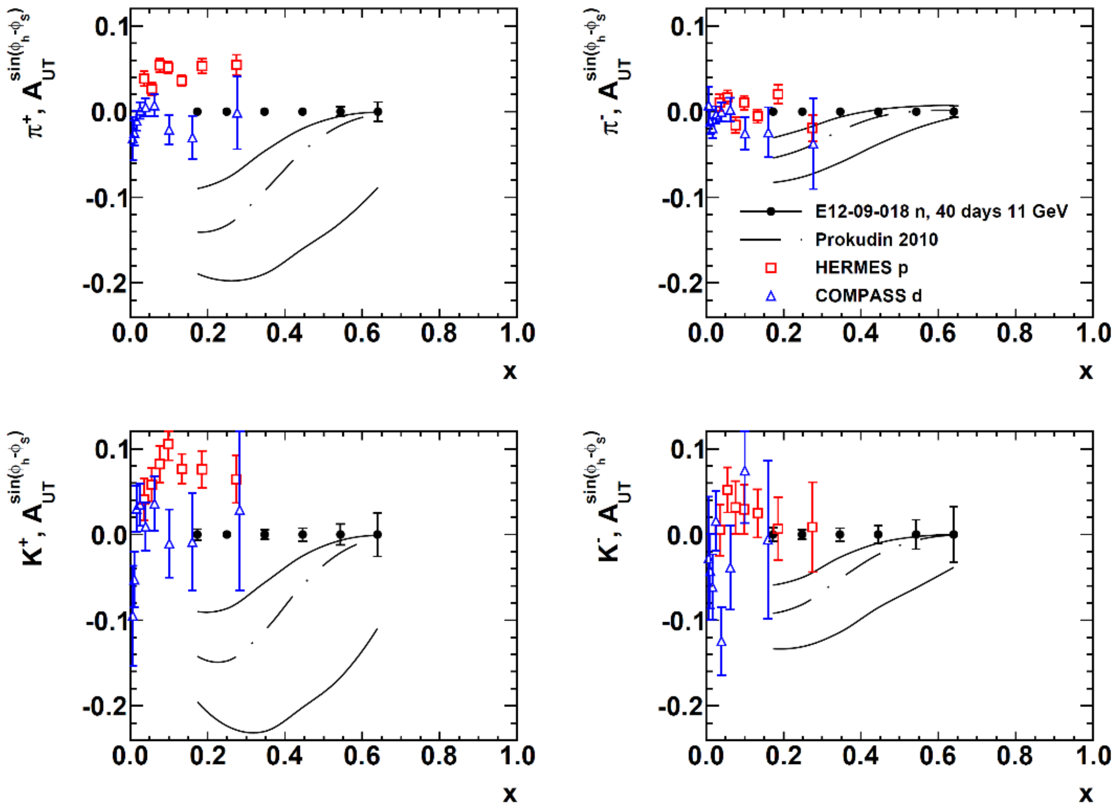
SBS FF Program Summary



- Expected data from JLab 12 GeV for G_E^p, G_E^n, G_M^n to $Q^2 \geq 10$ GeV² allows full flavor decomposition of FFs, severe constraints to most sophisticated theoretical descriptions of the nucleon (and to GPD modeling)
- First "run group": GMN+GEN-RP+nTPE+WAPP starting summer 2021

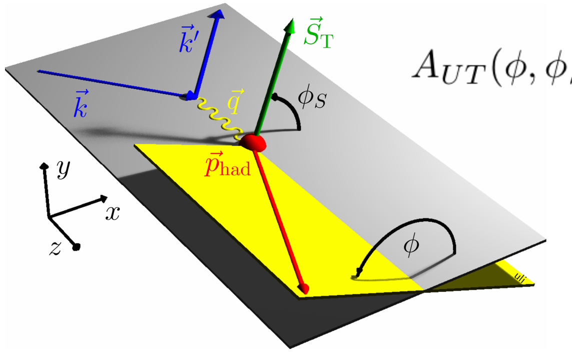
SBS SIDIS program: E12-09-018 (Transversity)





Example of projected E12-09-018 precision: neutron Sivers moments for charged pions and Kaons (11 GeV data only)

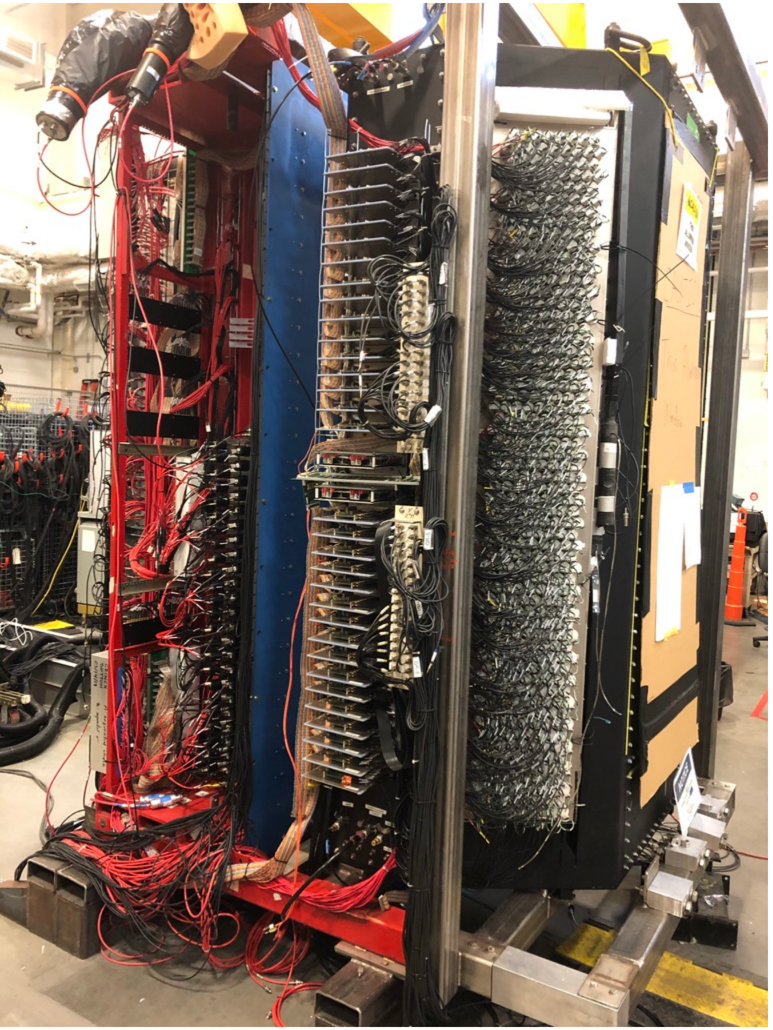
- **E12-09-018** in Hall A: 40 (20) days production at E = 11 (8.8) GeV—significant Q^2 range at fixed x
- Reach high x (up to ~0.7) and high statistical FOM (~1,000X Hall A E06-010 @6 GeV)

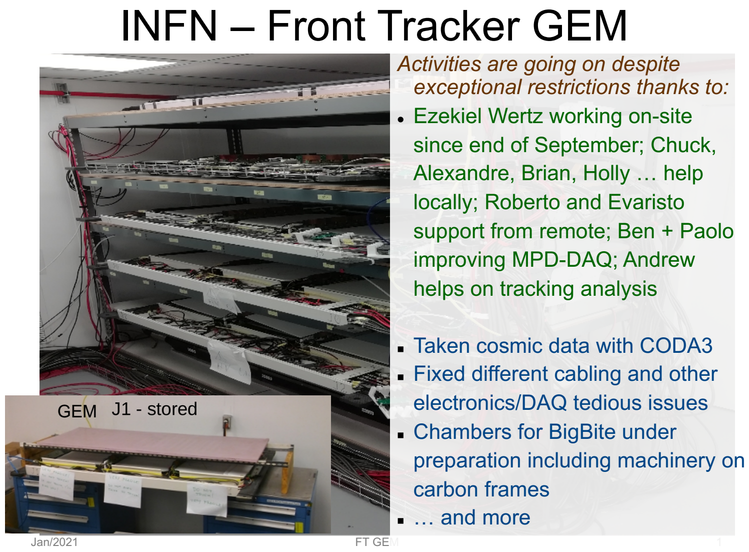


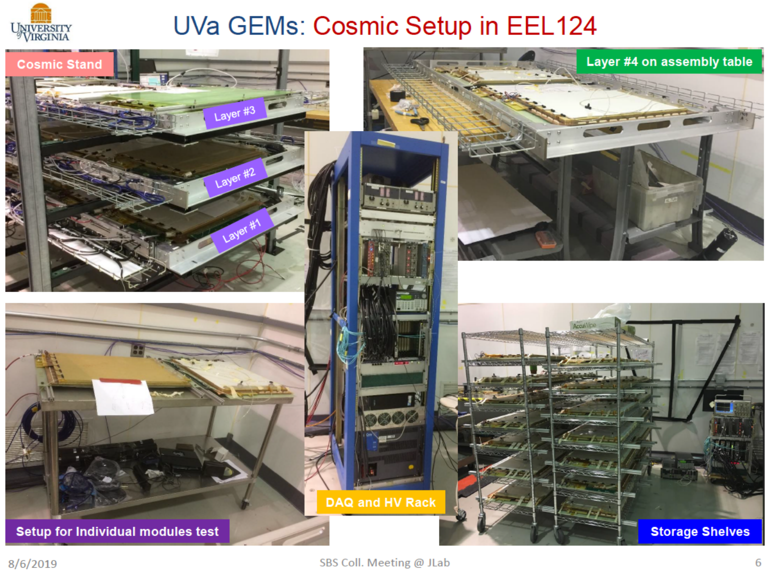
$$A_{UT}(\phi,\phi_S) = \frac{1}{P_T}\frac{d\sigma(\phi,\phi_S)-d\sigma(\phi,\phi_S+\pi)}{d\sigma(\phi,\phi_S)+d\sigma(\phi,\phi_S+\pi)}$$
$$= A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S) + A_{UT}^{Pretz}\sin(3\phi-\phi_S)$$

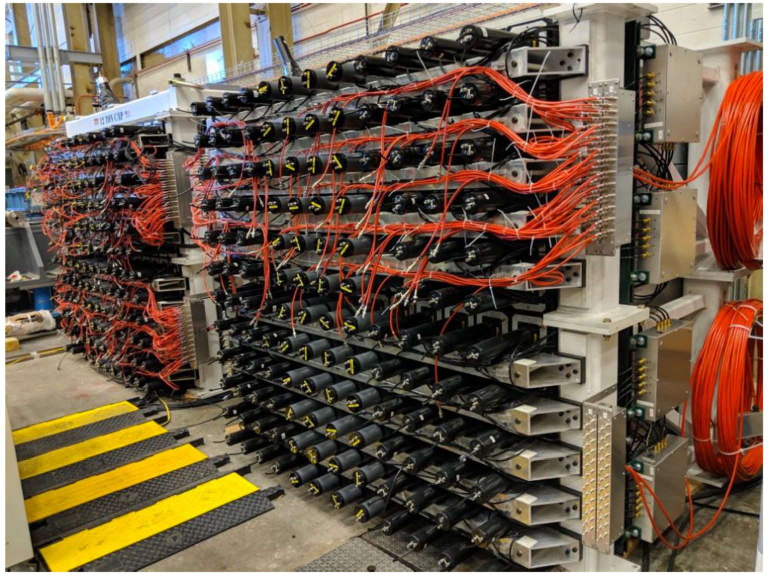
E12-09-018 STATUS: the collaboration is currently evaluating several options for realizing a SIDIS target that could deliver a large fraction of the proposal physics output on an accelerated timetable compatible with running immediately after GEN-II

SBS PICS! (some outdated)



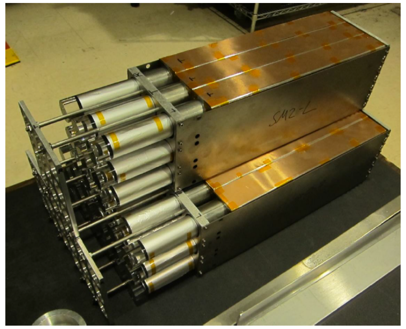






Work since Feb SBS meeting

- 126 of out 191 supermodules have been assembled
- JLab Detector Support Group is contributing manpower to assembling supermodules.



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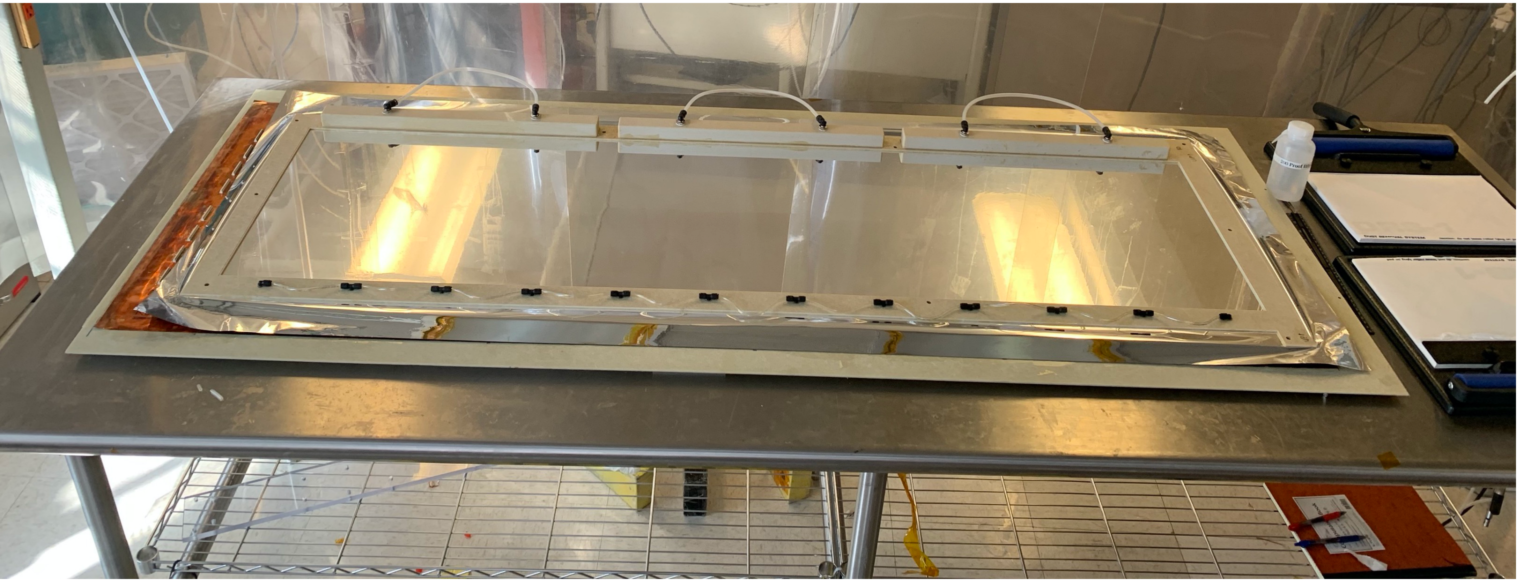
U/V GEM project at UVA



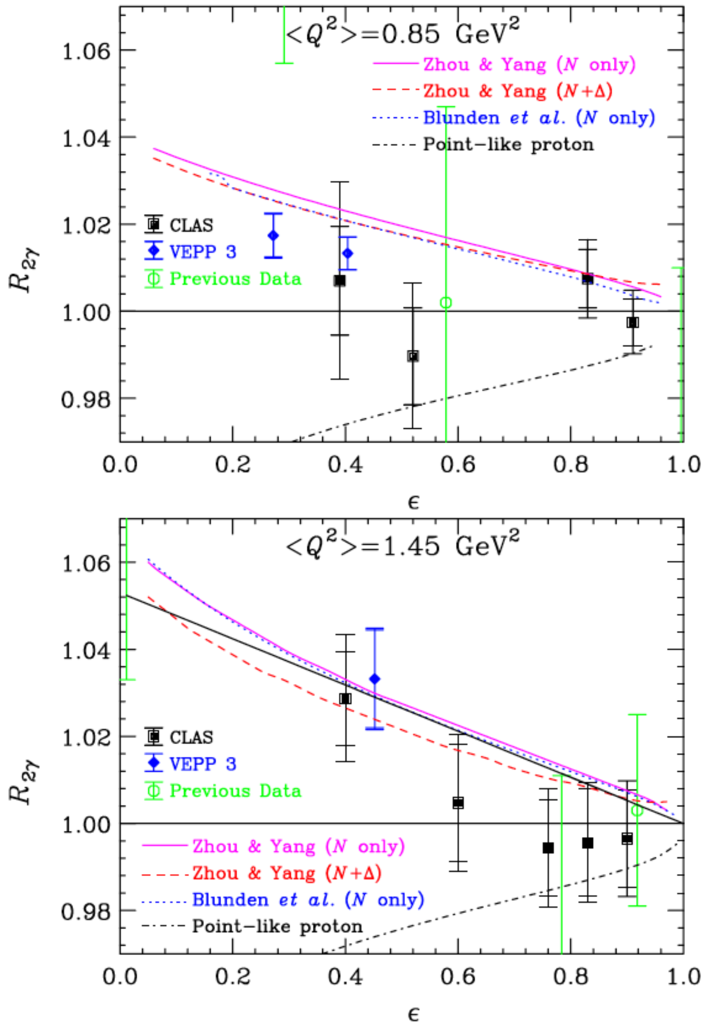
- UV GEM building going on at UVa.
- Advantages:
  - no dead areas within acceptance
  - $\pm 30°$ strip angles complementary to X/Y strips in other layers, help resolve tracking ambiguities
- Construction of 4 U/V GEM layers funded by JLab & SBS Collaboration
- The construction of first two detectors already complete: testing to start soon
- Expect to build the other two by April.

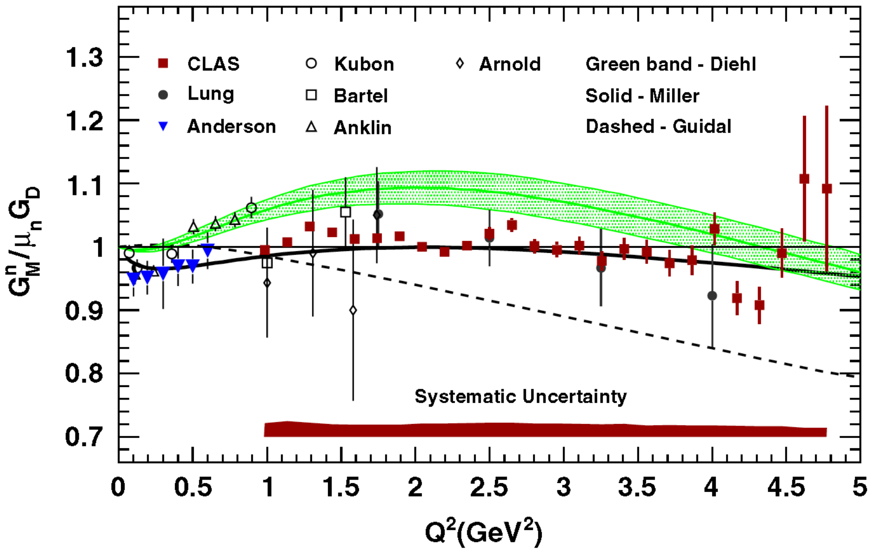
Summary and Conclusions

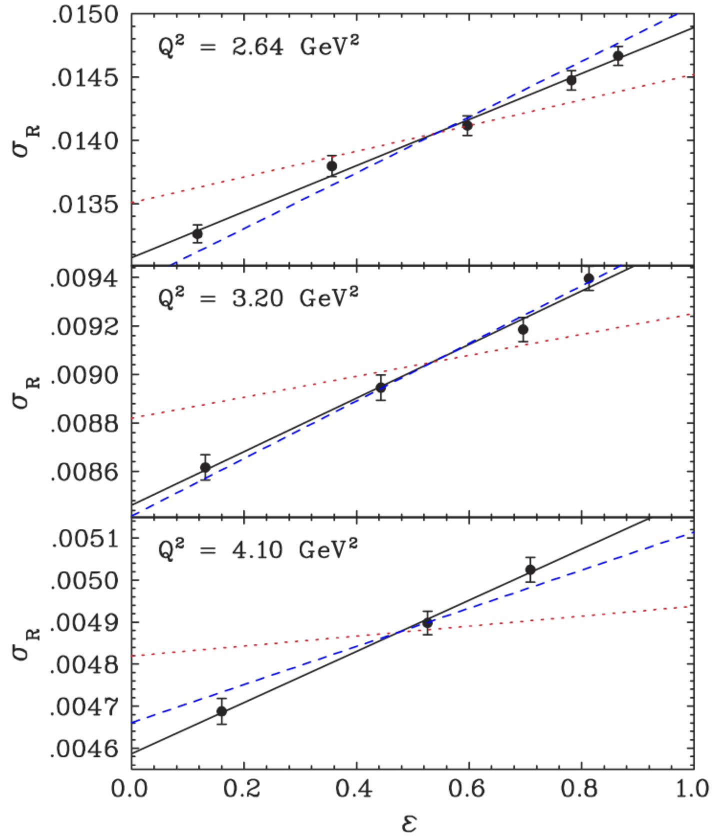
- ~13+ years after first proposal approved (SBS GEP, E12-07-109), the SBS program is finally about to begin!
- Core program of nucleon Form Factors and SIDIS will produce flagship/legacy results of the JLab 12 GeV program
- SBS equipment (which also includes upgraded BigBite/etc) adds significant generic science capabilities to Hall A, that could enable a rich physics program beyond the core program, IF there was room in the Hall A schedule…
- Installation and physics running SHOULD get underway in 2021—stay tuned/get involved!
- Thanks for your attention!

Backups

Nucleon FFs from the 6 GeV era at JLab: G_M^n, "Super-Rosenbluth", CLAS-TPE, etc.







- Above, middle: G_M^n from CLAS collaboration; Lachniet *et al.*, PRL **102**, 192001 (2009)
- Left: CLAS-TPE; D. Rimal *et al.*, PRC 95, 065201 (2017)

JLab $\frac{G_E^p}{G_M^p}$ polarization data inspired an outpouring of new effort on precise *ep* scattering measurements and theory

Above: "Super-Rosenbluth" data from Hall A; Qattan *et al.*, PRL **94**, 142301 (2005)

Form factors and "nucleon imaging": density interpretations

In the low-Q limit (static charge density), e^- scattering form factor is the Fourier transform of charge density:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} |F(\mathbf{q})|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \equiv \frac{\alpha^2(\hbar c)^2}{4E_e^2 \sin^4\frac{\theta}{2}} \frac{E'_e}{E_e} \cos^2\frac{\theta}{2}$$

$$F(\mathbf{q}) = \int \rho(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} d^3x$$

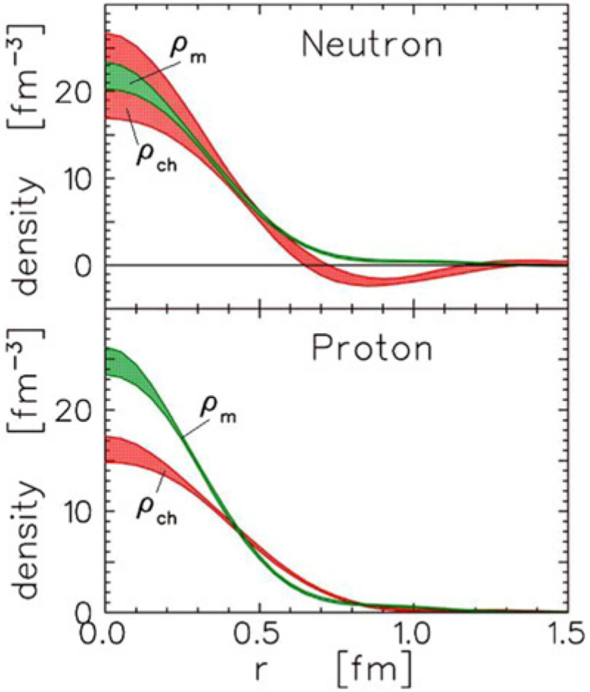
Traditional 3D density interpretation of nucleon FFs is invalidated by relativity at large Q^2, but still useful at low Q^2

Modern density interpretation:

- G. Miller, Annu. Rev. Nucl. Part. Sci., 60, 1 (2010)
- Through connection between FFs and GPDs, 2D Fourier transforms of F_1, F_2 give model-independent impact parameter-space densities:

$$\rho_{ch}(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(Qb) F_1(Q^2)$$

$$\tilde{\rho}_M(\mathbf{b}) = b \sin^2\phi \int_0^\infty \frac{Q^2 dQ}{2\pi} J_1(Qb) F_2(Q^2)$$



J. J. Kelly: PRC 66, 065203 (2002)

- Estimate of nucleon rest-frame radial densities in three dimensions from Sachs FFs with (model-dependent) relativistic corrections

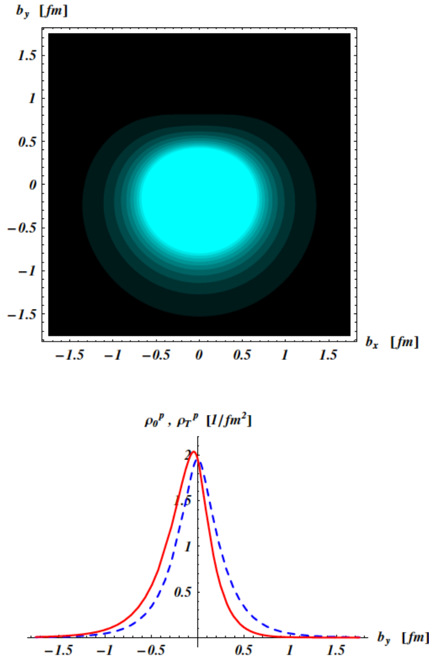


FIG. 1: Quark transverse charge densities in the *proton*. The upper panel shows the density in the transverse plane for a proton polarized along the x-axis. The light (dark) regions correspond with largest (smallest) values of the density. The lower panel compares the density along the y-axis for an unpolarized proton (dashed curve), and for a proton polarized along the x-axis (solid curve). For the proton e.m. FFs, we use the empirical parameterization of Arrington *et al.* [14].

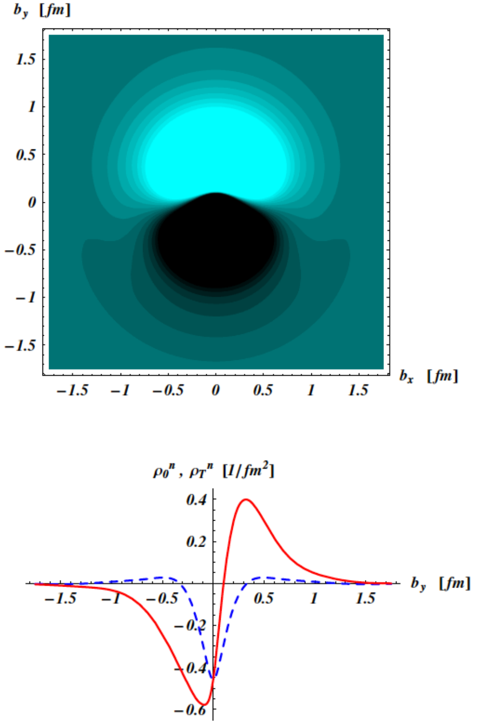


FIG. 2: Same as Fig. 1 for the quark transverse charge densities in the *neutron*. For the neutron e.m. FFs, we use the empirical parameterization of Bradford *et al.* [15].

Proton (left) and neutron (right) 2D polarized transverse charge densities from Carlson and Vanderhaeghen: Phys. Rev. Lett. 100, 032004 (2008)

- **Transverse charge density in a transversely polarized proton (left) and neutron (right), for polarization along the "x" axis**