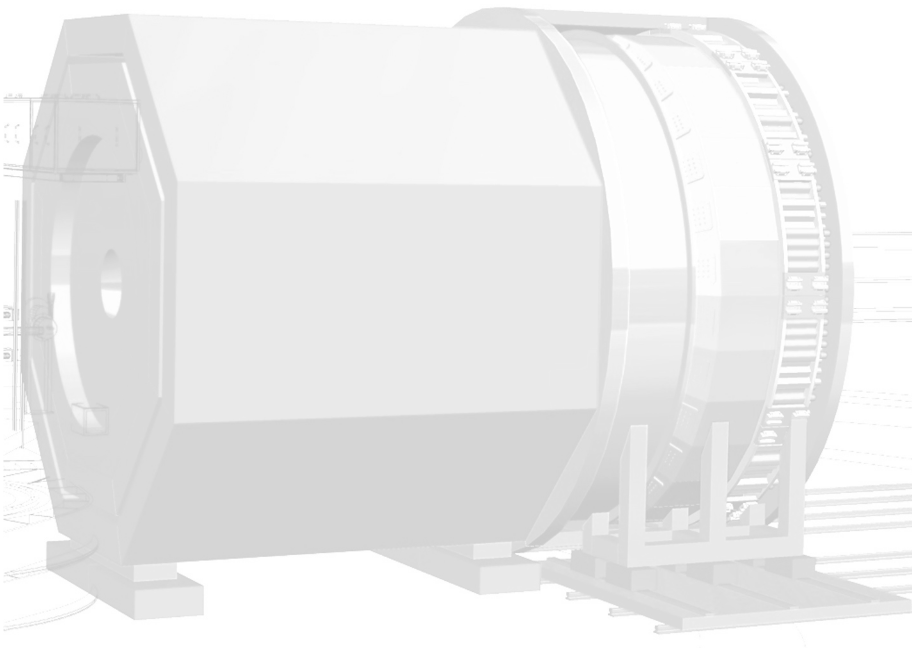
Neutron Spin Structure Studies with SoLID

Ye Tian (Syracuse University)
For the SoLID collaboration



- **SoLID Overview**
- **Physics Motivation on g_2 , d_2**
- **Experiment**
- **Expected Results**
- **Summary**

JLUO2024

06/12/2024

This work is supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357 and DE-FG02- 84ER40146. Acknowledgement to the entire SoLID collaboration, especially Jian- Ping Chen, Haiyan Gao, Zein-Eddine Meziani, and Paul Souder

Solenoidal Large Intensity Device (SoLID) with JLab 12-GeV Enables QCD at the Intensity Frontier

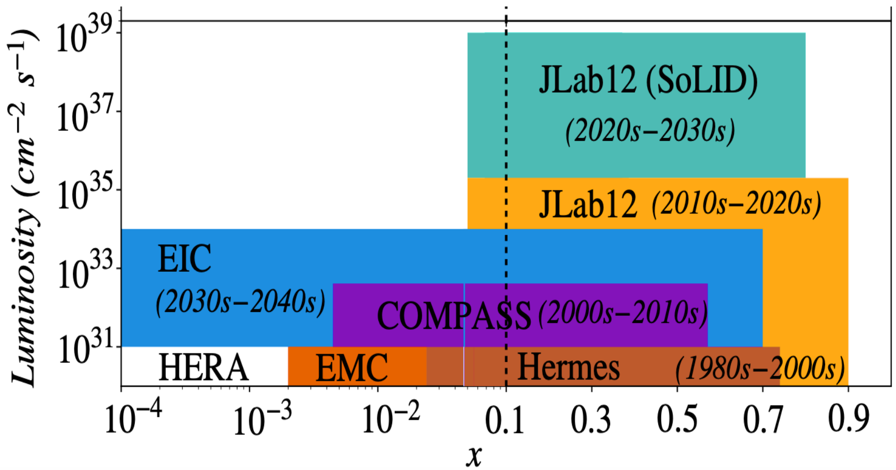
Research at SoLID will have the unique capability to explore the QCD landscape while complementing the research of other key facilities

High Luminosity
$10^{37\text{-}39}$/cm²/s

+

Large Acceptance
Full azimuthal ϕ coverage

J Arrington et al 2023 J. Phys. G: Nucl. Part. Phys. 50 110501



Part of Recommendation IV **LRP2023**

SoLID Scientific Questions

- **How does the spin of the nucleon arise?**
  Precision 3D momentum imaging of nucleon spin
- **How does the mass of the nucleon arise?**
  Precision J/ψ production near the threshold
- **New physics beyond Standard Model?**
  Precision test of the SM and search of new physics

SoLID Overview

- Website https://solid.jlab.org
- PreCDR 2019 https://solid.jlab.org/DocDB/0002/000282/001/solid-precdr-2019Nov.pdf
- Whitepaper 2022 https://arxiv.org/abs/2209.13357 *J. Phys. G: Nucl. Part. Phys.* **50** 110501 (2023)

☑ Semi-Inclusive Deep Inelastic Scattering (SIDIS) Program:

- E12-10-006(A): Single Spin Asymmetry on Transversely Polarized ^{3}He (90 days)
- E12-11-007(A): Single and Double Spin Asymmetry on Longitudinally Polarized ^{3}He (35 days)
- E12-11-108(A): Single Spin Asymmetry on Transversely Polarized Proton (120 days)
- Run groups: Dihadron (E12-10-006A), Ay (E12-11-108A/E12-10-006A), Kaon Production (E12-11-108B/E12-10-006D), **Measurement of Inclusive g2n and d2n with SoLID on a Polarized ^{3}He Target** (E12-11-007A/E12-10-006E)

☑ Parity Violation Deep Inelastic Scattering (PVDIS) Program:

- E12-10-007 (A): Parity Violating Asymmetry in DIS with LH_2 and LD_2 (169 days)
- PR12-22-002 (C2 approved): Flavor Dependence of Nuclear PDF Modification Using PVDIS with ^{48}Ca

☑ J/ψ Program: E12-12-006 (A) Near Threshold Electroproduction of J/ψ at 11 GeV (60 days)

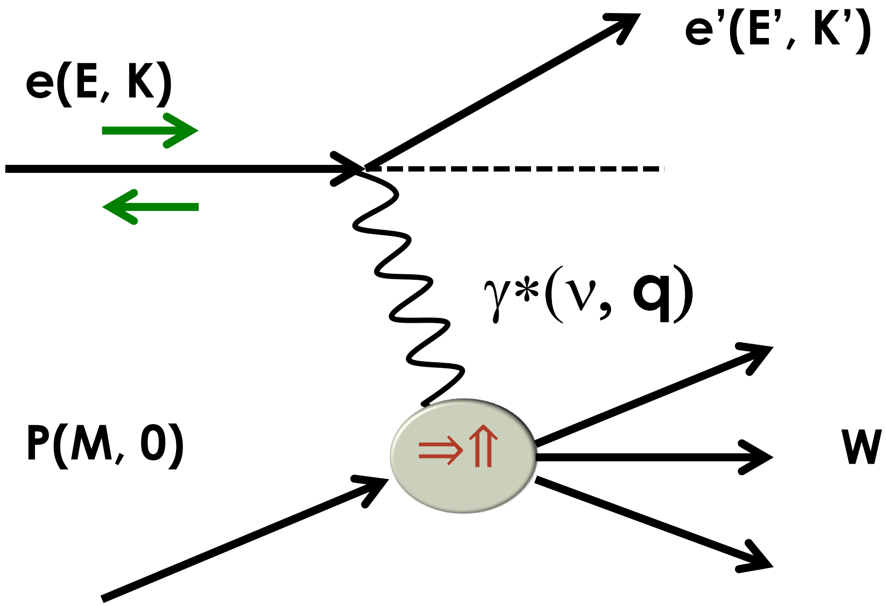
■ Two photon exchange study

- E12-22-004 (A$^-$): Beam Normal Single Spin Asymmetry in DIS with LH_2 (38 days)

■ Generalized Parton Distributions (GPDs) Programs

- E12-12-006A: Time-Like Compton Scattering (Run group).
- E12-10-006B: Deep Exclusive π^- production (DEMP) with polarized ^{3}He target and SIDIS configuration
- Under development: Other polarized-proton/neutron DVCS and Doubly DVCS on proton, etc.

Inclusive Electron Scattering



Q^2 : Four-momentum transfer

x : Bjorken variable($=Q^2/2M\nu$)

ν : Energy transfer

M : Nucleon mass

W : Final state hadronic mass

$$\frac{d^2\sigma}{dE'd\Omega} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)tan^2\frac{\theta}{2} + \gamma g_1(x,Q^2) + \delta g_2(x,Q^2)\right]$$

spin dependent Structure Function

Spin Structure Function in Parton Model

- g_1 related to the polarized parton distribution functions

$$g_1 = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) \qquad \Delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x)$$

- g_2 is zero in the naive parton model

  non-zero value carries information of quark-gluon interaction

  Ignoring quark mass effect of order O(m_q/Λ_{QCD})

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \boxed{\bar{g}_2(x,Q^2)}$$

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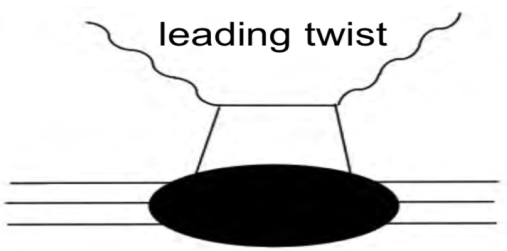


- leading twist related to g_1 by Wandzura-Wilczek relation

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

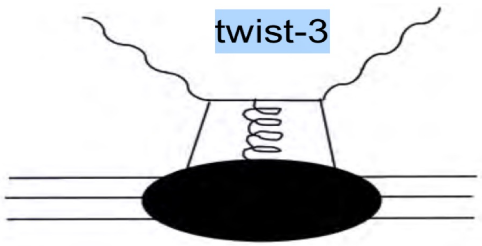
related to amplitude for scattering off asymptotically free quarks

d_2 : twist-3 matrix element

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

quark transverse momentum contribution

twist-3 part which arises from quark-gluon interactions



quark-gluon interaction and the quark mass effects

d_2: the x^2 moment of $\bar{g}_2(x,Q^2)$, twist-3 matrix element

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

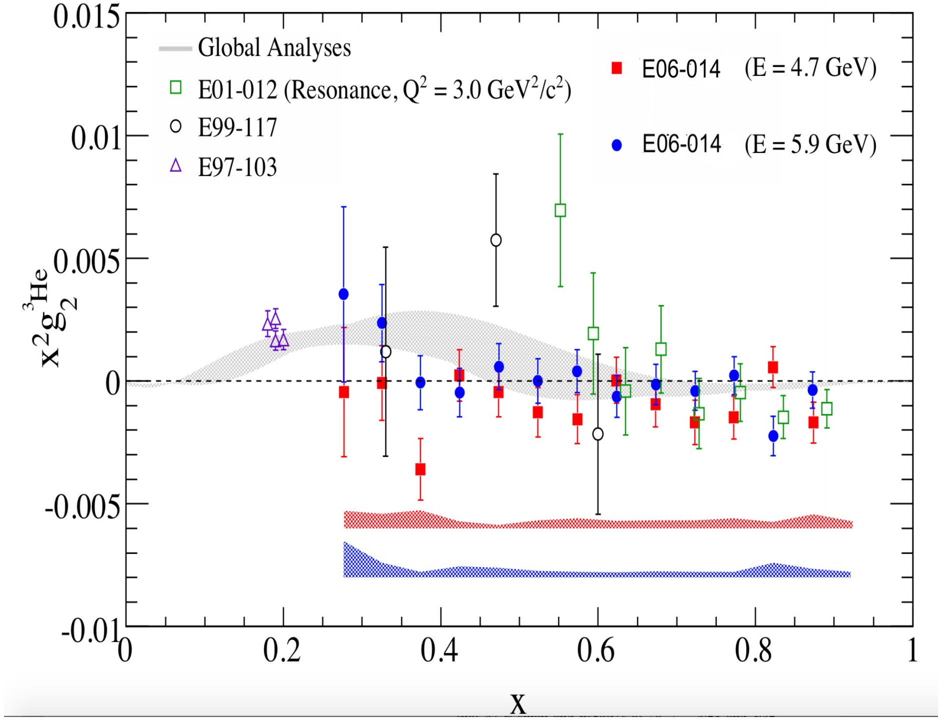
$$= \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

- ✓ Dominated by high x data because of weighting
- ✓ Calculable on the Lattice.
- ✓ A clean way to access twist-3 contribution

Existing Neutron g_2 Data

- First precise measurement of neutron g_2 from SLAC, averaged $Q^2 \approx 5$ GeV^2
- Measurement form Jefferson Lab: E<6GeV
- The Hall C d^n_2 E12-06-121, $0.2 < x < 0.95$ and $2.5 < Q^2 < 7$ GeV^2 with SHMS and upgraded HMS
- We propose to measure g^n_2 at x>0.1 and $1.5 < Q^2 < 10$ GeV

Figure from Phys. Rev. D 94, 052003 (2016)



^{3}He	g_2^n, d_2^n, Γ_2^n	$0.5 \le W \le 2.5\ GeV$	$0.1 \le Q^2 \le 0.9$	JLAB E94–010 [29]
^{3}He	g_2^n	$x = 0.2$	$0.57 \le Q^2 \le 1.34$	JLAB E97–103 [30]
^{3}He	g_2^n, d_2^n	$x = 0.33, 0.47, 0.6$	2.7,3.5,4.8	JLAB E99–117 [2]
^{3}He	g_2^n	$x < 0.1$	$0.035 \le Q^2 \le 0.24$	JLAB E97–110 [31]
^{3}He	g_2^n, d_2^n	$0.25 \le x \le 0.9$	3.21,4.32	JLAB E06–014 [14]
^{3}He	g_2^n, d_2^n	$0.55 \le x \le 0.9$	$0.7 \le Q^2 \le 4.0$	JLAB E01–012 [33]

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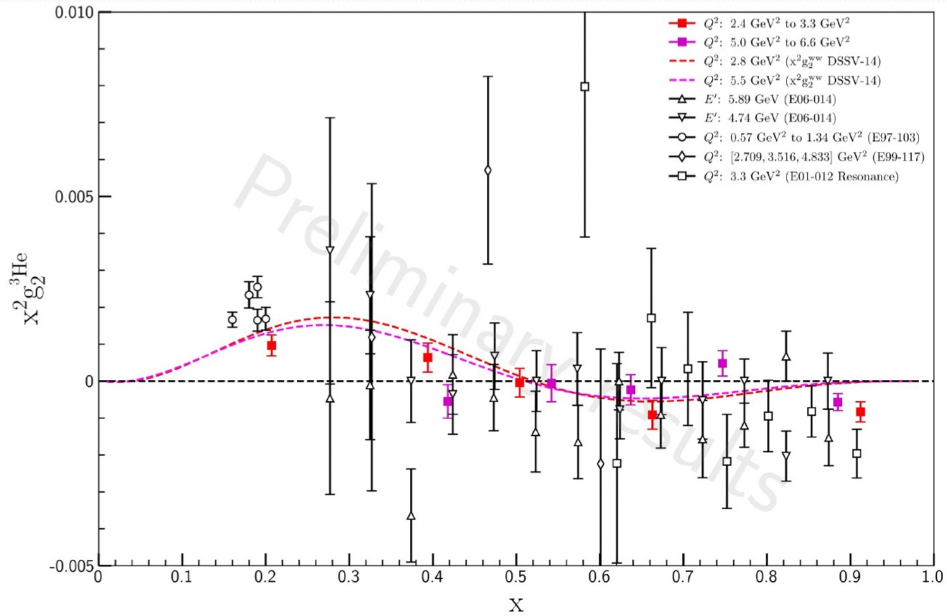
Figure from Jian-ping Chen SPIN2023 talk



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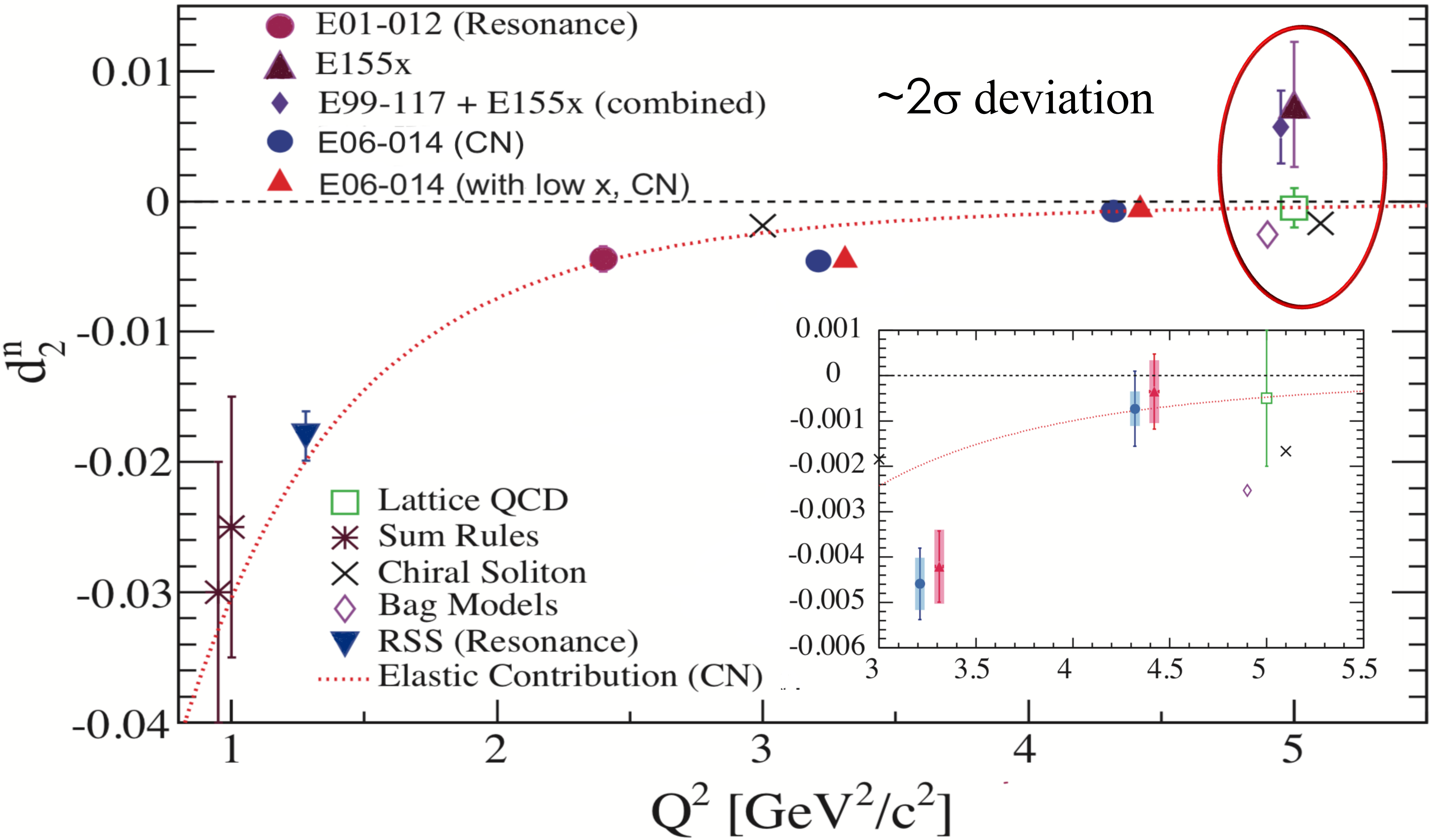
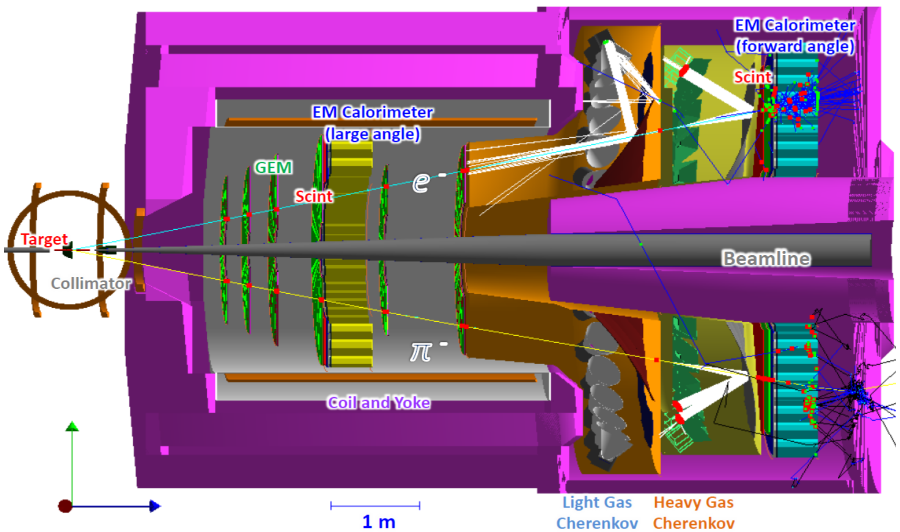
Existing Neutron d_2 Data

Figure from Phys. Rev. Lett., 113(2):022002, 2014



SoLID Detector Subsystems

SoLID (SIDIS He3)



SoLID SIDIS Configuration

- E12-10-006: Transversely polarized ^{3}He target
- E12-11-007: Longitudinally polarized ^{3}He target
- ^{3}He target cell 40cm
- High in-beam polarization ~ 60%
- Two Beam energies: 11 GeV and 8.8 GeV
- Polarized luminosity with 15uA current: $1e^{36}$ $cm^{-2}s^{-1}$

➢ Modern Technologies

- Gas Emission Multipliers (GEM's)---tracking
- **EM Calorimeter (ECal)**
  ---particle identification (PID)
- Cherenkov---pion rejection
- Pipeline DAQ
- Uses full capability of JLab electronics

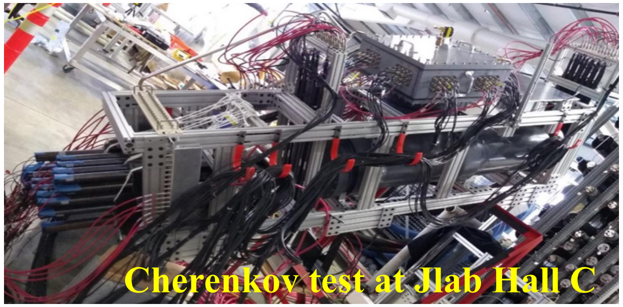
➢ Challenges

- High data rate
- Low systematics
- **High background**
- **High Radiation**

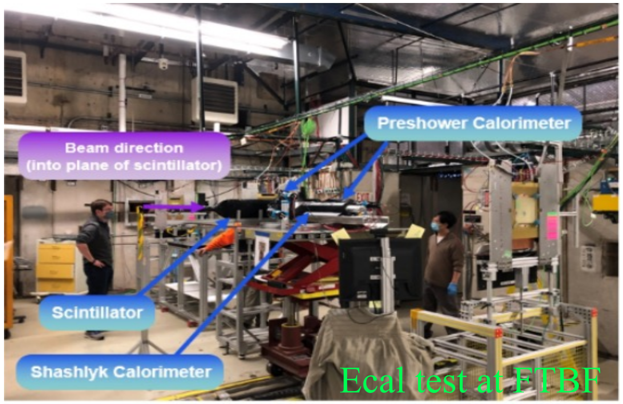
Pre-R&D beam test items: **LGC, GEM's, ECal, DAQ/Electronics**

SoLID Detector Beam Test

➢ Beam test of Cherenkov (pre-R&D in 2020) at Jlab Hall C
✓ Low-rate beam test of maPMTs: 3/2020
✓ High-rate beam test of maPMTs: 6-8/2020
- MaPMT works well in a high-rate environment of 300 kHz per cm2
- LAPPD exhibits a similar performance
✓ Low-rate beam test of LAPPD: 8-9/2020



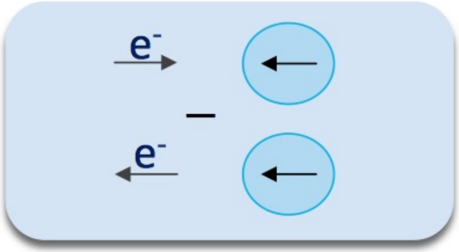
➢ Beam test of Ecal at Fermilab Test Beam Facility (1/2021)
✓ energy resolution $\frac{\sigma_E}{E} = 4.6\% \bigoplus \frac{10.4\%}{\sqrt{E}}$
✓ position resolution dX = 0.67 cm dY = 0.56 cm



Beam test of a full set of SoLID detector prototypes – GEM, LGC, LASPD, ECal, DAQ and associated electronics: (6/2022-3/2023)

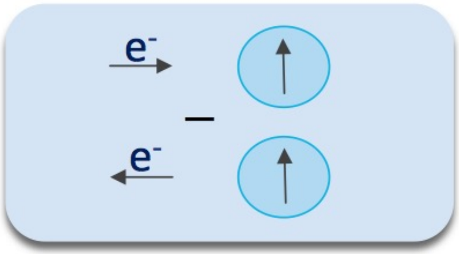
- Benchmarking simulation of rate and background
- Study **ECal** and **LASPD** performance under high rate, high radiation, high background condition
- Study ECal and LASPD PID

Extraction of g_2



E12-11-007:

$$A_{\parallel} = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}}$$



E12-10-006:

$$A_{\perp} = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}}$$

$$\Delta\sigma_{\parallel,\perp} = 2\sigma_0 A_{\parallel,\perp}$$

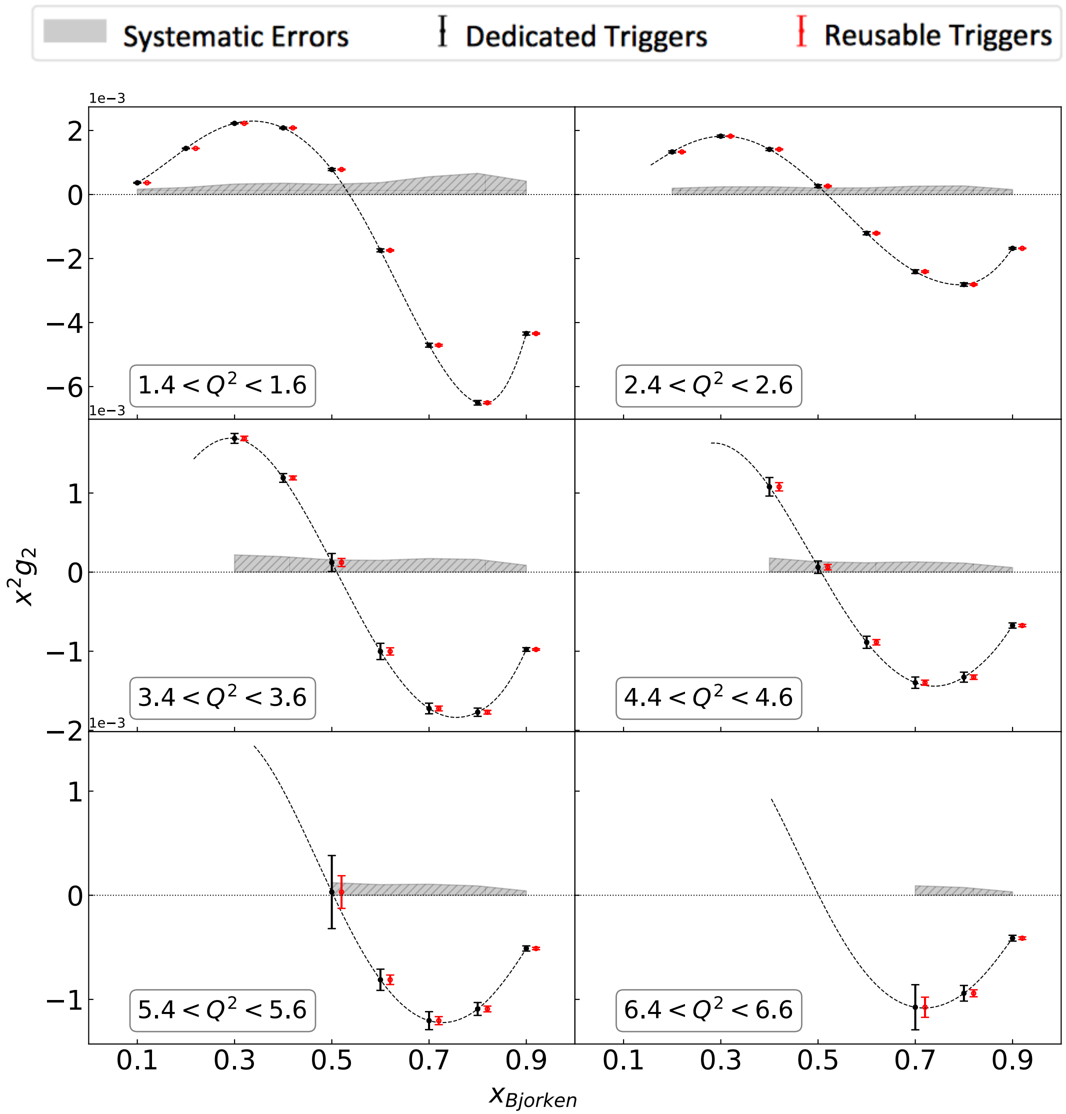
$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{\nu E}{(E-\nu)(2E-\nu)}\left[\Delta\sigma_{\parallel} + \tan\frac{\theta}{2}\Delta\sigma_{\perp}\right],$$

$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{\nu^2}{2(E-\nu)(2E-\nu)}\left[-\Delta\sigma_{\parallel} + \frac{E+(E-\nu)\cos\theta}{(E-\nu)\sin\theta}\Delta\sigma_{\perp}\right]$$

- The spin-dependent structure function g_2 heavily relies on the perpendicular cross section difference $\Delta\sigma_{\perp}$ due to the large kinematic factor within the proposed kinematic coverage.

Projections: x^2g_2 @ 8.8 GeV

55% target polarization, 85% beam polarization, and 0.17 nitrogen dilution

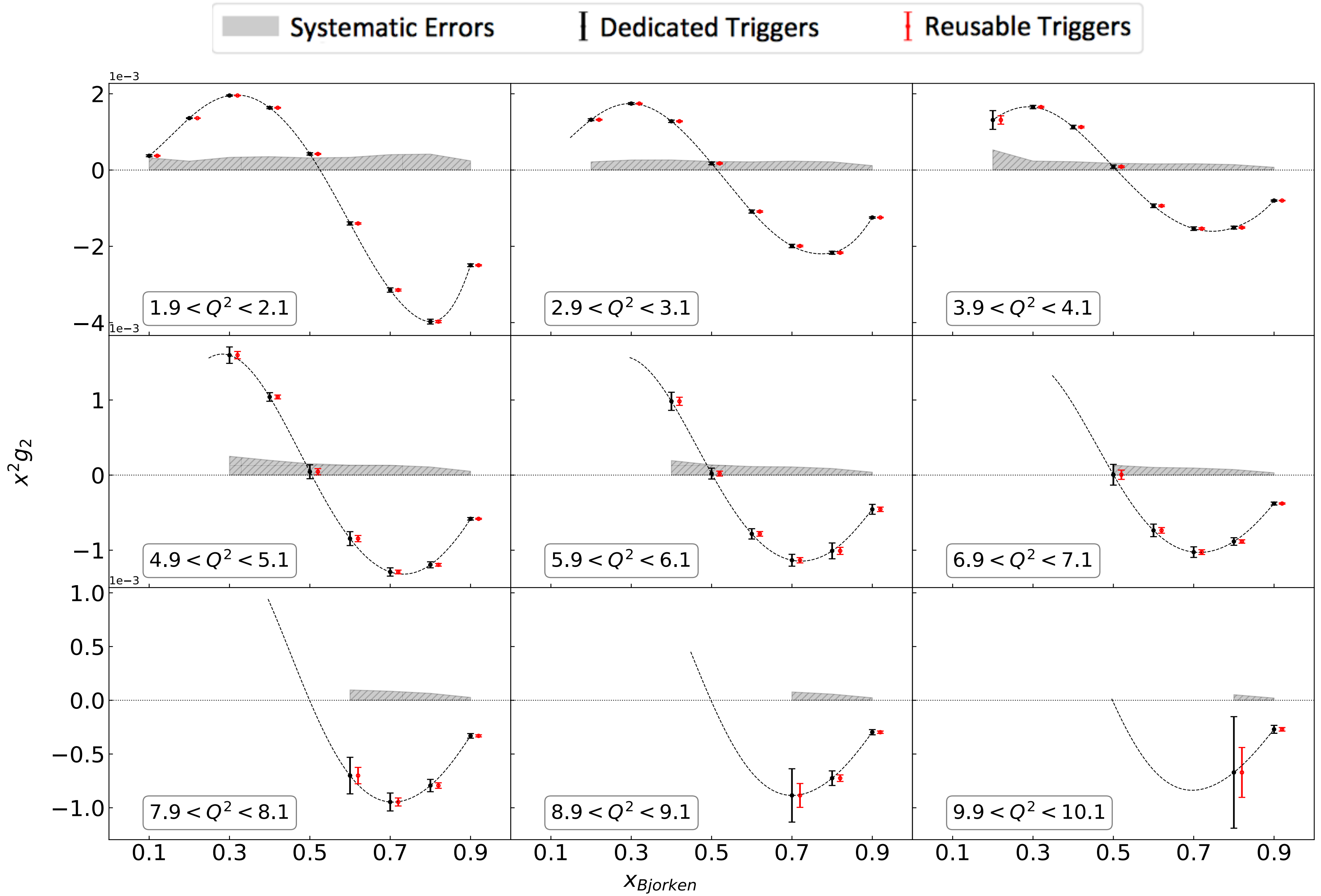


- Dedicated single electron trigger rate: 103 kHz/10 = 10.3 kHz
- Reusable random coincidence trigger rate: 69 kHz

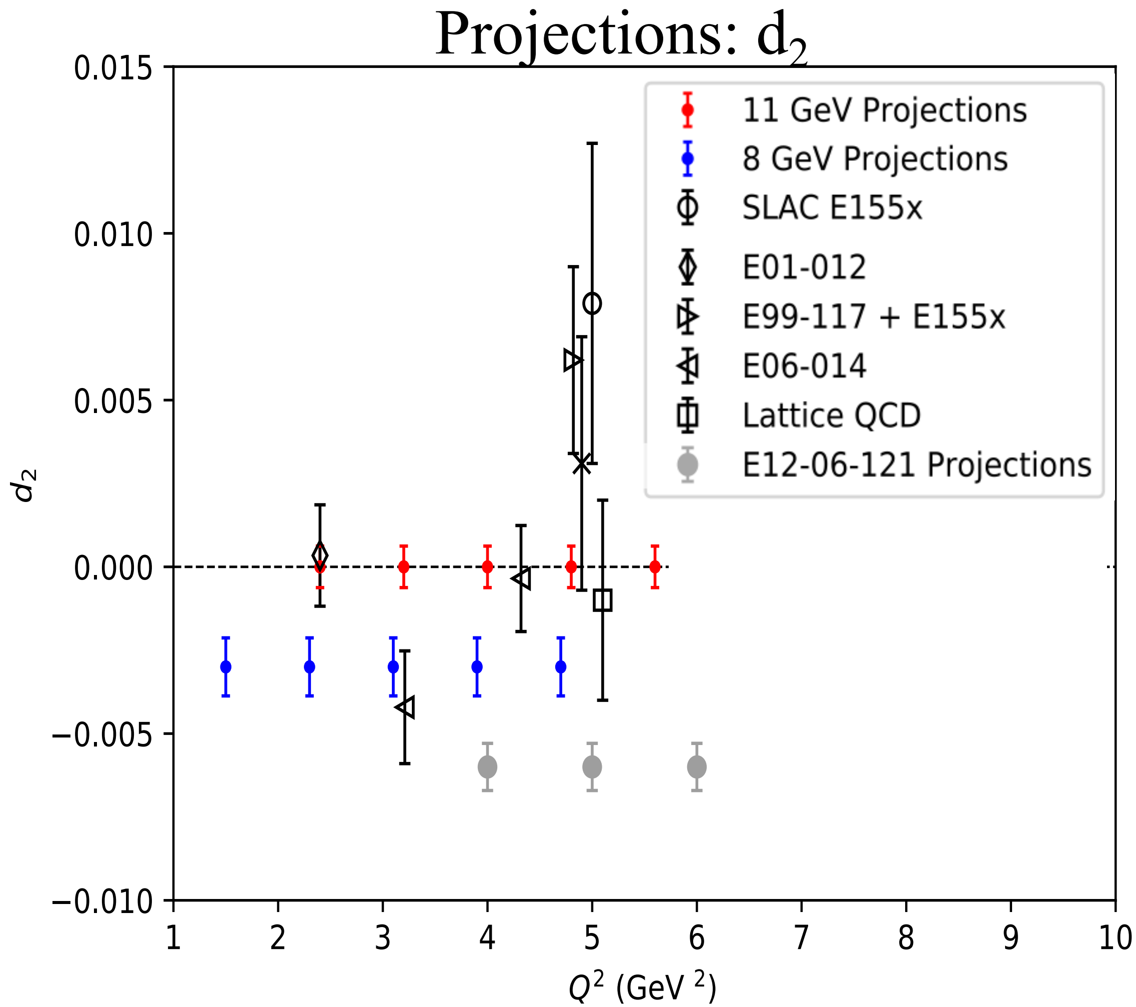
- F_2 from New Muon Collaboration (NMC) parameterization
- $R= g^n_1/F^n_1$ from SLAC
- Errors:
  - error bars ---- statistic errors
  - shadow regions----systematic error

Projections: $x^2 g_2$ @ 11 GeV

55% target polarization, 85% beam polarization, and 0.17 nitrogen dilution



d_2 : Twist-3 Matrix Element



- Results from triggers (prescale factor "10")
- d_2 projection to the region of $Q^2 < 6.5$ GeV^2
- x_{min}>0.4 to obtain d_2
- Assigned 15% error for the unmeasured region
- Statistic and systematic errors combined
- Systematic errors dominate

A Precision Measurement of Inclusive g2, d2 with SoLID on a Polarized 3He Target at 8.8 and 11 GeV.
https://www.jlab.org/exp_prog/proposals/20/E12-11-007A_E12-10-006E_Proposal.pdf

Whitney R. Armstrong, Sylvester J. Joosten, Chao Peng[1], Ye Tian[1,2], Weizhi Xiong, Zhiwen Zhao

[1] Spokesperson, [2] Contact person

Summary

- We propose a parasitic measurement with SoLID-SIDIS ^{3}He experiments E12-10-006 and E12-11-007 to extract neutron g_2 at x>0.1 and 1.5<Q^2<10 GeV^2, and d_2 at Q^2<6.5 GeV^2

- The proposed dataset provides an opportunity to better understand the twist-3 matrix element $d^n_2(Q^2)$ and hence the associated quark-gluon correlations inside the neutron.

- Q^2 dependence of d^n_2 will provide a direct test of Lattice QCD calculations.

Summary on SoLID Program

SoLID is at the intensity frontier with JLab 12 GeV upgrade

- Rich and highly rated physics programs: PVDIS, SIDIS, near-threshold J/ψ
- Many other experiments in development
- Great potentials for JLab 20+ GeV
- Address important questions in Nuclear Physics
- Complementary and synergistic to the EIC science programs

Active pre-R&D with the support from DOE and JLab

- Demonstrated the feasibility of key detector subsystems in a high-rate environment
- To reduce risk/cost for SoLID
- The Cherenkov and the calorimeter prototype modules underwent beam tests at Hall C
- Analysis for pre-R&D detector beam test is wrapping up

SoLID Project Status

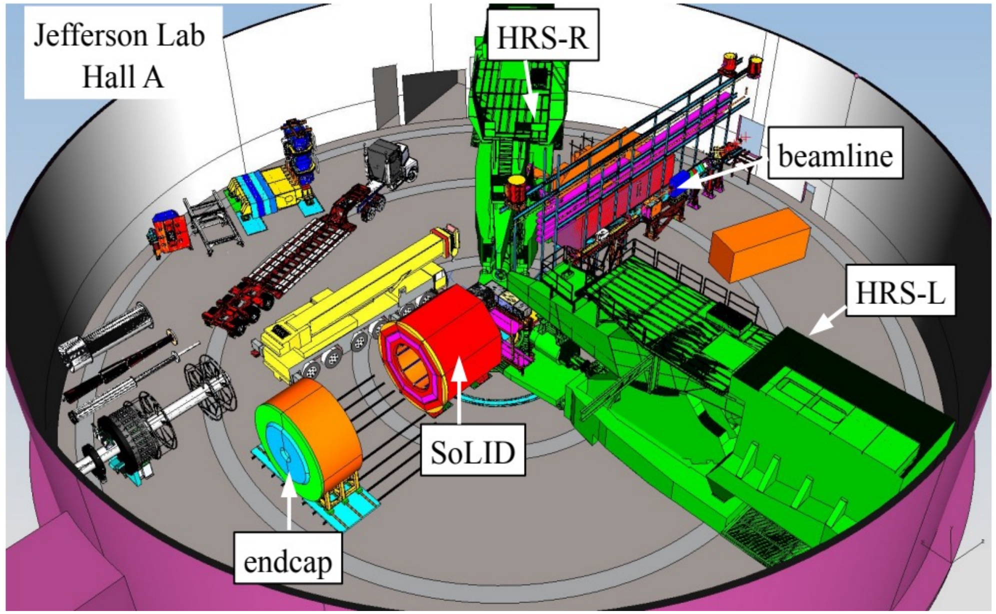
- Science Review Feedback**: positive feedback, recommend to move to next step**
- LRP: **SoLID In Recommendation #4**, prominently featured in the report
- **On the list of NP projects for the NSAC Facilities Charge**
- Ready to be launched

SoLID Collaboration

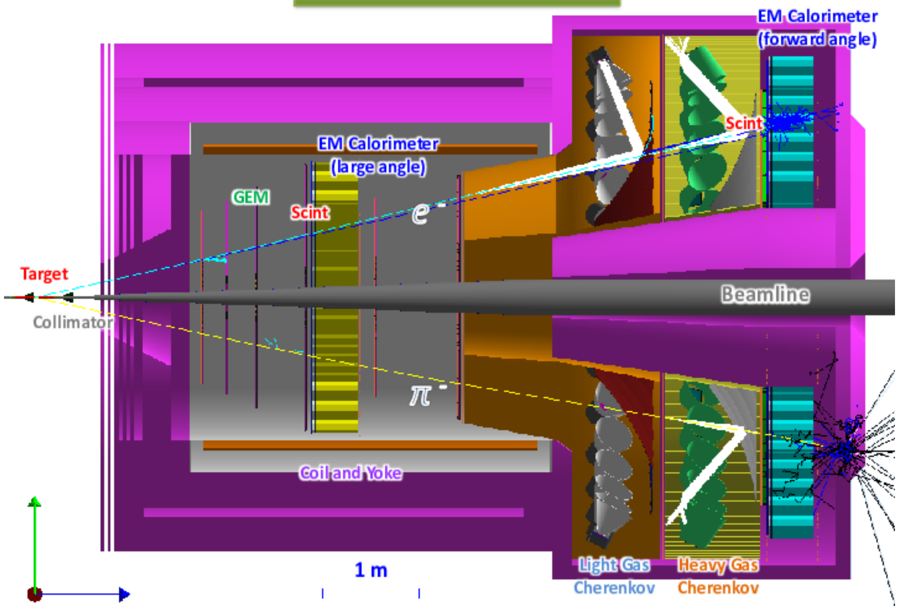
- 270+ collaborators, 70+ institutions from 13 countries
- Active development and validation of the pre-conceptual design
- Strong support from theorists

Thank you !

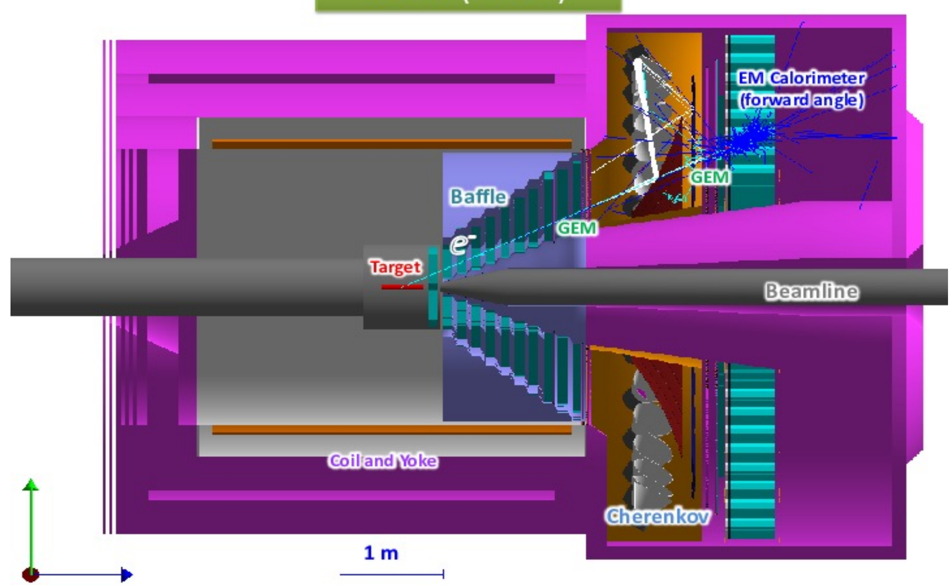
Back up



SoLID (SIDIS and J/ψ)

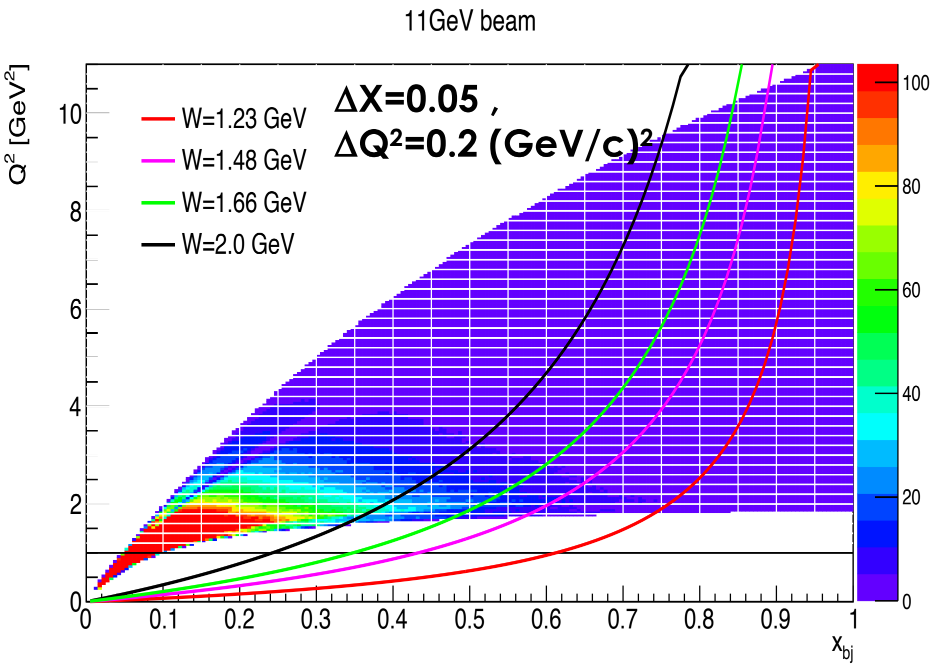


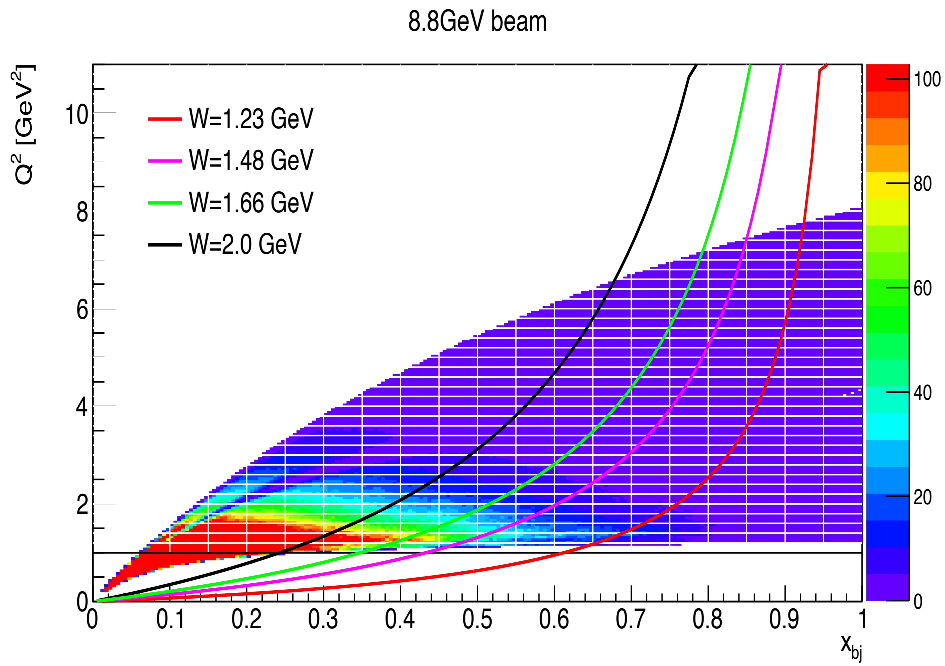
SoLID (PVDIS)



Kinematic Coverage

Configuration	Approved Beam time (hours)
E12-10-006 (Transverse) @ 11 GeV	1152
E12-10-006 (Transverse) @ 8.8 GeV	504
E12-11-007 (Longitudinal) @ 11 GeV	538
E12-11-007 (Longitudinal) @ 8.8 GeV	228





- More than 15 kHz free trigger space with 100 kHz DAQ limit
- Dedicated single electron trigger rate: 103 kHz/10 = 10.3 kHz
- Reusable random coincidence trigger rate: 69 kHz

Systematic Error Estimation

Source	Systematic Uncertainty
Cross Sections	
Detector acceptance	5.0%
Detector efficiencies	3.0%
Target density	2.0%
Beam charge	1.0%
Background subtraction	3.0%
Asymmetries	
Dilution effects	$< 1.0\%$
Beam polarization	$< 2.0\%$
Target polarization	3.0%
Charge asymmetry	$< 10^{-4}$
Pion asymmetry	$< 5 \times 10^{-4}$
Unfolding Procedure	
Nuclear corrections	$\sim 5.0\%$
Radiative corrections	$\sim 3.0\%$
Physics Results	
Cross sections	$< 10.0\%$
g_2 syst.	$\sim 10^{-3}$-10^{-4}
d_2 stat.	$\sim 3 \times 10^{-4}$
d_2 syst. (11 GeV)	$\sim 5 \times 10^{-4}$
d_2 syst. (8.8 GeV)	$\sim 8 \times 10^{-4}$

Expected Event Rates

Rate (kHz) Ecal 7 modules	EC+LGC+SPD 3He+up+ down widow
FA e^-	59+1.15+1.8
FA hadron no e^-	28.6+3.9+5.6
LA e^-	4.1+3.6+2.6
LA hadron no e^-	7.7+6.5+3.8
FA MIP (hadron) trigger	8013+2591+3887
SIDIS coincidence	31.2
Hadron coincidence	14.7+2.52+2.61=19.83
Total rate	<85 kHz

SIDIS-3He E12-10-006

48 days 11 GeV

21 days 8.8 GeV

DAQ limit 100kHz

Coincident trigger

20 – 30% fluctuation

>15kHz

Free prescaled single electron trigger

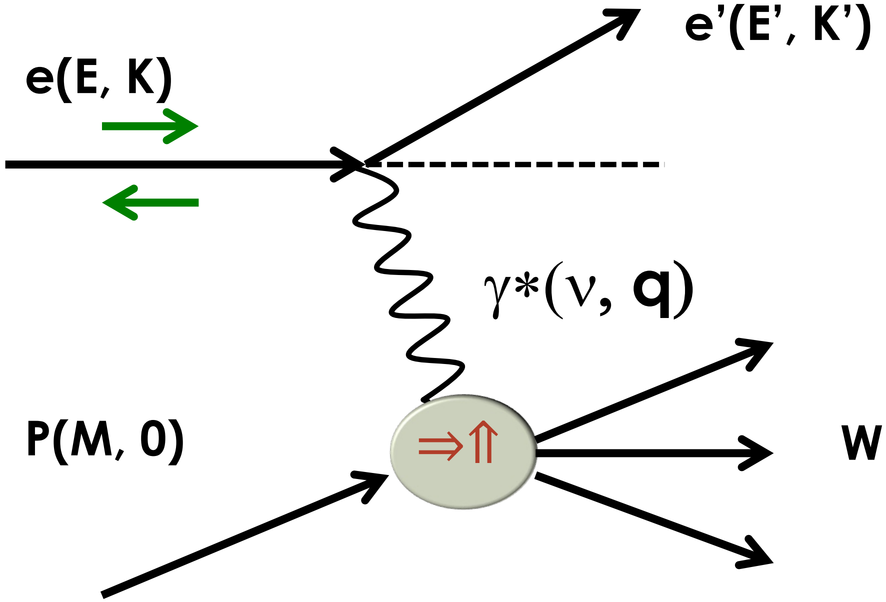
FA+LA single electron trigger rate: 103kHz/10=10.3KHz

Projection

Reusable random coincidence trigger rate:

54kHz+15kHz=69kHz, which is equivalent to103kHz/2

Extract g_2 from Cross Section Differences



Q^2: Four-momentum transfer

x: Bjorken variable ($=Q^2/2M\nu$)

ν: Energy transfer

M: Nucleon mass

W: Final state hadronic mass

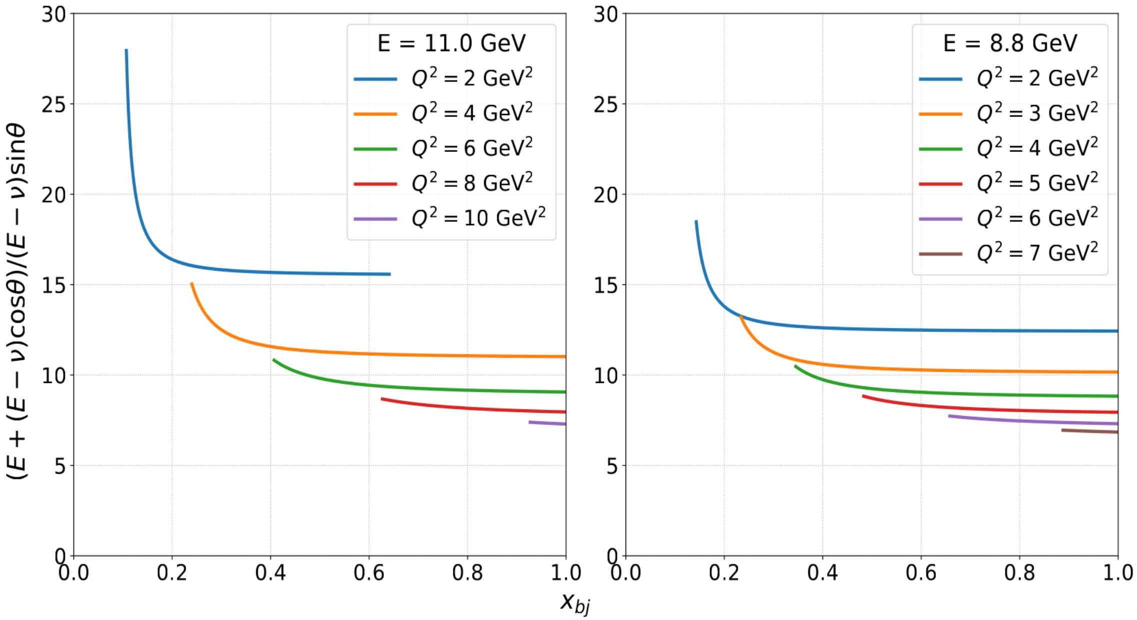
L $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

SoLID SIDIS Longitudinally Polarized 3He (E12-11-007)

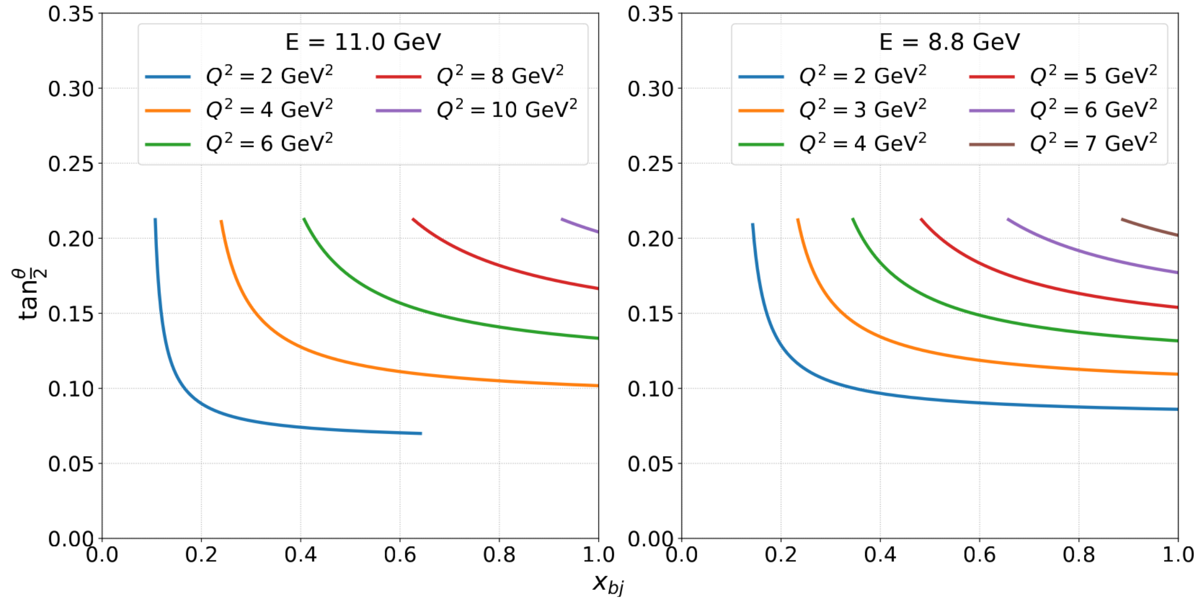
T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 E'^2}{MQ^2\upsilon^2 E}\sin\theta\cos\phi_{rela}\left[g_1(x,Q^2) + \frac{2E}{\upsilon}g_2(x,Q^2)\right]$$

SoLID SIDIS Transversely Polarized 3He (E12-10-006)

Extract g_2 from Cross Section Differences



- The kinematic factor C⊥/C∥ for g2 extraction from cross section differences.



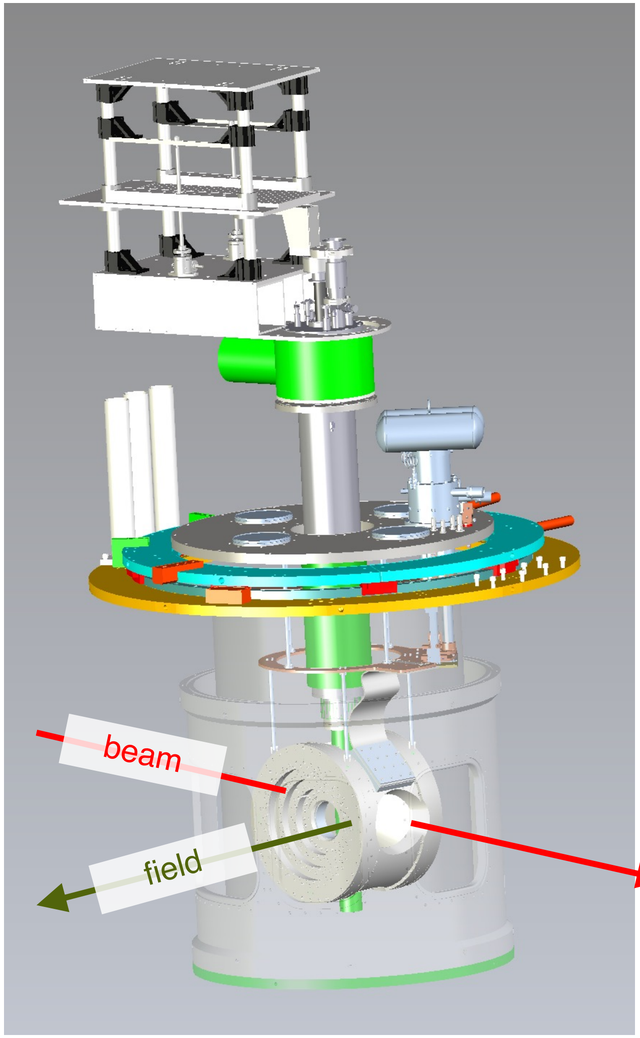
- The kinematic factor C⊥/C∥ for g1 extraction from cross section differences.

Interpretations of $d_2(Q^2)$ in the Literature

- The first one connects it with color electromagnetic fields induced in a transversely polarized nucleon probed by a virtual photon. (X.Ji 95, E. Stein et al. 95)

- The second one shows that the matrix element connected to d_2, which represents an average color Lorentz force acting on the struck quark due to the remnant di-quark system at the instant, and it is struck by the virtual photon (Matthias Burkardt. Phys. Rev. D, 88:114502, Dec 2013)

Transverse Polarized Target Status



Solid NH_3 & ND_3 dynamically polarized at 1 K & 5 T

- New superconducting 5 T magnet **on order**
  - 67% larger aperture in transverse orientation (± 25°)
  - Horizontal or vertical field direction
  - cryogen-free: cooled by one or more cryocoolers
- Existing infrastructure from previous g2p/GEp experiments
  - 1K refrigerator
  - vacuum chamber
  - microwaves
- New JLab NMR system for polarization measurement
- New 12,000 m^3/h pumping system

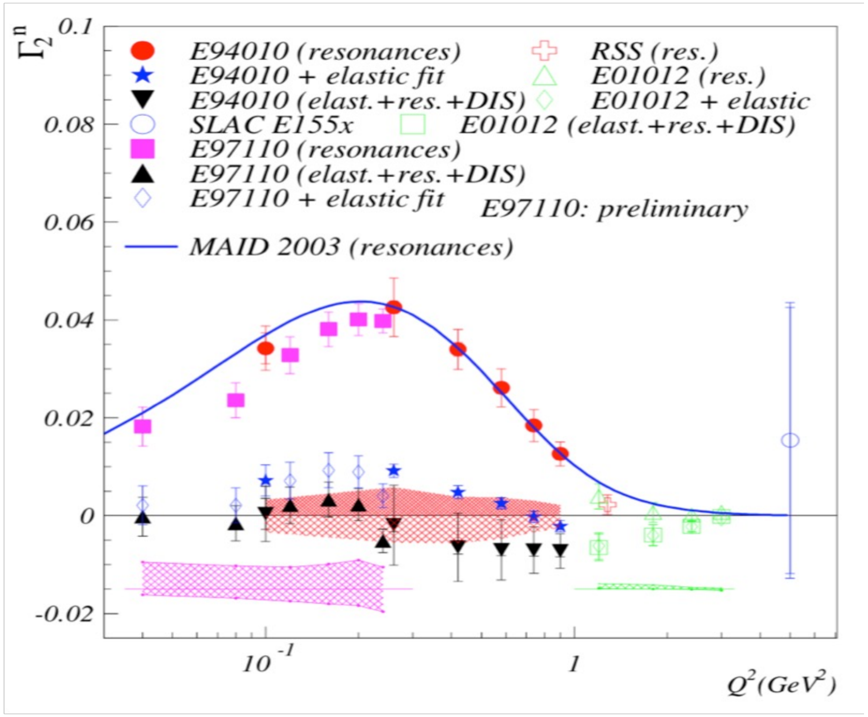
Expected operation in three experimental halls

- Hall C (NPS/CPS)
- Hall B (Run Group H)
- Hall A (SoLID)

Slide from Rolf Ent SoLID science review talk

Test the Burkhardt-Cottingham (BC) Sum Rule

Figure from 2019 Rep. Prog. Phys. **82** 076201



$$\Gamma_2 = \int_0^1 g_2(x)dx = 0$$

- Validity conditions:
- ✓ g_2 is well-behaved, Γ2 is finite
- ✓ g_2 is not singular at $x_{Bj} = 0$

- It is verified from world data at $0<Q^2<5$ GeV^2

- Elastic and the inelastic contributions to the twist moment of g_2 cancel for low and moderate Q^2

BC = Measured+low_*x*+Elastic

Measured: Measured x-range

low-*x*: refers to unmeasured low x part of the integral. Assume $g_2 = g_2^{WW}$

Elastic: From elastics form Factors