A Precision Measurement of Inclusive g^n_2, d^n_2 with SoLID on a Polarized ^{3}He Target at 8.8 and 11 GeV

A Run-Group Proposal in parallel to E12-10-006/E12-11-007

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Chao Peng (Argonne National Laboratory)
For the SoLID collaboration

- **Physics Motivation**
- **Experiment**
- **Expected Results**
- **Summary**

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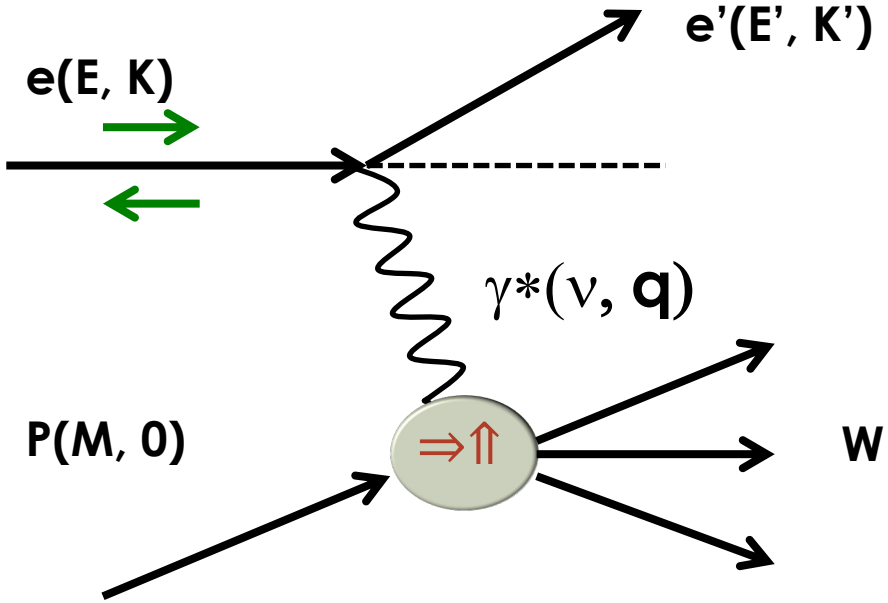
Inclusive Electron Scattering



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

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

number density of the quark carrying the fraction x of the momentum of the nucleon

- g_2 is zero in the naive parton model

If constituent quarks to have an intrinsic transverse momentum in the nucleon

non-zero value carries information of quark-gluon interaction

Ignoring quark mass effect of order $O(m_q/\Lambda_{QCD})$

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

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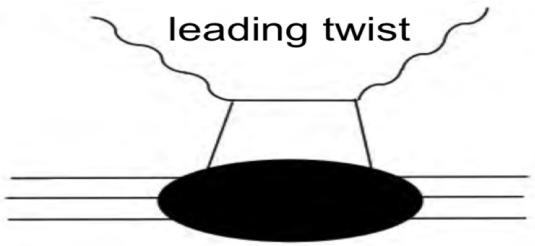

related to amplitude for scattering off asymptotically free quarks

- leading twist related to g_1 by Wandzura-Wilczek relation

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

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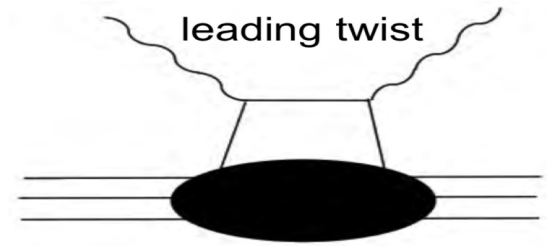

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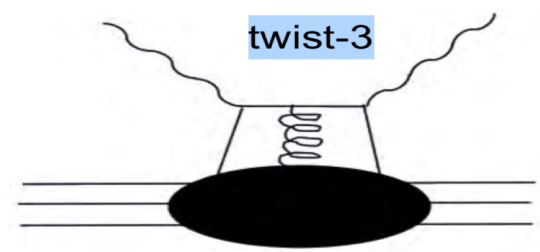
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

quark transverse momentum contribution

twist-3 part which arises from quark-gluon interactions



quark-gluon interaction and the quark mass effects

d_2 : twist-3 matrix element

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

Sensitive to large-x behavior

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

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

- ✓ 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, SHMS and upgraded HMS with six kinematic settings.
- We propose to measure g^n_2 at x>0.1 and $1.5 < Q^2 < 10$ GeV^2, SoLID SIDIS ^{3}He experiments.

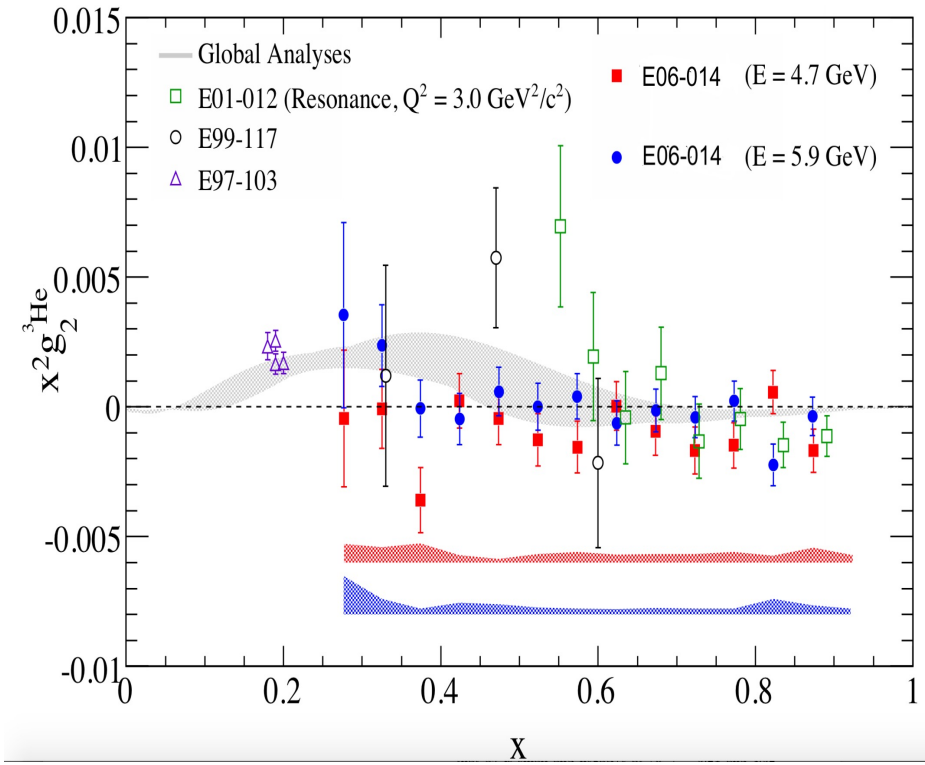


Figure from arXiv:1603.03612v3

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

Existing Neutron d_2 Data

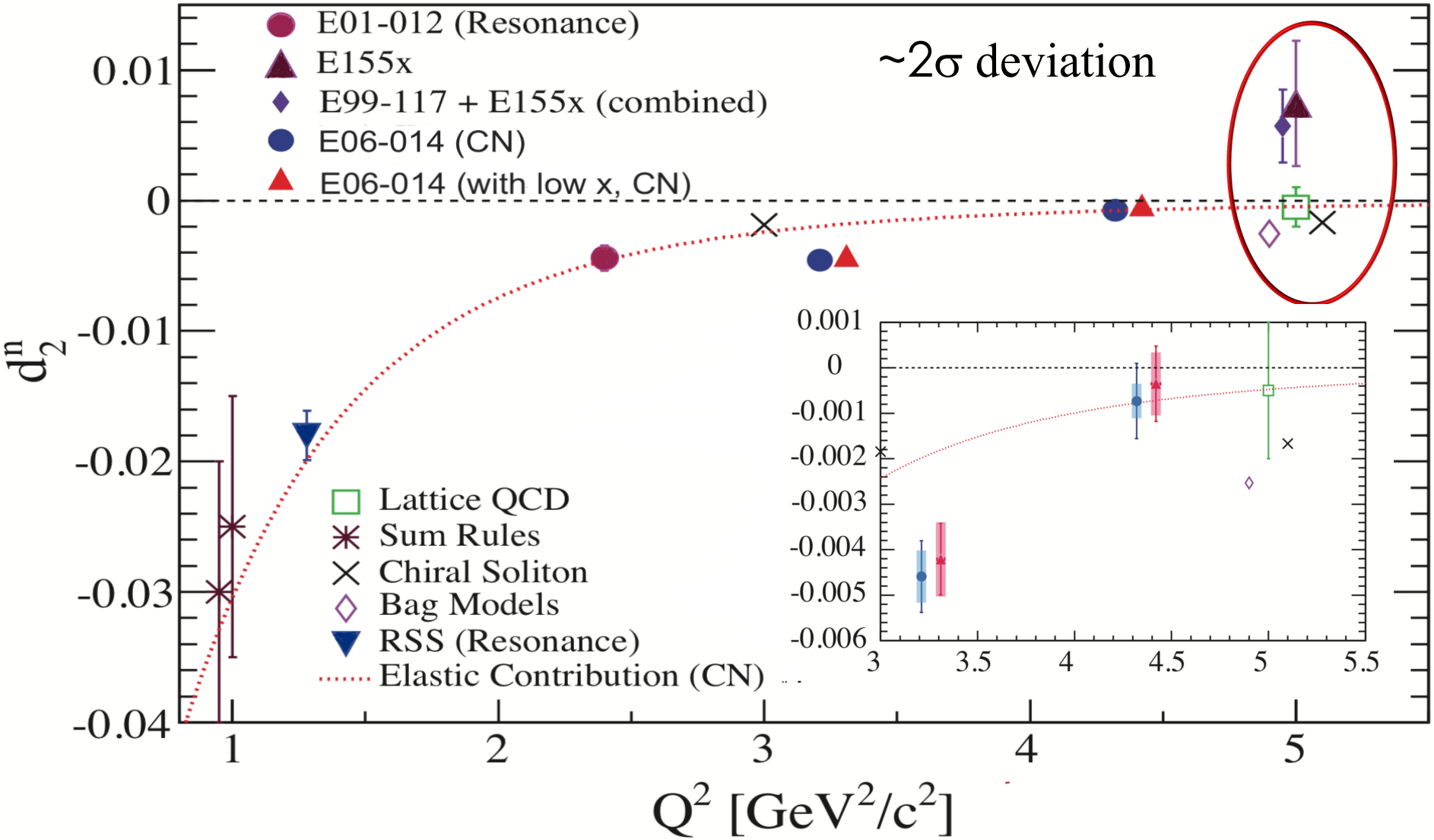


Figure from Arxiv:1805.08835

Test the Burkhardt-Cottingham (BC) Sum Rule

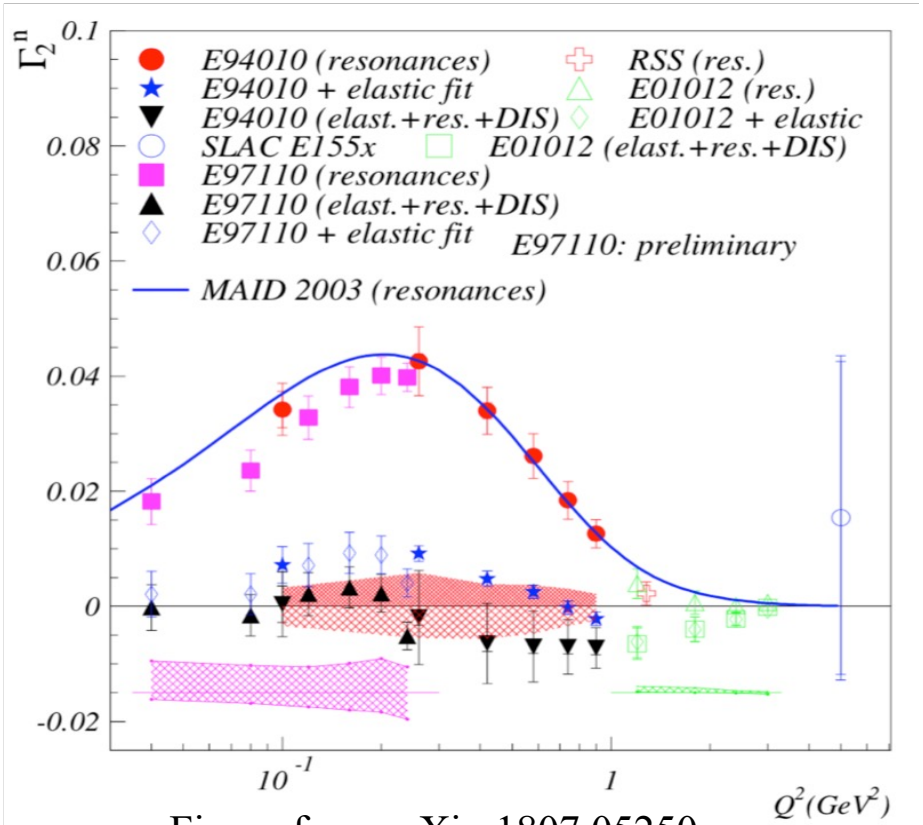


Figure from arXiv:1807.05250

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

- 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

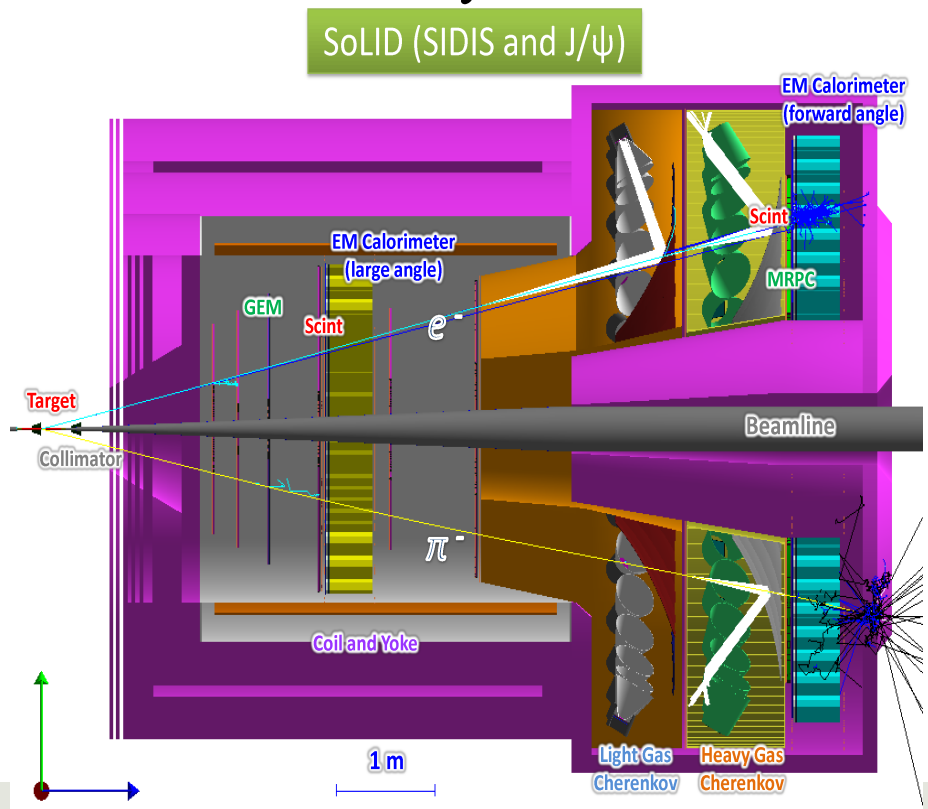
low-*x*: refers to unmeasured low x part of the integral. Assume $g_2 = g_2^{WW}$

Elastic: From elastics form Factors

This proposal will extract g_2 within x > 0.1 and provide an opportunity to further explore the large x contributions to this sum rule for the neutron.

SoLID SIDIS Polarized ^{3}He Experiments

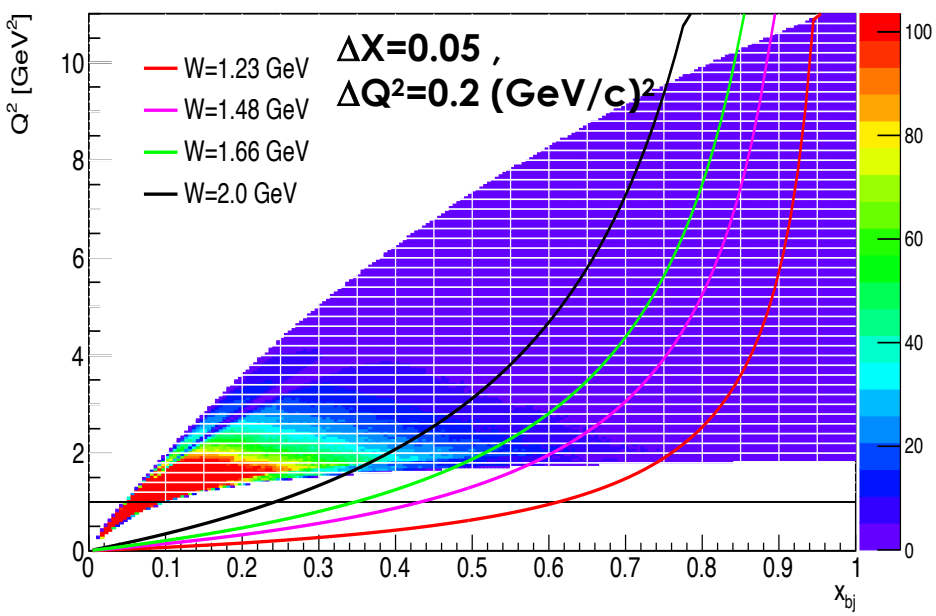
- SoLID SIDIS layout without changes
- E12-10-006: Transversely polarized ^{3}He target
- E12-11-007: Longitudinally polarized ^{3}He target
- High in-beam polarization ~ 60%
- Two Beam energies: 11 GeV and 8.8 GeV
- Polarized luminosity with 15uA current: $1e^{36}$ $cm^{-2}s^{-1}$



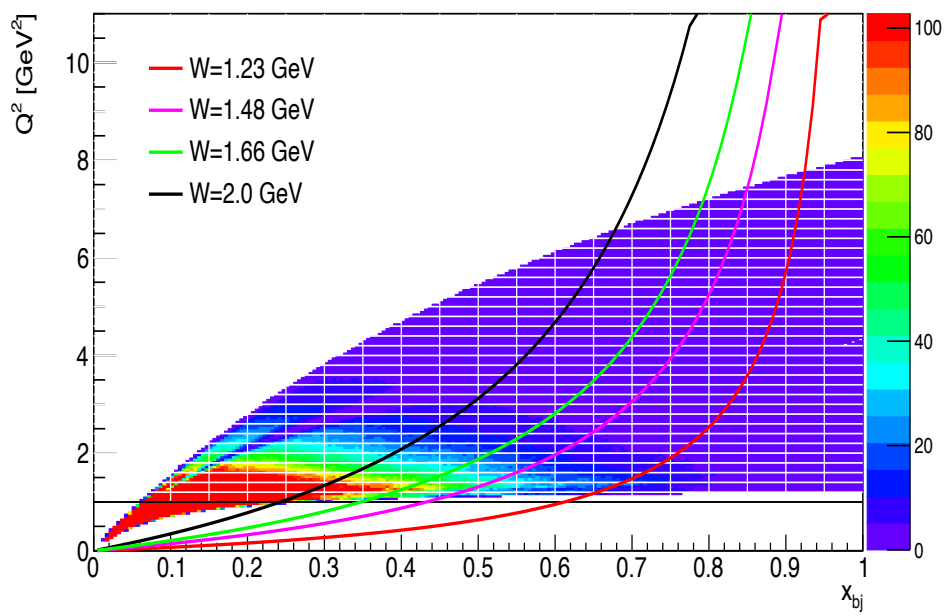
Kinematic Coverage

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

11GeV beam

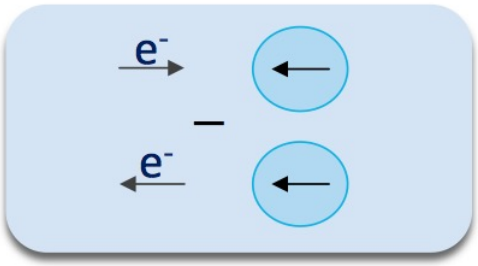


8.8GeV beam



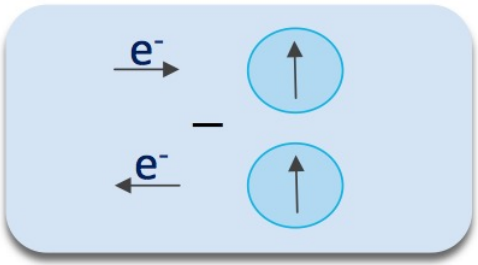
- More than 15 kHz free trigger space with 100 kHz DAQ limit
- Dedicated single electron trigger rate: 103 kHz/10 = 10.3 kHz
- Reusable random coincidence trigger rate: 69 kHz

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:

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

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

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

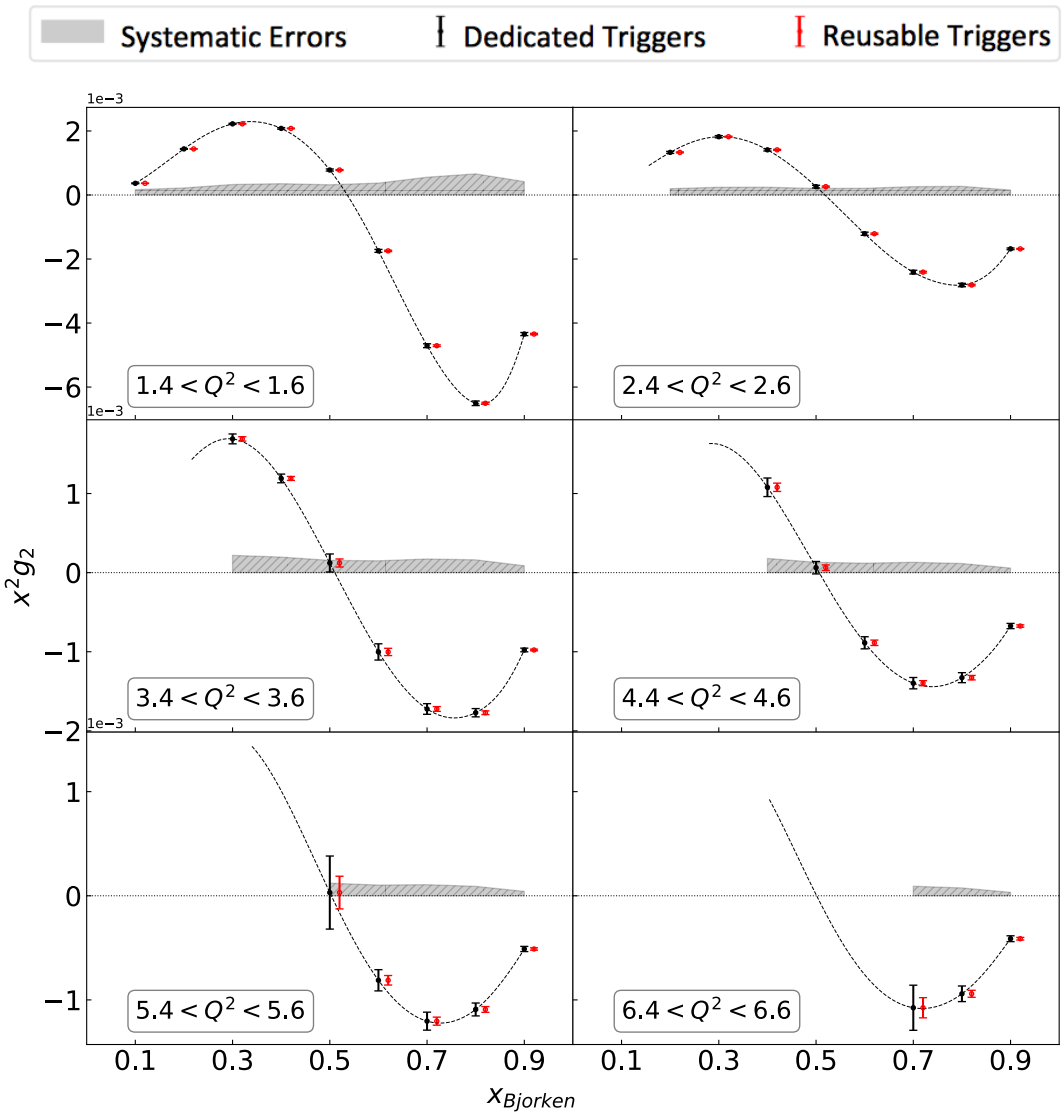
$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{\nu^2}{2(E-\nu)(2E-\nu)}\left[-\Delta\sigma_{\parallel} + \frac{E+(E-\nu)\cos\theta}{(E-\nu)\sin\theta}\Delta\sigma_{\perp}\right]$$

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)	$\sim 8 \times 10^{-4}$

Projections: x^2g_2 @ 8.8 GeV

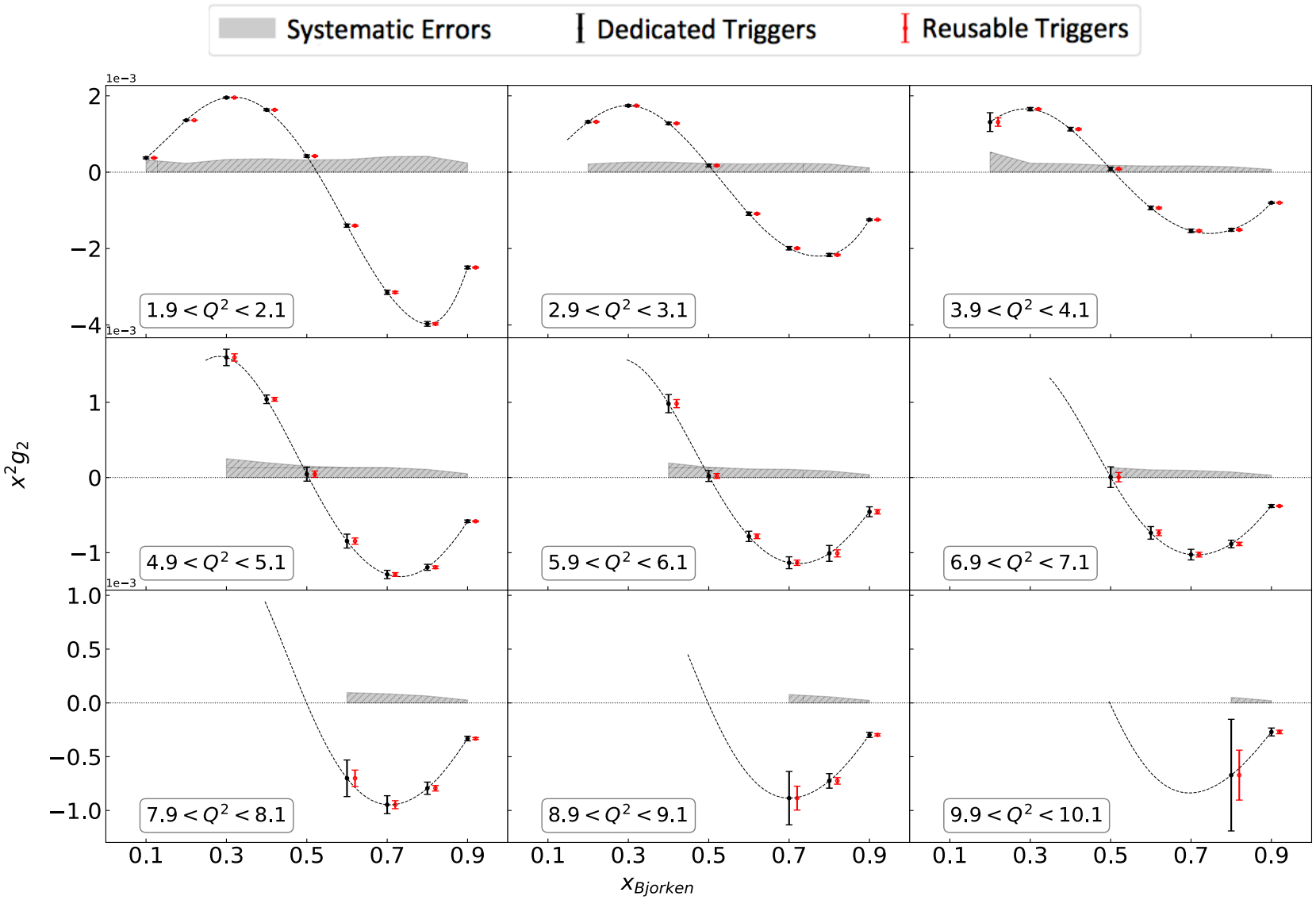
55% target polarization, 85% beam polarization, and 0.17 nitrogen dilution



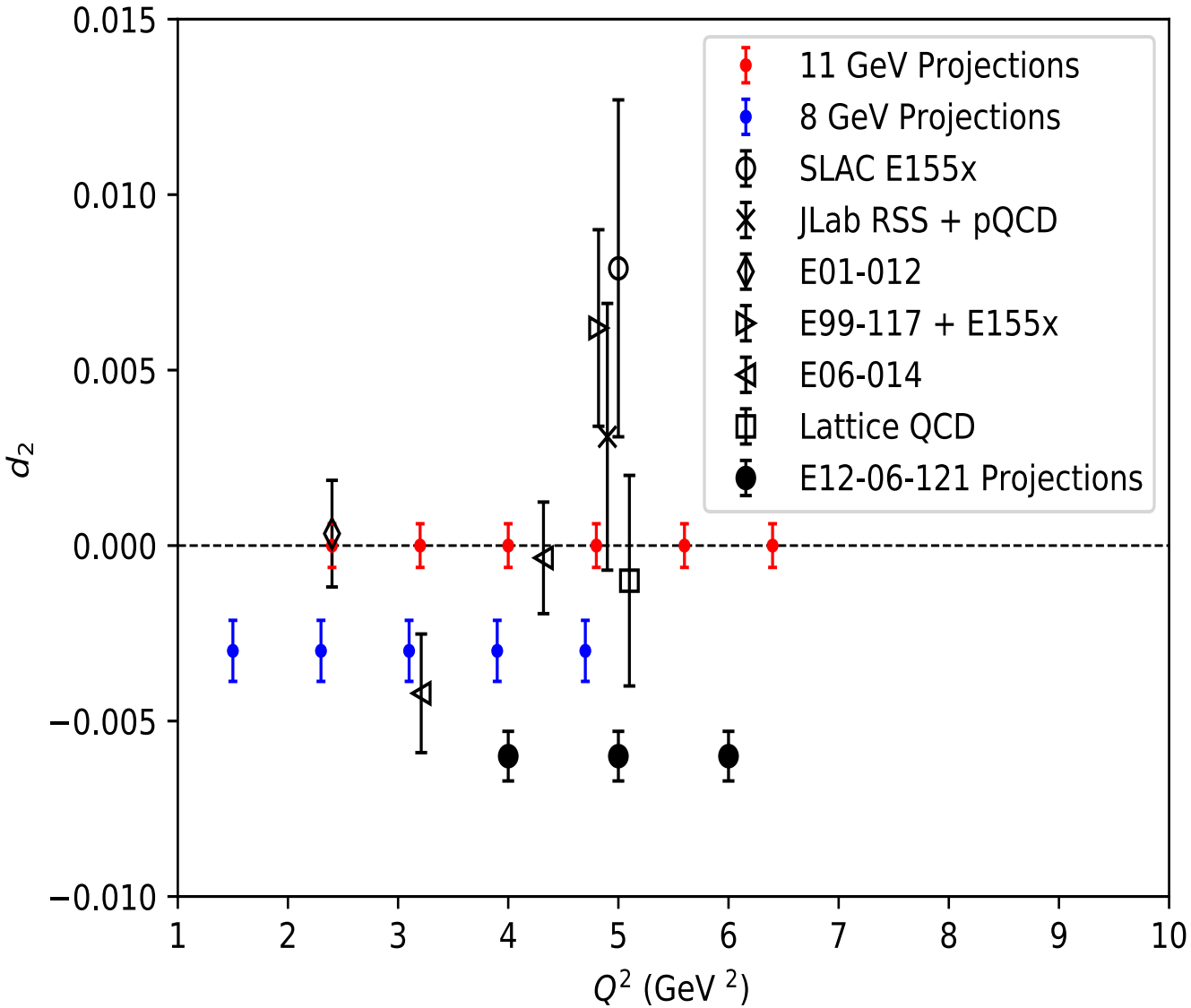
- F2 from New Muon Collaboration (NMC) parameterization
- $R = g^n_1/F^n_1$ from SLAC
- Errors:
  - error bars ---- statistic errors
  - shadow regions---- systematic error

Projections: x^2g_2 @ 11 GeV

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



Projections: d_2



- 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

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 a bound hadron.

- Q^2 dependence of d^n_2 ,with much smaller error bar than any existing phenomenological extractions, will provide a direct test of Lattice QCD calculations.

SoLID (SIDIS and J/ψ)

Thank you !

Back up

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

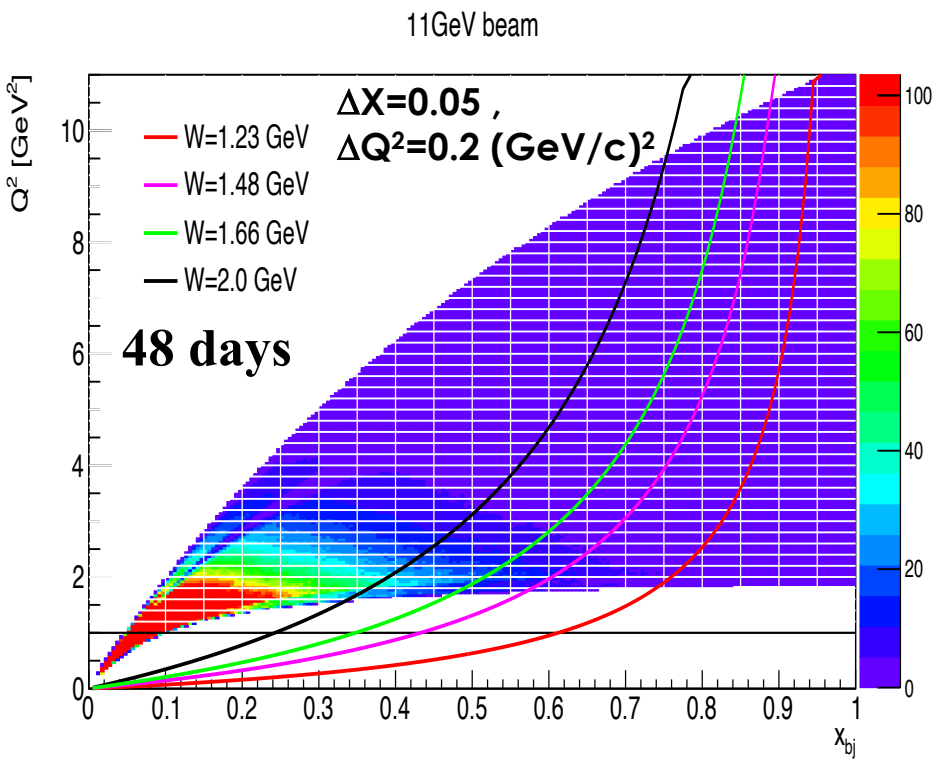
FA+LA single electron trigger rate: 103kHz/10=10.3KHz Projection

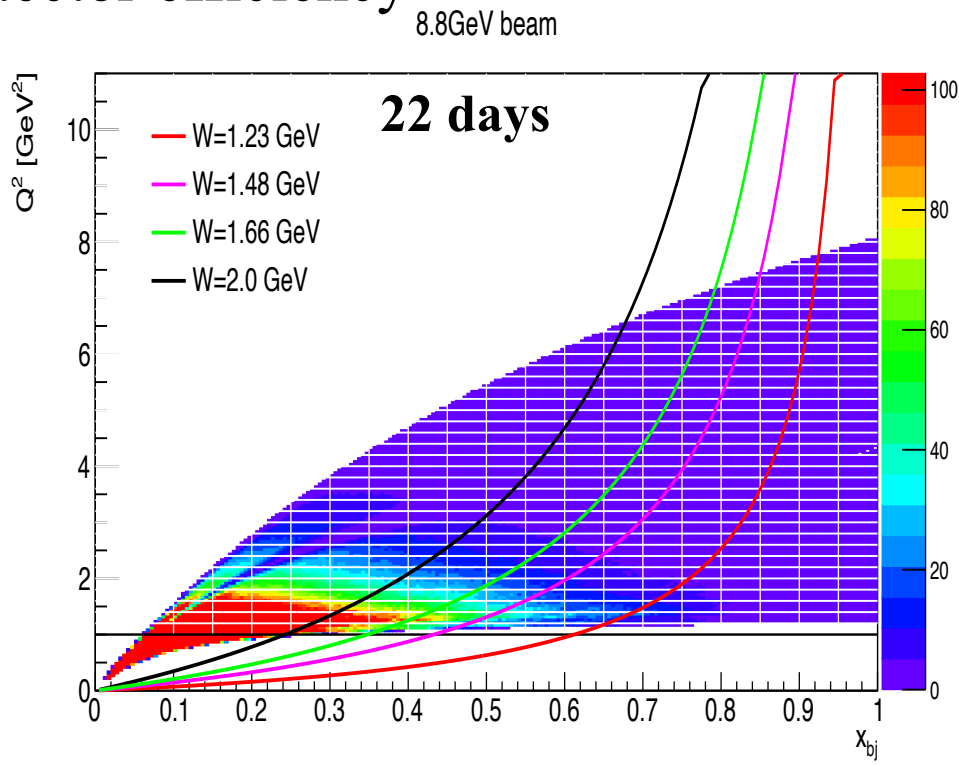
Reusable random coincidence trigger rate:

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

Kinematic Coverage

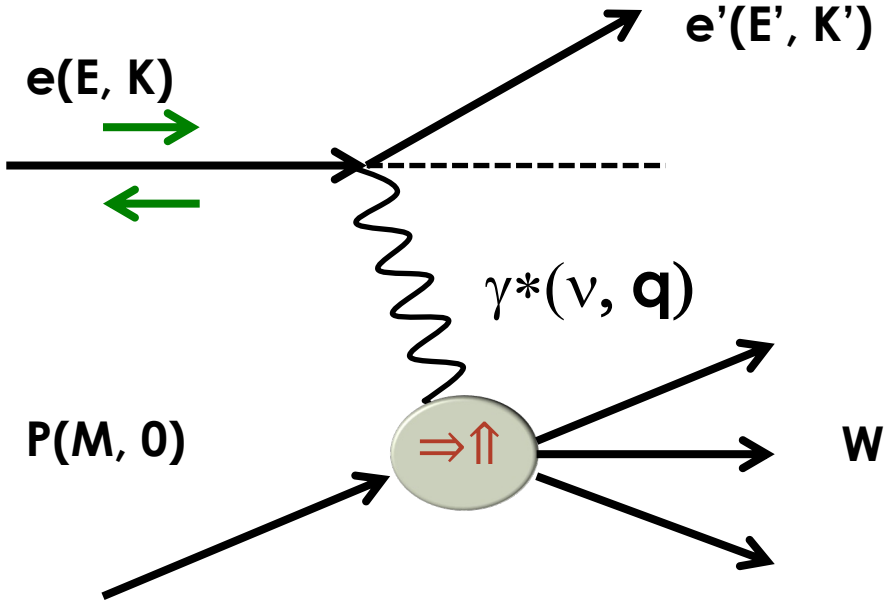
- Generated inclusive QE+resonance+DIS events:
  The W<3 GeV Peter Bosted fit
  The W>3 GeV world PDF sets
- GEMC+detector acceptance+detector efficiency





❖ Measure **neutron** spin structure function $\mathbf{g_2\ (x,\ Q^2)}$ at momentum transfer $1.5<Q^2<10\ GeV^2$ and Bjorken x >0.1. For $Q^2 > 8.5\ GeV^2$, we will measure the x > 0.6 region.

Extract g_2 from Cross Section Differences



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

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

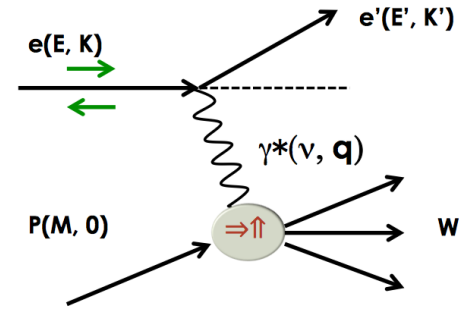
T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 E'^2}{MQ^2\upsilon^2 E}sin\theta cos\phi_{rela}\left[g_1(x,Q^2) + \frac{2E}{\upsilon}g_2(x,Q^2)\right]$$

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

Physics Motivation: g_2^n spin structure function

- g_1 related to the polarized parton distribution functions

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



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quark transverse momentum contribution

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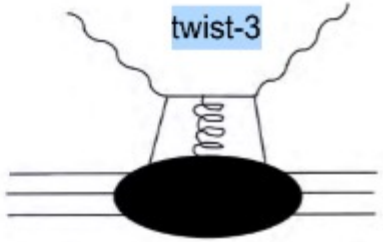

d_2: the x^2 moment of $\overline{g_2}(x,Q^2)$

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

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