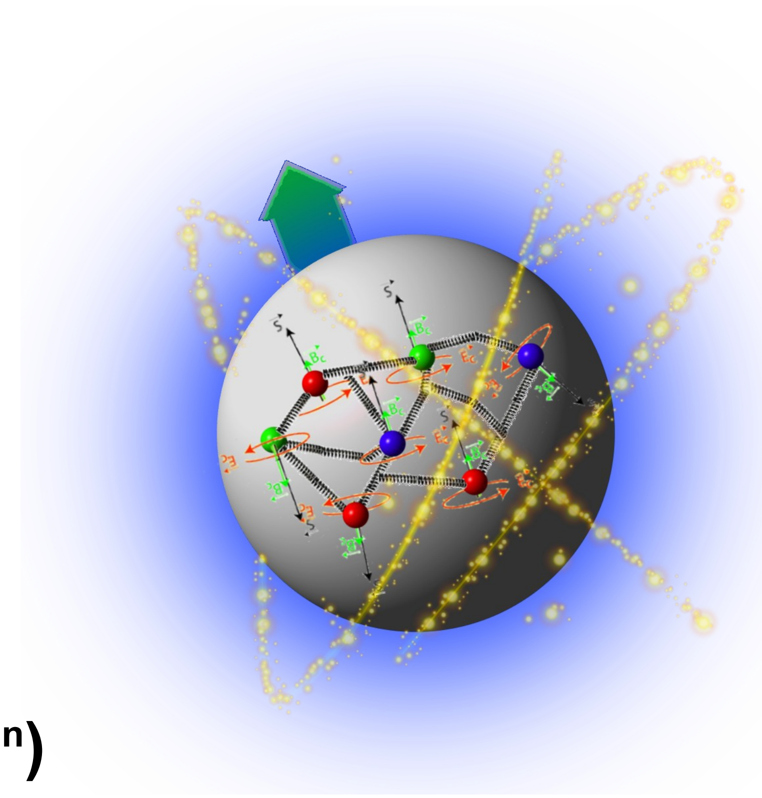
Probing the Spin Structure of the Nucleon:

Measurements of A_1, d_2, g_2 on the Neutron



Brad Sawatzky
for the
E12-06-110 (A_1^n) and E12-06-121 (d_2^n) Collaborations

Hall C Winter Workshop 2019

Polarized DIS cross sections

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[(E + E'\cos\theta)g_1(x, Q^2) - \frac{Q^2}{\nu}g_2(x, Q^2)\right] = \Delta\sigma_\parallel$$

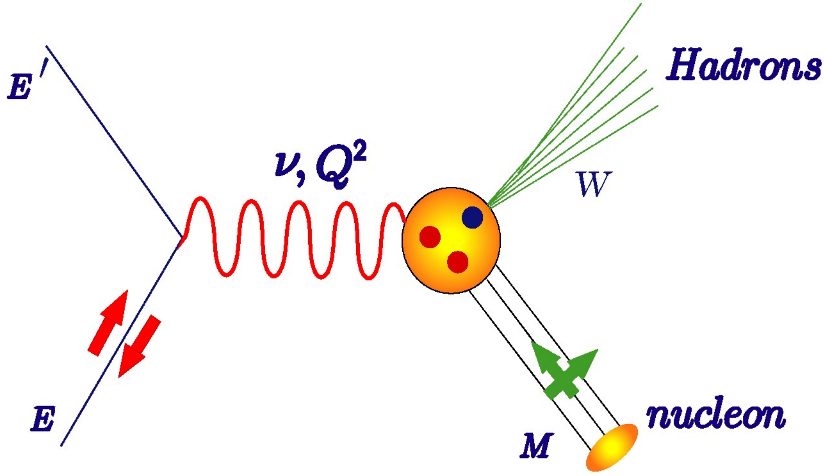
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x, Q^2) + 2E g_2(x, Q^2)\right] = \Delta\sigma_\perp$$

Q^2 = 4-momentum transfer squared of the virtual photon.

ν = energy transfer.

θ = scattering angle.

$x = \frac{Q^2}{2M\nu}$ fraction of nucleon momentum carried by the struck quark.



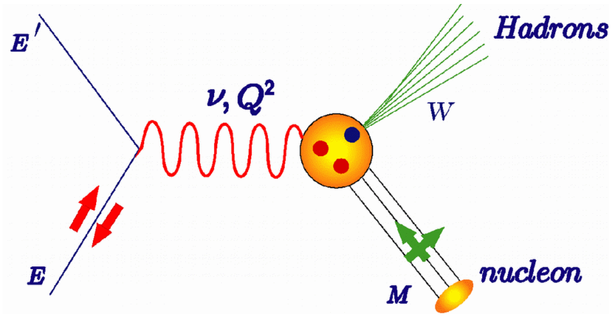
What are g_1 and g_2?

- The "g's" play a role analogous to the "F's" in the unpolarized cross section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)$$

- F encodes information about the momentum structure of the nucleon

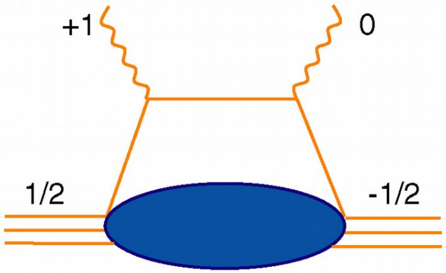
- g_1 and g_2 encode information about the spin structure of the target nucleon



- The Parton Model
  - → g_1 is a measure of the spin distribution among the individual constituent quarks (ie. aligned parallel and anti-parallel to the nucleon spin)
  - → g_2 ???

g_2 and Quark-Gluon Correlations

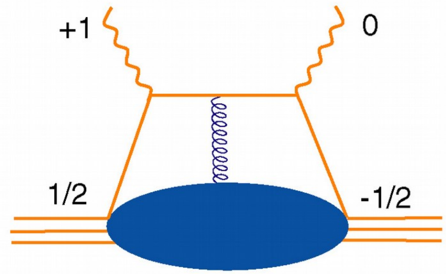
twist-2



Carry one unit of orbital angular momentum

QCD allows the helicity exchange to occur in two principle ways

twist-3



Couple to a gluon

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

- a twist-2 term (Wandzura & Wilczek, 1977):

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

- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

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

transversity

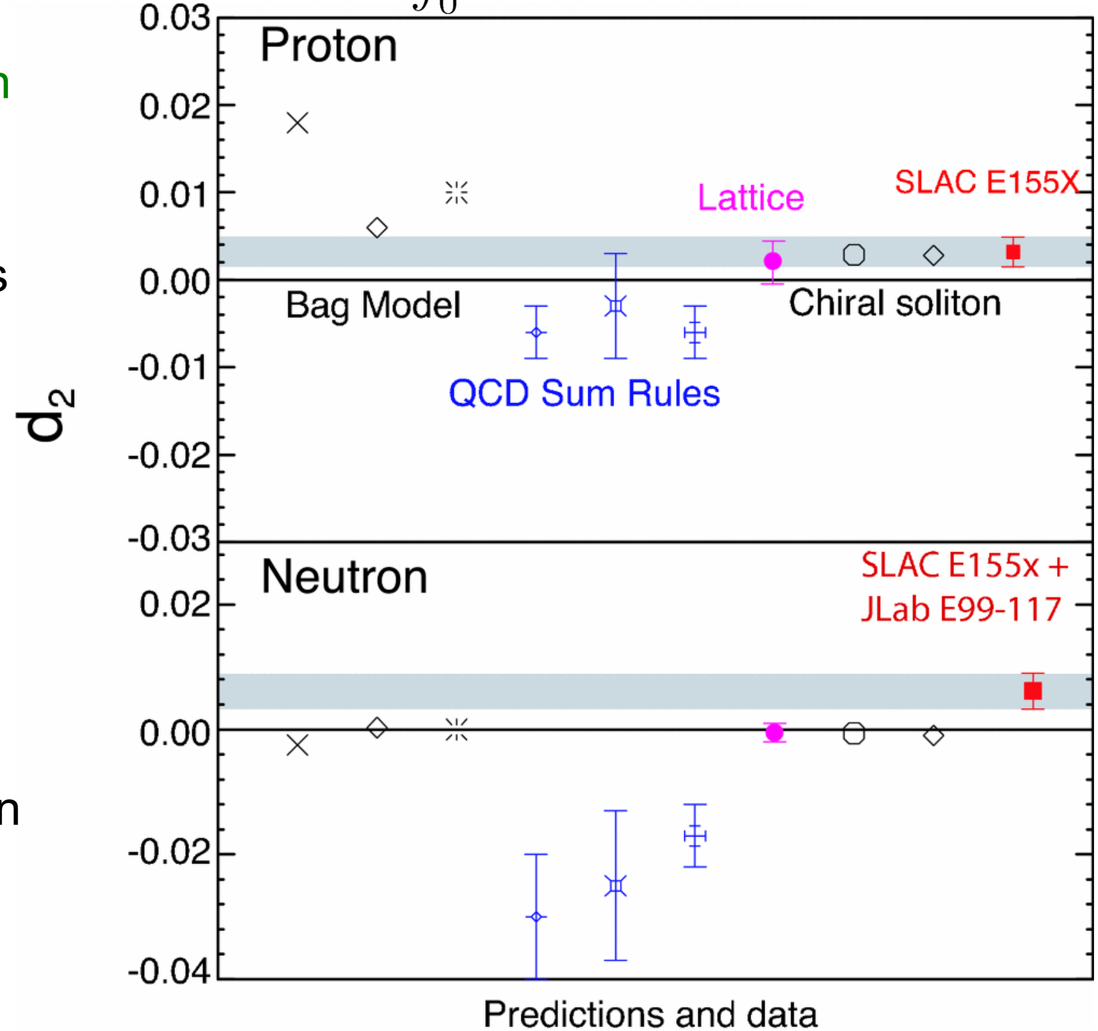
quark-gluon correlation

d_2: A clean probe of quark-gluon correlations

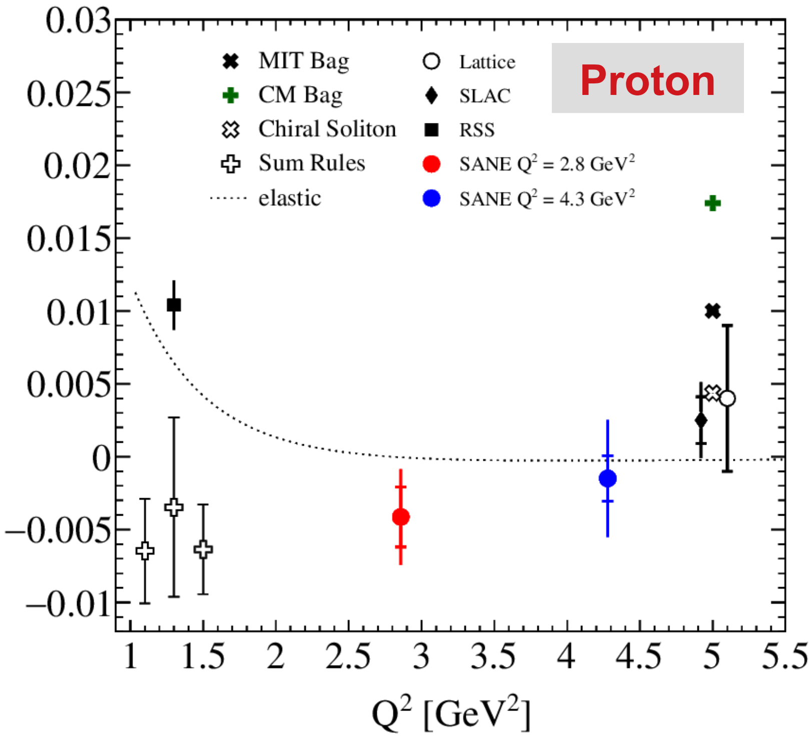
$$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = 3\int_0^1 x^2\overline{g_2}(x,Q^2)dx$$

- d_2 is a clean probe of quark-gluon correlations / higher twist effects
  - → d_2 is the 3rd moment of a sum of the spin structure functions
  - → matrix element in the Operator Product Expansion
    - » *it is cleanly computable using Lattice QCD*

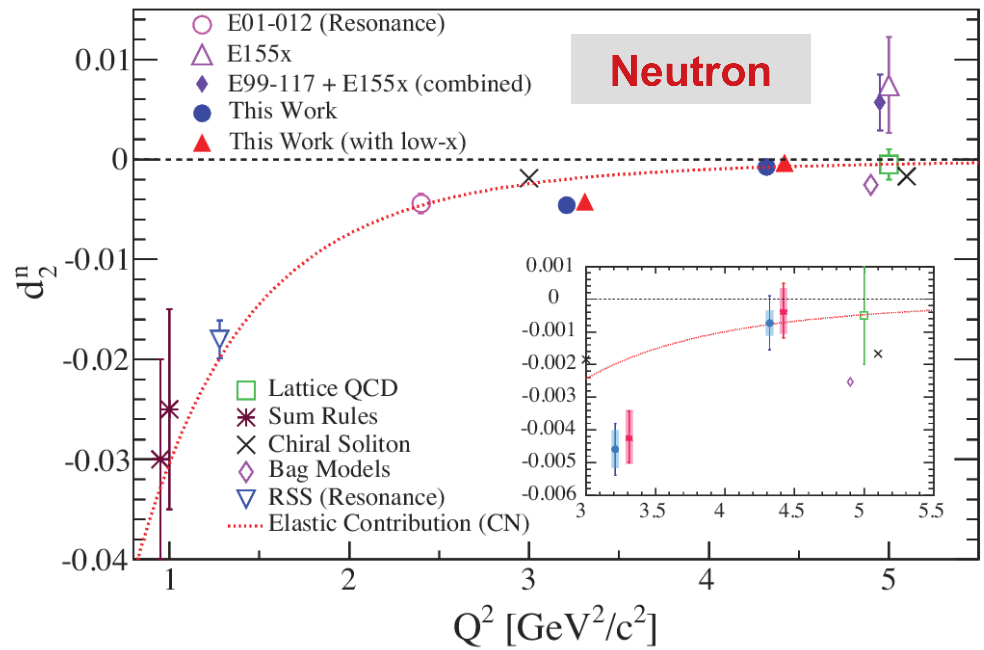
- Connected to the *color Lorentz force* acting on the struck quark (Burkardt)
  - → same underlying physics as in SIDIS $k_\perp$ studies



d_2 for the proton and neutron



Armstrong et al., PRL 122, 022002 (2019)



Posik et al., 10.1103/PhysRevLett.113.022002 (d2n, color force extraction)
Flay et al., 10.1103/PhysRevD.94.05200 (Archival paper: g1n, g2n, d2n)
Parno, et al., 10.1016/j.physletb.2015.03.067 (A1n)

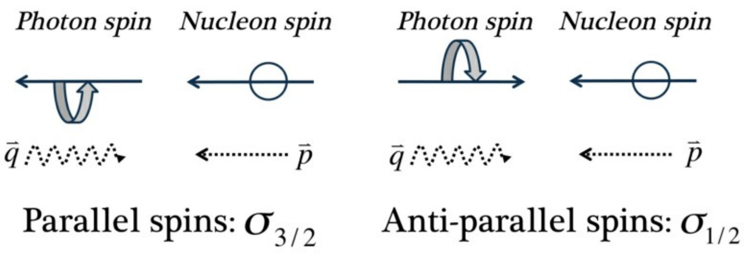
- Hint of a negative d_2^p, negative twist-3 at moderate $Q^2 \sim 3$ GeV^2

  → Similar hint of negative twist-3 (dips below CN elastic) in d_2^n data noted in SANE preprint – curious

Virtual Photon Asymmetry A_1

$$A_1 = \frac{1}{F_1}\left(g_1 - \frac{(2Mx)^2}{Q^2} g_2\right)$$

$$= \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



$$A_1 = \frac{1}{(E+E')D'}\left((E - E'\cos\theta) A_{\parallel} - \frac{E'\sin\theta}{\cos\phi} A_{\perp}\right)$$

- At large-x the quantity A_1 can be cleanly computed
  → different models give significantly different predictions!

Predictions for A_1 and $\Delta q/q$ at Large x

$$|p^{\uparrow}\rangle = \frac{1}{\sqrt{2}}|u^{\uparrow}(ud)_{00}\rangle + \frac{1}{\sqrt{18}}|u^{\uparrow}(ud)_{10}\rangle - \frac{1}{3}|u^{\downarrow}(ud)_{11}\rangle$$
$$- \frac{1}{3}|d^{\uparrow}(uu)_{10}\rangle - \frac{\sqrt{2}}{3}|d^{\downarrow}(uu)_{11}\rangle$$

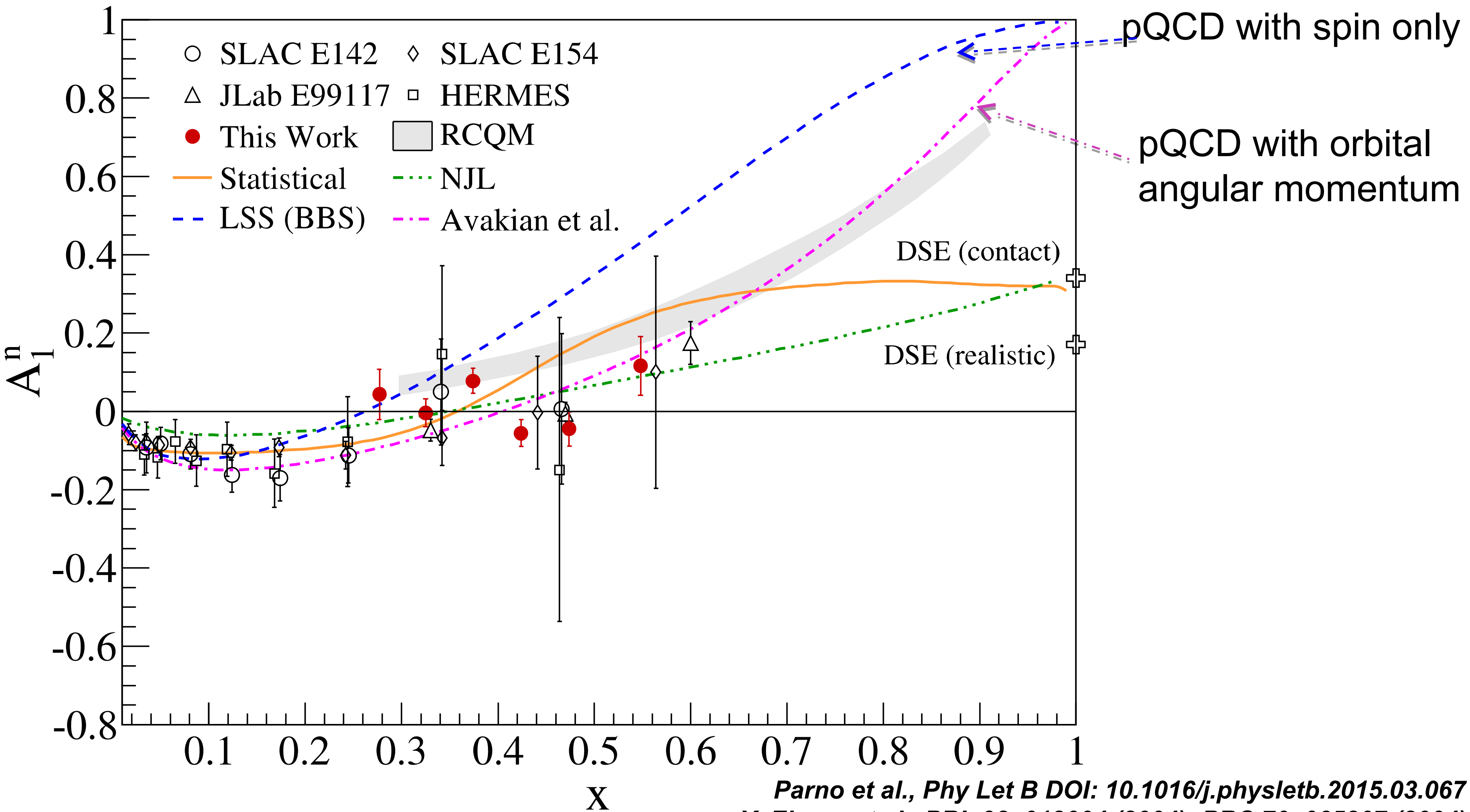
	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	−0.11	0.65	−0.26	0.17	0.59
DSE-2	0.41	0.18	−0.07	0.88	−0.33	0.34	0.88
$0^+_{[ud]}$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	−0.06	0.80	−0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

Table 1: Predictions for the x = 1 value of various models. From Craig D. Roberts et al. arXiv:1308.1236

- DSE-1 (or "DSE realistic") indicates use of the momentum-dependent dressed-quark mass-function;
- DSE-2 (or "DSE contact") corresponds to predictions obtained with a contact interaction.
- "pQCD" expresses predictions assuming a SU(6) spin-flavour wave function for the proton's valence-quarks and the corollary that a hard photon may interact only with a quark that possesses the same helicity as the target

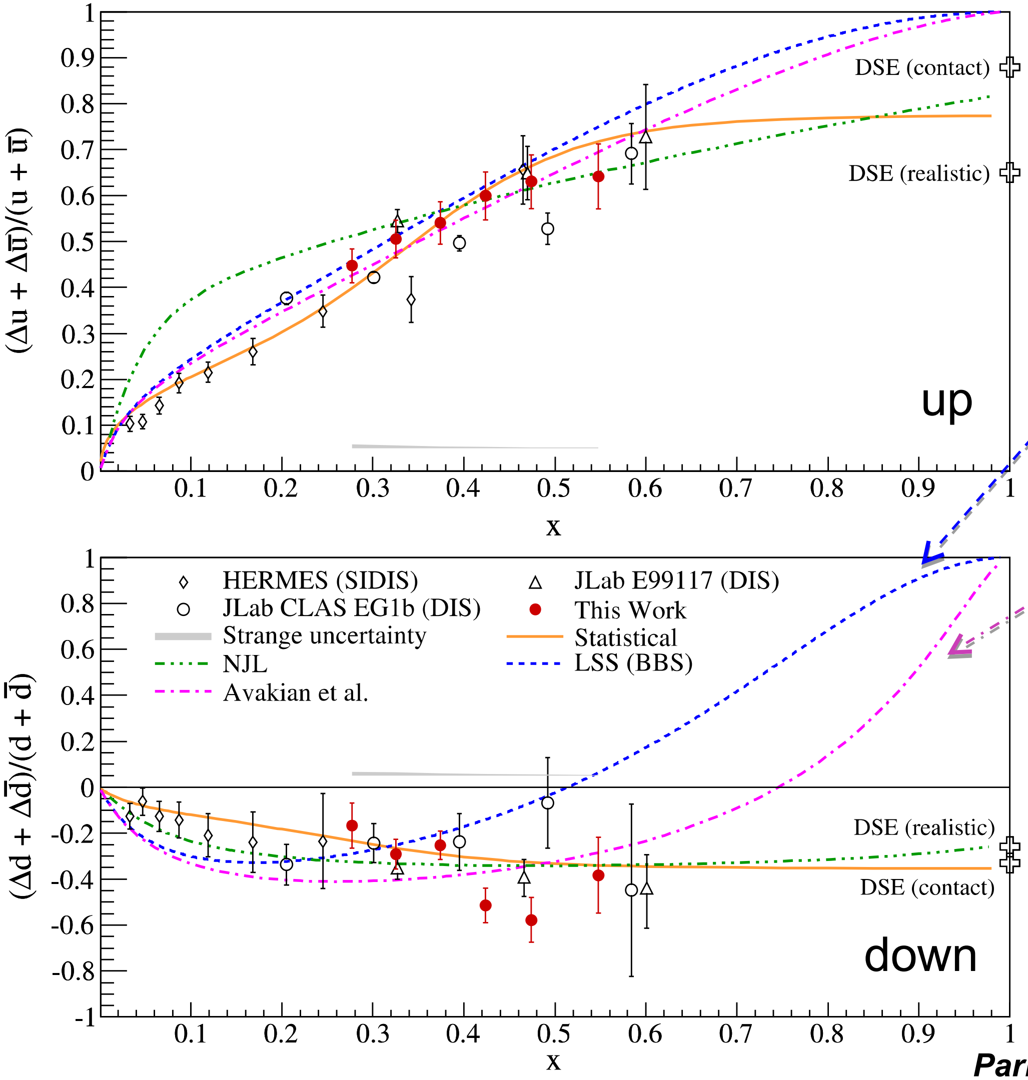
- The only place QCD (and many other models) can make absolute predictions for structure functions.

A_1 for Neutron



Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067
X. Zheng et al., PRL 92, 012004 (2004); PRC 70, 065207 (2004)

(Δu+Δū)/(u+ū) and (Δd+Δd̄)/(d+d̄)



pQCD with spin only

pQCD with orbital angular momentum

- Spin-only pQCD is strongly disfavored
- Must go higher in *x* to distinguish between other models

Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067
X. Zheng et al., PRL 92, 012004 (2004); PRC 70, 065207 (2004)

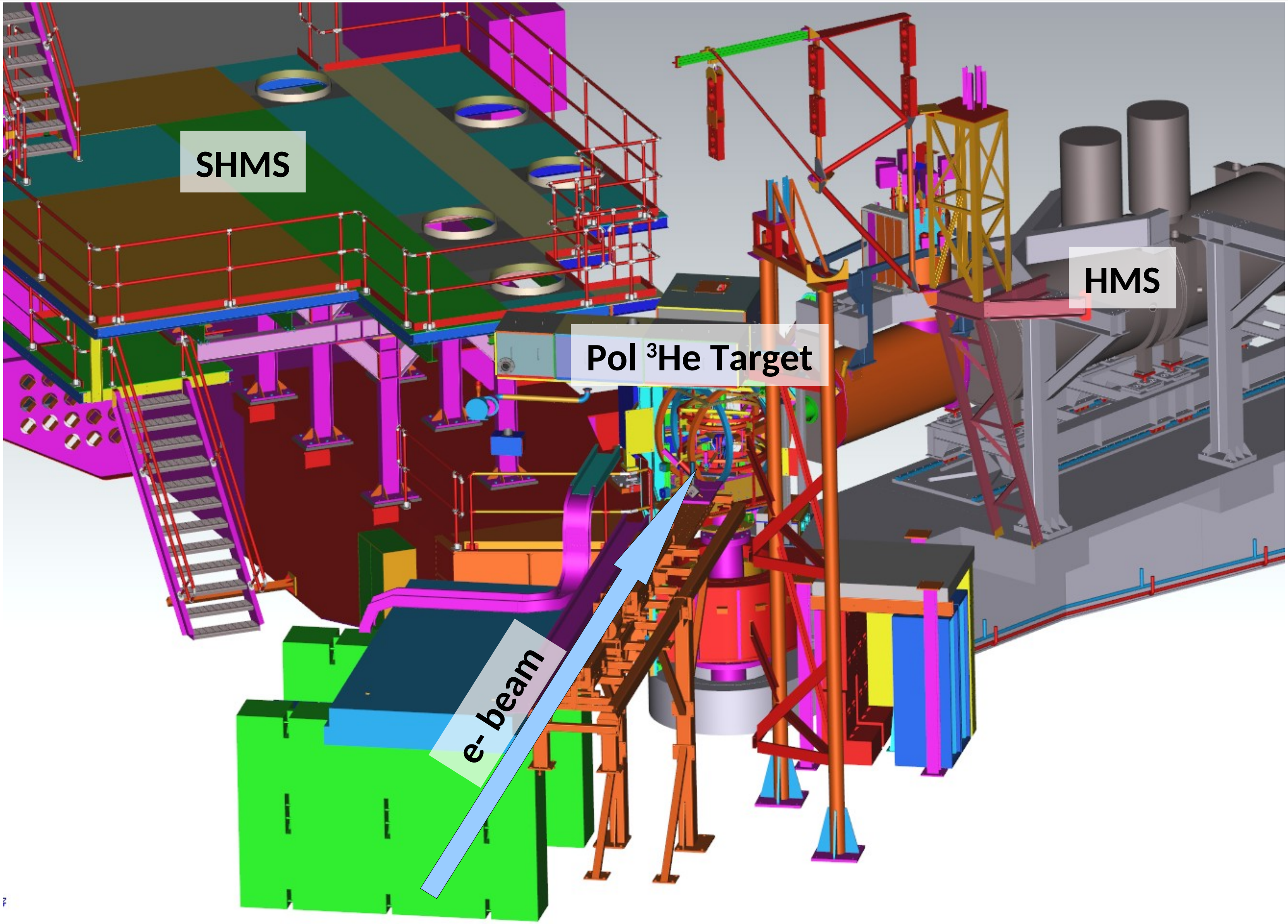
Upcoming Pol ^{3}He Experiments in Hall C

- Two 12 GeV Measurements in Hall C
  - → A_1^n (E12-06-110) *High Impact*
    - » 36 PAC days
  - → d_2n, g_2n (E12-06-121)
    - » 29 PAC days

  (Both measure g_1^n as well)

- Both make use of
  - → 11 GeV beam
  - → SHMS (+ HMS) spectrometers
  - → Upgraded 3He target

Polarized 3He Run Group in Hall C



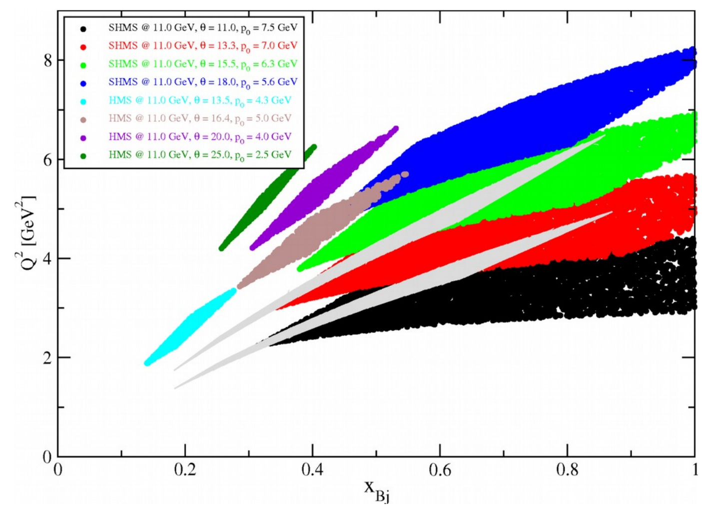
E12-06-121: d_2^n, g_2^n

- Hall C: SHMS + HMS
- Two beam energies:
  → 11 GeV/c (production)
  → 2.2 GeV/c (calib.)
- Beam Current
  → 30 uA (production)
  → 45 uA (max, I calib.)
- Target: 40 cm Polarized ^{3}He
- Each arm measures an absolute polarized cross section independent of the other arm (g_1, g_2)
  → $d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$

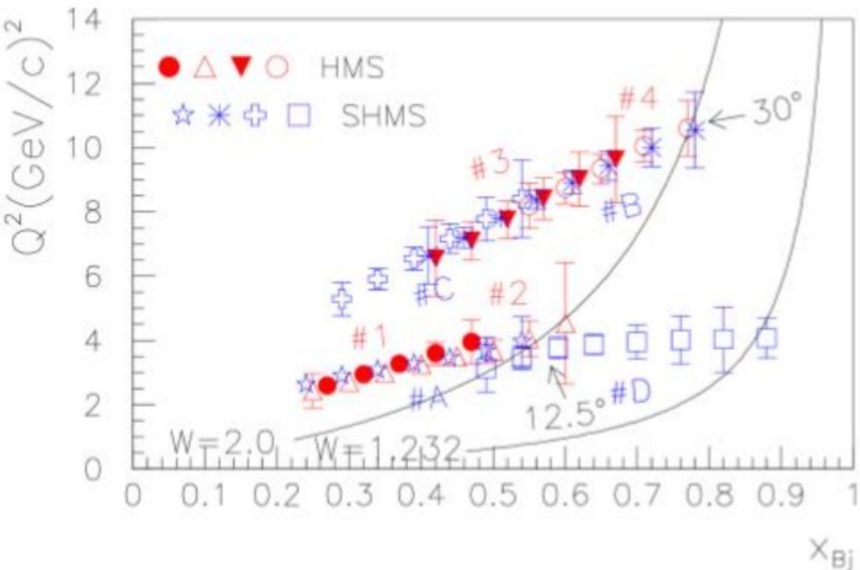
SHMS Production		
Setting	P_0	Angle
A	7.5	11.0°
B	7.0	13.3°
C	6.3	15.5°
D	5.6	18.0°

HMS Production		
Setting	P_0	Angle
A'	4.3	13.5°
B'	5.1	16.4°
C'	4.0	20.0°
D'	2.5	25.0°

- SHMS collects data at
  → Θ = 11°, 13.3°, 15.5° and 18.0° for 125 hrs each
    → data from each setting divided into 4 bins
- HMS collects data at
  → Θ = 13.5°, 16.4°, 20.0° and 25.0° for 125 hrs each



A_1^n Kinematics



Kine	E_b (GeV)		θ (°)	E_p (GeV)	e^- production (hours)	e^+ prod. (hours)	Tot. Time (hours)
DIS							
1	11.0	HMS	12.5	5.70	12	0	12
2	11.0	HMS	12.5	6.80	24	0	24
3	11.0	HMS	30.0	2.82	96	0	96
4	11.0	HMS	30.0	3.50	551	1	552
A	11.0	SHMS	12.5	5.80	36	0	36
B	11.0	SHMS	30.0	3.00	464	0	464
C	11.0	SHMS	30.0	2.25	88	0	88
Resonances							
D	11.0	SHMS	12.5	7.50	96	0	96

both $A_\parallel$ and $A_\perp$

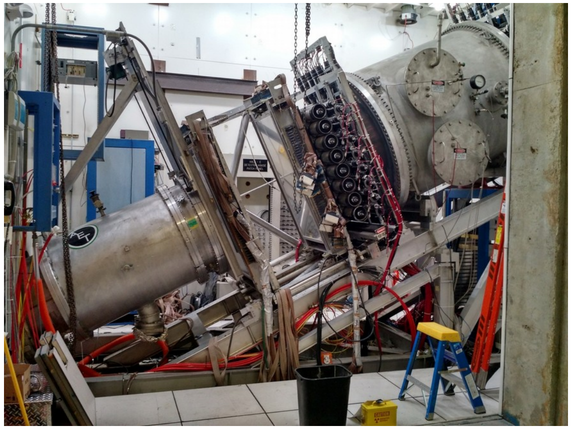
Kine	E_b GeV	E_p GeV	θ (°)	elastic x-sec (nb/sr)	elastic rate (Hz)	Asymmetry	Time (hours)
Elastic	2.200	2.160	12.5	106.986	1293.9	$A_\parallel = 0.0589$	11.2
$\Delta(1232)$	2.200	1.815	12.5	-	-	$A_\perp \sim$ a few %	6

$A_\parallel$

$A_\perp$

Standard Hall C Detector Packages

- SHMS ('default' detector package)
  - → Hodoscopes, Wire chambers, NGC, Calorimeter
  - → HGC tank remains installed: may pump to vacuum, or fill with Argon for auxiliary PID
- HMS ('default' detector package)
  - → Hodoscopes, Wire chambers, Calorimeter
  - → Gas Cer fill with Argon, or C_4F_{10} (sub-atmosphere)



- DAQs
  - → Standard DAQ and triggers

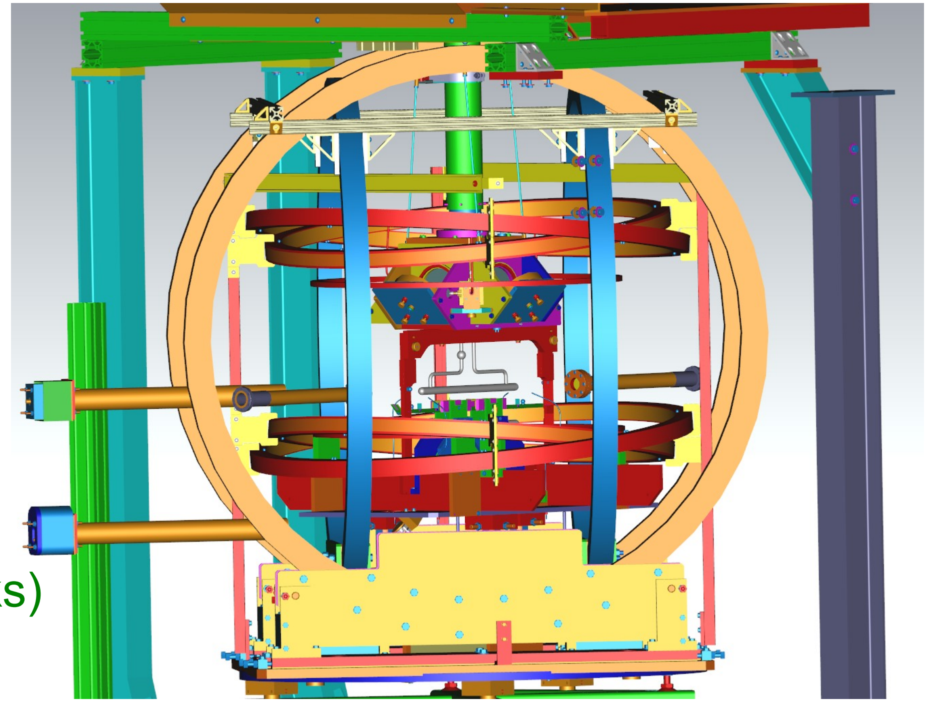
Nominal Beam Requirements

- Beam Characteristics
  - → 1-pass, 5-pass beam
  - → Beam polarization: 80%
    - » Measured to ~3% via Moller Polarimeter
  - → Circular beam raster @ 2.5mm radius
  - → Modest ramp rate to protect glass cell (0.5–1 uA/sec)
    - » Total beam trip rate really matters here!
  - → < 50 ppm charge asym (average over ~ 1–2 hr run)
  - → 30 uA (max) on glass cell targets
  - → 30 uA (max) on solid targets

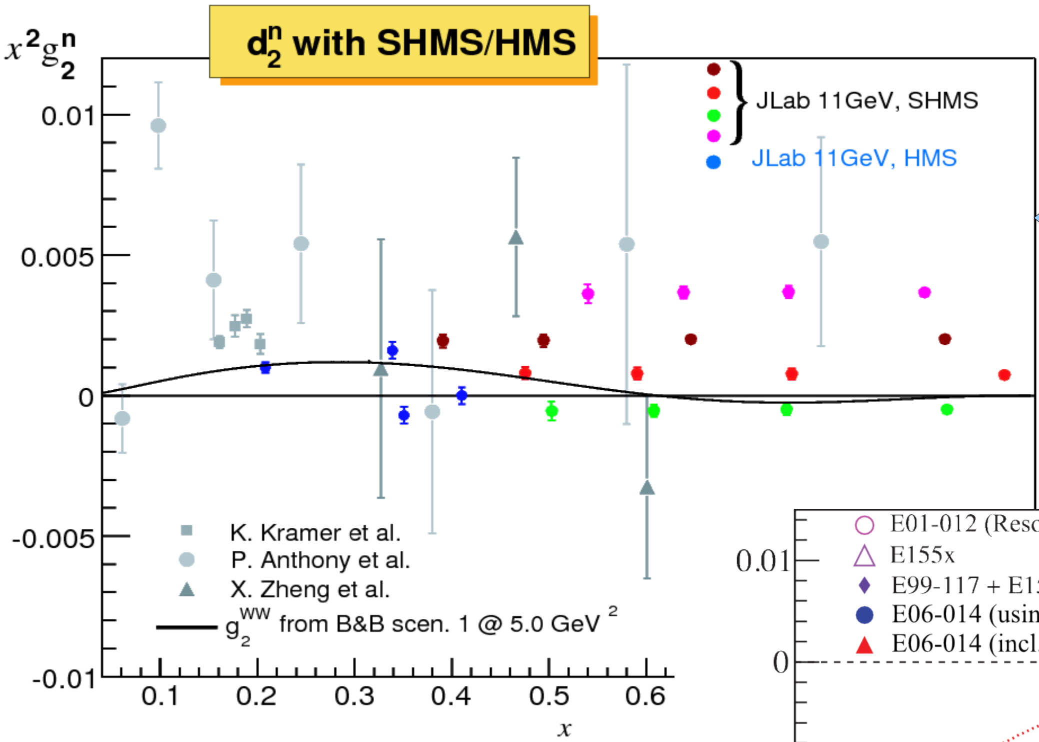
Nominal Target Requirements

- Polarized ^{3}He Target Requirements
  - → 55–60% polarization
  - → 30 uA beam current capability
  - → ~0.1 spin angle measurement (2 mrad)
    - » Challenging, but achievable

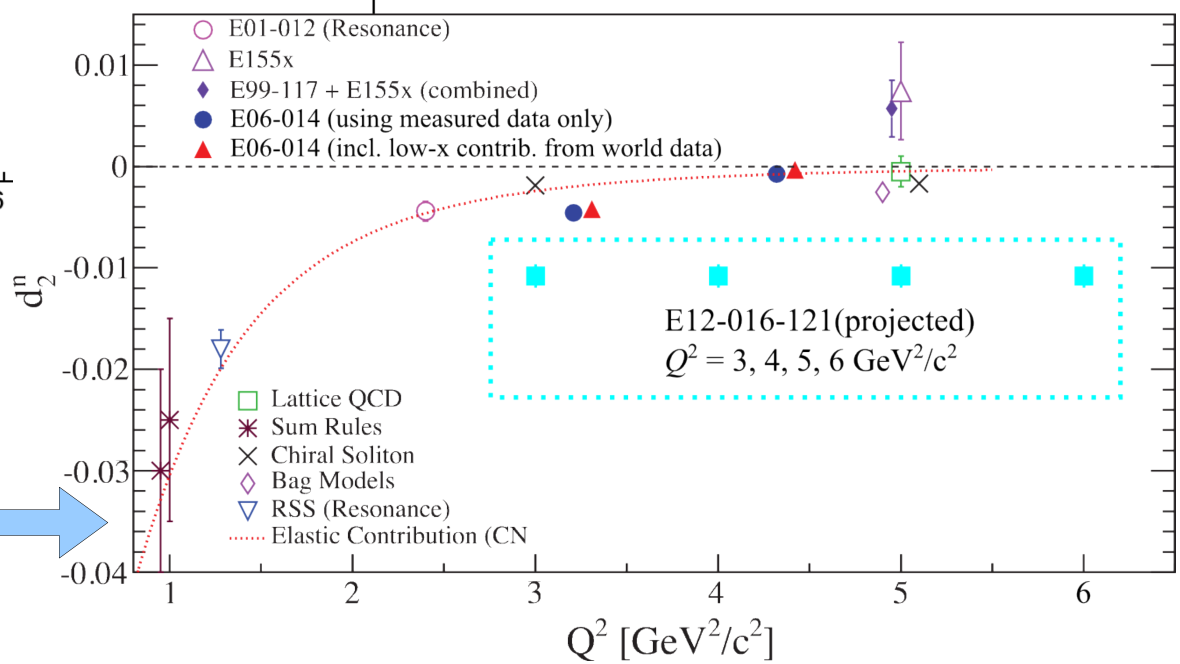
- Target Ladder components
  - → Polarized ^{3}He production cell (40cm)
  - → Reference cell:
    - » vacuum, H_2, ^{3}He, Nitrogen
  - → Optics foils (7)
  - → Single-carbon foil
  - → Carbon-hole (alignment, raster checks)



E12-06-121 Projected results



Projected g_2^n points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—7 GeV^2.



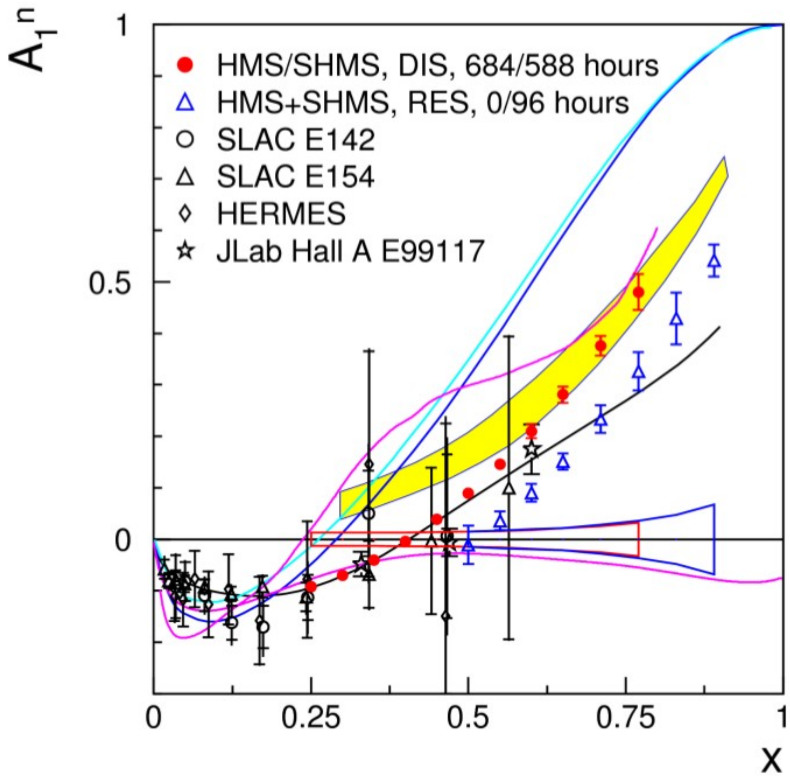
Q^2 evolution of d_2^n in a region where models are thought to be accurate.

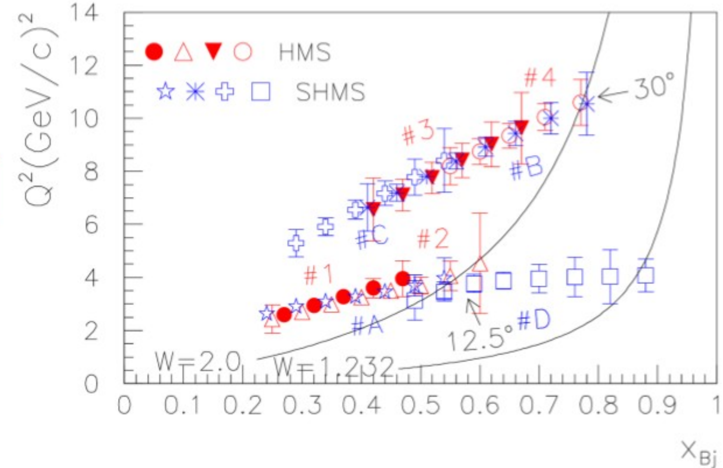
Direct overlap with 6 GeV Hall A measurements.

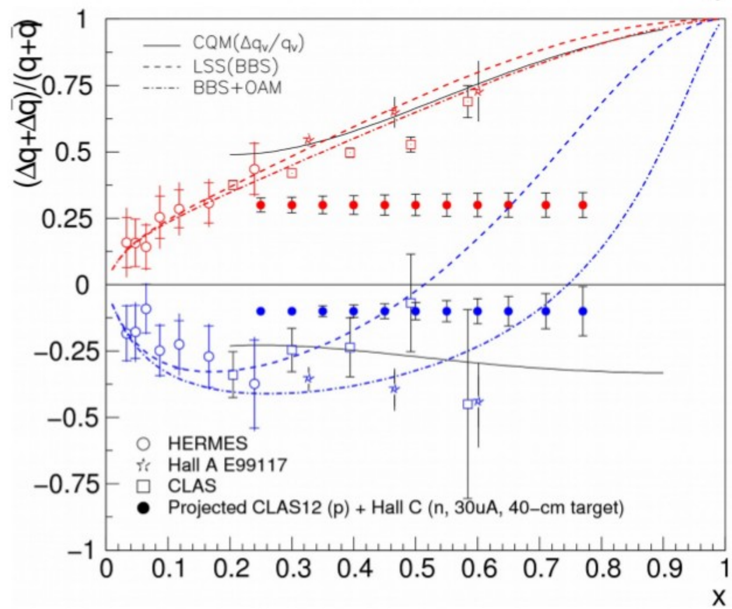
E12-06-110 A_1^n in Hall C

A_1^n Kinematics and Expected Results

30uA, 85% beam, 40cm, 60% target







Spokespeople: X. Zheng, G. Cates, JP Chen, Z-E Meziani

Slide from X. Zhang March 2018 readiness review

A_1^n, d_2^n Summary

- **12 GeV Hall C A_1^n and d_2^n, g_2^n measurements will run 2019–2020**
  - → Focus on high-x and Q^2 evolution of these quantities
    - » Large new precision data set in previously unmeasured domain
  - → Finally rule out DSE or pQCD A_1^n models?
  - → First evaluations of d_2^n at truly fixed Q^2 values
    - » Insight into quark-gluon correlations

- ***Major installation effort (Target focused) beginning this Summer!***

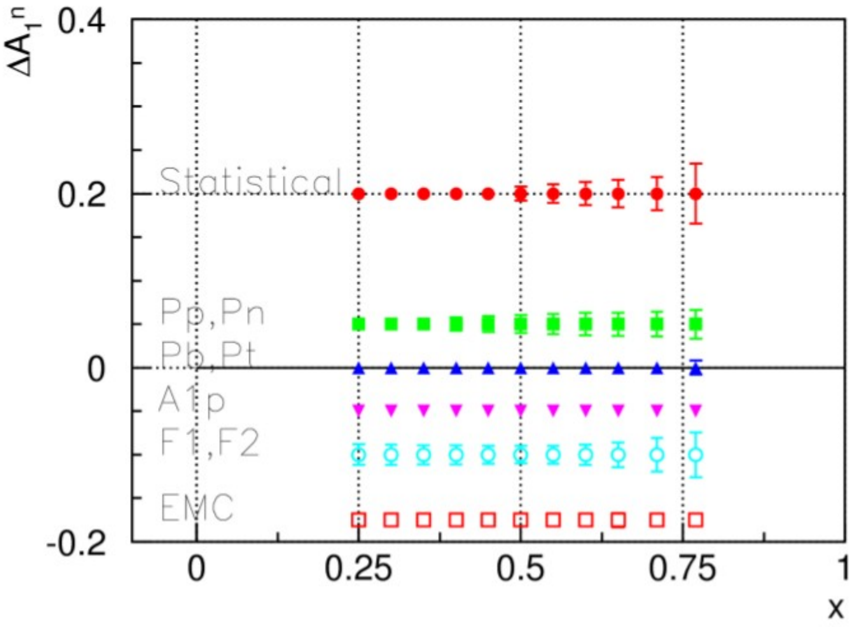
- **Large A_1^p, g_1^p data set from upcoming CLAS12 E12-06-109 as well!**
  - **→ Compliments Hall C neutron measurements for Δq/q extractions**

BACKUP

A_1^n Kinematics – x, W, and background estimation

Kine		E_b GeV	E_p GeV	θ (°)	(e,e') rate (Hz)	π^-/e	e^+/e^-	x (Q^2, in GeV^2) (W, in GeV) coverages
DIS								
1	HMS	11.0	5.70	12.5	575.42	< 0.4	< 0.1%	0.25-0.55 (2.59- 4.40) (2.1- 2.9)
2	HMS	11.0	6.80	12.5	426.14	< 0.2	< 0.1%	0.25-0.60 (2.43- 4.53) (2.0- 2.9)
3	HMS	11.0	2.82	30.0	2.69	< 10.7	< 0.1%	0.40-0.71 (6.55-10.19) (2.2- 3.3)
4	HMS	11.0	3.50	30.0	0.74	< 2.4	< 0.1%	0.50-0.77 (7.72-10.60) (2.0- 2.9)
A	SHMS	11.0	5.80	12.5	701.73	< 0.5	< 0.1%	0.25-0.60 (2.64- 4.42) (2.0- 3.0)
B	SHMS	11.0	3.00	30.0	2.70	< 12.2	< 0.1%	0.40-0.77 (6.63-10.54) (2.0- 3.3)
C	SHMS	11.0	2.25	30.0	6.96	< 91.0	< 0.1%	0.25-0.65 (4.71- 9.49) (2.4- 3.9)
Resonances								
D	SHMS	11.0	7.50	12.5	104.79	–	–	0.50-1.00 (3.12- 4.45) (0.9- 2.0)

Break-down of Uncertainties

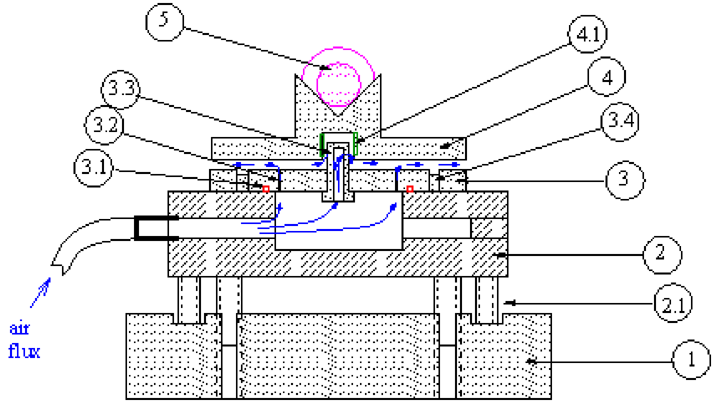


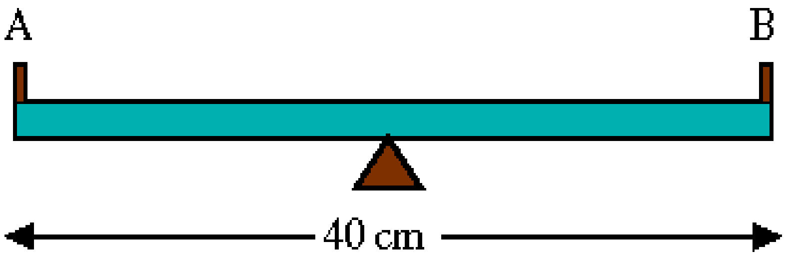
E12-06-121 Systematic Error Table

Item description	Subitem description	Relative uncertainty
Target polarization		1.5 %
Beam polarization		3 %
Asymmetry (raw)		
	• Target spin direction (0.1°)	$< 5 \times 10^{-4}$
	• Beam charge asymmetry	$<$ 50 ppm
Cross section (raw)		
	• PID efficiency	$<$ 1 %
	• Background Rejection efficiency	$\approx$ 1 %
	• Beam charge	$<$ 1 %
	• Beam position	$<$ 1 %
	• Acceptance cut	2-3 %
	• Target density	$<$ 2%
	• Nitrogen dilution	$<$ 1%
	• Dead time	$<$ 1%
	• Finite Acceptance cut	$<$ 1%
Radiative corrections		$\leq$ 5 %
From ^{3}He to Neutron correction		5 %
Total systematic uncertainty (for both $g_2^n(x,Q^2)$ and $d_2(Q^2)$)		$\leq$ 10 %
Estimate of contributions to d_2 from unmeasured region	$\int_{0.003}^{0.23} \tilde{d}_2^n \, dx$	4.8×10^{-4}
Projected absolute statistical uncertainty on d_2		$\Delta d_2 \approx 5 \times 10^{-4}$
Projected absolute systematic uncertainty on d_2 (*assuming* $d_2 = 5 \times 10^{-3}$)		$\Delta d_2 \approx 5 \times 10^{-4}$

- PREx-II, CREx ERR accepted < 0.1 ppm Charge Asym requirement as achievable
- Target spin direction precision achievable (see backup slide)

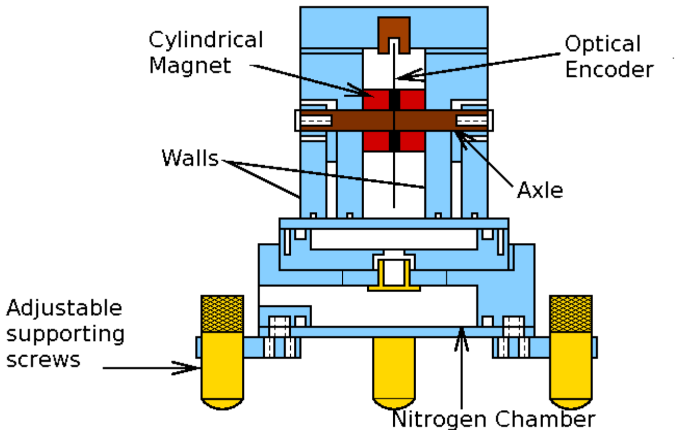
Magnetic Field Direction





Longitudinal Field: - air floating compass (left)
- needle compass (above)

$\Delta\Theta < 2$ mrad (< 0.1 degree)



Transverse Field: - air floating compass (left)

$\Delta\theta \sim 1$ mrad (~0.05 degree)

A. Kolarkar, Ph.D. Thesis, UKy, 2008
C. Dutta, Ph. D. Thesis, UKy, 2010

d2n Production Kinematics for HMS

Table 4: Expected rates for the three HMS settings. The uncertainties for $A_{\|}$ and $A_{\perp}$ are *statistical* only.

θ_0 [$\circ$]	E'_{cent} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_{\|}$ [hrs]	$t_{\perp}$ [hrs]	$\Delta A_{\|}$ [$\cdot 10^{-4}$]	$\Delta A_{\perp}$ [$\cdot 10^{-4}$]
13.5	4.305	2.617	0.208	3.293	954	765	8	117	2.0	0.6
16.4	5.088	4.555	0.410	2.727	218	15	12	113	3.9	1.2
20.0	4.000	5.31	0.404	2.951	76	66	10	115	6.0	1.8
25.0	2.500	5.15	0.323	3.417	20	84	13	112	10.7	3.1

- Rate table from PAC36
  - → 30 uA beam
  - → 55% polarization
  - → Assumed 60 cm long cell
- Current target
  - → 40 cm long cell
- As discussed in the PAC36 update, we have been conservative on our statistical run times and are not statistics limited, even with the shorter production cell.

d2n Production Kinematics for SHMS

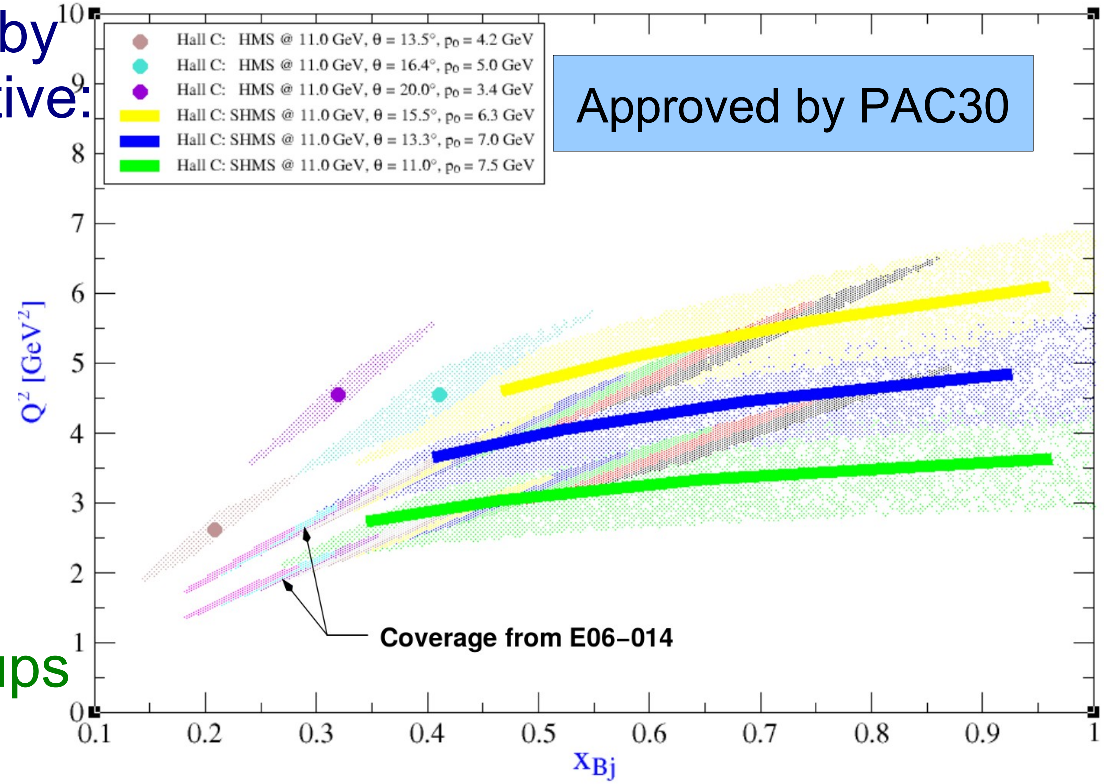
Table 3: Kinematic bins and expected rates for the SHMS. The uncertainties for $A_{\|}$ and $A_{\perp}$ are *statistical* only.

SHMS Setting	E'_{bin} [GeV]	Q^2 [GeV^2]	x	W [GeV]	e^- rate [Hz]	π^- rate [Hz]	$t_{\|}$ [hrs]	$t_{\perp}$ [hrs]	$\Delta A_{\|}$ [$\cdot 10^{-4}$]	$\Delta A_{\perp}$ [$\cdot 10^{-4}$]
$\theta_0 = 11^\circ$	7.112	2.875	0.394	2.305	1058	11	12	113	2.0	0.5
	7.709	3.116	0.504	1.988	708	3.1	12	113	2.3	0.7
$E'_{cent} = 7.5$	8.304	3.357	0.663	1.610	259	0.83	12	113	3.7	0.1
GeV	8.900	3.597	0.912	1.109	2.7	0.21	12	113	36	10
$\theta_0 = 13.3^\circ$	6.647	3.922	0.480	2.267	268	3.1	12	113	3.5	1.0
	7.203	4.250	0.596	1.941	139	0.8	12	113	4.8	1.5
$E'_{cent} = 7.0$	7.758	4.578	0.752	1.548	31.6	0.16	12	113	10	3.1
GeV	8.314	4.906	0.972	1.012	0.10	0.033	12	113	173	55
$\theta_0 = 15.5^\circ$	5.997	4.798	0.511	2.342	96	1.9	12	113	5.7	1.8
	6.496	5.197	0.614	2.037	49	0.47	12	113	7.8	2.5
$E'_{cent} = 6.3$	6.995	5.597	0.744	1.677	13.5	0.11	12	113	15	4.7
GeV	7.494	5.996	0.911	1.215	0.29	0.025	12	113	98	33
$\theta_0 = 18.0^\circ$	5.348	5.756	0.542	2.397	35	1.1	12	113	9.5	3.1
	5.790	6.235	0.637	2.106	17	0.25	12	113	13	4.4
$E'_{cent} = 5.6$	6.233	6.711	0.749	1.769	5.1	0.05	12	113	24	8.1
GeV	6.675	7.187	0.885	1.350	0.38	0.01	12	113	87	30

- Table from PAC36 update
  - → Same considerations as noted on prior slide apply.

Fallback / Contingency Plans

- Original proposal approved by PAC30 was more conservative:
  - →Beam
    - » 10 uA
    - » 80% polarized
  - →Target: 2008 params
    - » 40 cm long
    - » 50% polarization
  - → 3 'paired' kinematic groups (instead of 4)
    - » ~200 hours for each pair



- Worst case:
  - →Fall back to these params and we still have a viable measurement.
- See also:
  - → Section 5 of PAC36 Update (last few paragraphs)