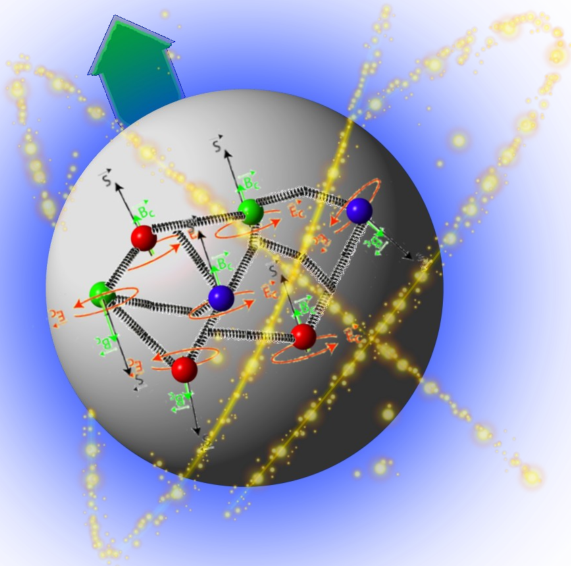
Probing the Spin Structure of the Nucleon:

Recent Results and Upcoming Measurements of SSFs and their Moments at JLab



Brad Sawatzky

SPIN 2018

Ferarra, Italy

SSF Measurements at JLab (6 GeV)

- g_1 measured in all Halls
  - → NH_3, ND_3 in all Halls
  - → ^{3}He in Hall A
- g_2 in A and C
- Duality in *g1*
- *A1* on both neutron and proton
- Transverse structures A_2 and g_T
- Moments and twist 3
  - → d_2
- Sum rules GDH, B-C, Bjorken
- *n* SSFs from ^{3}He and *d-p*

Inclusive Program at 6 GeV				
Experiment	**Hall**	**Target**	**Measured quantity**	**Kinematics Q^2 GeV^2**
94-010	A	^{3}He	A∥, A⊥	Resonances 0.1 – 0.9
CLAS eg1a-b	B	*p, d*	A∥	DIS, Resonances 0.2 – 3.5
97-103	A	^{3}He	A⊥	DIS 0.6 – 1.4
97-110	A	^{3}He	A∥, A⊥	Elastic, Resonances 0.02 – 0.5
99-117	A	^{3}He	A∥, A⊥	DIS 2.7, 3.5, 4.8
01-006 (RSS)	C	*p, d*	A∥, A⊥	Resonances 1.3
01-012	A	^{3}He	A∥, A⊥	Resonances 1 – 4
CLAS eg4	B	*p*	A∥	Elastic, Resonances 0.01 – 0.5
07-003 (SANE)	C	*p*	A∥, A⊥	DIS, Resonances 1.6 – 6
06-014	A	^{3}He	A∥, A⊥	DIS <3>
08-027 (g2p)	A	*p*	A∥, A⊥	Resonances 0.03 – 0.3

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06-014	A	^{3}He	A‖, A⊥	DIS <3>
08-027 (g2p)	A	*p*	A‖, A⊥	Resonances 0.03 – 0.3

Polarized DIS cross sections

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

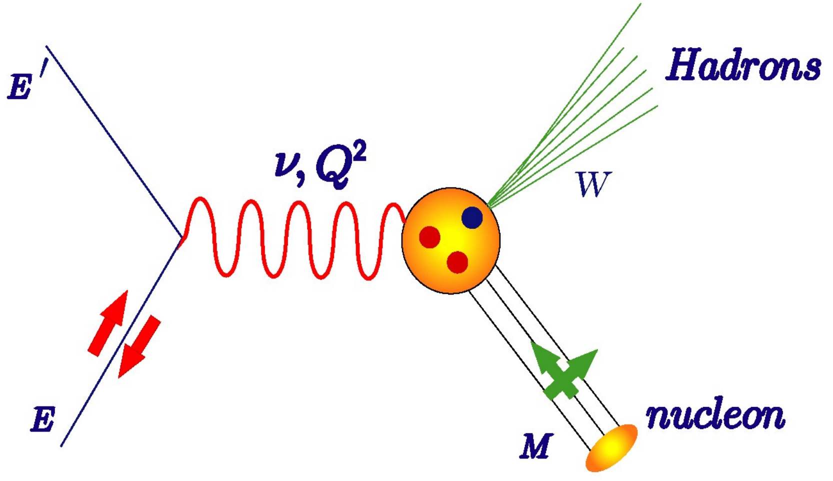
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right] = \Delta\sigma_\perp$$

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.



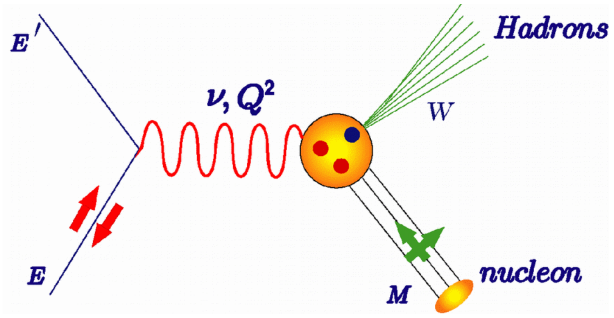
What are g_1 and g_2?

- 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

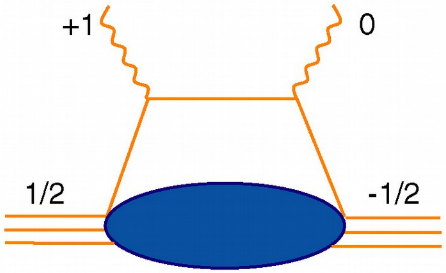
- g_1 and g_2 encode information about the spin structure of the target nucleon



- 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

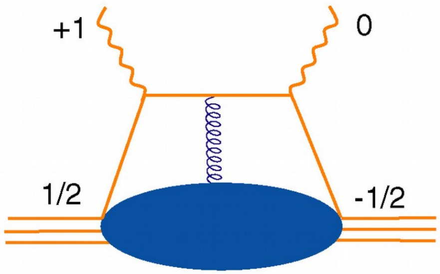
twist-2



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):

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

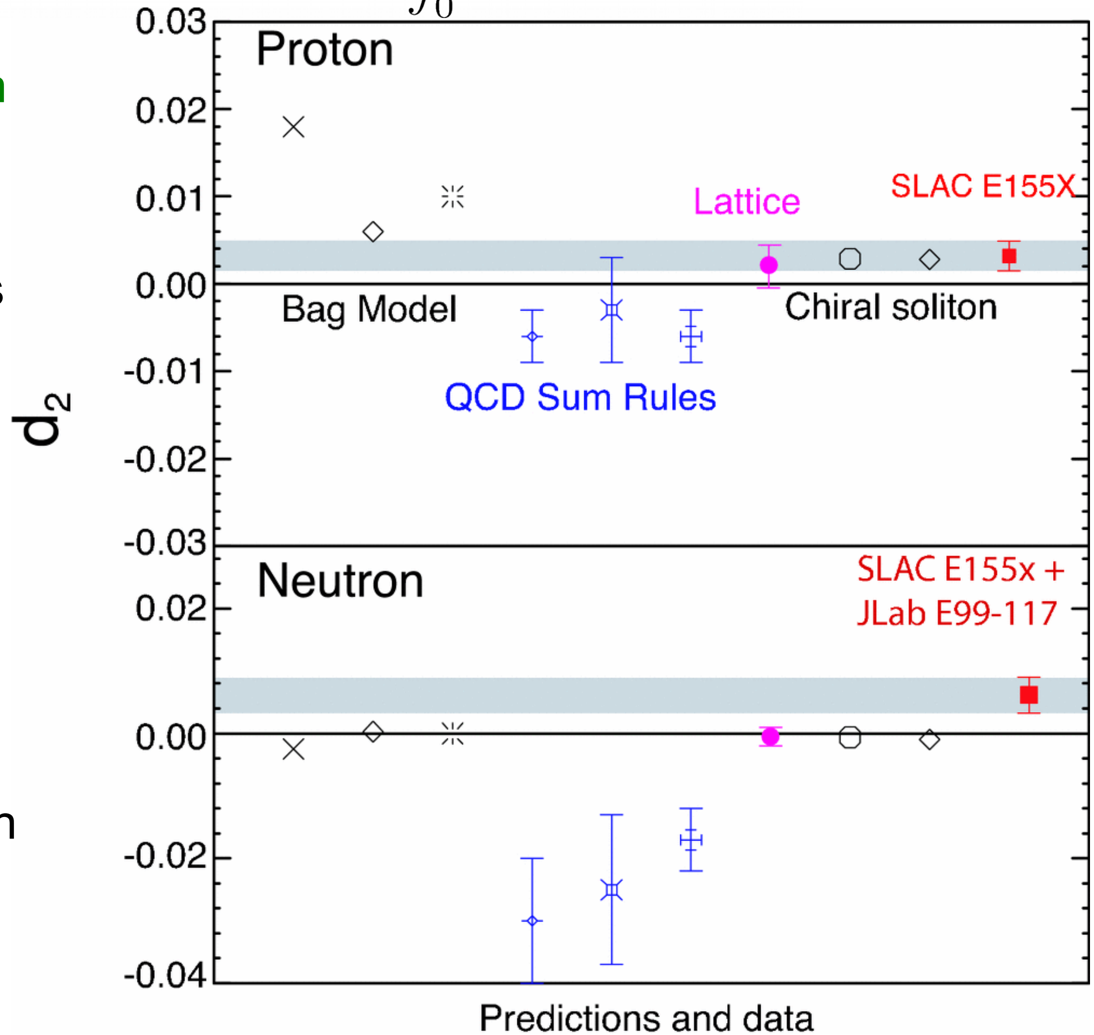
transversity

quark-gluon correlation

d_2: A clean probe of quark-gluon correlations

$$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$

- 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



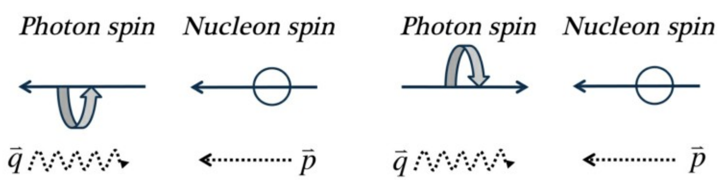
Virtual Photon Asymmetries

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

$$A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{\|} + \frac{E - E'\cos\theta}{E'\sin\theta\cos\phi} A_{\perp}\right)$$

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

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



Parallel spins: $\sigma_{3/2}$ Anti-parallel spins: $\sigma_{1/2}$

$$A_2 = \frac{\sqrt{Q^2}}{\nu}\frac{g_T}{F_1}$$

$$g_T = g_1 + g_2$$

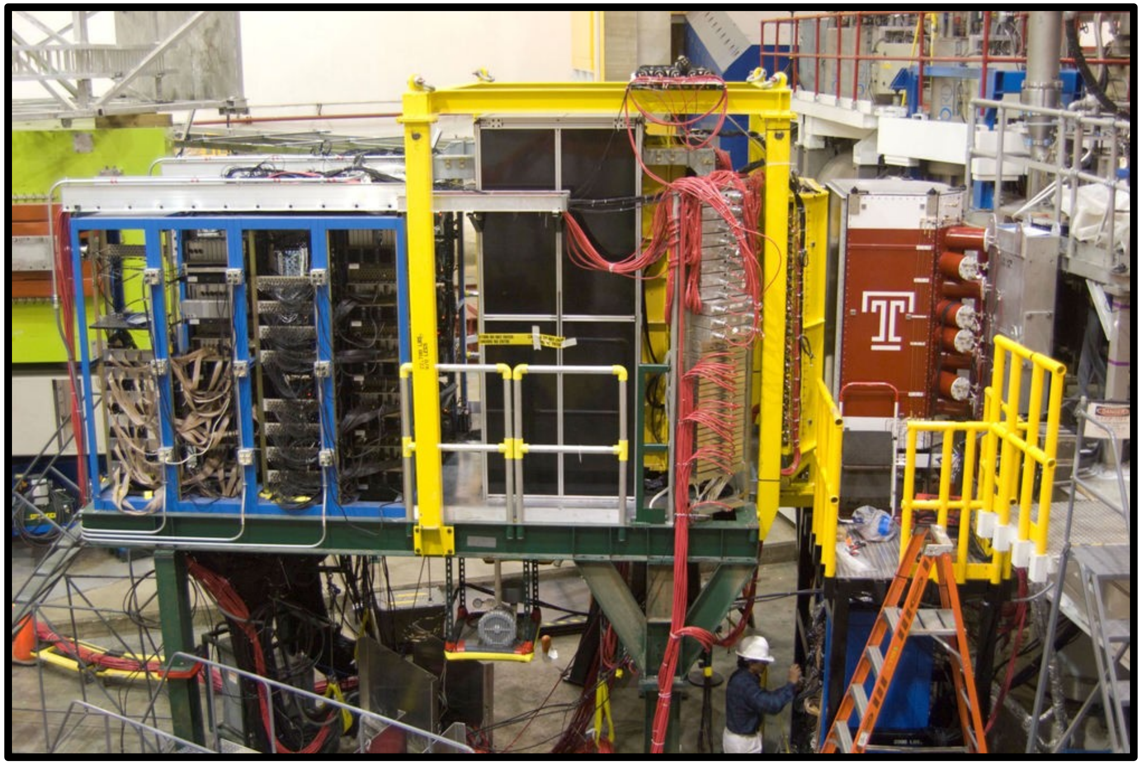
- g_T measures spin distribution normal to the virtual photon

The Experiments

E07-003 and E06-014

("SANE" and "d2n")

E07-003: SANE (Hall C)

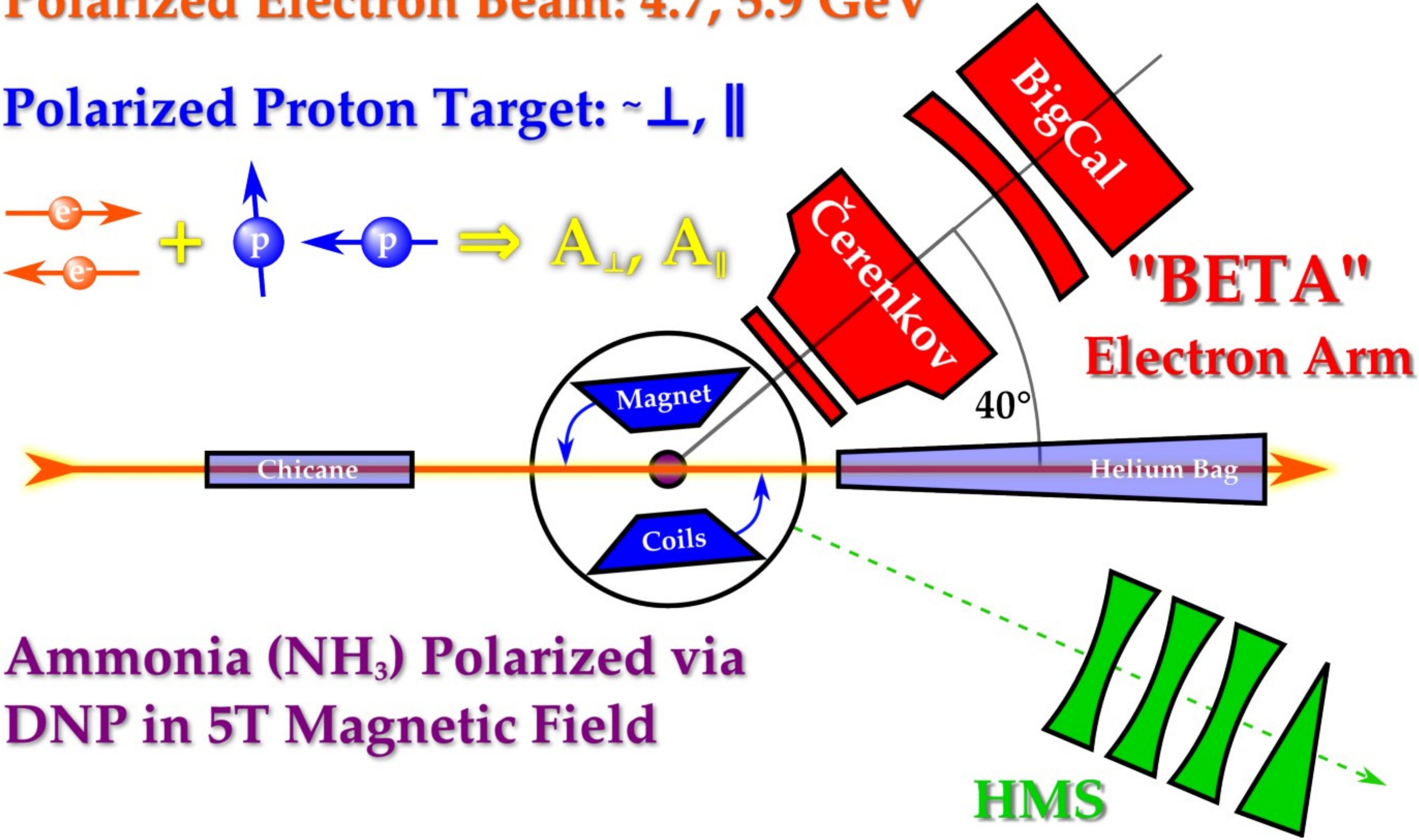


- Spin Asymmetries of the Nucleon Experiment
  - → Polarized NH_3 target
  - → Large acceptance detector to measure asymmetries
  - → Focus: A_1, g_2, d_2 for the proton

SANE: Experimental Layout

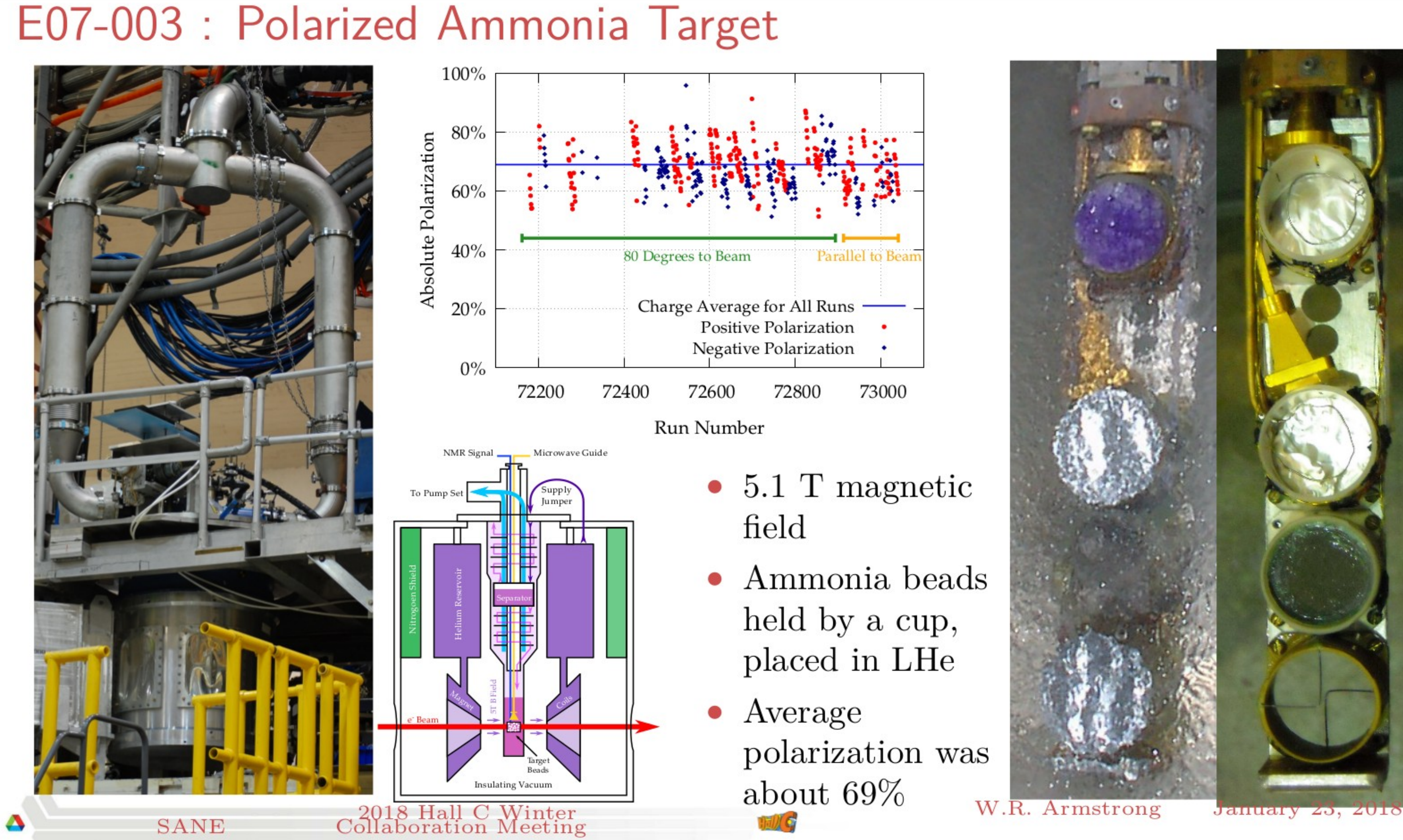
Polarized Electron Beam: 4.7, 5.9 GeV

Polarized Proton Target: ~⊥, ∥

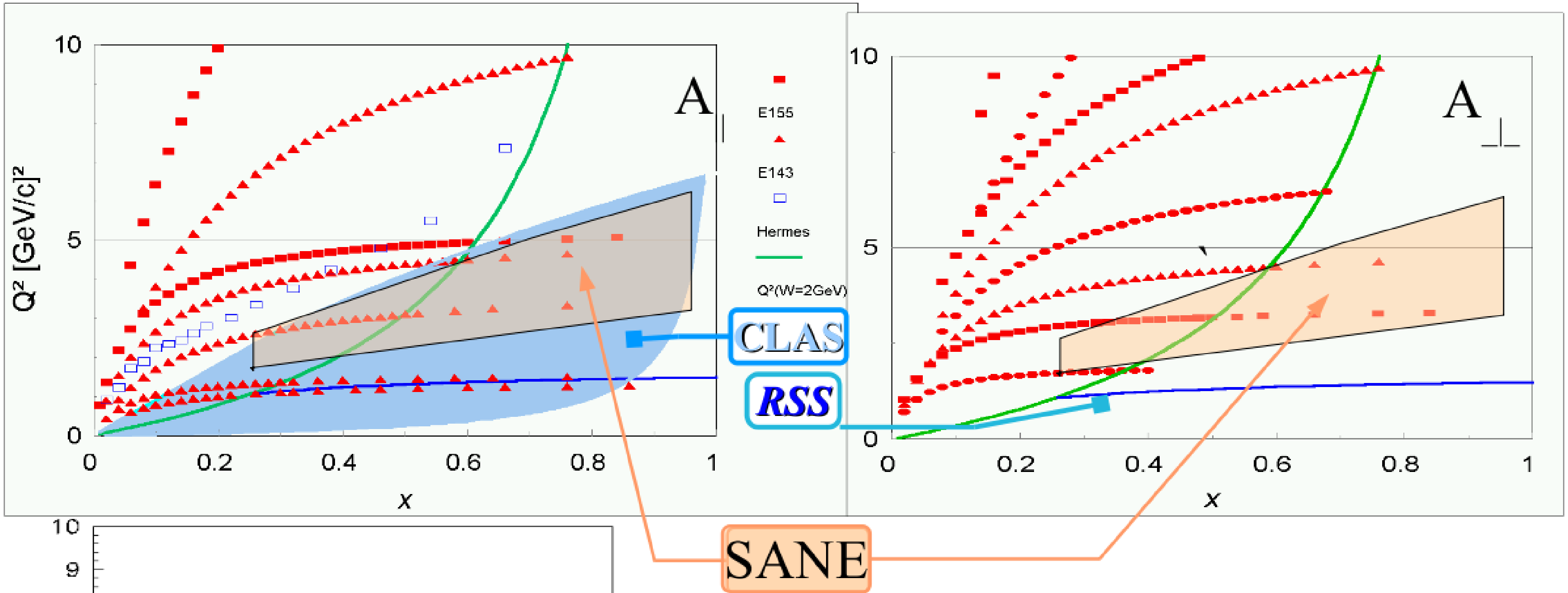


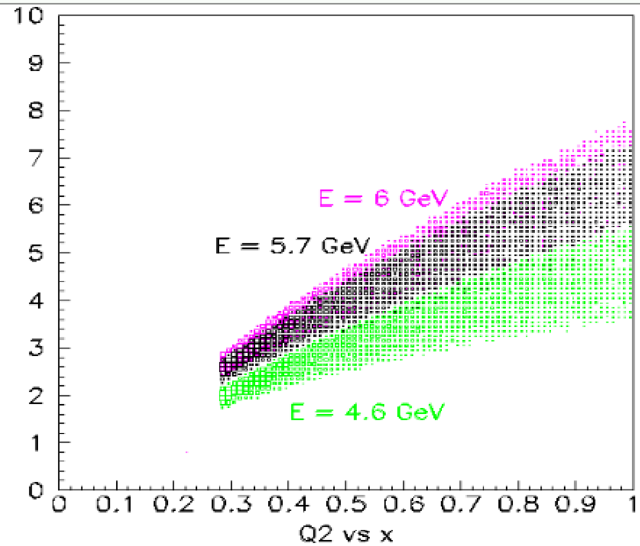
Ammonia (NH_3) Polarized via DNP in 5T Magnetic Field

Polarized NH_3 Target



World data on $A_\parallel$, $A_\perp$ and SANE kinematics



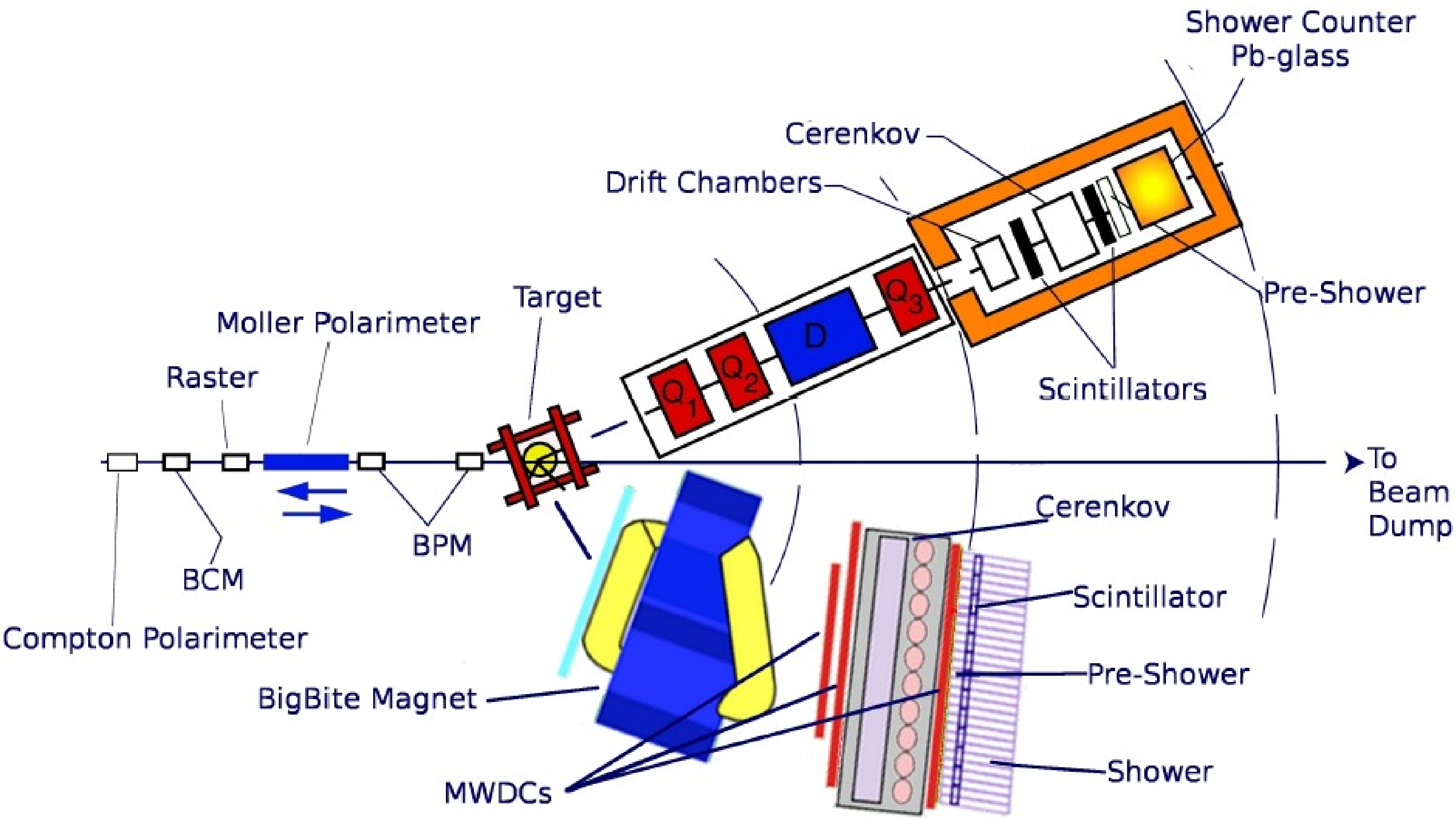


- Two beam energies: **5.9 GeV**, **4.7 GeV**
- Very good high *x* coverage with detector at 40°

E06-014: The Neutron d_2 (Hall A)

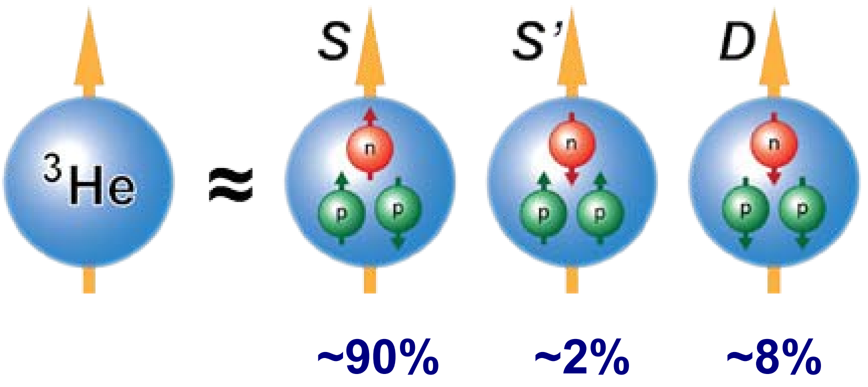
- A measurement of the neutron d_2
  - → Polarized ^{3}He target
  - → Large acceptance detector to measure asyms (BigBite)
  - → High-precision device to measure unpol. x-sec (HRS)
  - → Focus: d_2, g_2 on the neutron
    - » extracted A_1, g_1 as well

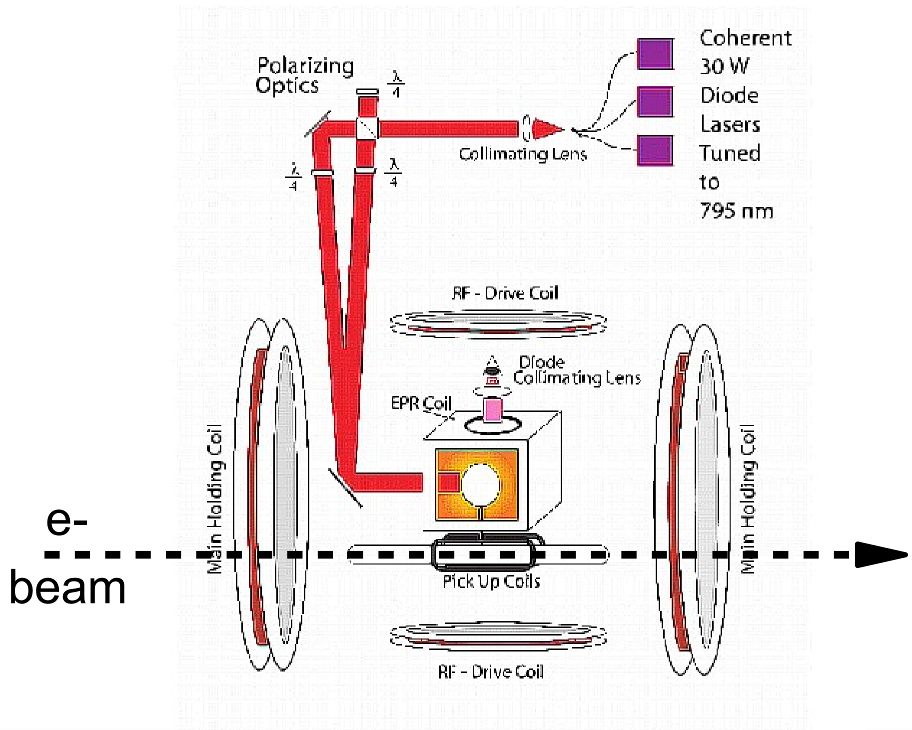
Floor configuration for d_2^n



Polarized ³He Target

- ³He is (almost) a polarized neutron target
  - → Dominant S state has neutron carrying the spin (proton spins cancel)

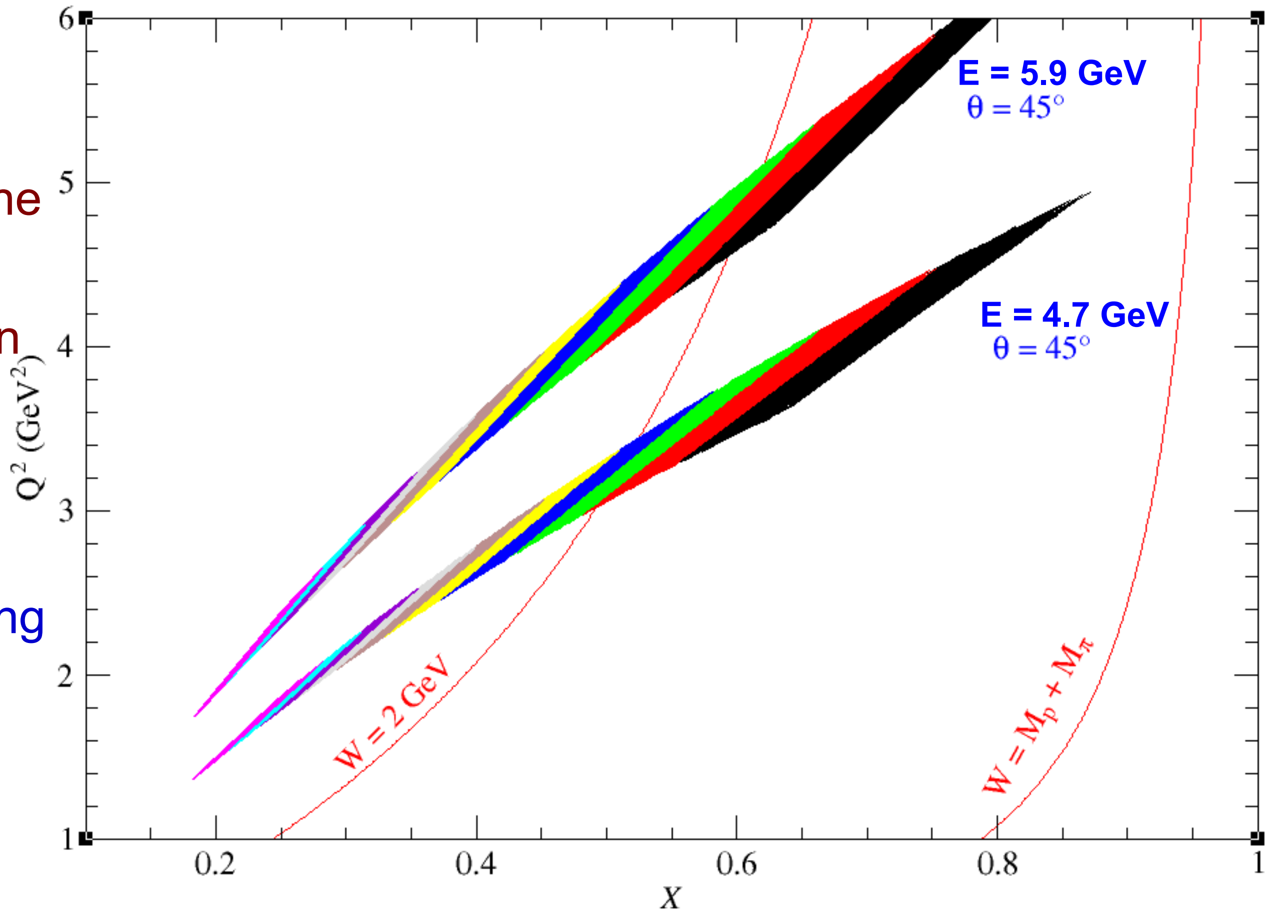




- ~10 atm ₃He cell with trace amounts of K, Rb
- Polarization achieved through optical pumping and 2-step spin exchange
  - » K → Rb
  - » Rb → ³He

Kinematics of the measurement

- Two beam energies 4.75 and 5.9 GeV (4 pass, 5 pass)
  - → provides a handle on the Q^2 dependence of g_2
  - → supports rad. correction calculations
- BigBite fixed at single scattering angle (θ=45°) (data divided into bins during analysis)
- Avoid resonance region as much as possible.



Recent (and revisited) Results

From

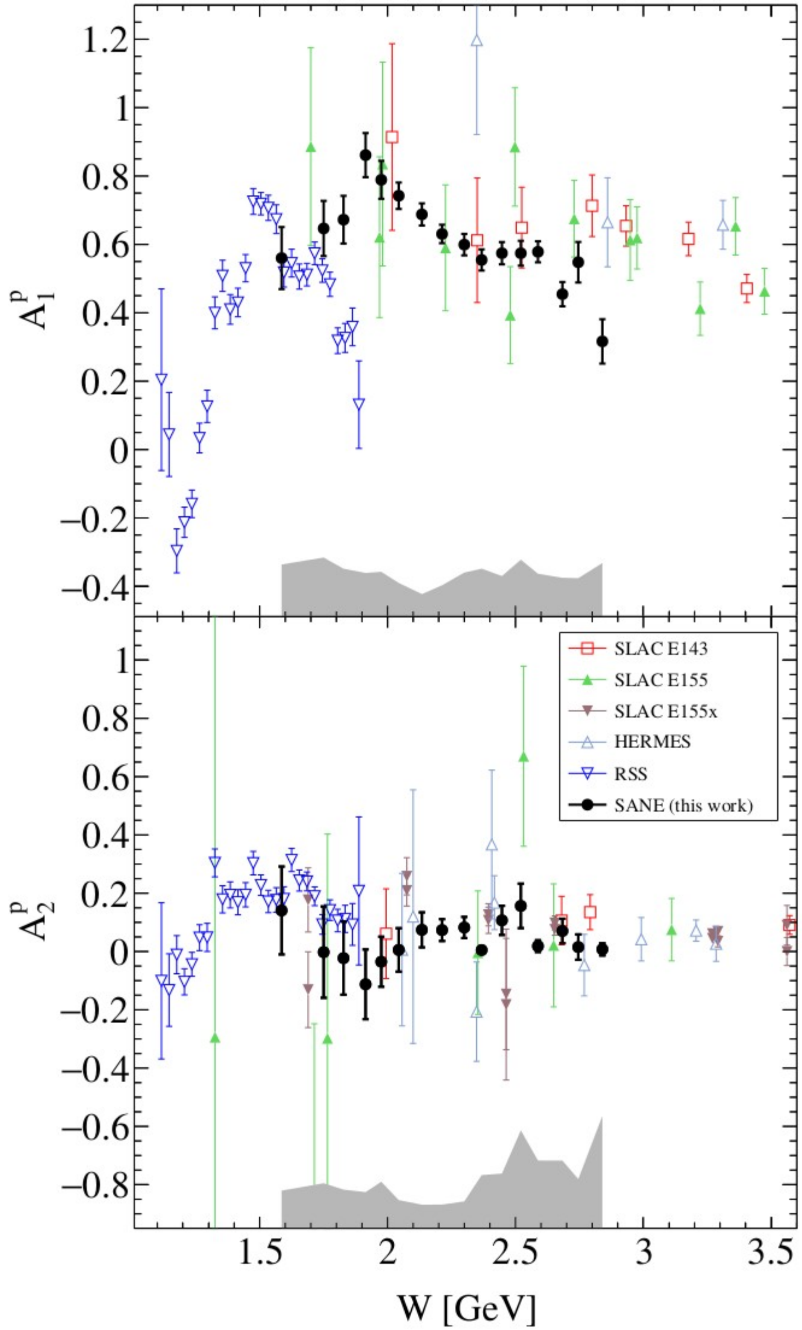
E07-003 and E06-014

("SANE" and "d2n")

A_1, A_2 for the proton (SANE)

Recent → arXiv:1805.08835 [nucl-ex]

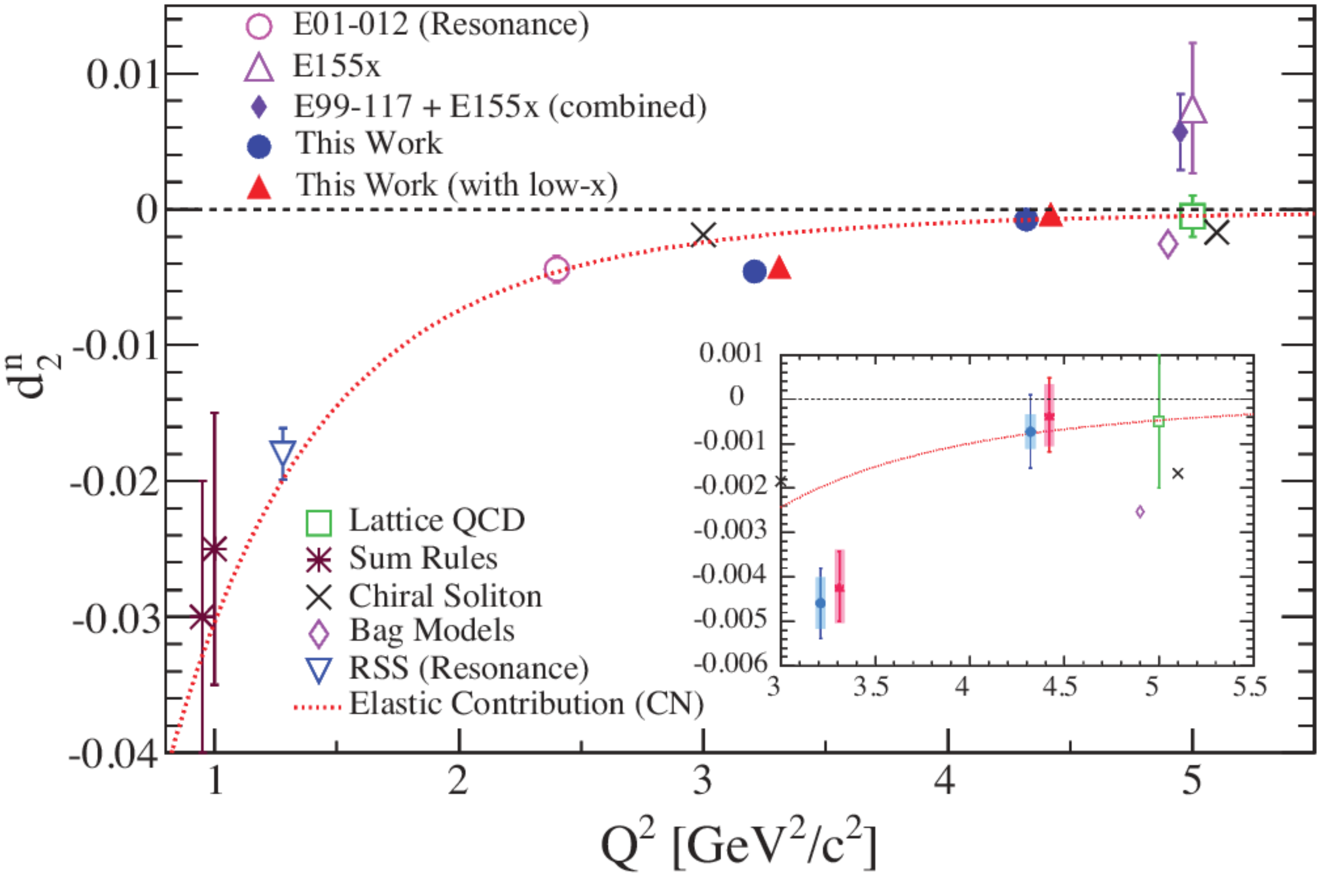
- A1 is roughly linear vs. ln(W)
  - → minimal Q^2 dependence
- A2 is consistent with E143 even though E143 has much greater Q^2
  - → minimal/weak Q^2 dependence for A2?



d_2 for the neutron (E06-014)

$$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = 3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$

*Posik et al., PRL **113** 022002 (2014)*

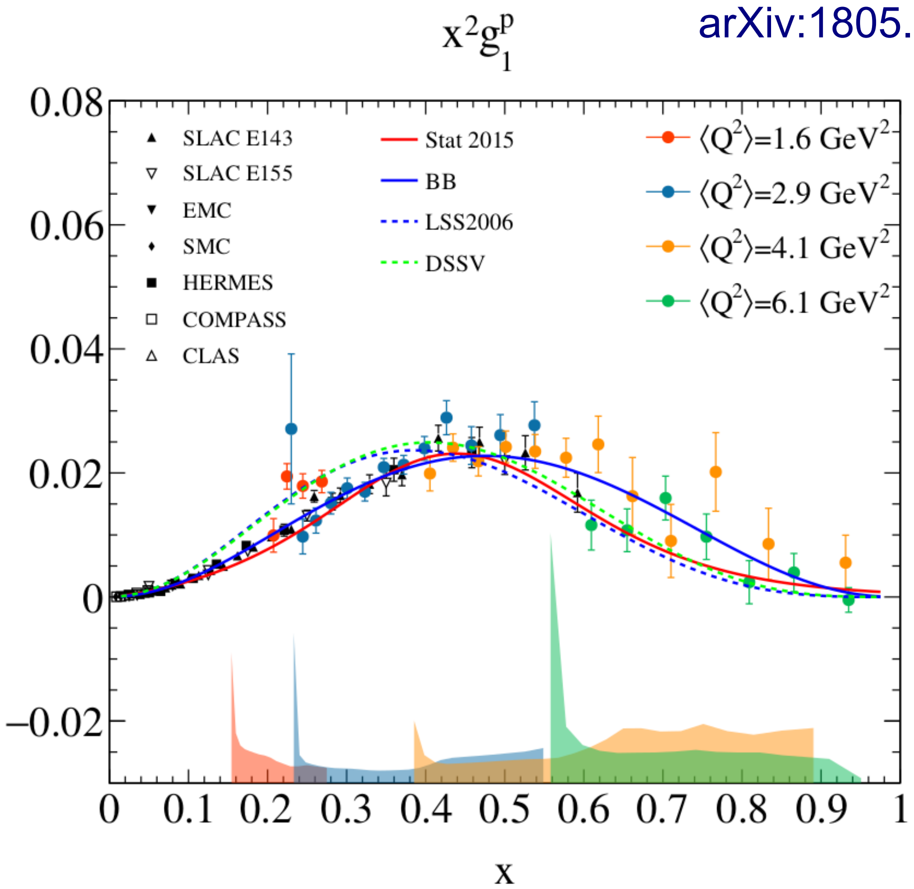


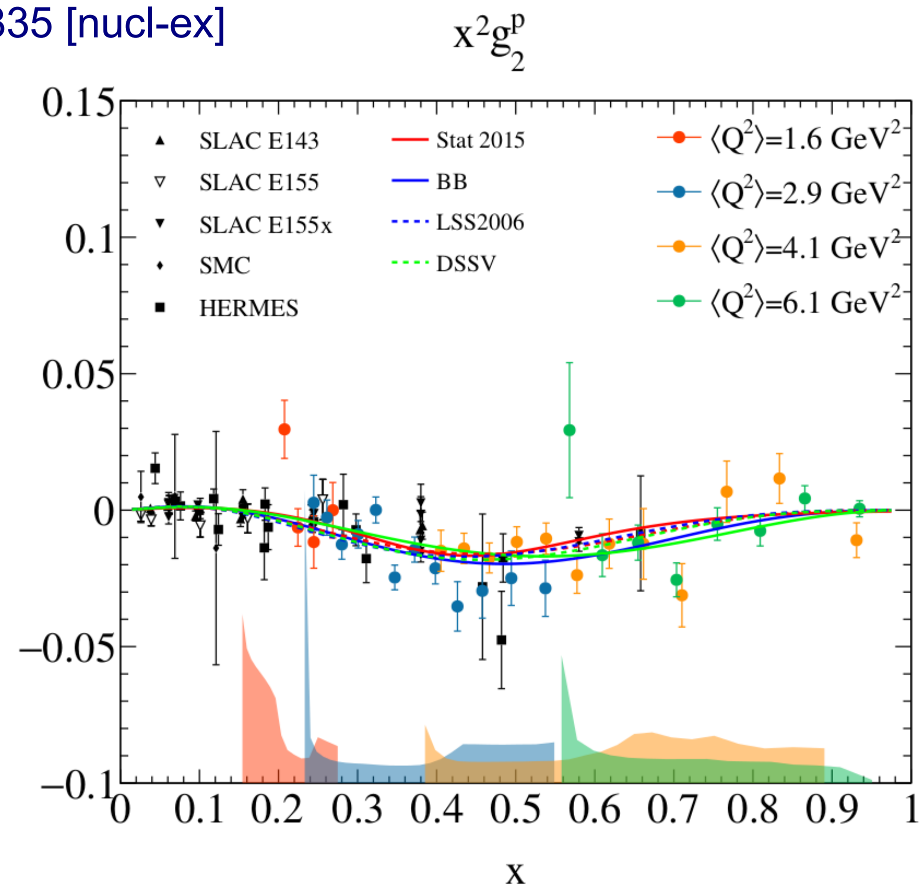
- Our 2014 results are consistent with Lattice QCD prediction
  - → now in tension with SLAC data
- d_2^n extracted at
  - → $\langle Q^2 \rangle \sim 3.3$ GeV^2 (E=4.7 GeV data)
  - → $\langle Q^2 \rangle \sim 4.3$ GeV^2 (E=5.9 GeV data)
- Shaded boxes in inset are systematic uncertainties
- Low-x contribution (0.02 < x < 0.25) is provided by fits to world data (small impact)
- ^{3}He → neutron correction using eff. polarization method applied to d_2
  - → (Bissey et al. Phys Rev C, 65:064137, 2002)

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)

g_1 & g_2 for the proton (SANE)

arXiv:1805.08835 [nucl-ex]





- Significant improvement to the world data for both g_1 and g_2 in the high-x region

  → Caveat: highest-x data are in the resonance

d_2 for the proton (SANE)

- Good agreement with prior proton d_2 data at higher Q^2
- Hint of a negative d_2^p, negative twist-3 at moderate $Q^2 \sim 3$ GeV^2?

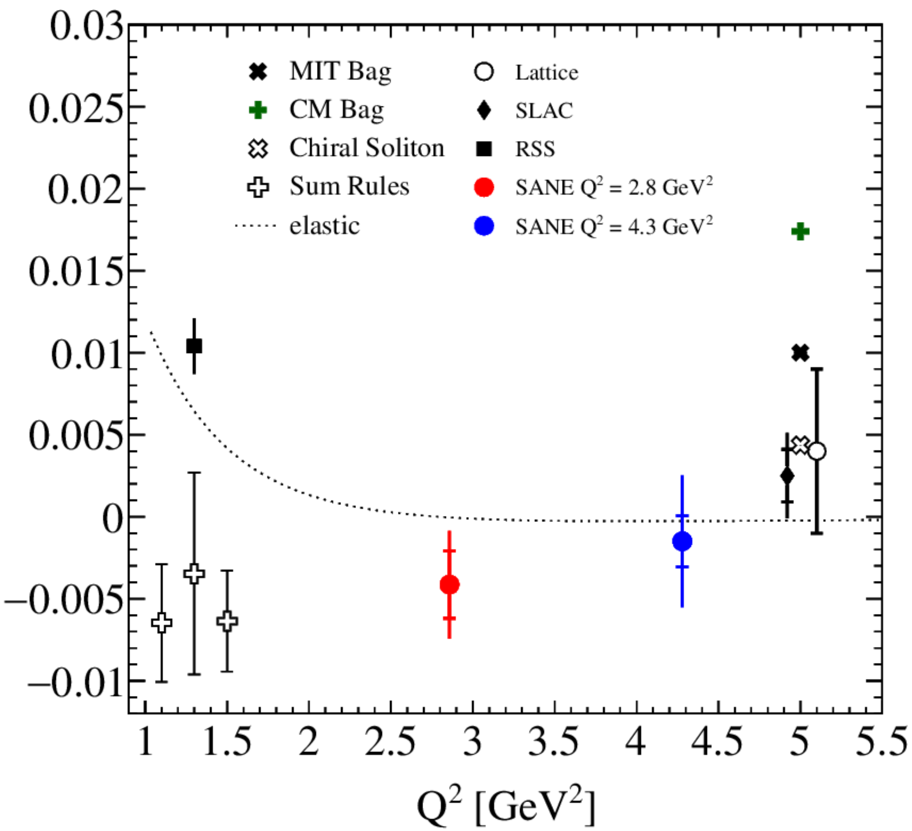
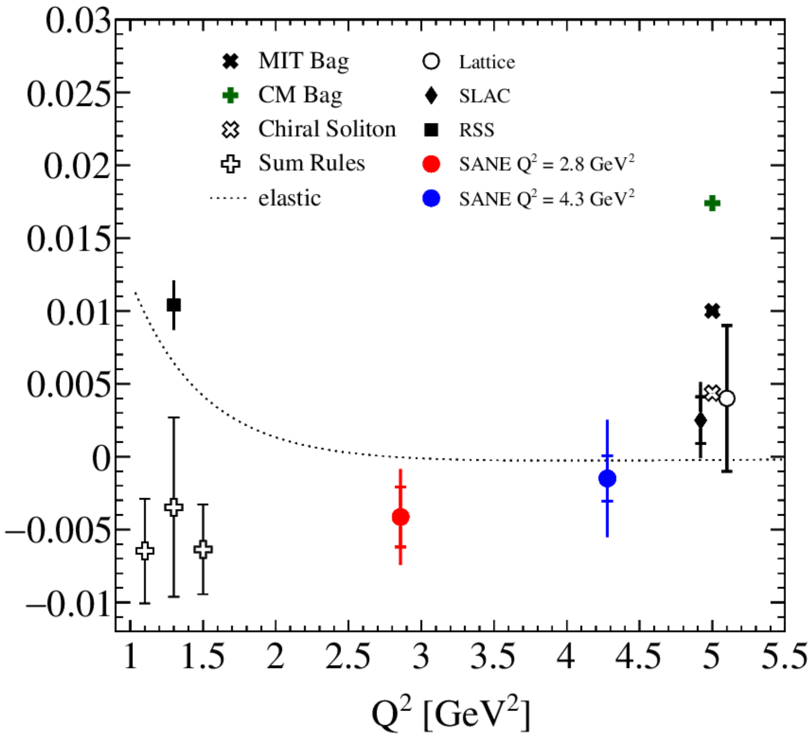


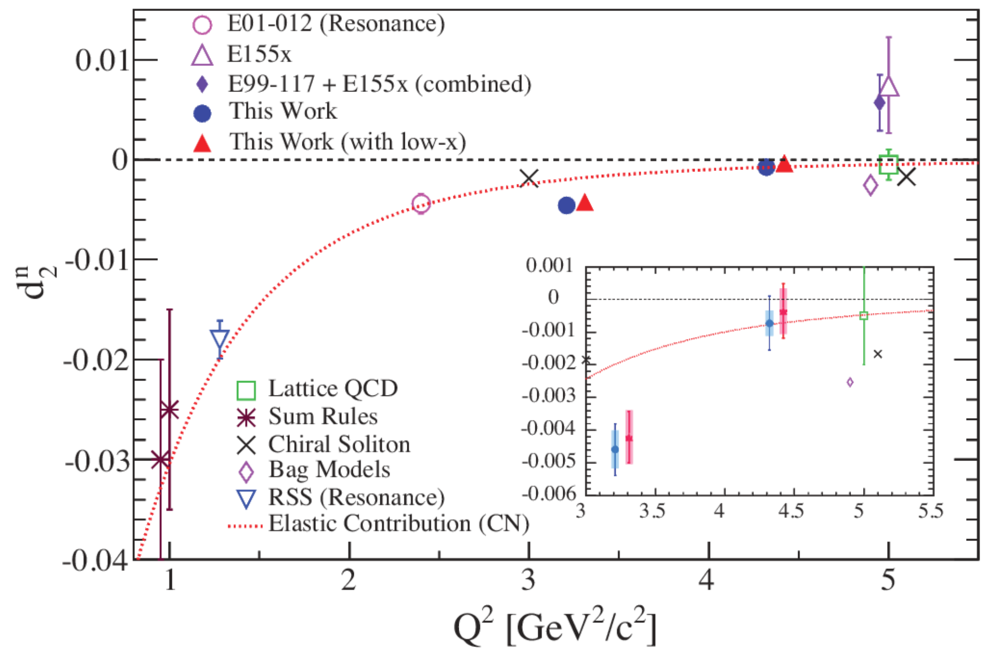
FIG. 2. The SANE results (filled circles) for $2M_2^3 \simeq \tilde{d}_2^p$. The lattice result (open circle) [14] and previous measurements from SLAC [23] and RSS [25, 32] are shown with the dotted line corresponding to the elastic contribution. Model calculations from sum rules [33, 34], the CM bag model [34, 35], and the chiral soliton model [36] are also shown.

arXiv:1805.08835 [nucl-ex]

d_2 for the proton and neutron



arXiv:1805.08835 [nucl-ex]



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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

Near-term SFF measurements in Hall C!

Upcoming Pol ^{3}He Experiments in Hall C

- Hall C
  - → A1n (E12-06-110)
  - → d2n, g2n (E12-06-121)
- Both make use of
  - → 11 GeV beam
  - → SHMS (+ HMS) spectrometers
  - → Upgraded 3He target
- JLab Experimental Readiness Review (ERR) held March '18
  - →Major item: 3He target
    - » No 'show-stoppers'
- *On the schedule to start running in Fall 2019!*
  - →Preliminary results 2020–21?

More details at ERR page

Both A_1^n and d_2^n Experiments Share the Same Layout in Hall C

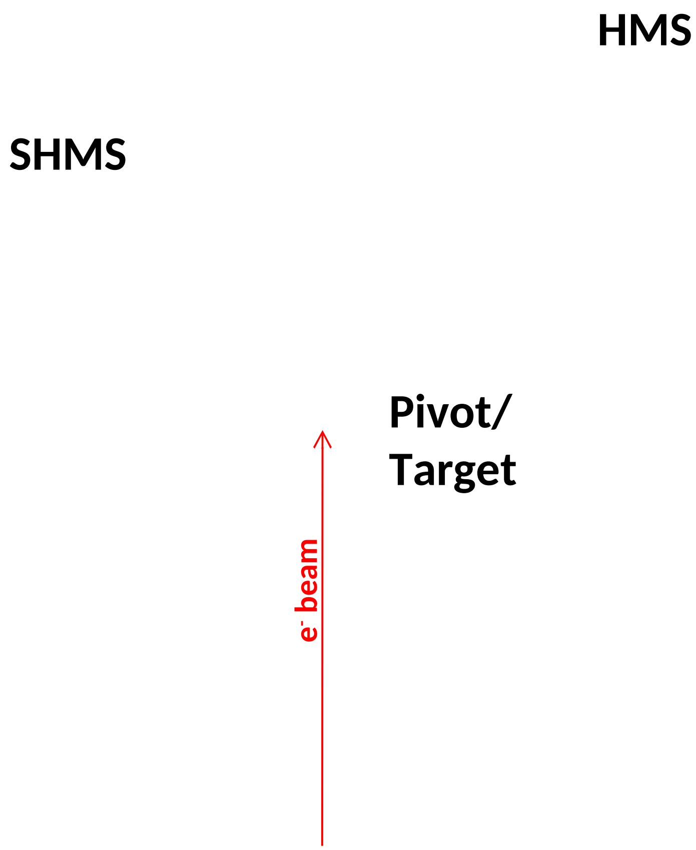
Super-High-Momentum Spectrometer (SHMS)

Retain Key Features of HMS:

- Pivot
- Rail System
- Point-Point Optics Design
- "Flat" Acceptances
- Shield House
- Redundancy in Detectors

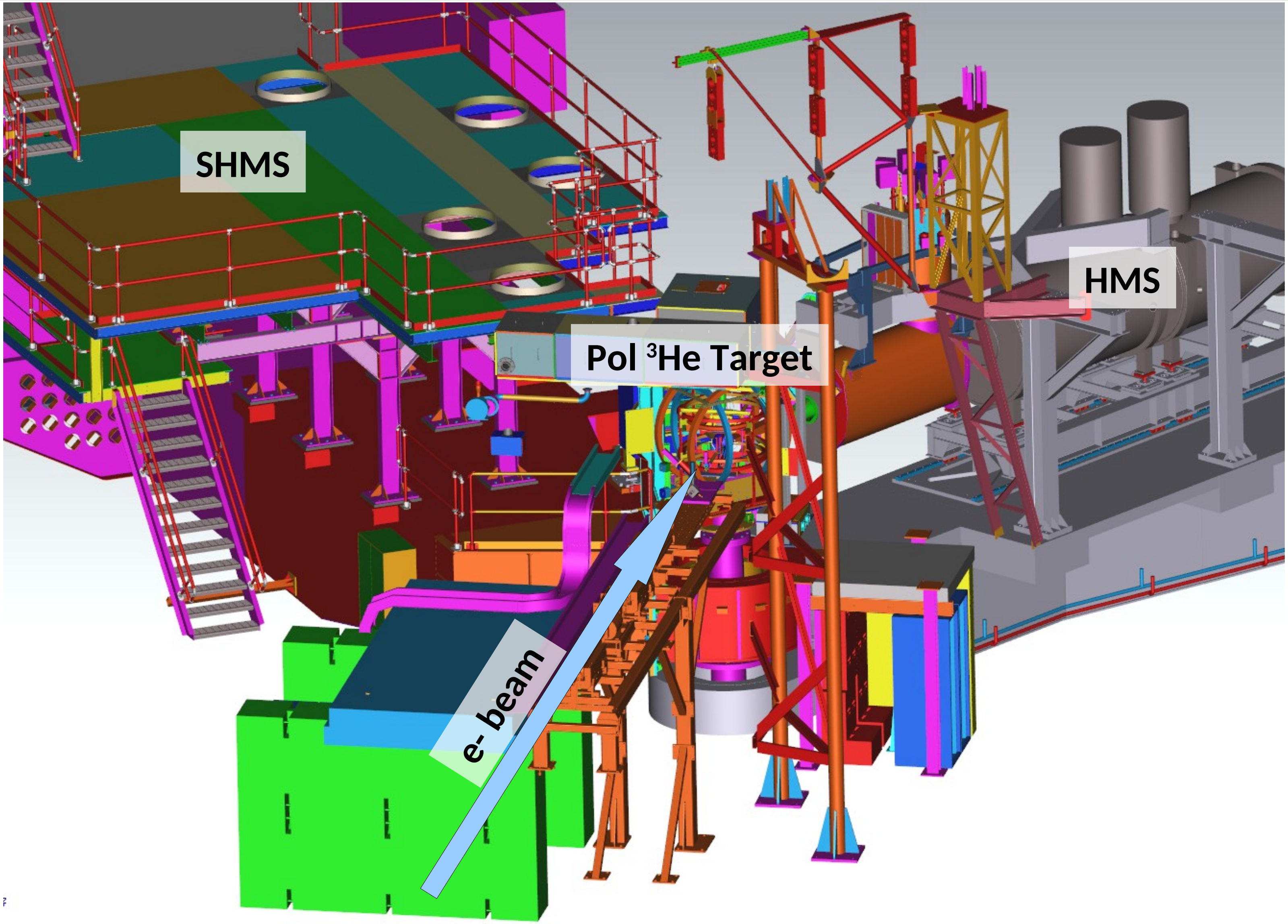
Incorporate them in the SHMS to Provide:

- Pair of magnetic spectrometers
- Full momentum capability
- Large acceptance
- Angle accuracy and reproducibility
- Small angle capability
- Very good particle identification
- Compatibility with all target configurations

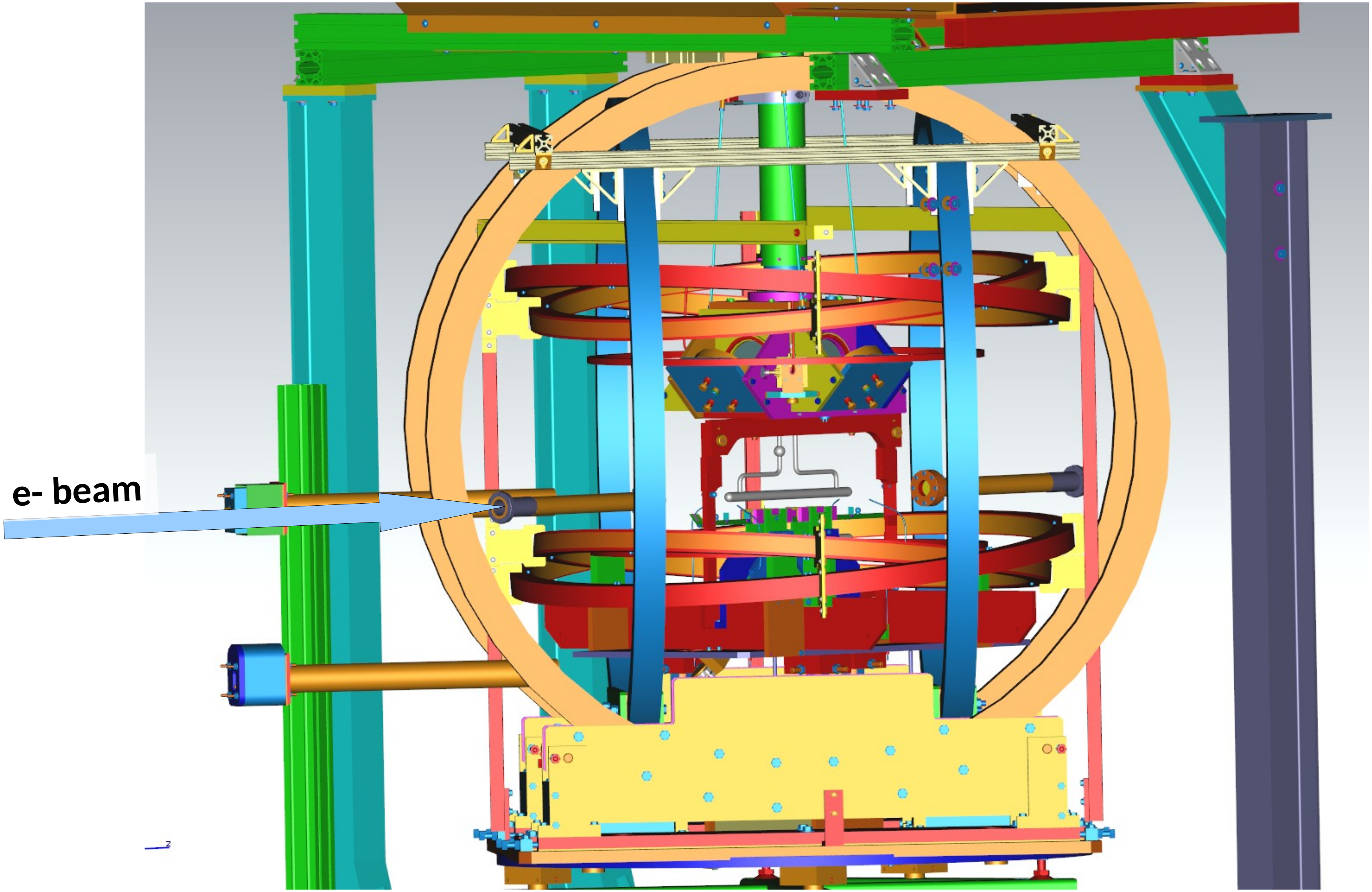


Slide from H. Fenker

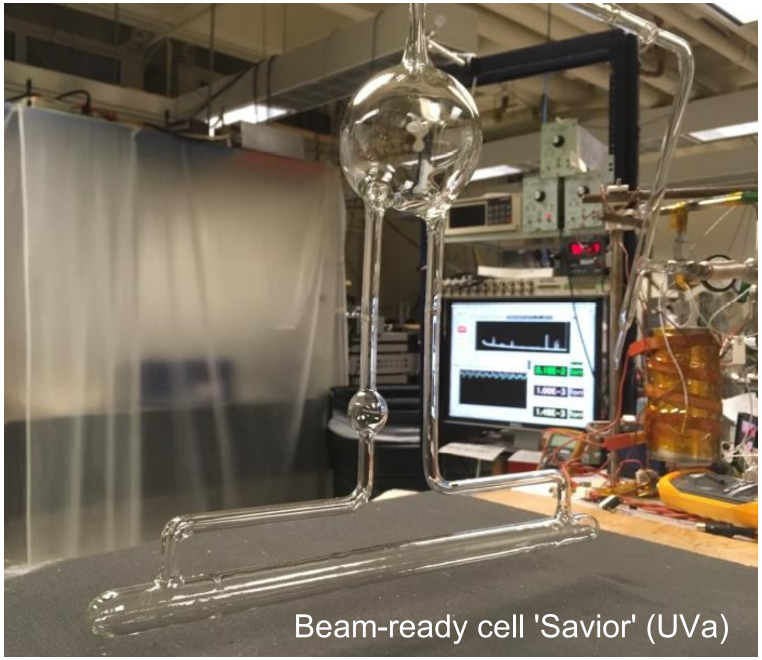
Polarized 3He Run Group in Hall C

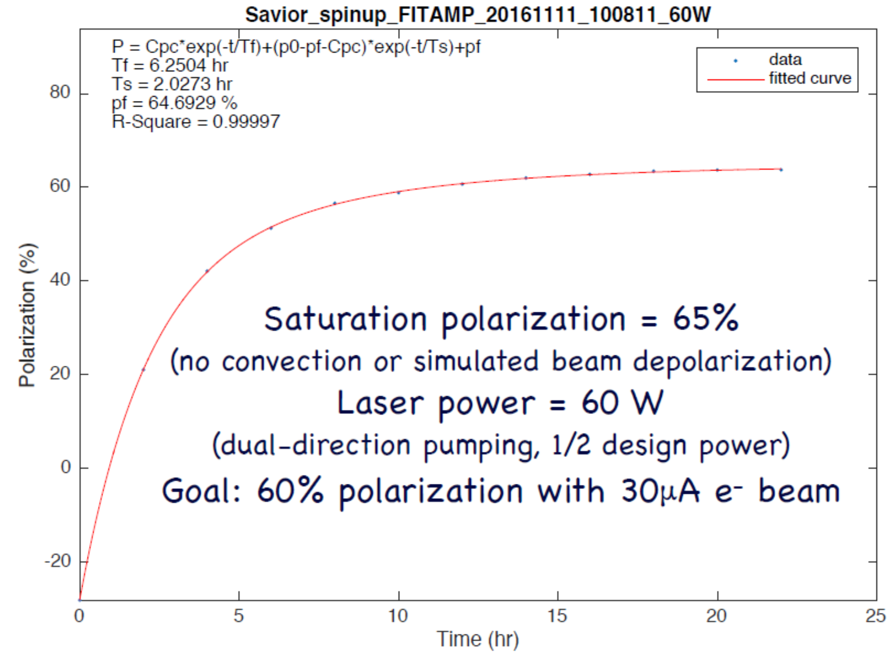


Polarized ^{3}He Target



^{3}He Target Upgrade

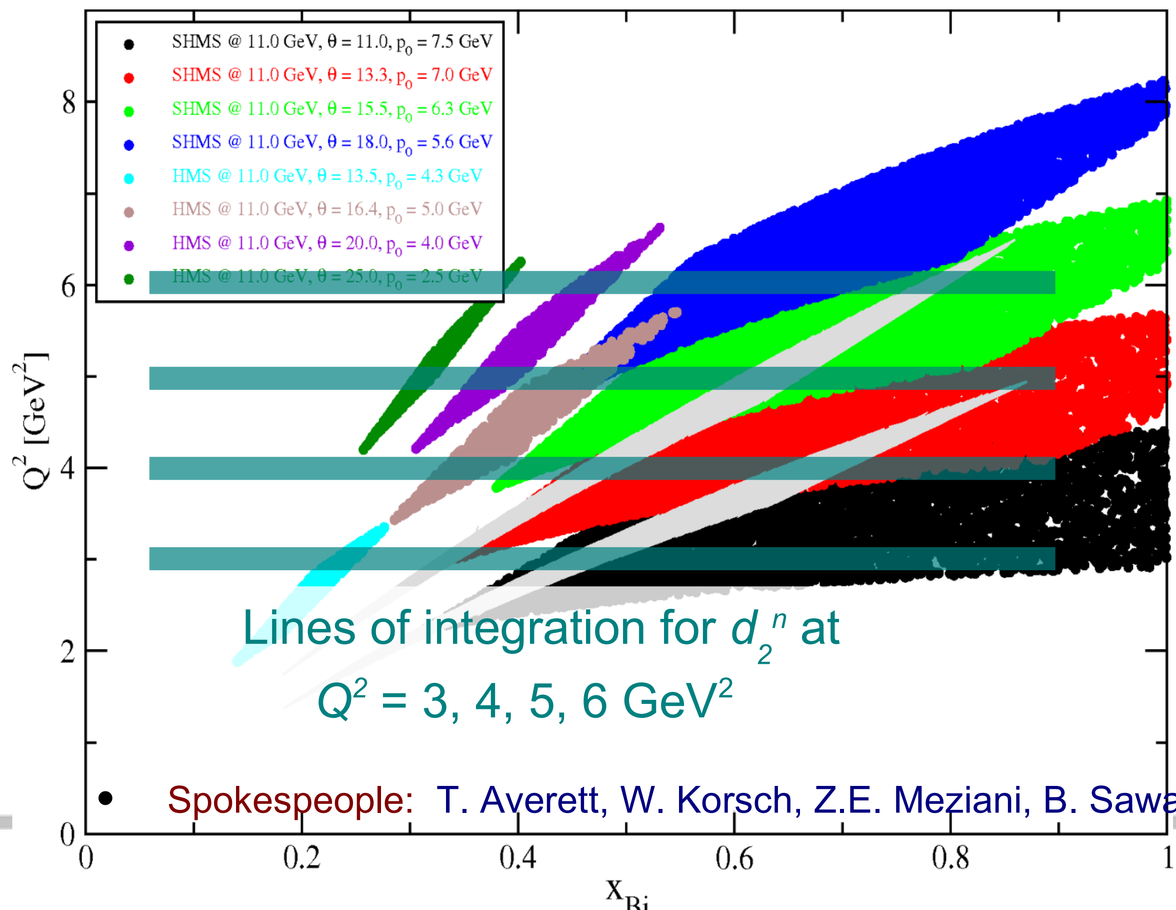

Beam-ready cell 'Savior' (UVa)



- Polarized ^{3}He target group has developed a new ^{3}He target design
  - → Upgrade from 2008 cell that induces a thermally-driven convection flow between the polarization cell and the target volume
  - → 40cm long target cells of this type to be used in 2019 Hall C $d_2^n + A_1^n$ run group
  - → *Goal* for this intermediate design is to reach 60% polarization @ 30 μA beam
- Longer term goal is to extend this design to support currents as high as 60 μA

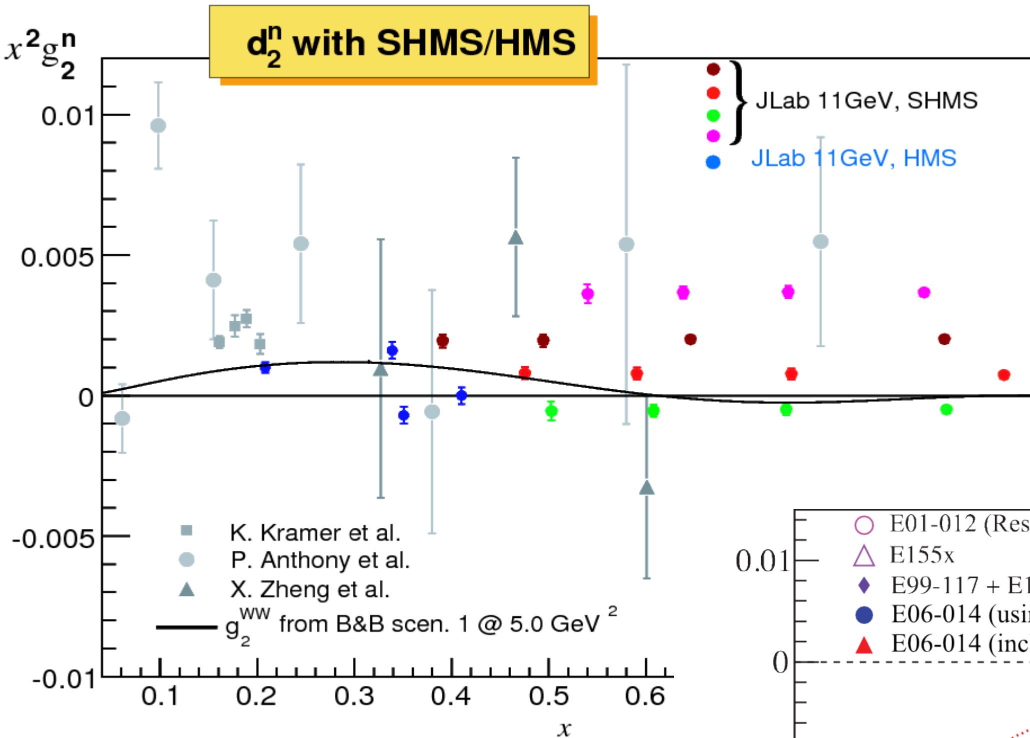
E12-06-121: d_2^n, g_2^n

- Directly measure the Q^2 dependence of the neutron $d_2^n(Q^2)$ at $Q^2 \approx 3, 4, 5, 6$ GeV^2 with the new polarized ^{3}He target.
  - The new Hall C SHMS is ideally suited to this task!
- Doubles number of precision data points for $g_2^n(x, Q^2)$ in DIS region.
  - Q^2 evolution of g_2^n over $(0.23 < x < 0.85)$



- Spokespeople: T. Averett, W. Korsch, Z.E. Meziani, B. Sawatzky

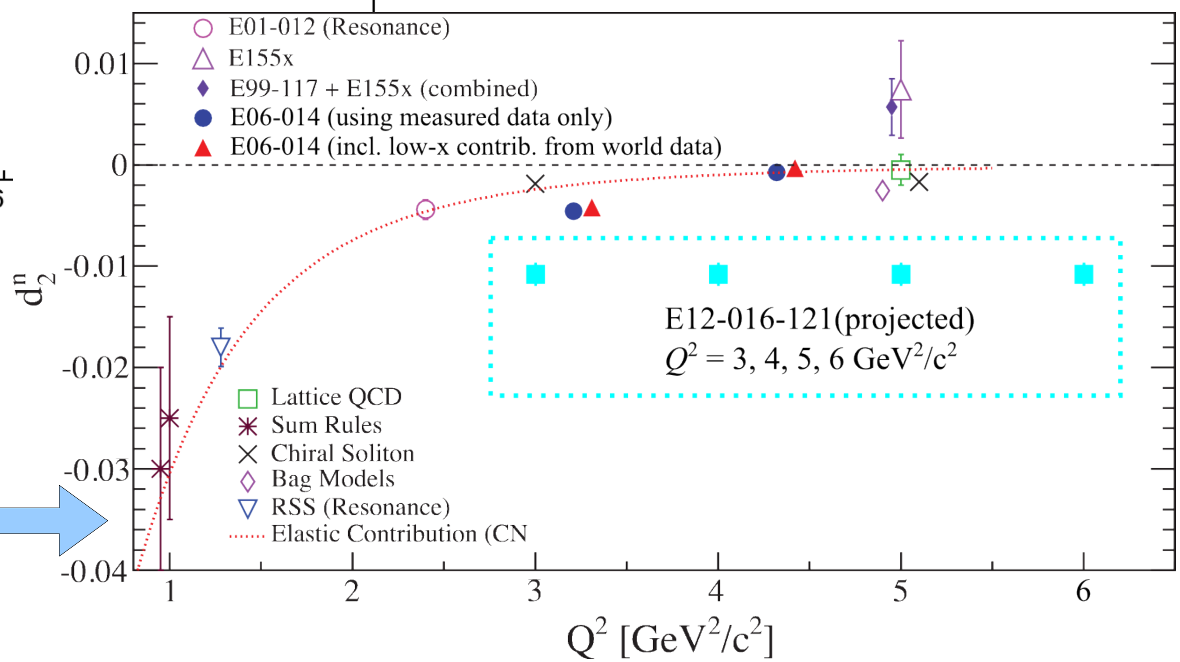
Projected results for E12-06-121



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.

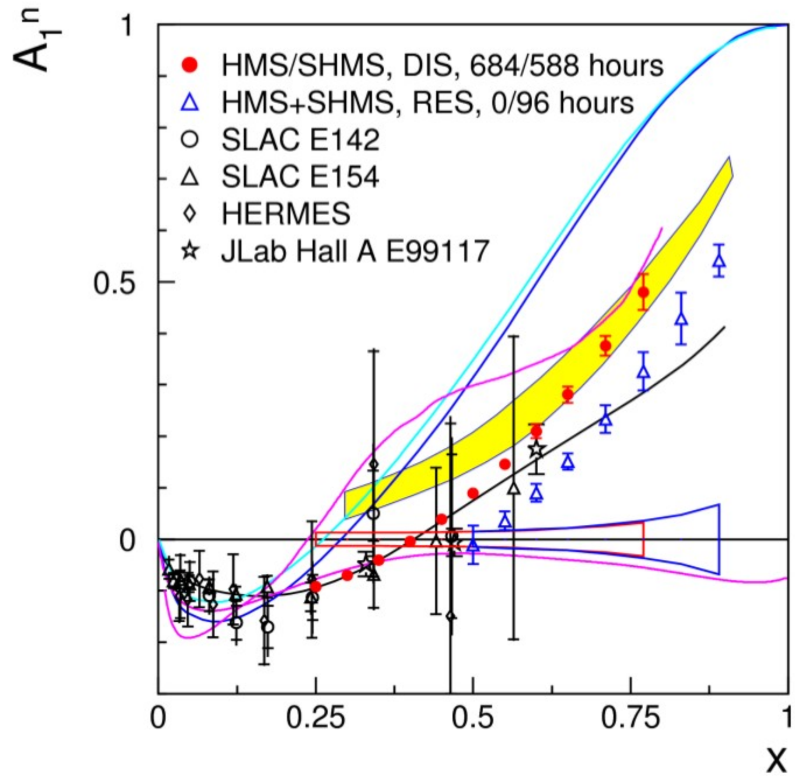
Direct overlap with 6 GeV Hall A measurements.

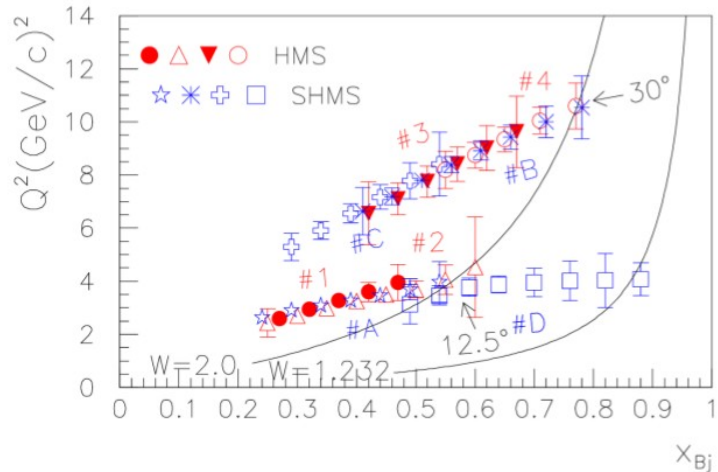


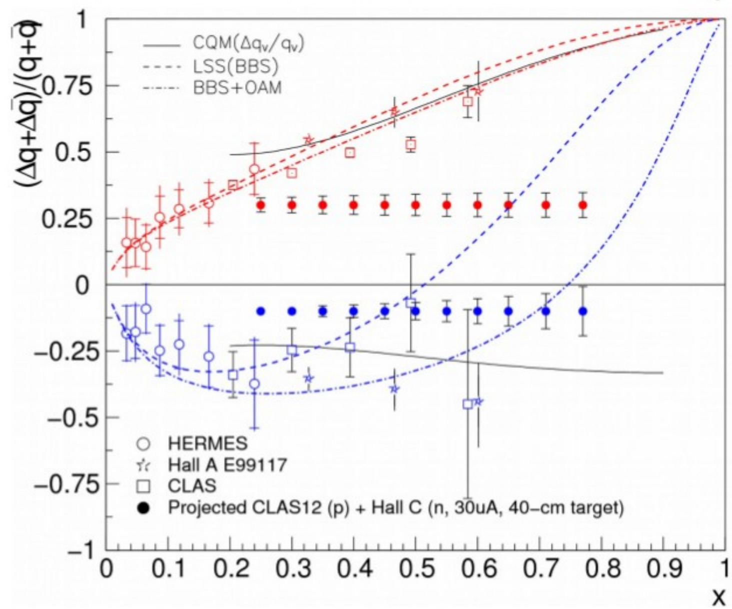
E12-06-110 A1n in Hall C

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

Summary

- **SANE (E07-003) Proton**
  - → A_1^p, A_2^p in good agreement with world data
    - » First hint of roll-over in A_1^p vs *x?*
    - » A_2 from SANE consistent with E143 hinting at weak Q^2 dependence?
  - → g_1 and g_2 in good agreement with parameterizations based on world data
  - → Significant increase in precision data in high-x and DIS regions!
  - → data hint at a negative d_2^p around 3 GeV^2?

- **"d2n" (E06-014) Neutron**
  - → A_1^n in good agreement with world data
  - → g_1 and g_2 in agreement with world data for both He3 and neutron extraction
  - → Significant increase in precision data in high-x and DIS regions!
  - → d_2-neutron data
    - » now consistent with Lattice result
      - – but in tension with older E155x
    - » hint at negative d_2^n at same Q^2 as d_2^p?

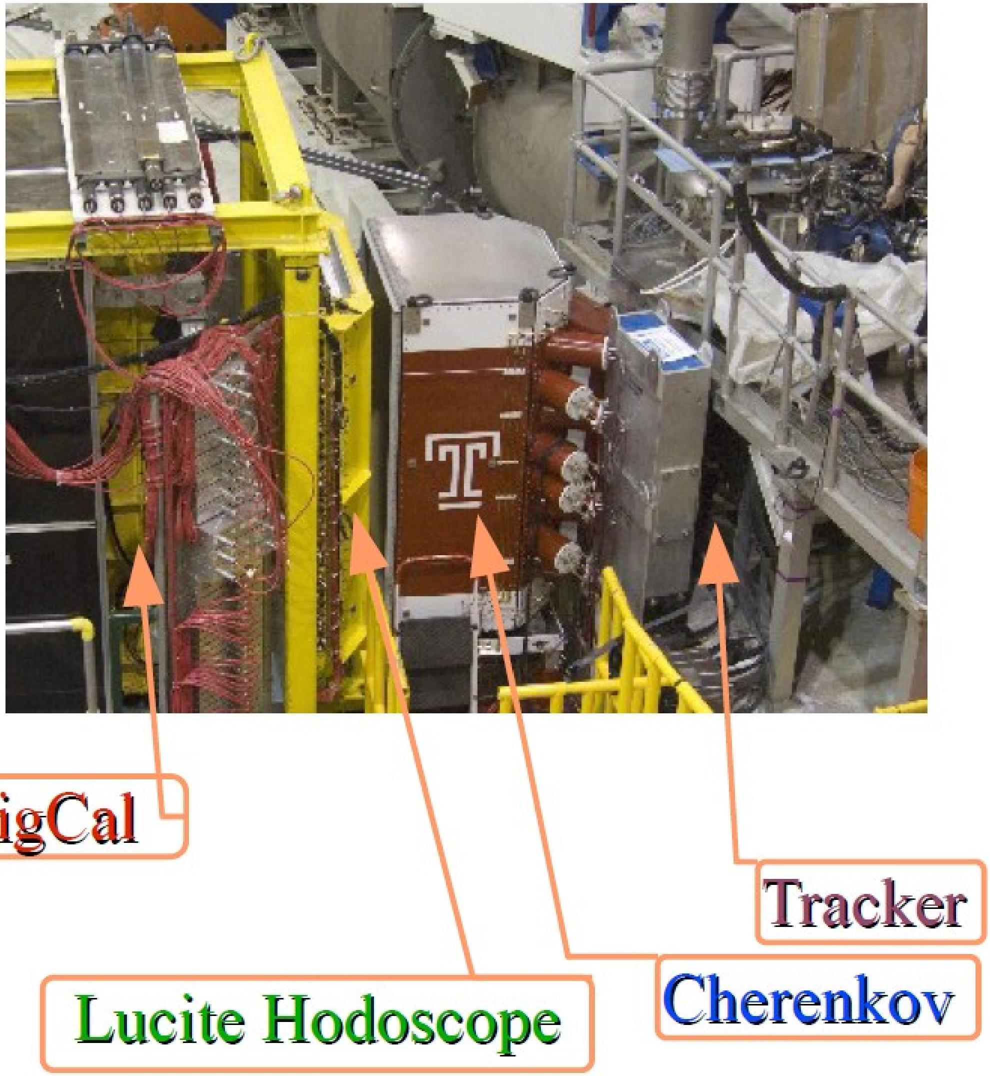
- **12 GeV Hall C A_1^n and d_2^n, g_2^n measurements scheduled to run ~2019**
  - → Focus on high-x and Q^2 evolution of these quantities
    - » Large new precision data set in previously unmeasured domain
  - → Finally rule out DSE or pQCD A_1^n models?
  - → First evaluations of d_2^n at truly fixed Q^2 values
    - » *Updates LQCD results long overdue! Now is the time!*
- **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**

Coming Soon!

BACKUP

Big Electron Telescope Array • BETA

- BigCal lead glass calorimeter: main detector used in *GEp-III*.
- Tracking **Lucite hodoscope**
- **Gas Cherenkov:** pion rejection
- Tracking fiber-on-scintillator **forward hodoscope**
- BETA specs
  - Effective solid angle = 0.194 sr
  - Energy resolution $9\%/\sqrt{E(\mathrm{GeV})}$
  - 1000:1 pion rejection
  - angular resolution ~ 1 mr
- Target field sweeps low *E* background
  - 180 MeV/c cutoff



E06-014 – d2n

- A 4.75 and 5.9 GeV polarized electron beam scattering off a polarized ^{3}He target
- Measure unpolarized cross section for $^3\vec{\mathrm{He}}(\vec{e}, e')$ reaction $\sigma_0^{^3\mathrm{He}}$ in conjunction with the parallel asymmetry $A_\perp^{^3\mathrm{He}}$ and the transverse asymmetry $A_\parallel^{^3\mathrm{He}}$ for 0.23 < x < 0.65 with 2 < Q^2 < 5 GeV^2.
  - → Asymmetries measured by BigBite
  - → Absolute cross sections measured by L-HRS
- Determine d_2^n using the relation

$$\begin{aligned}\tilde{d}_2(x,Q^2) &= x^2[2g_1(x,Q^2)+3g_2(x,Q^2)] \\ &= \frac{MQ^2}{4\alpha^2}\frac{x^2y^2}{(1-y)(2-y)}\sigma_0\left[\left(3\frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}+\frac{4}{y}\tan\frac{\theta}{2}\right)A_\perp+\left(\frac{4}{y}-3\right)A_\parallel\right]\end{aligned}$$

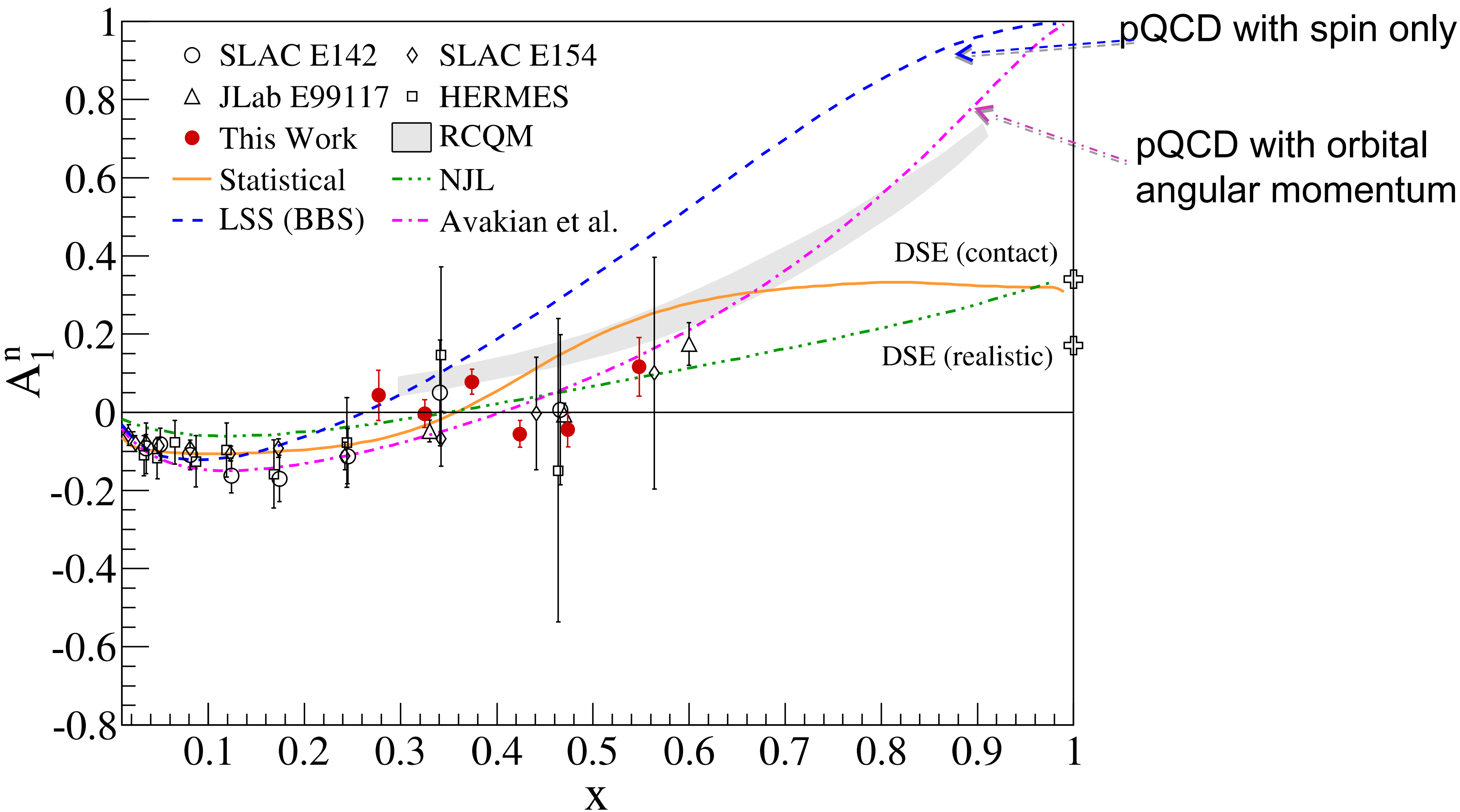
where,

$$A_\perp = \frac{\sigma^{\downarrow\Rightarrow}-\sigma^{\uparrow\Rightarrow}}{2\sigma_0} \qquad A_\parallel = \frac{\sigma^{\downarrow\Uparrow}-\sigma^{\uparrow\Uparrow}}{2\sigma_0}$$

$$A_\perp^{^3He} = \frac{\Delta_\perp}{P_bP_t\cos\phi} \qquad A_\parallel^{^3He} = \frac{\Delta_\parallel}{P_bP_t}$$

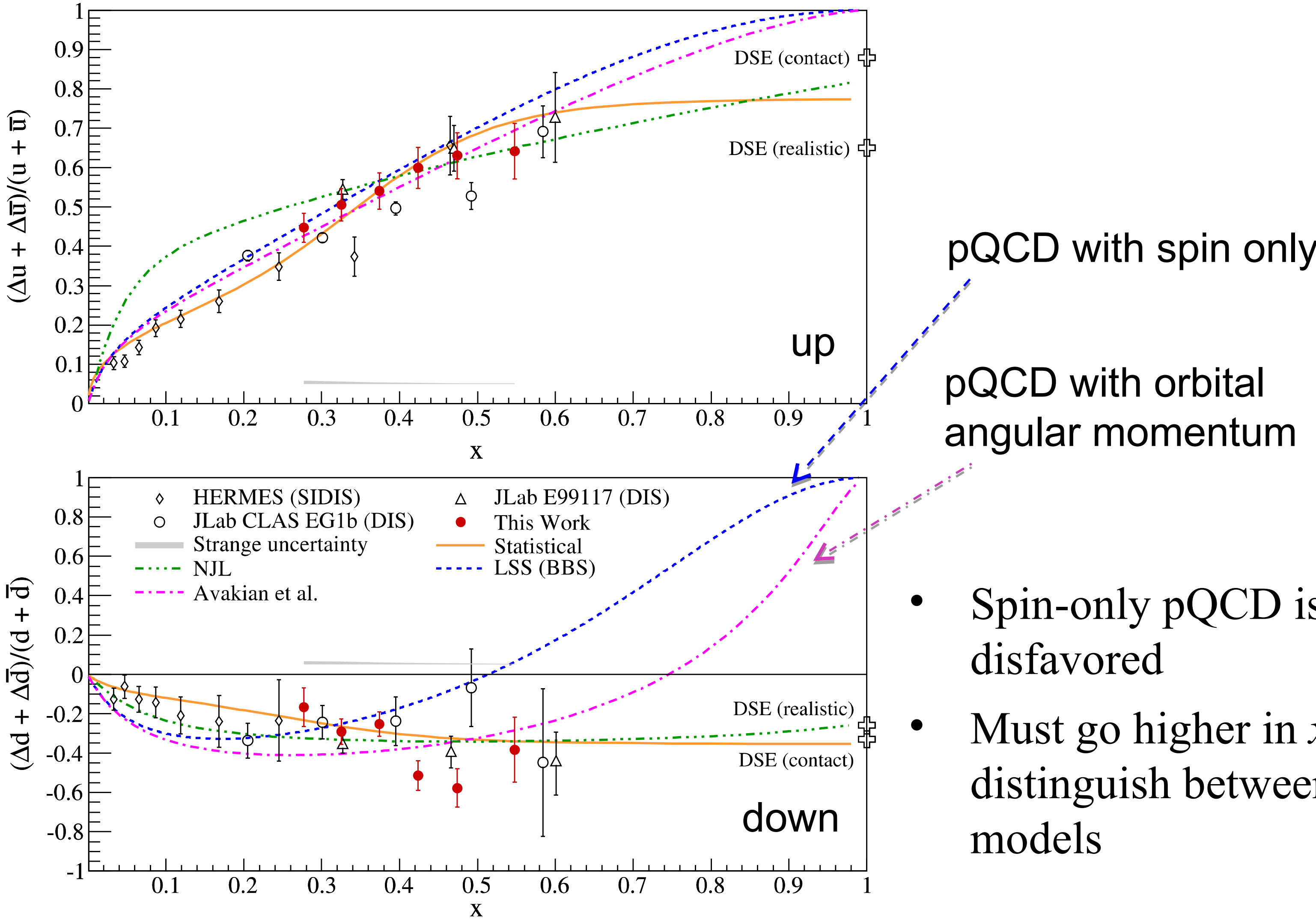
$$\Delta_\perp = \frac{(N^{\uparrow\Rightarrow}-N^{\uparrow\Rightarrow})}{(N^{\uparrow\Rightarrow}+N^{\uparrow\Rightarrow})} \qquad \Delta_\parallel = \frac{(N^{\downarrow\Uparrow}-N^{\uparrow\Uparrow})}{(N^{\downarrow\Uparrow}+N^{\uparrow\Uparrow})}$$

A_1 for Neutron



Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067

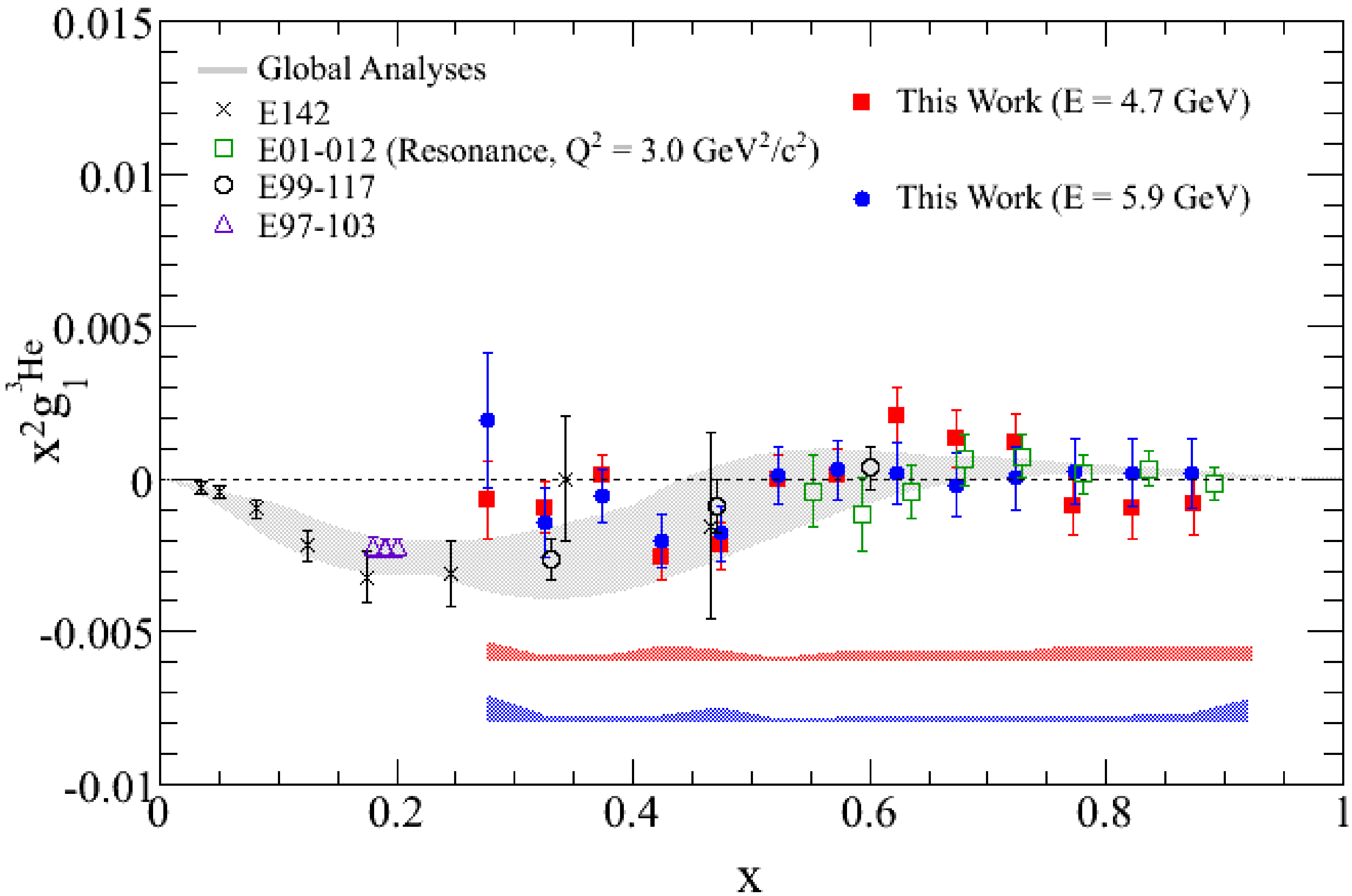
$(\Delta u+\Delta\bar{u})/(u+\bar{u})$ and $(\Delta d+\Delta\bar{d})/(d+\bar{d})$



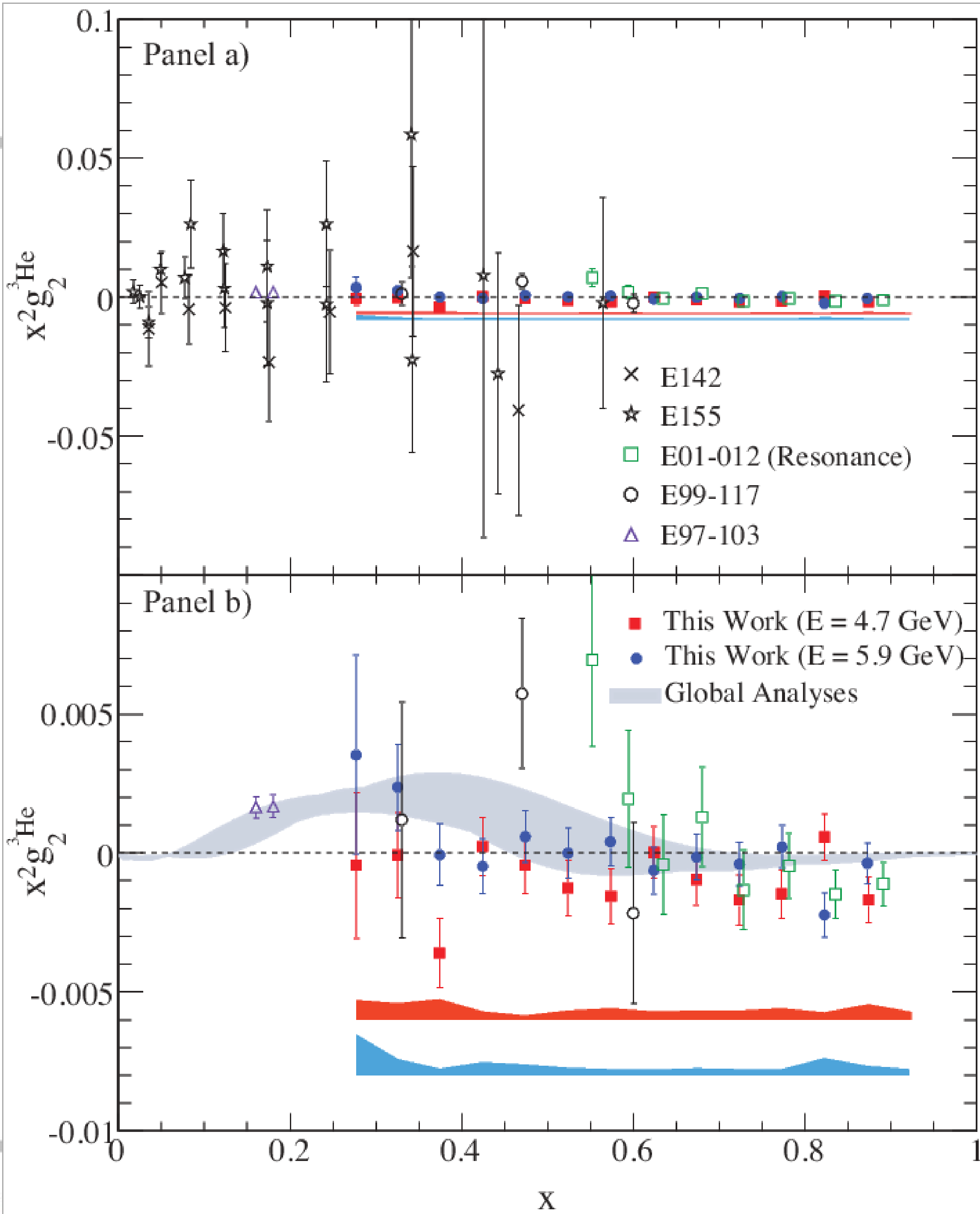
- Spin-only pQCD is strongly disfavored
- Must go higher in x to distinguish between other models

Parno et al., Phy Let B DOI: 10.1016/j.physletb.2015.03.067

x^2g_1 for ^3He



Global Analyses
E142
E01-012 (Resonance, Q² = 3.0 GeV²/c²)
E99-117
E97-103
This Work (E = 4.7 GeV)
This Work (E = 5.9 GeV)
x²g₁³He
x
0.015
0.01
0.005
0
-0.005
-0.01
0
0.2
0.4
0.6
0.8
1



$x^2 g_2$ for ^{3}He

- Panel (a) shows comparison to world data
- Panel (b) is zoomed on y-axis to show error bars

Posik et al., PRL ***113*** *022002 (2014)*

Upgraded Hall C: SHMS + HMS

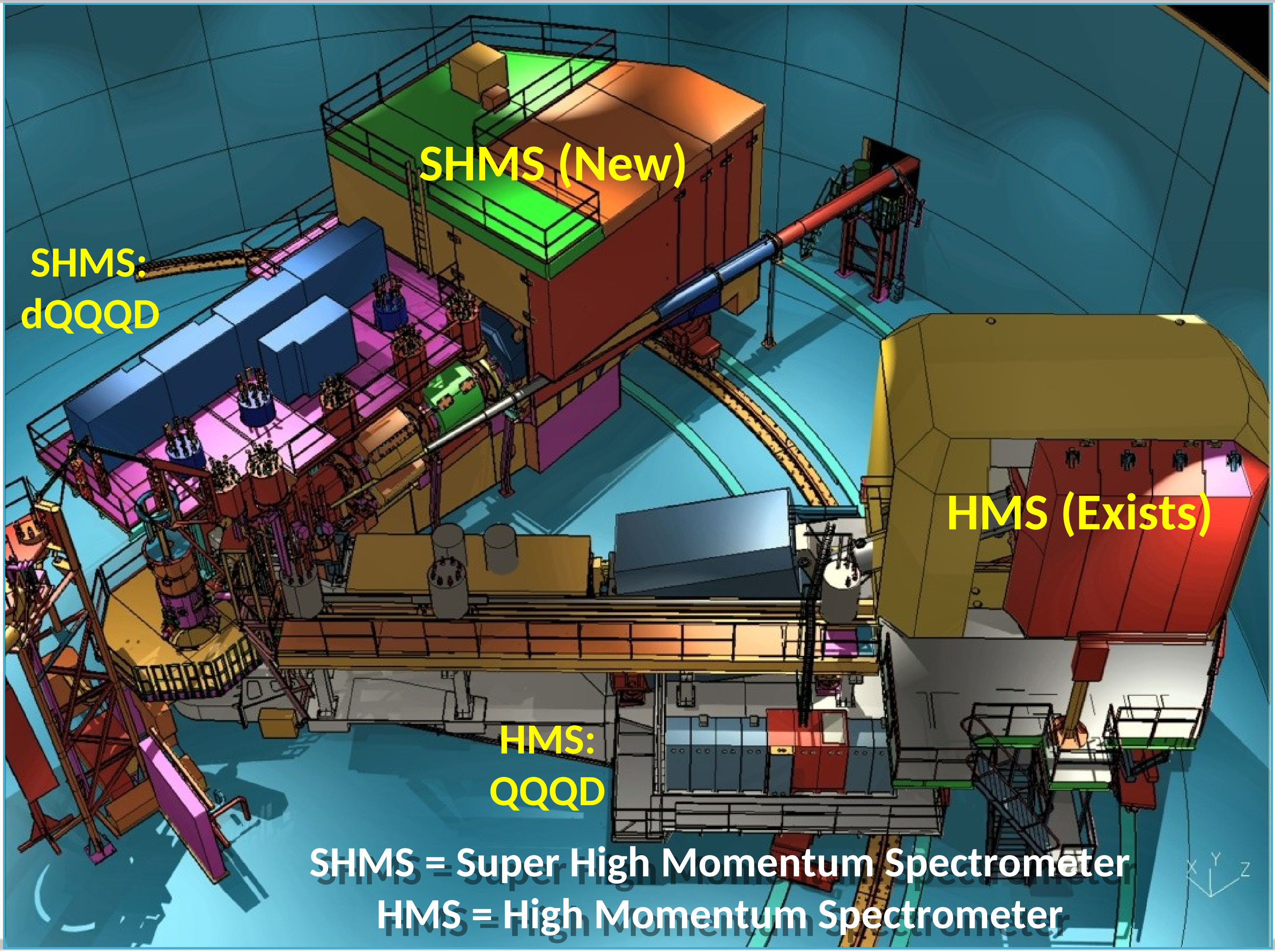
SHMS:
- 11-GeV Spectrometer
- Partner of existing 6–GeV **HMS**

MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS



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

- <u>Hall C: SHMS + HMS</u>
- Two beam energies:
  - → 11 GeV/c (production)
  - → 2.2 GeV/c (calib.)
- Beam Current
  - → 30 uA (production)
  - → 60 uA (max, calib.)
- Target: 40 cm Polarized ^{3}He
- Each arm measures an <u>absolute polarized cross section</u> independent of the other arm (g_1, g_2)

  → $d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,$
- 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

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°