A1n and d2n Experiments Overview

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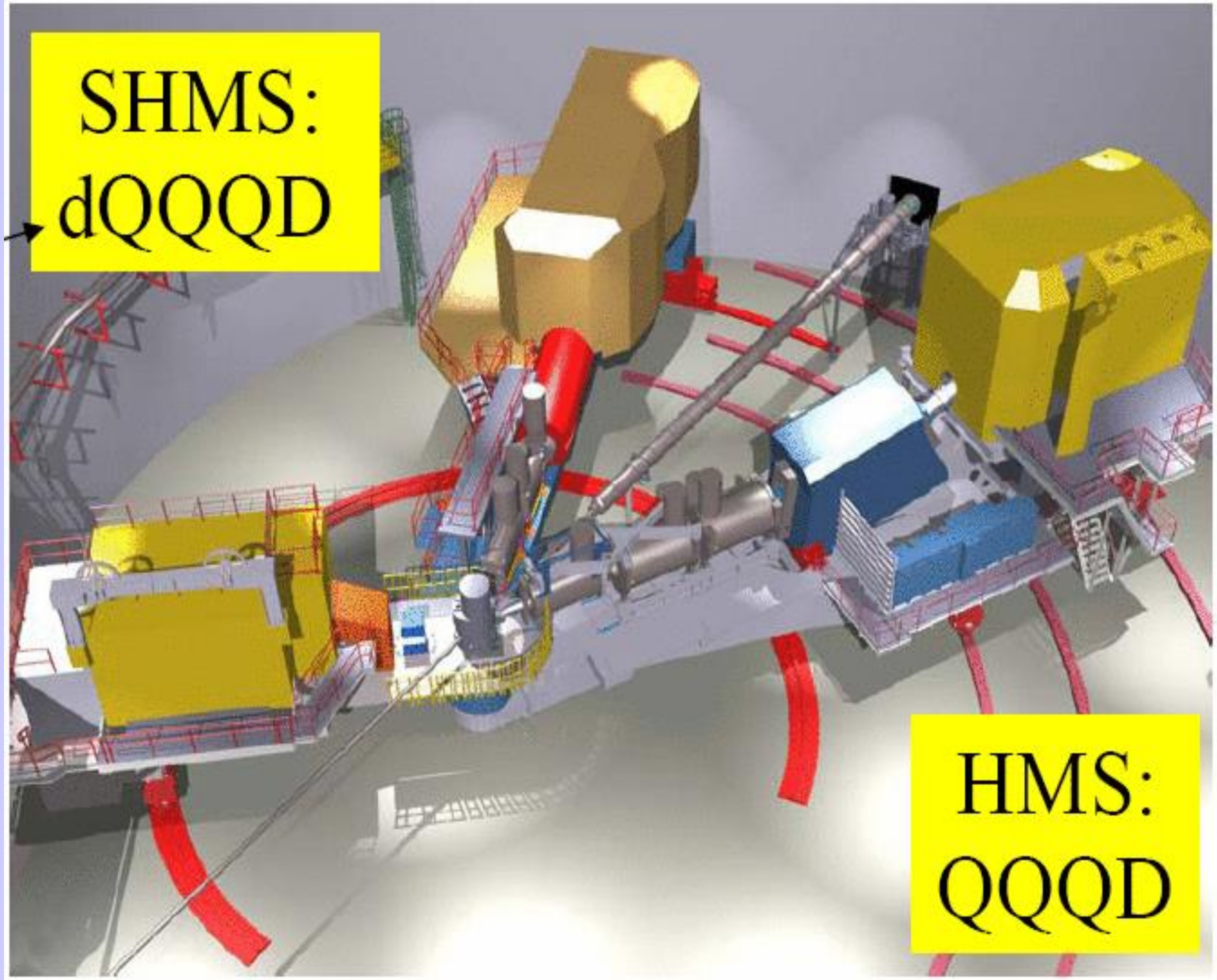
for the
E12-06-110 and E12-06-121 Collaborations

Outline

- Experiment Setup
- A1n Experiment (E12-06-110)
  - Physics Motivation
  - Kinematics
  - Projection
- d2n Experiment (E12-06-121)
  - Physics Motivation
  - Kinematics
  - Projection
- Current Status
- Summary and outlook

Experiment Setup



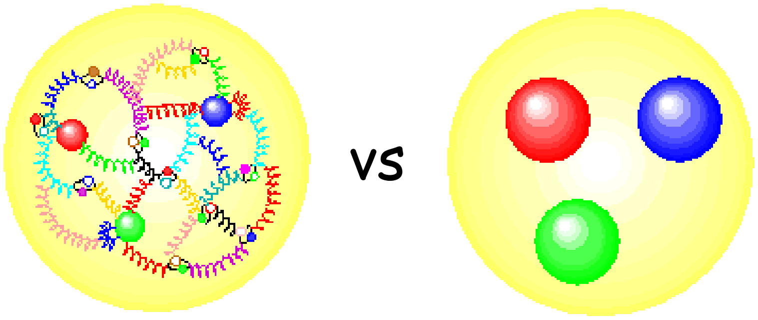
Hall C

- Beam:
  11 GeV,
  30 microA,
  85% polarization
- Polarized ^{3}He target:
  40cm long
  12 amg
  55-60% polarization
- Luminosity(n):
  ~2.2x10^{36}/cm^2/s.
- Beam time:
  36 days (A1n) +
  29 days (d2n)

A1n was A rated by PAC. It is one of the High Impact Experiments.
Prepare to run in Fall 2019 and continue into Spring 2020

A_1^n as Part of the Nucleon Structure Study

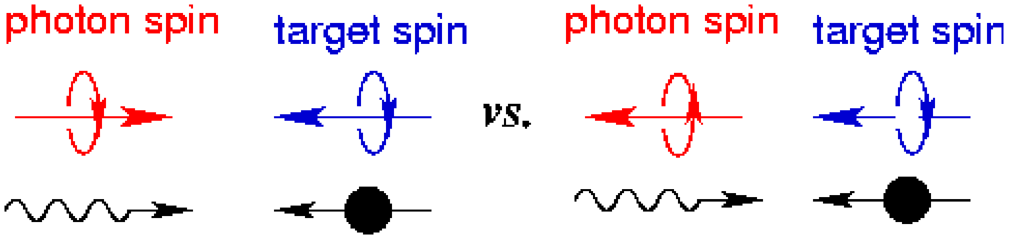
- We need structure functions for which QCD can make absolute predictions!



- F_2^p/F_2^n and d/u at large x

- A_1^p, A_1^n , or $\Delta u/u$ and $\Delta d/d$ at large x

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$ at large Q^2 $$\gamma^2 = \frac{Q^2}{\nu^2} = \frac{4M^2x^2}{Q^2}$$

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

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

$$-\frac{1}{3}\left|d^{\uparrow}(uu)_{10}\right\rangle - \frac{\sqrt{2}}{3}\left|d^{\downarrow}(uu)_{11}\right\rangle$$

Model	F_2^n/F_2^p	d/u	Δ u/u	Δ d/d	A_1^n	A_1^p
SU(6) = SU3 flavor + SU2 spin	2/3	1/2	2/3	-1/3	0	5/9
Valence Quark + Hyperfine	1/4	0	1	-1/3	1	1
pQCD + HHC	3/7	1/5	1	1	1	1
DSE-1	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2	0.41	0.18	0.88	-0.33	0.34	0.88

Table 1: Predictions for the x = 1 value of various models.

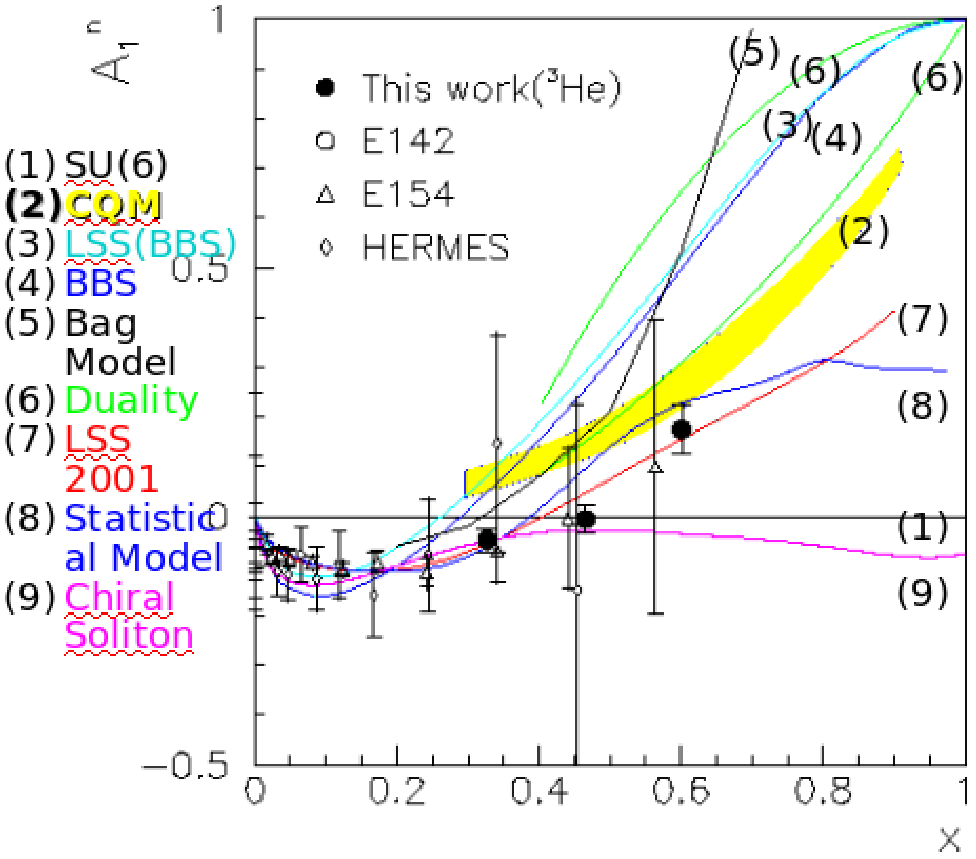
- DSE-1 (or "DSE realistic") indicates use of the momentum-dependent dressed-quark mass-function;

- 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

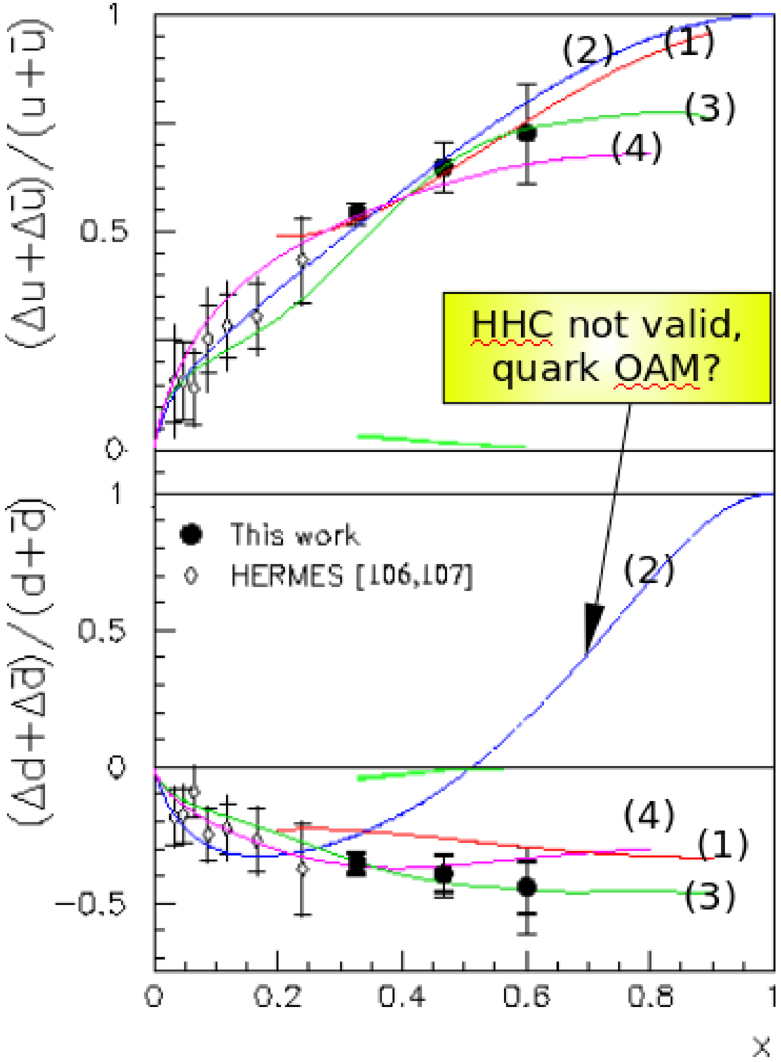
- The only place QCD (and many other models) can make absolute predictions for structure functions.

The 6 GeV Hall A Measurement (2001)



(1) SU(6)
(2) CQM
(3) LSS(BBS)
(4) BBS
(5) Bag Model
(6) Duality
(7) LSS 2001
(8) Statistical Model
(9) Chiral Soliton

(Deutron data not shown: E143, E155, SMC)

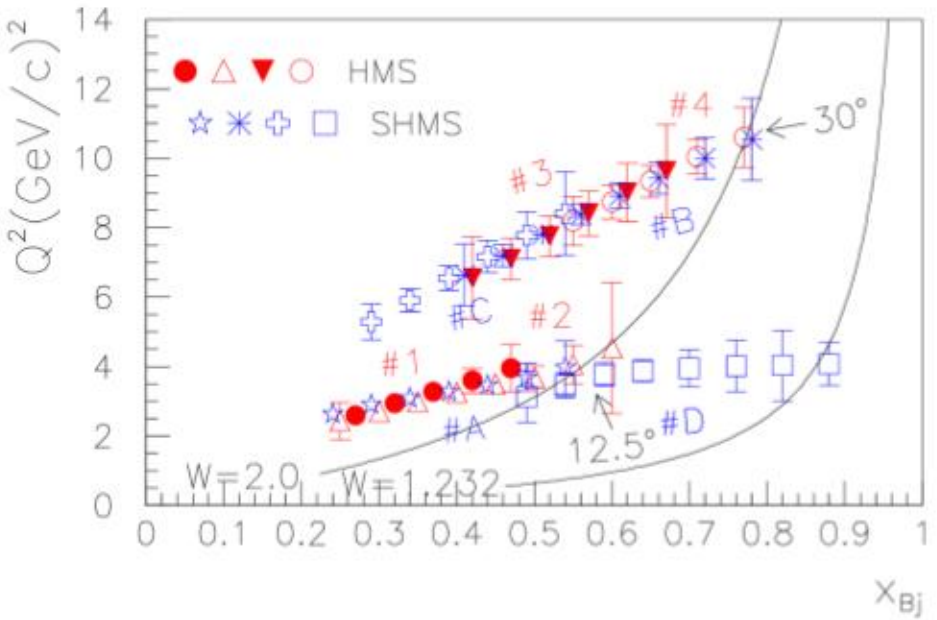


HHC not valid, quark OAM?

X. Zheng *et al.*, Phys. Rev. Lett. 92, 012004 (2004); Phys. Rev. C 70, 065207 (2004)

(1)CQM (2)LSS(BBS):pQCD+HHC
(3)Statistical Model (4)LSS 2001

A1n 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 $A_\perp$

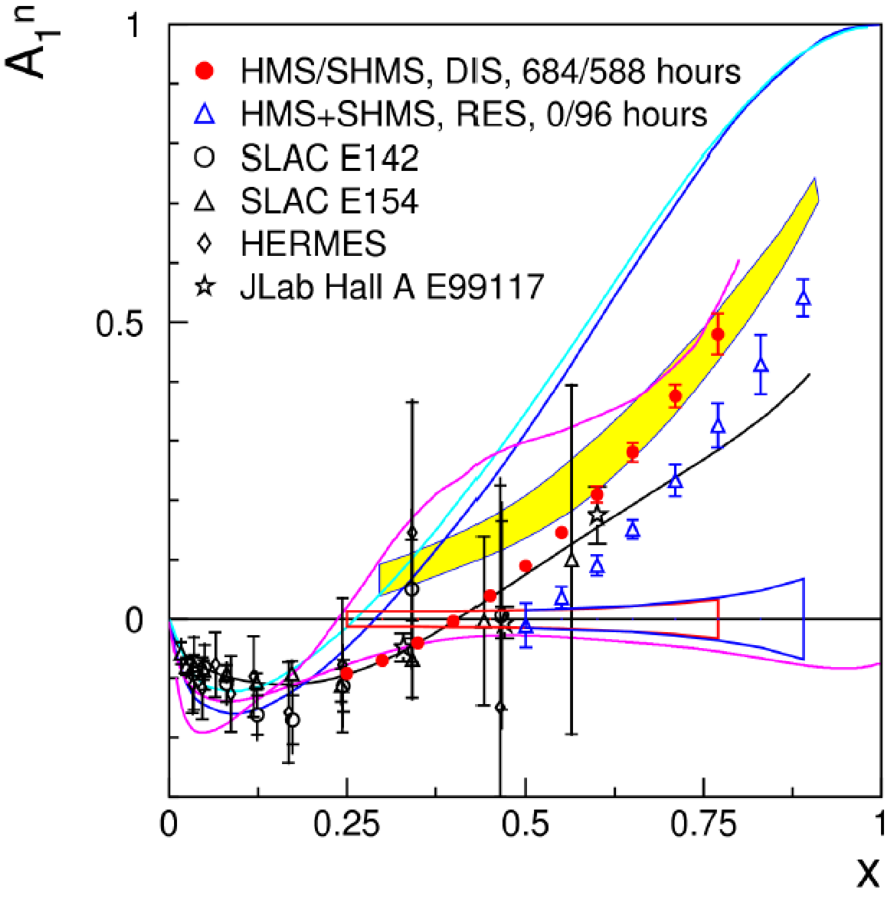
Kine	E_b GeV	E_p GeV	θ (°)	elastic x-sec (nb/sr)	elastic rate (Hz)	Asymmetry	Time (hours)
Elastic	2.200	2.160	12.5	106.986	1293.9	$A_\parallel = 0.0589$	11.2
$\Delta(1232)$	2.200	1.815	12.5	-	-	$A_\perp \sim$ a few %	6

$A_\parallel$

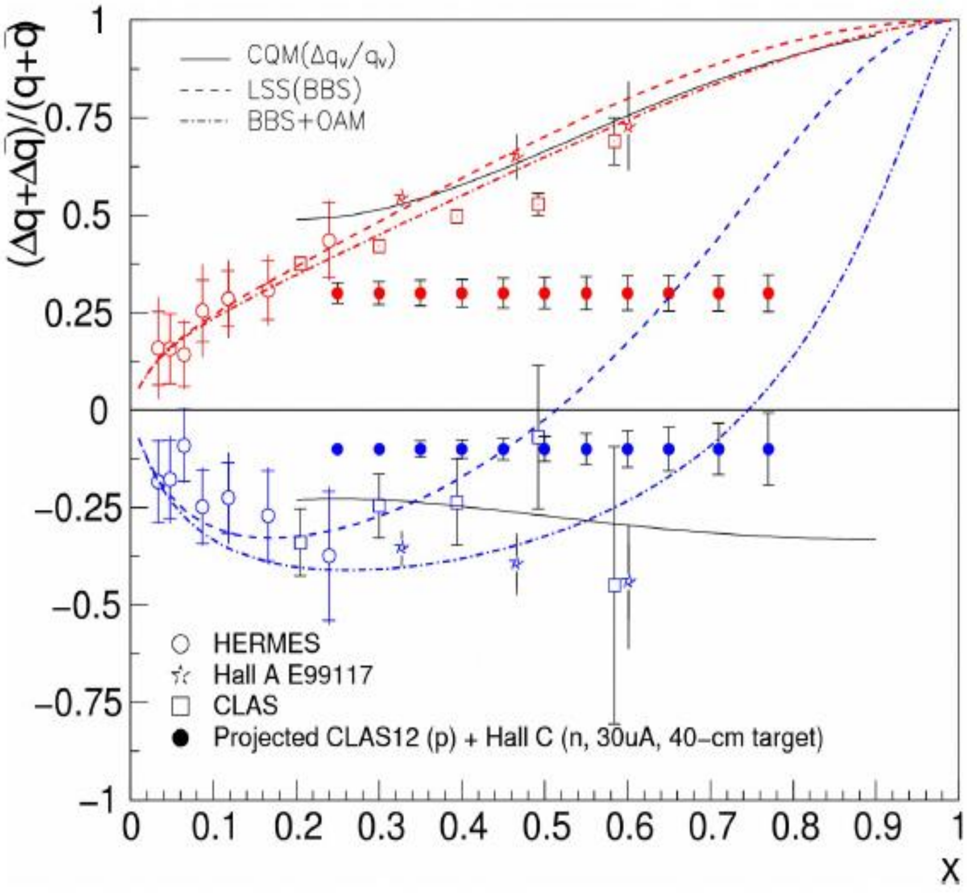
$A_\perp$

A1n Projected Results

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



- Combined results from Hall C (neutron) and CLAS12 (proton):



The d2n Experiment (E12-06-121)

- A polarized electron beam of 11.0 GeV and *new* polarized ^{3}He target
  - Measure $\Delta\sigma_\perp = \sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}$, $\Delta\sigma_\parallel = \sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}$ for $^3\vec{\mathrm{He}}(\vec{e},e')$ reaction using both the SHMS and HMS running in parallel for 4 kinematic settings of *125 hours* each
    - ↪SHMS: (7.5 GeV/c, 11.0°), (7.0 GeV/c, 13.3°), (6.3 GeV/c, 15.5°), *(5.6 GeV/c, 18.0°)*
    - ↪HMS: (4.3 GeV/c, 13.5°), (5.1 GeV/c, 16.4°), (4.0 GeV/c, 20.0°), *(2.5 GeV/c, 25.0°)*

- Polarized ^{3}He target will also be used with 12 GeV A1n, GeN experiments

- Determine d_2^n and g_2^n using the relations:

$$\tilde{d}_2 = x^2(2g_1+3g_2) = \frac{MQ^2\nu}{8\alpha_e^2}\frac{E}{E'}\frac{x^2(4-3y)}{(E+E')}\left[\Delta\sigma_\parallel + \left(\frac{4-y}{(1-y)(4-3y)\sin\theta_e} - \cot\theta_e\right)\Delta\sigma_\perp\right]$$

$$g_2 = \frac{MQ^2\nu^2}{4\alpha_e^2}\frac{1}{2E'(E+E')}\left[-\Delta\sigma_\parallel + \frac{E+E'\cos\theta_e}{E'\sin\theta_e}\Delta\sigma_\perp\right]$$

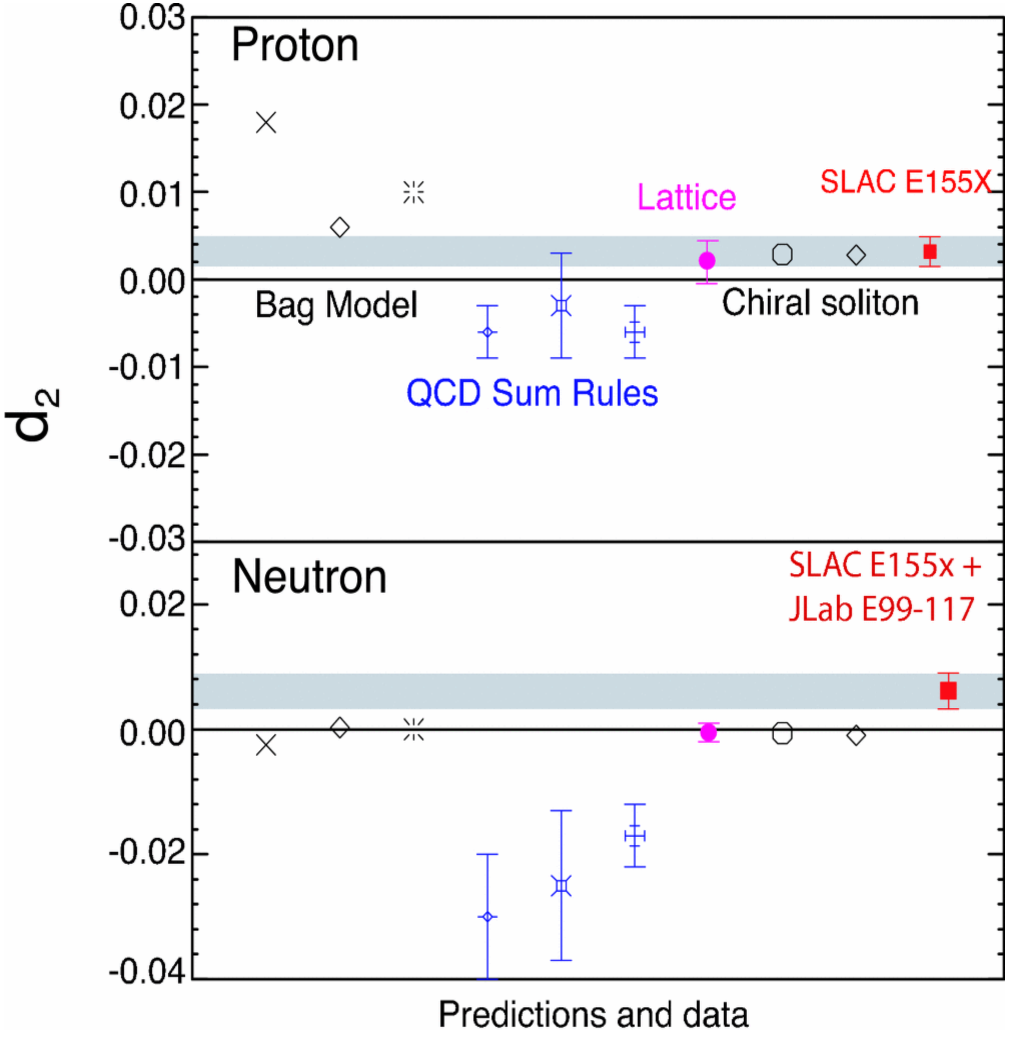
where $\Delta\sigma_\parallel = \sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}$, $\Delta\sigma_\perp = \sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}$ and $y = \nu/E$.

I = 30 μA
Pbeam = 0.8
Pbeam = 0.55
targ

d2n Physics Motivation

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

- d_2 is a clean probe of quark-gluon correlations / higher twist effects
  - ➔ d_2 is the 2nd 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 (transverse) force* acting on the struck quark (Burkardt)
  - ➔ same underlying physics as in SIDIS $k_\perp$ studies
- Investigate the present discrepancy between data and theories.

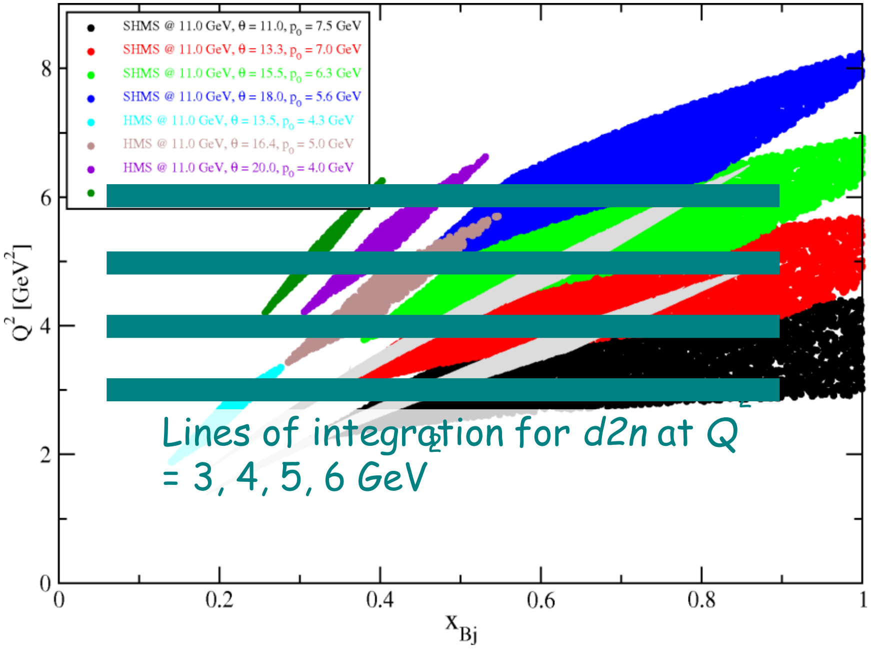


d2n Kinematics

- Hall C: SHMS + HMS
- 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 3He
- Each arm measures an absolute polarized cross section independent of the other arm (g_1, g_2)
- 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

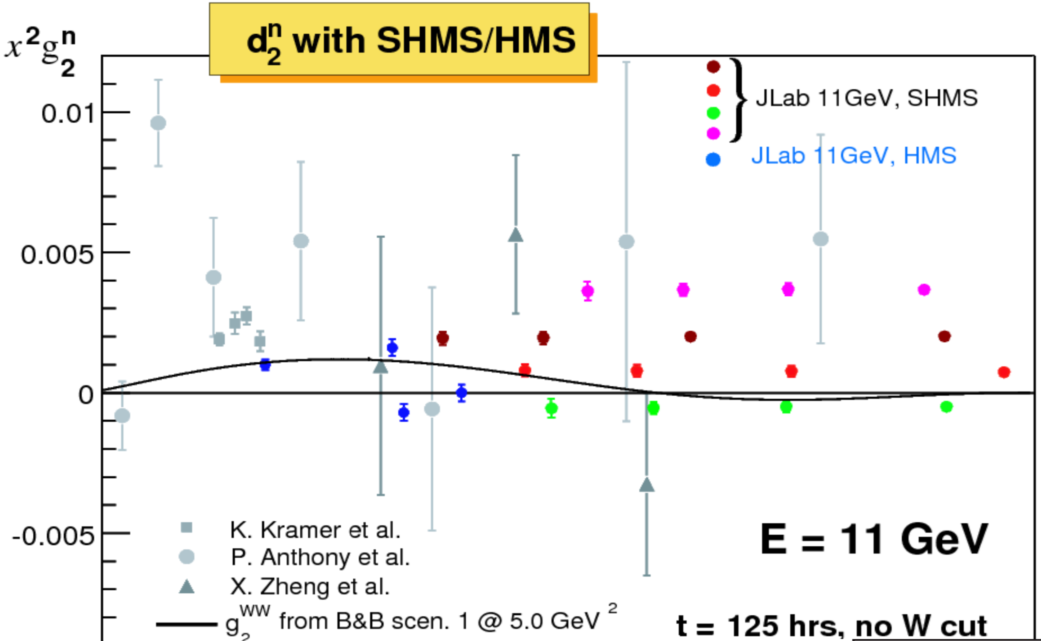
SHMS Production		
Setting	P_0	Angle
A	7.5	11.0°
B	7.0	13.3°
C	6.3	15.5°
D	5.6	18.0°

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°



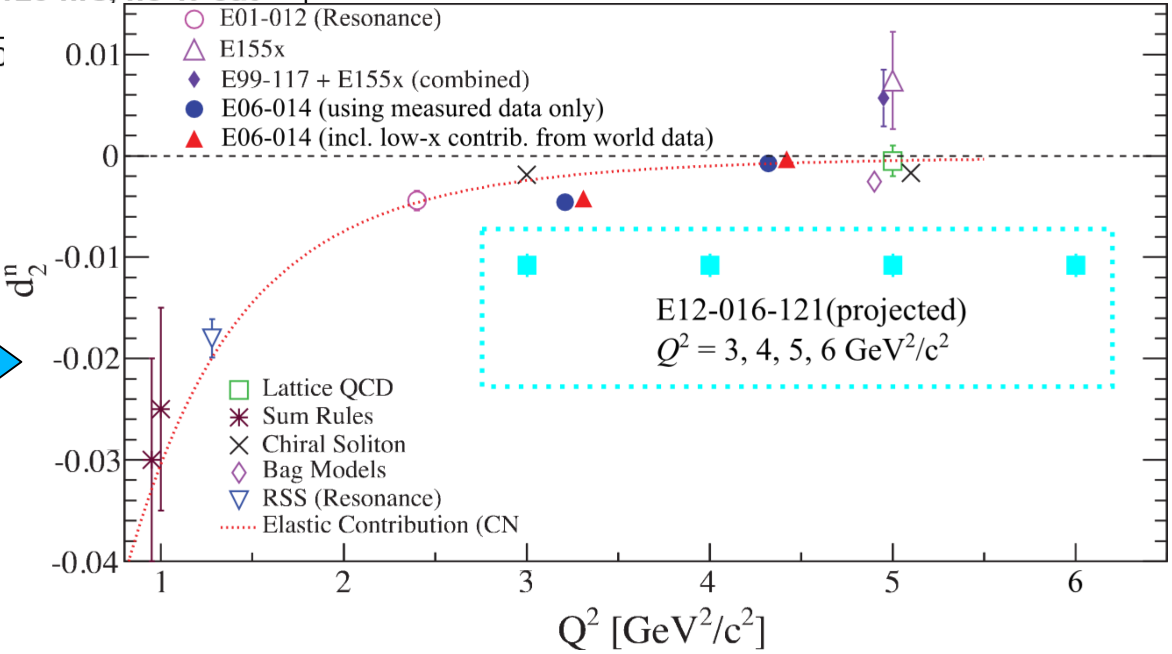
Lines of integration for d2n at Q^2 = 3, 4, 5, 6 GeV

Projected Results for d2n (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 *d2n* in a region where models are thought to be accurate.
- Direct overlap with 6 GeV Hall A measurement.



Polarized ^{3}He Target

Stage I goal:

- 30 uA on 40 cm, ~10 atm, $L \sim 2.2\times10^{36}\ \mathrm{cm^{-2}s^{-1}}$
- In-beam polarization ~60%,
- Polarization measurement precision ~ 3%
- Experiments: A1n Hall C (high impact), d2n in Hall C

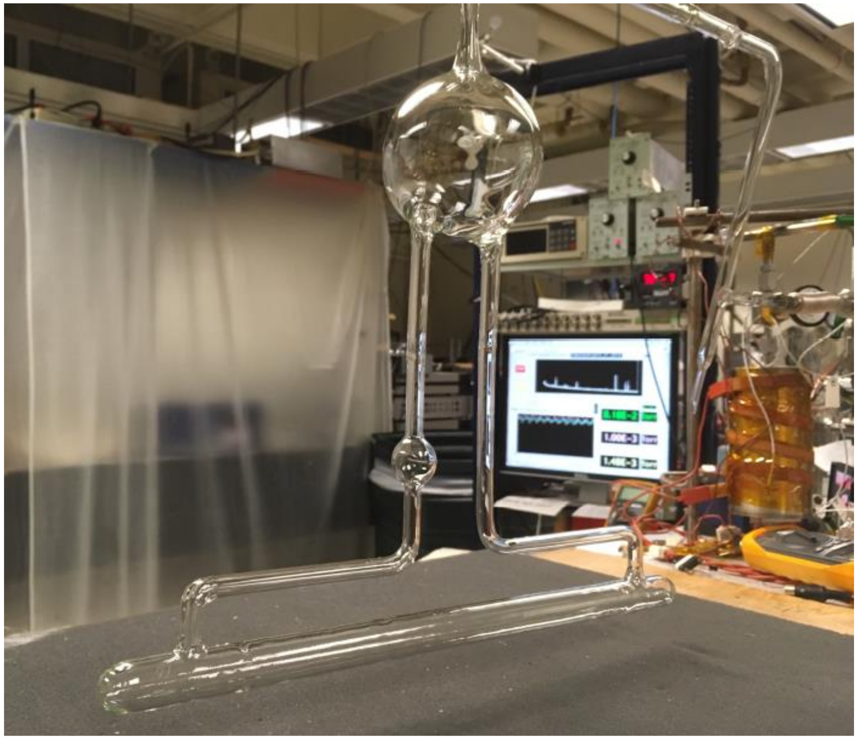
Approaches:

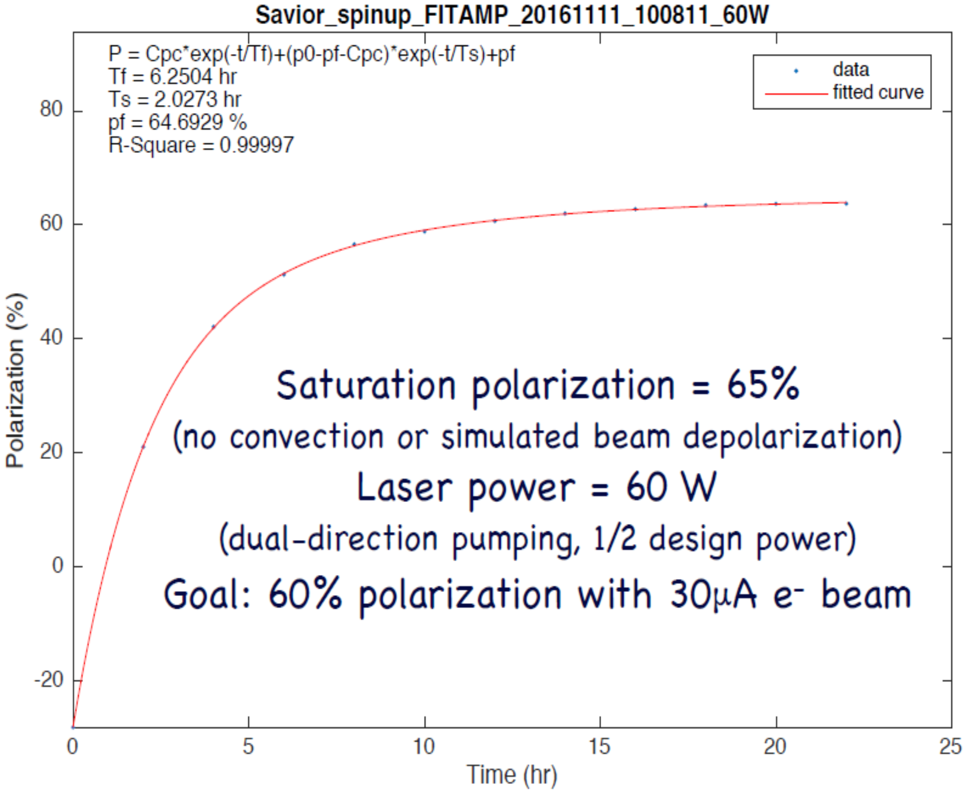
- Re-use existing Helmholtz coils and most existing hardware, electronics and optics
- Convection flow
- Target cell, pumping chamber size 3.5", glass cell
- Polarimetry ~ aim for 3%, Pulse NMR calibrated with AFP NMR, absolute calibration with EPR and AFP-NMR with water (optional)
- Modification to Hall C pivot area and new platform/laser optics line

Started preparation for hall installation

- Identifying installation requirements: space, shielding, electronics, cables …

Savior - First Beam-Ready Cell





Saturation polarization = 65%

(no convection or simulated beam depolarization)

Laser power = 60 W

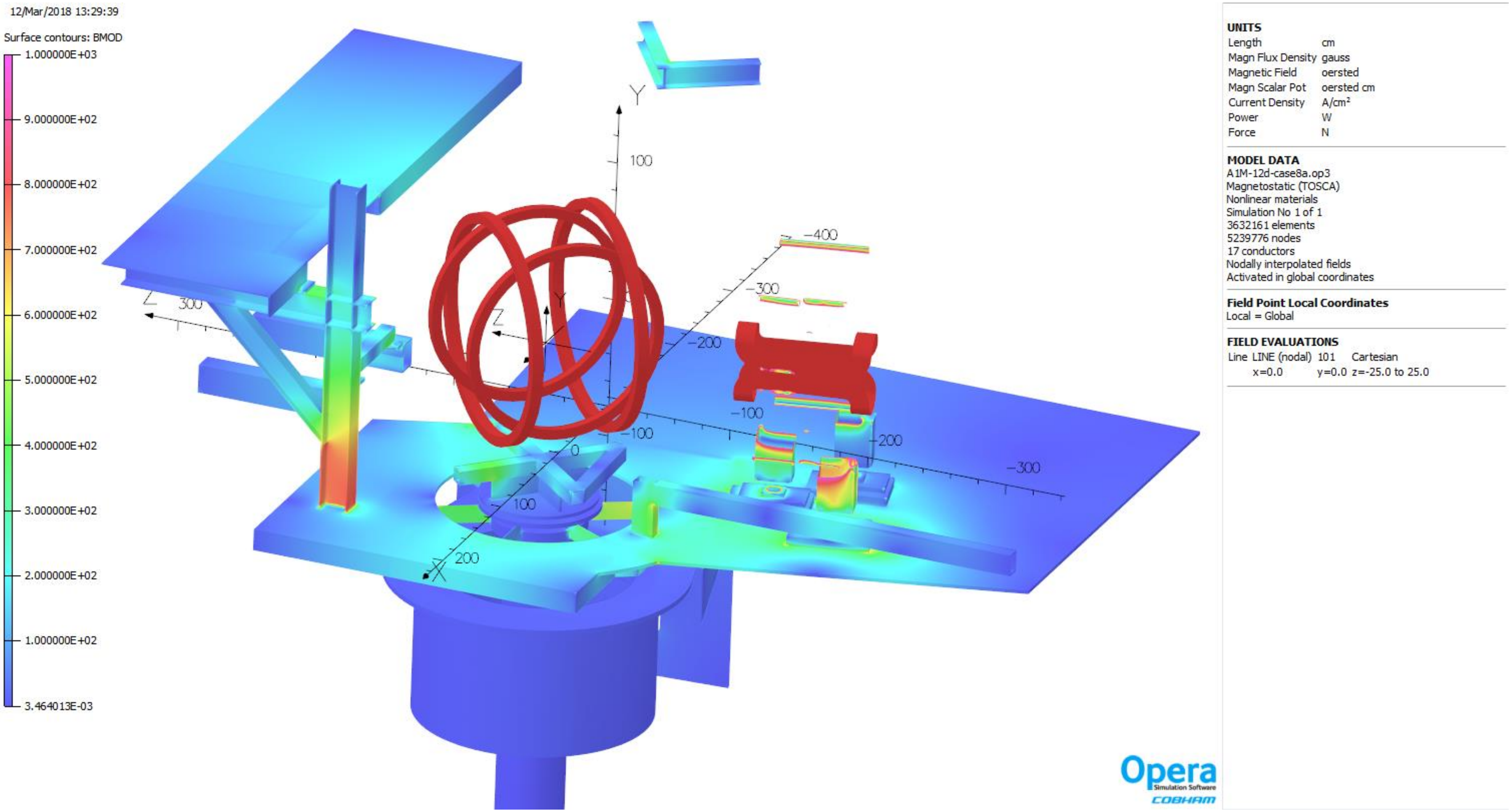
(dual-direction pumping, 1/2 design power)

Goal: 60% polarization with 30μA e⁻ beam

Short-term plan

- A new batch of thin end windows have been pressure tested and are ready to be incorporated into target cells.
- The first target cell of "Batch #2", with the recently tested end windows, has been received and is ready for filling.
- New laser system is expected to be ready to do characterizations when the next cells are filled.

Steve's TOSCA Model



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Surface contours: BMOD

UNITS

Length	cm
Magn Flux Density	gauss
Magnetic Field	oersted
Magn Scalar Pot	oersted cm
Current Density	A/cm²
Power	W
Force	N

MODEL DATA

A1M-12d-case8a.op3
Magnetostatic (TOSCA)
Nonlinear materials
Simulation No 1 of 1
3632161 elements
5239776 nodes
17 conductors
Nodally interpolated fields
Activated in global coordinates

Field Point Local Coordinates

Local = Global

FIELD EVALUATIONS

Line LINE (nodal) 101 Cartesian
x=0.0 y=0.0 z=-25.0 to 25.0

- Configuration shown above is with Helmholtz coils set for longitudinal running, and the HB correction coils are not turned on.
- Field gradient is under studying…

Progress on Other parts

Beamline:

- Hall C beamline modifications have begun, but last girder will still need work Summer 2019

Moller polarimeter:

- Møller polarimeter expected to provide measurements with <3% precision.
- Will connect to new power supply and do some detector checkout Summer 2018.
- Magnet coll down test is expected to be carried out in Fall 2018.
- Moller analyzer is under upgrading.

Circular raster:

- A circular raster that can smear the beam by 2.5mm radius is required.
- Existing system is a square pattern raster.
- Most equipment exists, but need to purchase spare parts. Some electronics need to be modified or replaced.
- EPICS software need to be upgraded.
- Testing of circular raster is underway.

HMS, SHMS:

- Detectors, DAQ are working as planned. Calibrations and in progress.

Manpower

- 6-8 PhD students:
  - Mingyu Chen (UVa/Zheng),
  - Melanie Rehfuss (Temple U/Meziani),
  - Michael Berkowitz (Columbia/Hughes) -- currently working on raster and Moller polarimeter
  - Chris Jantzi (UVa/Cates) -- target at UVa
  - Junhao Chen (W&M/Averett) -- target
  - Shuo Jia (Temple U/Meziani)
  - 1 TBD (Kentucky/Korsch)
  - 1 TBD (China)
- Postdoc: Temple, UVa, W&M, Jlab
- Spokespersons

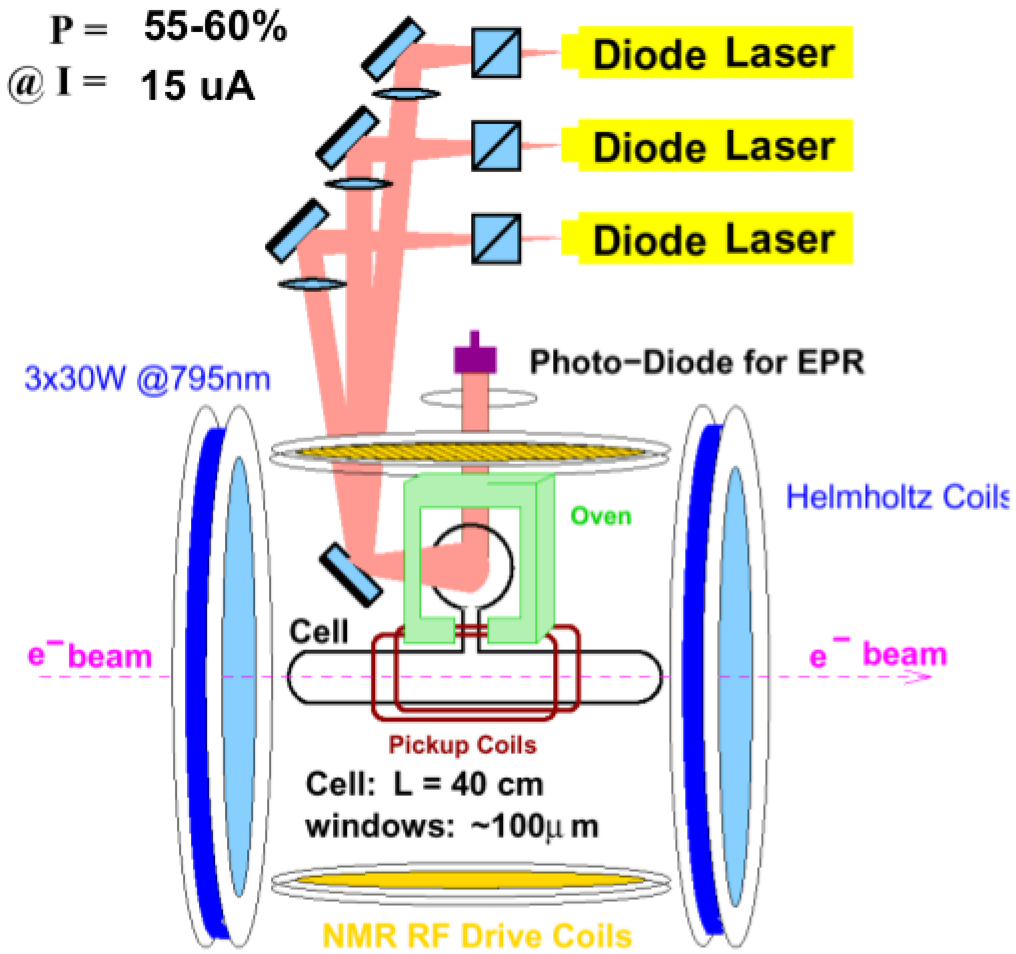
Summary and Outlook

- Overview of A1n (E12-06-110) and d2n(E12-06-121) is given.
- Experiment Readiness Review (ERR) completed in March 2018. Only a few formal recommendation in the resulting Report. No show stoppers were found. Reply to ERR recommendations is nearly final.
- 1st joined collaboration meeting just held in mid-June.
- Prepare to run from Fall 2019
- ^{3}He target has a lot of progress, but still has a lot of things in the to-do list.
- Started to look into preparation for hall installation.
- Beamline, circular raster and detectors are in planned progress.

Backup Slides

Target

JLab Polarized ^{3}He Target

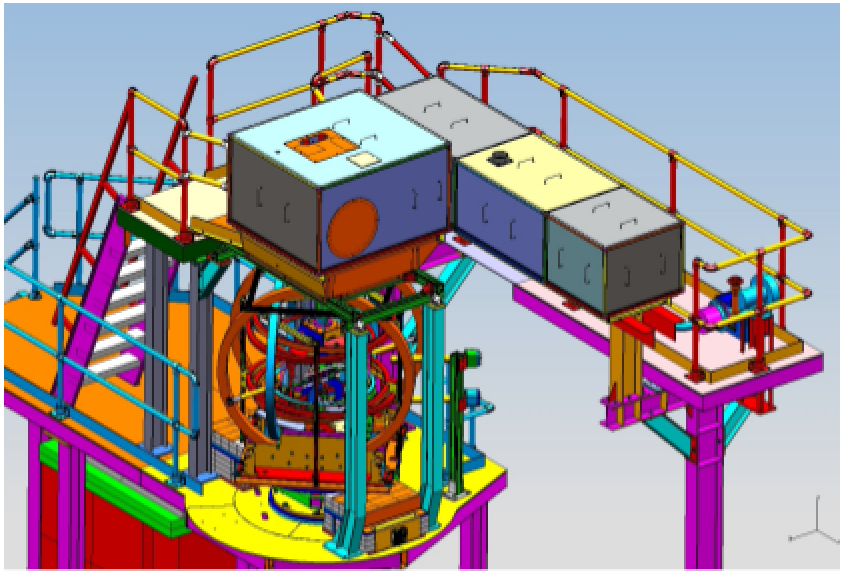


- ✓Effective pol neutron target
- ✓longitudinal, transverse
  (and vertical)
- ✓Luminosity=10^{36} (1/s)
  (highest in the world)
  upgrade : x2 (stage I)
  additional x3 (stage II)
- ✓High in-beam polarization
  60% (>70% no beam)
- ✓13 completed experiments
  9 approved with 12 GeV (A/C)

Progress Summary

Engineering/Design:

- target design complete:
  oven, ladder, support, optical line,
  enclosure, pivot area, access platform, …
- installation design mostly complete



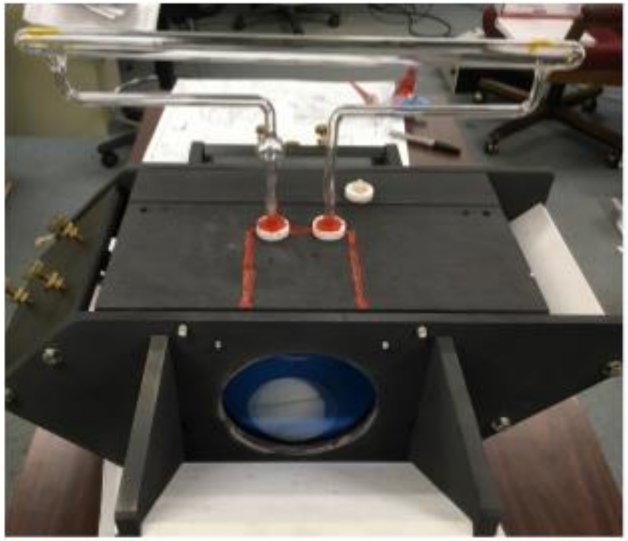
Mechanical:

- New parts ordered
- Target ladder manufactured
- Pivot area modified (poster cut)
- Existing parts (in storage) checked
  need test in advance

Field gradients at target area: (talk by Gordon Cates)

- Study bender field at the target region
  and magnetic material nearby
- Correct field gradients with correction coils

Progress Summary (cont.)



- New oven manufactured/installed/tested
- Target cells

✓ prototyping convection cell extensively tested,

✓ cell production started

○ 1st good cell: lifetime > 48 hours, tested at UVa, now at JLab for full characterization

○ five cell ordered and production started

○ five more cell order will be placed in FY18

○ order more in FY19 until reaching the goal of having 6-8 good cells.

○ produce/characterize ~one cell per month

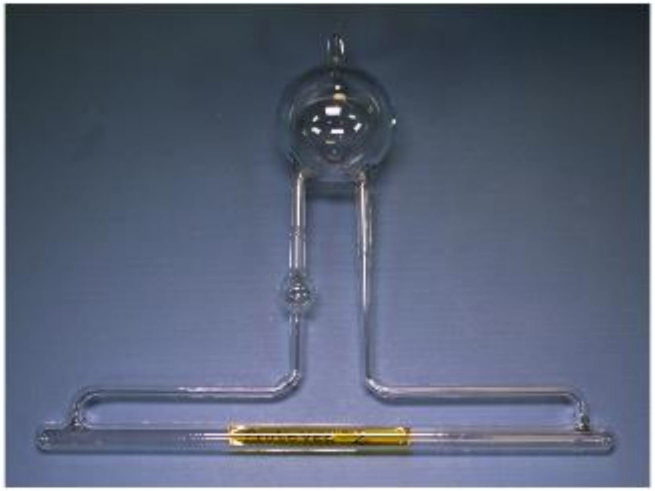
- Lasers/long optical fibers:

✓ five new lasers delivered/tested
more will be ordered as spares and for future

✓ ten long fibers delivered, tested

✓ five 4-1 combiners ordered, prototype tested

✓ polarization compensation study complete



Progress Summary (cont.)

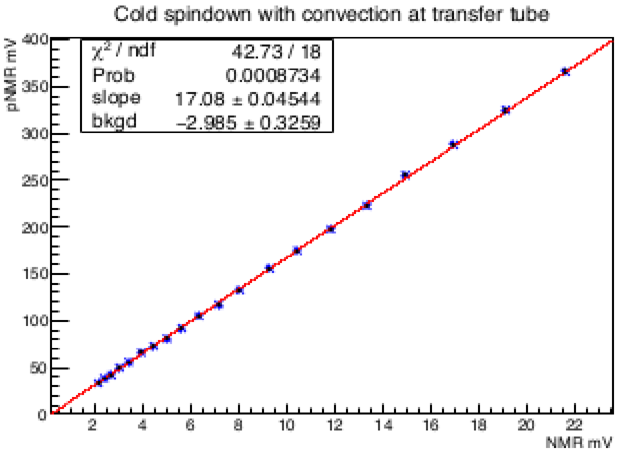
- **Polarimetry:**

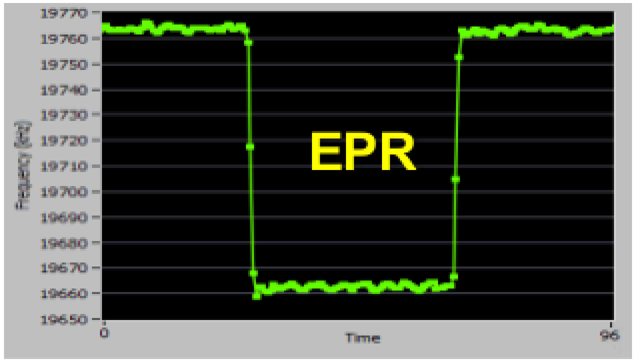
✓ pulse NMR systematic study/calibration (Nguyen Ton)

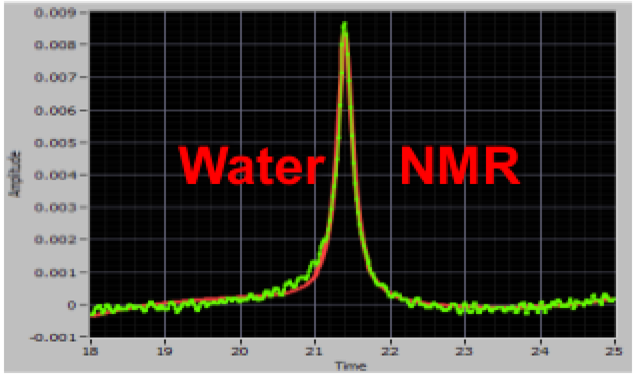
✓ EPR study (Kai Jin)

✓ κ_0 measurement (W&M/UVa) in progress (Averett/Cates)

will continue study to understand and improve systematics







- **Cell characterization:**

✓ Density measurement (August Williams)

✓ Wall and window thickness measurements

✓ Maximum polarization

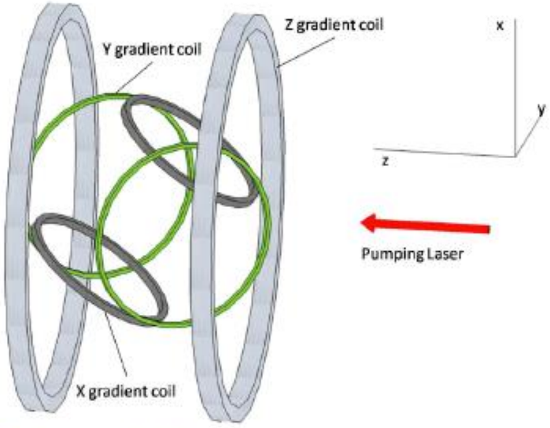
✓ Spin up

✓ Spin down/ AFP loss study

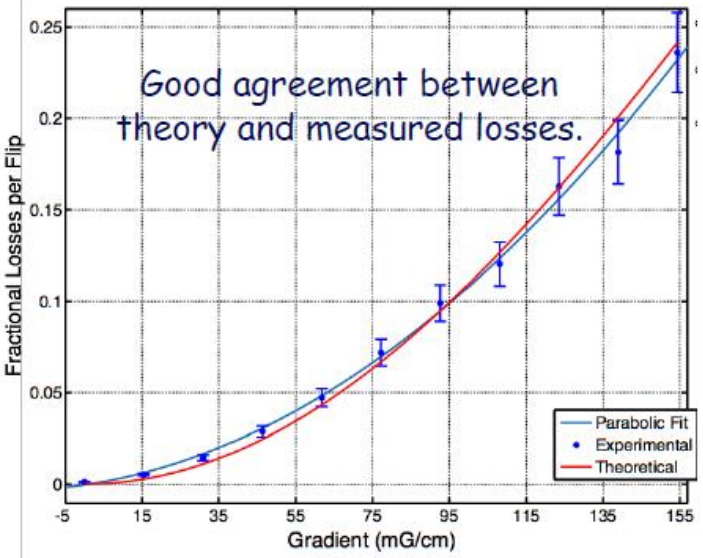
Spin relaxation during NMR AFP
(used during polarimetry)

During an "AFP sweep", all spins in the target are flipped by 180 degrees. The key issue here is the fractional loss of polarization per flip.

$$\text{fractional relaxation} = \frac{|\vec{\nabla} B_z|^2}{B_1^2} D \, \frac{\pi \, B_1}{2(\partial B_z / \partial t)}$$



Coils used for test



Good agreement between theory and measured losses.

$$If \;\; |\vec{\nabla} B_z|^2 = 10^{-3}\,\mathrm{G}^2/\mathrm{cm}^2, \quad loss = 0.5\%$$

For a value of 10^{-2} $\mathrm{G}^2/\mathrm{cm}^2$, the loss would be 5%, which would be an extreme, possibly livable, condition.

Spin relaxation due to magnetic field inhomogeneities under static conditions

- High polarization requires limiting spin-relaxation due to all mechanisms well below the spin-exchange rate.
- Spin relaxation due to magnetic field inhomogeneities under static conditions (that is, not during polarimetry measurements) is due to specific components of the magnetic field inhomogeneities, as described below.

$$\frac{1}{T_1} = D\,\frac{|\vec{\nabla} B_x|^2 + |\vec{\nabla} B_y|^2}{B_z^2}$$

Here $1/T_1$ is the spin relaxation rate, D is the self-diffusion coefficient of ^{3}He, and the magnetic field is assumed to be in the z-direction.

For simplicity, we will assume that a ^{3}He density of 10 atm STP. Under this assumption, D = 0.2 cm^2/s. For example:

$$If \quad \frac{|\vec{\nabla} B_x|^2 + |\vec{\nabla} B_y|^2}{B_z^2} = 10^{-5}\,\mathrm{cm}^{-2}, \quad 1/T_1 = 1/139\,\mathrm{hrs}$$

A good cell, in the absence of beam, might have an intrinsic value of $1/T_1$ = 1/40 hrs. Thus, a value of 10^{-5} cm^{-2} would certainly impact performance, but would not be the dominant factor. At a value of 10^{-6} cm^{-2}, the effects of the inhomogeneities are insignificant.

A1n

A1n Running Conditions

- First experiment to require polarized beam in Hall C after the upgrade: 85% requested, (minimum 80%), measured to 2%; transverse beam polarization < 1% desired.
- Beam size no larger than 300μm in σ, 200μm in σ desired.
- 11 GeV (min 10.5 GeV), 30 μA, beam trip goal: (6-10) per hour or less
- circular rastering of beam spot to a radius of 2.5 mm and "no hot spot", current ramping at (0.5-1.0) μA/sec on polarized target cell;
- changing beam IHWP status every 12 hours or at least half-way of each kinematics;
- beam charge asymmetry controlled to under 200ppm (average over each run);

- First time to use polarized 3He target in Hall C: Stage-I target upgrade: 12amg, 40cm, 30uA, Pt=(55-60)%; 3% polarimetry
- Both longitudinal and transverse spin configurations; spin direction known to ±0.5 degree desired and ±1.0 degree required; density known to 3% (2% from fill density and 2% from operating temperature).

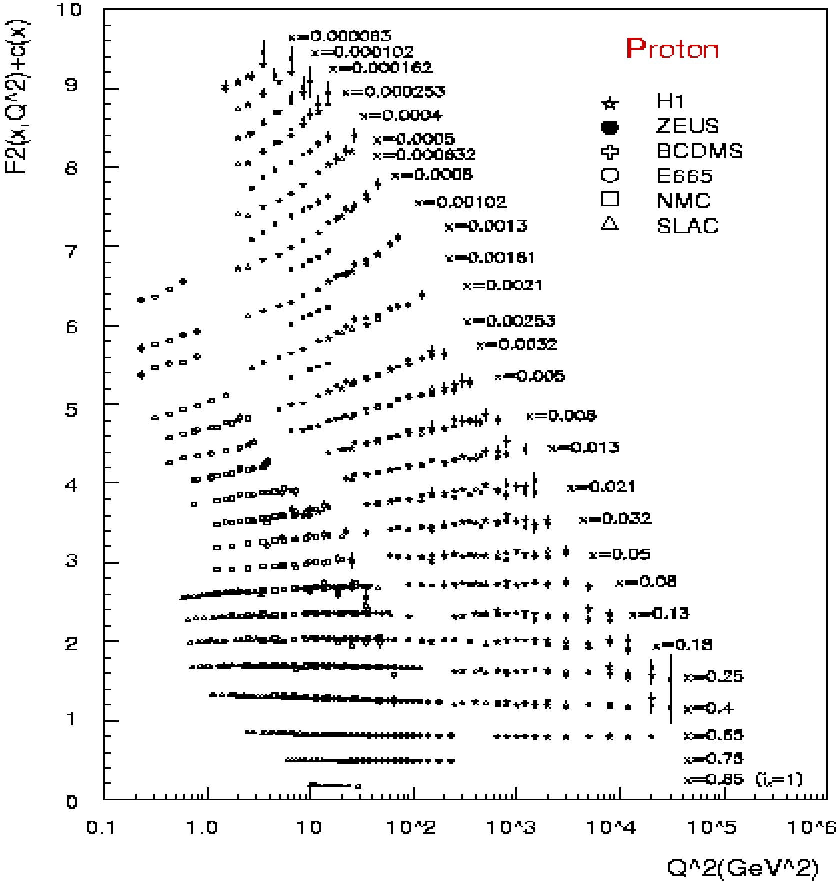
- Q^2 known to 1% desired (Ebeam at the ±1E-3 level; spectrometer momentum to ±1E-3, angle to ±0.06 deg).
- PID performance: pion rejection > 10,000 desired by combining calorimeter and Cherenkov, > 5000 required, while keeping electron efficiency at 99% (desired) or 95% (min) each (worst case at SHMS momentum 2.25 GeV/c and HMS 2.82 GeV/c).

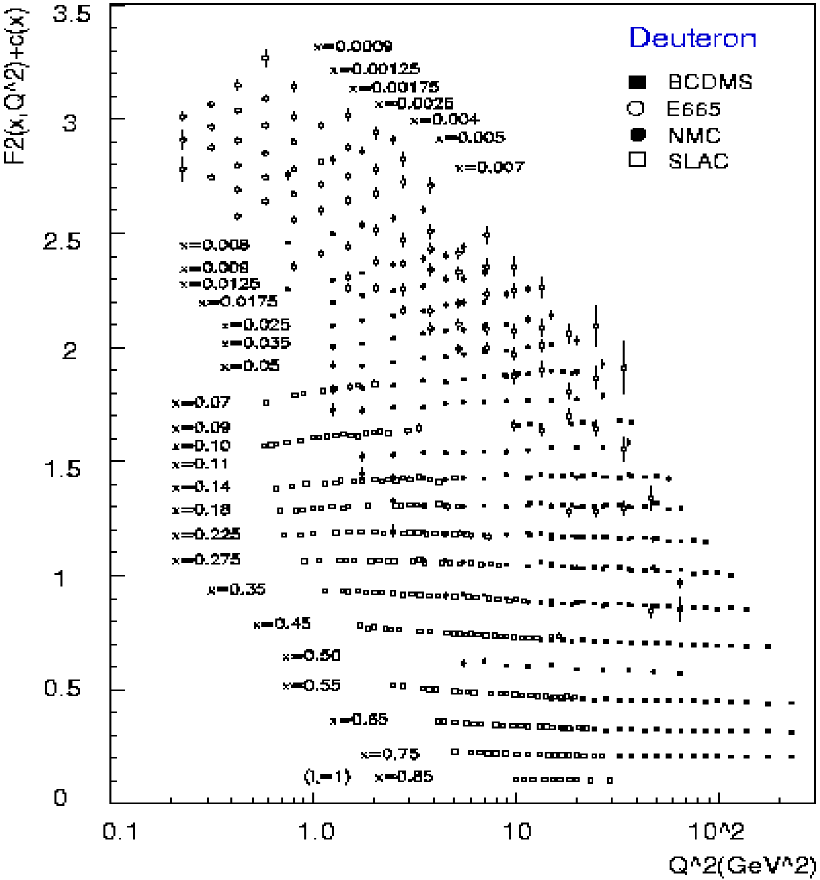
Unpolarized Nucleon Structure Study

- The nucleon structure provides one of the best testing ground for our understanding of the strong interaction and QCD.
- How do quarks and gluons carry the energy (momentum) of the nucleon?
- \- DIS, F1,F2, unpolarized Parton Distribution Functions: u,d,s,c...

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}[\alpha F_1(Q^2,\nu) + \beta F_2(Q^2,\nu)]$$

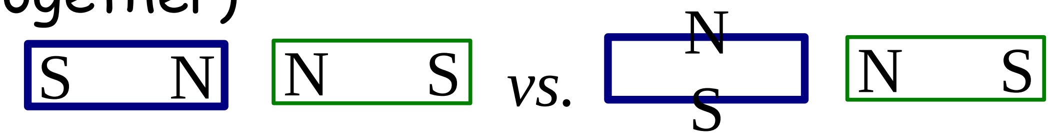
- Phys. Rev. D 66, 010001 (2002)



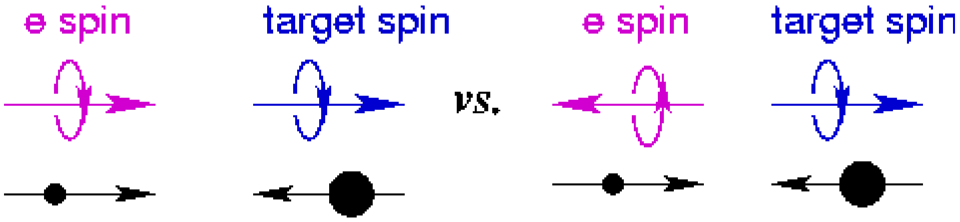


Polarized DIS

- Scattering cross section is spin-dependent (imagine throwing two small magnets together)

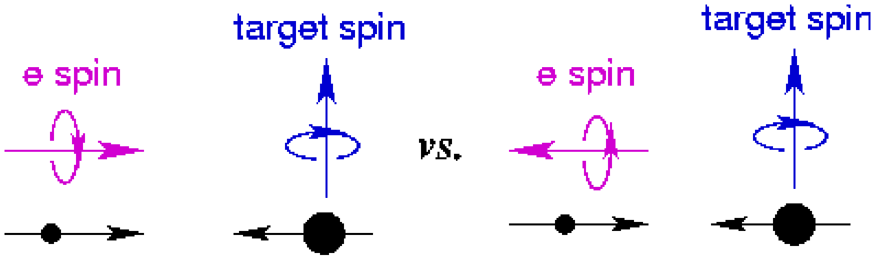


- Longitudinal



$$\frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} \propto \sigma_{point-like}[\alpha' g_1(x,Q^2) + \beta' g_2(x,Q^2)]$$

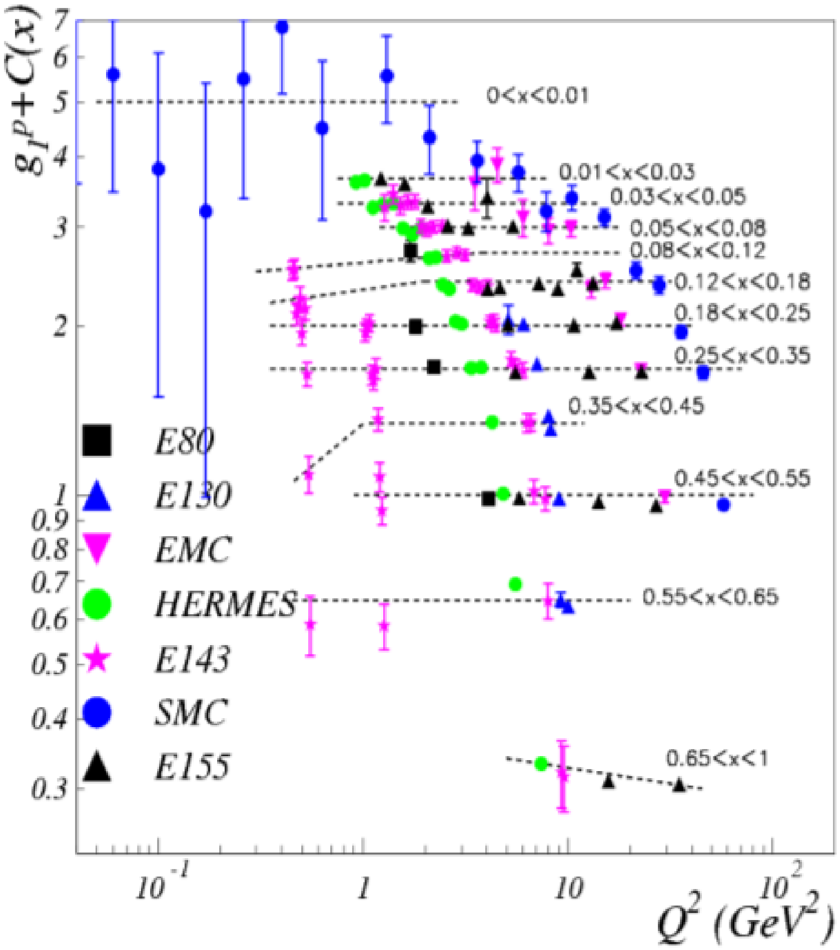
- Transverse



$$\frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\leftarrow}}{d\Omega dE'} \propto \sigma_{point-like}[\alpha'' g_1(x,Q^2) + \beta'' g_2(x,Q^2)]$$

A1n as Part of the Nucleon Structure Study

- Polarized observables provide additional degree of freedom
- How do quarks and gluons carry the spin of the nucleon? - DIS, g1,2, polarized Parton Distribution Functions: Δu/u, Δd/d, Δs/s

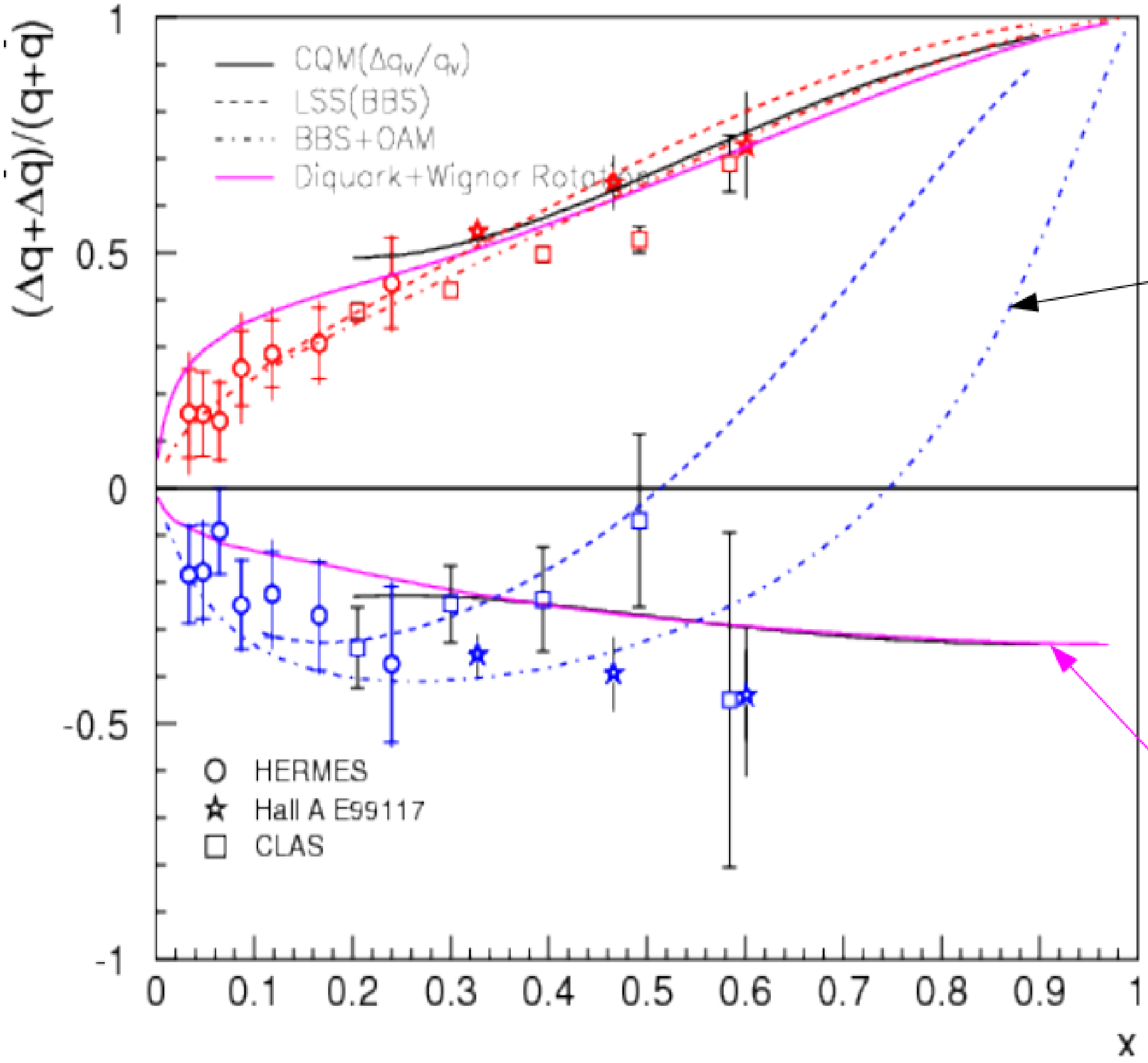


$$g_1(x) = \frac{1}{2}\Sigma\, e_i^2[q_i^\uparrow(x) - q_i^\downarrow(x)] = \frac{1}{2}\Sigma\, e_i^2[\Delta\, q_i(x)]$$

- The integral of $g_1(x)$ over x describes how much of the nucleon's spin is carried by quarks' spin - the puzzle of the nucleon spin

$$\frac{1}{2} = S_Z^N = S_Z^q + L_Z^q + J_Z^q$$

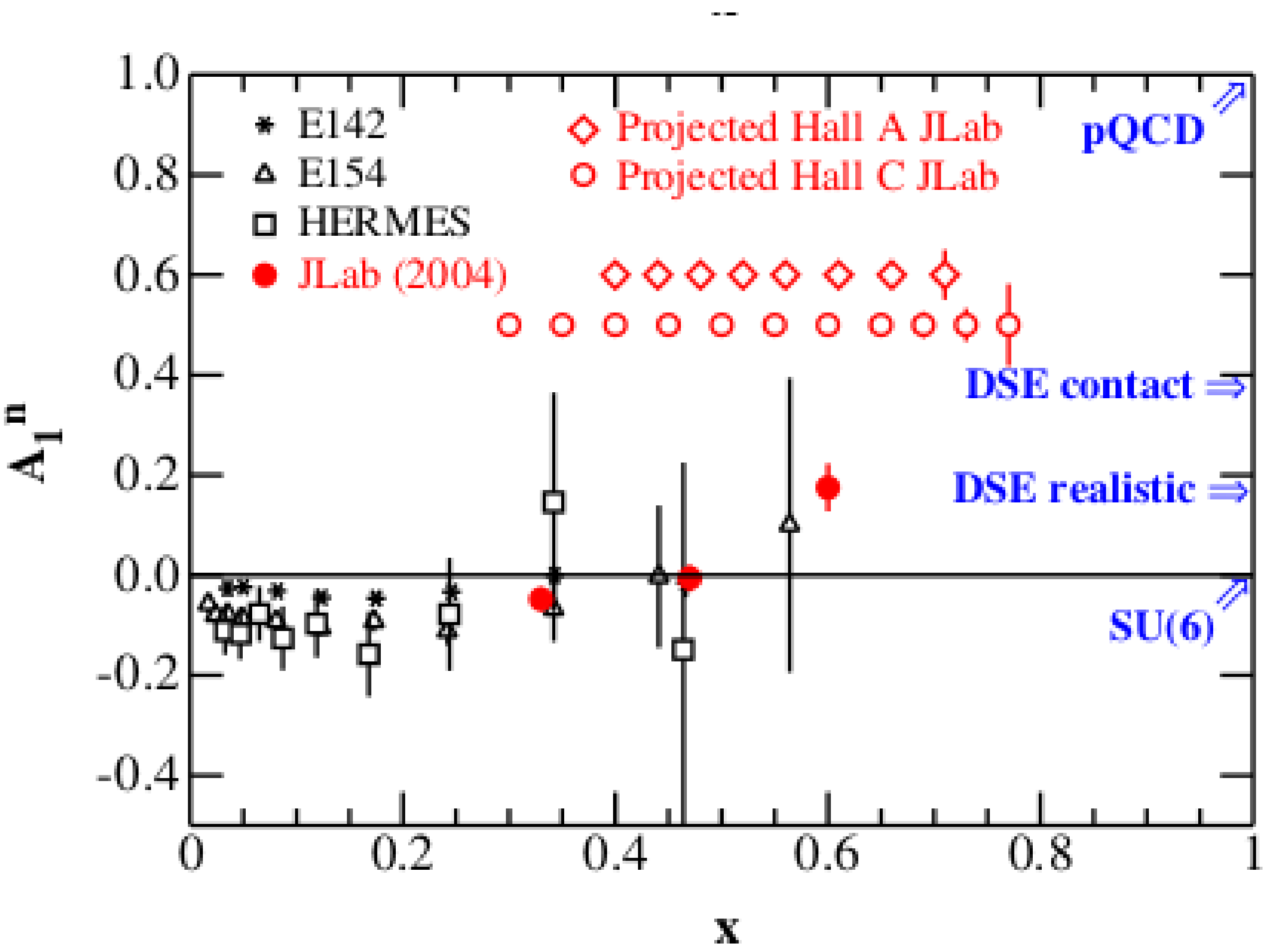
Polarized DIS and Nucleon Spin Structure



H. Avakian, S. Brodsky, A. Deur, F. Yuan,
Phys. Rev. Lett.99:082001(2007)

light-cone quark/diquark model
X. Chen, Y. Mao, B.-Q. Ma,
Nucl. Phys. A 759, 188 (2005)

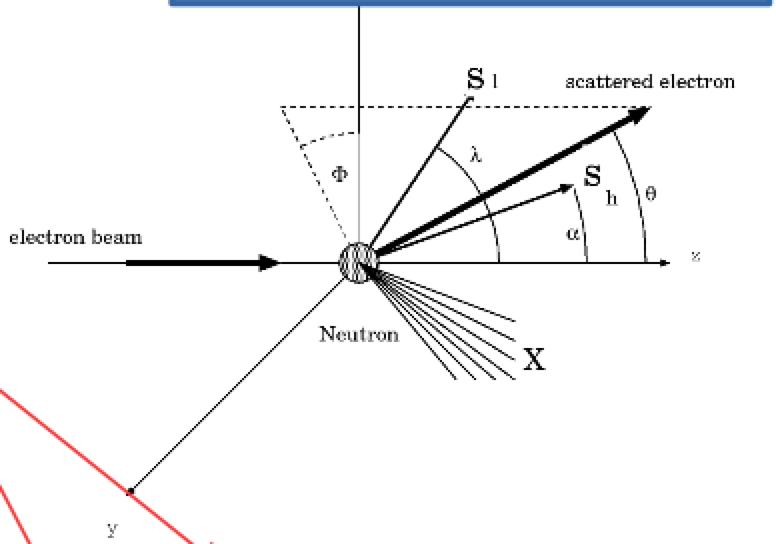
A1n Projection with Model Predictions



Blue arrows are predictions for the x = 1 value of various models. See details in *Craig D. Roberts et al.* arXiv:1308.1236

Beam Transverse Polarization

ref: E94010 tech note #6



transverse beam spin is suppressed by γe

$$A_{\parallel}^{Jlab} = \frac{\frac{d^2\sigma}{d\Omega dE'}^{\swarrow\Uparrow} - \frac{d^2\sigma}{d\Omega dE'}^{\nearrow\Uparrow}}{\frac{d^2\sigma}{d\Omega dE'}^{\swarrow\Uparrow} + \frac{d^2\sigma}{d\Omega dE'}^{\nearrow\Uparrow}}$$

$$= \frac{g_1[(2xy - \frac{Q^2(\nu+\frac{Q^2}{2E})}{2ME^2})\cos\lambda + \frac{E'\sin\theta(\nu+\frac{Q^2}{2E})}{ME}\frac{\sin\lambda}{\gamma_e}] - g_2\frac{xQ^2}{E^2}\cos\lambda}{xy^2F_1 + (1-y-\frac{y^2\gamma^2}{4})F_2}$$

and the transverse asymmetry :

$$A_{\perp}^{Jlab} = \frac{\frac{d^2\sigma}{d\Omega dE'}^{\swarrow\Leftarrow} - \frac{d^2\sigma}{d\Omega dE'}^{\nearrow\Leftarrow}}{\frac{d^2\sigma}{d\Omega dE'}^{\swarrow\Leftarrow} + \frac{d^2\sigma}{d\Omega dE'}^{\nearrow\Leftarrow}}$$

$$= \frac{g_1[(2xy - \frac{E'^2\sin\theta^2}{ME})\frac{\sin\lambda}{\gamma_e} + \frac{Q^2E'\sin\theta}{2ME^2}\cos\lambda] + g_2[2xy\frac{\sin\lambda}{\gamma_e} + \cos\lambda\frac{2xE'\sin\theta}{E}]}{xy^2F_1 + (1-y-\frac{y^2\gamma^2}{4})F_2}$$

Requirement on target angle

A1n analysis is dominated by $A_{||}$, which is less sensitive to the target field angle than Aperp:

$$\left(\frac{\Delta\sigma_{pol}}{\sigma_{pol}}\right)_{\alpha=0+\delta\alpha}=(\delta\alpha)\frac{E'\sin\theta}{\frac{g_1}{g_2}\left(yE+\frac{1}{2xM}\left[\nu-(E-E'\cos\theta)\right](E-E'\cos\theta)\right)+\left[yE-(E-E'\cos\theta)\right]}$$

$$\left(\frac{\Delta\sigma_{pol}}{\sigma_{pol}}\right)_{\alpha=\frac{\pi}{2}+\delta\alpha}=(\delta\alpha)\frac{\frac{g_1}{g_2}\left(2xyE-\frac{1}{M}\left[\nu-(E-E'\cos\theta)\right](E-E'\cos\theta)\right)+2xyE-2x(E-E'\cos\theta)}{2xE'\sin\theta}$$

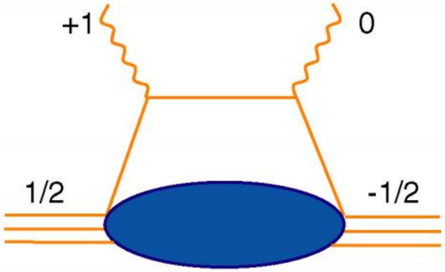
Requirement on Q^2

- dilution – relative cross sections
- kinematic variables used to extract $A_{1,2}$ from measured asymmetries
- $F_{1,2}$ (p, n, 3He) used in nuclear corrections
- A_1^p, PDF (d/u) used in extracting $\Delta q/q$

d2n Theory / Motivation

g_2 and Quark-Gluon Correlations

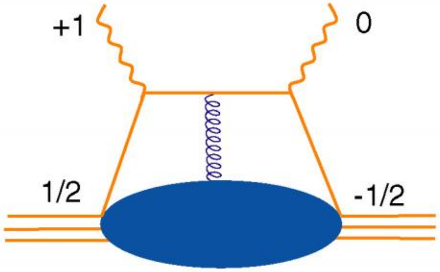
twist-2



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

Moments of Structure Functions

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\,dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

leading twist

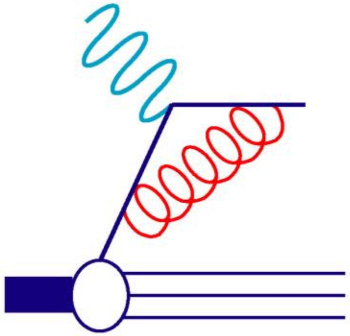
higher twist

$$\mu_2^{p,n}(Q^2) = \left(\pm\frac{1}{12}g_A + \frac{1}{36}a_8\right) + \frac{1}{9}\Delta\Sigma$$ + pQCD corrections

$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

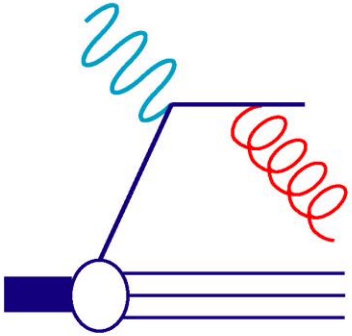
$\Delta\Sigma$ = singlet axial charge

(Extracted from neutron and hyperon weak decay measurements)



$$\begin{aligned} g_A &= \Delta u - \Delta d \\ a_8 &= \Delta u + \Delta d - 2\Delta s \\ \Delta\Sigma &= \Delta u + \Delta d + \Delta s \end{aligned}$$

pQCD radiative corrections



Moments of Structure Functions (continued)

$$\mu_4(Q^2) = \frac{M^2}{9}\left[a_2(Q^2) + 4d_2(Q^2) + 4f_2(Q^2)\right]$$

Twist - 2 (TMC) Twist - 3 Twist -4

where a_2, d_2 and f_2 are higher moments of g_1 and g_2

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

$$a_2(Q^2) = \int_0^1 x^2 g_1(x,Q^2)\,dx$$

Color “

Lorentz Force

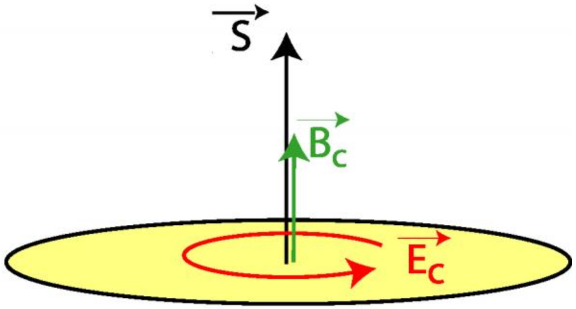
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | \vec{O}_{B,E} | PS \rangle$$

where $\vec{O}_B = \psi^\dagger g \vec{\boldsymbol{B}} \psi$

$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{\boldsymbol{E}} \psi$$



$$\chi_E^n = (4d_2^n + 2f_2^n)/3$$
$$\chi_B^n = (4d_2^n - f_2^n)/3$$

χ_B and χ_E represent an averaged transverse force acting on the struck quark after the system has absorbed the virtual photon.

Nuclear corrections

- Convolution method using the impulse approximation and realistic ground state wave functions of ^{3}He (in Bjorken limit: $g_1^{^3He}$ related to g_1^N).
  - ↑ Variational Method,
    - ↪C. Ciofi degli Atti & S. Scopetta, Phys. Lett. B 404 (1997) 223, for g_1, for g_2 , S. Scopetta. private communication
  - ↑ Faddeev
    - ↪F. Bissey et al. Phys. Rev. C 64 (2001) 024004
- Finite Q^2 effects (both g_1^N and g_2^N contribute to $g_1^{^3He}$ and to $g_2^{^3He}$)
  - ↑ S.A. Kulagin and W. Melnitchouk

Nuclear corrections (continued)

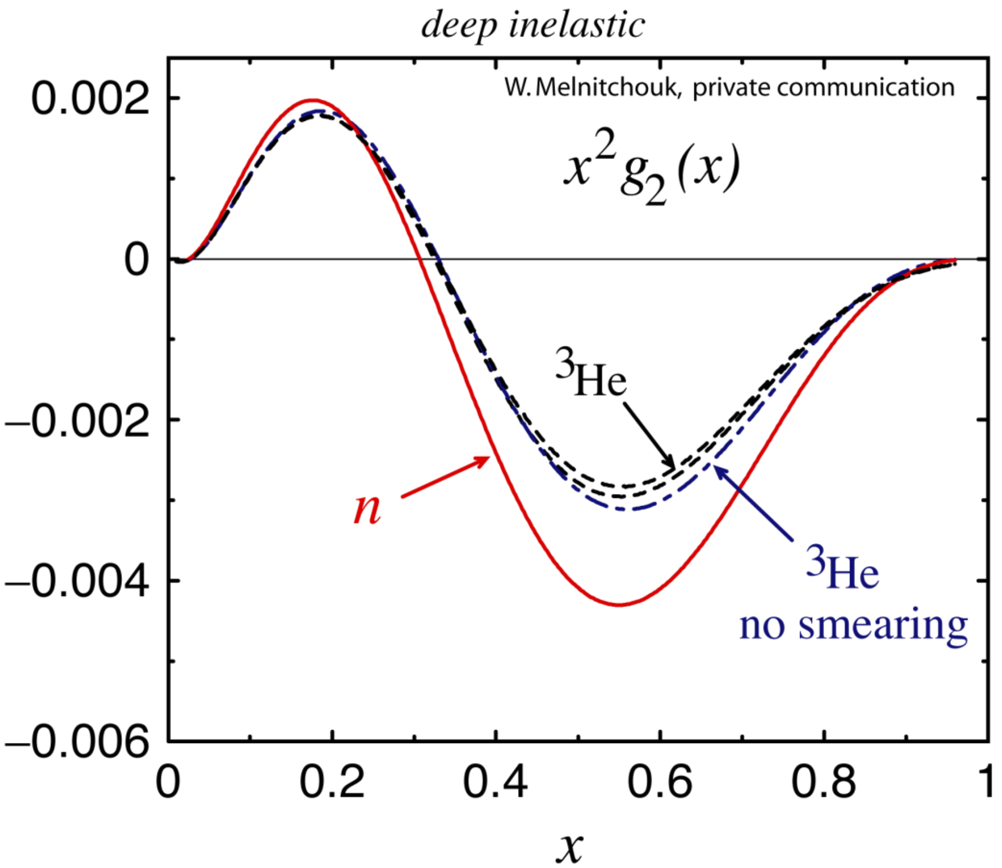
$$S(\vec{p}, E) \ = \ \frac{1}{2}\left(f_0 + f_1 \vec{\sigma}_N \cdot \vec{\sigma}_A + f_2 \left[\vec{\sigma}_N \cdot \hat{p}\ \vec{\sigma}_A \cdot \hat{p}\ - \frac{1}{3}\vec{\sigma}_N \cdot \vec{\sigma}_A\right]\right)$$

$$\begin{aligned} & x g_1^{{}^3\mathrm{He}}(x, Q^2) + (1-\gamma^2) x g_2^{{}^3\mathrm{He}}(x, Q^2) \\ = \ & \sum_{N=p,n} \int d^3p\ dE\ (1 - \frac{\epsilon}{M})\left\{\left[\left(1 + \frac{\gamma p_z}{M} + \frac{p_z^2}{M^2}\right) f_1 + \left(-\frac{1}{3} + \hat{p}_z^2 + \frac{2\gamma p_z}{3M} + \frac{2p_z^2}{3M^2}\right) f_2\right]\ z g_1^N(z, Q^2)\right. \\ & \left. + (1-\gamma^2)(1 + \frac{\epsilon}{M}\left[f_1 + \left(\frac{p_z^2}{\vec{p}^2} - \frac{1}{3}\right) f_2\right] \frac{z^2}{x} g_2^N(z, Q^2)\right\} \end{aligned}$$

$$\begin{aligned} & x g_1^{{}^3\mathrm{He}}(x, Q^2) + x g_2^{{}^3\mathrm{He}}(x, Q^2) \\ = \ & \sum_{N=p,n} \int d^3p\ dE\ (1 - \frac{\epsilon}{M})\left\{\left[\left(1 + \frac{p_x^2}{M^2}\right) f_1 + \left(\vec{p}_x^2 - \frac{1}{3} + \frac{2p_x^2}{3M^2}\right) f_2\right] z g_1^N(z, Q^2)\right. \\ & \left. + \left[\left(1 + \frac{p_x^2}{M^2}(1 - z/x)\right) f_1 + \left(\vec{p}_x{}^2 - \frac{1}{3} + \frac{2p_x^2}{3M^2}(1 - z/x) - \frac{\gamma p_z \hat{p}_x^2}{M}\frac{z}{x}\right) f_2\right] z g_2^N(z, Q^2)\right\} \end{aligned}$$

with $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$ a kinematical factor parameterizing the finite Q^2 correction, $\epsilon \equiv \vec{p}^2/4M - E$, and $z = x/(1 + (\epsilon + \gamma p_z)/M)$.

From ^{3}He to Neutron



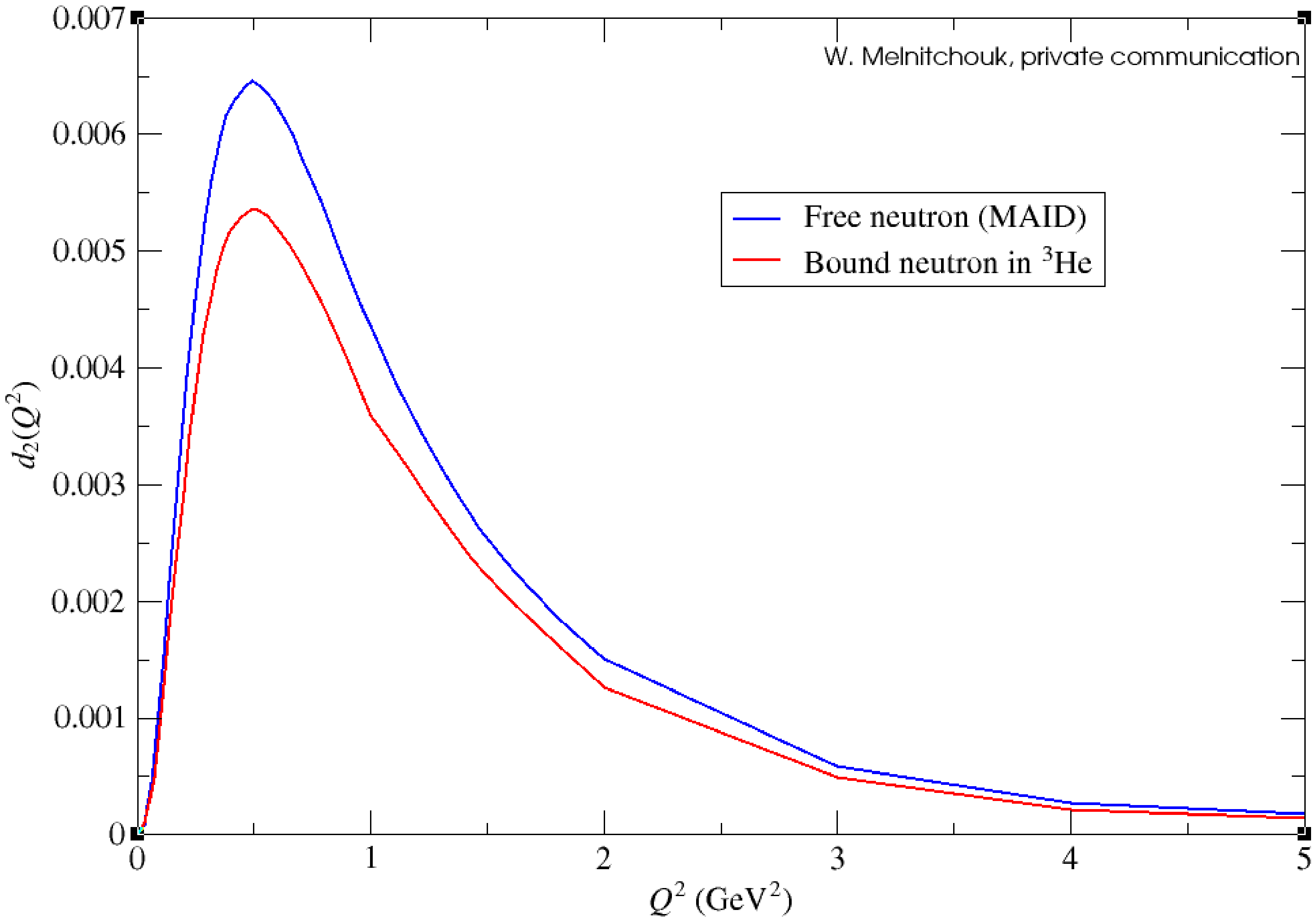
✓Correction large for g_2 but much smaller for d_2

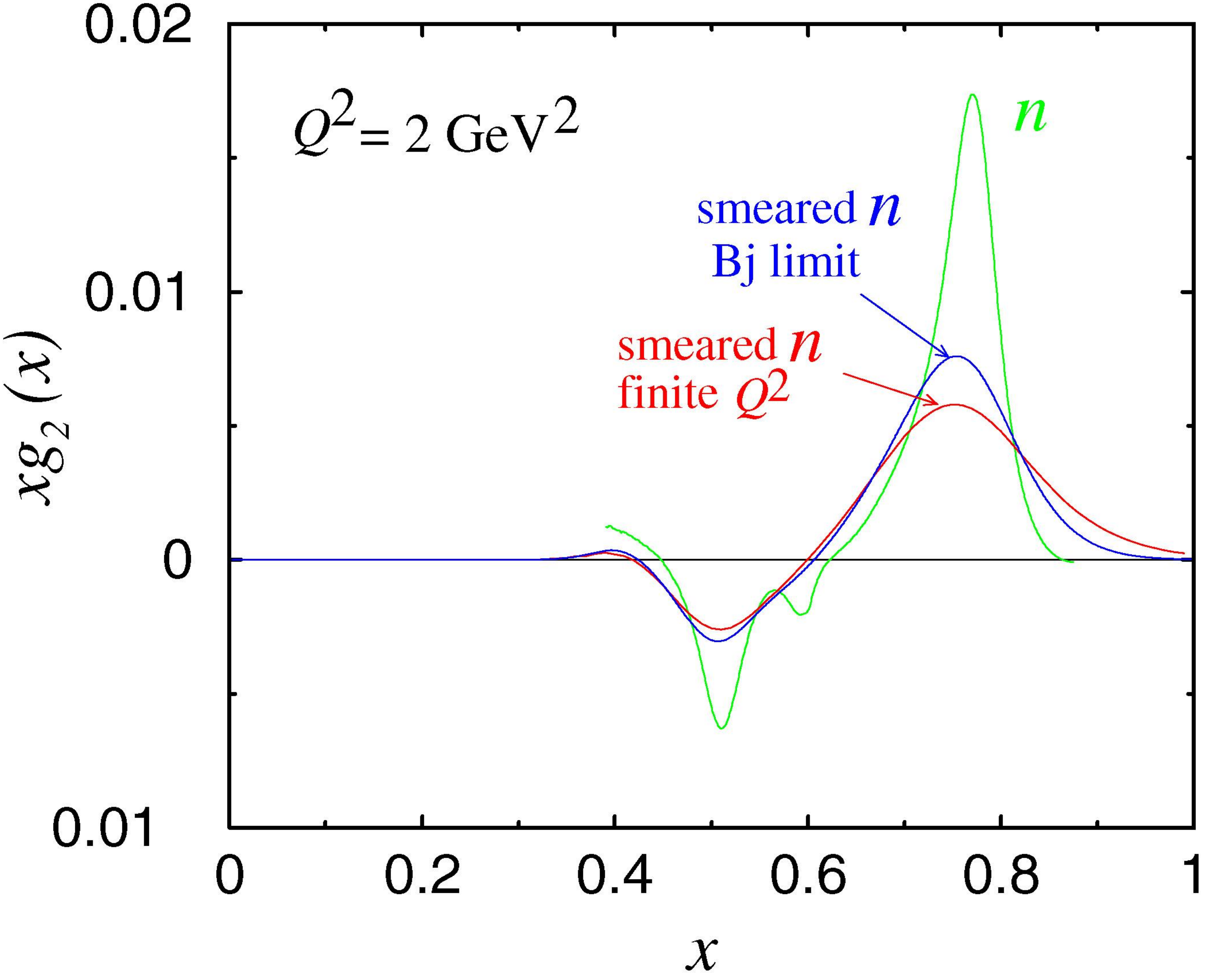
✓About 5% difference between additive or convolution methods or between potential models

$$d_2^n = d_2^{^3He}/(1-\delta^c) \qquad \text{with} \qquad \delta^c \approx 0.35$$

$$\Delta\delta^c \approx 0.15\delta^c \approx 0.05 \qquad \Rightarrow \qquad \Delta d_2^n/d_2^n \approx 5\%$$

Nuclear corrections (continued)




0.02
0.01
0
0.01
0
0.2
0.4
0.6
0.8
1
$xg_2(x)$
x
$Q^2 = 2$ GeV^2
n
smeared n
Bj limit
smeared n
finite Q^2

How $g_2(x,Q^2)$ is usually obtained

$$g_2(x,Q^2) = \frac{\nu}{2E}\left[\frac{\nu\left[1+\epsilon \boldsymbol{R}(x,Q^2)\right](1+\gamma^2)\boldsymbol{F_2}(x,Q^2)\boldsymbol{A_\perp}(x,Q^2)}{(1-\epsilon)2x\left[1+\boldsymbol{R}(x,Q^2)\right]E'\sin\theta_e} - \boldsymbol{g_1}(x,Q^2)\right]$$

where $\nu = E - E'$, $\gamma^2 = Q^2/\nu^2$ and $\epsilon^{-1} = 1 + 2\left[1+\gamma^{-2}\right]\tan^2\theta/2$

$\boldsymbol{F_2}(x,Q^2)$ NMC fit

$\boldsymbol{g_1}(x,Q^2)$ Fit to the data and evolution to a constant Q^2

$\boldsymbol{R}(x,Q^2)$ SLAC fit

d_2 integrand evolution from g_1 and g_2^{ww}