JLab Hall C Neutron A_1^n Experiment

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- How does nucleon spin study fit in QCD/strong interaction study?
- High x spin physics and the upcoming A1n experiment in Hall C of JLab
- Summary and outlook

How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? - Theoretical Aspect

- To understand the compositeness – how do partons form the nucleon spin? – the proton spin crisis/puzzle
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations
- non-perturbative/low-energy/long-distance regime: to test effective field theories that use the hadronic degrees of freedom
- to provide predictions for structure functions
- how hadrons arise from quark and gluon degrees of freedom? – lattice QCD

How does Nucleon Spin Physics Contribute to QCD/Strong Interaction Study? - Observables

- To understand the compositeness - how do partons form the nucleon spin? - moments of spin structure functions (SSF)
- perturbative/high-energy/short-distance regime: to verify perturbative QCD calculations - Q^2 evolution of $F_{1,2}$, g_1, etc
- non-perturbative/low-energy/long-distance regime: to test effective field theories that use the hadronic degrees of freedom
  - SSF moments at very low Q^2/long distances
- to provide/test predictions for structure functions
  - structure function ratios at large x
- How hadrons arise from quark and gluond degrees of freedom?
  - detailed Q2 dependence of SF or SSF moments

Lepton scattering spin structure experiments (mostly inclusive):

Experiment	Ref.	Target	Analysis	W (GeV)	x_{Bj}	Q^2 (GeV^2)
E80 (SLAC)	[101]	p	A_1	2.1 to 2.6	0.2 to 0.33	1.4 to 2.7
E130 (SLAC)	[102]	p	A_1	2.1 to 4.0	0.1 to 0.5	1.0 to 4.1
EMC (CERN)	[103]	p	A_1	5.9 to 15.2	1.5×10^{-2} to 0.47	3.5 to 29.5
SMC (CERN)	[250]	p, d	A_1	7.7 to 16.1	10^{-4} to 0.482	0.02 to 57
E142 (SLAC)	[244]	^{3}He	A_1, A_2	2.7 to 5.5	3.6×10^{-2} to 0.47	1.1 to 5.5
E143 (SLAC)	[245]	p, d	A_1, A_2	1.1 to 6.4	3.1×10^{-2} to 0.75	0.45 to 9.5
E154 (SLAC)	[246, 247]	^{3}He	A_1, A_2	3.5 to 8.4	1.7×10^{-2} to 0.57	1.2 to 15.0
E155/x (SLAC)	[248, 249]	p, d	A_1, A_2	3.5 to 9.0	1.5×10^{-2} to 0.75	1.2 to 34.7
HERMES (DESY)	[253, 254]	p, ^{3}He	A_1	2.1 to 6.2	2.1×10^{-2} to 0.85	0.8 to 20
E94010 (JLab)	[256]	^{3}He	g_1, g_2	1.0 to 2.4	1.9×10^{-2} to 1.0	0.019 to 1.2
EG1a (JLab)	[257]	p, d	A_1	1.0 to 2.1	5.9×10^{-2} to 1.0	0.15 to 1.8
RSS (JLab)	[258, 259]	p, d	A_1, A_2	1.0 to 1.9	0.3 to 1.0	0.8 to 1.4
COMPASS (CERN) DIS	[251]	p, d	A_1	7.0 to 15.5	4.6×10^{-3} to 0.6	1.1 to 62.1
COMPASS (CERN) low-Q^2	[280]	p, d	A_1	5.2 to 19.1	4×10^{-5} to 4×10^{-2}	0.001 to 1.
EG1b (JLab)	[260, 261, 262, 263]	p, d	A_1	1.0 to 3.1	2.5×10^{-2} to 1.0	0.05 to 4.2
E99-117 (JLab)	[264]	^{3}He	A_1, A_2	2.0 to 2.5	0.33 to 0.60	2.7 to 4.8
E99-107 (JLab)	[265]	^{3}He	g_1, g_2	2.0 to 2.5	0.16 to 0.20	0.57 to 1.34
E01-012 (JLab)	[266, 267]	^{3}He	g_1, g_2	1.0 to 1.8	0.33 to 1.0	1.2 to 3.3
E97-110 (JLab)	[268]	^{3}He	g_1, g_2	1.0 to 2.6	2.8×10^{-3} to 1.0	0.006 to 0.3
EG4 (JLab)	[269]	p, n	g_1	1.0 to 2.4	7.0×10^{-3} to 1.0	0.003 to 0.84
SANE (JLab)	[271]	p	A_1, A_2	1.4 to 2.8	0.3 to 0.85	2.5 to 6.5
EG1dvcs (JLab)	[270]	p	A_1	1.0 to 3.1	6.9×10^{-2} to 0.63	0.61 to 5.8
E06-014 (JLab)	[272, 273]	^{3}He	g_1, g_2	1.0 to 2.9	0.25 to 1.0	1.9 to 6.9
E06-010/011 (JLab)	[278]	^{3}He	single spin asy.	2.4 to 2.9	0.16 to 0.35	1.4 to 2.7
E07-013 (JLab)	[72]	^{3}He	single spin asy.	1.7 to 2.9	0.16 to 0.65	1.1 to 4.0
E08-027 (JLab)	[309]	p	g_1, g_2	1. to 2.1	3.0×10^{-3} to 1.0	0.02 to 0.4

JLab's focus is high precision, low to intermediate Q^2 values, and high x

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focus of this talk

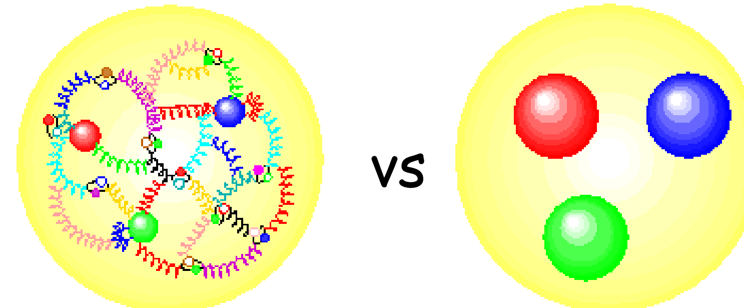
Upcoming Experiments

The A1n and d2n experiments are scheduled to run in Fall 2019 and Spring 2020, using the polarized 3He target in Hall C. These will be the first experiments to use the stage-I upgraded target after the 12 GeV upgrade of JLab

Similar proton measurements will be carried out in Hall B (CLAS12), using an upgraded NH3/ND3 target. It will likely run in or after 2021.

Nucleon (spin) Structure at High x_{Bj}

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

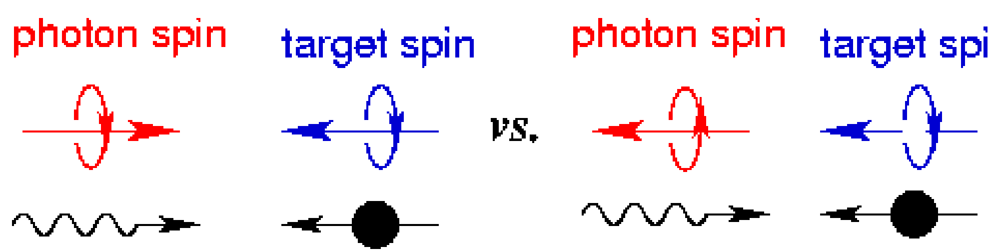


The far valence domain (x>0.5)

- involve only valence quarks
- is the only domain where QCD (and many other models) can make absolute predictions for (the ratio of) structure functions
- "the ratio of structure functions at x→ 1 provide unambiguous, scale invariant, non-perturbative features of QCD"

☆ F_2^p/F_2^n and d/u

☆ A_1^p, A_1^n , or $\Delta u/u$ and $\Delta d/d$



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

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1}$$ 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

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

Model	F_2^n/F_2^p	d/u	$\Delta u/u$	$\Delta d/d$	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 (realistic)	0.49	0.28	0.65	-0.26	0.17	0.59
DSE-2 (contact)	0.41	0.18	0.88	-0.33	0.34	0.88

- The only place where models and/or QCD can make absolute predictions for structure functions.

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

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

hyperfine interaction: the two quarks in the spectator di-quark prefer to form a S=0 to a S=1 state.
– based on nucleon-Delta mass splitting, etc.
– but the breaking of SU(6) may not be that big.

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

A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

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

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- Why hasn’t this been done done already?

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  - high x → small PDF → smaller x-section → low rate;   x=1 means xsec=0!

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➔ high x → high Q^2 → smaller x-section → low rate

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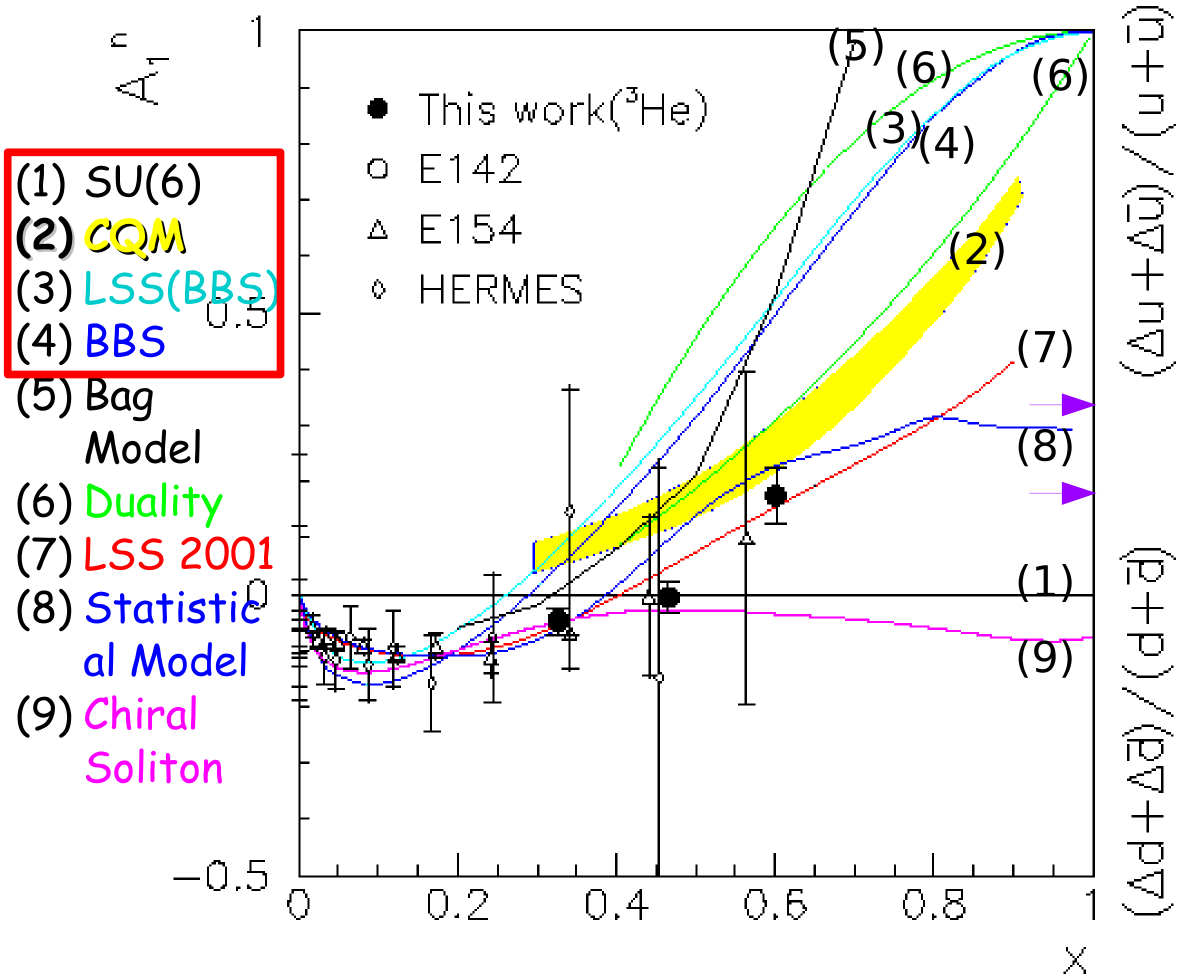
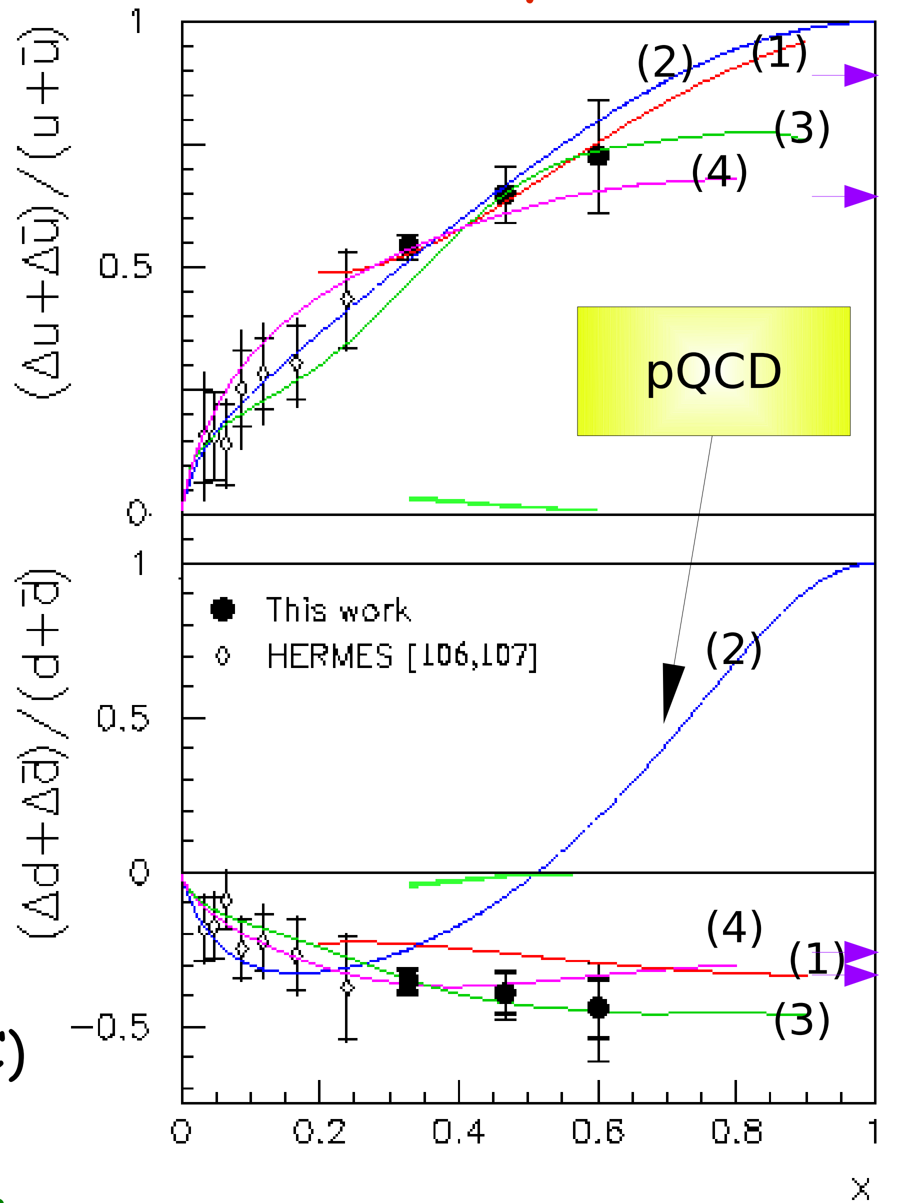
✔ need high intensity beam → JLab

✔ need dense polarized nucleon target → polarized NH_3, ND_3, polarized ^3He – with high polarization

The 6 GeV Hall A Measurement (21 PAC days, 2001)



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



E99117 spokespeople: Jianping Chen, Zein-Eddine Mezianie, Paul Souder;
PhD student: X. Zheng

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

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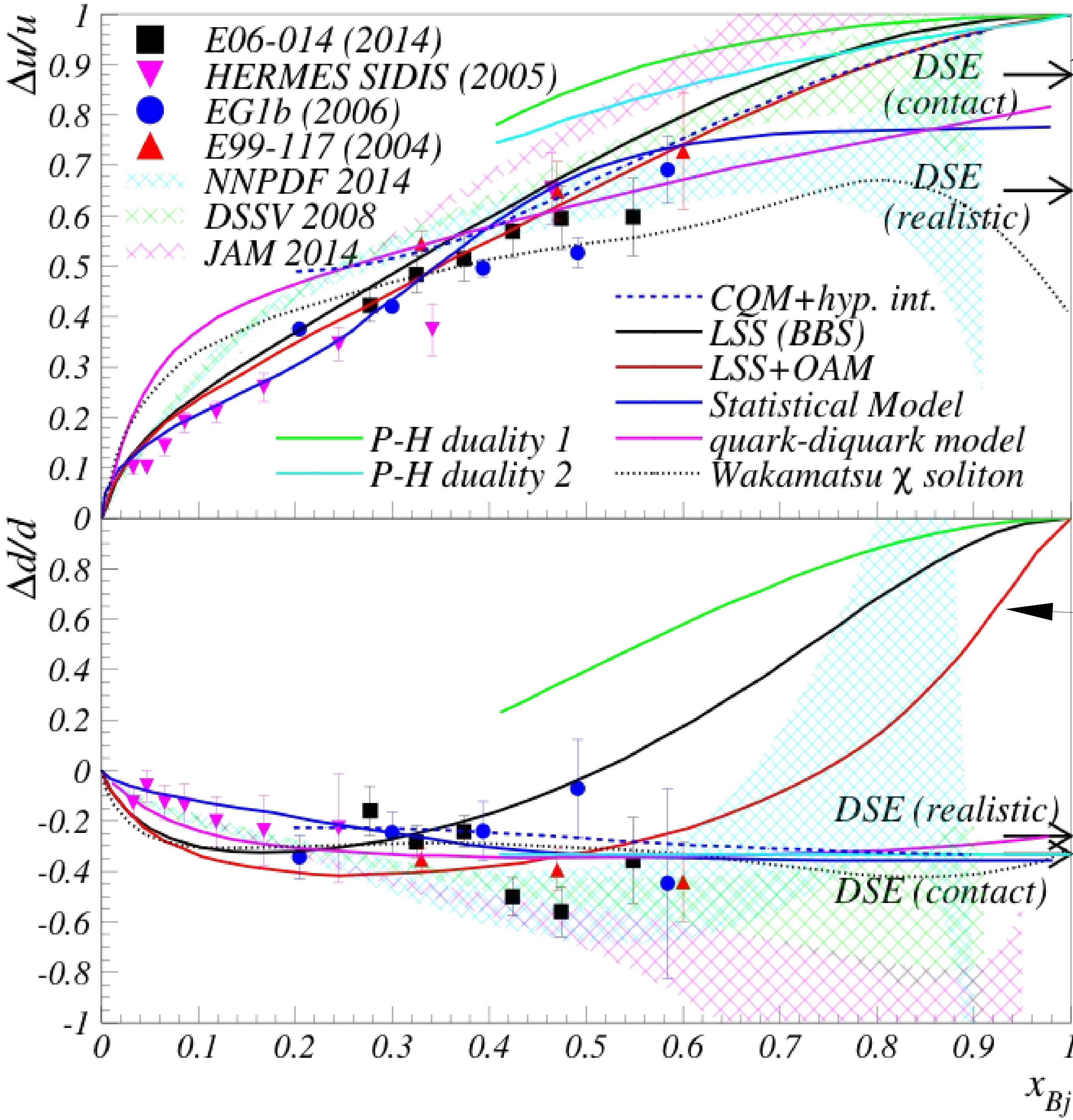

A non-perturbative, (low-energy) effective theory. Non-pointlike diquark correlations as a result of dynamical chiral symmetry breaking. Predictions used diquark probabilities extracted from nucleon elastic form factors

pQCD: the struck quark is free + constraint on the gluon exchange within the diquark → the struck quark must carry nucleon's helicity at $x \to 1$

now added quark OAM, but $\Delta d/d$ still must be 1 at $x=1$

- Thus, high x "valence quark" region is an ideal case to test our understanding of strong interaction, QCD, and models.
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✔ need high intensity beam → JLab

✔ need dense polarized nucleon target → polarized NH3, ND3, polarized 3He – with high polarization

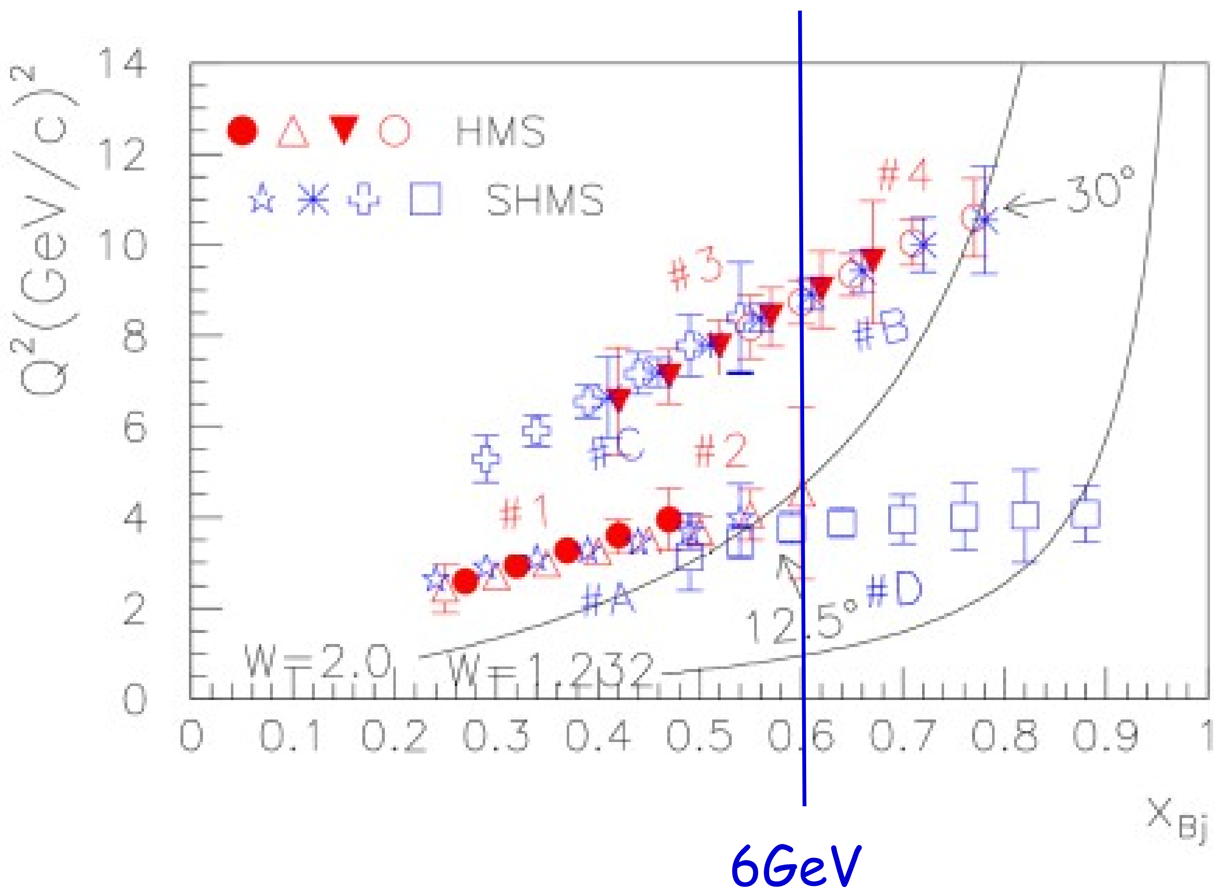
✔ need higher energy to reach high x → JLab 12 GeV upgrade

✔ Even smaller x-section → polarized 3He target upgrade.

Reaching Deeper Valence Quarks Region with 12 GeV

12 GeV A_1^n in Hall C

- First proposed in 2006 (simplified simulation), rated as high-impact in 2009;
- 30 uA 11 GeV polarized beam on 20-cm long polarized 3He target (~10atm)
- HMS and SHMS detect scattered electrons independently



CLAS12 Kinematics

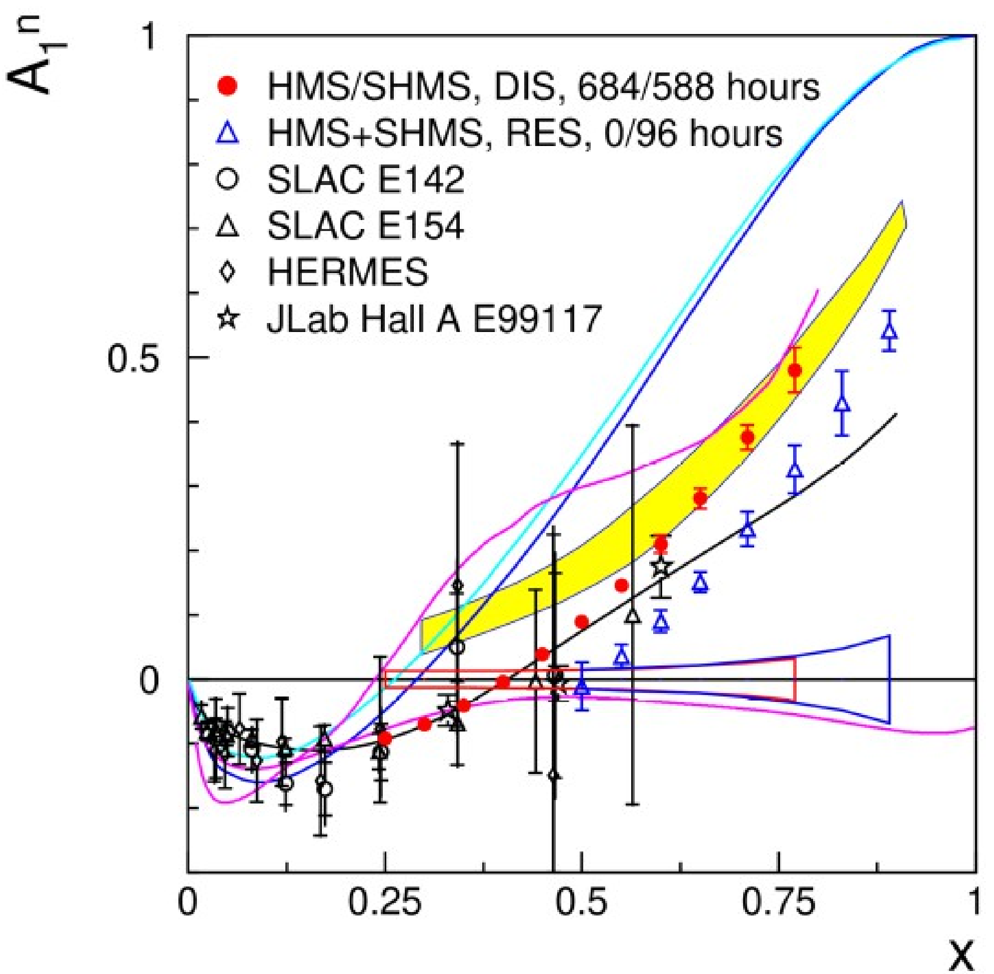
See next talk by S. Kuhn !

Expected Results

CLAS12 with 80 days

See next talk by S. Kuhn !

Hall C with 36 "PAC" days
assuming Pb=85%, Ptarg=55%



Spokespeople: Gordon Cates, JP Chen, Zein-Eddine Mezianni, X. Zheng;

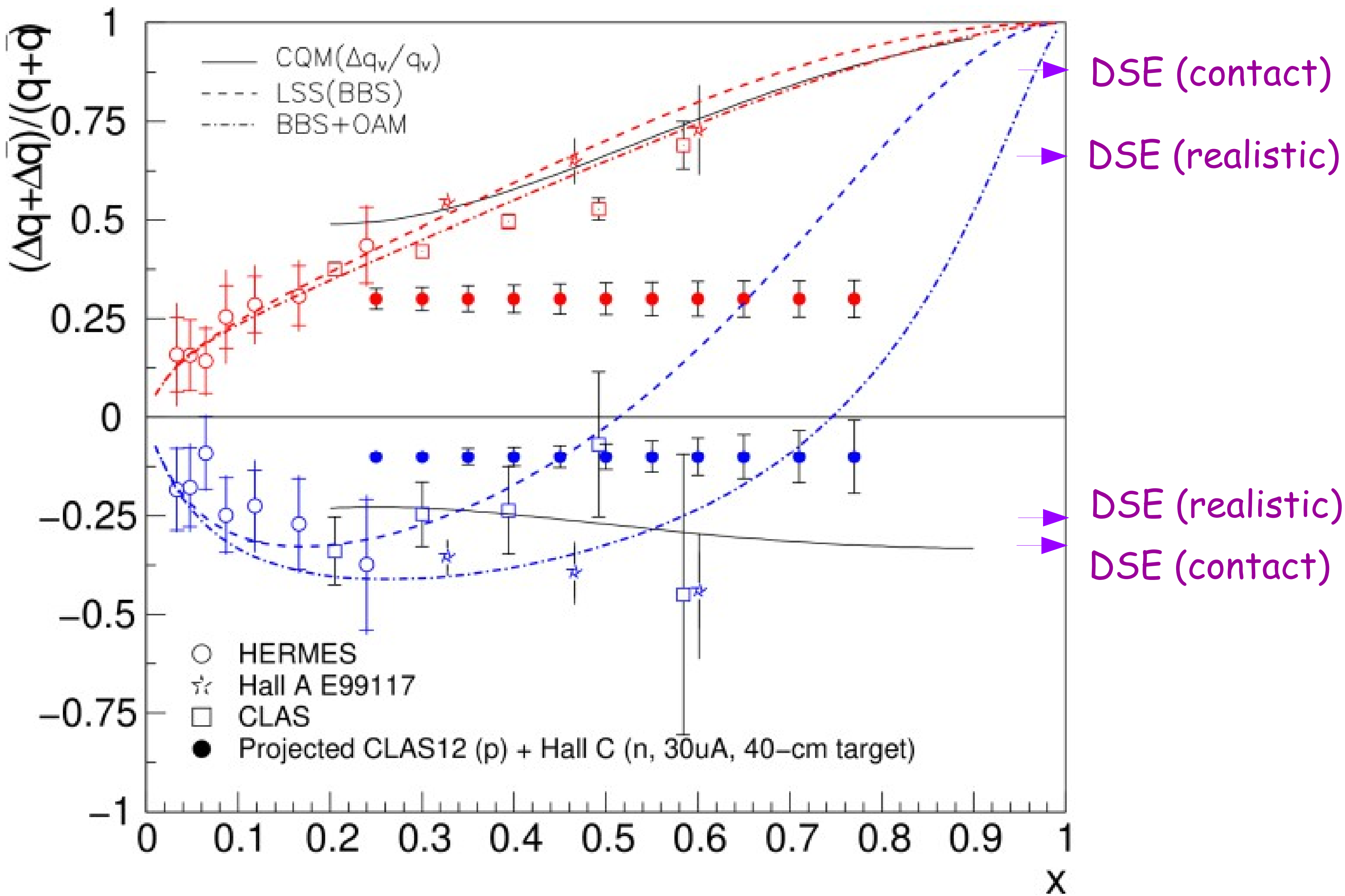
Ph.D. students: Mingyu Chen (UVa), Melanie Rehfuss (Temple);

Postdocs: Arun Tadepalli (JLab), Jixie Zhang (UVa) + others

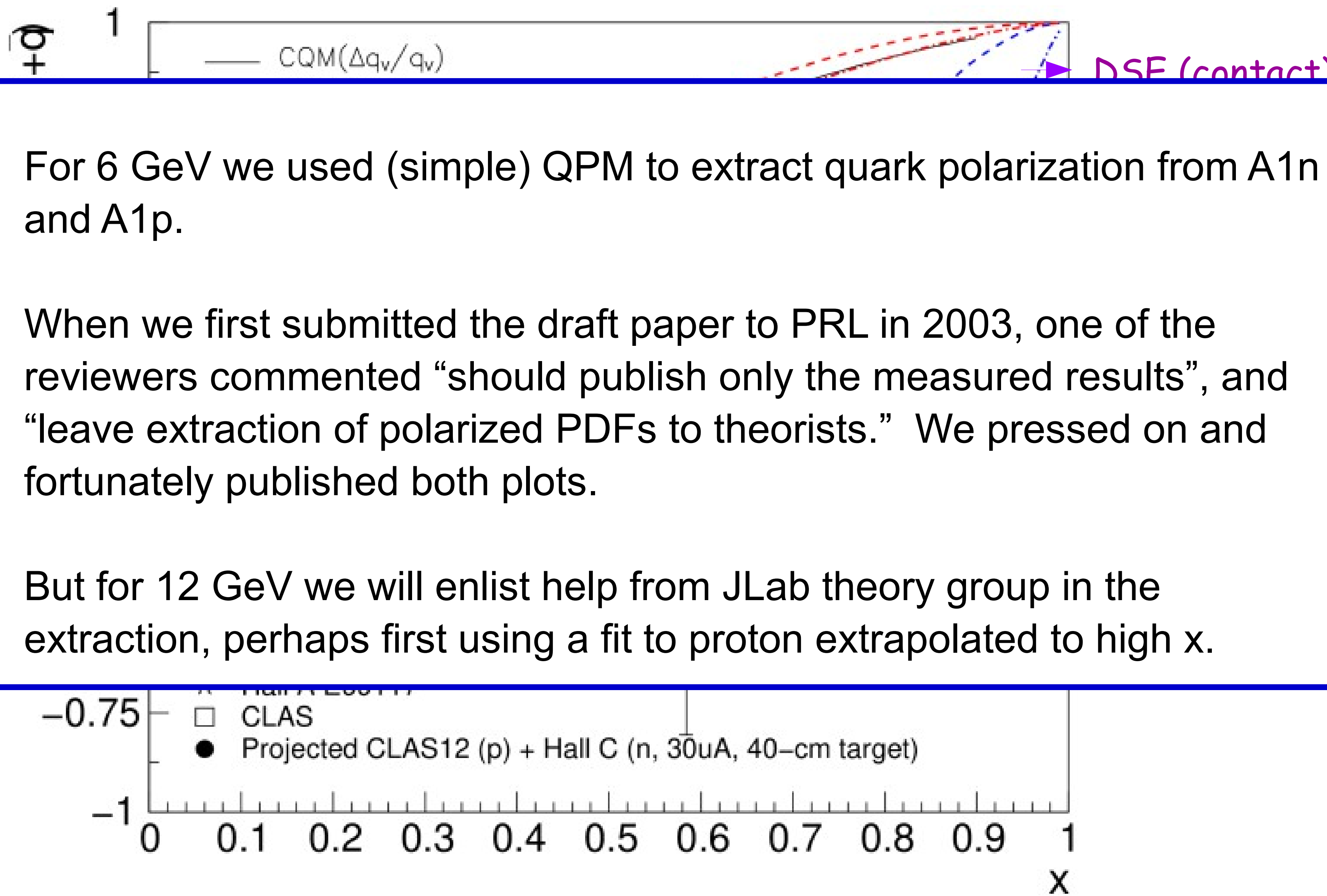
CLAS12 proton expected results:

See next talk by S. Kuhn !

Extracting Δq/q from both proton and neutron (^{3}He) data



Extracting Δq/q from both proton and neutron (^{3}He) data



For 6 GeV we used (simple) QPM to extract quark polarization from A1n and A1p.

When we first submitted the draft paper to PRL in 2003, one of the reviewers commented "should publish only the measured results", and "leave extraction of polarized PDFs to theorists." We pressed on and fortunately published both plots.

But for 12 GeV we will enlist help from JLab theory group in the extraction, perhaps first using a fit to proton extrapolated to high x.

Extracting $\Delta q/q$ from both proton and neutron (^{3}He) data

I happened to have a phone conversation with one of my theorist friends one day. It went like this:

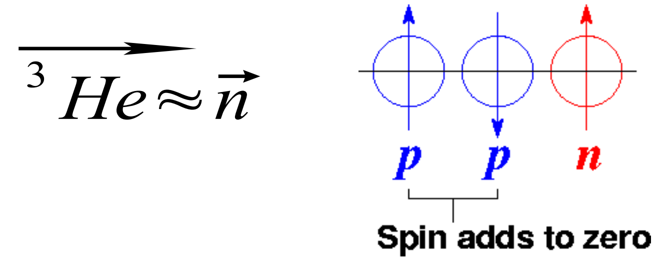
Th: "how are you doing? What are you working on these days?"
Me: "going slow, nobody has time to do anything while teaching, but A1n is coming up online this year."
Th: "Oh really? So you are going to see delta d/d turning positive?"
Me: "Why? We need to measure it. What if it stays negative? I have a feeling it will."
Th: "No it can't. If it doesn't turn positive we will all be in trouble…"

I have since wondered what kind of trouble we will be in.

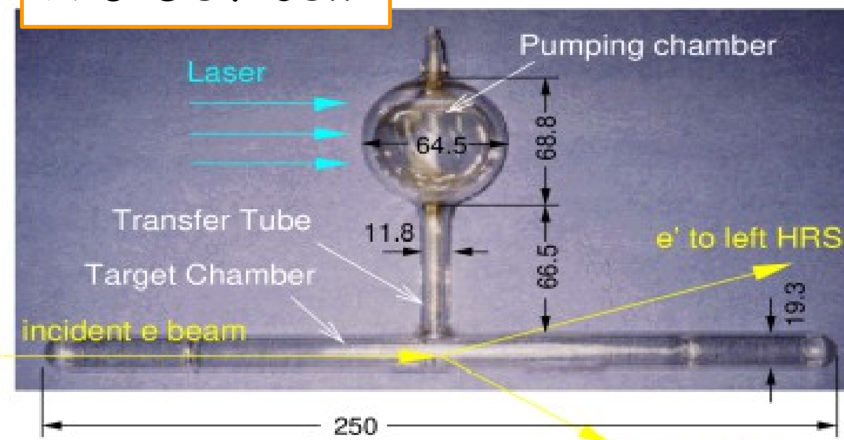
Polarized ^{3}He Target

Spin_Exchange Optical Pum

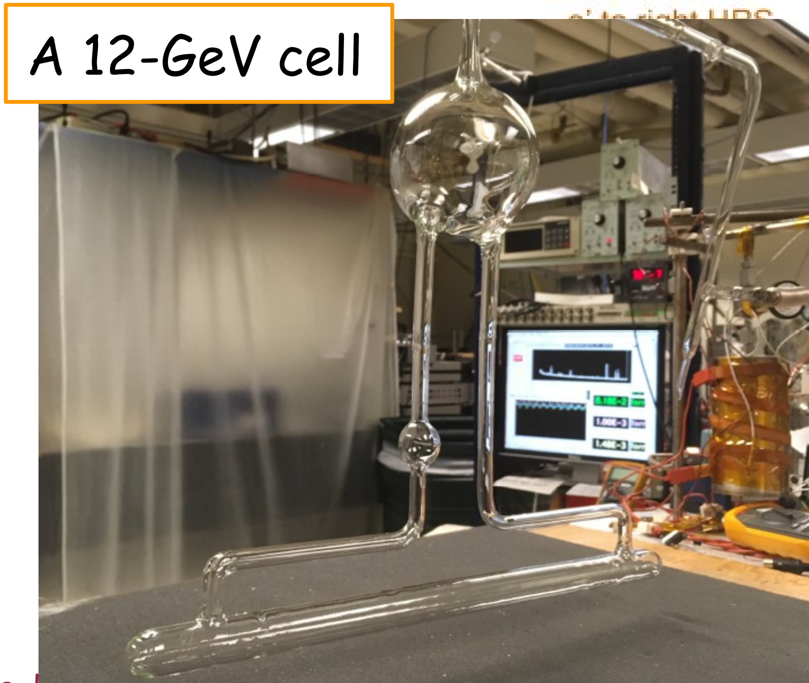
Rubidium atom

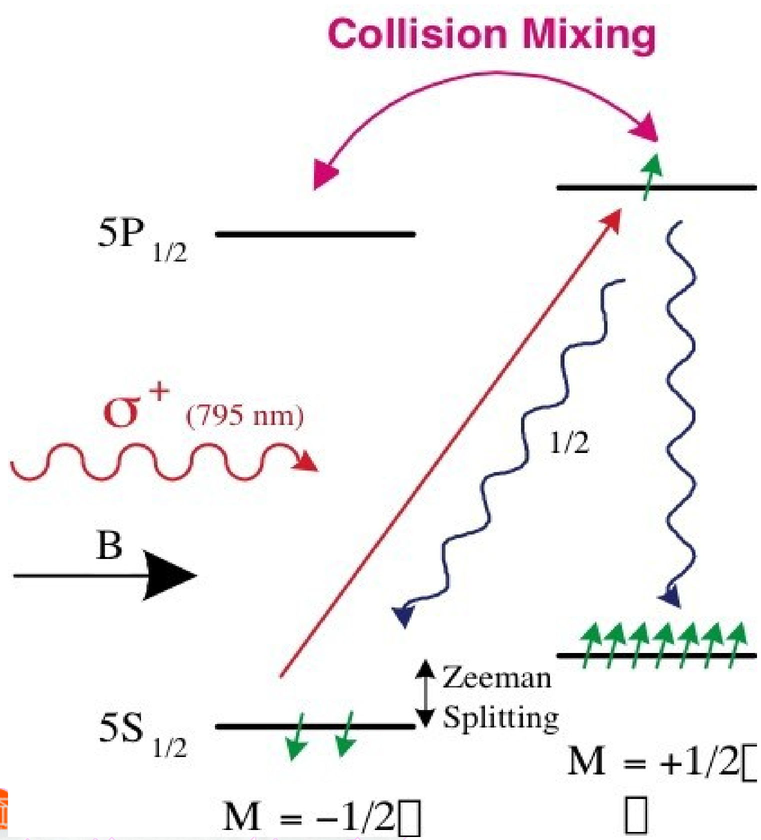


A 6-GeV cell



A 12-GeV cell





Stage-I Polarized 3He Target Upgrade

Polarized 3He target using spin-exchange optical pumping (SEOP) technique;

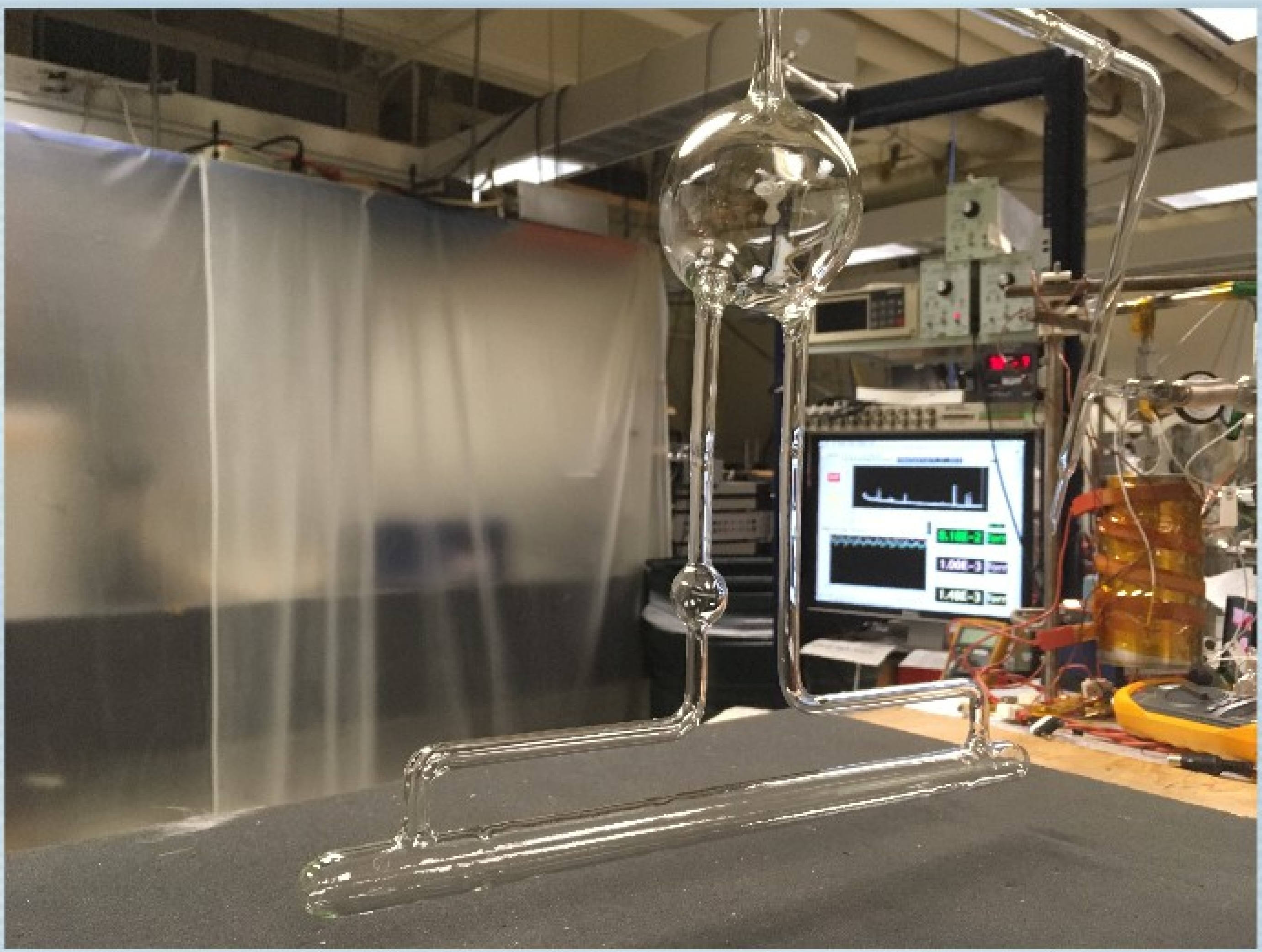
6 GeV era: reached 55%, 15uA, 40cm, 10amg;

11 GeV era:

stage I upgrade: 55% in beam , 30uA, 40cm, 10amg; (Hall C A1n/d2n)

stage II upgrade: 60% in beam, 60uA, 40cm, 10amg; (SBS GEn)

First production A_1^n target: Savior



On the gas system prior to being filled.

Current Target Cell Status for A1n/d2n

Cell name	Birthday (fill date)	cold spin down lifetime (hrs)	Max polarization	Expected in-beam polarization	Current status
Savior (?)	2016	42 (UVa); 28 (JLab)	65% (UVa); ? (JLab)	60% → ?	possible laser damage, back to UVa for re-testing
Fulla	9/7/2019	17 (UVa); 15 (JLab)	53% (UVa); 54% (JLab)	50%	in oven at JLab, finishing up
Brianna	3/27/2019	23 (UVa)	53% (UVa)	48%	possible laser damage
Flurence	9/28/2018	11 (UVa)	45% (UVa)	44%	

Other cells made: Elle, Sandy-II, Phoenix, Zoe;

Both UVa and W&M groups making new cells around the clock;

Cell testing around the clock for the past weeks (JLab, UVa Gordon Cates' group);

Will start moving the target into Hall C on Monday;

Summary and Outlook

- The upcoming (2019-2020) A_1 experiments in Hall C (neutron) will venture into a deeper valence quark region.
- Four Ph.D. students committed to two experiments A1n+d2n. Three have been working on the target for 2-3 years. In addition Chris Jantz UVa will be the Ph.D. student focusing on target upgrade (cell making + testing).
- At the moment, we are preparing for target installation.
- Experiment planned to start before Thanksgiving 2019 with A1n high x/high Q2 settings until ? Feb/March 2020 (with a 20-day break for X'mas + restore), then rotate the target coils, then run A1n low x/low Q2 settings and d2n. If all goes well, will run until May 2020.
- Shift schedule will be up later, please come take some shifts. Good food promised, and maybe even Turkey dinner!