Studying the Isovector EMC Effect with Parity-Violating Electron Scattering

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Outline

- Motivation
- Proposed Experiment
- Anticipated Results and Systematics

Collaboration

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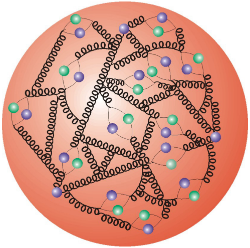
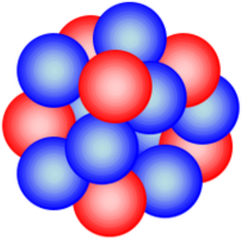
and the SoLID Collaboration

QCD in Nucleons and Nuclei

QCD Questions

- How do we reconcile the picture of quarks and gluons with nucleons and nuclei?
- What is the nature of bound nucleons and how are they modified?
- Is there a direct connection between nuclear and parton-level modification observables?





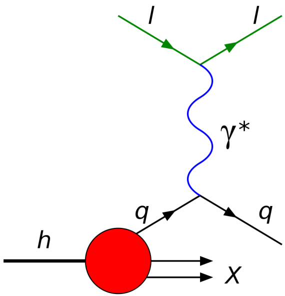
DIS

- DIS with leptons offers picture into partonic distributions

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

$$F_2(x,Q^2) = x\sum_q e_q^2\left(q(x,Q^2) + \bar{q}(x,Q^2)\right),$$

$$F_L \approx F_2 - 2xF_1$$



- Highly successful for our modern picture of quark degrees of freedom and pQCD
- PDFs have been well determined over a broad range after decades of study

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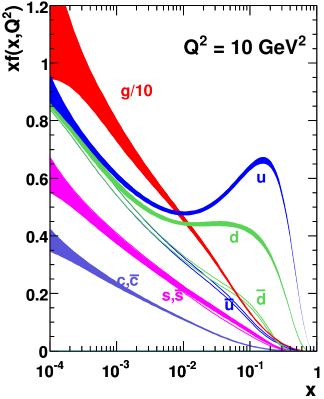

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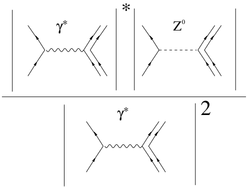
PVDIS

PVDIS proves new flavor combinations $\to$ isovector properties

$A_{\mathrm{PV}} \sim$



$\sim 100 - 1000$ ppm

$$\approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x)\right], y = 1 - \frac{E'}{E}$$

$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}, a_3(x) = 2\frac{\sum C_{2q} e_q (q-\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

Effective Weak Couplings

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W = -0.19 \qquad C_{2u} = -\frac{1}{2} + 2\sin^2\theta_W = -0.03$$

$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W = 0.34 \qquad C_{2d} = \frac{1}{2} + 2\sin^2\theta_W = 0.03$$

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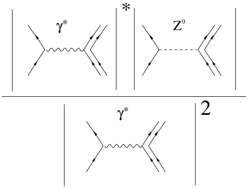

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Symmetric nucleus limit

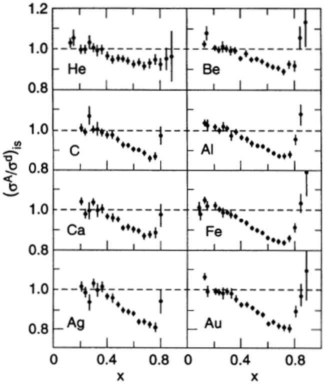
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$

where $u_A = u$ in p *and* u in n

EMC Effect

Nuclear Modification

- First observed in 1984 by EMC collaboration
- Showed reduced presence of partons in $0.3 < x < 0.7$
- Generally greater effect as one pushes to higher A
- Not due to simple binding effects - real modification of structure



J. Gomez et *al.*, *PRD49 4348 (1994)*

General assumption of $u \leftrightarrow d$ for $p \leftrightarrow n$

PVDIS can test this

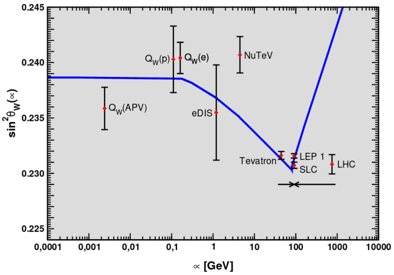
Isovector Dependence? - NuTeV

- Neutrino scattering (charged current and neutral current) is sensitive to different flavor combinations

Pachos-Wolfenstein relation:

$$R_{\mathrm{PW}} \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)}$$

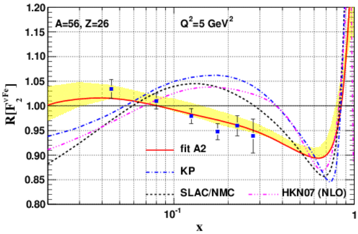
$$= \lim_{\to \mathrm{i.s.}} \frac{1}{2} - \sin^2 \theta_W$$

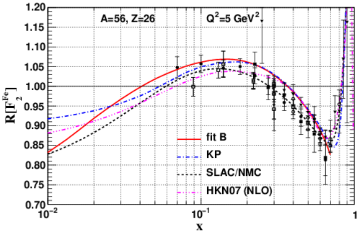


- Asymmetric nuclei (iron) need corrections
- CSV or IVEMC could play very important role and are not well constrained by data

Isovector Dependence? - Partitioned Fits

- Existing fits to world data show controversy
- Studies partitioning data between lepton/Drell Yan and ν show significant incompatibilities in nuclear corrections using common PDFs

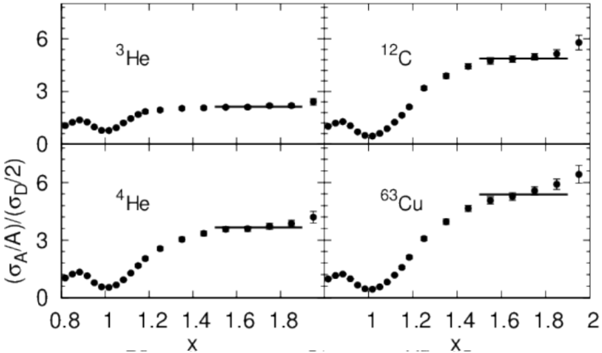




I. Schienbein et *al.* PRD77 054013 (2008); I. Schienbein et *al.* PRD80 094004 (2009)

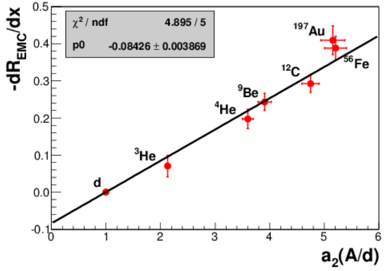
Isovector Dependence? - SRC

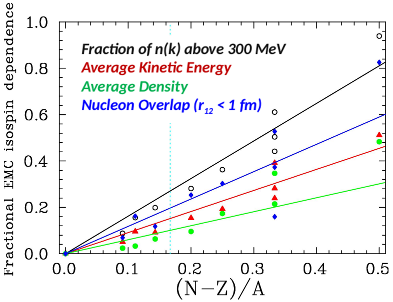
- SRC show strong preference to n-p pairs over p-p pairs
- Also show strong correlation to "plateau" parameter for $x > 1$ SFs



Isovector Dependence? - SRC

- SRC show strong preference to n-p pairs over p-p pairs
- Also show strong correlation to "plateau" parameter for $x > 1$ SFs
- Preliminary models make predictions of deviations for asymmetric nuclei

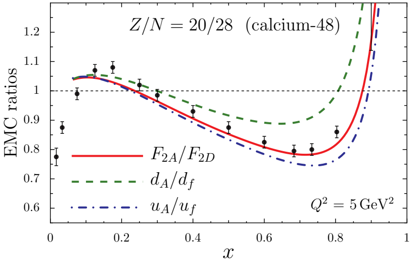


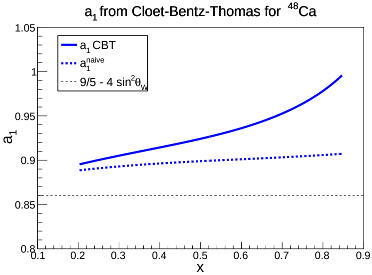


Arrington, EPJ Web Conf. 113, 01011 (2016)

Modeling - CBT Model

- Cloet et *al.* make predictions based on mean field calculations which give reasonable reproductions of SFs
- Explicit isovector terms are included constrained by nuclear physics data such as the symmetry energy
- Few percent effect in a_2, larger at larger x

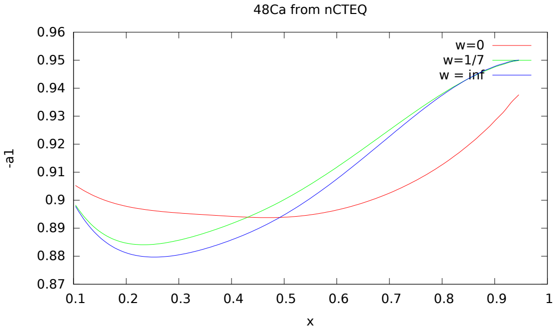




Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

Modeling - nPDFs

- Varying weights in fits between lepton/Drell Yan and ν can show tension between data sets
- nCTEQ fits show dramatic differences in a similar vein at CBT
- Few percent effect in a_2



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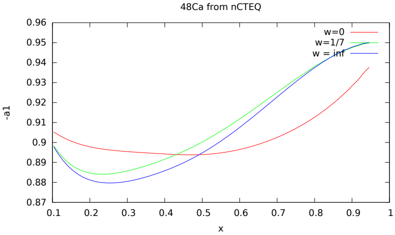
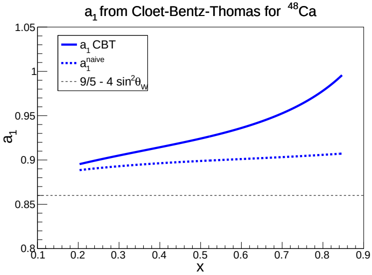


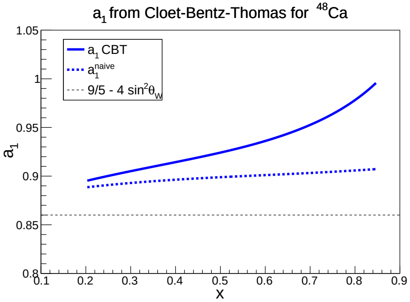


Where to get constraint

- Neutral currents will provide access to isovector observables
- Present data demands $\sim 1\%$ level for significant tests
- LD_2 will constrain CSV as isoscalar target (as well as $R^{\gamma Z}$)
- Asymmetric target will test isovector dependence - larger A gives larger EMC, larger $Z - N$ gives IV enhancement

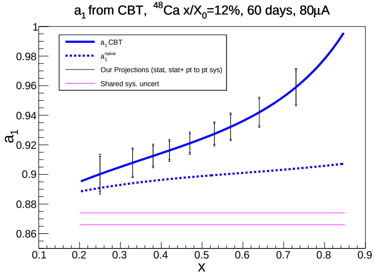
Symmetric nucleus limit

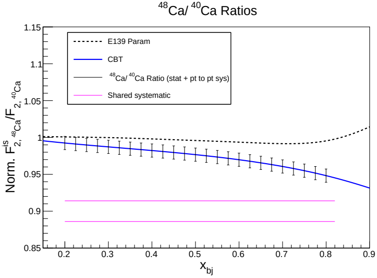
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$



Other Methods

PVDIS offers highest sensitivity and is required for full picture





	PVEMC (this prop.)	EMC E12-10-008
Statistics	0.7-1.3%	0.8-1.1%
Systematics	0.5%	0.7%
Normalization	0.4%	1.4%
CBT x-dependence	5%	3%
CBT sensitivity	5.6σ	$< 3\sigma$

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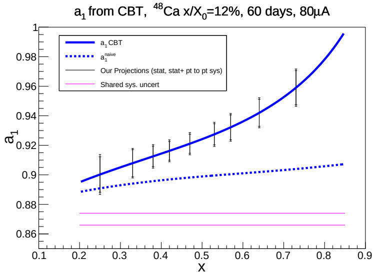
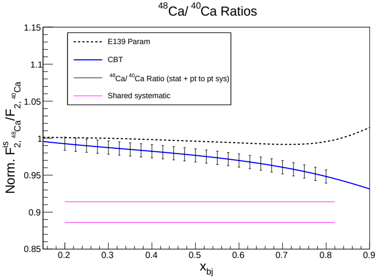
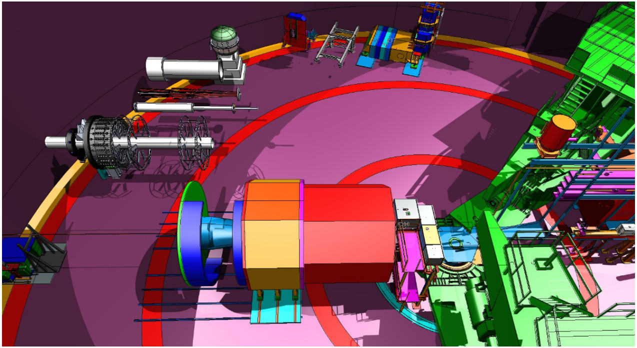




- PVDIS naturally sensitive to flavor *differences*
- DIS and PVDIS allows for flavor determination
- Other processes such as tagged SIDIS and π Drell-Yan offer complementary information
- Experiments such as SRC help motivate and tie into this program

SoLID

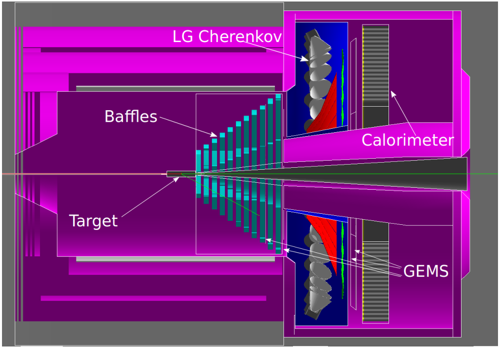
- High luminosity, large acceptance DIS and Parity Violation
- Opportunities for Several Measurements
  - SM Tests
  - Nucleon structure
  - Nuclear Medium Modification



PVDIS Measurements - SoLID Proposed Setup

Solenoidal **L**arge **I**ntensity **D**evice - 12 GeV Hall A at JLab

More than 200 collaborators at over 60 institutions



SoLID provides large acceptance

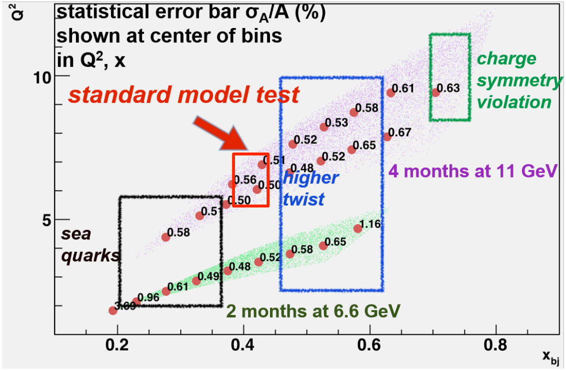
- $2 < p < 8$ GeV
- $2 < Q^2 < 10$ GeV^2
- $0.2 < x_{bj} < 1$
- Acceptance $\sim 40\%$
- Lumin $\sim 5 \times 10^{38}$ Hz/cm^2

- Parity-violation requires lots of statistics - need high rate
- Want to cover broad kinematic range - need large acceptance
- High impact \$ $\sim$50M project, 2020+ in the future
- Program also includes SIDIS, J/ψ at threshold, TCS, SSA, possible w/ EMC PVDIS, DDVCS, PV polarized PDFs...

Approved Measurement

- Approved at PAC 37 (2011) for 169 days (requested 338)

LD_2, 120 days:

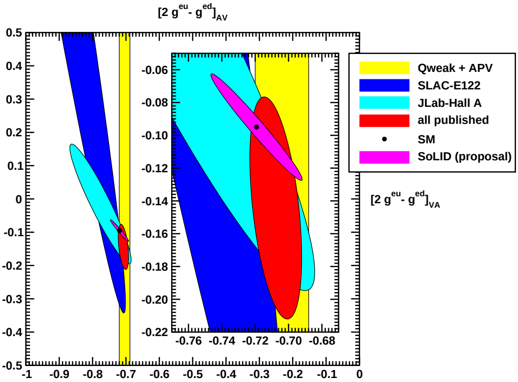


- 120 days on LD_2 (60 at 11 GeV, 60 at 6.6 GeV)
- Sub-1% precision - need polarimetry advances
- Also, 90 days on LH_2 11 GeV

PVDIS Physics - Precision

- Deuterium powerful, since $q(x)$ cancel for large x

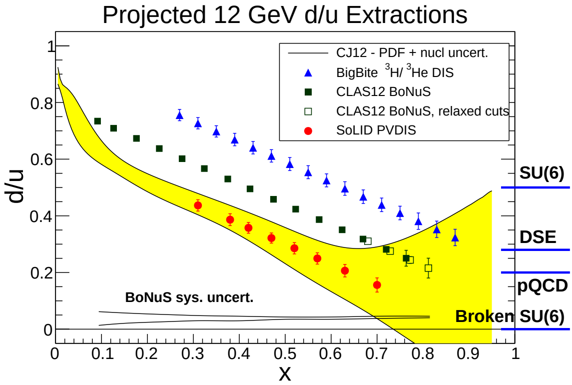
$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$



- Sub - 1% data at $Q^2 \sim 6-7$ GeV^2 range dramatically improves constraints
- New contact interactions $1/\Lambda^2$ contrained into ~ 10 TeV range

Clean Measurement of d/u with PVDIS

- d/u as $x \to 1$ gives information on valence quark dynamics - models give varying predictions on behavior
- Flavor extraction difficult at high x because no free neutrons
- Wally Melnitchouk tomorrow over PVDIS and nucleon structure



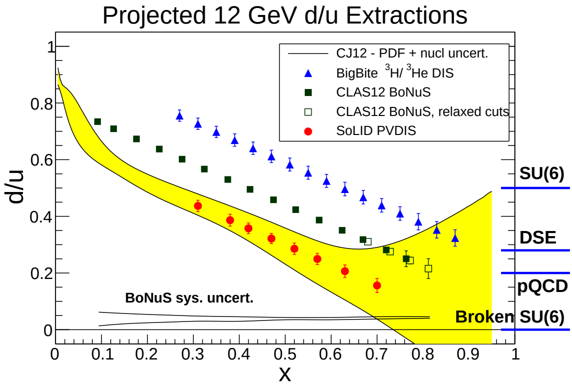
- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS ^{3}H/^{3}He Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*
- Disagreement would also signal CSV

DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

Clean Measurement of d/u with PVDIS

For high x on proton target:

$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$



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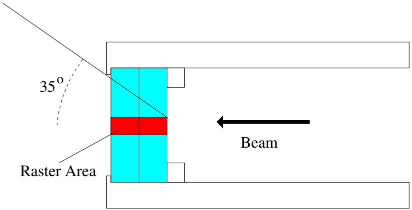
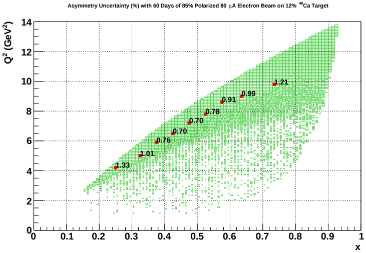
Target - ^{48}Ca

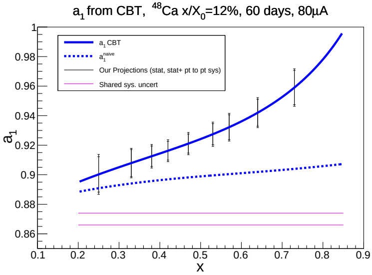
- ^{48}Ca target provides good balance between asymmetric target and not too high Z
- Has very good thermal conductance and high melting point - have operational experience with previous program and upcoming CREX
- 12% radiator - photons and photoproduced pions are main background concerns



Projections

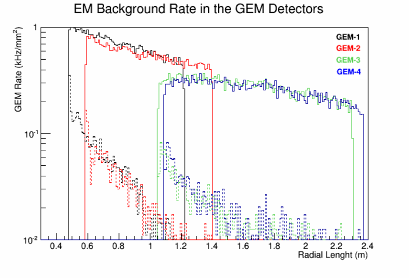
- Requesting 60 days at 80 μA 11 GeV production (71 days total) to get $\sim$1% stat uncertainties across a broad range of x
- In the context of the CBT model, this is few sigma in very simple interpolation model
- *This provides new and useful constraints in a sector where there is little data*





Rates and Backgrounds

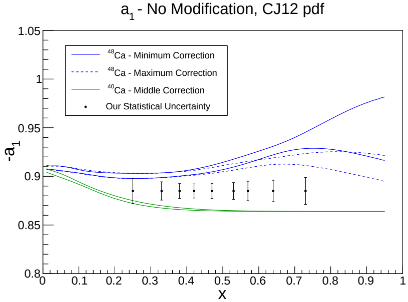
- Trigger defined by coincidence between Cherenkov and shower - 150 kHz total anticipated with background (well below SoLID spec)
- Pion contamination no worse than 4% in any given bin (worst at high x)
- GEM rates comparable to or smaller than design for LD_2

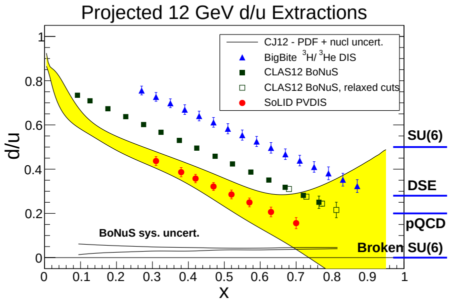


Particle	DAQ Coin. Trig.Rate (kHz)	
	$P > 1$ GeV	$P > 3$ GeV
DIS e^-	144	61
π^-	11	7
π^+	0.4	0.2
Total	155	68

Systematics

- Many potential nuclear effects come into play as this sector is not presently well constrained
- Requires measurements from LD_2 and LH_2 for information on size of nuclear effects
- CJ12 PDFS have poor d/u constraint





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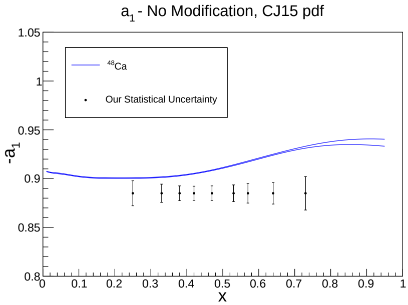
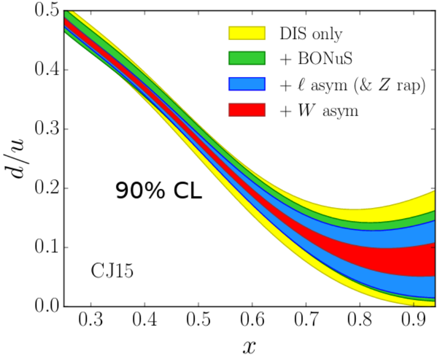
- CJ15 with Tevatron data better





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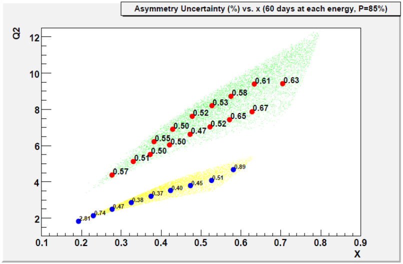
- Requires measurements from LD_2 and LH_2 for information on size of nuclear effects
- Higher twist effects will also be constrained by LD_2 using same kinematics, but also 6.6 GeV beam
- Charge symmetry violation will also be explored to better precision
- Nuclear dependence of $R^{\gamma Z}$ is an open question



Systematics and Experimental uncertainties

- Polarimetry and pions are main contributions
- Radiative working group has been established for PVDIS
- Total errors:

Effect	Uncertainty [%]
Polarimetry	0.4
$R^{\gamma Z}/R^{\gamma}$/HT	0.2
Pions (bin-to-bin)	0.1-0.5
Radiative Corrections (bin-to-bin)	0.5-0.1
Total for any given bin	$\sim$0.5-0.7

- Statistical uncertainty dominates any given bin

Status

- PAC 42 - Deferred
  - “novel and well developed proposal”
  - Site boundary limits were a concern
  - Cross section measurement sensitivity wasn’t formally studied
- PAC 44 - Deferred Again
  - Informally - workshop to organize between efforts and converge theory, radiation effects on the hall, target cost
  - Report: Want ^{48}Ca/^{40}Ca results first

From this Workshop

Questions posed:

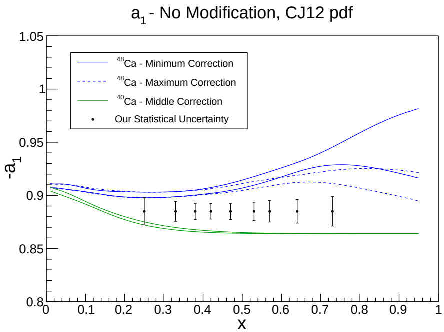
- What other models have predictions for this observable?
- What is useful to constrain mechanisms? (e.g. x dependence)
- Are particular light nuclei useful as a bridge?
- Are symmetric nuclei useful (high Z)?
- What would null result imply?

Summary

- Nuclear modification has many open important questions for our understanding of QCD
- PVDIS on asymmetric targets offers best opportunity to uncover isovector dependence in modification
- 60 days production will offer critical new information, help test leading hypotheses, and help resolve the NuTeV anomaly
- Proposal deferred twice by PAC in light of DIS ratio measurement

BACKUP

Why not ^{40}Ca?



^{40}Ca in CJ12 nPDF fit is green curve

- Would require similar beamtime commitment (60 days)
- ^{40}Ca tests isoscalar prediction - but isoscalar PDFs significantly cancel!
- Existing SoLID program has LD_2 planned which is sensitive to and constrains on a similar level effects such as charge symmetry violation
- ^{40}Ca would be useful if we need to search for effects such as modification-induced CSV - presently hard to argue for a commitment

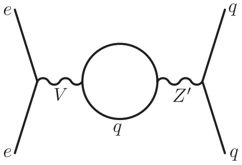
New Physics Example - Leptophobic Z'

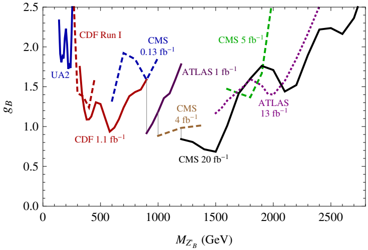
- New physics could be hiding in C_{2q} and not C_{1q}

$$C_{1q} = 2g_A^e g_V^q$$
$$C_{2q} = 2g_V^e g_A^q$$

- Leptophobic Z' could mix with photon through $q\bar{q}$ loops, requires vector coupling with $ee'\gamma$
- PVDIS could have sensitivity within some models to detect at 3σ level with $M_Z' \approx 100 - 200$ GeV range

Buckley *et al.*, Phys Lett B 712, 261 (2012)

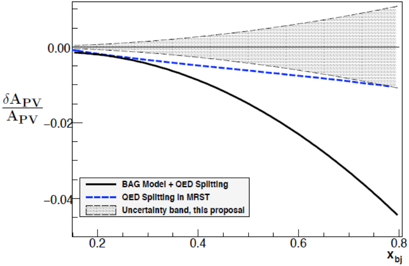


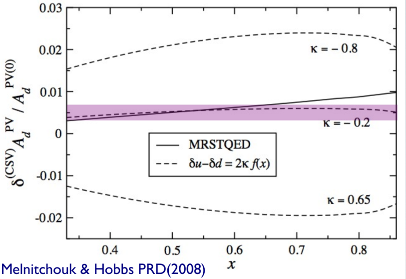


Dobrescu PRD 035021

Charge Symmetry Violation - $u \leftrightarrow d$?

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$





Melnitchouk & Hobbs PRD(2008)

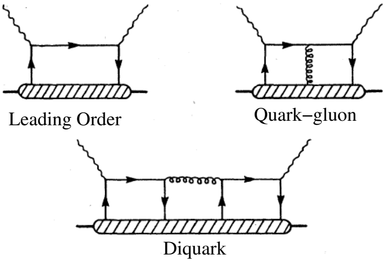
- Differences in distributions would be present in deviation in x dependence from constant
- Lattice in agreement with MRST fits and 1σ of NuTeV

Shanahan, Phys. Rev. D 87, 094515 (2013)

Higher Twist

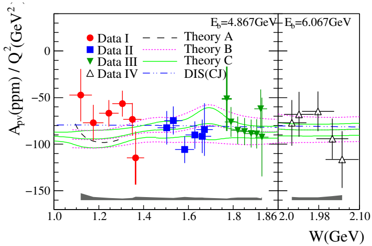
Large kinematic reach allows for evaluation of higher twist

- Higher twist Q^2 dependence from quark-quark and quark-gluon correlations
- In some diagrams DGLAP cancels in A_{PV} and $q(x)$ cancel for isoscalar targets exposing access
- Diquark-type structures are an interesting topic in terms of nucleon structure



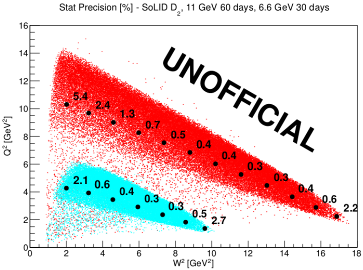
PV Resonance Data - New Publication

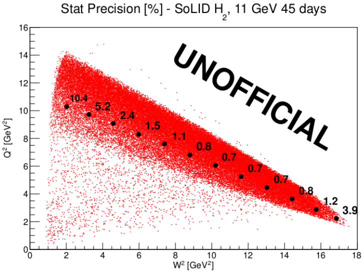
D. Wang *et al.*, Phys. Rev. Lett. 111, 082501 (2013)



Theory A = K. Matsui *et al.*
Theory B = M. Gorchtein *et al.*
Theory C = N.L. Hall *et al.*

- Results agree with models and QH duality, $Q^2 \sim 1\ \mathrm{GeV}^2$
- SoLID should provide few times more precise constraints
- Will vary over W with statistics





Site Boundary - Solenoid Shielding

Iron of magnet is significant shield of neutrons that contribute to site boundary limits

	^{48}Ca Flux (Hz/μA)	^{48}Ca Dose (80 μA for 60 days) (m^{-2})	LD_2 Flux (Hz/μA)	LD_2 Dose (50 μA for 60 days) (m^{-2})
with Solenoid Self- Shielding	2.93E+07	6.02E+12	2.62E+07	3.36E+12
without Solenoid Self- Shielding	5.55E+08	1.14E+14	3.53E+08	4.53E+13

- Calculated to be factor of 2 smaller than CREX

Site Boundary

Iron of magnet is significant shield of neutrons that contribution to site boundary limits

Experiment	Estimated DOSE (m^{-2})	(mrem)	Measured DOSE (mrem)
PREX-I	4.50E+12	4.2	1.3
PREX-II	5.80E+12	5.4	n/a
CREX	1.50E+13	9.2	n/a
PVDIS-LD_2	3.40E+12	3.2	n/a
PVDIS-^{48}Ca	6.00E+12	5.6	n/a

- Calculated to be factor of 2 smaller than CREX

Induced Radiation

Radiation from this experiment is on the level of the existing LD_2 measurement

		Radiation Power in the Hall	
Radiation Type	E-Range (MeV)	^{48}Ca (W/μA)	LD_2 (W/μA)
$e^{\pm}$	$E < 10$	0.11	0.11
	$E > 10$	0.18	0.16
n	$E < 10$	0.0002	0.0003
	$E > 10$	0.005	0.010
γ	$E < 10$	0.02	0.02
	$E > 10$	0.04	0.04

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PVDIS-^{48}Ca	6.00E+12	5.6	n/a

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Radiation on ECal

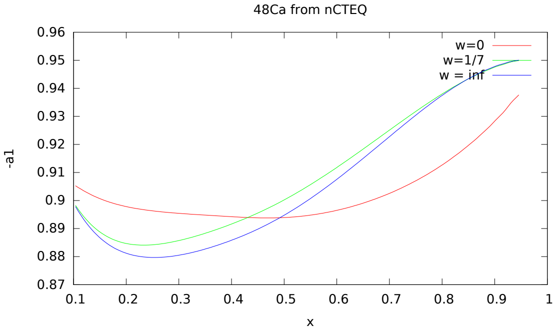
Table: Neutrons Flux at the Front of the ECAL

	E range (MeV)	^{48}Ca Flux (Hz/cm2)	LD_2 Flux (Hz/cm2)
Neutrons	$E < 10$	1.68E+06	1.72E+06
	$E > 10$	3.66E+04	3.30E+04
Total		1.72E+06	1.75E+06

- Total dose (neutron and EM) similar to LD_2
- Estimated 100 kRad on active components

Modeling - nPDFs

- Varying weights in fits between lepton/Drell Yan and ν can show tension between data sets
- nCTEQ fits show dramatic differences in a similar vein at CBT
- Few percent effect in a_2



GEM Rates

GEM plane	LD_2 background ($kHz/mm^2/\mu A$)	^{48}Ca EM background ($kHz/mm^2/\mu A$)	^{48}Ca EM background (no baffles) ($kHz/mm^2/\mu A$)
1	6.8	4.8	49.4
2	3.0	2.1	32.3
3	1.1	0.8	9.9
4	0.7	0.5	6.4

ECal Trigger Rates

region	full	high	low
rate entering the EC (kHz)			
e^-	240	129	111
π^-	5.9×10^5	3.0×10^5	3.0×10^5
π^+	2.7×10^5	1.5×10^5	1.2×10^5
$\gamma(\pi^0)$	7.0×10^7	3.5×10^7	3.5×10^7
p^+	4.8×10^5	2.1×10^5	2.7×10^5
sum	7.1×10^7	3.6×10^7	3.6×10^7
Rate for $p < 1$ GeV (kHz)			
sum	8.4×10^8	4.2×10^8	4.2×10^7
trigger rate for $p > 1$ GeV (kHz)			
e^-	152	82	70
π^-	4.0×10^3	2.2×10^3	1.8×10^3
π^+	0.2×10^3	0.1×10^3	0.1×10^3
$\gamma(\pi^0)$	3	3	0
p	1.6×10^3	0.9×10^3	0.7×10^3
sum	5.9×10^3	3.3×10^3	2.6×10^3
trigger rate for $p < 1$ GeV (kHz)			
sum	2.8×10^3	1.4×10^3	1.4×10^3
Total trigger rate (kHz)			
total	8.7×10^3	4.7×10^3	4.0×10^3

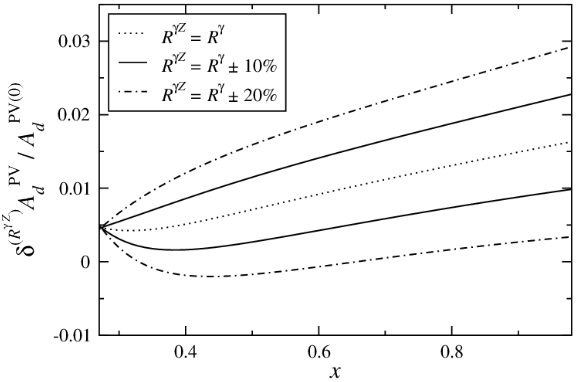
Cerenkov Trigger Rates

	Total Rate for $p > 0.0$ GeV (kHz)	Rate for $p > 3.0$ GeV (kHz)
DIS	240	73
π^-	5.9×10^5	1.6×10^3
π^+	2.7×10^5	40
$\gamma(\pi^0)$	7.0×10^7	40
p	4.8×10^5	4
Sum	7.1×10^7	1.7×10^3

Trigger Rate from Cherenkov (kHz)		
	Trigger Rate for $p > 1.0$ GeV (kHz)	Trigger Rate for $p > 3.0$ GeV (kHz)
DIS	223	66
π^-	193	49
π^+	22	1.6
$\gamma(\pi^0)$	0	0
p	0	0
Sum	438	116

Radiation

		Incident Radiation Power	
Radiation Type	E-Range (MeV)	^{48}Ca (W/μA)	LD_2 (W/μA)
$e^{\pm}$	$E < 10$	0.13	0.13
	$E > 10$	0.19	0.17
n	$E < 10$	0.0001	0.0006
	$E > 10$	0.02	0.04
γ	$E < 10$	0.02	0.02
	$E > 10$	0.04	0.05



$R^{\gamma Z} = R^{\gamma}$
$R^{\gamma Z} = R^{\gamma} \pm 10\%$
$R^{\gamma Z} = R^{\gamma} \pm 20\%$
0.03
0.02
0.01
0
-0.01
0.4
0.6
0.8
x
$\delta^{(R^{\gamma Z})} A_d^{PV} / A_d^{PV(0)}$