First Measurement of the Flavor Dependence of Nuclear PDF Modification Using Parity-Violating Deep Inelastic Scattering

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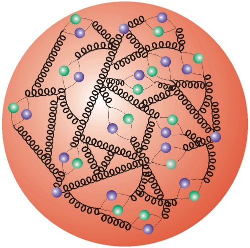
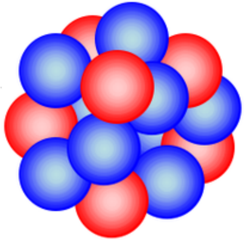
and the SoLID Collaboration

From QCD to Nucleons and Nuclei

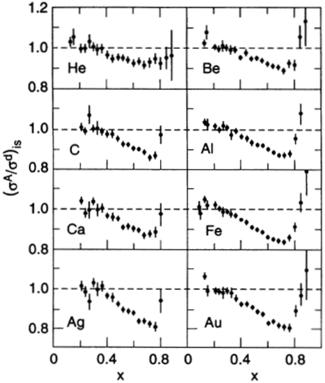
- How are protons and neutrons are modified when they are bound in a nucleus?
- How do we make the transition between QCD and nuclear physics?
- While the existence of nuclear modification of the pdfs is well established, important questions remain about the nature of the modification
- We have almost no experimental information on the spin- and flavor-dependence nuclear modification





EMC Effect and Nuclear Modification

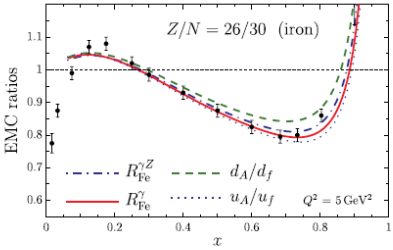
- Showed reduced presence of partons in $0.3 < x < 0.7$ but not due to simple binding effects - real modification of structure
- Generally greater effect as one pushes to higher A
- In the last several years, significant reason to believe that it differ for up- and down-quarks in non-isoscalar nuclei
- There is essentially no experimental evidence that supports this hypothesis

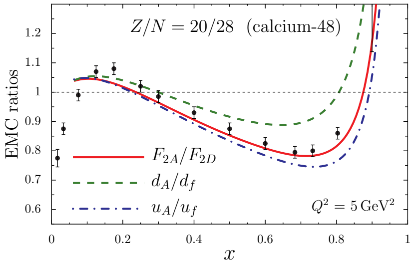


J. Gomez et *al.*, *PRD49 4348 (1994)*

Modeling Flavor Dependence

- At the quark level isovector nuclear forces affect the u and d quarks differently, leading to flavor-dependent modifications
- Cloet et *al.* (CBT) make predictions based on mean field calculations using explicit isovector terms are included (constrained by nuclear physics data such as the symmetry energy)
- Eliminates the largest uncertainty in the interpretation of the NuTeV $sin^2\theta_W$ result

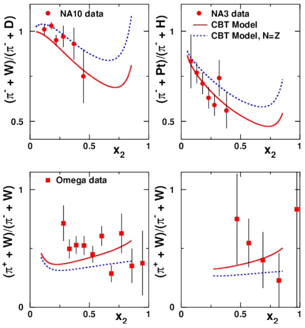




Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

Drell-Yan and flavor-dependent EMC effect

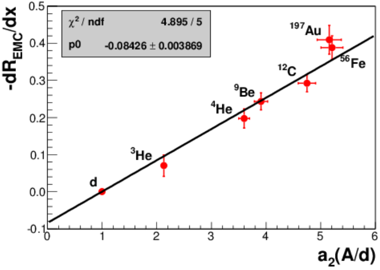
- Preference in existing pion induced Drell-Yan production ratios for flavor-dependent models over flavor-independent models
- The impact of the flavor-dependent nuclear PDF modification was evaluated in the Cloët-Bentz-Thomas (CBT) model
- CSV or Isovector EMC (IVEMC) could play very important role and **are not well constrained by data**

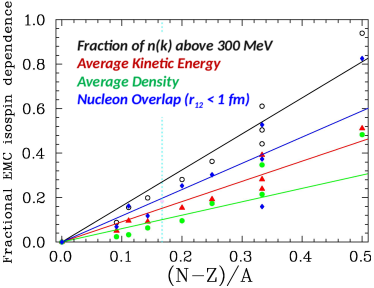


D. Dutta, J. C. Peng, I. C. Cloet, and D. Gaskell. PRC, 83:042201, 2011

Isovector Dependence in SRC ?

- SRC show strong preference to n-p pairs over p-p pairs
- Left Plot: The slope of the EMC effect plotted versus the SRC scaling factor
- Right Plot: Isospin dependence of the EMC effect vs. fractional neutron excess of the nucleus for the four scaling models
- Observed EMC-SRC correlation plus np dominance suggests possible flavor dep. but only have a limited direct sensitivity.





DIS

- DIS with leptons offers picture into partonic distributions

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

- 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

Structure Function (SF),

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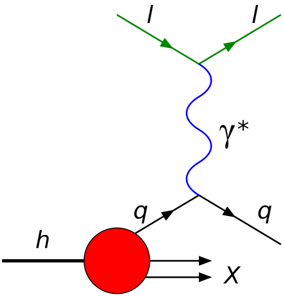
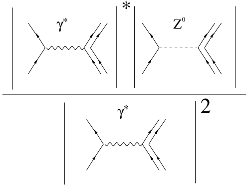


Flavor Dependence Observations with PVDIS

PVDIS probes flavor combinations $\rightarrow$ isovector properties

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

$\sim$ 

$\sim 100 - 1000$ ppm

$$a_1(x) = -2g_A^e \frac{F_{2A}^{\gamma Z}}{F_{2A}^{\gamma}}, a_3(x) = -2g_V^e \frac{F_{3A}^{\gamma Z}}{F_{2A}^{\gamma}}$$

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Expanding about symmetric nucleus limit

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

Therefore, a_1 will provide information about the flavor dependence of the nuclear quark distributions and a reliable extraction of the u and d quark distributions of a nuclear target

Flavor Dependence Observations with PVDIS

- 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 $R^{\gamma Z}$)
- ^{48}Ca target will test isovector (IV) dependence - larger A gives larger EMC, larger $Z - N$ gives IV enhancement

Symmetric nucleus limit

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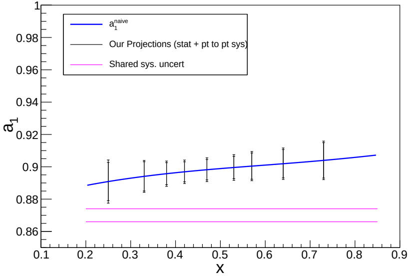
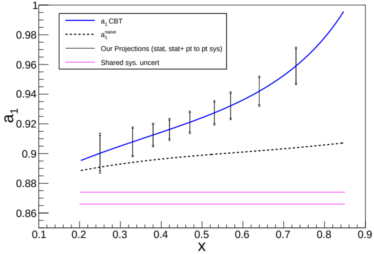


PVEMC Sensitivity

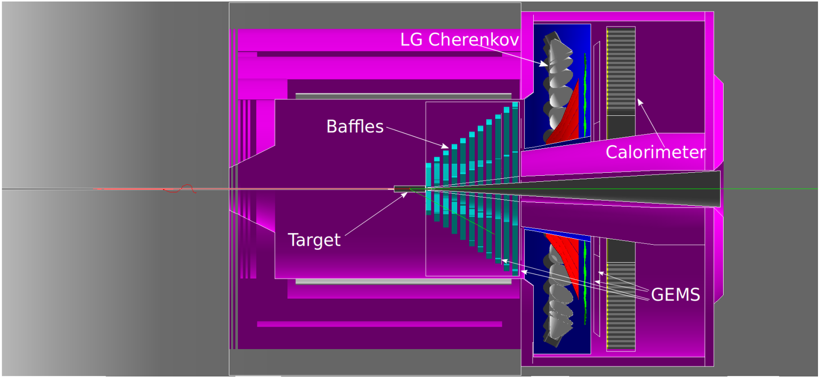


	PVEMC
Statistics	0.7-1.3%
Systematics	0.5%
Normalization	0.4%
data(CBT) vs. naive	6.2σ

- PVDIS naturally sensitive to flavor *differences*
- Other processes such as tagged SIDIS and π Drell-Yan offer complementary information
- Experiments such as SRC help motivate and tie into this program
- PVEMC offers large sensitivity and is required for full picture

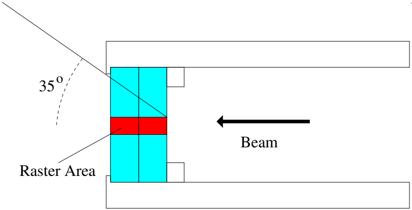
SoLID Configuration

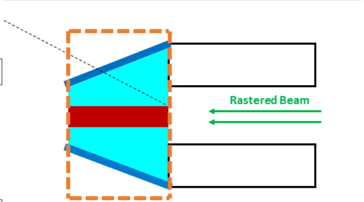
- Experimental configuration practically identical to approved SoLID PVDIS measurement
- Lead baffles serve as momentum collimators
- GEMs, Cherenkov, and calorimeter provide tracking and PID
- Rates are better or comparable to existing LD_2 measurement



Target - ^{48}Ca

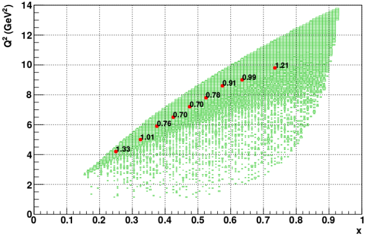
- ^{48}Ca target provides good balance between asymmetric target and not too high Z
- Has very good thermal conductance and high melting point - have operational experience and updated design/protocols from previous program including CREX
- 12% radiator - photons and photoproduced pions are main background concerns
- We propose to use a 2.4 g/cm^2 ^{48}Ca target (reduced volume design on right), assumed to be 95% isotopically pure.

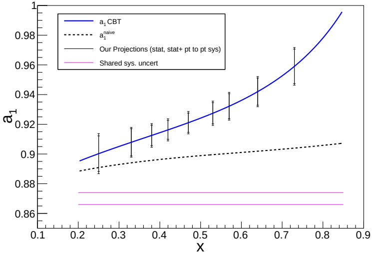




Projections

- Requesting 66 days at 80 μA 11 GeV production (81 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*





Systematic and Experimental uncertainties

- Charge Symmetric Background ($\pi^0 \to e^+e^-\gamma$)
- Hadronic and Nuclear uncertainties (HT, CSV, PDF uncertainties, and free PDF nuclear model uncertainties)
- Radiative working group has been established for PVDIS to work on these systematic contributions
- Systematic errors:

Effect	Uncertainty [%]
Polarimetry	0.4
$R^{\gamma Z}/R^{\gamma}$	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

Summary

- It is critical to have a measurement that can cleanly isolate the flavor dependence of the EMC effect, independent of other nuclear effects, and with the precision to quantify the flavor dependence
- PVDIS on asymmetric target offers one of the most direct, precise, and theoretically clean way to isolate the flavor dependence of the EMC effect
- 66 days production will offer critical new information, help test leading hypotheses, and help resolve the NuTeV anomaly
- Important input to parameterization of the EMC effect and to guide detailed calculations of the underlying physics.

BACKUP

Beam Time Request

We request 66 days of production data at 11 GeV at 80 μA with full beam polarization. We also request time for commissioning, calibration and background runs, and polarimetry, summarized in Table

	Time (days)	E (GeV)	Current (μA)
^{48}Ca Production	66	11	80
Optics	2	4.4	Up to 80
Positive polarity	4	11	80
Moller Polarimetry	4	11	2
Commissioning	5	11	Up to 80
Total	81		

Our Motivation to Submit Again

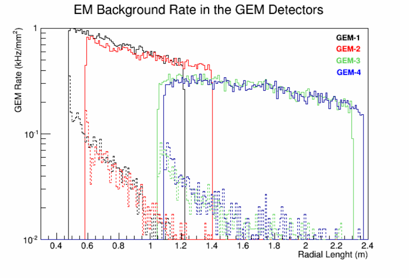
- The PAC 44 Proposal deferred by PAC in light of DIS the ^{48}Ca/^{40}Ca ratio measurement (E12-10-008)
- A detailed examination shows that the E12-10-008 ^{48}Ca/^{40}Ca measurement cannot provide 3σ evidence for a flavor-dependent EMC effect unless the effect is significantly larger than any of the models we have considered
- We determined that no other measurement currently planned or under discussion can provide the sensitivity proposed by this measurement
- We show that the PVEMC measurement will be critical to understanding flavor dependence in nuclei no matter what is observed in the ^{48}Ca/^{40}Ca ratios
- Provided additional detail on the radiation in the hall and at the site boundary

PAC Previous 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
  - Full report not out - usually six weeks or so after PAC

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

DIS

- DIS with leptons offers picture into partonic distributions

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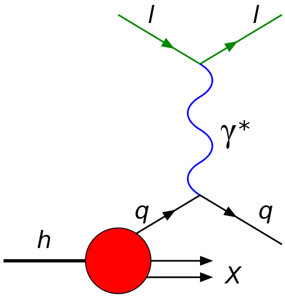

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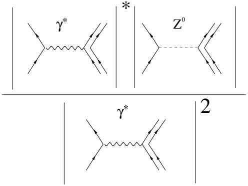
$\sim$  $\sim 100 - 1000 \text{ ppm}$

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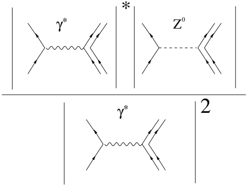
$\sim$ 

$\sim 100 - 1000$ ppm

$$a_1(x) = 2\frac{\sum_i C_{1q_i} e_{q_i} q_i^+}{\sum_i e_{q_i}^2 q_i^+}, a_3(x) = 2\frac{\sum_i C_{2q_i} e_{q_i} q_i^-}{\sum_i e_{q_i}^2 q_i^+}$$

e_{q_i} is the quark charge, $q_i^+(x) = q_i(x) + \bar{q}_i(x)$ and $q_i^-(x) = q_i(x) - \bar{q}_i(x)$

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

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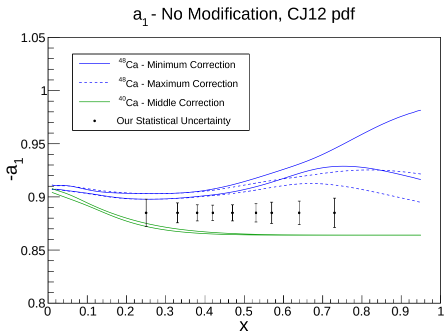
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + ...$$

Therefore, a_1 will provide information about the flavor dependence of the nuclear quark distributions and a reliable extraction of the u and d quark distributions of a nuclear target

Free PDF Error and CSV

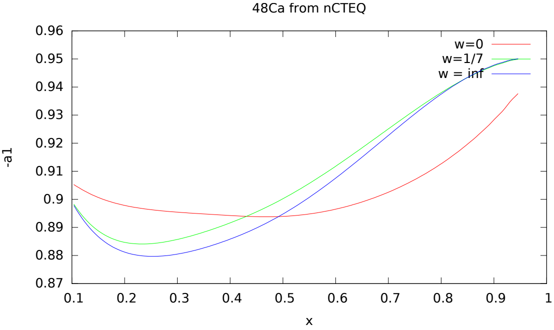


^{40}Ca in CJ12 nPDF fit is green curve

- 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

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



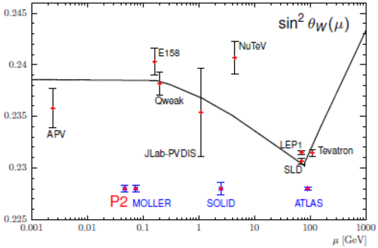
Isovector Dependence in NuTeV Anomaly

- Neutrino scattering (charged and neutral currents) is sensitive to different flavor combinations including Isovector EMC (IVEMC)

Pachos-Wolfenstein relation:

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

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



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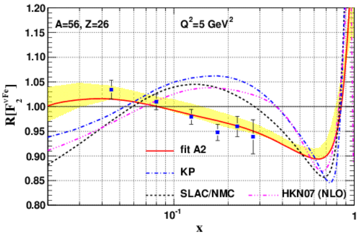
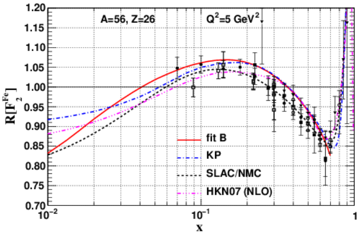
Isovector Dependence in Nuclear PDF

- Nuclear correction ratio for structure functions F_2^{Fe}/F_2^D
- Comparison between lepton/Drell Yan ($l^{\pm}A$) and neutrino (νA) data show significant discrepancies in nuclear corrections using common PDFs
- The nuclear corrections for the $l^{\pm}A$ and νA processes are different: Flavor dependent nuclear effects?

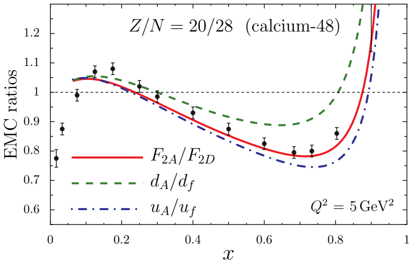


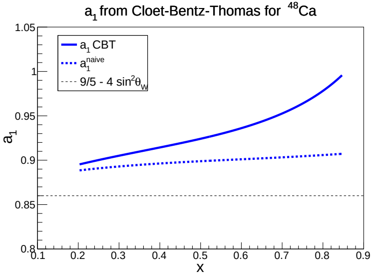


I. Schienbein et *al.* PRD77 054013 (2008); I. Schienbein et *al.* PRD80 094004 (2009)

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_1, larger at larger x





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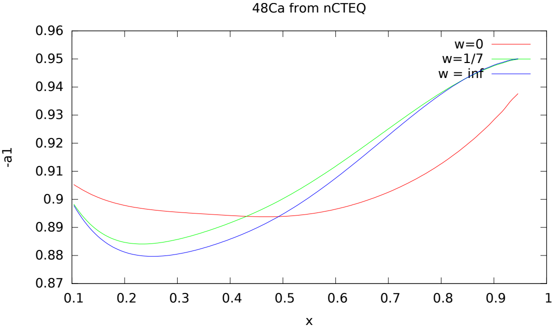
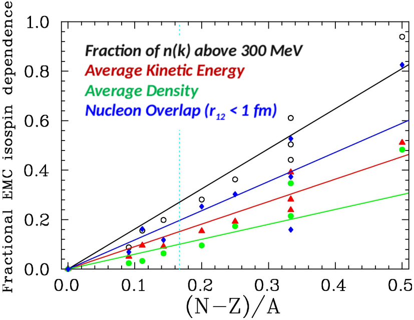
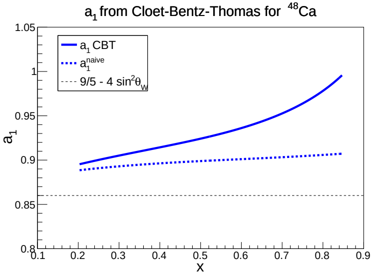
- nCTEQ fits show dramatic differences in a similar vein at CBT
- Few percent effect in a_2



Modeling - Simple Scaling

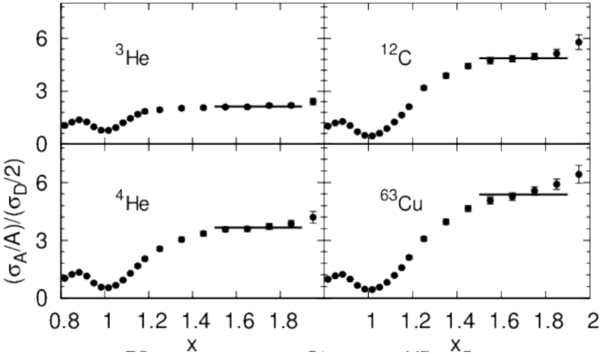
- simple scaling models yield a results varying from 50% to 110% of the CBT calculation





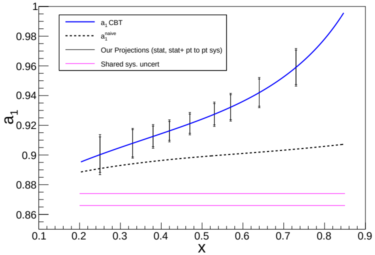
Isovector Dependence? - SRC

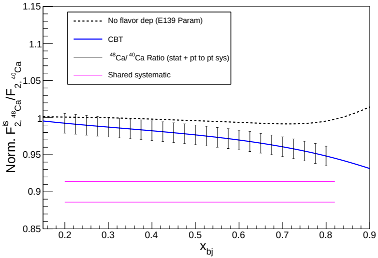
- SRC show strong preference to n-p pairs over p-p pairs
- Also show strong correlation to "plateau" parameter for $x > 1$ SFs



PVEMC vs. ^{48}Ca/^{40}Ca Ratios

PVDIS offers highest sensitivity and is required for full picture

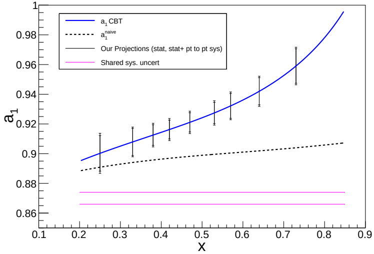


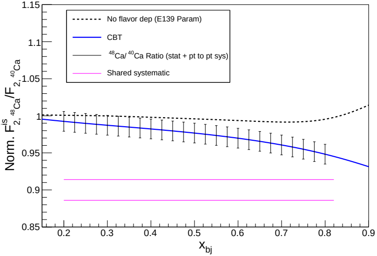


	PVEMC (this prop.)	EMC E12-10-008
Statistics	0.7-1.3%	0.8-1.1%
Systematics	0.5%	0.7%
Normalization	0.4%	1.4%
slope in x	3.7σ	2.0σ
slope in high-x values	5.5σ	2.1σ
data vs. null hypothesis	6.2σ	$<2\sigma$
min vs. max flavor dependence	4.4σ	N/A

PVEMC vs. ^{48}Ca/^{40}Ca Ratios

PVDIS offers highest sensitivity and is required for full picture





- 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

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

Site Boundary

Experiment	Hall Top Neutron Dose (m^{-2})	Estimated Boundary Dose (mrem)	Measured Boundary Dose (mrem)
PREX-I	4.50E+12	4.2	1.3
PREX-II	5.80E+12	2.0	1.2
CREX	1.50E+13	1.8	1.0
LD-PVDIS 6 GeV	1.90E+12	0.7	n/a
LD-PVDIS 11 GeV	3.40E+12	1.3	n/a
^{48}Ca-PVDIS 11 GeV	6.00E+12	2.5	n/a

These measurements have shown that Geant4 simulations have improved over the years to consistently match (within factor of 2) the expected boundary dose

Solenoid Shielding Effect

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 66 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

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

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

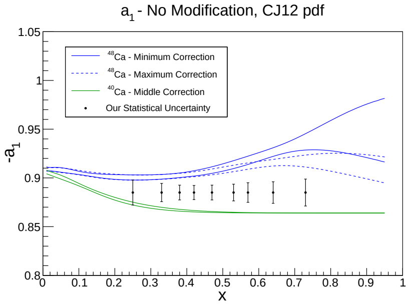
- Total dose (neutron and EM) similar to LD_2
- Estimated to be less than 40 kRad on the ECAL
- Total estimated dose based on current SoLID program is less than 200 kRad
- ECAL is rated for 400 kRad total dose before degradation

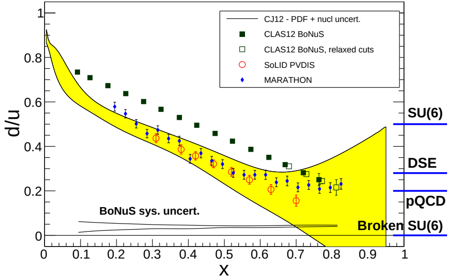
Superconducting Coil Radiation Dose

- The total dose on coils due to LD2 and ^{48}Ca will less than 5×10^{14} neutrons/cm2
- The degradation happens above 2×10^{17} neutrons/cm2 (L. Zana: Director's Review 2019)
- We cannot verify the totla coil dose during CLEO running
- CLEO maximum luminosity was $10^{32} cm^{-2} s^{-1}$ while SoLID-PVDIS will run at about $10^{39} cm^{-2} s^{-1}$
- We thinks CLEO never got a dose anywhere near what it will get while running SOLID-PVDIS

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
- Existing free PDFS (recent CJ12) have poor d/u constraint





Systematics

- 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