

FIRST MEASUREMENT OF THE FLAVOR  
DEPENDENCE OF NUCLEAR PDF  
MODIFICATION USING PARITY-VIOLATING  
DEEP INELASTIC SCATTERING

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# OUTLINE

- ▶ Motivation
- ▶ Proposed Experiment
- ▶ Projected Results and Systematics

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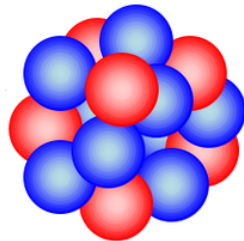
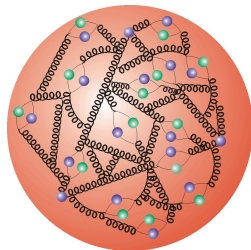
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**and the SoLiD Collaboration**

## AN OPEN AND IMPORTANT QUESTIONS

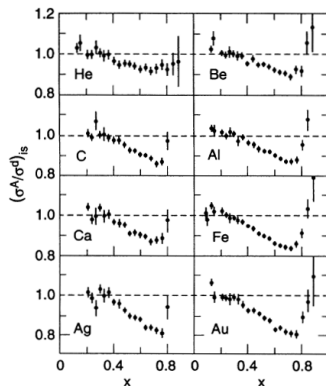
- ▶ How protons and neutrons are modified when they are bound in a nucleus?
- ▶ How we make the transition between QCD and nuclear physics?

But our effective nuclear theories are based around the concept that nucleons in the nuclear environment strongly maintain their identities



## 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



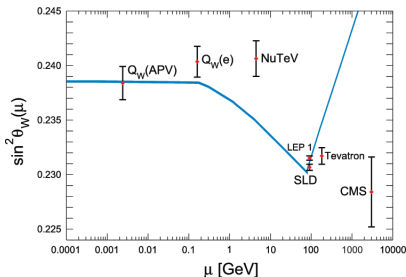
J. Gomez et al., *PRD49* 4348  
(1994)

# ISOVECTOR DEPENDENCE IN NUTeV ANOMALY

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

Pachos-Wolfenstein relation:

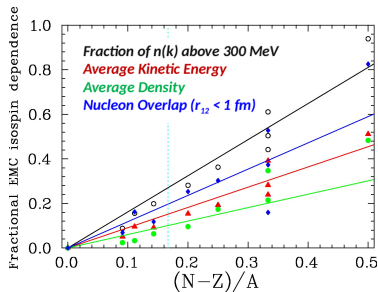
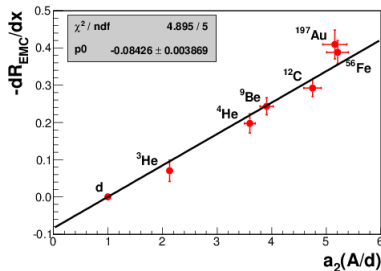
$$R_{\text{PW}} \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} \sin^2 \theta_W(\mu)$$
$$= \lim_{\rightarrow \text{i.s.}} \frac{1}{2} - \sin^2 \theta_W$$



- ▶ The impact of the flavor-dependent nuclear PDF modification on the NuTeV anomaly 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**

# ISOVECTOR DEPENDENCE? - 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
- ▶ Unfortunately have a limited direct sensitivity to the flavor dependence of the EMC effect



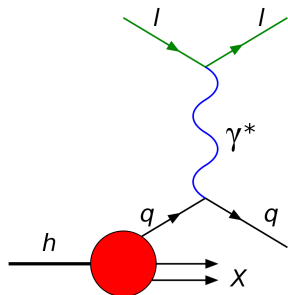
- ▶ DIS with leptons offers picture into partonic distributions

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

- ▶ 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),

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





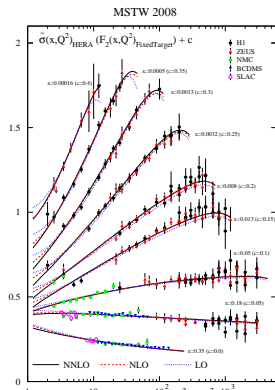
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# FLAVOR DEPENDENCE OBSERVATIONS WITH PVDIS

PVDIS proves new flavor combinations  $\rightarrow$  isovector properties

$$A_{PV} \sim \frac{\left| \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \right|^2}{\left| \text{Diagram 3} \right|^2} \sim 100 - 1000 \text{ ppm}$$

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

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

## EFFECTIVE WEAK COUPLINGS

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

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

# FLAVOR DEPENDENCE OBSERVATIONS WITH PVDIS

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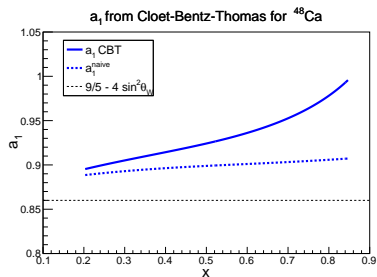
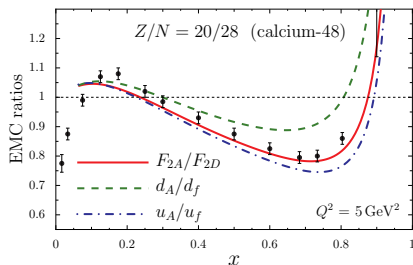
SYMMETRIC NUCLEUS LIMIT

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

where  $u_A = u$  in  $p$ ,  $u$  in  $n$  and  $q^\pm = q(x) \pm \bar{q}(x)$

# MODELING - CBT MODEL

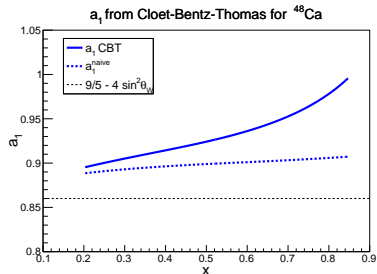
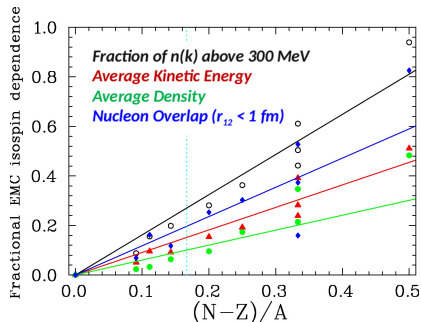
- ▶ Cloet et *al.* make predictions based on mean field calculations which give reasonable reproductions of SFs
- ▶ Explicit isovector terms are included constrained by nuclear physics data such as the symmetry energy
- ▶ Few percent effect in  $a_1$ , larger at larger  $x$



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

# MODELING - SIMPLE SCALING

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

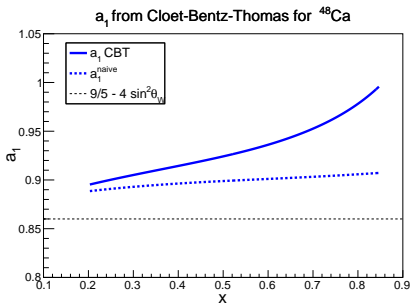


# WHERE TO GET CONSTRAINT

- ▶ 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 (IV) dependence - larger  $A$  gives larger EMC, larger  $Z - N$  gives IV enhancement

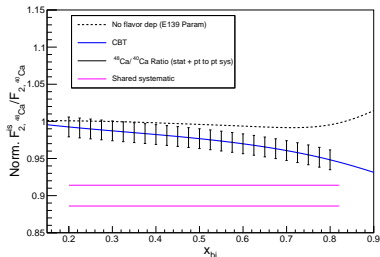
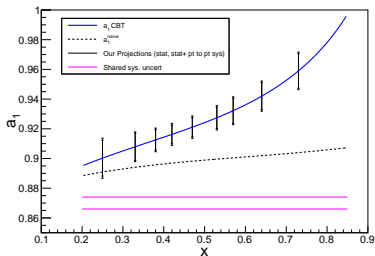
## SYMMETRIC NUCLEUS LIMIT

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



# PVEMC vs. $^{48}\text{Ca}/^{40}\text{Ca}$ RATIOS

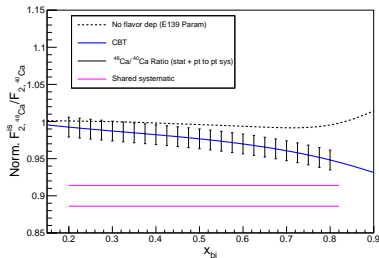
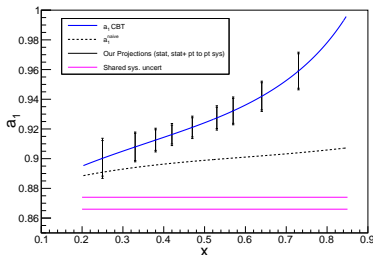
PVDIS offers highest sensitivity and is required for full picture



	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 $x$	$3.7\sigma$	$2.0\sigma$
slope in high- $x$ values	$5.5\sigma$	$2.1\sigma$
data vs. null hypothesis	$6.2\sigma$	$<2\sigma$
min vs. max flavor dependence	$4.4\sigma$	N/A

# PVEMC vs. $^{48}\text{Ca}/^{40}\text{Ca}$ RATIOS

PVDIS offers highest sensitivity and is required for full picture

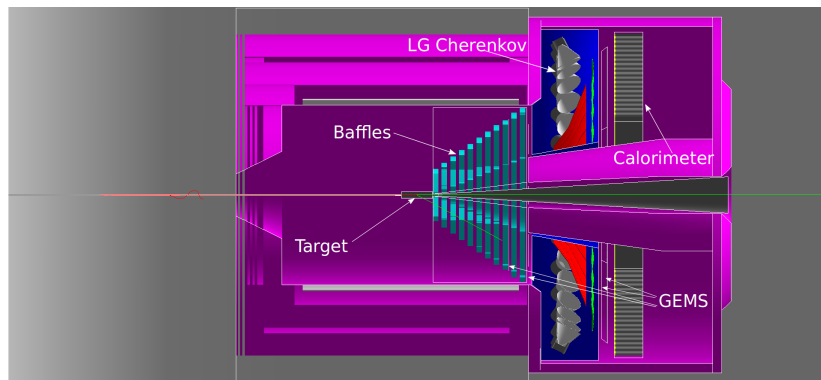


- ▶ PVDIS naturally sensitive to flavor *differences*
- ▶ DIS and PVDIS allows for flavor determination
- ▶ Other processes such as tagged SIDIS and  $\pi$  Drell-Yan offer complementary information
- ▶ Experiments such as SRC help motivate and tie into this program



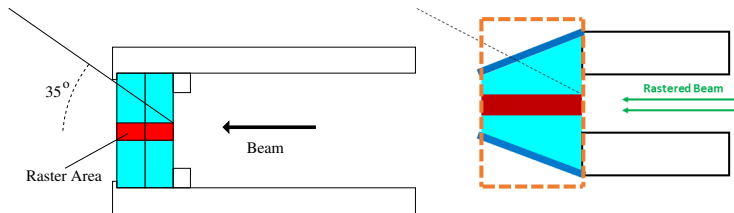
# SoLID CONFIGURATION

- ▶ 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



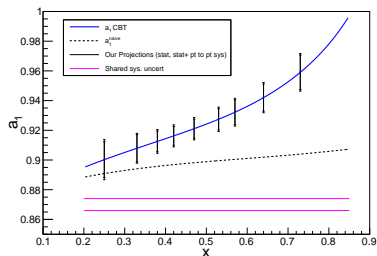
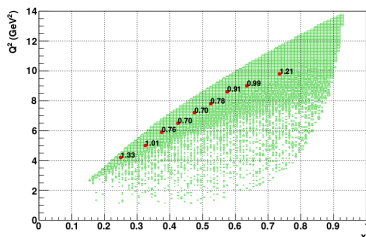
# TARGET - $^{48}\text{Ca}$

- ▶  $^{48}\text{Ca}$  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 including CREX
- ▶ 12% radiator - photons and photoproduced pions are main background concerns
- ▶ We propose to use a  $2.4 \text{ g/cm}^2$   $^{48}\text{Ca}$  target (reduced volume design on right), assumed to be 95% isotopically pure.



# PROJECTIONS

- ▶ Requesting 66 days at 80  $\mu\text{A}$  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*



# SITE BOUNDARY

Experiment	Hall Top Neutron Dose ( $\text{m}^{-2}$ )	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
$^{48}\text{Ca}$ -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 the expected boundary dose as shown

- ▶ Pion Contamination
- ▶ Charge Symmetric Background ( $\pi^0 \rightarrow e^+e^-\gamma$ )
- ▶ Radiative Corrections
- ▶ Hadronic and Nuclear uncertainties (HT, CSV, PDF uncertainties, and free PDF nuclear model uncertainties)

# BEAM TIME REQUEST

We request 66 days of production data at 11 GeV at 80  $\mu\text{A}$  with full beam polarization. We also request time for commissioning, calibration and background runs, and polarimetry, summarized in Table

	Time (days)	E (GeV)	Current ( $\mu\text{A}$ )
$^{48}\text{Ca}$ 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		

# 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
$R^{\gamma Z} / R^{\gamma}$	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

# OUR MOTIVATION TO SUBMIT AGAIN

- ▶ The PAC 44 Proposal deferred by PAC in light of DIS the  $^{48}\text{Ca}/^{40}\text{Ca}$  ratio measurement (E12-10-008)
- ▶ A detailed examination shows that the E12-10-008  $^{48}\text{Ca}/^{40}\text{Ca}$  measurement cannot provide  $3\sigma$  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  $^{48}\text{Ca}/^{40}\text{Ca}$  ratios
- ▶ Provided additional detail on the radiation in the hall and at the site boundary



# 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
- ▶ 66 days production will offer critical new information, help test leading hypotheses, and help resolve the NuTeV anomaly
- ▶ The first direct and precise measurement of the flavor dependence will motivate calculations that explicitly attempt to account for flavor or isospin dependence.

BACKUP

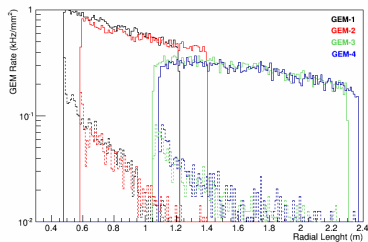
# PAC PREVIOUS STATUS

- ▶ 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<sub>2</sub>

EM Background Rate in the GEM Detectors



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

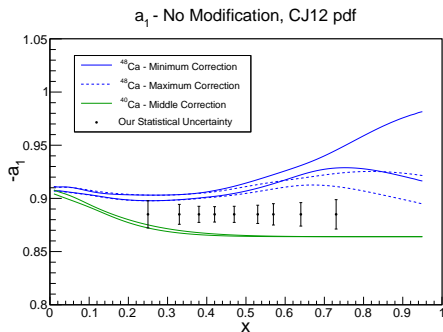
# SITE BOUNDARY - SOLENOID SHIELDING

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

	$^{48}\text{Ca}$ Flux (Hz/ $\mu\text{A}$ )	$^{48}\text{Ca}$ Dose (80 $\mu\text{A}$ for 66 days) ( $\text{m}^{-2}$ )	LD <sub>2</sub> Flux (Hz/ $\mu\text{A}$ )	LD <sub>2</sub> Dose (50 $\mu\text{A}$ for 60 days) ( $\text{m}^{-2}$ )
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

# WHY NOT $^{40}\text{Ca}$ ?



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

- ▶ Would require similar beamtime commitment (60 days)
- ▶  $^{40}\text{Ca}$  tests isoscalar prediction - but isoscalar PDFs significantly cancel!
- ▶ Existing SoLID program has  $\text{LD}_2$  planned which is sensitive to and constrains on a similar level effects such as charge symmetry violation
- ▶  $^{40}\text{Ca}$  would be useful if we need to search for effects such as modification-induced CSV - presently hard to argue for a commitment

# INDUCED RADIATION

Radiation from this experiment is on the level of the existing LD<sub>2</sub> measurement

Radiation Type	E-Range (MeV)	Radiation Power in the Hall	
		<sup>48</sup> Ca (W/ $\mu$ A)	LD <sub>2</sub> (W/ $\mu$ A)
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
$\gamma$	E < 10	0.02	0.02
	E > 10	0.04	0.04

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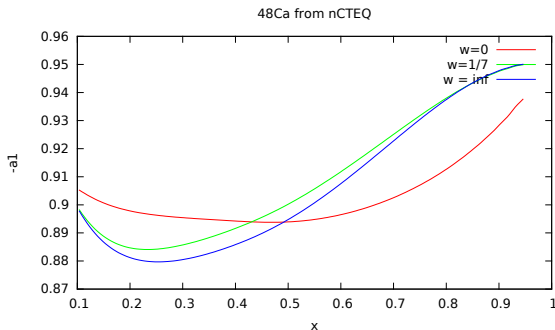
TABLE: Neutrons Flux at the Front of the ECAL

	E range (MeV)	$^{48}\text{Ca}$ Flux (Hz/cm <sup>2</sup> )	LD <sub>2</sub> Flux (Hz/cm <sup>2</sup> )
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<sub>2</sub>
- ▶ Estimated 100 kRad on active components

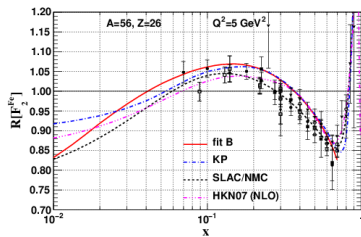
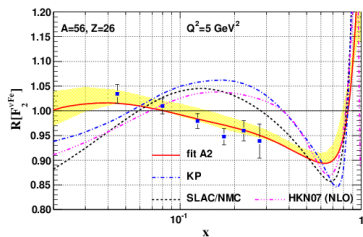
# MODELING - NPDFS

- ▶ Varying weights in fits between lepton/Drell Yan and  $\nu$  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 NUCLEAR PDF

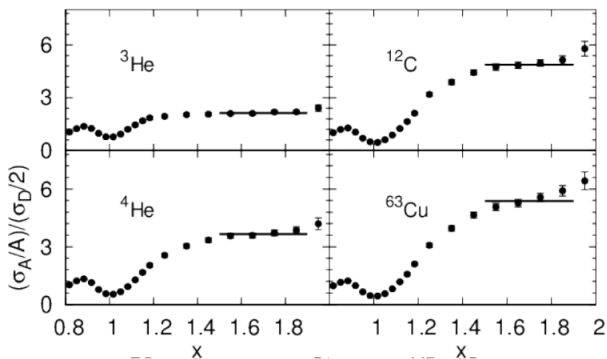
- ▶ Nuclear correction ratio for structure functions  $F_2^{Fe}/F_2^D$
- ▶ Comparison between lepton/Drell Yan ( $l^\pm A$ ) and neutrino ( $\nu A$ ) data show significant discrepancies in nuclear corrections using common PDFs
- ▶ The nuclear corrections for the  $l^\pm A$  and  $\nu A$  processes are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



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



# GEM RATES

GEM plane	LD <sub>2</sub> background (kHz/mm <sup>2</sup> /μA)	<sup>48</sup> Ca EM background (kHz/mm <sup>2</sup> /μA)	<sup>48</sup> Ca EM background (no baffles) (kHz/mm <sup>2</sup> /μA)
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
$\pi^-$	$5.9 \times 10^5$	$3.0 \times 10^5$	$3.0 \times 10^5$
$\pi^+$	$2.7 \times 10^5$	$1.5 \times 10^5$	$1.2 \times 10^5$
$\gamma(\pi^0)$	$7.0 \times 10^7$	$3.5 \times 10^7$	$3.5 \times 10^7$
$p^+$	$4.8 \times 10^5$	$2.1 \times 10^5$	$2.7 \times 10^5$
sum	$7.1 \times 10^7$	$3.6 \times 10^7$	$3.6 \times 10^7$
Rate for $p < 1$ GeV (kHz)			
sum	$8.4 \times 10^8$	$4.2 \times 10^8$	$4.2 \times 10^7$
trigger rate for $p > 1$ GeV (kHz)			
$e^-$	152	82	70
$\pi^-$	$4.0 \times 10^3$	$2.2 \times 10^3$	$1.8 \times 10^3$
$\pi^+$	$0.2 \times 10^3$	$0.1 \times 10^3$	$0.1 \times 10^3$
$\gamma(\pi^0)$	3	3	0
$p$	$1.6 \times 10^3$	$0.9 \times 10^3$	$0.7 \times 10^3$
sum	$5.9 \times 10^3$	$3.3 \times 10^3$	$2.6 \times 10^3$
trigger rate for $p < 1$ GeV (kHz)			
sum	$2.8 \times 10^3$	$1.4 \times 10^3$	$1.4 \times 10^3$
Total trigger rate (kHz)			
total	$8.7 \times 10^3$	$4.7 \times 10^3$	$4.0 \times 10^3$

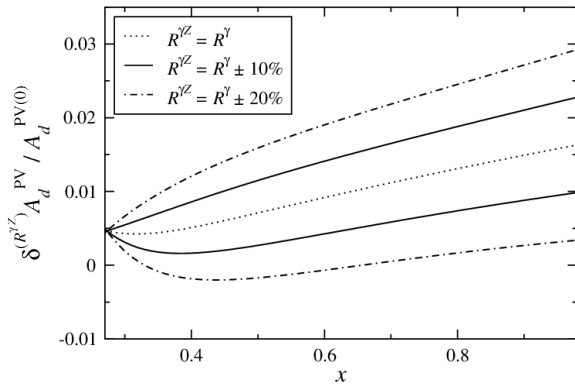
# CERENKOV TRIGGER RATES

	Total Rate for $p > 0.0$ GeV (kHz)	Rate for $p > 3.0$ GeV (kHz)
DIS	240	73
$\pi^-$	$5.9 \times 10^5$	$1.6 \times 10^3$
$\pi^+$	$2.7 \times 10^5$	40
$\gamma(\pi^0)$	$7.0 \times 10^7$	40
$p$	$4.8 \times 10^5$	4
Sum	$7.1 \times 10^7$	$1.7 \times 10^3$
Trigger Rate from Cherenkov (kHz)		
	Trigger Rate for $p > 1.0$ GeV (kHz)	Trigger Rate for $p > 3.0$ GeV (kHz)
DIS	223	66
$\pi^-$	193	49
$\pi^+$	22	1.6
$\gamma(\pi^0)$	0	0
$p$	0	0
Sum	438	116

# RADIATION

Radiation Type	E-Range (MeV)	Incident Radiation Power	
		$^{48}\text{Ca}$ (W/ $\mu\text{A}$ )	LD <sub>2</sub> (W/ $\mu\text{A}$ )
$e^{\pm}$	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
$\gamma$	E < 10	0.02	0.02
	E > 10	0.04	0.05

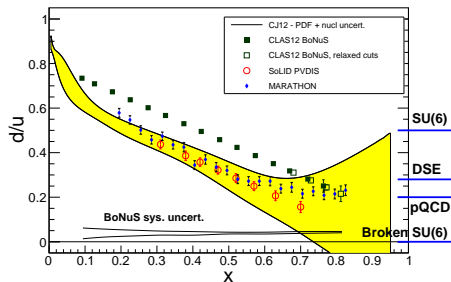
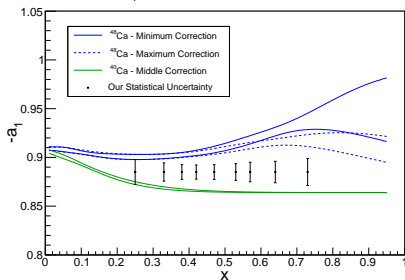




# SYSTEMATICS

- ▶ Many potential nuclear effects come into play as this sector is not presently well constrained
- ▶ Requires measurements from LD<sub>2</sub> and LH<sub>2</sub> for information on size of nuclear effects
- ▶ Existing free PDFs (recent CJ12) have poor  $d/u$  constraint

$a_1$  - No Modification, CJ12 pdf



- ▶ Higher twist effects will also be constrained by LD<sub>2</sub> 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

