Measurements of the EMC Effect Using PVDIS Update

Seamus Riordan
Stony Brook University
seamus.riordan@stonybrook.edu

with

John Arrington
Argonne National Laboratory

Rakitha Beminiwattha
Syracuse University

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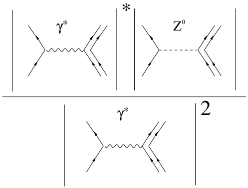
Overview

- Went to PAC42 - deferred
  - Cited desire to run Hall C $^{48}Ca/^{40}Ca$ first
  - Concerns about beam time and radiation budget for site boundaries
- John Arrington has joined as spokesperson
- Working on updating proposal for resubmision
  - Need to consider strengthening (and clarifying) physics case
  - more detailed radiation calculations
  - ^{48}Ca target update with status

PVDIS

PVDIS proves new flavor combinations → isovector properties

$A_{\rm PV} \sim$  $\sim 100 - 1000$ 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

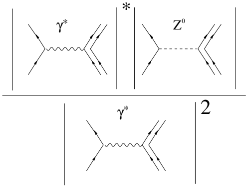
$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W = -0.19 \qquad C_{2u} = -\frac{1}{2} + 2\sin^2\theta_W = -0.03$$

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

PVDIS

PVDIS proves new flavor combinations → isovector properties

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



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

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

Symmetric nucleus limit

Probing *isovector* quantity through parity violation:

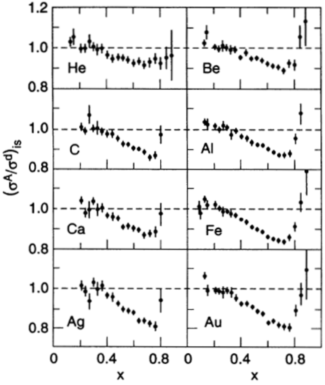
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\left[\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}\right] + \ldots$$

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



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

PVDIS can test this

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

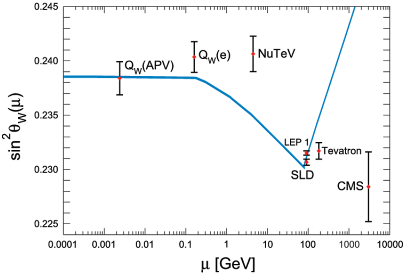
Isovector Dependence? - NuTeV

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

Pachos-Wolfenstein relation:

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

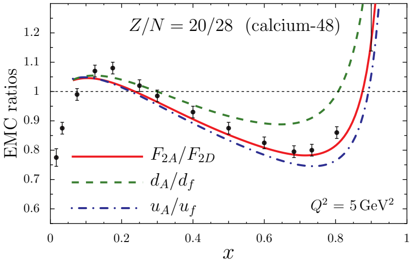
$$= \lim_{\to \mathrm{i.s.}} \frac{1}{2} - \sin^2\theta_W$$

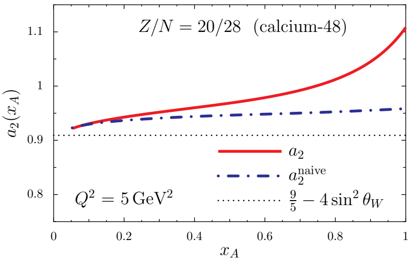


- Asymmetric nuclei (iron) need corrections
- CSV or IVEMC (effective CSV) will change this result and are not well constrained by data

Modeling - CBT Model

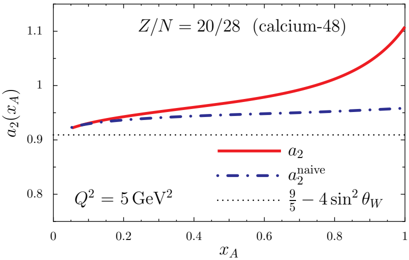
- Cloet et *al.* make predictions based on mean field calculations which give reasonable reproductions of SFs
- Explicit isovector terms are included constrained by symmetry energy
- Few percent effect in a_2, larger at larger x

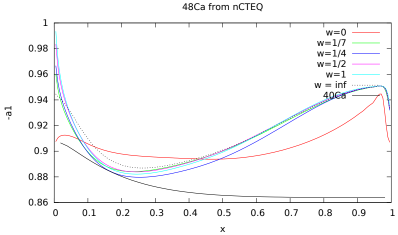




Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

Data Tension





- Data fits varying EM and ν data weights support discrepancy on the same level

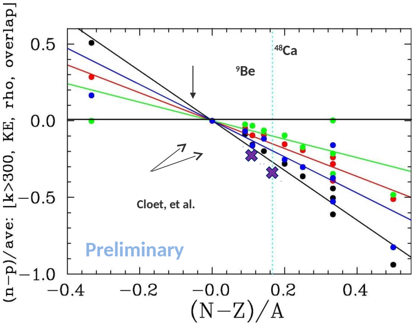
Isospin dependence vs fractional neutron excess

<u>4 simple models of EMC scaling:</u>

Fraction of n(k) above 300 MeV
Average Kinetic Energy
Average Density
Nucleon Overlap (r_{12} < 1 fm)

EMC effect isospin asymmetry:
(neutron-proton)/average

Cloet estimates: scaled from NM



Can be probed directly in parity-violating electron scattering
•*^{48}Ca measurements proposed at JLab*
•*Light nuclei (e.g. ^{9}Be) may also have good sensitivity; help disentangle effects*

New and tie into CREX?

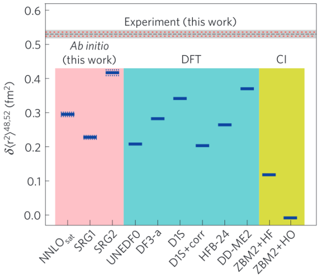
Neutron and weak-charge distributions of the 48Ca nucleus

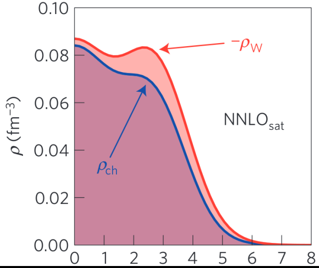
Hagen et al, Nature 12 (2016) 186-190

Unexpectedly large charge radii of neutron-rich calcium isotopes

Ruiz et al, Nature (2016)

doi:10.1038/nphys3645

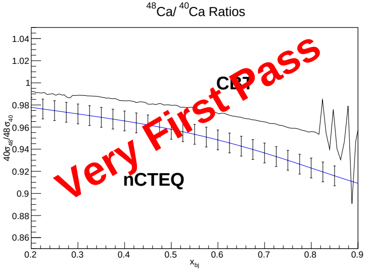




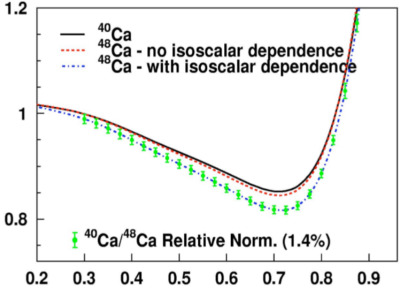
- New ^{48}Ca coupled clustered calculations and ISOLDE results show small neutron skin in calcium isotopes
- Could prove to have interesting/testable consequences?

Case for DIS

- Working on quantifying sensitivity in Hall C Measurment
- Have numbers for uncertaintines from Dave Gaskell
- Zhihong will continue calculations

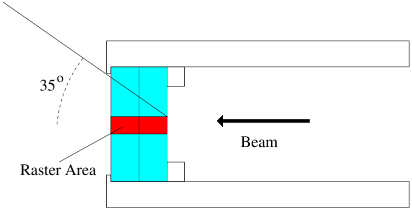


From Dave Gaskell:



Target - ^{48}Ca

- ^{48}Ca target provides good balance between asymmetric target and not too high Z
- 12% radiator - photons and photoproduced pions are main background concerns

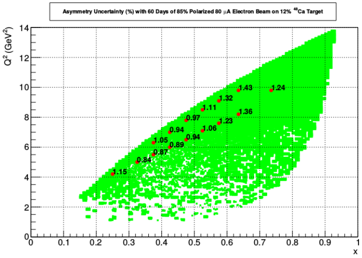


- Learned that ^{48}Ca is not isotopically pure and has ∼10% ^{40}Ca and other contaminations - needs to be put under consideration
- Probably only going to have single target already in position - needs to be recast - holder needs to be redesigned
- Run sideways?

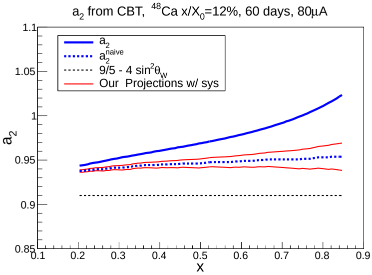
Radiation Concerns

- Was flagged during PAC presentation for site boundary limits
- Neutrons should stay bottled up in magnet, but calculations are necessary
- Have tentative statment that should be less than PVDIS LD_2 in all respects - need to get more firm (but probably won't have full calculations)

- 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*



$$A = A_{\text{naive}} + \alpha \Delta A_{\text{CBT}}$$



Summary

- Nuclear modification has many open important questions for our understanding of QCD and can be tested with SoLID PVDIS
- Working on improving proposal to address PAC concerns
- Updates need to be made on target and radiation estimates

BACKUP

Quark Parton Model

$$R^{\gamma(\gamma Z)} \equiv \frac{\sigma_L^{\gamma(\gamma Z)}}{\sigma_T^{\gamma(\gamma Z)}} = r^2 \frac{F_2^{\gamma(\gamma Z)}}{F_1^{\gamma(\gamma Z)}} - 1$$

$$r^2 = 1 + \frac{Q^2}{\nu} = 1 + \frac{4M^2x^2}{Q^2}$$

$$A_{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + \frac{g_V^e}{2} Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$Y_1 = \frac{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma Z})\right) - 2xyM/E}{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma})\right) - 2xyM/E}\left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right)$$

$$Y_3 = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma})\right) - 2xyM/E}\left(\frac{r^2}{1+R^{\gamma}}\right)$$

$$F_1^{\gamma} = \frac{1}{2}\sum_i e_i^2\left(q_i(x)+\bar{q}_i(x)\right); \; F_2^{\gamma} = 2xF_1^{\gamma},$$

$$F_1^{\gamma Z} = \sum_i e_i g_V^i\left(q_i(x)+\bar{q}_i(x)\right); \; F_2^{\gamma Z} = 2xF_1^{\gamma Z},$$

$$F_3^{\gamma Z} = 2\sum_i e_i g_A^i\left(q_i(x)-\bar{q}_i(x)\right).$$

Possible future extensions

Experiment	Constraint	Reason
LD_2	CSV, Q^2 dependence	
LH_2	d/u	
^{48}Ca	Isovector EMC properties	
^{40}Ca	$R^{\gamma Z}$, CSV dependence on A	Effects are very large or in serious disagreement with NuTeV or other data
Co, Cu?	Less direct test on NuTeV	Effects are very large or in serious disagreement with NuTeV or other data
^{56}Fe	Direct test of NuTeV	Seperate data point
^{208}Pb	Very high Z	Seperate data point

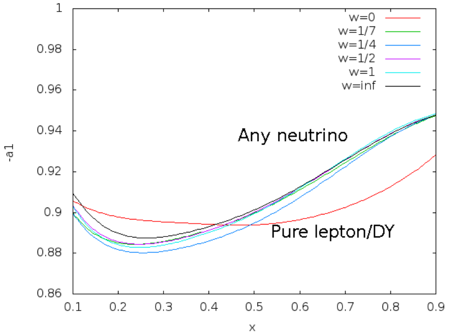
Approved

This Proposal

Can't with SoLID

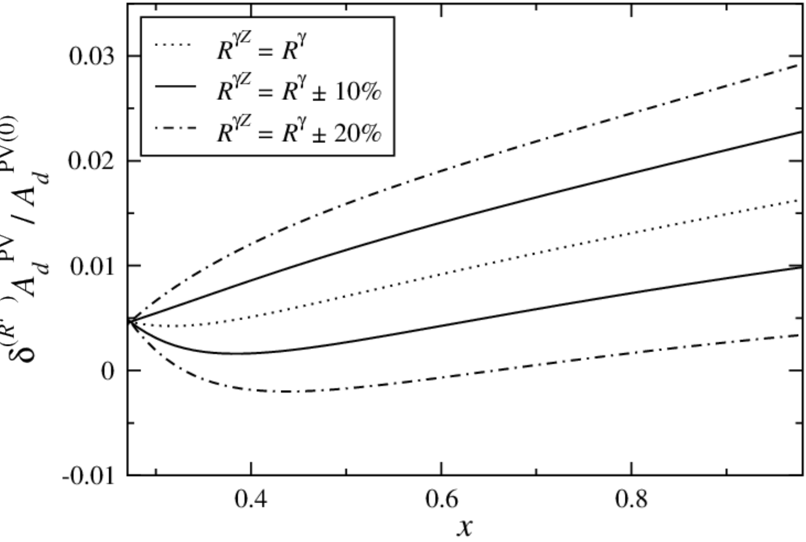
Modeling - nPDFs

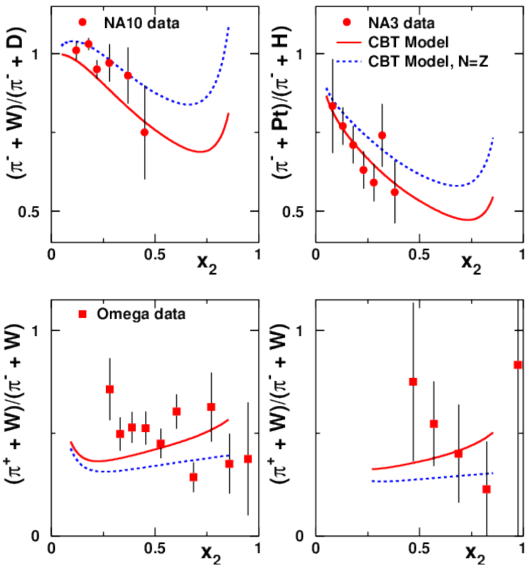
- Varying weights in fits between lepton/Drell Yan and ν can show tension between data sets
- nCTEQ fits show dramatic differences in a similar vein at CBT
- Few percent effect in asymmetry

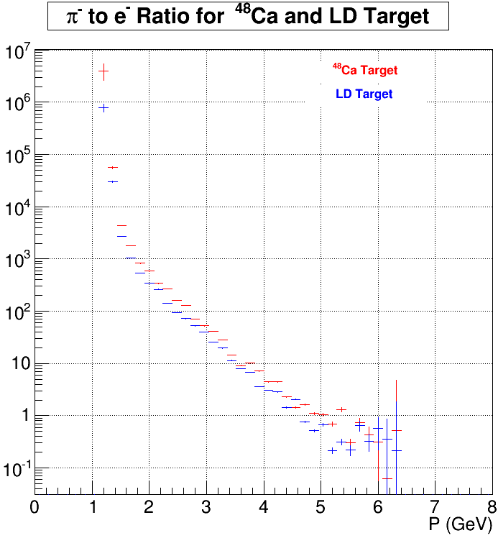


- w relative weighting of ν data with lepton/DY
- Suggests softness in this channel through lepton/DY
- PVDIS can provide differentiation

- Nuclear dependence of $R^{\gamma Z}$ data doesn't exist




NA10 data
$(\pi^- + W)/(\pi^- + D)$
NA3 data
CBT Model
CBT Model, N=Z
$(\pi^- + Pt)/(\pi^- + H)$
Omega data
$(\pi^+ + W)/(\pi^- + W)$
x_2
0
0.5
1


π⁻ to e⁻ Ratio for ⁴⁸Ca and LD Target
⁴⁸Ca Target
LD Target
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
0
1
2
3
4
5
6
7
8
P (GeV)

GEM Rates

GEM plane	LD_2 background ($\mathrm{kHz/mm^2/\mu A}$)	^{48}Ca EM background ($\mathrm{kHz/mm^2/\mu A}$)	^{48}Ca EM background (no baffles) ($\mathrm{kHz/mm^2/\mu A}$)
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 Rates

Momentum range (GeV)	π^- (MHz)	π^+ (MHz)	$\pi^0(\gamma)$ (MHz)	Proton (MHz)	EM $(\gamma, e\pm)$ (GHz)
$p > 0.0$ GeV	618	283	70123	483	844
$p > 0.3$ GeV	439	153	438	417	n/a
$p > 1.0$ GeV	123	18	37	51	0.0
$p > 3.0$ GeV	2	0.01	0.04	0.004	0.0

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)

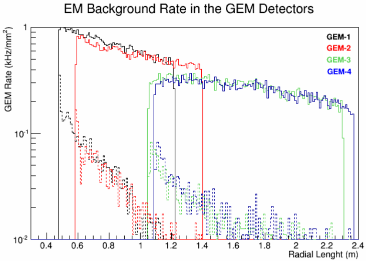
	Trigger Rate for $p > 1.0$ GeV (kHz)	Trigger Rate for $p > 3.0$ GeV (kHz)
DIS	223	66
π^-	193	49
π^+	22	1.6
$\gamma(\pi^0)$	0	0
p	0	0
Sum	438	116

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

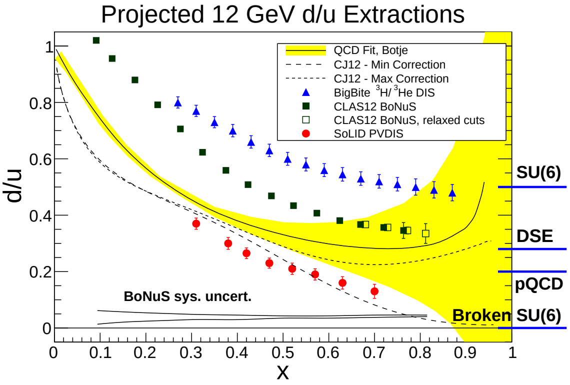
Rates and Backgrounds

- 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

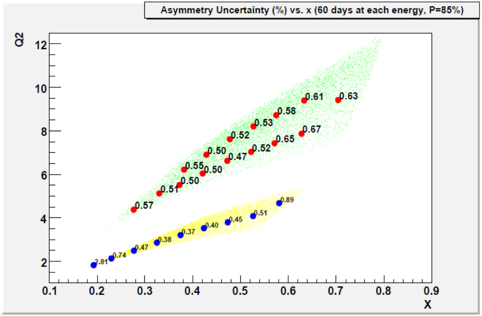
- Many potential nuclear effects come into play as this sector is not presently well constrained
- Requires measurements from LD_2 and LH_2 for information on size of nuclear effects
- Free PDFs will be constrained by LH_2 et al



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
- Higher twist effects will also be constrained by LD_2 using same kinematics, but also 6.6 GeV beam

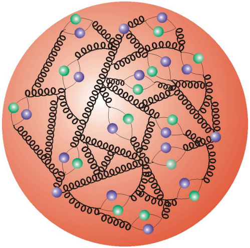
Approved LD_2 (120 days):

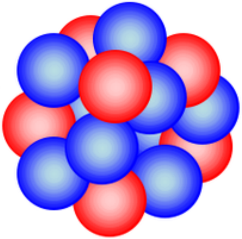


QCD in Nucleons and Nuclei

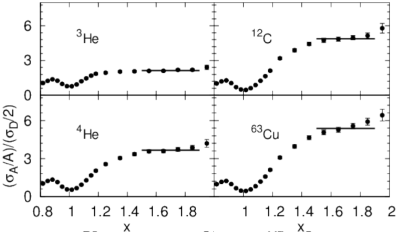
Modification Questions

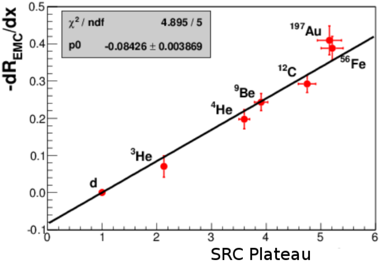
- Possible new degrees of freedom must be considered for nucleon modification - can CSV effectively be induced in asymmetric nuclei?
- Are data such as those from NuTeV hinting at us that these effects are important?
- Is there a direct connection between nucleon and parton-level modification observables?





- SRC show strong preference to n-p pairs over p-p pairs
- Show strong correlation to "plateau" parameter for $x > 1$ SFs
- Different high momentum tails for *n* and *p* in asymmetric nuclei could drive modification and IVEMC





Systematics and Experimental uncertainties

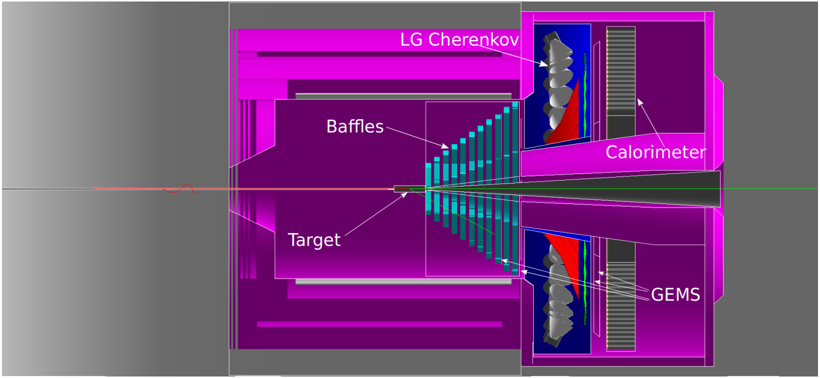
- Polarimetry and pions are main contributions
- Radiative working group has been established for PVDIS
- Dominant errors:

Effect	Uncertainty [%]
Polarimetry	0.4
Q^2-dependent effects	0.2
Pions (bin-to-bin)	0.1-0.5
Radiative Corrections (bin-to-bin)	0.5-0.1
e^- from pair production	0.5-0.0
Total for any given bin	$\sim$0.5-0.8

- Statistical uncertainty dominates

Configuration

- Experimental configuration practically identical to approved SoLID PVDIS measurement
- Rates are better or comparable to existing LD_2 measurement



Radiation Summary

- Beam on target simulation using Remoll
  - Limited statistics – about 20% uncertainty on neutrons
- No Polythene yet

Radiation Power with No Poly

		Ca48	LD2	PREX_I	PREX_II
Type	E range	Power	Power	Power	Power
	(MeV)	(W/uA)	(W/uA)	(W/uA)	(W/uA)
e±	E<10	0.11	0.11	0.17	0.01
	10<E	0.18	0.16	1.29	0.06
Photons	E<10	0.02	0.02	0.75	0.08
	10<E	0.04	0.04	2.03	0.11
Neutrons	E<10	0.0002	0.0003	0.0023	0.0003
	10<E	0.0047	0.0098	0.0039	0.0012

		Ca48 @ 80 uA	LD2 @ 50 uA	PREX_I @ 70 uA	PREX_II @ 70 uA
Type	E range	Power	Power	Power	Power
	(MeV)	(W)	(W)	(W)	(W)
e±	E<10	9.02	5.67	11.64	0.64
	10<E	14.45	8.13	90.16	3.93
Photons	E<10	1.94	1.13	52.19	5.34
	10<E	3.11	2.05	142.31	7.49
Neutrons	E<10	0.02	0.02	0.16	0.02
	10<E	0.38	0.49	0.28	0.08

Radiation Flux with No Poly

		Ca48	LD2	PREX_I	PREX_II
Type	E range	Flux	Flux	Flux	Flux
	(MeV)	(Hz/uA)	(Hz/uA)	(Hz/uA)	(Hz/uA)
e±	E<10	3.83E+11	4.08E+11	3.45E+11	2.05E+10
	10<E	3.84E+10	3.23E+10	2.10E+11	9.42E+09
Photons	E<10	2.22E+11	2.83E+11	5.49E+12	6.41E+11
	10<E	6.77E+09	6.70E+09	3.43E+11	1.93E+10
Neutrons	E<10	7.86E+08	1.44E+09	1.62E+10	1.79E+09
	10<E	2.62E+08	3.31E+08	3.93E+08	1.34E+08

		Ca48 @ 80 uA	LD2 @ 50 uA	PREX_I @ 70 uA	PREX_II @ 70 uA
Type	E range	Flux	Flux	Flux	Flux
	(MeV)	(Hz)	(Hz)	(Hz)	(Hz)
e±	E<10	3.06E+13	2.04E+13	2.42E+13	1.44E+12
	10<E	3.07E+12	1.62E+12	1.47E+13	6.59E+11
Photons	E<10	1.78E+13	1.41E+13	3.85E+14	4.49E+13
	10<E	5.41E+11	3.35E+11	2.40E+13	1.35E+12
Neutrons	E<10	6.29E+10	7.21E+10	1.13E+12	1.25E+11
	10<E	2.10E+10	1.65E+10	2.75E+10	9.39E+09