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

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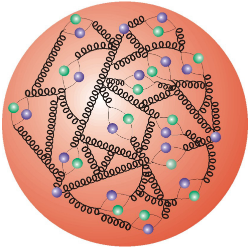
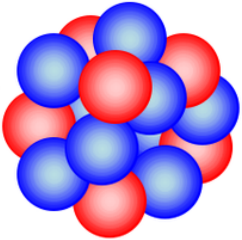
For more details on physics

http://arxiv.org/abs/2304.04622

From QCD to Nucleons and Nuclei

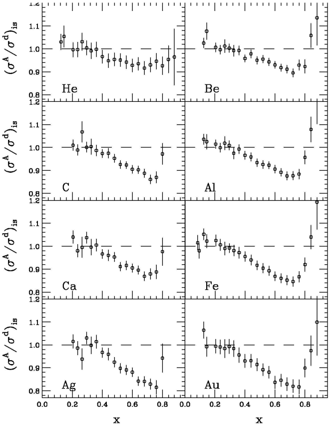
- How are protons and neutrons are modified when they are bound in a nucleus?
- How do we make the transition between QCD and nuclear physics?
- While the existence of nuclear modification of the pdfs is well established, important questions remain about the nature of the modification
- We have almost 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 or refutes this hypothesis

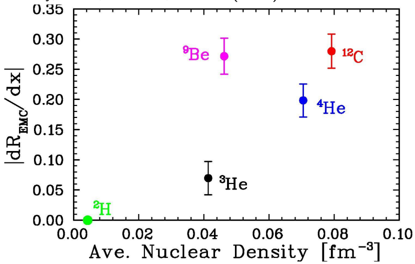


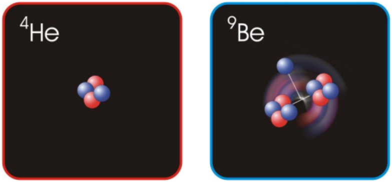
J. Gomez et *al.*, *PRD49 4348 (1994)*

Isovector Dependence in SRC ?

- High-x EMC slope for 3He, 4He, 9Be, 12C
  - Shows universal x-dependence
- Size of EMC effect does NOT scale with density
  - 9Be is low density, but has 'large' EMC effect

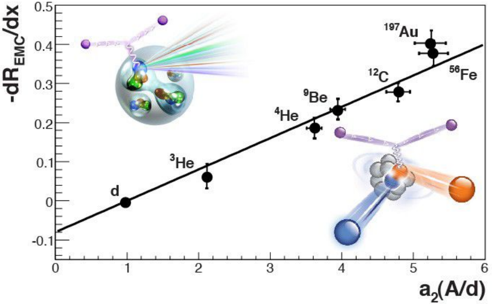
J.Seely, et al., PRL103, 202301 (2009)





Isovector Dependence in SRC ?

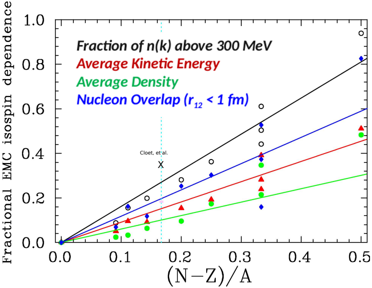
- SRC show strong preference to n-p pairs over p-p pairs
- EMC effect shows correlation with SRCs
- Observed EMC-SRC correlation plus np dominance suggests mechanism for possible flavor dependence with limited sensitivity



L. Weinstein, et al., PRL 106, 052301 (2011) and J. Arrington, et al., PRC 86, 065204 (2012)

ISOVECTOR DEPENDENCE IN EMC ?

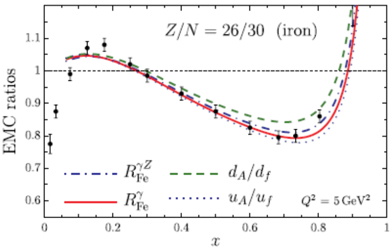
Isospin dependence of the EMC effect vs. fractional neutron excess of the nucleus for the four scaling models based on GFMC calculations for $A <= 12$

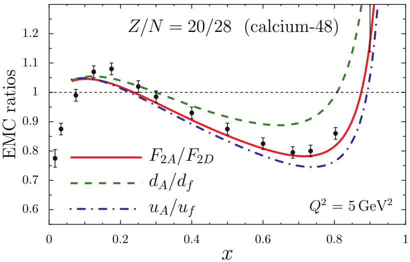


J. Arrington, EPJ Web Conf. 113 (2016) 01011, arXiv: 1508.05042

Modeling Flavor Dependence

- At the quark level isovector nuclear forces affect the u and d quarks differently, leading to flavor-dependent modifications
- **Cloët-Bentz-Thomas (CBT)** predicts significant flavor dependent based on mean field calculations
  - Using explicit isovector terms (constrained by nuclear physics data such as the symmetry energy)
- CBT result significantly reduces NuTeV $sin^2\theta_W$ anomaly

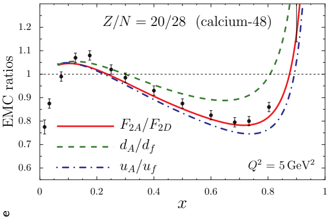


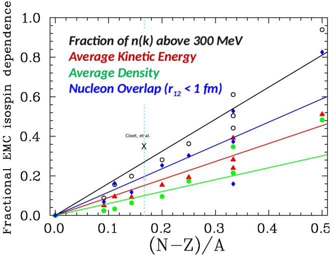


Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

Estimates of flavor dependence?

- CBT calculation – mean-field model; impact of QCD scalar, vector fields modifies up, down quark differently for N > Z nuclei
- Simple assumptions about underlying cause: EMC scales with density,high-momentum nucleons, avg nucleon kinetic energy, amount of short-distance configurations: All can be calculated for p, n separately for isospin dependence
- "Extreme cases" – EMC is 100% up (or down) quarks: Not very realistic, but help us understand the flavor dependence





DIS

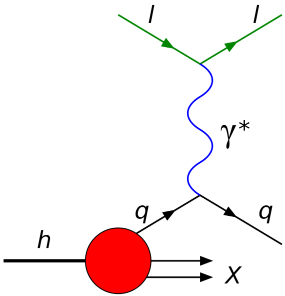
- DIS with leptons offers picture into partonic distributions

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

- 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),

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

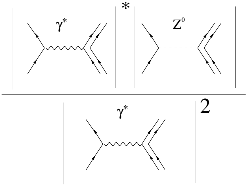


Flavor Dependence Observations with PVDIS

PVDIS probes flavor combinations $\rightarrow$ isovector properties

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

$\sim$



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

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

$F_{2A}^{\gamma Z}$: Structure functions arising from γZ interference and F_{2A}^{γ}: traditional DIS SF

Flavor Dependence Observations with PVDIS

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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

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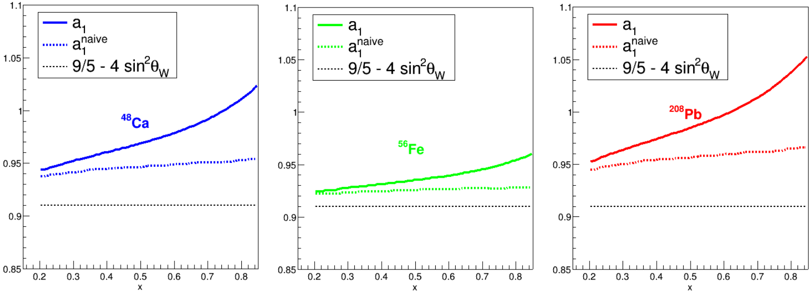
a_1 PREDICTIONS

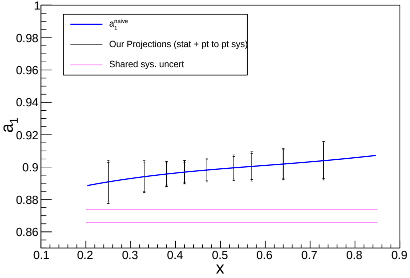


Flavor Dependence Observations with PVDIS

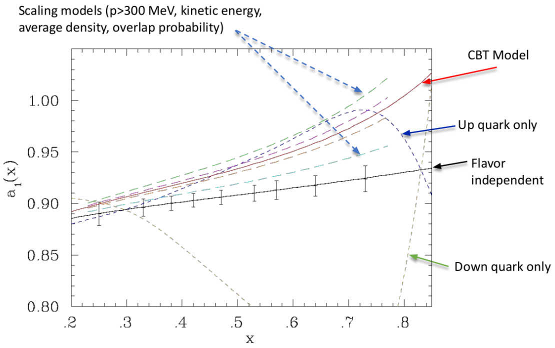
- Neutral currents will provide access to isovector observables
- ^{48}Ca target will test isovector (IV) dependence - larger A gives larger EMC, larger $Z - N$ gives IV enhancement
- Present data demands $\sim 1\%$ level for significant tests

Symmetric nucleus limit

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



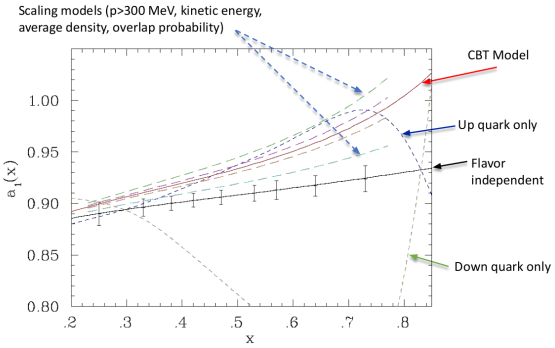
PVEMC Sensitivity



Precision to differentiate models, set significant limit if results consistent with flavor-independent result

- 8σ sensitivity to CBT model (neglecting normalization);
- $> 3\sigma$ sensitivity to the smallest prediction (cyan curve)
- Smallest prediction (cyan) is 8σ from largest (green), 4.5σ from CBT

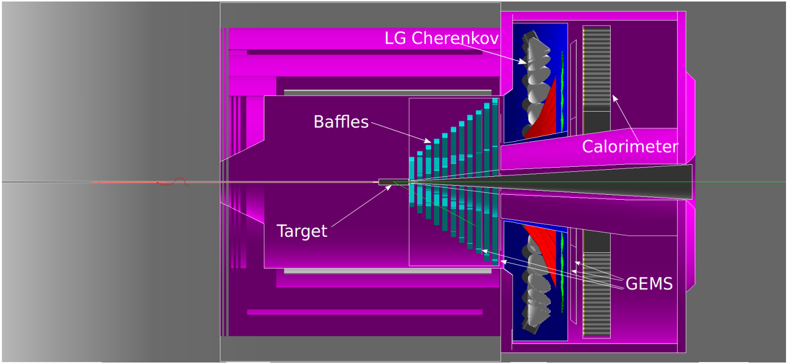
PVEMC Sensitivity



- PVDIS naturally sensitive to flavor *differences*
- PVEMC is cleaner and more precise than SIDIS and pionic Drell-Yan
- Experiments such as SRC helped motivate PVEMC and tie into results from this program
  - Spin EMC and tagged DIS from highly off-shell nucleons can provide complementary information

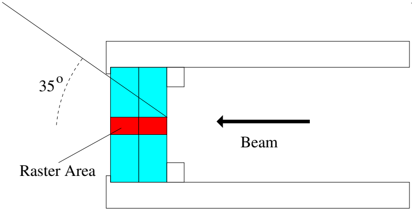
SoLID Configuration

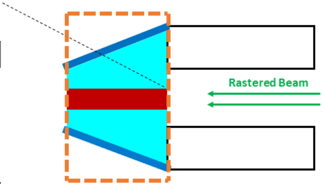
- Experimental configuration is identical to approved SoLID PVDIS measurement
- Lead baffles serve as momentum collimators
- GEMs, Cherenkov, and calorimeter provide tracking and PID
- ^{48}Ca Rates are lower compared to existing LD_2 measurement



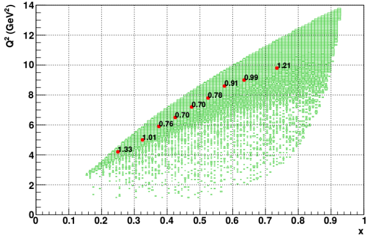
Target - ^{48}Ca

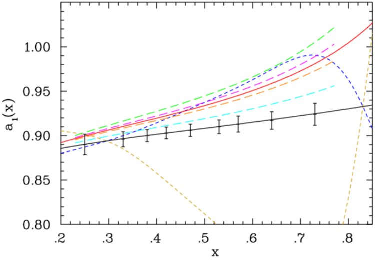
- ^{48}Ca target provides good balance between asymmetric target and not too high Z
- Has very good thermal conductance and high melting point - have operational experience and updated design/protocols from previous program including CREX
- 12% radiator - photons and photoproduced pions are main background 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.





- Requesting 68 days at 80 μA 11 GeV production (plus 15 days for commissioning, optics runs, background studies, and polarimetery) to get $\sim$1% stat uncertainties on A_{PV} across a broad range of x
- Precision to differentiate models, set significant limit if results consistent with flavor-independent result
- Significant ability to differentiate between different predictions
- *This provides new and useful constraints in a sector where there is little data*





Systematic and Experimental uncertainties

Effect	Uncertainty [%]
Polarimetry	0.4
Pions (bin-to-bin)	0.1-0.5
Charge-symmetric background	<0.1
Radiative Corrections (bin-to-bin)	0.5-0.1
$R^{\gamma Z}/R^{\gamma}$	0.2
Other corrections including CSV	0.2
pdf uncertainties	0.2
Total systematic	0.6-0.7
Statistics	0.7-1.3

- Charge symmetric background ($\pi^0 \to e^+e^-\gamma$)
- Hadronic and Nuclear uncertainties (HT, CSV, PDF uncertainties, and free PDF nuclear model uncertainties)
- SOLID LD_2 program (isoscalar target) will constrain CSV and $R^{\gamma Z}$
- Statistical uncertainty dominates any given bin

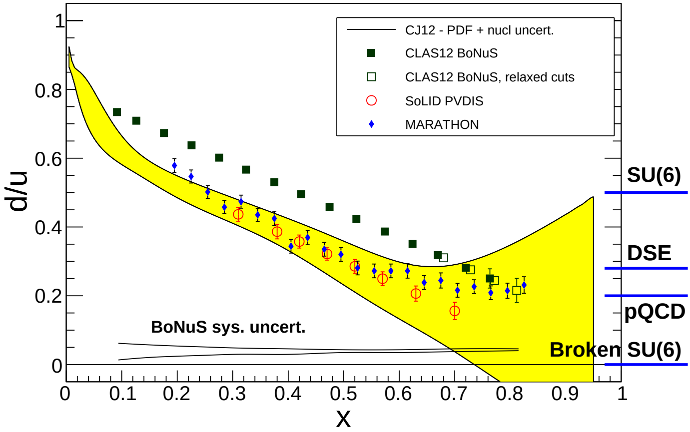
Systematic Errors: Pions

- Excellent π^- to e^- ratio when the coincidence trigger between calorimeter and Cerenkov is applied but
- We proposed to measure pion rate and asymmetry from dedicated runs to apply a correction for residual pion contamination in electron data.
- We assumed zero pion asymmetry as a conservative estimate
  - As it was measured to be smaller but same sign as $A_{PV}(DIS)$ in a previous measurement
- Based on estimated pion contamination and asymmetry, we assign a systematic error of 0.1-0.5% bin-to-bin, larger at larger x

Systematic Errors: Free PDF (d/u)

- At low x values, the full range of the CJ12 fit provides uncertainties in a_1 around the $\pm 0.2\%$ level
- The combined uncertainty from the fit and model dependence at larger x (0.55-0.65) is 0.6-1.0% but
- Either PVDIS-hydrogen data by itself, or global analyses including MARATHON and BoNUS results, should provide the necessary reduction to reach $\pm 0.2\%$ level
- The PVDIS data on hydrogen will provide a measurement of d/u, free from nuclear corrections

Systematic Errors: Free PDF (d/u)



Anticipated data for measurements on d/u, see text for references. Recently published MARATHON results are also shown

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	68	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	83		

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 neutron-rich target offers one of the most direct, precise, and theoretically clean way to isolate the flavor dependence of the EMC effect
- 68 days production will offer critical new information, help test leading hypotheses, and help elucidate the NuTeV anomaly
- Important input to parameterization of the EMC effect and to guide detailed calculations of the underlying physics.
- Helps understand PDFs for nuclei
  - Relevant for many high-energy lepton-scattering and nuclear collision measurements.

Link to our proposal:
`https://solid.jlab.org/DocDB/0004/000469/001/SoLID_PVEMC_Proposal_PAC50_Final.pdf`

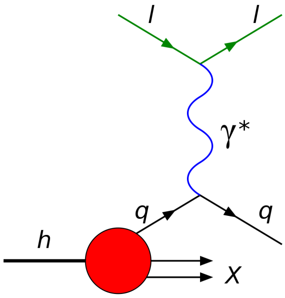
BACKUP

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



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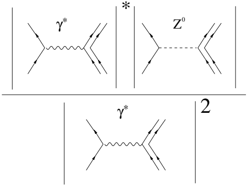
$\sim$ 

$\sim 100 - 1000$ ppm

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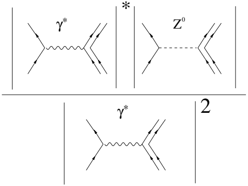

$\sim 100 - 1000\ \mathrm{ppm}$

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

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

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

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

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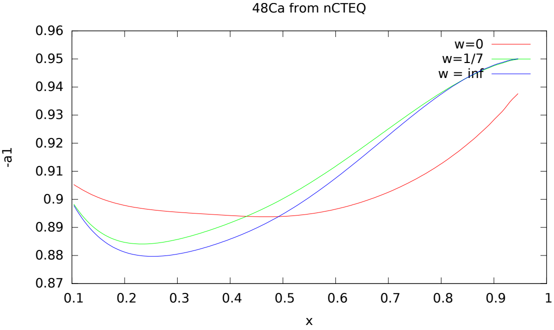
Therefore, a_1 will provide information about the flavor dependence of the nuclear quark distributions and a reliable extraction of the u and d quark distributions of a nuclear target

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



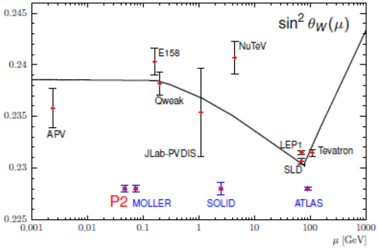
Isovector Dependence in NuTeV Anomaly

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

Pachos-Wolfenstein relation:

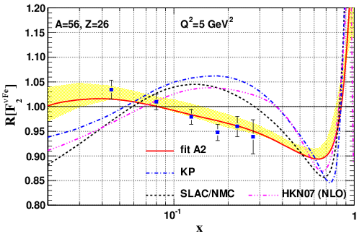
$$R_{\mathrm{PW}} \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)}$$

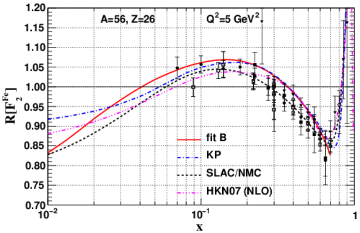
$$= \lim_{\to \mathrm{i.s.}} \frac{1}{2} - \sin^2\theta_W$$



- The impact of the flavor-dependent nuclear PDF modification on the NuTeV anomaly was evaluated in the Cloët-Bentz-Thomas (CBT) model
- CSV or IVEMC could play very important role and **are not well constrained by data**

- 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?

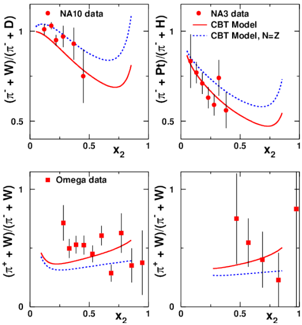




I. Schienbein et *al.* PRD77 054013 (2008); I. Schienbein et *al.* PRD80 094004 (2009)

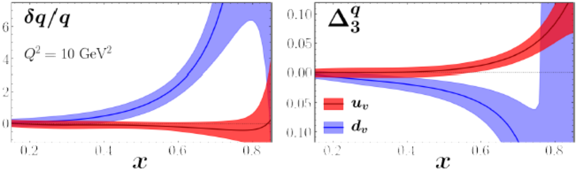
Drell-Yan and flavor-dependent EMC effect

- 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 EMC Effects from MARATHON



Preliminary Results

- The impact of the MARATHON data on the off-shell corrections is shown in left
- The strength of the isovector EMC (IVEMC) effect for u and d quarks
- A nonzero and opposite sign for u and d quarks strongly suggests the presence of an IVEMC effect.

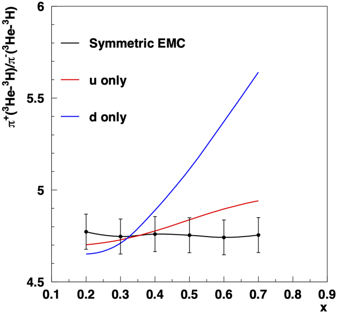
Isovector EMC effect from global QCD analysis with MARATHON data. (2021) arXiv:2104.06946

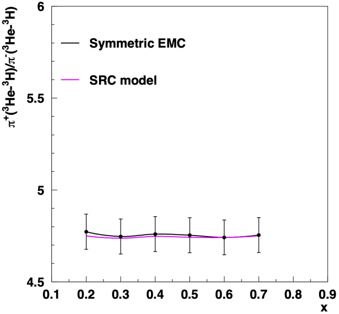
SIDIS

- Semi-inclusive deep inelastic scattering provides access to quark flavors with an electromagnetic probe by tagging pions in the final state of the reaction.
- A super-ratio of π^-/π^+ between deuterium and an asymmetric nuclear target would be sensitive to variations in the flavors
- Proposal PR12-09-004 aimed to use a comparison of π^+ and π^- production from Au to look for flavor dependence in the EMC effect.
  - The proposal was deferred, in large part due to questions about how well the data could be interpreted in terms of flavor dependence,
- A Letter of Intent for CLAS (LOI12-19-005) examined the possibility of making such a measurement via the comparison of π^+ and π^- production in ^{3}H and ^{3}He.

SIDIS

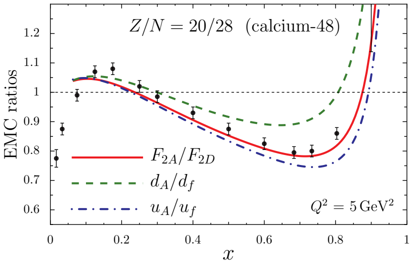
- The prediction from a flavor-independent EMC effect (black curve) compared to the an extreme projection assuming that the EMC effect is carried entirely by the up (red curve) or down (blue curve) quarks (left plot)
- The same observable assuming the flavor dependence (magenta curve), indicating no sensitivity in this more realistic flavor dependence (right plot)

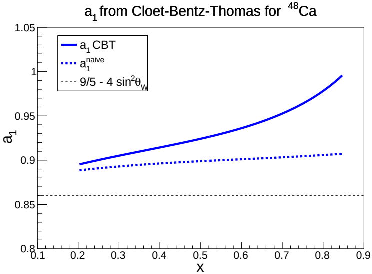




Modeling - CBT Model

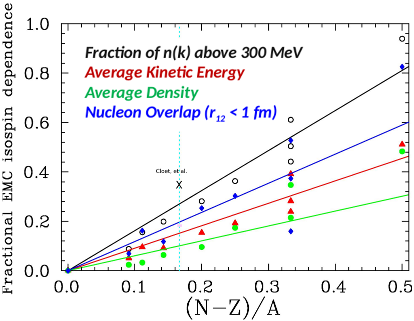
- Cloet et *al.* make predictions based on mean field calculations which give reasonable reproductions of SFs
- Explicit isovector terms are included constrained by nuclear physics data such as the symmetry energy
- Few percent effect in a_1, larger at larger x



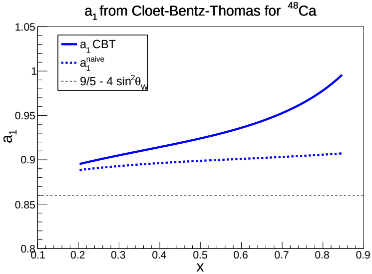


Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

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

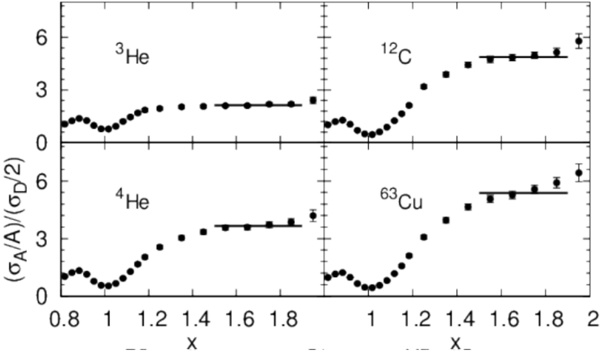


EPJ Web Conf., 113:01011, 2016



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

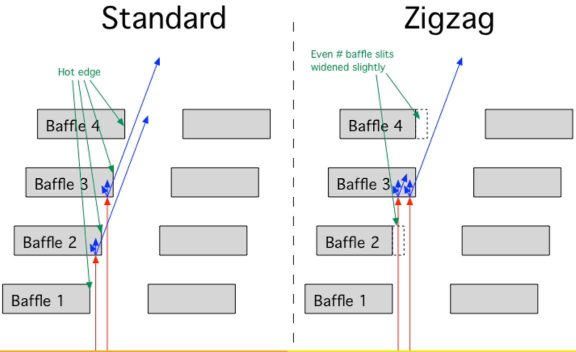


Target - ^{48}Ca Status

- The plan is to use the existing ^{48}Ca to form the new target.
- Target group estimates that recovery from existing supply would provide sufficient target material, but with 93% rather than 95%
- This would take some time, but work can begin after the experiment is approved
- No need to purchase any additional ^{48}Ca, **If** sufficient material is not recovered in which case a small additional amount may be purchased

Background Suppression with Baffles

- raytraced electron trajectories used in baffle width design that was fine-tuned to the solenoid field such that acceptance is optimized to allow charge particles in the acceptance while disfavoring particles outside that range
- Baffle design on left was improved by opening up the slits in the even-numbered plates to have reduced background design shown on right



GEM Rates

GEM plane	LD_2 background (kHz/mm^2/μA)	^{48}Ca EM background (kHz/mm^2/μA)	^{48}Ca EM background (no baffles) (kHz/mm^2/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
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

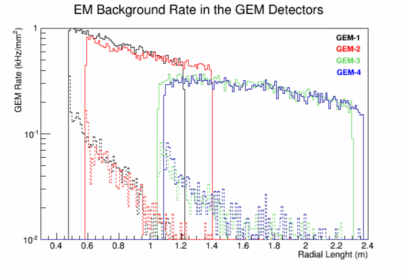
Cerenkov Trigger Rates

	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

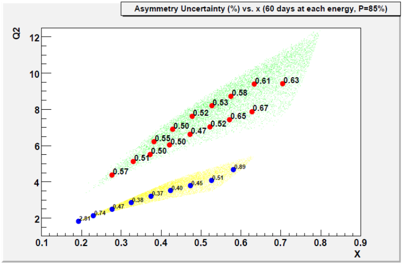
- Trigger defined by coincidence between Cherenkov and shower - 150 kHz total anticipated with background (well below SoLID spec)
- Pion contamination no worse than 4% in any given bin (worst at high x)
- GEM rates comparable to or smaller than design for LD_2



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

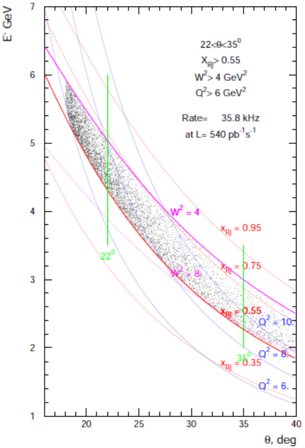
Systematics

- 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 but we addressed with best possible information available at the moment in our response



SoLID-PVDIS Acceptance

- The useful kinematic range of the scattered electrons
- The acceptance in the scattering angle θ is limited at $\theta > 18^o$ by the $Q^2 > 6GeV^2$ cut



Systematic Errors: Radiative Corrections

- To aid with the determination of radiative effects, independent aluminum targets with $x/X_0 = 1\%$, 5%, and 10% will be included. (SoLID-PVDIS LD2)
- These will aid in the verification of scattering rate distributions under different radiative conditions and the overall unfolding procedure

EM Radiative Correction

- We have a good momentum acceptance to measure these events to sufficient accuracy within the Q^2 acceptance of the measurement.
- Beam time includes lower beam energy systematic studies that have access to lower W and Q^2 regions
- We anticipate that A/Q^2 will be roughly constant everywhere.
- Using measurements and the theory for radiative corrections the error on the radiative corrections can be controlled
- We assign a $0.1\% - 0.5\%$ bin-to-bin systematic, worse for small x

Weak Radiative Correction

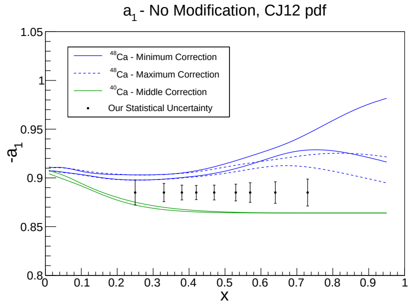
Weak radiative corrections will be calculated for our kinematics and are not likely to change in a way that is sensitive to this experiment.

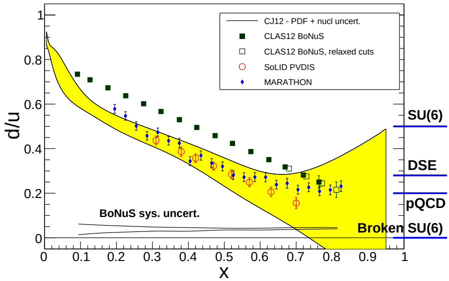
Systematic Errors: d/u

- At low x values, the full range of the CJ12 fit provides uncertainties in a_1 around the $\pm 0.2\%$ level
- The combined uncertainty from the fit and model dependence at larger x (0.55-0.65) is 0.6-1.0% but
- Either PVDIS-hydrogen data by itself, or global analyses including MARATHON and BoNUS results, should provide the necessary reduction to reach $\pm 0.2\%$ level
- The PVDIS data on hydrogen will provide a measurement of d/u, free from nuclear corrections

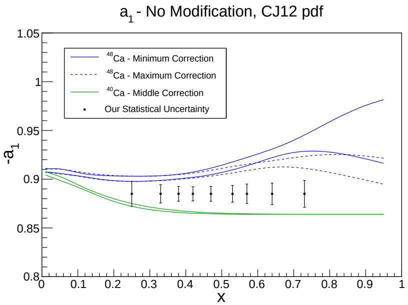
SYSTEMATIC: d/u

- 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





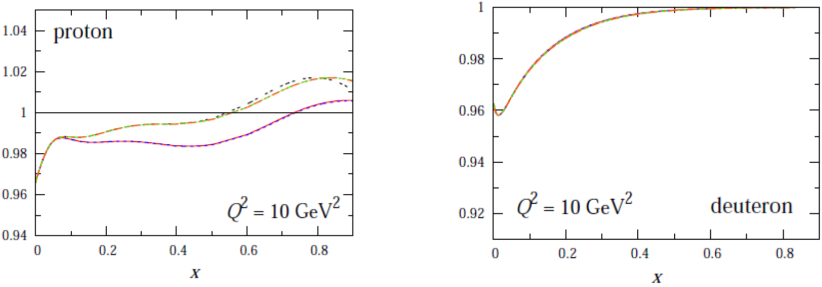
Systematic: d/u, Free PDF Error and CSV



- 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
- Would require similar beamtime commitment (60 days)
- ^{40}Ca tests isoscalar prediction - but isoscalar PDFs significantly cancel! (^{40}Ca in CJ12 nPDF fit is green curve)

Systematic Errors: $R^{\gamma Z}/R^{\gamma}$

- The impact of target mass effects on the difference between $R_{\gamma Z}$ and R_{γ} is shown
- Expected difference is, at most 4% in the x range sampled by this proposal, corresponding to a 0.2% uncertainty on a_1.
- Caveat: There is some additional uncertainty due to the impact of non-perturbative contributions



Phys.Rev.D 84 (2011) 074008

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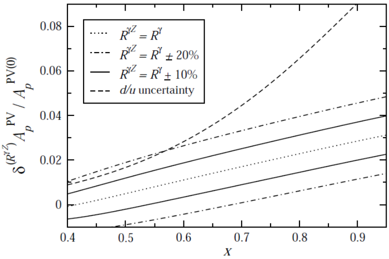
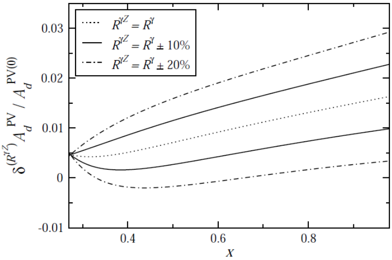


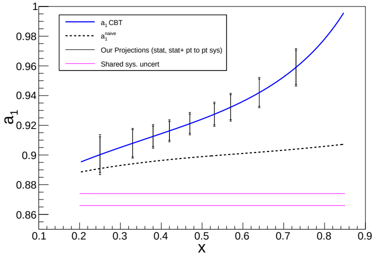


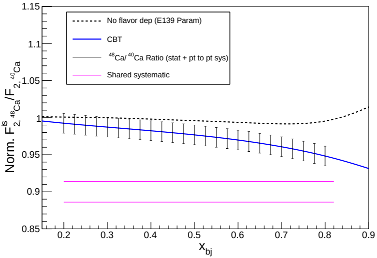
Polarimetry

- Two independent polarimeters will be deployed for this experiment.
- A continuous monitoring by the upgraded Compton polarimeter is anticipated to give 0.4% systematic uncertainty
- The Møller polarimeter will provide an additional invasive measurements periodically with a projected uncertainty of about 0.8% (Will improve after MOLLER).

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 at $x = 0.7$	5.5σ	2.1σ
IVEMC vs. naive hypothesis	6.2σ	$<2\sigma$
min vs. max IVEMC	4.4σ	N/A

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

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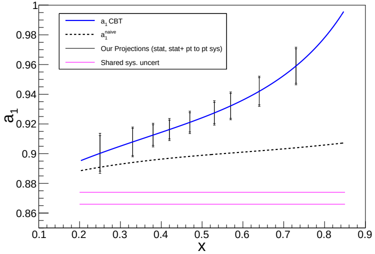

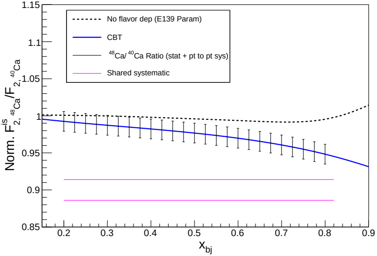

- PVDIS naturally sensitive to flavor *differences*
- DIS and PVDIS allows for flavor determination
- Other processes such as tagged SIDIS and π Drell-Yan offer complementary information
- Experiments such as SRC help motivate and tie into this program

We define

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

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

The full parity-violating asymmetry is in terms of the structure functions $F_1^{\gamma}(\gamma Z)$ and $F_2^{\gamma}(\gamma Z)$

$$A_{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right) \frac{g_A^e \left(2xyF_1^{\gamma Z} - 2\left[1 - 1/y + xM/E\right] F_2^{\gamma Z}\right) + g_V^e x(2-y) F_3^{\gamma Z}}{2xyF_1^{\gamma} - 2\left[1 - 1/y + xM/E\right] F_2^{\gamma}} \quad (3)$$

We can then write it in the reduced from by

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

with

$$\begin{aligned} Y_1 &= \frac{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma Z})\right) - 2xyM/E}{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma})\right) - 2xyM/E}\left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right) \\ Y_3 &= \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left(1-r^2/(1+R^{\gamma})\right) - 2xyM/E}\left(\frac{r^2}{1+R^{\gamma}}\right) \end{aligned}$$

and

$$F_1^{\gamma} = \frac{1}{2}\sum_i e_i^2\left(q_i(x)+\bar{q}_i(x)\right); F_2^{\gamma} = 2xF_1^{\gamma}, \quad (5)$$

$$F_1^{\gamma Z} = \sum_i e_i g_V^i\left(q_i(x)+\bar{q}_i(x)\right); F_2^{\gamma Z} = 2xF_1^{\gamma Z}, \quad (6)$$

$a_1(x)$ Term

The $F_{2A}^{\gamma Z}$ structure function has a different flavor structure to that of F_{2A}^{γ} and, as a consequence, $a_2(x_A)$ is sensitive to flavor-dependent effects. Expanding $a_2(x_A)$ about $u_A^+ \simeq d_A^+$ and assuming $s_A^+ \ll u_A^+ + d_A^+$ gives

$$a_2(x_A) \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+(x_A) - d_A^+(x_A) - s_A^+(x_A)}{u_A^+(x_A) + d_A^+(x_A)}, \quad (6)$$

where we have ignored heavier quark flavors. The correction from strange quarks given in Eq. (6) may be of importance in the low-x region [14], however, recent HERMES data [15] has confirmed that $s^+(x)$ is negligible compared with $u^+(x) + d^+(x)$ in the region $x > 0.1$. Therefore, a measurement of $a_2(x_A)$ will provide information about the flavor dependence of the nuclear quark distributions and when coupled with existing measurements of F_{2A}^{γ}, a reliable extraction of the u and d quark

EMC Ratio Definition

The EMC effect can be defined for both the traditional DIS and γZ interference structure functions, via the ratio

$$R^i = \frac{F^i_{2A}}{F^{i,\text{naive}}_{2A}} = \frac{F^i_{2A}}{ZF^i_{2p} + NF^i_{2n}}, \tag{9}$$

where $i \in \gamma, \gamma Z$. The target structure function is labelled by F^i_{2A}, while $F^{i,\text{naive}}_{2A}$ is the naive expectation with no medium effects whatsoever, and can be expressed as a sum over the free proton and neutron structure functions. Therefore, if there were no medium effects R^i would be unity. Expressing the EMC effect in terms of the PDFs we find the parton model expressions

$$R^\gamma \simeq \frac{4u^+_A + d^+_A}{4u^+_f + d^+_f}, \qquad R^{\gamma Z} \simeq \frac{1.16u^+_A + d^+_A}{1.16u^+_f + d^+_f}, \tag{10}$$

EMC Ratio Definition

The fact that $u_A/u_f < d_A/d_f$ and as a consequence $R^\gamma < R^{\gamma Z}$ in nuclei with a neutron excess is a direct consequence of the isovector mean field and is a largely model independent result. In Ref. [20] it was demonstrated that the isovector mean field leads to a small shift in quark momentum from the u to the d quarks, and hence, the in-medium depletion of u_A is stronger than that of d_A in the valence quark region. Because u_A is multiplied by a factor four in the ratio R^γ, the depletion is more pronounced for this ratio than for $R^{\gamma Z}$, where the d quark quickly dominates as Z/N becomes less than one.