Measurements of the Flavor Dependence of the EMC Effect Using Parity-Violating Deep Inelastic Scattering

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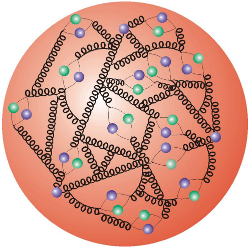
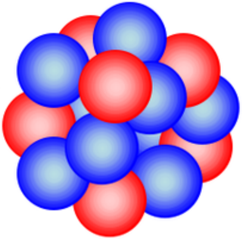
QCD in Nucleons and Nuclei

QCD Questions

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





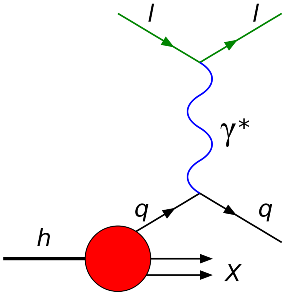
DIS

- DIS with leptons offers picture into partonic distributions

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

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

$$F_L \approx F_2 - 2xF_1$$



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

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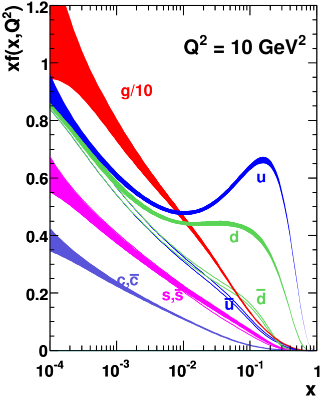

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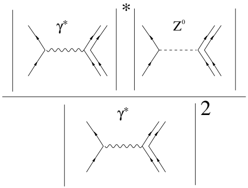
PVDIS

PVDIS proves new flavor combinations $\rightarrow$ isovector properties

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



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

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

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

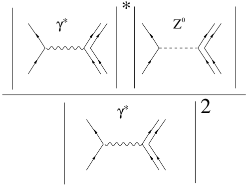
Effective Weak Couplings

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

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

PVDIS

PVDIS proves new flavor combinations $\rightarrow$ 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

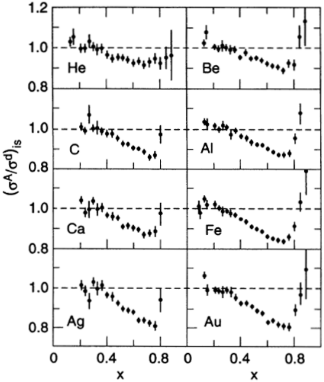
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \ldots$$

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

EMC Effect

Nuclear Modification

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



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

General assumption of $u \leftrightarrow d$ for $p \leftrightarrow n$
PVDIS can test this

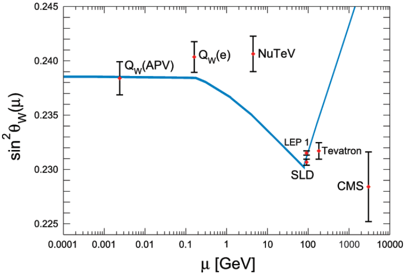
Isovector Dependence? - NuTeV

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

Pachos-Wolfenstein relation:

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

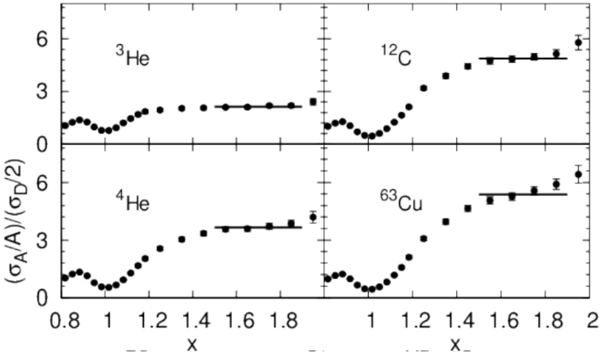
$$= \lim_{\to \text{i.s.}} \frac{1}{2} - \sin^2\theta_W$$



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

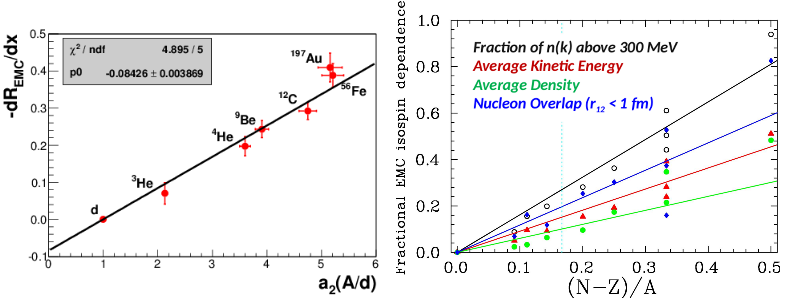
Isovector Dependence? - SRC

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



Isovector Dependence? - SRC

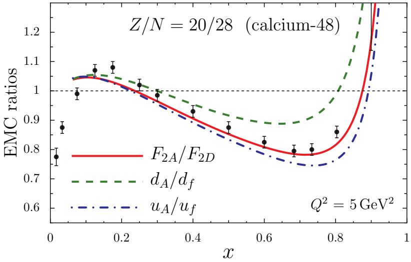
- SRC show strong preference to n-p pairs over p-p pairs
- Also show strong correlation to "plateau" parameter for $x > 1$ SFs
- Preliminary models make predictions of deviations for asymmetric nuclei

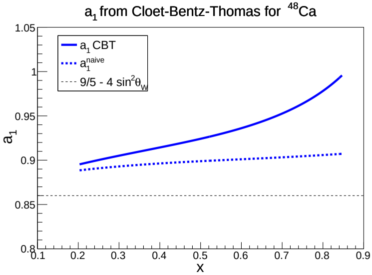


Arrington, EPJ Web Conf. 113, 01011 (2016)

Modeling - CBT Model

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





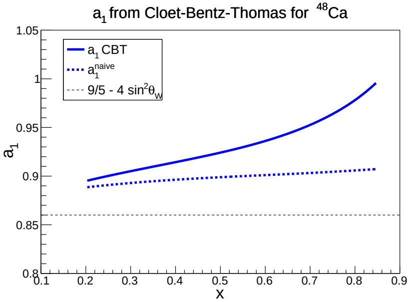
Cloet et *al.* PRL102 252301 (2009), Cloet et *al.* PRL109 182301 (2012)

Where to get constraint

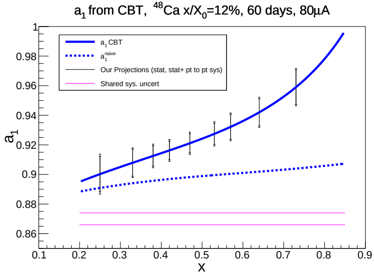
- Neutral currents will provide access to isovector observables
- Present data demands $\sim 1\%$ level for significant tests
- LD_2 will constrain CSV as isoscalar target (as well as $R^{\gamma Z}$)
- Asymmetric target will test isovector dependence - larger A gives larger EMC, larger $Z - N$ gives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

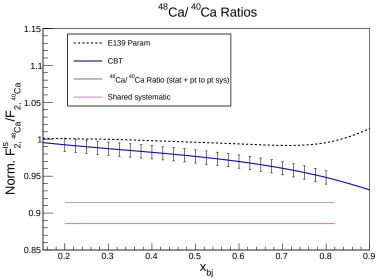
Symmetric nucleus limit

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



PVDIS offers highest sensitivity and is required for full picture

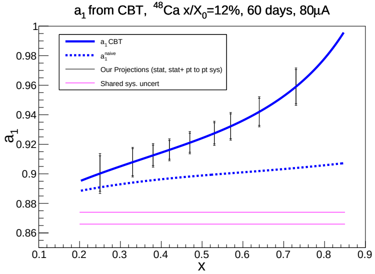


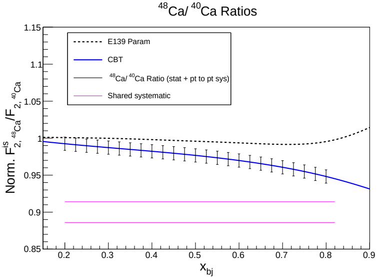


	PVEMC (this prop.)	EMC E12-10-008
Statistics	0.7-1.3%	0.8-1.1%
Systematics	0.5%	0.7%
Normalization	0.4%	1.4%
CBT x-dependence	5%	3%
CBT sensitivity	5.6σ	$< 3\sigma$

Other Methods

PVDIS offers highest sensitivity and is required for full picture

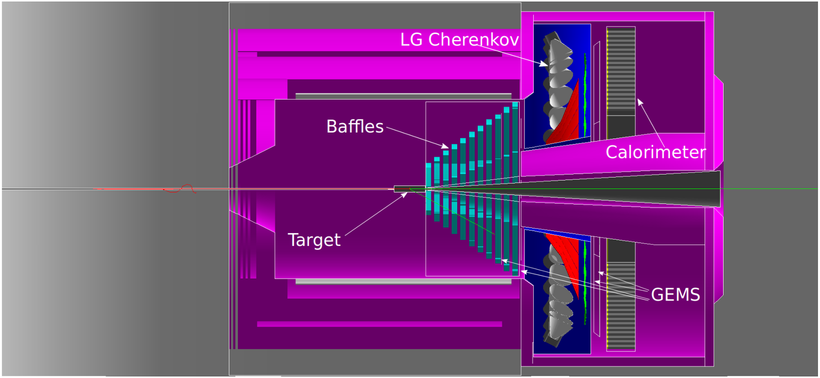




- PVDIS naturally sensitive to flavor *differences*
- DIS and PVDIS allows for flavor determination
- Other processes such as tagged SIDIS and π Drell-Yan offer complementary information
- Experiments such as SRC help motivate and tie into this program

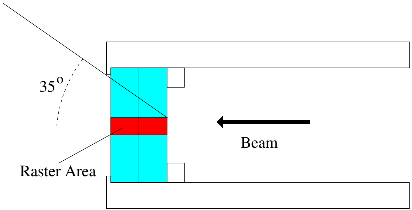
Configuration

- 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 with previous program and upcoming CREX
- 12% radiator - photons and photoproduced pions are main background concerns



Backgrounds and Induced Radiation in the Hall

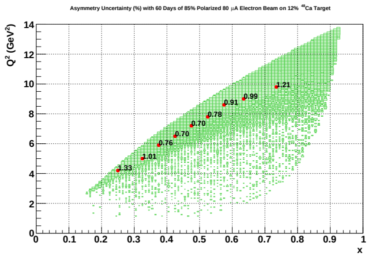
- Radiation in hall comparable to LD_2 measurement
- Backgrounds, trigger rates, etc experiment is also or better and within SoLID specifications

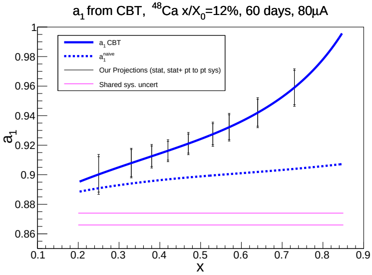
		Radiation Power in the Hall	
Radiation Type	E-Range (MeV)	^{48}Ca (W/μA)	LD_2 (W/μA)
$e^{\pm}$	$E < 10$	0.11	0.11
	$E > 10$	0.18	0.16
n	$E < 10$	0.0002	0.0003
	$E > 10$	0.005	0.010
γ	$E < 10$	0.02	0.02
	$E > 10$	0.04	0.04

GEM plane	LD_2 background (kHz/mm^2/μA)	^{48}Ca EM background (kHz/mm^2/μA)
1	6.8	4.8
2	3.0	2.1
3	1.1	0.8
4	0.7	0.5

Projections

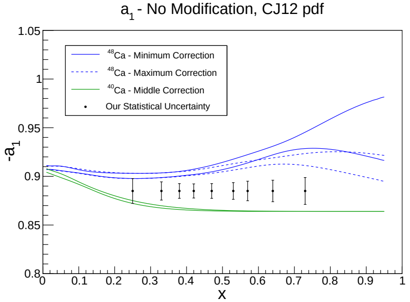
- Requesting 60 days at 80 μA 11 GeV production (71 days total) to get $\sim$1% stat uncertainties across a broad range of x
- In the context of the CBT model, this is few sigma in very simple interpolation model
- *This provides new and useful constraints in a sector where there is little data*

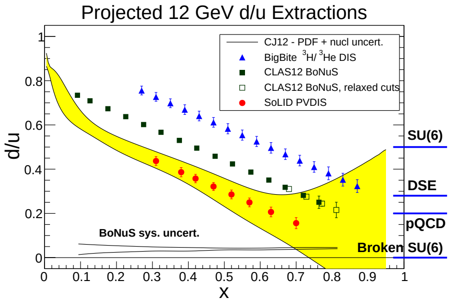




Systematics

- 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 and Experimental uncertainties

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

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

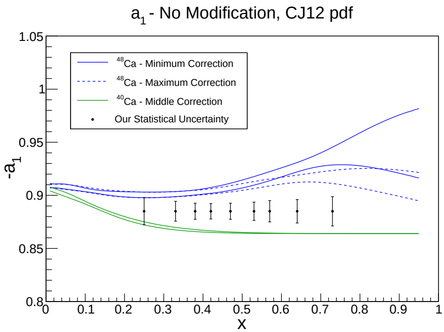
- Statistical uncertainty dominates any given bin

Summary

- Nuclear modification has many open important questions for our understanding of QCD
- PVDIS on asymmetric targets offers exciting opportunity to uncover isovector dependence in modification
- 60 days production will offer critical new information, help test leading hypotheses, and help resolve the NuTeV anomaly

BACKUP

Why not ^{40}Ca?



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

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

Induced Radiation in the Hall

- Radiation in hall comparable to LD_2 measurement
- Backgrounds, trigger rates, etc experiment is also or better and within SoLID specifications

Radiation Type	E-Range (MeV)	Radiation Power in the Hall ^{48}Ca (W/μA)	LD_2 (W/μA)
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Site Boundary - Relative Comparison to LD_2

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

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

Site Boundary

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

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

- Black mrem numbers from radcon - Blue extrapolated by us
- Have 10 mrem/yr administrative limit
- Calculated to be factor of 2 smaller than CREX

Radiation on ECal

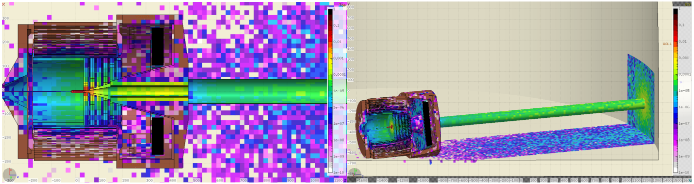
Table: Neutrons Flux at the Front of the ECAL

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

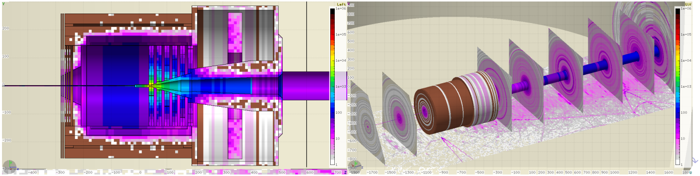
- Total dose (neutron and EM) similar to LD_2
- Estimated 100 kRad dose in ECal active components for LD_2, $\sim$50 kRad for this experiment
- Expect 20% yield loss at $\sim$400 kRad

SoLID PVDIS: Power and Activation

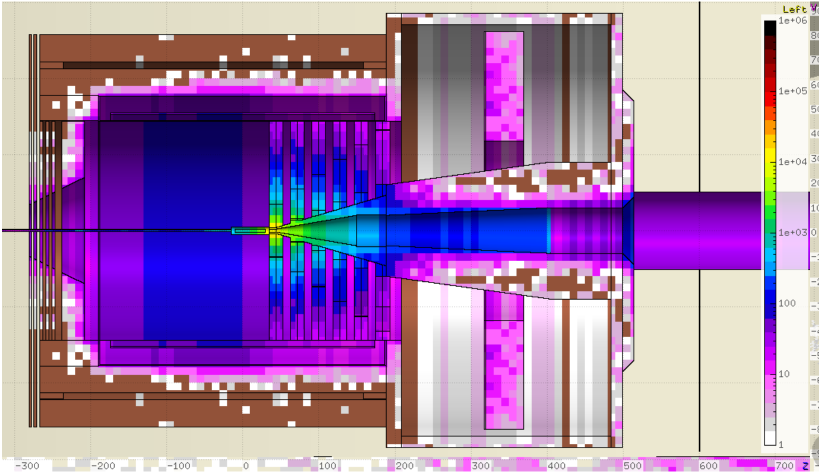
$E_{dep}(W)/cm^3$ PVDIS, Liquid D target ($100\mu A$)



$Dose_{eq}(mrem)/h$ after $1hour$ from beam exposure (1 Month running time)



1 month running, 75% duty cycle, mrem on contact after 1 hour



SoLID PVDIS: Power and Activation

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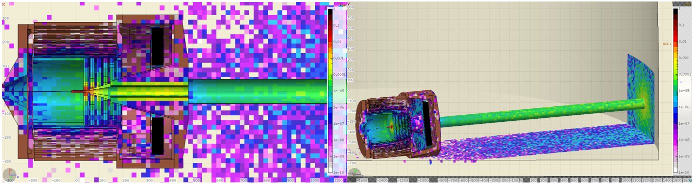
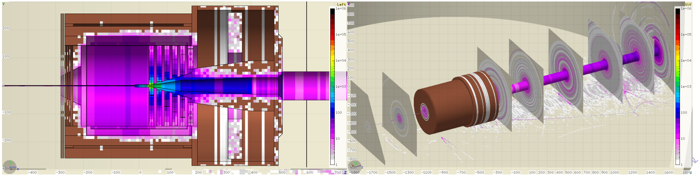


$Dose_{eq}(mrem)/h$ after $1day$ from beam exposure (1 Month running time)



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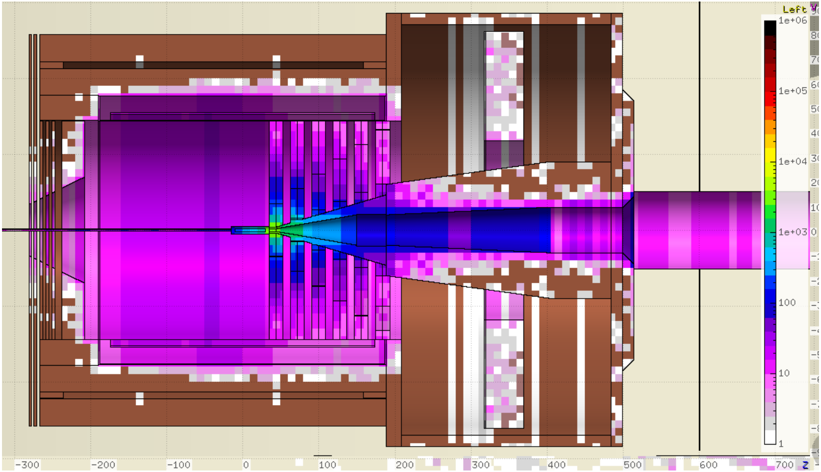
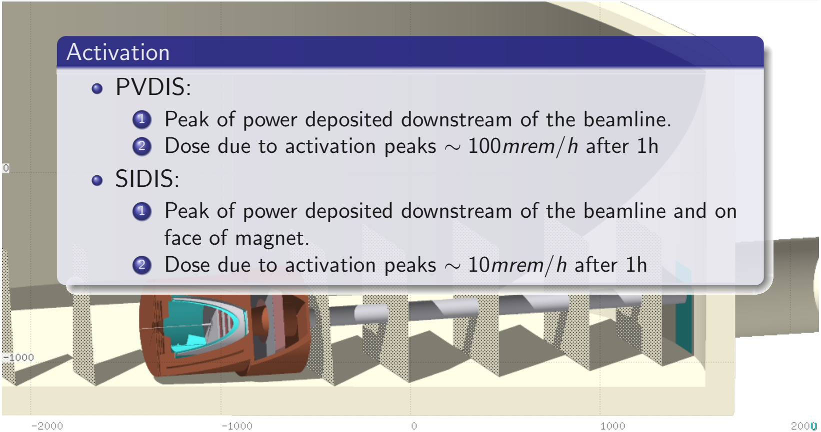


Conclusions

Activation

- PVDIS:
  1. Peak of power deposited downstream of the beamline.
  2. Dose due to activation peaks $\sim 100 mrem/h$ after 1h
- SIDIS:
  1. Peak of power deposited downstream of the beamline and on face of magnet.
  2. Dose due to activation peaks $\sim 10 mrem/h$ after 1h



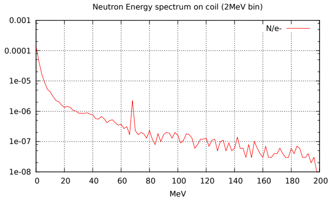
Radiation on Coils

Radiation limit $\frac{Neutron_{(E_N>0.1MeV)}}{cm^2} = 10^{19}\frac{N}{cm^2}$ for NbTi

see
http://supercon.lbl.gov/WAAM/WAAM_Talks/Al%20Zeller%0WAAM.pdf

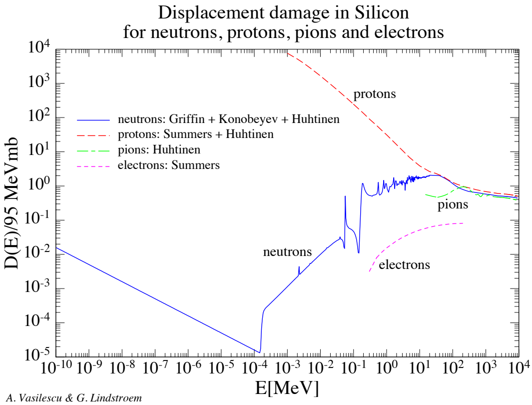
FLUKA Simulation FULL FLUX integrated in the total Coil

Also considering that FLUKA is off of an order of magnitude in this angle range, we are expecting a flux of $Neutron_{(E_N>0.1MeV)} = 10^{18}N$, well in the limit for NbTi



Displacement damage in Si, NIEL

(Non Ionizing E-Loss) for e^-, p, π, n

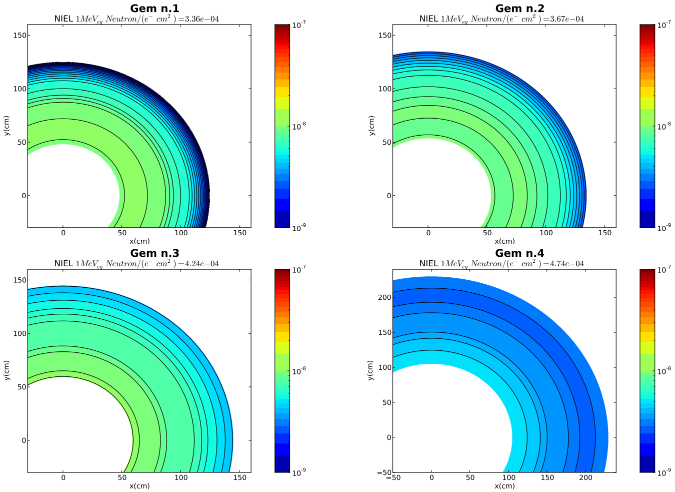


Displacement damage in Si, NIEL

What is a tolerable level for APV25 (GEM) ?

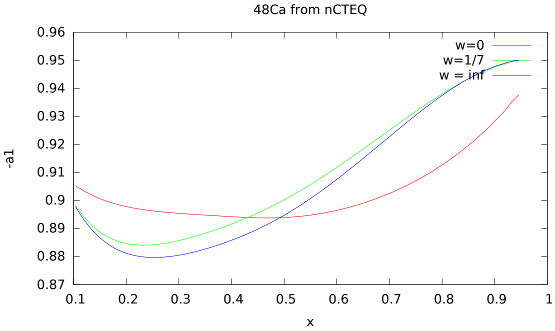
- CMS Silicon STRIP Tracker (the APV25 chip was designed for this detector) total fluence expected to peak around $2.4x10^{14}\frac{1MeV_{eq}N}{cm^2}$
- Our flux is ($2000h$ at $100\mu A$) $2.4x10^{14}\frac{1MeV_{eq}N}{cm^2} \Rightarrow 5.3x10^{-8}\frac{1MeV_{eq}N}{e^- cm^2}$

PVDIS $1MeV_{eq}$ $\frac{N}{e^{-}cm^{2}}$ WITH SHIELDING (ABS/SHLD = POLY)



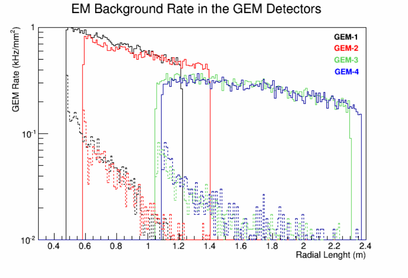
Modeling - nPDFs

- 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



Rates and Backgrounds

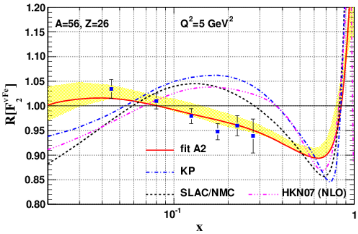
- Trigger defined by coincidence between Cherenkov and shower - 150 kHz total anticipated with background (well below SoLID spec)
- Pion contamination no worse than 4% in any given bin (worst at high x)
- GEM rates comparable to or smaller than design for LD_2

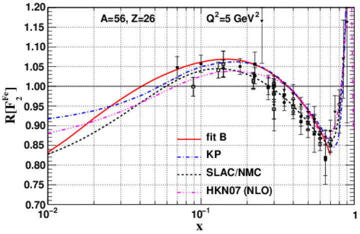


Particle	DAQ Coin. Trig.Rate (kHz) P > 1 GeV	P > 3 GeV
DIS e^-	144	61
π^-	11	7
π^+	0.4	0.2
Total	155	68

Isovector Dependence? - Partitioned Fits

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





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

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 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)

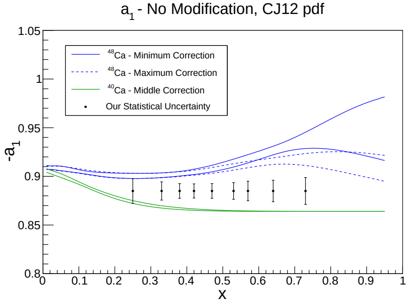
	Trigger Rate for $p > 1.0$ GeV (kHz)	Trigger Rate for $p > 3.0$ GeV (kHz)
DIS	223	66
π^-	193	49
π^+	22	1.6
$\gamma(\pi^0)$	0	0
p	0	0
Sum	438	116

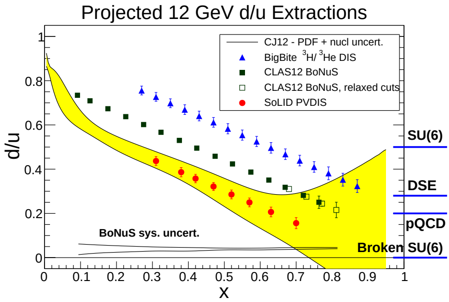
Radiation

Radiation Type	E-Range (MeV)	Incident Radiation Power ^{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

Systematics

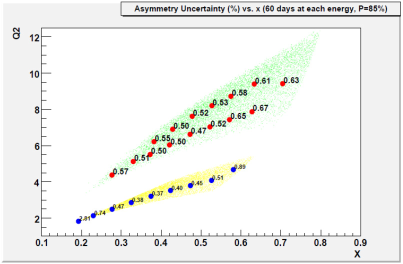
- Many potential nuclear effects come into play as this sector is not presently well constrained
- Requires measurements from LD_2 and LH_2 for information on size of nuclear effects
- Existing free PDFS (recent CJ12) have poor d/u constraint

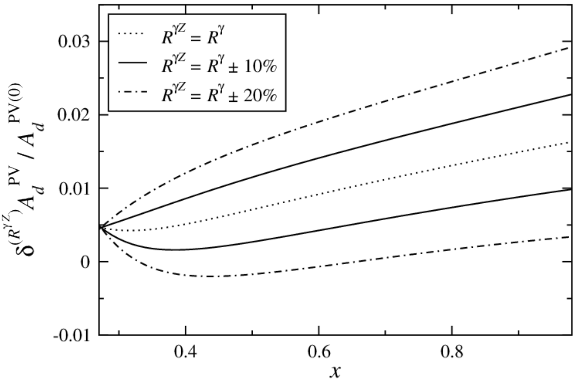




Systematics

- 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
- Charge symmetry violation will also be explored to better precision
- Nuclear dependence of $R^{\gamma Z}$ is an open question





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