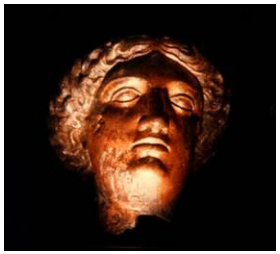
MINERvA Light: D_2 or H_2

Deborah Harris
Kevin McFarland

FNAL PAC

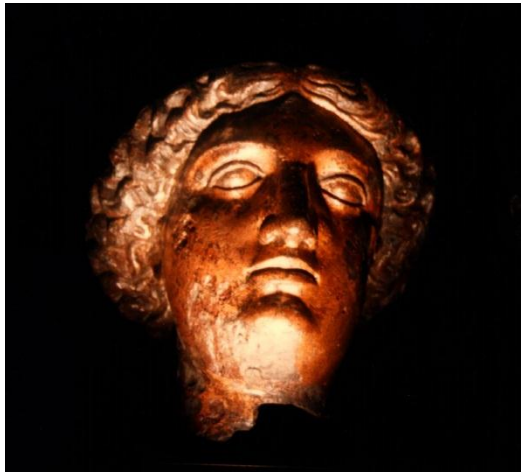
23 June 2011

Outline

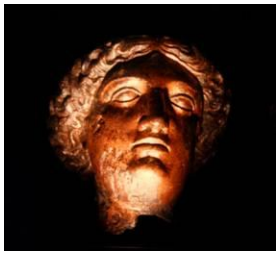


- Context for the Letter of Intent
- Mechanics
- Physics Case for D_2/H_2 Target

Context

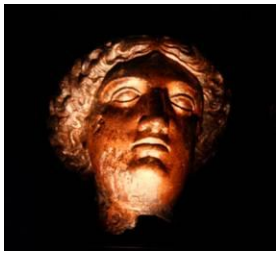


Physics Goals of MINERvA

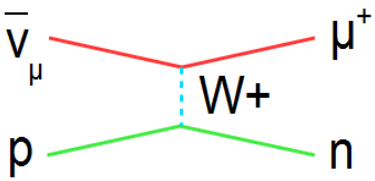


- Goals of MINERνA:
  - Low Energy (LE) Beam
    - MINERvA was built to study both signal and background reactions relevant toT2K, NOvA, and LBNE
    - Nuclear effects on exclusive final states
      - as function of a measured neutrino energy
      - may be different for neutrino and anti-neutrino
    - Precise understanding important for oscillation expt's
  - Medium Energy (ME) Beam in NOνA era
    - Structure Functions on various nuclei

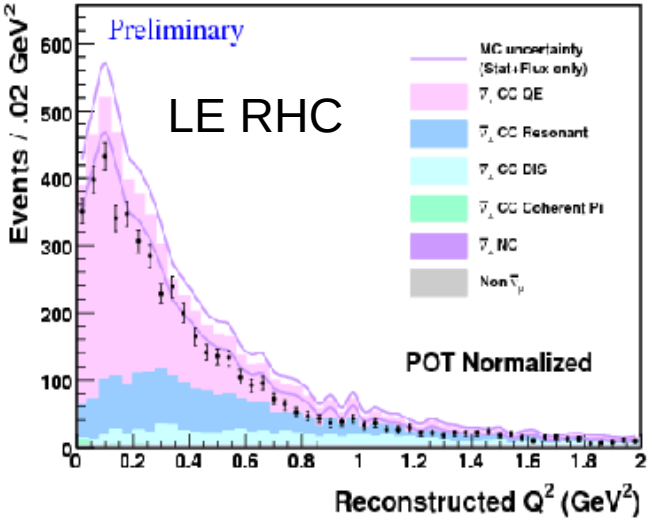
Progress on Low Energy Physics Goals

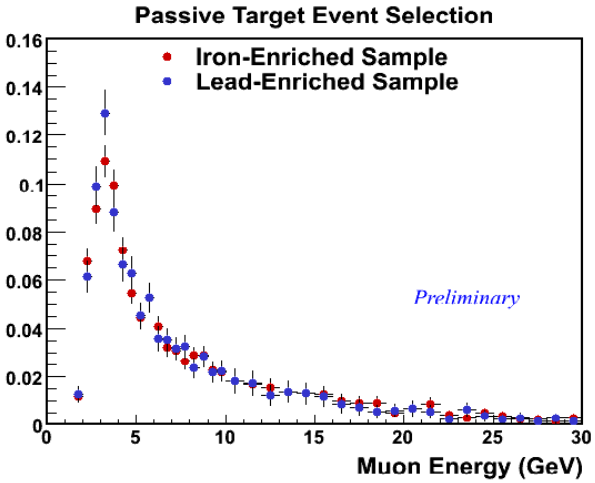


- Making good progress on highest priority analyses (highest priority = easiest and/or unique to MINERvA)
  - Quasi-elastic analysis
  - First nuclear target analysis
  - Flux Tuning Procedure
- Protons on Target in Low Energy Beam continue to be a concern: only have 1/3 of 4.9E20 to date

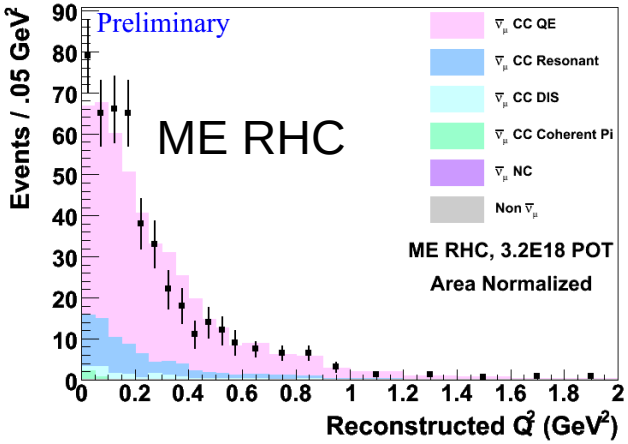


Low/Medium Energy Anti-neutrinos, 4.E19POT /3.2E18POT, QE candidates

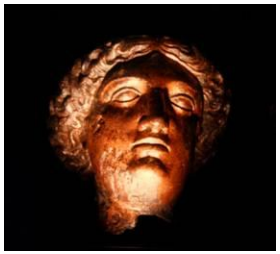




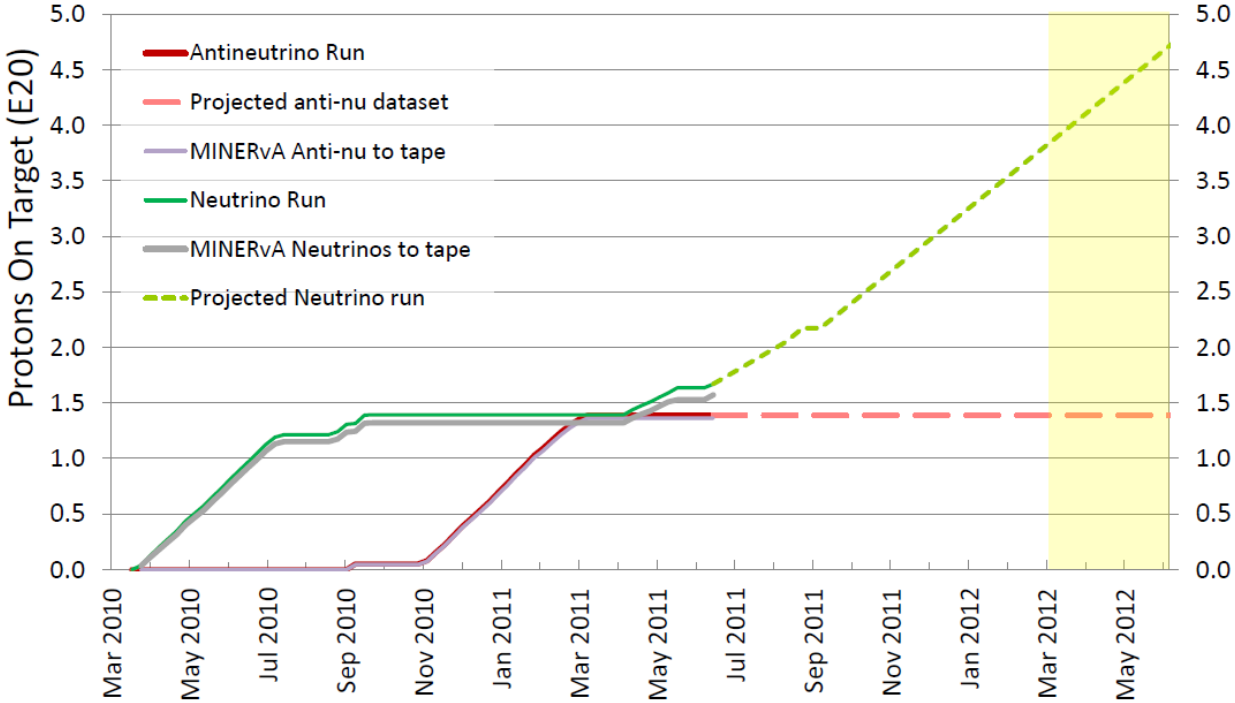
First muon energy spectra in Iron and Lead targets; ratios coming soon! Plot at left for 1.3E20POT, target 5 (1/5 of sample)



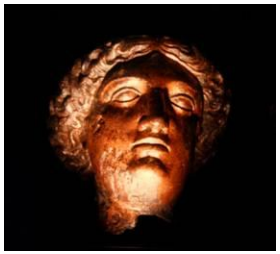
Protons on Target in Low Energy Beam



- Optimistically will see 3.8E20 of 4.9E20 POT by March 1
- If NT01 fails July 1, lose 0.15E20. If NT07+NT08 survive only 4 months, lose 0.8E20. If can run extra intensity after TeVatron ends, gain 0.2-0.3E20. Three month extension gains 0.8E20.
- Plot at right assumes 2.5Eppp until Sept 1, then 2 week target change to NT07 and no other significant downtime.

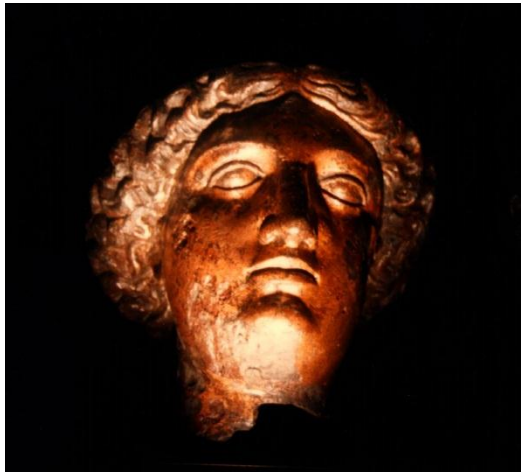


MINERvA in the Medium Energy Era

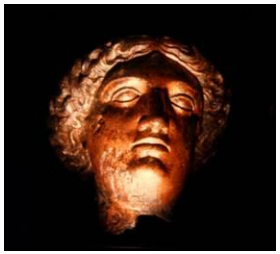


- Medium Energy Beam for NOvA era means
  - More events per proton on target
  - More protons on target per month
  - Higher acceptance of muons into MINOS near detector
  - Higher fraction of Deep Inelastic Scattering events
- Statistics allows us to map broad range of x and Q^2
- NOvA's run plan (3 years neutrino + 3 years anti-neutrino) well suited to structure function measurements
- Approved proposal (February 2004) provided statistics for a four year run, assuming 4E20/year.
  - This was written at a time when NOvA's run plan was not determined.

Mechanics

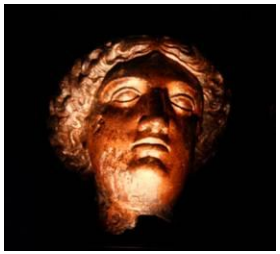


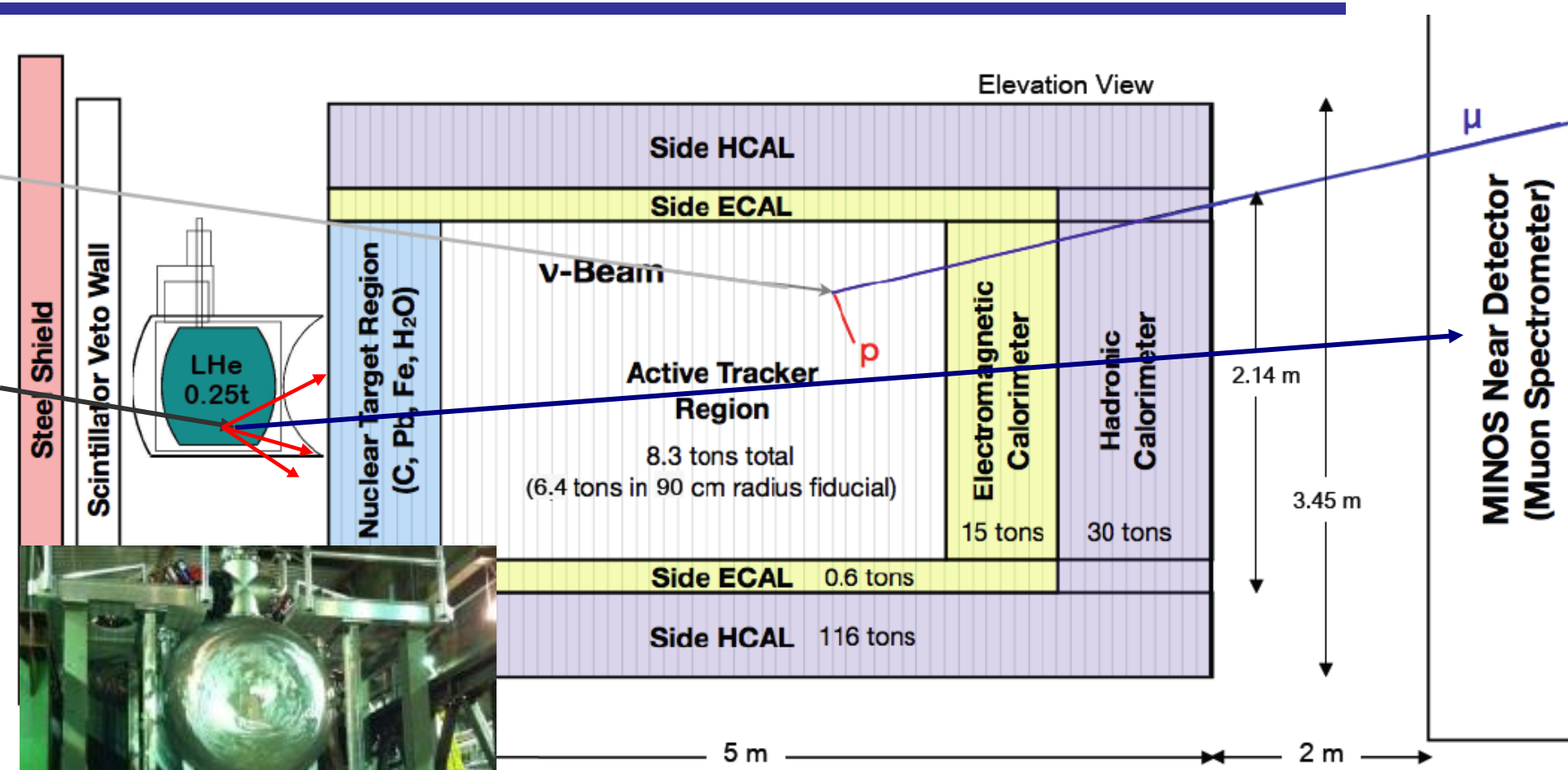
Infrastructure and Impact



- Cryostat already exists and is designed for this
  - Expect to start filling with liquid helium this summer
  - Mechanically able to hold H_2, D_2, or He
  - H_2 or D_2 requires less cooling power than He
- MINERvA already plans to run;
  this proposal is to just change the cryogen

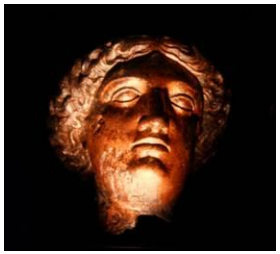
MINERνA Cryogenic Target





Targets: carbon, lead, iron, water, and helium.

Infrastructure and Impact



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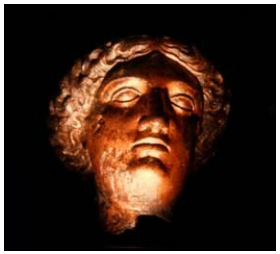
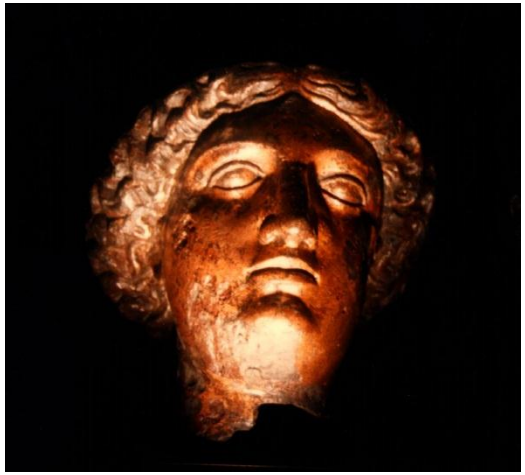
  - Mechanically able to hold H_2, D_2, or He
  - H_2 or D_2 requires less cooling power than He
- MINERvA already plans to run;
  this proposal is to just change the cryogen
- So what has to be done to run with D_2 or H_2?
  - Cost of deuterium if filled with deuterium (best physics case)
  - Safety systems to allow 370kg (160kg) of liquid deuterium (hydrogen) underground in the MINOS near detector hall
  - Upgrade to surface venting system (and addition of a capture system if deuterium)
  - The latter two need engineering studies to properly evaluate costs (little value in making “physicist guess” estimates)

Deuterium vs. Helium

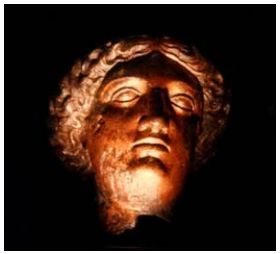


	Deuterium	Helium
Density	~0.169 g/cm^3 ✓	~0.114 g/cm^3
Temperature	~22K ✓	~5K
Nuclear Effect	A=2, lightest isoscalar nucleus, very low nuclear density ✓	A=4, but nucleus as dense as Carbon
Cost	Existing Deuterium? Else ~$1-2M	~$10K to fill✓
Safety	Flammable+Cryogenic hazard	Only cryogenic hazard ✓

Physics Case

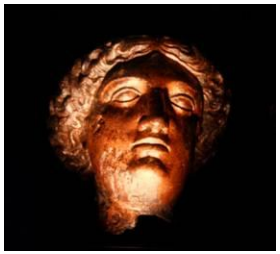


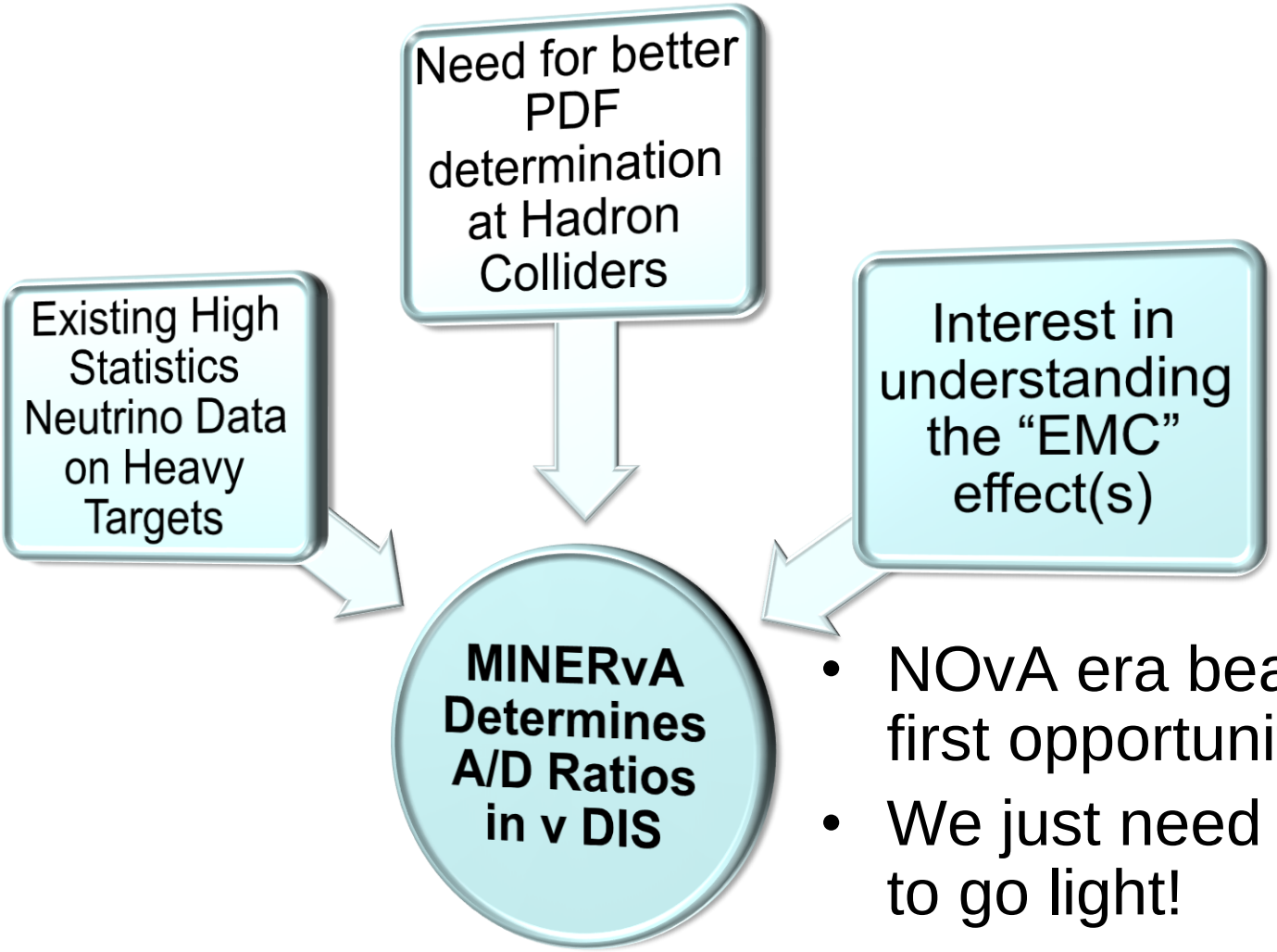
Overview



- νN scattering is a very useful input for understanding partons in the nucleon
  - Flavor-sensitive probe means separation of *u,d,s* quark content of the nucleon
  - Neutrino and Anti-neutrino beams means a separation of valence and sea quarks
  - PDF determination important for hadron colliders
- Neutrino data today would play a key role in global PDF fits, except…
  - Very little data on nuclear effects in neutrinos
  - Theory of nuclear effects not well enough understood for a reliable *a priori* prediction

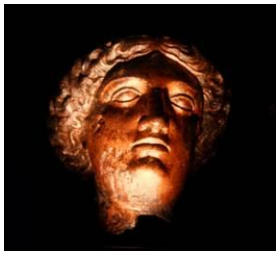
MINERvA could be the rug that ties this room together





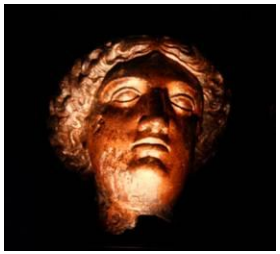
- NOvA era beam power is first opportunity to do this
- We just need MINERvA to go light!

Some Important Details in the Letter of Intent

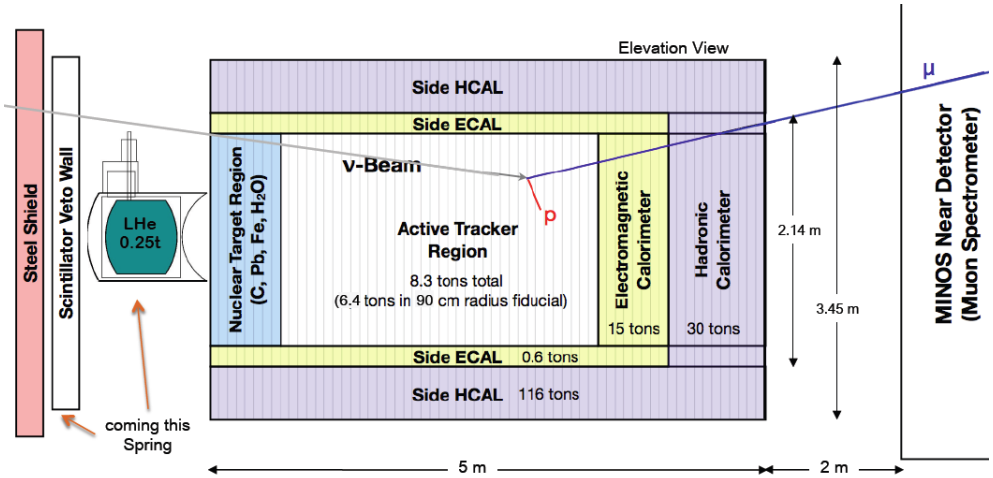


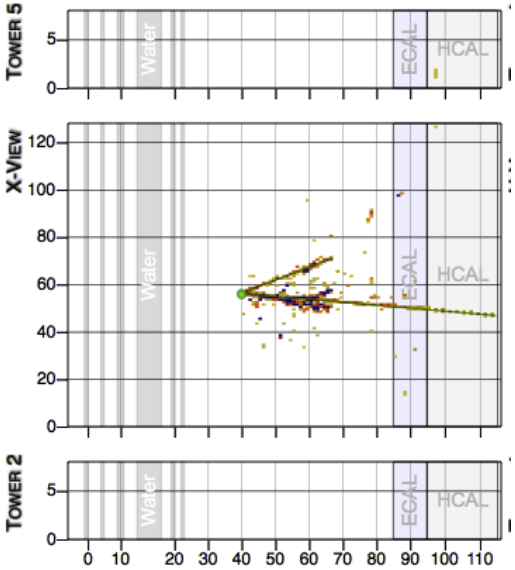
- We don't have time for a few key topics
  - What is known about nuclear effects from charged lepton scattering and theory, and why neutrinos might be different, theoretically and experimentally
  - Why helium isn't "almost" as good as deuterium
  - DIS scattering formalism that justifies the statements about separation of quark flavors and valence and sea quarks
- *This material is available in the backup slides, so we are prepared to answer questions now or in discussion time.*

How will MINERvA measure DIS in its Cryotarget?



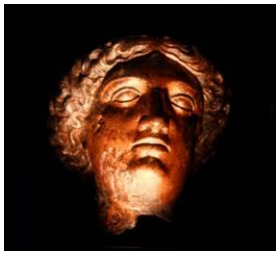
- Recall detector geometry:
  - Veto system to signal upstream muons
  - Cryogenic vessel
  - Fine trained tracking surrounded on the sides and back by calorimetry
  - MINOS Near Detector as muon spectrometer
- We have already seen how three out of four of these components work
- Physics capabilities informed by this knowledge





Found tracks and vertex in green

MINERvA's DIS Event Reconstruction

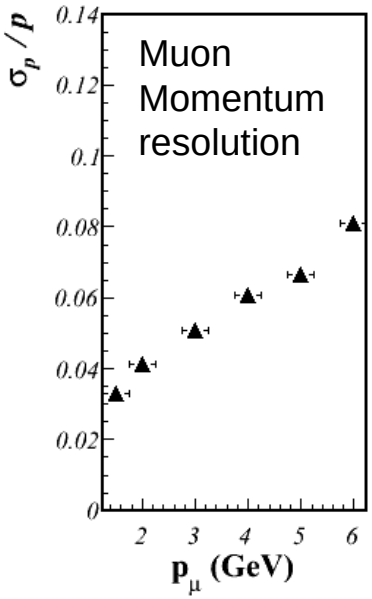


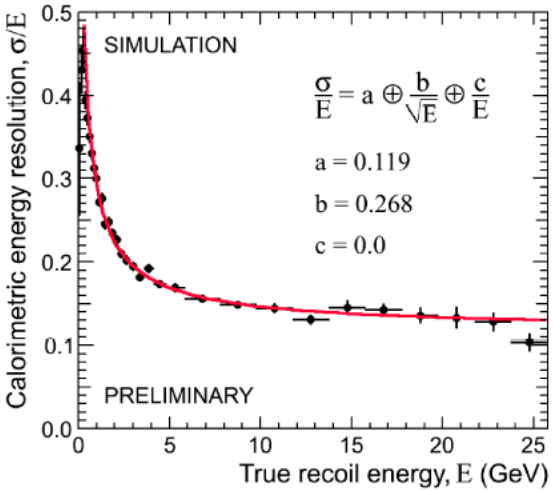
- Crucial Ingredients to determine x,y,Q^2:
  - Muon Energy and angle (E_μ, θ_μ)
    - Tracking well understood, tie to MINOS reconstruction
  - Hadronic (recoil) Energy Measurement (E_{had})
    - Studies underway, will tie to 2010 test beam data
  - Charge (for ν/anti-ν discrimination)
    - Use MINOS Near Detector for muon charge

$$E_\nu = E_{had} + E_\mu \qquad y = \frac{E_{had}}{E_\nu}$$

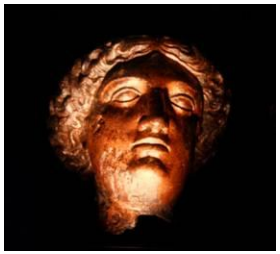
$$Q^2 = 4E_\mu E_\nu \sin^2\left(\frac{\theta_\mu}{2}\right) \qquad x = \frac{Q^2}{2M_p\nu}$$

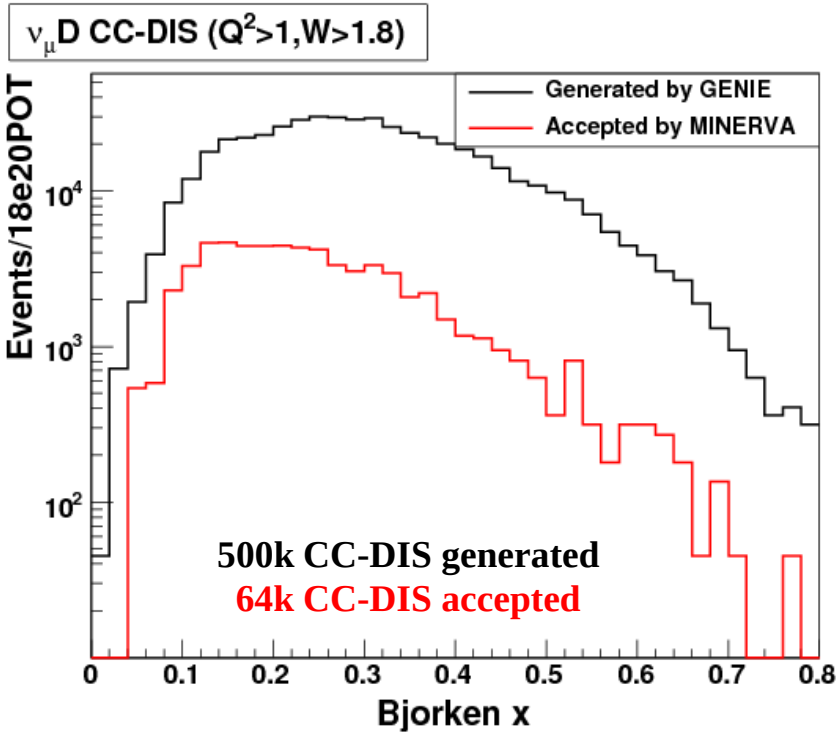
- For Cryogenic Target events, vertex resolution is also important (to remove cryostat events)
  - Studies already show 25/94mm position resolution in transverse/longitudinal direction for D_2 events



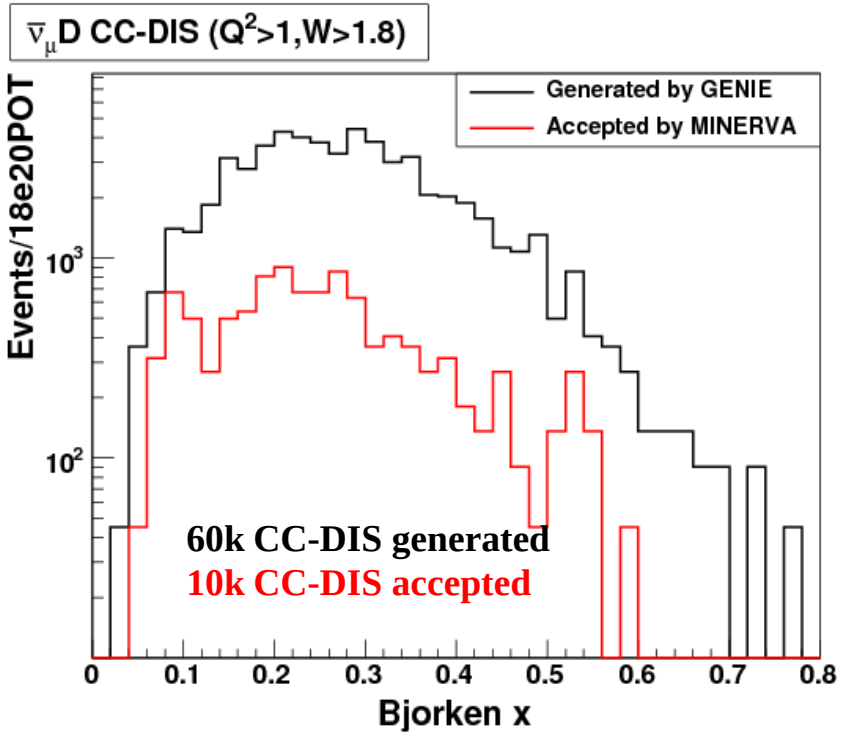


CC-DIS Events from D_2



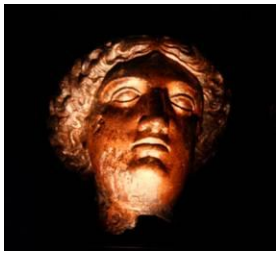


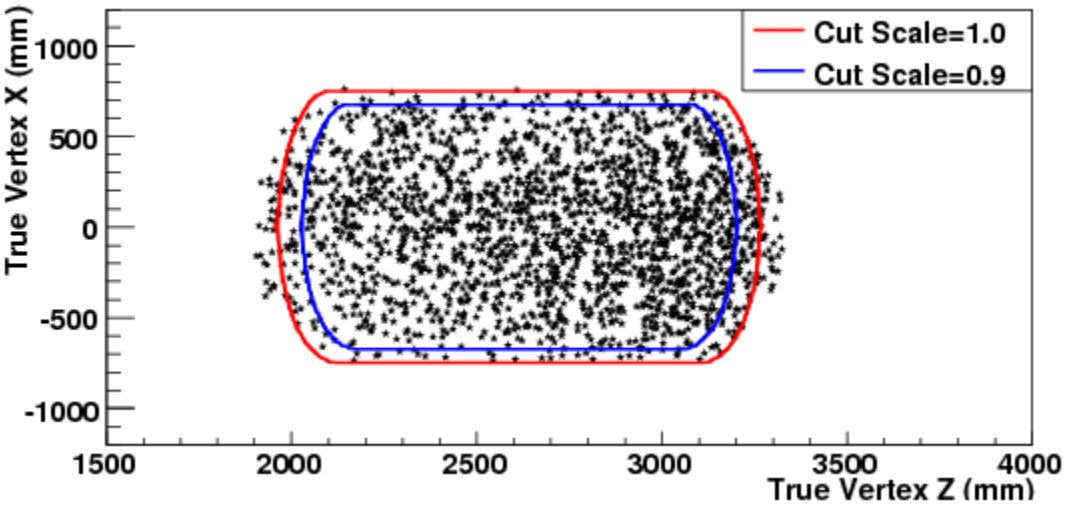
ν

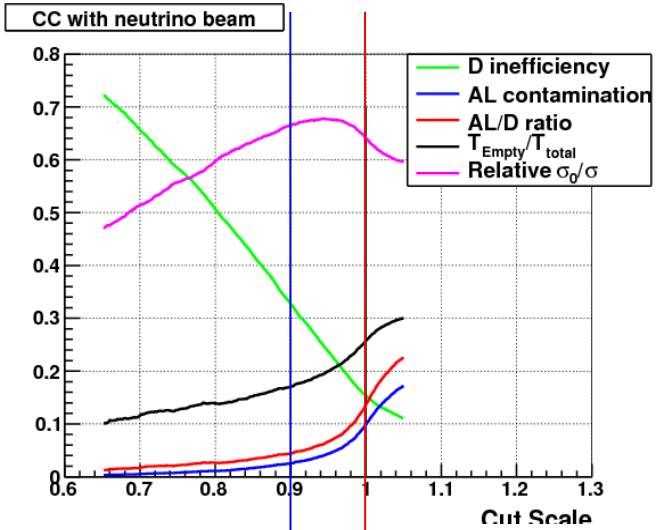


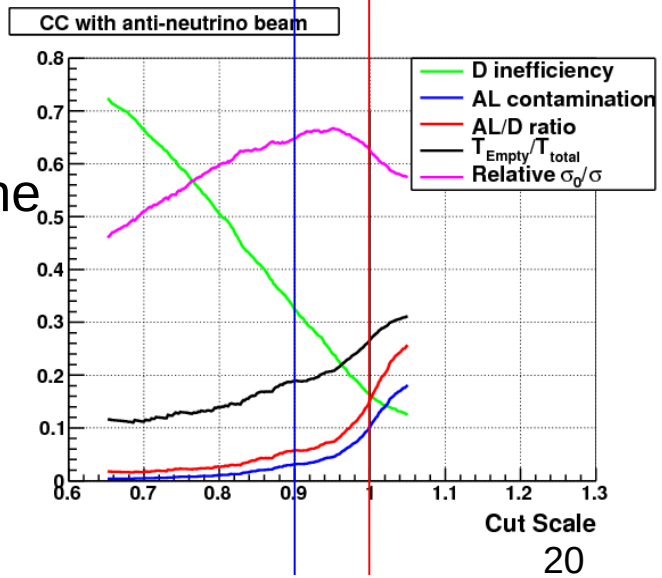
- Accepted by MINERνA means two+ tracks passing 4+ planes including a momentum analyzable muon.
- The mass of the deuterium to fill the existing cryogenic target is 0.372 ton
- For both neutrino and anti-neutrino cases, the beam is $18*10^{20}$ POT ME flux, which is the nominal beam for NOνA and will be used by MINERνA.

Empty Target Subtraction



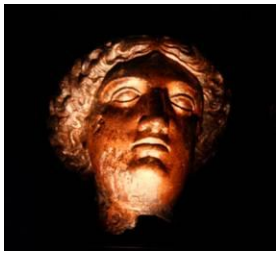


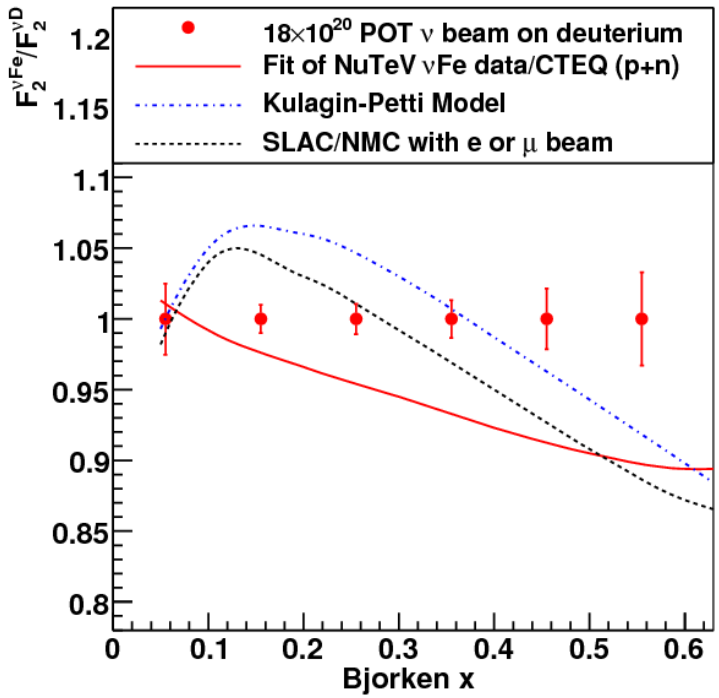


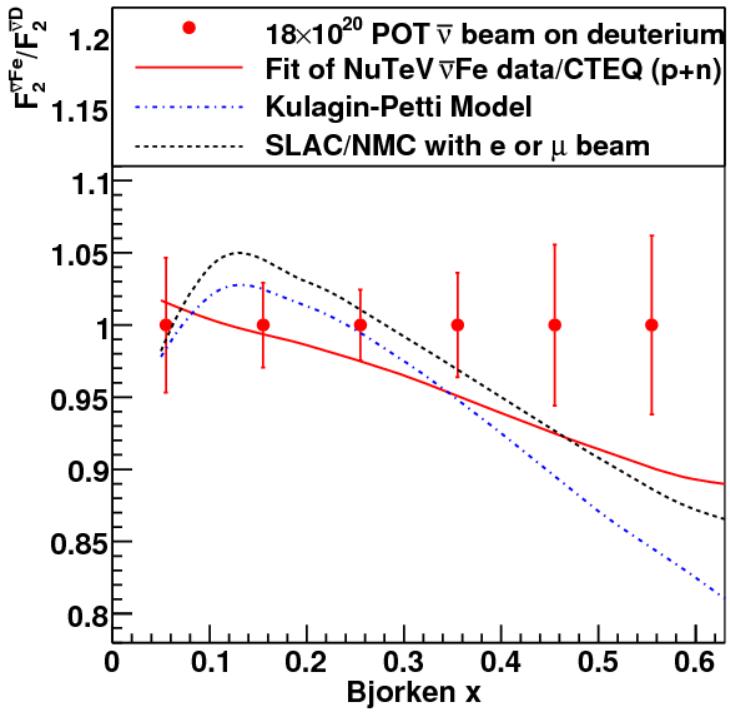


- Aluminum vessel is substantial source of background events
- The tighter the vertex position cut, the lower the statistics, but the lower the background
- Optimize measurement by including some empty target running, statistical error is ~1.3 times larger
  - Sensitivity plots include empty target

Projected Sensitivity to A/D DIS Ratio



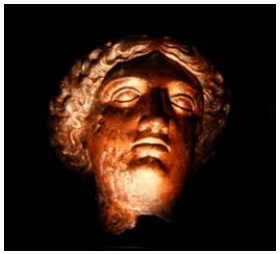




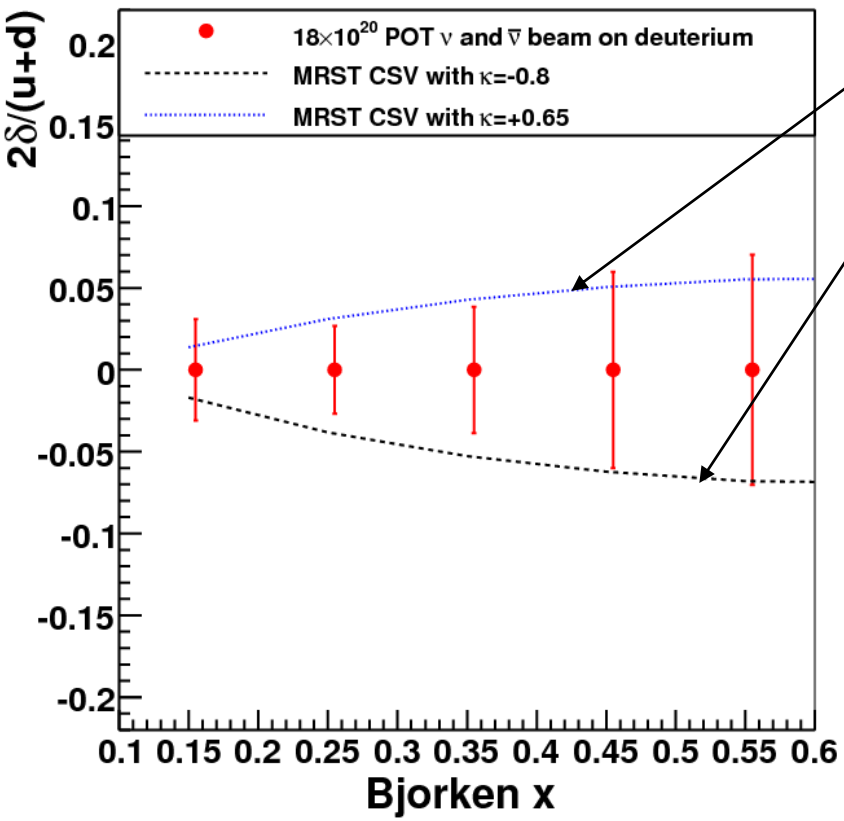
Curves from: Ingo Schienbein *et al.,* Phys.Rev.D80(2009)094004; PRD77(2008)054013

The statistical uncertainties of Fe/D ratios as well C/D and Pb/D mostly come from deuterium.
Most systematic uncertainties due to beam flux will cancel in the ratios.

Another Possible Goal: CSV Measurement with D_2



The neutrino to anti-neutrino cross section ratio on deuterium is a direct measurement of Charge Symmetry Violation (CSV).



The 90% confidence region based on the MRST fit with assumed x dependence for CSV effects $\delta = \kappa\, f(x)$

$$u_p - d_n = -(d_p - u_n) \equiv \delta(x)$$

$$f(x) = (1-x)^4 x^{-0.5}(x - 0.0909)$$

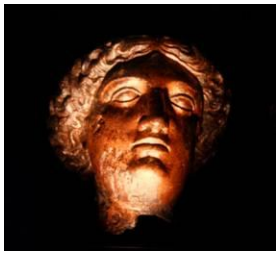
Ignoring sea (large x):

$$\frac{d^2\sigma^{\nu D}}{d^2\sigma^{\bar{\nu} D}} \sim \frac{d_p(x) + d_n(x)}{u_p(x) + u_n(x)} \cdot \frac{1}{(1-y)^2}$$

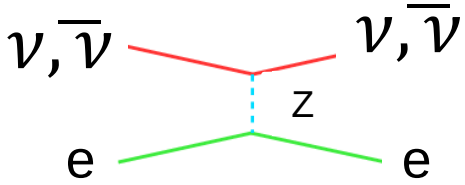
$$2\delta(x)/[u(x) + d(x)] \sim 1 - (1-y)^2 \frac{d^2\sigma^{\nu D}}{d^2\sigma^{\bar{\nu} D}}$$

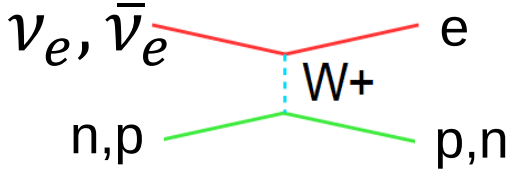
But… requires precise flux ratio!

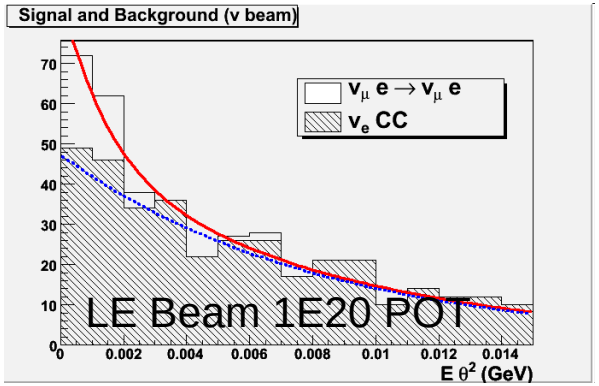
Neutrino-Electron Scattering for Flux Constraint

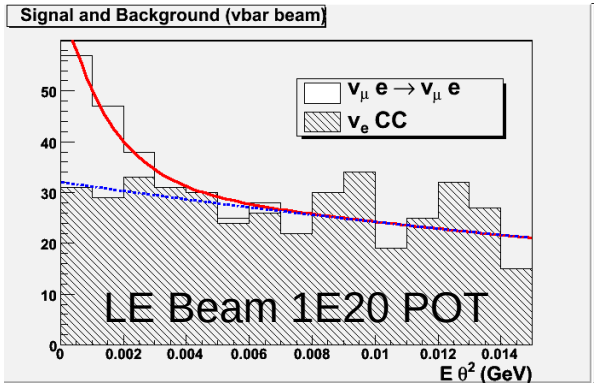


- Would provide an independent flux ratio:
  - Cross-section calculable from first principles
  - But very low statistics; integral measurement doesn't give spectrum
  - Background: ν_e Quasi-elastic scattering
  - Background rejection: outgoing electron angle
    (plots below from Low energy beam, Medium Energy beam should be better since fewer ν_e's/ ν_μ are present, higher signal/background σ ratio))





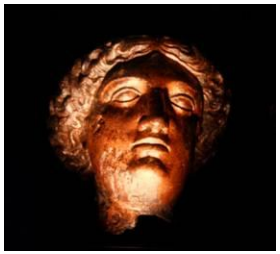




Very preliminary work on ve scattering in LE beam. (Reconstructed quantities.)

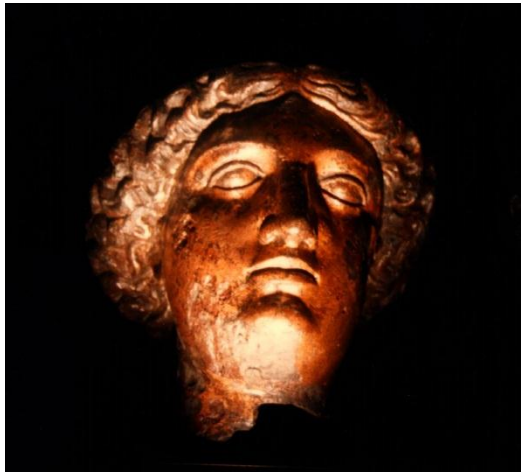
- Expected Statistics from 3+3 year run: 7.6k (neutrino), 6.2k (anti-neutrino)

Possible Detector Upgrade

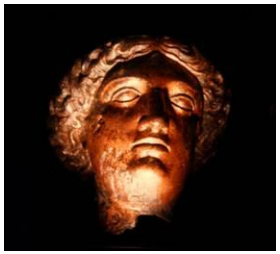


- By adding more scintillator just upstream of the outer detector of MINERvA, we could get improved acceptance of D2 events
  - Goal is to reconstruct Quasi-Elastic recoil proton position and angle
  - Additional scintillator coverage is small fraction (<5%) of total active area of MINERvA
  - MINERvA triangle position resolution more than adequate for this purpose

What could be measured with a H_2 target instead?

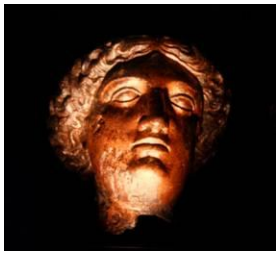


Hydrogen vs. Deuterium

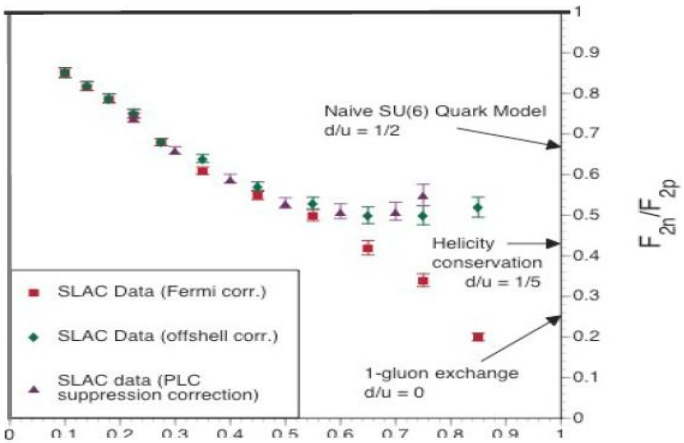


- Lower density of hydrogen means statistics drop (roughly) a factor of two
- Hydrogen is (clearly) highly non-isoscalar, so ratios of heavy targets to hydrogen are not very meaningful
- However, comparison of neutrino and anti-neutrino scattering is very sensitive to d/u of proton
  - Current data situation is not very good at high x
    - Both charged lepton DIS and Drell-Yan data on protons see 4u+d at large x
    - At very high x, there are nuclear effects in deuterium that
  - Several experiments that are part of the JLab 12 GeV program are trying to improve this situation
    - deuterium target with spectator tagging (BONUS)
    - electron DIS on A=3 helium/tritium target (MARATHON)
    - parity violating DIS on proton targets (PVDIS)

Primary Goal: d/u at large x



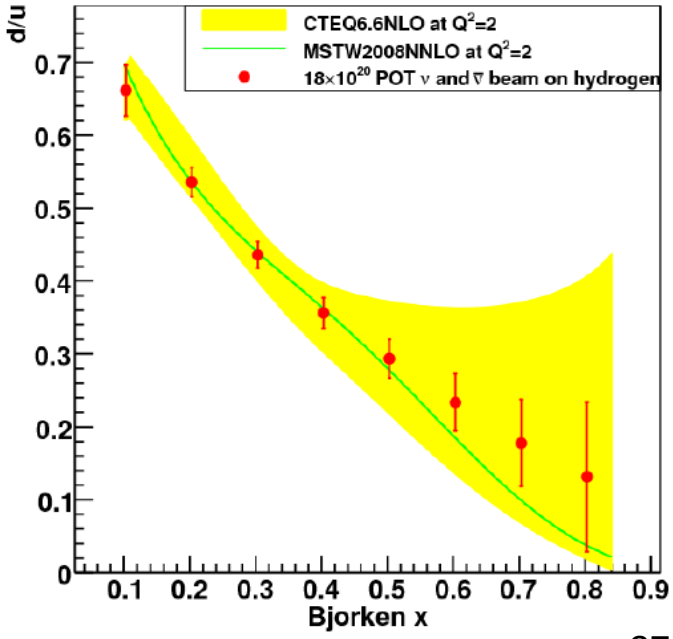
- Different theoretical arguments give wildly different expectations for d/u at large x



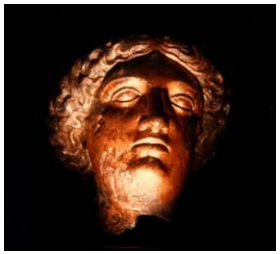
- Ratio of neutrino to anti-neutrino scattering at high x (ignore sea):

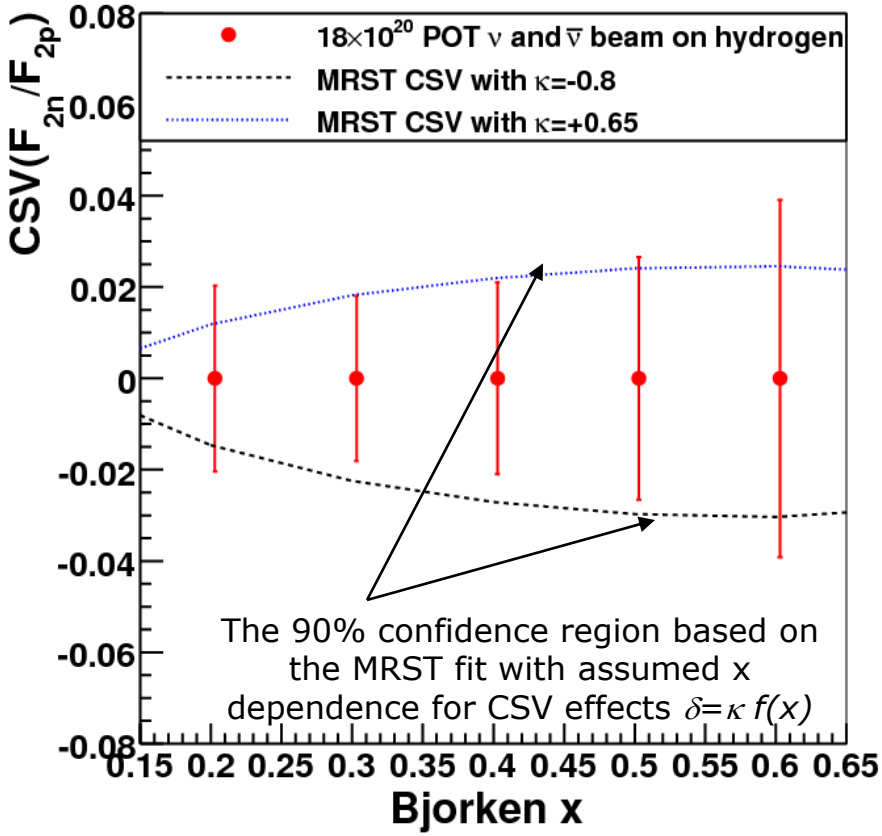
$$\frac{d}{u} \sim (1-y)^2 \frac{d^2\sigma^{\nu p}}{d^2\sigma^{\bar{\nu} p}}$$

  - For MINERvA, flux uncertainty small compared to statistical uncertainty at high x (x>0.6)



Secondary Goal: CSV Measurement with H_2





From charged lepton data:

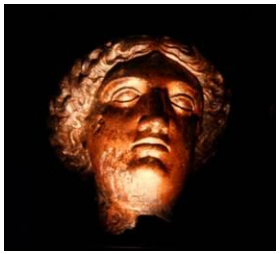
$$\left[\frac{F_{2n}}{F_{2p}}\right]_{D/p} = \frac{(\sigma_d - \sigma_p)}{\sigma_p} = \frac{(4u_n + d_n)}{(4u_p + d_p)}$$

From neutrino data on hydrogen assuming charge symmetry:

$$\left[\frac{F_{2n}}{F_{2p}}\right]_{p} = \frac{(4d_p + u_p)}{(4u_p + d_p)}$$

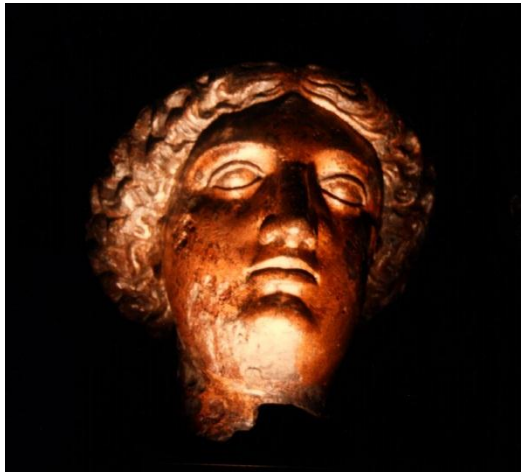
By comparing neutrino proton data and charged lepton d/p data we can measure CSV. This too will need reduced flux uncertainties

Summary of Physics Case

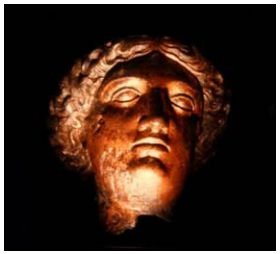


- The high intensity neutrino and anti-neutrino beam from NuMI makes it possible to perform a statistically significant experiment on D_2 or H_2
- Best physics case: Measure A/D cross section ratio so that high statistics SF measurements on heavy targets can be applied to nucleon PDFs
  - Deuterium also has higher statistics because of its higher density

MINERvA's "Ask"

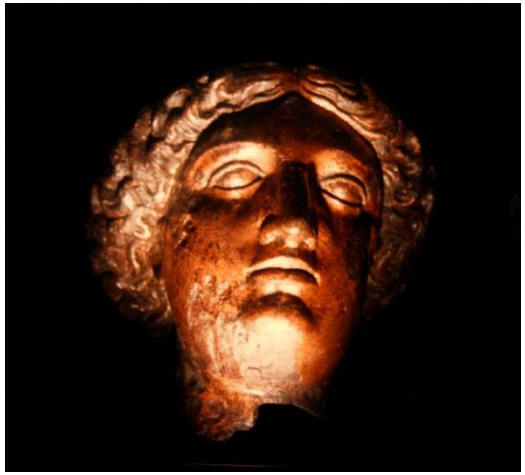


The Advice We Seek from you to the Directorate

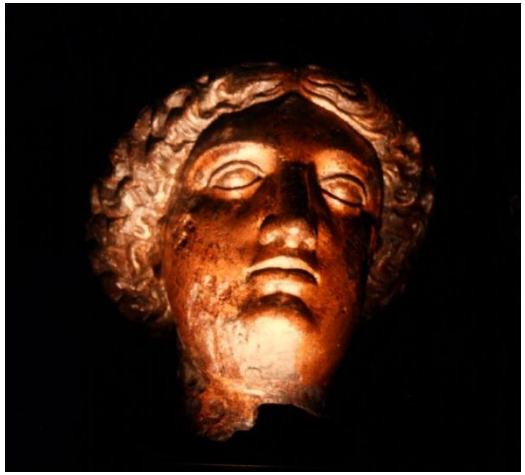


- Is the physics interesting enough to proceed with the engineering studies today?
  - Timing is important because this work would have to be scheduled with constraints of long “NOvA” shutdown
- If yes, is the physics case here good enough to weigh costs against physics benefit?
  - Or should we go away and develop the case further?
- Assuming a positive outcome today and directorate consent, we would target time of November PAC meeting to finalize cost and benefit case

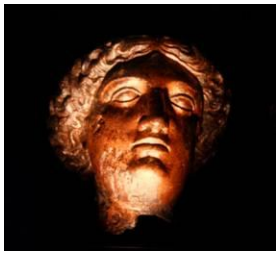
Thank you for your attention. MINERvA looks forward to your comments and questions.

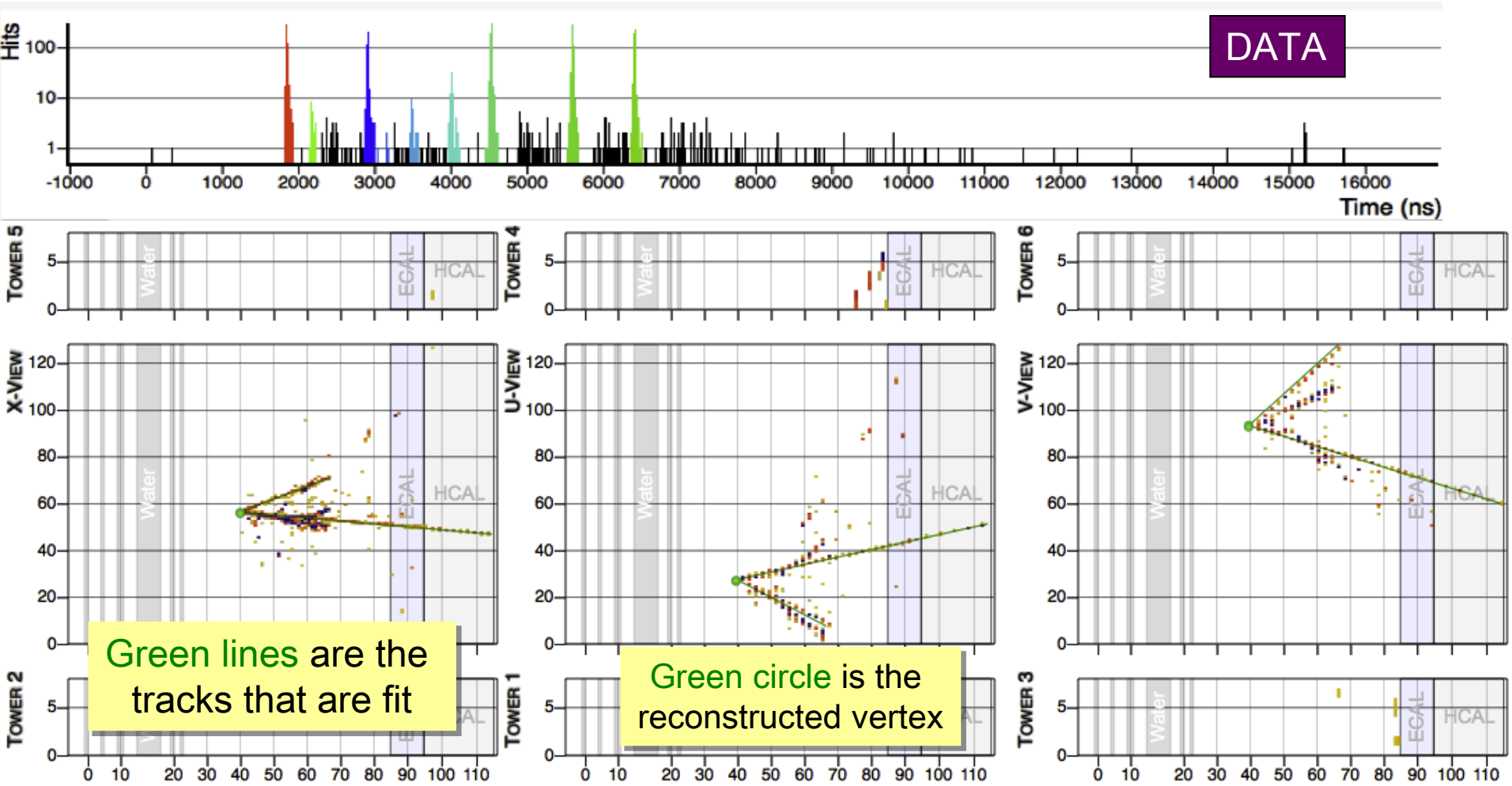


Backup: Supplementary Information on Reconstruction

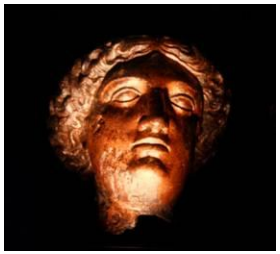


An Event Example

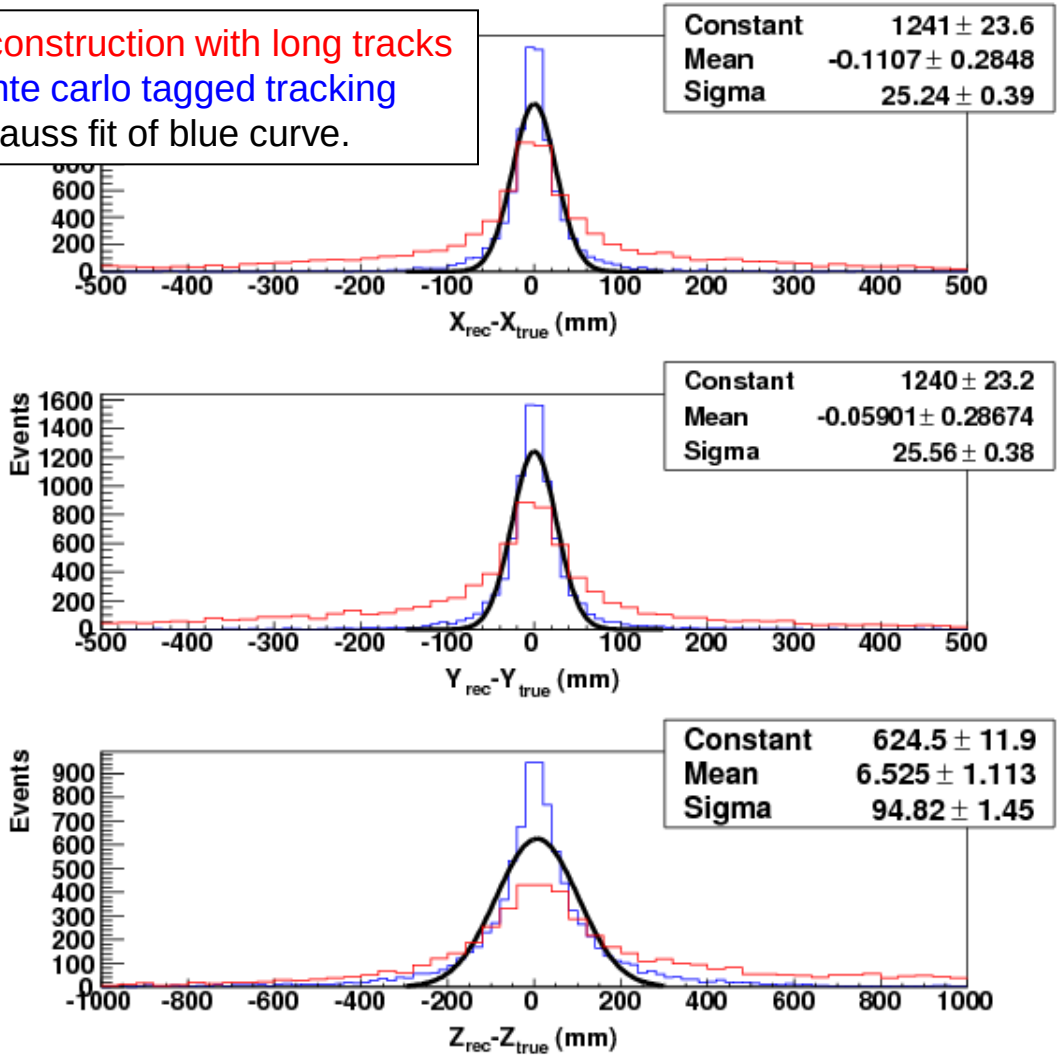




Vertex Reconstruction in Light Targets



Reconstruction with long tracks
Monte carlo tagged tracking
A Gauss fit of blue curve.

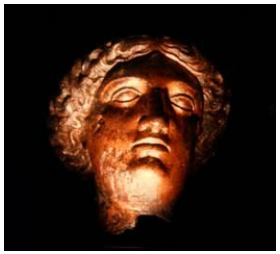


Helium CC events only

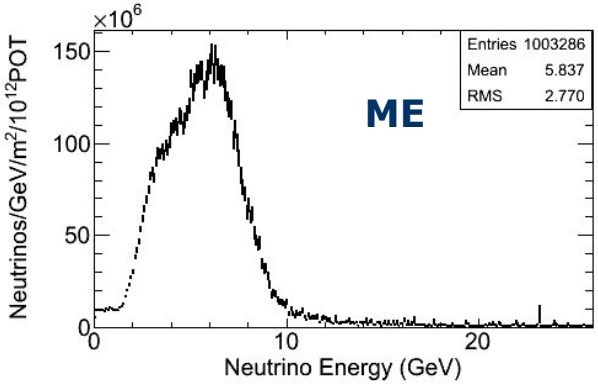
The vertices are reconstructed from two tracks in MINERνA detector.

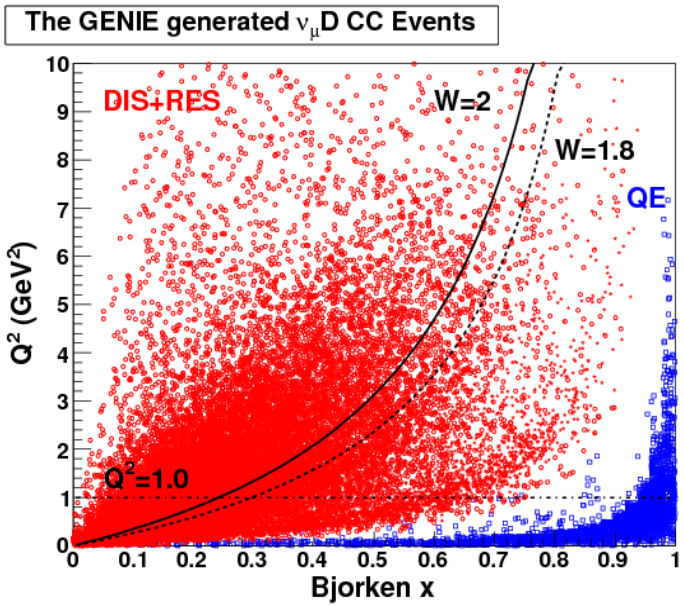
The current reconstruction (red curve) is expected to improve greatly by including the vertex reconstruction from the short tracks.

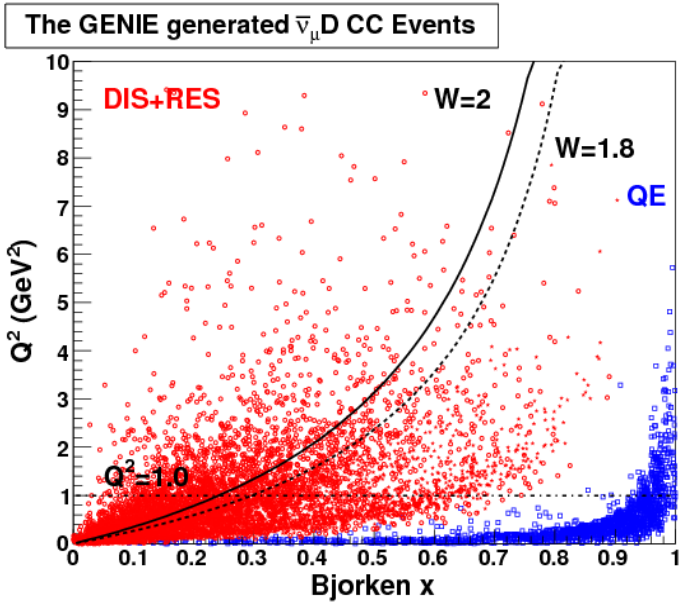
The CC Events from D_2



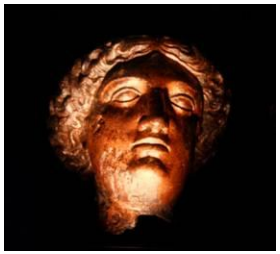
Software: MINERνA simulation (GENIE+GEANT4)
Flux: NOνA neutrino and anti-neutrino ME beam

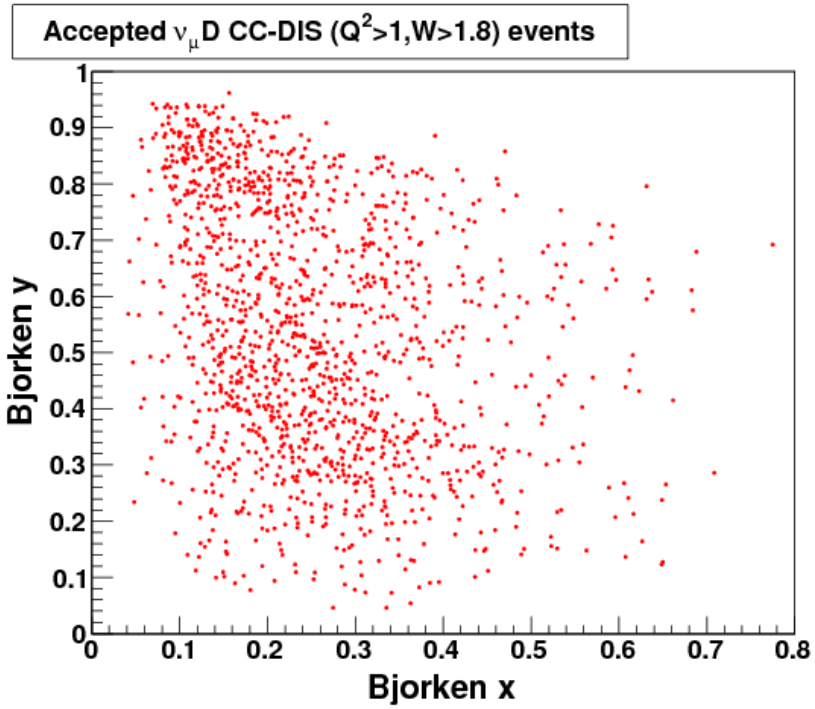


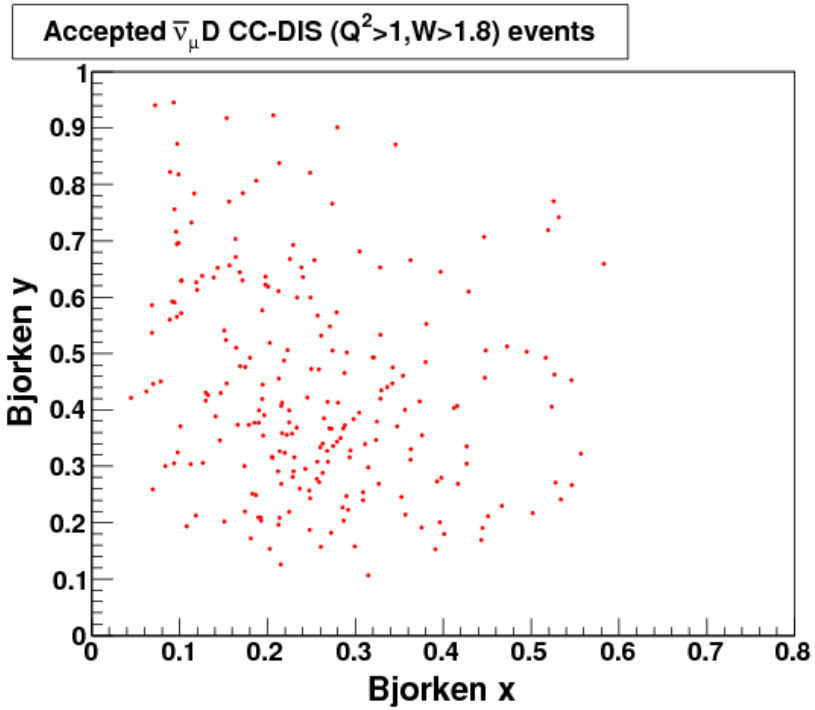




The y Coverage of CC-DIS





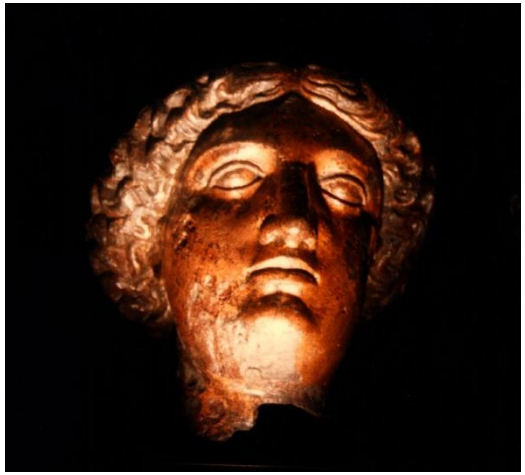


Accepted

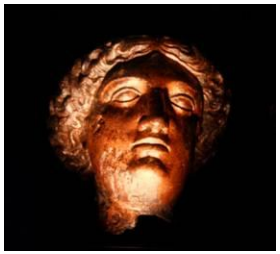
means two+ tracks (# of planes>3) including a momentum analyzable muon in MINERνA.

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M_p E_{\nu(\bar{\nu})}}{\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \Big[xy^2 F_1^{\nu(\bar{\nu})}(x,Q^2) + (1-y-\frac{M_p xy}{2E_{\nu(\bar{\nu})}})F_2^{\nu(\bar{\nu})}(x,Q^2) \pm y(1-\frac{y}{2})xF_3^{\nu(\bar{\nu})}(x,Q^2)\Big]$$

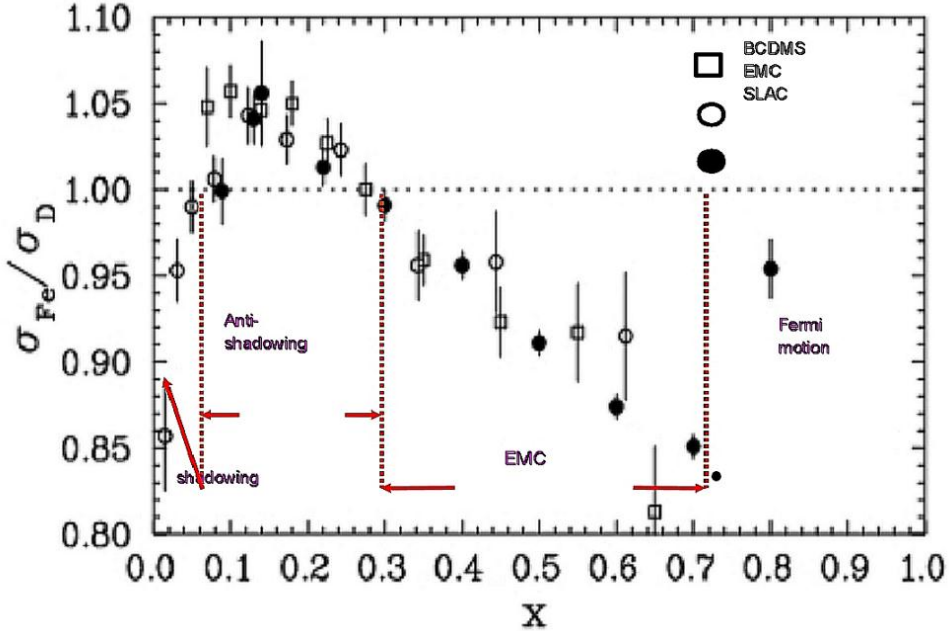
Backup: What is the State of the Art of Including Neutrino Data on Heavy Targets in PDF fits?



What we know now about Nuclear Effects



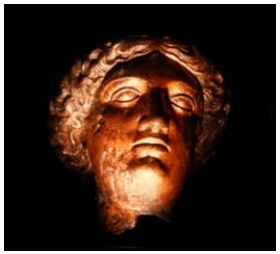
- 25 years of e(μ)-A scattering tells us that nucleon structure is *modified* in the nucleus



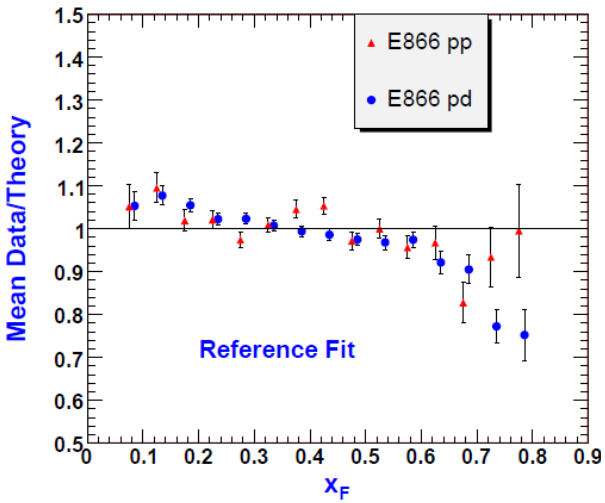
- Baseline is ratio to simplest Isoscalar Target (D)
- Independent of possible nuclear effects in the deuteron itself
- This is an experimental fact; theoretical models to explain all of this are not comprehensive or unique.

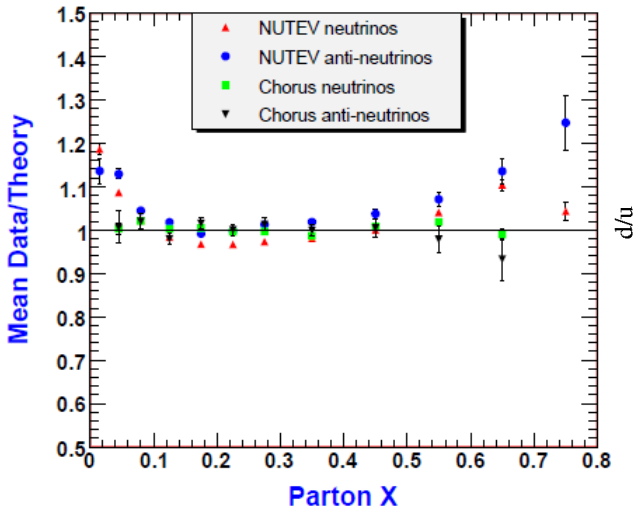
- Nuclear effects in ν-A could be different from those in e(μ)-A scattering, and could differ for neutrinos and anti-neutrinos as well
  - May also be different in the different regions (shadowing, EMC, etc.) where different microphysical mechanisms are postulated

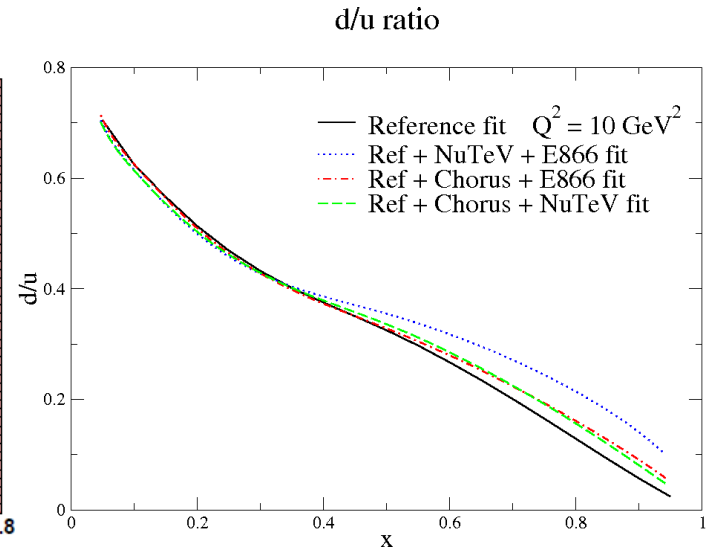
Using Neutrino Data for PDFs



- At large *x*, the neutrino data on iron target from NuTeV experiment seem to pull the PDF fits in a different way from the E866 Drell-Yan data. Reducing the nuclear corrections for NuTeV can reduce the tension.

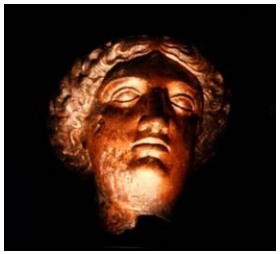




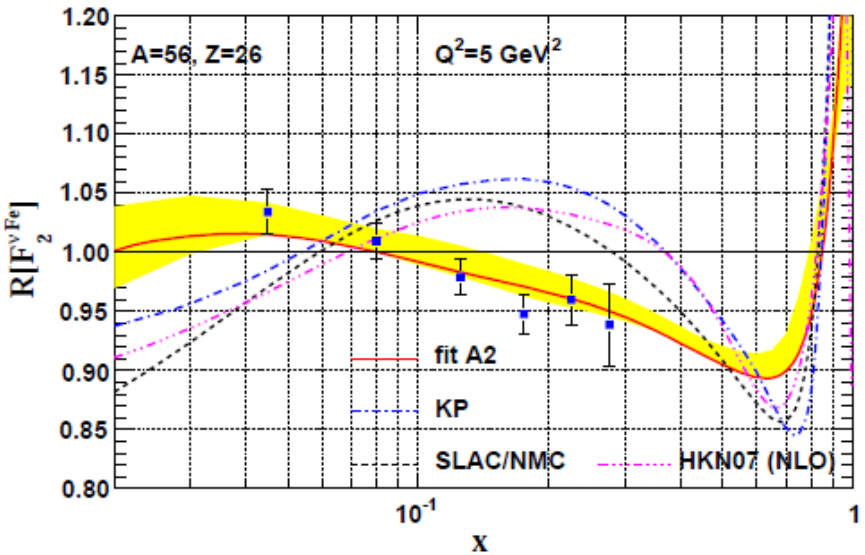


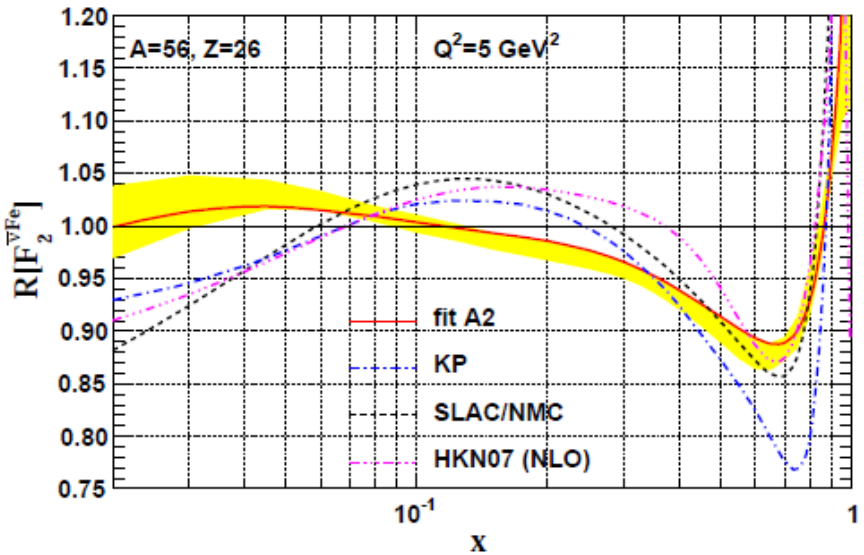
J. F. Owens *et al.*, Phys.Rev.D75(2007)054030

Nuclear Effects for Neutrino Data



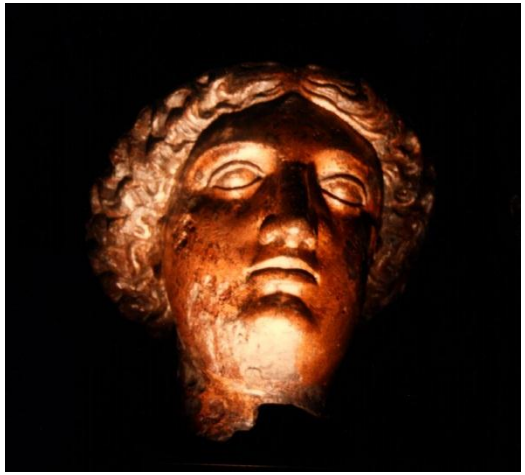
- The Fe/D ratios extracted from NuTeV data and the free-nucleon PDFs differ in both shape and magnitude from those in charged lepton DIS data and the Kulagin-Petti model.



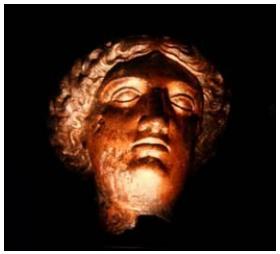


Ingo Schienbein *et al.,* Phys.Rev.D80(2009)094004;PRD77(2008)054013

Backup:
DIS Formalism



Deep Inelastic Scattering Formalism

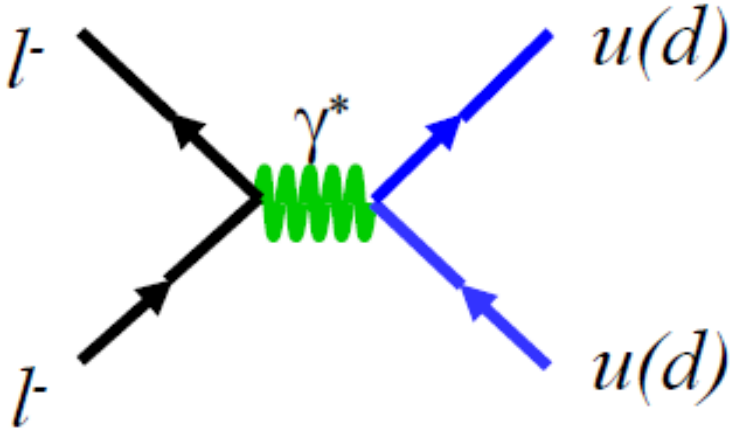


- Cross Section for Charged Lepton Scattering:

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma \frac{4\pi^2\alpha}{x(W^2 - M^2)}\left[2xF_1(x,Q^2) + \epsilon\left(\left(1 + \frac{4M^2x^2}{Q^2}\right)F_2(x,Q^2) - 2xF_1(x,Q^2)\right)\right]$$

  - At leading twist:

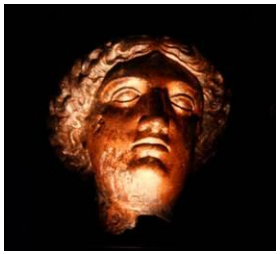
$$F_2 \sim 2xF_1 \propto x\sum_q {e_q}^2(q + \bar{q})$$



  - Ignoring sea (large x):

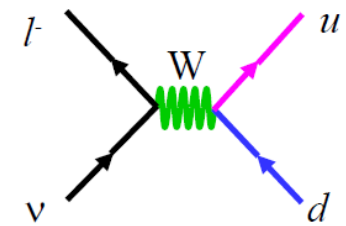
$$F_2 \propto x(4u + d)$$

DIS Formalism, Neutrino style



- Cross Section for Charged Current:

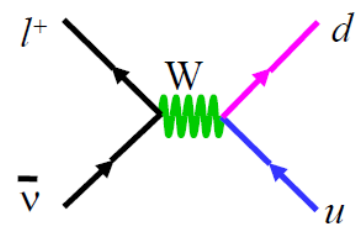
$$\frac{d^2\sigma}{dxdy} = \frac{{G_F}^2 M_p E_{\nu,\bar{\nu}}}{\pi}\left(\frac{{M_W}^2}{{M_W}^2 + Q^2}\right)^2 \left[xy^2 {F_1}^{\nu,\bar{\nu}}(x,Q^2) + \left(1 - y - \frac{M_p xy}{2E_{\nu,\bar{\nu}}}\right){F_2}^{\nu,\bar{\nu}}(x,Q^2) \pm y\left(1 - \frac{y}{2}\right) x{F_3}^{\nu,\bar{\nu}}(x,Q^2)\right]$$



- At leading twist with $m_N << Q^2 << m_W$

$$\frac{d^2\sigma^{\nu(p+n)}}{dxdy} \approx \frac{{G_F}^2 M_p E_\nu}{\pi} \cdot 2x\left[\left(d_{p+n} + s_{p+n}\right) + (1-y)^2\left(\bar{u}_{p+n} + \bar{c}_{p+n}\right)\right]$$

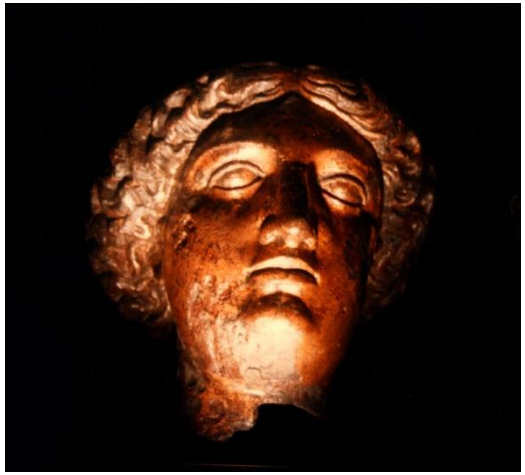
$$\frac{d^2\sigma^{\bar{\nu}(p+n)}}{dxdy} \approx \frac{{G_F}^2 M_p E_{\bar{\nu}}}{\pi} \cdot 2x\left[\left(u_{p+n} + c_{p+n}\right) + (1-y)^2\left(\bar{d}_{p+n} + \bar{s}_{p+n}\right)\right]$$



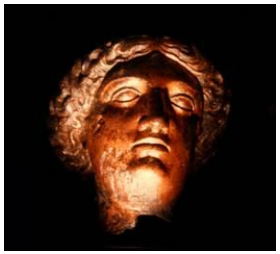
- Ignoring sea (large x):

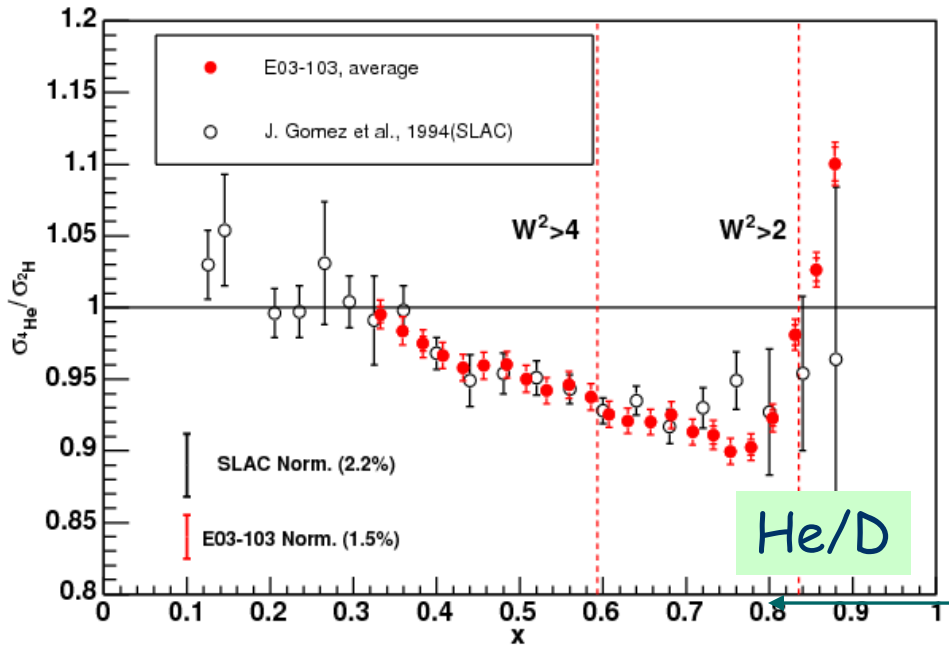
$$\frac{d^2\sigma^{\nu(D)}}{dxdy} \propto 2xE_\nu(u+d) \qquad \frac{d^2\sigma^{\bar{\nu}(D)}}{dxdy} \propto 2xE_{\bar{\nu}}(u+d)(1-y)^2$$

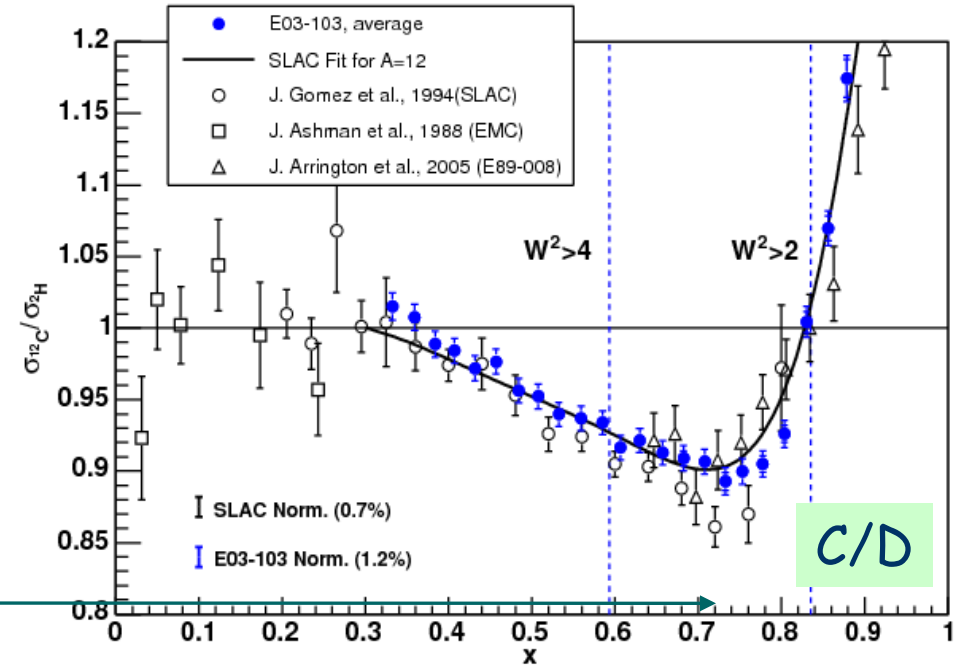
Backup:
Why not just Helium?



Isn't Helium Light Enough?



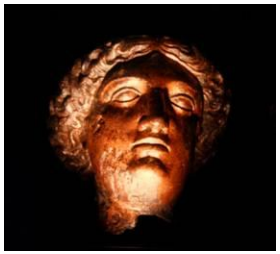


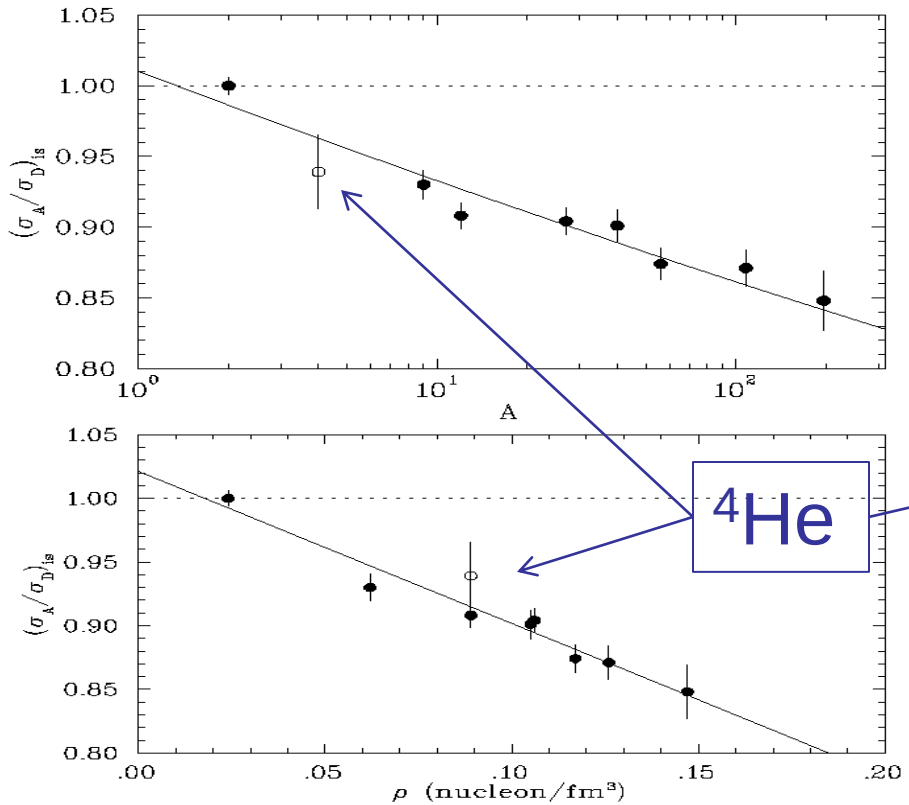


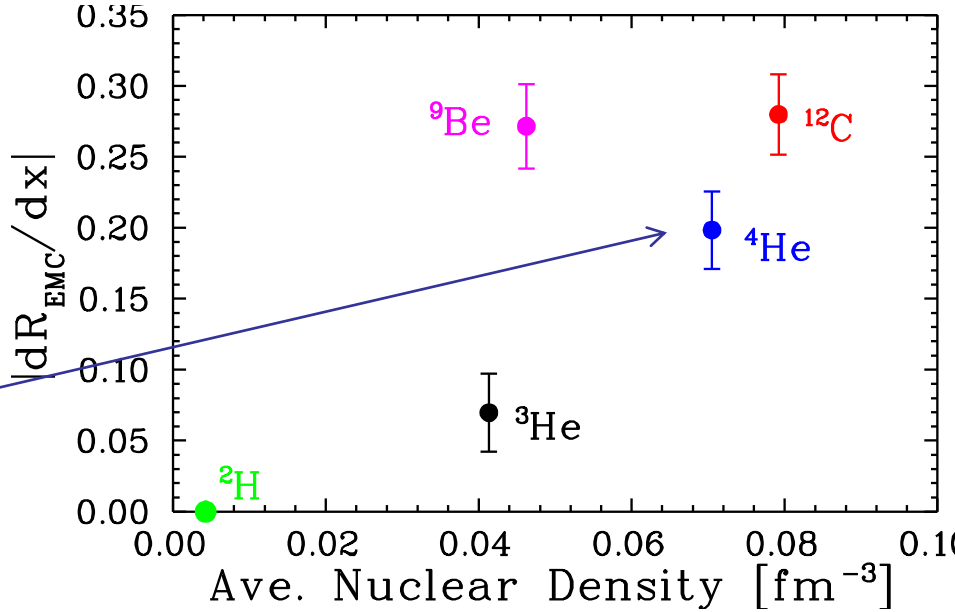
Figures from J. Arrington, nucl-ex/0701017

- Helium shows similar nuclear EMC effect as Carbon
- Post-diction is that nuclear *density* matters, not atomic number
- The nuclear effects in Fe/D can be 4 times those in Fe/C or Fe/He
- H or D is our only way to get "free" nucleons

Nuclear Density

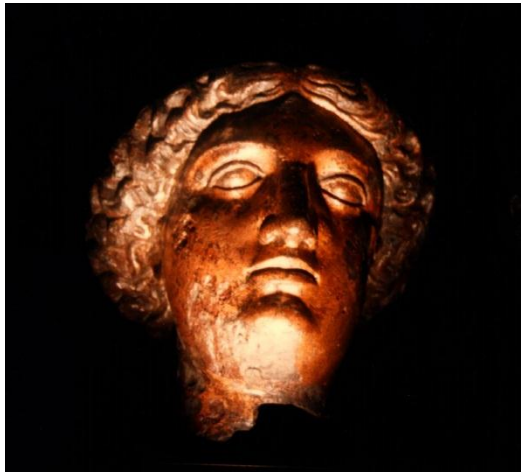




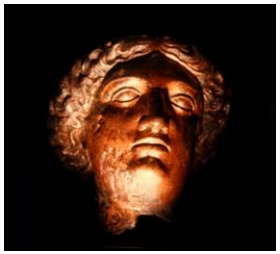


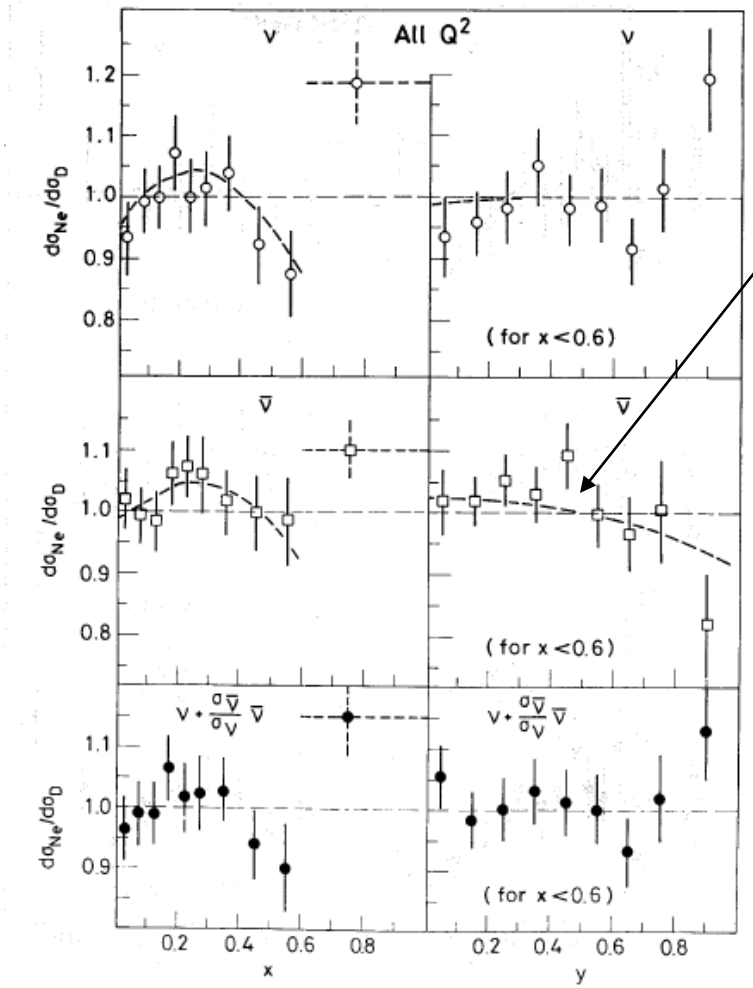
- Arguably better scaling with nuclear density than A
  - Or at least no clear guidance which is better
  - D_2 covers the bases in a way that He does not

Backup: What Neutrino Data Exists?



Ne/D ratio from WA59/WA25



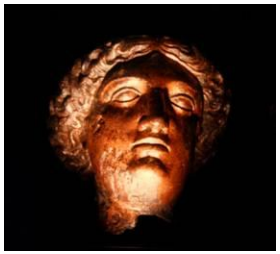


J. Guy [WA25 and WA59] ZPC36,337(1987)

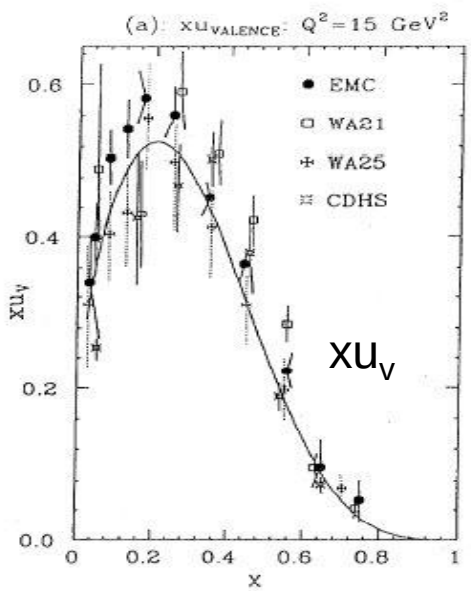
A fit to data

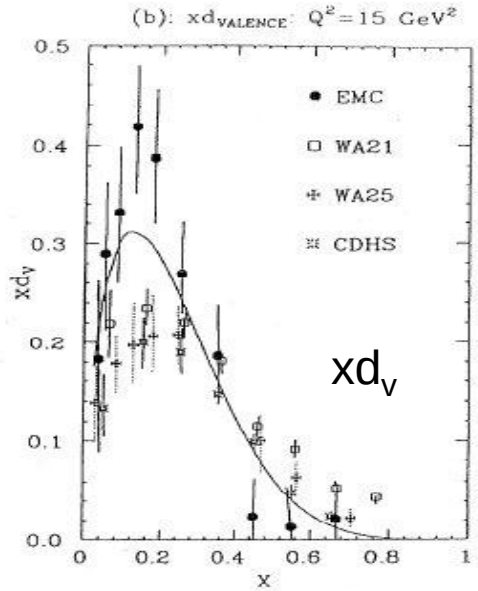
- There is some data from old bubble chamber experiments (WA21, WA25, WA59, CDHS)
- For example, Ne (from WA59) to D (from WA25) ratios here
- However, this data is not usually included in PDF fits because the valence quark distributions on hydrogen (WA21, CDHS) disagree significantly with charged lepton data.

Valence PDFs from WA21

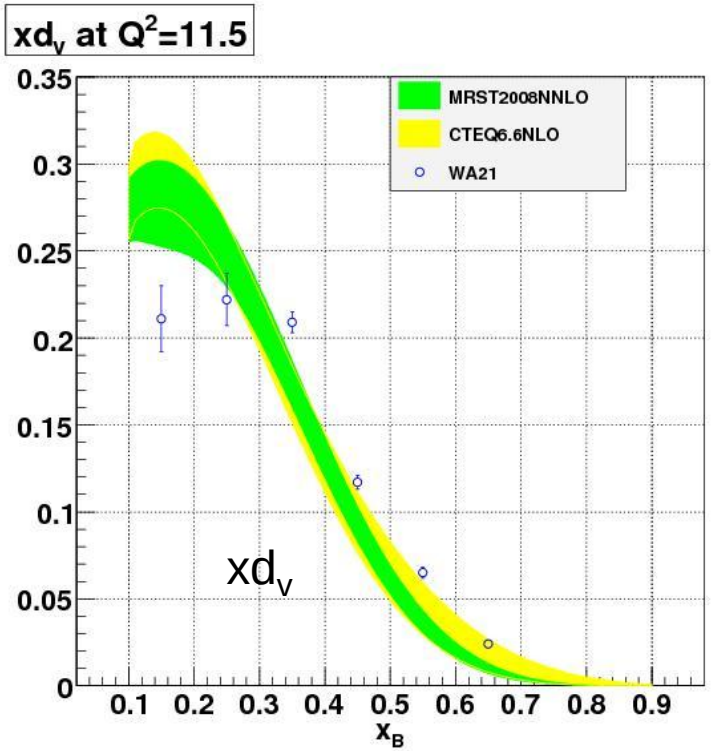


Handbook of perturbative QCD [Sterman *et al*, Rev. Mod. Phys. 67(1995)157]

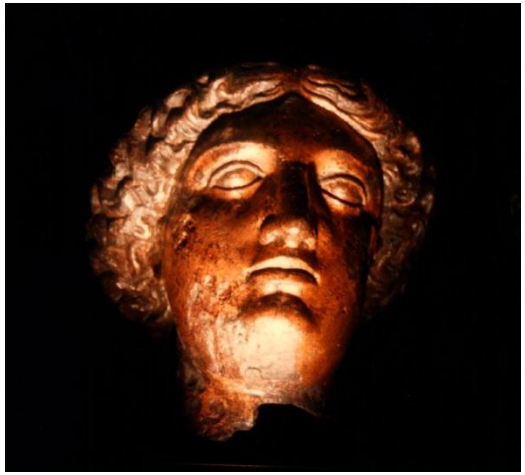




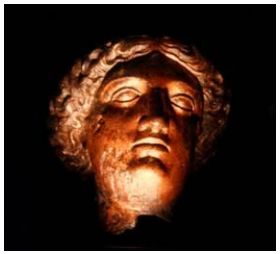
The neutrino data on hydrogen target (WA21 and CDHS) are consistent with each other. But they differ from the charged lepton DIS data (EMC) in the valence quark distributions.



Backup:
More on Safety Strategy

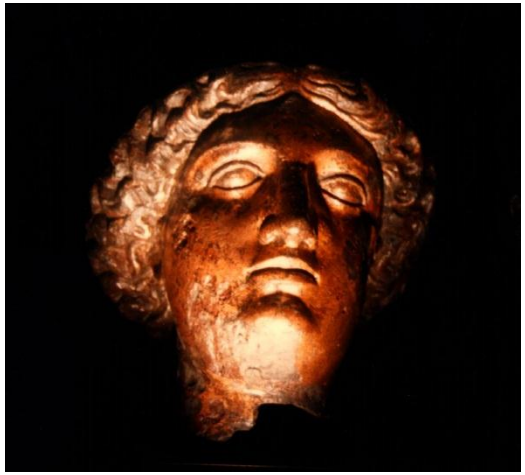


Safety Concerns for Deuterium or Hydrogen

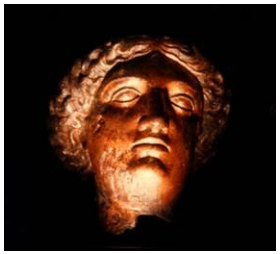


- Understanding and meeting the safety requirements to use deuterium target will require a significant engineering effort with a serious and prompt independent safety review team.
- In case of a need to vent, must guide the deuterium away from possible ignition sources while simultaneously eliminating these possible sources that exist within 30 ft of the deuterium or atmosphere mix.
  - Needs a secondary enclosure (a “tent”) completely surrounding the cryotarget to capture and remove leaking deuterium, via an exhaust duct, to the surface. Existing exhaust duct will need to be upgraded.
  - Also requires electrical modifications to the underground hall to automatically shut off all ignition sources (PMTs, power supplies, light bulbs if not changed to “group B” lights) if concentrations in the tent reach a certain level.

Backup:
Deuterium Costs



Deuterium Costs



- Market Value *(Ref: D. Meekins of JLAB target group)*
  - D_2 fluctuates from $0.6 to $0.9 per STP liter from Linde/Spectra
  - To fill the target alone, need 370kg, or 1.9M STP liters, or 1.1-1.8M$
  - Would need additional D_2 for cryostat and storage volumes
- Deuterium from DOE-NP *(Ref: G. Garvey of Los Alamos)*
  - Large quantities of D_2O stored at Savannah river
  - May be able to "borrow" 2-4 tons of this, in which case cost is
    - Special materials handling (it's 3x more radioactive than SNO's D_2O)
    - Processing from D_2O to D_2
    - Insurance / Security issues
- Fermilab Deuterium Supply *(Ref: J. Kilmer of FNAL)*
  - FNAL has 400-500 liters (<80kg) of pure D_2, could trade for larger mass of slightly less pure D_2