Using Neutrinos as a Probe of the Strong Interaction

The Future Fermilab Neutrino Scattering Program

DIS05 - Madison, WI
29 April 2005

Jorge G. Morfín
Fermilab

Neutrino Experiments have been studying QCD for over 30 years

- For example, Gargamelle made one of the first measurements of Λ_{ST} in the early 1970's using sum rules and the x-Q^2 behavior of the structure functions F_2 and xF_3 measured off heavy liquid while BEBC followed with QCD studies using $\nu + p$ and $\nu + D$ scattering.
- Interacting with the weak current means a **much smaller interaction rate** than e/μ scattering however **can select which set of quarks involved in the interaction via** ν **or** $\overline{\nu}$
- There followed a long string of ν scattering experiments with **increasing statistics** and **decreasing systematic errors** culminating with the ….

Latest ν Scattering Results - NuTeV

Martin Tzanov

NuTeV accumulated over 3 million neutrino/antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

NuTeV considered 23 systematic uncertainties.

NuTeV σ agrees with **CCFR** for $x < 0.4$ but is systematically higher at high x : 4% at x=0.45, 10% at x=0.55, 20% at x=0.65.

NuTeV agrees with **charge lepton** data for $x < 0.5$.
Perhaps smaller nuclear correction at high-x for neutrino scattering.

NuTeV F_2 and xF_3 agrees with **theory** for medium x.
At low x different Q^2 dependence.
At high x (x>0.6) NuTeV is systematically higher.

Current open Questions to be addressed via neutrino scattering

- Low-x: Better understanding of shadowing with incoming neutrino necessary.
- High-x: What is happening with the valence quarks as x --> 1.0. NuTeV gives opposite indication compared to E866 (D-Y)
- Low W: What is happening in the transition region between resonance production and DIS.
- All x and Q^2 : What is yet to be learned if we can measure all six ν / $\bar{\nu}$ structure functions to yield maximal information on PDFs. NuTeV has measured $\Delta xF_3^{\nu} = xF_3^{\nu} - xF_3^{\bar{\nu}}$
- To address these questions, Fermilab has TWO neutrino scattering experiments: MINOS Near Detector (Gallagher) and **MINERνA**.

The Near Future

MINERνA - **approved 4/2004**

(Main INjector ExpeRiment ν-A)

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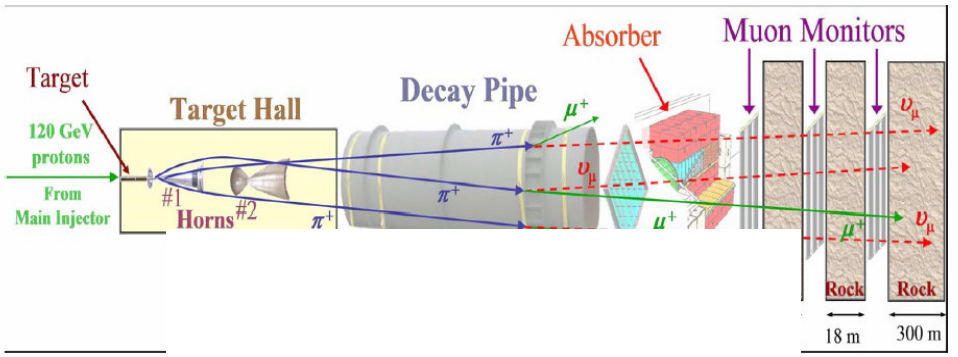
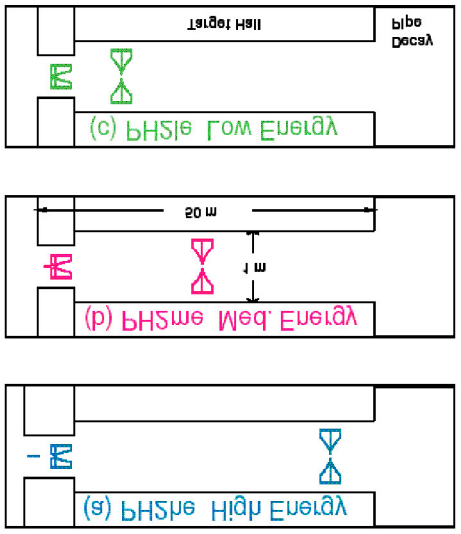
Use the NuMI beam to collect a **large** sample of ν and $\bar{\nu}$ scattering events…

- LE-configuration: **Events-** (E_μ >0.35 GeV)
  E_{peak} = 3.0 GeV, <E_ν> = 10.2 GeV,
  rate = **60 K events/ton - 10^{20} pot**

- ME-configuration: **Events-**
  E_{peak} = 6.0 GeV, <E_ν> = 8.0 GeV,
  rate = 230 K events/ton - 10^{20} pot

- HE-configuration: **Events-**
  E_{peak} = 9.0 GeV, <E_ν> = 12.0 GeV,
  rate = 525 K events/ton - 10^{20} pot





With E-907 at Fermilab to measure Particle spectra from the NuMI target, expect to know neutrino flux to ≈ ± 4 - 5%.

MINERνA will have the statistics to cover a wide variety of important ν physics topics

Assume 4.0x10^{20} in LE ν beam, 8x10^{20} in ME, 1.5x10^{20} in HE and and 2.5x10^{20} in HEbar

ν_μ Event Rates in 3 fiducial tons of CH			
Process	CC	NC	CCbar
Quasi-elastic	835 K	275 K	105 K
Resonance	1605 K	495 K	130 K
Transition	2000 K	635 K	230 K
DIS	4080 K	1215 K	455 K
Coherent	85 K	43 K	20 K
TOTAL	**8600 K**	**2665 K**	**940 K**

Typical Fiducial Volume =
3-5 tons CH, 0.6 ton C, ≈ 1 ton Fe and ≈ 1 ton Pb
8.6 - 14.3 M ν events in CH
1.0 - 1.5 M $\bar{\nu}$ events in CH
1.4 M ν events in C
2.9 M ν events in Fe
2.9 M ν events in Pb

16 Million total CC events in a 4 - year run

Main Physics Topics of interest for this conference

- **Transition Region** — **2 M events (I. Niculescu & C. Keppel)**
- **DIS and Structure Functions** — **4 M DIS events (W > 2, Q > 1)**
- **Nuclear PDF's and Effects** — **C:1.4 M, Fe: 2.9 M and Pb: 2.9 M**

Event Distribution in x - Q^2

(in units of 1000 events)

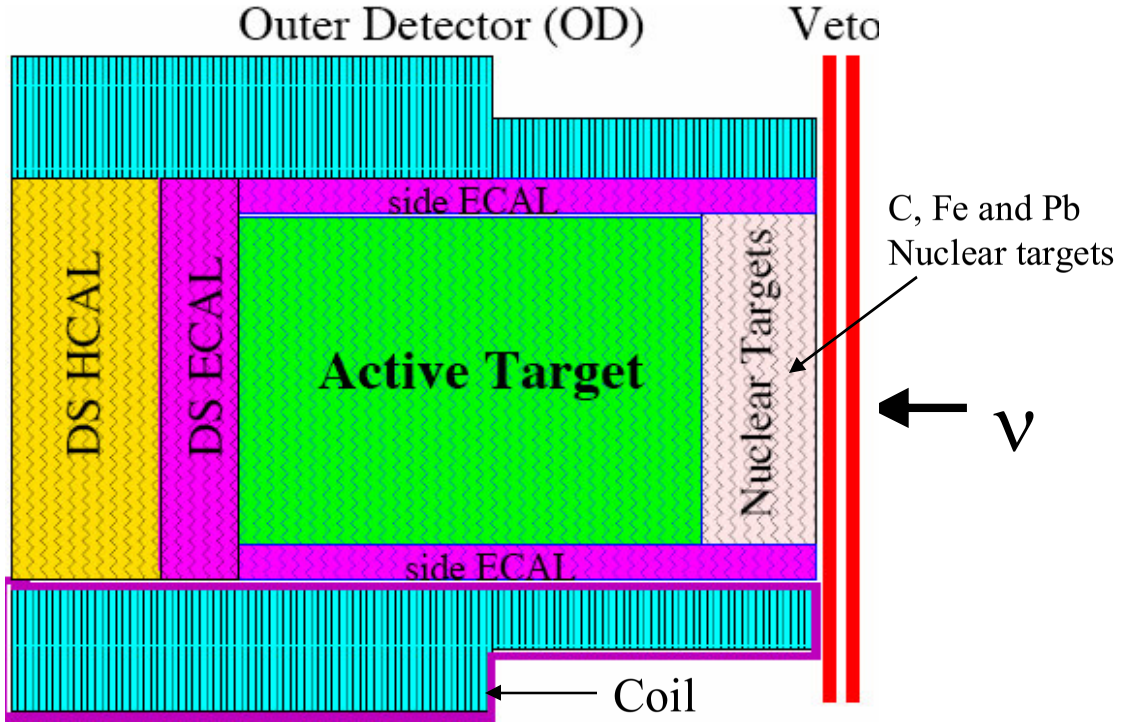
Q^2 =	0.0	2.0	4.0	8.0	16.0	>32.0
X=0.0						
	723	3.2	1.3	0	0.0	0.0
0.03						
	499	19.2	3.2	1.6	0.0	0.0
0.05						
	563	76.8	16.0	1.9	0.32	0.0
.075						
	477	179	19.2	6.4	0.64	0.0
0.10						
	368	208	54.4	8.0	0.64	0.0
0.125						
	285	227	99.2	16.4	1.0	0.0
0.15						
	419	381	272	41.6	9.6	0.0
0.20						
	387	586	570	208	25.6	0.32
0.30						
	70.0	435	547	381	64.0	1.0
0.45						
	28.8	54.4	221	221	89.6	6.4
0.65						
	3.2	16.0	25.6	25.6	16.0	0.32
1.00						

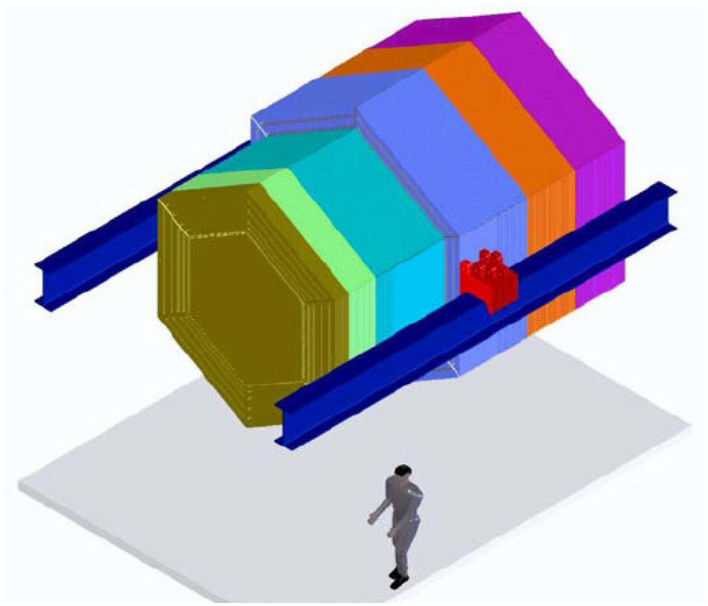
Based on 8.6 M ν events on CH.

Additional 7.5 M on C, Fe and Pb targets

66 K events with $X > 0.65$ and $Q^2 > 4$ GeV^2

For the MINERνA physics program:a fine-grained, fully-active neutrino detector





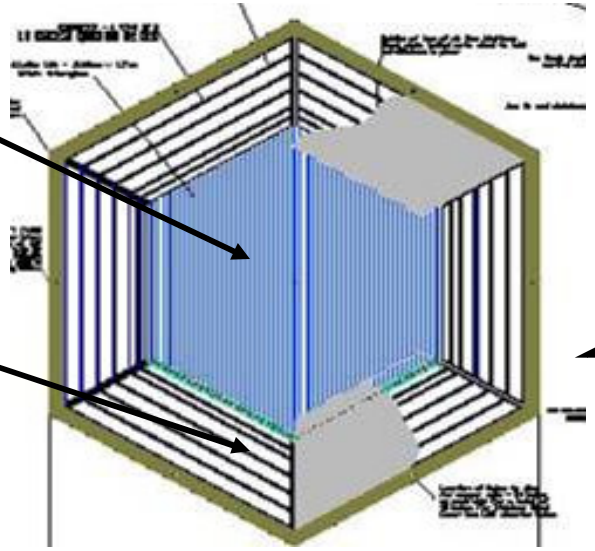
- Active target of scintillator bars (6t total, 3 - 5 t fiducial)
- Surrounded by calorimeters
  - upstream calorimeters are Pb, Fe targets (~1t each)
  - magnetized side tracker/calorimeter

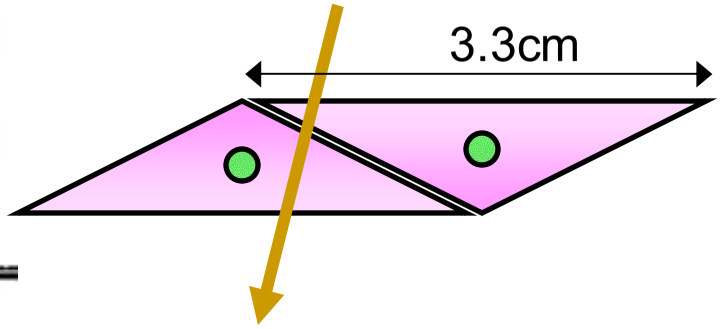
Active Target Module

- Planes of strips are hexagonal
  - inner detector: active scintillator strip tracker rotated by 60° to get stereo U and V views
  - Pb "washers" around outer 15 cm of active target
  - outer detector: frame, HCAL, spectrometer
  - XUXV planes → module

Inner, fully-active strip detector

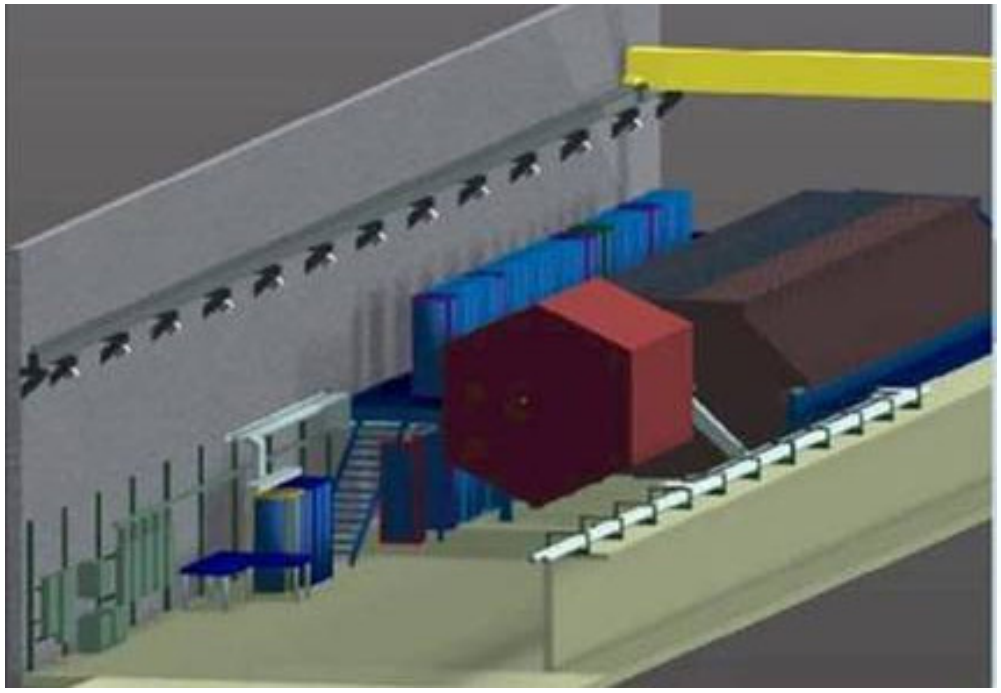
Outer Detector magnetized sampling calorimeter - muon identifier/spectrometer

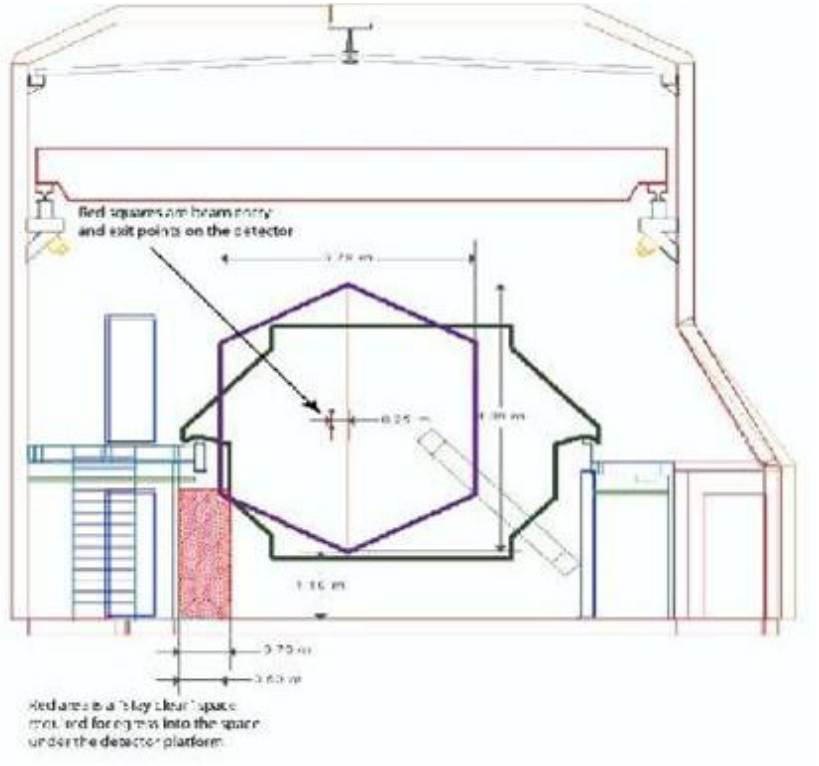




Location in NuMI Near Hall

- MINERvA just upstream of the MINOS near detector, which helps MINERvA as a high energy muon spectrometer.





MINERνA ν Scattering Physics Program

- Quasi-elastic
- Resonance Production - 1pi
- Resonance Production - npi / **Transition region - res. to DIS** (Niculescu and Keppel)
- **Deep-Inelastic Scattering**
- Coherent Pion Production
- Strange and Charm Particle Production
- σ_T **, Structure Functions and PDFs**
  - **High-x parton distribution functions**
- **Nuclear Effects - including nuclear PDFs** (Kolhinen)
- Generalized Parton Distributions

Parton Distribution Functions:
What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, d and s.

Using Leading order expressions:

$$F_2^{\bar{\nu}N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2\bar{s}+2c\right]$$

$$F_2^{\nu N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2s+2\bar{c}\right]$$

$$xF_3^{\bar{\nu}N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}-2\bar{s}+2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}+2s-2\bar{c}\right]$$

Taking combinations of the Structure functions

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u}+\bar{d}+2\bar{c}\right)$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u}+\bar{d}+2\bar{s}\right)$$

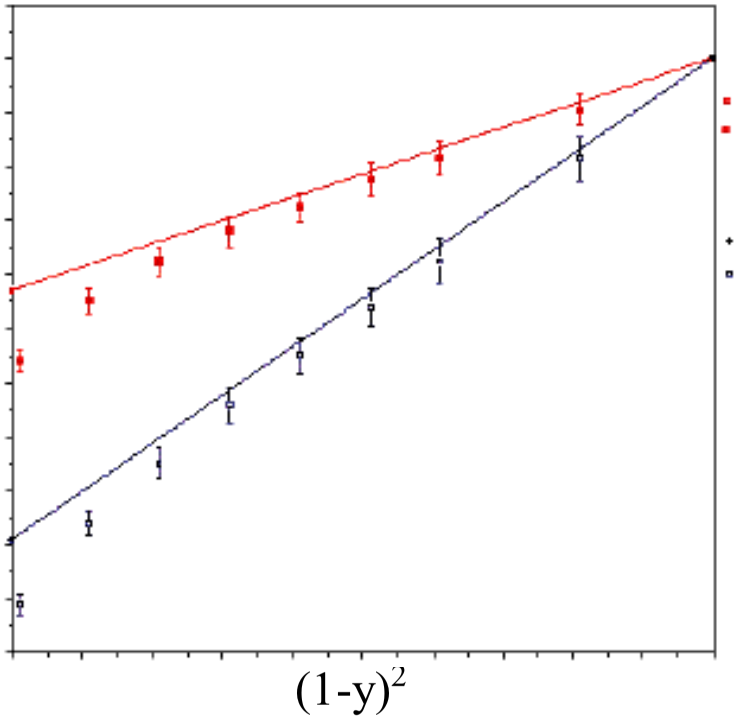
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[\left(s+\bar{s}\right)-\left(\bar{c}+c\right)\right]$$

Physics Results: Six Structure Functions for Maximal Information on PDF's

$$\frac{d\sigma^{\nu A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right)\right] + y^2 F_L$$

$$\frac{d\sigma^{\bar{\nu} A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) - xF_3^{\bar{\nu} A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\bar{\nu} A}(x,Q^2) + xF_3^{\bar{\nu} A}(x,Q^2)\right)\right]$$

$$\frac{\sigma\left(x, Q^2, (1-y)^2\right)}{G^2/2\pi x}$$



Neutrino
Statistical + 5% systematic

Anti-Neutrino
Statistical only

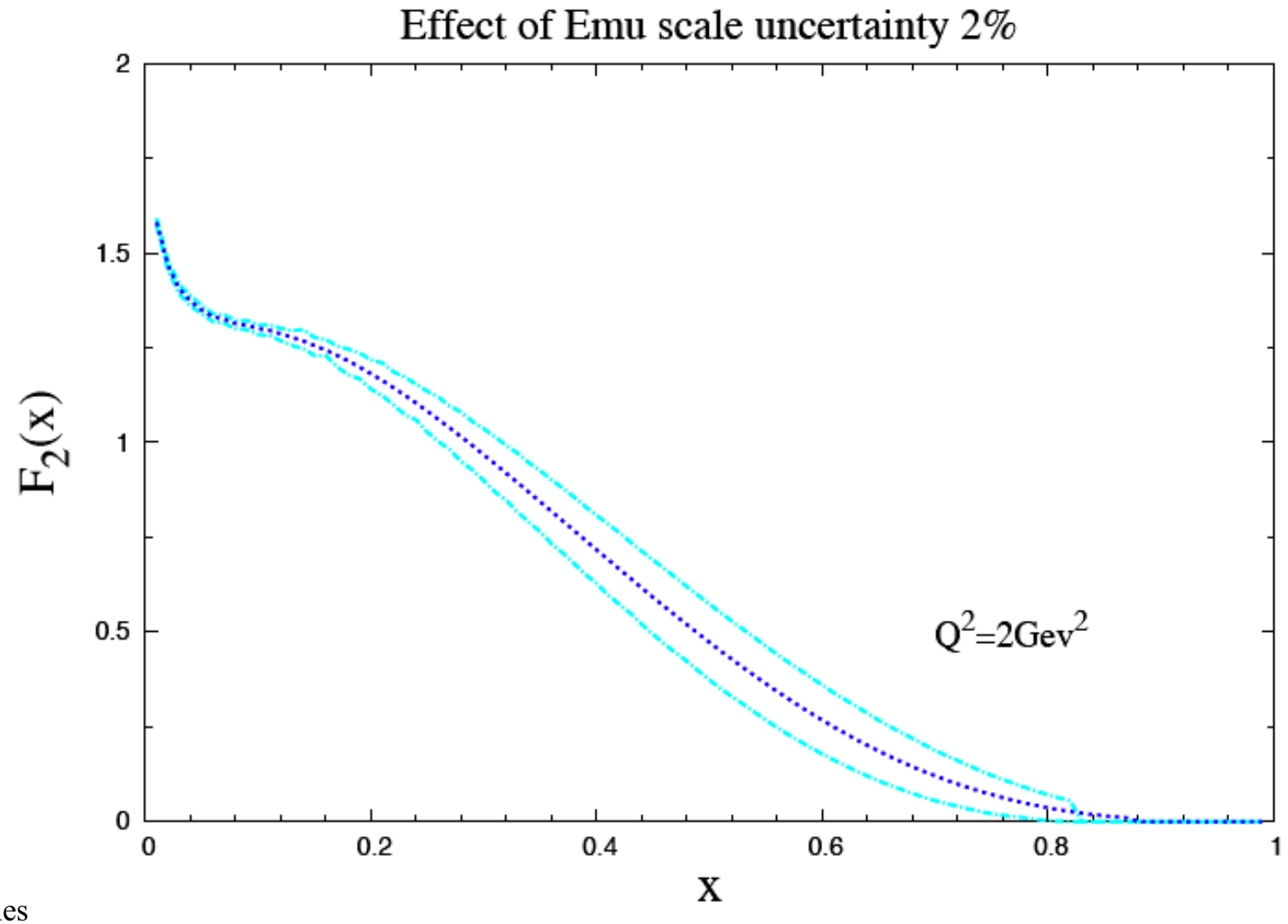
$R = R_{whitlow}$

$X = 0.1 - 0.125$
$Q^2 = 2 - 4\ GeV^2$

Meant to give an impression only!
Kinematic cuts in (1-y) not shown.

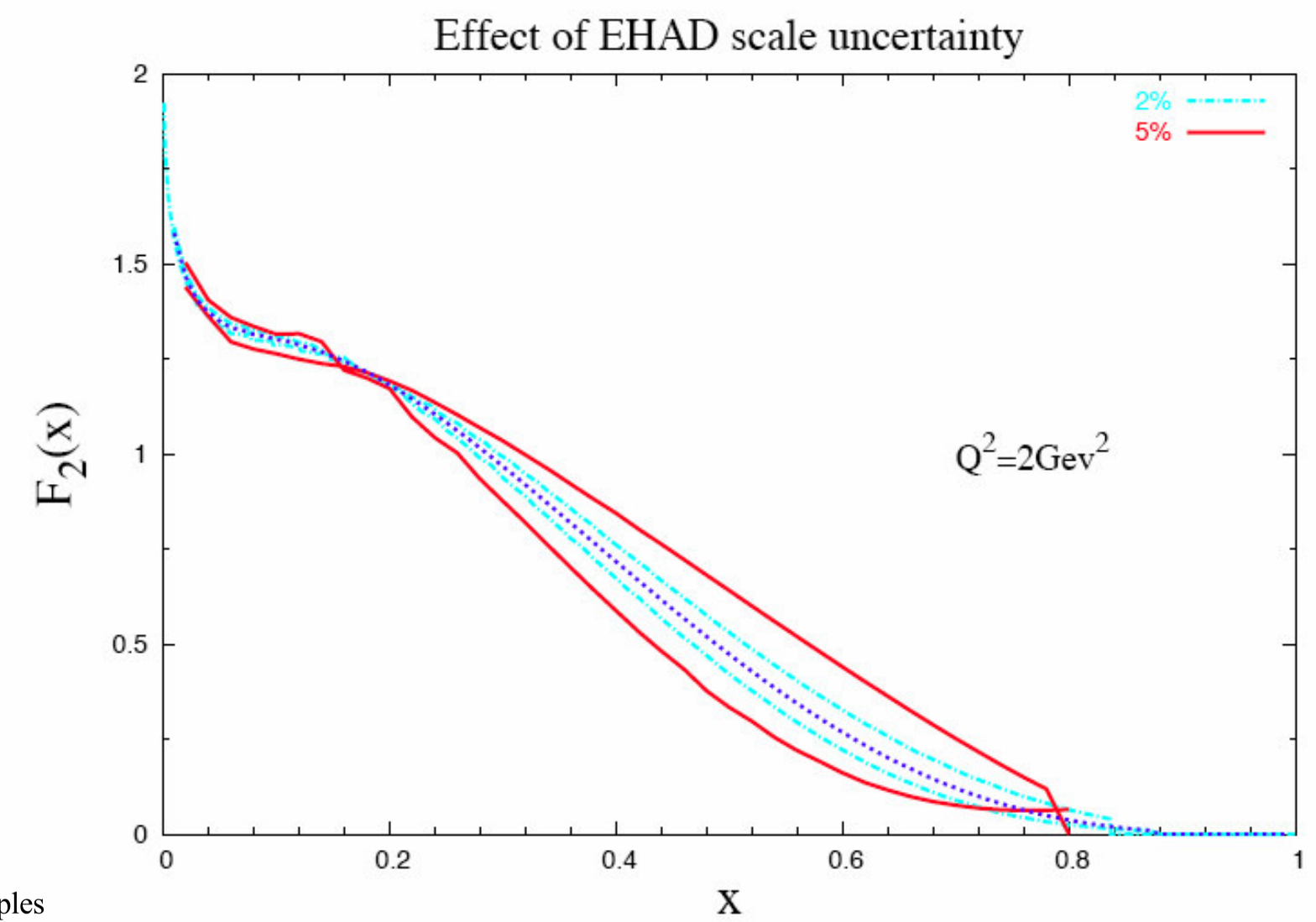
Estimated systematic error: E_μ scale

NuTev achieved 0.7%



Estimated systematic error: E_{had} scale

NuTev achieved 0.43%

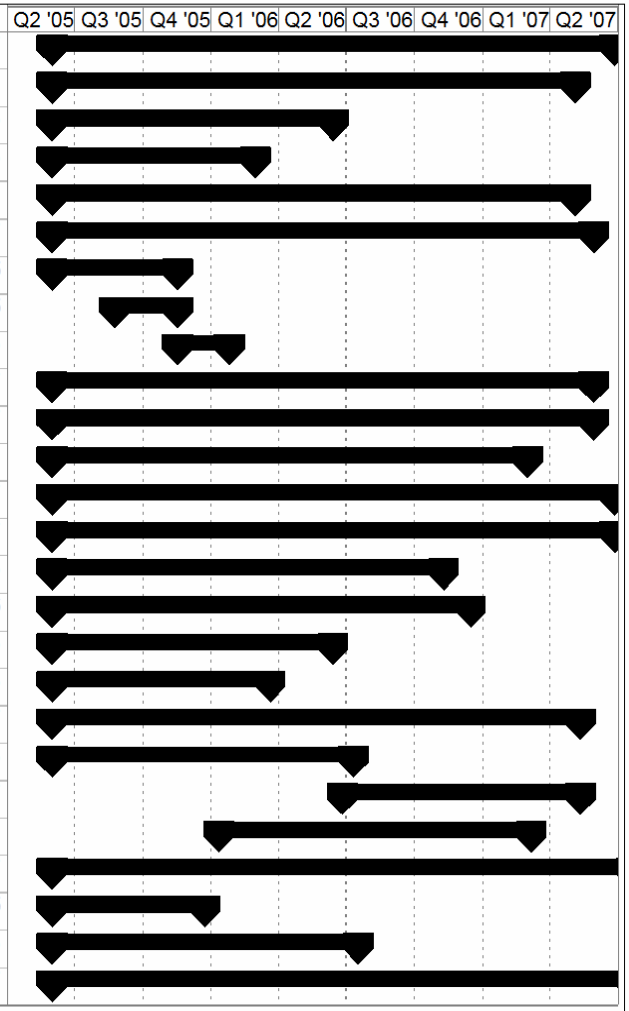


MINERνA Schedule

26 months: design, fabrication and installation

Current projection is to start taking data in late 2008

ID	WBS	Task Name	Duration	Start	Finish
1	1	Detector Construction	540 days	6/1/05	6/26/07
2	1.1	Scintillator Planes	503 days	6/1/05	5/4/07
3	1.1.1	Scintillator Extrusion	270 days	6/1/05	6/13/06
14	1.1.2	WLS Fibers	195 days	6/1/05	2/28/06
19	1.1.3	Scintillator Plane Assembly	503 days	6/1/05	5/4/07
24	1.2	Clear Fiber Cables	520 days	6/1/05	5/29/07
25	1.2.1	Connector Procurement	120 days	6/1/05	11/15/05
29	1.2.2	Clear Fiber Prep	60 days	8/24/05	11/15/05
32	1.2.3	RTV Boots	50 days	11/16/05	1/24/06
37	1.3	Photo Sensors	520 days	6/1/05	5/29/07
38	1.3.1	PMT Boxes	520 days	6/1/05	5/29/07
43	1.3.2	PMTs	457 days	6/1/05	3/1/07
48	1.4	Electronics and DAQ	540 days	6/1/05	6/26/07
49	1.4.1	Front-End Electronics	540 days	6/1/05	6/26/07
63	1.4.2	Readout (CROC) Board	376 days	6/1/05	11/8/06
72	1.4.3	DAQ and Slow Control	403 days	6/1/05	12/15/06
86	1.5	Frame and Absorbers	269 days	6/1/05	6/12/06
87	1.5.1	Outer Detector Frames	209 days	6/1/05	3/20/06
94	1.6	Module Assembly	508 days	6/1/05	5/11/07
95	1.6.1	Prototype Assembly	289 days	6/1/05	7/10/06
98	1.6.2	Assembly and Mapping	230 days	6/26/06	5/11/07
104	1.7	Coil	300 days	1/11/06	3/6/07
108	2	Detector Installation	556 days	6/1/05	7/18/07
109	2.1	Installation Preparations	147 days	6/1/05	12/22/05
117	2.2	NuMI Near Hall Infrastructure	294 days	6/1/05	7/17/06
124	2.3	Detector Module Installation	556 days	6/1/05	7/18/07

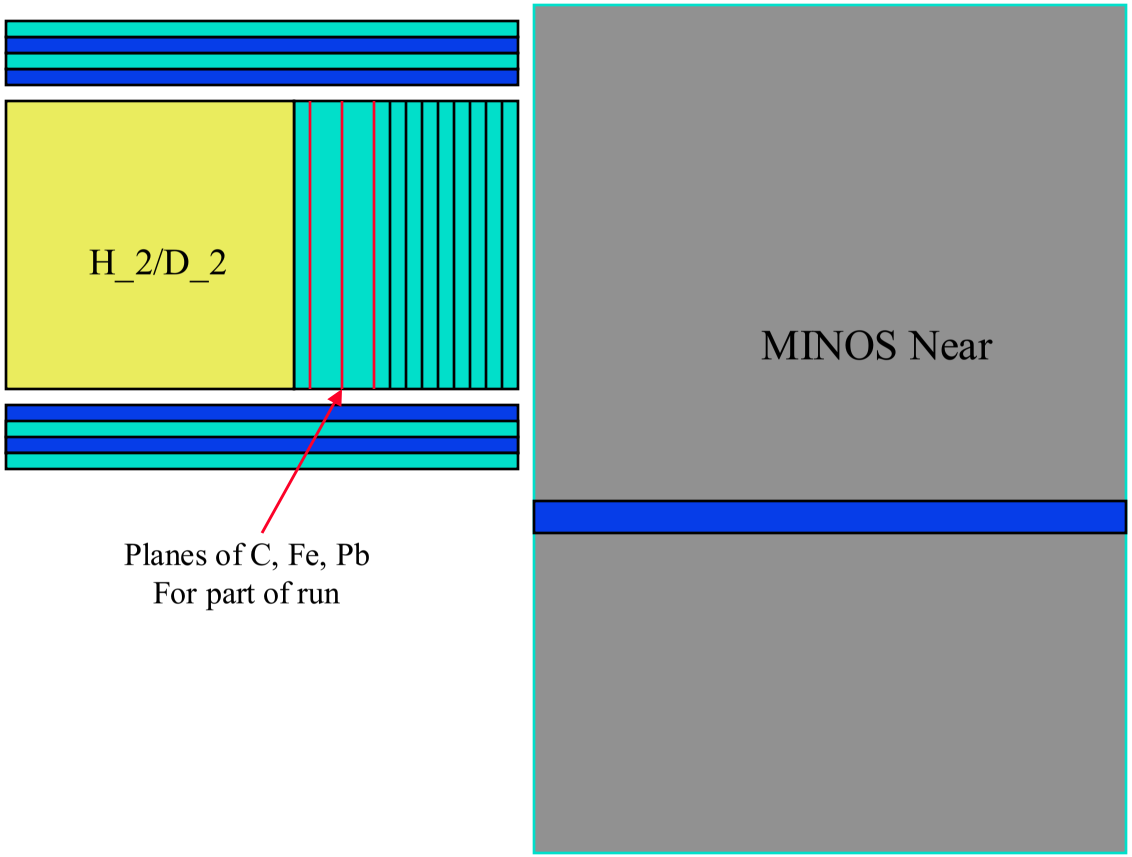


Not-as-near future
a Liquid H_2/D_2(/O/Ar) Target

NOT YET APPROVED FOR THIS

Fid. vol:
r = 80 cm. l = 150 cm.

560 K CC events in LH_2
1280 K CC events in LD_2
per year he-ν running.



Meeting **safety** requirements will be a challenge.

High-x PDFs

ν - p Scattering

$$F_2^{\nu p} = 2x\,(d + \bar{u} + s)$$

$$F_2^{\bar{\nu} p} = 2x\,(\bar{d} + u + \bar{s})$$

At high x

$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}$$

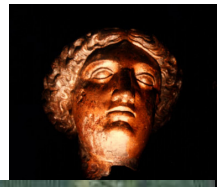
Add in…

$$xF_3^{\nu p} = 2x\,(d - \bar{u} + s)$$

$$xF_3^{\bar{\nu} p} = 2x\,(-\bar{d} + u - \bar{s})$$

$$F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$$

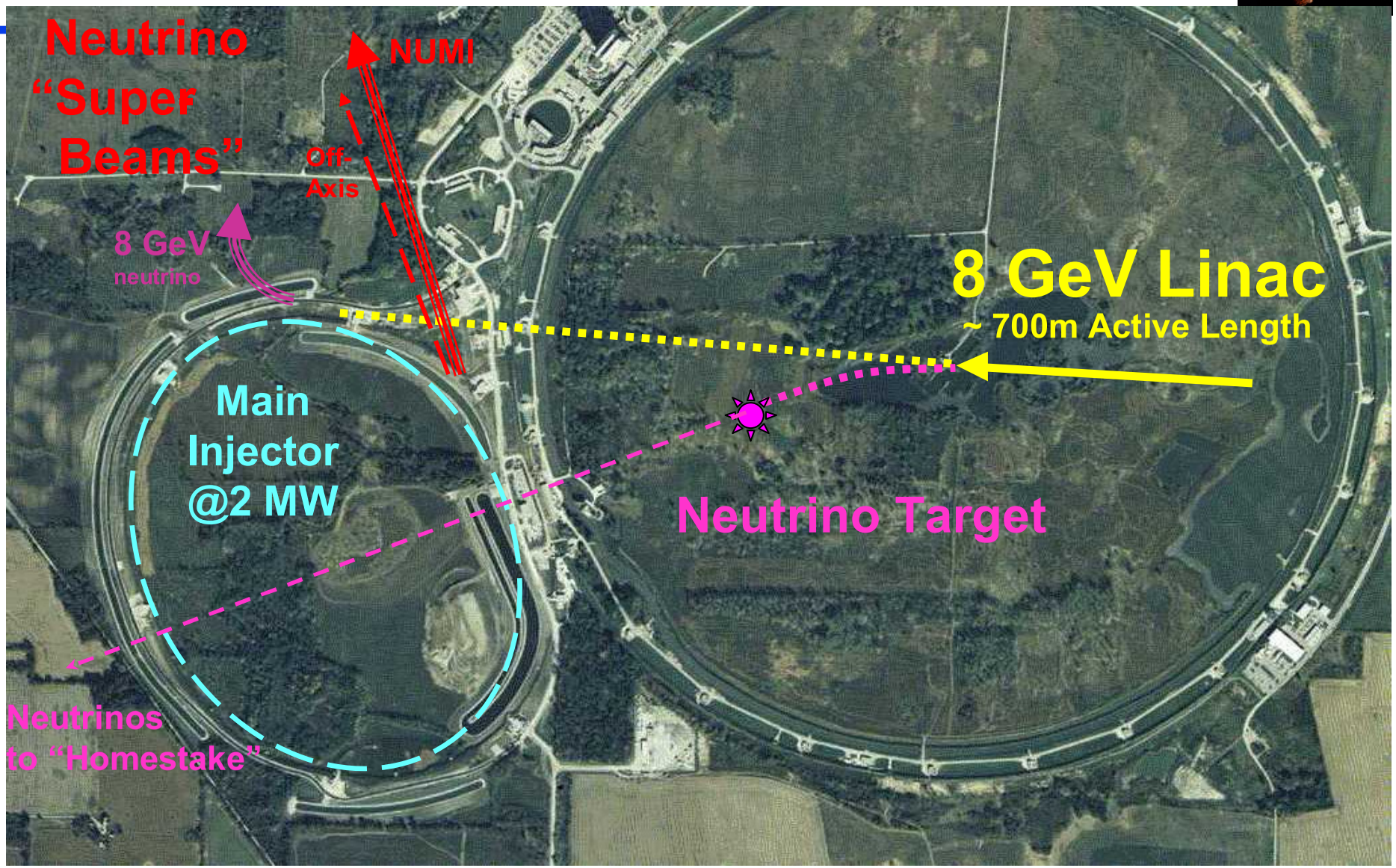
$$F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} = 4xu$$



Further in the Future

The Fermilab Proton Driver Project

8 GeV Super Conducting LINAC



Main Injector + Proton Driver Super-Beam Parameters

- 8.0 GeV Kinetic Energy at Injection
- 120 GeV Maximum Energy at Extraction
- **1.5 x 10^{14} Protons in Main Injector**
  4 - 5 x Main Injector Design
- 1.5 Second Main Injector Cycle Time
  (1.8 seconds for Synchrotron Option)

  } May be able to Improve

- Main Injector Beam Power **2 MW**

Timescale for a Proton Driver ?

- Always hard to guess
- Technically limited schedule
  - CD0 in 05
  - CD1 in 06 (preliminary: acquisition strategy, conceptual design report, project scope, baseline cost/schedule range, Hazard analysis, etc)
  - CD 2/3a in 07-08 (project baseline approved, approval to start construction)
- Funds in FY09 ? DOE speaks of funding such projects in this time frame
- Once funding is approved, typical projects of this scale (MI, SLAC B factory, KEK-B, SNS) have construction times of 4-5 years
- The timescale will also depend on how the Linear Collider plays out, over the next few years

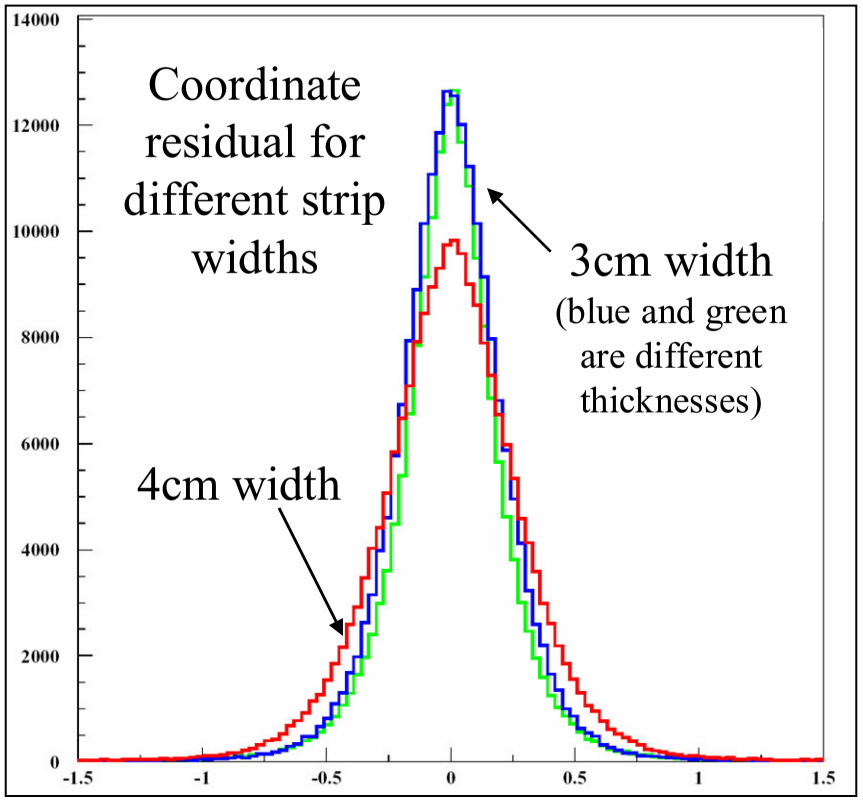
Summary

- The MINERνA experiment, with Stage I approval, brings together the expertise of the HEP and NP communities.
- MINERνA will accumulate significantly more events in important exclusive channels across a wider E_ν range than currently available as well as a huge sample of DIS events. With excellent knowledge of the beam, σ and structure functions should be well-measured.
- With C, Fe and Pb targets MINERνA will enable a systematic study of nuclear effects in ν-A interactions, known to be different than well-studied e-A effects.
- MINERνA is being established as a Fermilab PPD project, with significant personnel and financial support, and is projecting first data in Fall of 2008.
- MINERνA would also run with the Fermilab Proton Driver at 5x the intensity. FPD CD0 document ready for the DOE. Could be operational around 2014-2015.

We welcome additional collaborators!!

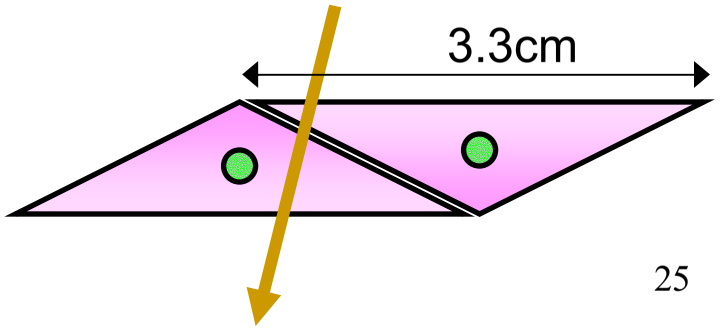
Additional Details

Performance: Optimization of Tracking in Active Target

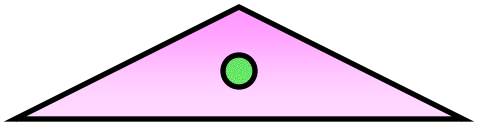


- technique pioneered by D0 upgrade pre-shower detector

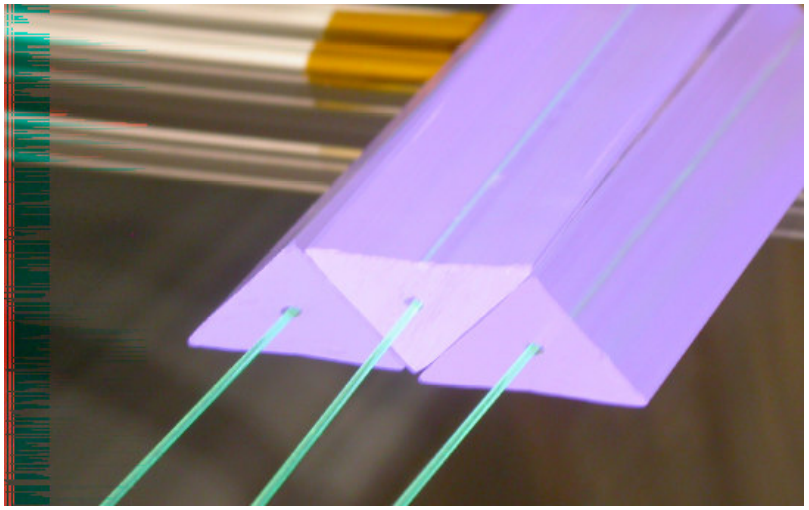
- Excellent tracking resolution w/ triangular extrusion
  - σ~3 mm in transverse direction from light sharing
  - More effective than rectangles (resolution/segmentation)
  - Key resolution parameters:
    - transverse segmentation and light yield
    - longitudinal segmentation for z vertex determination



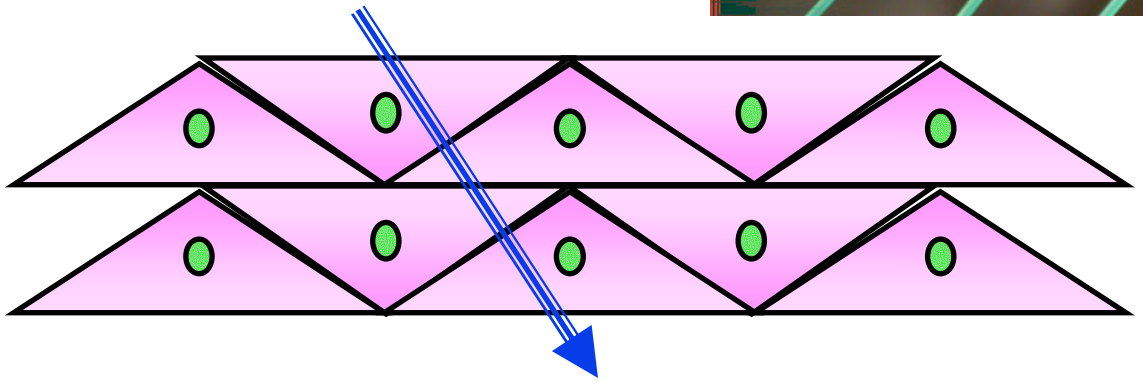
Extruded Scintillator and Optics



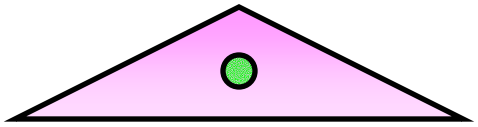
Basic element: 1.7x3.3cm triangular strips. 1.2mm WLS fiber readout in center hole



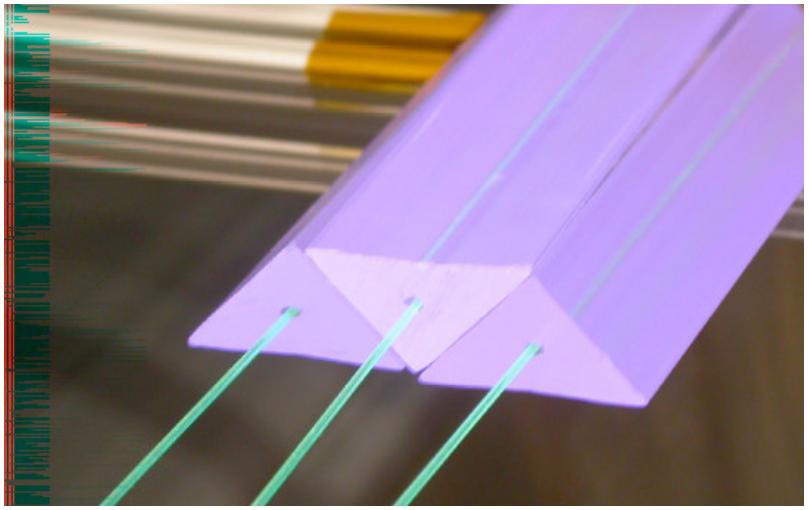
Assemble into planes



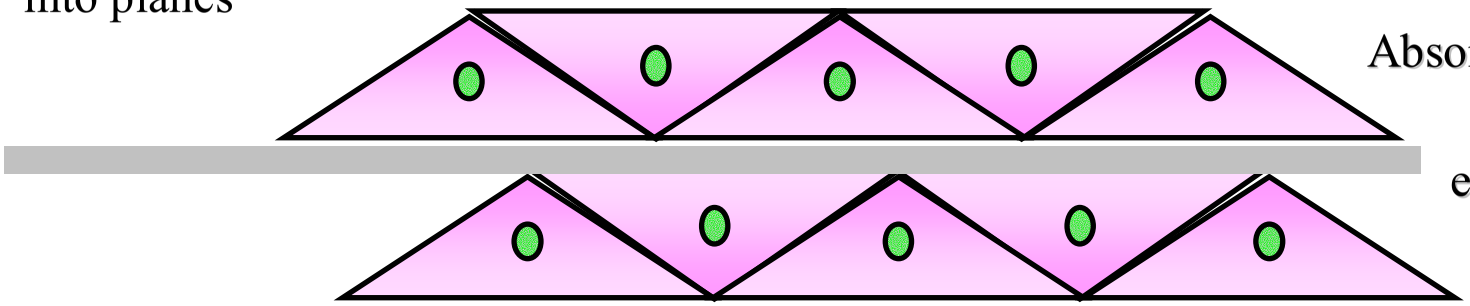
Extruded Scintillator and Optics



Basic element: 1.7x3.3cm triangular strips. 1.2mm WLS fiber readout in center hole



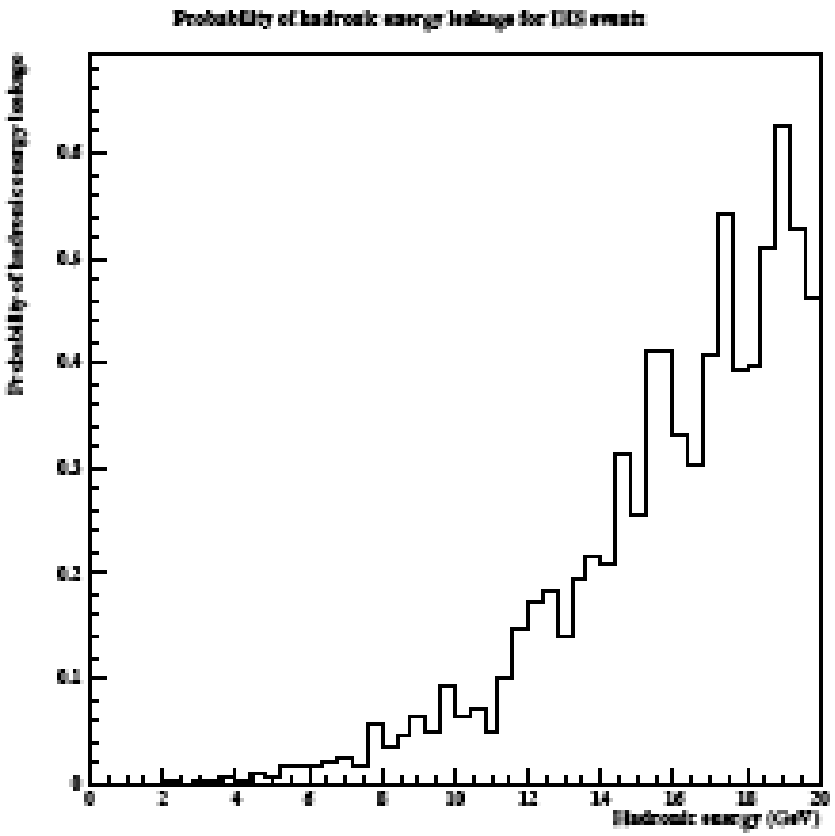
Assemble into planes



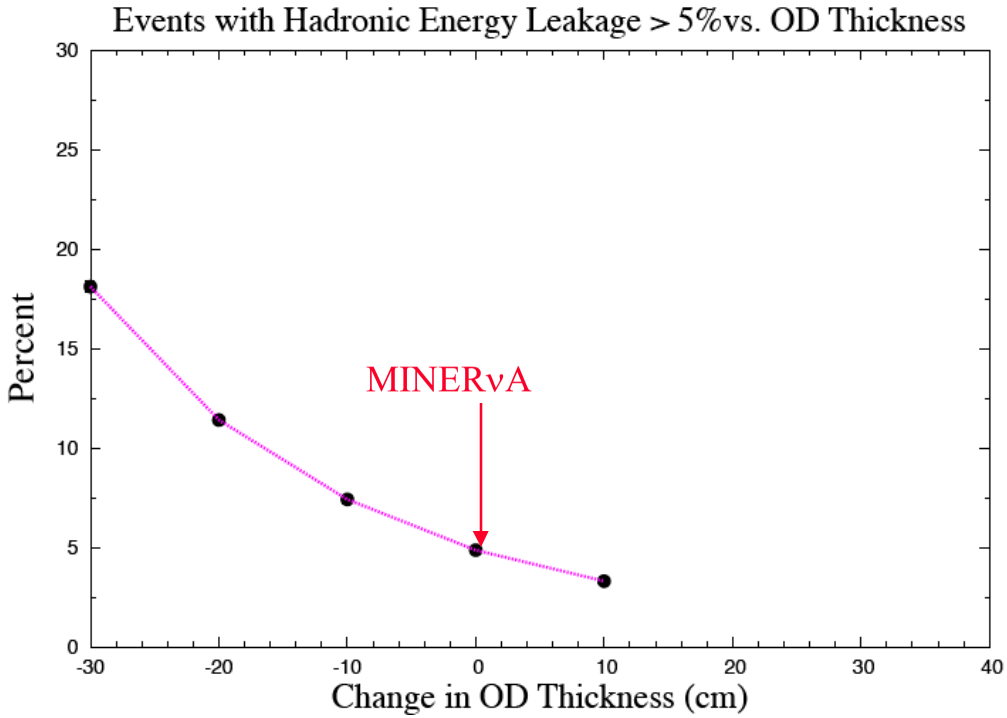
Absorbers between planes

e.g., E- or H-CAL, nuclear targets

Performance: Energy Containment for DIS events



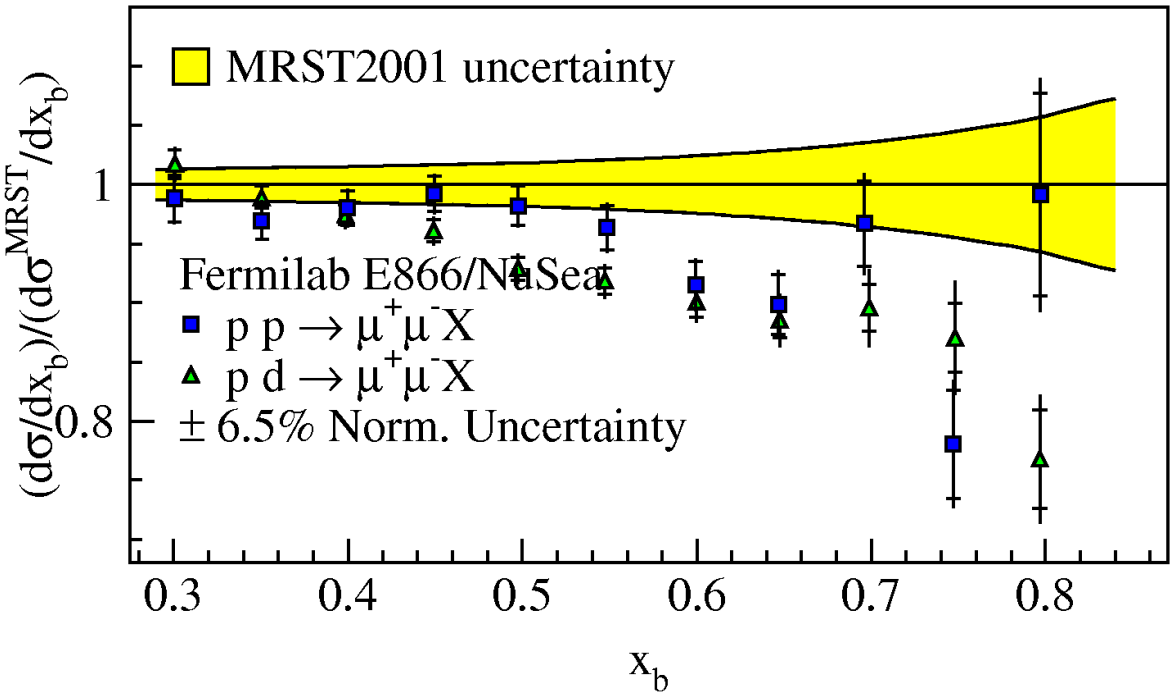
Probability that **any** visible hadronic energy escapes active detector undetected for DIS events

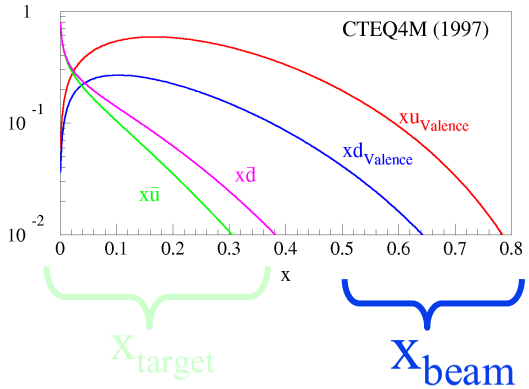


Percentage of DIS events with greater than 5% of the hadronic energy leaking out of the **outer detector.**

Further indications that the valence quarks not quite right at high-x??

E866 -Drell-Yan Preliminary Results (R. Towell - Hix2004)



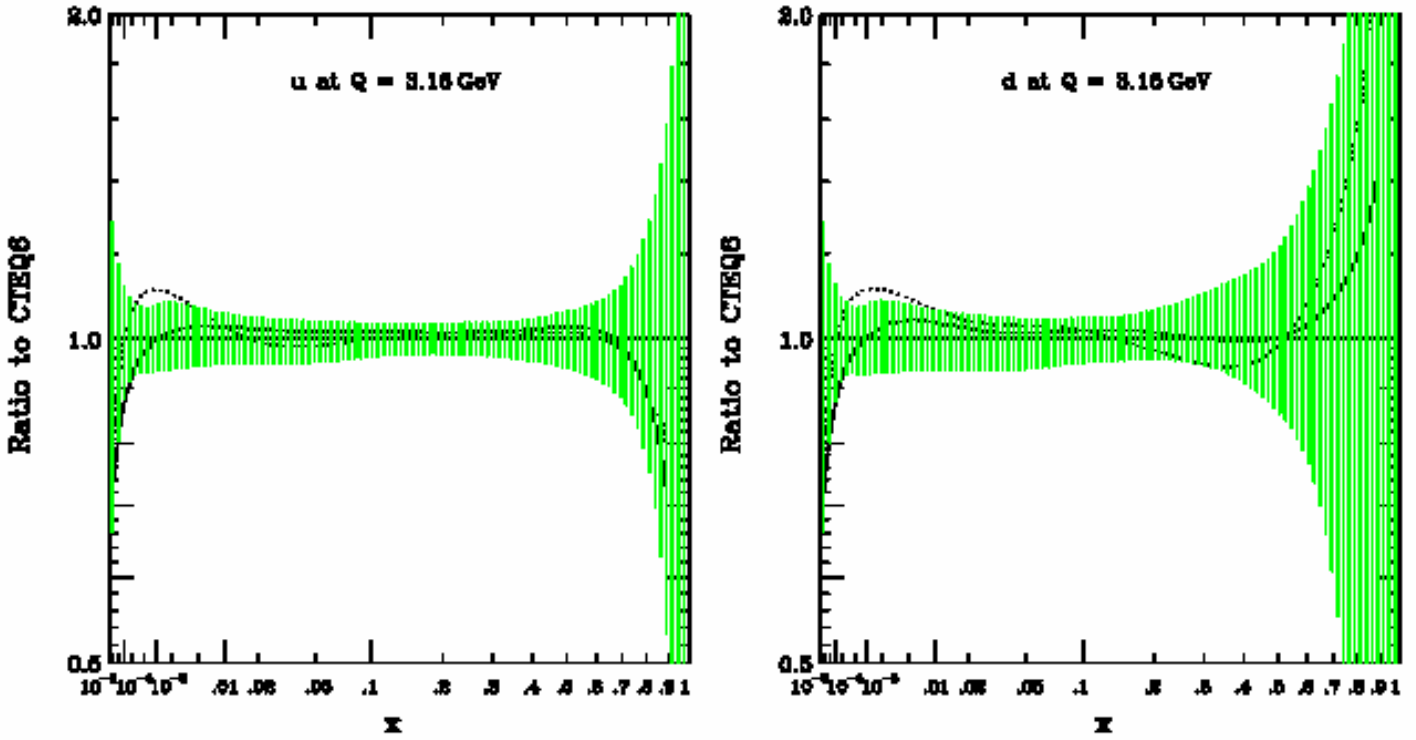


- **x_{beam} distribution measures *4u + d* as *x--> 1.***
- **Both MRST and CTEQ *overestimate* valence distributions as *x* --> *1* by 15-20%.**
- **Possibly related to *d/u* ratio as *x* --> *1*, but requires full PDF-style fit.**
- *Radiative corrections have recently been calculated. (Not yet fully applied)*

Major Milestones

- December 2002 - Two EOIs for neutrino scattering experiments using the NuMI beam and similar detector concepts presented to the PAC. PAC suggests uniting efforts and preparing proposal.
- December 2003 - MINERνA proposal presented to PAC. PAC requests more quantitative physics studies and details of MINERνA's impact on Fermilab.
- April 2004 - Proposal addendum containing additional physics studies and report from the Impact Review Committee presented to PAC. **Receive Stage I approval**.
- Summer 2004 - **Very Successful** R&D Program concentrating on front-end electronics, scintillator extrusions and a "vertical slice test"
- January 2005 - **Successful Director's Review** of MINERνA
- March 2005 - Fermilab agrees to assume more significant funding role and submits **MIE** for full funding of MINERνA to DOE. **The MINERνA project established in Fermilab-PPD.**

Present Status: ν-scattering
High x_{Bj} parton distributions



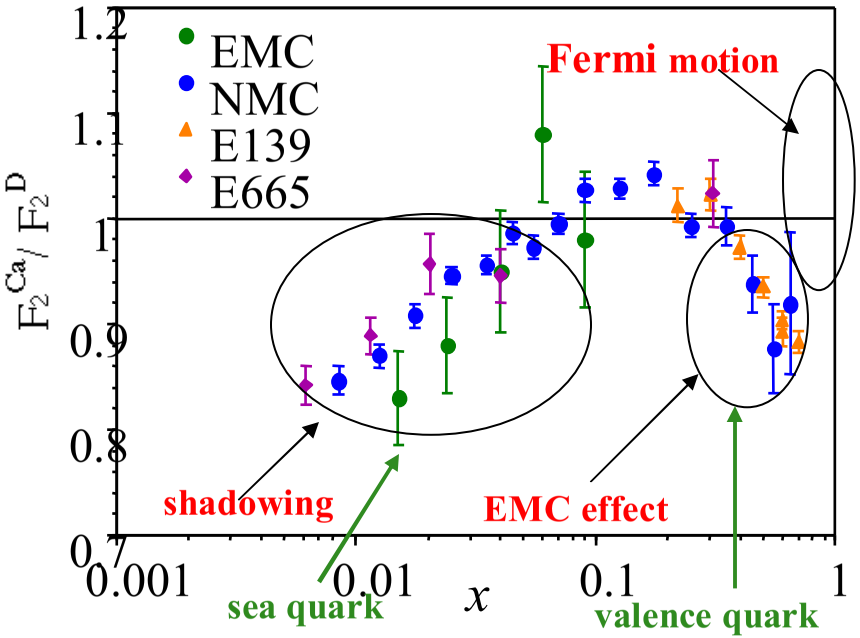
- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10\ GeV^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

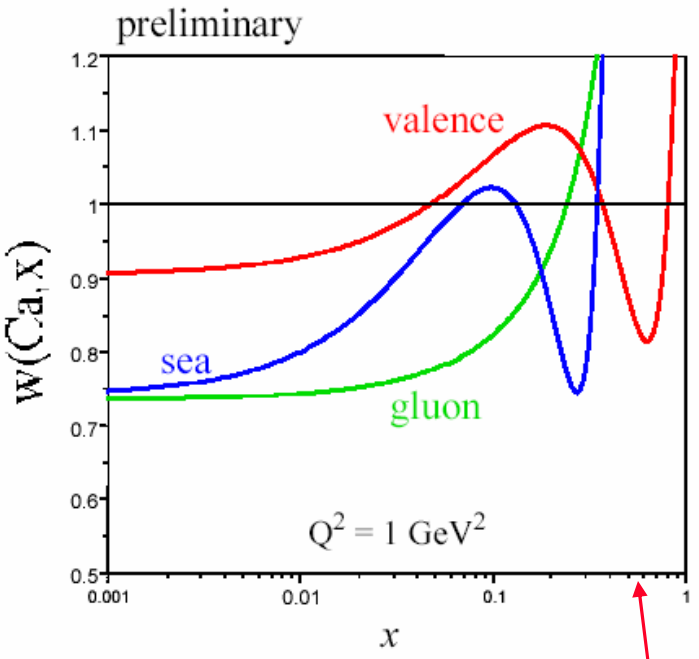
- CTEQ / MINERνA working group to investigate high-x_{Bj} region.

NuMI

Knowledge of Nuclear Effects with Neutrinos: essentially NON-EXISTENT

MINERνA

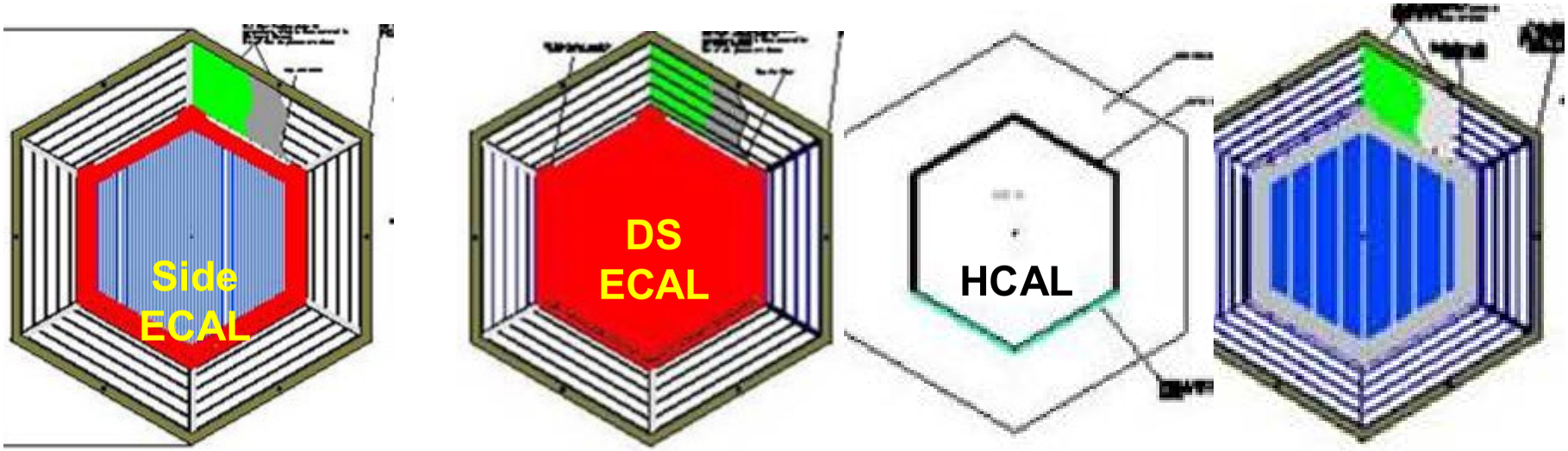




- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν – A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**

Calorimeters

- Three types of calorimeters in MINERvA
  - ECAL: between each sampling plane,
    1/16” Pb laminated with 10mil stainless ($X_0/3$)
  - HCAL: between each sampling plane, 1” steel ($\lambda_0/6$)
  - OD: 4” and 2” steel between radial sampling layers
- ECAL and HCAL absorbers are plates, rings



Latest Result - NuTeV

- for x>0.4 NuTeV result is increasingly higher than CCFR
  - x=0.45 - 5%
  - x=0.55 - 10%
  - x=0.65 - 20%