DIS with Neutrinos: Now and When

DIS12 Workshop
University of Bonn
March, 2012

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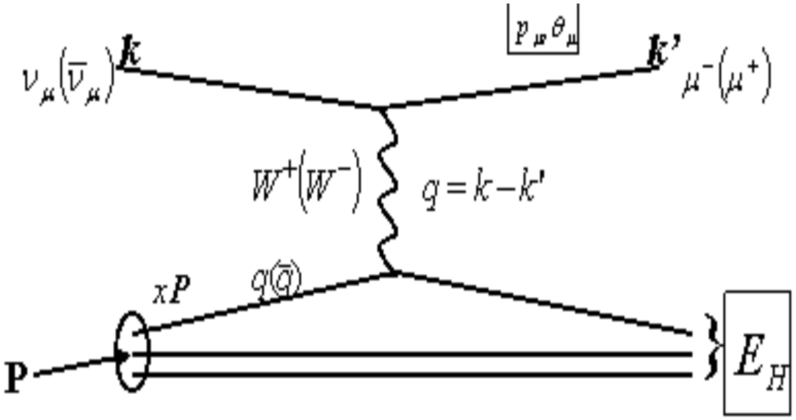
With thanks for the contributions of Trung Li (Rutgers), Rosen Matev(Sofia) and Martin Tzanov (LSU)

Studying Deep-Inelastic Scattering with $\nu/\bar{\nu}$

- Interacting with the weak current means a **much smaller interaction rate** than e/μ scattering
  - Need huge, higher-A detectors and/or intense neutrino beams to get reasonable statistics
- The incoming neutrino energy is not a priori known and even the neutrino energy dependent flux is difficult to predict – solution wait until end of talk!
- However **can select which set of quarks involved in the interaction via ν or $\bar{\nu}$**
- While F_2 is measured precisely by the charge lepton scattering, **xF_3 is accessible by neutrino DIS** and yields increased sensitivity to the **valence quark distributions.**
- Measuring charm production with **ν and $\bar{\nu}$** also gives us insight into the **s and $\bar{s}$ quark distributions** **within a nucleon in a nucleus.**
- **Measuring the difference between $xF_3(\nu)$ and $xF_3(\nu)$ ($\Delta xF_3 = s - c$) gives information on heavy quarks**

- Being forced to use heavy nuclear targets presents some challenges in disentangling nuclear effects from the study of nucleON PDFs. **Need to study nuclear effects with neutrinos (as compared to charged lepton scattering) or use lighter targets, like H_2/D_2, …. or do both!**

The Parameters of ν DIS



$Q^2 = 4E_\nu E_\mu \sin^2\frac{\theta}{2},$ Squared 4-momentum transferred to hadronic system

$x = \frac{Q^2}{2ME_{HAD}},$ Fraction of momentum carried by the struck quark

$y = \frac{\nu}{E_\nu} = \frac{E_{HAD}}{E_\nu},$ Inelasticity

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu}\frac{d^2\sigma^{\nu(\bar\nu)}}{dxdy} = \frac{G_F^2 M}{\pi\left(1+Q^2/M_W^2\right)^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}\right)F_2^{\nu(\bar\nu)} \pm \left(y-\frac{y^2}{2}\right)xF_3^{\nu(\bar\nu)}\right]$$

Structure Functions in terms of parton distributions (for ν-scattering)

$$F_2^{\nu(\bar\nu)N} = \sum\left[xq^{\nu(\bar\nu)N}(x)+x\bar q^{\nu(\bar\nu)N}(x)+2xk^{\nu(\bar\nu)N}(x)\right],$$

$$xF_3^{\nu(\bar\nu)N} = \sum\left[xq^{\nu(\bar\nu)N}(x)-x\bar q^{\nu(\bar\nu)N}(x)\right] = x\left(d_V(x)+u_V(x)\right) \pm 2x\left(s(x)-c(x)\right),$$

$$R = \frac{\sigma_L}{\sigma_T}$$

Parton Distribution Functions:

What Can We Learn With All Six ν and ν̄ Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: ν interacts with d, s, ū, and c̄ while ν̄ interacts with u, c, d̄ and s̄.

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

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

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

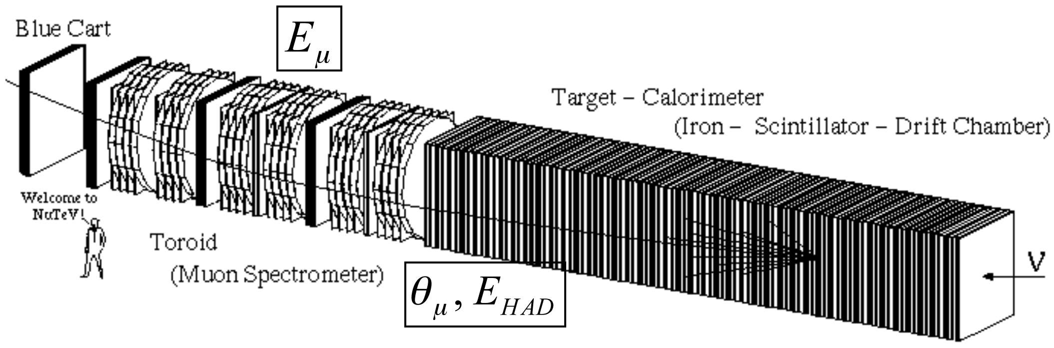
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[\left(s + \bar{s}\right) - \left(\bar{c} + c\right)\right]$$

Most “Recent” ν DIS Experiments

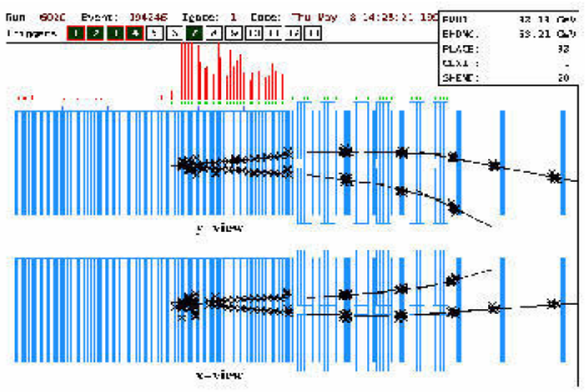
	E_ν range (< E_ν>) (GeV)	Run	Target A	E_μ scale	E_{HAD} scale	Detector
NuTeV (CCFR)	30-360(120)	96-97	Fe	0.7%	0.43%	Coarse
NOMAD	10-200(27)	95-98	Various (mainly C)	--	---	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINOS	3-15	05-10	Fe	2.5%	5.6%	Coarse

Old Style: The NuTeV Experiment: 800 GeV Protons

> 3 million neutrino/antineutrino events with $20 \le E_\nu \le 400\ GeV$



Refurbished CCFR detector



Target Calorimeter:

- Steel-Scintillator Sandwich (10 cm)

$$\frac{\delta E}{E} \approx \frac{0.86}{\sqrt{E}} \text{ -resolution}$$

- Tracking chambers for muon track and vertex

- Muon Spectrometer:

  Three toroidal iron magnets with
  five sets of drift chambers

$$\langle B_\varphi \rangle \approx 1.7T,\ p_t \approx 2.4GeV/c$$

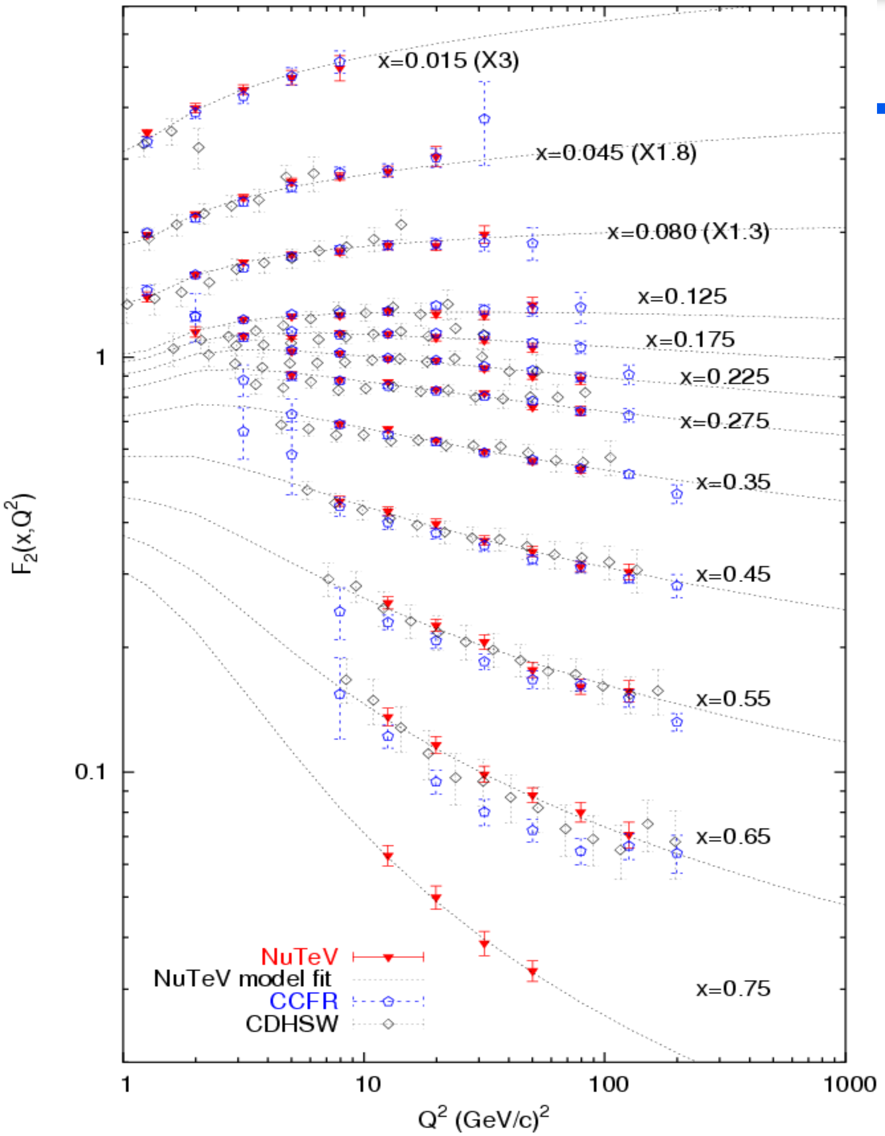
$$\delta(1/p)/(1/p) \sim 11\% \text{ MCS dominated}$$

- Always focusing for leading muon

1170 ν and 966 $\bar{\nu}$ data points with seven correlated systematic errors.

To confront leading systematic errors, there was a continuous calibration beam

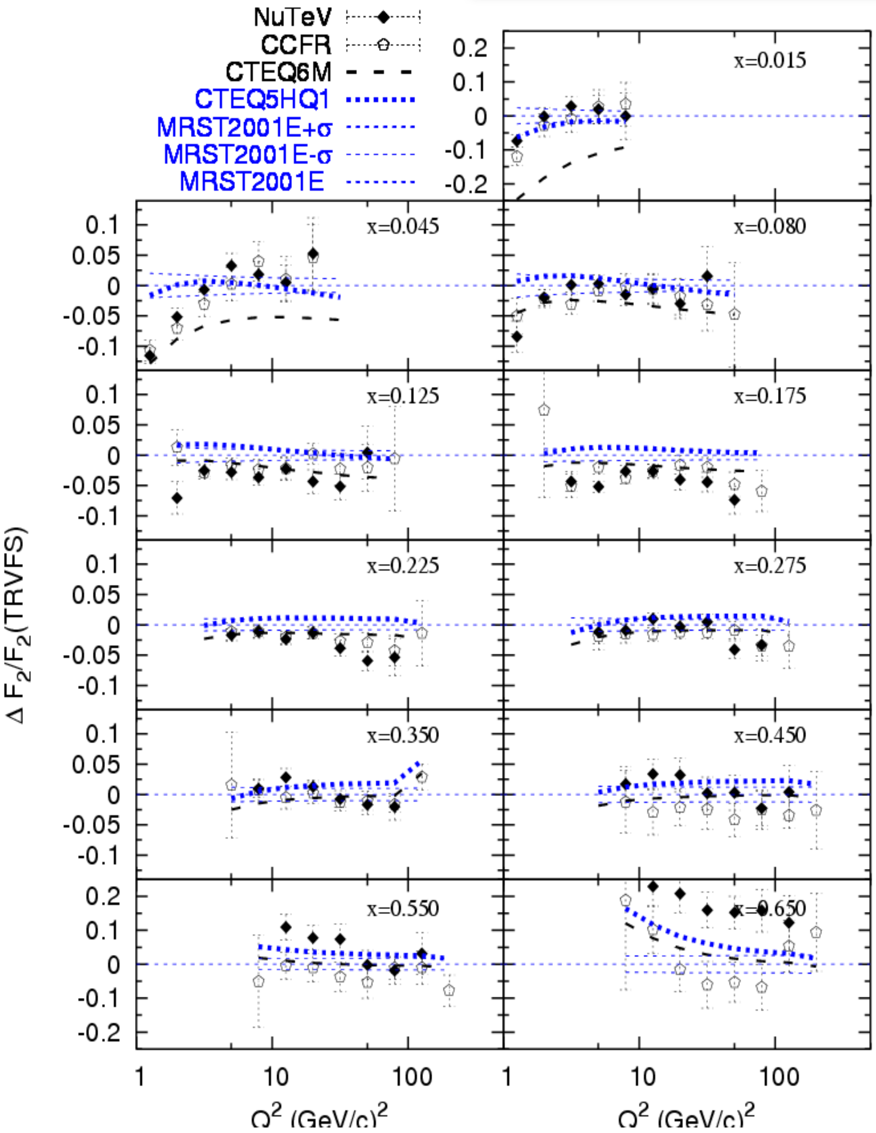
Average F_2 Measurement



Notice the Q^2 range!

- Isoscalar ν-Fe F_2
- NuTeV F_2 compared with CCFR and CDHSW results
- All systematic uncertainties are included
- All data sets agree for $x<0.4$.
- At $x>0.4$ NuTeV agrees with CDHSW.
- At $x>0.4$ NuTeV is systematically above CCFR.

Comparison with Global Fits for F_2



- Baseline is TRVFS(MRST2001E)

- NuTeV and CCFR F_2 are compared to TRVFS(MRST2001E)

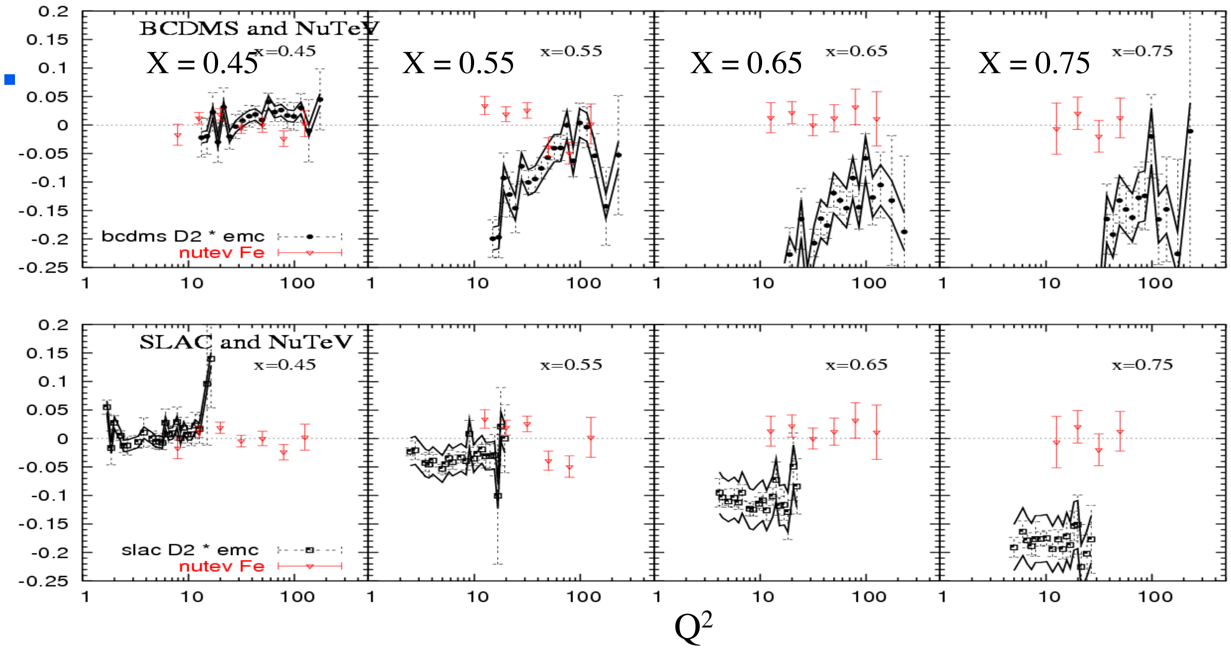
$$\frac{F_2^{NuTeV} - F_2^{TRVFS}}{F_2^{TRVFS}}$$

- Theoretical models shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)

- Theory curves are corrected for:
  - target mass *(H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829)*
  - nuclear effects – **parameterization from charge lepton data, assumed to be the same for neutrino scattering** (no Q^2 dependence added) nuclear effects parameterization is dominated by SLAC (lower Q^2 in this region) data at high-x

- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

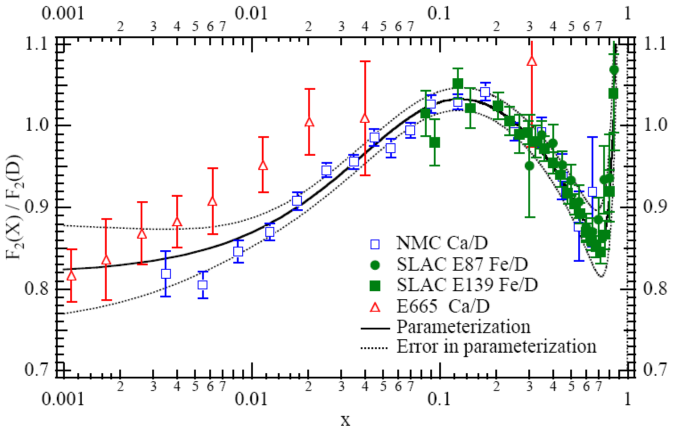
Comparison with Charge Lepton Data for *x>0.4*



- Baseline is NuTeV model fit
- data points are $\dfrac{F_2^{DATA} - F_2^{BG}}{F_2^{BG}}$

•charge lepton data is corrected for:

- $\dfrac{F_2^{\nu}}{F_2^{l}}$ using CTEQ4D
- heavy target $\dfrac{F_2^{N}}{F_2^{D}}$



• NuTeV agrees with charge lepton data for x=0.45.

•NuTeV is higher than BCDMS(D_2), different Q^2 dependence

- *7%* at *x=0.55*, *12%* at *x=0.65*, and *15%* at *x=0.75*

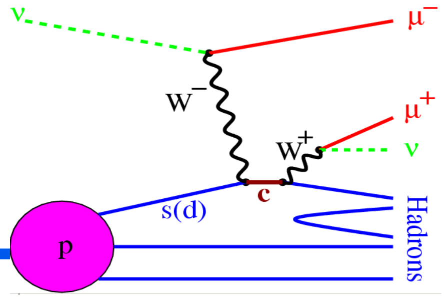
• NuTeV is higher than SLAC(D_2) (bottom 4 plots)

- *4%* at *x=0.55*, *10%* at *x=0.65*, and *17%* at *x=0.75*

the nuclear correction is dominated by SLAC data, which is at lower Q^2 than NuTeV in this region

> **"Perhaps the nuclear correction is smaller for neutrino scattering at high x."**
>
> Martin Tzanov

Charm Production by Neutrinos
a direct look at strange sea.



- Charm quark is produced from CC neutrino interaction with s(d) quark in the nucleon. d-quark interaction is CKM suppressed
- Detect charm via the semi-leptonic decay which yields a very clear signature – two opposite sign muons
- It is sensitive to m_c through E_ν dependence.
- With high-purity ν and $\bar{\nu}$ beams, NuTeV made high statistics separate s and $\bar{s}$ measurements: 5163 ν and 1380 $\bar{\nu}$
- Could then make a measurement of $s - \bar{s}$.

This is an analysis of strange quarks in an Fe nucleus!

Summary ν Scattering Results – NuTeV

NuTeV accumulated over 3 million neutrino / antineutrino events with $20 \leq E_\nu \leq 400$ GeV. Most accurate results available until NOMAD.

NuTeV considered multiple correlated systematic uncertainties.

NuTeV agrees with other ν experiments and theory for medium x.

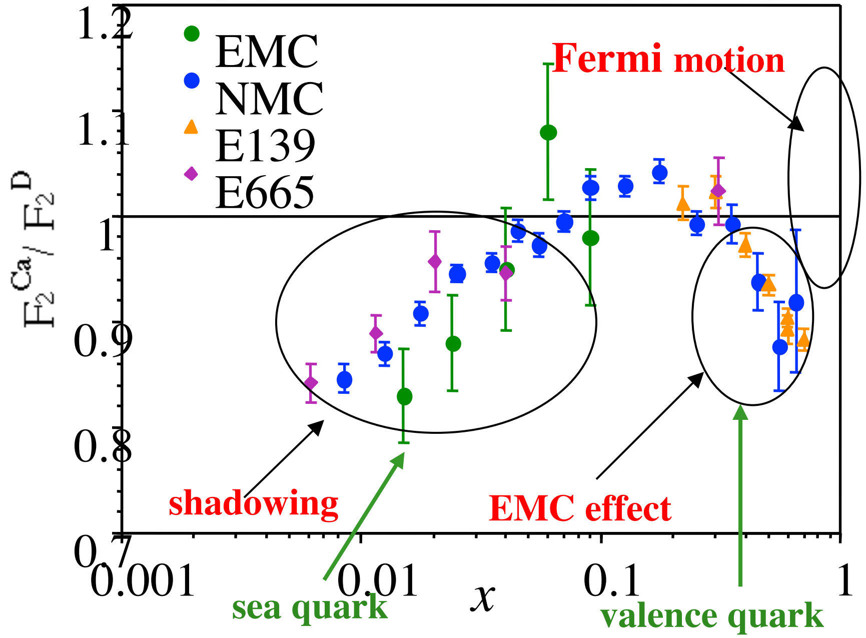
NuTeV has a different Q^2 dependence at low x .

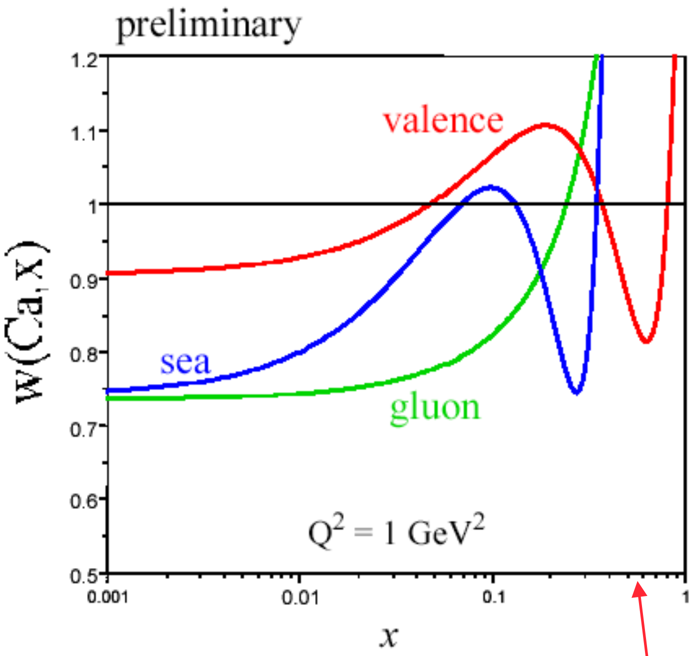
NuTeV **is systematically higher at high x ($x > 0.6$).**

How do we now incorporate these NuTeV results in the analysis of nucleon structure?

We need to understand neutrino nuclear correction factors (NCF) to bring $\nu / \overline{\nu}$ – Fe to $\nu / \overline{\nu}$ – N!

Knowledge of Nuclear Effects with Neutrinos: Very sparse





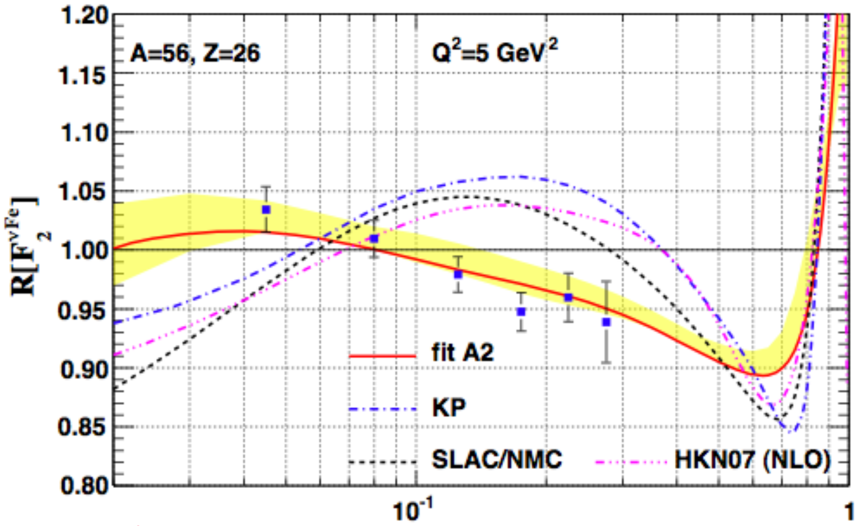
- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear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

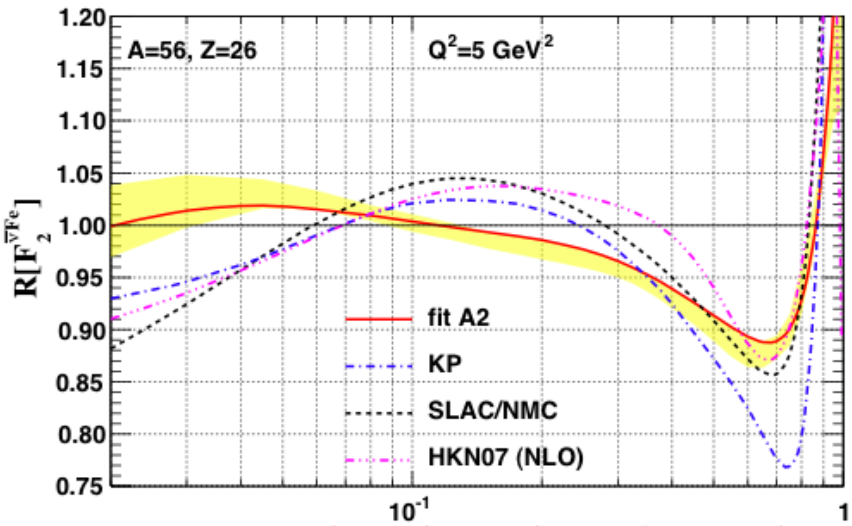
Nuclear PDFs from neutrino deep inelastic scattering

Karol Kovarik Presentation – this afternoon in SF session

I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Owens (Florida State U)

F_2 Structure Function Ratios: ν-Iron and ν-Iron





This would suggest that the nuclear parton distribution function for ν are different than those found by ℓ

Where are we now: Conclusions

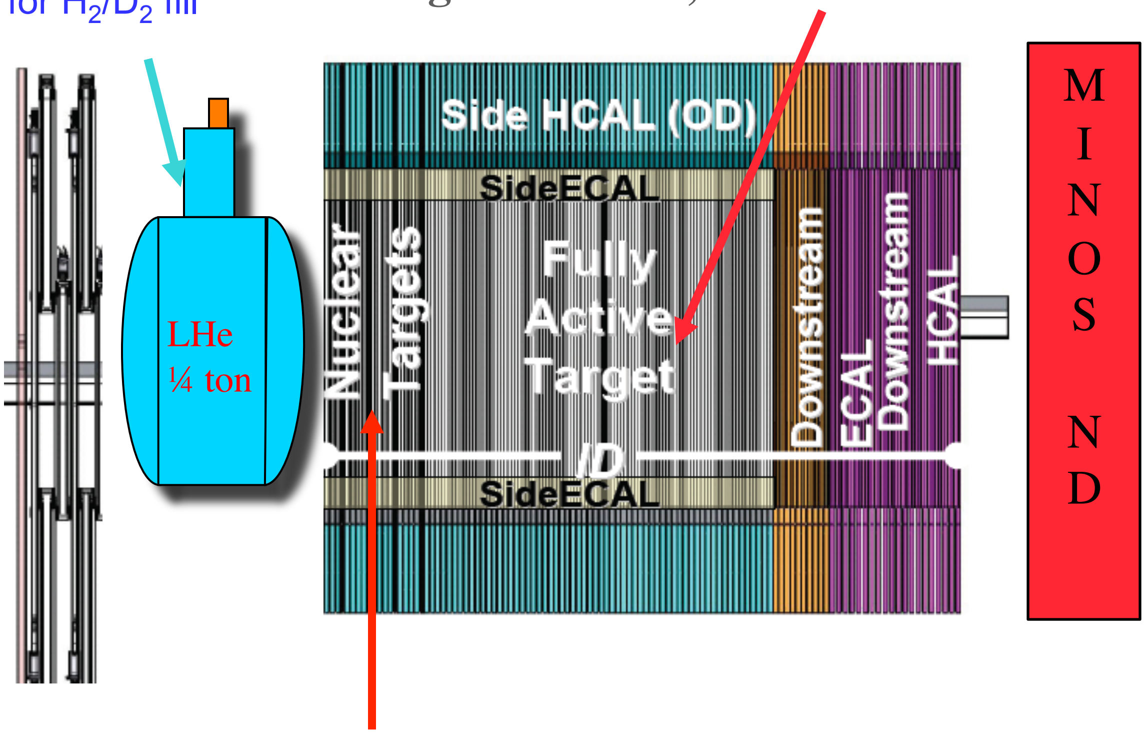
- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in fits with nucleon data.
- Nuclear correction factors (R) seems to be different for **ν**-Fe scattering compared to $\ell^{\pm}$-Fe.
  - **Results from one experiment on one nuclear target… careful.**
- We need **ν−**experiments to measure these nuclear correction factors!
  - For the cleanest study of nucleon structure, $\nu/\bar{\nu}$ - H_2/D_2 experiment would be excellent!
- **Aside from the question of nuclear correction factors, there are differences between the highly accurate NuTeV results and results from other neutrino experiments and theory we need to understand.**
- **How do we answer these questions?**

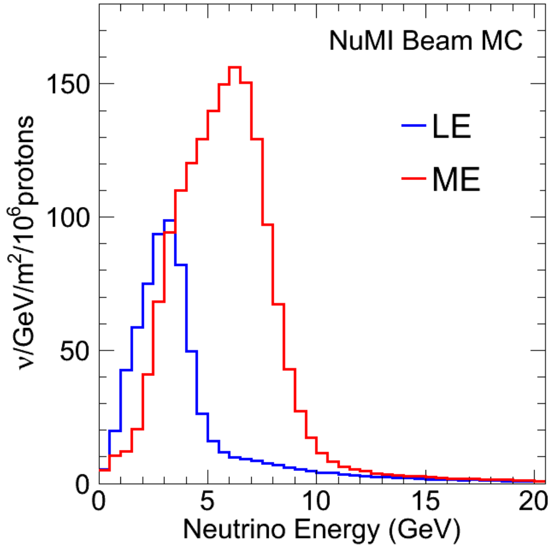
The MINERνA Experiment – First of the New Style High-Statistics Neutrino Detectors

Joel Mousseau (Univ. Florida) - just described this

Cryotarget: ready for H_2/D_2 fill

Fully Active Fine Segmented Scintillator Target: 8.3 tons, 3 - 5 tons fiducial





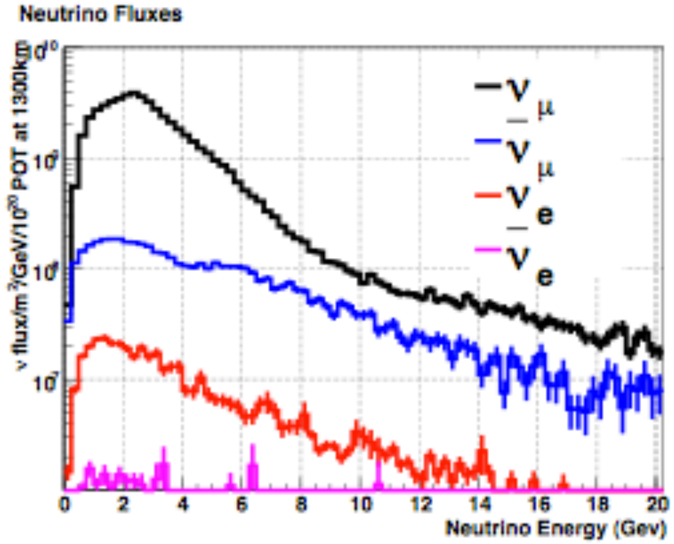
Nuclear Targets with Pb, Fe, C, H_2O,CH
Simultaneous in the same neutrino beam reduces systematic errors between nuclei

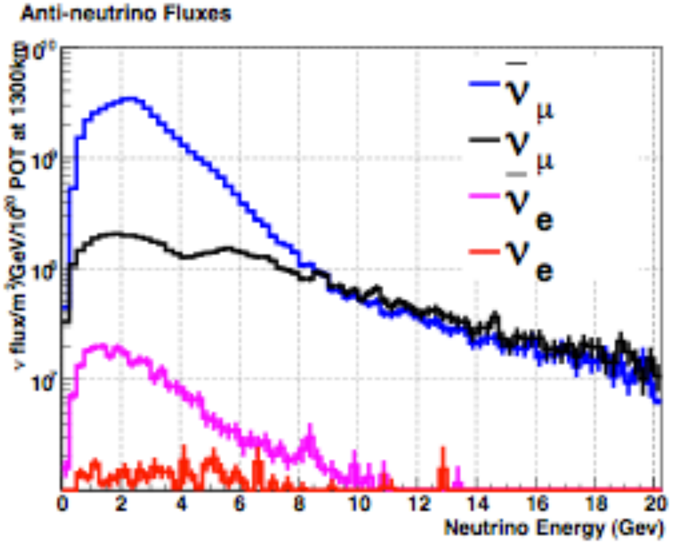
The ME beam peaks at 7 GeV rather than the LE beam peak of 3.5 GeV. Not exactly designed for DIS

Where do we go after MINERνA?

- With MINERνA and the ME exposure, we will begin to resolve the question of neutrino nuclear correction factors… however:
  - Will know the neutrino flux to within (5 – 10)%
  - Was designed to understand the low-E_ν, low multiplicity QE → transition resonance region.
  - Even with the ME beam cannot investigate the full x range at high-Q^2
- To make significant advances in DIS studies with neutrinos we have to work on lowering the **systematics** (there's that word again!)
  - Beam: Need a higher energy beam and to understand the neutrino flux to within 1% or so.
  - Detector: Need a detector with excellent acceptance over full Q^2 range.
  - Detector: Need a detector with improved measurement accuracy of E_μ and θ_μ.
  - Detector: Need to reduce the error on the E_{hadron} shower measurement.

What’s Next…. LBNE (but we have to wait awhile!)





- Beam energy lower than ME!
- Uses same double-horn, pion-decay source neutrino beam – not much help there same flux errors!
- However has the beam power (0.7 MW) and the time is right to employ a new type of neutrino detector to reduce systematics.
  - 7 ton interaction volume
- DIS event rates: 5 year $\boldsymbol{\nu}$ and 5 year $\bar{\boldsymbol{\nu}}$ yields 20 M $\boldsymbol{\nu}$ and 4 M $\bar{\boldsymbol{\nu}}$.
  - **Statistics fine – systematics!**

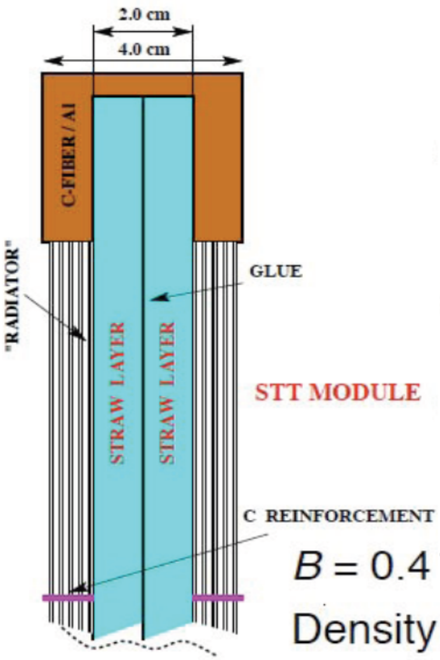
Straw-tube Tracker Design

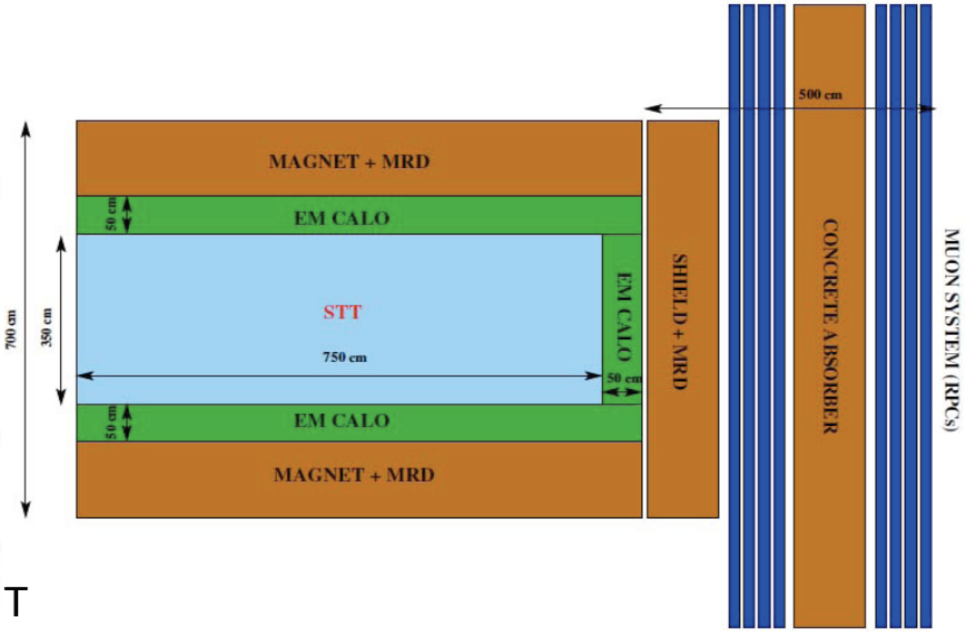
S. Mishra – Univ. S. Carolina

Electronic Bubble Chamber with 10^9 events

High resolution magnetised detector (*HiResMν*) – LBNE Standard Near detector

Builds on NOMAD experience, ATLAS TRT and COMPASS detector designs





$B = 0.4$ T

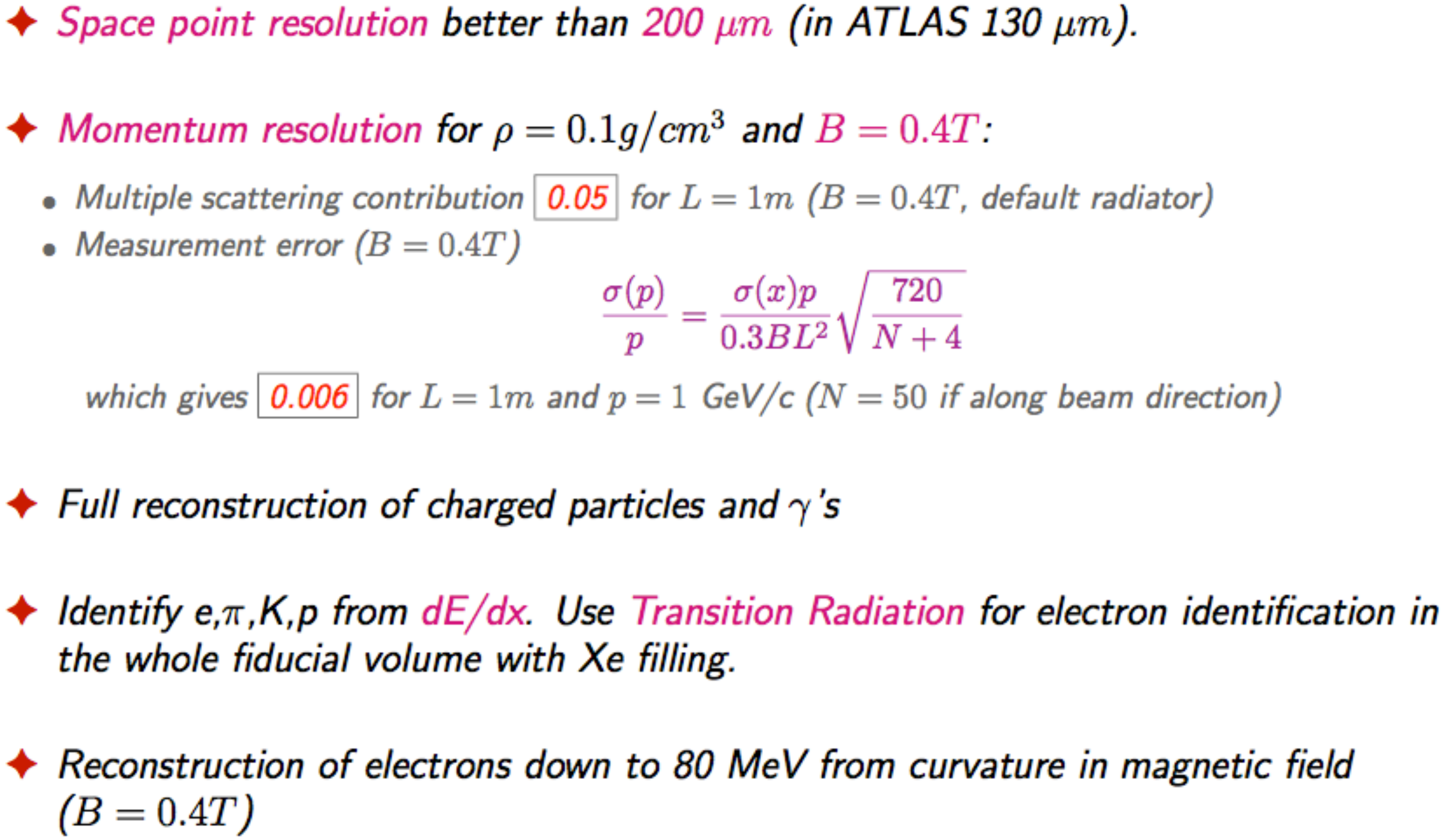
Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ↠ e-/e+ ID ⇒ γ (w. Kinematics)

dE/dx ↠ Proton, π+/-, K+/- ID

Magnet/Muon Detector ↠ μ+/-

HiResMν design parameters



- *Space point resolution* better than *200 μm* (in ATLAS 130 μm).
- *Momentum resolution* for $\rho = 0.1 g/cm^3$ and $B = 0.4T$:
  - Multiple scattering contribution $\boxed{0.05}$ for $L = 1m$ ($B = 0.4T$, default radiator)
  - Measurement error ($B = 0.4T$)

$$\frac{\sigma(p)}{p} = \frac{\sigma(x)p}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

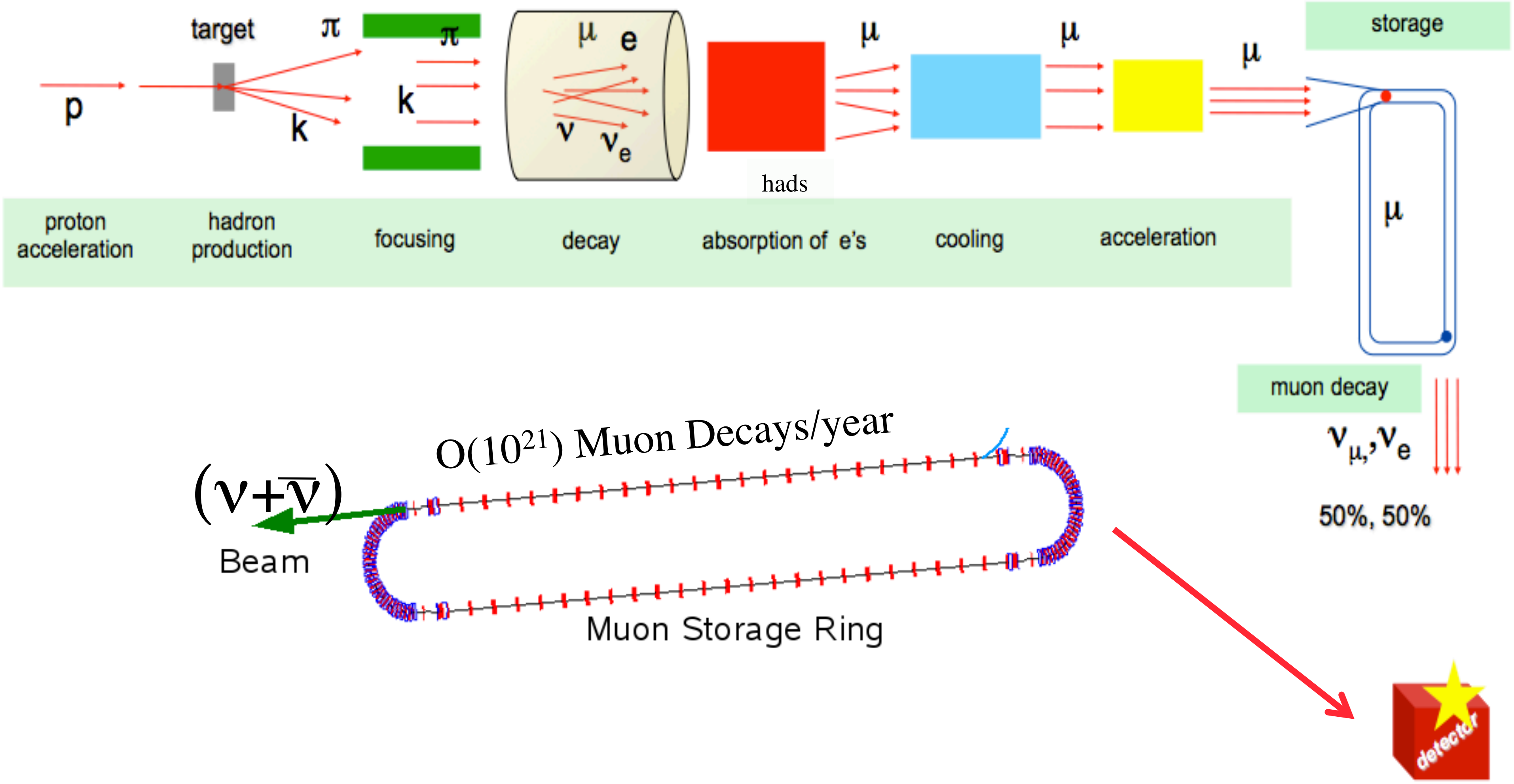
which gives $\boxed{0.006}$ for $L = 1m$ and $p = 1$ GeV/c ($N = 50$ if along beam direction)

- Full reconstruction of charged particles and γ's
- Identify e,π,K,p from *dE/dx*. Use *Transition Radiation* for electron identification in the whole fiducial volume with Xe filling.
- Reconstruction of electrons down to 80 MeV from curvature in magnetic field ($B = 0.4T$)

Now - How do we improve the BEAM?

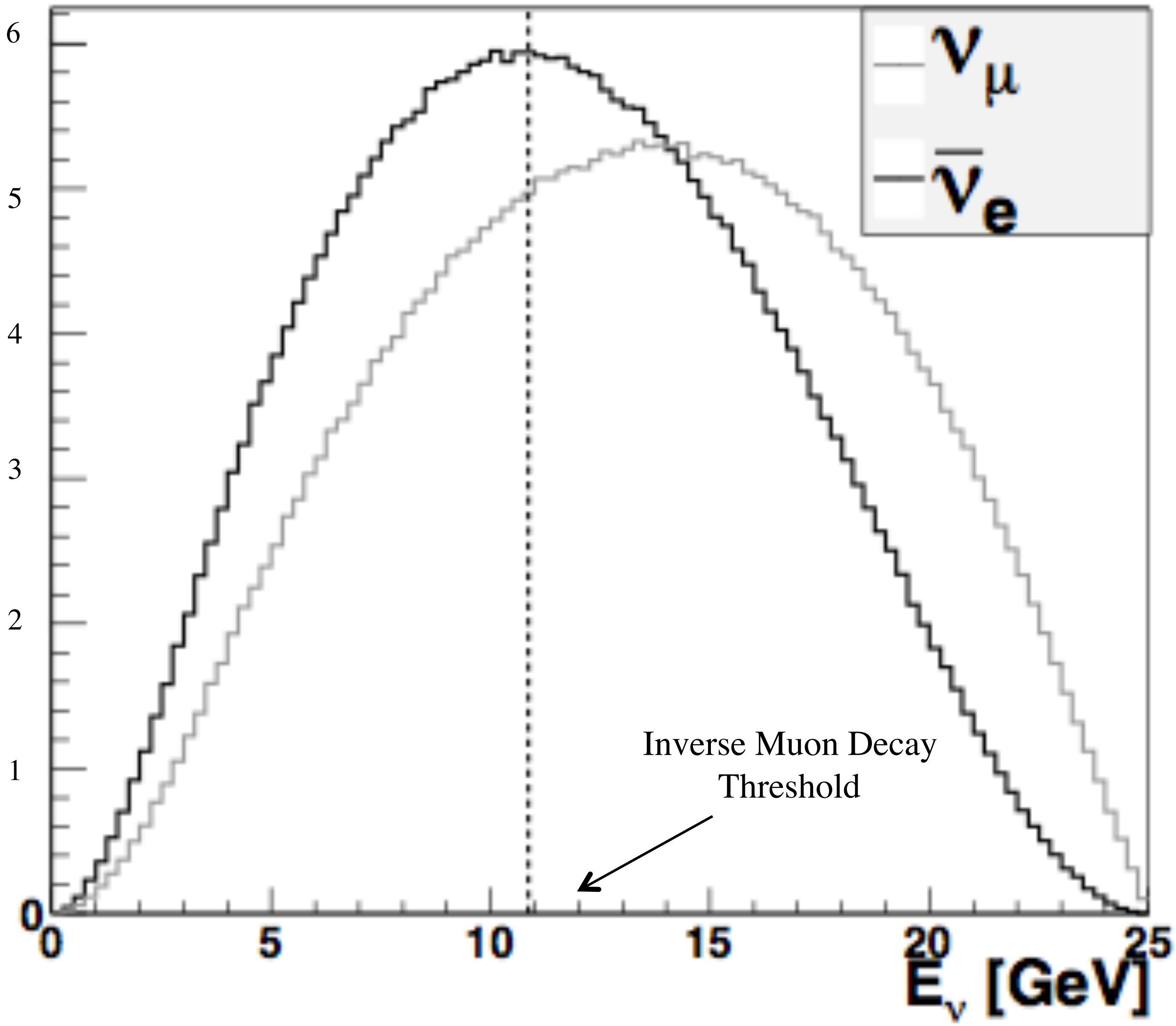
Ultimate ν – DIS Experiment: Neutrino Factory

$\mu^+ \rightarrow \overline{\nu}_\mu + \nu_e + e^+$ $\mu^- \rightarrow \nu_\mu + \overline{\nu}_e + e^-$



Example Event Energy Distribution

25 GeV μ^-



Inverse Muon Decay Threshold

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Near Detector Design Requirements

- **Determination of the neutrino flux (through the measurement of neutrino-electron scattering) to < 1%!**

- Magnetic field for muon momentum (δp/p~1%)

- Muon catcher and capability for and e^+/e^- identification

- **Good resolution on neutrino energy – goal δE/E~1%**

Neutrino Factory Near Detector(s)

E_μ = 25 GeV ±80 MeV

Straight section length = 600 m

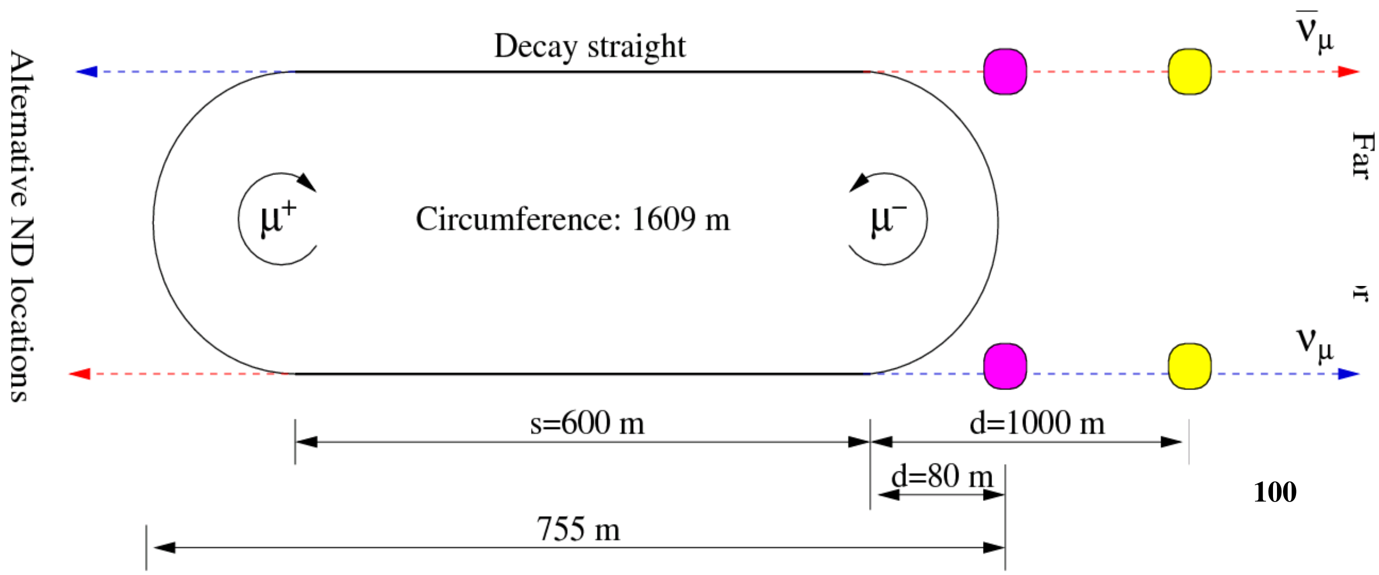
Muon angular spread 0.5 mrad

Event Rates

$2.5\text{x}10^{20}$ μ-decays/year
3 Years of μ^+ and μ^-
Fid.Mass 3.5 Tons

μ^+:
ν_u-CC: $1.8\text{x}10^9$ Events
IMD: $1.3\text{x}10^6$ Events
ν_ue QE: $1.1\text{x}10^6$ Events

μ^-:
$\bar{\nu}_u$-CC: $0.9\text{x}10^9$ Event
ν_ue QE: $1.3\text{x}10^6$ Event



Summary: Neutrino DIS Now and Soon

- Currently the most accurate measurement of neutrino DIS scattering is the NuTeV ν/ν̄ – Fe results.
- There are inconsistencies between NuTeV and other ν/ν̄ – Fe results.
- Absolute rates limited by neutrino flux determinations.
- Attempts to extract neutrino nuclear correction factors yield a different NCF for ν/ν – Fe than for $\ell^{\pm}$ - Fe.
- Current generation experiments (MINERνA) can measure NCF off different A. Pb / C could be a few %
- Next generation detectors can reduce detector systematics to the per cent level.
- Need Neutrino Factory beams to reach < 1% errors on the flux.
- **It could be a bit of a wait for the next great ν DIS experiment.**

Additional Details

Formalism

- PDF Parameterized at Q_0 = 1.3 GeV as

$$xf_i(x,Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

$$f_i^A(x,Q) = \frac{Z}{A}\, f_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, f_i^{n/A}(x,Q)$$

- Resulting in nuclear structure functions:

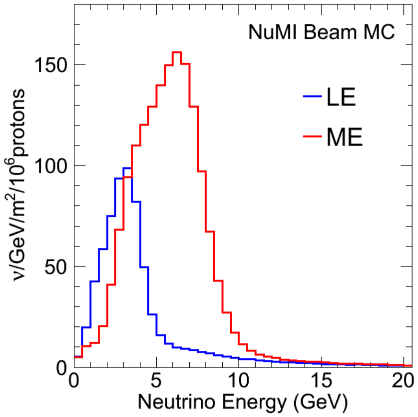
$$F_i^A(x,Q) = \frac{Z}{A}\, F_i^{p/A}(x,Q) + \frac{(A-Z)}{A}\, F_i^{n/A}(x,Q)$$

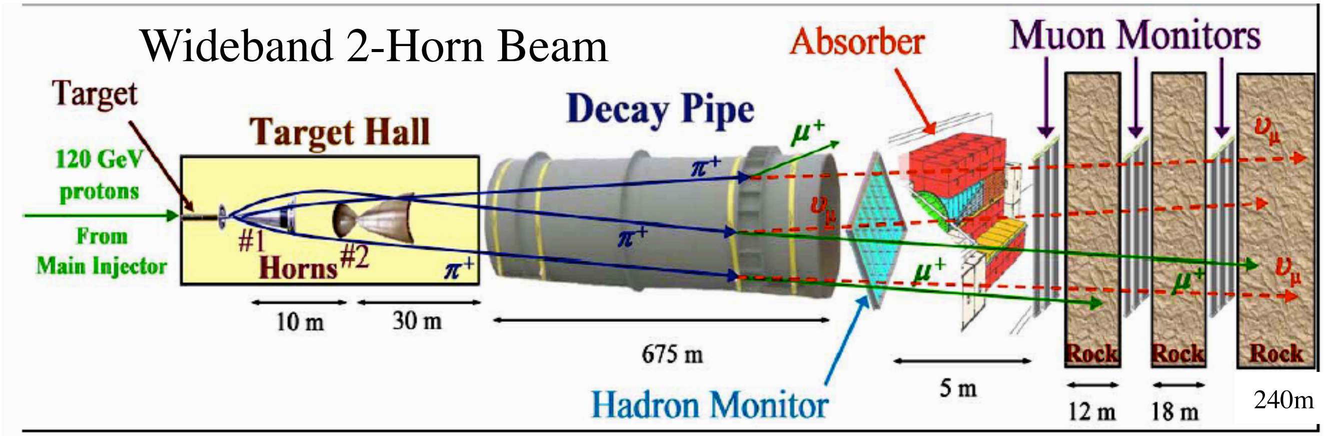
- The differential cross sections for CC scattering off a nucleus::

$$\frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu}A} = \frac{G^2 ME}{\pi}\left[(1-y-\frac{Mxy}{2E})F_2^{\overset{(-)}{\nu}A} + \frac{y^2}{2} 2xF_1^{\overset{(-)}{\nu}A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu}A}\right]$$

Neutrino Beamlines

- Intense proton beam on a target and collect π and K and focus into a decay space.
- Absorb hadrons and muons leaving only neutrinos.
- Do not know individual E_ν a priori and absolute flux known to 5-10%.





F_2 and xF_3 Measurement

F_2

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu}+\frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME}=$$
$$=2\,\overline{F}_2\left(1-y-\frac{Mxy}{2E}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right)+y\left(1-\frac{y}{2}\right)\quad \Delta xF_3$$

- ◆ Perform 1-parameter fit for F_2
- ◆ $\Delta \mathrm{xF}_3$ model
- ◆ R_L model

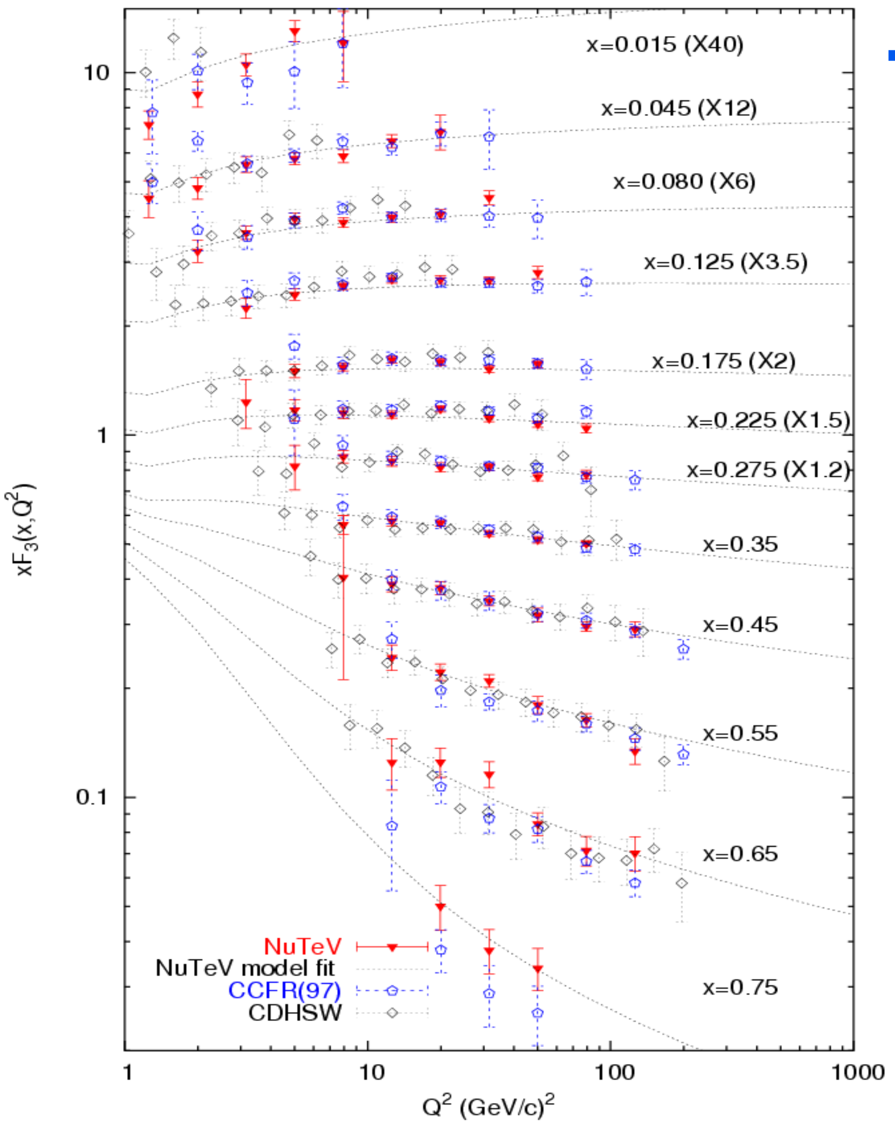
xF_3

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu}-\frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME}=$$
$$=\Delta F_2\left(1-y-\frac{Mxy}{2E}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right)+2\,y\left(1-\frac{y}{2}\right)\quad x\overline{F}_3$$

- ◆ Perform 1-parameter fit for xF_3
- ◆ $\Delta \mathrm{F}_2$ is very small and is neglected

- ◆ Radiative corrections applied
- ◆ Isoscalar correction applied

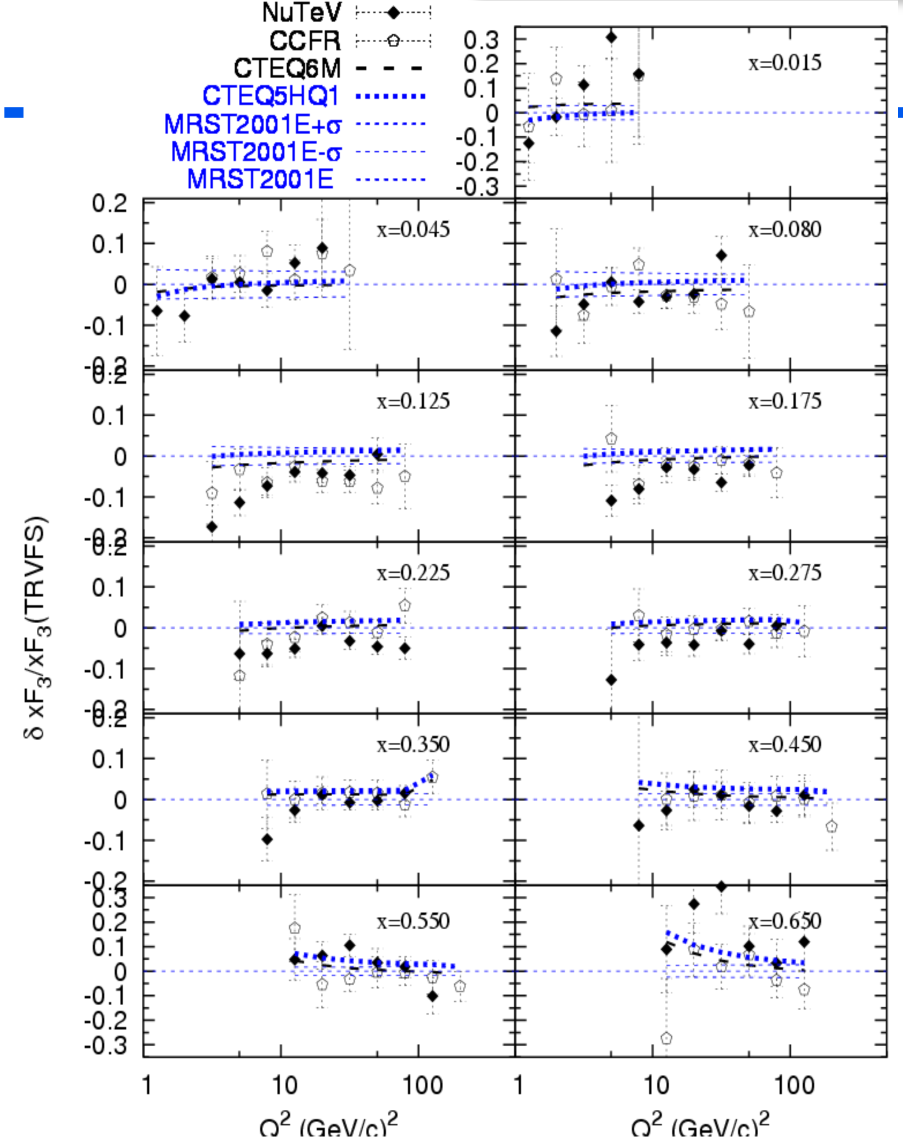
xF_3 Measurement



- NuTeV xF_3 compared to CCFR and CDHSW
- All systematic uncertainties are included
- All data sets agree for $x<0.4$.

- At $x>0.4$ NuTeV agrees with CDHSW
- At $x>0.4$ NuTeV is systematically above CCFR

Comparison with Global Fits for xF_3



- Baseline is TRVFS(MRST2001E).

- NuTeV and CCFR xF_3 are compared to TRVFS(MRST2001E)

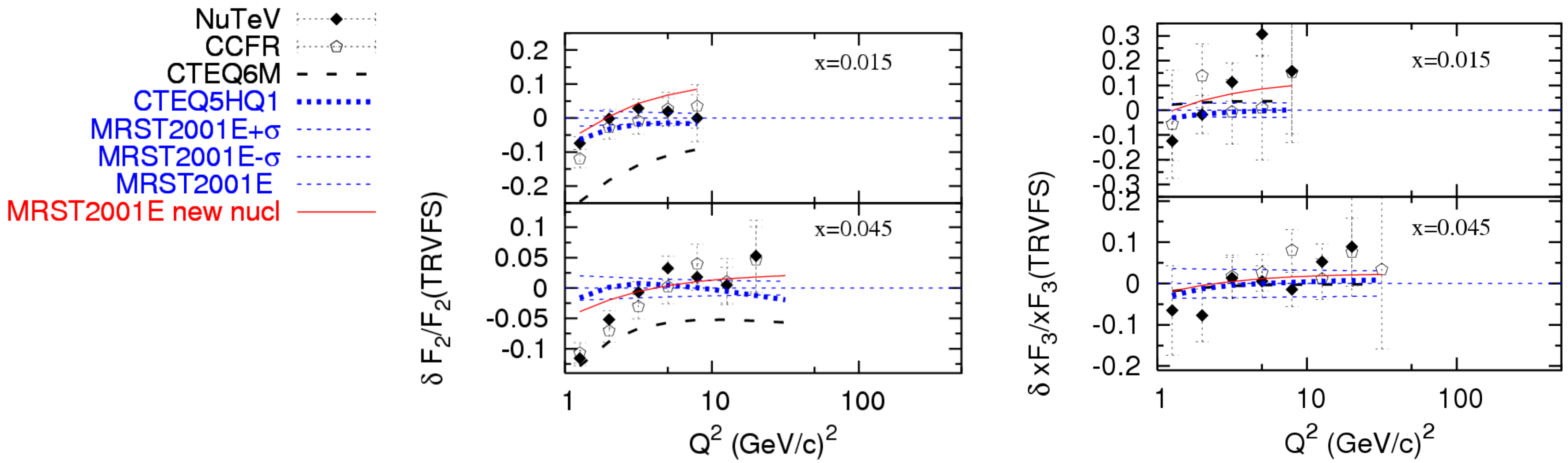
$$\frac{xF_3^{NuTeV} - xF_3^{TRVFS}}{xF_3^{TRVFS}}$$

- Theoretical models shown are:
  - ACOT(CTEQ6M)
  - ACOT(CTEQ5HQ1)
  - TRVFS (MRST2001E)

- theory curves are corrected for:
  - target mass *(H. Georgi and H. D. Politzer, Phys. Rev. D14, 1829)*
  - nuclear effects – **parameterization from charge lepton data, assumed to be the same for neutrino scattering** (no Q^2 dependence added) nuclear effects parameterization is dominated by SLAC (lower Q^2 in this region) data at high-x

- NuTeV 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.

Comparison with Theory at Low x

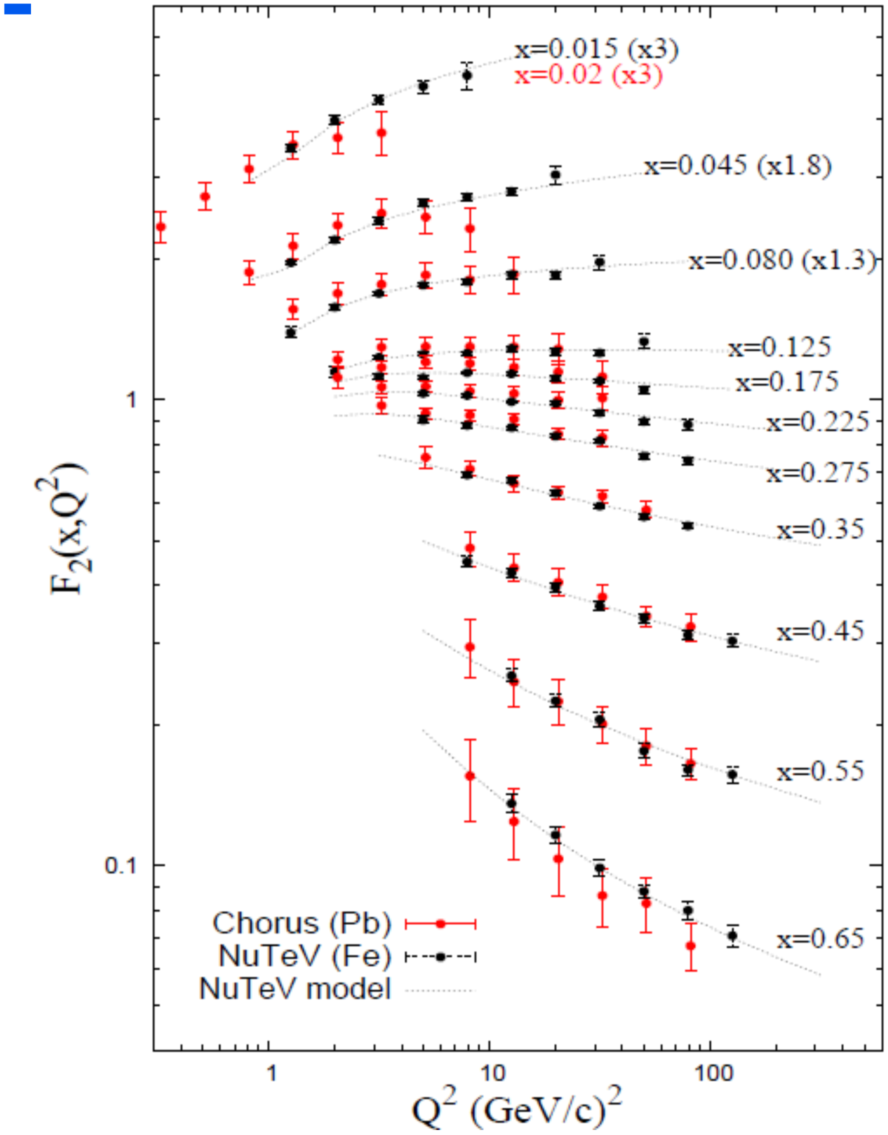


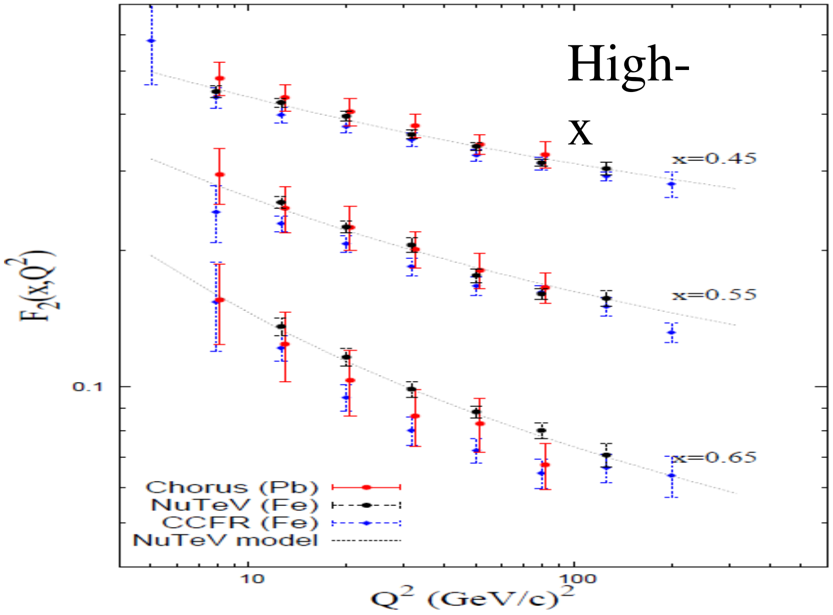
- both NuTeV and CCFR agree in level with theory in the shadowing region (except CTEQ6M)

- the red curve is TRVFS(MRST) using the following model for nuclear correction:

NUCLEAR SHADOWING IN NEUTRINO NUCLEUS DEEPLY INELASTIC SCATTERING.
By Jianwei Qiu, Ivan Vitev (Iowa State U.),. Jan 2004. 7pp.
Published in Phys.Lett.B587:52-61,2004
e-Print Archive: hep-ph/0401062

CHORUS (using Pb targets and nuclear emulsions), NuTeV and CCFR F_2 Comparison

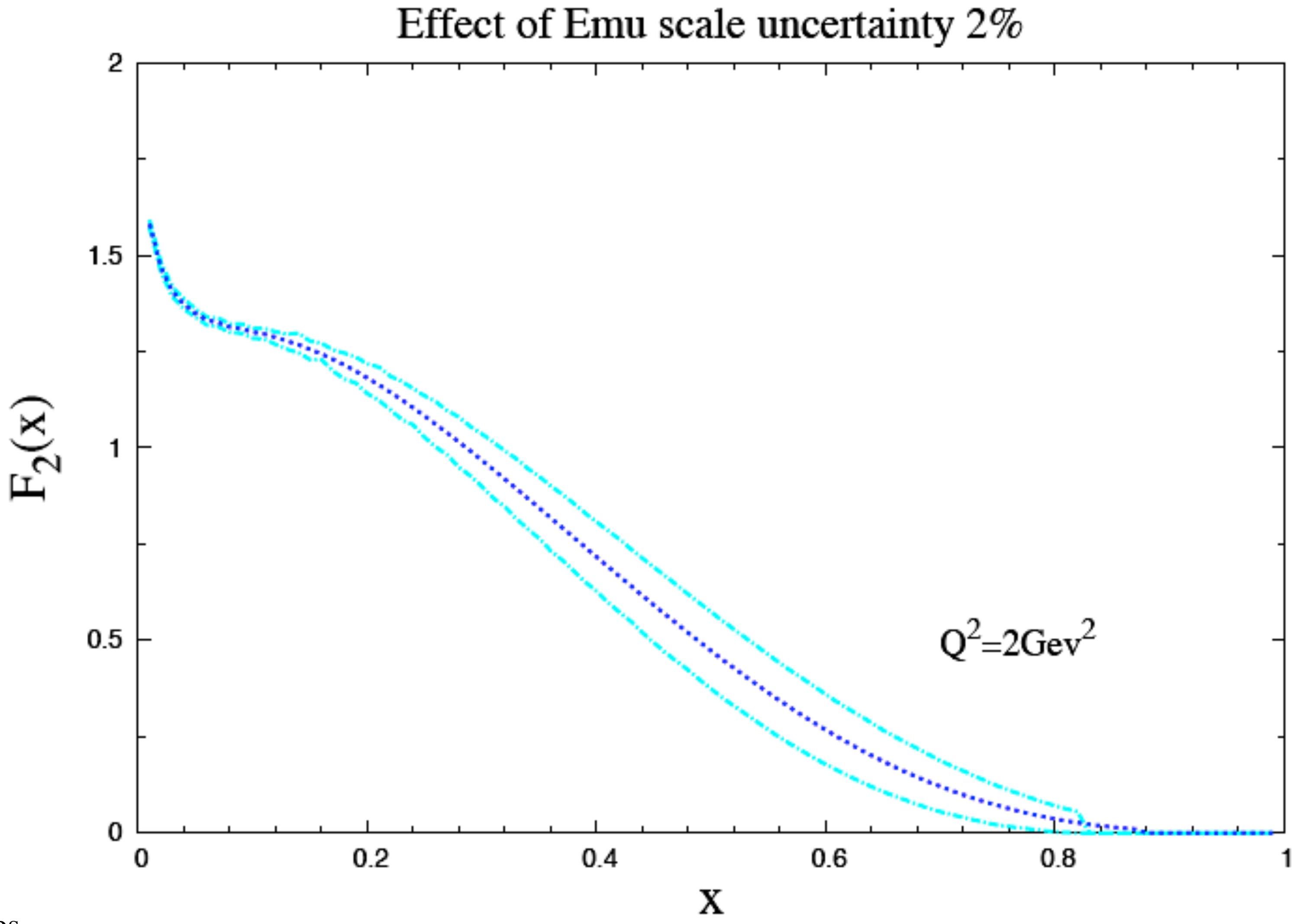



High-x

- CHORUS is not as precise,
- CHORUS agrees well with NuTeV **and** CCFR over the whole range,
- hint of a different Q^2 shape at low-x
- This comparison assumes nuclear corrections similar for Fe and Pb.

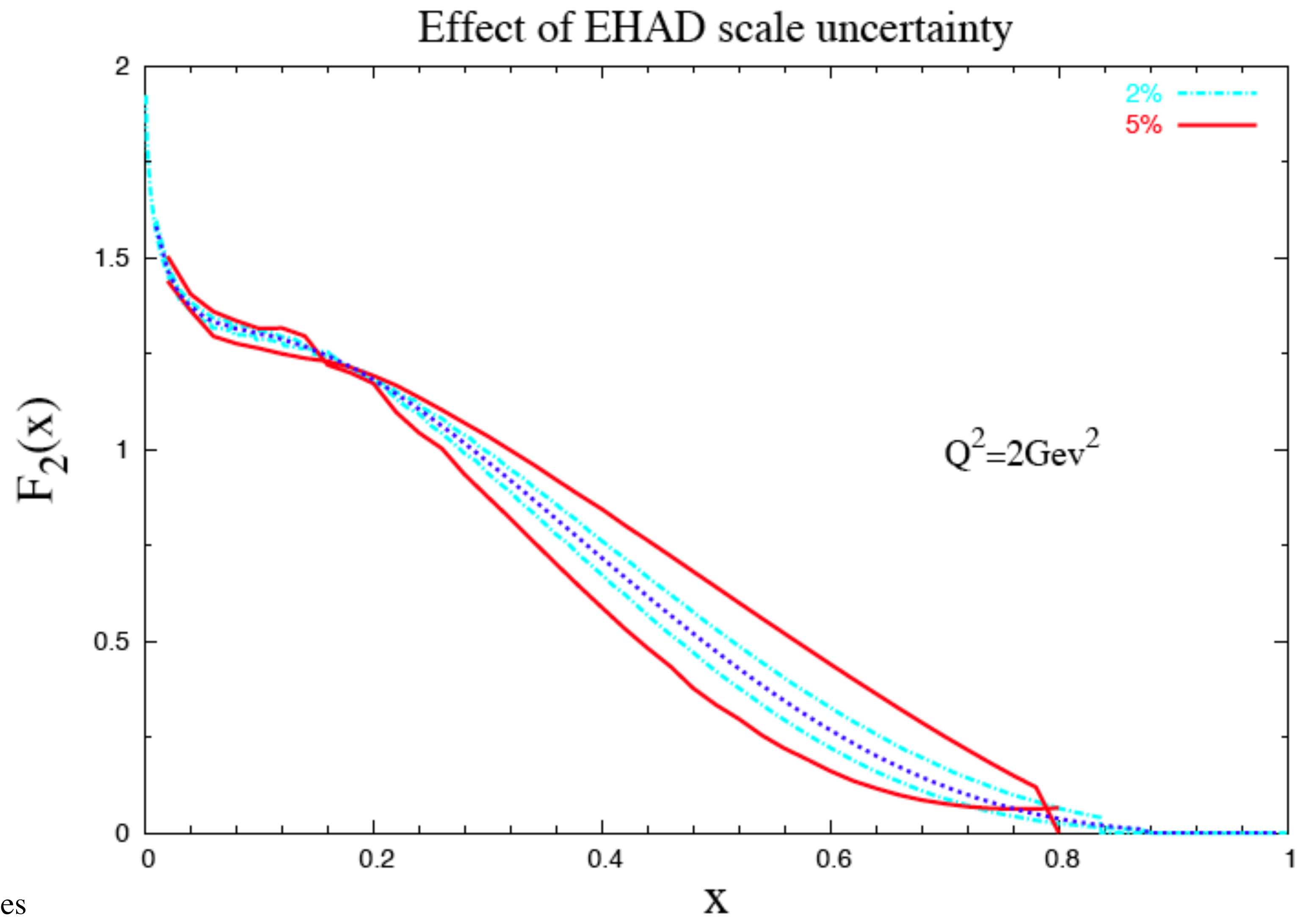
Estimated systematic error: E_μ scale

NuTev achieved 0.7%

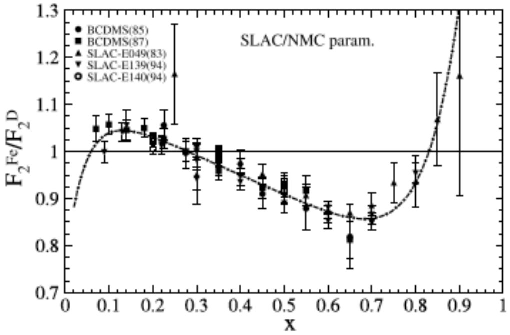


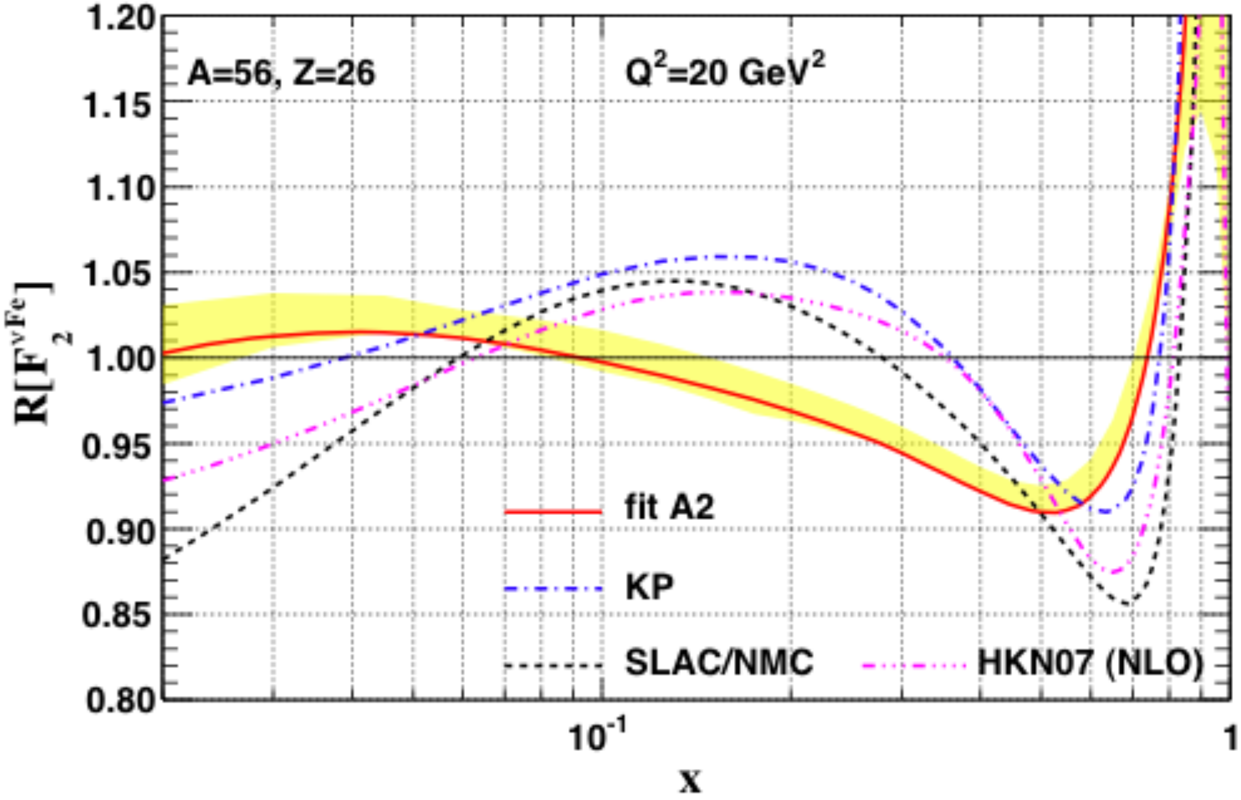
A leading systematic error: E_{had} scale

NuTev achieved 0.43%

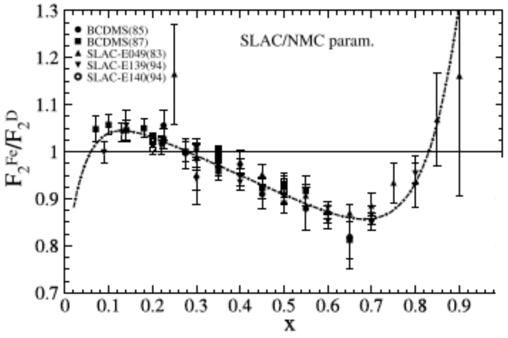


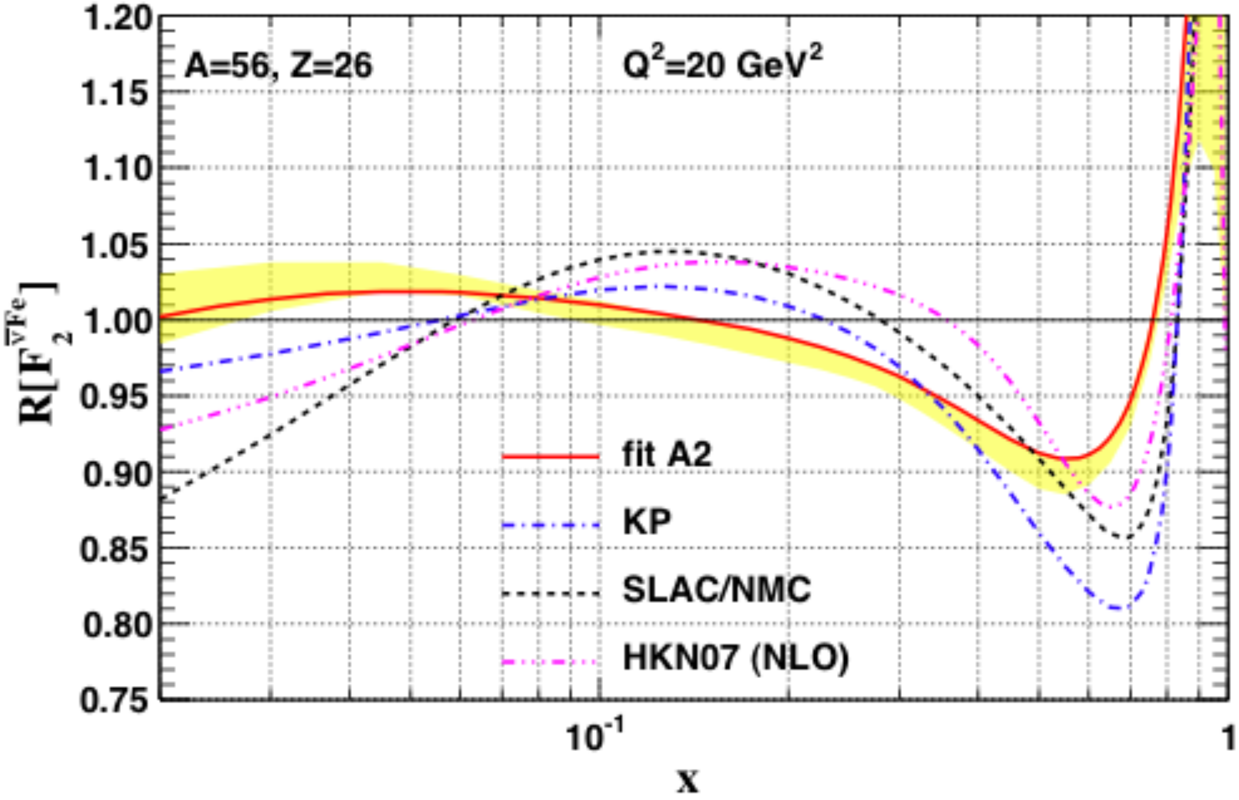
F_2 Structure Function Ratios: ν-Iron





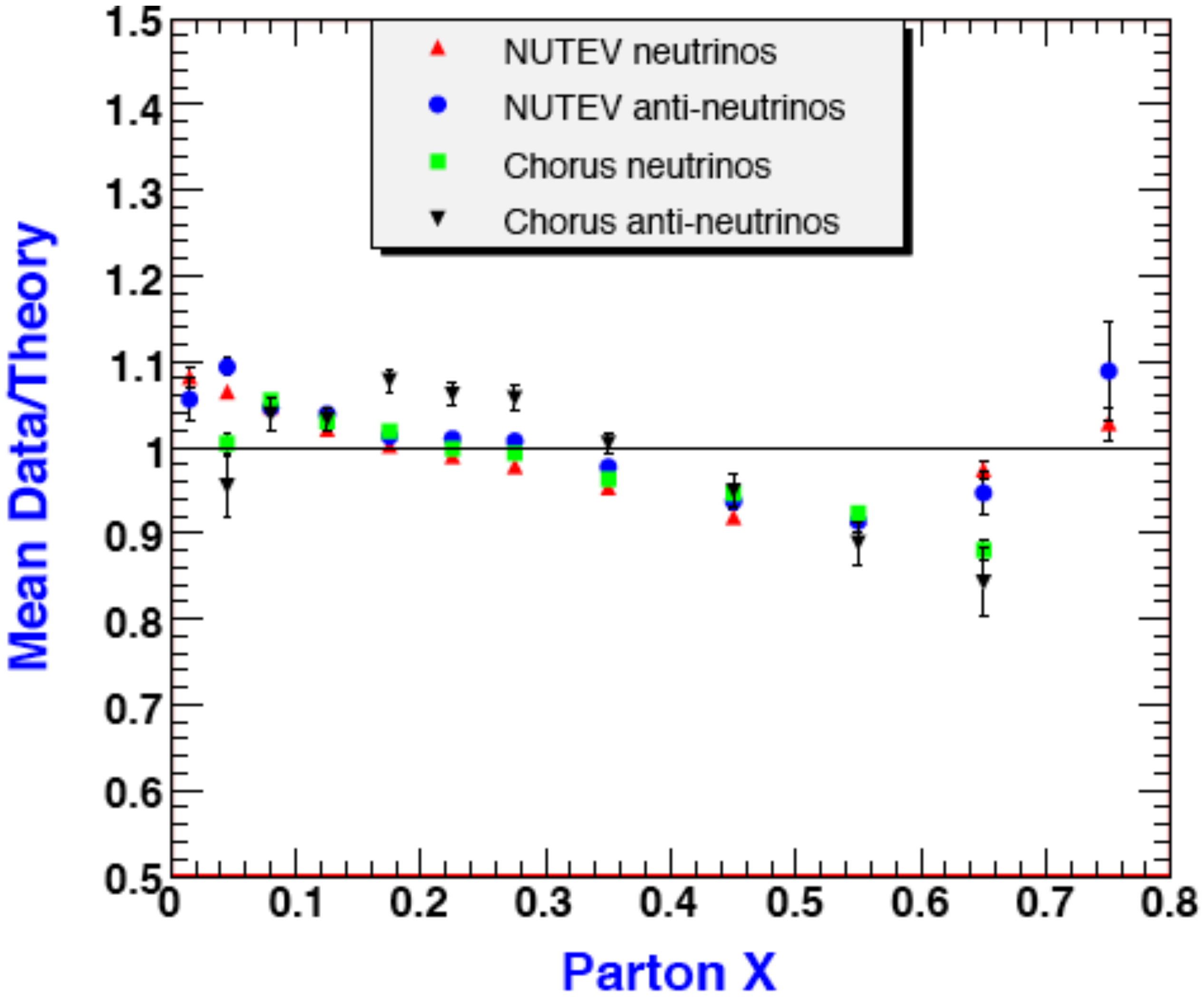
F_2 Structure Function Ratios: $\overline{\nu}$-Iron





NuTeV(Fe) and CHORUS (Pb) ν scattering (unshifted) results compared to reference fit

no nuclear corrections

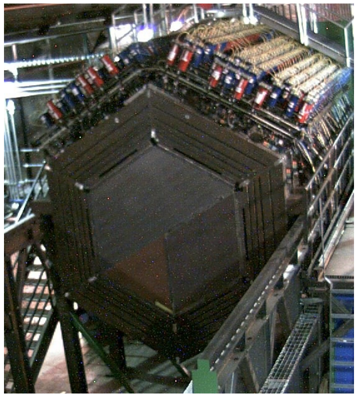


Broad Range of Nuclear Targets

Acceptance for μ’s in MINOS from the nuclear targets…complicated!

- 5 nuclear targets + water target
- He target upstream of detector
- Near million-event samples
  (4×10^{20} POT LE beam + 12×10^{20} POT in ME beam

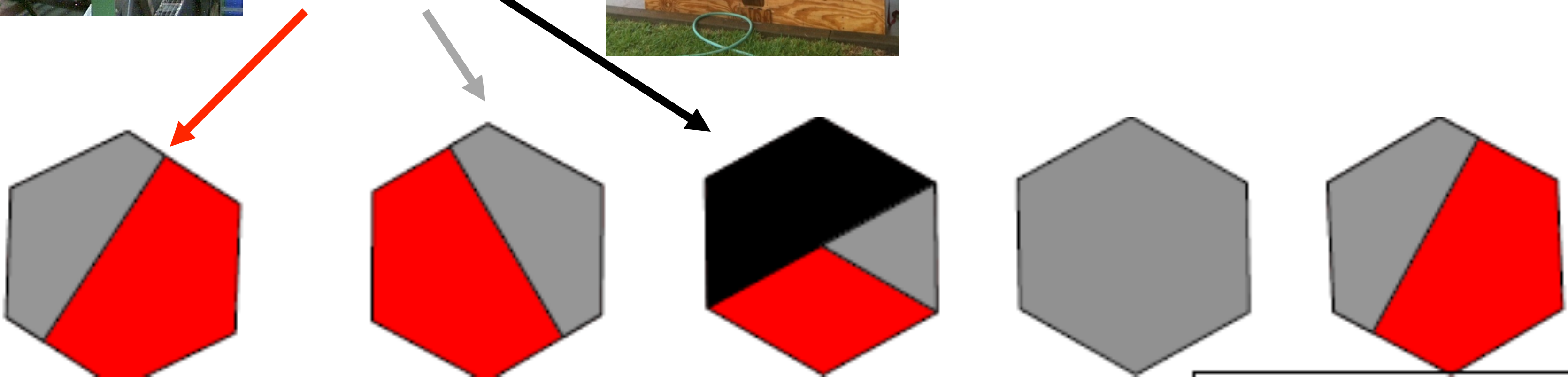
Target	**Mass in tons**	**CC Produced Events (Million)**
Scintillator	3	9
He	0.2	0.6
C (graphite)	0.15	0.4
Fe	0.7	2.0
Pb	0.85	2.5
Water	0.3	0.9



Water target

5 Nuclear Targets

Fe Pb C



High-*x* Structure Functions & PDFs

ν - p Scattering

$$\left.\begin{aligned} F_2^{\nu p} &= 2x\,(d + \overline{u} + s) \\ F_2^{\overline{\nu} p} &= 2x\,(\overline{d} + u + \overline{s}) \end{aligned}\right\} \xrightarrow{\text{At high x}} \boxed{\frac{F_2^{\nu p}}{F_2^{\overline{\nu} p}} \approx \frac{d}{u}}$$

Add in…

$$\left.\begin{aligned} xF_3^{\nu p} &= 2x\,(d - \overline{u} + s) \\ xF_3^{\overline{\nu} p} &= 2x\,(-\overline{d} + u - \overline{s}) \end{aligned}\right\} \longrightarrow \begin{aligned} F_2^{\nu p} - xF_3^{\nu p} &= 4x\overline{u} \\ F_2^{\overline{\nu} p} + xF_3^{\overline{\nu} p} &= 4xu \end{aligned}$$