The Future of ν Physics

Jorge G. Morfín
Fermilab

We are surrounded by **Neutrinos**

- Over 10^{14} ν from the sun passing through each of us every second.
- Over 10^{3} ν from cosmic ray interactions in the atmosphere passing through us every second.
- ν 's are literally all over the place.
- We have experimented **with** them for over 30 years.

Perhaps it would be nice to know just a little bit more about them... such as do they have mass?

Why do we care if they have mass?

- If neutrinos have even a small mass then it is sign for **NEW PHYSICS** beyond the Standard Model of weak/electromagnetic interactions.

- Since there are so many neutrinos throughout the universe, even a small mass makes the neutrino a **heavyweight** in the mass density of the universe!

- Are there any hints that we might be dealing with massive neutrinos?

Hints that ν might have a (small) mass!

- There is a deficit of ν_e coming from the sun - verified by many experiments. (SuperK: Obs/Expt = .47±.06)

- There are missing ν_μ coming from cosmic ray interactions in the upper atmosphere, again verified by many experiments (SuperK: $R_{data/MC}$ = .67±.02±.05)

- The LSND experiment has found evidence - yet to be verified - for $\nu_\mu \rightarrow \nu_e$.

What's going on here ??

- One possibility is that ν_l is oscillating into $\nu_{l'}$
- Difference between:
  - flavor states; ν_l interacts with matter it yields a charged lepton of flavor l and
  - Mass states; ν_l need not be a mass eigenstate but rather a superposition of mass eigenstates, at least 3 mass eigenstates and perhaps more.

$$|\nu_l\rangle = \sum_m U_{lm} |\nu_m\rangle$$

What are neutrino oscillations?

- The U_{lm} are known as the leptonic mixing matrix U.
- If ν_l is a superposition of several mass states with differing masses which cause them to propagate differently, we have neutrino oscillations.
- The amplitude for the transformation ν_l --> $\nu_{l'}$ is:

$$A(\nu_l \rightarrow \nu_{l'}) = \sum A(\nu_l \text{ is } \nu_m) A(\nu_m \text{ propagates}) A(\nu_m \text{ is } \nu_{l'})$$

$$A(\nu_m \text{ propagates}) = \exp\left(-i \frac{M_m^2}{2} \frac{L}{E} \right)$$

Example of Two Flavor Oscillations

- If there are only two flavors involved in the oscillations then the U matrix takes on the following form and the probability (square of the amplitude) can be expressed as:

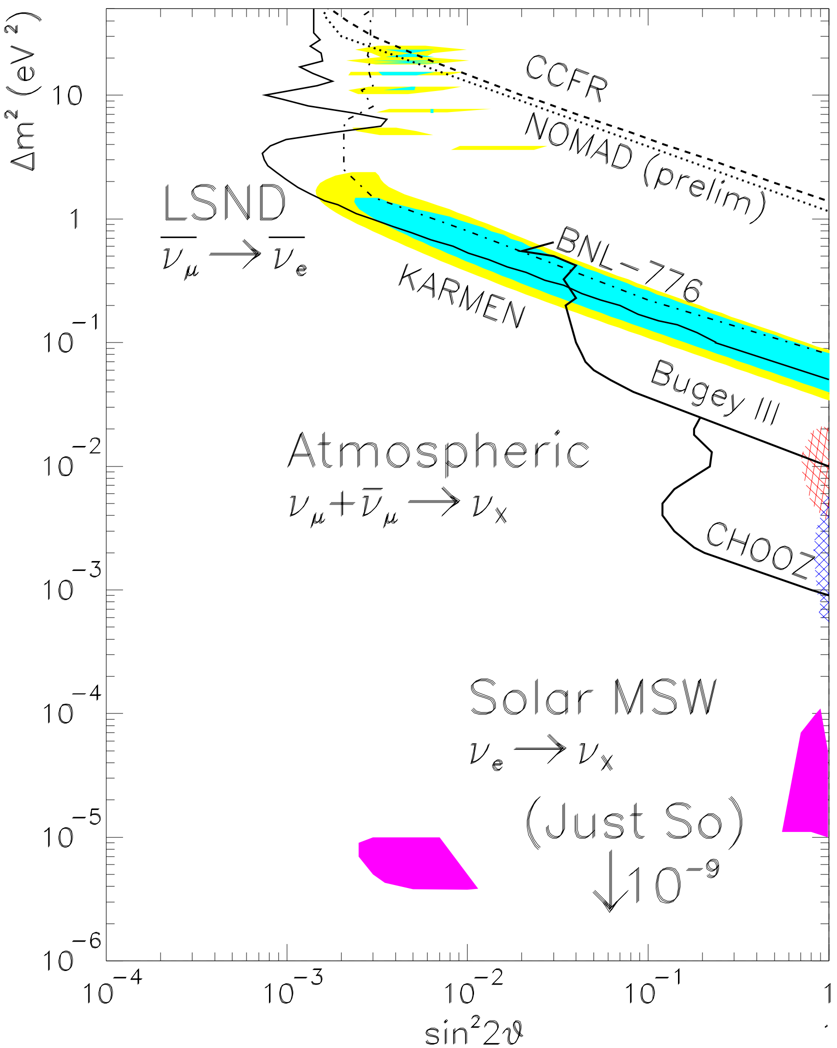
$$U = \begin{pmatrix} \cos\theta & e^{i\delta}\sin\theta \\ -e^{-i\delta}\sin\theta & \cos\theta \end{pmatrix} \text{ and}$$

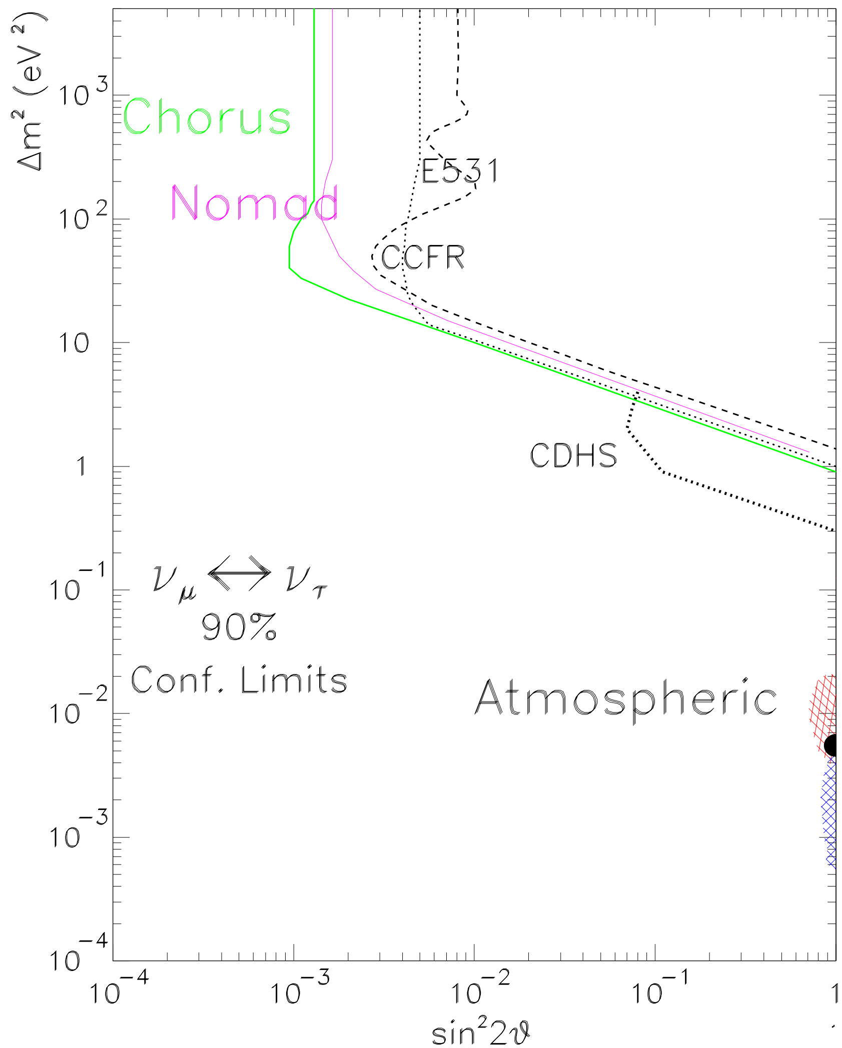
$$P(\nu_l \to \nu_{l'}) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right]$$

$$\text{with } \Delta m^2 \equiv M_2^2 - M_1^2$$

Current Sum of all Experimental Results

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland





What about 3 (or more) neutrinos

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

- Naturally, life is more complicated, but the principle is the same and we get the bonus of CP violations as in the quark sector $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$.
- The components of U now involve θ_{13} , θ_{23} ,θ_{12} and δ and the probabilities involve Δm_{13} , Δm_{23} and Δm_{12} .

- Standard Theorists Scenario: $\Delta m^2_{23} >> \Delta m^2_{12}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & \boldsymbol{U} & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Produce Weak Eigenstate...
Detect Weak Eigenstate...
Propage Mass Eigenstate

In the Next 10 years ….

- LSND will be checked by MiniBooNe: Sterile ν_s ?
- SNO, Borexino and Kamland will study the solar neutrino deficit: Know whether SMA or LMA is preferred. Gives us Δm^2_{12} and θ_{12}
- The Atmospheric Anomaly will be examined by accelerator experiments K2K and MINOS: Δm^2_{23} to 10-15% and θ_{23} to 10%.
- Tau appearance experiments at CNGS?

Remaining Questions: How to Answer Them.

- Is θ_{13} non-zero?
- What is the mass hierarchy?
- Is there CP violation?
- Are there sterile neutrinos?

What do we need to answer them?

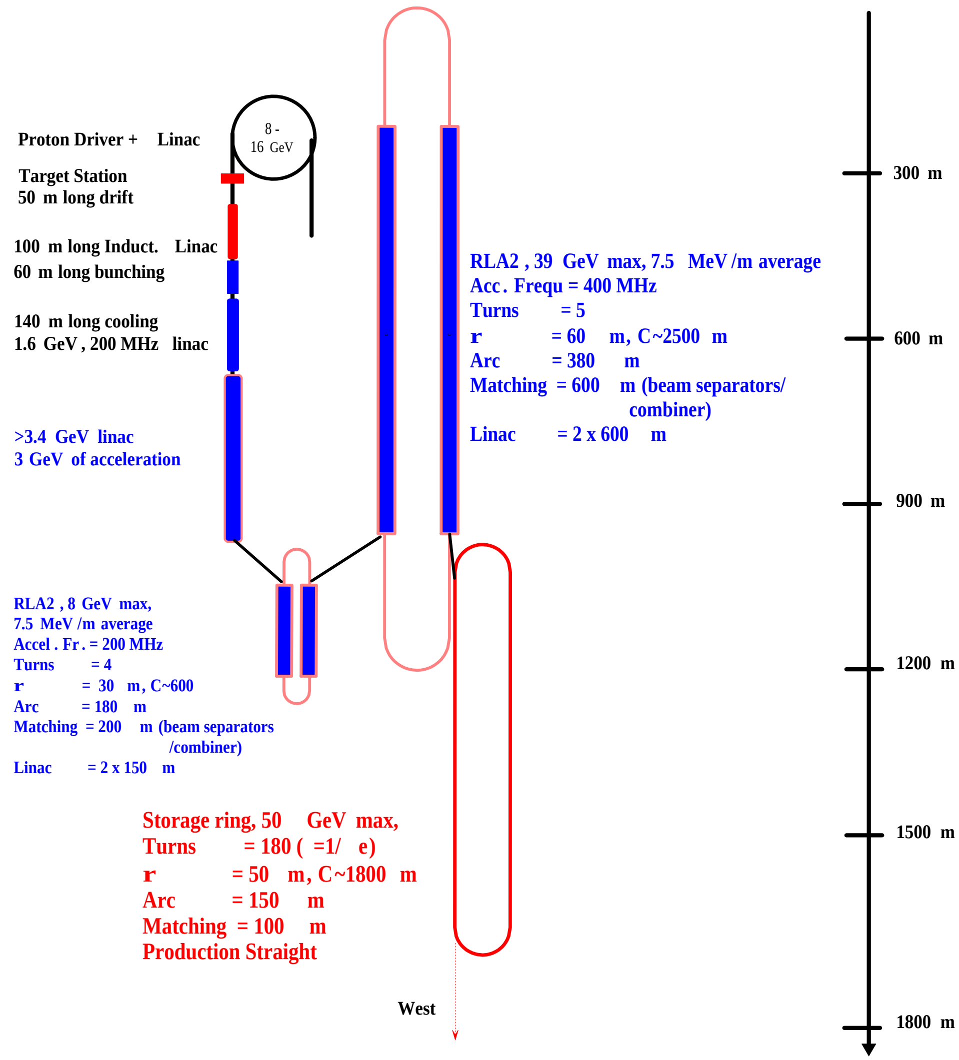
- Appearance Measurements.
- Have to Exploit Matter Effects.
  - Have to go to > 1000 km baseline.
  - Need to see ν_e in the initial or final state.
- Separate ν_a and $\bar{\nu}_a$ beams.
- Best to have two a real mix of ν_μ and ν_e beams.

The Neutrino Factory

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

- Design already exists for a 20 GeV Storage Ring with 6 x 1019 m decays per year.

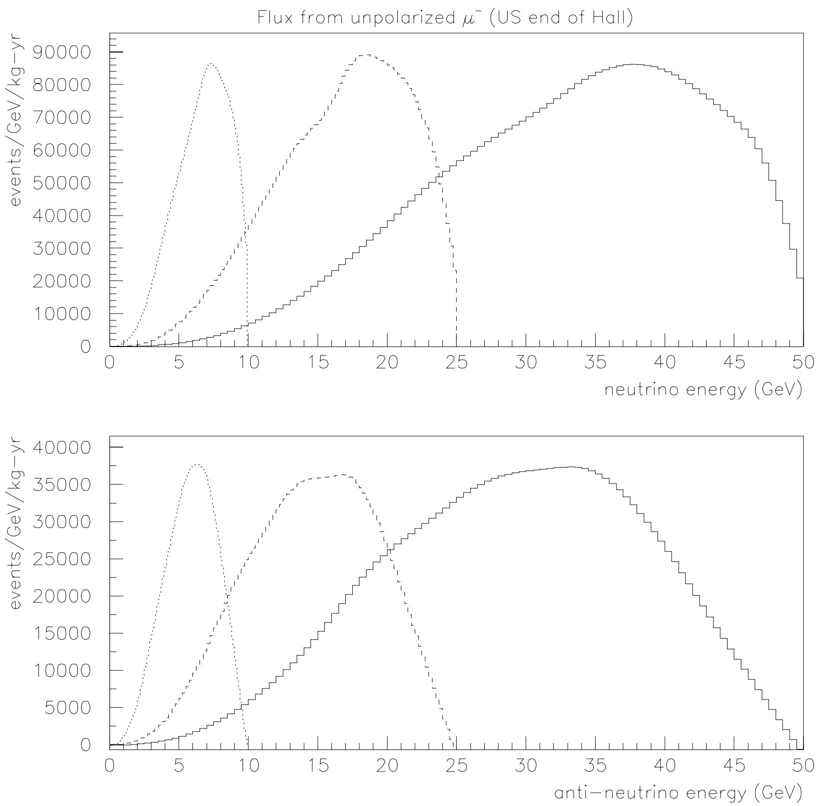
- Active working groups pushing the design with R&D projects in the U.S., Europe and Japan.

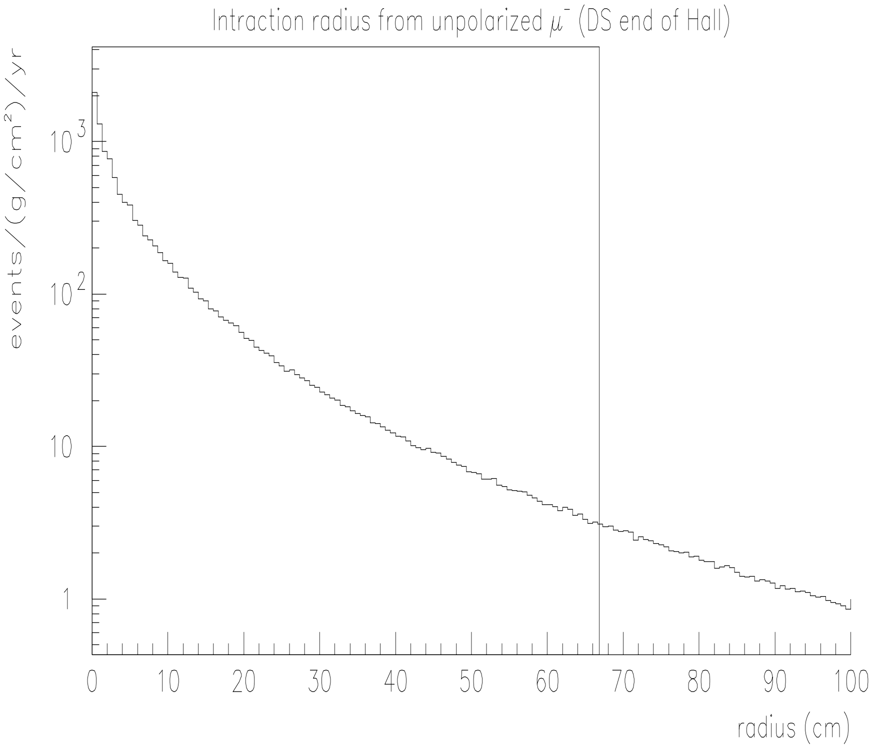


Neutrino Factory:
Event Energy and Radial Distribution

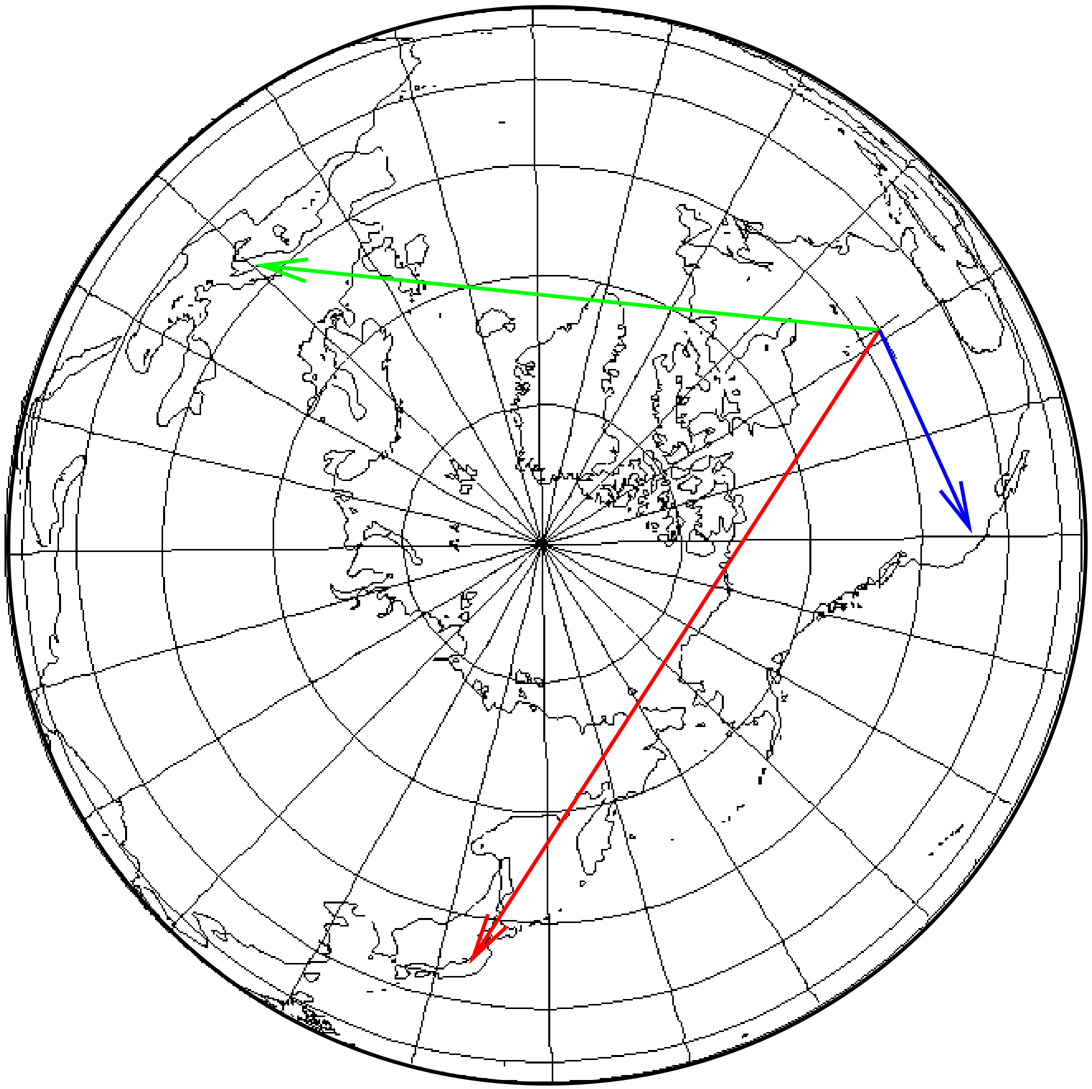
Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

10, 25 and 50 GeV Muons





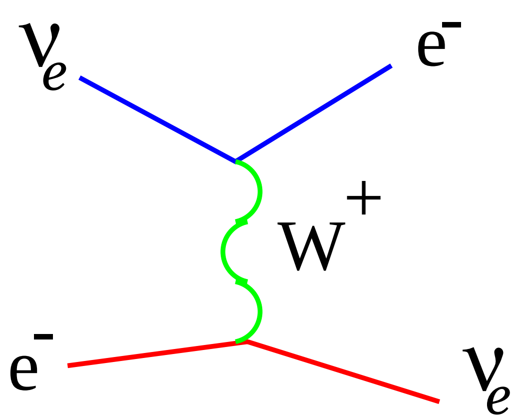
What about LONG Baselines?

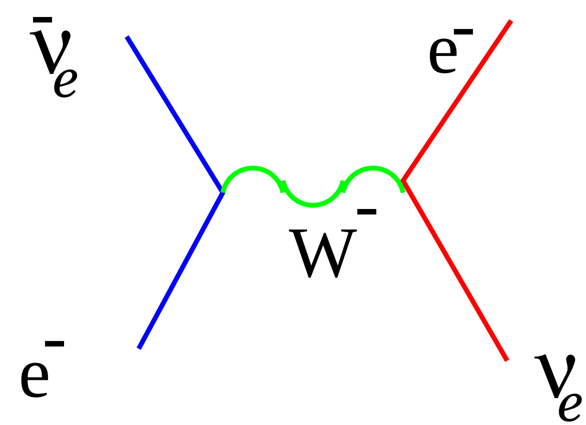


Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

The Importance of Matter Effects!

- When a neutrino propagates through matter, rather than vacuum, its oscillation probability can be greatly enhanced!
- Comes from coherent elastic scattering which is for ν_e only.
- These effects can determine the SIGN of a mass difference.
- Need L > 1000 km to see this. Need ENORMOUS detectors!





Coherent Elastic
Scattering: ν_e $\bar{\nu}_e$ only!

Near and Far Future ν Osc. Detectors

- Magnetized Steel / Scintillator - MINOS
- Liquid Ar TPC + Spectrometer - ICANOE/ICARUS
- H2O Cerenkov + Spectrometer - SuperK
- Emulsion Detector - OPERA

Can any/all of these detectors help reach our goals?

- Is θ_{13} non-zero?
- What is the mass hierarchy?
- Is there CP violation?
- Are there sterile neutrinos?

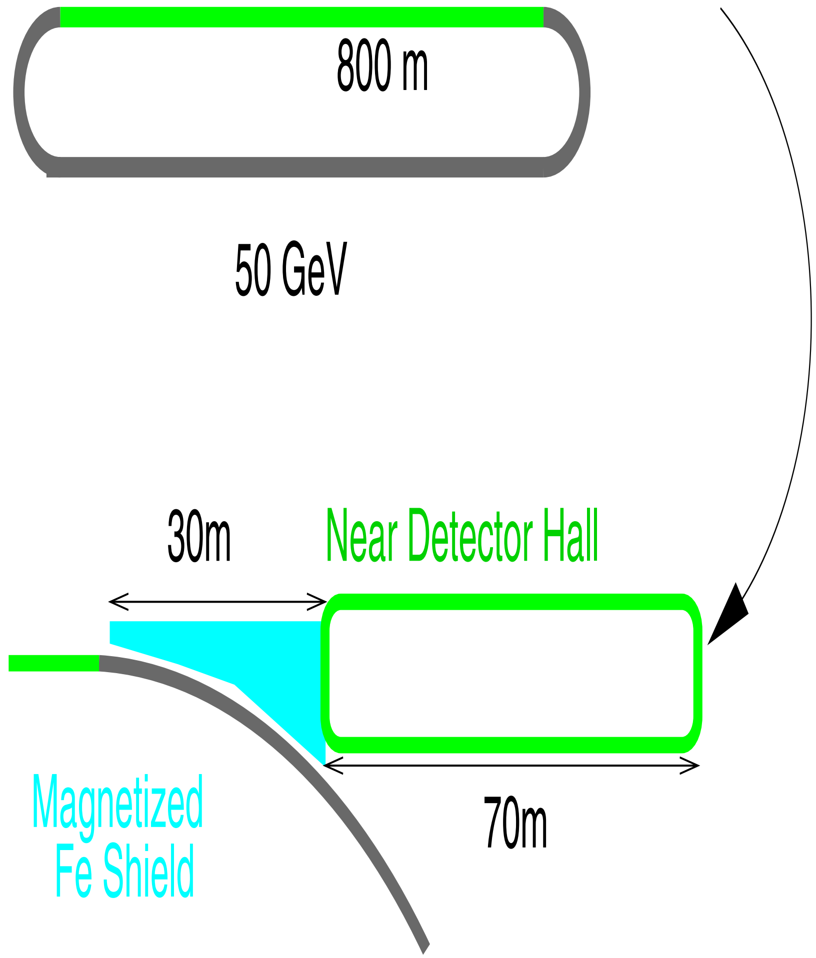
Wait…there's a lot more physics to go..
Near Detector Physics

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

- 10^{20} 50 GeV μ decays in the straight section yields ≈ **4.5 x 10^6 events/ kg-year** within r = 10 cm.

- Radial Distribution:
  35% within r = 10 cm
  85% within r = 50 cm).

- Not only is the event rate a factor 100 increase over NuMI but concentrated in center allowing smaller near detectors



The Vocabulary of Deep Inelastic Lepton-Hadron Scattering

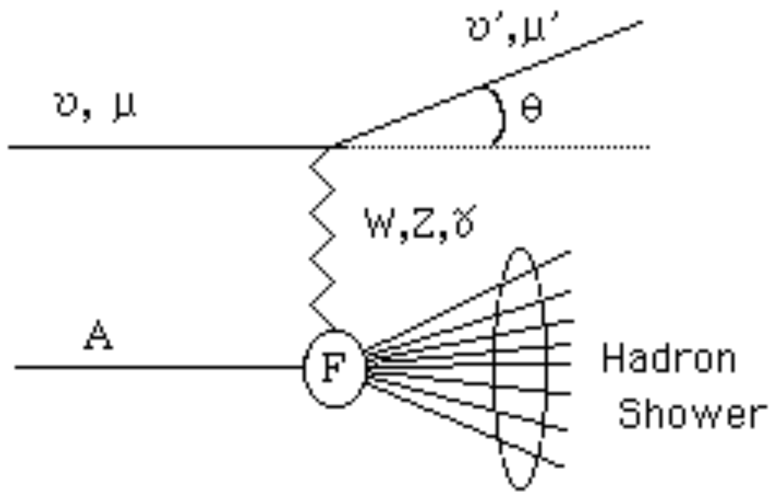
- Standard Kinematic Variables:

$$Q^2 = 4EE'\sin^2\theta/2 = -q^2$$

$$\nu = E - E'$$

$$x_{Bj} = Q^2 / 2M\nu$$

$$y = \nu / E$$



The Advantages of Neutrino DIS Experiments

- 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, $\bar{d}$ and $\bar{s}$.
- ν/ $\bar{\nu}$ have **definite** spin/helicity states, which can be used to determine partonic spin contribution to the nucleon

- **The ν is currently a very hot topic because of possible mass and consequent oscillation phenomena tests. Very intense beams will be developed for this purpose . It's logical to use them for conventional physics also!**

Although Successful -
ν DIS Studies Can Be **Improved**

1) Heavy nuclear targets have been required to accumulate sufficient statistics - measuring ν - Fe not ν - N.
2) No high statistics measurement of these nuclear effects (interesting in their own right). Had to assume ν - Fe same as μ/e - Fe to include ν data in global fits. Particularly limiting for valence quark and high x parton distribution functions
3) Statistics and systematics have not yet reached the level to allow extraction of all possible information. Independent ν and ν structure functions have not yet been well measured.
4) Although CCFR/NuTeV have made great progress. Beam systematics will still be a limit for high statistics experiments.

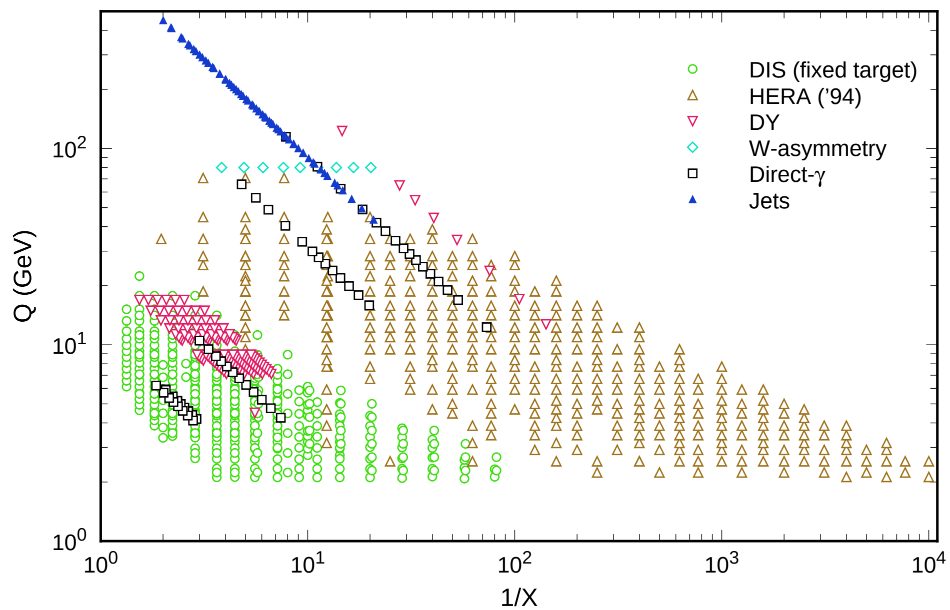
1) - 3) indicate need for more intense ν & $\bar{\nu}$ beams

while 4) suggests need for better knowledge of those beams

Global Fitting Needs

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland

- Improved Statistics at high x. (Fit into the resonance region?)
- Improved estimate of s & s
- Improved understanding of leading exponential contribution.
- Improved understanding of nuclear corrections and/or ν - H_2/D_2



How Do We Address these Needs?

- **NuMI**
  - Uses high intensity Main Injector (plus new Proton Driver ?) with 120 GeV protons and horn focussed π & K beam for ν.
  - A 2nd generation higher energy DIS expt. could happen > 2007?
  - Knowledge of beam improved over other horn-focussed beams.

- **Neutrino Factory**
  - Uses muon storage ring with production of ν_μ and ν_e via decay of $\mu^\pm$
  - Entry level facility possible in 2010 - 2015 time frame.
  - Excellent knowledge of beam.

Beam	$\langle E_\nu \rangle$ (GeV)	Evts/kg-year
CCFR/NuTeV	100	O(10)
NuMI (HE - configuration)	17	(.3 - 1.0) x 10^4
ν Factory (25 GeV μ)	17	3 x 10^5

Compare Event Rates for Two Future Experiments

Jorge G. Morf n
CTEQ SS2001
St. Andrews, Scotland

MIDIS in the NuMI Beam

- 10^{20-21} protons/year on the NuMI target.
- **$(.3 - 1.0) \times 10^4$ CC ν or**
  $(.7 - 2.5) \times 10^3$ CC $\bar{\nu}$ events /**kg-**yr
  (in high energy configuration)
- Know $\phi(E_\nu)$ and $\int\phi(E_\nu)$ to $< 2\%$
- First Beam 2003.
  HE beam run > 2007

Near Detector/50 GeV NuFact
(50 m away from 800 m straight section)

- 10^{20} μ decays/year
- **4.5×10^6 CC ν_μ and**
  1.9×10^6 CC ν_e events/**kg-**year (fid. vol. r < 10 cm)
- Know $\phi(E_\nu)$ and $\int\phi(E_\nu)$ to
  < 1.0 %
- First Beam .... 2012 - 1015?

What Information is yet to be Gained?

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

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

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

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

- What do we gain by measuring separate ν and $\bar{\nu}$ structure functions?
- Does $s = \bar{s}$ and $c = \bar{c}$ over all x?
- If so.....

$$F_2^{\nu} - F_2^{\bar{\nu}} = 2\left[(s - \bar{s}) + (\bar{c} - c)\right]$$

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u} + \bar{d} + 2\bar{c}\right) = 2U + 4\bar{c}$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u} + \bar{d} + 2\bar{s}\right) = 2U + 4\bar{s}$$

$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[(s + \bar{s}) - (\bar{c} + c)\right] = 4\bar{s} - 4\bar{c}$$

The Challenge of d/u at High x

John Arrington - ANL

Neutron Structure Function.

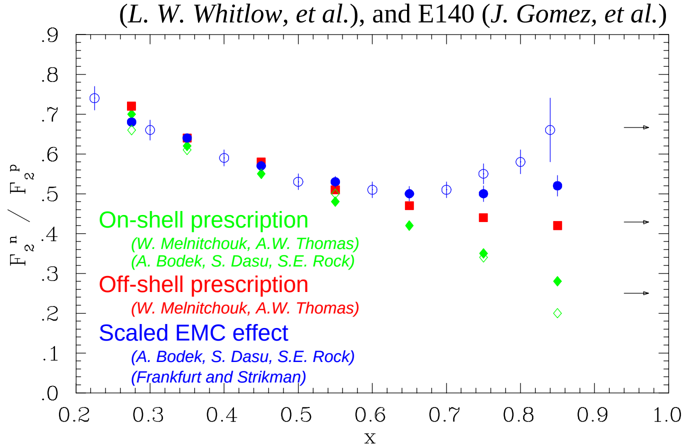
Nucleon structure functions at large x are sensitive to valence quark distributions.

The ratio of F_2^p / F_2^n allows one to separate up and down quark distributions.

	d_v^p/u_v^p ratio	F_2^n / F_2^p
SU(6) symmetry	1/2	2/3
diquark S=1 suppression *(Close, et al.; Carlitz, et al.)*	0	1/4
diquark S_z=1 suppression *(Farrar and Jackson; Brodsky et al.)*	1/5	3/7

Extracting the neutron structure function from deuteron measurements requires a model of the nuclear effects.

Proton and deuterium data from SLAC E139 (*L. W. Whitlow, et al.*), and E140 (*J. Gomez, et al.*)



The extraction of F_2^n is limited by our understanding of nuclear effects in deuterium.

- A high statistics experiment with ν and $\bar{\nu}$ off a hydrogen target gives d/u (relatively) cleanly

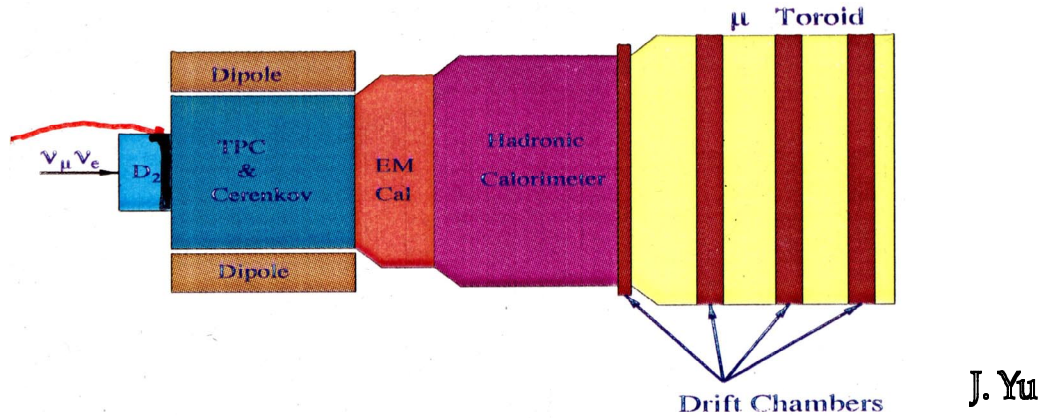
$$F_2^{\bar{\nu}P}(x,Q^2) = 2x\left[u + \bar{d} + \bar{s} + c\right]$$

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

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

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

Near Detector for Neutrino Factory



- Liquid hydrogen/deuterium cryogenic target (followed by high A targets).

- All targets (r = 10 cm) acquire 10^7 ν_μ events and 4 x 10^6 $\bar{\nu}_e$ /year.

- H_2 @ 120 cm long or D_2 @ 50 cm, C @ 3.7 cm and W @ 0.45 cm

The Complete Differential Cross Sections for High Energy Neutrinos

Jorge G. Morf n
CTEQ SS2001
St. Andrews, Scotland

Physics at the Front-End of a Neutrino Factory: A Quantitative Appraisal - M.L. Mangano et al - CERN-TH/2001-131, May 15, 2001

$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 ME}{2\pi\left(1+Q^2/M_W^2\right)} *$$

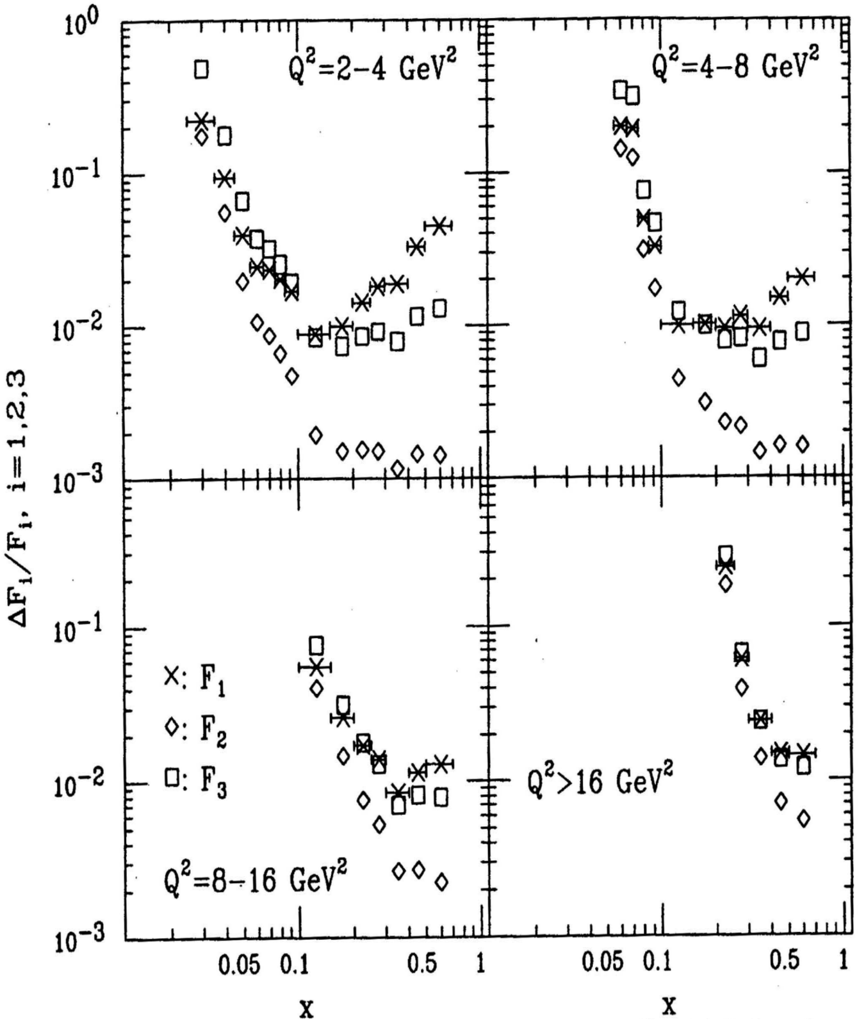
$$\left[xF_1^{\nu N}(x,Q^2)\mathbf{y^2} \ + \ F_2^{\nu N}(x,Q^2)(\mathbf{1}-\mathbf{y}) + xF_3^{\nu N}(x,Q^2)\mathbf{y}\left(\mathbf{1}-\frac{\mathbf{y}}{\mathbf{2}}\right)\right]$$

$$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy} = \frac{G_F^2 ME}{2\pi\left(1+Q^2/M_W^2\right)} *$$

$$\left[xF_1^{\bar{\nu} N}(x,Q^2)\mathbf{y^2} \ + \ F_2^{\bar{\nu} N}(x,Q^2)(\mathbf{1}-\mathbf{y}) - xF_3^{\bar{\nu} N}(x,Q^2)\mathbf{y}\left(\mathbf{1}-\frac{\mathbf{y}}{\mathbf{2}}\right)\right]$$

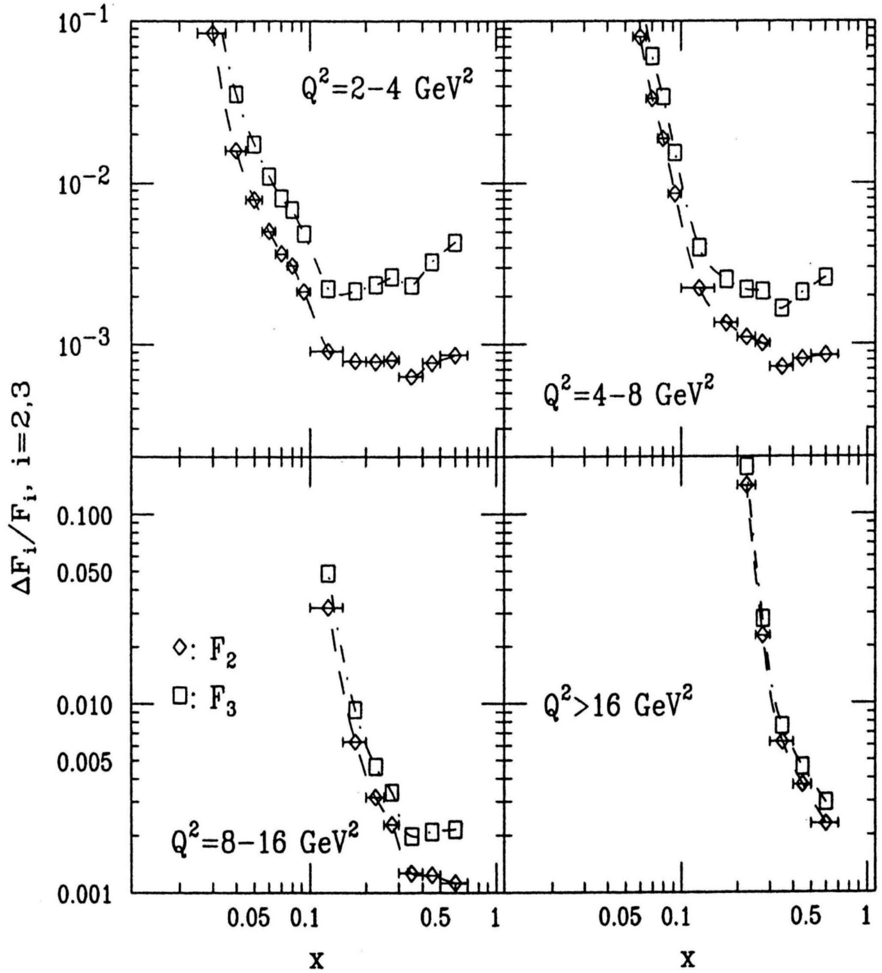
Expected Errors on Measured F's

- Deuterium Target:
  r = 50 cm & l = 60 cm.
- One year exposure.
- Errors on F_1 betterthan 10%.
- As x--> 1.0, F_2 --> xF_3



Expected Errors on Measured F's

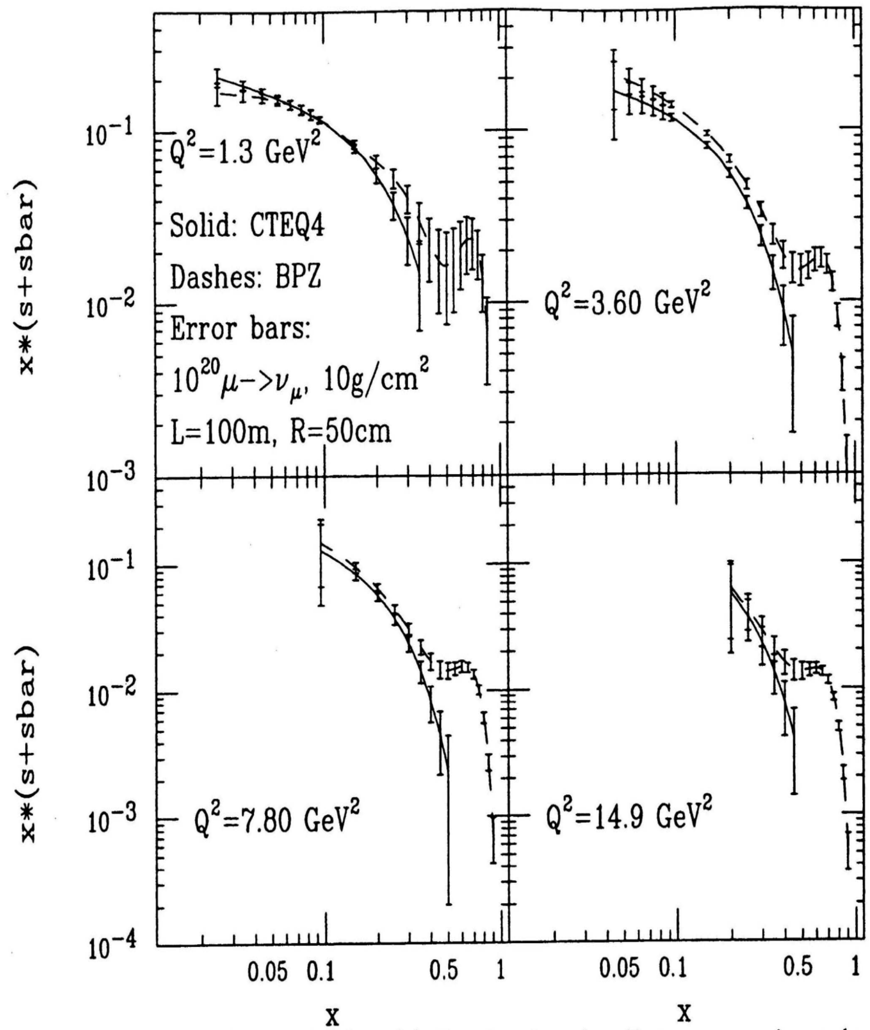
- Assume the Callan-Gross relationship eliminating F_1.
- Errors now O (1%) or better over most of the x-range.



Extracting the Strange Sea

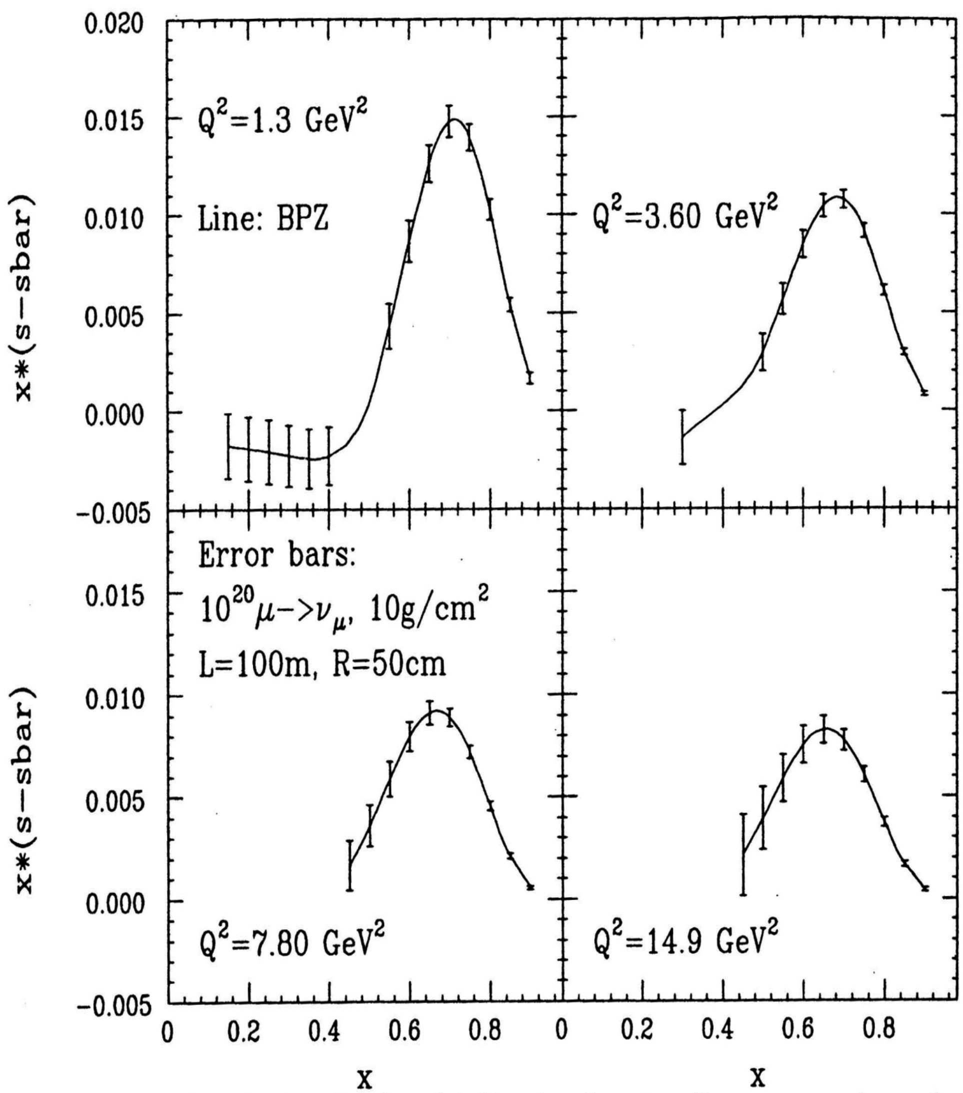
Jorge G. Morfín
CTEQ SS2001
St. Andrews,
Scotland

- Current knowledge of s & $\bar{s}$ comes from CCFR/NuTeV.
- Closely related to the c-quark distribution.
- We must independently measure charm or neglect it.
- 1 year ν and 1 year $\bar{\nu}$ would result in these errors on s + $\bar{s}$
- Barone, Pascaud and Zomer (BPZ) find evidence for intrinsic strange sea at high x.



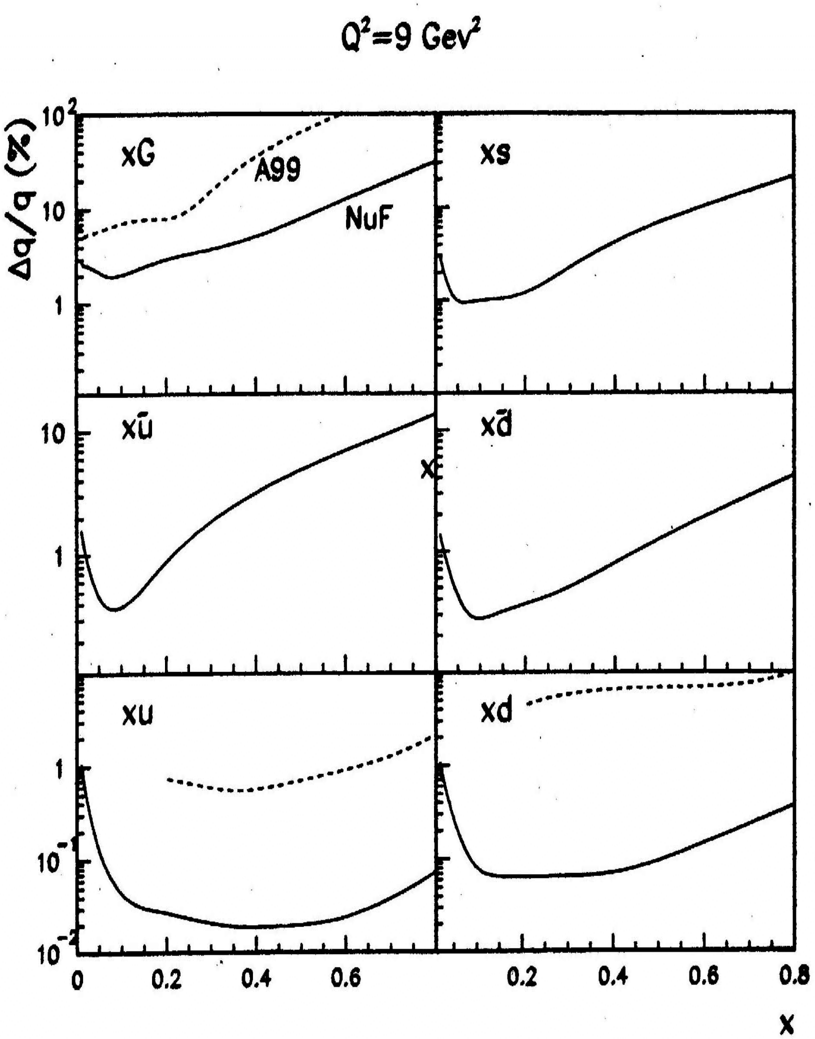
BPZ is Quite Strange!

Jorge G. Morf n
CTEQ SS2001
St. Andrews,
Scotland



Extracting PDFs at a Neutrino Factory

- Generate eight sets of fake data (F_2 and xF_3 for ν and $\overline{\nu}$ on hydrogen and deuterium) with errors as previously shown.
- Central values from Alekhin et al - charged lepton DIS.
- Dashed lines show error from Alekhin et al analysis



NuFact-Specific Physics Topics: Polarized Target - M. Velasco

- Sufficiently intense and compact ν beam to envision reasonable statistics in O(10 kg) polarized target.
- Recent development of an "ICE" targets which is a solid polarizable HD material ($\rho = 0.11\ g/cm^3$). $P_H = 80\ \%$ and $P_D = 50\ \%$.
- ICE target with r = 20 cm and l = 50 cm would accumulate 20 M events / year ($10^{20}\ \mu$).
- Could also use more traditional polarized butanol target a la SMC with r = 6 cm and l = 60 cm would get the same statistics but with P = 0.1.

NuFact-Specific Physics Topics: Reference

- For more details on the NuFact topics covered in this brief summary plus other topics such as:
  - Charmed Particle Production and Analysis
  - Electroweak Physics
  - Rare neutrino properties such as magnetic moment…… see

The Potential for Neutrino Physics at Muon Colliders and Dedicated High Current Muon Storage Rings, I. Bigi et al, **BNL 68106**, Jan. 2001 (submitted to Physics Reports)

SUMMARY

- Neutrino Oscillations have become more of a sure thing since the SNO results.
- Need to study the oscillations consistent with the atmospheric anomaly which will be done with K2K and MINOS.
- The question of whether we are dealing with the SMA or LMA solar neutrino solution will come from KAMLAND if not from SNO plus BOREXINO.
- To answer all the remaining neutrino oscillation questions we need either Superbeams or a Neutrino Factory based on a muon storage factory.
- A Superbeam or a Neutrino Factory with a near detector consisting of H_2, D_2 , and nuclear targets as well as polarized targets:
  - Extract individual pdf's for each flavor in each x - Q bin.
  - Complete measurements of the partonic spin structure of nucleon.
  - High statistics charm production with "clean" final state ($E_\mu \geq$ 50 GeV).
  - Precision electroweak measurements; ν-e scattering …………