NuSOnG:

Neutrino Scattering On Glass

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References

1. "Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG," 0803.0354 [hep-ph].

2. "Renaissance of the ∼1 TeV Fixed-Target Program," 0905.3004 [hep-ex].

3. "QCD Precision Measurements and Structure Function Extraction at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG," 0906.3563 [hep-ex].

4. "Expression of Interest for Neutrinos Scattering on Glass: NuSOnG," 0907.4864 [hep-ex].

Effort of about 40 people (about 20 institutions, including FNAL and ANL), including 10 theorists.

`http://www-nusong.fnal.gov`

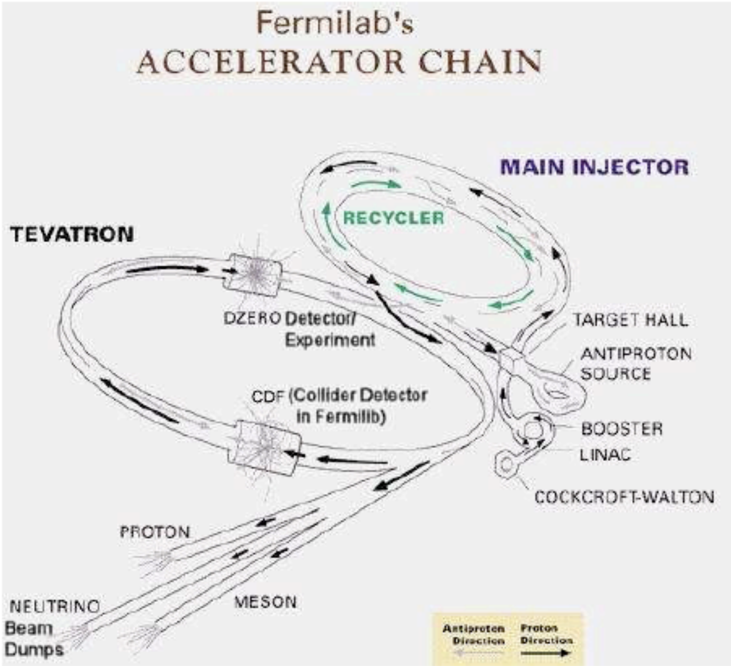
Neutrino Scattering On Glass

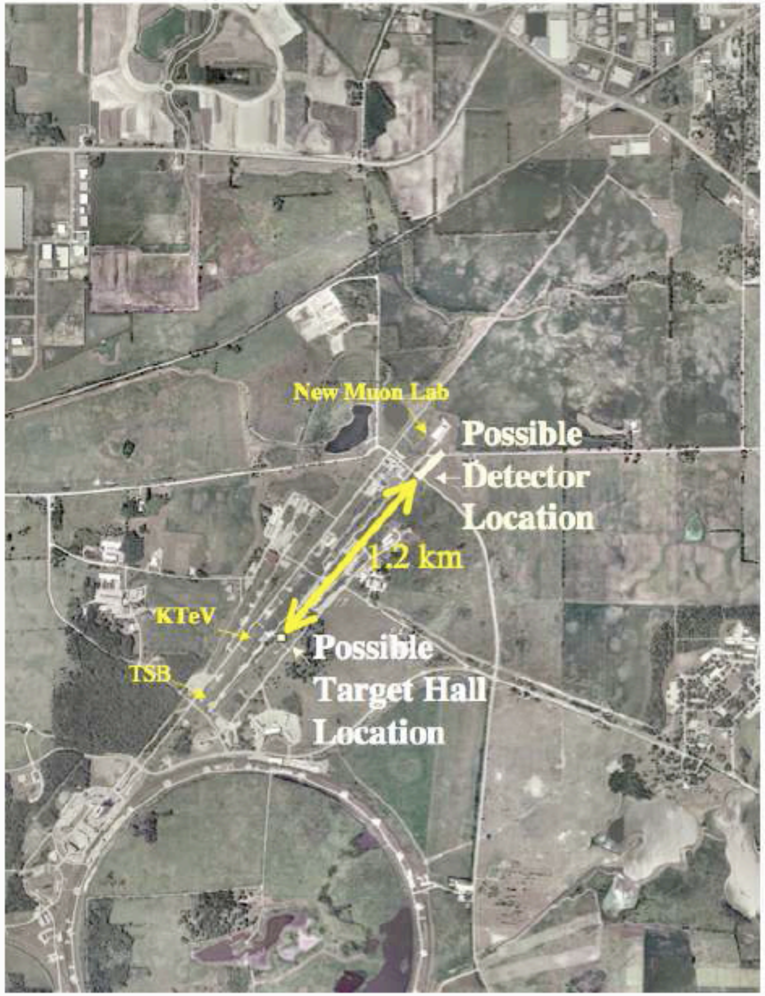
NuSOnG is a proposal to study fixed-target neutrino – matter interactions

- High Energies – protons from the Tevatron
- High Statistics – lots of protons from the Tevatron, large detector
- "Rare" Processes – highly segmented detectors capable of "seeing" electrons
- Well Understood Neutrino Flux – "ratio-like" measurements

NuSOnG will use 800 GeV Protons from the Tevatron

(Another Option: SPS+ at CERN)



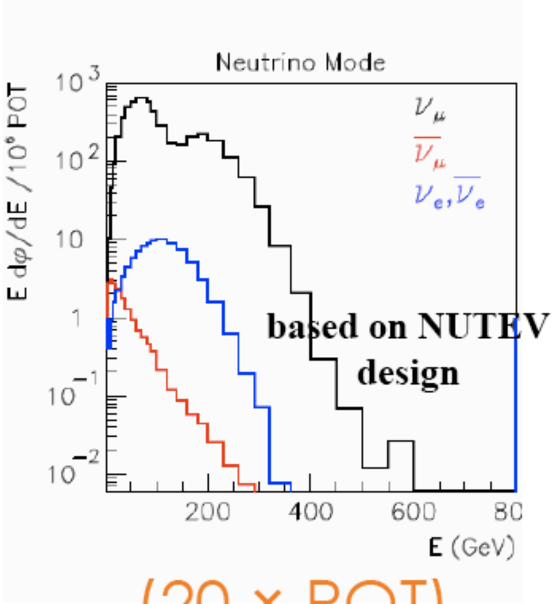


This requires the TeVatron to achieve new records:

5× the number of protons per fill,
1.5 × faster cycle time,
66% uptime per year

[but it doesn't need any antiprotons…]

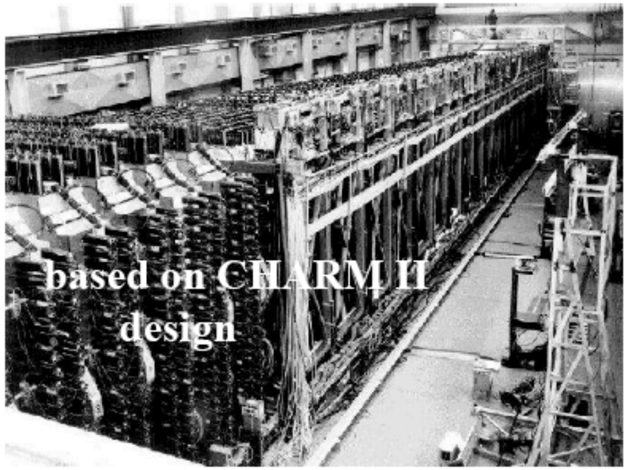
High-energy, very flavor-pure neutrino beam



(20 × POT)

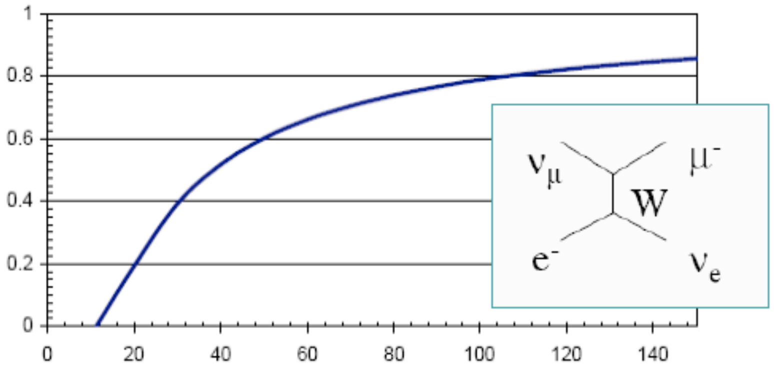
×

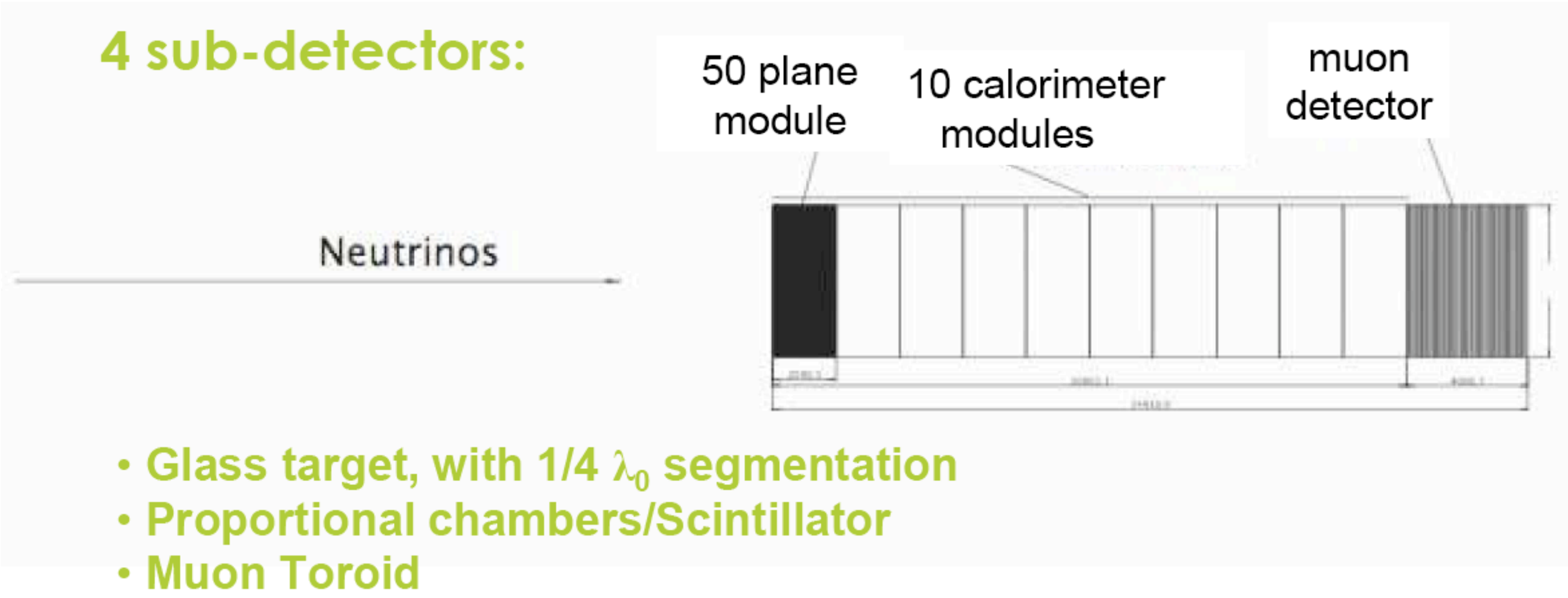
Well-segmented, massive detector

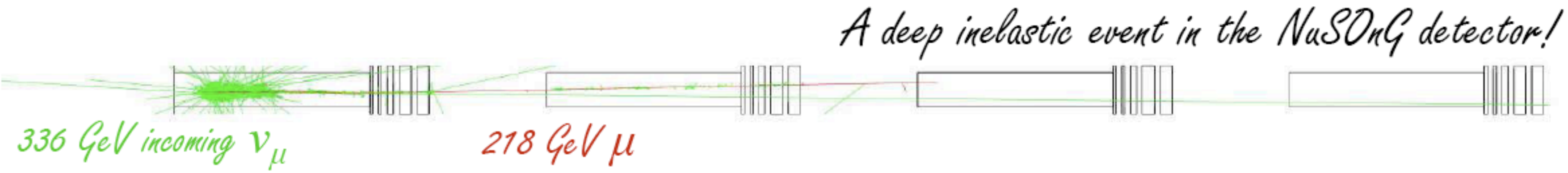


(6 × mass)

High-energy, because we'd like to use IMD events to constrain our flux prediction




4 sub-detectors:
50 plane module
10 calorimeter modules
muon detector
Neutrinos
• Glass target, with 1/4 λ_0 segmentation
• Proportional chambers/Scintillator
• Muon Toroid


A deep inelastic event in the NuSOnG detector!
336 GeV incoming ν_μ
218 GeV μ

NuSOnG

Neutrino Scattering On Glass

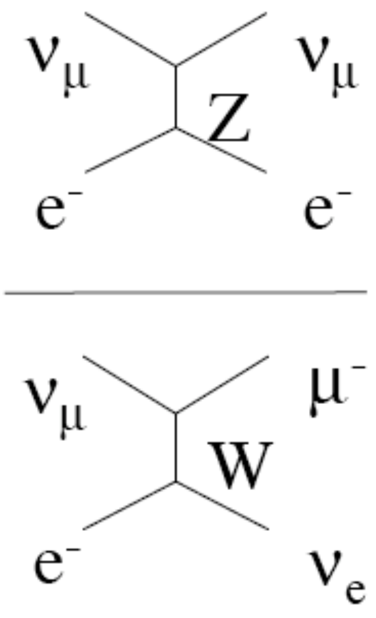
may become

NuSONG

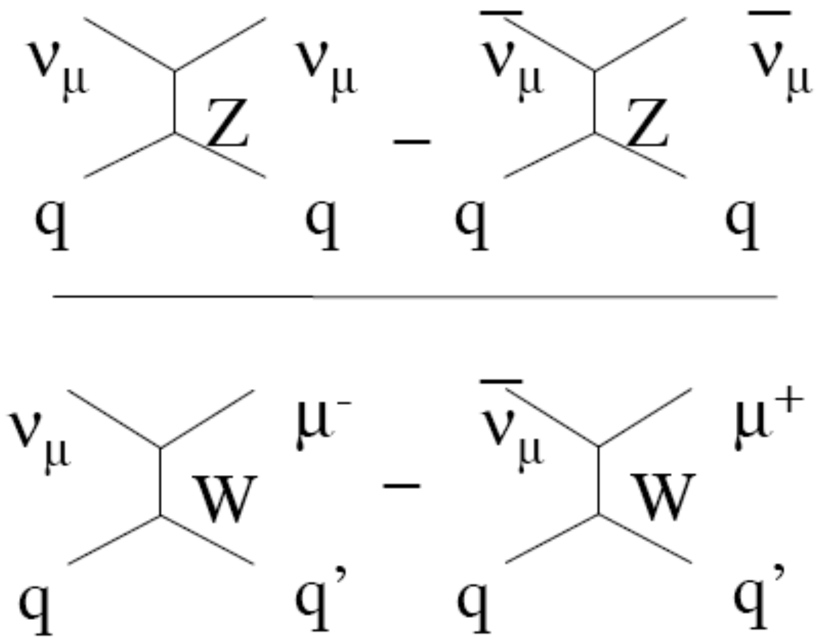
Neutrino Scattering On (liquid) Noble Gas

NuSOnG will work with ratios….

New!



Purely leptonic



NuTeV-style
"Paschos-Wolfenstein"

Expected errors

0.7% conservative,
0.4% best case

0.4% conservative
0.2% best case

In more detail, NuSOnG will measure . . .

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ [ES]

$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ [IMD]

$\nu_\mu + q \rightarrow \nu_\mu + X$

$\bar{\nu}_\mu + q \rightarrow \bar{\nu}_\mu + X$

$\nu_\mu + q \rightarrow \mu^- + X$ [DIS]

$\bar{\nu}_\mu + q \rightarrow \mu^+ + X$

600M	ν_μ CC Deep Inelastic Scattering
190M	ν_μ NC Deep Inelastic Scattering
75k	ν_μ electron NC elastic scatters (ES)
700k	ν_μ electron CC quasi-elastic scatters (IMD)
33M	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering
12M	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering
7k	$\bar{\nu}_\mu$ electron NC elastic scatters (ES)
0k	$\bar{\nu}_\mu$ electron CC quasi-elastic scatters (WSIMD)

!

TABLE I: Rates assumed for this paper. NC indicates "neutral current" and CC indicates "charged current."

. . . with sub-percent precision!

Physics of Neutrino – Charged Fermion Scattering

Neutrino matter scattering provides a unique and clean environment to study purely weakly interacting processes. In the Standard Model, at low enough center of mass energies, $\nu_\mu + f$ elastic scattering is governed by the following effective Lagrangian.

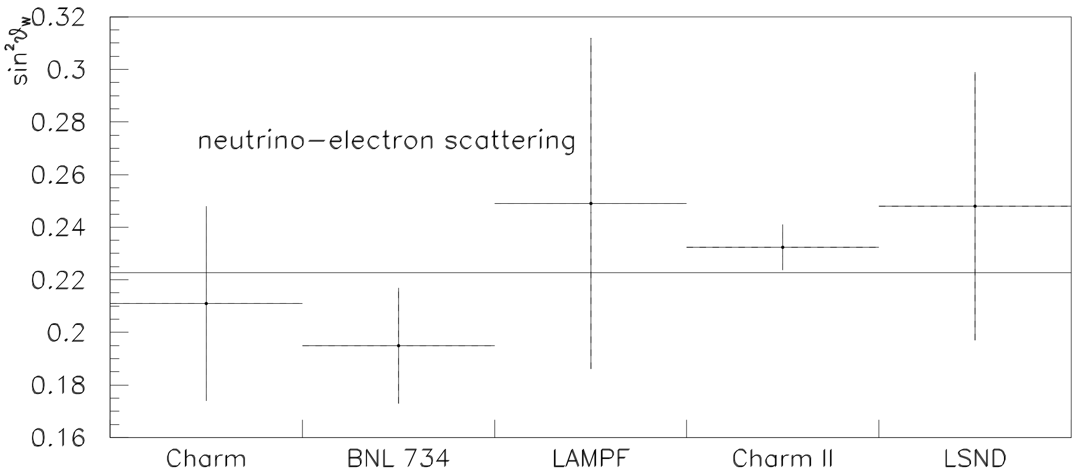
$$\mathcal{L} = -2\sqrt{2}G_F\,(g_L^\nu\,\bar{\nu}_L\gamma_\mu\nu_L) \times \left[g_L^f\,\bar{f}_L\gamma^\mu f_L + g_R^f\,\bar{f}_R\gamma^\mu f_R\right]$$

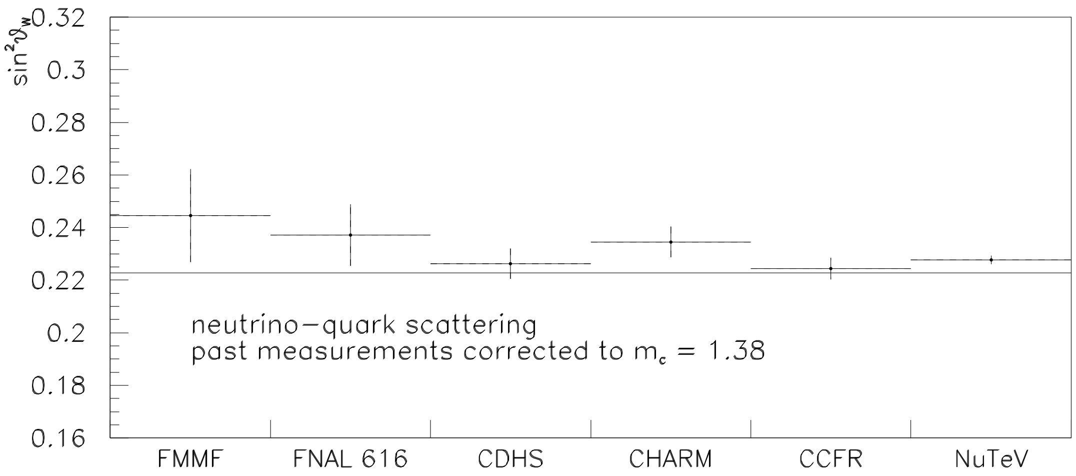
where

$$\begin{aligned} g_L^\nu &= \sqrt{\rho}\left(+\frac{1}{2}\right)~, \\ g_L^f &= \sqrt{\rho}\left(I_3^f - Q^f\sin^2\theta_W\right)~, \\ g_R^f &= \sqrt{\rho}\left(-Q^f\sin^2\theta_W\right)~. \end{aligned}$$

At tree-level, $\rho = 1$. Loop corrections affect both ρ and what we mean by $\sin^2\theta_W$.

One can interpret $\nu + f$ as measuring the Weinberg angle ...

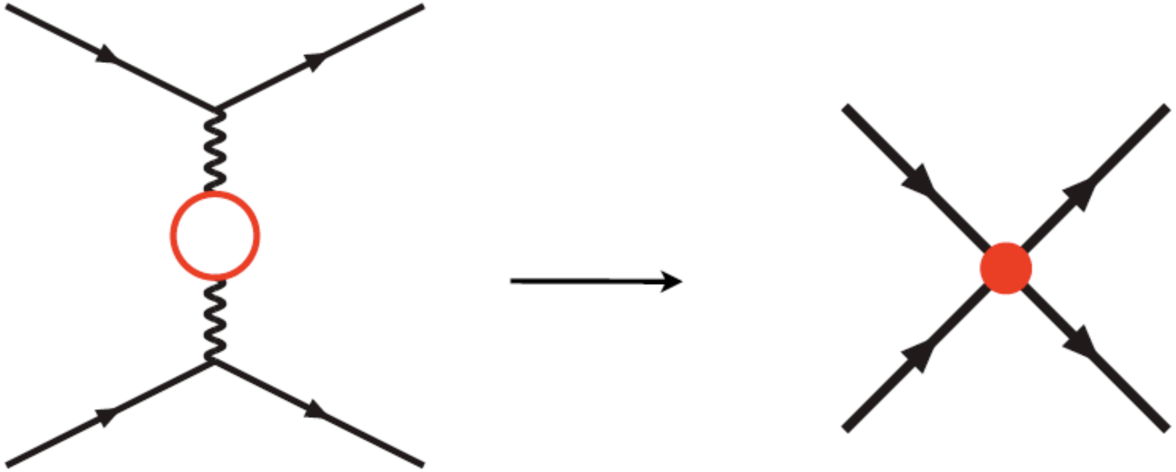




...but it measures $g_L^\nu g_L^f$ and $g_L^\nu g_R^f$ independently. Much more information.

Example: $\nu_\mu + e$ elastic scattering

Oblique Shifts (S, T)



$$\sim \frac{1}{\Lambda^2}\left[\bar{\nu}_{L\mu}\gamma^a\nu_{L\mu}\right]\left[\cos\theta\ \bar{e}_L\gamma_a e_L + \sin\theta\ \bar{e}_R\gamma_a e_R\right]$$

$$\frac{1}{\Lambda^2} = 4\sqrt{2}G_F$$

$$\cos\theta = \frac{\alpha}{2}\left(g_L^e T + \frac{\tan^2\theta_W}{4}\left[S - 2T\right]\right)$$

$$\sin\theta = \frac{\alpha}{2}\left(g_R^e T + \frac{\tan^2\theta_W}{4}\left[S - 2T\right]\right)$$

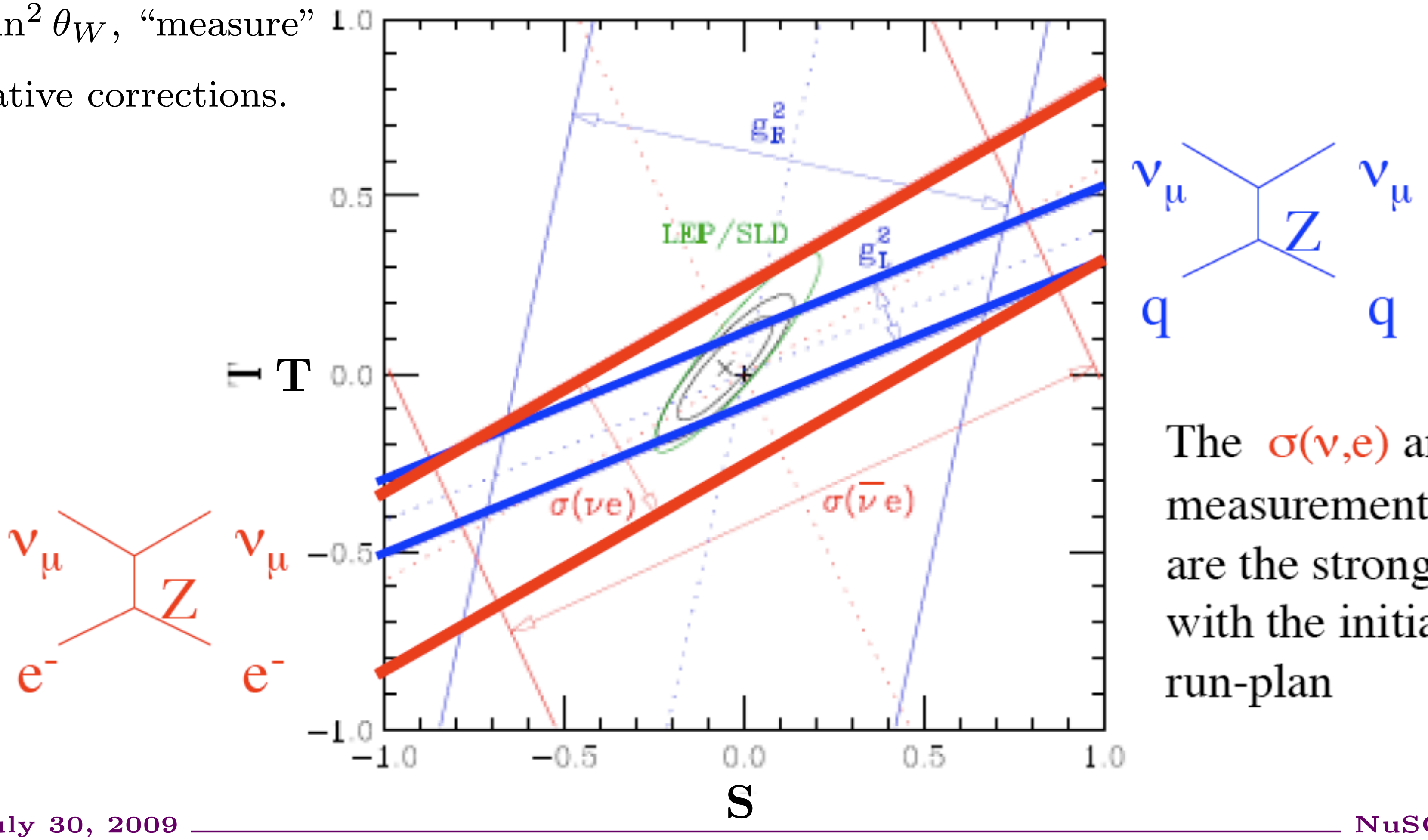
Consider four NuSOnG measurements:

1) $\sigma(\nu, e)$,
2) $\sigma(\bar{\nu}, e)$,

3) $$g_L^2 = (2g_L^\nu g_L^u)^2 + (2g_L^\nu g_L^d)^2 = \rho^2(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W),$$

4) $$g_R^2 = (2g_L^\nu g_R^u)^2 + (2g_L^\nu g_R^d)^2 = \rho^2(\frac{5}{9}\sin^4\theta_W).$$

fix $\sin^2\theta_W$, "measure" radiative corrections.



The σ(ν,e) and g_L^2 measurements are the strongest with the initial run-plan

Here, I'll concentrate on $\nu_\mu + e$ elastic scattering.

- Another channel to study neutral currents with neutrinos (*cf.* NuTeV).
- Significant improvements over world's data sample – CHARM II had less than 6000 events, ν and $\bar{\nu}$ combined.
- This is a very, very clean process! (Among First Standard Model calculation, G. 't Hooft, "Predictions For Neutrino - Electron Cross-Sections In Weinberg's Model Of Weak Interactions," Phys. Lett. B **37** (1971) 195.)

Neutrino–Electron Elastic Scattering and New Physics

This is what one is able to measure:

$$\frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + (g_V^{\nu e} \mp g_A^{\nu e})^2 (1-y)^2\right] ,$$

in the limit $m_e \ll E_\nu$, for $y = \frac{T_e}{E_\nu}$ for the recoil electron. Sign ambiguity for neutrino and antineutrino scattering, respectively.

New “heavy” physics will modify the coeffiicents

$$g_L^\nu g_L^e = g_V^{\nu e} + g_A^{\nu e}$$

$$g_L^\nu g_R^e = g_V^{\nu e} - g_A^{\nu e}$$

Most general effective Lagrangian one can probe with $\nu_\mu + e$ scattering

$$\mathcal{L}^e_{\rm NSI} = +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_\alpha\gamma_\sigma P_L\nu_\mu\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right].$$

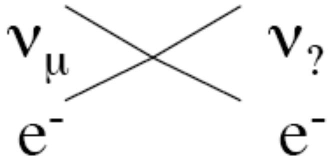
Λ = New Physics scale.

θ parameterizes "handedness" of the new physics. Note: signs matter.

Assumption 1: no scalar–scalar interaction ("suppressed" by neutrino and electron masses)

Assumption 2: charged current – IMD – NOT modified. This is not true of specific models

NSI reach for **neutrino-lepton scattering**



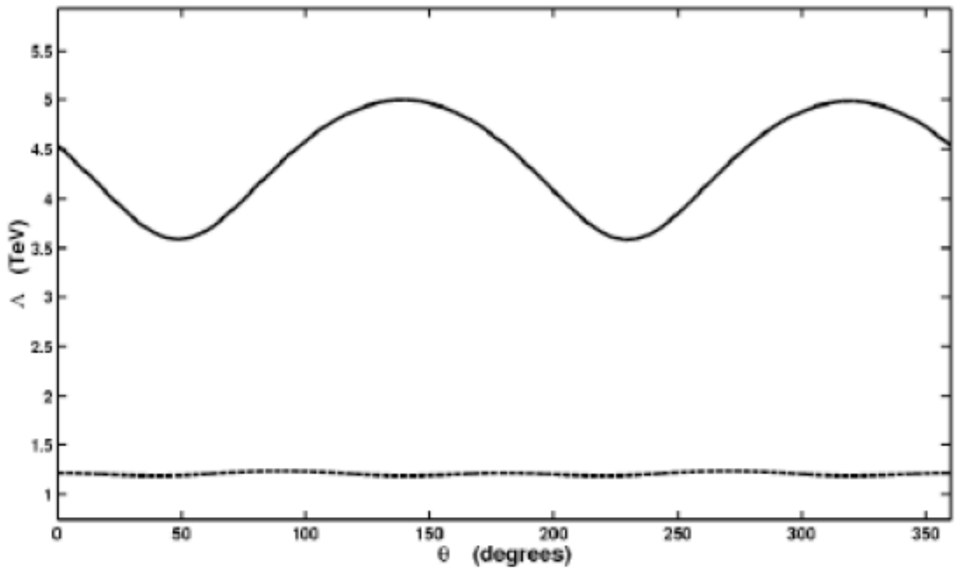
$$\mathcal{L}^{e}_{\rm NSI} = +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_\alpha\gamma_\sigma P_L \nu_\mu\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right]$$

mass scale

outgoing flavor

Relative mixture of handedness

Λ



θ

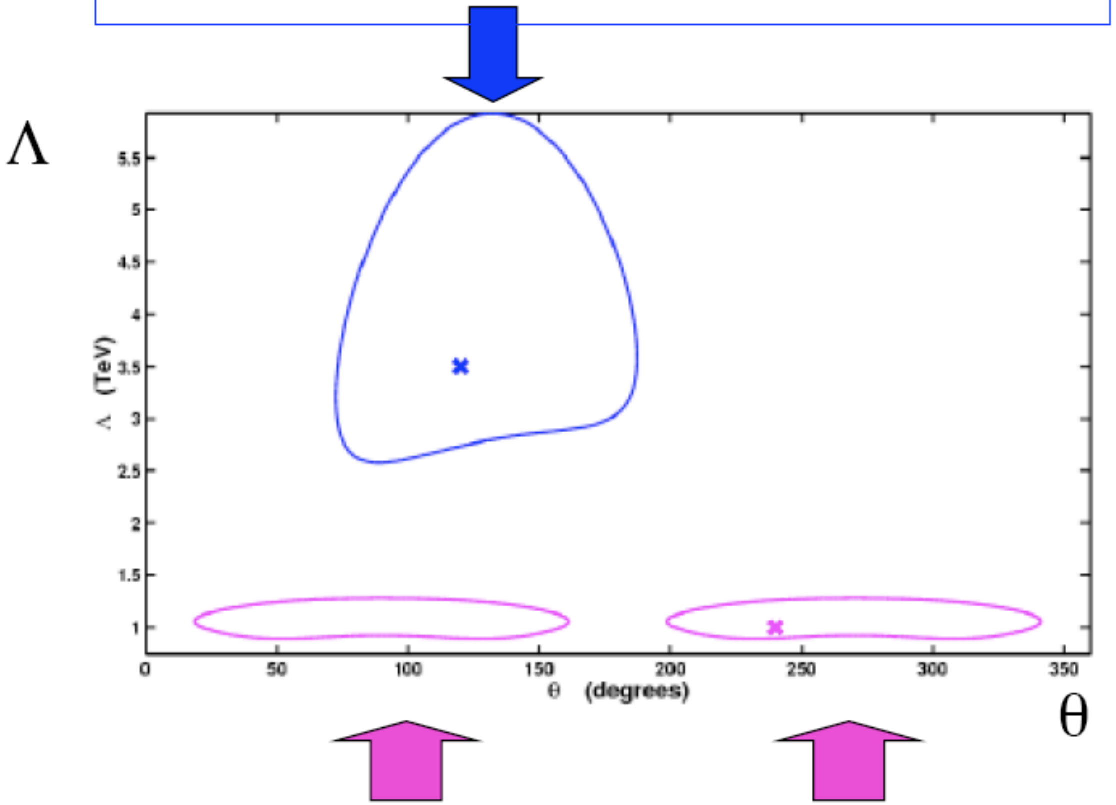
95% CL sensitivity

if α = muon flavor ~4.5 TeV

if α ≠ muon flavor ~1.25 TeV

But we might see a signal!

Assume Λ=3.5 TeV, θ =2π/3, α=μ…
this is the 2σ contour from NuSOnG



Assume Λ=1 TeV, θ =4π/3, α≠μ…
these are the 2σ contours from NuSOnG

How can we learn more about this "new physics"? We need information from other sources, including

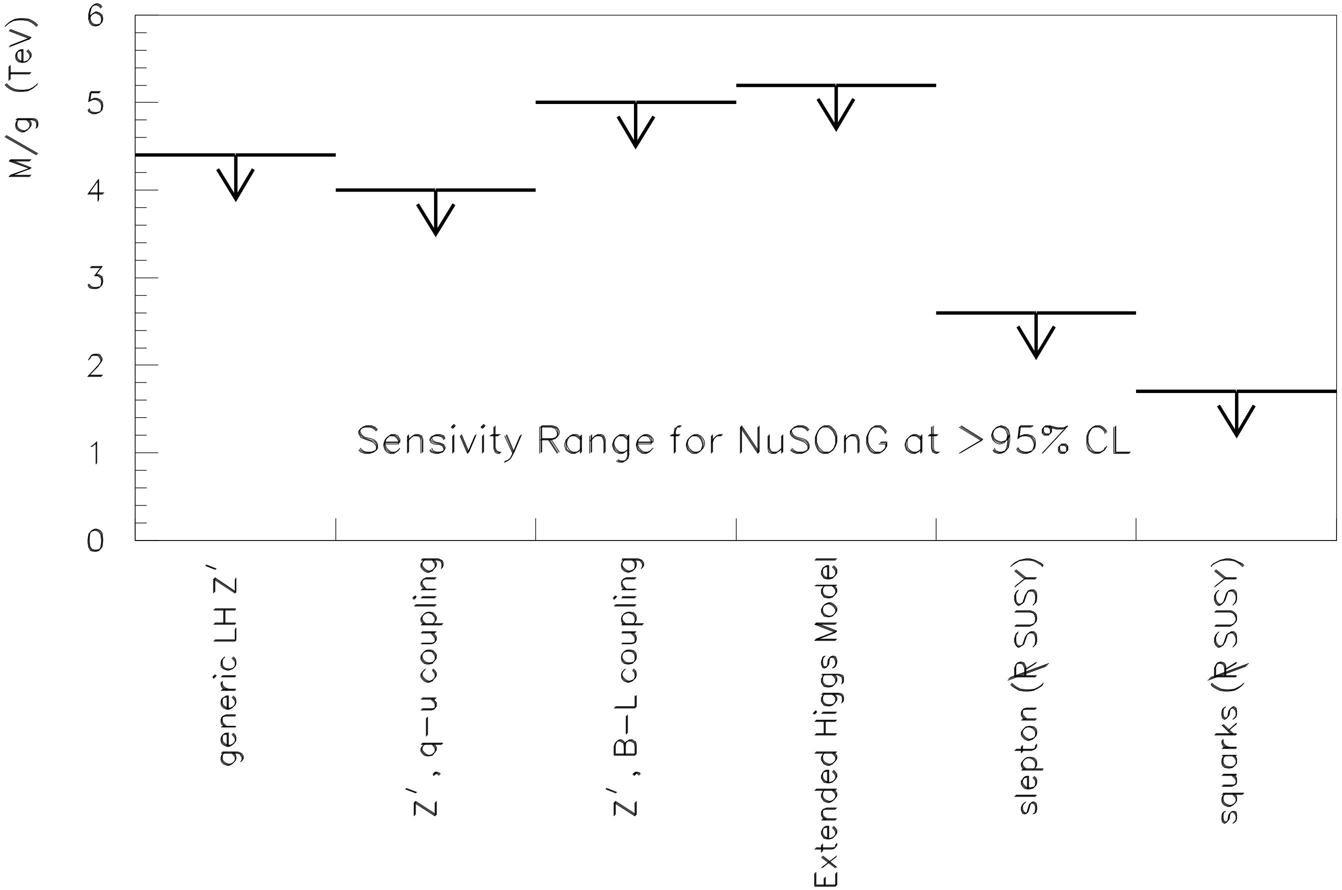
- NuSOnG neutrino quark scattering;
- Other TeV-sensitive experiments, including the LHC.

The types of new physics fall under different categories:

- They affect all "electroweak precision" observables in the same way (all loop-level effects that modify the W and Z boson propagators);
- They affect only neutrino neutral current measurements;
- They affect only neutrino-quark or neutrino-lepton measurements;
- . . .

Examples:

New Heavy Physics



Model	Contribution of NuSOnG Measurement
Typical Z' Choices: $(B-xL)$,$(q-xu)$,$(d+xu)$	At the level of, and complementary to, LEP II bounds.
Extended Higgs Sector	At the level of, and complementary to τ decay bounds.
R-parity Violating SUSY	Sensitivity to masses ~ 2 TeV at 95% CL. Improves bounds on slepton couplings by $\sim 30\%$ and on some squark couplings by factors of 3-5.
Intergenerational Leptoquarks with non-degenerate masses	Accesses unique combinations of couplings. Also accesses coupling combinations explored by π decay bounds, at a similar level.

TABLE VI: Summary of NuSOnG's contribution in the case of specific models

A little on Structure Function Measurements (see reference 3!)...

What makes NuSOnG special?

1) We have an accurate flux measurement! (via IMD events)
2) We have an enormous number of DIS events!

Method: Pick an x and Q^2 bin
Plot the data as a function of y
Vary the structure functions to
get the same y-distribution

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

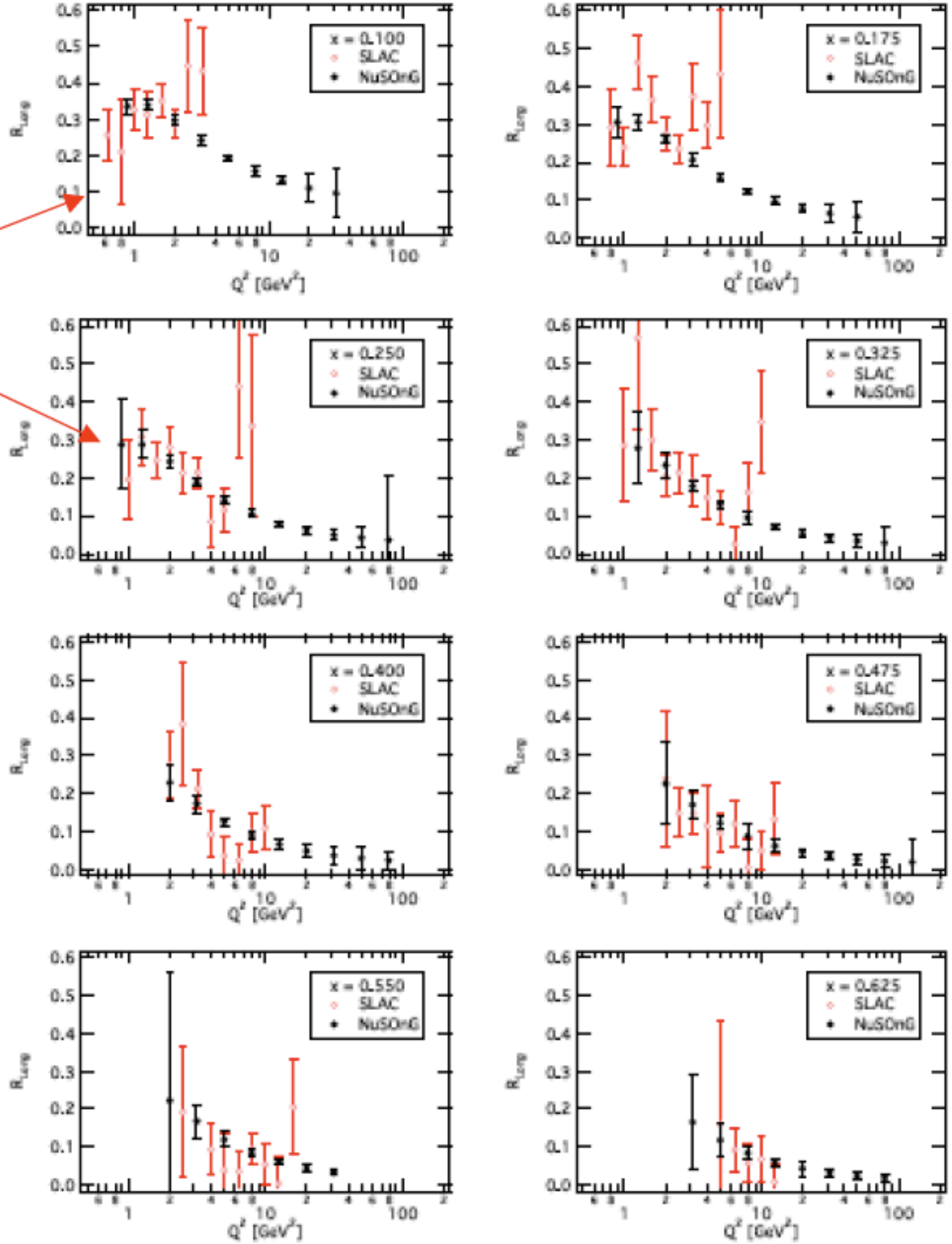
[from J. Conrad's talk at Nufact2009]

Tremendous improvement over past experiments!

$R=\sigma_L/\sigma_T$ in x and Q^2

WOW!

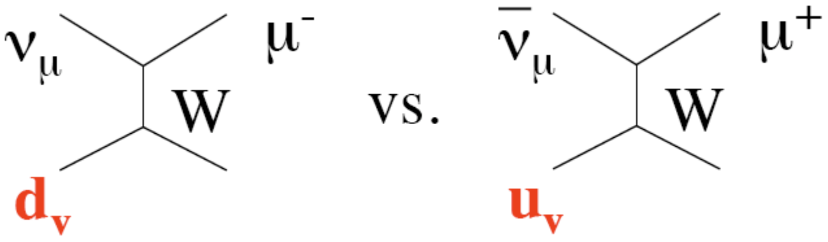
[J. Conrad, Nufact2009]



Understanding Valence Quarks and Isospin Breaking: step towards understanding the NuTeV Anomaly

Another interesting question
(important for the electroweak studies…

Is this:



being modeled correctly?

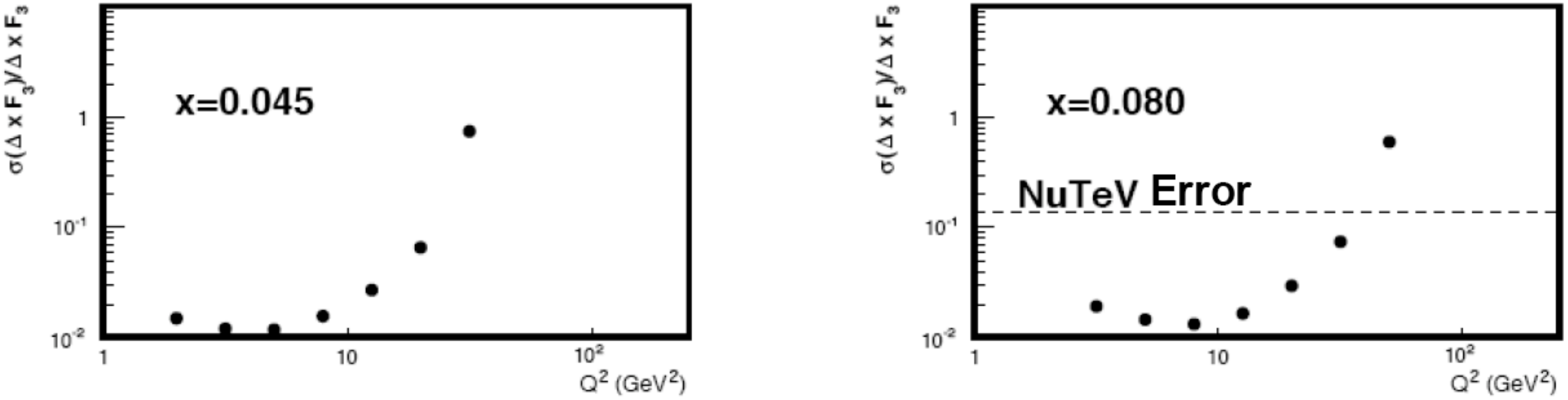
This is extracted from

$$\Delta xF_3 = xF_3^{\nu} - xF_3^{\bar{\nu}}$$

[J. Conrad, Nufact2009]

The existing data on $\Delta x F_3$ is sparse and imprecise

NuSOnG can measure this in a model-independent way!
$\Delta x F_3$ is extracted from a simultaneous fit to ν and $\bar{\nu}$ data



The NuSOnG measurements will be very high precision!

[J. Conrad, Nufact2009]

Summary and Conclusions

- A large, well-understood sample of $\nu_\mu + e$ ES events should prove to be a powerful tool for exploring TeV scale new physics. NuSOnG aims at (at least) an order of magnitude more events than all previous neutrino experiments combined.
- Any new physics result at NuSOnG should prove to be complementary to anything we may discover at the LHC – including only a standard model Higgs boson! NuSOnG will likely help elucidate the nature of the new physics discovered at the LHC.
- By measuring $\nu_\mu + e$ and $\nu_\mu + q$, NuSOnG can test most new physics interpretations of the NuTeV anomaly.
- Record number of $\nu_\mu + q$ DIS events allow not only precision electroweak measurements and sensitivity to new physics but also several key QCD measurements (structure functions as a funciton of x and Q^2, including xF_3, etc).

- An experiment like NuSOnG can (only) be performed "right now" at Fermilab. No one else has the Tevatron accelerator! Different future possibility is the SPS+ at CERN (TeV proton machine to feed the LHC). REMEMBER: key ingredient to understand the flux is IMD $\rightarrow$ high energy neutrinos!

- NuSOnG would serve as a great flagship experiment for a next-generation of Tevatron-based fixed target experiments.

	# Detected to Date, All Energies, All Detectors	# Expected at NuSOnG, All Energies
$\nu_\mu, \bar{\nu}_\mu$	$< 20 \times 10^6$	$> 600 \times 10^6$
$\nu_e, \bar{\nu}_e$	$< 0.5 \times 10^6$	$> 6 \times 10^6$
$\nu_\tau, \bar{\nu}_\tau$	**10**	OPPORTUNITY?