NuSOnG

A High-Statistics, High-Energy Neutrino Scattering Experiment at Fermilab

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NuFACT'08,Valencia,Spain

Valencia, 3 July 08

Outline

I. **Introducing NuSOnG** (What, Why, How, Where,...)

II. **Physics Opportunities** (QCD, EW Precision, Searches,...)

III. **Conclusions** (Unique experiment,...)

Reference: arXiv:0803.0354 (to appear in PRD)

http://www-nusong.fnal.gov

I. Introducing NuSOnG

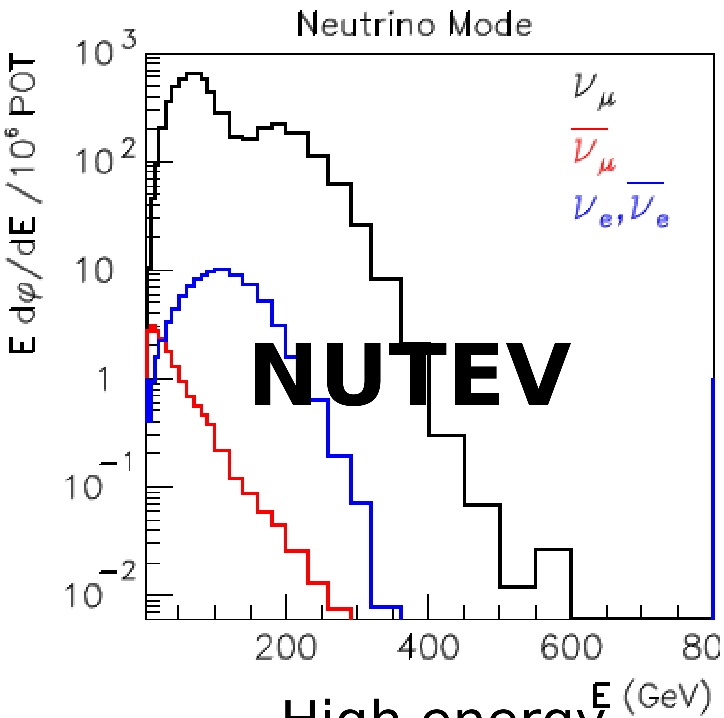
NuSOnG: **Neu**trino **S**cattering **On G**lass

A proposed new fixed-target neutrino experiment at FNAL

- High Energy: 800 GeV protons from the Tevatron
- High Statistics: high intensity, sign-selected beam, large detector
- Leptonic Processes: large fine-grained detector to measure outgoing electrons with good resolution
- High Precision: “ratio-like” measurements

The Experimental Design

Go beyond the best of the NuTeV and CHARM II experiments



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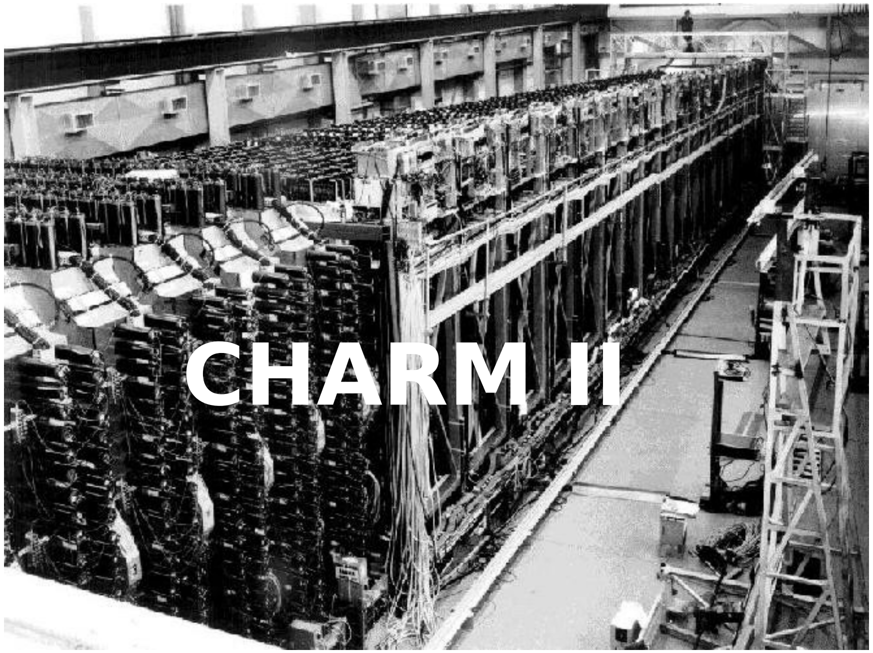


High energy,
very pure beam
(×20 POT)

Fine-grained,
massive detector
(×6 mass)

Physics in this talk assumes 1.5E20 POT in ν , 0.5E20 POT in $\bar{\nu}$

NuSOnG will measure:

- NC ES

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

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

Goal:

ν_μ-ES/IMD at 0.7% precision!

- CC QE (IMD)

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

- NC DIS

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

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

- CC DIS

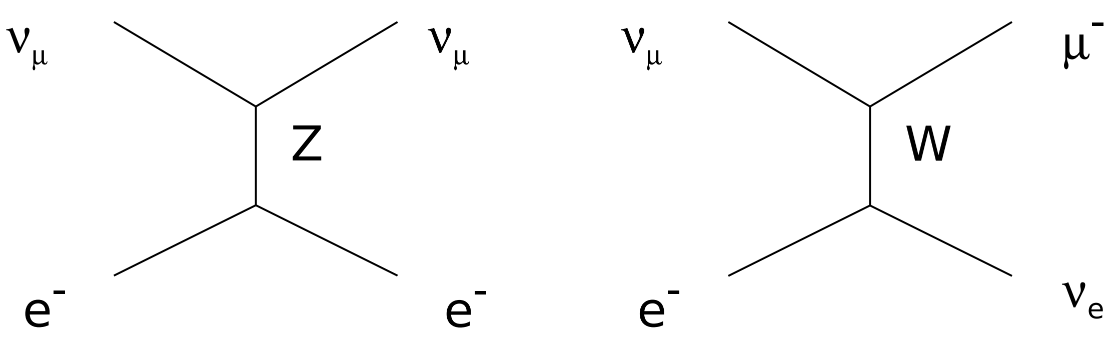
$$\nu_\mu + q \rightarrow \mu^- + X$$

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

Expected NuSOnG Event Rates (5 yr Run)

600M	ν_μ CC Deep Inelastic Scattering	x100 NuTeV
190M	ν_μ NC Deep Inelastic Scattering	
75k	ν_μ electron NC elastic scatters	x20 CHARM II
700k	ν_μ electron CC quasielastic scatters (IMD)	x40 CHARM II
33M	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering	
12M	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering	
7k	$\bar{\nu}_\mu$ electron NC elastic scatters	
0k	$\bar{\nu}_\mu$ electron CC quasielastic scatters	

A unique opportunity for precision measurements in these channels!



Leptonic Precision Observables

$$\nu_\mu + e^- \longrightarrow \nu_\mu + e^-$$
$$\bar{\nu}_\mu + e^- \longrightarrow \bar{\nu}_\mu + e^-$$

- **NC ES:** y-spectra **and** total x-secs

leptonic: very clean SM physics, but lower statistics

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

$$\sigma = \frac{G_F^2 m_e E_\nu}{2\pi}\left[(g_V^{\nu e} \pm g_A^{\nu e})^2 + \frac{1}{3}(g_V^{\nu e} \mp g_A^{\nu e})^2\right]$$

$$(g_V^{\nu e} \pm g_A^{\nu e})^2 = \rho^2(1 - 4s_w^2 + 4s_w^4)\,,\ (g_V^{\nu e} \mp g_A^{\nu e})^2 = \rho^2(4s_w^4)$$

$$\sigma(\nu_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi}\rho^2\left[1 - 4s_w^2 + \frac{16}{3}s_w^4\right]$$
$$\sigma(\bar{\nu}_\mu e) = \frac{G_F^2 m_e E_\nu}{2\pi}\rho^2\left[\frac{1}{3} - \frac{4}{3}s_w^2 + \frac{16}{3}s_w^4\right]$$

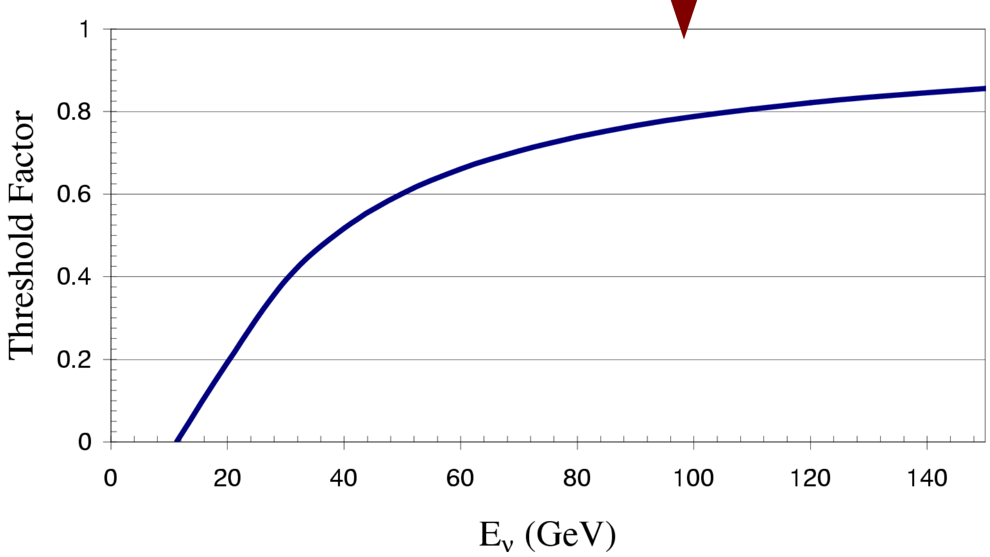
- **CC QE (IMD):**

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

Well determined in the SM from muon decay!

$$\frac{d\sigma}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi} 4 \times (1 - \frac{m_\mu^2}{2 m_e E_\nu})$$

$$\sigma = \frac{G_F^2 m_e E_\nu}{2\pi} 4 \times (1 - \frac{m_\mu^2}{2 m_e E_\nu})^2$$



IMD requires high energy flux!

Tevatron-based beam necessary

Rem:
IMD has interesting kinematic property:
E_mu(lab) > 10.9 GeV!

Ratios for precision measurements:

$$R_{\nu/\bar{\nu}} = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3\,\frac{1-4s_w^2+\frac{16}{3}s_w^4}{1-4s_w^2+16s_w^4}$$

NEW

$$R_{\mathrm{ES/IMD}} = \frac{\sigma(\nu_\mu e)}{\sigma(\mathrm{IMD})} = \rho^2\left[\frac{1}{4} - s_w^2 + \frac{4}{3}s_w^2\right](1 - \frac{m_\mu^2}{2m_e E_\nu})^{-2}$$

R_ES/IMD rather unique!

- Fluxes in the numerator and denominator **cancel exactly**!
- rho-Parameter not canceled. Sensitive to NP!
- Only possible with **high-energy neutrino flux** due to IMD threshold

For a review of radiative corrections to ES and IMD see: hep-ph/0403168

Hadronic Precision Observables

$$R^{\nu} = \frac{\sigma^{\nu}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}}} \simeq g_L^2 + r g_R^2$$

$$R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\bar{\nu}}_{\mathrm{CC}}} \simeq g_L^2 + r g_R^2$$

$$r = \frac{\sigma^{\bar{\nu}}_{\mathrm{CC}}}{\sigma^{\nu}_{\mathrm{CC}}}$$

g_L and g_R are effective L and R νq couplings

$$g_L^2 = \rho^2\left(\frac{1}{2} - s_w^2 + \frac{5}{9}s_w^4\right)$$

$$g_R^2 = \rho^2\left(\frac{5}{9}s_w^4\right)$$

Paschos-Wolfenstein (PW):

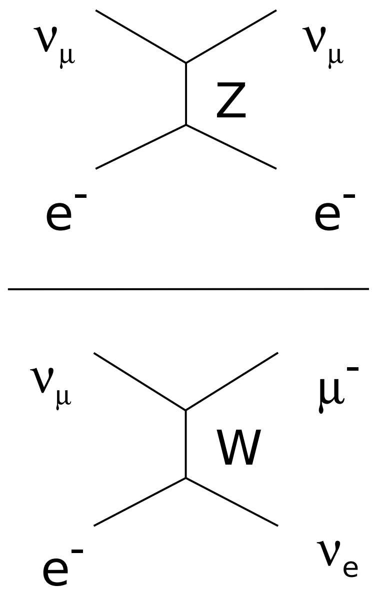
$$R^{-} = \frac{\sigma^{\nu}_{\mathrm{NC}} - \sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}} - \sigma^{\bar{\nu}}_{\mathrm{CC}}} \simeq g_L^2 - g_R^2 = \rho^2\left(\frac{1}{2} - s_w^2\right)$$

Much higher statistics, but involves hadrons/nuclei!

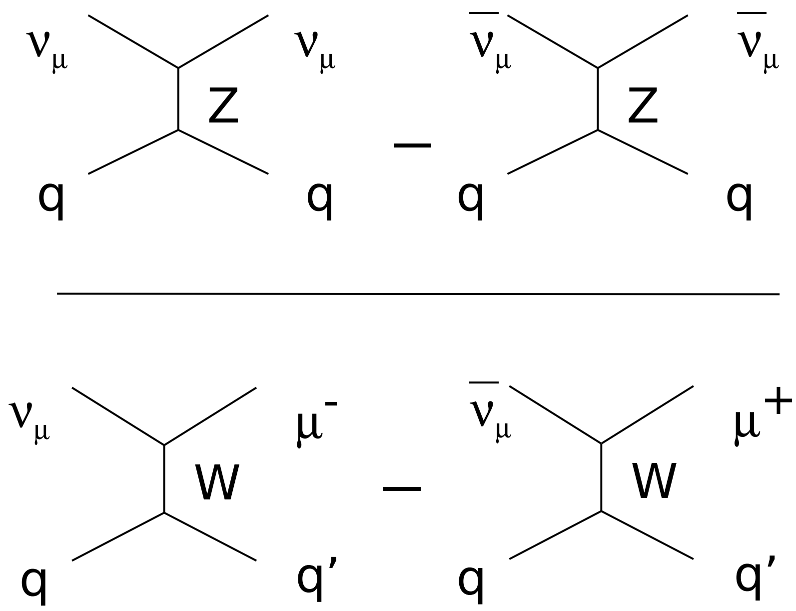
NuSOnG measurement goals

New!

R_ES/IMD



Purely leptonic



R^-

NuTeV-style
“Paschos-Wolfenstein”

goal: 0.7% error

goal: 0.4% error

Furthermore:

- Measure $\sigma(\bar{\nu}_\mu e)$ to 1.3%

(normalized to IMD using the 'low nu method')

- Reduce the error on the DIS effective couplings by a factor 2:

$$\begin{aligned} \Delta g_L^2 &= 0.0007 \\ \Delta g_R^2 &= 0.0006 \end{aligned}$$

- Goals are based on detailed, conservative estimates It is likely to obtain even better precision!

see, arXiv:0803.0354

Source	NuTeV Error	Method of reduction in NuSOnG
Statistics	0.00135	Higher statistics
ν_e, $\bar{\nu}_e$ flux prediction	0.00039	Improves in-situ measurement of $\bar{\nu}_e$ CC scatters, thereby constraining prediction, due to better lateral segmentation and transverse detection. Also, improved beam design to further reduce $\bar{\nu}_e$ from K^0.
Interaction vertex position	0.00030	Better lateral segmentation.
Shower length model	0.00027	Better lateral segmentation and transverse detection will allow more sophisticated shower identification model.
Counter efficiency and noise	0.00023	Segmented scintillator strips of the type
		developed by MINOS [22] will improve this.
Energy Measurement	0.00018	Better lateral segmentation.
Charm production, strange sea	0.00047	In-situ measurement, See Sec. VI.
R_L	0.00032	In-situ measurement, see Sec. VI.
$\sigma^{\bar{\nu}}/\sigma^{\nu}$	0.00022	Likely to be at a similar level.
Higher Twist	0.00014	Recent results reduce this error [23].
Radiative Corrections	0.00011	New analysis underway, see text below.
Charm Sea	0.00010	Measured in-situ using wrong-sign muon production in DIS.
Non-isoscalar target	0.00005	Glass is isoscalar

TABLE IV: Source and value of NuTeV errors on $\sin^2\theta_W$, and reason why the error will be reduced in the PW-style analysis of NuSOnG. This paper assumes NuSOnG will reduce the total NuTeV error by a factor of two. This is achieved largerly through the improved statistical precision and requires only a 90% reduction in the overal NuTeV systematic error. This table argues that a better than 90% reduction is likely, but further study, once the detector design is complete, is required.

II. NuSOnG Physics Opportunities

- **EW precision measurements** [see part I.]
  - in the leptonic sector
  - in the hadronic sector

- **EW precision measurements provide**
  - tests of the SM; indirect probes of New Physics
  - model-independent constraints on NP
  - model-dependent constraints on NP (of course)

- **QCD studies**
- **Direct Searches of New Physics**

Model-independent Constraints on NP

Topic	Contribution of NuSOnG Measurement
Oblique Corrections	Four distinct and complementary probes of S and T. In the case of agreement with LEP/SLD: ∼25% improvement in electroweak precision.
Neutrino-lepton NSIs	Order of magnitude improvement in neutrino-electron effective couplings measurements. Energy scale sensitivity up to $\sim$ 5 TeV at 95% CL.
Neutrino-quark NSIs	Factor of two improvement in neutrino-quark effective coupling measurements. Energy scale sensitivity up to $\sim$ 7 TeV at 95% CL.
Mixing with Neutrissimos	30% improvement on the e-family coupling in a global fit. 75% improvement on the μ-family coupling in a global fit.
Right-handed Couplings	Complementary sensitivity to g_R/g_L compared to LEP. Order of magnitude improvement compared to past experiments.

TABLE V: Summary of NuSOnG's contribution to general Terascale physics studies.

A lot of exciting physics!

see talk by A. de Gouvea in WG2

Model-dependent Constraints on NP

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

Any explanation for new physics found at the LHC **has to be consistent with (ew) precision measurements!**

Precision measurements serve as Lie Detectors (Polygraphs)!

Also the little lies of the SM will be detected...if there are any

see talk by A. de Gouvea

QCD studies with NuSOnG

- NuSOnG can do all what NuTeV/CCFR could, but better: fine-grained detector, very high statistics

Experiment	ν DIS events	$\bar{\nu}$ DIS events	main target	isoscalar correction
CCFR	0.95M	0.17M	iron	5.67% [77]
NuTeV	0.86M	0.24M	iron	5.74% [78]
NuSOnG	606M	34M	glass	isoscalar

- Some QCD-studies are <u>required</u> for the ew precision measurements in the hadronic sector [strangeness asymmetry, isospin violation, nuclear effects]

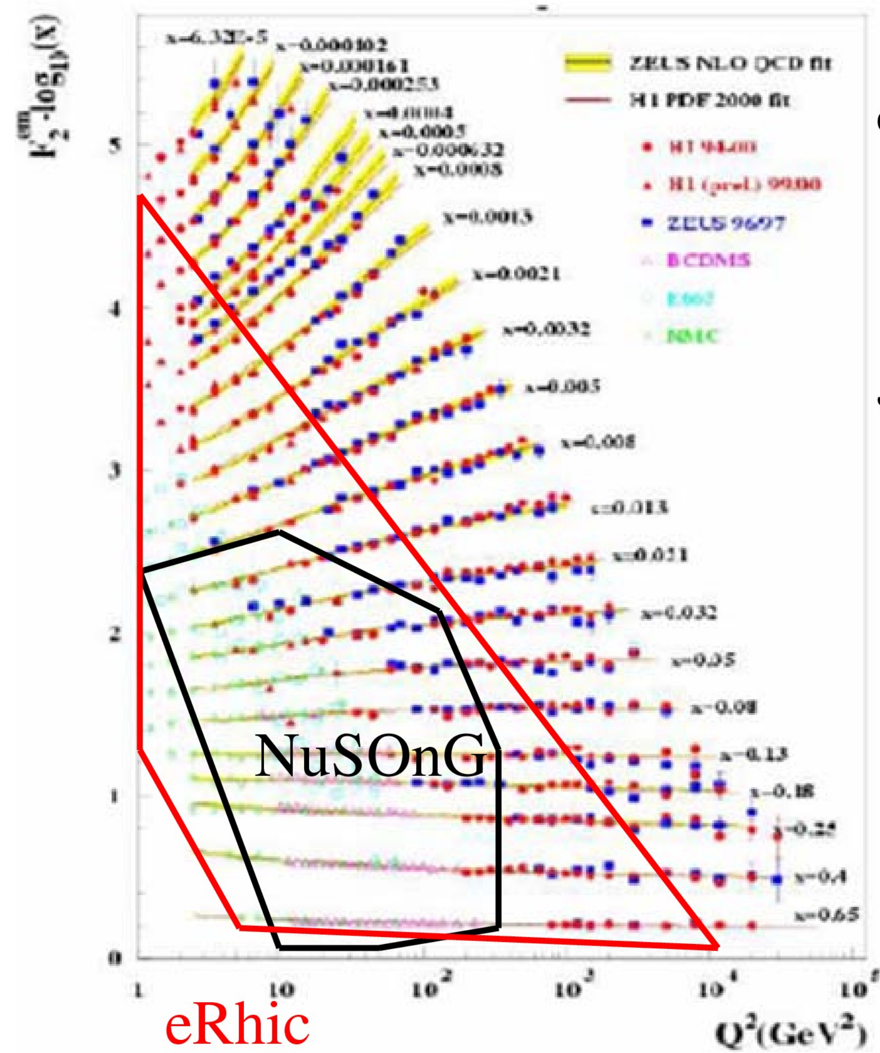
- NuSOnG will have several targets: The kinematic range matches eRHIC and complements Minerva

$$SiO_2 \, , C \, , Al \, , Fe \, , Pb$$

CHORUS (→ Pb)

NuTeV (→ Fe)

Kinematic coverage of NuSOnG



Figures courtesy J. Conrad

Observables

Differential fully inclusive DIS cross section:

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

High statistics: Measurement of **all** 6 structure functions!

→ Flavor separation of the PDFs! (wide kinematic range)

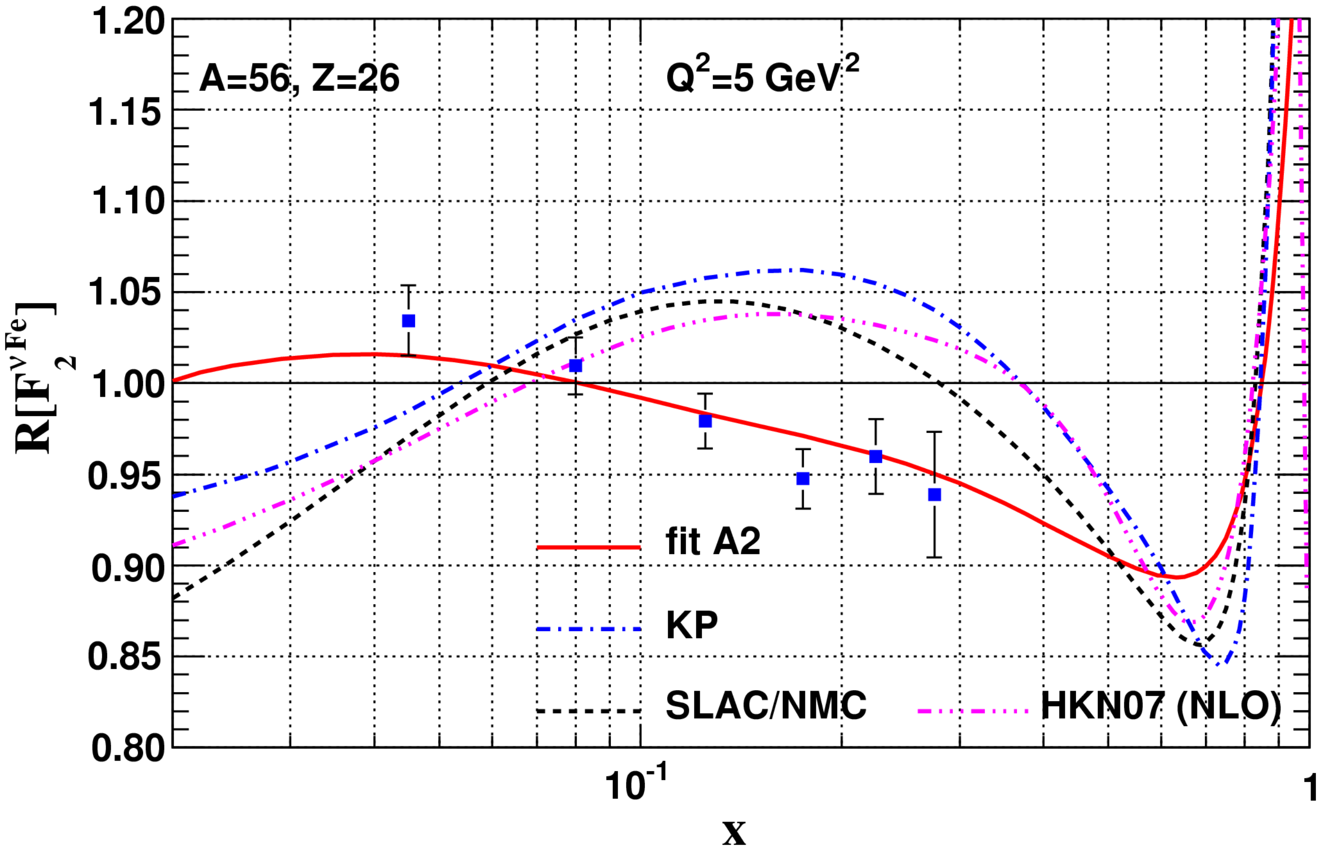
NOTE: These are nuclear structure functions and nuclear PDFs (NPDF)

However, the data are very interesting for the global proton PDF fits

Need to understand nuclear effects: **use different targets**

Nuclear correction factors for F_2(iron)

Are nuclear corrections in charged-lepton and neutrino DIS different?



Note that the correction factors for different observables are expected to differ!

Correction factor for F_3 could be different!

NuSOnG can study these issues and test the universality of the NPDFs! **VERY IMPORTANT**

see talk by Jorge Morfin, WG2

Observables -cont-

<u>Inclusive charm production:</u> 'opposite sign dimuon events'

$$\nu_\mu + N \rightarrow \mu^- + c + X$$
$$\hookrightarrow s + \mu^+ + \nu_\mu$$

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + \bar{c} + X$$
$$\hookrightarrow \bar{s} + \mu^- + \bar{\nu}_\mu$$

$$s + W^+ \rightarrow c$$

$$\bar{s} + W^- \rightarrow \bar{c}$$

- Directly sensitive to the strange quark PDF
- <u>Sign-selected beam</u>: independent meas. of $s(x), \bar{s}(x)$
- ~1% of the total CC event sample! High statistics!
- Allows also extraction of charm quark mass, V_cd, semileptonic branching ratio B_c~10%

xF_3 and Isospin Violation

- xF_3 uniquely determined by neutrino-DIS

$$\frac{1}{2}F_3^{\nu A}(x) = d_A + s_A - \bar{u}_A - \bar{c}_A + ...,$$
$$\frac{1}{2}F_3^{\bar{\nu} A}(x) = u_A + c_A - \bar{d}_A - \bar{s}_A + ...$$

- The sum is sensitive to the valence quarks

→ Nonsinglet QCD evolution, determination of $\alpha_s(Q)$

- The difference can be used to constrain isospin violation

$$\Delta xF_3 = xF_3^{\nu A} - xF_3^{\bar{\nu} A} = 2xs_A^+ - 2xc_A^+ + x\,\delta I^A + \mathcal{O}(\alpha_S)$$
$$\delta I^A = \left(d_{p/A} - u_{n/A}\right) + \left(d_{n/A} - u_{p/A}\right) + \left(\bar{d}_{p/A} - \bar{u}_{n/A}\right)\left(\bar{d}_{n/A} - \bar{u}_{p/A}\right)$$

QCD for PW-style analysis

$$R^- = \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} \simeq \frac{1}{2} - s_w^2 + \delta R_A^- + \delta R_{QCD}^- + \delta R_{EW}^-$$

- δR_A^-: non-isoscalarity of the target
- δR_{QCD}^-: QCD effects
- δR_{EW}^-: higher order ew effects

NuSOnG can address this in-situ with high precision!

$$\delta R_{QCD}^- = \delta R_s^- + \delta R_I^- + \delta R_{NLO}^-$$

- δR_s^-: due to strangeness asymmetry: $s^- \equiv s - \bar{s} \neq 0$
- δR_I^-: due to isospin violation: $u^p(x) \neq d^n(x)$
- δR_{NLO}^-: higher order QCD effects

see, e.g., hep-ph/0405221

QCD studies: Summary

NPDFs, Nuclear correction factors, neutrino vs antineutrino,

PDFs, strange PDF, strangeness asymmetry,Isospin violation,

precise strong coupling constant,

all 6 neutrino structure functions,
low-x and low-Q structure functions,
diffractive charm production, NC charm production,

Fragmentation functions (?),

V_cs, B_c

A RICH Program

Direct Searches of NP

- Search for IMD in the anti-neutrino mode:

$$\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$$

forbidden in the SM

- Non-unitarity of the neutrino mixing matrix

- Searches for new particles observed through decays in the regions between the detector subsections

Direct Tests for New Physics
e.g. “Matrix Freedom”

Nonunitarity of the 3 neutrino mixing matrix

$$\sum_j |U_{\alpha j}|^2 = 1 - X_\alpha,$$

hep-ph/0705.0107

$$P^{general}_{\alpha\alpha} = P^{unitary}_{\alpha\alpha} - 2X_\alpha[1 - 2|U_{\alpha 3}|^2 \sin^2 \Delta_{31}] + X^2_\alpha.$$

L/E dependent

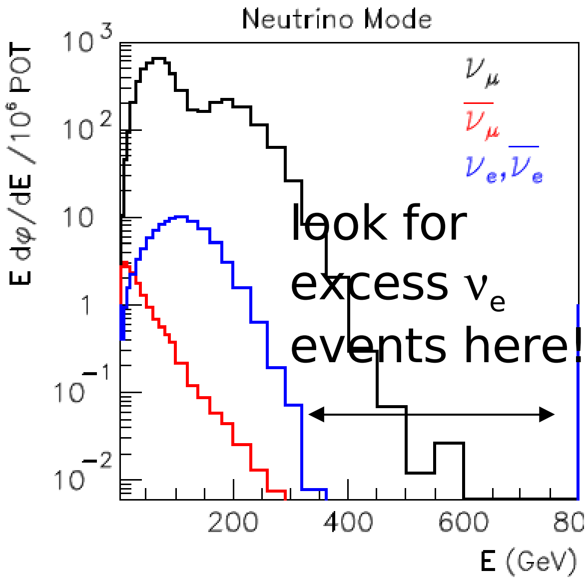
Not!

Appearance has same effect!

At L=0 there will be an instantaneous transition between neutrino species!

Strongest constraints (from rare decays) for instantaneous $\nu_\mu \rightarrow \nu_e$ are at the 1×10^{-4} level

- Look for excess ν_e's in a range not expected



Instantaneous $\nu_\mu \rightarrow \nu_e$
at the 1×10^{-4} level
gives an ~10% increase
in ν_e rate at E_ν~350 GeV

Seeing both would be a striking signature!

- Look for "wrong sign" IMD

$\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$ -- this should not occur!

But if $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, then $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$ … same signature!

improve the present limit by a factor of 10,

and reach few x 10^{-4} level

Unique Capability!

III. Conclusions

NuSOnG can

- perform ew precision measurements in **both** the leptonic and hadronic sector
- test the SM and constrain new physics at the TeV scale
- make important QCD measurements (PDFs, NPDFs are needed in many experiments...)
- perform direct searches for new physics