The Terascale Physics Reach of NuSOnG

William Loinaz for NuSOnG

Amherst College

Pheno 2008, Madison WI

Outline

- Impressive INDIRECT new physics reach of NuSOnG
  - model-independent analysis
  - consider specific models
- Plays well with others (LHC)

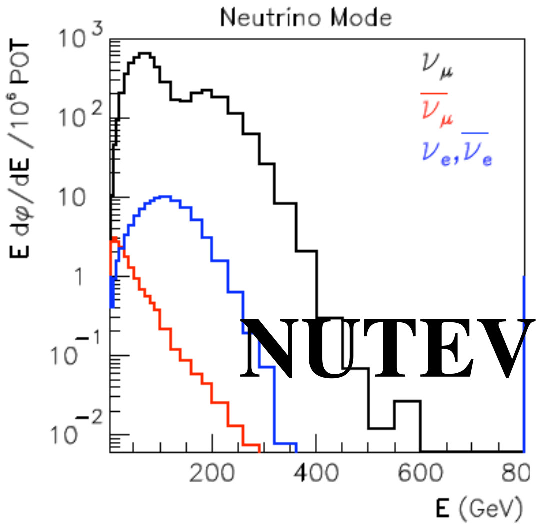
References

- arXiv:0803.0354 (accepted by PRD)

  Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG

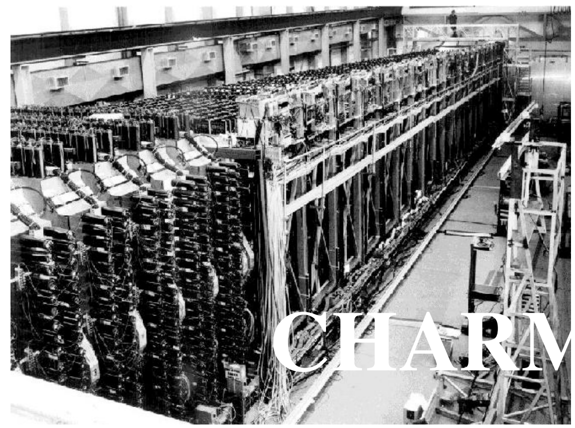
- NuSOnG EoI: http://www-nusong.fnal.gov

A high-statistics, high energy neutrino experiment…



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 $\overline{\nu}$

NuSOnG will measure…

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^- \quad \text{ES}$$
$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$
$$\nu_\mu + q \rightarrow \nu_\mu + X \quad \text{DIS}$$
$$\bar{\nu}_\mu + q \rightarrow \bar{\nu}_\mu + X$$
$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e \quad \text{IMD}$$

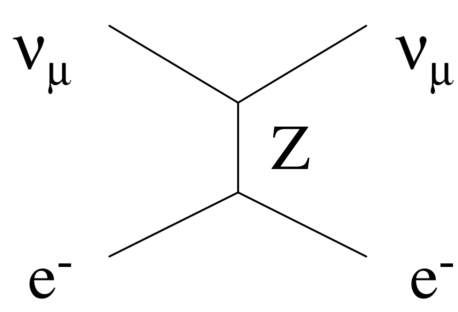
…with high precision. target:

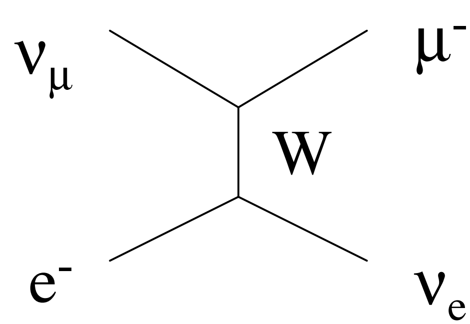
- neutrino ES/IMD at 0.7%
- cut NuTeV errors in half

Very high statistics!

600M	ν_μ CC Deep Inelastic Scattering
190M	ν_μ NC Deep Inelastic Scattering
75k	ν_μ electron NC elastic scatters
700k	ν_μ electron CC quasielastic 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
0k	$\bar{\nu}_\mu$ electron CC quasielastic scatters

A unique opportunity for these channels!





SM: simple expressions in terms of a few parameters

[ρ, $\sin^2\theta_W$ are predicted by precision EW data]

leptonic:
very clean
SM physics,
but lower
statistics

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

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

ES

$$\frac{d\sigma_{IMD}}{dy} = \frac{G_F^2(s - m_\mu^2)}{\pi(1 - q^2/M_W^2)^2}$$

IMD

DIS:
hadron /
nuclear
more complex,
but more events

$$R^\nu = \frac{\sigma_{NC}^\nu}{\sigma_{CC}^\nu} = g_L^2 + r\, g_R^2 ,$$

$$R^{\bar{\nu}} = \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\bar{\nu}}} = g_L^2 + \frac{1}{r}\, g_R^2 ,$$

$$r = \frac{\sigma_{CC}^{\bar{\nu}}}{\sigma_{CC}^\nu},$$

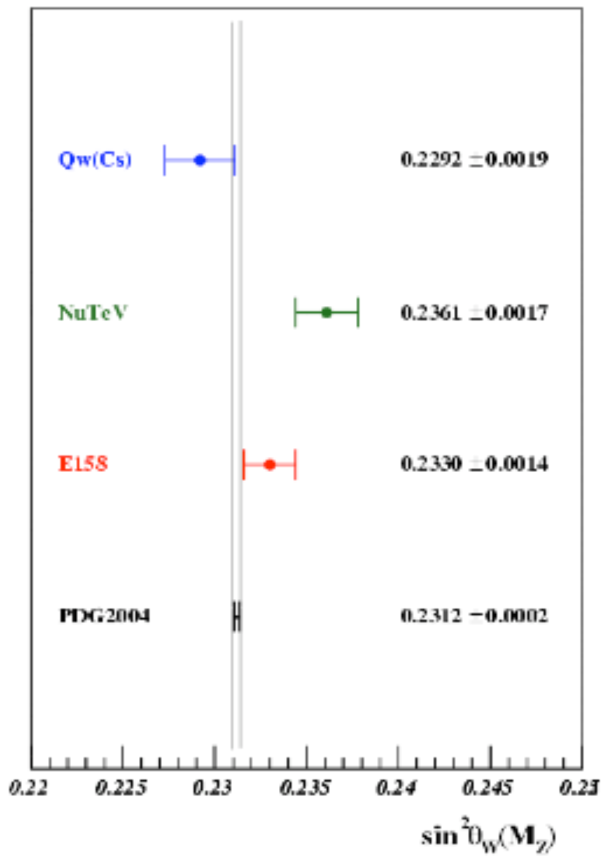
$$g_L^2 = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\right),$$

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

$g_L^{\,2}$ and $g_R^{\,2}$ are effective L and R νq couplings before jumping into NP…

NuTeV anomaly: new physics or old physics?

NuTeV (neutrino DIS) finds $\sin^2\theta_W$ 2.7σ above predictions



Many issues must be addressed by neutrino expts

- SM explanations
  - strange sea asymmetry
  - radiative corrections
  - isospin asymmetry
- BSM explanations

[Updated NuTeV analysis this summer]

<u>NuSOnG</u> will help clarify

– will cut NuTeV errors in half for (anti-)ν-q scattering

– can measure $\sin^2\theta_W$ in both νe and νq channels

$\sin^2\theta_W$ at NuSOnG

Measurements using both neutrino-electron and neutrino quark scattering techniques

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 will improve this.
Energy Measurement	0.00018	Better lateral segmentation.
Charm production, strange sea	0.00047	In-situ measurement.
R_L	0.00032	In-situ measurement.
$\sigma^{\bar{\nu}}/\sigma^{\nu}$	0.00022	Likely to be at a similar level.
Higher Twist	0.00014	Recent results reduce this error.
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

NuSOnG (self-consistently) addresses SM physics issues to search for new physics

Looking for new physics (indirectly)

a few (quasi) model-independent approaches..

- Oblique Corrections
- Neutrino-lepton NSIs
- Neutrino-quark NSIs
- Modified neutrino-gauge boson couplings
  - Nonuniversal couplings
  - Right-handed coupling to the Z

… "generic ways" that new physics might show up

… then look at some specific models

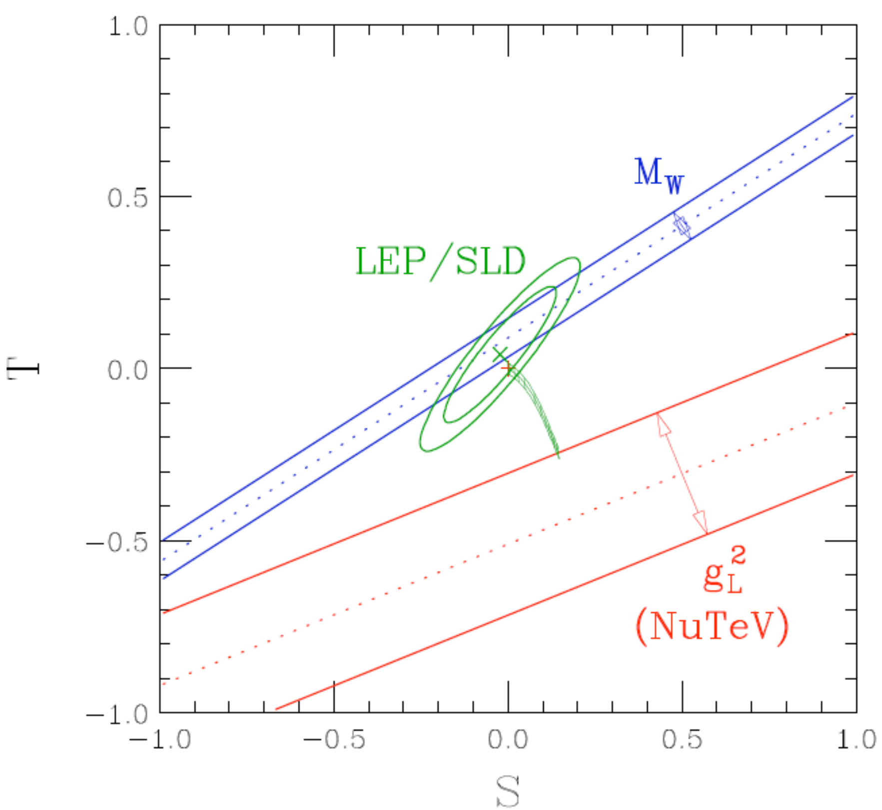
New physics through ***oblique corrections***

NP appears in vacuum polarizations only…

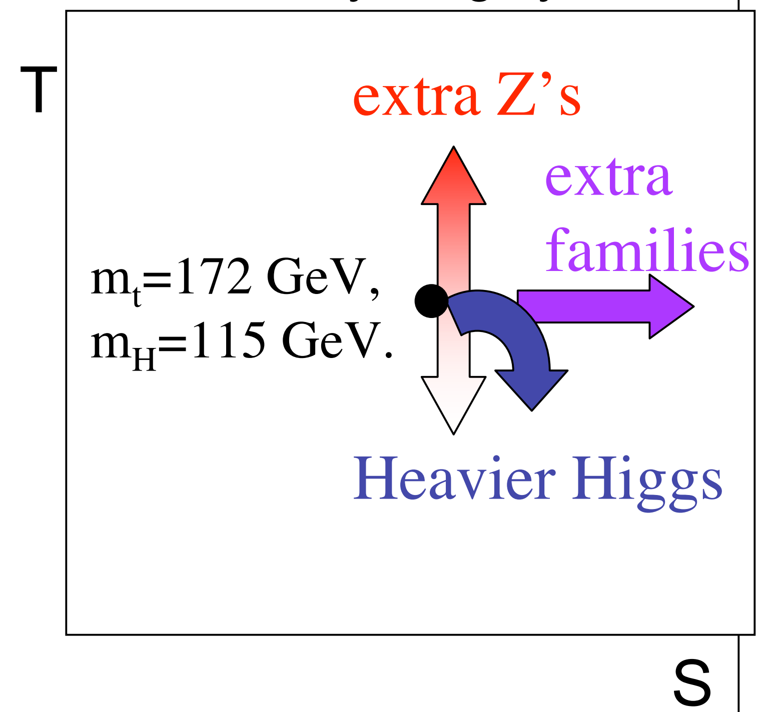
$\sin^2\theta_W$ and ρ and map to S and T:

S = weak isospin conserving

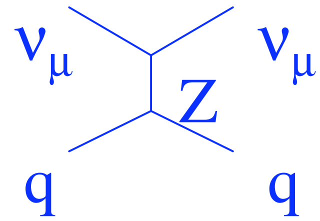
T = weak isospin violating



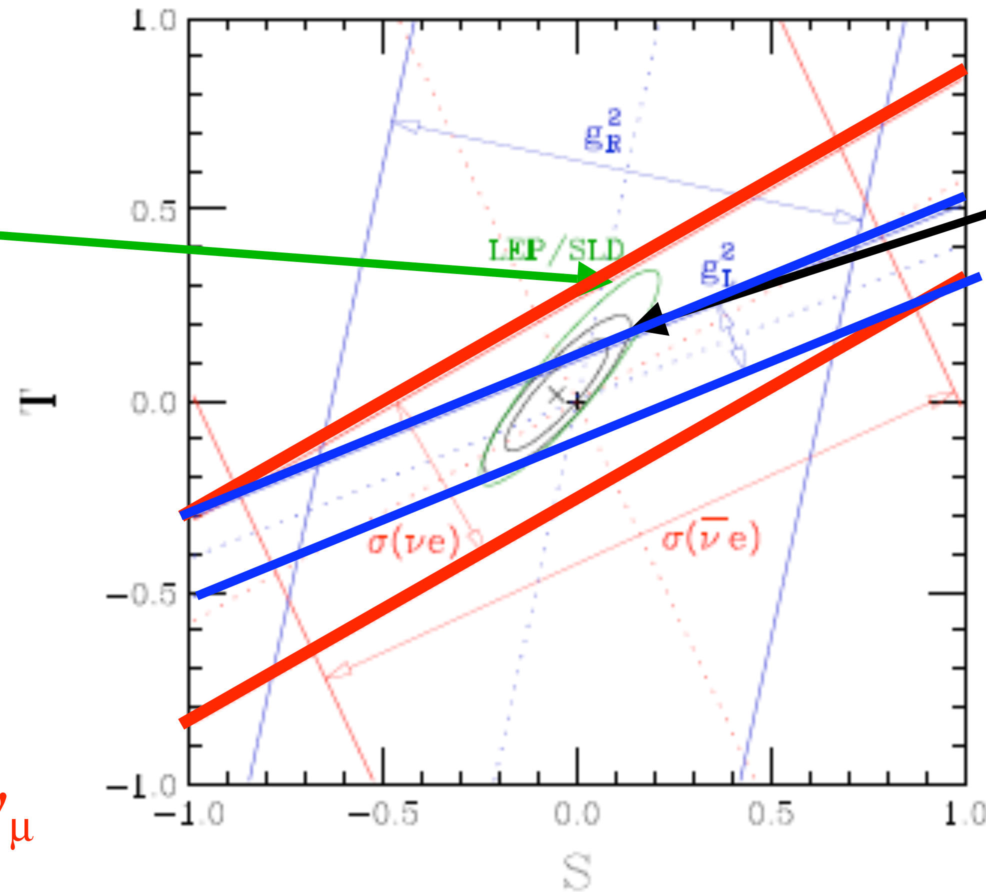
very roughly:



NuSOnG improves oblique correction constraints

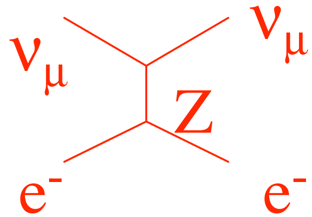


Present status



If NuSOnG agrees with the SM

NuSOnG improves the result by ~25%

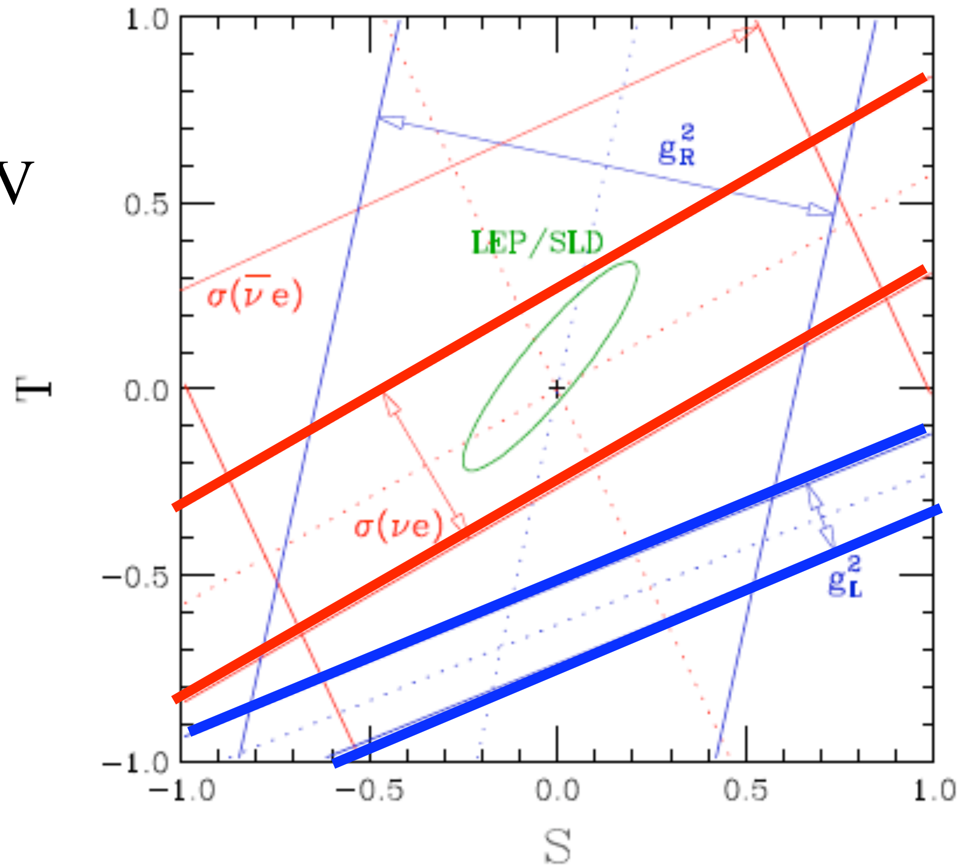


The $\sigma(\nu,e)$ and g_L^2 measurements are the strongest with the initial run-plan

But of course the more interesting case is…
disagreement with SM!

A "realistic" possibility:
NuSOnG agrees with NuTeV

a 6σ deviation from the SM
in g_L^2 only



(This particular case, where all other measurements agree with the SM, is a triplet Leptoquark)

Non-standard interactions (NSI)

NC effective Lagrangian of SM:

$$\mathcal{L} \;=\; -2\sqrt{2}G_F\left[\bar{\nu}\gamma_\mu P_L \nu\right]\left[g_L^{\nu f}\,\bar{f}\gamma^\mu P_L f + g_R^{\nu f}\,\bar{f}\gamma^\mu P_R f\right]$$

$$g_L^{\nu f} \;=\; 2 g_L^\nu g_L^f \;=\; \rho\left(I_3^f - Q^f \sin^2\theta_W\right)$$
$$g_R^{\nu f} \;=\; 2 g_L^\nu g_R^f \;=\; \rho\left(-Q^f \sin^2\theta_W\right)$$

Parametrize new physics of neutrino-fermion interactions with four-fermion effective operators:

$$\mathcal{L}_{\rm NSI} \;=\; -2\sqrt{2}G_F\left[\bar{\nu}_\alpha\gamma_\sigma P_L \nu_\beta\right]\left[\varepsilon_{\alpha\beta}^{fL}\,\bar{f}\gamma^\sigma P_L f + \varepsilon_{\alpha\beta}^{fR}\,\bar{f}\gamma^\sigma P_R f\right].$$

For $\alpha=\beta$ the ε simply shift effective couplings, so uncertainty in g corresponds to uncertainty in ε

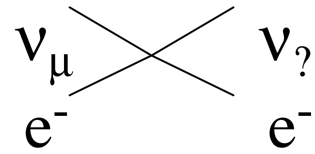
$$g_L^{\nu f} \longrightarrow \tilde{g}_L^{\nu f} = g_L^{\nu f} + \varepsilon_{\mu\mu}^{fL}$$
$$g_R^{\nu f} \longrightarrow \tilde{g}_R^{\nu f} = g_R^{\nu f} + \varepsilon_{\mu\mu}^{fR}$$

[similar framework for CC corrections]

Neutrino-lepton NSI

[CC NSI strongly constrained by muon decay]

[with more intuitive parameters]



$$\mathcal{L}^e_{\rm NSI} = \frac{4\pi}{\Lambda^2}\left(\bar{\nu}_{\alpha L}\gamma_\alpha \nu_{\mu L}\right)\left[\cos\theta\, \bar{e}_L\gamma^\alpha e_L + \sin\theta\, \bar{e}_R\gamma^\alpha e_R\right]$$

NP scale

outgoing flavor

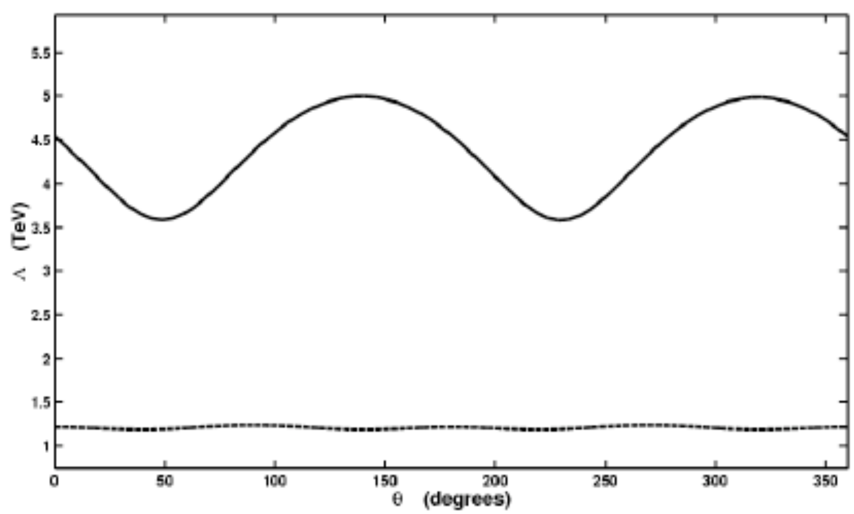
Relative mixture of handedness

Look for look new physics in:

- change cross section
- outgoing electron energy spectrum

$\Lambda/3$ (TeV)

95% CL sensitivity



if α = muon flavor
~15 TeV [elastic]

if $\alpha \neq$ muon flavor
~4 TeV ["pseudoelastic"]

Competitive with E158 (Moller scattering)

$$\mathcal{L}_{\rm new} = \pm \frac{4\pi}{2\Lambda_{LL}^{\pm 2}} \left(\bar{e}_L \gamma_\mu e_L\right) \left(\bar{e}_L \gamma^\mu e_L\right) .$$

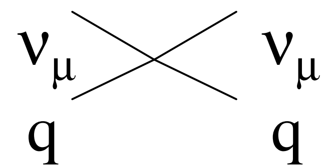
$$\Lambda_{LL}^{+} \geq 7\,\text{TeV} , \qquad \Lambda_{LL}^{-} \geq 16\,\text{TeV} .$$

[E158 only sensitive to parity-violating physics, unlike NuSOnG]

… and LLEP2 $\mathcal{L} = \pm \frac{4\pi}{\Lambda_{eP}^{\pm 2}} \left(\bar{e}_P \gamma_\sigma e_P\right) \left(\bar{\mu}_L \gamma^\sigma \mu_L\right) , \qquad P = L, R.$

	Λ_{eL}^{-}	Λ_{eL}^{+}	Λ_{eR}^{-}	Λ_{eR}^{+}
L3	3.8 TeV	8.5 TeV	2.0 TeV	6.5 TeV
OPAL	7.3 TeV	8.1 TeV	6.3 TeV	6.3 TeV
DELPHI	7.6 TeV	7.3 TeV	2.0 TeV	6.3 TeV
ALEPH	9.5 TeV	6.6 TeV	2.0 TeV	6.1 TeV

What about neutrino-quark NSI's ?



NC: $$\mathcal{L}_{\rm NSI} = (\bar{\nu}_{\alpha L}\gamma_\alpha \nu_{\mu L})\left[\frac{4\pi}{\Lambda^2_{qL}}\bar{q}_L\gamma^\alpha q_L + \frac{4\pi}{\Lambda^2_{qR}}\bar{q}_R\gamma^\alpha q_R\right]$$

We consider only the flavor conserving case, $\alpha=\mu$

Sensitivity ranges from $\Lambda\sim$ 9 to 21 TeV

coupling:	present constraint (TeV)	NuSOnG factor improvement
uL	< 14	× 1.4
dL	< 15.5	× 1.4
uR	< 10.5	×1.35
dR	< 7	×1.35

[careful: if corresponding CC NSI exists, had better be included!]

Modify neutrino-gauge boson couplings

SM singlet fermions with mass > $M_Z/2$ (neutrissimos). Sterile states mix with active neutrinos, suppress gauge couplings

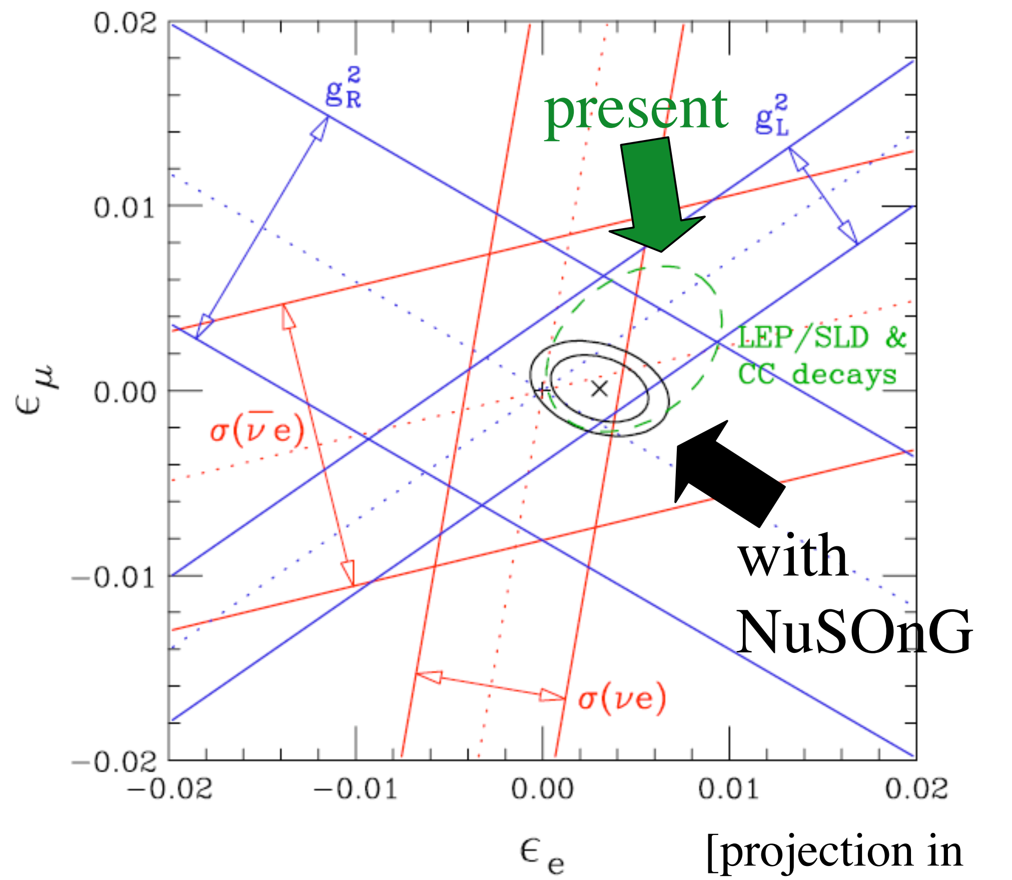
$$\epsilon_\ell \equiv 1 - \cos^2\theta_\ell$$

The CC coupling is modified by: $\frac{\epsilon_\ell}{2}$

The NC coupling is modified by: ϵ_ℓ

NC and CC corrections from neutrino-neutrissmo mixing

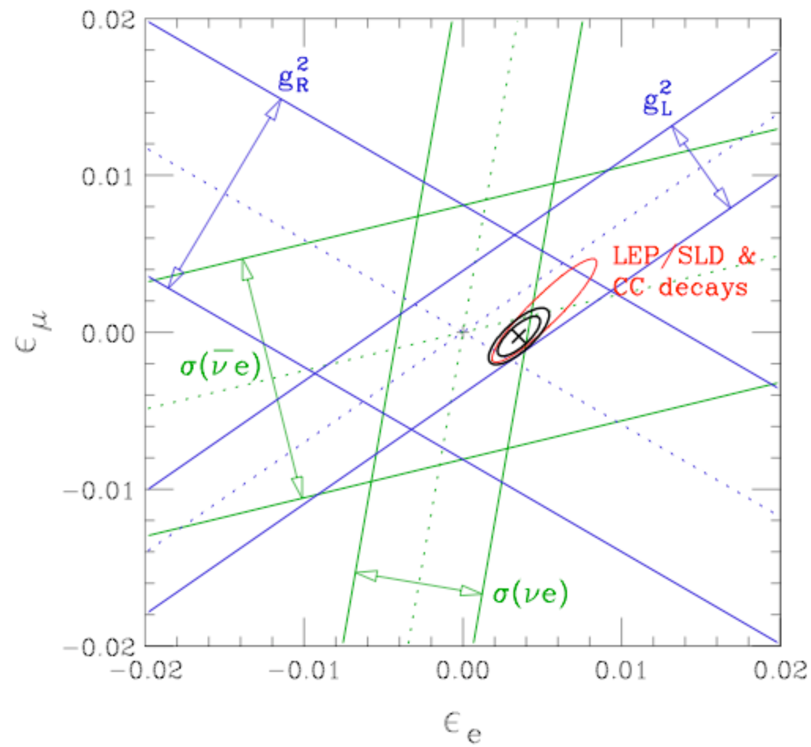
[possible solution to NuTeV anomaly]



[projection in 4-parameter fit to S,T, ε_e, ε_μ]

NuSOnG constrains S,T, ε_e, ε_μ

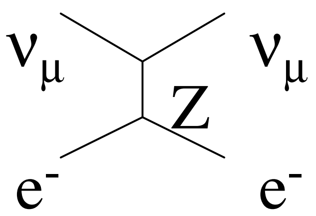
… and when combined with projected improvements in τ branching ratios (from BaBar) and π decay (from PINUE) the constraints become even stronger.



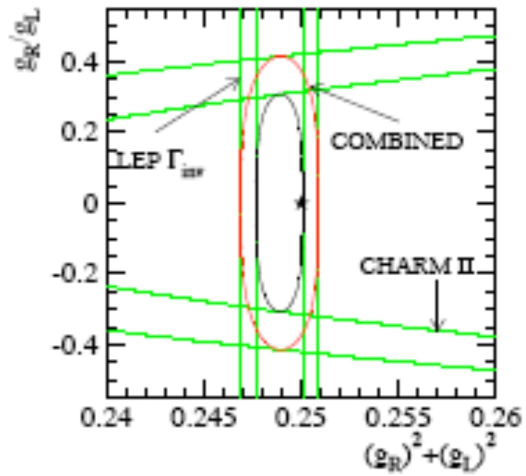
[projection in 4-parameter fit to S,T, ε_e, ε_μ]

Modified Gauge Couplings:

Probing right handed couplings of the neutrino to the Z



Present



Z invisible width probes $(g^\nu_L)^2+(g^\nu_R)^2$

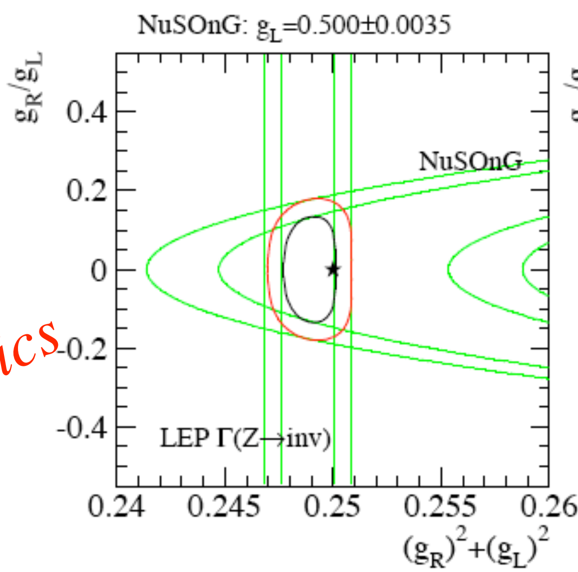
ν-e scattering probes g^ν_L

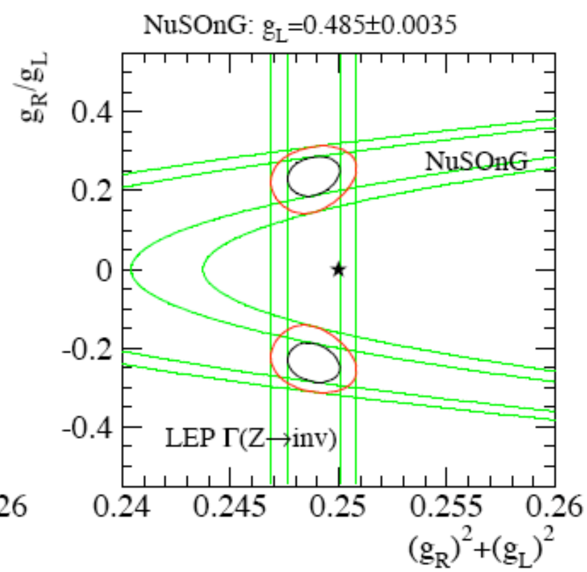
combine to get g^ν_R

NuSOnG improves on CHARMII by factor of 2

NuSOnG

In the case of agreement… and disagreement…. with SM





A unique probe of new physics

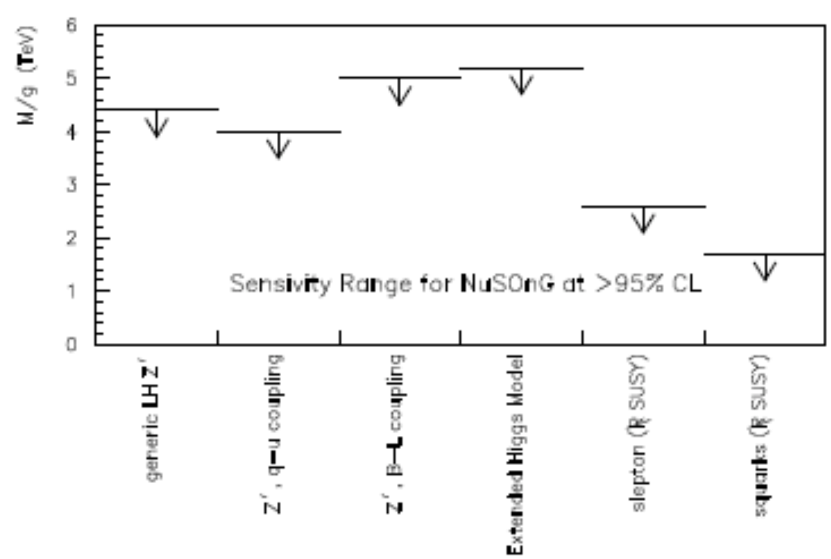
NuSOnG in the Context of Specific "Typical" Models

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

Models imply relations among
four-fermion operators
(may affect both CC and NC)

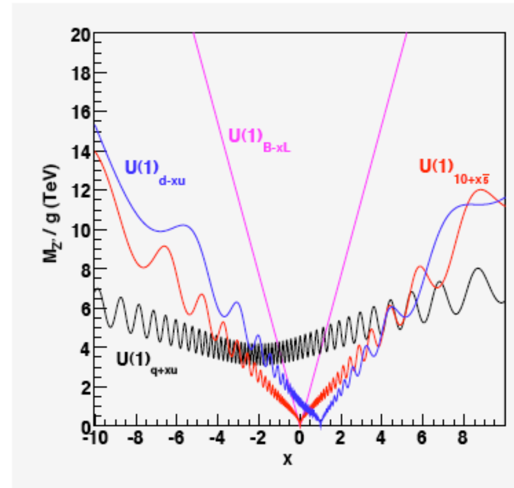
Again, typical (M/g) reach is
1 to 5 TeV,
depending on the model



Heavy Z' Models

Four examples of types of couplings…

	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
$\nu_{\mu L}, e_L$	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	$-x$	$-(2+x)/3$	$-1/3$	$x/3$



Reach extends to many TeV, depending on the U(1)' symmetry.

R-parity Violating SUSY

Coupling	95% NuSOnG bound	current 95% bound
$\lvert\lambda_{121}\rvert$	0.03	0.05 (V_{ud})
$\lvert\lambda_{122}\rvert$	0.04	0.05 (V_{ud})
$\lvert\lambda_{123}\rvert$	0.04	0.05 (V_{ud})
$\lvert\lambda_{231}\rvert$	0.05	0.07 (τ decay)
$\lvert\lambda'_{211}\rvert$	0.05	0.06 (π decay)
$\lvert\lambda'_{212}\rvert$	0.06	0.06 (π decay)
$\lvert\lambda'_{213}\rvert$	0.06	0.06 (π decay)
$\lvert\lambda'_{221}\rvert$	0.07	0.21 (D meson decay)
$\lvert\lambda'_{231}\rvert$	0.07	0.45 ($Z \to \mu^+\mu^-$)

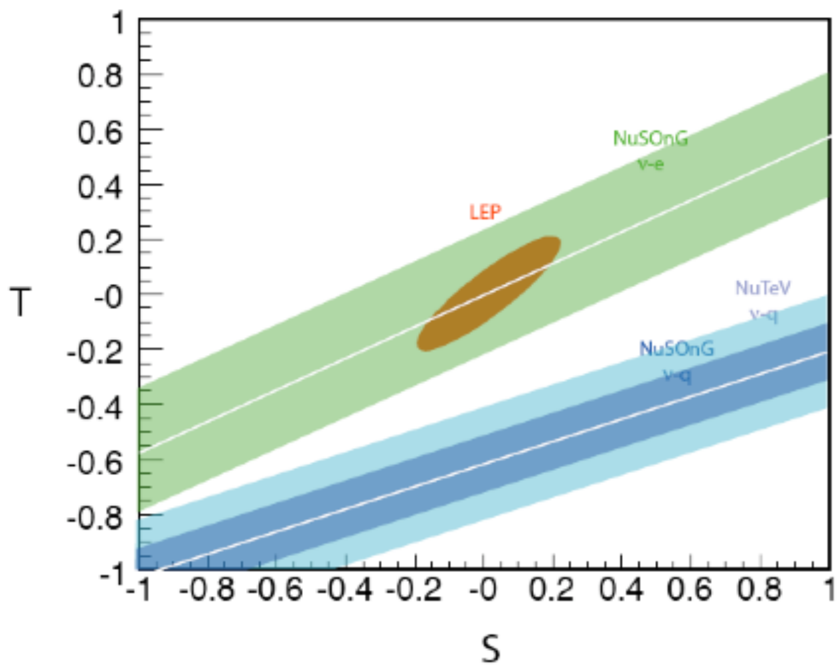
} 20% to 40% improvements on LLE

} Factors of 3 to 5 improvement! on LQD

NuSOnG complements LHC

NuSOnG + LHC: TeV-scale leptoquarks

non-degenerate 0.5-1.5 TeV $SU(2)_L$ triplet leptoquark



NuTeV anomaly due to BSM physics

<u>LHC</u> gives mass measurement, but little info on coupling

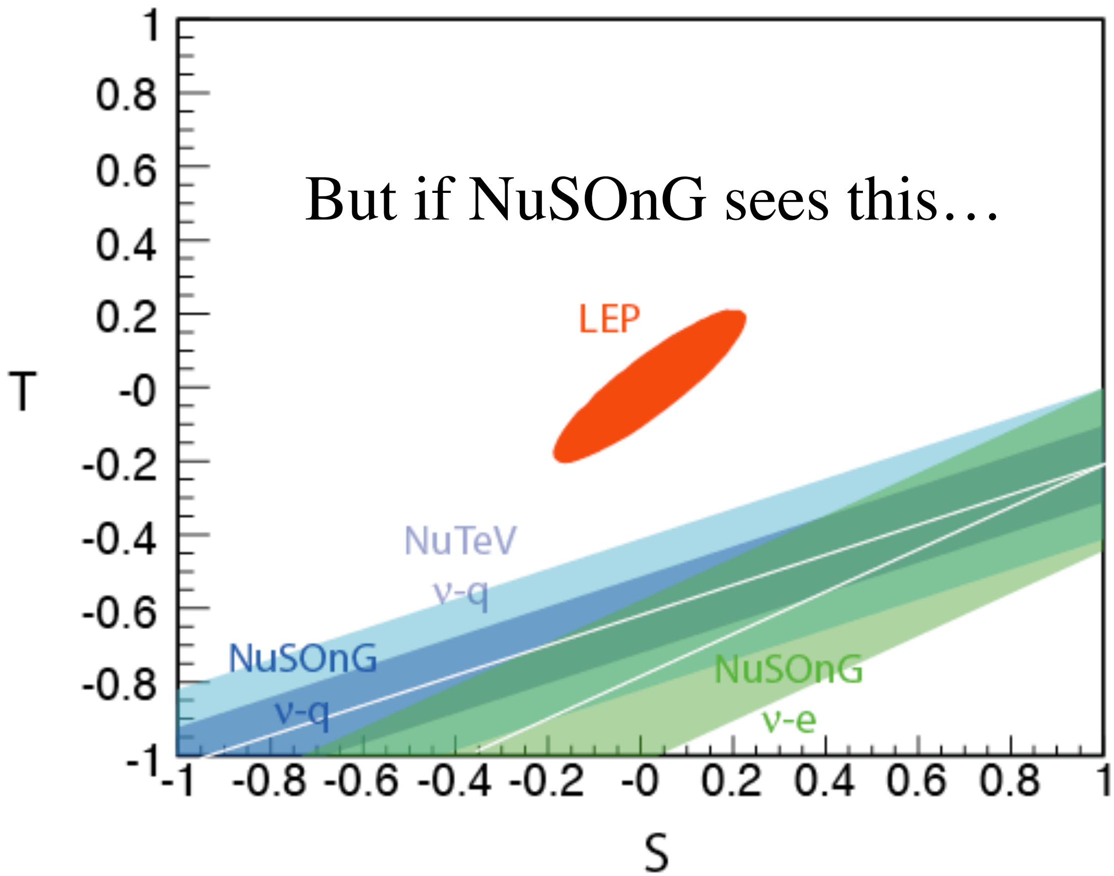
NuSOnG

- νe, g_R^2 agree with LEP
- g_L^2 agrees with NuTeV

combination of g_L^2 and leptoquark mass will constrain couplings

The "God-forbid" Scenario

LHC sees a standard model Higgs and no signs of new physics



There is new physics in the neutrino sector!

Summary

NuSong can

- constrain new physics at the TeV scale
- complement LHC and other experiments
- probe solutions to NuTeV
- make important QCD measurements
- perform direct searches for new physics

NuSOnG + LHC: A Chiral 4th Generation Family

LHC:

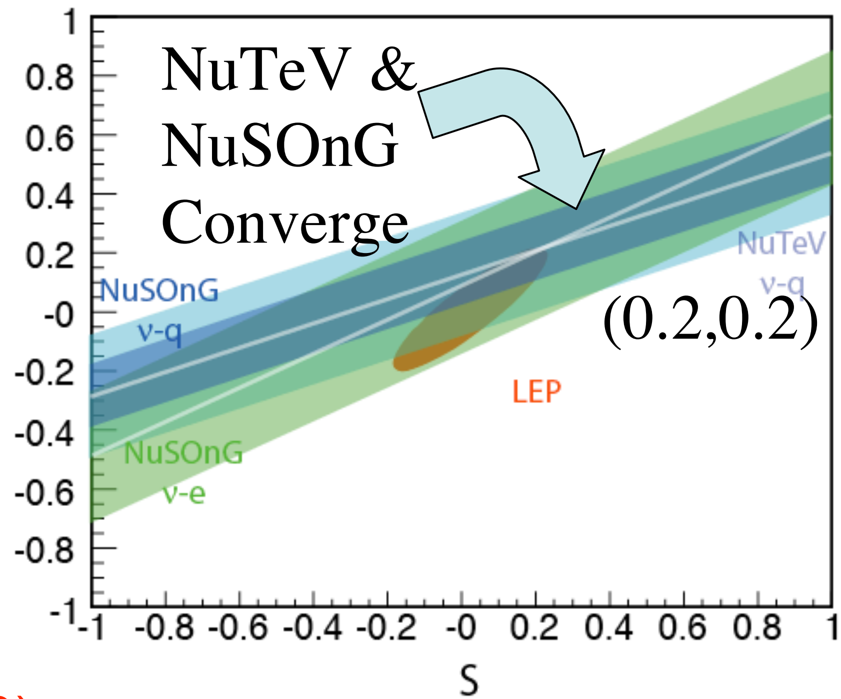
- Highly enhanced H →ZZ
- The Higgs mass,
  lets say 300 GeV
- complex decay modes
  (e.g. 6W's and 2 b's)

And what it doesn't…

- Measure mass of new quarks
- Observe new charged leptons
  (off mass shell Drell-Yan produced)
- Reconstruct the decay modes fully

NuSOnG:

QCD explanation for NuTeV is found, allowing NuTeV to be corrected



A Chiral 4th generation ($\Delta S=0.2$)
with isospin violation ($\Delta T=0.2$)

(Four Generations and Higgs Physics, hep-ph/0706.3718
G. D. Kribs, Y. Plehn, M. Spannowsky, T.M.P. Tait)