Neutrino Scattering at High Energies

Janet Conrad,
NuFact 09
July 24,2009

A range of interesting physics

- Electroweak
- QCD
- Searches for rare events

A suite of interesting experiments:

- NuSOnG
- A new ν_τ experiment
- A small dedicated search for neutrissimos
  (moderately-heavy neutral heavy leptons)

An interesting opportunity in the near future
and for a Neutrino Factory

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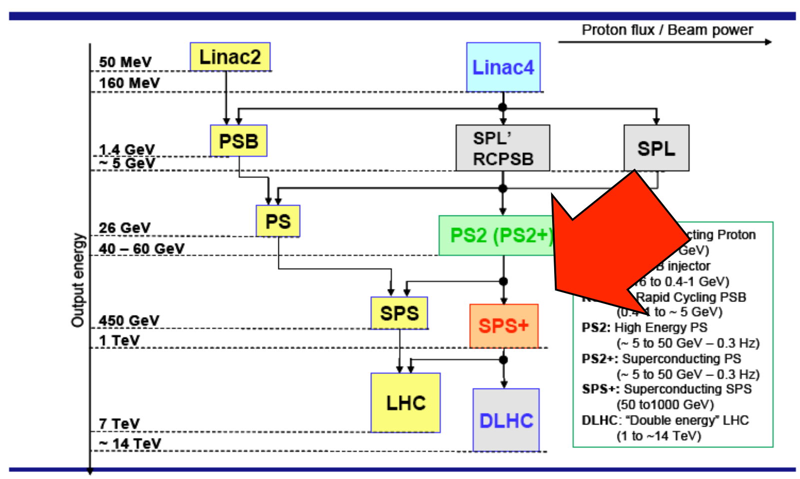
An interesting opportunity in the near future
and for a Neutrino Factory

High energy neutrinos → High energy proton source

Available very soon:
The FNAL Tevatron

Available in future:
The CERN SPS+

Evolution of the CERN accelerator complex – Studied by PAF working group



Inspired by this opportunity…

A trilogy of papers!

arXiv.org > hep-ph > arXiv:0803.0354

Search

High Energy Physics – Phenomenology

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

T. Adams, P. Batra, L. Bugel, L. Camilleri, J.M. Conrad, A. de Gouvea, P.H. Fisher, J.A. Formaggio, J. Jenkins, G. Karagiorgi, T.R. Kobilarcik, S. Kopp, G. Kyle, W.A. Loinaz, D.A. Mason, R. Milner, R. M
Olness, J.F. Owens, S.F
Schienbein, M.J. Syphe
Yamamoto, J.Y. Yu

arXiv.org > hep-ex > arXiv:0905.3004

Search

High Energy Physics – Experiment

Renaissance of the ~1 TeV Fixed-Target Program

T. Adams, J. A. Appel, K. E. Arms, A. B. Balantekin, J. M. Conrad, P. S. Cooper, Z. Djurcic,
W. Dunwoodie, J. Engelfried,
Ignarra, G. Karagiorgi, S. Kwa
Naples, P. Nienaber, S. F. Pat
Russ, A. J. Schwartz, W. G. Se
Syphers, T. M. P. Tait, F. Van

arXiv.org > hep-ex > arXiv:0906.3563

Sea

High Energy Physics – Experiment

QCD Precision Measurements and Structure Function Extraction at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG

T. Adams, P. Batra, L. Bugel, L. Camilleri, J. M. Conrad, A. de Gouvêa, P. H. Fisher, J. A. Formaggio, J. Jenkins, G. Karagiorgi, T. R. Kobilarcik, S. Kopp, G. Kyle, W. A. Loinaz, D. A. Mason, R. Milner, R. Moore, J. G. Morfín, M. Nakamura, D. Naples, P. Nienaber, F. I. Olness, J. F. Owens, S. F. Pate, A. Pronin, W. G. Seligman, M. H. Shaevitz, H. Schellman, I. Schienbein, M. J. Syphers, T. M. P. Tait, T. Takeuchi, C. Y. Tan, R. G. Van de Water, R. K. Yamamoto, J. Y. Yu

All accepted or published in IJMPA

This offers a neutrino physics program which…

Is complementary to LHC,

Is complementary to the existing neutrino program,

& Moves neutrino technology forward

… and it offers a lot of physics topics/theses!

NuSOnG: Neutrino Scattering On Glass

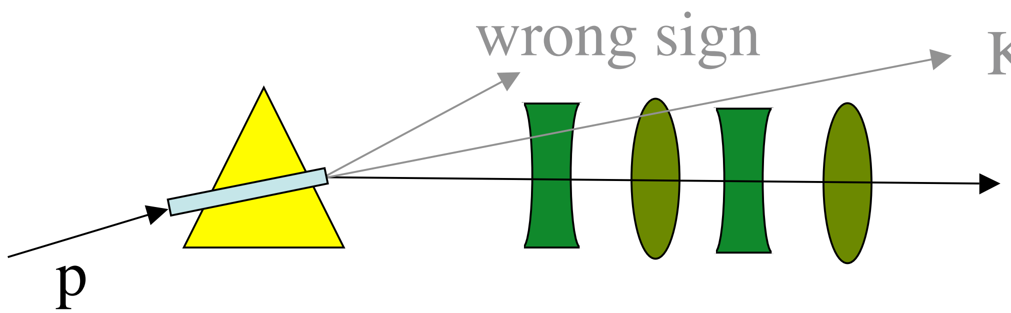
http://www-nusong.fnal.gov

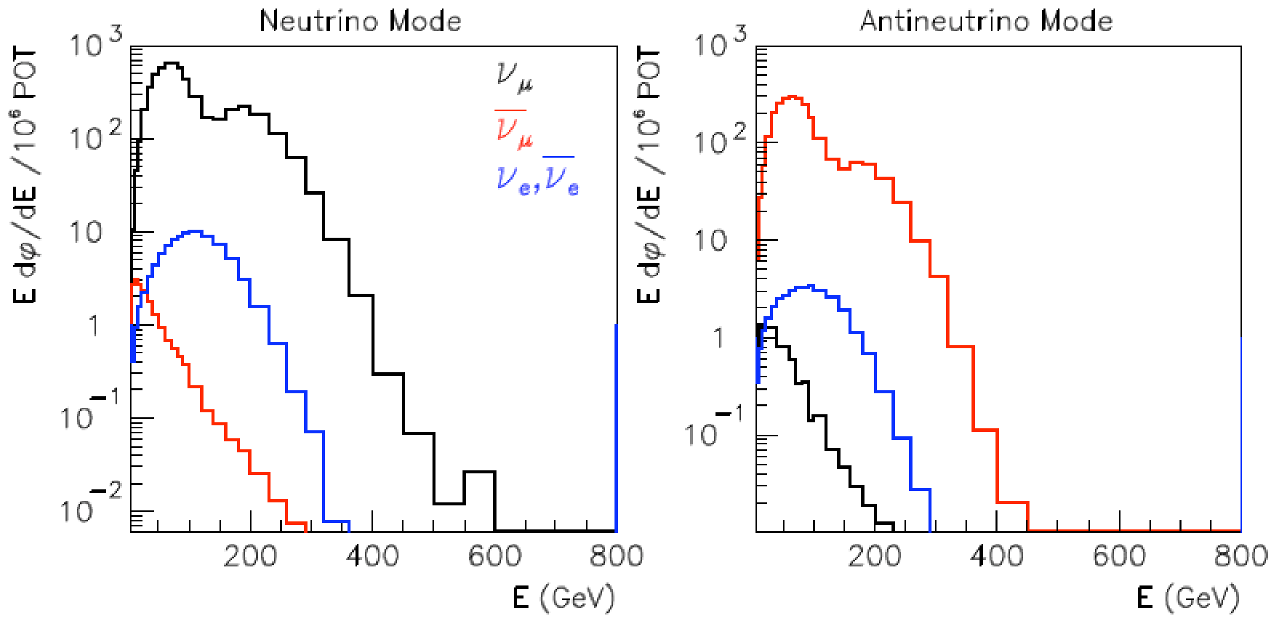
Outline for the remainder of this talk:

1) The NuSOnG Design
2) The Electroweak Physics Reach
3) QCD Measurement Opportunities

A "NuTeV-style" Neutrino Flux

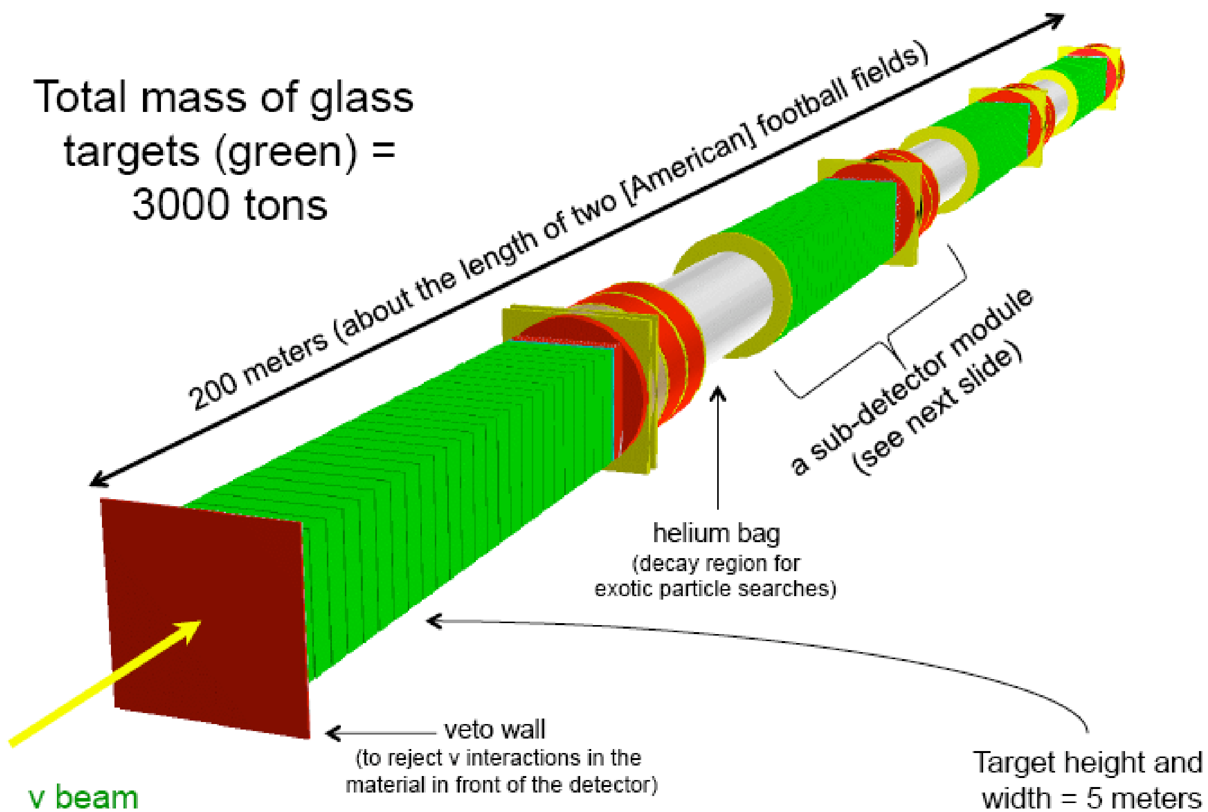
Uniquely high energy, and low background,





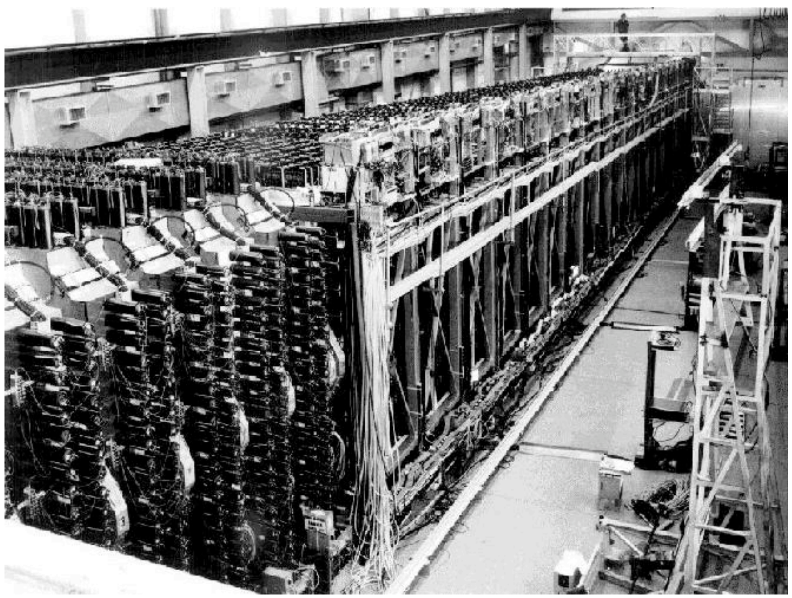
NuSOnG will have a decay length 3 times longer than NuTeV

The NuSOnG Detector

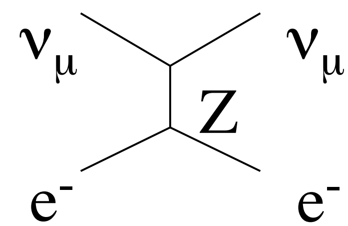


Why Glass?

- Silicon is the highest A isoscalar (p=n) target
- It is relatively inexpensive to obtain
- It is relatively easy to handle, even in thin (1/4 λ) sheets
- You can instrument it if you like…



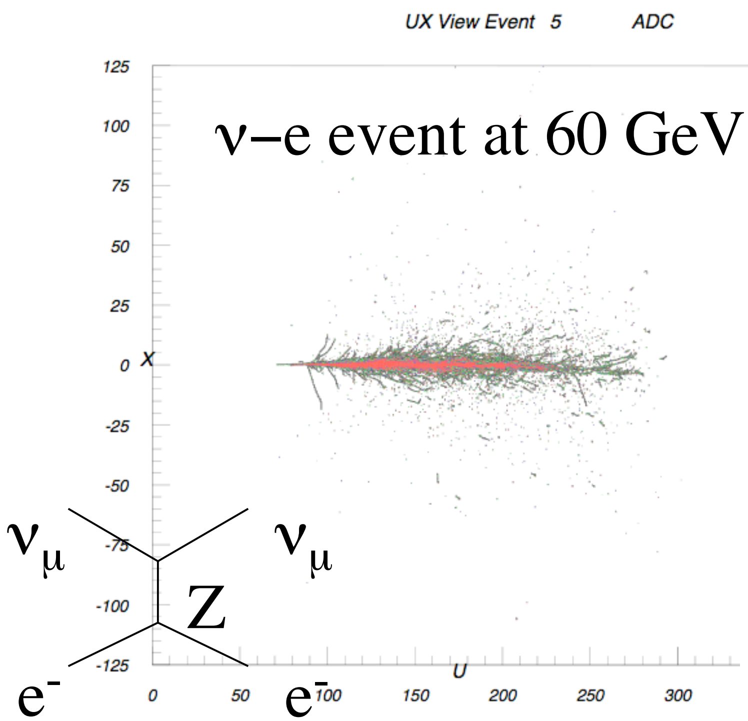
We want to identify



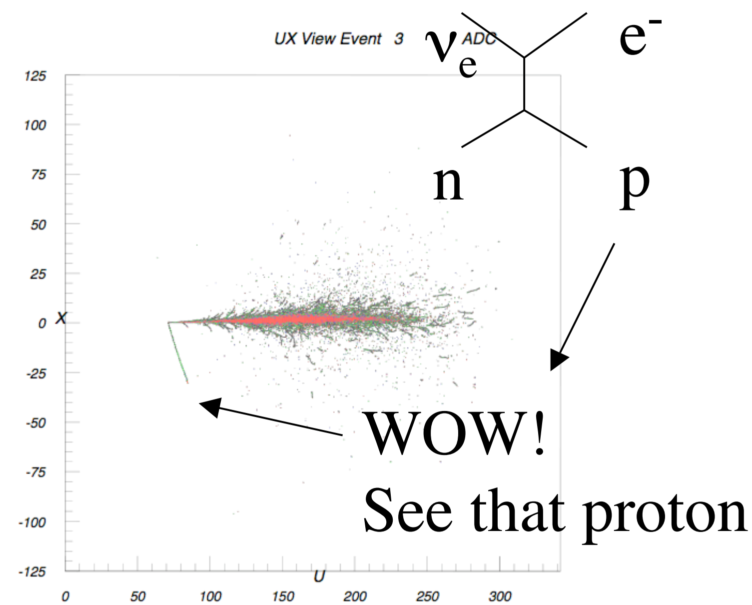
CHARM II is a proof
that this style of detector
works well.

An alternative: ~3 ktons of LAr

- Less electronics (cheaper)
- No dead regions



The most pernicious background: ν_e CCQE



NuSOnG

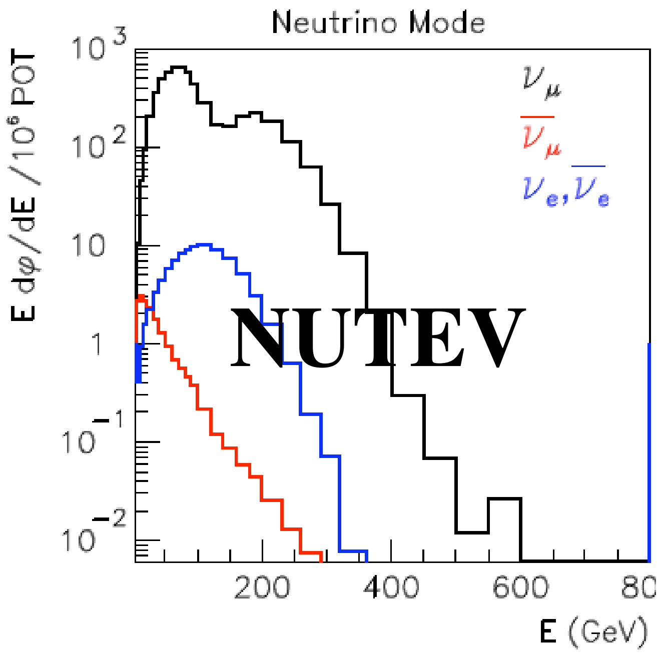
Neutrino Scattering On Glass

may become

NuSONG

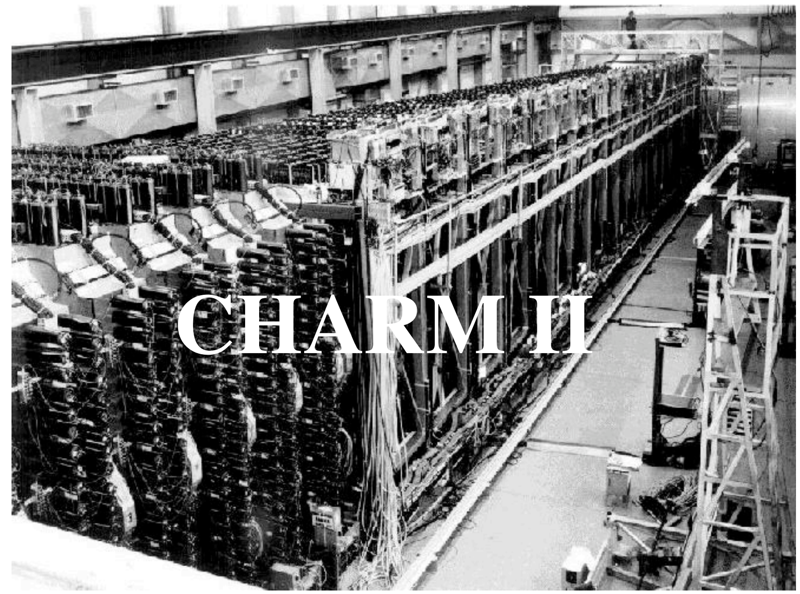
Neutrino Scattering On (liquid) Noble Gas

For the remainder of the talk we assume



High energy,
very pure beam
(×20 POT)

+



Fine-grained,
massive detector
(×6 mass)

1.5E20 POT in ν , 0.5E20 POT in $\overline{\nu}$

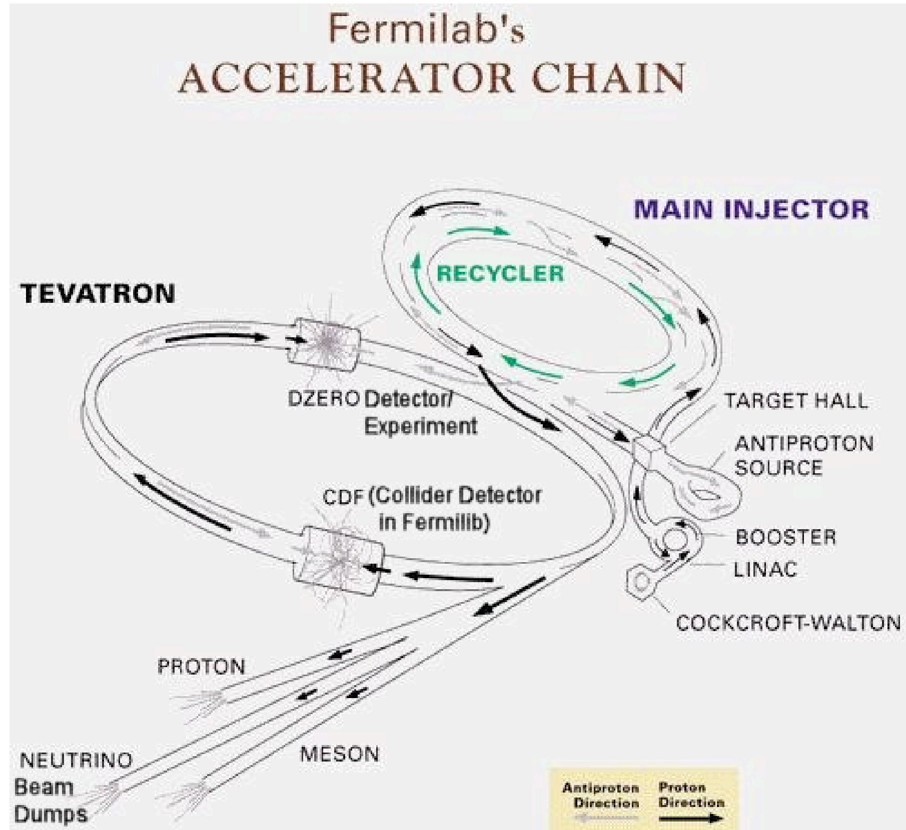
Can the Tevatron Deliver the rate?

5×10^{19} POT/year

$3\times$ the number of protons per fill,
$1.5 \times$ faster cycle time
66% uptime per year

YES.

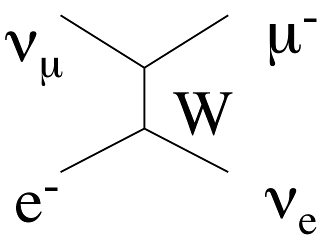
Cost of running complex in FT mode is \$15M/year

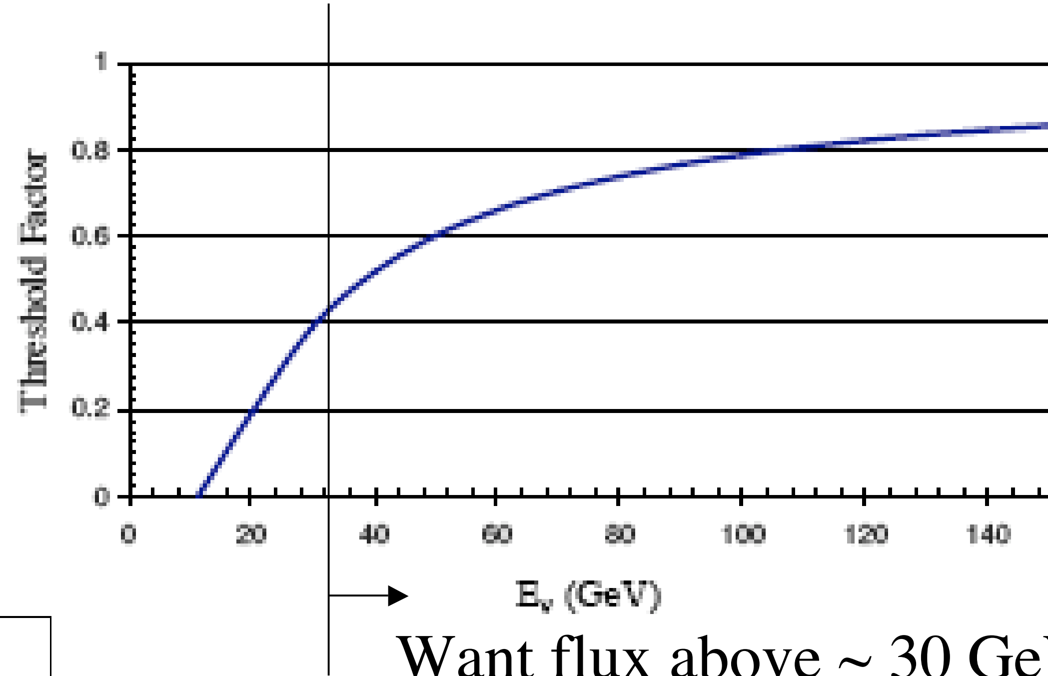


Two useful publicly-available memos:

http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2222
http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2849

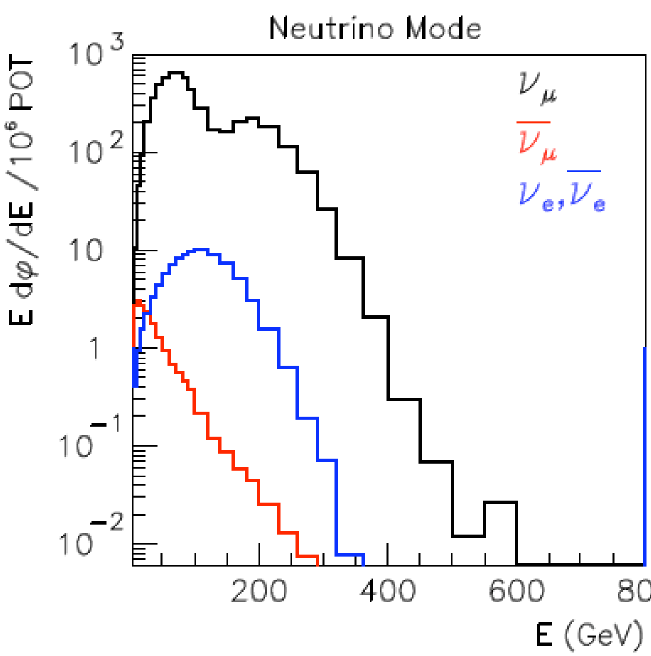
This is an experiment that can precisely measure its flux!!!





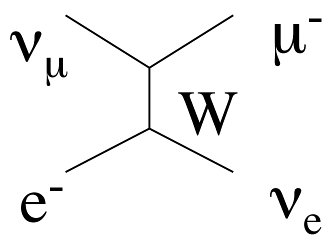
Want flux above ~ 30 GeV

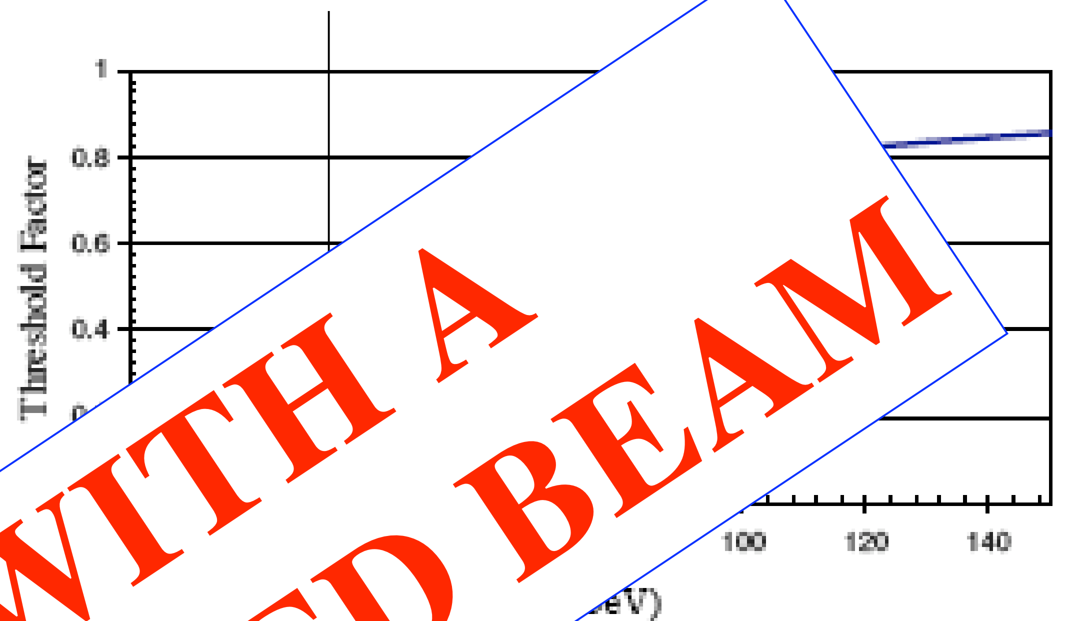
Need no flux below!

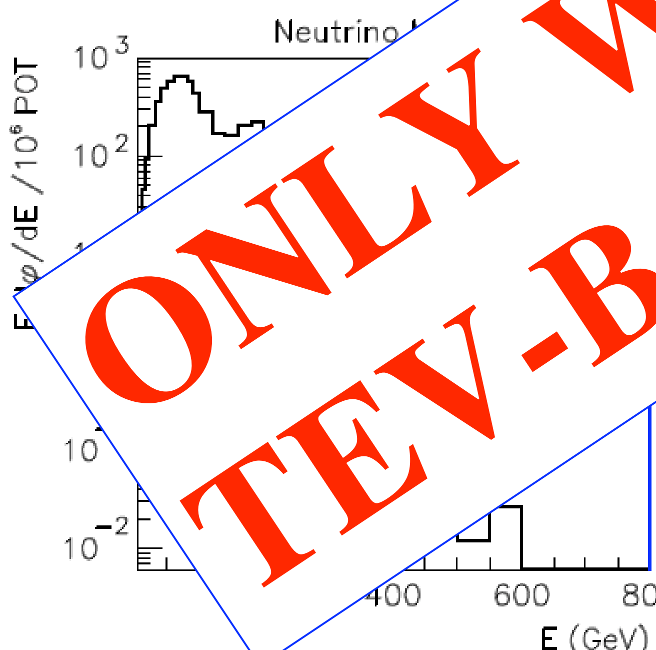


The strong cutoff at low energy is due to the energy-angle correlation in π decay

This is an experiment that can precisely measure its flux!!!







ONLY WITH A TEV-BASED BEAM

...nt flux above ~ 30 GeV

Need no flux below!

The strong cutoff at low energy is due to the energy-angle correlation in π decay

NuSOnG Events

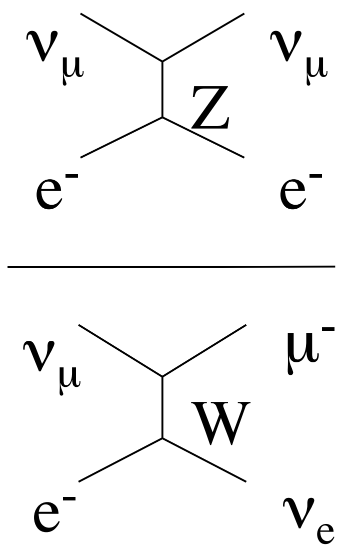
rare event & high precision studies

Process	Rate	Physics	
$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ [IMD] $\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$	700k 0	**normalization, "WSIMD", non-standard interactions**	40x CHARM II
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ [ES] $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$	75k 7k	**new "heavy" physics (Z', ν mixing with heavy singlets), new "light" physics, modified couplings, $\sin^2\theta_W$,** ρ, R-parity, extended Higgs	20x CHARM II
$\nu_\mu + q \rightarrow \nu_\mu + X$ [DIS] $\bar{\nu}_\mu + q \rightarrow \bar{\nu}_\mu + X$ $\nu_\mu + q \rightarrow \mu^- + X$ $\bar{\nu}_\mu + q \rightarrow \mu^+ + X$	190M 12M 600M 33M	ν-q non-standard interactions, **$\sin^2\theta_W$,** ΔxF_3, F_2, isospin violation, heavy quarks, nuclear effects	100x NuTeV
decays in low density decay regions	*60??*	**new long-lived heavy neutral particles**	30x NuTeV

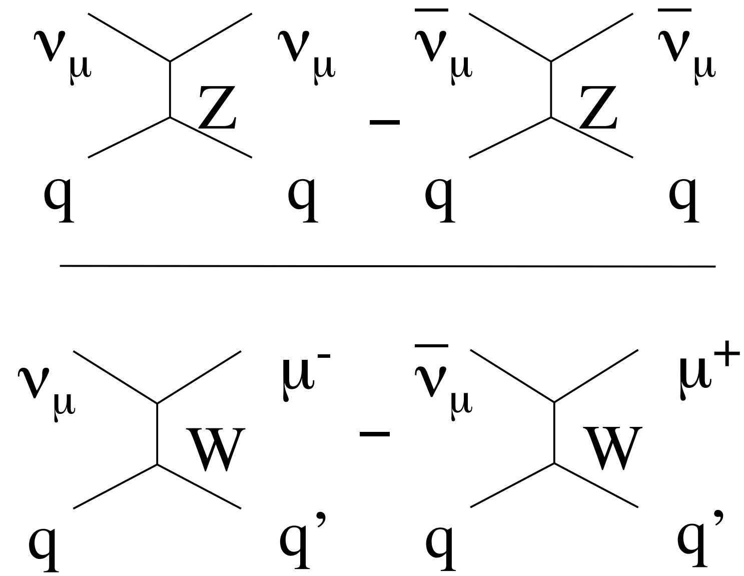
Precision Electroweak Measurements

NuSOnG will work with ratios….

New!



Purely leptonic



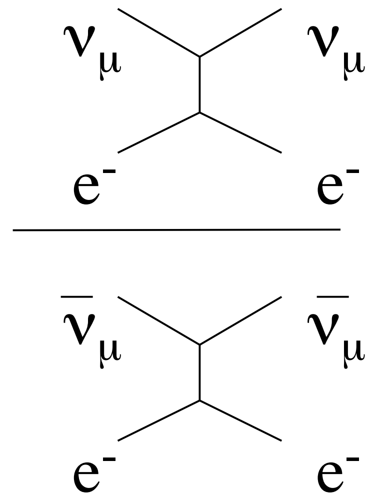
NuTeV-style
"Paschos-Wolfenstein"

Expected errors
0.7% conservative,
0.4% best case

0.4% conservative
0.2% best case

Our case is based on the conservative estimates

Why do we not focus on:



Like past experiments?

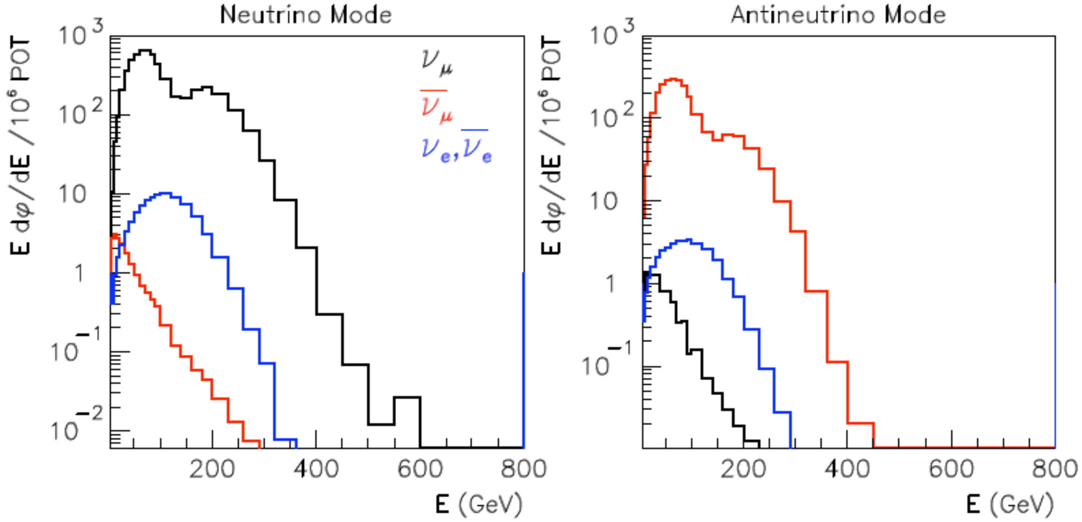
Theory-based reason:

Sensitivity to new physics arises from ρ= NC/CC coupling

-- which cancels in this ratio

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

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



Experimental reason:

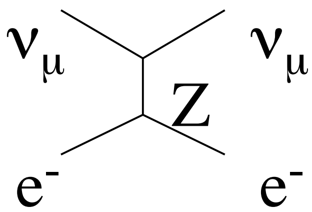
ν and $\overline{\nu}$ fluxes are never identical,

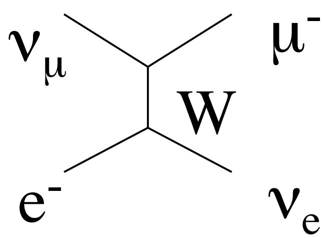
so one cannot do a precision (<1%) measurement

Practical reason:

Equal statistics in $\overline{\nu}$ running takes ×3 the proton on target!

New!





Purely leptonic

ONLY WITH A TEV-BASED BEAM

From our paper:

5 general classes of new physics searches…

Oblique Corrections
Neutrino-lepton NSIs
Neutrino-quark NSIs
Nonuniversal couplings
Right-handed coupling to the Z

… “generic ways” that new physics might show up

From our paper:

5 general classes of new physics searches…

Oblique Corrections

Neutrino-lepton NSIs

Neutrino-quark NSIs

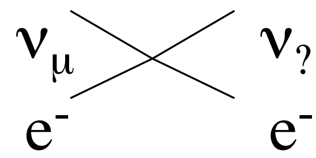
Nonuniversal couplings

Right-handed coupling to the Z

… "generic ways" that new physics might show up

Non-standard interactions (NSIs):

Neutrino-lepton NSI



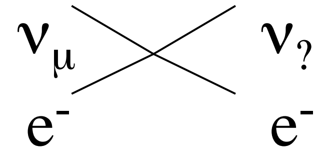
New physics is characterized by

- The mass scale of the new physics (Λ)
- The probability of left vs. right-handed coupling to the *e*, described by a mixing angle (cos θ)
- The flavor of the outgoing neutrino ("α" flavor) *i.e.* "pseudo-elastic" neutrino scattering

Look for this new physics via:

- change in cross section
- angular dependence of outgoing electron

NSI reach for **neutrino-lepton scattering**



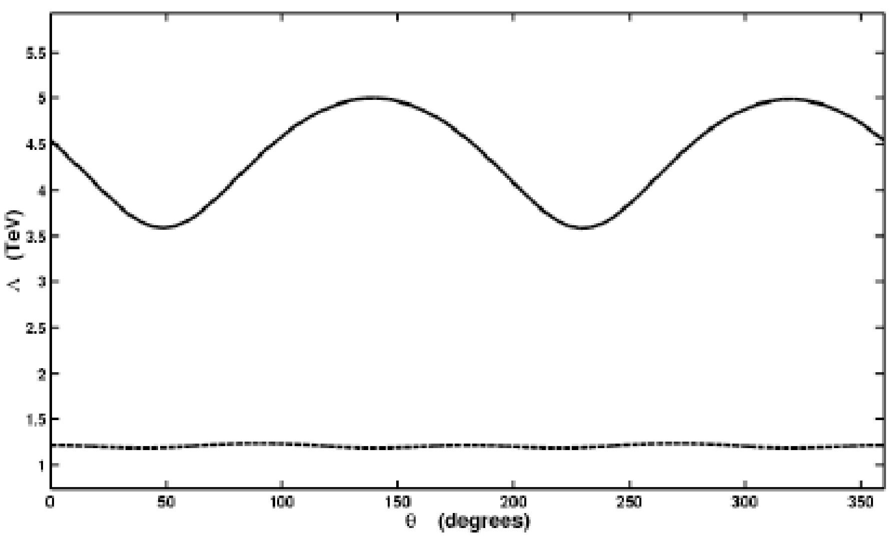
$$\mathcal{L}^{e}_{\mathrm{NSI}} = +\frac{\sqrt{2}}{\Lambda^2}\left[\bar{\nu}_\alpha \gamma_\sigma P_L \nu_\mu\right]\left[\cos\theta\,\bar{e}\gamma^\sigma P_L e + \sin\theta\,\bar{e}\gamma^\sigma P_R e\right]$$

mass scale

outgoing flavor

Relative mixture of handedness

Λ



θ

95% CL sensitivity

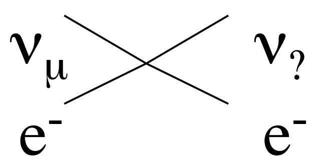
if α = muon flavor
~4.5 TeV

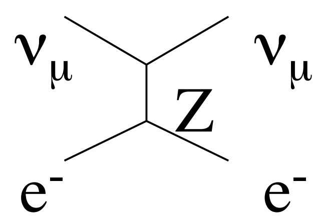
if $\alpha \neq$ muon flavor
~1.25 TeV

Why is the mass-scale sensitivity lower for
$\alpha \neq \mu$ compared to $\alpha = \mu$?

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

The sensitivity to this term comes from the combination
of this diagram…   and this diagram….



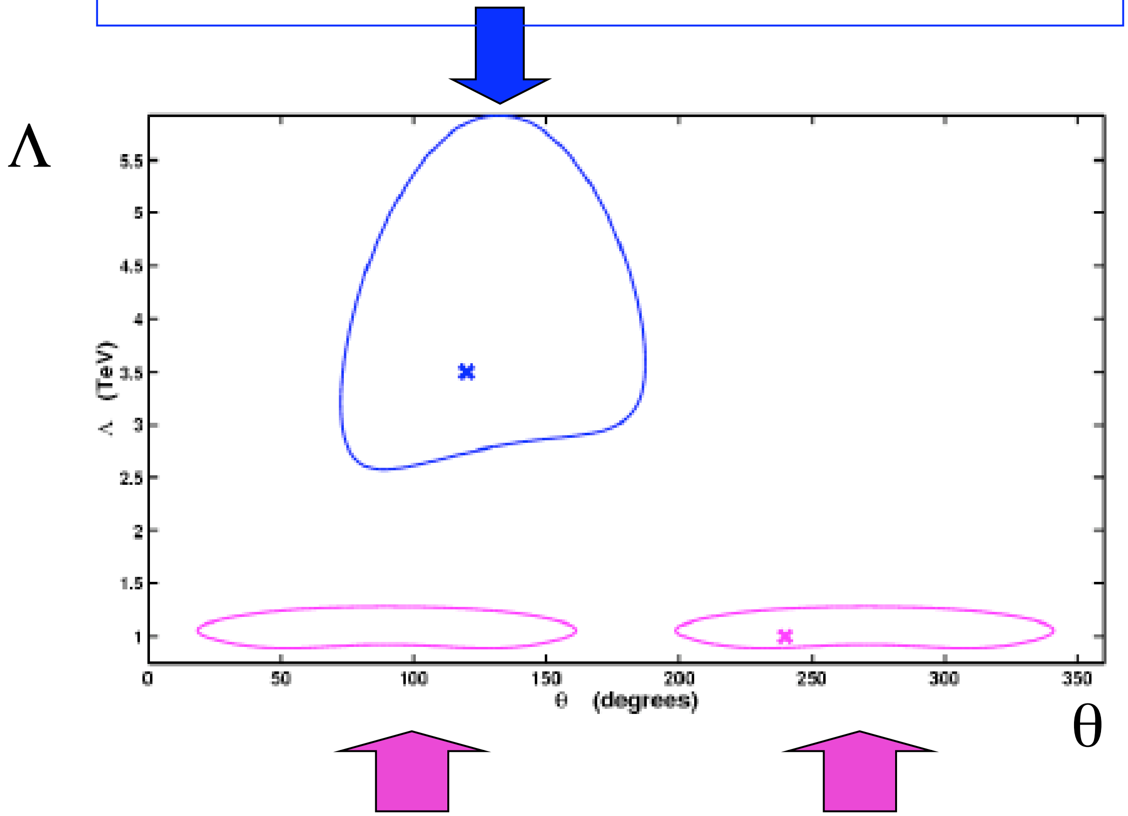


You will have an interference term
if the final state is identical ($\alpha = \mu$),
But not for $\alpha \neq \mu$

The larger the interference, the higher the sensitivity!

But we might see a signal!

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

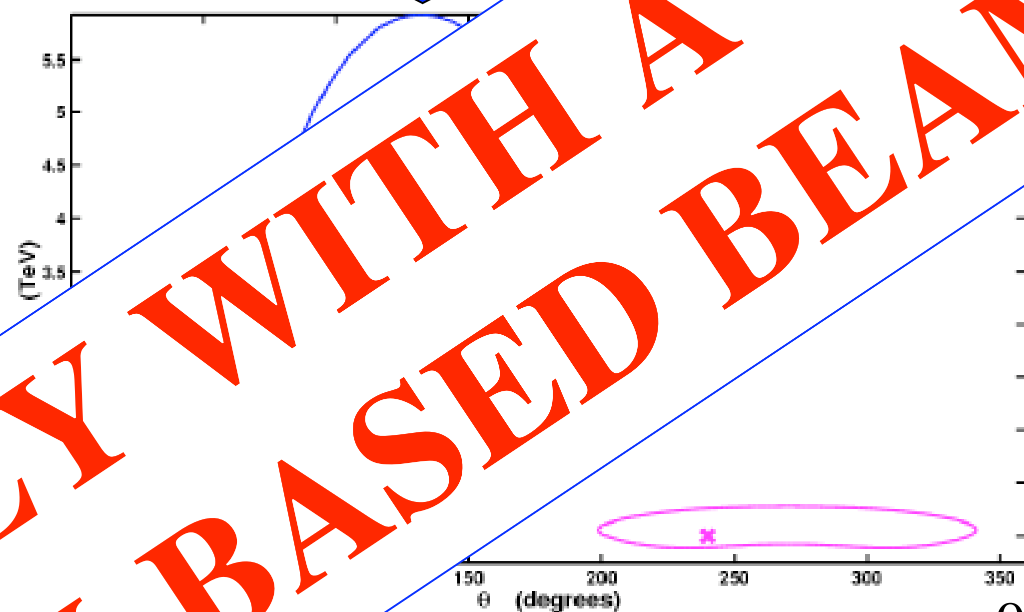


Assume Λ=1 TeV, θ =4π/3, α≠μ…
these are the 2σ contours from NuSOnG

But we might see a signal!

Assume Λ=3.5 TeV, θ =2π/3
this is the 2σ contour fro

Λ



θ

ONLY WITH A
TEV-BASED BEAM

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

NuSOnG's Terascale reach…

- Mass reach: 1 to 7 TeV
- Unique information on the couplings
- Many ways to probe for new physics with high sensitivity.

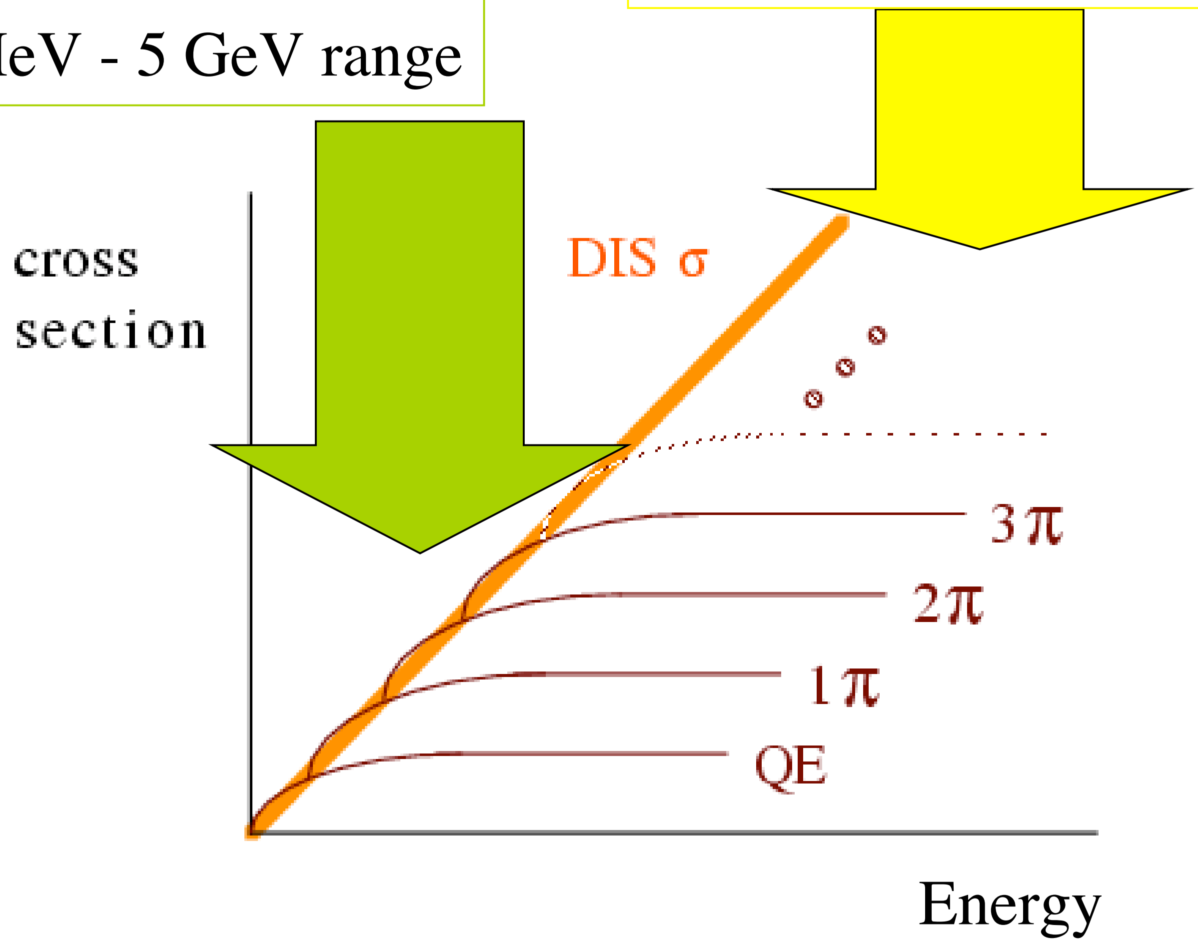
Some aspects complement LHC
Some studies are unique to the neutrino sector

A QCD Program at NuSOnG

Deep Inelastic Scattering:

most present ν expts
are here in the
100 MeV - 5 GeV range

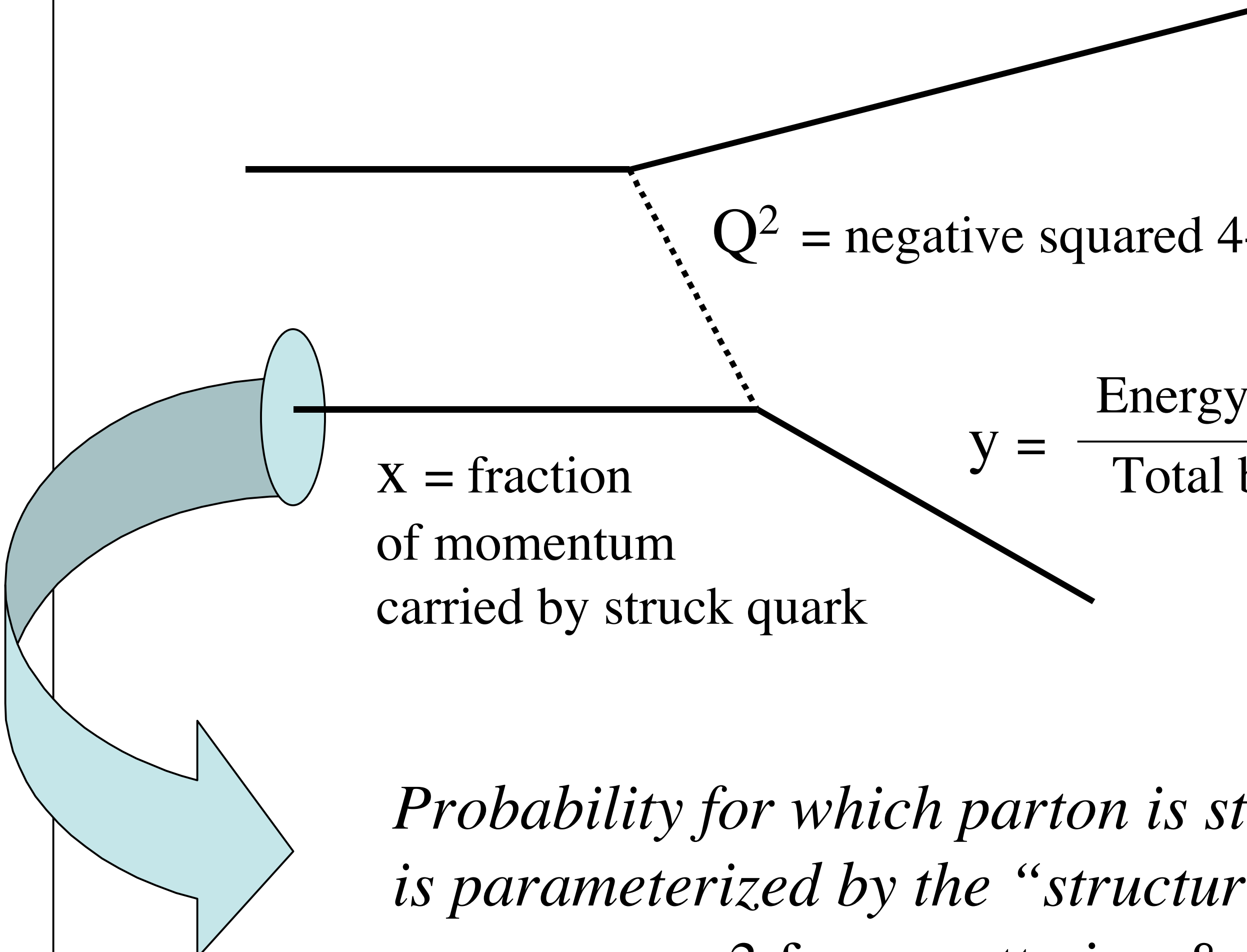
The Tev-based neutrinos
are up here at ~100 GeV



Deep =
large 4-mom transfer

Inelastic =
Target nucleon is obliterated, becoming a hadronic shower

DIS Kinematics:



Probability for which parton is struck,
is parameterized by the "structure functions"

3 for ν scattering & 3 for $\bar{\nu}$ scattering

Three assumptions...

1) the generic cross section formula:

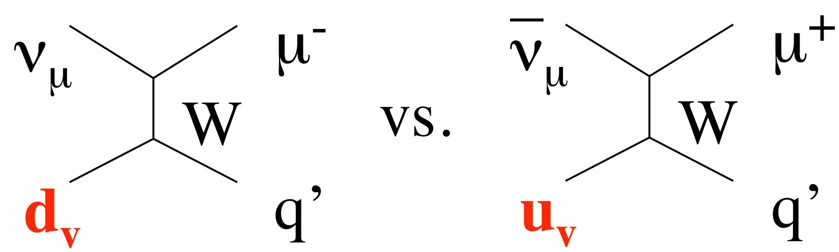
$$\frac{d^2\sigma^{\nu(\overline{\nu})N}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi\left(1+Q^2/M_W^2\right)^2}\left[F_2^{\nu(\overline{\nu})N}(x,Q^2)\left(\frac{y^2+(2Mxy/Q)^2}{2+2R_L^{\nu(\overline{\nu})N}(x,Q^2)}+1-y-\frac{Mxy}{2E_\nu}\right)\pm xF_3^{\nu(\overline{\nu})N}\,y\left(1-\frac{y}{2}\right)\right]$$

Related to the sum of the q and $\overline{q}$ distributions

σ^L/σ^T, encodes information about the gluon distribution

Related to the valence quark dists. -- different for ν vs $\overline{\nu}$!

2) $F_2^{\nu} = F_2^{\overline{\nu}}$, and
3) $R^{\nu} = R^{\overline{\nu}}$



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

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

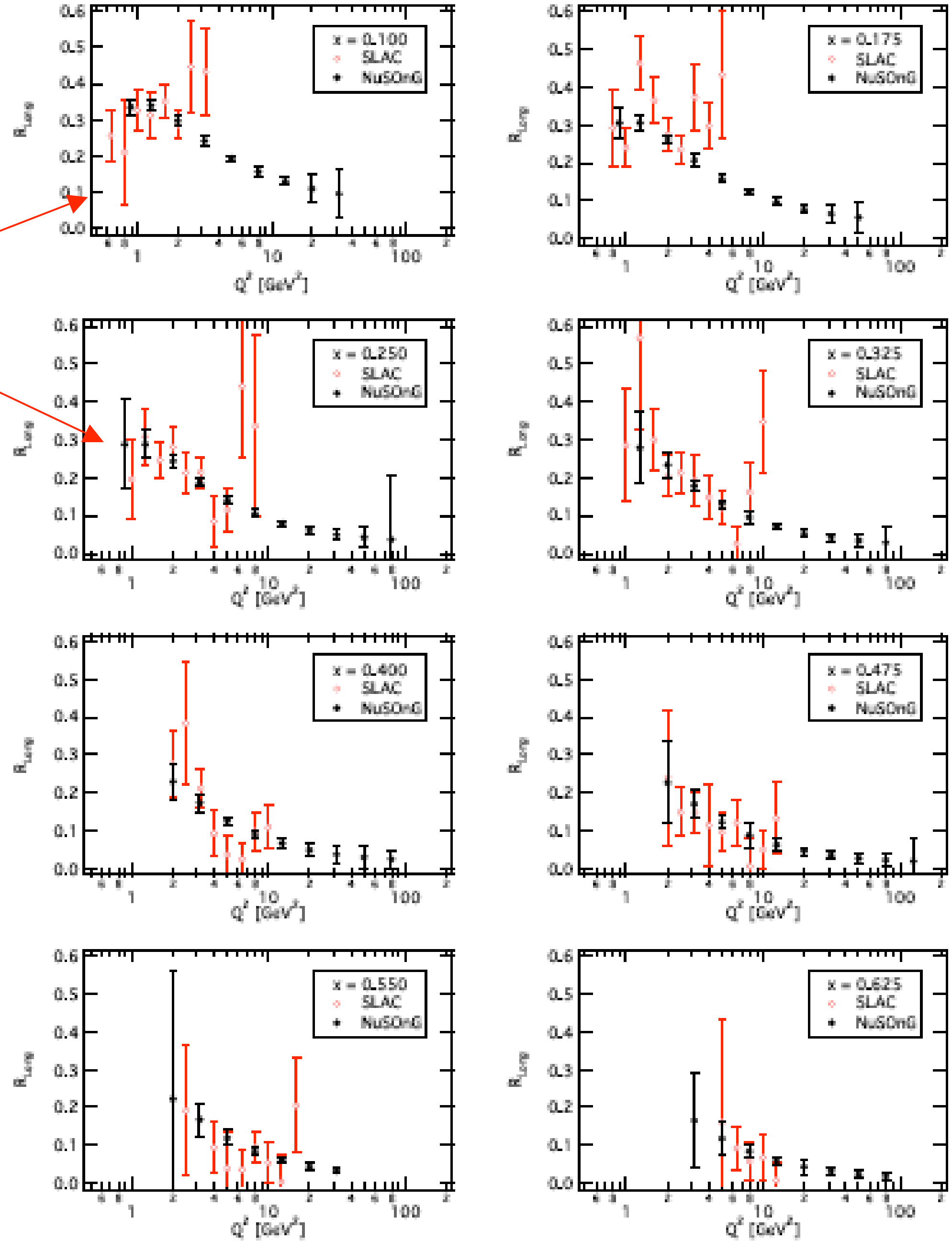
Bin-by-bin, minimize:

$$\chi^2 = \sum_{\nu,\overline{\nu}}\sum_{y-\mathrm{bins}}\frac{\left(N_{data}^{\nu(\overline{\nu})} - N_{MC,pred}^{\nu(\overline{\nu})}\left(SF_{fit}\right)\right)^2}{N_{data}^{\nu(\overline{\nu})}}$$

Tremendous improvement over past experiments!

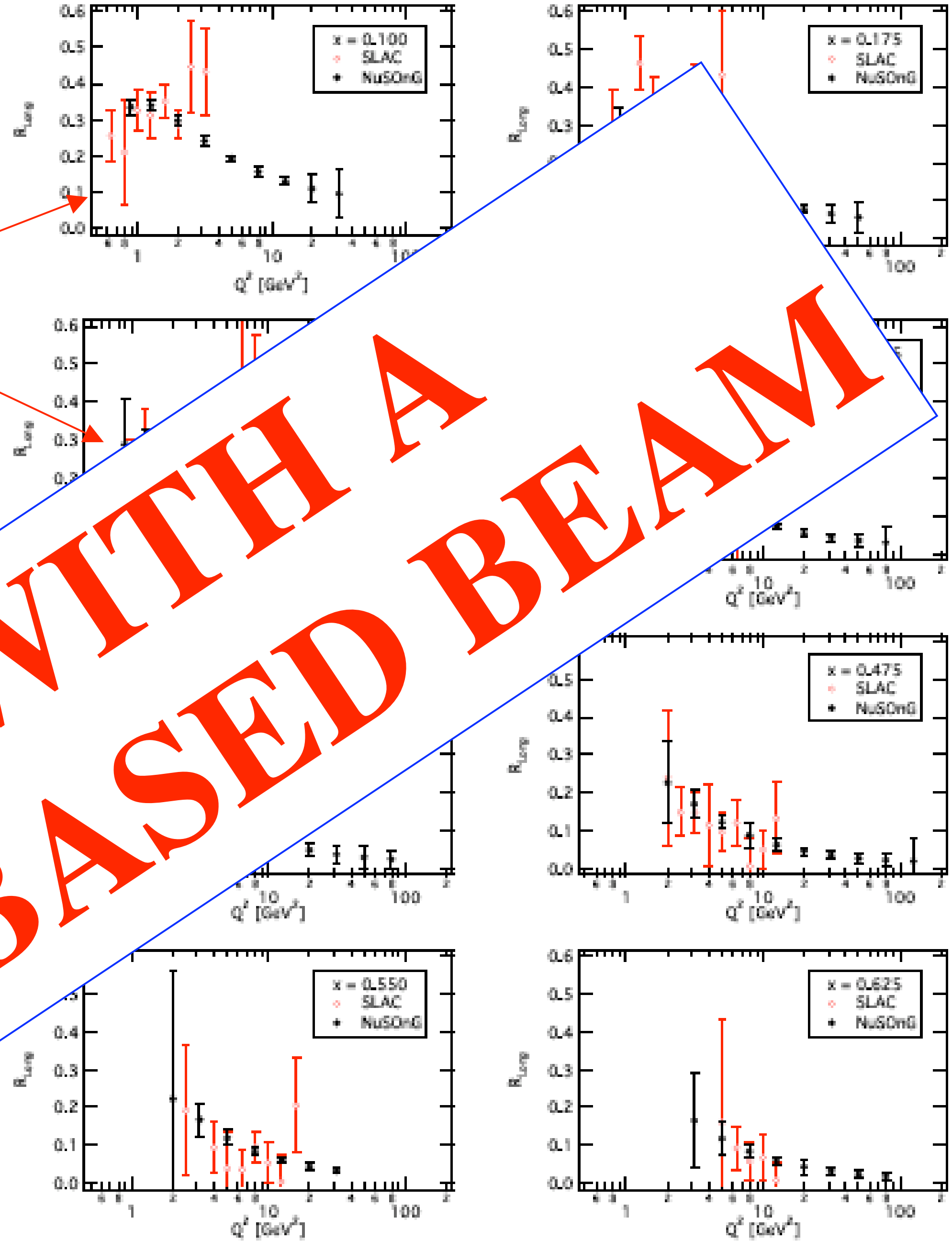
$R = \sigma_L / \sigma_T$ in x and Q^2

WOW!



Tremendous improvement over past experiments!

$R=\sigma_L/\sigma_T$
in x an



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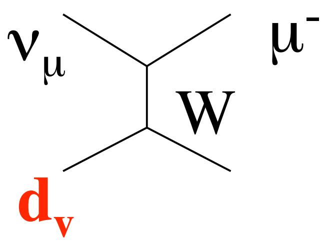
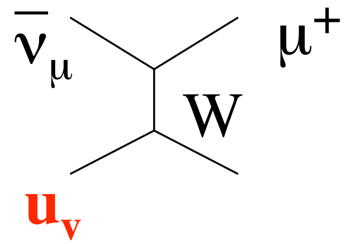
Another interesting question
(important for the electroweak studies…

Is this:



vs.



being modeled correctly?

This is extracted from

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

The question of "nuclear isospin violation"

$$\delta u_v(x,Q^2) = u_v^p(x,Q^2) - d_v^n(x,Q^2) \qquad \neq 0\ ?$$

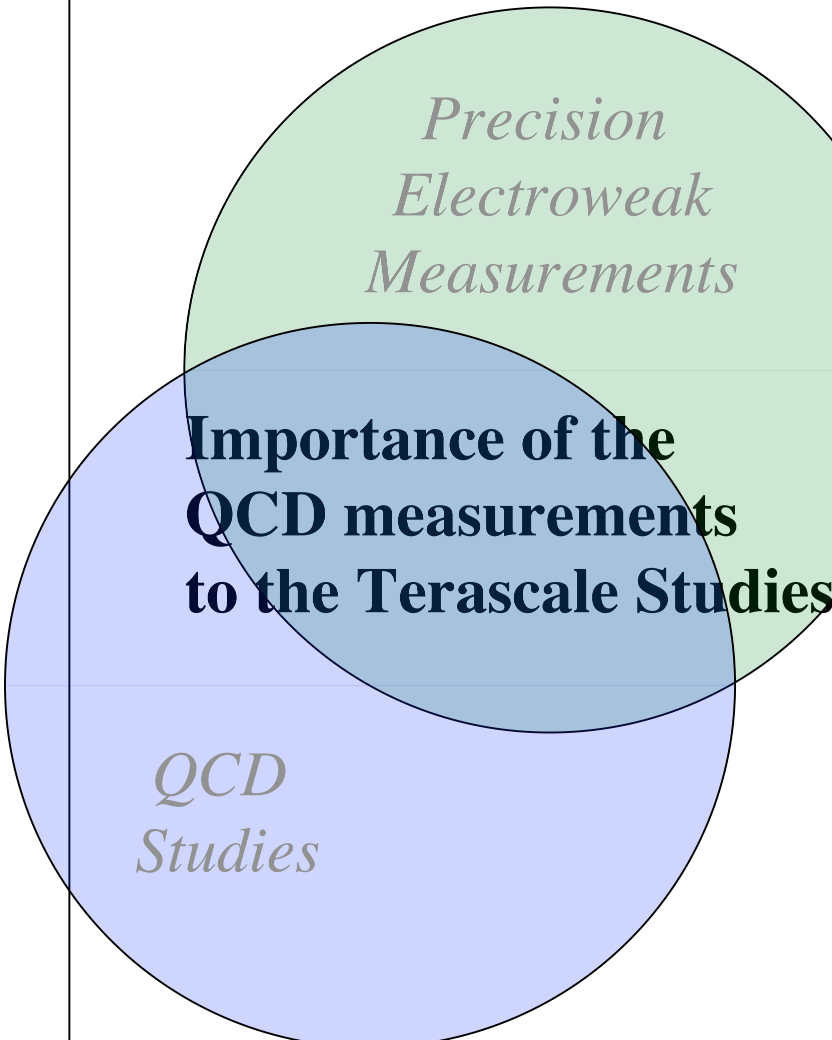
$$\delta d_v(x,Q^2) = d_v^p(x,Q^2) - u_v^n(x,Q^2) \qquad \neq 0\ ?$$

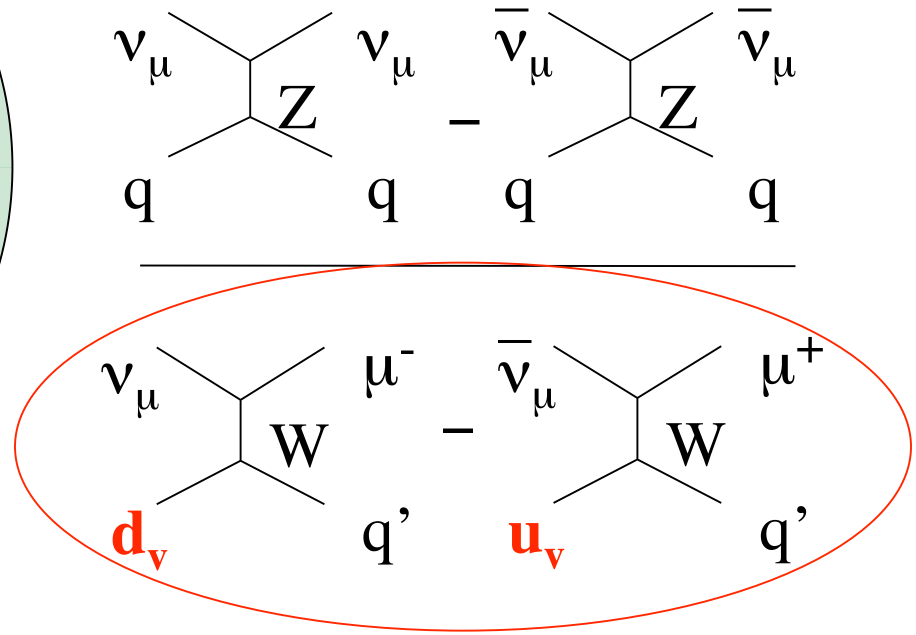
Surely at some level!

- u and d quarks have different masses
  (biggest effect in "bag model")
- Difference in the virtual meson (pion) cloud
- QED corrections (different because u is +2/3, d is -1/3)

Calculations differ significantly on the size of the effect

How does this relate back to the Electroweak studies?





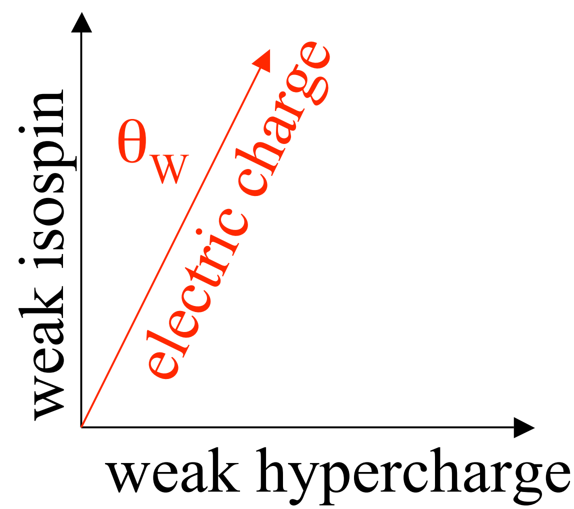
NuTeV-style
"Paschos-Wolfenstein"
Electroweak Measurement

This ratio depends on

The Weak Mixing Angle

SU(3) × SU(2) × U(1)

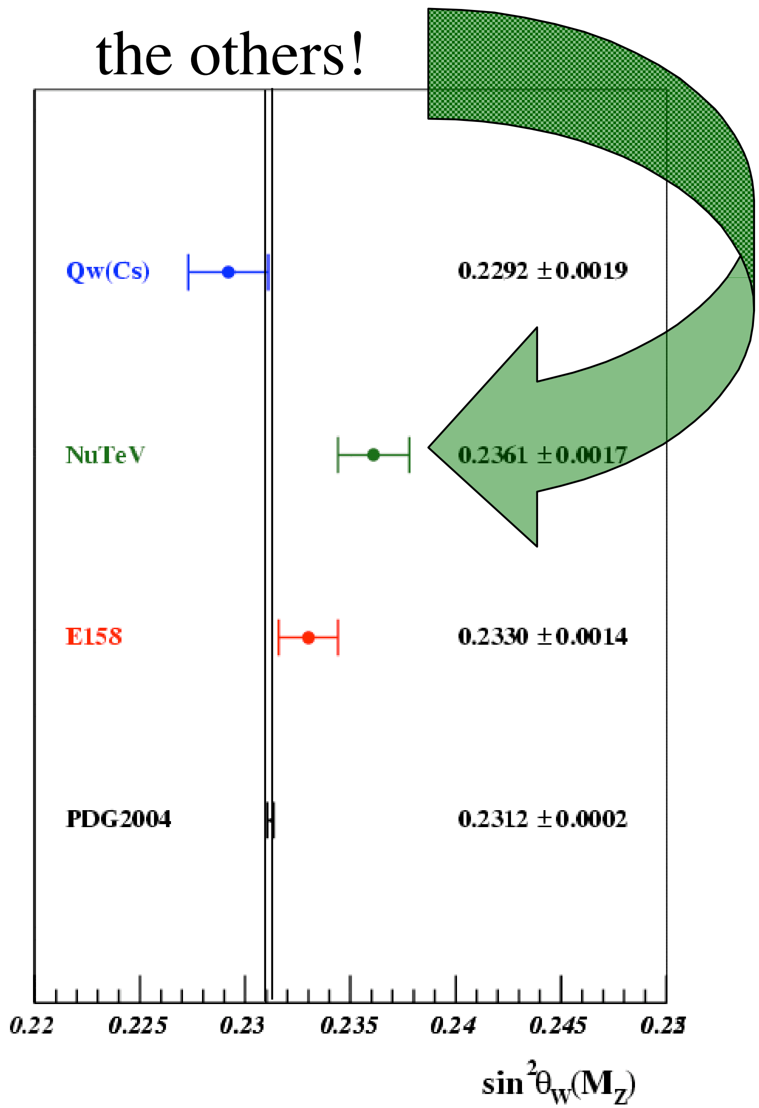
Parameterizes the mixing between
$Z_{SU(2)}$ and $\gamma_{U(1)}$ in the electroweak theory



$$\sin^2 \theta_W = 1 - (M_W/M_Z)^2$$

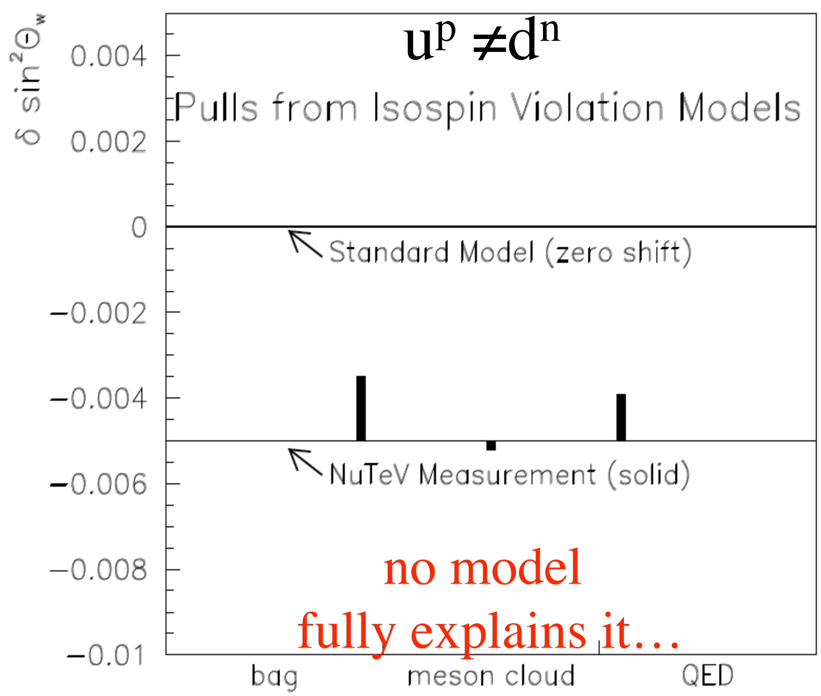
A *fundamental* parameter
accessible in all processes with Z-exchange

NuTeV is 3σ off from the others!



Is it a problem with the denominator in the ratio?

i.e.
is it nuclear isospin violation?



The obvious take-away…

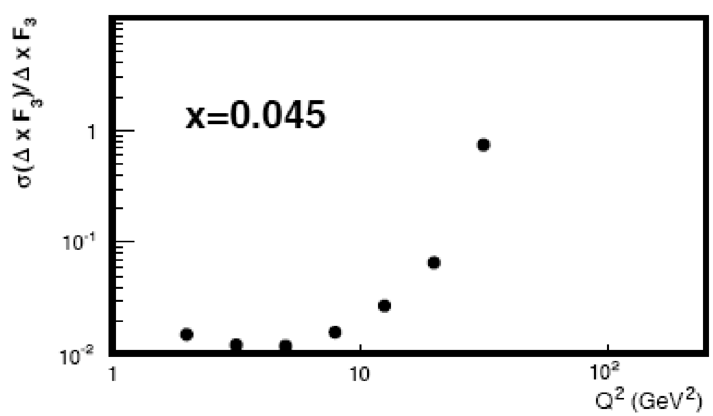
if one wants to search for
Beyond Standard Model phenomena…

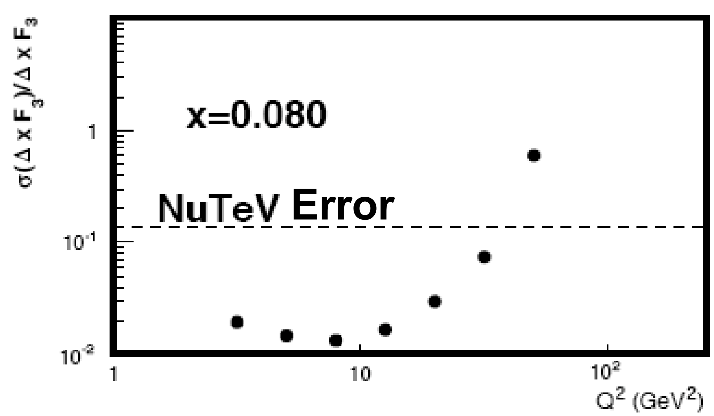
Thou shalt know thy quarks!

The existing data on ΔxF_3 is sparse and imprecise

NuSOnG can measure this in a model-independent way!

ΔxF_3 is extracted from a simultaneous fit to ν and $\bar{\nu}$ data





The NuSOnG measurements will be very high precision!

Conclusion about the QCD studies:

They are exciting in their own right!
And they meet the needed precision
for the electroweak physics

Conclusion about the EW studies:

They are complementary to LHC
and probe exciting physics at TeV scales…

Conclusion … in general:

ONLY WITH A TEV-BASED BEAM