Short-Baseline Opportunities and Challenges at a Neutrino Factory

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ν-FACT
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Outline

1. What Role does Near-Detector Physics Play?
2. Weak Interactions
3. Nucleon Structure
4. Neutrino Interactions
5. Conclusions

Baa Baa Black Sheep

Near detector physics will not drive the design or construction of a neutrino factory

So why are my lips still moving?

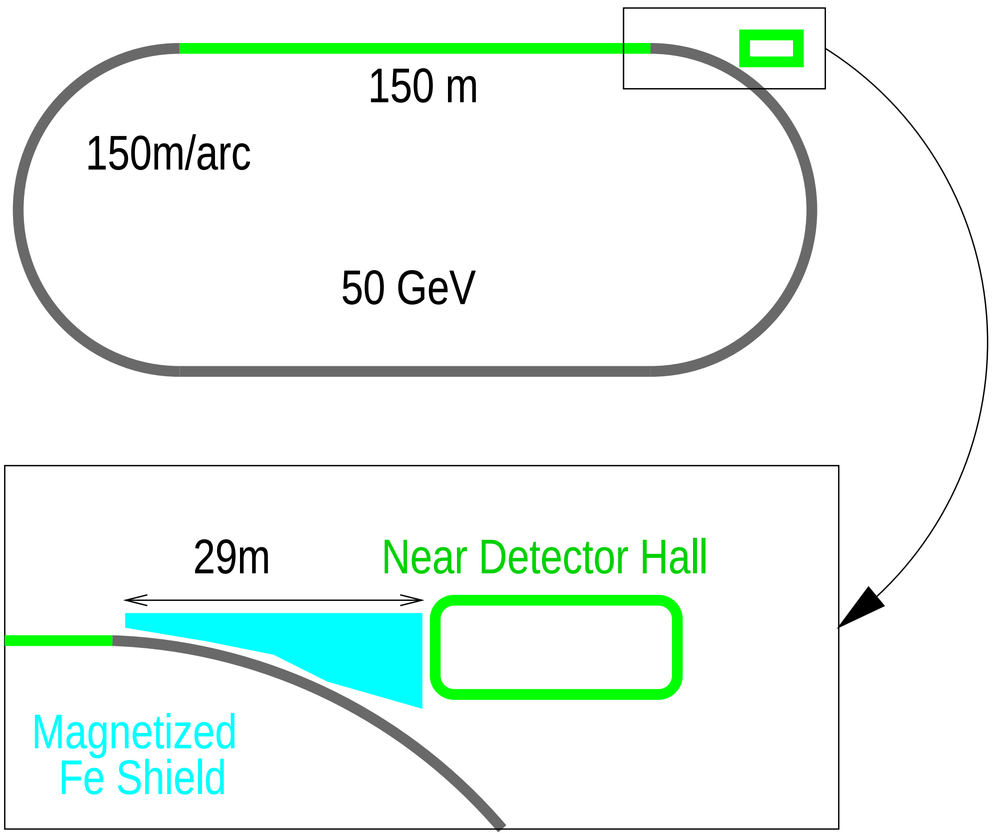
- If this facility is built, it has the opportunity to be a true facility – an endeavor that supports a diverse community of interests
- There is compelling case for using intense neutrino beams to probe problems other than neutrino oscillations
- There is an opportunity here for new ideas and creativity

The Opportunity

$\sim \times 10^{21}$ muon decays per year

10% of all decay neutrinos in detector 10 cm in radius

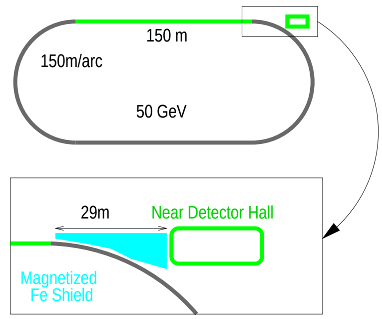
$\approx 2.5 \times 10^{7} \times \frac{E_\mu}{50 \text{ GeV}}$ interactions per year per kg

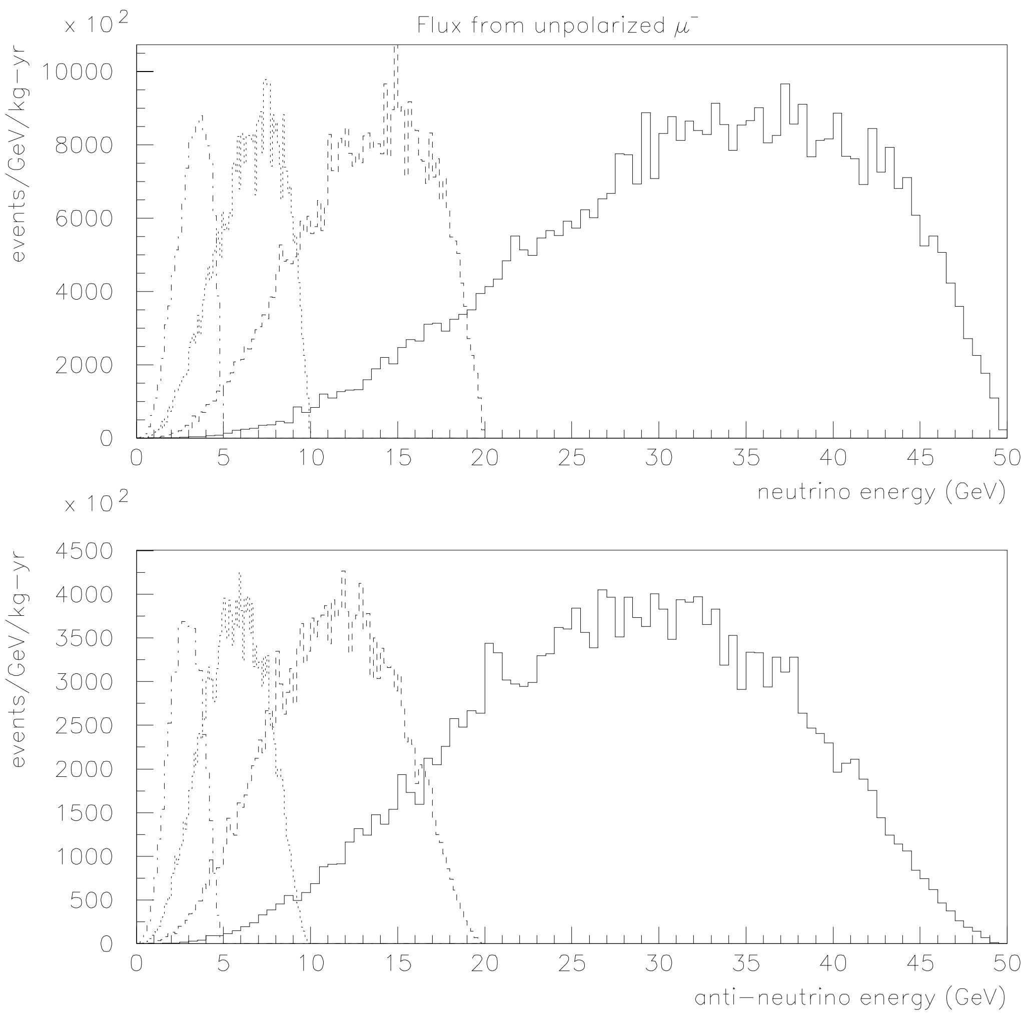


c.f.: Competing facilties

Beam	$\langle E_\nu \rangle$ [GeV]	ν per year
NuTeV/CCFR (Fermilab)	100	$\sim 10^{15}$
CHORUS/NOMAD (CERN)	30	$\sim 3 \times 10^{16}$
MINOS Near (Fermilab)	15	$\sim 10^{18}$

Fluxes





(50, 20, 10, 5 GeV beams shown)

The Opportunity II

The properties of the neutrino make it a wonderful laboratory for searching for new physics

. . . because backgrounds
from neutrino
interactions
are small!

- Weak Interaction is featured
- Clean probe of hadron structure
- Rare ν processes

Status of Precision Electroweak Measurements

Ten years ago…

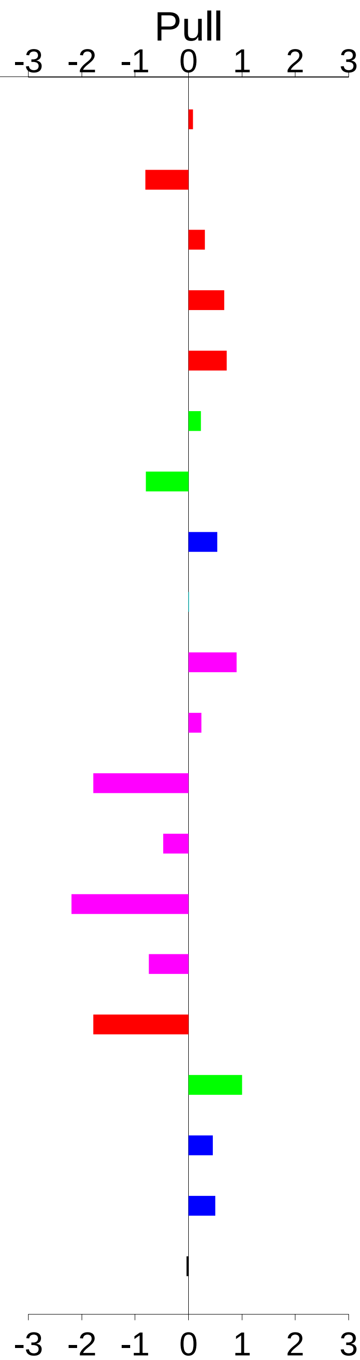
- The basic structure of the electroweak Standard Model appeared correct
  - ▷ Low-energy measurements of $\gamma - Z$ interference and Z exchange
  - ▷ Crude boson masses
- Time was ripe for a quick BIG SURPRISE
  - ▷ Fat Z?
  - ▷ Generation dependence in couplings?
  - ▷ Physics at TeV mass scales appearing in precision measurements?
  - ▷ Other

- Instead, we got …

Status of Precision Electroweak Measurements (cont'd)

Vancouver 1998

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ_Z [GeV]	2.4939 ± 0.0024	-.80
σ^0_{hadr} [nb]	41.491 ± 0.058	.31
R_e	20.765 ± 0.026	.66
$A_{fb}^{0,e}$	0.01683 ± 0.00096	.72
A_e	0.1479 ± 0.0051	.24
A_τ	0.1431 ± 0.0045	-.80
$\sin^2\theta_{eff}^{lept}$	0.2321 ± 0.0010	.54
m_W [GeV]	80.370 ± 0.090	.01
R_b	0.21656 ± 0.00074	.90
R_c	0.1733 ± 0.0044	.24
$A_{fb}^{0,b}$	0.0991 ± 0.0021	-1.78
$A_{fb}^{0,c}$	0.0714 ± 0.0044	-.47
A_b	0.856 ± 0.036	-2.18
A_c	0.638 ± 0.040	-.74
$\sin^2\theta_{eff}^{lept}$	0.23101 ± 0.00031	-1.78
$\sin^2\theta_W$	0.2255 ± 0.0021	1.06
m_W [GeV]	80.410 ± 0.090	.45
m_t [GeV]	173.8 ± 5.0	.50
$1/\alpha$	128.896 ± 0.090	-.04



(Figure courtesy of LEP EWWG)

And in the Time of a neutrino factory?

- Marginal improvements on Z^0 pole at best
- $\delta M_W \sim 30$ MeV, $\delta M_t \sim 2$ GeV

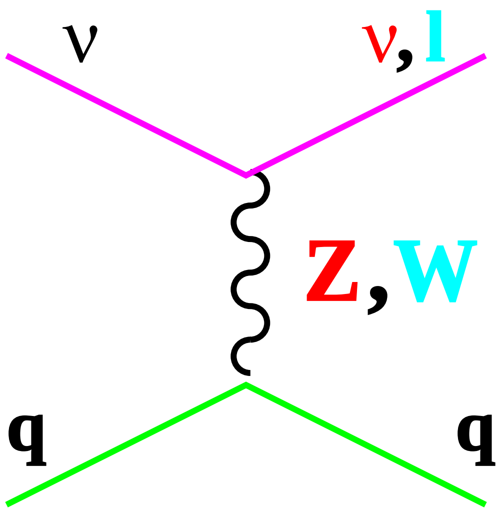
$$\Rightarrow \delta M_H/M_H \sim 0.2$$

- Found a 200 GeV Higgs at LHC?
- Or maybe have found a whole spectrum of SUSY…

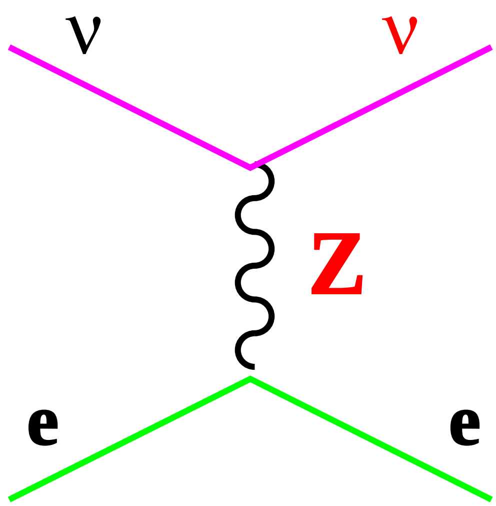
Of course, the low energy frontier holds one of the most interesting results

- Bennett and Wieman:
  $Q_W = -72.06 \pm 28 \pm 34$ ($Q_W^{\rm SM} = -73.2$)
- Future:
  - ▷ SLAC-E158
  - ▷ improved APV theory/experiment?
  - ▷ ν?

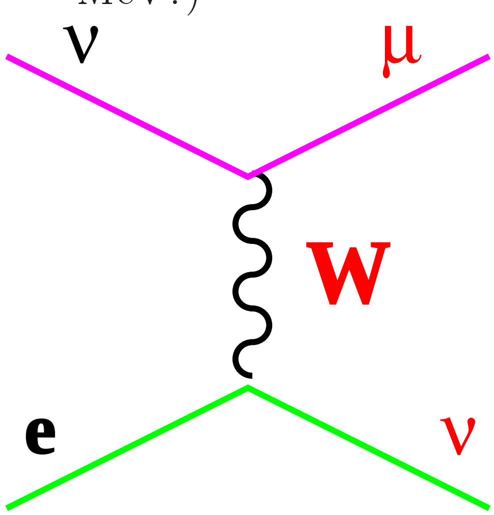
Processes for Study



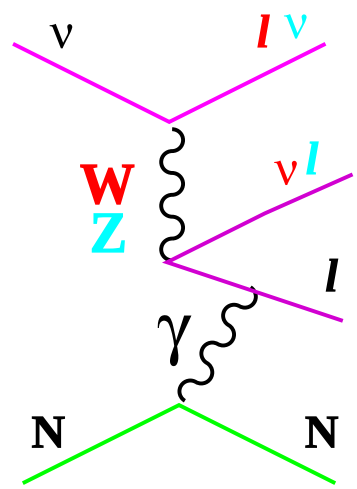
- High statistics
- Needs high energy
- Cross-section systematics significant ($\delta M_W \sim 20$ MeV?)



- Possible at low energy
- Low rate
- Normalization problem

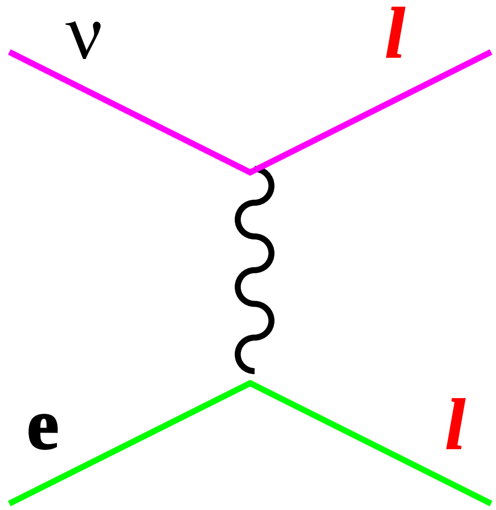


- Low rate
- Backgrounds



- W-Z interference
- But N is a problem

Neutrino-Electron Scattering



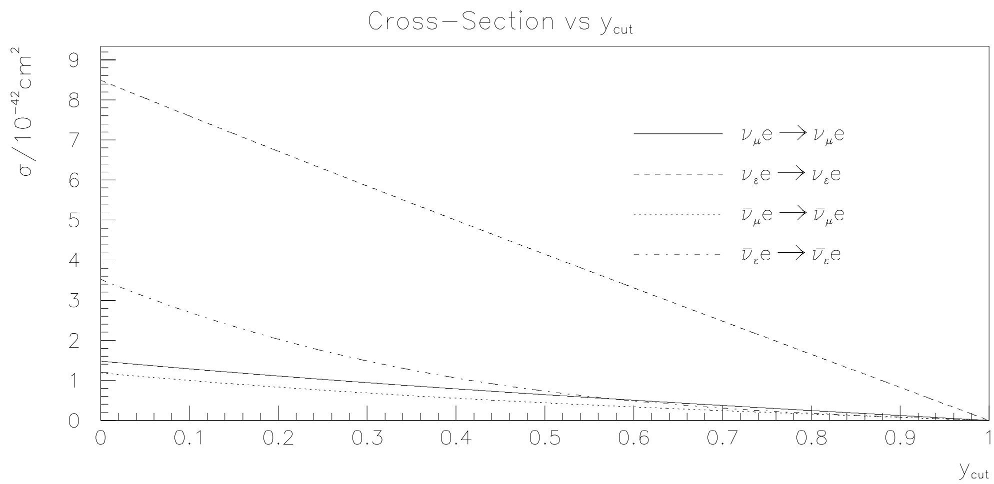
$\nu_\mu e^- \to \nu_\mu e^-$	NC only
$\nu_\mu e^- \to \nu_e \mu^-$	CC only ("inverse muon decay")
$\overline{\nu_\mu} e^- \to \overline{\nu_\mu} e^-$	NC only
$\nu_e e^- \to \nu_e e^-$	NC and CC
$\overline{\nu_e} e^- \to \overline{\nu_e} e^-$	NC and CC
$\overline{\nu_e} e^- \to \overline{\nu_\mu} \mu^-, \overline{\nu_\tau} \tau^-, \overline{u} d \ldots$	s-channel annihilation

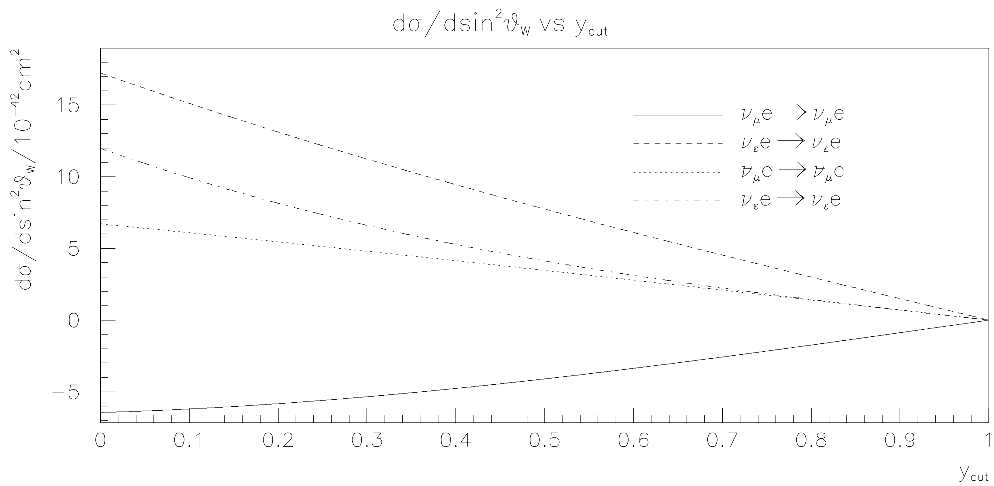
Why are these interesting?

- Target is a point particle: well-predicted cross-section
- NC processes sensitive to new physics ($\nu\nu ee$ coupling)

Neutrino-Electron Scattering (normalization)

$\sigma(E_\nu = 1\ GeV)$



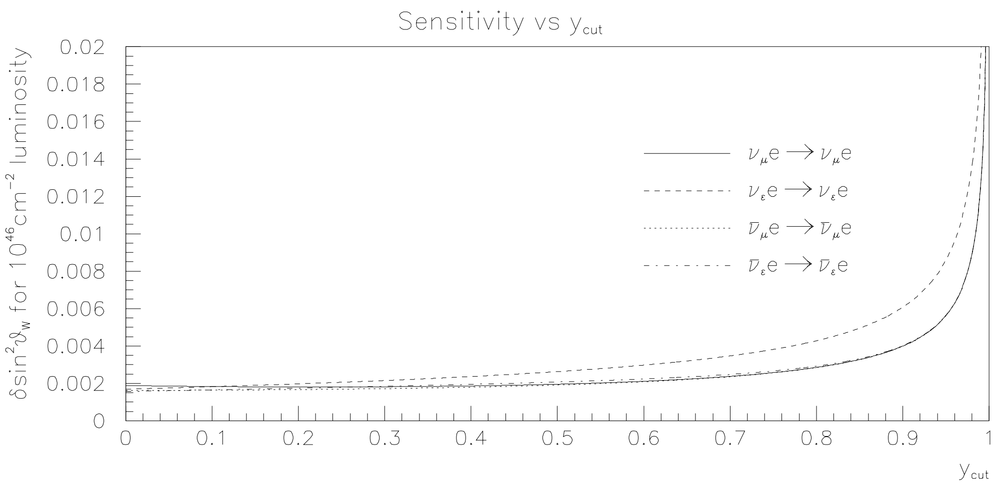


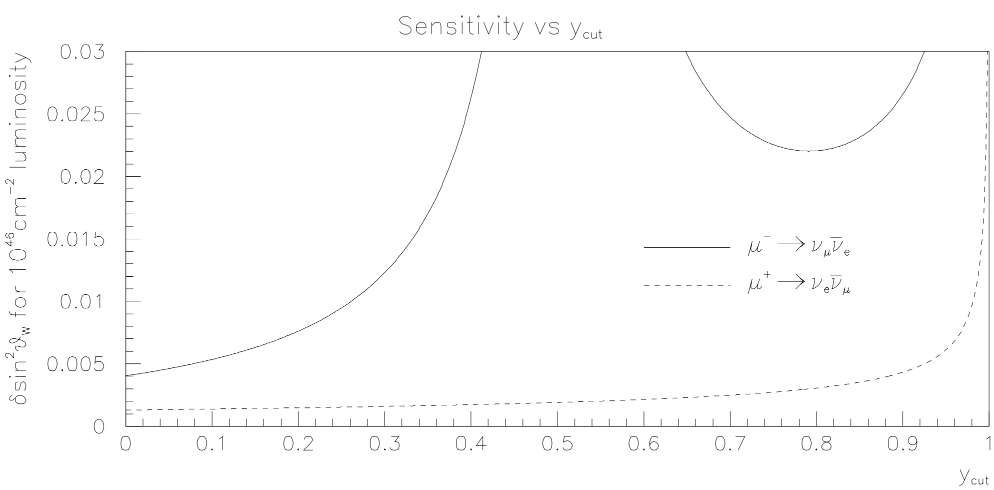
- CC-only process in μ^- beam (IMD) easy to normalize
- μ^+ beam, $\nu_e e \rightarrow \nu_e e$ varies by 0.1% for $\delta \sin^2\theta_W \sim 0.0005$
- Part per mil normalization available for 40 kg-yr

Neutrino-Electron Scattering ($\sin^2\theta_W$)

(B. King, J. Yu, KSM)

For 1 GeV neutrinos,





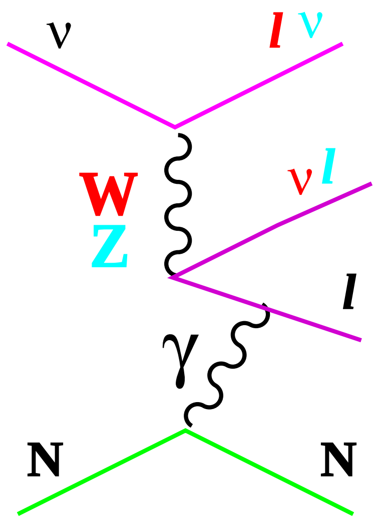
(10^{46} cm^{-2} is 2.5 kg of material in beam)

- Reasonable to imagine $\delta\sin^2\theta_W$(stat)$\sim$ 0.0001$-$0.0004 (250kg-yr)
- μ^- beam easy to normalize (IMD) but less sensitive

$\Rightarrow$ Probably systematics dominated

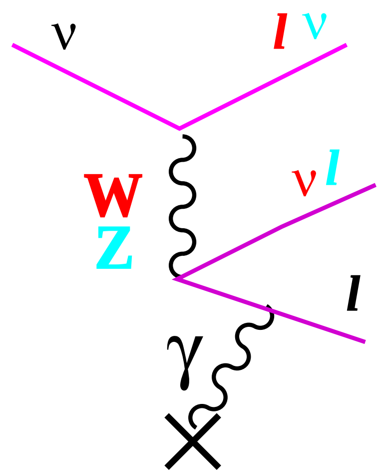
"External Tridents"

(A. Melissinos, KSM)



Nuclear form-factor leads to a large uncertainty in the cross-section

External field!
(well-determined, but weaker)



$$\sigma_{\nu\gamma} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{s_{\min}}$$

“External Tridents” (cont’d)

(A. Melissinos, KSM)

In an external magnetic field:

$$P_{\ell^+\ell^-} = \frac{\alpha G_F^2 s}{9\pi^2} \log \frac{s}{(2m_e)^2} \frac{B^2 E_\nu}{2m_\ell^2} l$$

For a 2 T, 10 m long field 10 cm in radius (50 GeV μ beam),

$$N_{e^+e^-} \sim 10^4/\text{yr}$$
$$N_{\mu^+\mu^-} \sim 0.1/\text{yr}$$

- Signal is low mass, forward e^+e^- pairs from external field and nothing else
- High rate
- Needs a ν_e or $\overline{\nu}_e$ beam to test interference of W/Z terms (T. Bolton)
- Sensitive to anomolous $W\gamma$ or $Z\gamma$ couplings(?)

$D^0 - \overline{D}^0$ Mixing

(D. Summers, B. King, T. Bolton)

- $D^0 - \overline{D}^0$ is a clean signature of new physics if seen above 10^{-6} level
- Charm production is large in 50 GeV beam ($\sim 10^8$/yr in 40 kg target)
- $\nu(\overline{\nu})N \to \ell^{\mp} c\overline{c}X$, $(\overline{c}) \to \ell^{\pm}\nu$ ($\sim 10\%$)
- Like-sign/opposite-sign sensitive to mixing
- Vertex detector to reduce backgrounds? (long-lived meson anti-tag)

Nucleon Structure

Why use neutrinos to probe nucleon structure?

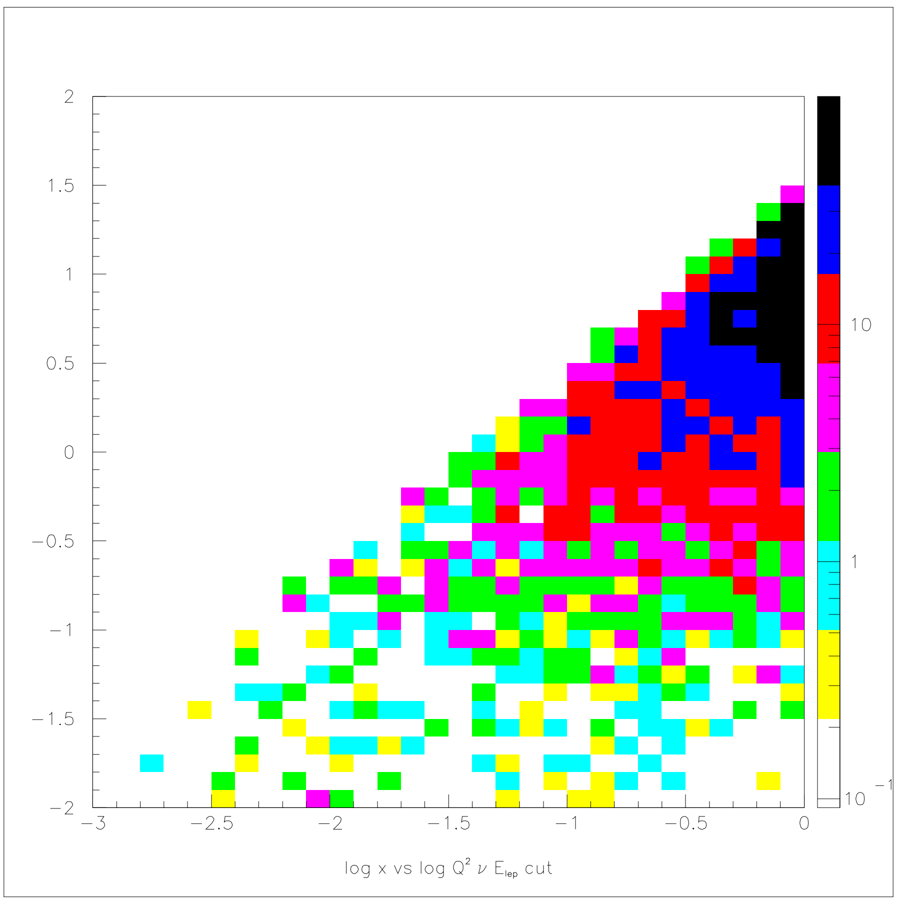
- xF_3
  - ▷ Separation of sea and valence
    - ∗ Fundamental for dynamical models
    - ∗ Evolution to high Q^2 (LHC)
  - ▷ Nuclear effects in xF_3?
- Polarization of Beam
  - ▷ Can't do better
  - ▷ Polarized targets?
- Flavor tagging
  - ▷ $\nu s \to \mu^- c$, $c \to X\ell\nu$ tags strange quarks
  - ▷ $\nu d \to \mu^- u$ but $\overline{\nu} u \to d\mu^+$
  - ▷ $\nu c \to \nu^- c$, $c \to X\ell\nu$ (? hard…)
- High rate means we can wean νN from its addiction to isoscalar targets
  - ▷ Can finally take advantage of the above!

The Deal with the Devil

A neutrino factory solves the rate problem . . .

. . . but high energy may be far away

20 GeV μ Beam



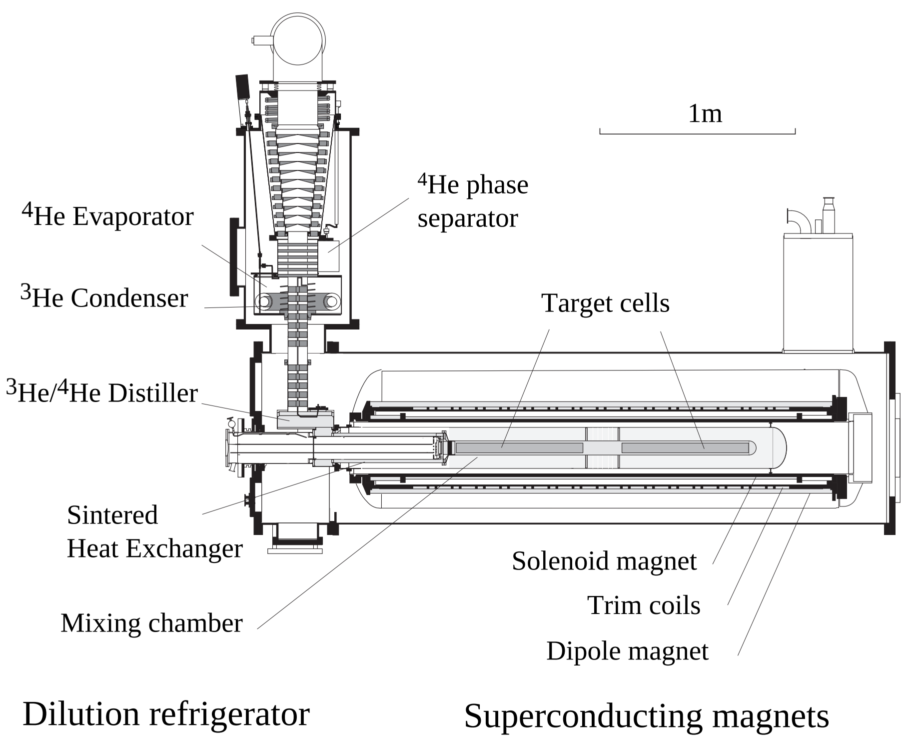
- Can't go as low in x as one might like for sum rules

Polarized Targets

(D. Harris, KSM)

Proof of principle: SMC target

- Solid Butanol ($CH_3(CH_2)_3OH$) target
- Two cells 60cm long, 5cm diameter: $2 \times 1.42\,\text{kg}$ each
- 2.5T B Field, 1K 100% polarized electrons
- Dilution factor: f=0.1 (SMC, `hep-ex/9702005`)



Imagine a 30 kg (1.5 m long, 10 cm radius) Target:
is this crazy?

Polarized Targets (cont'd)

(D. Harris, KSM)

Goal: Flavor-Separated Spin

$$\nu u \to \mu^- d \qquad \nu \overline{d} \to \mu^- \overline{u}$$
$$\overline{\nu} d \to \mu^+ u \qquad \overline{\nu u} \to \mu^+ \overline{d}$$
$$\overline{\nu} s \to \mu^+ c \qquad \nu \overline{s} \to \mu^- \overline{c}$$

- q and $\overline{q}$ from the inelasticity distributions
- $\nu/\overline{\nu}$ from lepton flavor

$\overline{\nu}(\nu)s(\overline{s}) \to \mu^\pm c(\overline{c})$ separated from $c \to \ell\nu X$ final states ($\sim$ 1% of cross-section at 50 GeV)

$\Rightarrow$ Measure strange sea polarization to 1.5% in one year!!

- Vastly superior flavor separation compared to hadron-based separation in HERMES

Neutrino Properties

What is the role of the near detector in measurements of neutrino properties?

- Oscillations
  - ▷ Unlikely to observe oscillations in near detector ($\nu_e \rightarrow \nu_\tau$ untested)
  - ▷ Measurement/normalization of flux
  - ▷ Measurement of $\sigma(E_\nu)$
- Direct Problems of Neutrino Properties
  - ▷ Electromagnetic properties: e.g., $\nu \rightarrow \nu_\gamma$
  - ▷ Direct Effects of m_ν?

Near Detector as Flux Monitor

Projective geometry is problematic

- Far detector at 10 kTon subtends perhaps 1 μrad
- Projecting to near detector, get about 1 mm^2

$$\delta x_\mu \delta\theta_\mu \gg 10^{-3} \text{ mm-mrad}$$

If we assume $\delta\theta_\mu \sim \frac{1}{r\gamma}$, then

$$\frac{\delta E}{E} \sim \frac{1}{2r^2}$$

So if r has an uncertainty σ_r, there is an E_ν uncertainty in the far detector relative to the near,

$$\sigma_E \sim E\frac{1}{r^2}\sigma_r$$

No problem relating ν_μ and ν_e fluxes, unless your beam is polarized.
Effective polarization measured from the near detector is uncertain at the far detector by

$$\sigma_P \sim P\frac{2}{r^2}\sigma_r$$

Will have to rely on beam for
effect of polarization and absolute energy

Near Detector as Cross-Section Monitor

Key measurements here are

- $\langle\sigma_{\overline{\nu}}\rangle / \langle\sigma_\nu\rangle$
  (average rates for neutrinos and antineutrinos)
- $\sigma_{\nu,\overline{\nu}}(E_{\text{reconstructed}})$
  (correction to $\sigma \propto E_\nu$ based on reconstructed energy)
- Measurements should be done with detector materials (thin target modules)
- Detector *performance* measurements should be done separately
  (low intensity beam)

Wildcard here, again, is polarization.
Uncertainty in $R_E \equiv \langle E_{\nu_\mu}\rangle / \langle E_{\nu_e}\rangle$ from the near detector, projected to the far detector, due to polarization and beam divergence will be approximately

$$\sigma_{R_E} \sim \frac{P}{r^2}\sigma_r$$

Absolute normalizations to σ can come from

- Beam prediction (current the most uncertain?)
- $\nu - e$ scattering

Direct Probes of Neutrino Properties

Some of the laundry list:

- Charge radius $< r^2 >$ as an elastic form-factor or radiative emission
- Decays of heavy neutrinos with $m_{L^0} \sim 50$ MeV
  $m_{L^0} \to e^+e^-\nu$
- Interaction/modification of ν beam in high external field
- ...

Why persue these at a neutrino factory?

- 10^3—10^5 increase in available neutrinos
- Beam small transversely

Rantings – or – A Plea

We shouldn't give up on rare interactions providing a way to probe mass directly!

Two examples:

- Neutrinos in external fields
  $\left|\vec{E}\right|$ seen by ν is $\sim \frac{E_\nu}{m_\nu}\left\{\vec{E},\vec{B}\right\}$
- $\nu \to \nu\gamma$
  Process requires momentum transfer

  $$q_{\min} \sim \frac{(2m_\nu)^2}{E_\nu}$$

  and so has a coherence length $L \propto m_\nu^{-2}$

Do these lead anywhere? Maybe not...

...but we have time to think

Conclusions

1. Short Baseline Physics is an important part of a neutrino factory
   - Neutrino "facility" for many different types of physics
   - Unique capabilities to probe strong, weak interactions
2. Near detector lab crucial for long baseline measurements
   - Flux, cross-sections, testbeam
3. Like the long baseline frontier, this rate of neutrinos in another unexplored opportunity
   - May yield surprises!