A Departure From Prediction: Electroweak Physics at NuTeV

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NuFact 2002

Outline

The NuTeV Collaboration

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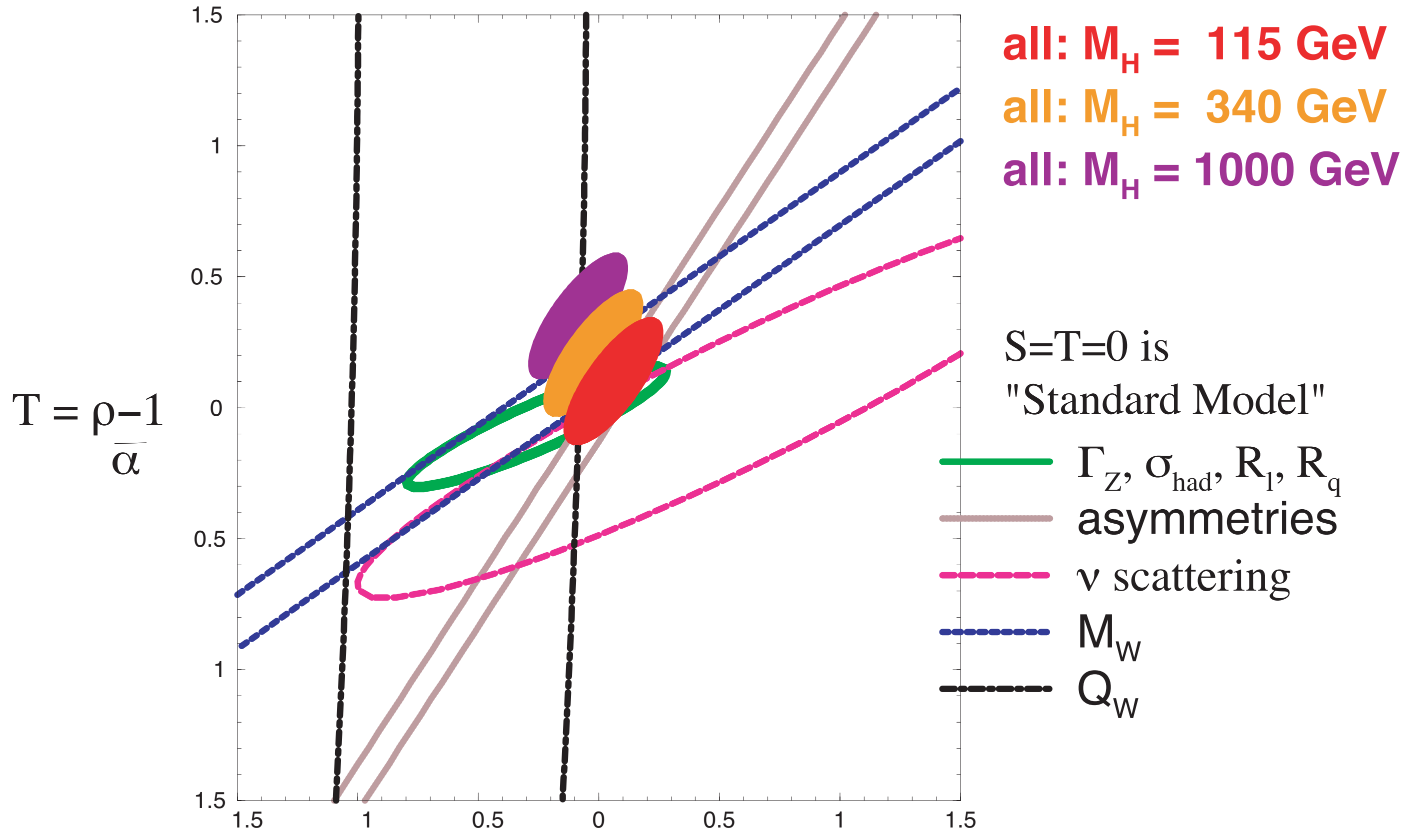
Electroweak Measurements

- Measure $\sin^2\theta_W$ in A Variety of Processes
  And Demand Consistency



(S, T from Peskin and Takeucki) Langacker, hep-ph/0110129 v1

S => $\sin^2\theta_W$

Table I: Electroweak observables described in fit.

Quantity	Experimental value	Theoretical value
Q_W (Cs)	72.2 ± 0.8 a)	73.19 b) 0.800 S 0.007 T
Q_W (Tl)	115.0 ± 4.5 c)	116.8 d) 1.17 S 0.06 T
M_W (GeV/c^2)	80.451 ± 0.033 e)	80.385 f) 0.29 S +0.45 T
(Z) (MeV)	83.991 ± 0.087 g)	84.011 f) 0.18 S +0.78 T
$\sin^2\theta_W$	0.23152 ± 0.00017 g)	0.23140 f) +0.00362 0.00258 T
"M_W" (GeV/c^2)	80.136 ± 0.084 h)	80.385 f) 0.27 S +0.56 T

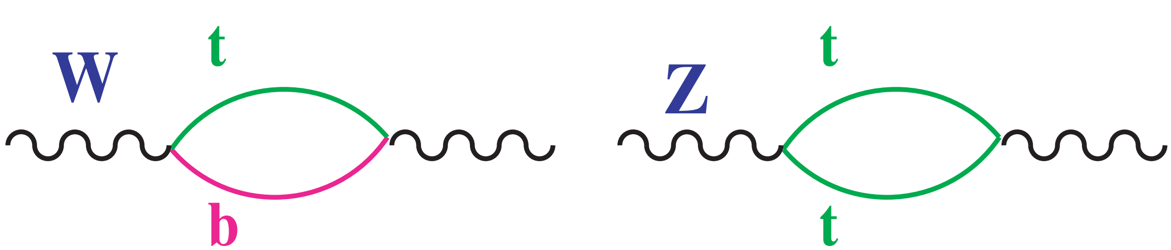
J. Rosner, hep-ph/0109239

What's Different About Neutrinos?

- Neutrinos Measure a
  Different Quantity from Direct Mass: ρ

$$\sin^2\theta_W(\text{on}-\text{shell}) = 1 - \frac{M_W^2}{M_Z^2}$$
$$\sin^2\theta_W = 1 - \frac{M_W^2}{\rho M_Z^2}$$

- $\sin^2\theta_W$ describes the *mixing* between the Z^o and the γ in Spontaneous Symmetry Breaking
- $\rho = G_F(NC)/G_F(CC)$ sets the relative strength of charged, neutral current interactions
- Is $G_F^{\mathrm{CC}} = G_F^{\mathrm{NC}}$?
- Precise Measurements With Different EW Corrections:
  Probe for New Physics



Comparison in Different Processes

All happy families are alike. Each unhappy family is unhappy in its own way. —L. Tolstoy

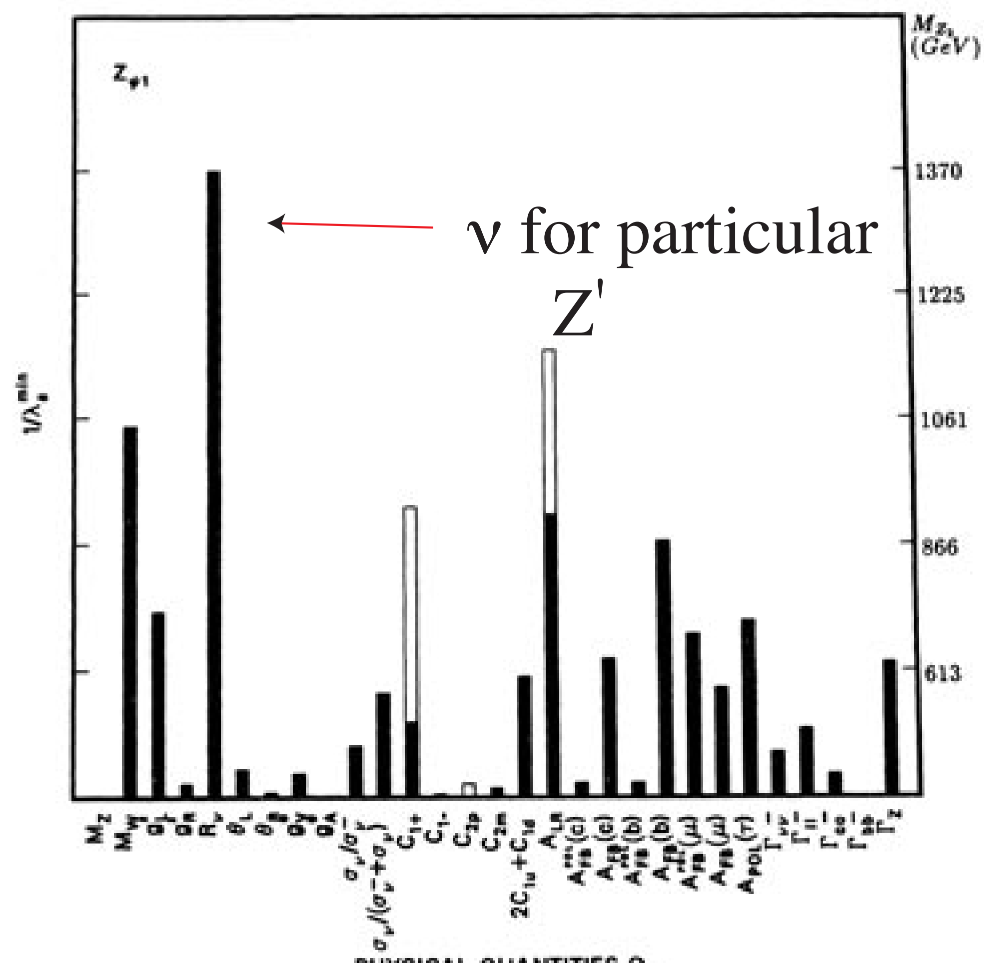
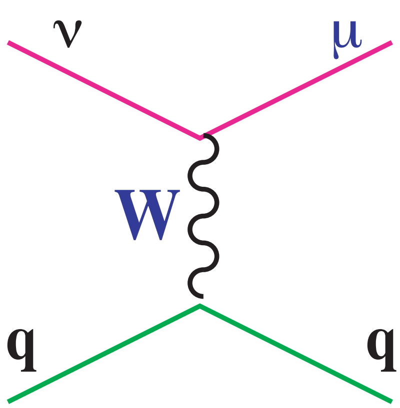
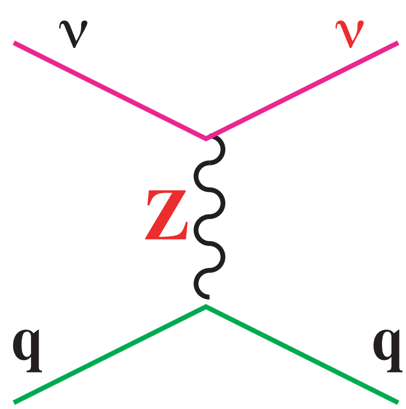


FIG. 36. The new physics of Z_ψ with $C=(2/3)^{1/2}$: solid bar for C_{1+}, C_{2p}, and A_{LR}(SLC); open bar for C_{1+}(iso), C_{2p}(1), and A_{LR}(LEP).

Methodology



Coupling $\propto\ I^{(3)}_{\mathrm{weak}}$



Coupling $\propto \left(\, I^{(3)}_{\mathrm{weak}} - Q_{\mathrm{em}} \sin^2\theta_W \right)$

Want

$$R \;=\; \frac{\sigma(\nu, \mathrm{NC})}{\sigma(\nu, \mathrm{CC})}$$

Measure

$$R\mathrm{meas} \;=\; \frac{\text{Neutral Current Events}}{\text{Charged Current Events}} \Leftrightarrow \frac{\text{no} - \text{muon events}}{\text{with muon events}}$$

$$=\; R_{\mathrm{meas}}(\sin^2\theta_W, \rho, \mathrm{flux}, \mathrm{QPM}, \mathrm{detector})$$

Taking Ratios

- W, Z Scattering $\Leftrightarrow \rho$ and $\sin^2\theta_W$:

  Llewellyn Smith Relations:

$$R^{\nu} = \frac{\sigma^{\nu}_{NC}}{\sigma^{\nu}_{CC}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + r\right)\right)$$

$$R^{\overline{\nu}} = \frac{\sigma^{\overline{\nu}}_{NC}}{\sigma^{\overline{\nu}}_{CC}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{1}{r}\right)\right)$$

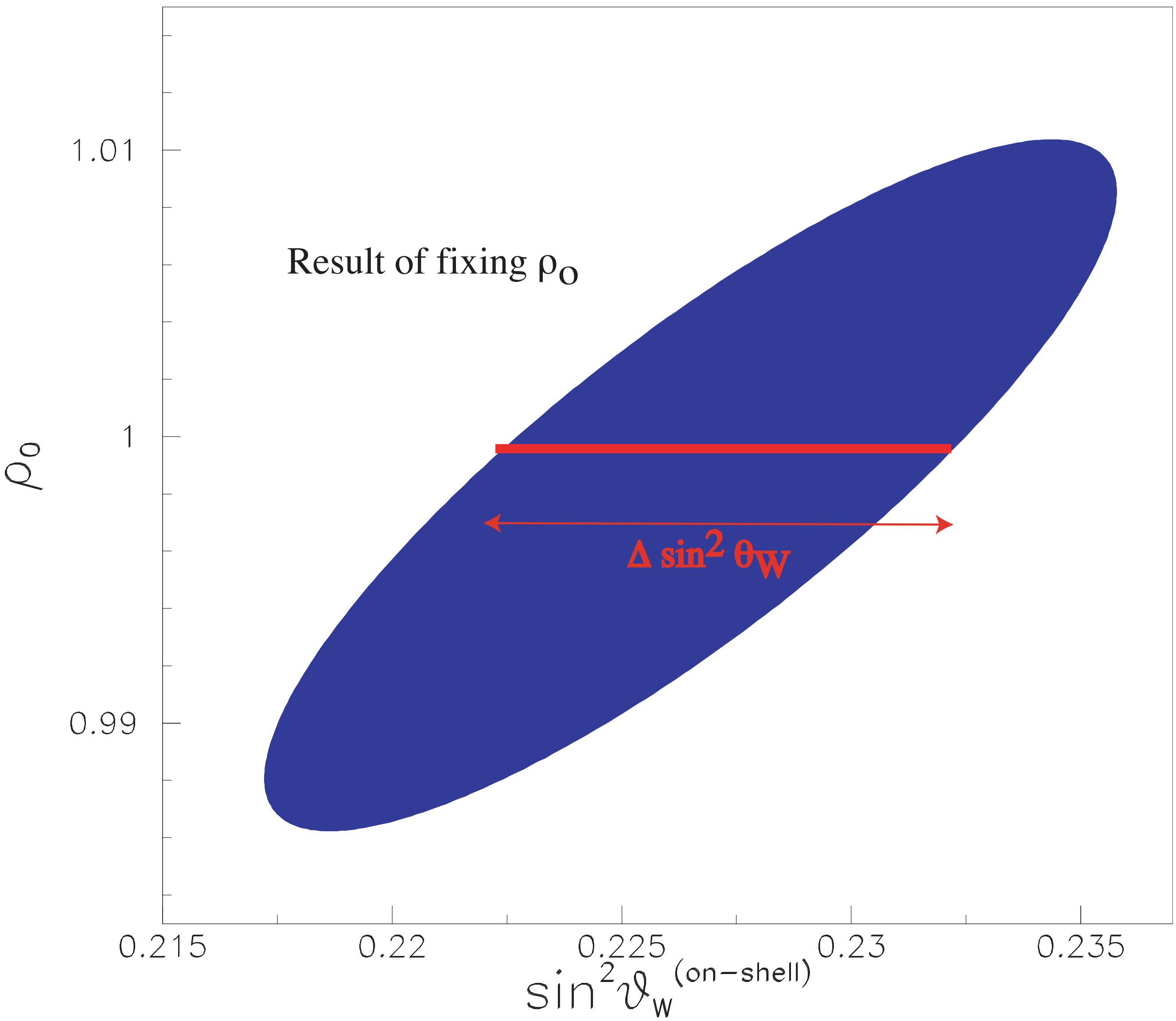
$$r = \frac{\sigma^{\overline{\nu}}_{CC}}{\sigma^{\nu}_{CC}} \text{ Measured From Data}$$

Isoscalar target composed of only u,d quarks at tree level

- Typically Have *Assumed* ρ from SM and fit $\sin^2\theta_W$
- Big Change With NuTeV:
  - Now Two Equations, Two Unknowns:

$$R^{\nu}, R^{\overline{\nu}} \Leftrightarrow \rho, \sin^2\theta_W$$

Soundbite Version



- Fixing ρ and reporting R^-, R_ν is very close to

$$\sin^2\theta_W \; = \; 1 - \frac{M_W^2}{M_Z^2}$$

- This Is What We Usually Quote

The Result

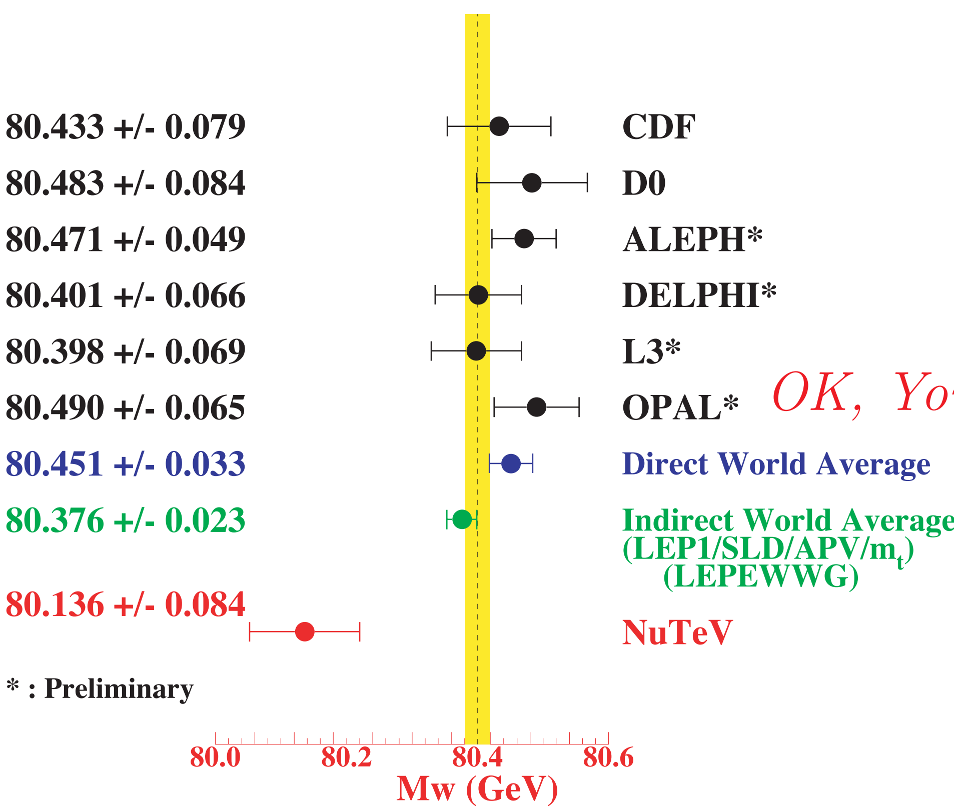
NuTeV Measures:

$$
\begin{aligned}
\sin^2\theta_W^{(\mathrm{on-shell})} &= 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst}) \\
&- 0.00022\times\left(\frac{M_{\mathrm{top}}^2-(175\ \mathrm{GeV})^2}{(50\ \mathrm{GeV})^2}\right) \\
&+ 0.00032\times\ln\left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}}\right)
\end{aligned}
$$

cf. standard model fit (LEPEWWG): 0.2227 ± 0.00037

A discrepancy of 3σ...

$$
\sin^2\theta_W^{(\mathrm{on-shell})} \equiv 1 - \frac{M_W^2}{M_Z^2}
$$



OK, You can Leave Now . . .

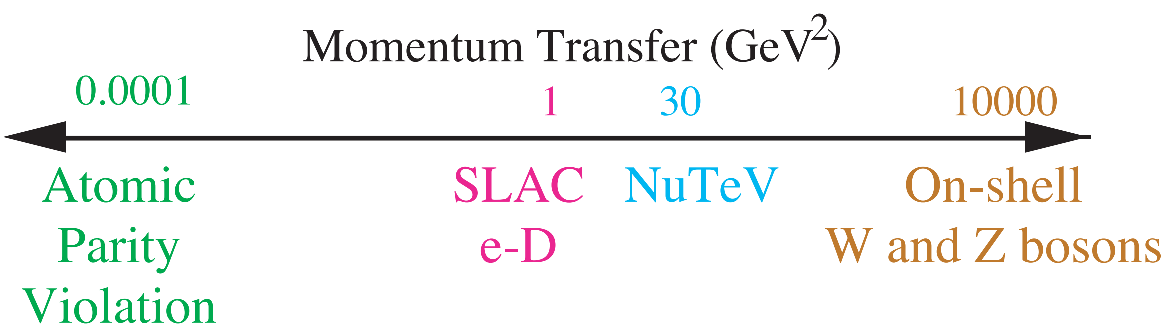
Theory Recap:

- NuTeV is precise: M_W comparable to collider precision

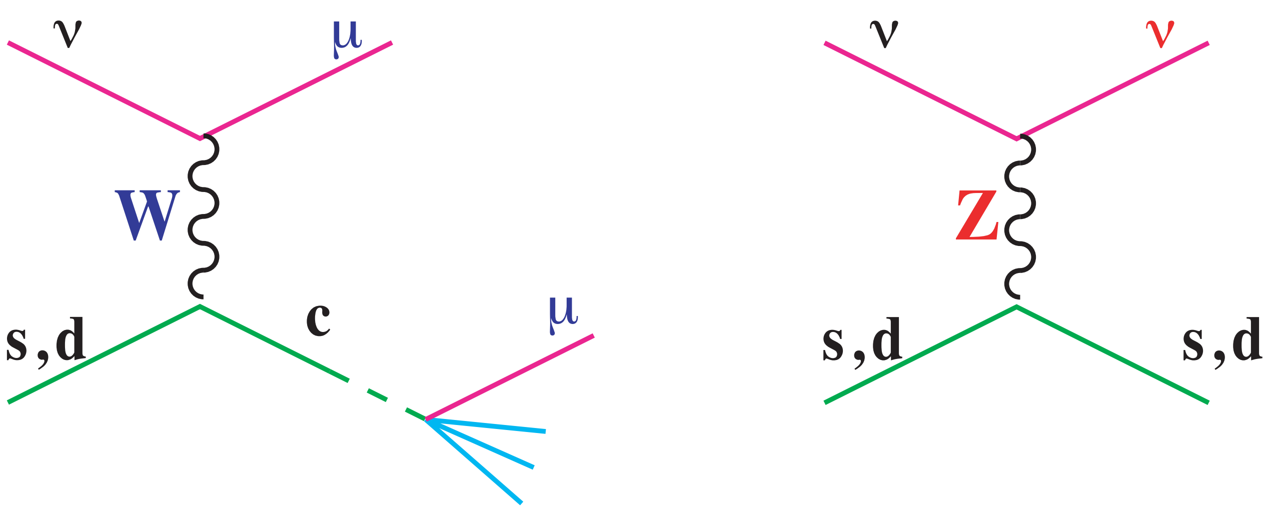
Toby vs. Godzilla

- NuTeV is sensitive to different new physicsthan other precision experiments
  - Sensitive to different radiative corrections
  - Measurement is off the Z pole
    - ⋆ i.e. exchange is not guaranteed to be a Z
  - Measure neutral current neutrino couplings
    - ⋆ LEP I invisible line width is only other precise measurement
  - Measure light quark couplings
    - ⋆ also APV, Tevatron Z production

- Testing in a wide range of processes and momentum scales ensures universalityof the electroweak theory



What's the Limiting Error?: Charged-Current Production of Charm



- Suppression of CC cross section for interactions with massive charm quark in final state
- Modeled by leading-order slow-rescaling

$$\xi = x\left(1 + \frac{mc^2}{Q^2}\right) \quad \text{where} \quad x = \frac{Q^2}{2ME_{\mathrm{had}}}$$

- m_c a parameter, not real mass
- Can Measure Within Data, But Not Well Enough
- Need to Drastically Reduce this Error to Progress

R_ν, R^- and Systematics

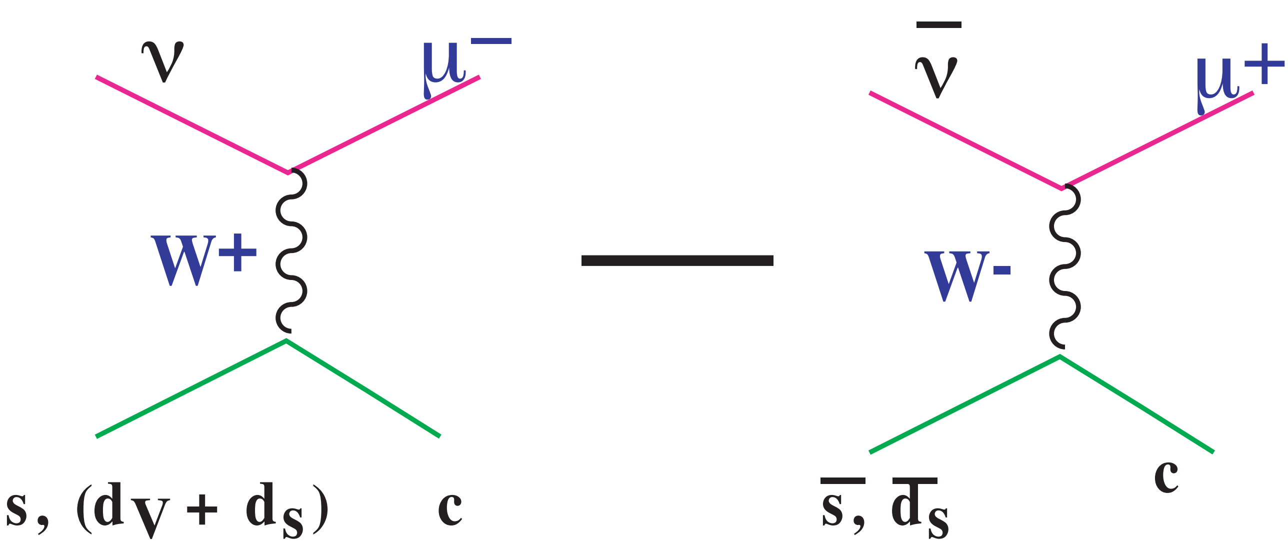
With Just A Neutrino Beam:

$$R^\nu = \frac{\sigma(\nu,\mathrm{NC})}{\sigma(\nu,\mathrm{CC})} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\,(1+r)\right)$$

With Both Neutrinos and Antineutrinos:

$$R^- = \frac{\sigma(\nu,\mathrm{NC}) - \sigma(\bar{\nu},\mathrm{NC})}{\sigma(\nu,\mathrm{CC}) - \sigma(\bar{\nu},\mathrm{CC})} = \rho^2(\frac{1}{2} - \sin^2\theta_W)$$

And in the PW Denominator:



$$= d_v \sin^2\theta_C \; Error Down \times 5$$

How Do You Get R^-?

$$R^- = \frac{R_\nu - r R_{\bar\nu}}{1-r}$$

$$R^+ = \frac{R_\nu + r R_{\bar\nu}}{1+r}$$

$$r = \sigma(\bar\nu, \mathrm{CC})/\sigma(\nu, \mathrm{CC})$$

(R^+ is the companion to R^- with cross-section sums)

- Experiment Measures R_ν, $R_{\bar\nu}$

Two Choices:

§1. Use R^+ to Reduce Systematics on R^-

§2. Feed in SM ρ

§3. Extract Precise $\sin^2\theta_W$

§1. Use Both R_ν, $R_{\bar\nu}$

§2. By "Conservation of Information", Same as R^+, R^-

§3. Do Genuine Two-Parameter Fit and Extract ρ

We, of course, will do both …

What Do You Need for a Neutrino Experiment?

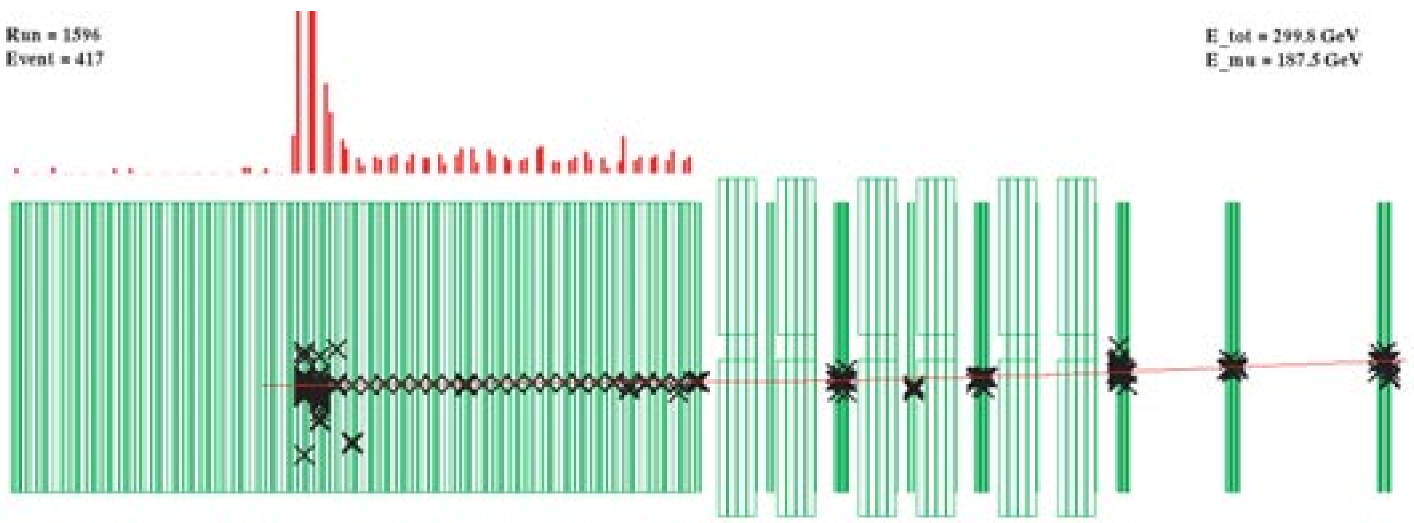
Requirements Driven by Small ν Cross-Section

- Neutrino Detector
  - Hundreds of Tons
- Neutrino Beam
  - Intense, Lots of Protons
- Auxiliary Measurements
  - Calibration of Detector Response
    - §1. Muons
    - §2. Hadrons
    - §3. Electrons

Detector: Advantages and Disadvantages

Lab E Detector - Fermilab E815(NuTeV)
690 tons: Fe-Scint-DC

Massive, Simple, Understood, but Coarse



- Easy to Detect:

  §1. Presence of Outgoing Muon ⇒ Charged Current

  §2. Absence of Outgoing Muon ⇒ Neutral Current

- But coarse, and therefore

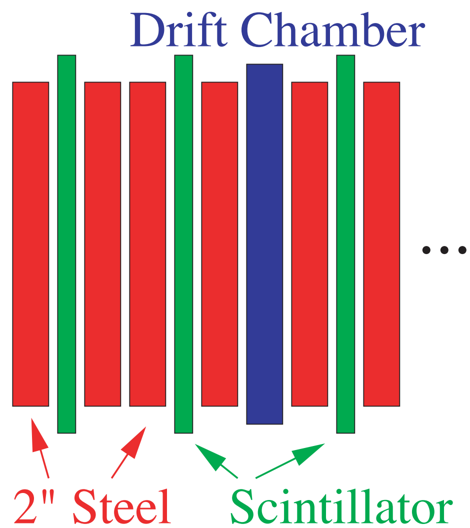
  §1. Sometimes miss muon

  – Low Energy Muons Range Out in Shower ($\approx$ 3 GeV)

  §2. $\nu_e N \to eX$ are a NC Background:

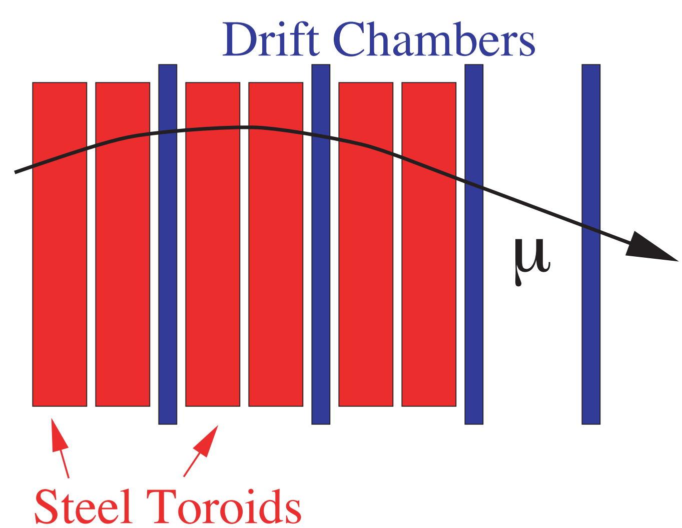
  – outgoing e gets Lost in Hadronic Shower X

Detector Details



Target/Calorimeter:

- 168 Fe plates (3m $\times$ 3m $\times$ 5.1cm)
- 84 liquid scintillation counters
  Trigger the detector
  Visible energy
  Neutrino interaction point
  Event length
- 42 drift chambers
  Localized transverse shower position



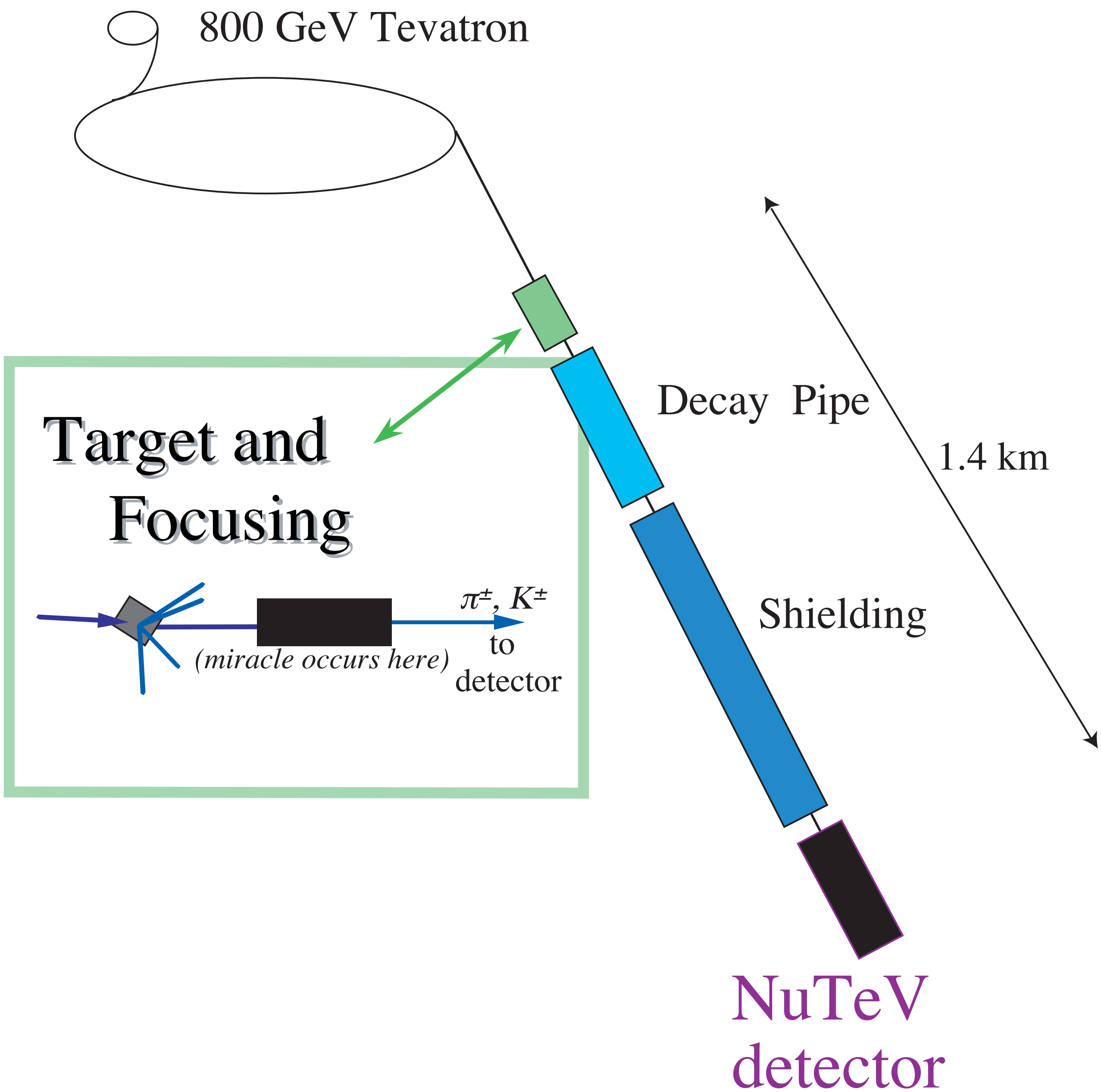
Toroidal Spectrometer:

- 11 kG field ($P_T = 2.4\, GeV/c$)

Continuous Test Beam: every beam spill

- Hadron, muon and electron beams
  Map toroid and calorimeter response
- Understand Behavior of Hadronic Showers

NuTeV Beamline: Overall



What's New About NuTeV?: The Beam

Prior Beams

§1. Horn (MINOS)

- Low Energy Portion
- Separate $\nu, \bar{\nu}$

§2. Dichromatic (Cross-Section Measurements)

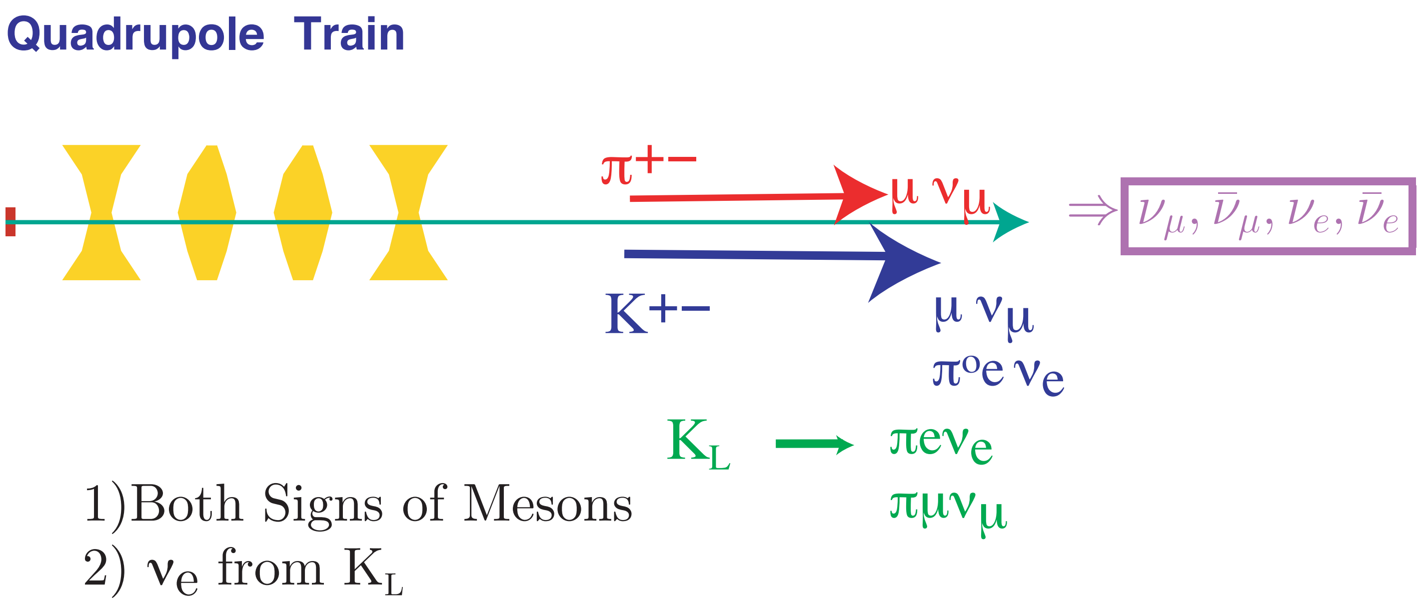
- Selects Mesons of Particular Momentum
- Low Flux

§3. Quadrupole Train (Structure Functions)

- Mixed $\nu, \bar{\nu}$
- High Energy, High Statistics

Why Not More Quad Triplet?

Quadrupole Triplet Was Best, but Problems



§1. Mixed $\nu, \bar{\nu}$ Meant Can't
Experimentally Separate
neutral current $\nu, \bar{\nu}$

Measure Combination of $R_\nu, R_{\bar{\nu}} \Leftrightarrow \sin^2\theta_W, \rho$

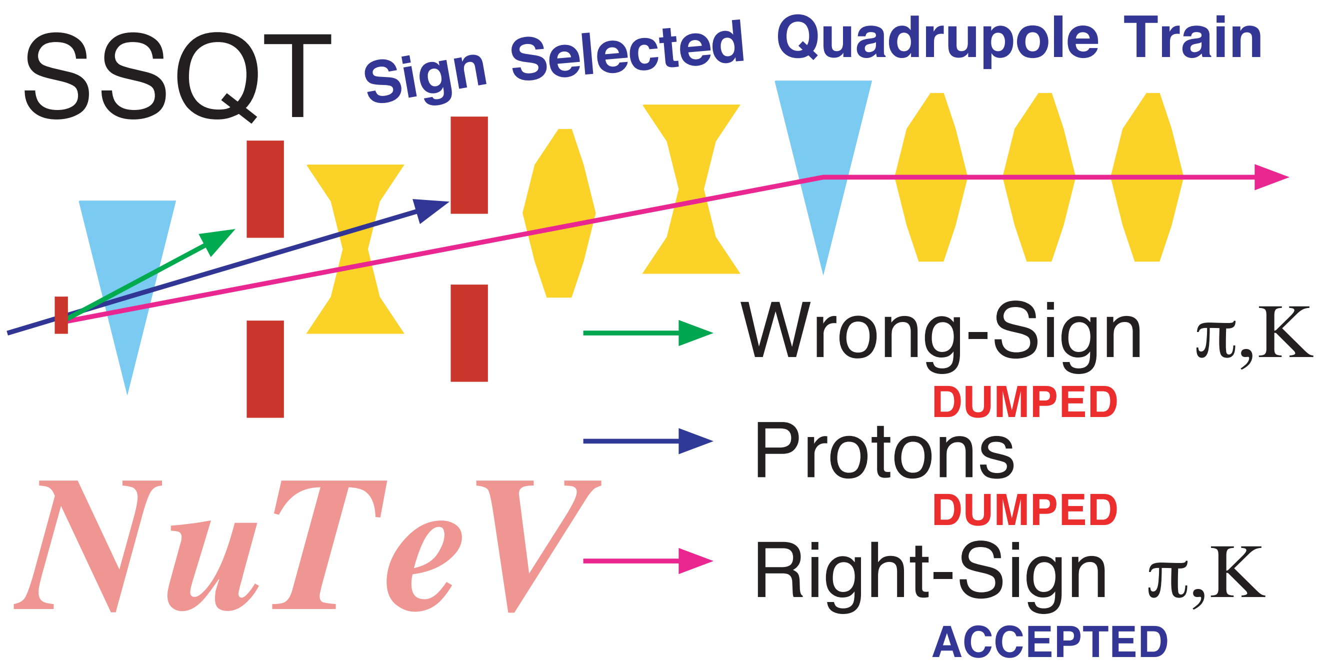
§2. Also Have Charm Mass Problem:

- No Subtraction in $R_\nu = \sigma(\nu, \mathrm{NC})/\sigma(\nu, \mathrm{CC})$

§3. Allows $K_L \longrightarrow \pi e \nu_e$

- Source of ν_e which can fake neutral currents
- Production not well known enough, big error!

NuTeV Beamline: SSQT



- Resulting beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is $\sim$1.8% electron neutrinos
  - But Troublesome $K_L \rightarrow \nu_e$ Gone,
    Since K_L Head off Into Dumps,
    Away From Beam Direction
- About Half of QT flux/per proton
  - Experiment will end up being statistics-limited!

Experimental Errors

Beam

- Have to get Flux
- Estimate ν_e (from $K^{\pm} \rightarrow \pi^o e \nu_e$)

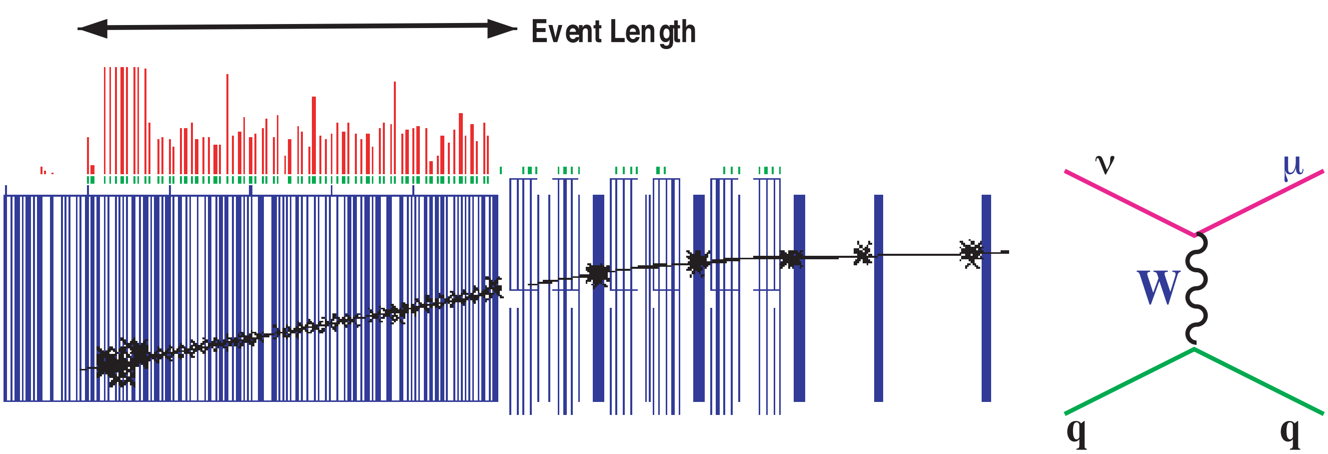
Detector

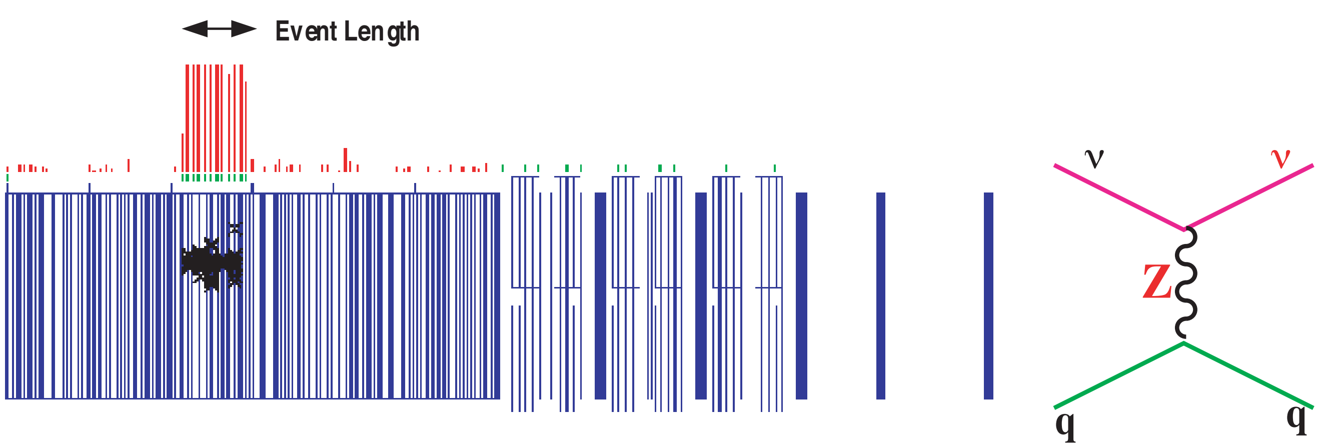
- Crosstalk from Neutral to Charged
- ν_e (from $K \rightarrow \pi^o e \nu_e$) all look like NC
- Acceptance Differences

QPM

- To extract $\sin^2\theta_W$ from the measured ratio
  $\Rightarrow$ corrections: isovector target, radiative corrs,
  heavy quark effects, higher twist, R_L
- Most of SF dependence, many of systematic uncertainties, and sensitivity to neutrino spectrum cancel in the ratio
- Major theoretical uncertainty m_c
  $\rightarrow$ mainly affects CC

Neutral Current/Charged Current Event Separation



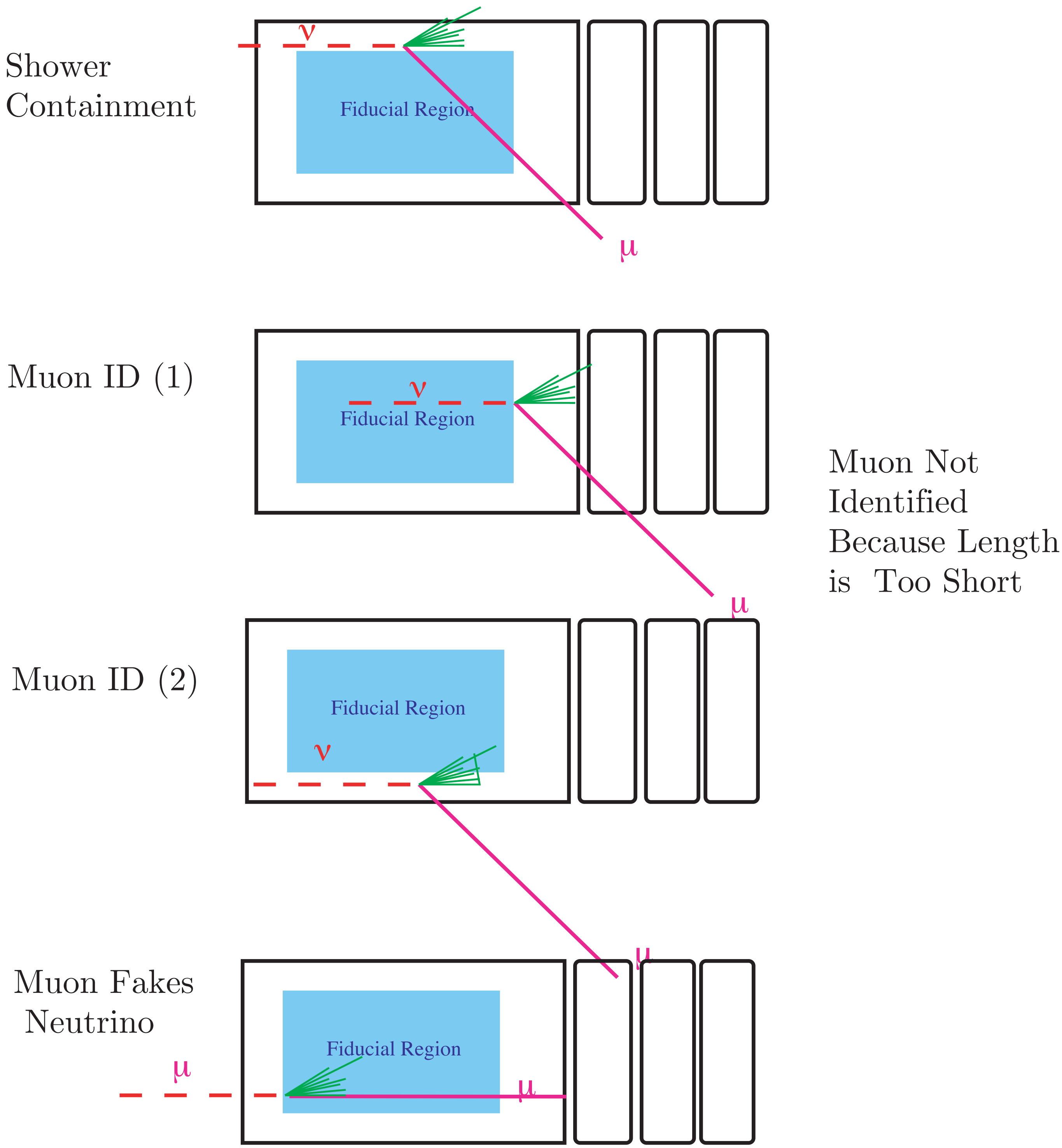


Statistical separation of NC and CC events based solely on "event length":

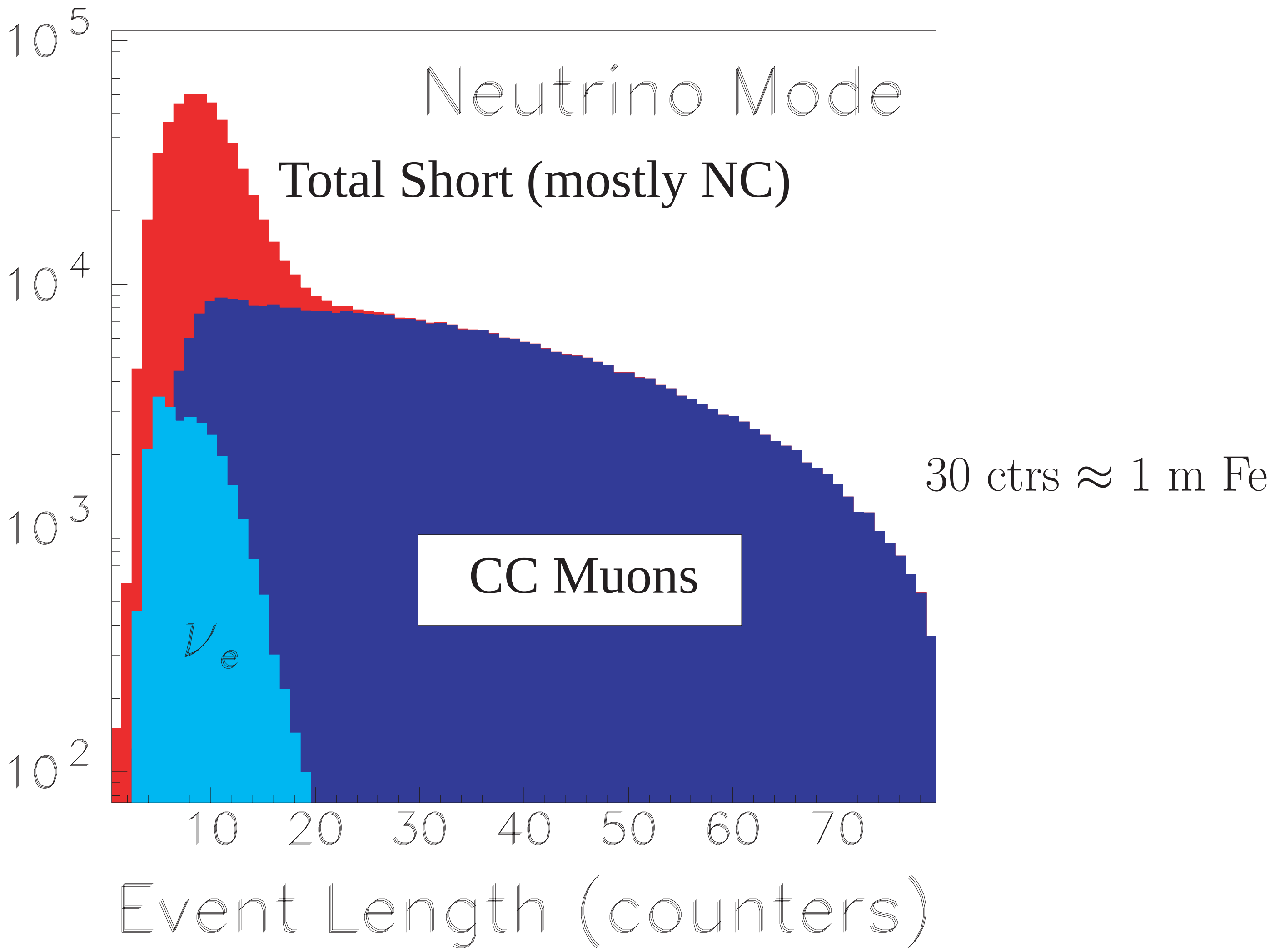
$$R_{\mathrm{exp}} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\mathrm{L} \leq \mathrm{Lcut}}{\mathrm{L} > \mathrm{Lcut}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

(measure this ratio in both ν and $\overline{\nu}$ modes)

Fiducial Cuts: Energy and Length



Length Distribution and Sources



§1. Model Shape of CC Distribution

- How Many CC's Under NC peak?
  ⇒ Structure Functions/PDFs

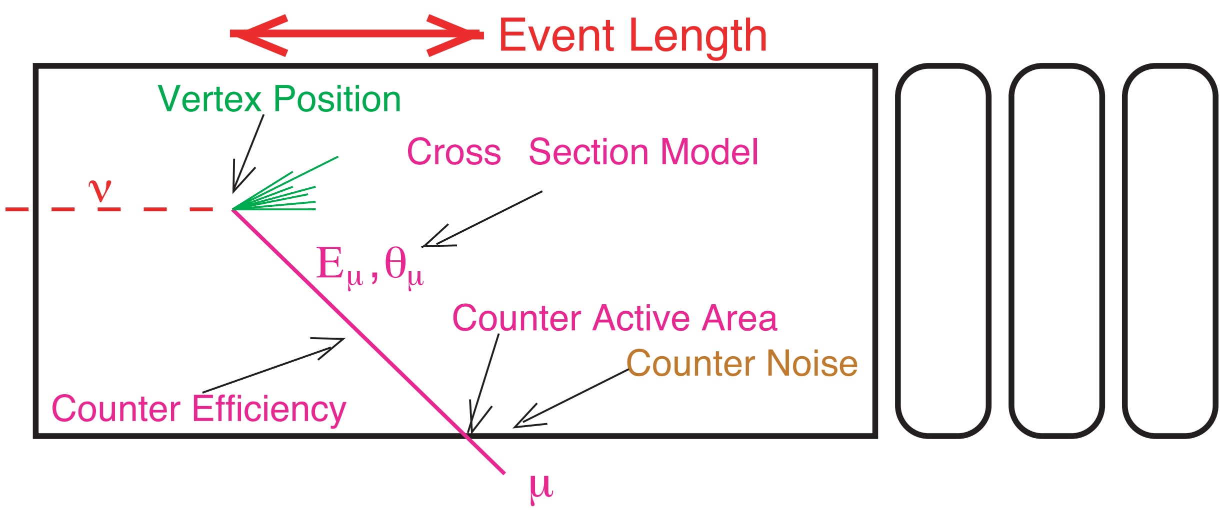
§2. How Many ν_e's?

- Flux Modeling

§3. How Many "Long NC"'s?

- Shower Length from Hadron Test Beam

Sources of Error in NC/CC Separation



CROSS SECTION MODEL

- LO pdfs (CCFR)
- Radiative corrections
- Isoscalar corrections ($\frac{N-Z}{A} \approx 5.67\%$, $\overline{d}/\overline{u} \neq 1$)
- Heavy quark corrections
- R_L
- Higher twist

DETECTOR RESPONSE

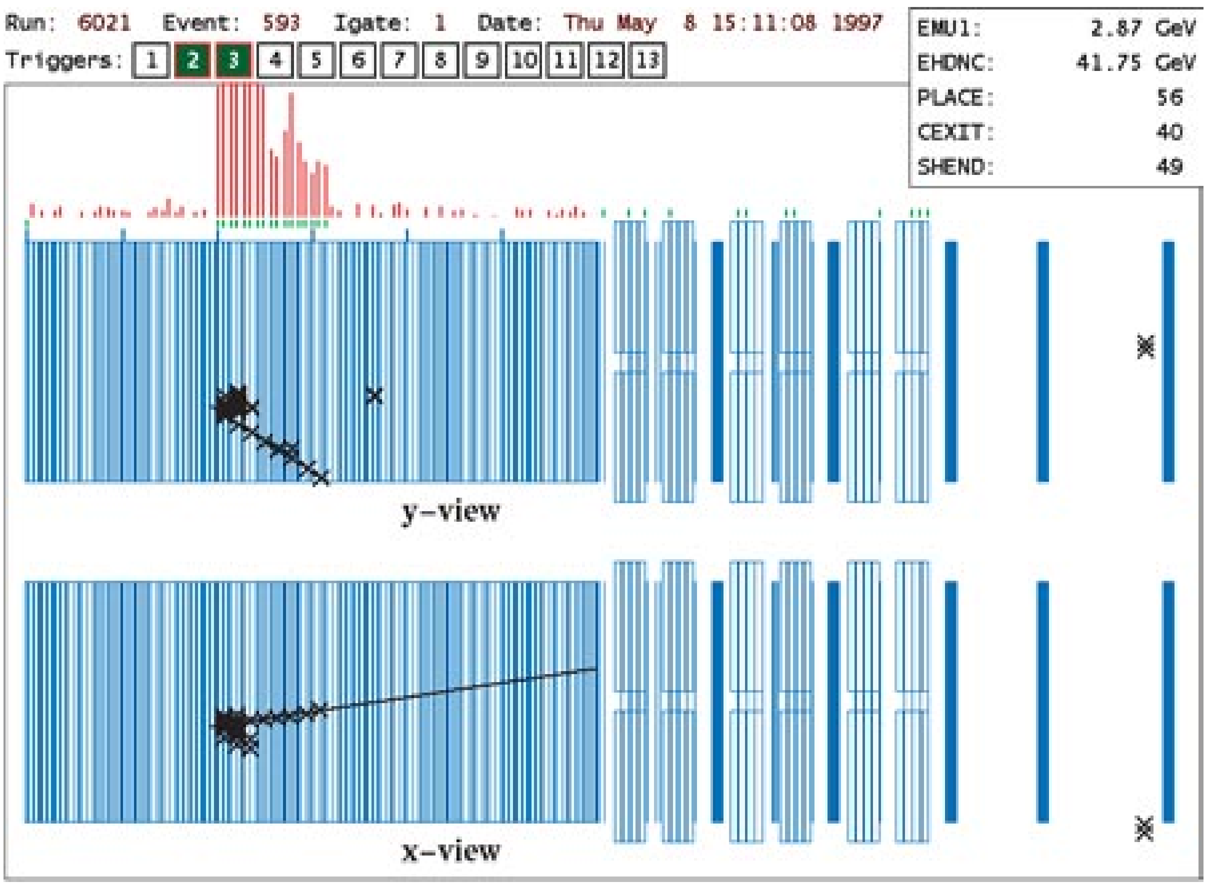
- CC↔NC cross-talk
- Beam contaminations
- Muon simulation
- Calibrations
- Event vertex

NEUTRINO FLUX

- ν_μ and ν_e

Backgrounds

- Even After Fiducial Cuts:



- Short ν_μ CC's (20% ν, 10% $\overline{\nu}$)

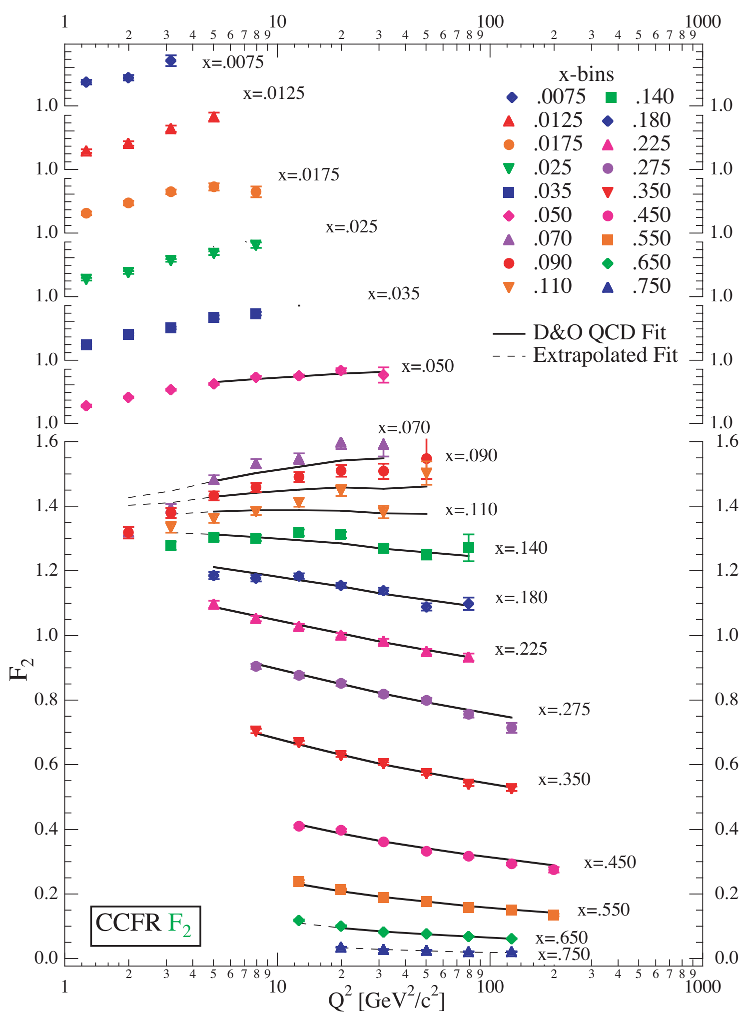
  muons exit, range out

- Why Not Track?: *Systematics*
  - Differences in Efficiency for
    NC (no track) *vs.* CC (track)
  - Error Would Dominate
  - Very Hard to Estimate/Control

This is Why We Use Length

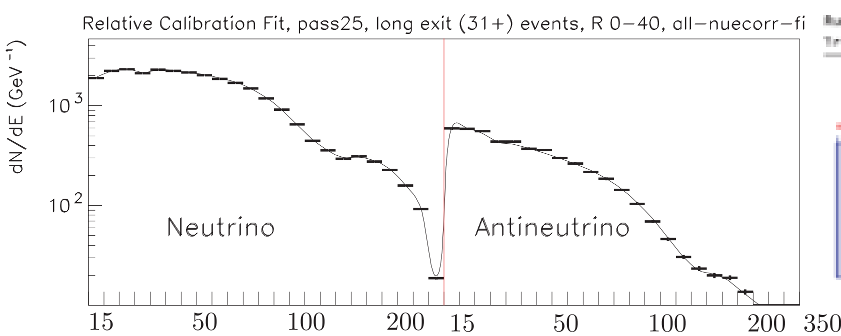
Determine Structure Functions from this Data

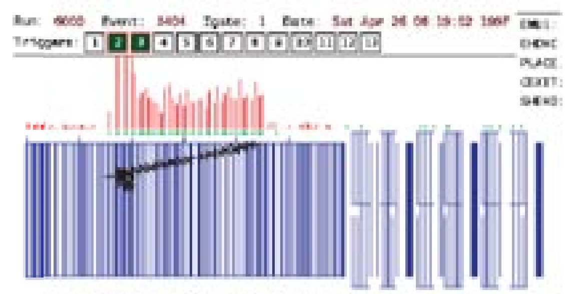
- Measure Structure Functions $\Rightarrow$ PDFs
  (Among Best PDF Inputs)
- Measured Internally With *Same Data Set*
  - Be Careful Applying External Corrections
  - Can't Just Take Your Favorite PDFs and Apply
  - We Try to produce Model-Independent Results

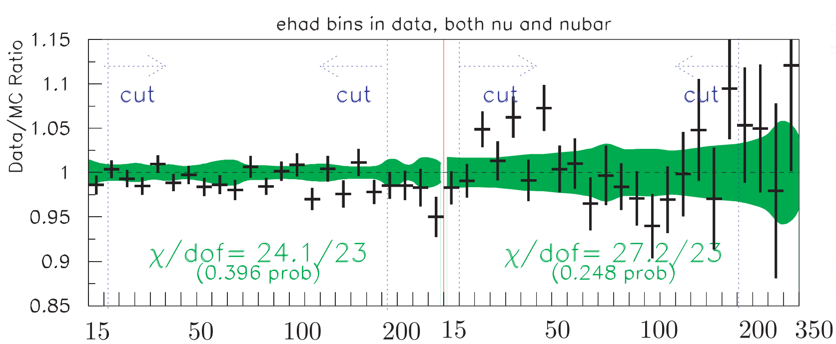


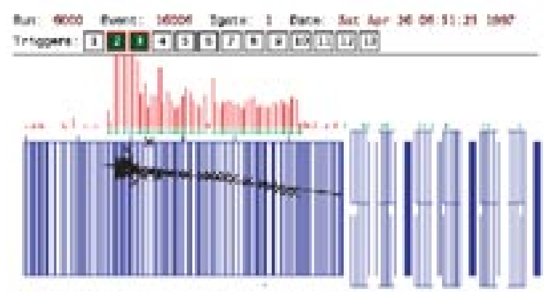
Charged-Current Control Sample

- High y charged-current is background to NC sample
  - CC subtraction is 20%/10% in $\nu/\overline{\nu} \Rightarrow$ want $\sim 1\%$ accuracy
- Check by looking at "long exit" CC events which start in the detector center and stop before toroid
- Kinematically Similar to Short Events, but no ν_e









Data/MC ratio

- Agreement in this "short" charged-current sample is good within systematic uncertainties

NuTeV Neutrino Flux

Approximately 5% of all short events are ν_e CC.

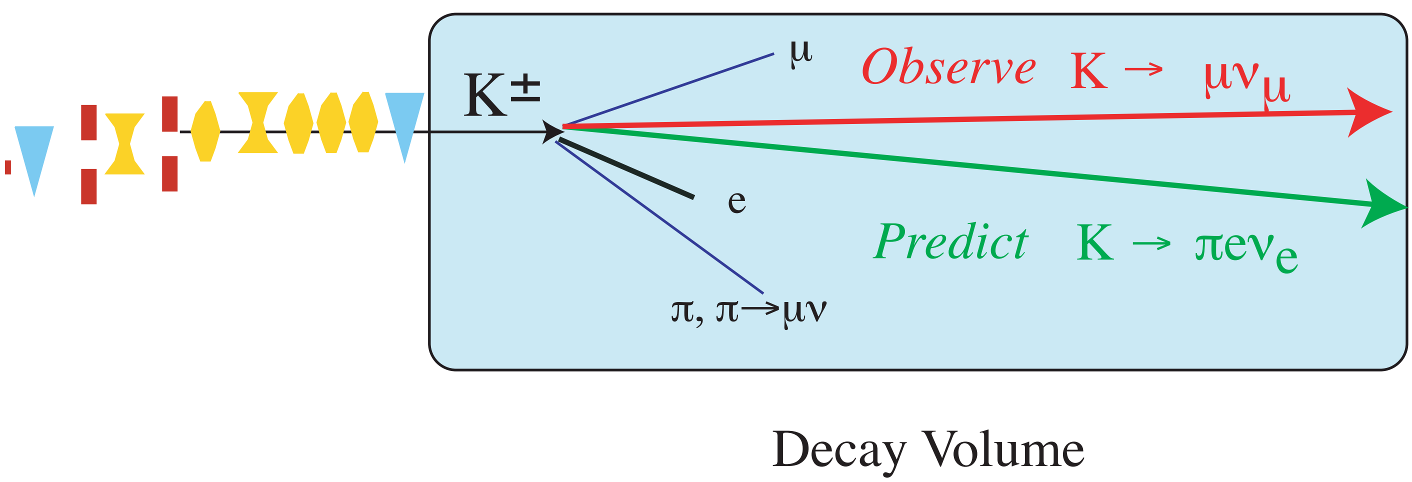
Sources of Neutrinos and Event Fractions

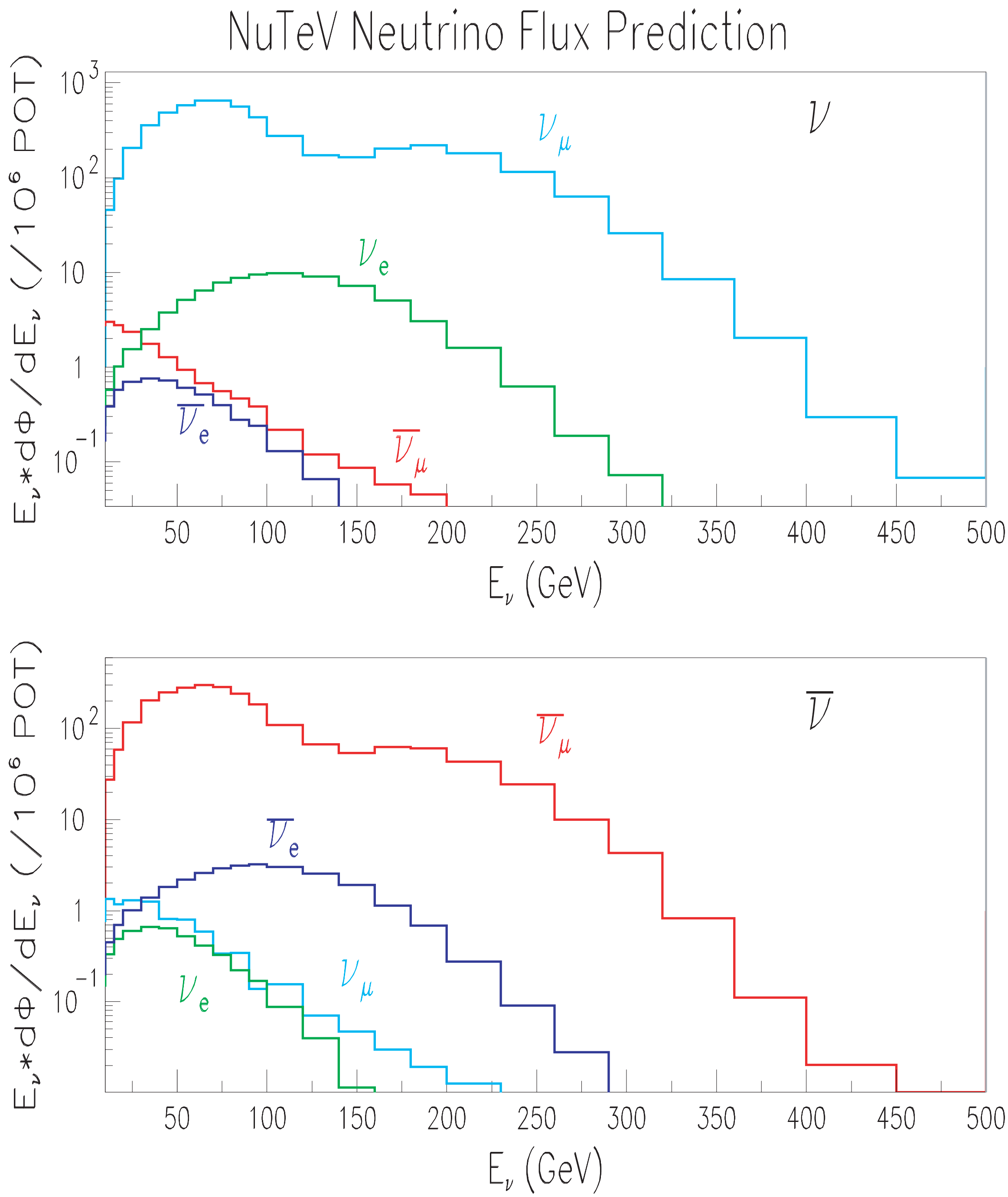
Source	ν Mode	$\overline{\nu}$ Mode
$\pi^\pm, K^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu$	0.982	0.973
$K^\pm_{e3}$	0.0157 ± 0.0003	0.0115 ± 0.0002
K_{Le3}, K_{Se3}	0.00065 ± 0.00007	0.00290 ± 0.0003
Charm Meson$\to \nu_e$	0.00042 ± 0.00006	0.00155 ± 0.0002
$\mu \to \nu_e$	0.00007 ± 0.00001	0.00010 ± 0.00001
Λ_c, Λ, Σ	0.00003 ± 0.00003	0.00023 ± 0.0002

$\Rightarrow$ *It would take a 20% mistake in ν_e to move $\sin^2\theta_W$ to SM value*

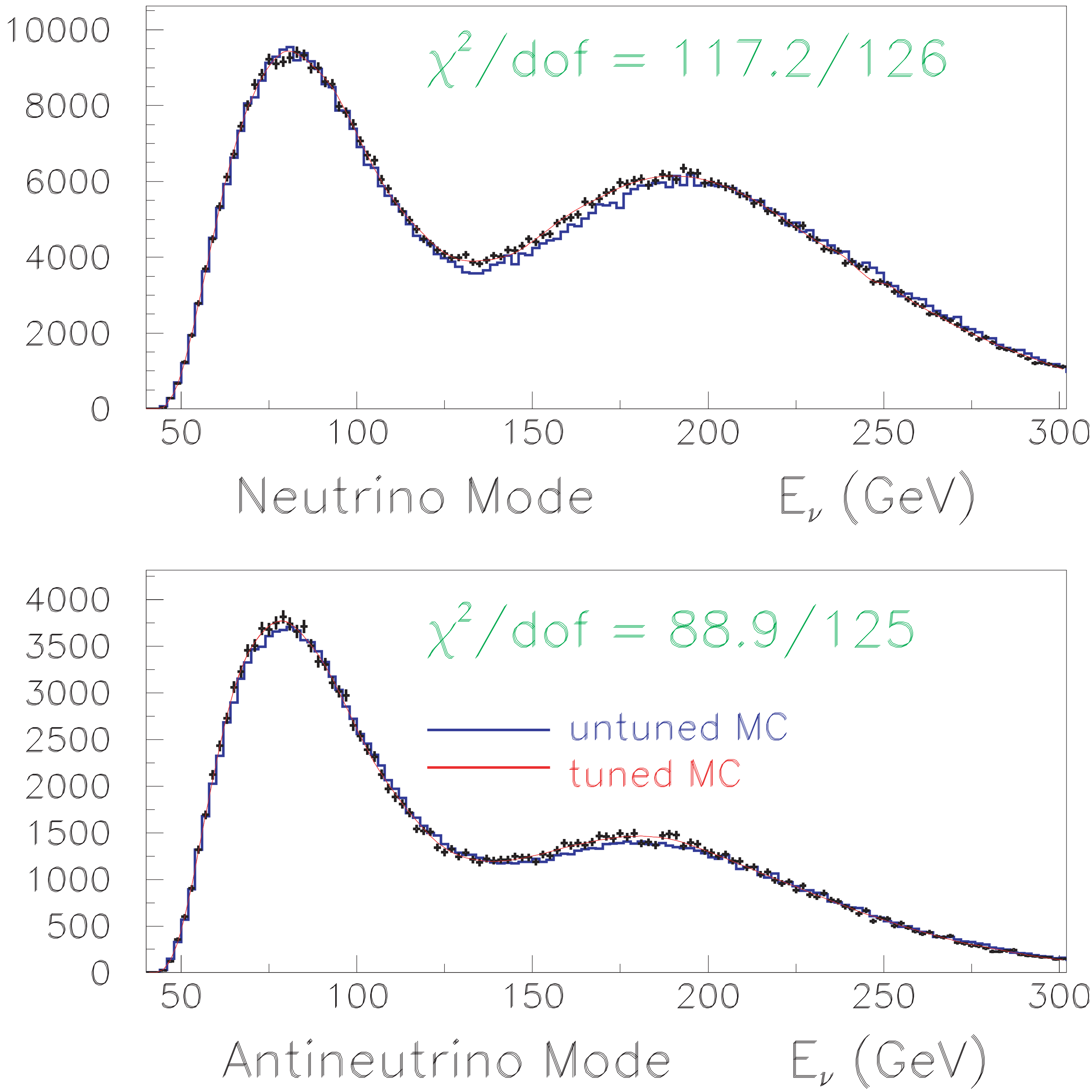
But $K^\pm_{e3}$ constrained by $K^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu$

Use Measurement to Remove Particle Production and Beam Optics





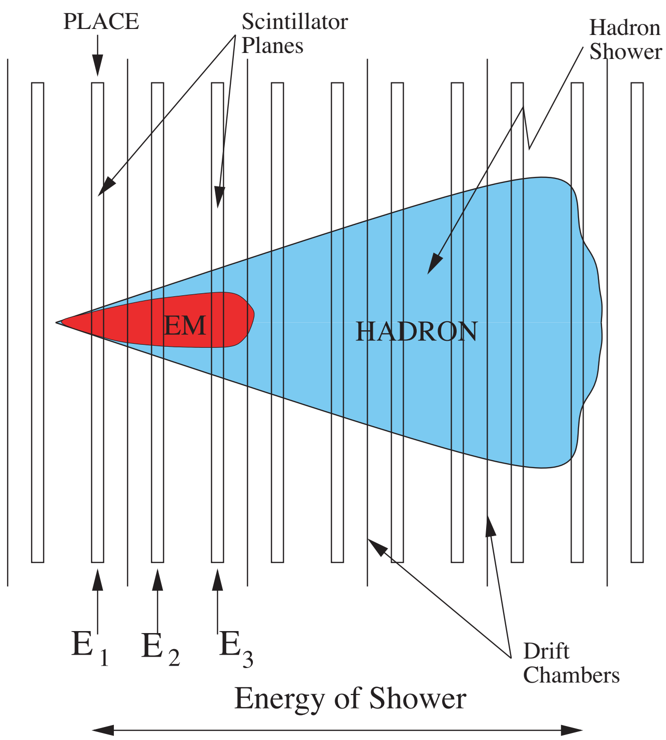
NuTeV Neutrino Flux Prediction
$E_\nu * d\Phi / dE_\nu$ (/10^6 POT)
10^3
10^2
10
1
10^{-1}
ν
ν_μ
ν_e
$\bar{\nu}_e$
$\bar{\nu}_\mu$
50
100
150
200
250
300
350
400
450
500
E_ν (GeV)
$\bar{\nu}$



10000
8000
6000
4000
2000
0
χ^2/dof = 117.2/126
50
100
150
200
250
300
Neutrino Mode
E_ν (GeV)
4000
3500
3000
2500
2000
1500
1000
500
0
χ^2/dof = 88.9/125
untuned MC
tuned MC
50
100
150
200
250
300
Antineutrino Mode
E_ν (GeV)

Direct Measurements of ν_e Flux

Longitudinal Shower Development



e^- Showers Concentrate Energy At Beginning

$$\eta_3 = 1 - \frac{\Sigma_{\text{first three counters}} E_i}{\Sigma_{\text{all counters}} E_i}$$

- ν_e electron showers ($80 < E_\nu < 180$ GeV)

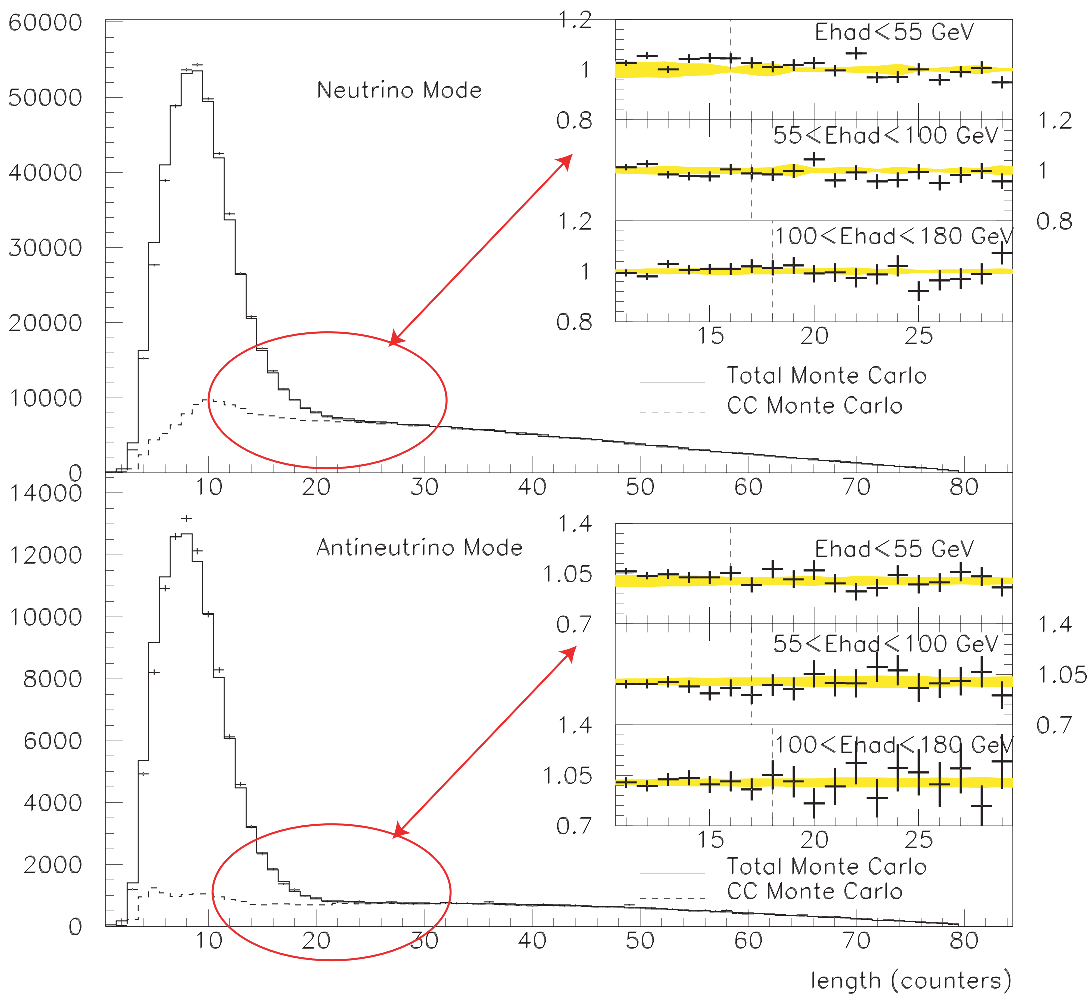
ν_e	$\overline{\nu}_e$
1.05 ± 0.03	1.01 ± 0.04

$N_{\text{meas}}/N_{\text{pred}}$

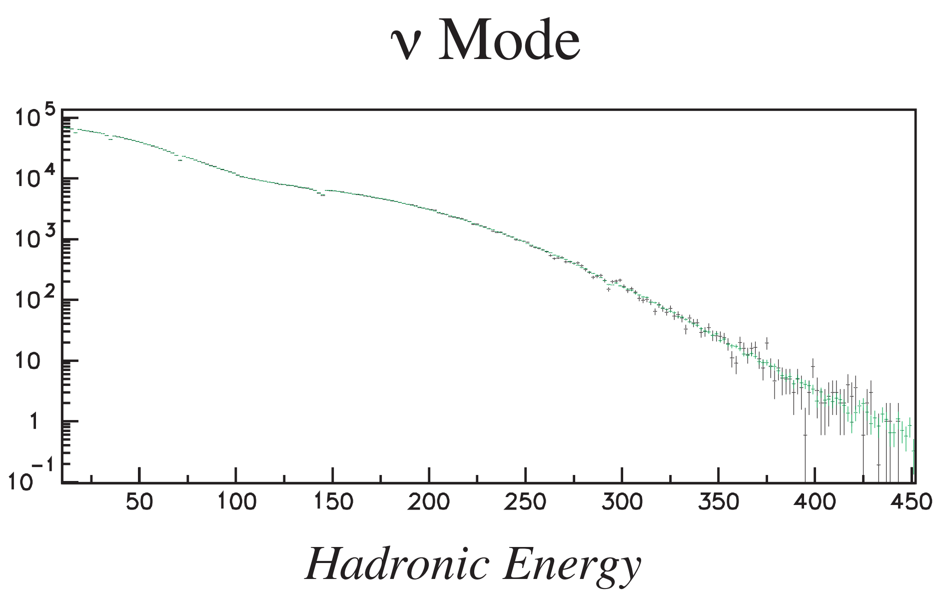
- Approximately 5% of all short events are ν_e CC.

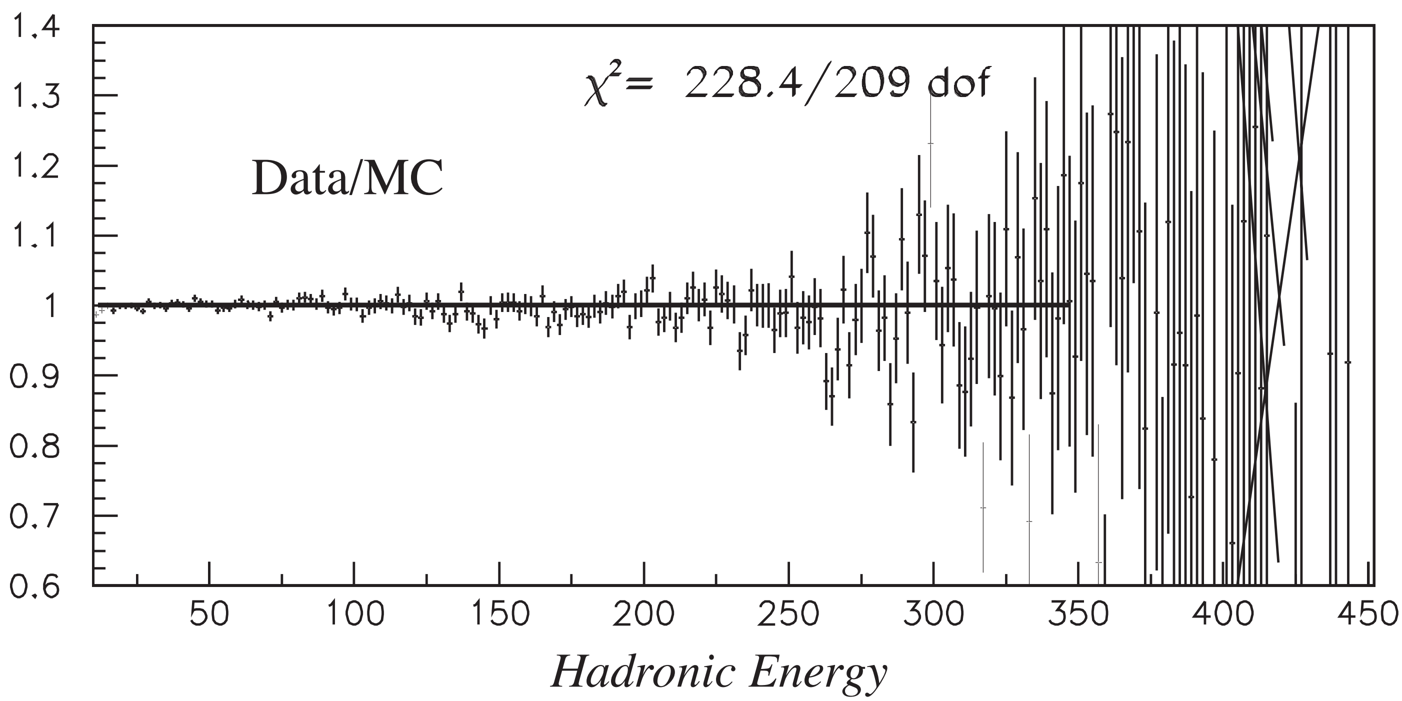
Hadron Shower Length

- All events have showers from recoil of hadronic system
  - Determines event length for NC
  - NC→CC sample (0.7% of NC)
  - ⇒ Want to model punch-through at 10% level
- *Testbeam hadrons measure punch-through*
  - Use LEPTO simulation to study difference between ν-induced and hadron-induced showers



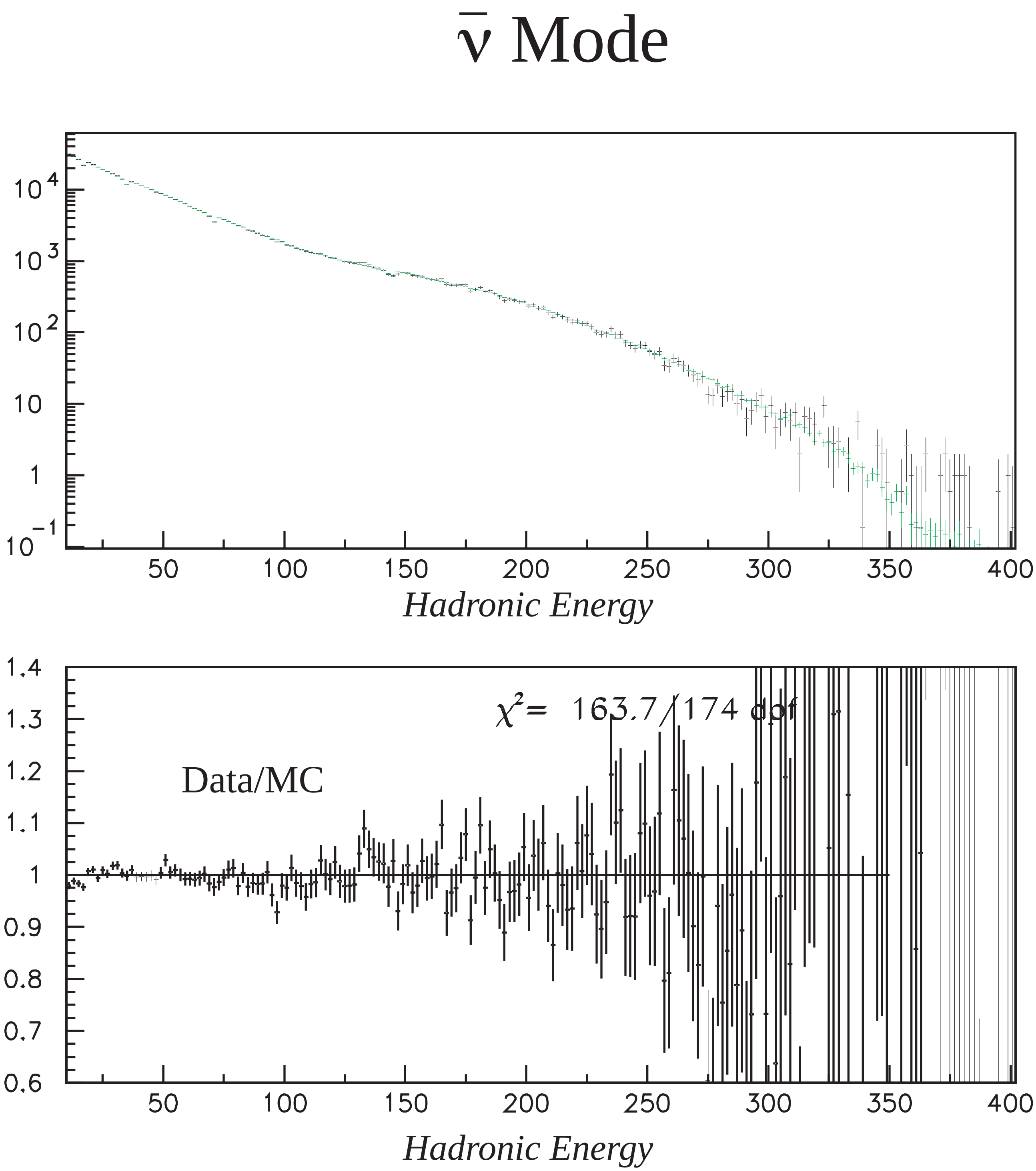
Compare Hadronic Energy





1.62×10^6 events
in the ν beam

The Raw Data: $\bar{\nu}$



0.35×10^6 events in the $\overline{\nu}$ beam

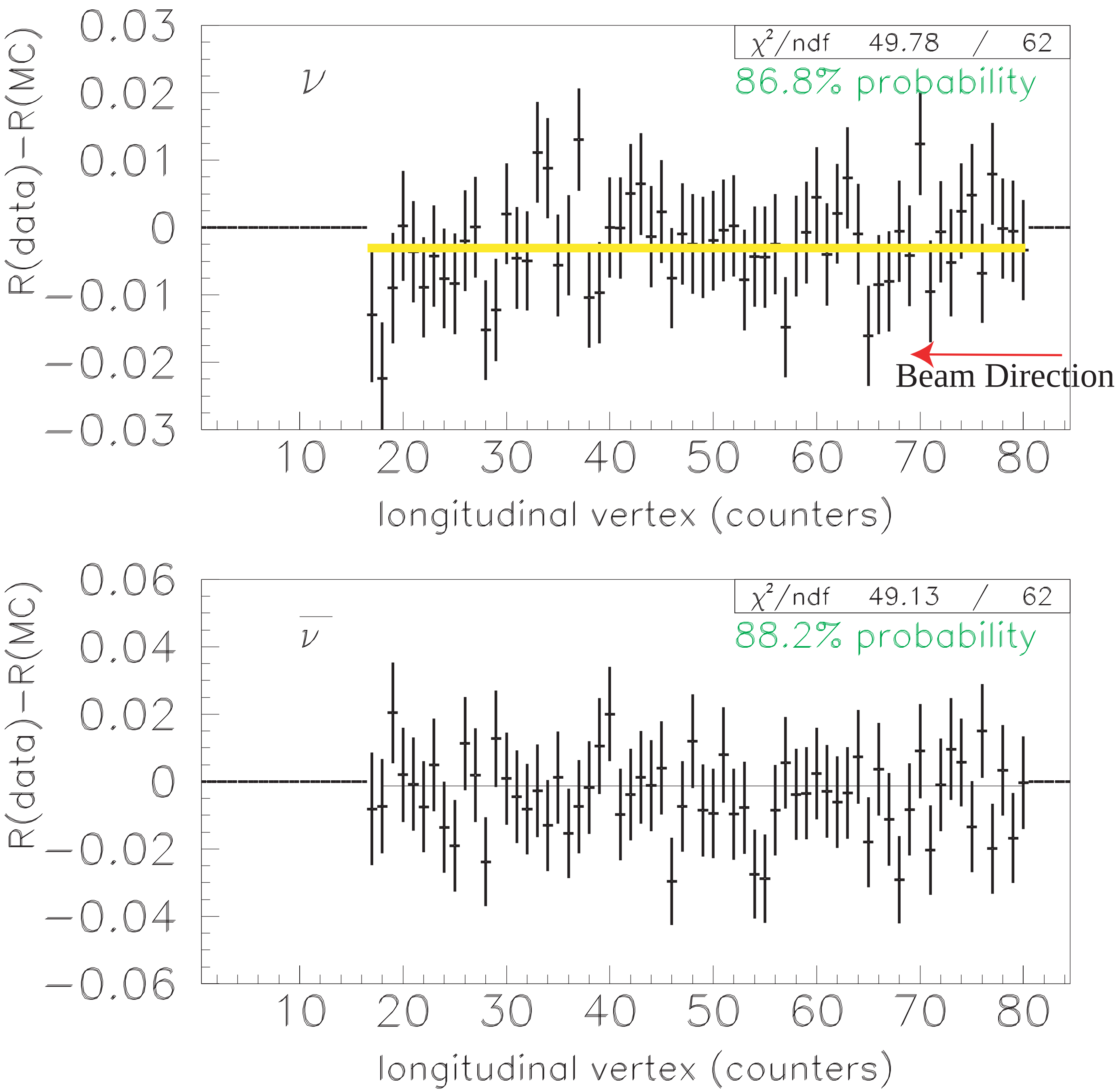
Stability of R_{exp}

- We have evaluated systematic uncertainties and believe they are under control
  - Now want to verify this with data...
- Strategy: verify that the R_{exp} comparison to Monte Carlo is consistent under changes in fiducial cuts and different ranges of event variables
  - Use χ^2 probability test to evaluate comparisons
  - Compare to expected values
- Event observables:
  - Longitudinal Vertex: check detector uniformity
  - Short/Long at Intermediate/Long Length: check CC$\leftrightarrow$NC
  - Transverse Vertex: more NC background near edge
  - Visible Energy

Stability of R_{exp} (cont'd)

R as a function of longitudinal vertex

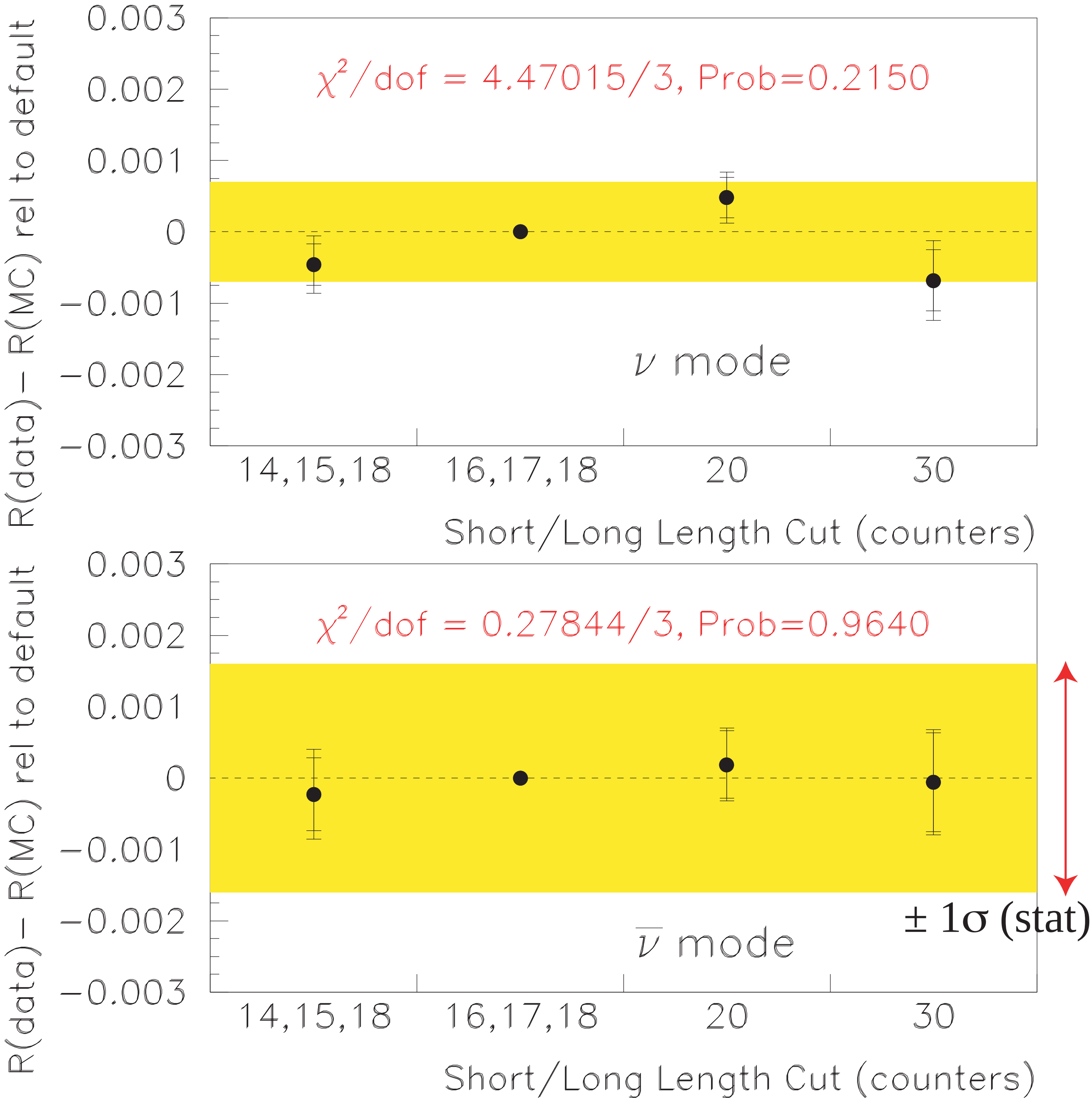
- Both Are Flat, So Stable: not leakage into front
- Note ν A Little Low: *that's the answer!*



Stability of R_{exp} (cont'd)

R as a function of length cut

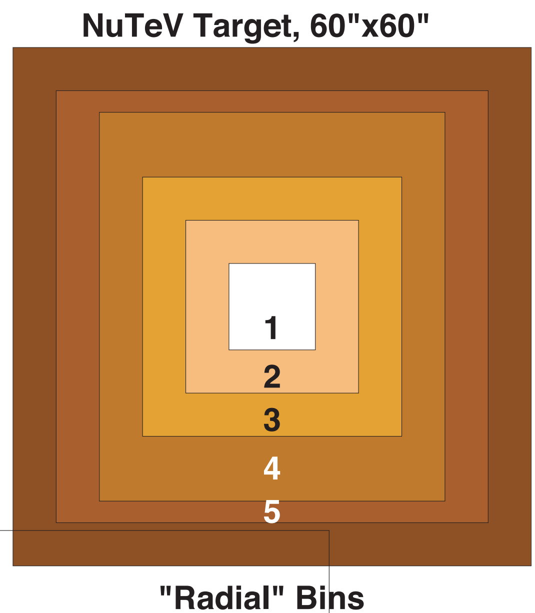
- "16,17,18" [counters] is default; tighten↔loosen NC selection
- Measurements are correlated; uncertainties are on *difference*

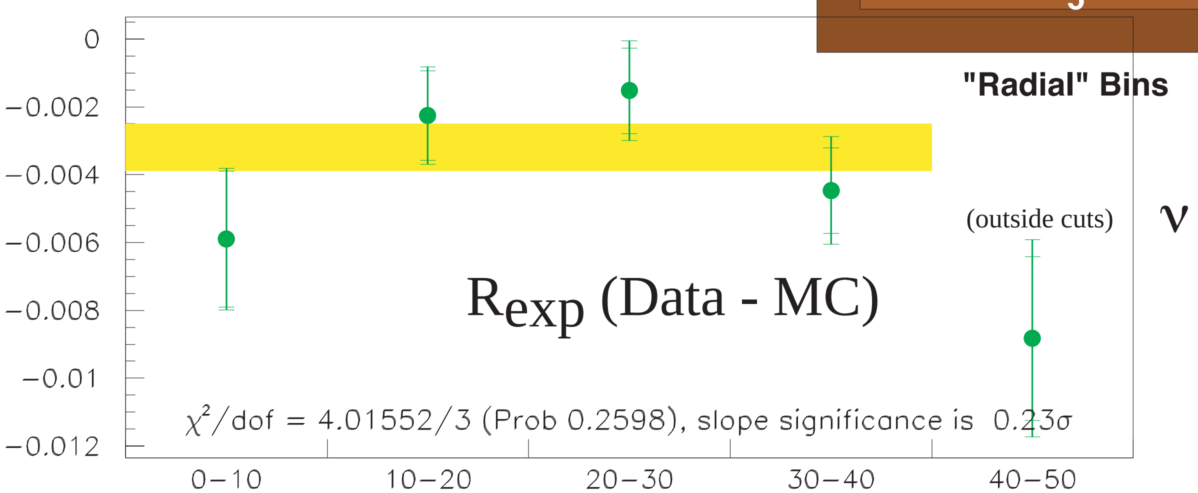


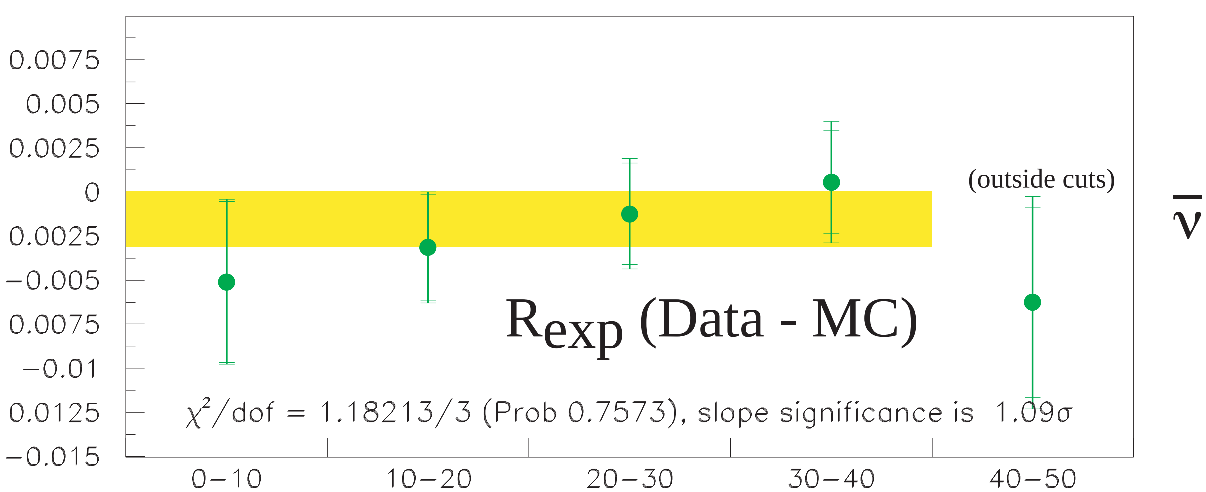
Stability of R_{exp} (cont'd)

R as a function of "radial" bin

- These are exclusive bins
- Bins 1-4 in result (5 is a check)
- Sensitive to mistakes in ν_e, short CC

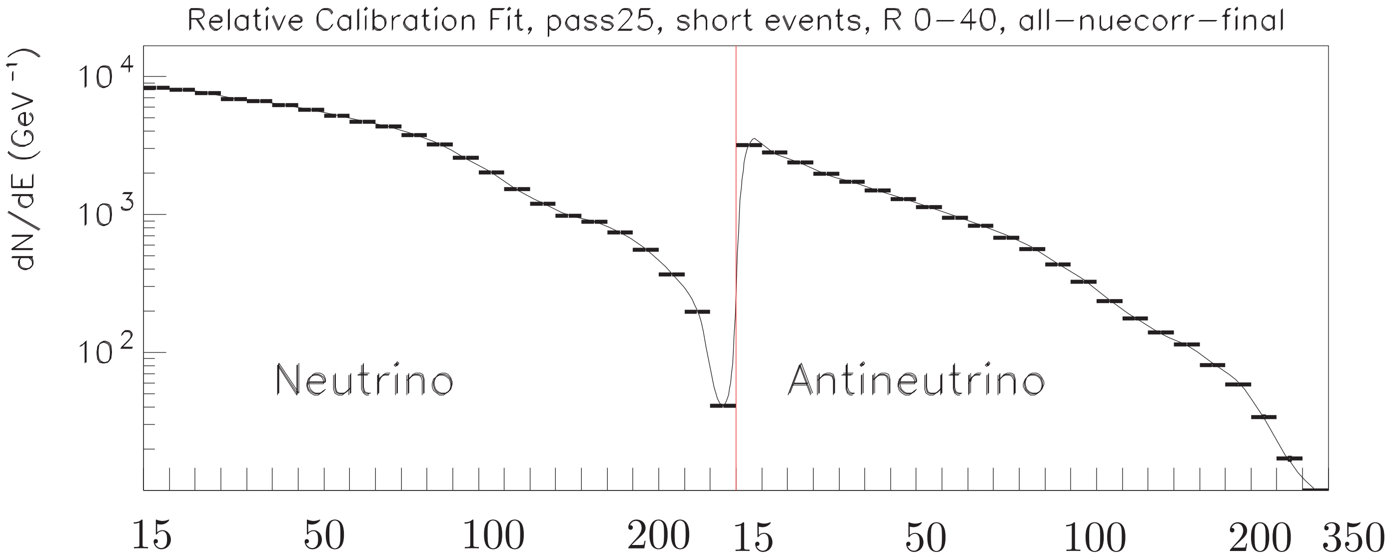


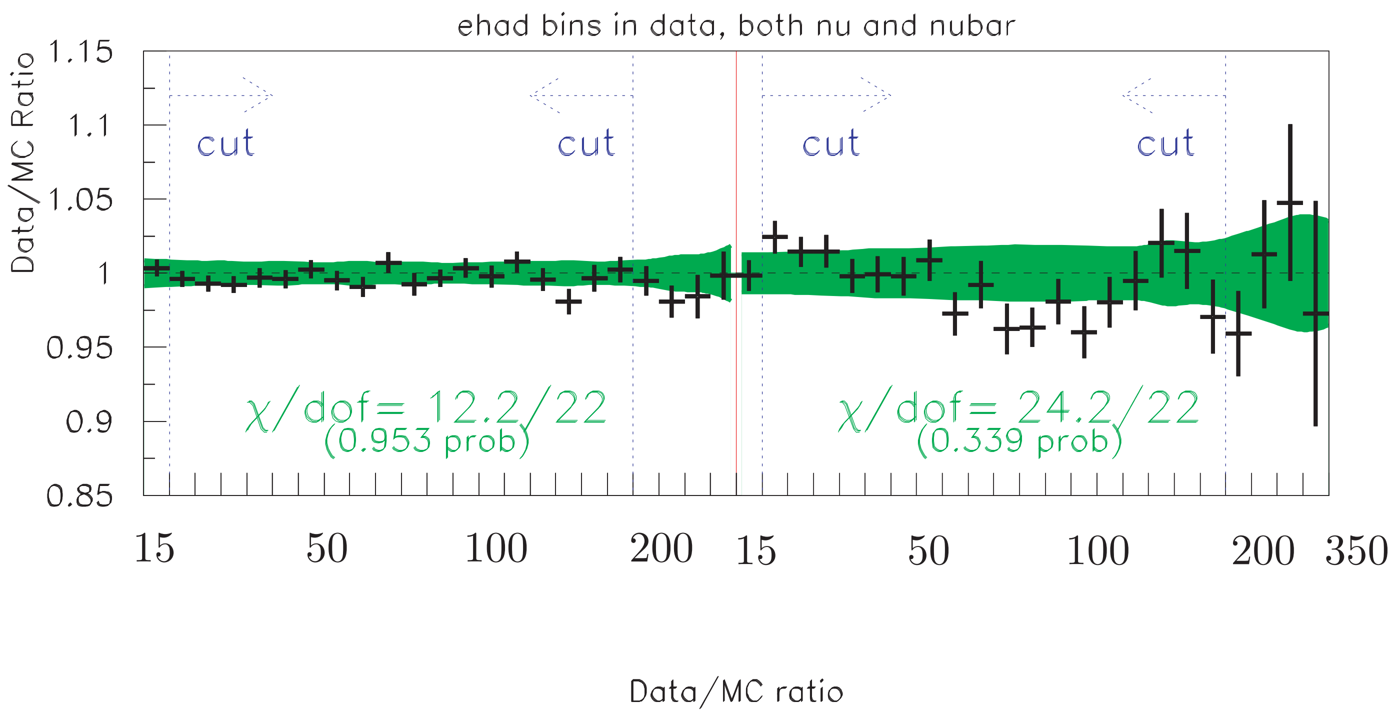




Stability of $R_{\rm exp}$ (cont'd)

Short Events (NC Candidates) vs. $E_{\rm had}$

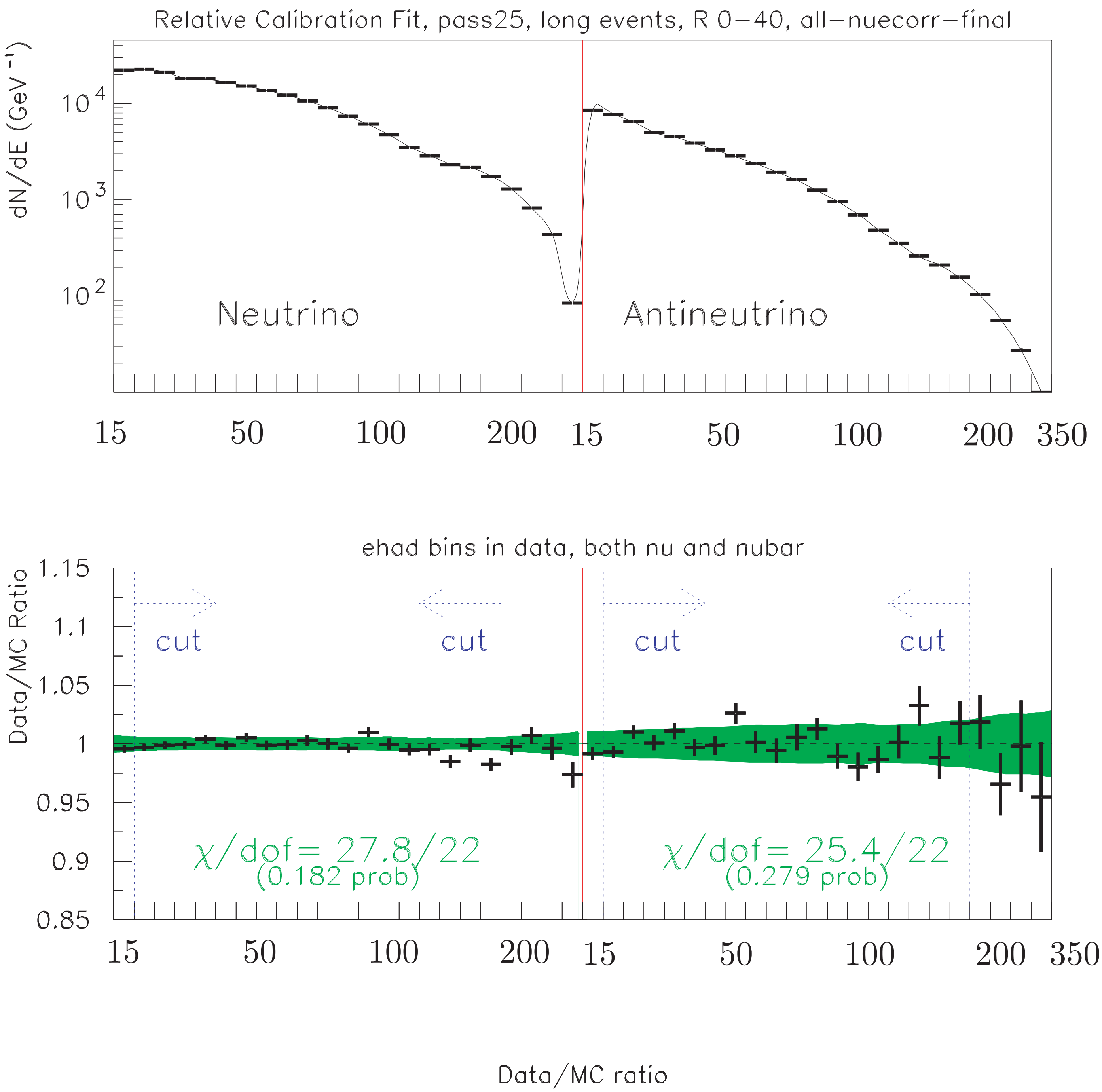




(Green band is $\pm1\sigma$ systematic uncertainty)

Stability of $R_{\rm exp}$ (cont'd)

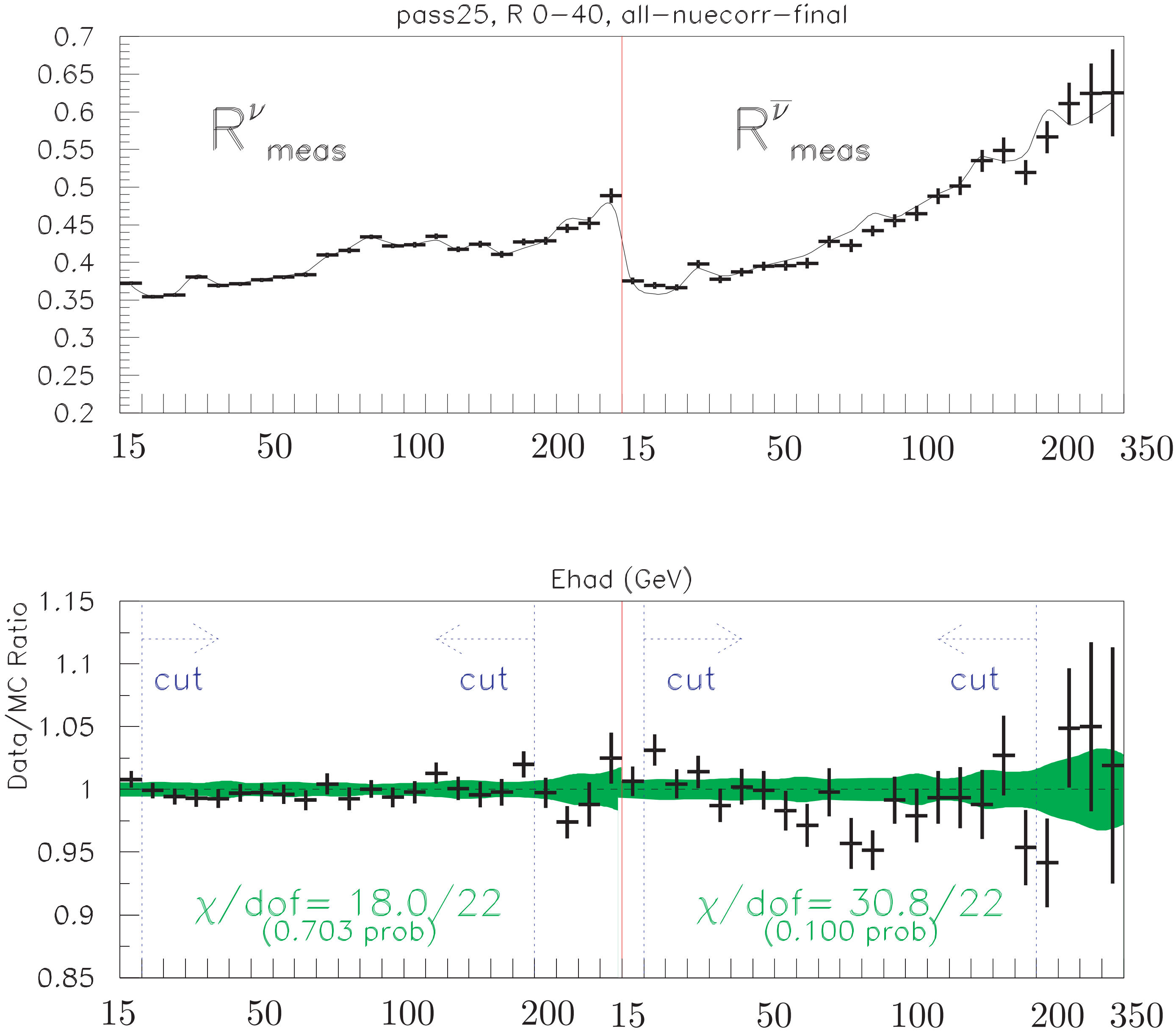
Long Event (CC Candidates) vs. $E_{\rm had}$



(Green band is $\pm 1\sigma$ systematic uncertainty)

Stability of R_{exp} (cont'd)

R_{exp} vs. E_{had}



(Green band is $\pm 1\sigma$ systematic uncertainty)

The $\sin^2\theta_W$ Fit

$$R_\nu = \frac{\sigma(\nu,\mathrm{NC})}{\sigma(\nu,\mathrm{CC})}$$
$$\frac{dR_\nu}{d\sin^2\theta_W} \approx -0.65$$

Strong $\sin^2\theta_W$ *Dependence but* m_c *Systematics of pre-NuTeV*

Weak $\sin^2\theta_W$ *Dependence*
$\Rightarrow$ *MEASURE* m_c

$$R_{\bar\nu} = \frac{\sigma(\bar\nu,\mathrm{NC})}{\sigma(\bar\nu,\mathrm{CC})}$$
$$\frac{dR_{\bar\nu}}{d\sin^2\theta_W} \approx +0.03$$

- Largest theoretical uncertainty is in parameterization of charged-current charm production via m_c
- Use $R^{\overline{\nu}}_{\mathrm{exp}}$ (which is insensitive to $\sin^2\theta_W$) to "measure" m_c then feed back into R^{ν}_{exp}

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013 \pm 0.0009$$
$$m_c = 1.32 \pm 0.09 \pm 0.06 \text{ GeV (cf. input } m_c = 1.38 \pm 0.14)$$

- $\sin^2\theta_W^{(\mathrm{on-shell})}$ determined by a quantity that is $\approx R^-$

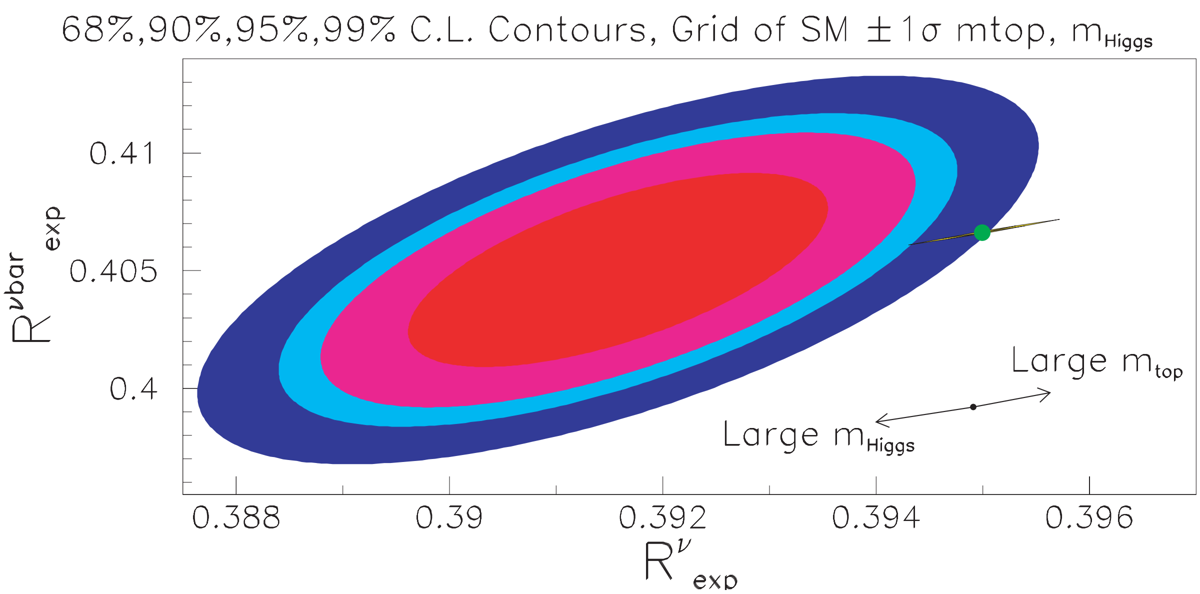
The Result (da capo)

NuTeV Measures:

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$$
$$- \; 0.00022\times\left(\frac{M_{\mathrm{top}}^2-(175\,\mathrm{GeV})^2}{(50\,\mathrm{GeV})^2}\right)$$
$$+ \; 0.00032\times\ln\left(\frac{M_{\mathrm{Higgs}}}{150\,\mathrm{GeV}}\right)$$

cf. standard model fit (LEPEWWG): 0.2227 ± 0.00037

A discrepancy of 3σ...



R^{ν}_{exp} and $R^{\overline{\nu}}_{\mathrm{exp}}$ measured to a precision of 0.3%, 0.65%, respectively

(systematics lead to correlated uncertainty)

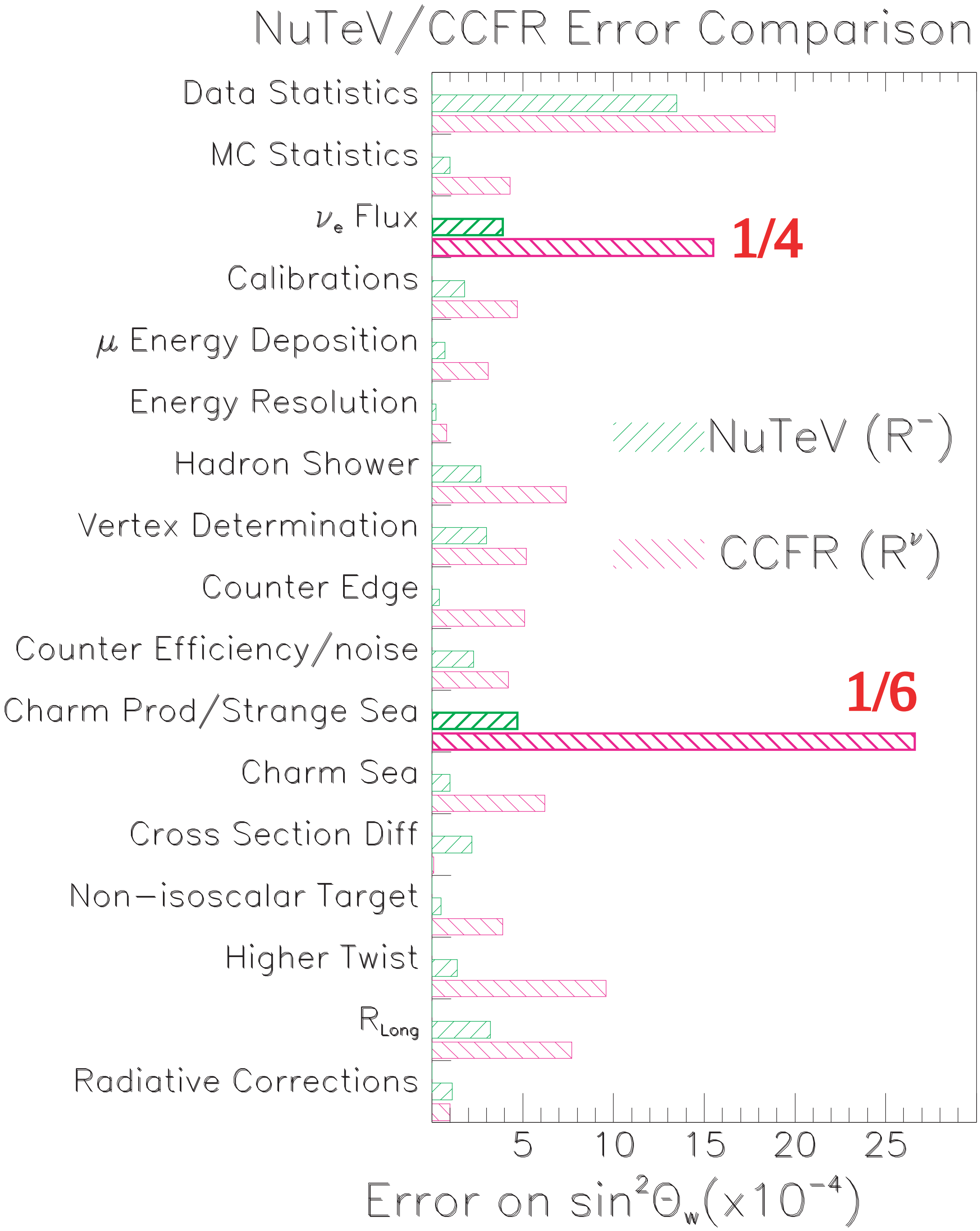
From Corrections to Uncertainties

- Theoretical model uncertainties dominate $R^{\nu}_{\rm exp}$, $R^{\overline{\nu}}_{\rm exp}$
- R^{-} technique $\Rightarrow \sin^2\theta_W^{(\rm on-shell)}$ *statistically* dominated

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Interaction Vertex	0.00030	0.00022	0.00017
Shower Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Energy Measurement	0.00018	0.00015	0.00024
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, $s(x)$	0.00047	0.00089	0.00184
R_L	0.00032	0.00045	0.00101
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022	0.00007	0.00026
Higher Twist	0.00014	0.00012	0.00013
Radiative Corrections	0.00011	0.00005	0.00006
Charm Sea	0.00010	0.00005	0.00004
Non-Isoscalar Target	0.00005	0.00004	0.00004
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272

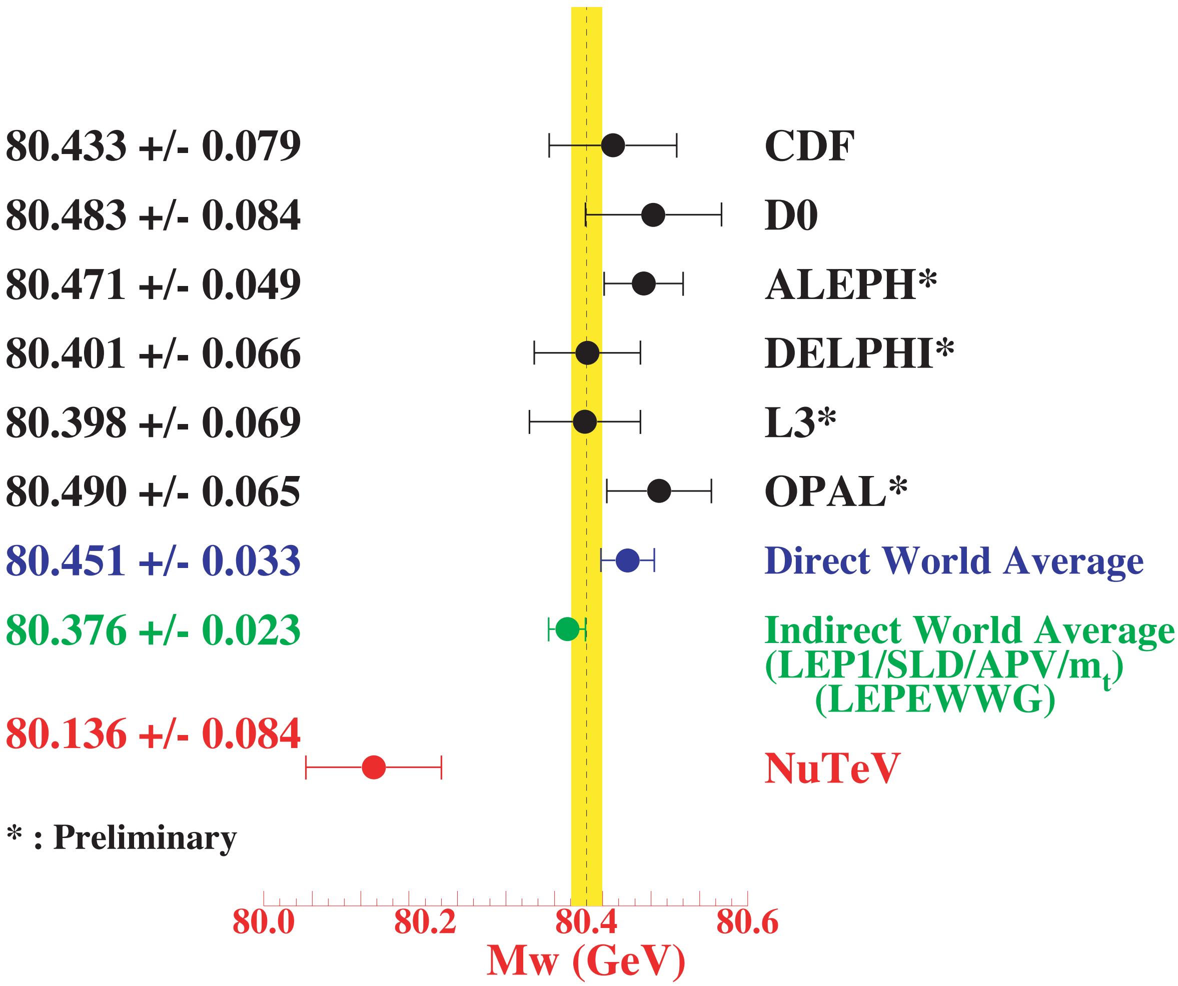
How Well Did The New Beam Work?

Comparison to CCFR :



Comparison with M_W

$$\sin^2\theta_W^{(\text{on-shell})} \equiv 1 - \frac{M_W^2}{M_Z^2}$$



- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W

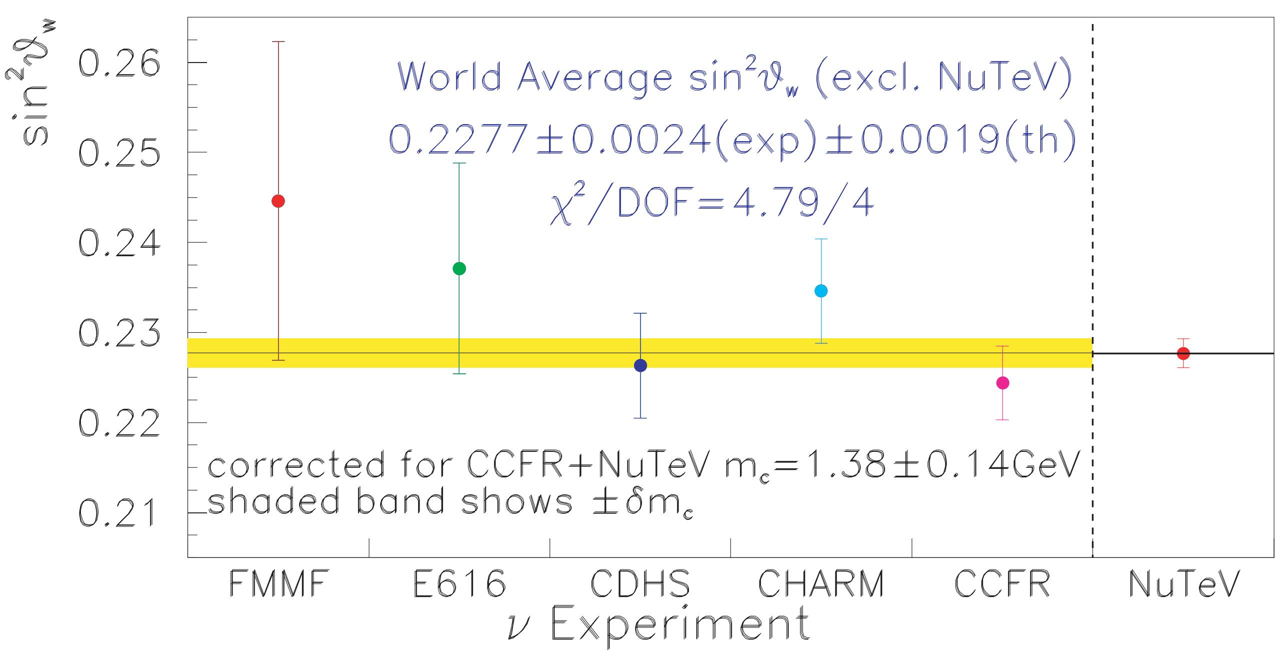
ΔM_W	
CDF/D0	NuTeV
79/84	84 MeV

νN Experiments Before NuTeV

And the result is consistent with past neutrino measurements ...
but much smaller errors

$$\sin^2\theta_W^{\text{on-shell}} \equiv 1 - \frac{{M_W}^2}{{M_Z}^2} = 0.2277 \pm 0.0036$$

$$\begin{aligned} M_W(\text{LEPEWWG}) &= 80.376 \pm 0.023 \text{ GeV} \\ M_W(\text{before NuTeV}) &= 80.14 \pm 0.19 \text{ GeV} \\ M_W \quad (\text{NuTeV}) &= 80.136 \pm 0.084 \text{ GeV} \end{aligned}$$

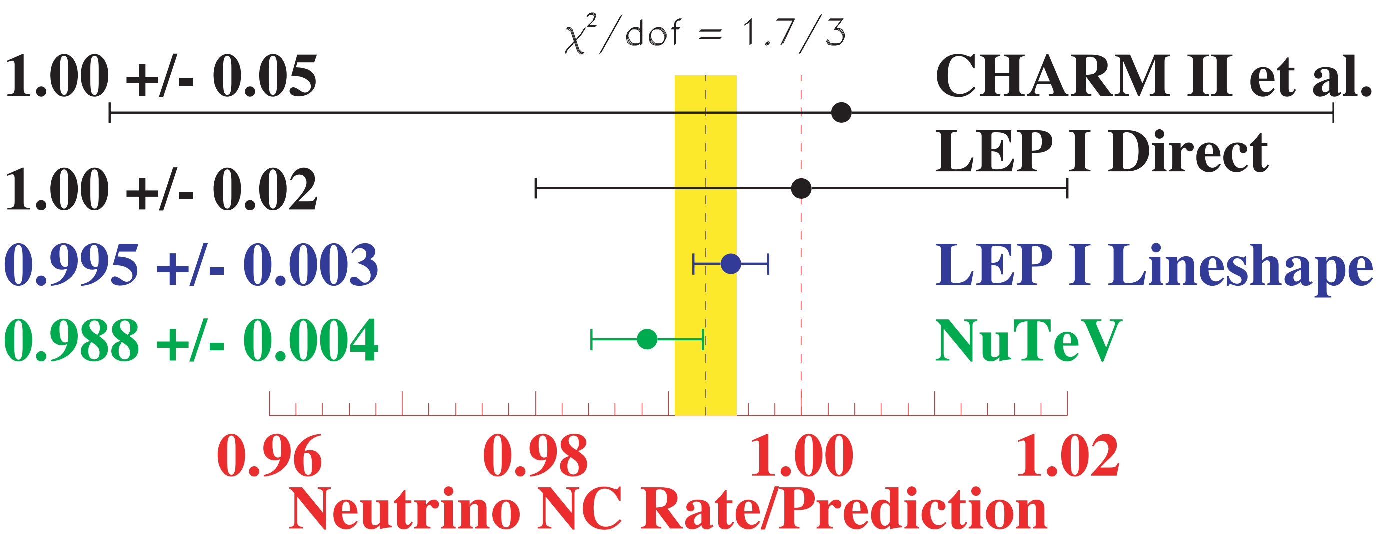


All other experiments are corrected to NuTeV/CCFR m_c and to large M_{top} ($M_{\text{top}} > M_W$)

Neutral Current ν Interactions: Is it Just Neutrinos?

- LEP I measures Z lineshape and decay partial widths to infer the "number of neutrinos"
  - Their result is $N_\nu = 3\frac{\Gamma_{\rm exp}(Z\to\nu\overline{\nu})}{\Gamma_{\rm SM}(Z\to\nu\overline{\nu})} = 3 \times (0.9947 \pm 0.0028)$
  - LEP I "direct" partial width $(\nu\nu\gamma) \Rightarrow N_\nu = 3\times(1.00\pm0.02)$

- NuTeV can fit for a deviation in $\nu\&\overline{\nu}$ NC rate
  - $\rho_0^2 = 0.9884 \pm 0.0026(\mathrm{stat}) \pm 0.0032(\mathrm{syst})$



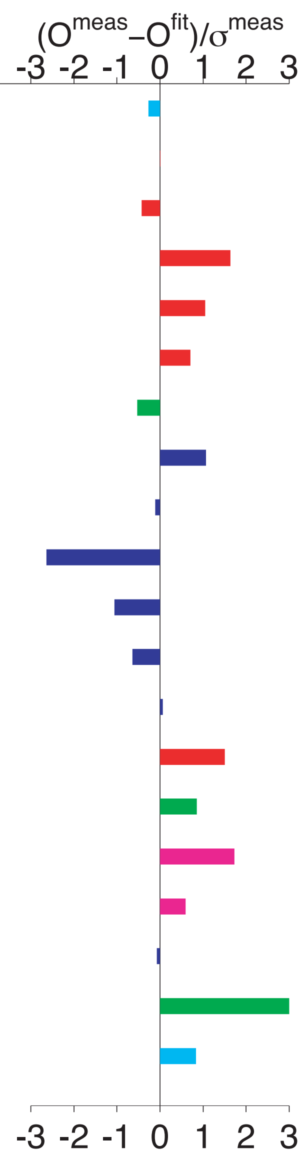
- In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current

NB: This is not unique or model-independent!

SM Fit with NuTeV $\sin^2\theta_W$

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84



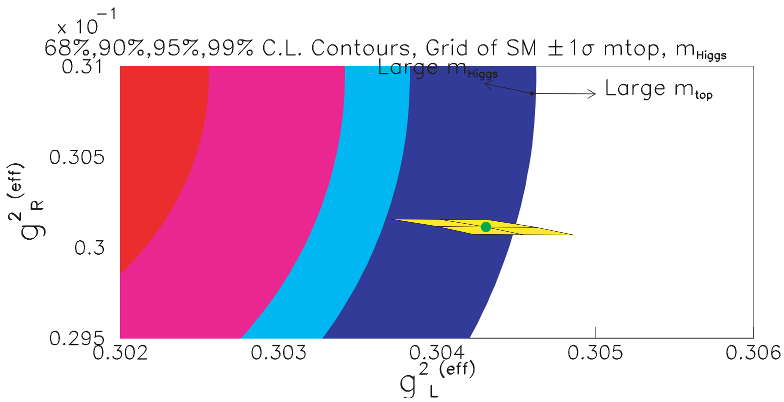
(Courtesy M. Grunewald, LEPEWWG)

Without NuTeV: $\chi^2/\text{dof} = 19.6/14$, probability of 14.3%

With NuTeV: $\chi^2/\text{dof} = 28.8/15$, probability of 1.7%

Upper m_{Higgs} limit weakens slightly

Quark Couplings: $(g_L^{\text{eff}})^2$ and $(g_R^{\text{eff}})^2$

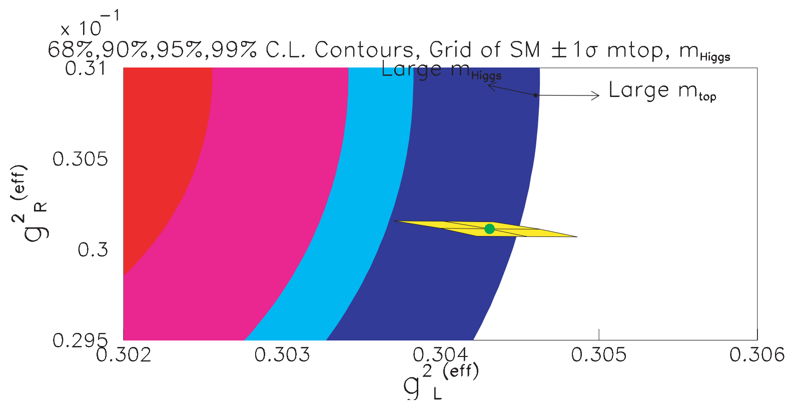


$$R_\nu = g_L^2 + g_R^2 r \qquad g_L^2 \equiv u_L^2 + d_L^2$$
$$R_{\bar\nu} = g_L^2 + \frac{g_R^2}{r} \qquad g_R^2 \equiv u_R^2 + d_R^2$$

NuTeV measures:

$(g_L^{\text{eff}})^2 = 0.3001 \pm 0.0014$

$(g_R^{\text{eff}})^2 = 0.0308 \pm 0.0011$



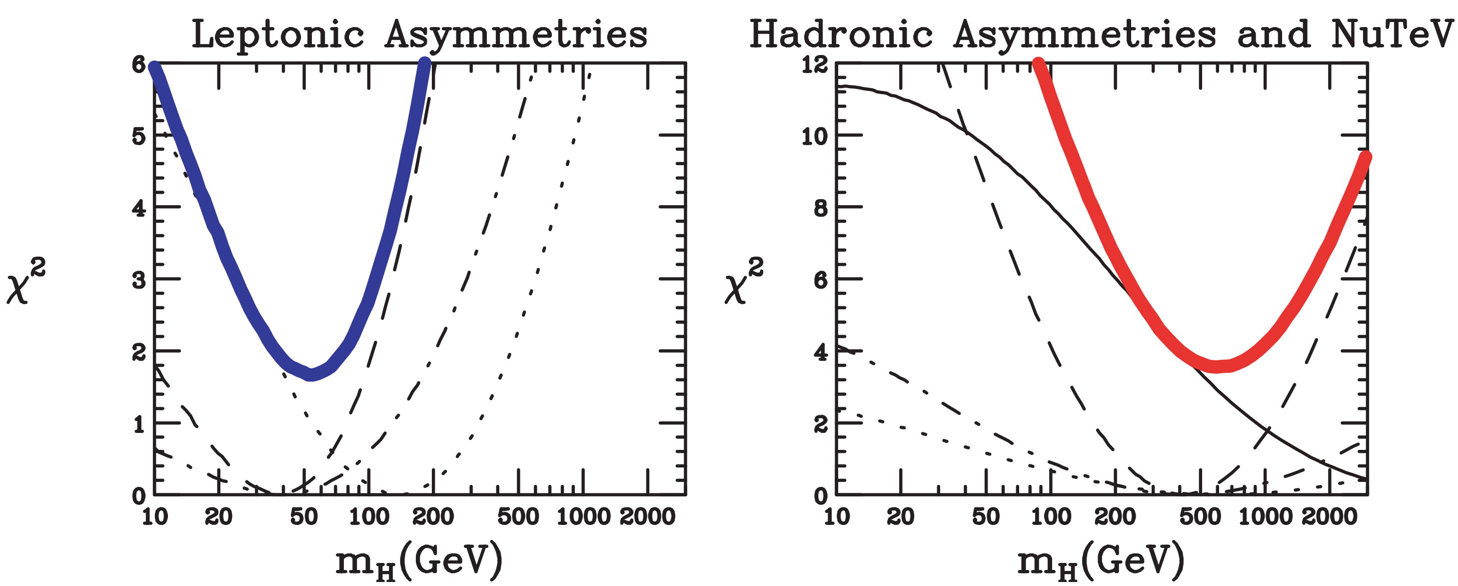
- Assuming predicted ν coupling, $(g_L^{\text{eff}})^2$ appears low

The Higgs Mass

Honest, Mom, it was broke when I got here!...

- A_{FB} already a problem:

> The set of measurements that are consistent with the global fit are inconsistent with the search limit while the measurements that are essential for consistency with the search limit are inconsistent with the global fit.
>
> —Chanowitz, hep-ph/0104024 v5



- A_{FB} mostly responsible for Hadronic m_H Dependence
- Chanowitz Lose-Lose theorem:

  Removing A_{FB} data that drives high χ^2 would drive Higgs mass further into LEP 2 excluded region

Standard Model Explanations

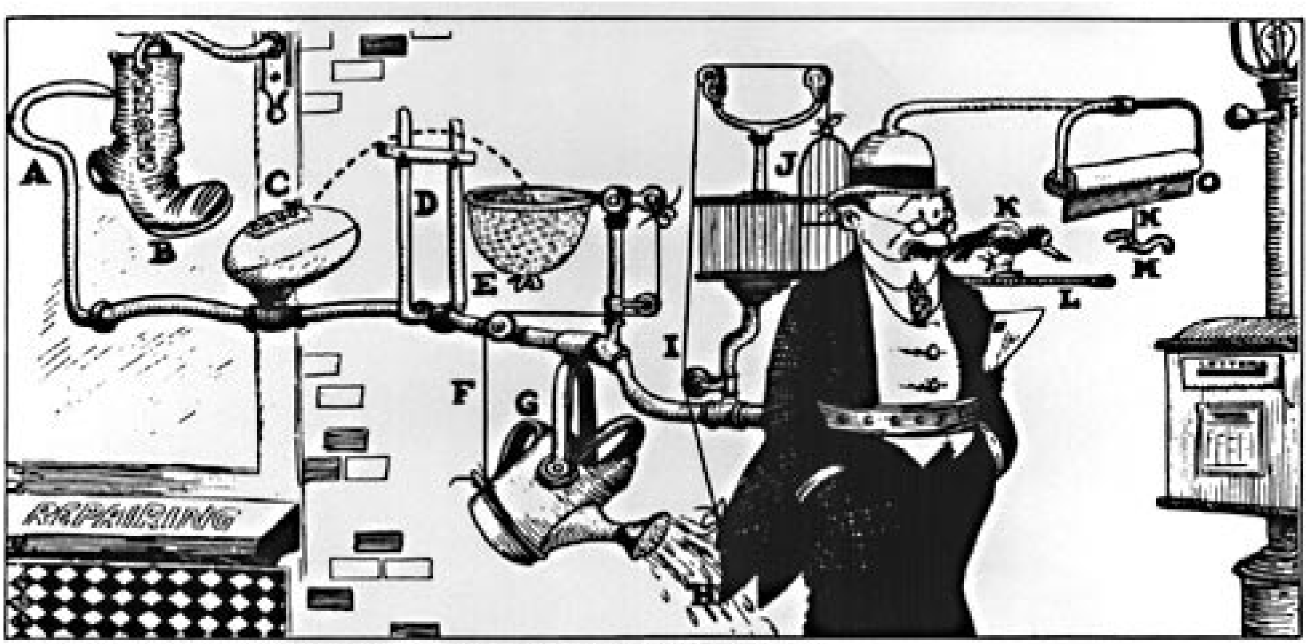
§1. Isospin Violation (1$\star$) (reasonable, but no clear model)

§2. Strange Sea Asymmetry (0$\star$)

- Davidson et al., hep-ph/0112302 v4
- Reasonable *a priori* , but ruled out within our data
- See Next Talk

§3. Neutrino Oscillations ($-2\star$)

- $\nu_e \rightarrow \nu_S$ (Giunti et al., hep-ph/0202152)
- Ruled Out By Direct Measurement of ν_e Flux
  (which is in our talks and paper. . .)



Keep You From Forgetting To Mail Your Wife's Letter RUBE GOLDBERG (tm) RGI 049

Unnamed Theorist Mailing Preprint to xxx.lanl.gov

Isospin Violating PDFs

- Isospin symmetry may not be good for PDFs ($u^p \neq d^n$).
  - PDF fits performed under this assumption ... but $m_n \neq m_p$
  - NuTeV is sensitive since make this assumption to assign u,d types to scatterers
  - Has been calculated in several classes of non-perturbative model

Bag model

Thomas *et al.*, Phys. Lett˙**A9**, 1799

- $\delta \sin^2 \theta_W^{(\text{on-shell})} = -0.0001$
- $\sim$ 0.0004 shifts at high, low x cancel

Meson Cloud model

Cao & Signal, Phys. Rev. **C62**, 015203.

- $\delta \sin^2 \theta_W^{(\text{on-shell})} = +0.0002$

- NC/CC Shadowing Differences:

  Talking with Miller and Thomas but disagreement about applicability of shadowing model in hep-ex/0204007:

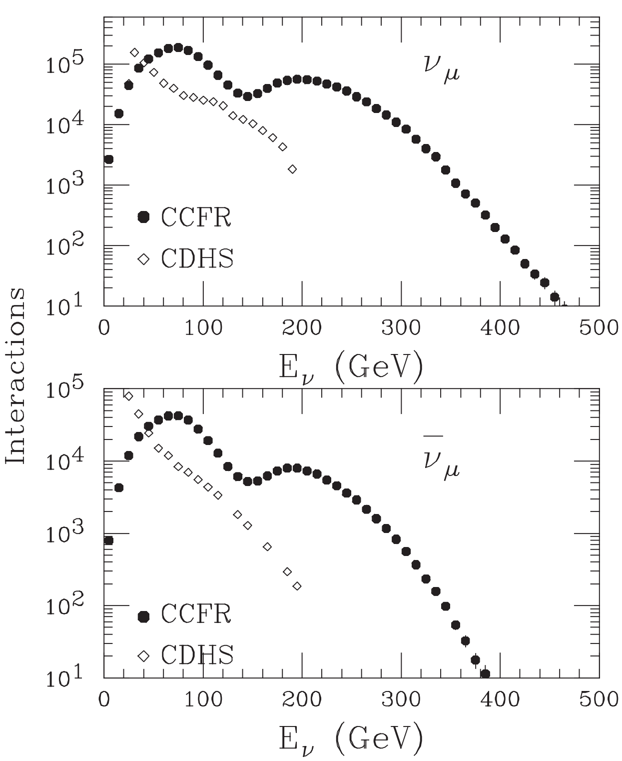
  Comment on "A Precise Determination of Electroweak Parameters in Neutrino-Nucleon Scattering"

  - Experimentally x, Q^2 distribution needs to be included – they use same value of correction for entire range, not convoluted over actual data
  - No Comment about theoretical validity
  - Looking forward to working together to nail this down
  - Miller now agrees effect would increase anomaly . . . (APS Conf., Priv. Comm.) $\Rightarrow$ New Paper?

Strange Sea Asymmetry

Is $xs(x) = x\bar{s}(x)$*?*

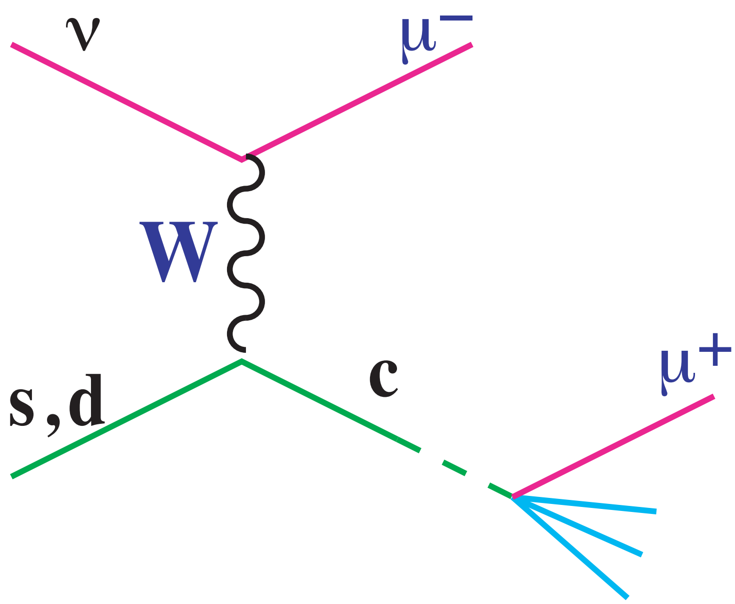
- Davidson *et al.* suggest
  - Asymmetry in strange sea could explain 0.0026 (1/2) of result. . ., "eliminating anomaly"
  - Quote Re-Analysis of CDHS Data, hep/ph-0004268 (Barone, Pascaud, Zomer)
  - Effect is -1.75σ, $s > \bar{s}$



	ν_μ	$\bar{\nu}_\mu$
CCFR	951000	170000
CDHS	638605	551390
$E_H > 25$	187688	13625
CCFR/CDHS	$\times 5.1$	$\times 12.5$

P.Berge *et al.*, Z.Phys C49,187(1991)

- We use our own NuTeV/CCFR Dimuon Data



Goncharov *et al.*, Phys.Rev.D64 (2001) 112006

- Effect is $\approx +2.0\sigma$, $\bar{s} > s$ at high-x:
  Opposite Sign, *Increasing Anomaly*

- We claim consistent with zero,
  but -1.7σ of BPZ strongly disfavored

see hep-ex/0203004, Phys.Rev.D65: (2002) 111103

- We are not fitting models,
  we are fitting our *data*

- We are open to suggestions for strange sea
  models which explain effect
  without contradicting data

- Recall most of ocean at low x and requires high E_{had} to make charm

§1. Poor Statistics at high E_{had}

§2. What About low x?

- Quote 1 from BPZ:

  "The small-x ($x < 0.1$) ν Fe and $\bar{\nu}$ Fe are excluded in our analysis."

- Quote 2 from BPZ:

  Finally, we reject the CDHSW data with $x < 0.1$. The reason for this cut is threefold: i) the systematic errors in the low-x region are large [44]; ii) the nuclear corrections at small x are not completely under control, as discussed in section 3.2; iii) at low-x the CDHSW results disagree with the CCFR findings for the cross sections [76] and for the structure functions [3].

- We couldn't have said it better ourselves …

- CCFR Energy Much Higher
  —Above Charm Threshold
- Since Determine $s, \bar{s}$ from $s \rightarrow c$
  enormous advantage in statistics

§1. Less Sensitive to Slow-Rescaling Form
In Determining Shape, Level of $s, \bar{s}$

§2. Data Analyzed Consistently Within
Same Structure as WMA

§3. LO, NLO *etc.* Not Relevant if
Parameterization Fits Data and
used in same kinematic range

Conclusions

- NuTeV measures R^{ν}, $R^{\overline{\nu}}$ to precisely determine $\sin^2\theta_W$
- NuTeV expects 0.2227 ± 0.0003; measures

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$$

- Given inconsistency with Standard Model, we also present result in model-independent framework
  - Data prefers lower effective left-handed coupling
- Neutral-current couplings of neutrinos may be suspect
  - NuTeV result consistent with earlier νN measurements
  - Only other precise measurement, LEP Invisible Z Width, also suggests a discrepancy

Pending *confirmation*, *refutation*, or *alternative explanations*, it's a puzzle.

Summary of Corrections to R_{exp}

Corrections Applied to Data

Effect	$\delta R^{\nu}_{\mathrm{exp}}$	$\delta R^{\overline{\nu}}_{\mathrm{exp}}$	Coping Techniques
Cosmic Ray Background	–0.0036	–0.019	†
Beam μ Background	+0.0008	+0.0012	†
Vertex Efficiency	+0.0008	+0.0010	†

Effects in Monte Carlo that relate $R^{\overset{(-)}{\nu}}$ to $R^{\overset{(-)}{\nu}}_{\mathrm{exp}}$

Effect	$\delta R^{\nu}_{\mathrm{exp}}$	$\delta R^{\overline{\nu}}_{\mathrm{exp}}$	Coping Techniques
Short CC Background	–0.068	–0.026	†, $\surd$
Electron Neutrinos	–0.021	–0.024	♮,$\surd$
Long NC	+0.0028	+0.0029	†, $\surd$
Counter Noise	+0.0044	+0.0016	†
Heavy m_c	–0.0052	–0.0117	†, ♣
R_L	–0.0026	–0.0092	†, ♣
EM Radiative Correction	+0.0074	+0.0109	
Weak Radiative Correction	–0.0005	–0.0058	
d/u	–0.00023	–0.00023	†
Higher Twist	–0.00012	–0.00013	†
Charm Sea	–0.00005	+0.00004	♮

Recall: R^{ν}_{exp} and $R^{\overline{\nu}}_{\mathrm{exp}}$ measured to a precision of 0.0013 and 0.0027, respectively

Key to coping techniques

- †: Determined from data
- $\surd$: Checked with data
- ♮: Independent Simulation
- ♣: R^{-} technique

NuTeV Neutrino Flux

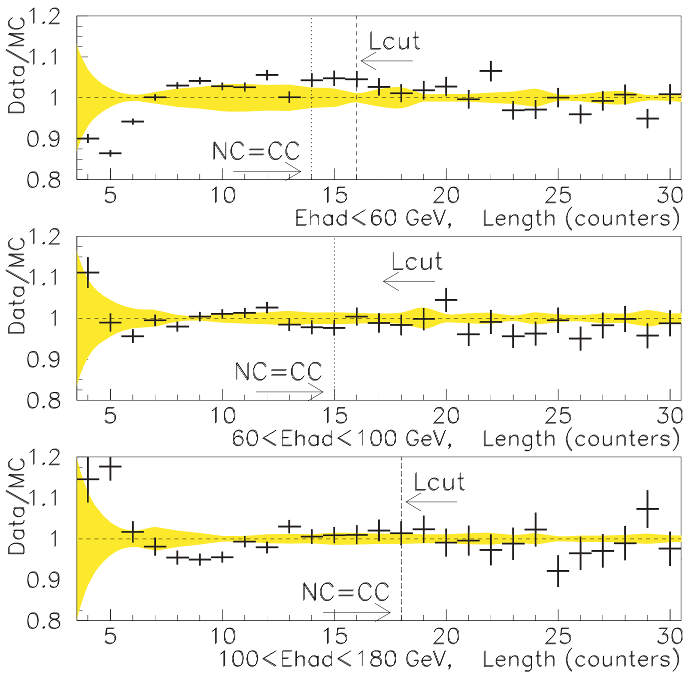
- K^+_{e3} decay is very well understood
  K$^\pm$ production is constrained by ν_μ and $\overline{\nu}_\mu$ flux
- Tune the beam MC prediction to match observed ν_μ spectrum (CC events in the data: $E_\nu = E_{\rm had} + E_\mu$)
- Tune K/π fraction and small spectral shift
- Similar Technique to E744/E770
  - Tuning procedure is robust at 0.5% level
- Find

Beam	E_π	E_K	K/π
ν	-0.2%	-1.3%	$+2.7\%$
$\overline{\nu}$	-0.4%	-0.9%	$+2.8\%$

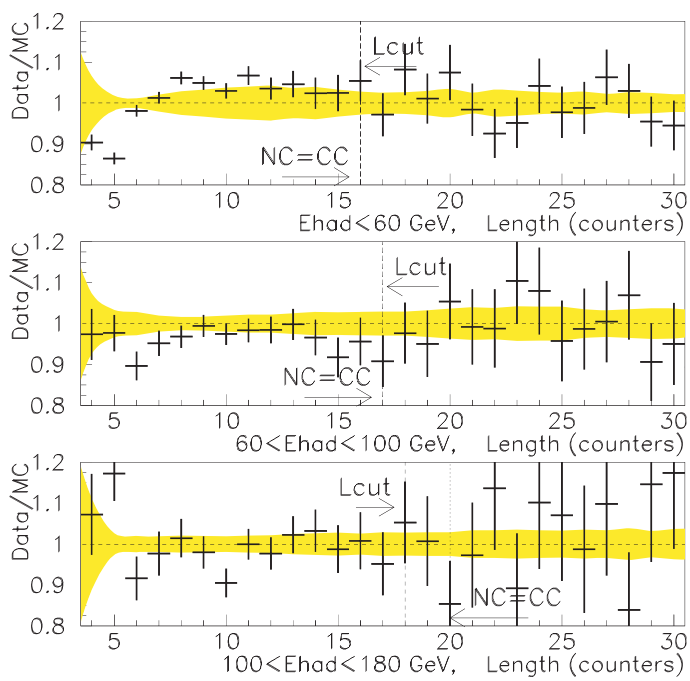
Need 20% Error

  - Reflects small uncertainties in SSQT alignment and large production uncertainties
  - Sensitive to calorimeter calibration ($\delta E_{\rm cal} = 0.43\%$)
- $K^\pm_{e3}$ branching ratio (1.4%) dominates ν_e flux uncertainty!!!

Data/MC Length Agreement

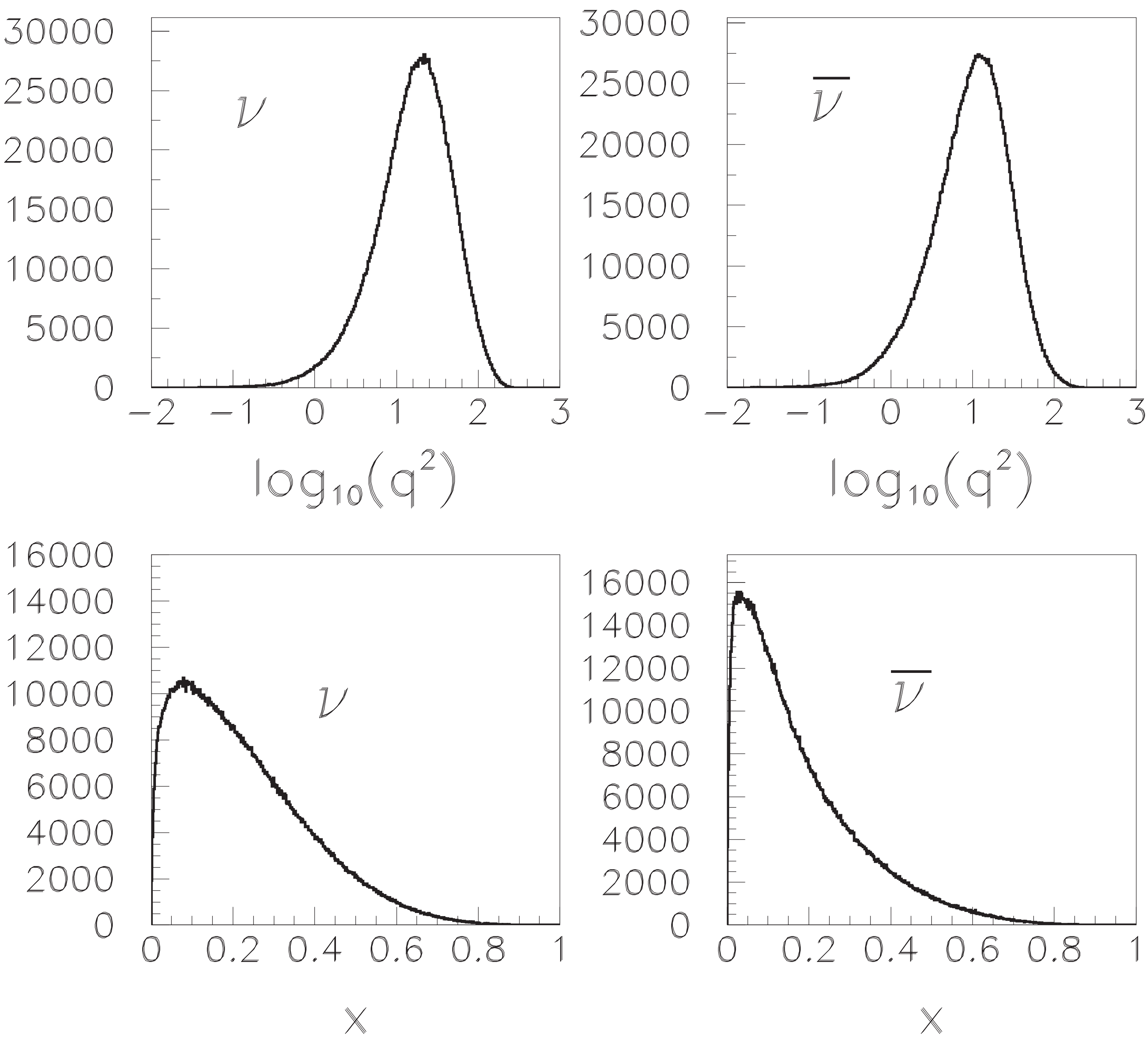


Neutrino Mode



Antineutrino Mode

Event Kinematics



ν: mean $Q^2 \sim 25$ GeV^2

$\overline{\nu}$: mean $Q^2 \sim 15$ GeV^2

Since the Preliminary Result...

- Statistical error reduced
  ($\delta\sin^2\theta_W = 0.0019 \rightarrow 0.0014$)
  - -14% from m_c constrained fit
  - -8% from change in length cut
  - -4% from added data statistics
  - -3% from added fiducial volume
- Systematic error comparable
  ($\delta\sin^2\theta_W = 0.00010 \rightarrow 0.00009$)
- Many improvements to the analysis:

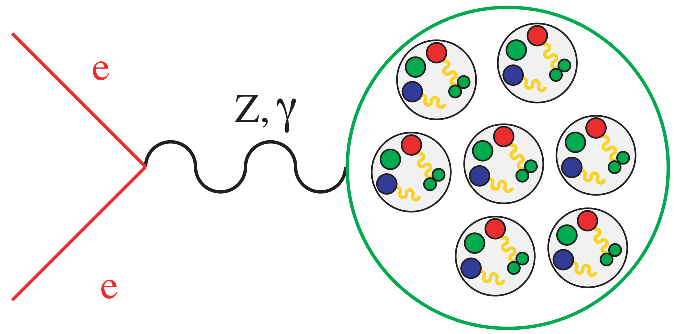
Change	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$	$\delta\sin^2\theta_W$
new pdfs 9par $\longrightarrow$ 20par	+0.00001	+0.00112	-0.00044
$Q^2 < 1$ pdf evolution	-0.00047	-0.00104	-0.00034
d/u	+0.00023	+0.00023	+0.00028
higher twist	+0.00012	+0.00013	+0.00014
charm sea	+0.00005	-0.00004	+0.00010
correction to longexits	-0.00021	+0.00035	-0.00048
change in length cut	+0.00048	+0.00018	+0.00069
TOTAL	+0.00021	+0.00093	-0.00005

- Big shift is in ν_e analysis, as previously noted

Low-Energy Experiments

$\gamma - Z$ Interference

Suppressed by q^2/M_Z^2

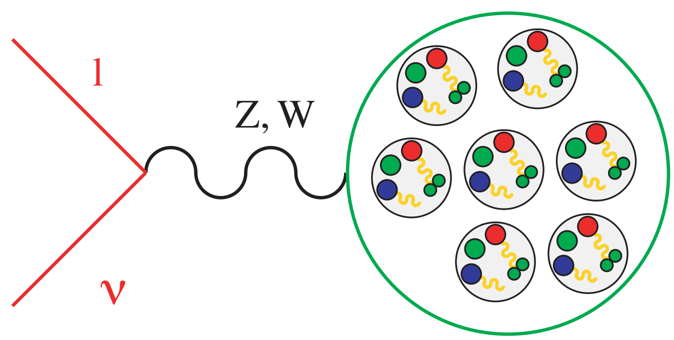


- Magnitude of interference (parity-violating) relative to γ-exchange:

$$\langle Q_W \rangle \, / \, \langle Q_{\mathrm{EM}} \rangle \text{ (light quarks)}$$

Neutrino Scattering

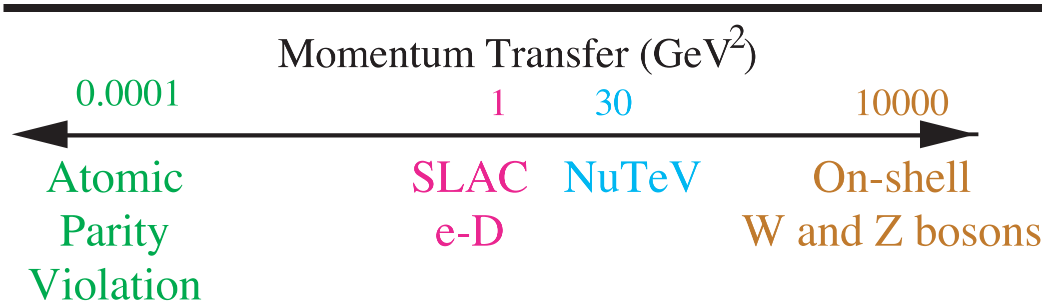
$\sigma \approx 10^{-38}$ cm^2



- Magnitude of neutral currentrelative to charged-current gives

$$\langle Q_Z \rangle \, / \, \langle Q_W \rangle \text{ (light quarks)}$$

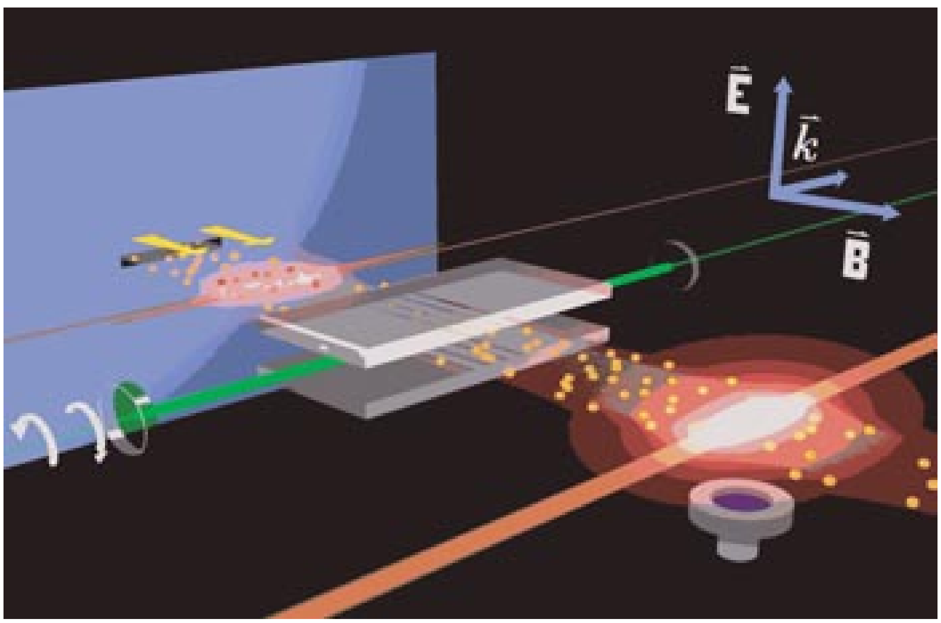
- Separate left and right-handed couplings (ν and $\overline{\nu}$)



Atomic Parity Violation

Recent APV measurement (JILA/Boulder;Ce):
Bennett,S.C. and Wieman,C.E. PRL 82, 2482-2487 (1999)

$Q_W = -72.06(28)_{exp}(34)_{theory}$ $\Rightarrow$ 2.5σ deviation from SM



Later authors have re-evaluated theory
"average" $Q_W = -72.5 \pm 0.8$
(Kozlov *et al.*, PRL **85**, 1618. Dzuba *et al.*, PR **A63**, 044103.
Average: Rosner, hep-ph/0109239)

$$\frac{Q_W^{\rm exp} - Q_W^{\rm SM}}{Q_W^{\rm SM}} = 0.014 \pm 0.006 \quad (\text{or } 0.008 \pm 0.011)$$

$$= 5.1436(\delta u_L + \delta u_R) + 5.7729(\delta d_L + \delta d_R) - 2\,\delta g_A^e$$

Counter Efficiency

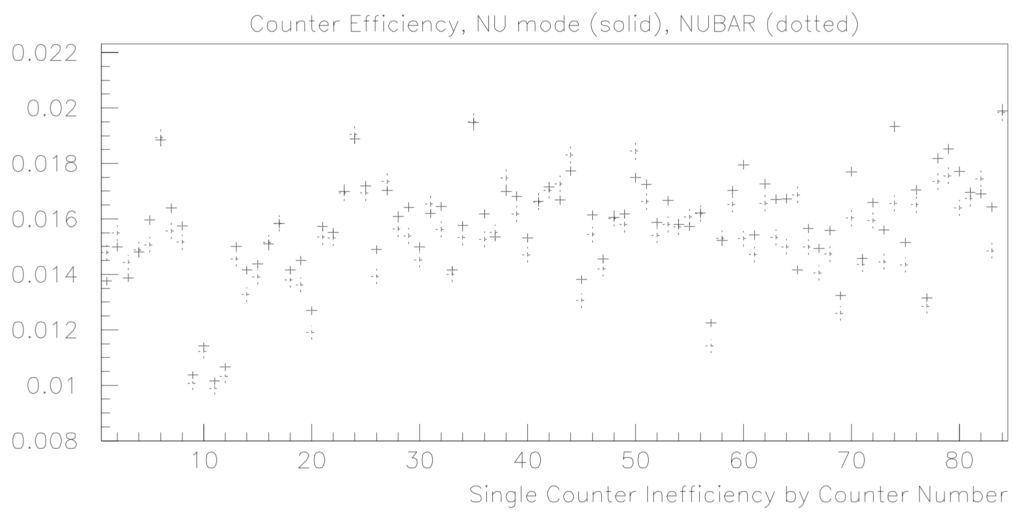
- Why is this important?

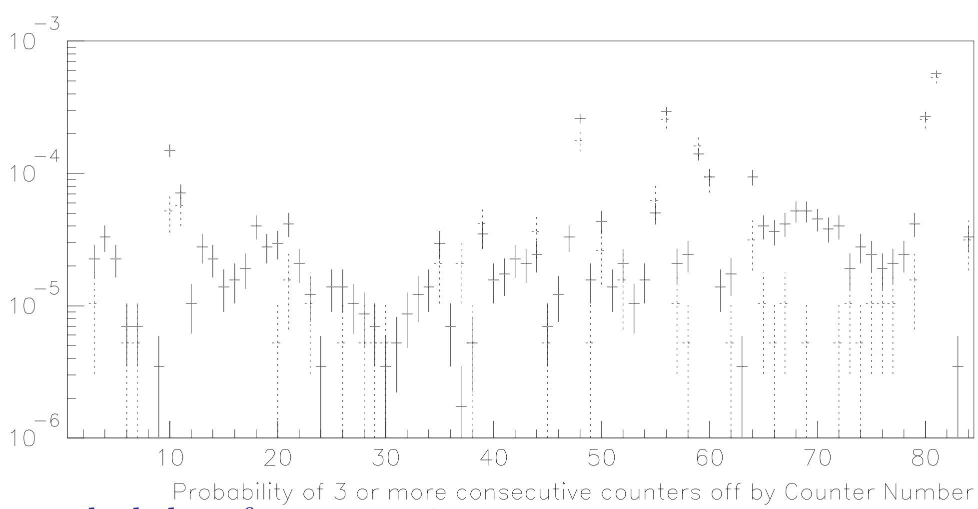
  Inefficiencies in response of counters can lead to a gap of 3 or more consecutive quiet counters signaling a false event end

- How do we study this?

  Use sample of straight-through muons

  Look for gaps in counter response





Average probability for seeing 3 consecutive counters not responding to a muon $\rightarrow$ 3 x 10^{-5}

Counter Noise

- The importance

  Noise in counters can artificially extend the length of an event causing a short event to become long

- How do we study this?

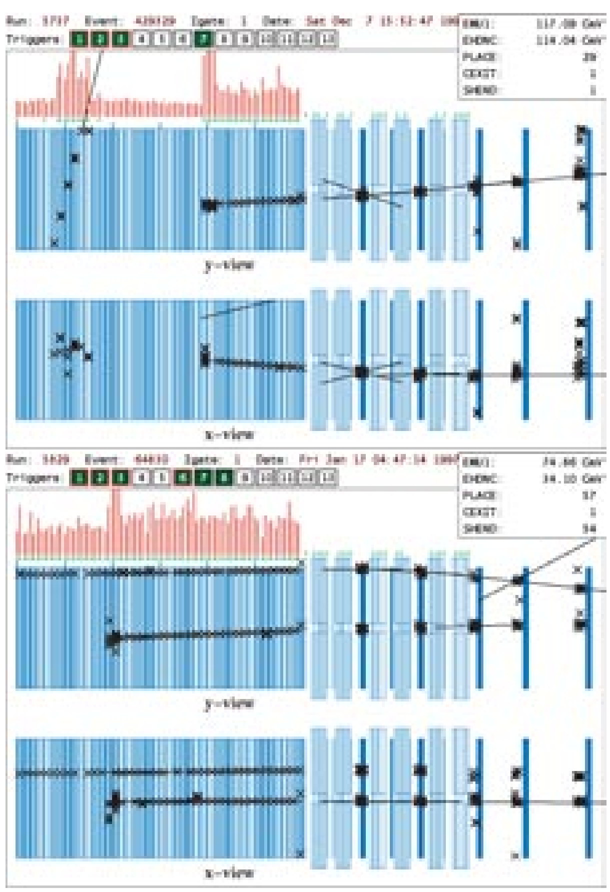
  Large sample of neutrino events

  Examine sections far away from interaction region

- Two effects:

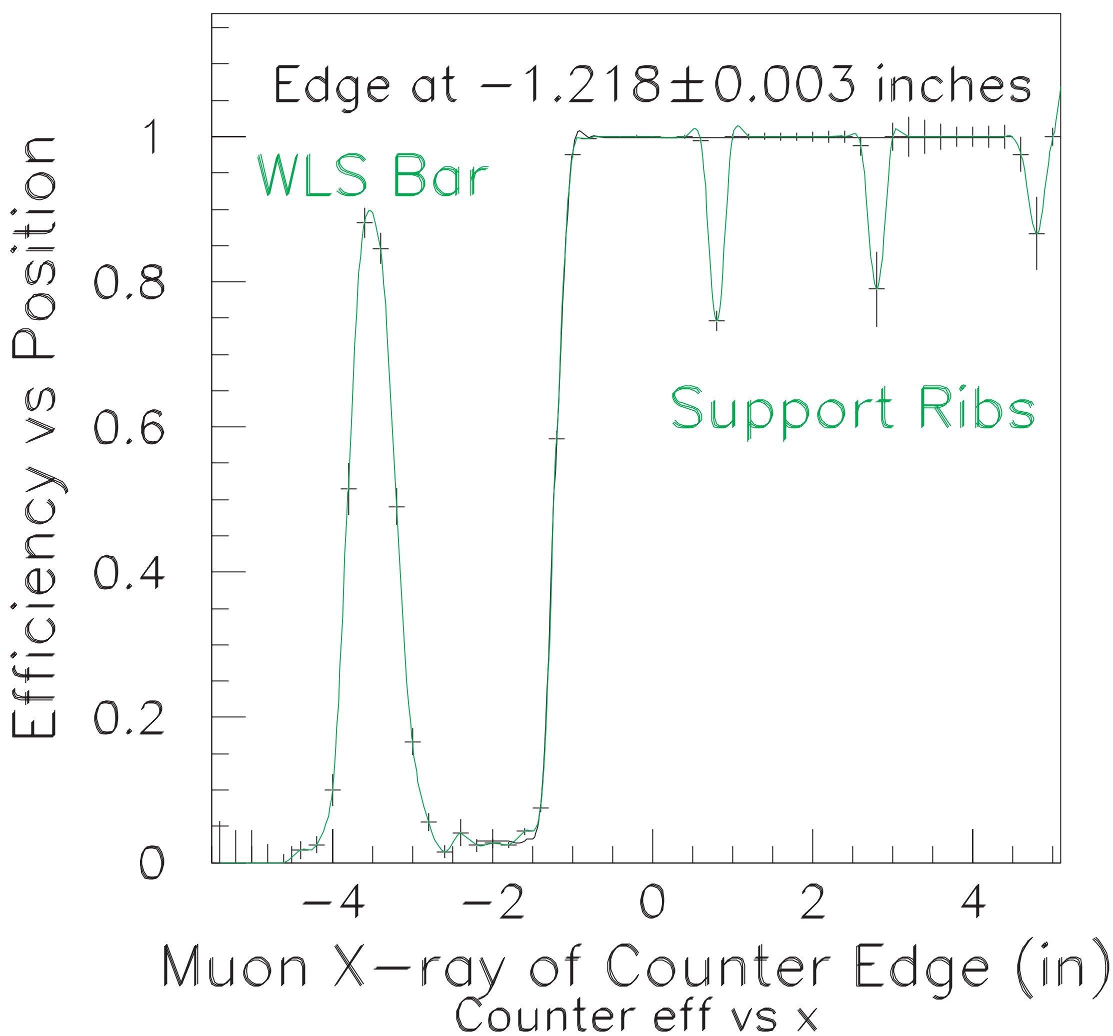
  Counters can fire even when a muon is not present

  Real detector pile-up



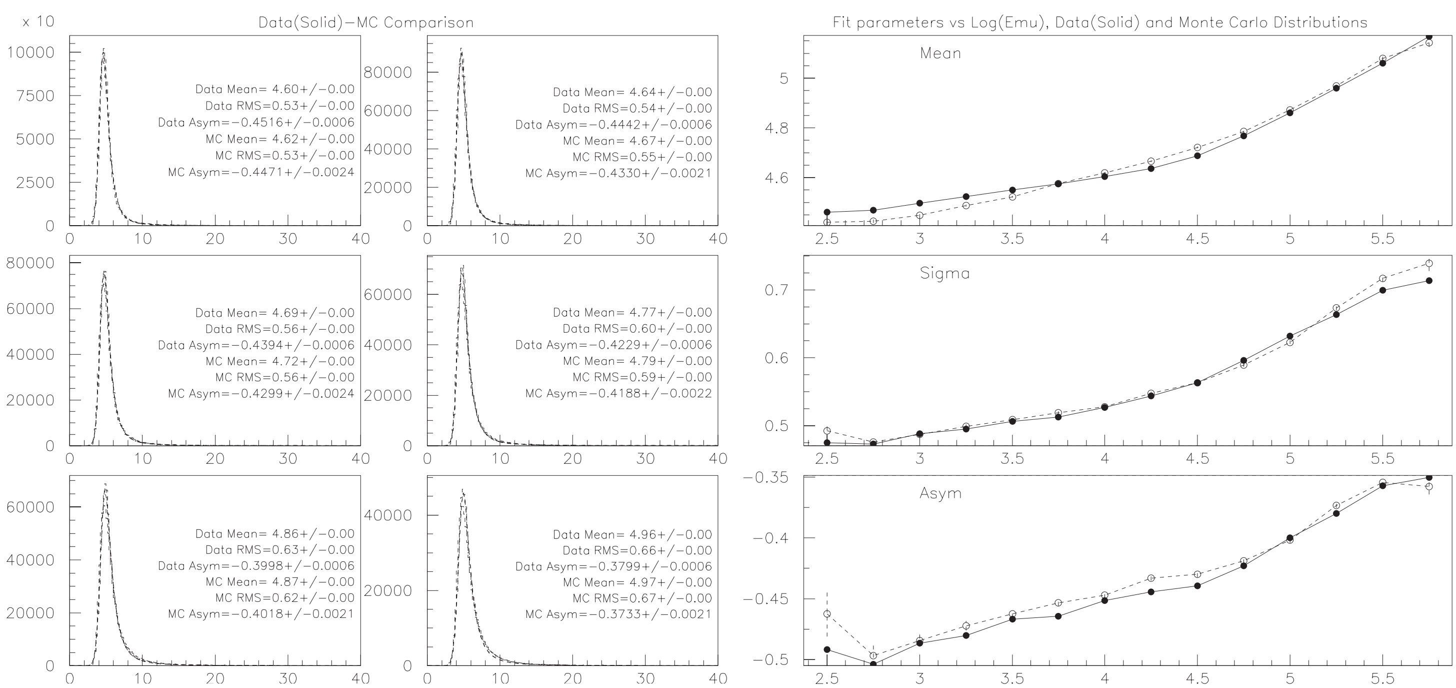
Counter Active Area

- Measurement of counter position and effective size is important to properly simulate detector's fiducial volume
- We are sensitive to this since muons exit out side of detector
- Image counters with muons to map out counter response



Muon Calorimeter Energy

- Muons deposit about 250 MeV/counter
  - NC/CC E_{had} is different
  - Measure in data using CC neutrino interactions far away from hadron shower

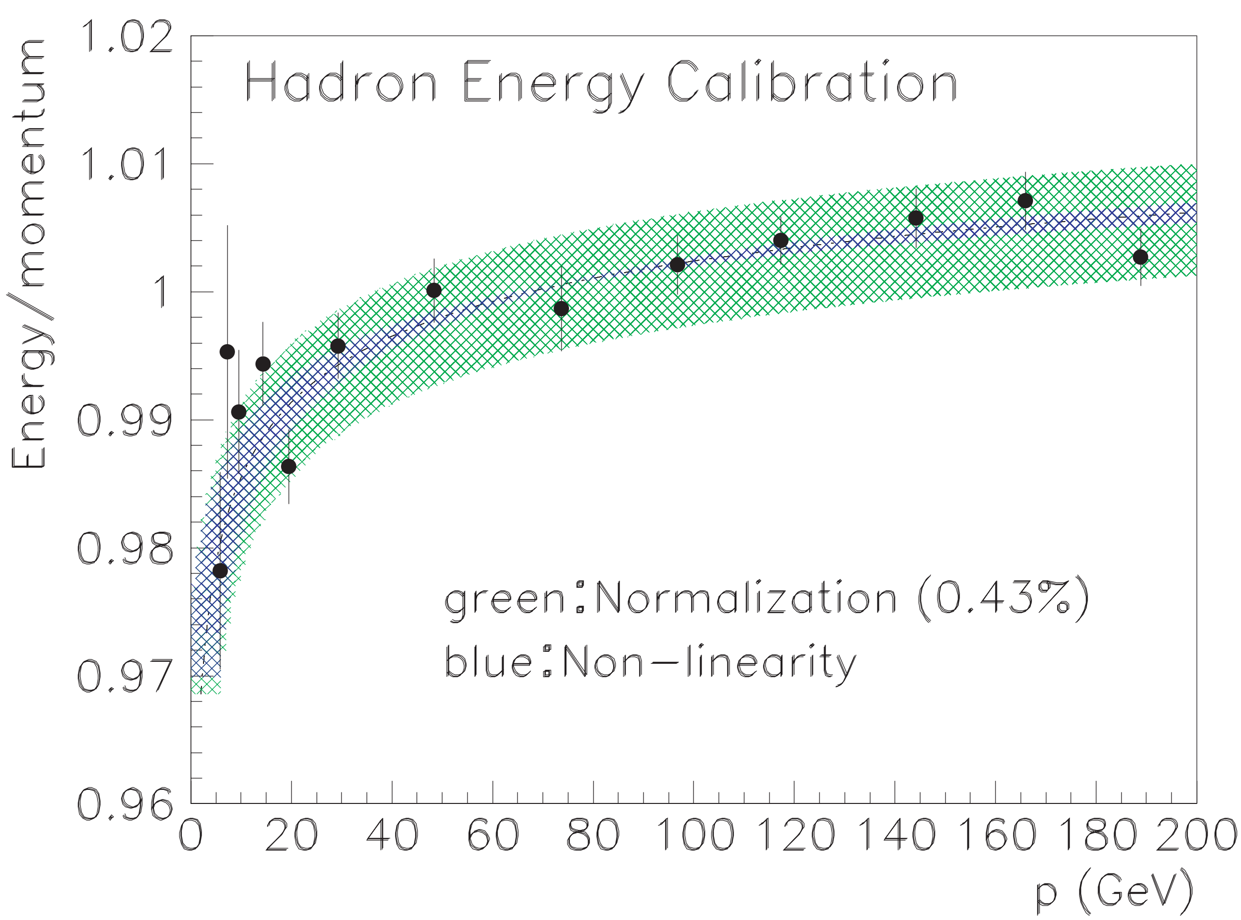


Systematic uncertainty of 2 MeV/counter (coherent)

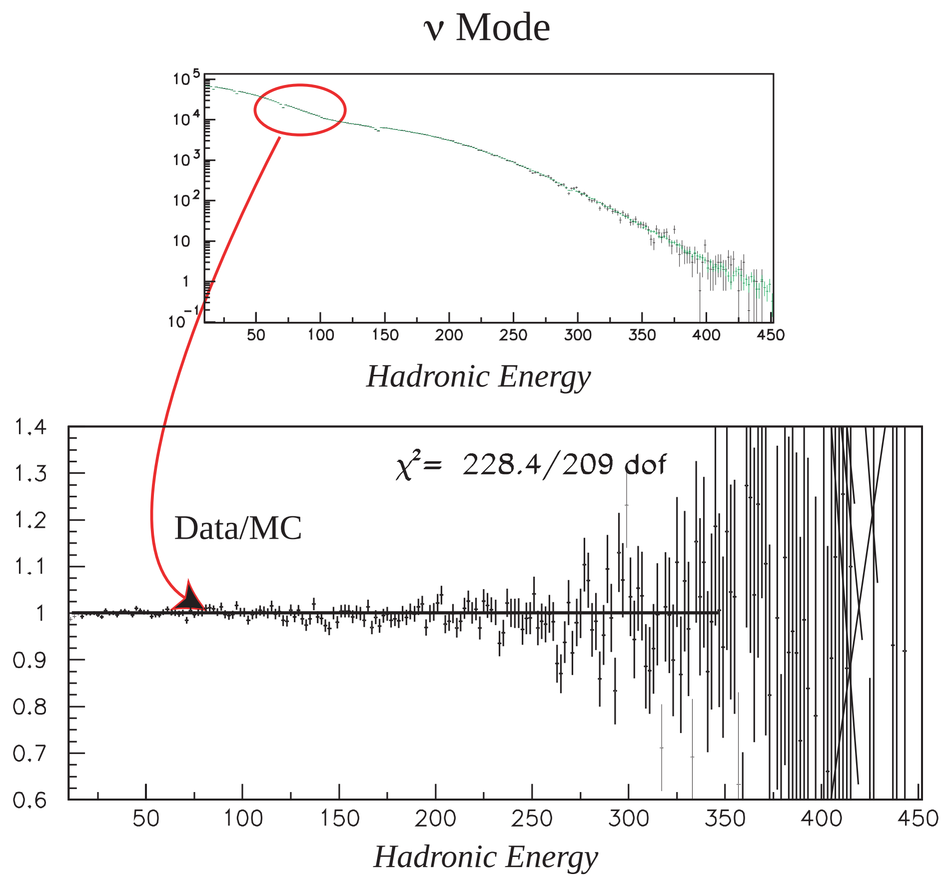
Energy Scale

Main energy uncertainty comes from hadron and muon energy calibrations.

- Hadron Energy Scale
  - Directly affects measured E_{had}
  - Measured to high precision with testbeam data over a wide range of energies
  - Assign a 0.43% uncertainty



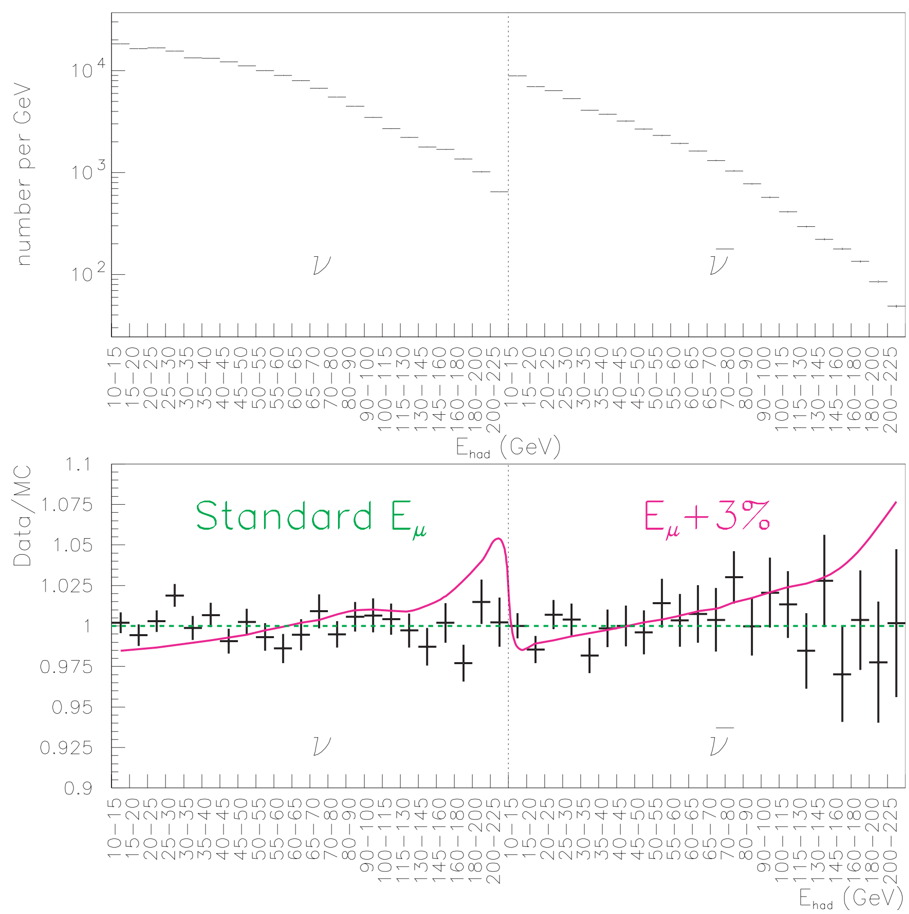
What are the Funny Dips on the $E_{\rm had}$ plot?



- They are real!
- The $E_{\rm had}$ algorithm sums over an energy-dependent number of scintillation counters
- At the transition between numbers of counters summed, get a "jump", because most events ($\sim$ 70%) have a muon in the final state
  - So each counter has a MIP of energy, or about 0.2 GeV
- We simulate this very well

Energy Scale

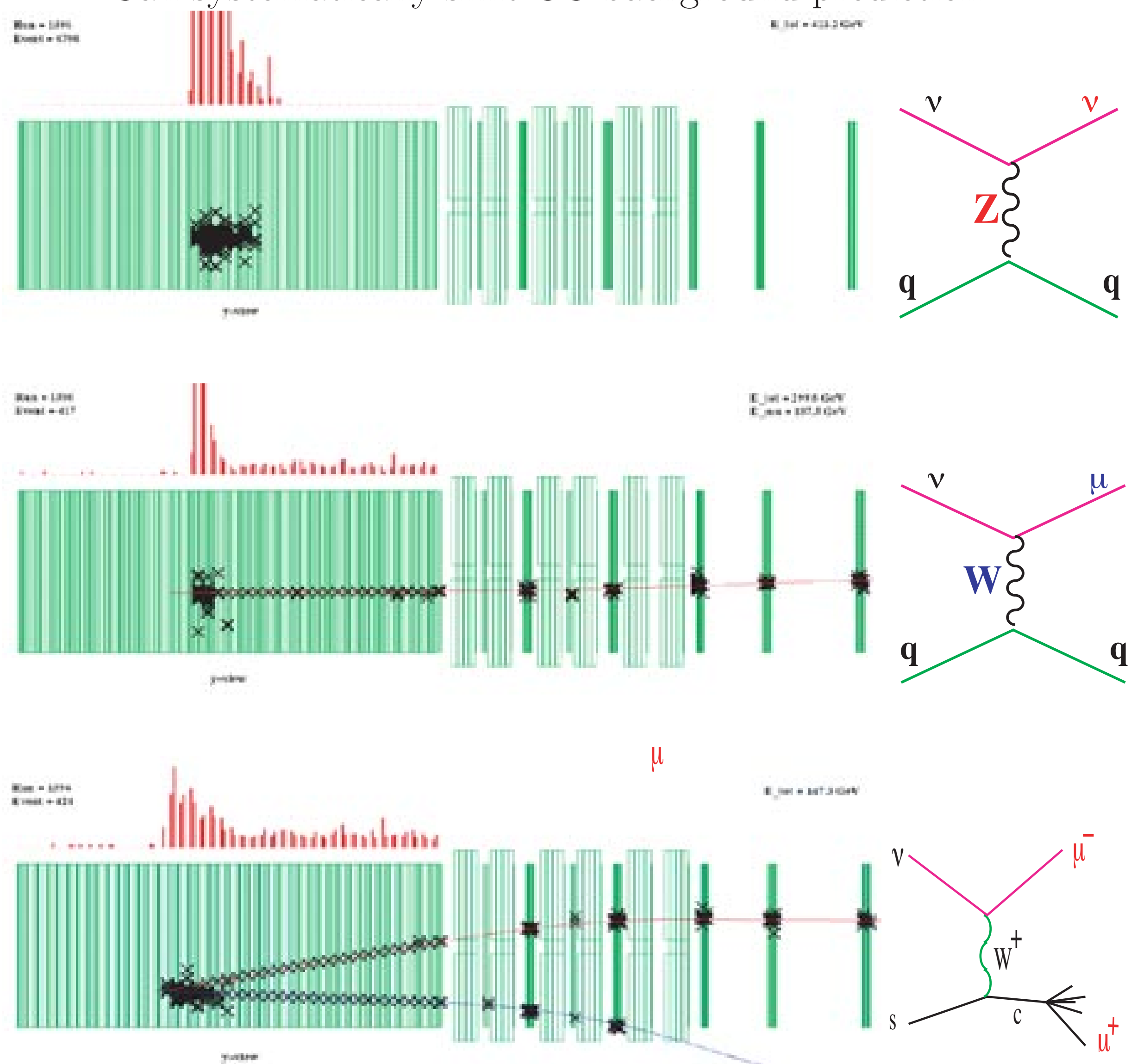
- Muon Energy Scale
  - Indirectly effects analysis through flux extraction
  - Constrained by E_{had} distribution of CC events



  - Agrees with testbeam
  - Assign a 0.25% (0.4%) uncertainty in ν ($\overline{\nu}$) mode

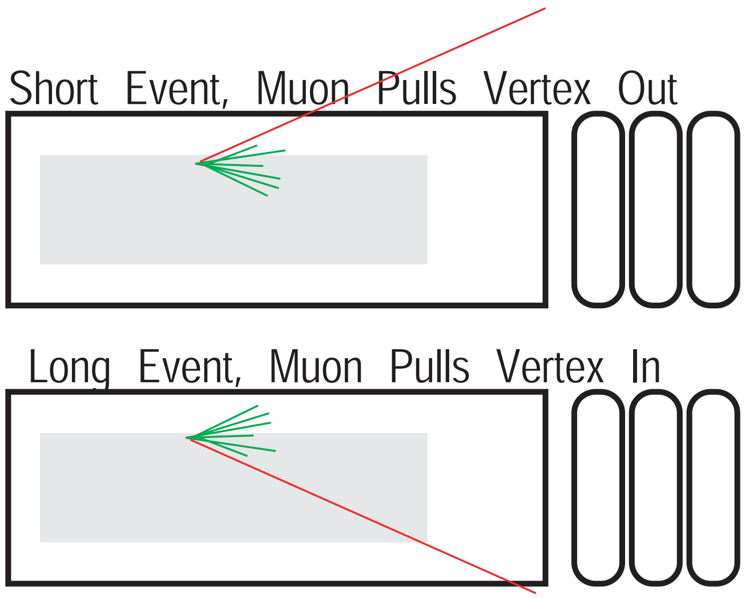
Vertex Location

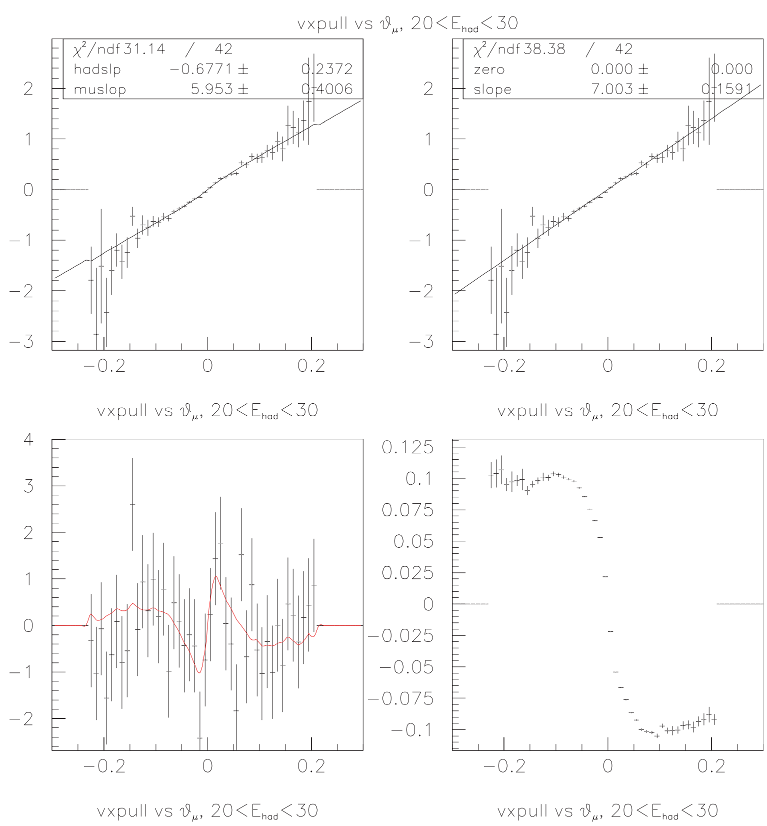
- Longitudinal vertex important since simulation muons originate from vertex
  - Can systematically shift CC background prediction



Measure 1.0 ± 0.2 inch shift from true vertex

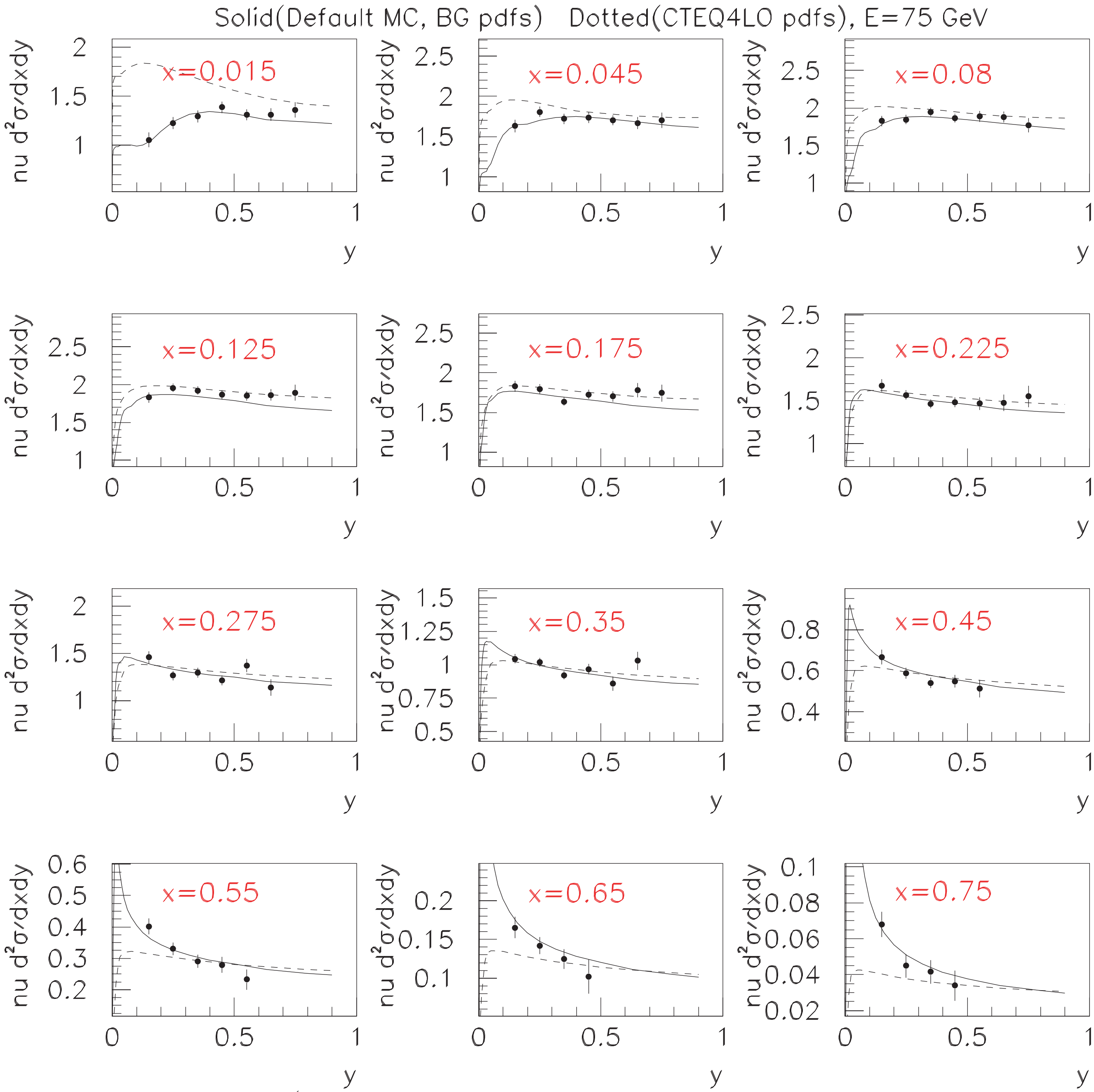
- Transverse vertex important, particularly muon effect since not common to CC and NC



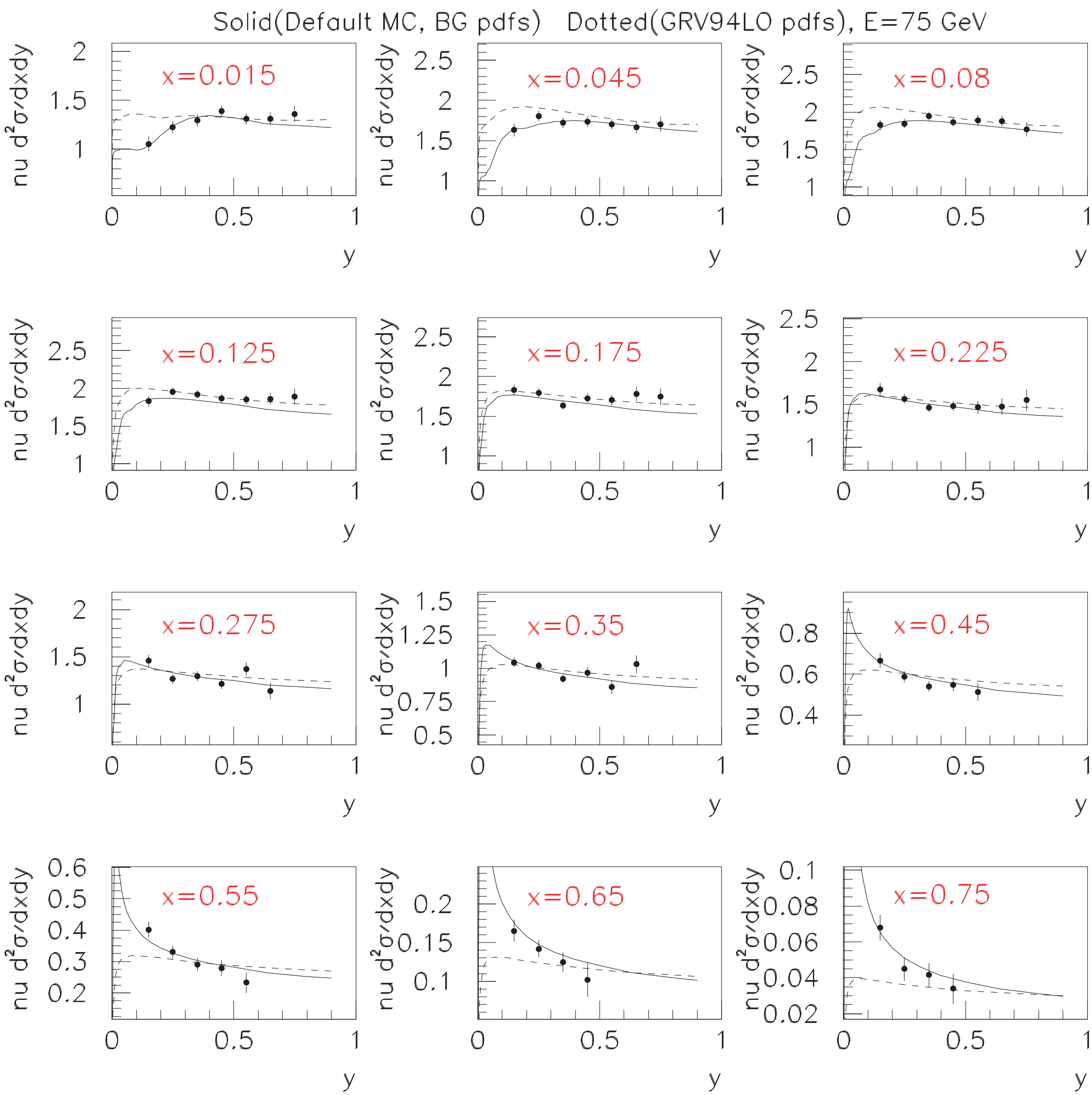


Single E_{cal} bin measurement of effect of muon on vertex in CC data

Cross Section with Outside PDFs



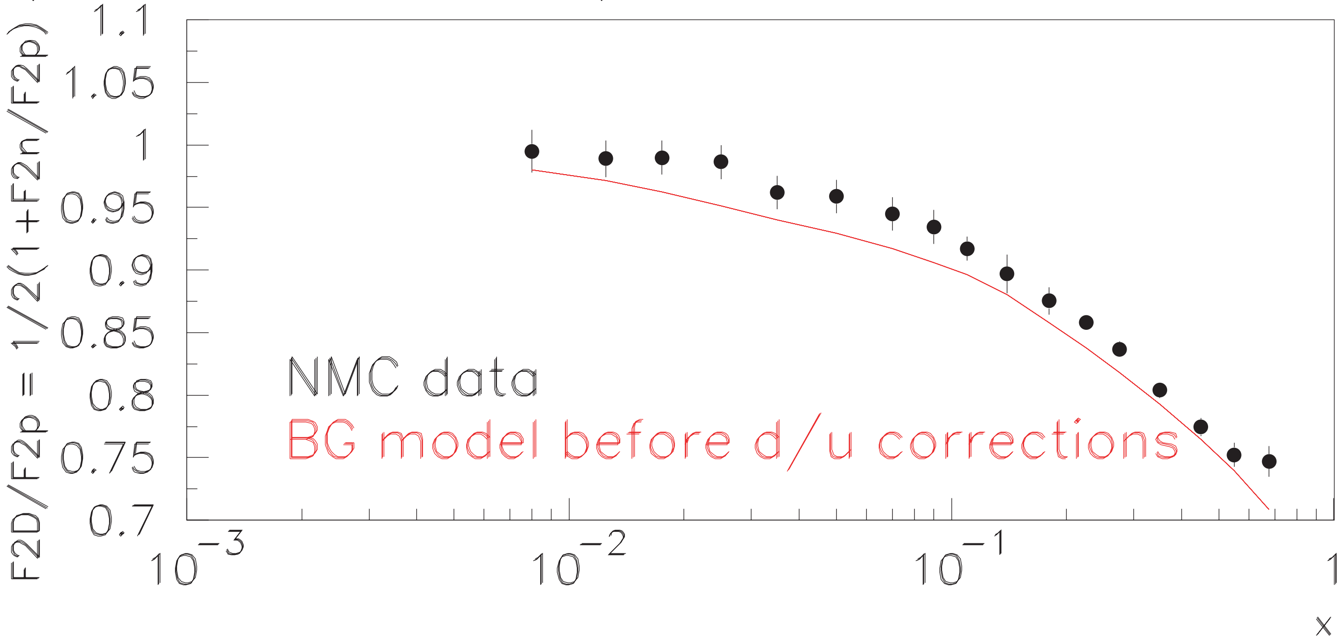
CTEQ4LO pdfs (with Callan-Gross $R_L = 0$, not tuned)

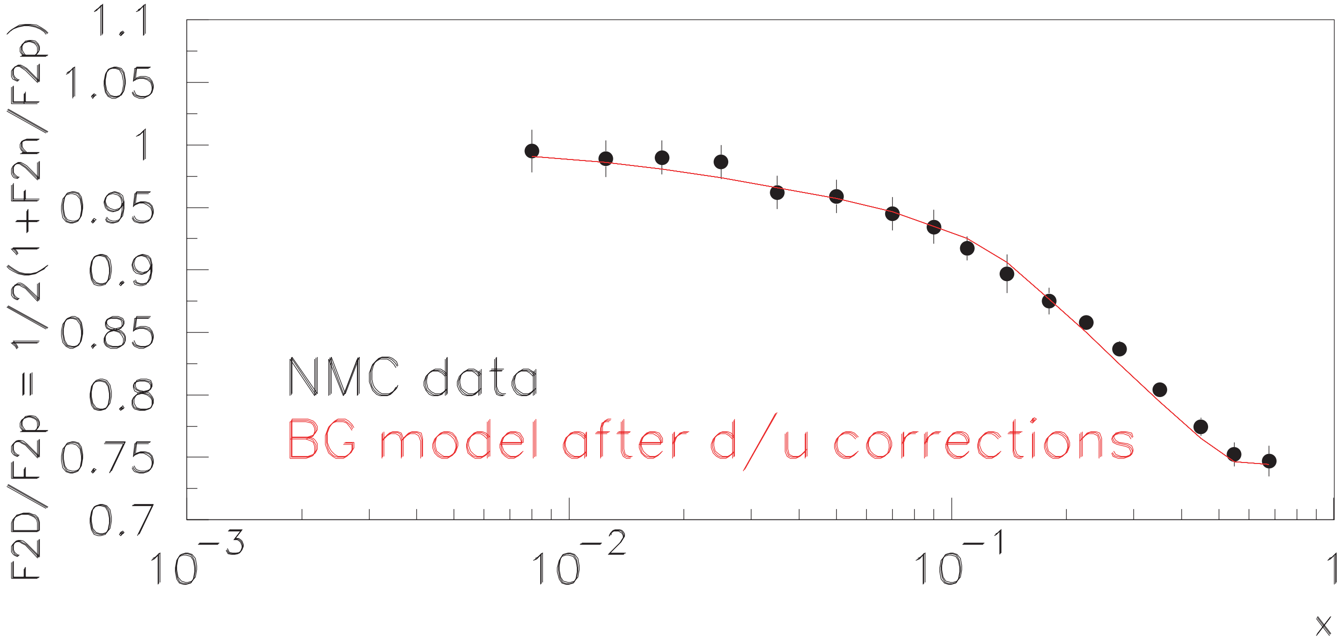


GRV94LO pdfs

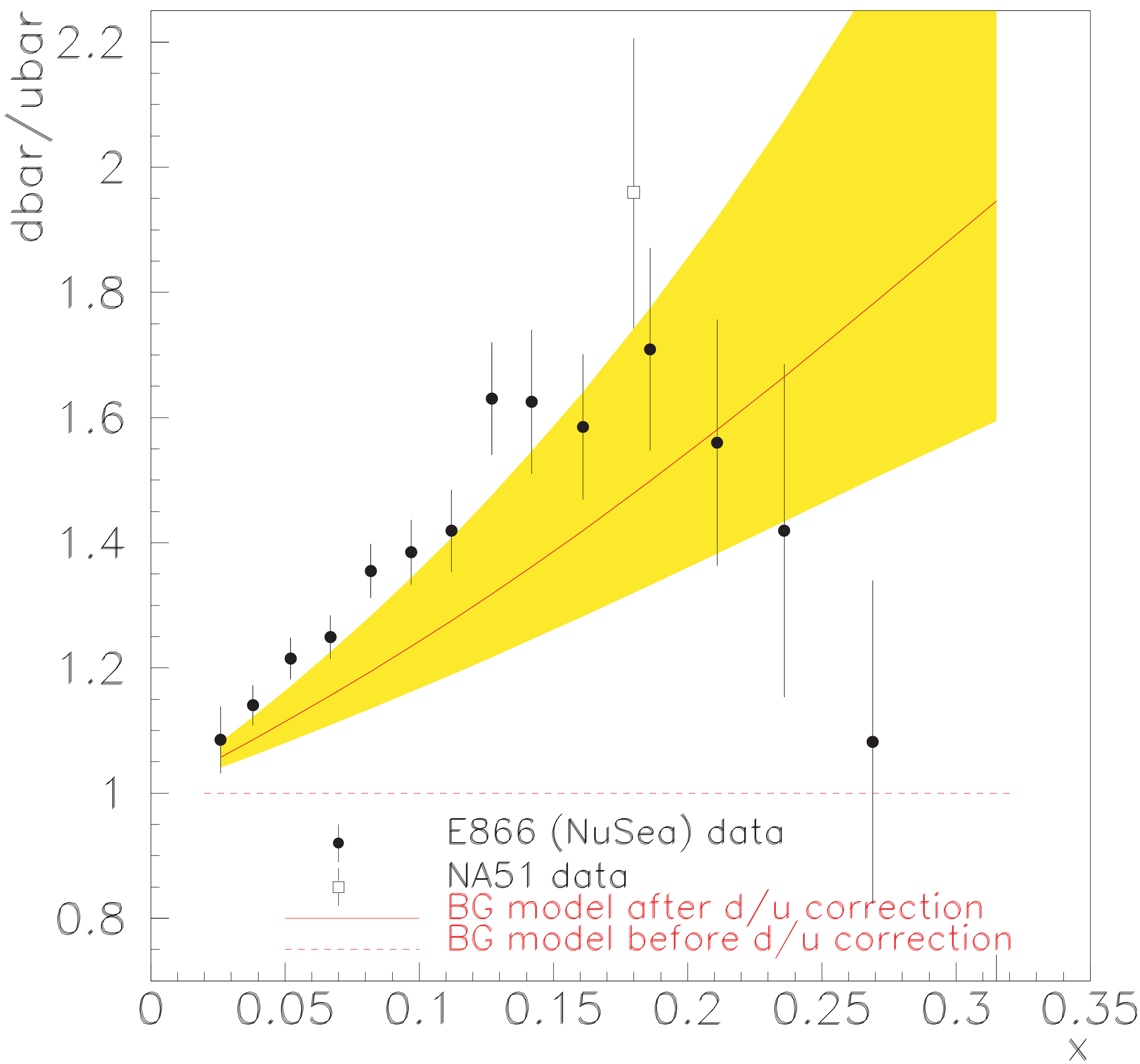
d/u Corrections to Cross-Section

- d/u constrained by NMC F_2 D_2/H_2 ratio





- NUSEA d $\overline{d}/\overline{u}$ in Drell-Yan p+D_2/H_2



(NuTeV $\overline{d}/\overline{u}$ was tuned to preliminary result)

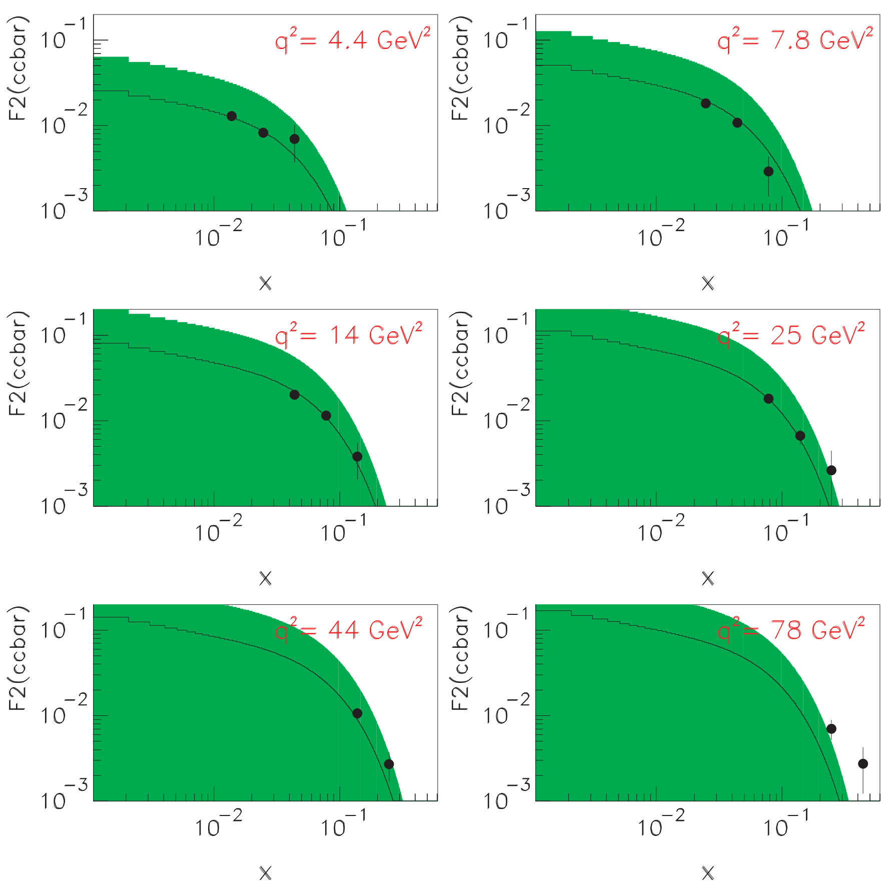
- $\Delta R^{\nu}_{\rm exp} \sim 0.00023$, $\Delta R^{\overline{\nu}}_{\rm exp} \sim 0.00023$
  $\Rightarrow \Delta \sin^2\theta_W \sim 0.00028$

NC Charm Production

Need to model:

$$\nu N \to \nu c\bar{c} X$$

- Use LO model of "intrinsic" charm sea
- Heavy quark suppression uses slow rescaling *(as with our CC charm production model)*
- "Intrinsic charm" is chosen to match EMC $F_2^{c\bar{c}}$

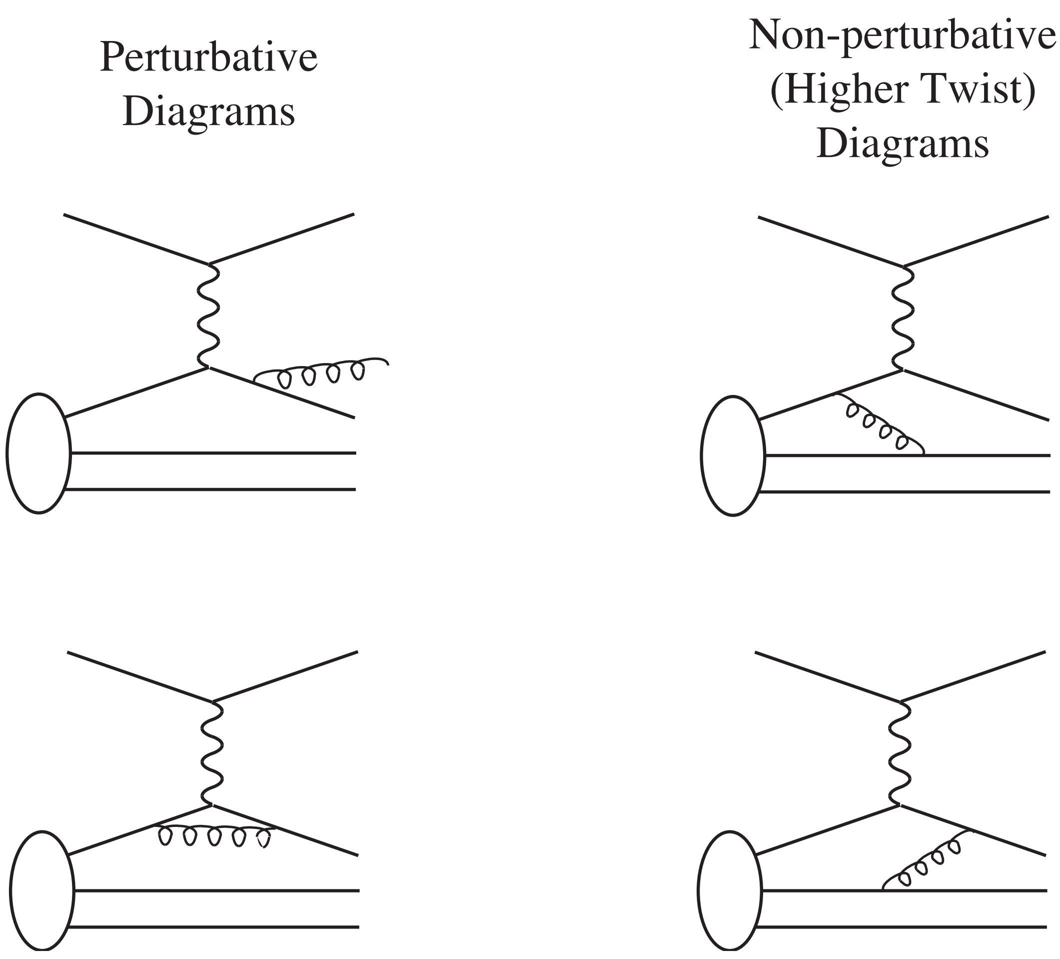


- Assume 100% uncertainty on size of process
- TINY! $\Delta R^{\nu}_{\text{exp}} \sim 0.00005$, $\Delta R^{\overline{\nu}}_{\text{exp}} \sim 0.00004$

  $\Rightarrow \Delta \sin^2\theta_W \sim 0.00010$

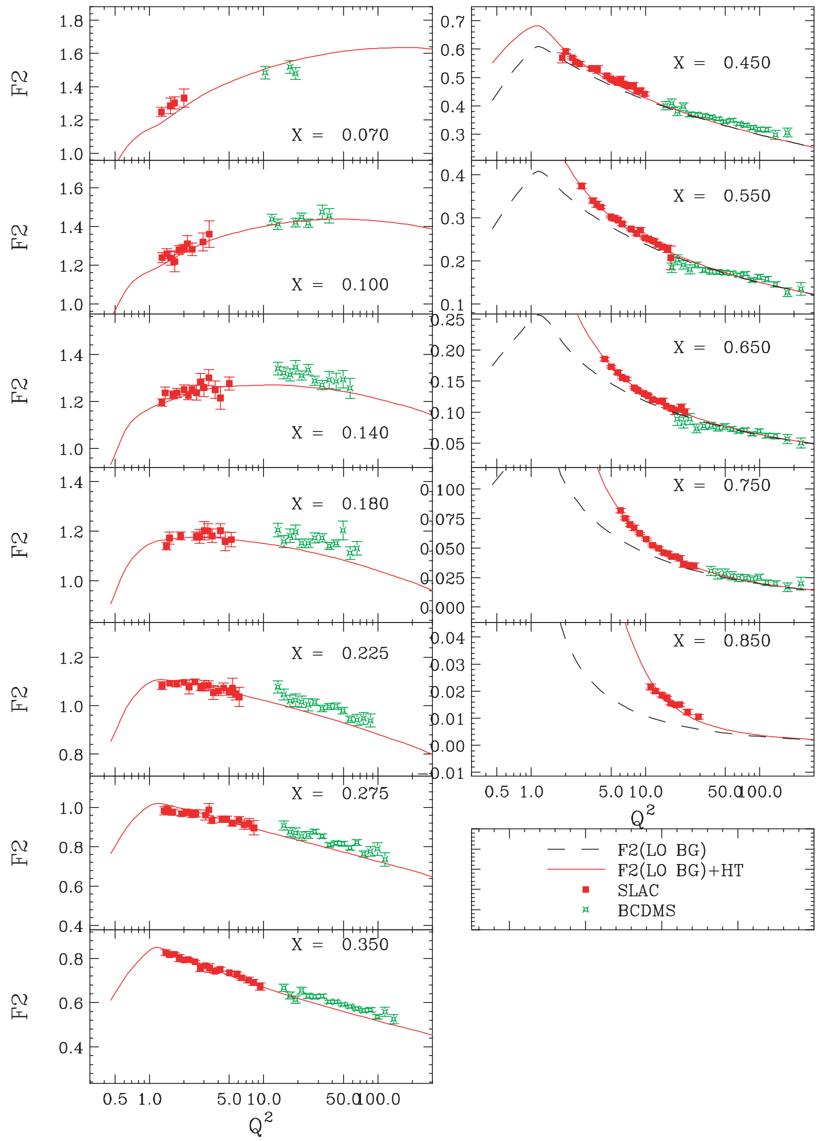
Higher Twist Effects in Cross-Section

- Need higher twist contributions added to LO cross-section at high x and low Q^2



Higher Twist Effects in Cross-Section

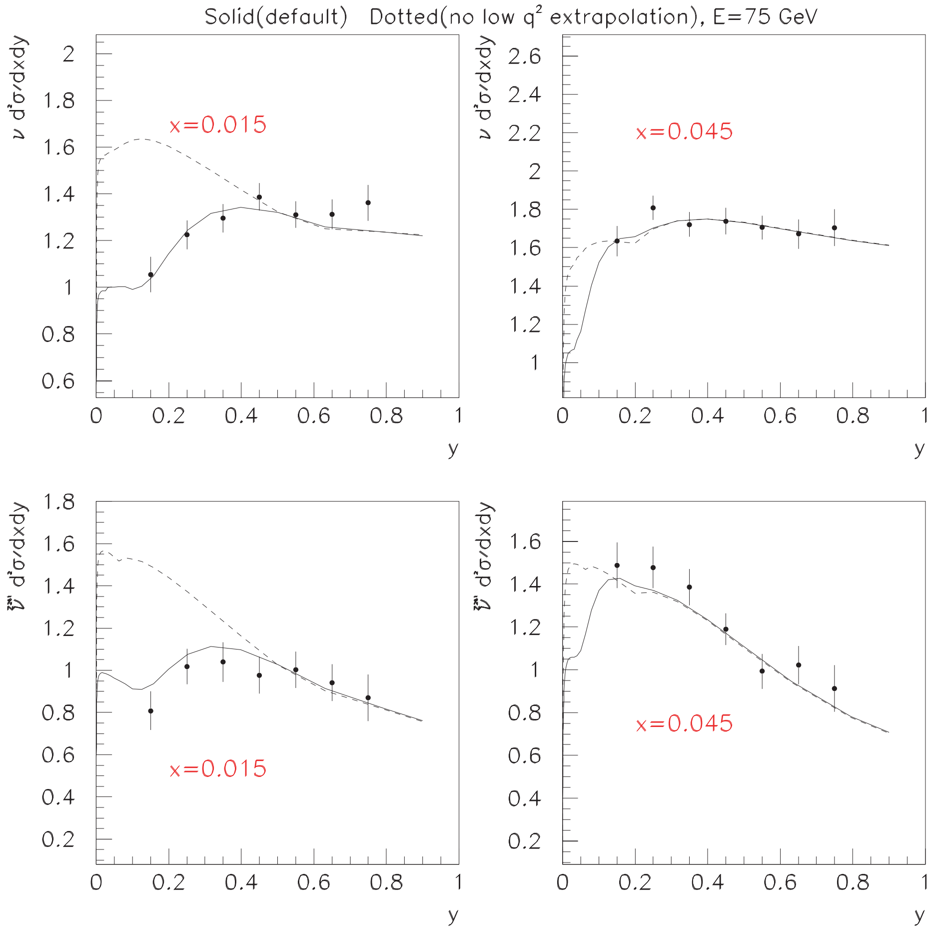
- Fit higher twist contribution from SLAC/BCDMS F_2



- Assume 100% uncertainty on higher twist correction
- TINY! $\Delta R^{\nu}_{\text{exp}} \sim 0.00012$, $\Delta R^{\overline{\nu}}_{\text{exp}} \sim 0.00013$
  $\Rightarrow \Delta \sin^2 \theta_W \sim 0.00014$

$Q^2 < 1$ PDF Evolution

- At very low Q^2, our Buras-Gaemers model for PDF evolution breaks down
- Effect is evident in the lowest x, y points of σ_{CC} measurement

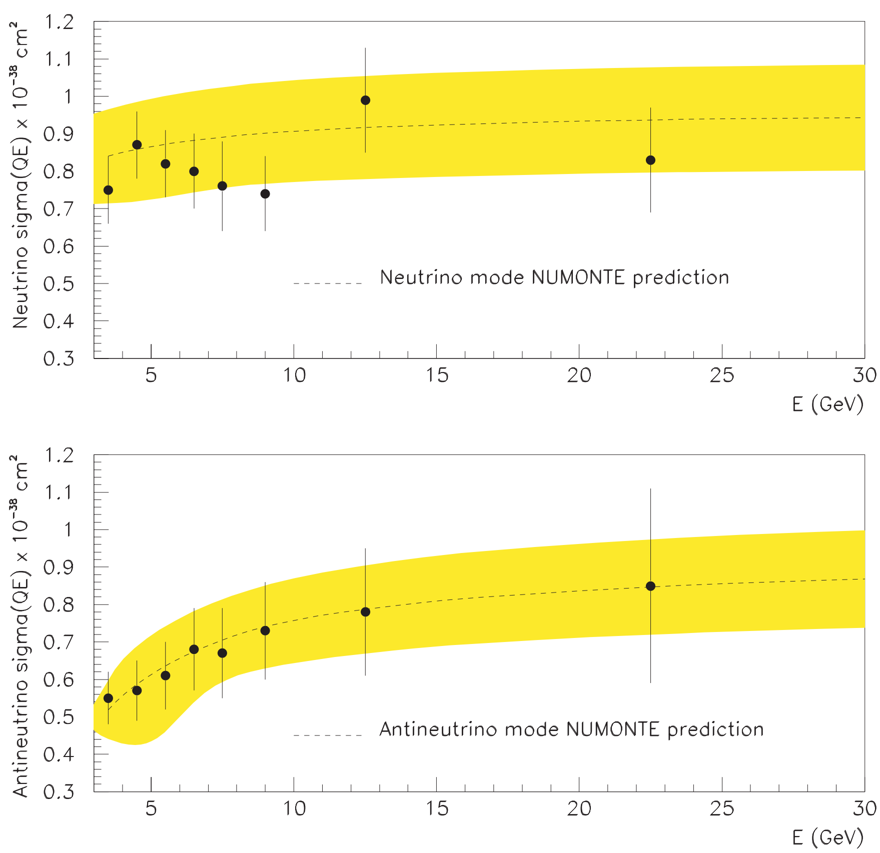


- Use GRV94LO PDF evolution to model low Q^2
  - Vastly improved description of low Q^2 cross-section
  - New since preliminary result
- $\Delta R^{\nu}_{\rm exp} \sim 0.00020$, $\Delta R^{\overline{\nu}}_{\rm exp} \sim 0.00012$
  $\Rightarrow \Delta \sin^2\theta_W \sim 0.00027$

Quasi-Elastic Cross-Section

$$\nu N \to \ell N$$

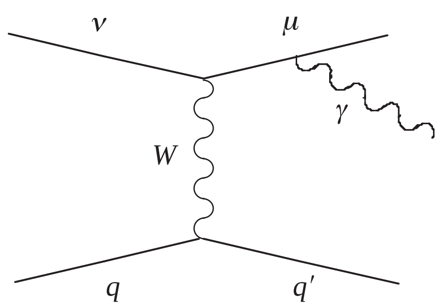
- Why do we care? These have very low $E_{\rm had}$!
  - ν_e quasi-elastics are 1.3% of ν_e events
- Use Serpukhov data (low energy) to check theoretical cross-section



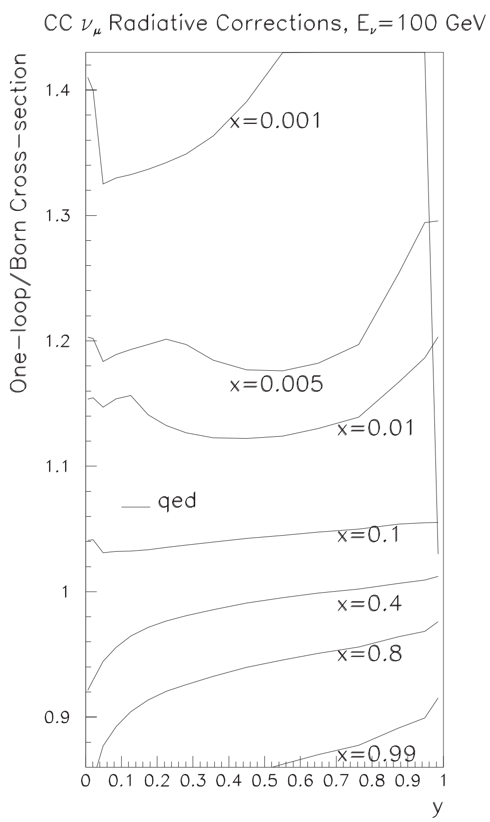
- Total size of QE contribution: $R^{\nu}_{\rm exp} \sim 0.00032$, $R^{\overline{\nu}}_{\rm exp} \sim 0.00089$ $\Rightarrow \sin^2\theta_W \sim 0.00015$
- Assign a 15% error

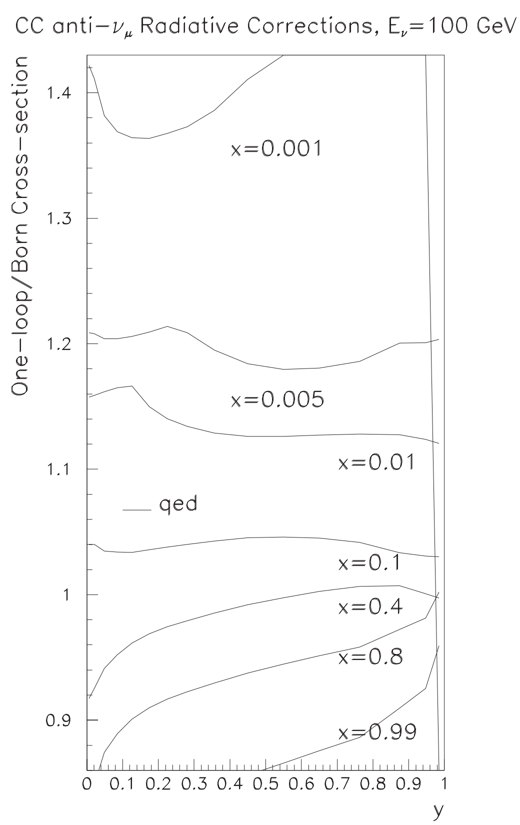
QED Radiative Corrections

D. Yu. Bardin and V. A. Dokuchaeva, JINR-E2-86-260, (1986)



(also smaller contributions from radiation from quarks, vertex corrections, box diagrams)





Weak Radiative Corrections

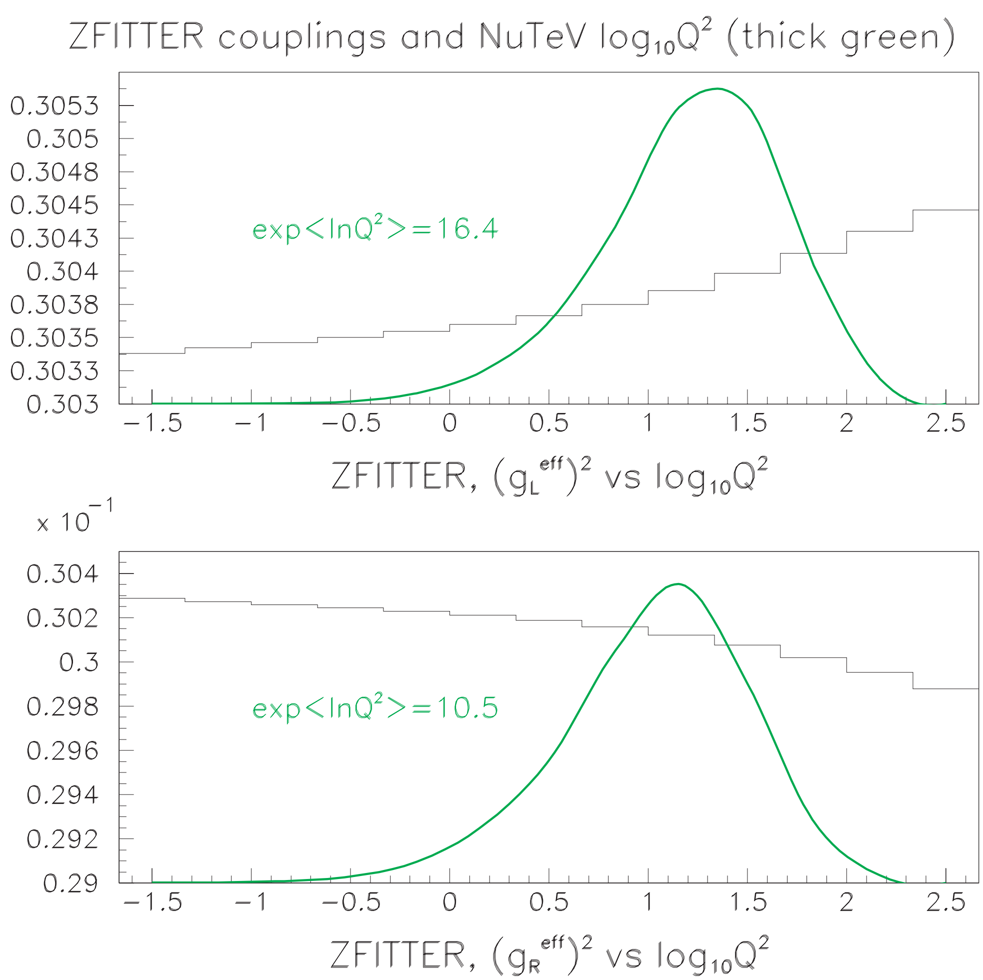
- Tree level couplings (LEPEWWG $\sin^2\theta_W^{(\mathrm{on-shell})}$):

$$g_L^2 = 0.3049,\ g_R^2 = 0.0276$$

- Use ZFITTER/DIZET 6.34 (Jan 2001)
- With weak radiative corrections for $\langle q^2 \rangle \sim 20$ GeV^2:

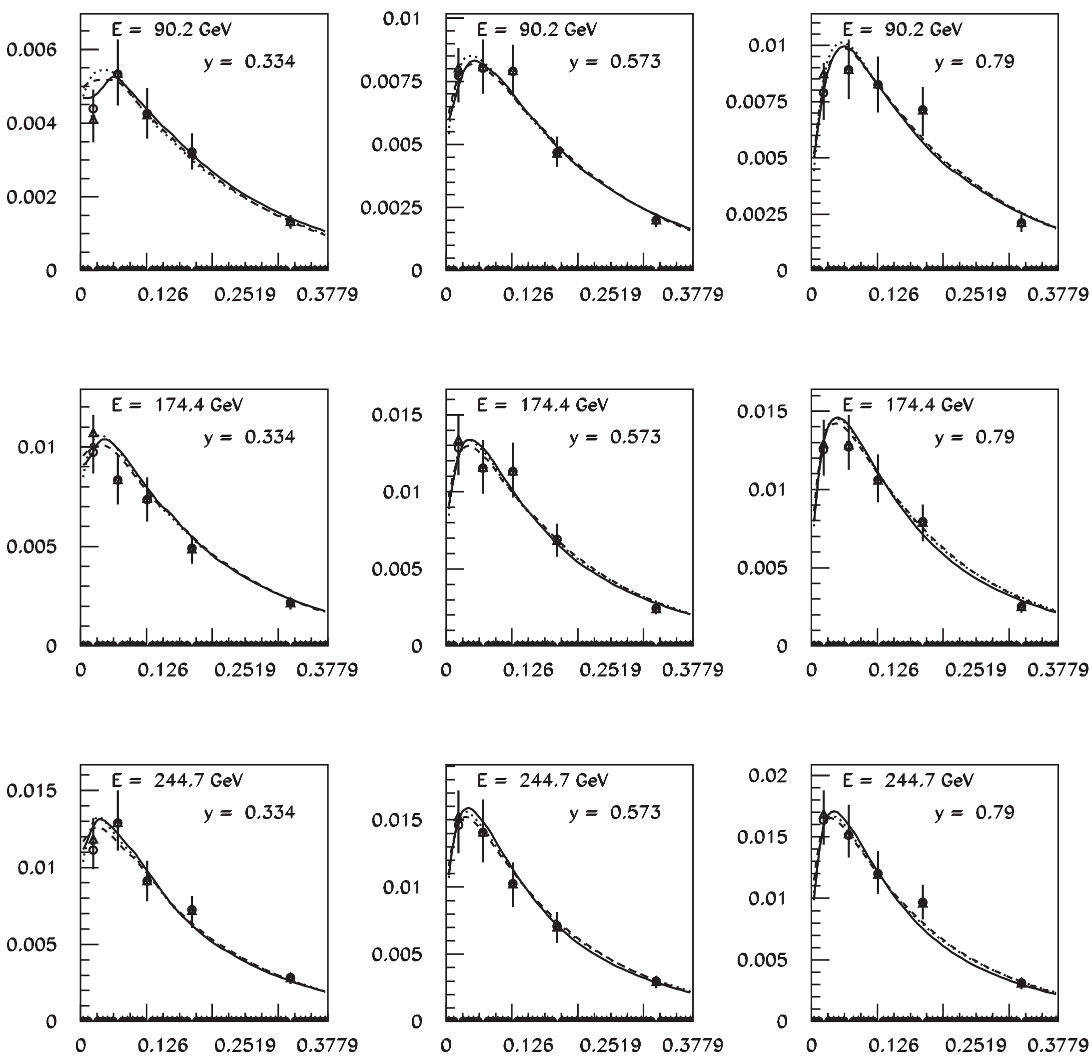
$$g_L^2 = 0.3039,\ g_R^2 = 0.0301$$

  - $M_{\mathrm{top}} = 175$ GeV, $M_{\mathrm{Higgs}} = 150$ GeV



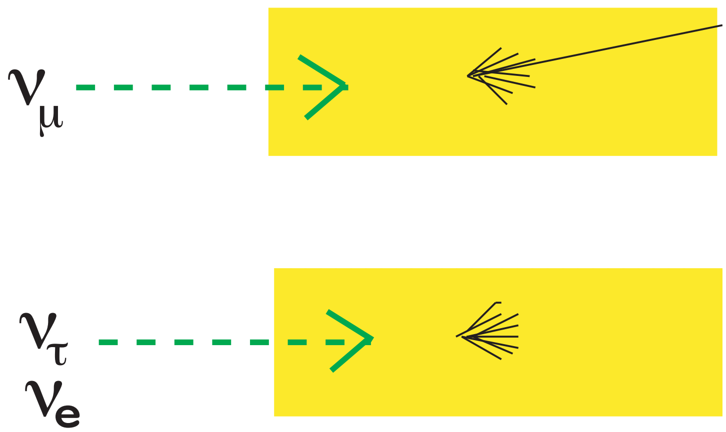
NuTeV/CCFR Dimuon Analysis

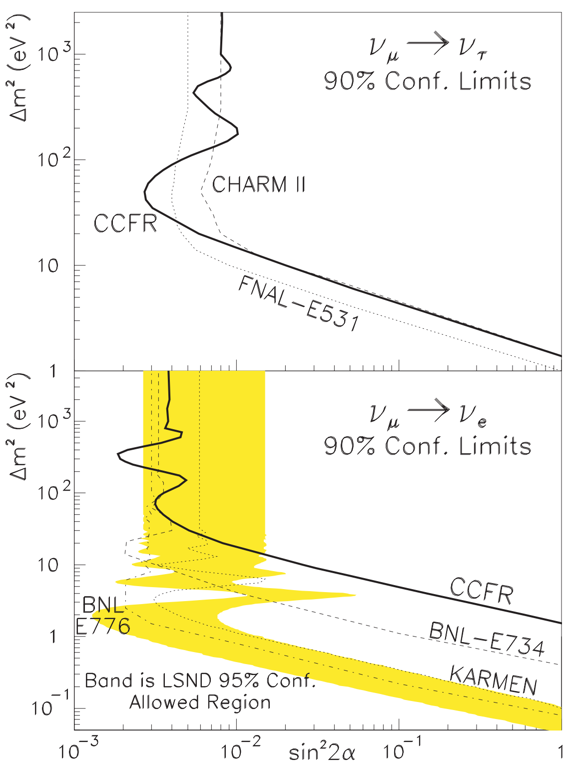
$$\nu N \rightarrow \mu^+\mu^- X \quad (c \rightarrow \mu^+ X)$$



Fits of cross-section model to data
as a function of x in E, y bins.
(Thesis work of Max Goncharov, Kansas State)

Neutrino Oscillations?





- CC ν_e, ν_τ events would be misidentified as NC ν_μ
- Would observe excess of short events $\Rightarrow$ larger NC rate
- Used lack of excess in CCFR to search for oscillations

  (K. S. McFarland, D. Naples *et al.*, Phys. Rev. Lett. **75**, 3993)

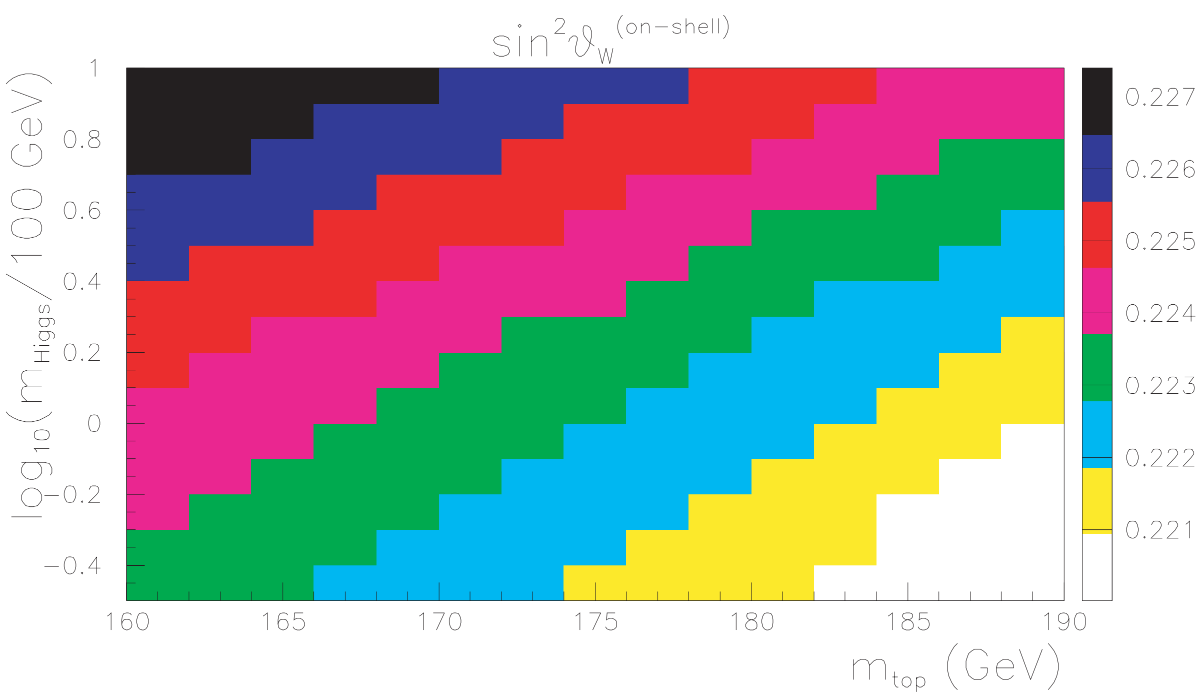
NuTeV Result and M_{top}, M_{Higgs}

NuTeV Measures

$$\begin{aligned}\sin^2\theta_W^{(\mathrm{on-shell})} &= 0.2277 \pm 0.0013(\mathrm{stat.}) \pm 0.0009(\mathrm{syst.}) \\ &- 0.00022 \times \left(\frac{M_{\mathrm{top}}^2 - (175\ \mathrm{GeV})^2}{(50\ \mathrm{GeV})^2}\right) \\ &+ 0.00032 \times \ln\left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}}\right)\end{aligned}$$

- Therefore, the top and Higgs mass corrections to the measurement are $\ll 0.001$.

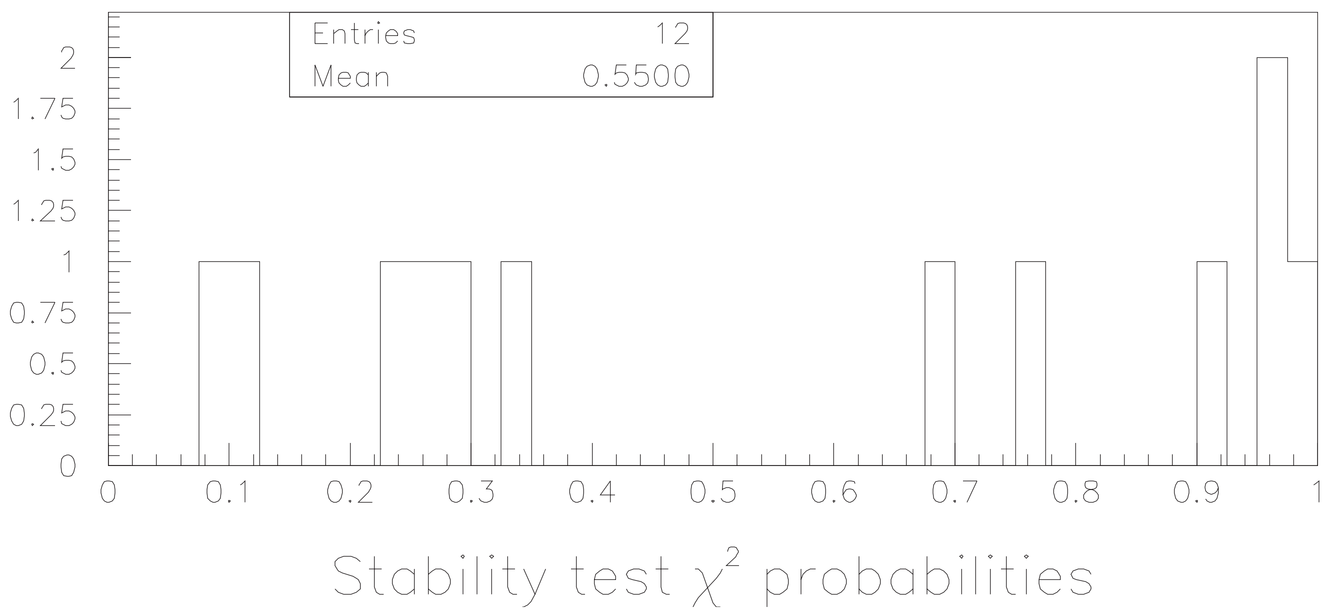
Standard Model Predictions



“Stability” Test χ^2 Probabilities

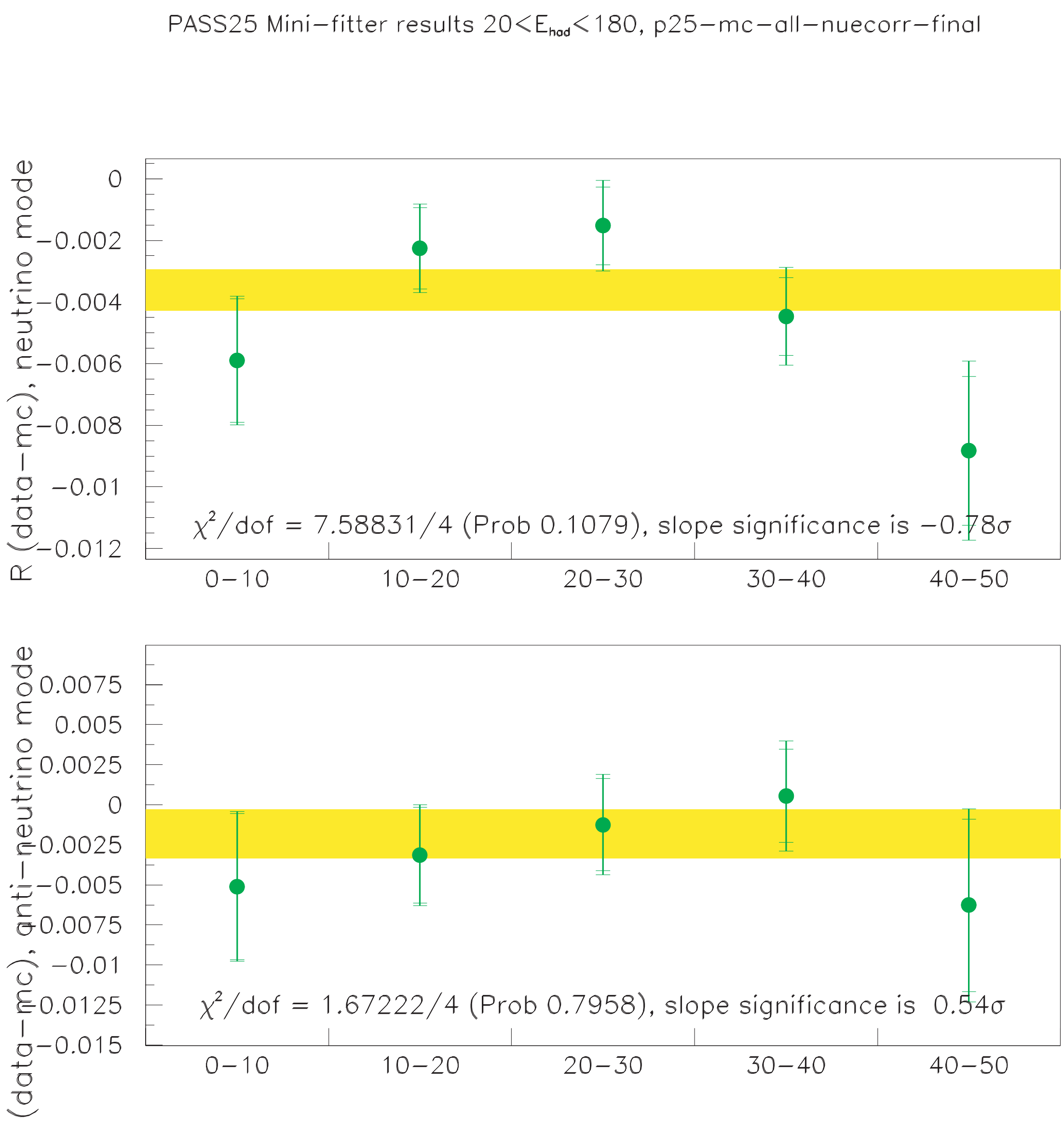
- What is the χ^2 Distribution for Changing Cuts, etc?
- Does it look too good or too bad?

No obvious indication of a problem



Stability of R_{exp} (out to bin 5)

R as a function of "radial" bin:



Was the Analysis Blind?

Sort of.

- We had a preliminary result, based on R^-, that included 80% of the data in this analysis
- After the preliminary result, we rewrote significant parts of the simulation relating $R_{\rm exp}^{\overset{(-)}{\nu}}$ to $R^{\overset{(-)}{\nu}}$
  - At this time, we "hid" the true $\sin^2\theta_W^{\rm (on-shell)}$ from ourselves in the Monte Carlo
  - We "revealed" the result after making all analysis choices
- Nevertheless, we knew preliminary result had a larger $\sin^2\theta_W^{\rm (on-shell)}$ than the standard model prediction.

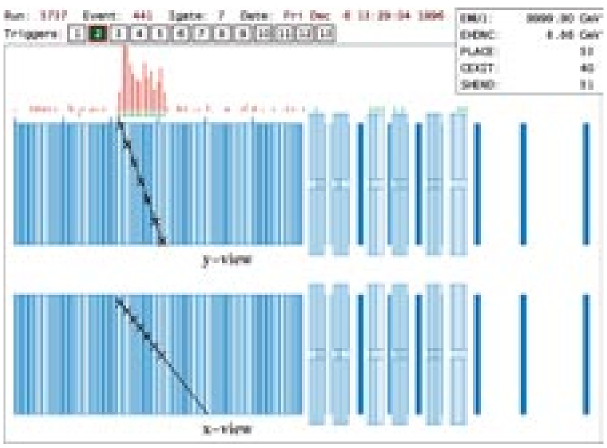
Background Subtraction from Data

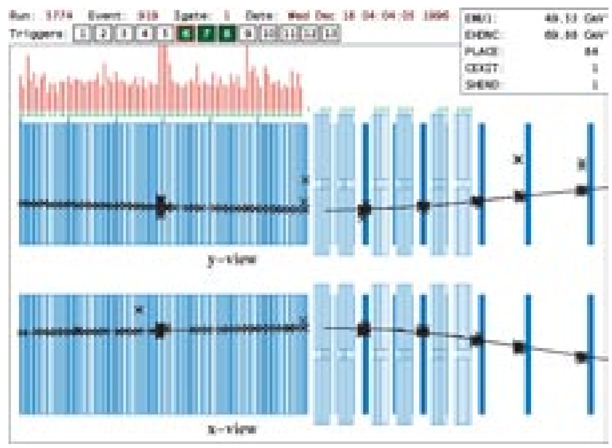
Cosmic Rays

- Short $\Rightarrow$ NC candidates
- Beam-off gate

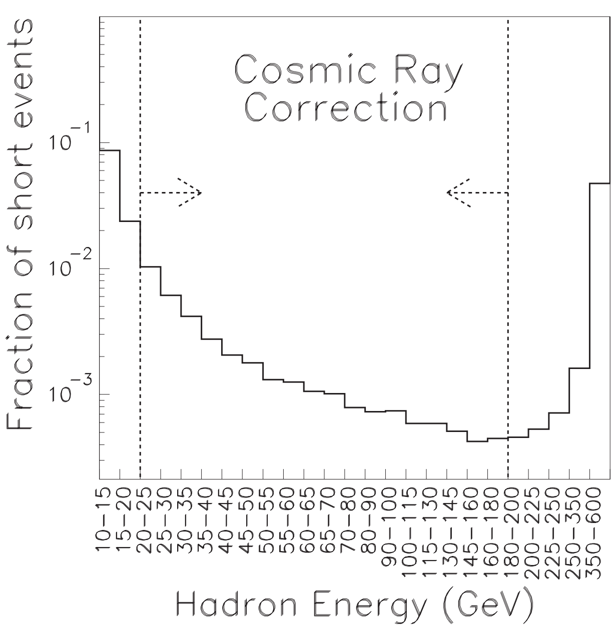
Hard μ Bremsstrahlung

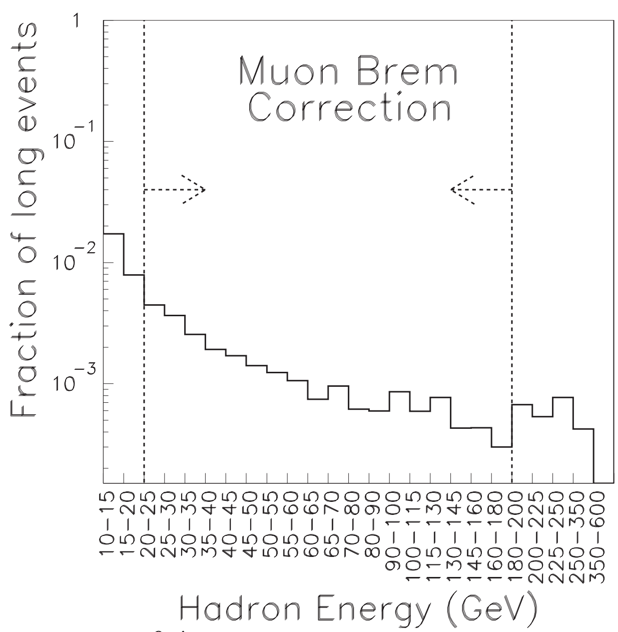
- Long $\Rightarrow$ CC candidates
- Identify and subtract





Size of correction:





0.9% of Short ν Events
4.7% of Short $\overline{\nu}$ Events

0.2% of Long ν Events
0.3% of Long $\overline{\nu}$ Events

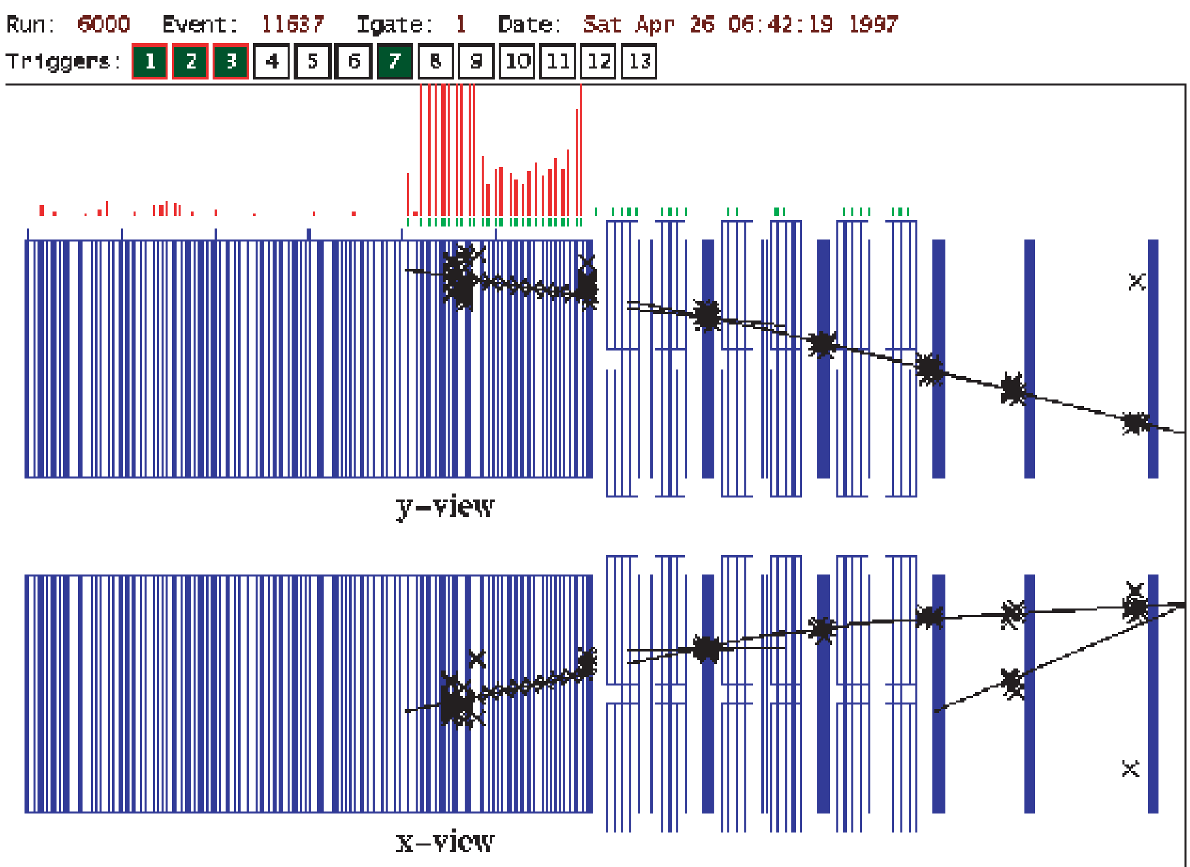
Vertex Inefficiencies From Data

Longitudinal Vertex Inefficiency

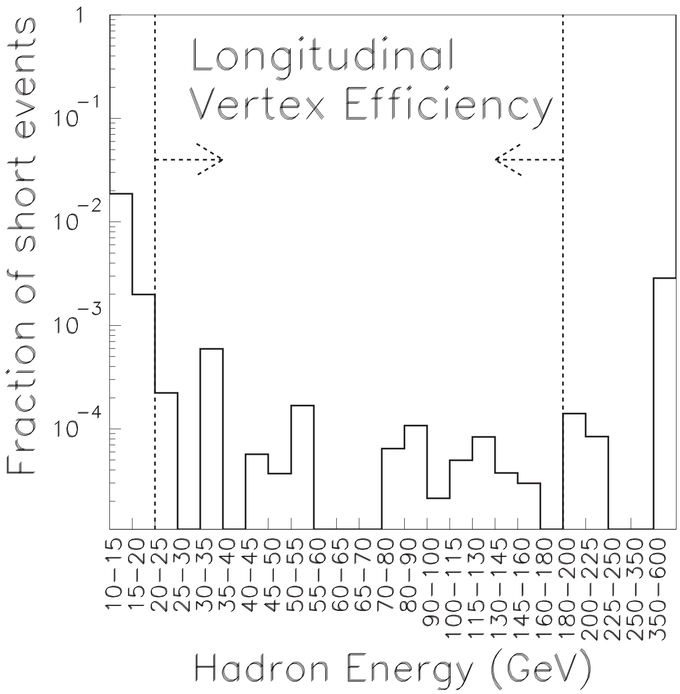
- Effect for low energy events
- Corrected using sbit quantities to tell us location and length of event

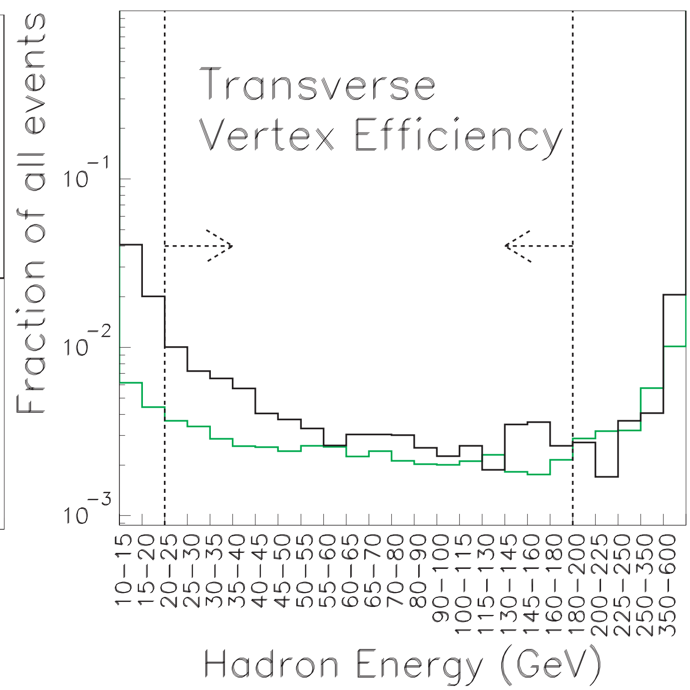
Transverse Vertex Inefficiency

- Event "lost" if missing hits in first 3 drift chambers
- Correct using PMT vertex



Size of correction:

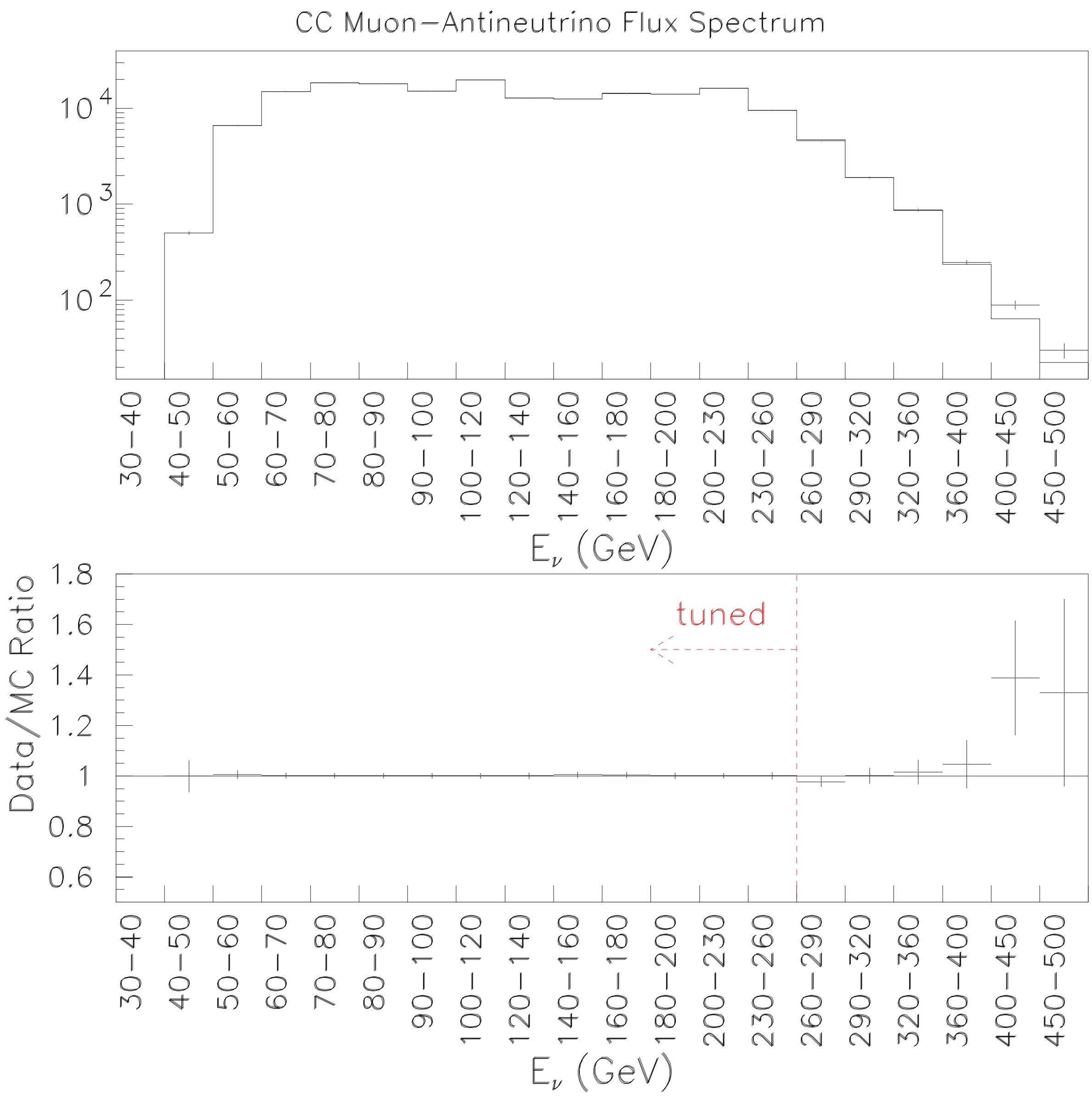


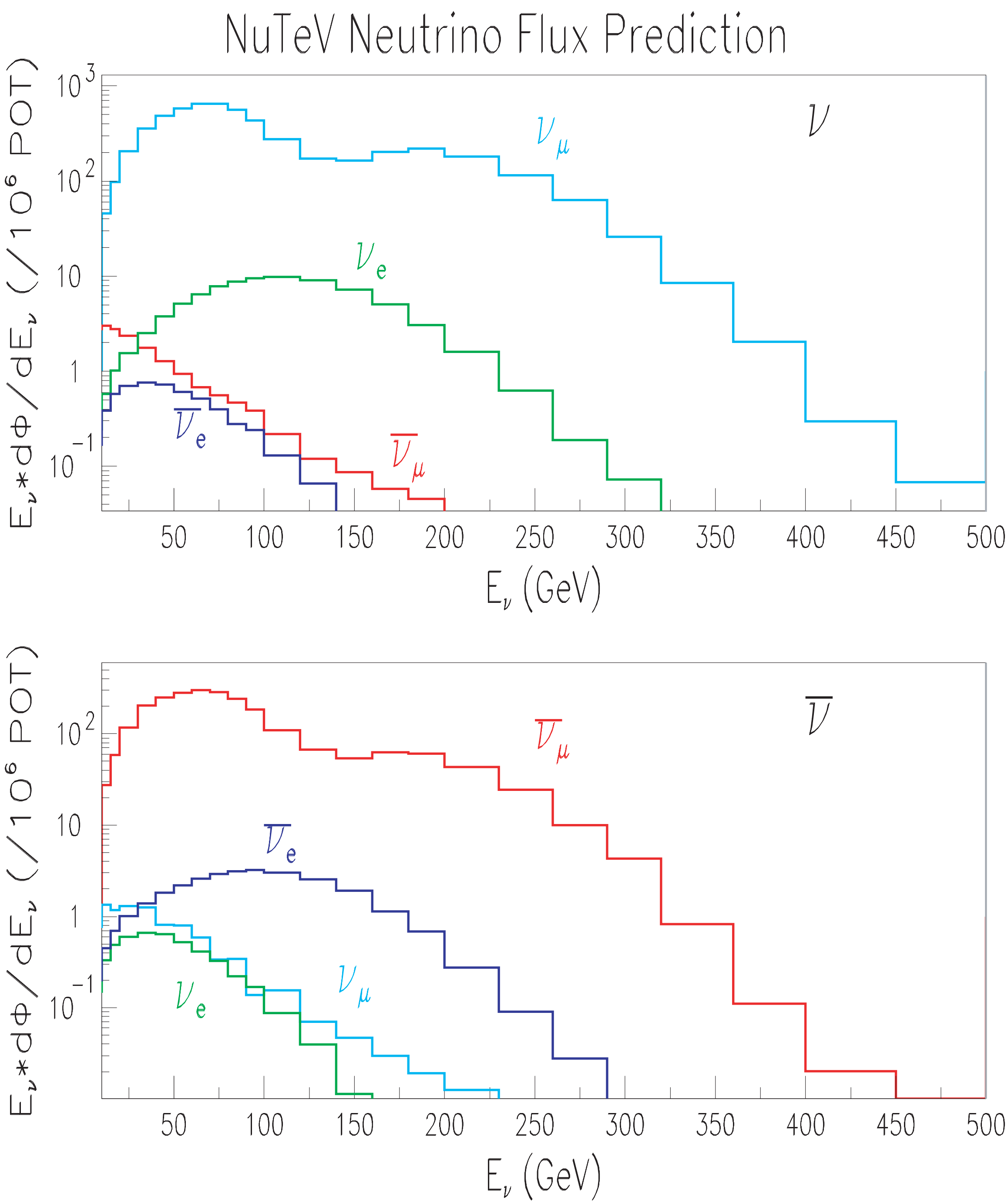


0.006% of Short ν Events
0.042% of Short $\overline{\nu}$ Events

0.44% (0.26%)of Short (Long) ν
0.58% (0.37%) of Short (Long) $\overline{\nu}$

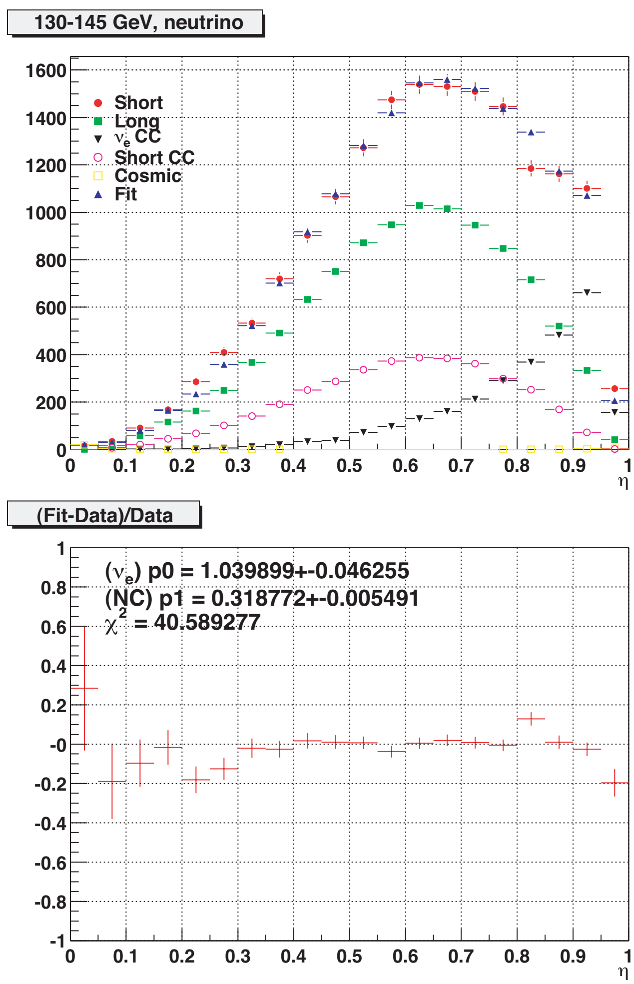
High Energy Flux





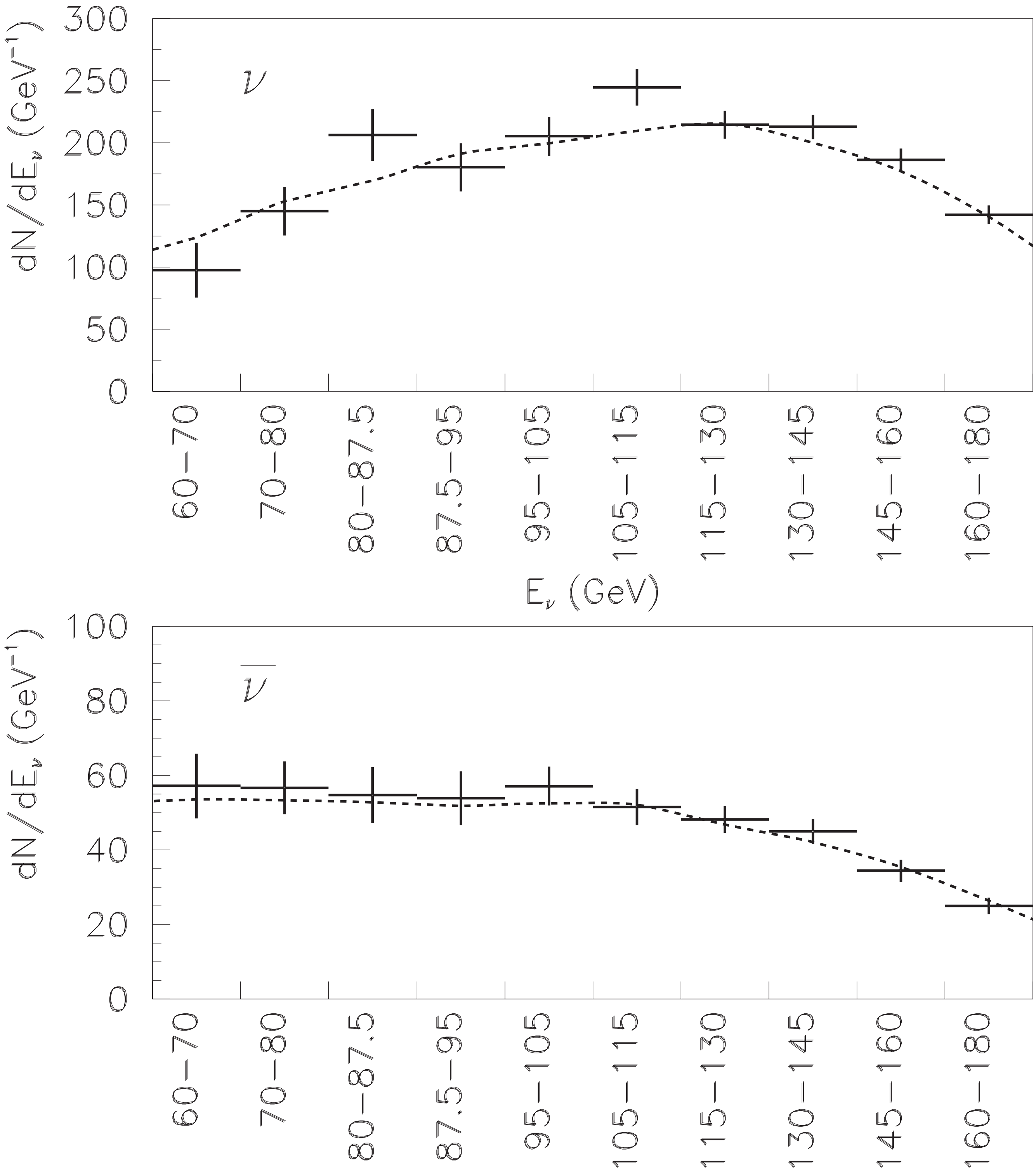
- Highest energy $\overline{\nu}_\mu$ (and ν_μ) show an excess in data
  - From high p, high p_t $K^\pm$ in beam
- These $K^\pm$ produce highest energy $\overset{(-)}{\nu}_e$'s

Direct ν_e Measurement (η)



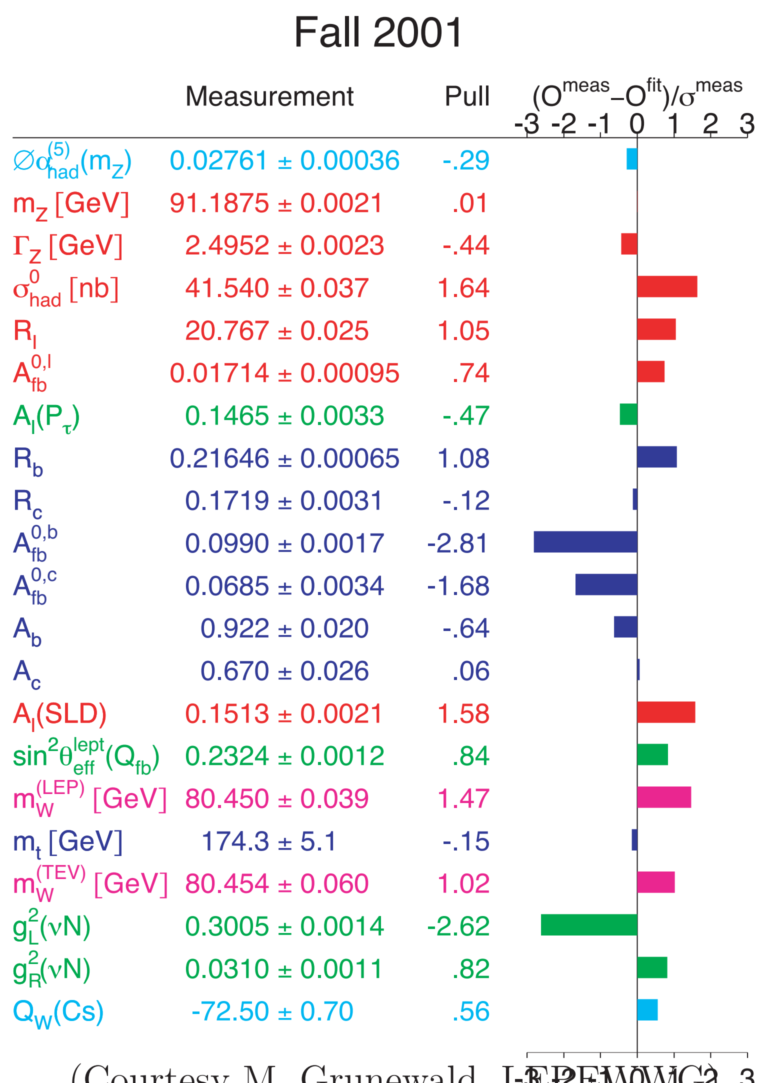
Thesis of Sergei Avvakumov (Rochester)

- ν_e showers develop more quickly than ν_μ showers because of electron
- Fit to hadron shower from ν_μ events and electrons from Monte Carlo tuned on calibration beam
- Constrains (mostly) $K^{\pm}_{e3}$ at moderate energy ($80 < E_\nu < 180$ GeV)
- $N_{\rm meas}/N_{\rm pred}$: 1.05 ± 0.03 (ν_e), 1.01 ± 0.04 ($\overline{\nu}_e$)



dN/dE$_\nu$ (GeV^{-1})
ν
300
250
200
150
100
50
0
60−70
70−80
80−87.5
87.5−95
95−105
105−115
115−130
130−145
145−160
160−180
E$_\nu$ (GeV)
dN/dE$_\nu$ (GeV^{-1})
$\bar{\nu}$
100
80
60
40
20
0
60−70
70−80
80−87.5
87.5−95
95−105
105−115
115−130
130−145
145−160
160−180

SM Fit with $(g_L^{\text{eff}})^2$ and $(g_R^{\text{eff}})^2$



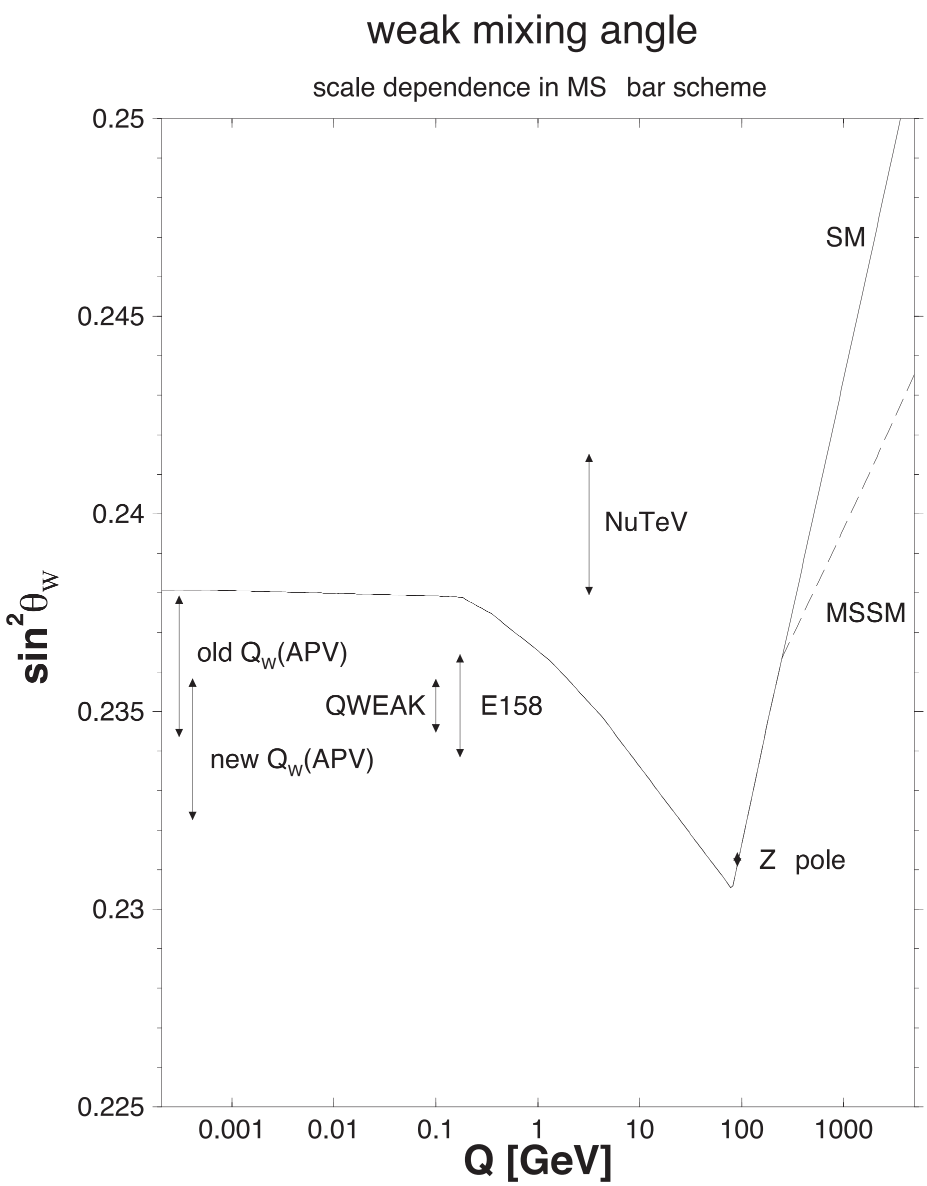
(Courtesy M. Grunewald, LEP EWWG)

Without NuTeV: $\chi^2/\text{dof} = 21.5/14$, probability of 9.0%

With NuTeV: $\chi^2/\text{dof} = 29.1/16$, probability of 2.3%

Upper m_{Higgs} limit weakens slightly

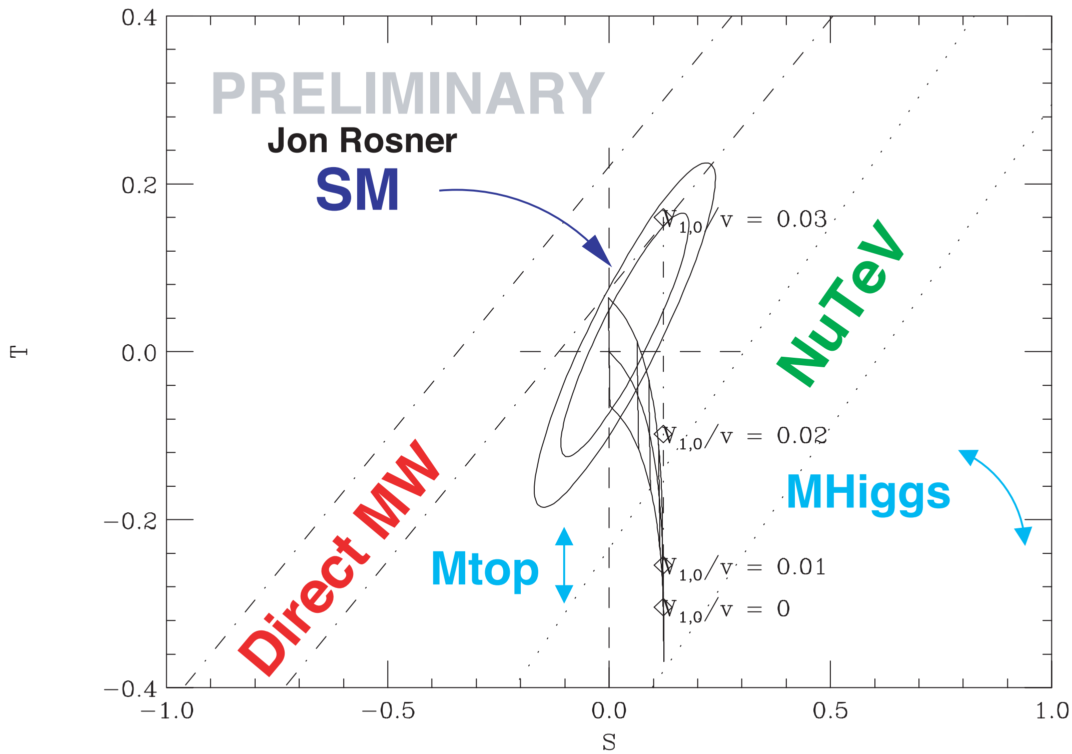
Running of $\sin^2\theta_W$



(Jens Erler and Paul Langacker)

- E158, Q_{weak} (JLab) numbers are projected uncertainties
- "old" APV is Bennett and Wieman with corrections
- "new" APV is Bennett and Wieman, with "new" corrections

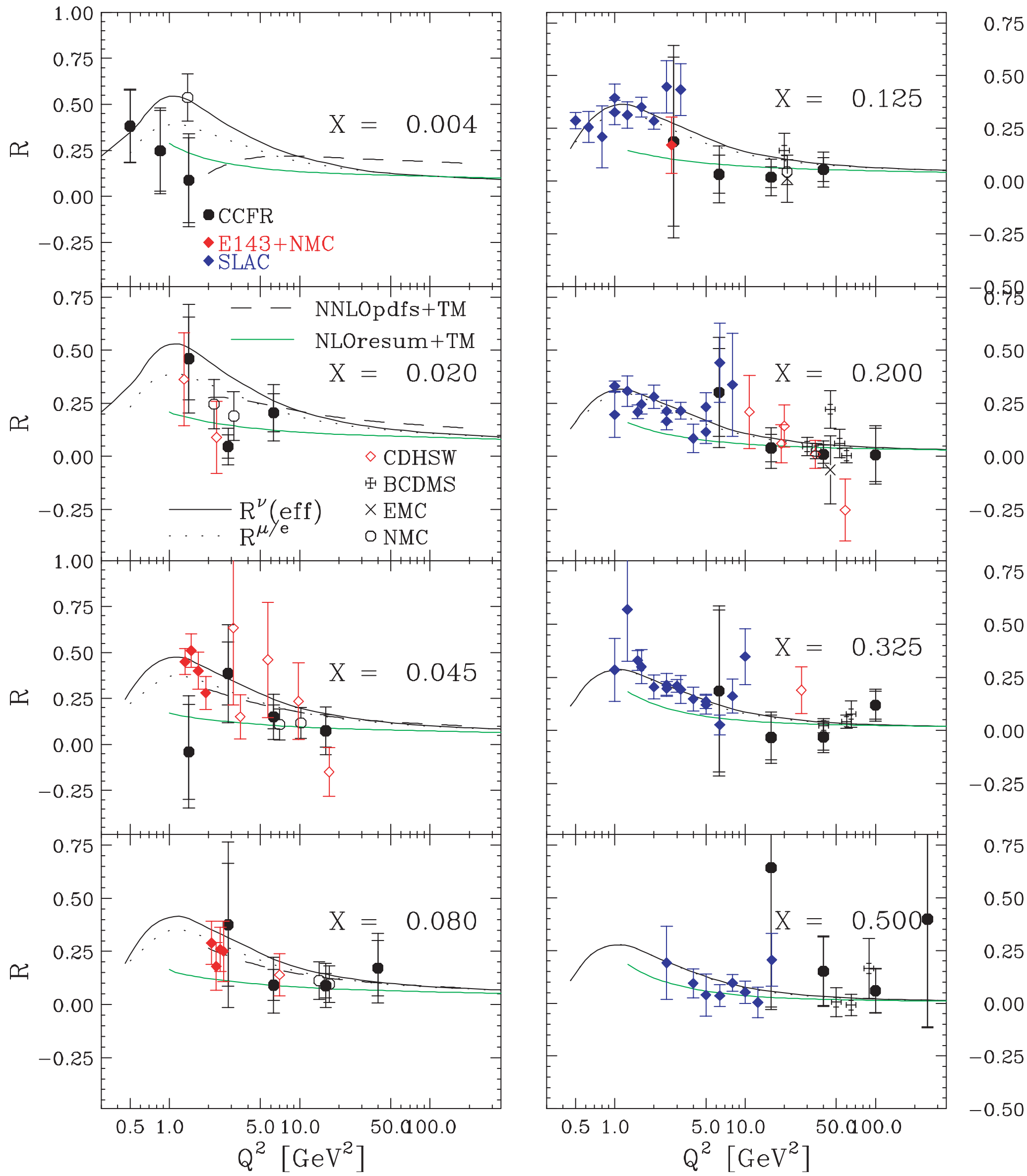
S-T Plane



(See: J. Rosner, hep-ph/0109239 v2 November 23, 2001)

- S and T parameterize oblique radiative corrections (sensitive to all forms of new physics)
- T parameter contains $\delta\rho$ effects
- S parameter modifies relationship between masses and couplings
- Note lack of overlap between direct M_W and NuTeV

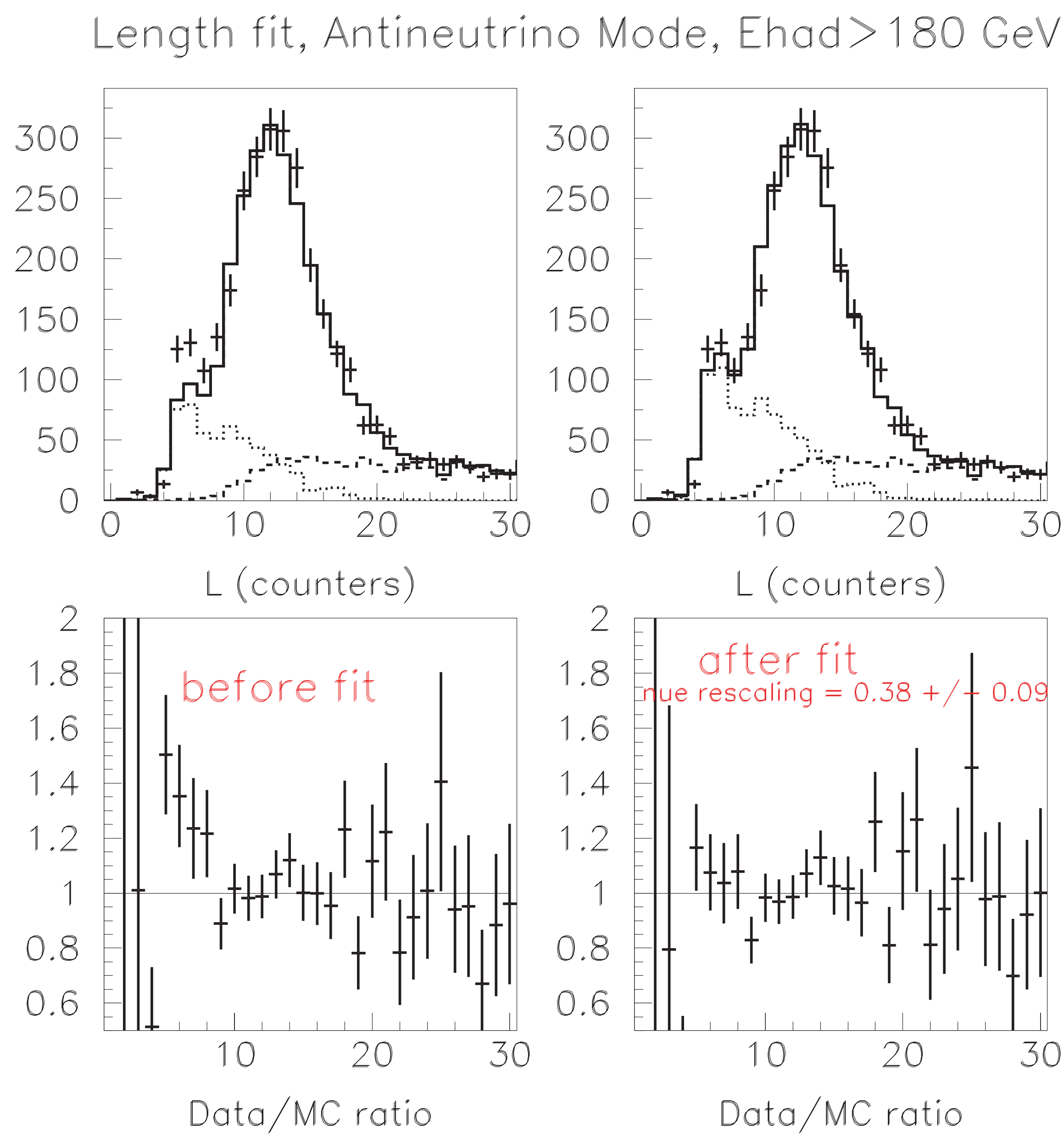
R_L

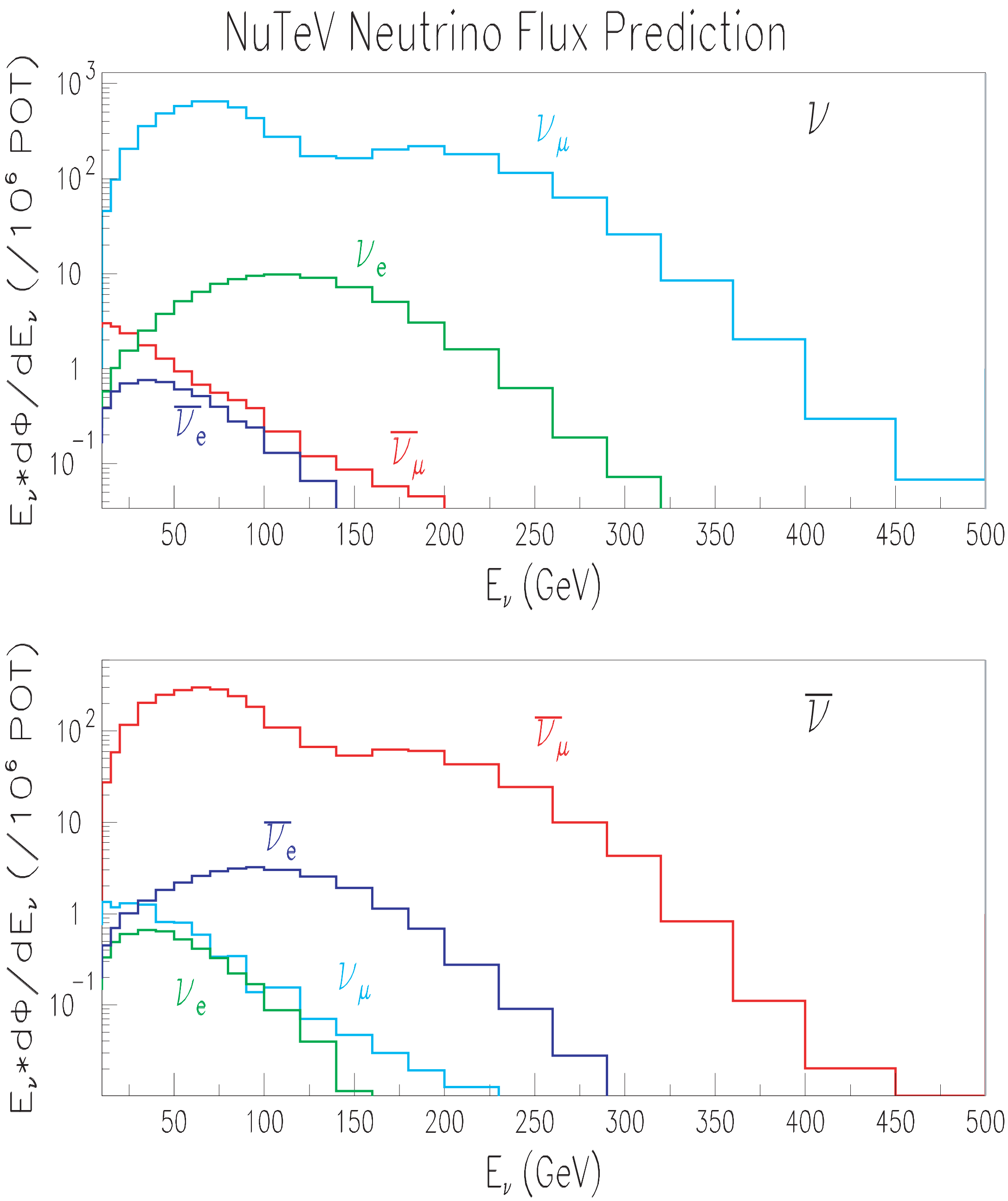


- Vary $R_L = F_L/F_T$ within data errors at low x
- At high x, where theoretical prediction of R_L is reliable, take NNLO-NLO difference as systematic
- Important for prediction of high y cross-section

Direct High Energy ν_e Flux

- Extremely short events at very high visible energy are very likely to be nearly-elastic electron neutrino charged-current interactions
- Observe significant excess in both beams over MC prediction

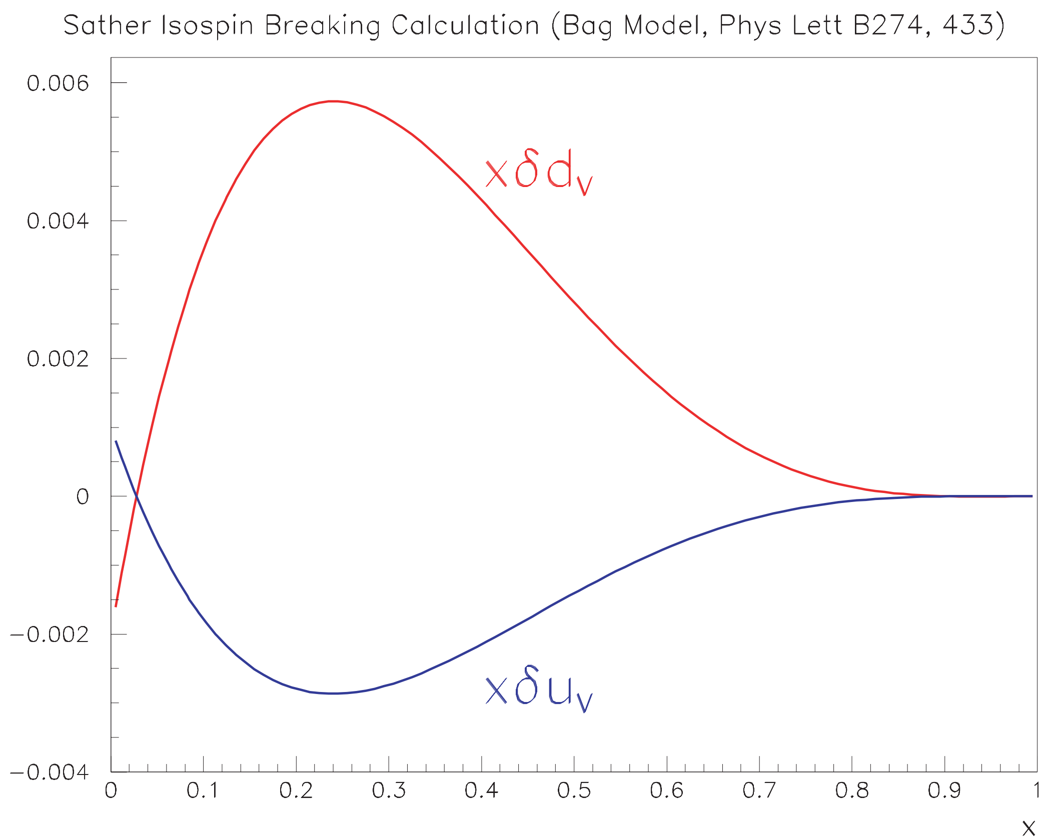




$E_\nu > 180$ GeV is tail of flux

Sather Nucleon Isospin Breaking Model

- Estimate of diquark mass difference in MIT bag model
- Calculated at $Q^2 = 0$ and evolved to experimental Q^2



$$u_v^p - d_v^n = \delta u_v \qquad d_v^p - u_v^n = \delta d_v$$

$$\begin{aligned} \int x\delta d_v dx &= 0.0023 \\ \int x\delta u_v dx &= -0.0011 \end{aligned}$$

- To shift the NuTeV $\sin^2\theta_W$ to agree with prediction would an effect $\approx 2.5\times$ larger than Sather's

R^- and Isospin-Breaking

Isospin breaking occurs in
proton, nucleon and nuclear PDFs

1. In proton PDFs

$$\begin{aligned} u_v^p &\neq d_v^p \quad (F_2^d/F_2^p) \\ \overline{u}^p &\neq \overline{d}^p \quad (\mathrm{NUSEA\ Drell-Yan}) \end{aligned}$$

These enter in R^- when target is not $n \leftrightarrow p$ isoscalar
(NuTeV, 5.67% n excess)

2. In nucleon or nuclear PDFs

$$\begin{aligned} u_v^p \neq d_v^n, &\quad d_v^p \neq u_v^n \\ \overline{u}^p \neq \overline{d}^n, &\quad \overline{u}^n \neq \overline{d}^p \end{aligned}$$

i.e., move d quarks to higher x and u quarks to lower x or vice versa

These enter in R^- event for $Z = N$ target
($m_d \neq m_u$ in nucleon, Coulomb in nucleus
both thought to be small)

R^- and Isospin-Breaking (cont'd)

Write

$$\Delta N = \frac{A-2Z}{A}$$
$$\delta D_v = \frac{\int x(d_v^p - u_v^n)dx}{\int x(u_v^p + d_v^p)dx} \quad (\text{analogous } \delta U_v)$$
$$\delta \overline{D} = \frac{\int x(\overline{d}^p - \overline{u}^n)dx}{\int x(\overline{u}^p + \overline{d}^p)dx} \quad (\text{analogous } \delta \overline{U})$$

Then, for $\overline{s}$, $\overline{c} = 0$,

$$R^- \approx \frac{1}{2} - \sin^2\theta_W + \left[\frac{\int x(u_v^p - d_v^p)dx}{\int x(u_v^p + d_v^p)dx}\right]\left(\frac{7}{3}\sin^2\theta_W - 1\right)\Delta N + \left(\frac{1}{2} - \frac{7}{6}\sin^2\theta_W\right)(\delta U_v - \delta D_v)\,.$$

No dependence on $\delta\overline{U}, \delta\overline{D}$, $\frac{\int x(\overline{u}^p - \overline{d}^p)dx}{\int x(\overline{u}^p + \overline{d}^p)dx}$.

At NuTeV $\langle Q^2 \rangle$,

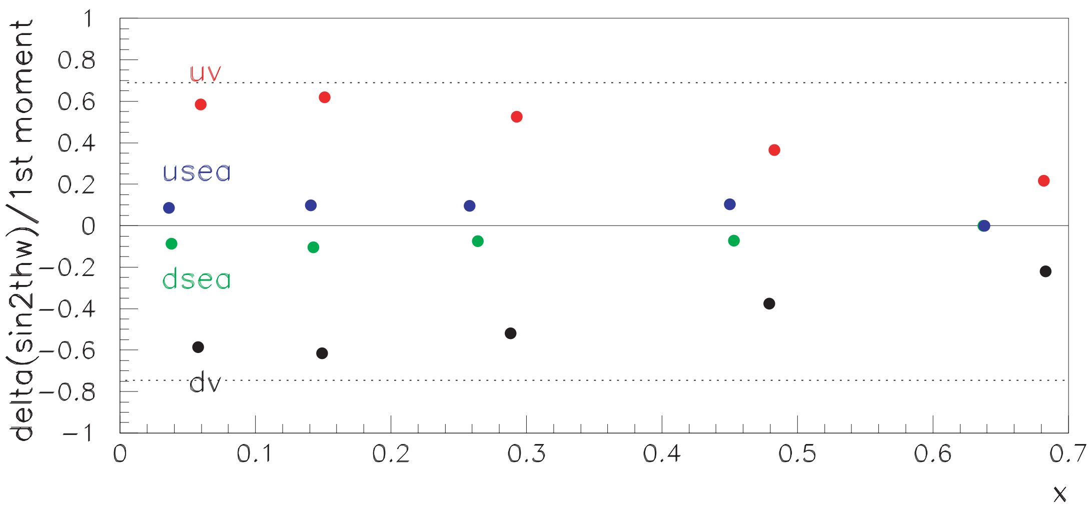
$$\int x(u_v^p + d_v^p) = .333; \quad \int x(\overline{u}^p + \overline{d}^p) = .063$$

R^- and NuTeV Result

NuTeV's $\sin^2\theta_W$ measurement isn't exactly sensitive to

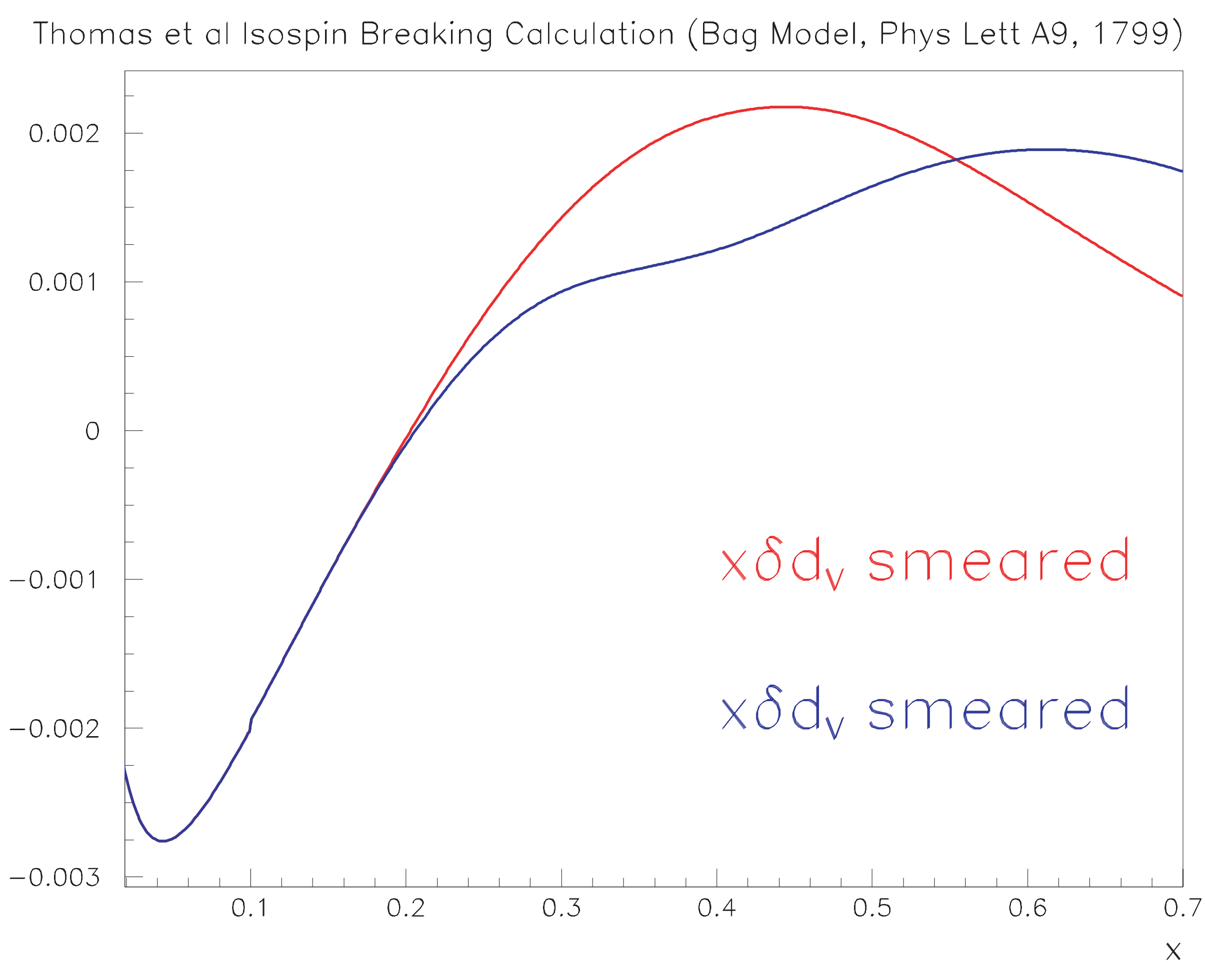
$$0.72 \times (\delta d_v - \delta u_v) = \int x\,[(d_v^p - u_v^n) - (u_v^p - d_v^n)]\,dx$$

$d\sin^2\theta_W/d\delta q$



Thomas *et al.* Nucleon Isospin Breaking Calculation

- Effect of d-u mass difference evaluated in MIT bag model
- Full calculation includes: nucleon mass difference, nucleon radius difference, quark and diquark mass difference



$$\int x(d_v^p - u_v^n)dx \; = \; 0.0006$$

Comparison of Isospin Breaking Models

- MIT Bag Model:
  Sather estimate and Thomas *et al.* full calculation
- Meson cloud model