Studies of Strong and Weak Interactions at CCFR/NuTeV

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Standard Model

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Studies of **Strong** and *Weak* Interactions at CCFR/NuTeV

1. Overview
   - Why test the Standard Model with neutrinos?
2. Measurement of α_s
   - Evolution of Structure Functions
   - Gross Llewellyn-Smith Sum Rule
3. Precision Electroweak Measurements
   - Measurement of $\sin^2\theta_W \;\Rightarrow\; M_W$
   - Physics Beyond the Standard Model
4. Conclusions

CCFR and NuTeV Collaborations

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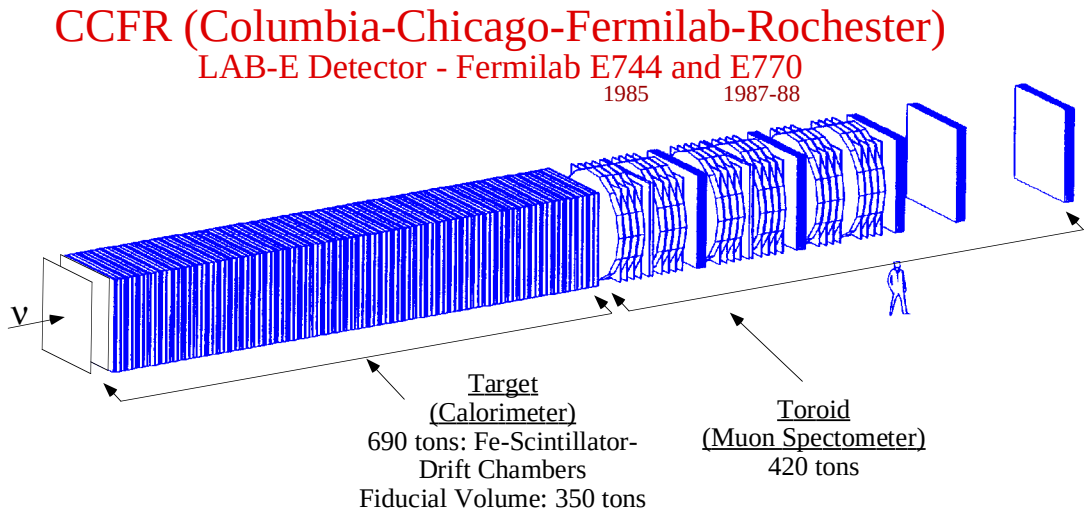
νN Deep Inelastic Scattering at CCFR/NuTeV

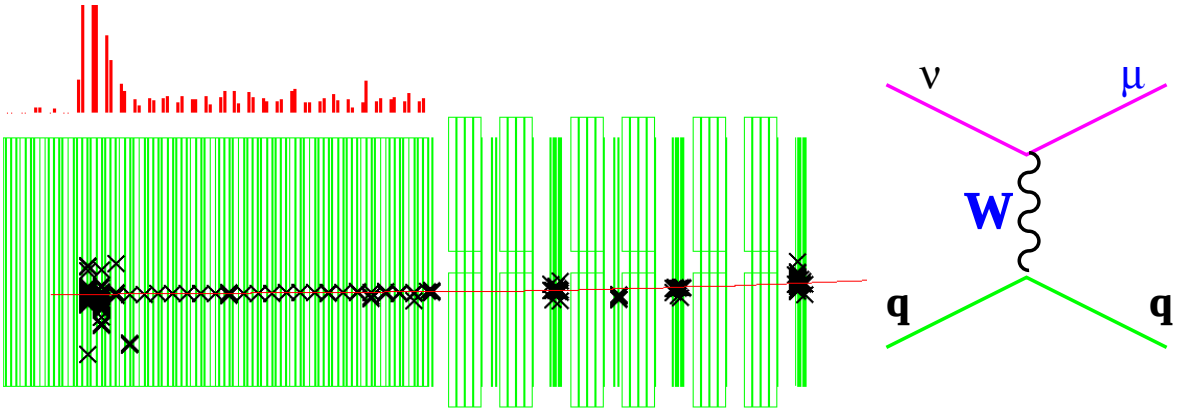


- Neutrino interacts in target calorimeter
- Calorimeter has unsegmented scintillator and drift chambers
- Toroidal Spectrometer for muons ($\nu_\mu N \to \mu^- X$)

CCFR/NuTeV are part of a long-running Fermilab neutrino program

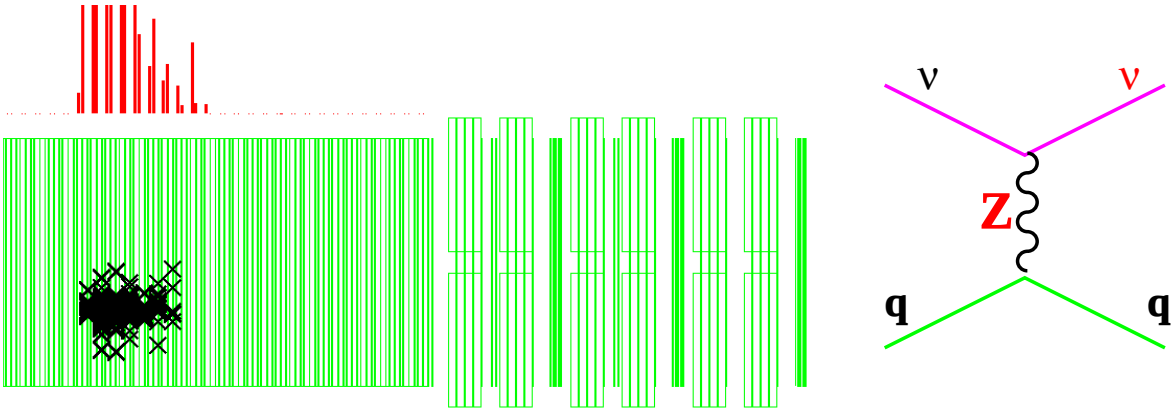
Beam	$\nu_\mu/\overline{\nu}_\mu$	Analyzed $\nu_{CC}/\overline{\nu}_{CC}$	$\langle E_\nu \rangle$	ν_e,$\overline{\nu}_e$
CCFR QT	simultaneous	1270K/270K	160 GeV	2.3%
NuTeV SSQT	separate	1500K/385K	140 GeV	1.8%

Neutrino Reconstruction

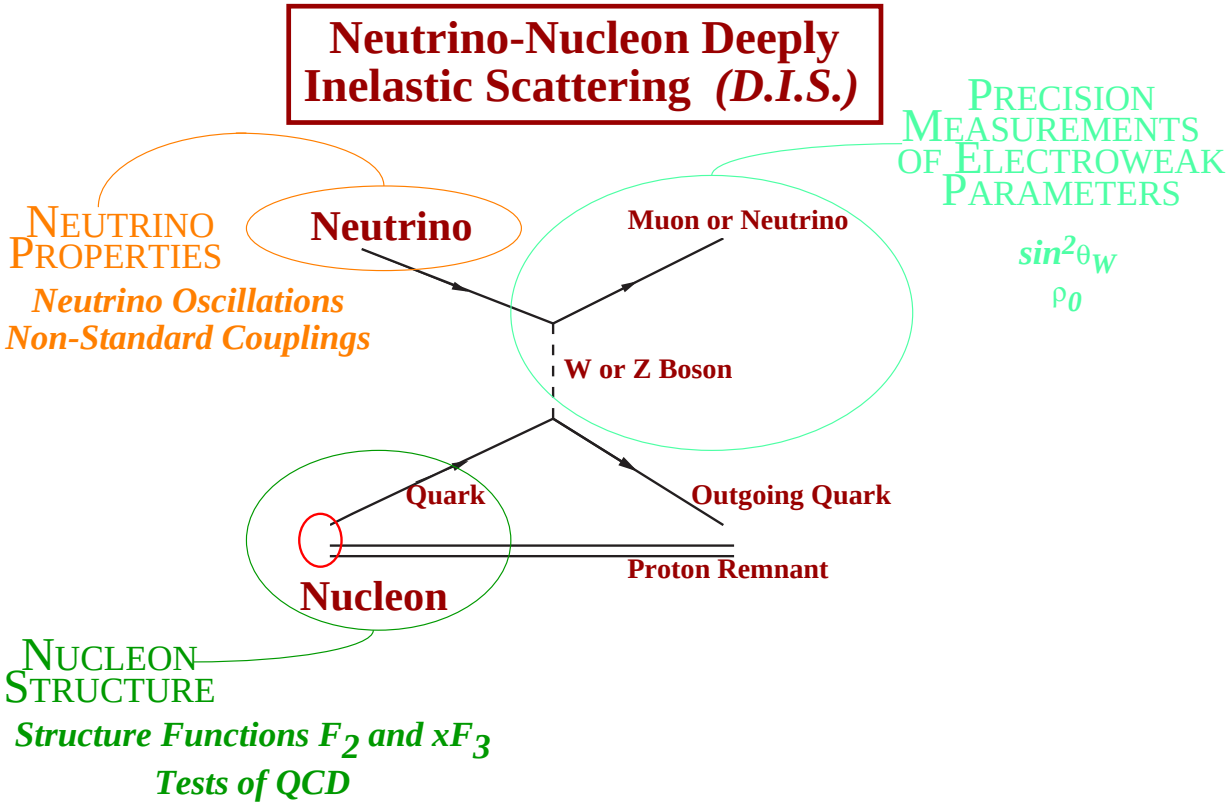


- Hadronic energy (struck quark) from calorimeter scintillator
- Vertex, Muon angle from calorimeter tracking
- Absence of muon from calorimeter ($\nu_\mu N \to \nu_\mu X$ signature)
- Muon momentum from toroid tracking

$$
\begin{aligned}
Q^2 &= (E_{\rm had} + E_\mu) E_\mu {\theta_\mu}^2 \\
W^2 &= 2 M_N E_{\rm had} \\
&\quad - M_N^2 - Q^2 \\
x &= \frac{(E_{\rm had} + E_\mu) E_\mu {\theta_\mu}^2}{2 M_N (E_{\rm had} - M_N)} \\
y &= \frac{(E_{\rm had} - M_N)}{(E_{\rm had} + E_\mu)}
\end{aligned}
$$



Physics Topics Accessible to CCFR/NuTeV



- α_s from . . .

  . . . evolution of F_2, xF_3 structure functions

  . . . $\int F_3$ (GLS Sum Rule)

- $\sin^2\theta_W$ from $\sigma_\nu^{NC}/\sigma_\nu^{CC}$

Capabilities at e^+e^-, ep and $p\overline{p}$ Colliders vs. CCFR/NuTeV: QCD Studies and Electroweak Physics

QCD

- νN kinematic range is limited

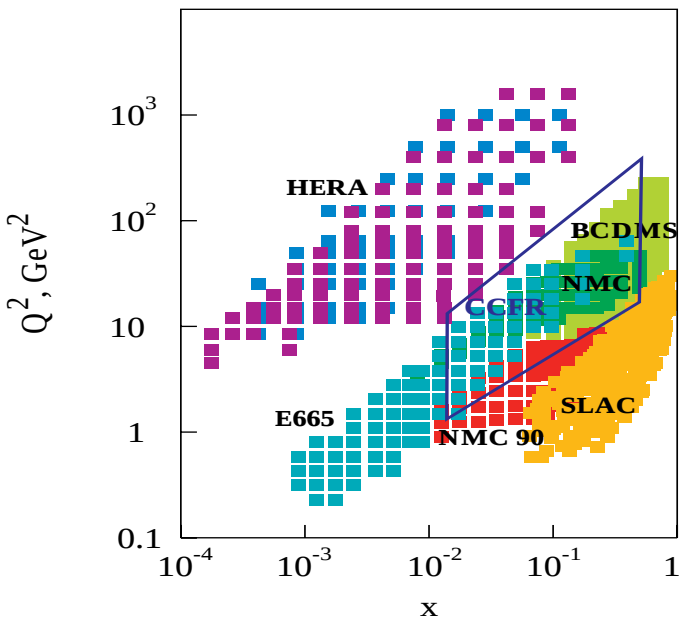
	x range	Q^2 range (GeV^2)
CCFR	$10^{-2} < x < 0.7$	$1 < Q^2 < 200$
HERA	$5 \times 10^{-4} < x < 1$	$3 < Q^2 < 30000+$
Tevatron	$10^{-2} < x$	$Q^2 < 250000$

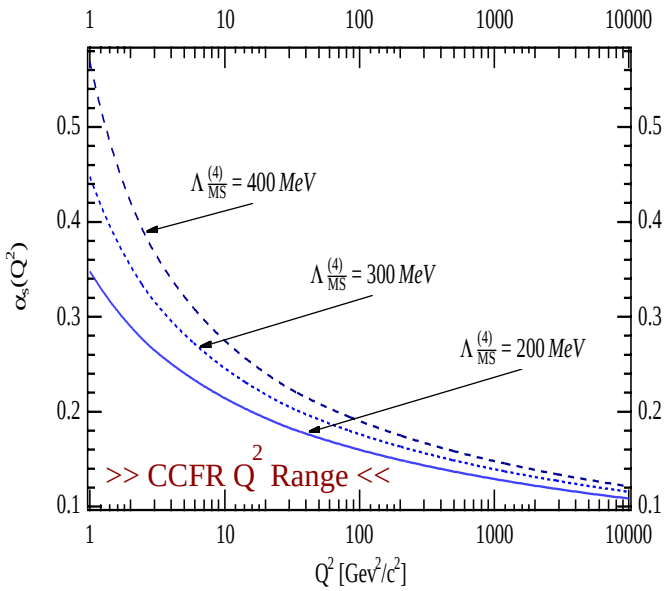
- νN ideal for α_s measurement
  - ▷ Cross-section flat in Q^2 (smearing)
  - ▷ Technique is inclusive $\rightarrow$ no $1/Q$ corrections
  - ▷ α_s largest at low Q^2!

Electroweak Physics

- νN sees everything in t-channel (low $\sqrt{s}$)
  - ▷ $p\overline{p}$, e^+e^- can produce W, Z on shell!
  - ▷ $p\overline{p}$, e^+e^-, $HERA$ weak cross-sections are high
- νN does have advantages...
  - ▷ Luminosities are $\mathcal{O}(10^6)$ pb^{-1}
  - ▷ Statistics comparable ($\mathcal{O}(10^6)$ events)
  - ▷ Background to new physics from Standard Model is low!

Kinematic Reach and Cross-Sections





Cross-Section and Structure Functions

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

LO pQCD ν-N Structure Functions (isoscalar target)

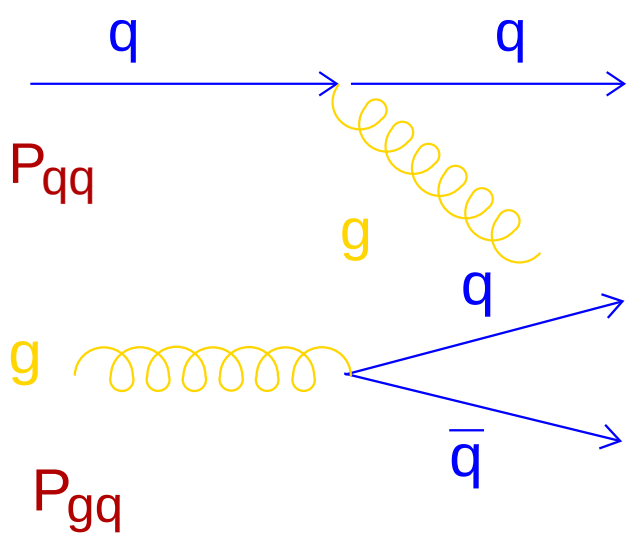
$$\begin{aligned} F_2^{\nu,\overline{\nu}} &= xq + x\overline{q} \\ xF_3^{\nu,\overline{\nu}} &= xq - x\overline{q} \pm 2(s-c) \\ \frac{1}{2}\left(xF_3^{\nu} + xF_3^{\overline{\nu}}\right) &= xu_v + xd_v \\ R_L^{\nu,\overline{\nu}} &= 0 + \mathcal{O}(\alpha_s) \end{aligned}$$

α_s and Scaling Violations of F_2, xF_3

$$F_2(x,Q^2) = x\int_x^1 dz\left[C_2^q\left(\frac{x}{z},Q^2\right)q_S(x,Q^2) + C_2^G\left(\frac{x}{z},Q^2\right)G(x,Q^2)\right]$$

$$F_3(x,Q^2) = \int_x^1 dz\left[C_3^q\left(\frac{x}{z},Q^2\right)q_{NS}(x,Q^2)\right]$$

(At LO, $C_i^q \propto \delta(1-\frac{x}{z})$, $C^G = 0$)



$$\frac{dq_{NS}}{d\log(Q^2)} = \frac{\alpha_s(Q^2)}{\pi}\int_x^1[(P_{qq}(z)q_{NS}(z,Q^2)]dz$$

$$\frac{dq_S}{d\log(Q^2)} = \frac{\alpha_s(Q^2)}{\pi}\int_x^1[(P_{qq}(z)q_S(z,Q^2)+P_{qG}(z)G(z,Q^2)]dz$$

Measure Structure Functions from Cross-Sections and Extract α_s from their Scaling Violations

Measuring Structure Functions at CCFR

$$\frac{d\sigma^{\nu,\overline{\nu}}}{dy} \xrightarrow{y\to 0} E_\nu \times \text{constant}$$

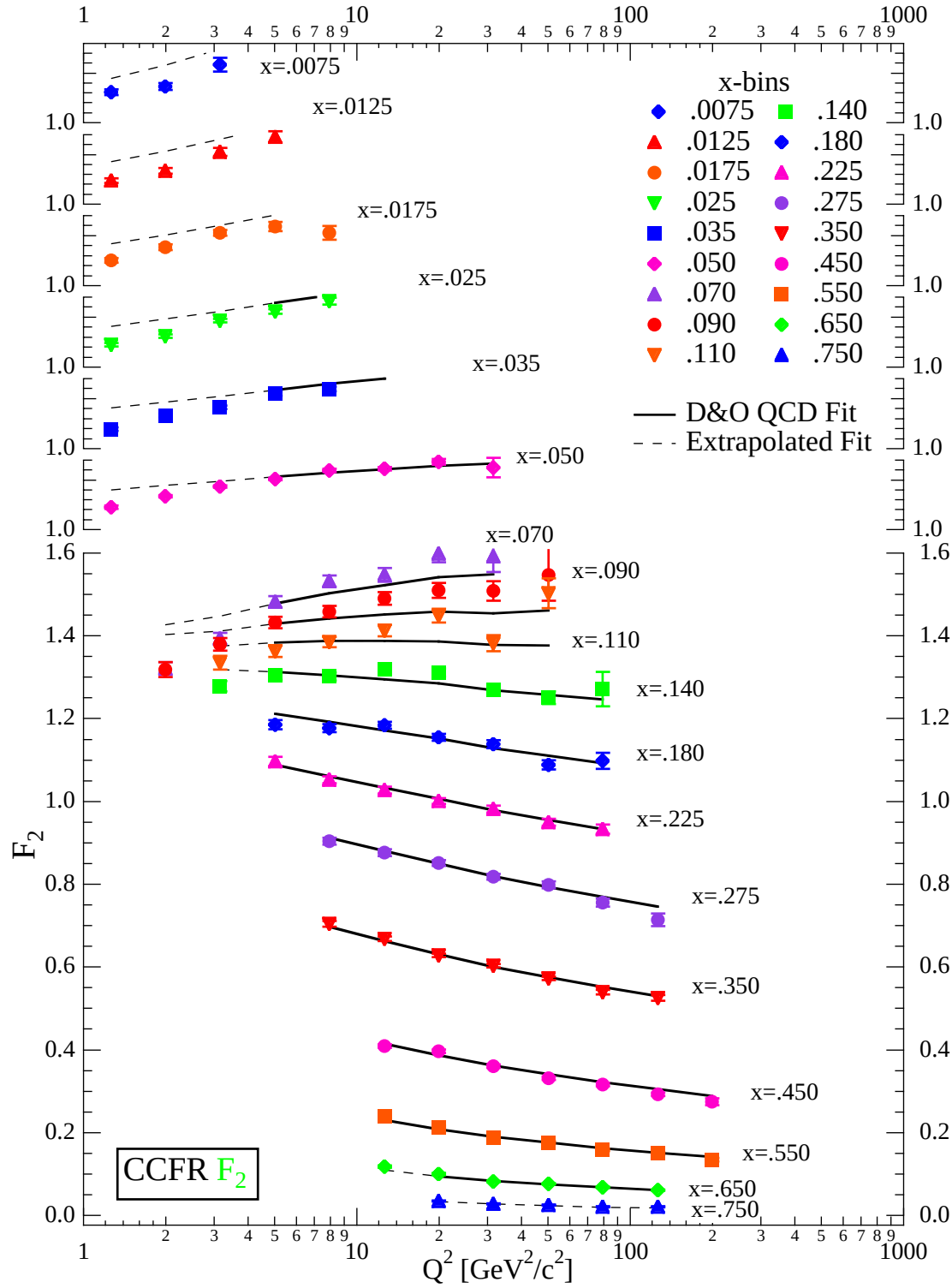
- Low y events are used to measure the flux
- All other events determine structure functions

Corrections:	Detector	Physics Model
	Acceptance	Bin-Center Correction
	Resolution smearing	Strange Sea
		Isovector target correction
		Charm production threshold
		Radiative correction
		Propagator correction (M_W)

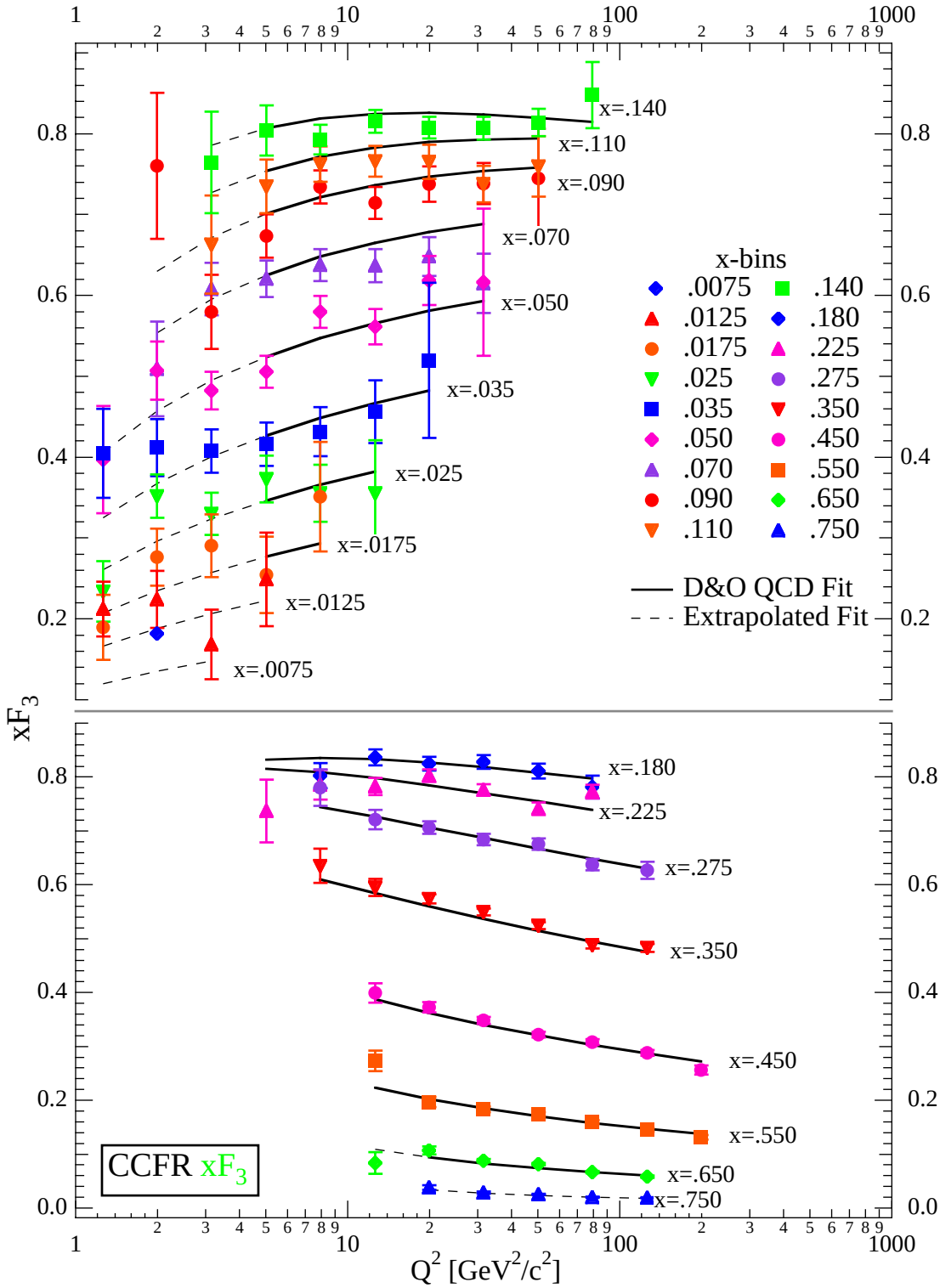
Why new Structure Functions
from CCFR (1985-1988) data?

- **New detector energy calibration**
- Improved radiative corrections (Bardin)
- Improved physics model corrections (R_L, strange sea)

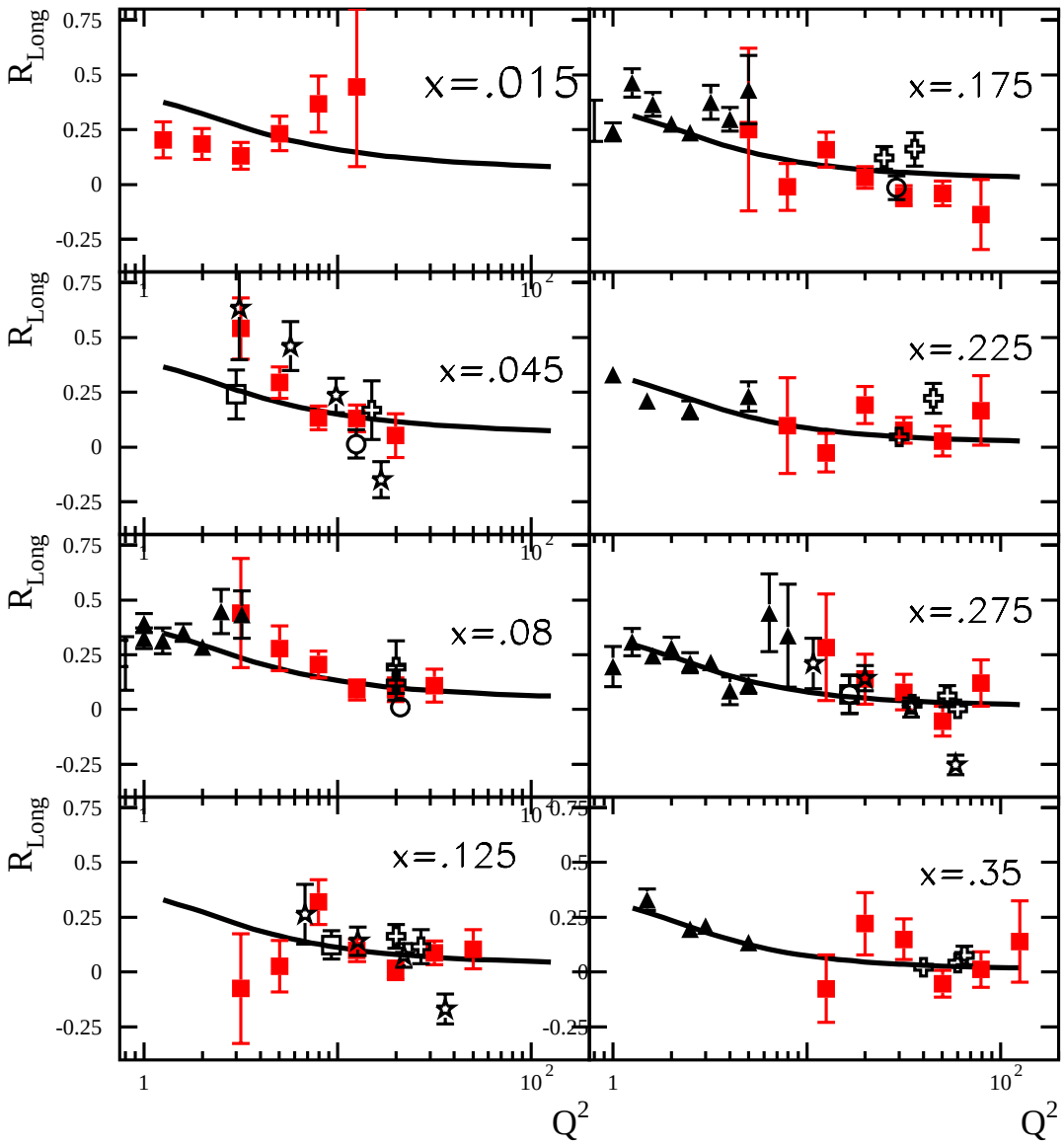
CCFR F_2 Structure Function



CCFR xF_3 Structure Function



CCFR R_L (from fit to y distribution)



CCFR ■

CDHS ★ CHARM □ BCDMS ♯ SLAC ♠ (parameterization from Whitlow *et al.*, Phys. Lett. **B250**, 193)

CCFR NLO QCD fit to F_2, xF_3

Measured F_2, xF_3 $Q > 5$ GeV^2, $W^2 > 10$ GeV^2, $x < 0.7$

PDF Parameterization in x: q_{NS}, q_S, G at Q_0.
(Form of parameterization is varied as a check)

NLO P_{qq}, P_{Gq}, P_{GG}, C_i^q, C_2^G

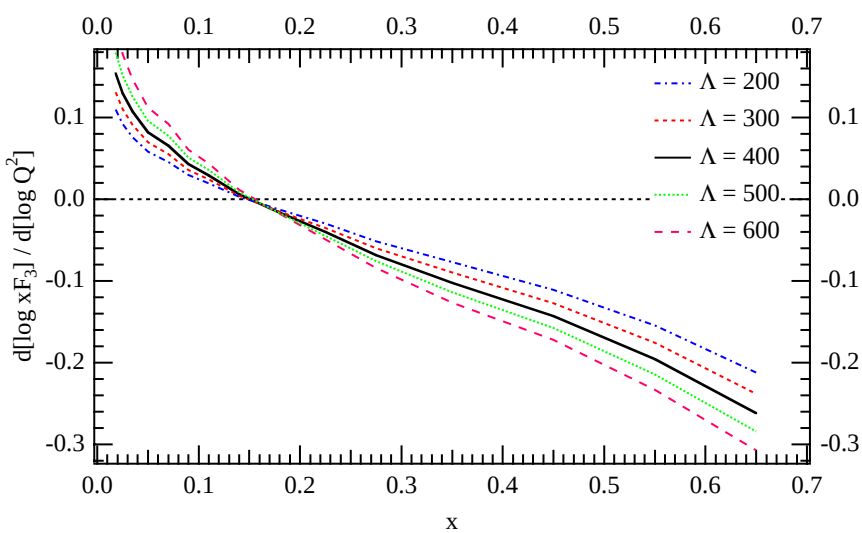
Target Mass Correction to F_2, xF_3 (Georgi-Politzer)

Higher Twist from renormalon-based calculation of $1/Q^2$ and $1/Q^4$ terms (Dasgupta and Webber)

- ΔF_2^{HT} made to agree with SLAC/BCDMS data
- ΔxF_3^{HT} then overestimated? (Sidorov)

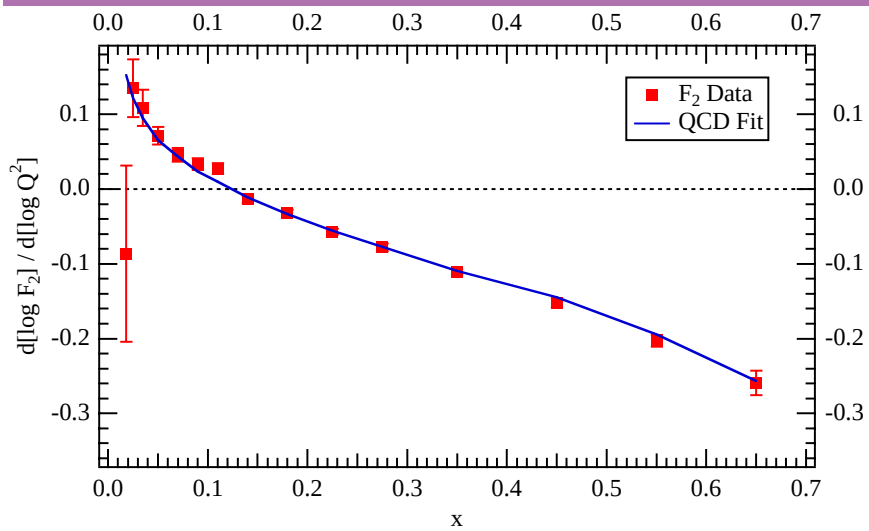
(Vary from full Dasgupta-Webber effect to no Higher-Twist)

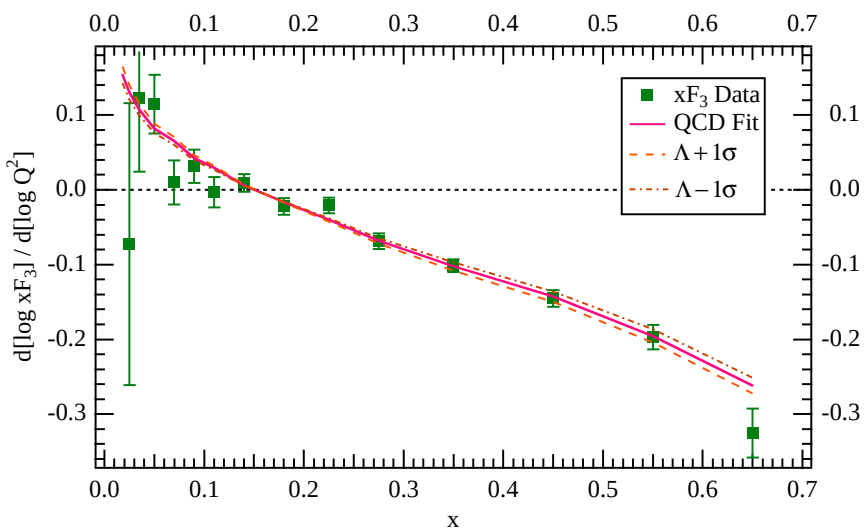
Experimental Systematics are determined by re-extracting F_2, xF_3 with $\pm 1\sigma$ from each source of uncertainty.



Logarithmic Slopes determine
agreement with NLO pQCD and $\Lambda_{\rm QCD}$

Results of NLO QCD fit to F_2, xF_3





$\underline{xF_3 \text{ only}}$

$\Lambda^{(4)\ NLO}_{\overline{MS}} = 387 \pm 42(\text{stat}) \pm 93(\text{syst})$, $\chi^2 = 81/82$ dof

$\underline{F_2 \text{ and } xF_3}$

$\Lambda^{(4)\ NLO}_{\overline{MS}} = 381 \pm 23(\text{stat}) \pm 51(\text{syst})$, $\chi^2 = 190/164$ dof

Good agreement with NLO pQCD...

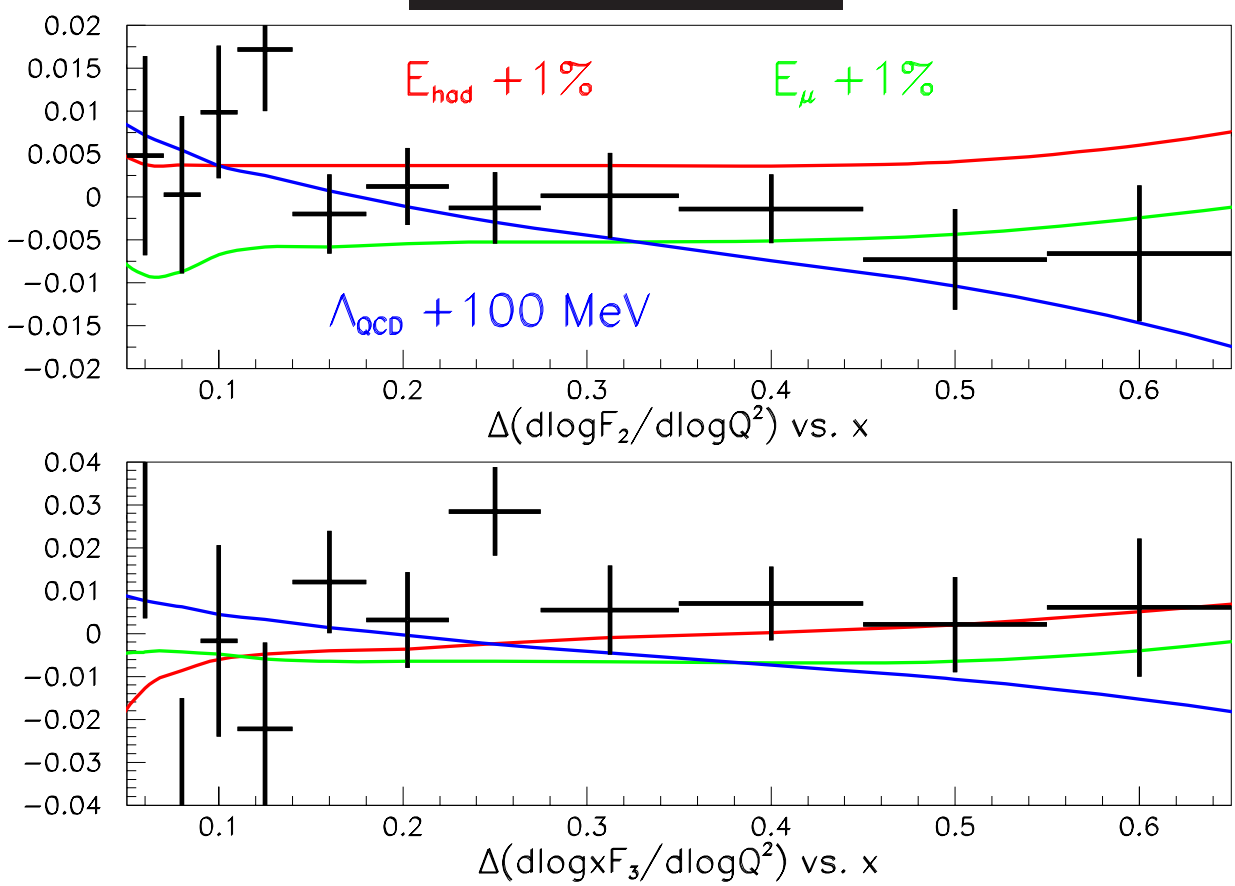
...can α_s precision be improved?

Systematic Uncertainties

Large experimental contributions

Systematic	Shift	$\delta(\Lambda_{\overline{MS}})$
Muon Energy	1%	32 MeV
Hadron Energy	1%	25 MeV
Hadron Energy shift	150 MeV	23 MeV

Systematic Fit



By assuming NLO pQCD is valid...

...can use it to separate systematics from Λ_{QCD}

Systematic Fit Results

xF_3 only

$\Lambda^{(4)\ NLO}_{\overline{MS}} = 381 \pm 53(\text{stat\&syst})$, $\chi^2 = 69/82$ dof

F_2 and xF_3

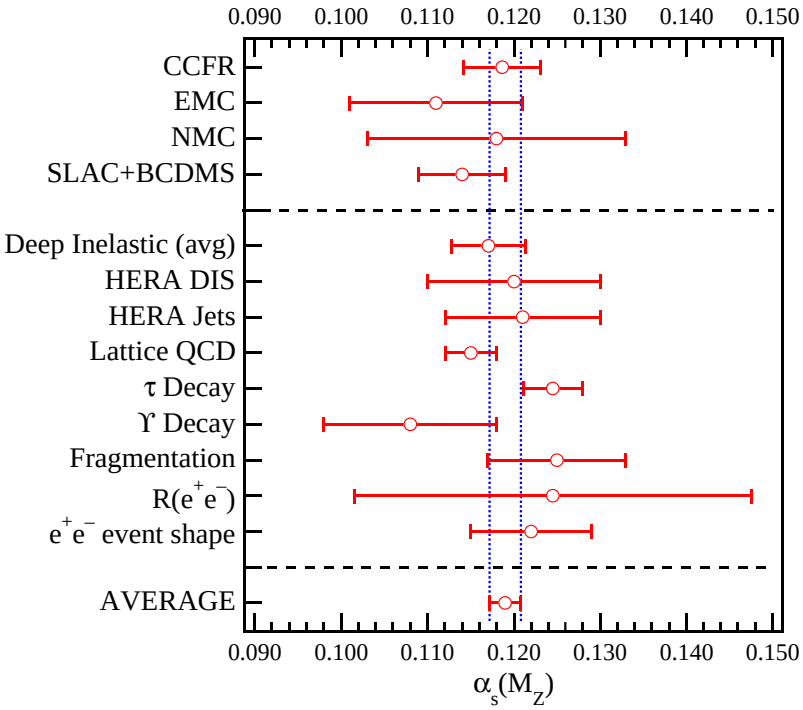
$\Lambda^{(4)\ NLO}_{\overline{MS}} = 337 \pm 28(\text{stat\&syst})$, $\chi^2 = 158/164$ dof

Systematic F_2/xF_3 fit pulls Λ by 44 MeV.
(largely from energy scale, offset)

CCFR Final $\Lambda^{(4)\ NLO}_{\overline{MS}} = 337 \pm 28(\text{exp}) \pm 13(\text{HT})$

$$\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{exp}) \pm 0.001(\text{HT}) \pm 0.004(\text{scale})$$

(renormalization and factorization scale error estimated by Martin, Roberts, Stirling, PLB266, 173; Virchaux, Milsztajn, PLB274, 221)



The Gross-Llewellyn-Smith Sum Rule

At Leading-Order, $xF_3 = xq - x\overline{q}$

$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3$$

Gross Llewellyn Smith Sum Rule

- ⇒ "Gold-plated" Prediction of QCD
- ⇒ Only Dependent on Valence Quark Distribution
- ⇒ Can be Measured Over Large Low Q^2 Range
- ⇒ QCD prediction done to O(α_s^3), O(α_s^4) estimated

$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3(1 - \frac{\alpha_s}{\pi} - a(n_f)(\frac{\alpha_s}{\pi})^2 - b(n_f)(\frac{\alpha_s}{\pi})^3) - \Delta HT$$

for $Q^2 = 3GeV^2$, $a \approx 3.3$, $b \approx 12$

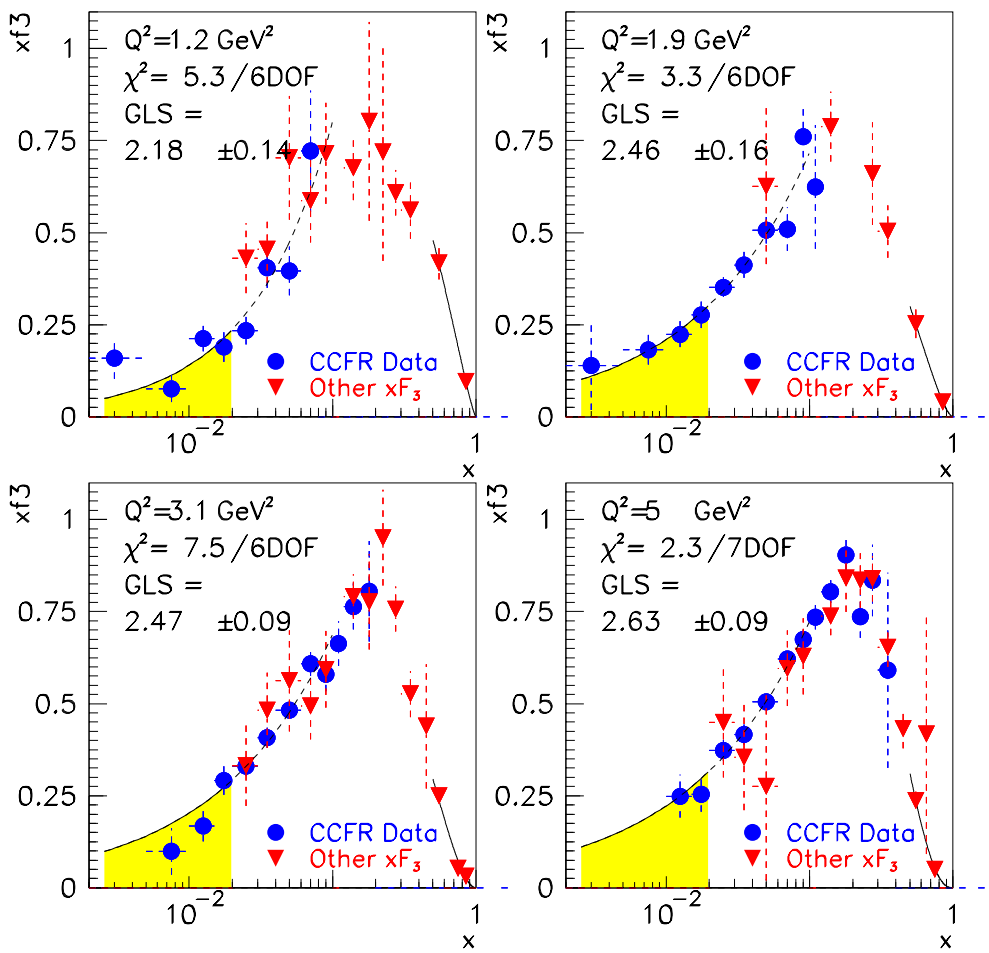
ΔHT = Higher Twist Corrections ($\frac{0.27\pm0.14}{Q^2}$)

Ref: Braun & Kolesnichenko, *Nucl. Phys.* **B283** (1987)

GLS Sum Rule(Q^2) ⇒ $\alpha_s(Q^2)$ → evolve to $\alpha_s(M_Z^2)$

xF_3 vs x at low Q^2

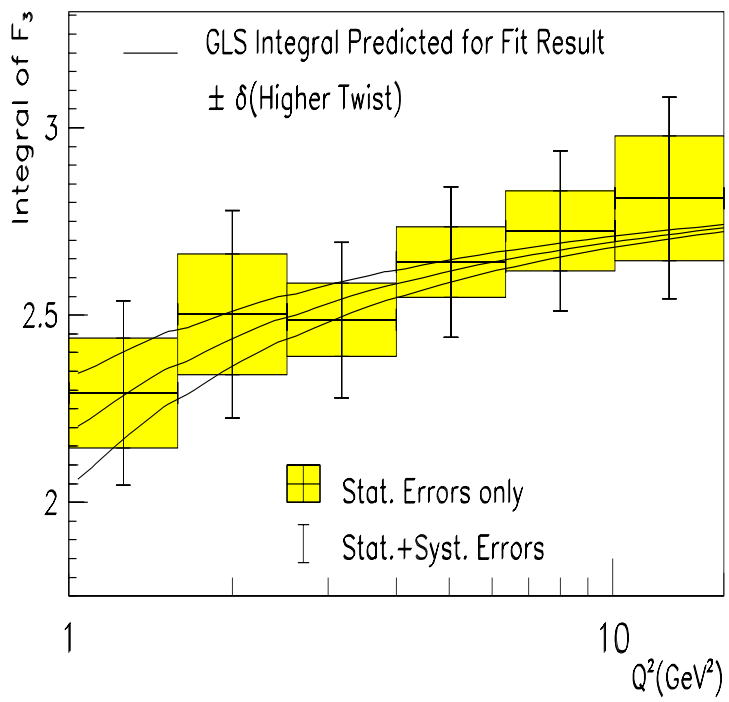
CCFR can measure to $x \sim 0.01$ below Q^2 of 5 GeV^2...
...but cannot access *all* x at these low Q^2



- Use other low energy $\nu-$N DIS data to fill in high x at low Q^2
  WA59, WA25, SKAT,FNAL-E180, BEBC-Gargamelle
- Data fit to power-law for $x < 0.1$ and for $x > 0.5$
- Integrate using the fits for $x < 0.02$ and $x > 0.5$

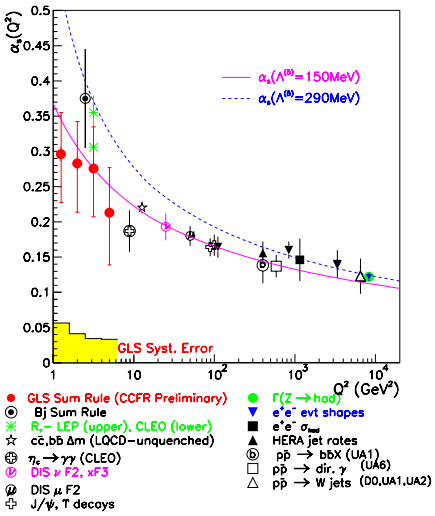
Preliminary α_s from GLS

Source of Uncertainty	$\delta\alpha_s(M_Z^2)$	
Statistics	0.005	
Experimental Systematics	0.011	*PRELIMINARY, will reduce by 50%*
Renormalization Scale	0.001	*NNNLO!*
Higher Twist	0.005	



$$\alpha_s(M_Z^2) = 0.112^{+0.004}_{-0.005}(\text{stat})^{+0.010}_{-0.011}(\text{syst})^{+0.004}_{-0.005}(\text{HT})$$

The World's α_s Measurements



1995

An α_s crisis?

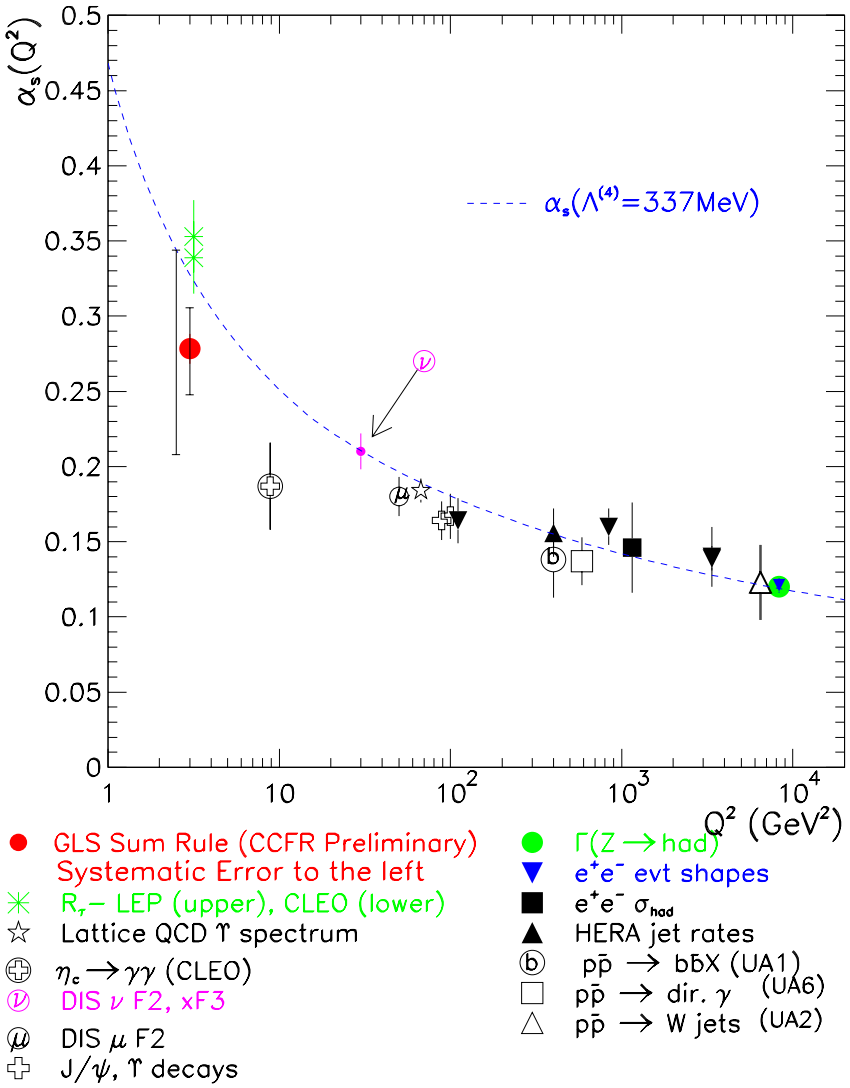
1997

An impressive verification of the running of α_s over four decades in Q^2

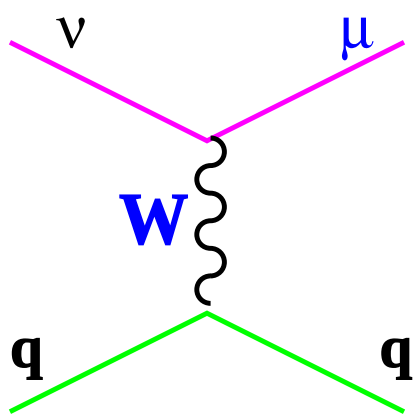
In CCFR α_s, scale error dominates (more so in NuTeV!)

$\Downarrow$

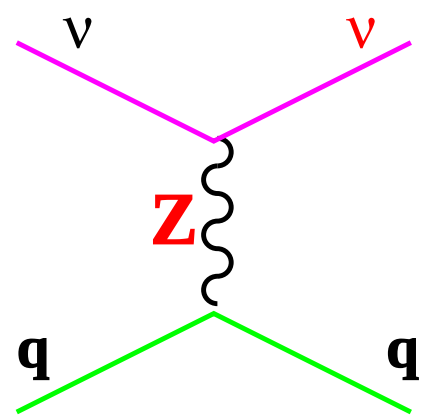
need NNLO calculation



Precision Tests of Electroweak Standard Model at CCFR/NuTeV



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



Coupling $\propto$ $I^{(3)}_{\text{weak}} - Q_{\text{em}} \sin^2\theta_W$

Llewellyn Smith Formula (for isoscalar targets)

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

Corrections

Massive quarks (m_c,$\overline{s}$,$\overline{c}$)

R_L

Radiative Corrections

Lepton, Target Mass

Isovector Target

1-loop Electroweak Corrections

$R_\nu \sin^2\theta_W \approx \sin^2\theta_W{}^{(\text{on-shell})}$,

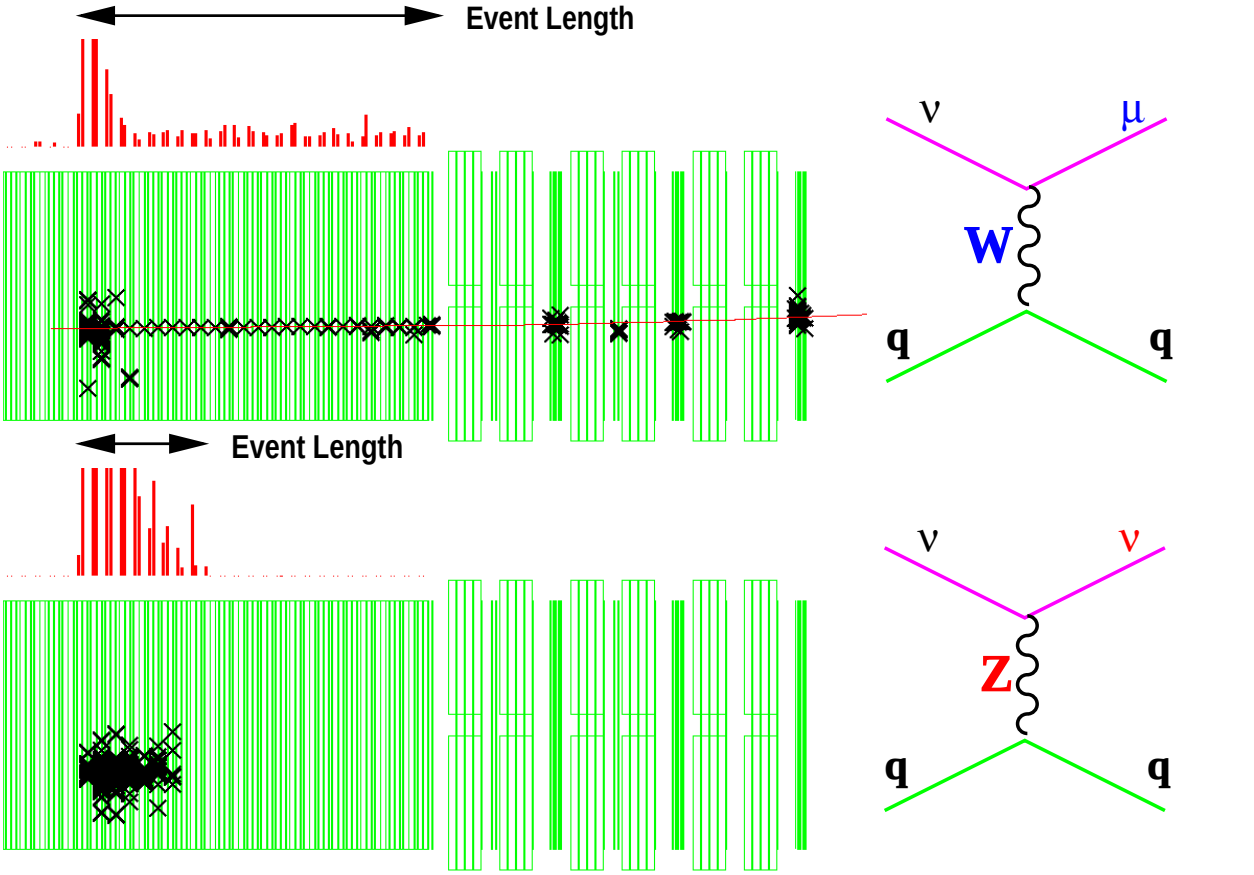
almost independent of m_t, m_H.

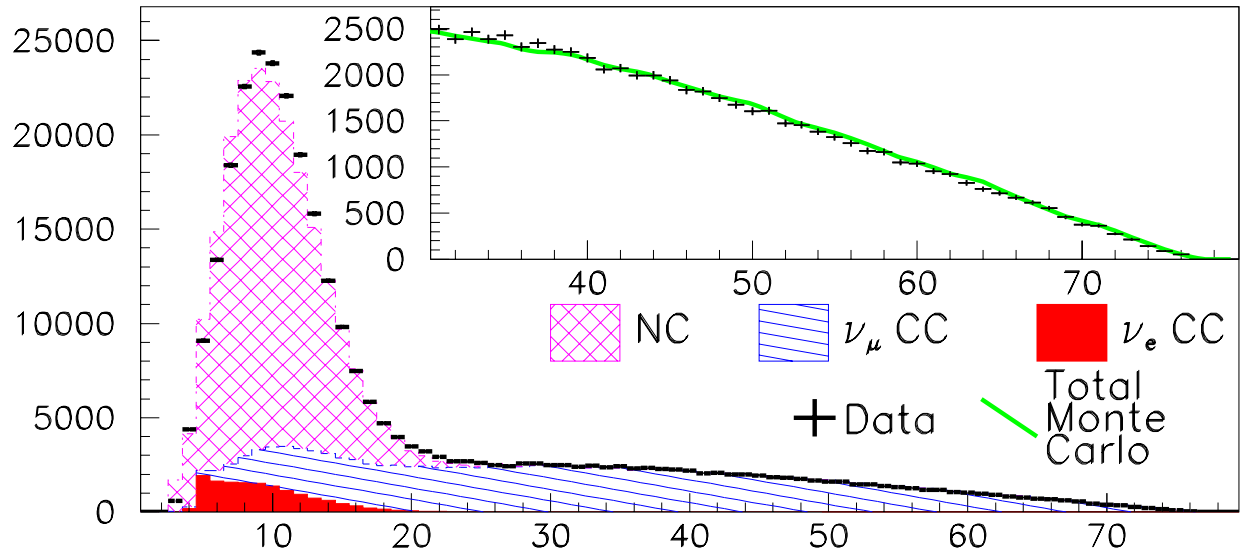
For CCFR, $\mathcal{O}(\alpha)$ correction to $\sin^2\theta_W$ is 0.0020 ± 0.0009.

($150 < m_t < 200$ GeV,

$60 < m_H < 1000$ GeV)

Neutral Current/Charged Current Separation

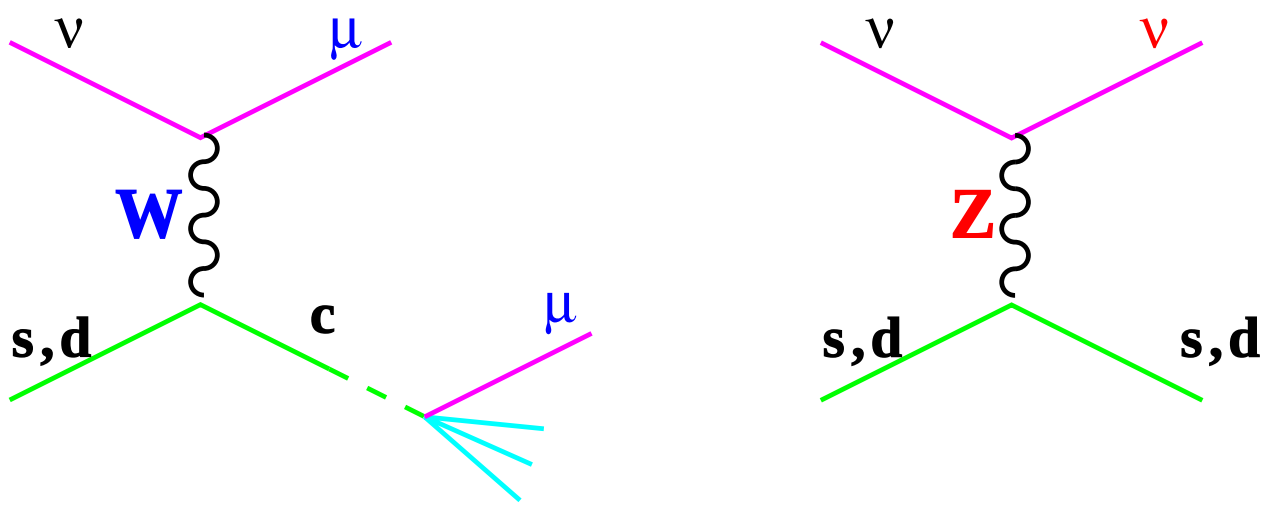




Event Length

Systematic Uncertainties in $\sin^2\theta_W$

1. Charged-Current Production of Charm



- Modeled by leading-order slow-rescaling
- Parameters of the model measured by CCFR in dimuon events ($c \to \mu X$) (S. Rabinowitz, A. Bazarko)
- $m_c = 1.31 \pm 0.24$ GeV, $\kappa = 0.37 \pm 0.05$

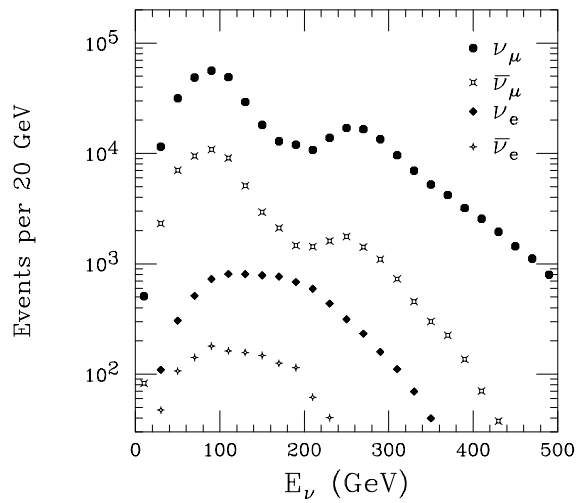
remaining uncertainty still large...

$$\ldots \delta \sin^2\theta_W = 0.0027$$

Systematic Uncertainties (cont'd)

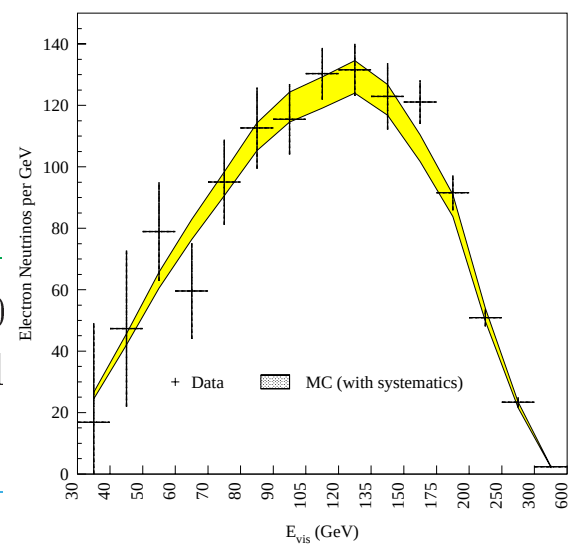
2. Electron Neutrino Content of Beam

- 80% of ν_e's from $K^{\pm}_{e3}$ decay which is constrained by observed $K^{\pm}_{\mu 2}$ spectrum
- 16% from K_{Le3} decays; large (20%) production uncertainty



- 4.1% uncertainty in number of ν_e's from Monte Carlo

- Also measured independently to 3.5% in E770 by studying longitudinal shower development
  A. Romosan *et al.*, to appear in PRL



- Average methods $\Longrightarrow$ 2.9% fractional uncertainty

$\ldots \delta \sin^2 \theta_W = 0.0015$

$\sin^2\theta_W$ from CCFR

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$
STATISTICAL ERROR	**0.0019**
ν_e flux (4.2%)	0.0015
Event Length	0.0010
Energy Measurement	0.0005
Transverse Vertex	0.0004
TOTAL EXP. SYST.	**0.0019**
Charm Production ($m_c = 1.31 \pm 0.24$ GeV)	0.0027
Higher Twist	0.0010
Charm Sea	0.0006
TOTAL PHYSICS MODEL	**0.0030**
TOTAL UNCERTAINTY	**0.0041**

$$\begin{aligned}\sin^2\theta_W{}^{(\text{on-shell})} &= 0.2236 \pm 0.0041 \\ &\quad +0.0006 \times (m_{\text{top}}^2 - (175\text{ GeV})^2)/(100\text{ GeV})^2 \\ &\quad -0.0002 \times \log(m_{\text{Higgs}}/150\text{ GeV})\end{aligned}$$

- Replaces previous measurement (E770 only)
  (C.A. Arroyo *et al.*, PRL **72**, 3452 (1994))
- Previous uncertainty was ± 0.0059
  - ▷ Increased statistics by 65%
  - ▷ Improved understanding of calibration, charm sea and R_L systematics
  - ▷ Direct measurement of ν_e background

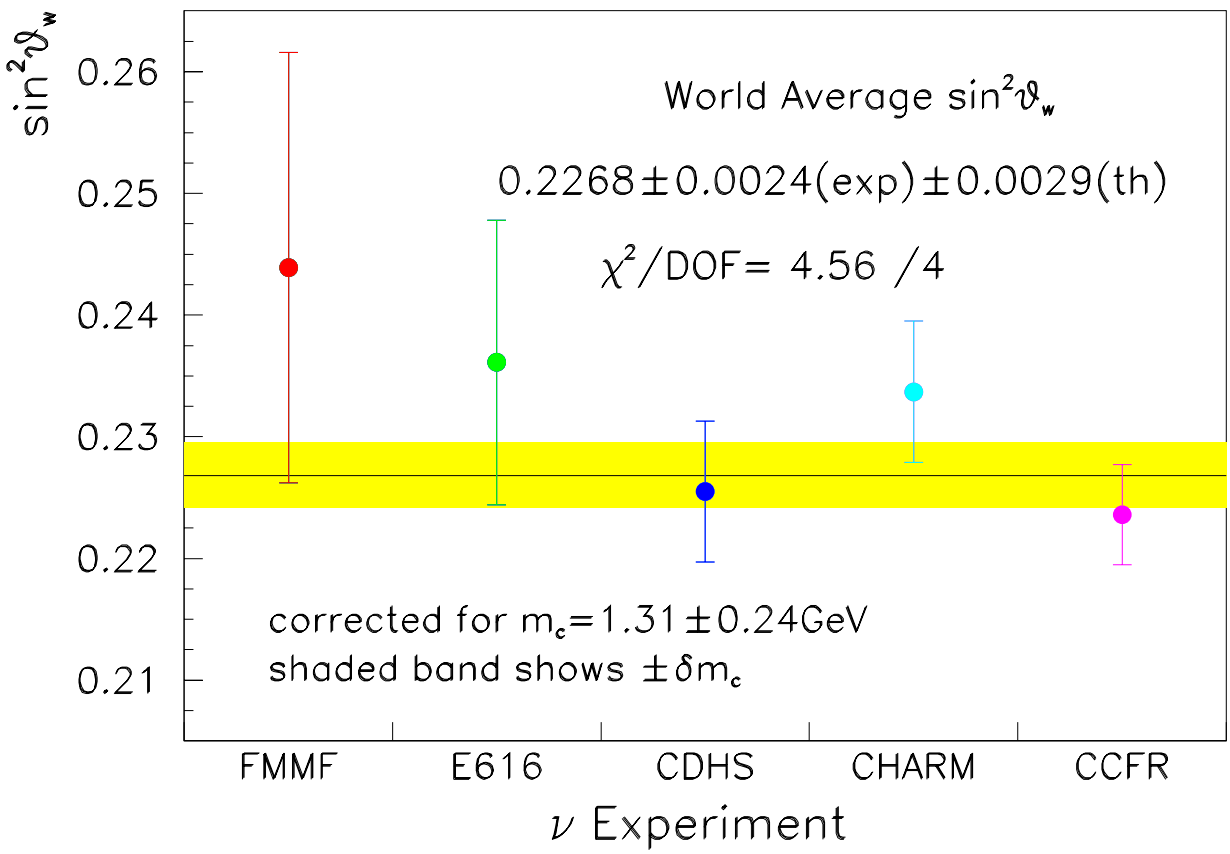
World Average νN $\sin^2\theta_W$

CCFR Final $\sin^2\theta_W = 0.2236 \pm 0.0041$

Can average with other νN measurements of $\sin^2\theta_W$

$$\Longrightarrow \quad \sin^2\theta_W = 0.2268 \pm 0.0037$$

Improvement is small because of large correlated m_c uncertainty



All other experiments are corrected to

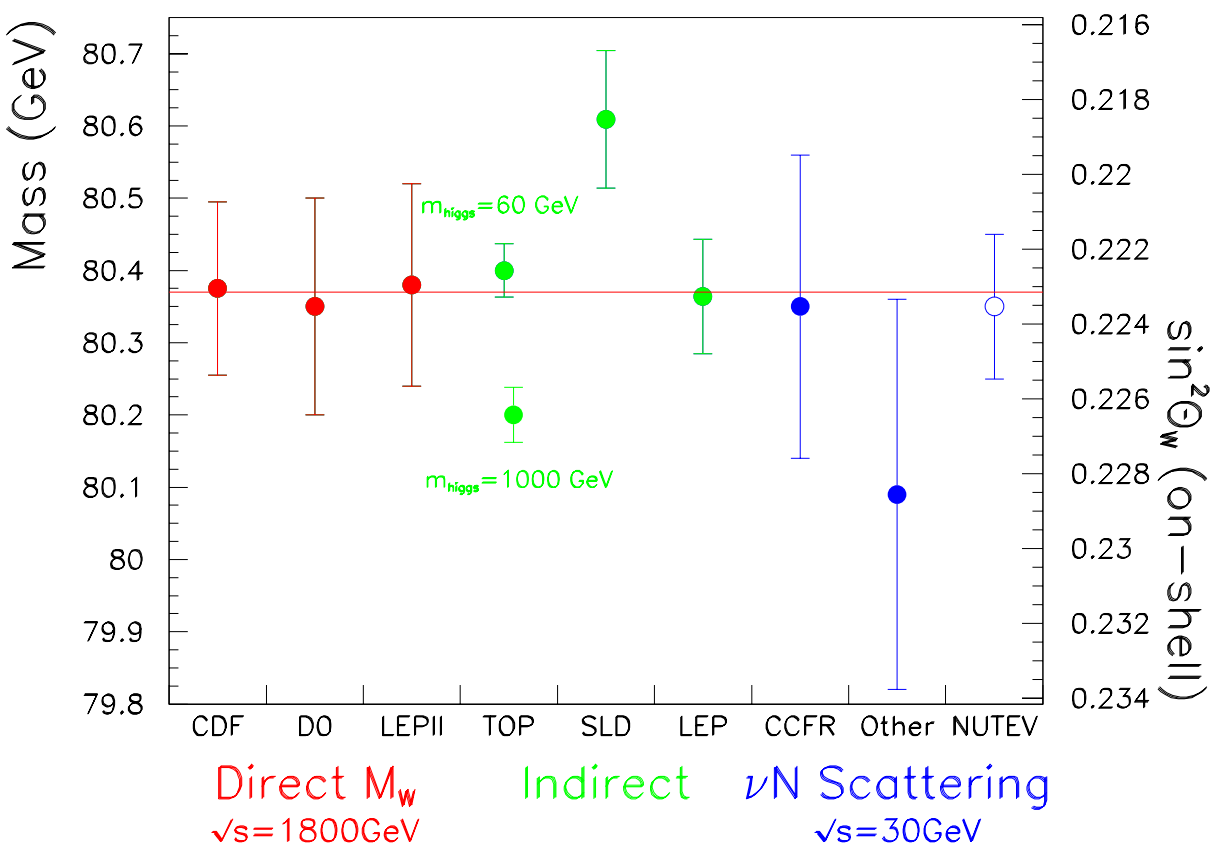
CCFR & CDHS average m_c and to large m_{top} ($m_{top} > m_W$)

In the Sirlin (on-shell) renormalization scheme,

$$\sin^2\theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}.$$

CCFR $M_W = 80.35 \pm 0.21$ GeV

All νN **DIS** $M_W = 80.18 \pm 0.19$ GeV



- LEP/SLD compares Z-pole asymmetries with M_Z to extract radiative corrections for calculation to M_W
- A direct m_{top} measurement gives a prediction for radiative corrections (up to m_{Higgs} effects) for calculating M_W from M_Z

Model-Independent CCFR Electroweak Result

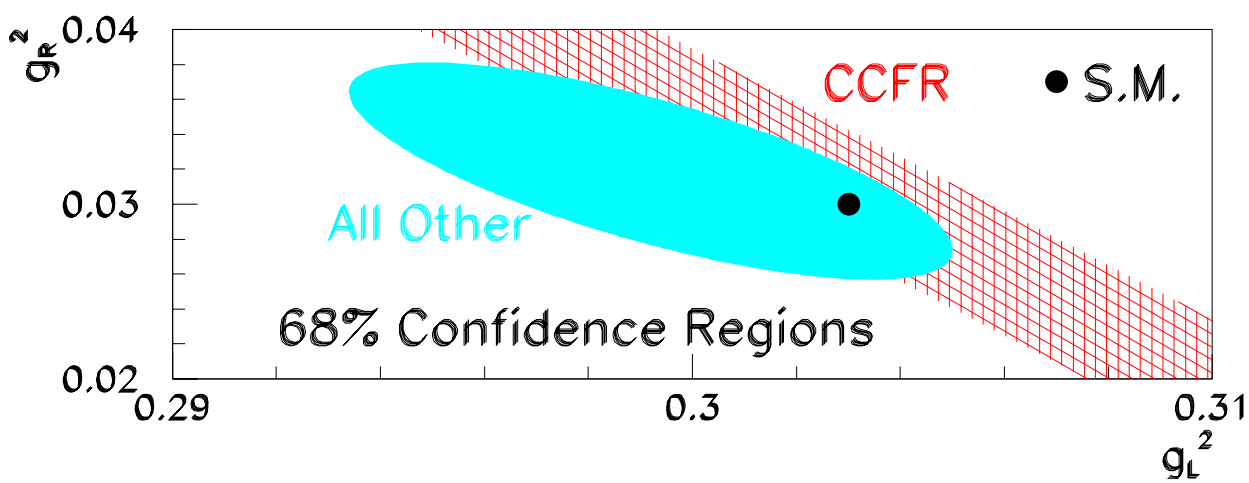
- CCFR measurement can be presented in terms of neutral-current couplings to quarks at $\langle q^2 \rangle = -35$ GeV^2
- Easy to incorporate extensions to Standard Model

$$g^2_{L,R} \equiv u^2_{L,R} + d^2_{L,R} \qquad \delta^2_{L,R} \equiv u^2_{L,R} - d^2_{L,R}$$

Couplings Based on CCFR Final Result:

$$0.5820 \pm 0.0041 = 1.7897 g_L^2 + 1.1479 g_R^2 - 0.0916 \delta_L^2 - 0.0782 \delta_R^2$$

(c.f. : 0.5817 ± 0.0013 from M_Z, $m_{\rm top}$, $m_{\rm Higgs}$, M_W)



- CCFR uses measured $m_c = 1.31 \pm 0.24$ GeV
- Other experiments from global fit which uses $m_c = 1.54 \pm 0.33$ GeV (Fogli and Haidt, Z. Phys. **C40, 379 (1988)**)

Sensitivity to New Physics

- **Compositeness Search** ($\nu\nu qq$ Contact Term)

$$-\mathcal{L} = \sum_{H\in\{L,R\}} \frac{\pm 4\pi}{\left(\Lambda^{\pm}_{H_l H_q}\right)^2} \bar{l}_{H_l}\gamma^{\mu} l_{H_l} \bar{q}_{H_q}\gamma_{\mu} q_{H_q}.$$

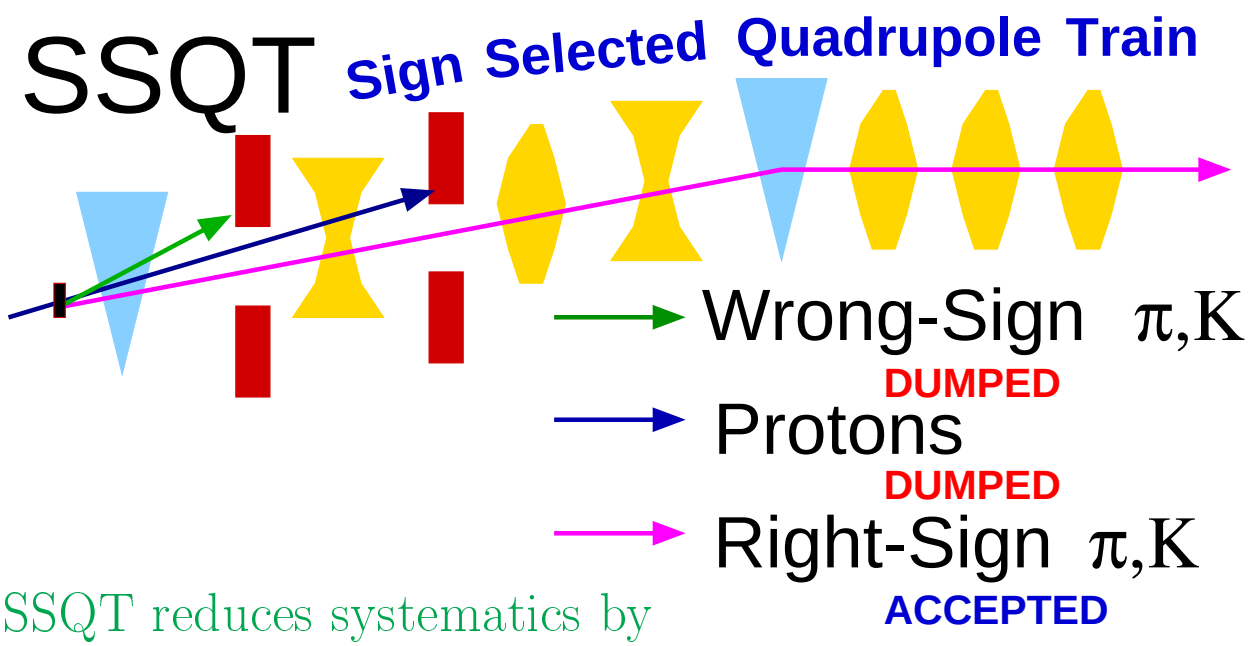
CCFR constraint on νq couplings $\Rightarrow$

Type of Interaction	95% Confidence Lower Limit on Λ^+	Λ^-
LL	4.7 TeV	5.1 TeV
LR	4.2 TeV	4.4 TeV
RL	1.3 TeV	1.8 TeV
RR	3.9 TeV	5.2 TeV
VV	8.0 TeV	8.3 TeV
AA	3.7 TeV	5.9 TeV

How Can νN Measurement of $\sin^2\theta_W$ Be Improved?

Charm Production and Charm Sea Errors are Large
$\Rightarrow$ Need a Technique Insensitive to Sea Quarks

Paschos-Wolfenstein: $R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right)$



SSQT reduces systematics by

- Separating ν and $\overline{\nu}$
  - ▷ Paschos-Wolfenstein relations reduce charm mass effect
- Removing K_L's from the beam.
  - ▷ $K_L \to \pi e \nu_e$ decays were responsible for most of the ν_e uncertainty in CCFR

Estimated Systematics for $\sin^2\theta_W$:

- Charm mass error reduced from 0.0027 to 0.0009
- ν_e error reduced from 0.0015 to 0.0006

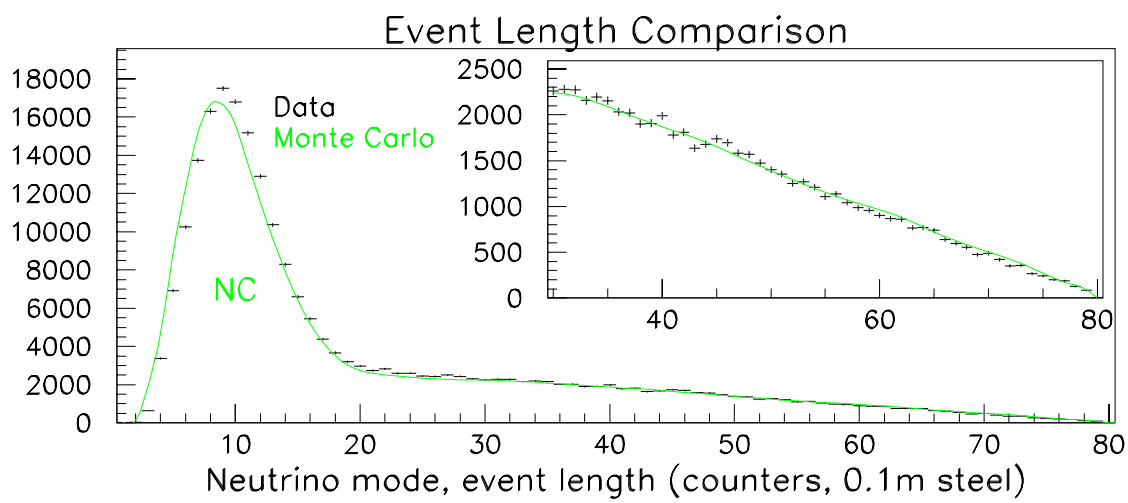
Current Status of NuTeV $\sin^2\theta_W$

NuTeV has analyzed 30% of expected data set

$\longrightarrow$ *Extracted* $\sin^2\theta_W$ *from* R^ν *only* $\longleftarrow$

SOURCE OF UNCERTAINTY	CCFR $\delta\sin^2\theta_W$	NuTeV $\delta\sin^2\theta_W$
STATISTICAL ERROR	**0.0019**	**0.0020**
ν_e flux	0.0015	$\sim$0.0006
Event Length	0.0010	same
Energy Measurement	0.0005	same
Transverse Vertex	0.0004	same
TOTAL EXP. SYST.	**0.0019**	**$\approx$0.0013!!**
TOTAL PHYSICS MODEL	**0.0030**	same
TOTAL UNCERTAINTY	**0.0027$\oplus$0.0030**	**0.0024$\oplus$0.0030!!!**

NuTeV ***PRELIMINARY*** **Event Length**



Conclusions

α_S

- CCFR $\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{exp}) \pm 0.001(\text{HT}) \pm 0.004(\text{scale})$
- NNLO calculation needed for substantial improvement
- No sign of an α_s crisis

$\sin^2\theta_W$

- CCFR $\sin^2\theta_W \Rightarrow M_W = 80.35 \pm 0.21$ GeV
- Probe of quark-lepton coupling at multi-TeV scale
- Best measurement of light quark NC couplings

NuTeV

- α_s improved by NuTeV continuous calibration beam
  - ▷ $\delta\alpha_s \sim 0.002$ without systematic fit
- NuTeV can improve $\sin^2\theta_W$ to equivalent $\delta M_W \sim 100$ MeV
- NuTeV running well (May 1996-September 1997)
  - ▷ first results soon!