Current Status of the NuTeV Experiment

Beyond the Standard Model?? "QCD Effects"??

NuTeV – charged, neutral currents induced by neutrinos
New measurement of Weinberg angle
Possible "New Physics" beyond the Standard Model?
Normal ("QCD") Explanations of NuTeV Anomaly?

- radiative corrections
- parton Charge Symmetry Violation
- strange quark momentum asymmetry
- nuclear, shadowing corrections

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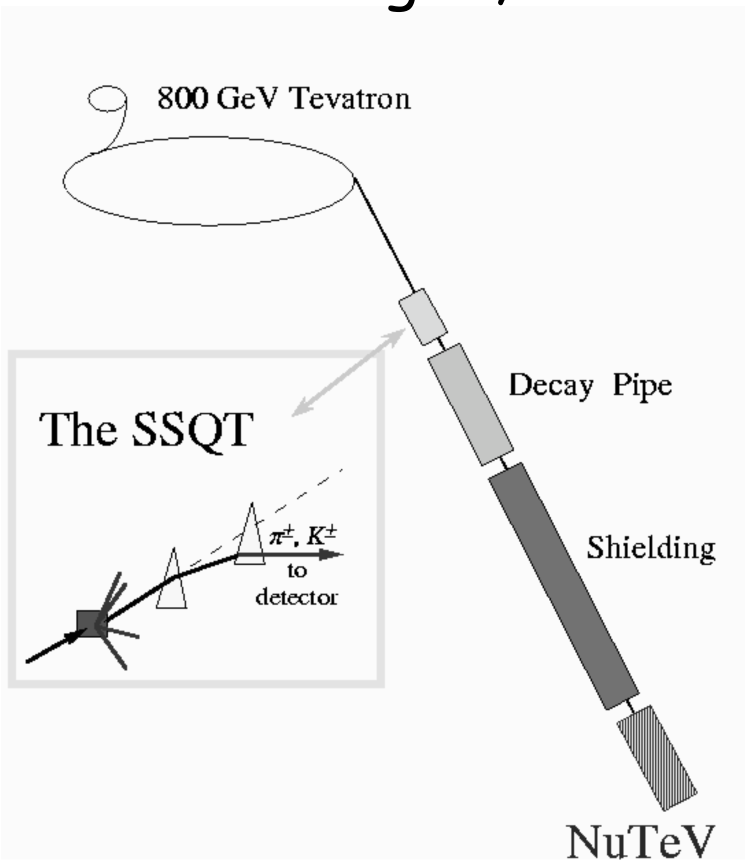
JLab Electroweak Workshop
Dec 11-13, 2006

Supported by NSF PHY- 0555232
With Tony Thomas (JLab), Dave Murdock (Tenn Tech)

The NuTeV Experiment:
charged, neutral currents from neutrino DIS



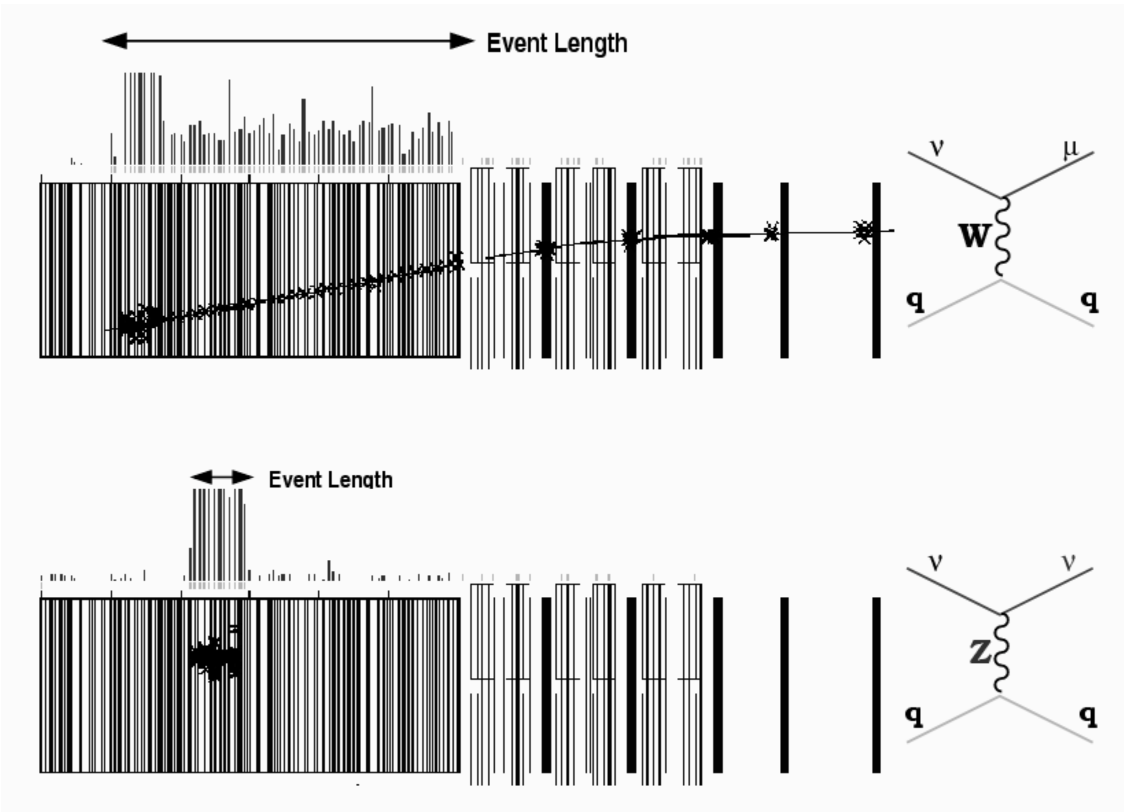
800 GeV p at FNAL produce pi, K from interactions in BeO target;
Decay of charged pi, K produces neutrinos, antineutrinos;
Almost pure muon neutrinos;
(small ν_e contamination from K_{e3} decay)
Only neutrinos penetrate shielding

Dipoles select sign of charged meson:
- Determine nu/nubar type
- remove ν_e from K_L

NuTeV: Rochester/Columbia/FNAL/Cincinnati/Kansas State/Northwestern/Oregon/Pittsburgh neutrino collaboration
G. Zeller etal, PRL **88**, 091802 (02); PR D**65**, 111103 (02)

Separate Neutral, Charged-Current Events

NuTeV Detector: 18 m long, 690-ton steel scintillator;
Steel plates interspersed with liq scintillator, drift chambers



Charged current:
Track through several plates
Large visible energy deposit

Neutral current:
Short visible track
Large missing energy

NuTeV Events:
- 1.62 million ν
- 351,000 $\overline{\nu}$

NuTeV event selection:
- Large E in calorimeter $20 < E_{\text{vis}} < 180 \text{ GeV}$
- event vertex in fiducial volume

The Paschos-Wolfenstein Ratio:

Neutrino Total Cross Sections on Isoscalar Target:

$$R^{\nu} \equiv \frac{\sigma\langle \nu\, N_0 \longrightarrow \nu\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle} = g_L^2 + r\, g_R^2$$

$$R^{\overline{\nu}} \equiv \frac{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\nu}\, X\rangle}{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle} = g_L^2 + \frac{1}{r}\, g_R^2$$

$$r \equiv \frac{\sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle}$$

R^{ν} is more sensitive to $\sin^2\theta_W$

NuTeV measure both $R^{\nu}, R^{\overline{\nu}}$

Paschos & Wolfenstein (PR **D7**, 91 (73)):
Independent measurement of Weinberg angle, using ratio of total X-sections for neutrinos, antineutrinos on isoscalar target:
PW ratio → minimizes sensitivity to PDFs, higher-order corrections

$$R^{PW} \equiv \frac{R^{\nu} - r\, R^{\overline{\nu}}}{1-r} = \frac{\sigma\langle \nu\, N_0 \longrightarrow \nu\, X\rangle - \sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\nu}\, X\rangle}{\sigma\langle \nu\, N_0 \longrightarrow \mu\, X\rangle - \sigma\langle \overline{\nu}\, N_0 \longrightarrow \overline{\mu}\, X\rangle} = \frac{1}{2} - \sin^2\theta_W$$

The Paschos-Wolfenstein Ratio:

$$R^{PW} \equiv \frac{R^{\nu} - r\,R^{\overline{\nu}}}{1-r} = \frac{\sigma\langle \nu\,N_0 \longrightarrow \nu\,X\rangle - \sigma\langle \overline{\nu}\,N_0 \longrightarrow \overline{\nu}\,X\rangle}{\sigma\langle \nu\,N_0 \longrightarrow \mu\,X\rangle - \sigma\langle \overline{\nu}\,N_0 \longrightarrow \overline{\mu}\,X\rangle} = \frac{1}{2} - \sin^2\theta_W$$

PW Ratio depends on the following assumptions:

- Isoscalar target (N=Z)
- include only light (u, d) quarks
- neglect charm quark mass
- assume isospin symmetry for PDFs
- no nuclear effects (parton shadowing, EMC, ...)
- no contributions outside Standard Model

NuTeV Determination of Weinberg Angle:

- Construct ratios $R^{\nu}, R^{\overline{\nu}}$

  Individual ratios less dependent on overall normalization

  Very precise charged/neutral current ratios:

  Different cuts, acceptance: don't construct PW ratio directly
- R^{ν} : depends strongly on Weinberg angle
- $R^{\overline{\nu}}$: weak dependence on Weinberg angle

$$R^{\nu} = 0.3916 \pm 0.0013 \, [\mathrm{SM} : 0.3950]$$ ← **3σ below SM**

$$R^{\overline{\nu}} = 0.4050 \pm 0.0027 \, [\mathrm{SM} : 0.4066]$$ ← **agree with SM**

These ratios lead to a NuTeV value for the Weinberg angle:

$$s_W^2 = 0.2276 \pm 0.0013_{stat} \pm 0.0006_{syst} \pm 0.0006_{th} - .00003[M_t - 175] + .00032 \ln[M_H/100]$$

The NuTeV result is **~ 3σ above the very precise value** (from EW processes at LEP)

$$s_W^2 = 0.2229 \pm 0.0004$$

$$\delta \, s_W^2 = +0.0046$$

NuTeV Result: 3σ Discrepancy from LEP value

NuTeV work at LO in QCD (with improvements) and find

$$s^2_w(\text{NuTeV})=0.2276\pm0.0013_{stat}\pm0.0006_{syst}\pm0.0006_{th}$$
$$-0.00003(M_t/\text{GeV}-175)+0.00032\ \ln M_H/100\text{GeV}$$

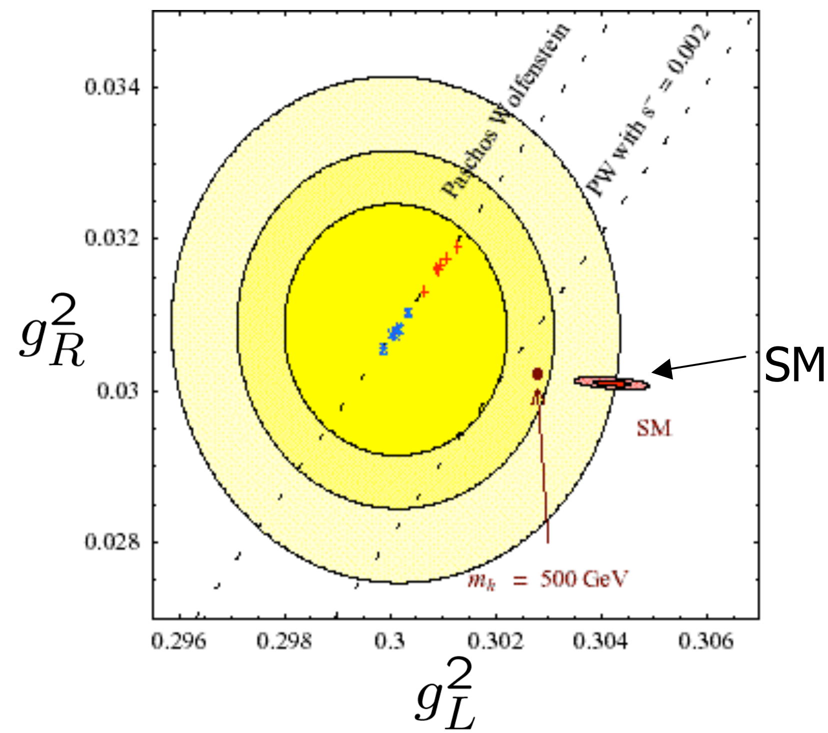
where $s^2_w=1-M^2_w/M^2_z$ (on-shell)

$$s^2_w= 0.2229\pm0.0004$$

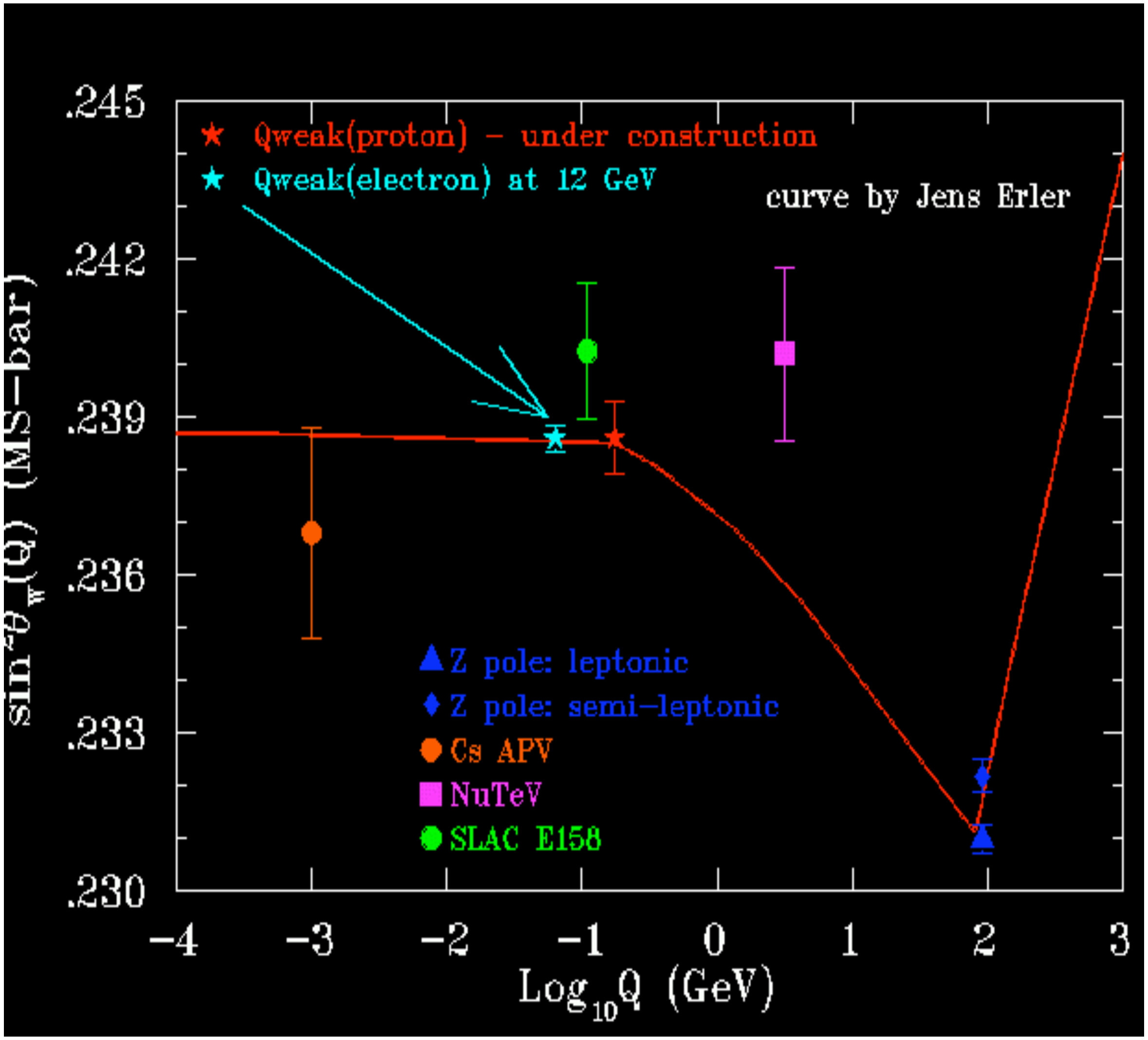
~2.8σ discrepancy

Nuclear effects and ν oscillation explanations very unlikely

Corresponds to **1.2% decrease in g_L^2**;
This is **large** compared to precision of EW measurements!

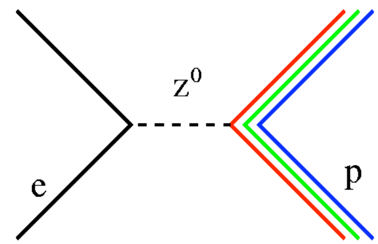


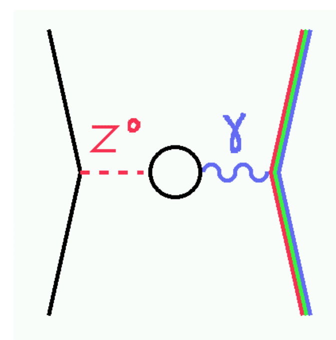
Running of the Weak Mixing Angle



CS APV, PRL**82** 2484 ('99)
E158 Moller, PRL**95** 081601 ('05)
NuTeV, PRL**88** 091802 ('02)
LEP, e^+e^- at Z pole

Erler, Kurylov, Ramsey-Musolf
PR **D68** 016006 ('03)





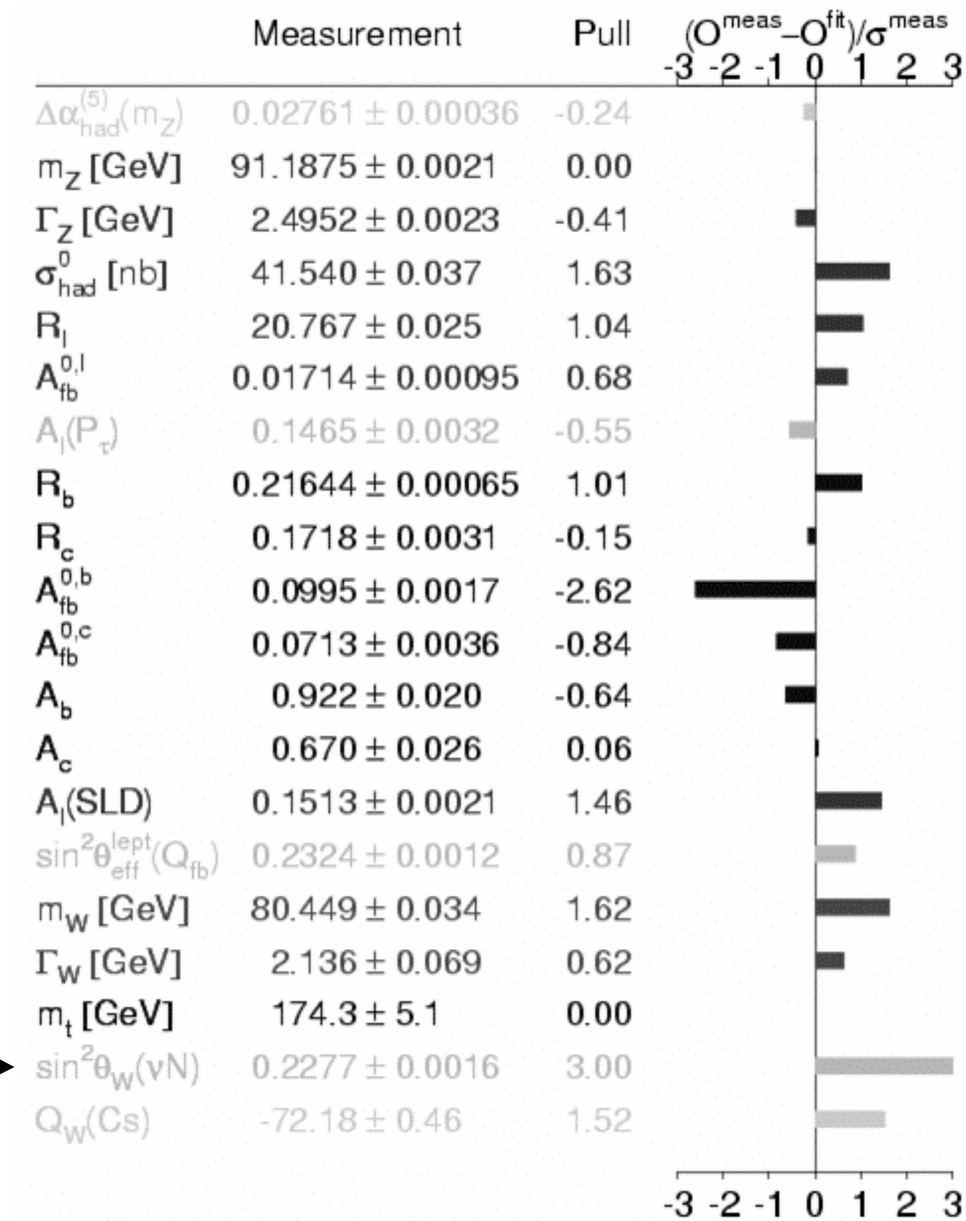
The Cs APV, Z pole and (particularly) SLAC E158 clearly demonstrate the running. The NuTeV result is an "outlier".

“New Physics” explanation for NuTeV?

The problem: extremely precise EW data supports SM!

- Mass, width of Z, W
- X-sections, branching ratios at Z peak [LEP, SLD]
- LR and FB asymmetries in e^+e^- scattering
- new particles must satisfy all these constraints
- EW constraints ~ 0.1% level [NuTeV ~ 1.2%]
- “new physics” **hard to satisfy EW constraints!**

NuTeV →

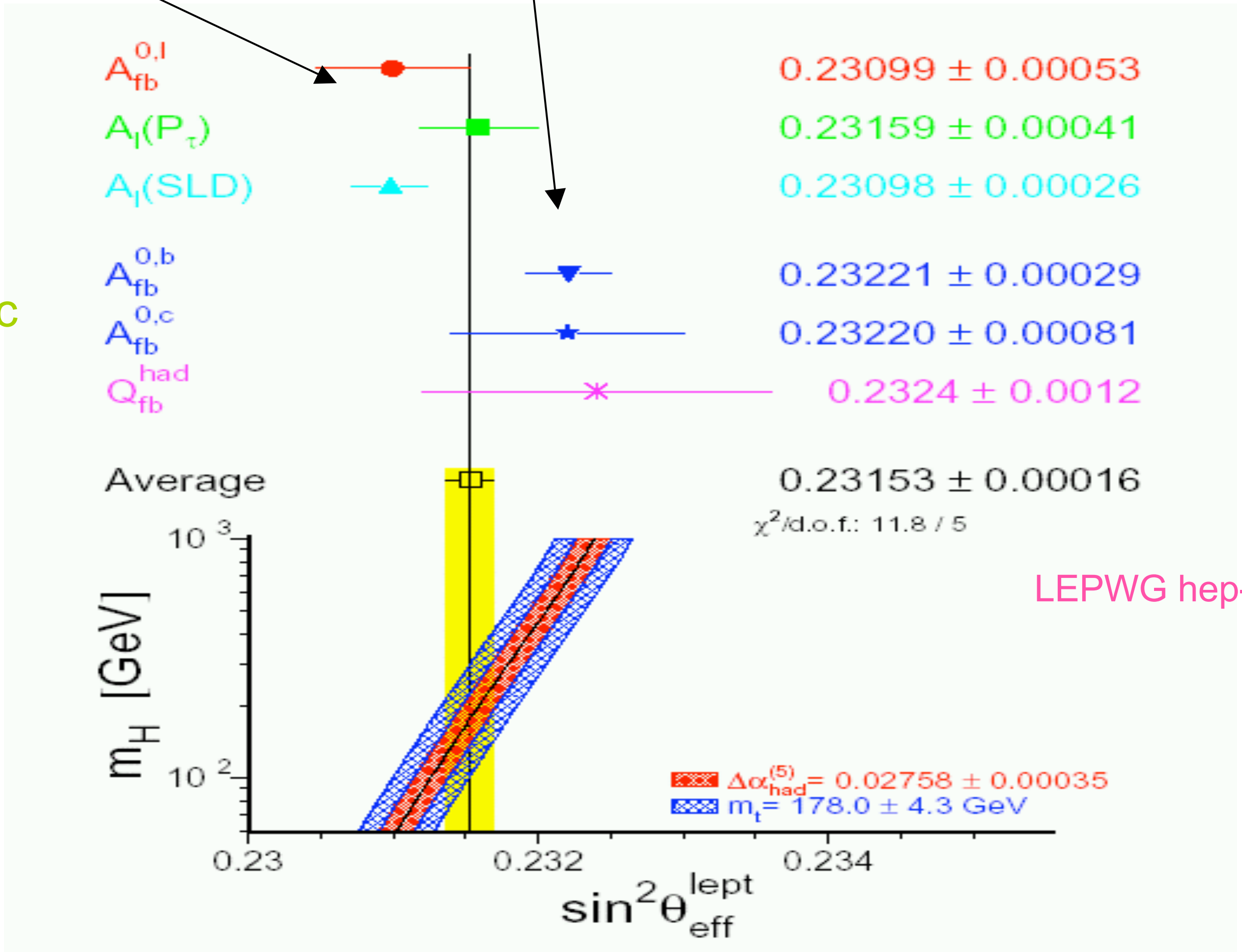


Precision (*Inconsistent?*) Determinations of $\sin^2\theta_W$

- Two precise measurements of $\sin^2\theta_W$ at the Z pole (leptonic and semi-leptonic) are inconsistent.

leptonic

semi-leptonic



LEPWG hep-ex/0509008

Physics Outside the Standard Model?

Attempts to explain NuTeV with "new physics"

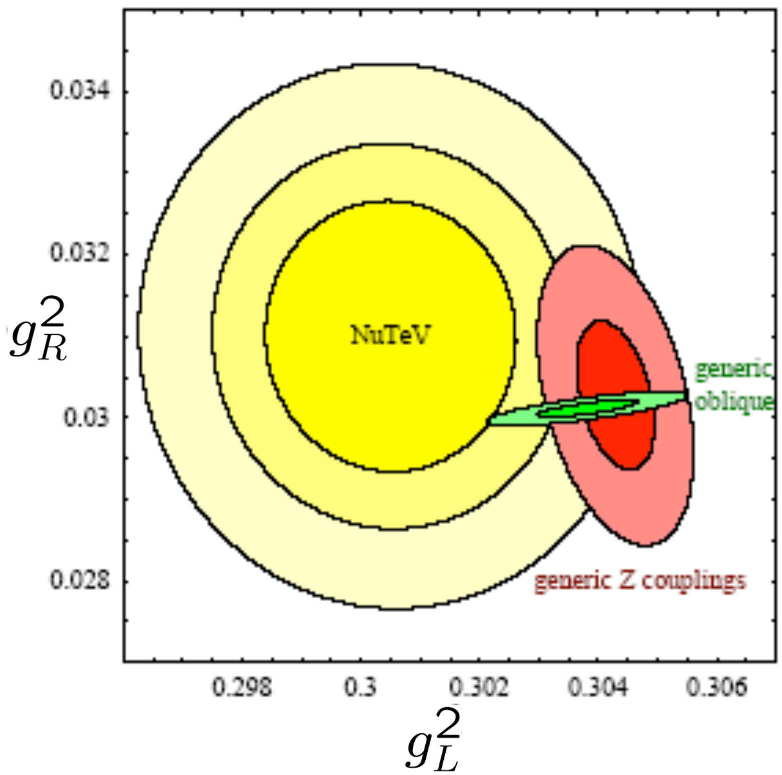
- **Davidson et al** [J High E Phys **2**, 37 ('02)] considered various scenarios (oblique corrections, extra Z's, SUSY loops, leptoquarks) – very difficult to explain NuTeV result

- **Kurylov, Ramsey-Musolf, Erler** [NP **B667**, 321 ('03)]
  detailed analysis of SUSY contributions to NuTeV:
  SUSY loops cannot explain NuTeV
  R-parity violating (RPV) contributions →
  in principle could explain NuTeV anomaly
  in practice, ruled out by other precision EW data

"Designer Particles" I:

physics beyond Standard Model

delicately adjust to fit all existing data + NuTeV



- **oblique corrections** [high mass scale, couples only to vector bosons]: parameters constrained by EW data – can't fit NuTeV

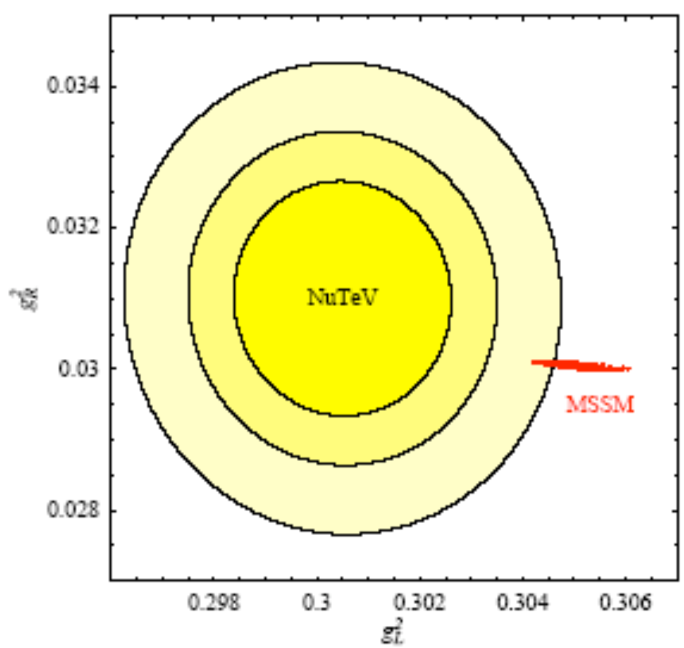
- **extra Z' (mixed with Z)** – doesn't fix; strongly constrained by LEP/SLD (also by latest muon g-2)

[Davidson *etal*, J HE Phys **2**, 37 (2002)]

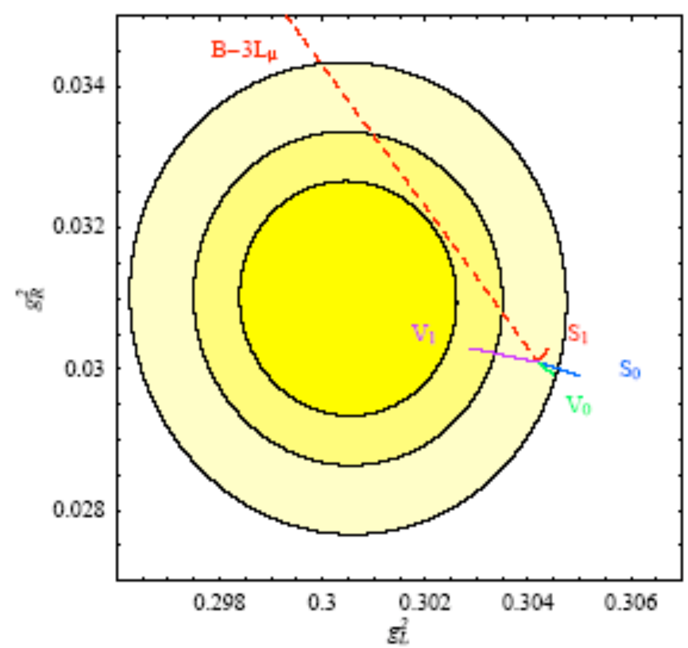
"Designer Particles" II: More Attempts to fit NuTeV

- minimal SUSY loops – No – most have wrong sign; others violate existing constraints
- Leptoquarks (bosons that couple to leptons & quarks): very carefully tuned mass splittings still possible – could be tested at LHC [Davidson *etal*, *J HE Phys 2, 37 (2002)*]
- Unmixed extra Z′ – might help reduce NuTeV anomaly (fine tuning)

MSSM, light sleptinos, gauginos



Leptoquark (solid); extra **gauge bosons** (red)



Summary, "New Physics" Contributions to NuTeV:

Contributions outside Standard Model?

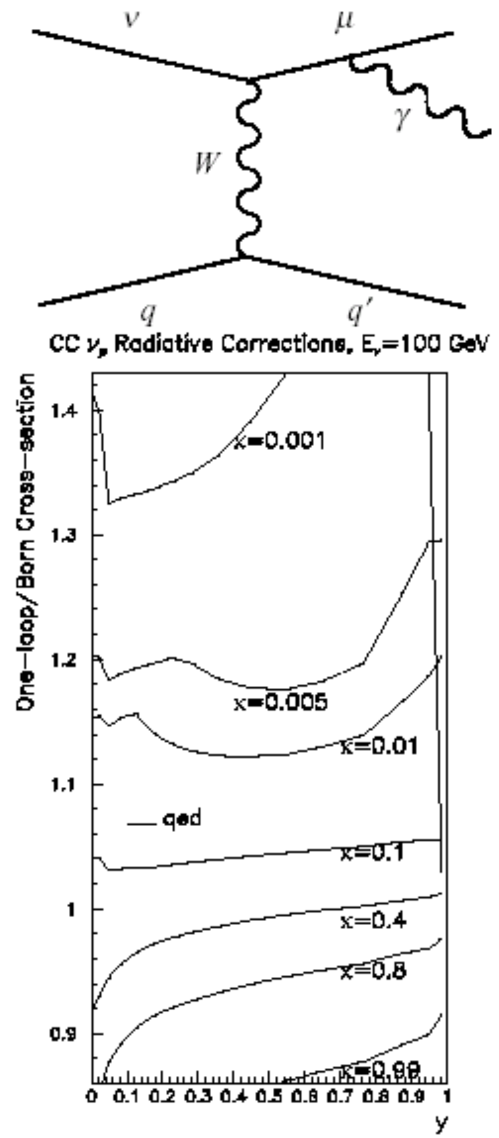
- Difficult to achieve
- Strong constraints from extremely precise LEP/SLD results
- Requires very delicate choice of particles & properties

EW Radiative Corrections

- EM radiative corrections, process specific to NuTeV, are large
  - Bremsstrahlung from final state lepton in CC → significant correction.
    - Not present in NC (promotes CC events to higher y so they pass energy cut)
    - $\{\delta R^{\nu}, \delta R^{\bar{\nu}}, \delta \sin^2\theta_W\} \approx \{+.0074, +.0109, -.0030\}$

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

  - New calculation of this effect (Diener, Dittmaier, Hollik PR **D69**, 073005 (04))
    - NuTeV data currently under re-analysis
    - Corrections likely larger than NuTeV estimate



Isospin Violation and the NuTeV Experiment

Isospin violation in PDFs will contribute to NuTeV exp't

PW Correction → valence parton **charge symmetry violation (CSV)**
parton charge symmetry: $u_V \leftrightarrow d_V$, and $p \leftrightarrow n$.

CS: (rotation of 180^o about "2" axis in isospin space)

NuTeV: slight dependence on sea quark CSV,
but dominated by valence CSV

Origins of parton CSV; convenient to ascribe to →
o quark mass difference: $\delta m \equiv m_d - m_u \sim 4$ MeV

o Electromagnetic contributions: most important EM effect:

n-p mass difference $\delta M \equiv M_n - M_p = 1.3$ MeV

Isospin Violating Corrections to PW Ratio:

Changes in PW ratio from isospin violating PDFs:

$$\delta R^{PW}_{CSV} = \delta\left(\sin^2\theta_W\right) = \frac{\delta U_V - \delta D_V}{2(U_V + D_V)}\left[1 - \frac{7}{3}\sin^2\theta_W + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)\right]$$

$$\delta R^{PW}_{CSV} \propto \frac{U^p_V + U^n_V - \left(D^p_V + D^n_V\right)}{2(U_V + D_V)}$$

$$\delta U_V \equiv \int_0^1 x\left[u^p_V(x) - d^n_V(x)\right]dx; \qquad \delta D_V \equiv \int_0^1 x\left[d^p_V(x) - u^n_V(x)\right]dx$$

Isospin violating PW Correction → depends completely
on valence **CSV momentum difference**
(2nd moment of valence CSV PDFs)

Quark models suggest →
These quantities may be reasonably model-independent
Londergan & Thomas, PR **D67**, 111901 ('03)

Models for CSV in Valence PDFs

Construct quark models that reproduce qualitative features of PDFs

Examine their behavior under charge symmetry operations

$$\delta m \equiv m_d - m_u \approx 4 \ MeV$$

$$\delta M = M_n - M_p = 1.3 \ MeV$$

$$\delta q_{\mathrm{V}} \approx \frac{\partial q_{\mathrm{V}}}{\partial m}\delta m + \frac{\partial q_{\mathrm{V}}}{\partial M}\delta M$$

Sather: Analytic Quark Model Approximation for Valence Parton CSV.

$$\delta d_{\mathrm{V}}(x) = d^p_{\mathrm{V}}(x) - u^n_{\mathrm{V}}(x) = -\frac{\delta M}{M}\frac{d}{dx}[x d_{\mathrm{V}}(x)] - \frac{\delta m}{M}\frac{d}{dx} d_{\mathrm{V}}(x)$$

$$\delta u_{\mathrm{V}}(x) = u^p_{\mathrm{V}}(x) - d^n_{\mathrm{V}}(x) = \frac{\delta M}{M}\left(-\frac{d}{dx}[x u_{\mathrm{V}}(x)] + \frac{d}{dx} u_{\mathrm{V}}(x)\right)$$

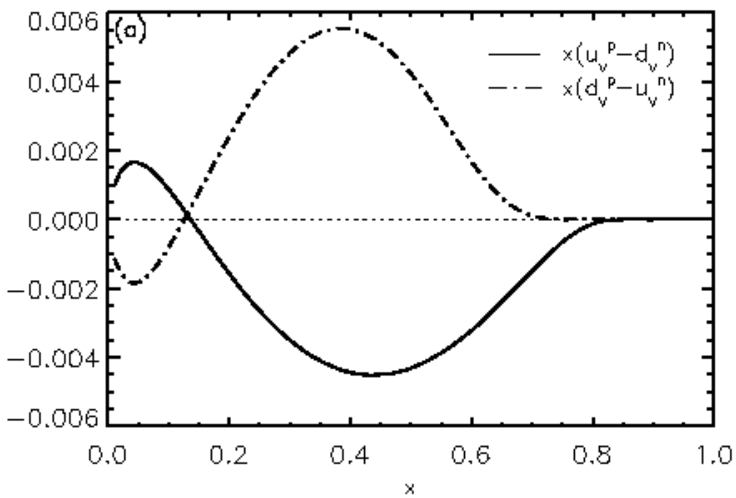
$$\delta D_{\mathrm{V}} = \langle\, x \delta d_{\mathrm{V}}(x)\,\rangle = \frac{\delta M}{M} D_{\mathrm{V}} + \frac{\delta m}{M} \quad > 0$$

$$\delta U_{\mathrm{V}} = \langle\, x\, \delta u_{\mathrm{V}}(x)\,\rangle = \frac{\delta M}{M}(U_{\mathrm{V}} - 2) \quad < 0$$

Leads to analytic results (~ model-independent)

Quark models → predict sign, magnitude for 2nd moment of valence parton CSV

CSV Contribution to NuTeV Result:



PW Ratio CSV Corr'n using Sather:

Rodionov: $\delta R^{PW} = -.0021$

Sather:

CTEQ4LQ: $\delta R^{PW} = -.0020$ ← 40% decrease in anomaly!

NuTeV: **Don't evaluate** PW Ratio!

CSV Contrib'n to NuTeV result:

- Calculate parton CSV at low (quark model) momentum scale
- Evolve up to Q^2 of NuTeV exp't (20 GeV^2)
- Evaluate with NuTeV functional $\delta R^{NT}_{CSV} \sim -0.0014$ ← 30% decrease in anomaly

Phenomenological Parton CSV PDFs

MRST PDFs from global fits include CSV for 1st time:

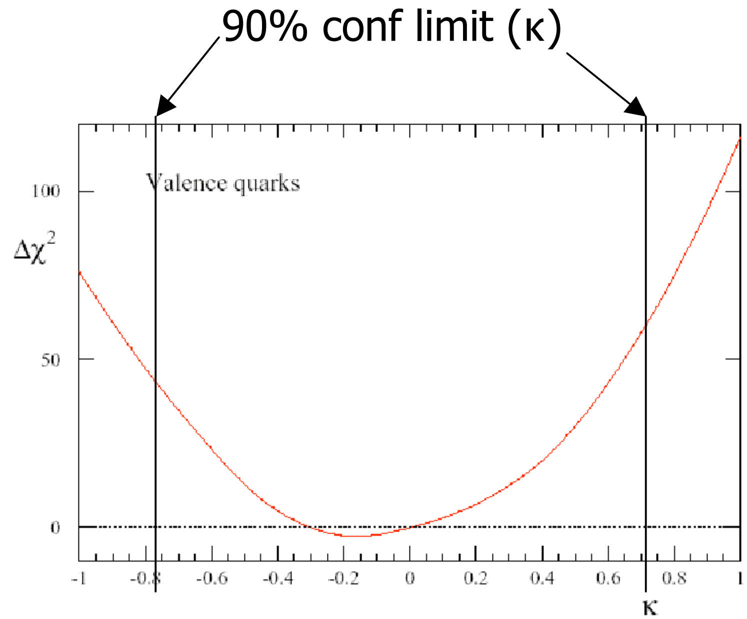
Martin, Roberts, Stirling, Thorne [Eur Phys J C**35**, 325 (04)]:

Choose restricted form for parton CSV:

$$\delta d_V(x) = -\kappa f(x) = -\delta u_V(x)$$
$$f(x) = x^{-0.5}(1-x)^4(x - .0909)$$

- f(x) similar to valence PDFs at large, small x
- f(x) has zero first moment (preserves valence quark normalization)

- requires δd_v, δu_v equal & opposite



Very shallow minimum found in global fit to HE data

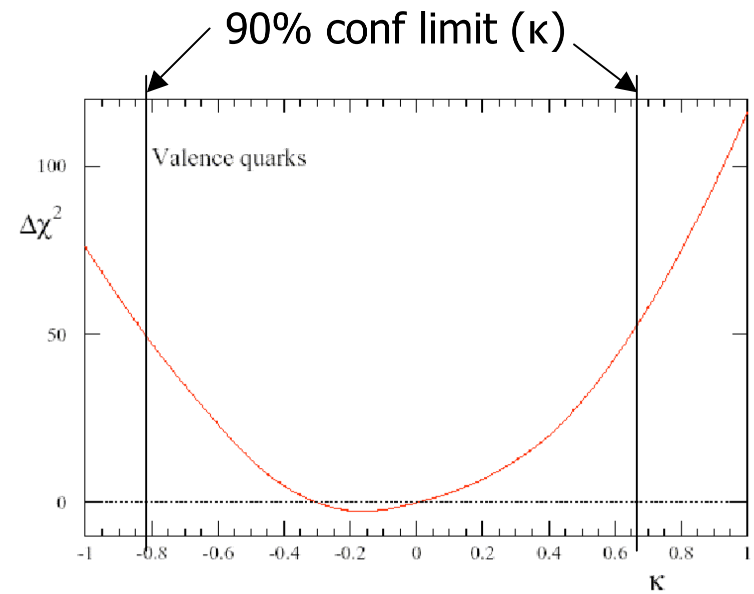
Best fit: **κ = -0.2**, large uncertainty !

90% confidence limit: -0.8 ≤ κ ≤ +0.65

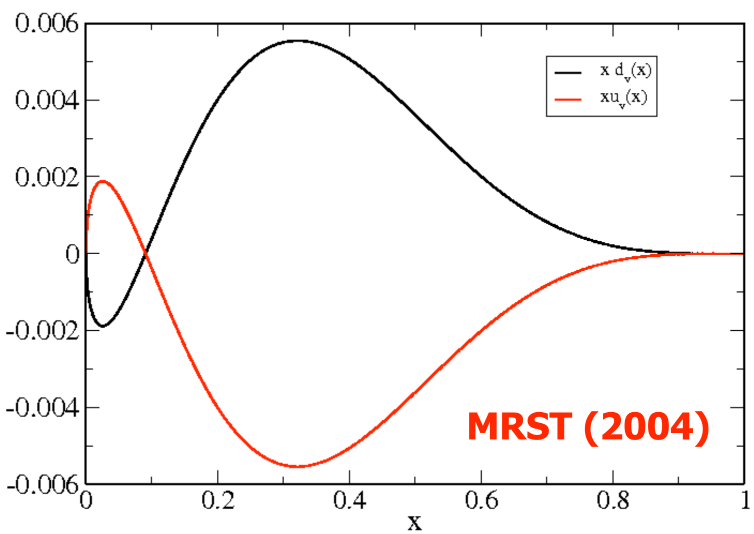
Phenomenological Parton CSV PDFs

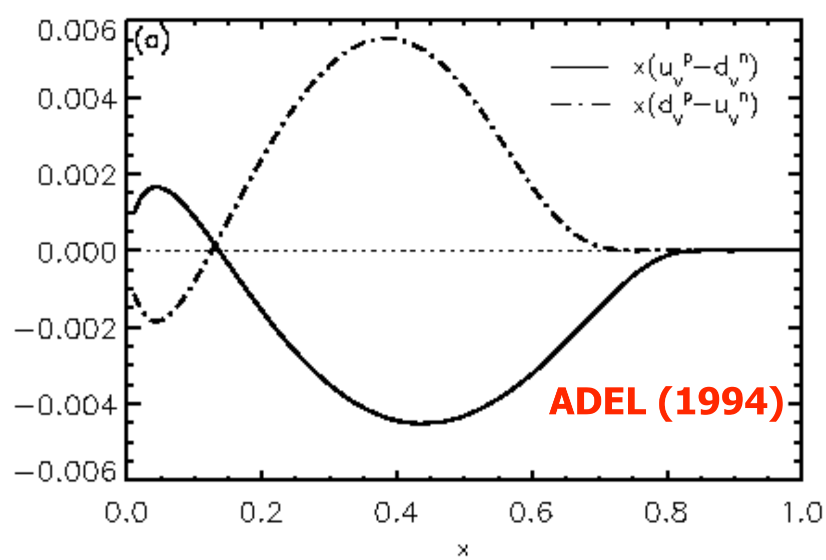
MRST PDFs → global fits including CSV:
Martin, Roberts, Stirling, Thorne [Eur Phys J C**35**, 325 (04)]:

$$\delta d_V(x) = -\kappa f(x) = -\delta u_V(x)$$
$$f(x) = x^{-0.5}(1-x)^4(x - .0909)$$



Best fit: **κ = -0.2**, large uncertainty !
Best fit remarkably similar to quark model CSV calculations

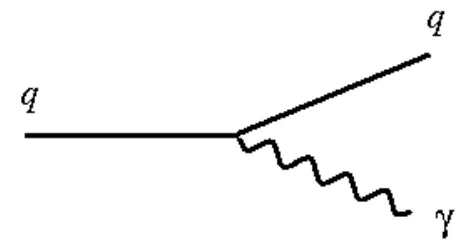




"QED Splitting": a New Source of Isospin Violation

MRST, Eur.Phys.J. **39**, 155 (05);
Glueck, Jimenez-Delgado, Reya,
PRL**95**, 022002 (05)

"QED evolution", quark radiates photon
Evolve in Q^2



$$\frac{d}{d\,lnQ^2}\,\delta q_V(x,Q^2) \sim \pm\frac{\alpha}{2\pi}P\otimes q_V$$

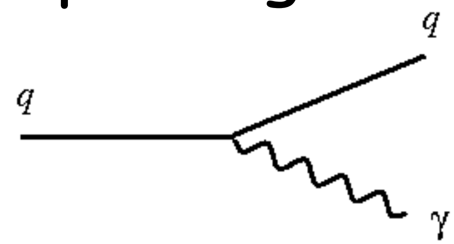
$$P(z) = (e_u^2 - e_d^2)\left(\frac{1+z^2}{1-z}\right)_+$$

$$\delta u_V(x,Q^2) = \frac{\alpha}{2\pi}\int_{m_q^2}^{Q^2} d\ln q^2 \int_x^1 \frac{dy}{y}P\left(\frac{x}{y}\right)u_V(y,q^2)$$

- correct to lowest order in α_{QED}
- qualitatively similar to quark model CSV
- QED varied while QCD force "fixed"
- contributes even if $m_u = m_d$ and $M_n = M_p$
- evolve from m_q to Q
- for $m_q^2 < q^2 < Q_0^2$, Glueck "freeze" quark PDFs
- (Q_0^2 = starting scale for QCD evolution)

CSV Effects arising from "QED Splitting":

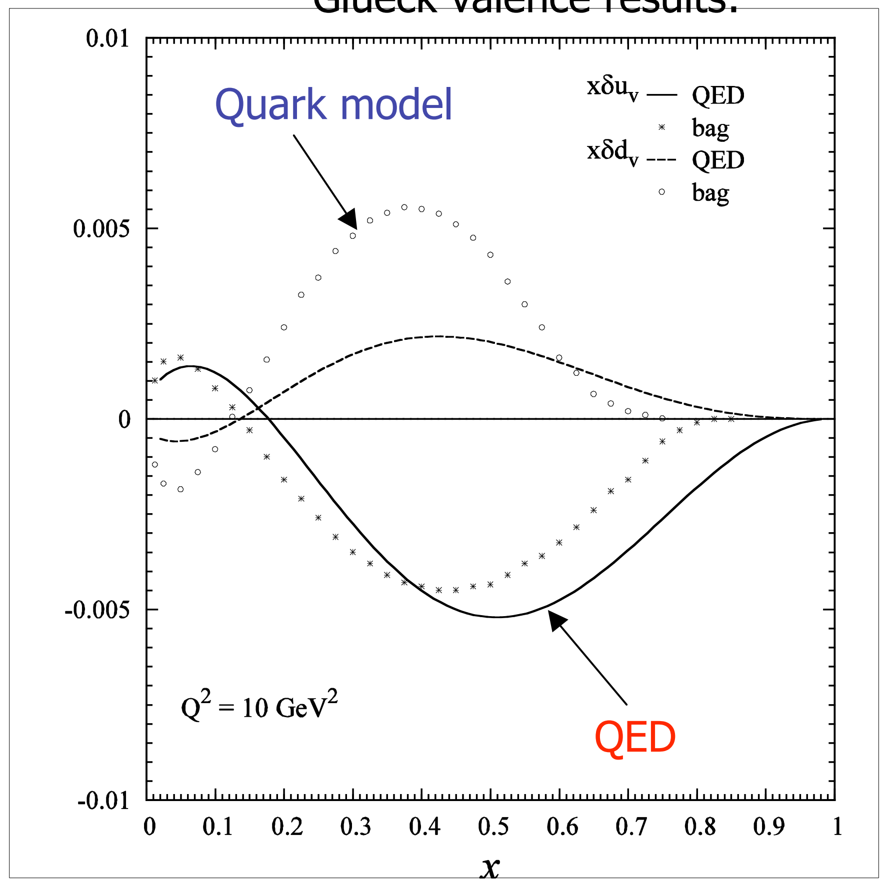
MRST, Eur.Phys.J. **39**, 155 (05);
Glueck etal, PRL**95**, 022002 (05)



$$\frac{d}{d\,lnQ^2}\,\delta q_V(x,Q^2) = \pm\frac{\alpha}{2\pi}P\otimes q_V$$

$$P(z) = (e_u^2 - e_d^2)\left(\frac{1+z^2}{1-z}\right)_+$$

Glueck valence results:



- **add to** quark model CSV term →
- **increase CSV ~ factor 2**
- MRST incorporate QED splitting with PDFs in global fit to high energy data
- Glueck: CSV effects relatively large at high x

Summary, CSV Effects on Weinberg angle

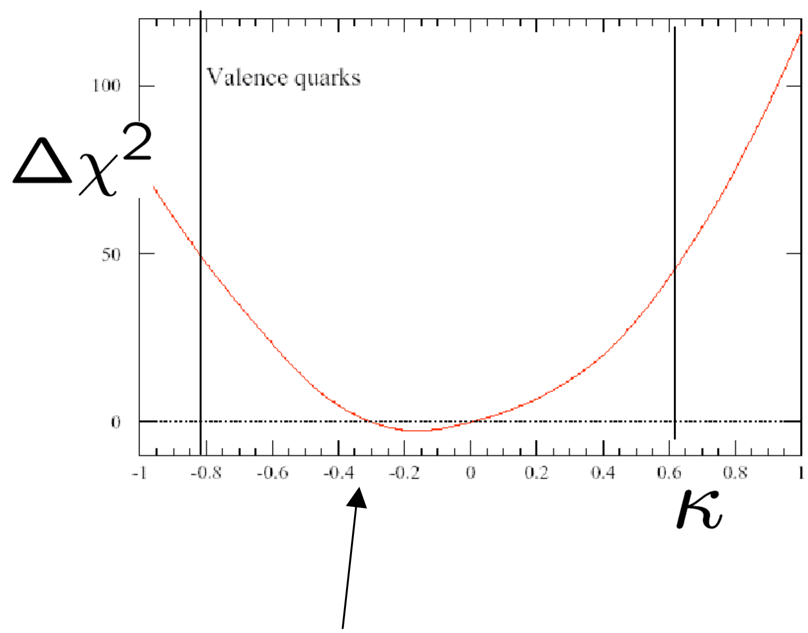
Phenomenology:
MRST global fit → limits valence CSV
 $-0.8 \leq \kappa \leq +0.65$
 $\kappa = -0.6$ → remove 100% of NuTeV anomaly!
 $\kappa = +0.6$ → anomaly twice as large!

Theoretical estimates:

- quark model remove ~1/3 anomaly
- "QED splitting" remove ~1/3
- (phenomenology includes both effects)

→ at current limits, CSV could produce **observable effects** (~ 5-6%) (or more?) in certain reactions

90% confidence limits:



MRST global fit
to valence CSV

Strange Quark Contributions to PW Ratio:

PW contribution from strange quarks:

$$\delta R_S^{PW} = \delta\left(\sin^2\theta_W\right) \approx \frac{-S^-}{U_v + D_v}\left[2\Delta_d^2 + 3(\Delta_d^2 + \Delta_u^2)\epsilon_c\right]$$

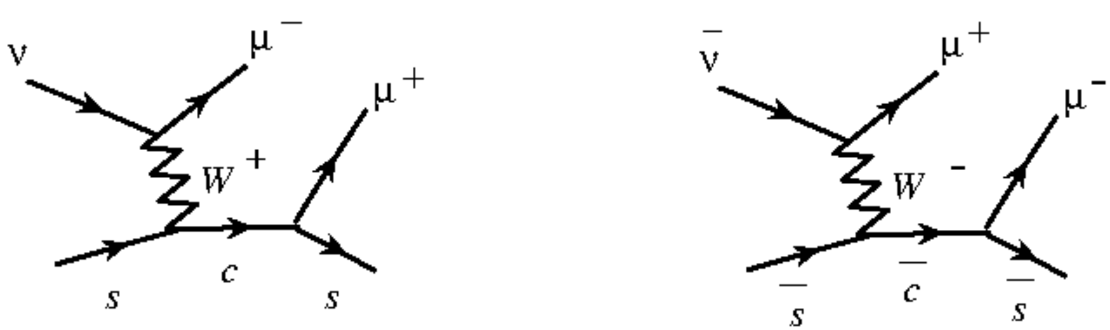
$$S^- \equiv \int_0^1 x[s(x) - \bar{s}(x)]\,dx$$

s-sbar momentum asymmetry

Strange quark normalization: constrained $\langle\, s - \bar{s}\,\rangle = 0$
(no net strangeness in nucleon)

If s quarks carry more momentum than sbar $\Longrightarrow$ decrease anomaly

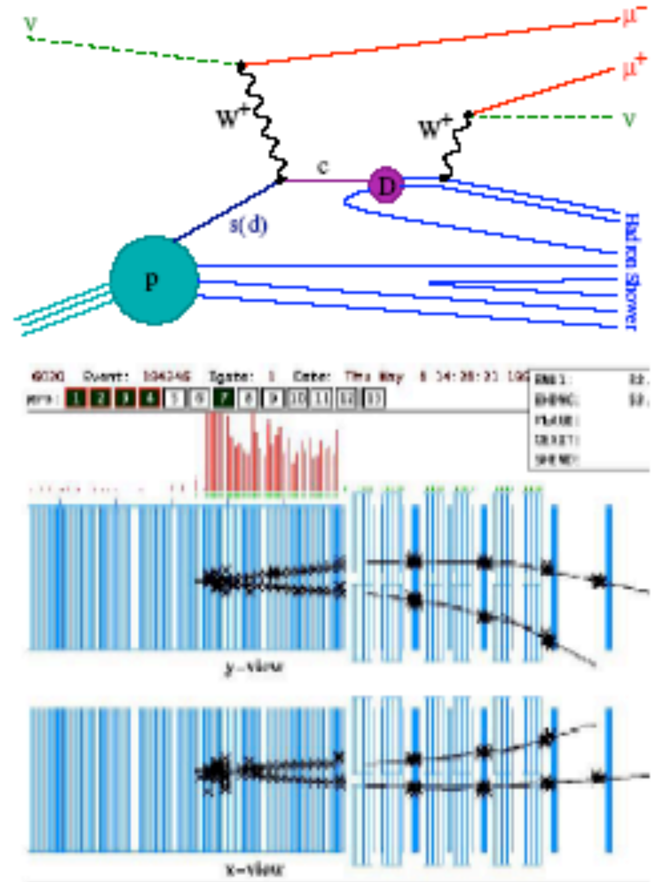
Determination of s, sbar quark PDFs: **Opposite sign dimuons from neutrinos**



- CCFR: charge of faster muon determines neutrino or antineutrino;
- most precise way to determine s, sbar PDFs→ **CCFR, NuTeV**

Charm Production ⇒ Dimuons

- CC νN makes charm
  $\longrightarrow$ fragmentation
  $\longrightarrow$ semileptonic decay to μ
- Very clear signature
- Direct look at strange sea
- With sign selected beam NuTeV can look at $s(x)$, $\bar{s}(x)$ independently
- Can also measure charm mass



Analyses of s quark momentum asymmetry

Two extensive fits of s quark distributions.

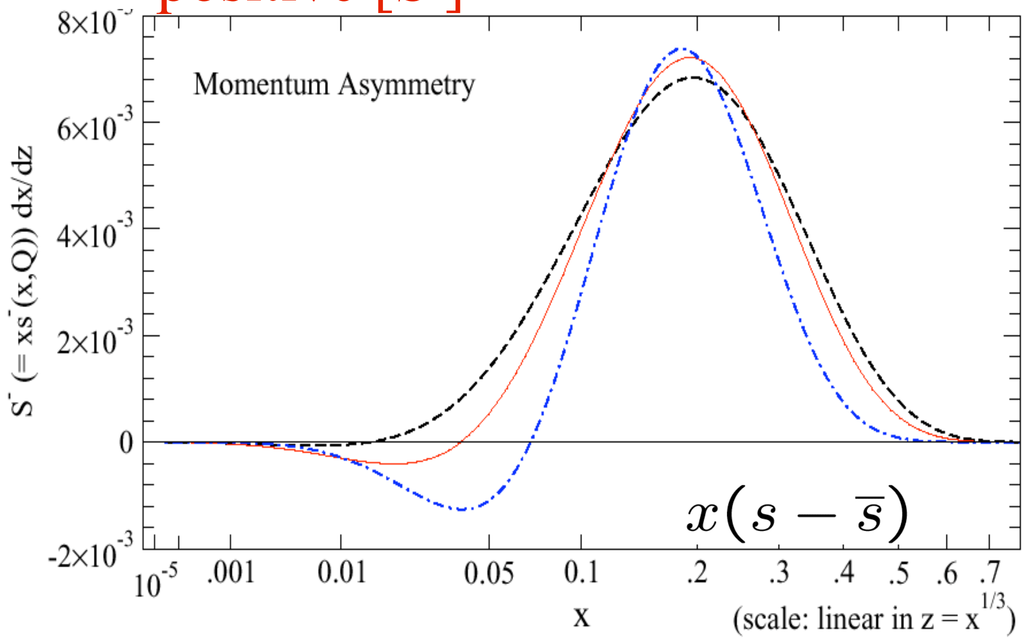
CTEQ: [Kretzer etal, PRL **93**, 041802 (04), Olness etal, Eur Phys J C**40**, 145 (05)]

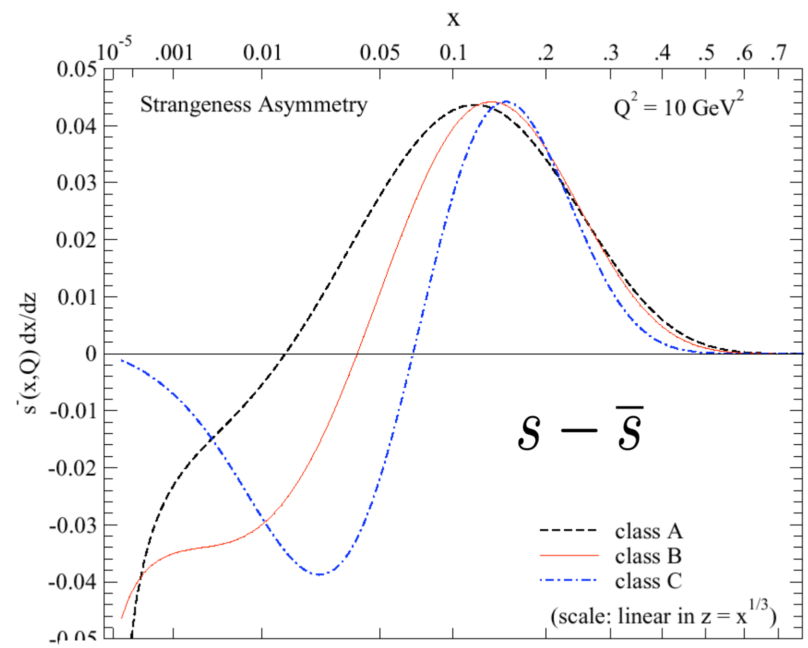
- Global analysis of parton PDFs → CTEQ6
- Includes CCFR, NuTeV dimuon data
- (includes expt'l cuts on dimuons)
- Extract "best fit" for s, sbar dist'ns
  [enforce s normalization cond'n]

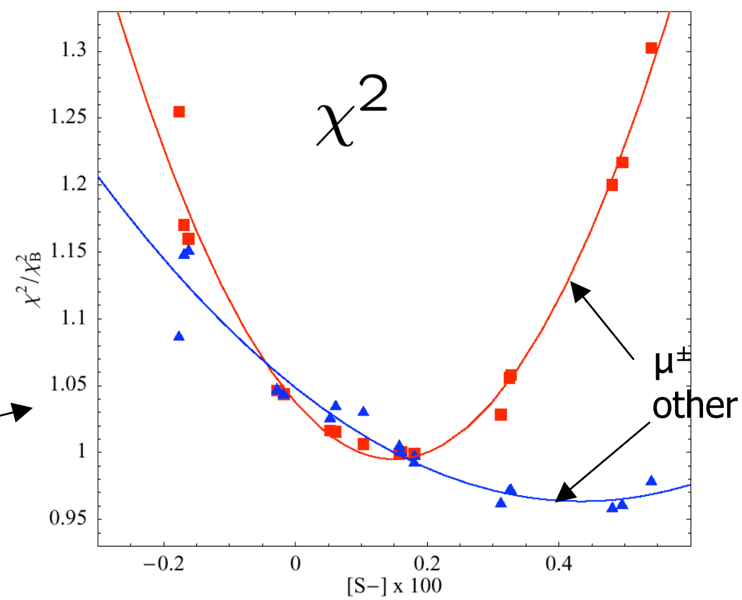
- **NuTeV:** analyzed s, sbar for small $0 < x \leq 0.3$
- Initially, reported best fit $S^- < 0$
  (opposite to CTEQ)
- CTEQ, NuTeV **collaborated on analysis**
- Qualitative differences persisted, until this year

CTEQ Global fit vs. Bjorken x

positive [S⁻]







- CTEQ: **S⁻ > 0**, strange asymmetry
  decreases NuTeV anomaly;
- dimuon data: most sensitive for s PDFs
- CTEQ: s contrib'n removes
  0 → 25% of anomaly
  (but consistent with zero)

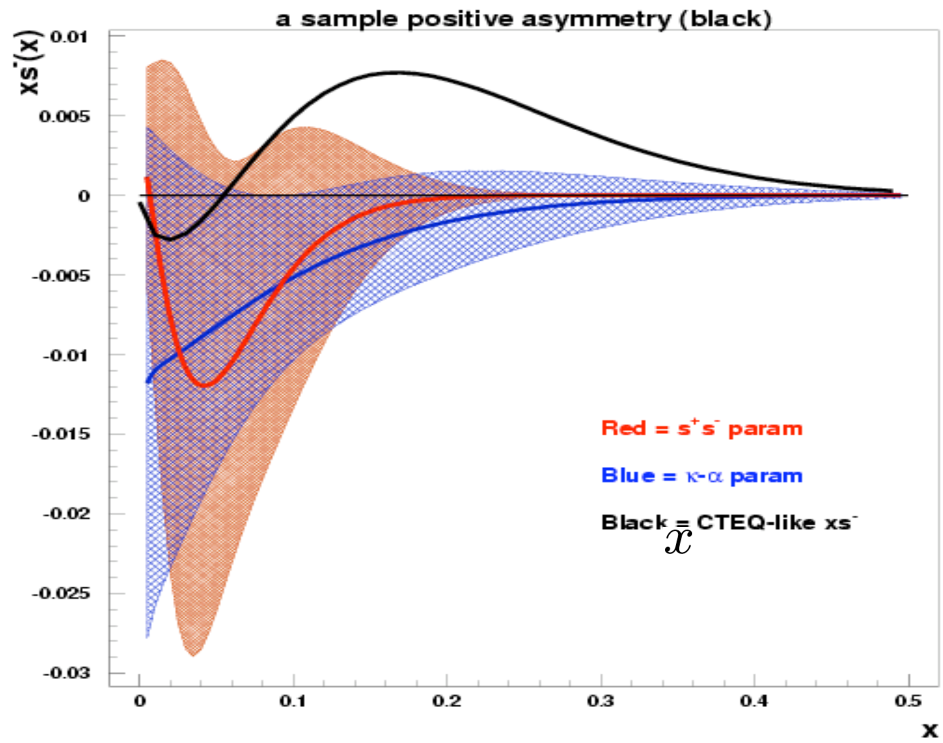
-.001 < [S⁻] < +.004

Initial NuTeV Analysis of s, sbar Quark Dist'n:

Analysis of dimuon data:
- preliminary analysis $[S^-] \sim 0$
- $s - \overline{s}$ appears negative
- NLO treatment of dimuon prod'n

NuTeV group:
- used CTEQ PDFs (u,d)
- acceptance corrections?
- fragmentation functions?
- charm mass (CTEQ uses HERA data)?

$x(s - \overline{s})$



Qualitative disagreement between NuTeV/CTEQ **??**

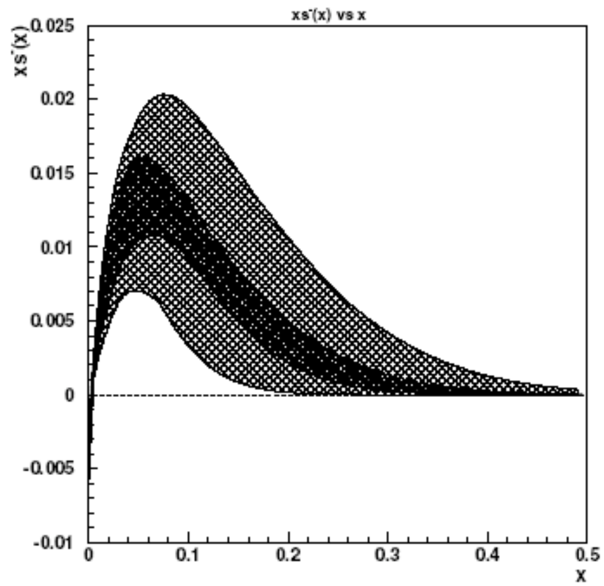
New NuTeV Analysis of s, sbar Quark Dist'n:

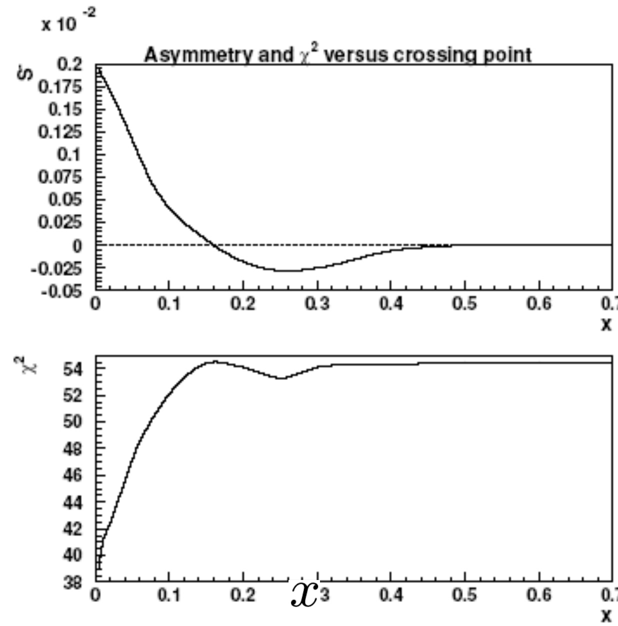
(D. Mason, DIS06)

$$x(s-\overline{s})$$

Re-analyzed dimuon data (Mason '06):

- now agrees with CTEQ result
- S^- is positive
- 1σ result also includes zero.





$$S^- = +0.00196 \pm \underset{\text{(stat)}}{0.00046} \pm \underset{\text{(syst)}}{0.00045} \pm \underset{\text{(external)}}{0.00128}$$

$$m_c = 1.41 \pm \underset{\text{(stat)}}{0.10} \pm \underset{\text{(syst)}}{0.08} \pm \underset{\text{(external)}}{0.12} \text{ GeV}/c^2$$

NuTeV, CTEQ now agree both qualitatively, quantitatively !

Nuclear Effects in Neutrino DIS?

NuTeV: Measured nu, nubar DIS on iron
Nuclear modification of PDFs:

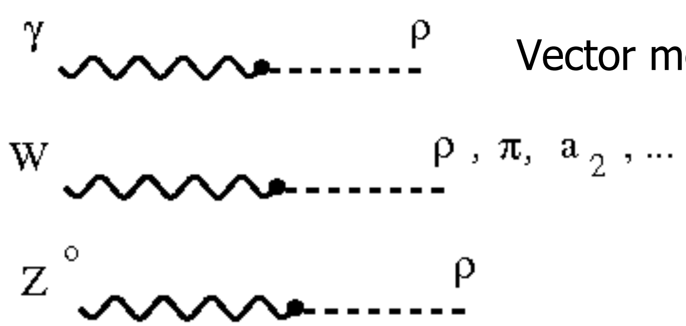
Shadowing — low x
EMC Effect — intermed x
Fermi motion .... — large x

Shadowing effect for NuTeV??

charged leptons:

ν CC events:

ν NC events:



Vector meson dominance

Miller/Thomas Int J Mod Phys A**20**, 95 (05):
ν shadowing very different from μ

Z^o: very small coupling to ρ → NC shadowing ~ 0

Nuclear effects in ν reactions: Hirai, Kumano, Nagai, PR D**71**, 113007 (05)

Is Shadowing Important for NuTeV ?

Miller/Thomas Int J Mod Phys A**20**, 95 (05): Perhaps

1) NC shadowing ~ 0 (Z doesn't couple to ρ)

2) NC/CC different for nu, nubar

3) Different shadowing for $R^{\nu}, \ R^{\overline{\nu}}$

→ **account for anomaly??**

NuTeV: **NO !**

- Shadowing low Q^2 phenomenon (~ 1 GeV^2)
- Average data much higher Q^2 (~ 20 GeV^2)
- $R^{\overline{\nu}}$ value very close to SM value (should be quite different in M/T scenario)
- Shadowing likely to **increase** NuTeV anomaly?

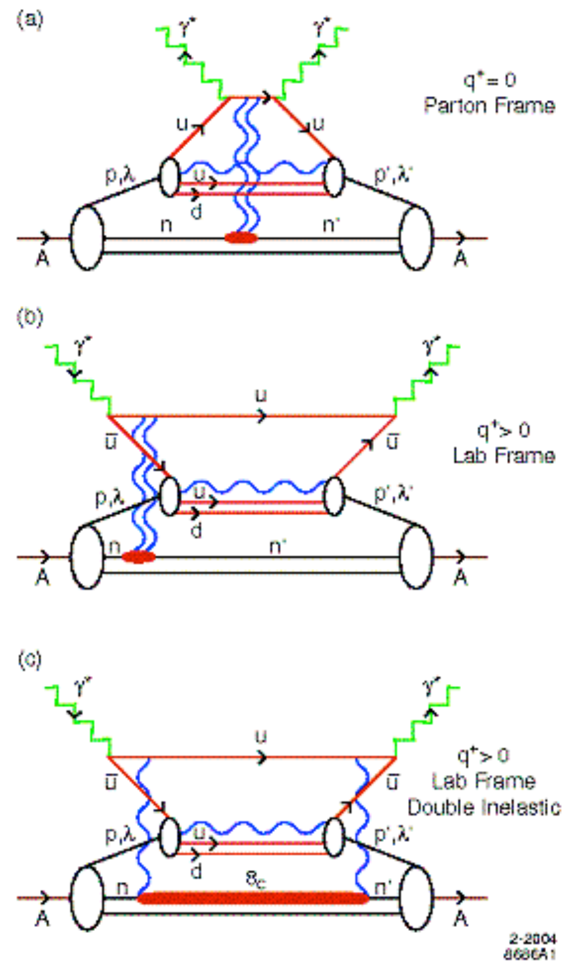
Nuclear Effects in Neutrino DIS

Brodsky, Schmidt, Yang (PR D**70**, 116003 (04))
Shadowing/Antishadowing ν-A processes

- include Pomeron, Odderon, Reggeon effects
- obtain both shadowing, antishadowing effects
- both constructive, destructive interference
- $\nu, \overline{\nu}$ processes modified in different ways

Predict greater effect on $R^{\overline{\nu}}$ than R^{ν}

Remove ~ 20% of Weinberg angle anomaly
Partial contribution along with CSV, s quarks ??



Conclusions:

✓ NuTeV: Measured CC, NC X-sections for $\nu, \overline{\nu}$ on Fe

✓ Large (~ 3σ), surprising discrepancy for $\sin^2 \theta_W$

✓ "New Physics" – difficult to fit LEP results, NuTeV
"designer particles" unlikely → very delicate

✓ "QCD Corrections" to NuTeV measurement??

- radiative corr'ns → new calc'n, re-analysis in progress
- **parton CSV** → ~ could remove effect [MRST] (model dependence?)
- **strange quark** asymmetry ~ 1σ [CTEQ]
- **nuclear effects** ~ 20%, Brodsky etal

✓ CSV, strangeness: **at present, most plausible explanations for NuTeV anomaly**

✓ small additive contrib'ns from **CSV, strangeness, nuclear effects** ??