Electroweak radiative corrections to neutrino-nucleon scattering and Finite Fermion Mass Effects at NuTeV

Kwangwoo Park
SMU

PHENO2010, May 10 2010

in collaboration with Ulrich Baur and Doreen Wackeroth (SUNY at Buffalo)

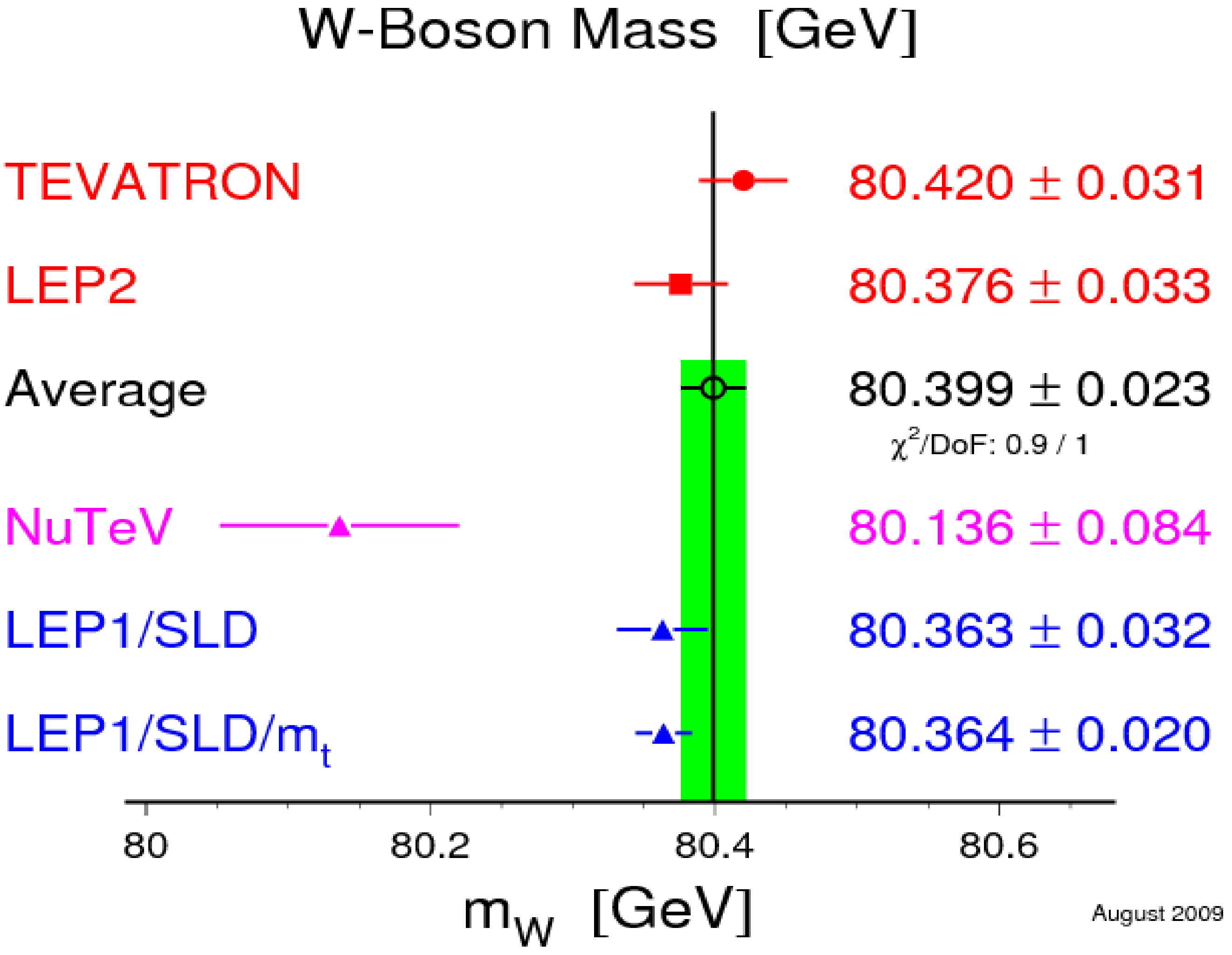
Outline

1. NuTeV anomaly

2. What's new in our calculation
   - Finite muon and charm quark masses !

3. Phase space slicing method
   for the not-so-heavy fermion mass

4. Numerical result



$\sin^2\theta_W$

0.2227 ∓ 0.0004

0.2277 ∓ 0.0014 (stat)

∓ 0.0009 (syst)

$\delta \sin^2\theta_W \simeq -0.005$

$\sin^2\theta_W$ measured at NuTeV differs from the average by about 3σ (NuTeV anomaly)

LEP EWWG 2008(http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2009/)

Our Calculation

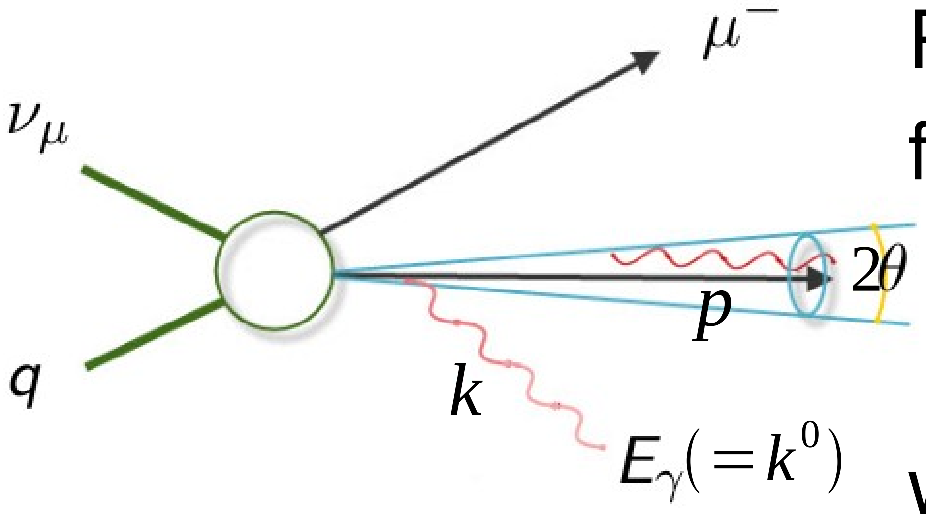
- ► Include full electroweak $O(\alpha)$ corrections.
- ► study the effect of finite fermion mass

“Massless” and **“Massive”** calculations

“Massless” : All fermion masses have only been used to regularize mass singularities, otherwise neglected.

“Massive” : Heavy fermion masses (muon, charm quark) have been taken as non-zero value everywhere.

Phase Space Slicing Method for not-so-heavy muon mass



Photon radiation from a fermion leg has the term:

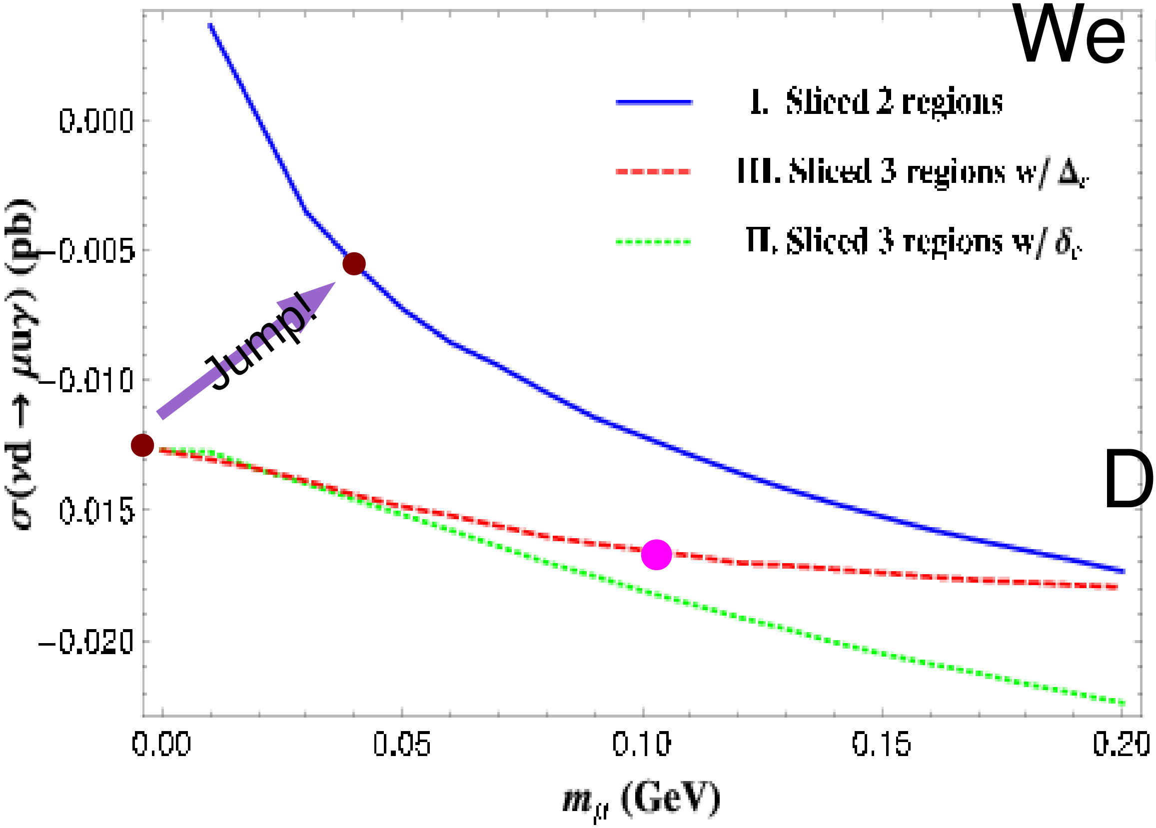
$$\frac{1}{k\cdot p}=\frac{1}{k^0\, p^0(1-\cos\theta)}$$

when the fermion is massless.

Phase space can be sliced into three regions:

1. The region of soft photon radiation (2→2)
   - $k^0\le\delta_s\sqrt{s}/2$
2. The region of collinear radiation (2→2)
   - $1-\cos\theta\le\delta_c$
3. Finite hard photon radiation (2→3)

Phase Space Slicing Method for not-so-heavy muon mass



We modified collinear region:

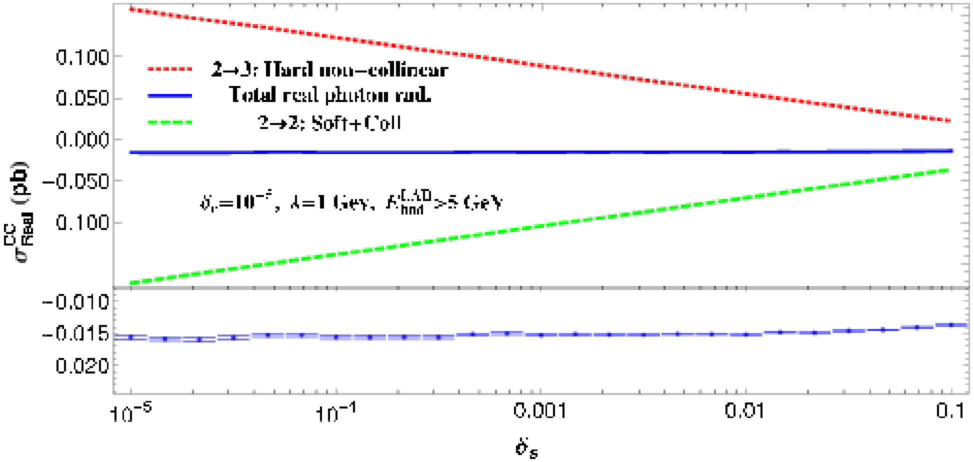
$$\frac{1}{k\cdot p} = \frac{1}{k^0 p^0 \left(1 - \frac{|\mathbf{p}|}{p^0}\cos\theta\right)}$$

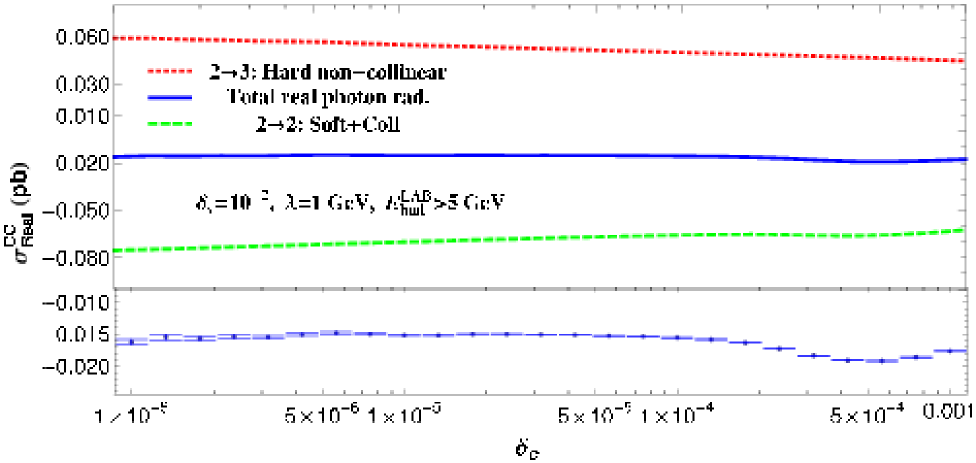
Define new parameter Δ_c

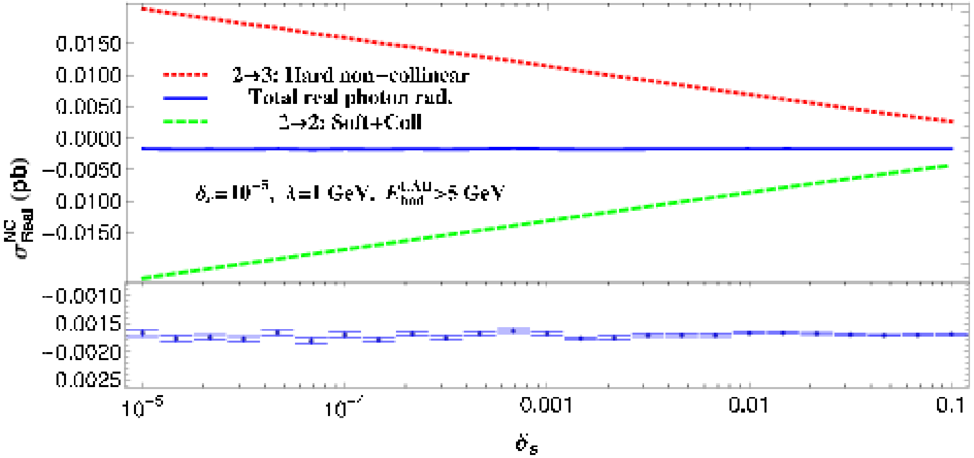
$$\cos\theta \geq \frac{|\mathbf{p}|}{p^0}(1-\delta_c) = 1 - \Delta_c$$

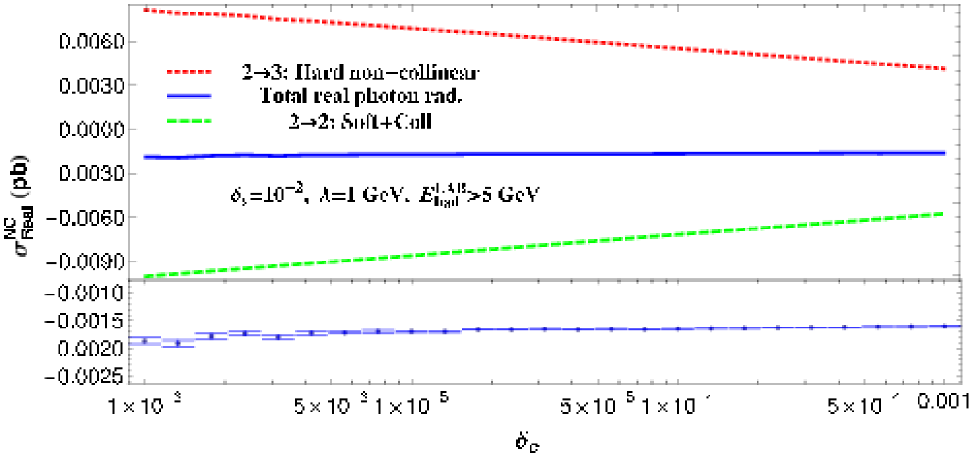
Numerically, collinear singularity is
NOT a point BUT a region !!

Independence on phase space parameters

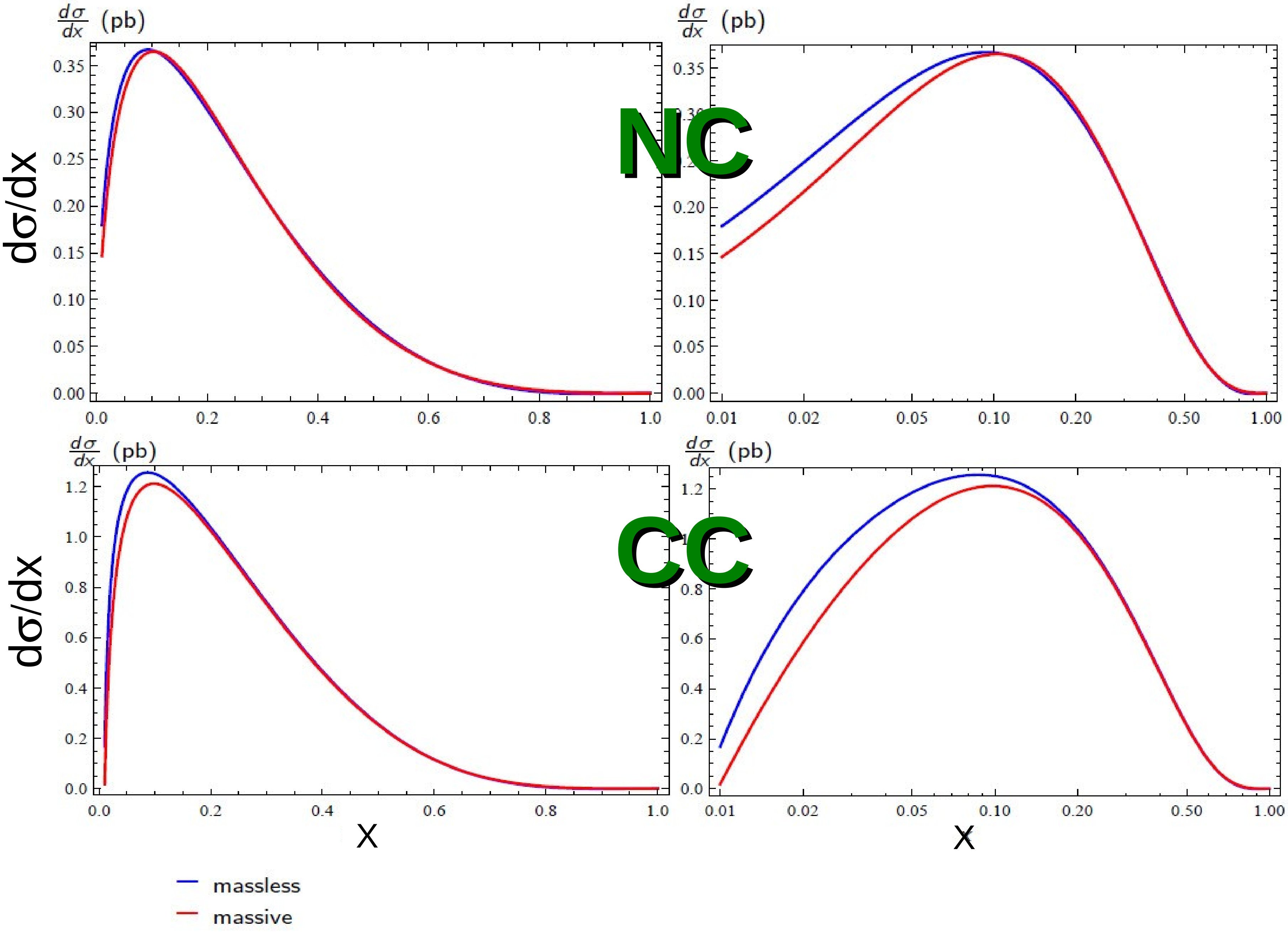

Massive Charged Current (δ_s)


Massive Charged Current (δ_c)

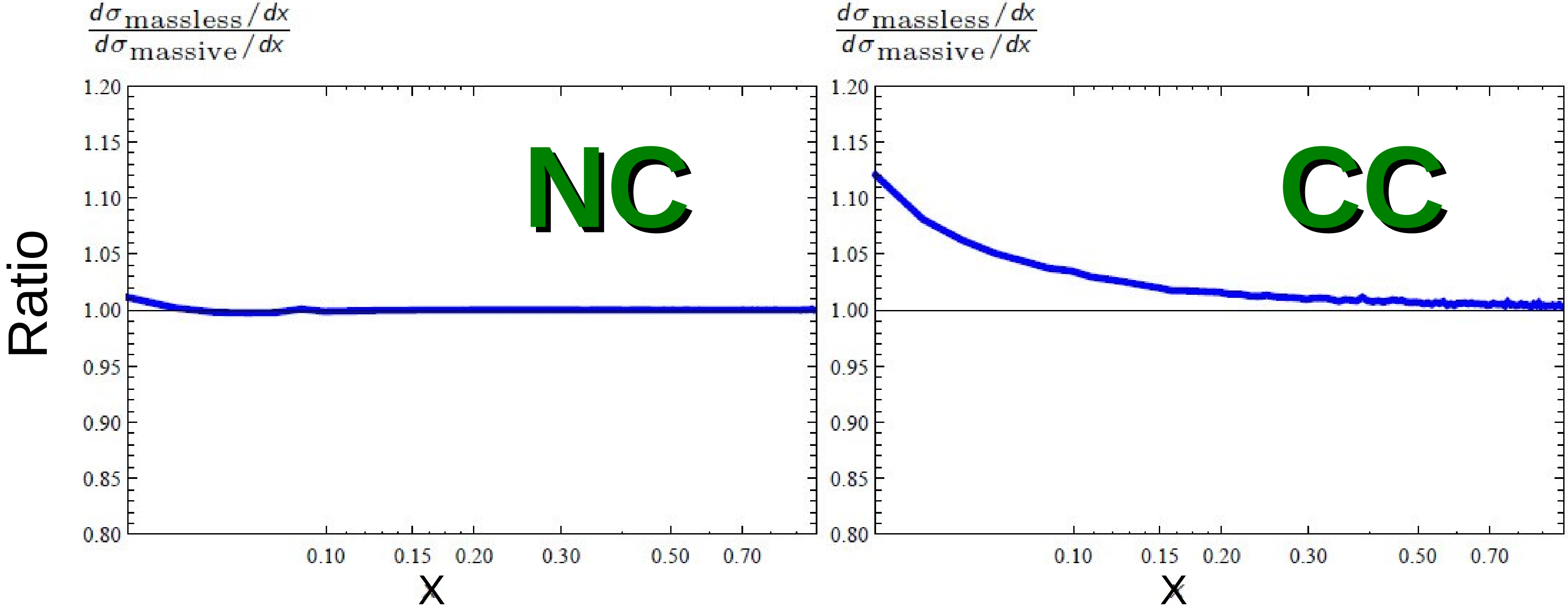

Massive Neutral Current (δ_s)


Massive Neutral Current (δ_c)

Effect of Mass: NC,CC plots



Numerical Results: Ratio plots



$$R=\frac{\sigma_{NC}^{\nu}(\nu N\rightarrow\nu X)-\sigma_{NC}^{\bar{\nu}}(\bar{\nu}N\rightarrow\bar{\nu}X)}{\sigma_{CC}^{\nu}(\nu N\rightarrow l X)-\sigma_{CC}^{\bar{\nu}}(\bar{\nu}N\rightarrow\bar{l}X)}$$

$$=\rho^2\left(\frac{1}{2}-\sin^2\theta_W\right)$$

E. A. Paschos and L. Wolfenstein, Phys. Rev. **D7**, 91 (1973)

Effect on $\sin\theta_W$ and M_W

We define the leading order ratio(R_o^ν), the contribution of *O*(®) corrections for NC(δR_{NC}^ν) and CC(δR_{CC}^ν) as follows:

$$R_o^\nu = \frac{\sigma_{o,NC}^\nu}{\sigma_{o,CC}^\nu}, \qquad \delta R_{NC}^\nu = \frac{\delta\sigma_{NC}^\nu}{\sigma_{o,NC}^\nu}, \qquad \delta R_{NC}^\nu = \frac{\delta\sigma_{CC}^\nu}{\sigma_{o,CC}^\nu}.$$

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta\sin^2\theta_W$
Massless	0.3052(0.04)	0.0532(0.38)	-0.0784(1.43)	-0.0118(0.69)
Massive	0.3152(0.04)	0.0540(0.59)	-0.0622(0.80)	-0.0038(0.46)

$$\Delta\sin^2\theta_W = -\delta\sin^2\theta_W = \frac{\frac{1}{2} - \sin^2\theta_W + \frac{10}{27}\sin^4\theta_W}{1 - \frac{40}{27}\sin^2\theta_W}\left(\delta R_{NC}^\nu + \delta R_{NC}^\nu\right)$$

Difference between massless and massive:

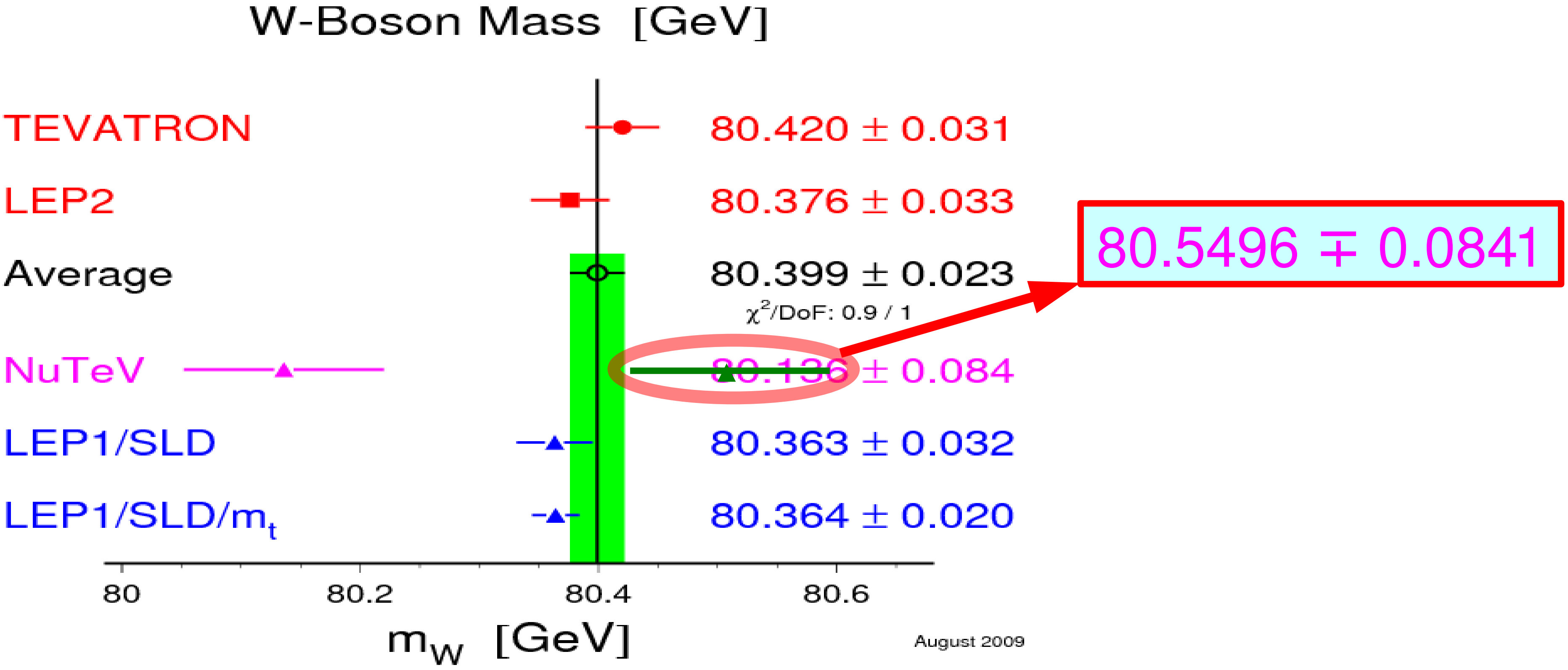
≈ **-0.0080 ∓ 0.00008**

(CTEQ6.6, Mc=1.3Gev, $E_{had}^{LAB} \geq 20\,GeV$)

Shift of M_W

Using $\sin^2\theta_W = 1 - M_W^2 / M_Z^2$,
we can estimate
the change in M_W:

$$\begin{aligned}\Delta M_W &= M_W(massive) - M_W(massless)\\ &\approx \frac{-M_Z^2}{2M_W}\left[\Delta \sin^2\theta_W\right]_{massless}^{massive}\\ &= 0.4136 \pm 0.0043 \quad GeV\end{aligned}$$



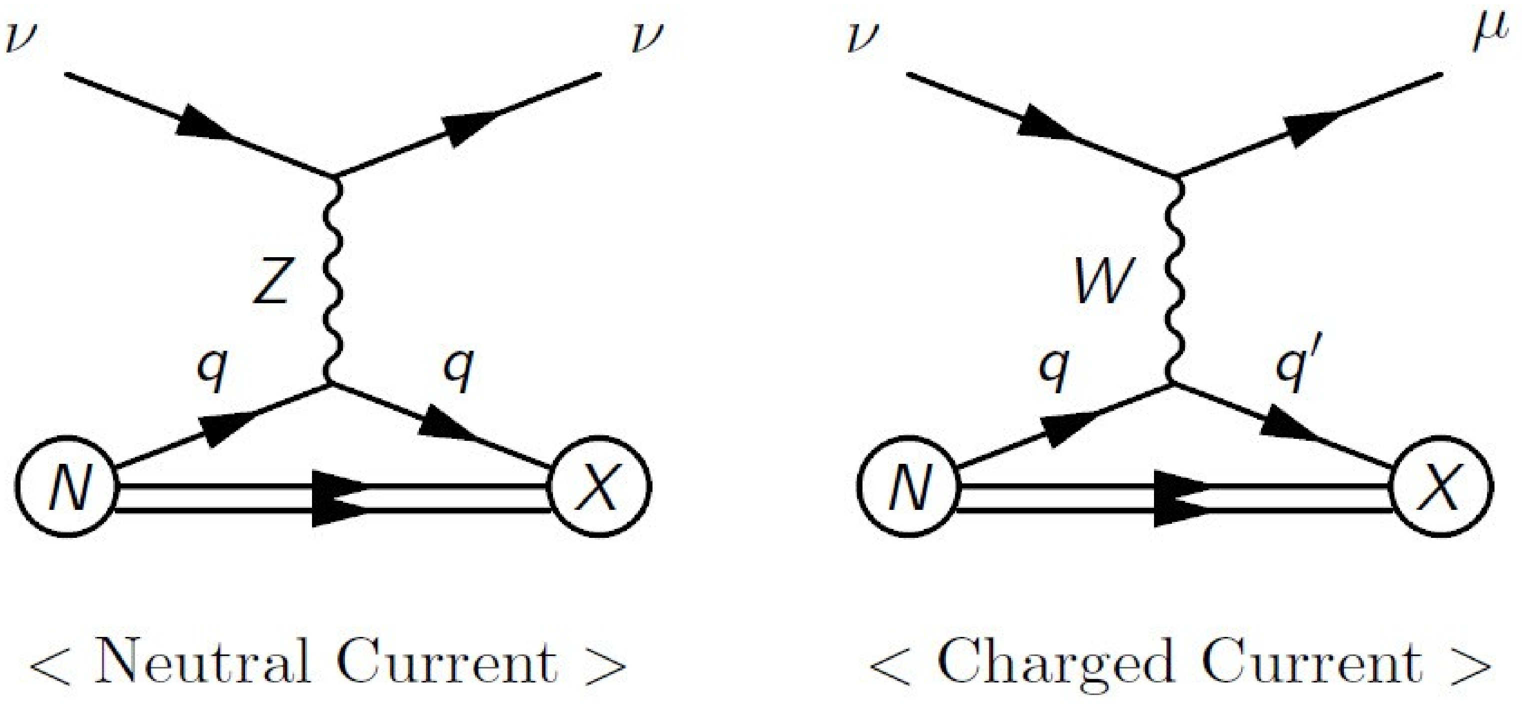
80.5496 ∓ 0.0841

Conclusion

- We calculated the complete eletroweak $O(\alpha)$ corrections to neutrino-nucleon scattering processes based on the massless fermion approximations (used in the NuTeV analysis) and with the full fermion mass dependence.
- The calculation is implemented in a Monte Carlo program
- We studied the shift in $\sin^2\theta_W$ and M_W due to fermion mass effect and found that there was a finite fermion mass effect !
- Although more detailed studies are needed with more realistic cuts, this result shows that fermion mass effects may explain some of the deviations observed by the NuTeV collaboration. (we are preparing another paper for this work with NuTeV collaboration.)

BackUp Slides

Calculation: Leading Order

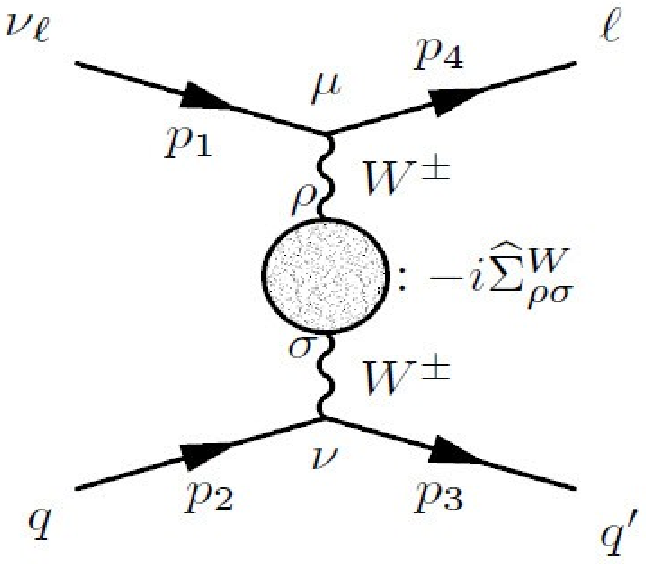


- Cr
multiplication of leptonic(L¹) and hadronic(Hº) currents
- L¹ and Hº are function of fermion masses:

¾$_{NC}$ ~ L¹(mº, mº , ...) Hº(mq, mq, ...) — massive terms vanish (NC)

¾$_{CC}$ ~ L¹(mº, m¹ , ...) Hº(mq, mq',...) — massive terms survive (CC)

Calculation: Mass effect



Consider self-energy correction:

► Two-point self-energy function:

$$\hat{\Sigma}^W_{\rho\sigma} = \left(g_{\rho\sigma} - \frac{k_\rho k_\sigma}{k^2} \right) \hat{\Sigma}^W_T + \frac{k_\rho k_\sigma}{k^2} \hat{\Sigma}^W_L$$

► Contribution to cross section:

$$\sigma_{se} \sim \sigma_o \left(\frac{2\hat{\Sigma}^W_T}{t + M_W^2} - \frac{m_\mu^2 m_c^2 u (\hat{\Sigma}^W_L - \hat{\Sigma}^W_T)}{4t(t + M_W^2)} \right)$$

where, t and u are Mandelstam variables.

- Vertex and Box Corrections also have similar expression like this
- In small t region, second term is NOT negligible.
- Small t region corresponds to small x region,
  where x is momentum fraction

Numerical Results: Input parameters

$\alpha(0) = 1/137.03599911$

$M_Z = 91.1876 \; GeV$

$m_e = 0.51099892 \; MeV$

$m_u = 66 \; MeV$

$m_c = 1.3 \; GeV$

$m_t = 178 \; GeV$

$V_{ud} = 0.9754$

$V_{cd} = 0.2205$

$M_W = 80.425 \; GeV$

$M_H = 115 \; GeV$

$m_\mu = 105.658369 \; MeV$

$m_d = 66 \; MeV$

$m_s = 150 \; MeV$

$m_b = 4.3 \; GeV$

$V_{us} = 0.2205$

$V_{cs} = 0.9754$

Calculation

$$R=\frac{\sigma^{\nu}_{NC}(\nu N\rightarrow\nu X)-\sigma^{\bar{\nu}}_{NC}(\bar{\nu} N\rightarrow\bar{\nu} X)}{\sigma^{\nu}_{CC}(\nu N\rightarrow l X)-\sigma^{\bar{\nu}}_{CC}(\bar{\nu} N\rightarrow\bar{l} X)}$$

$$=\rho^2\left(\frac{1}{2}-\sin^2\theta_W\right)$$

- $\sin^2\theta_W=1-\frac{M_W^2}{M_Z^2}$ (On-shell scheme)
- Data(¾) + Theory(½) → sin^2 μ$_\mathrm{W}$ → M$_\mathrm{W}$
- NuTeV : sin^2 μ$_\mathrm{w}$ = 0.22773 ∓ 0.00135 (stat) ∓ 0.00135 (stat)
- Average: sin^2 μ$_\mathrm{W}$ = 0.2227 ∓ 0.00037

NuTeV G. P. Zeller et al., Phys. Rev. Lett. **88**, 091802 (2002)
E. A. Paschos and L. Wolfenstein, Phys. Rev. **D7**, 91 (1973)

Possible explanations

► QCD corrections

- Perturbative QCD corrections

  → small

- Uncertainties on Parton Distribution Function (PDF)

  → in future global analysis

- Isospin breaking

  → large isospin violation in PDF could explain NuTeV anomaly

► Electroweak radiative corrections

This talk is about both mainly Electroweak radiative corrections and slightly isospin breaking.

Kevin S. McFarland and Sven-Olaf Moch, hep-ph/0306052