

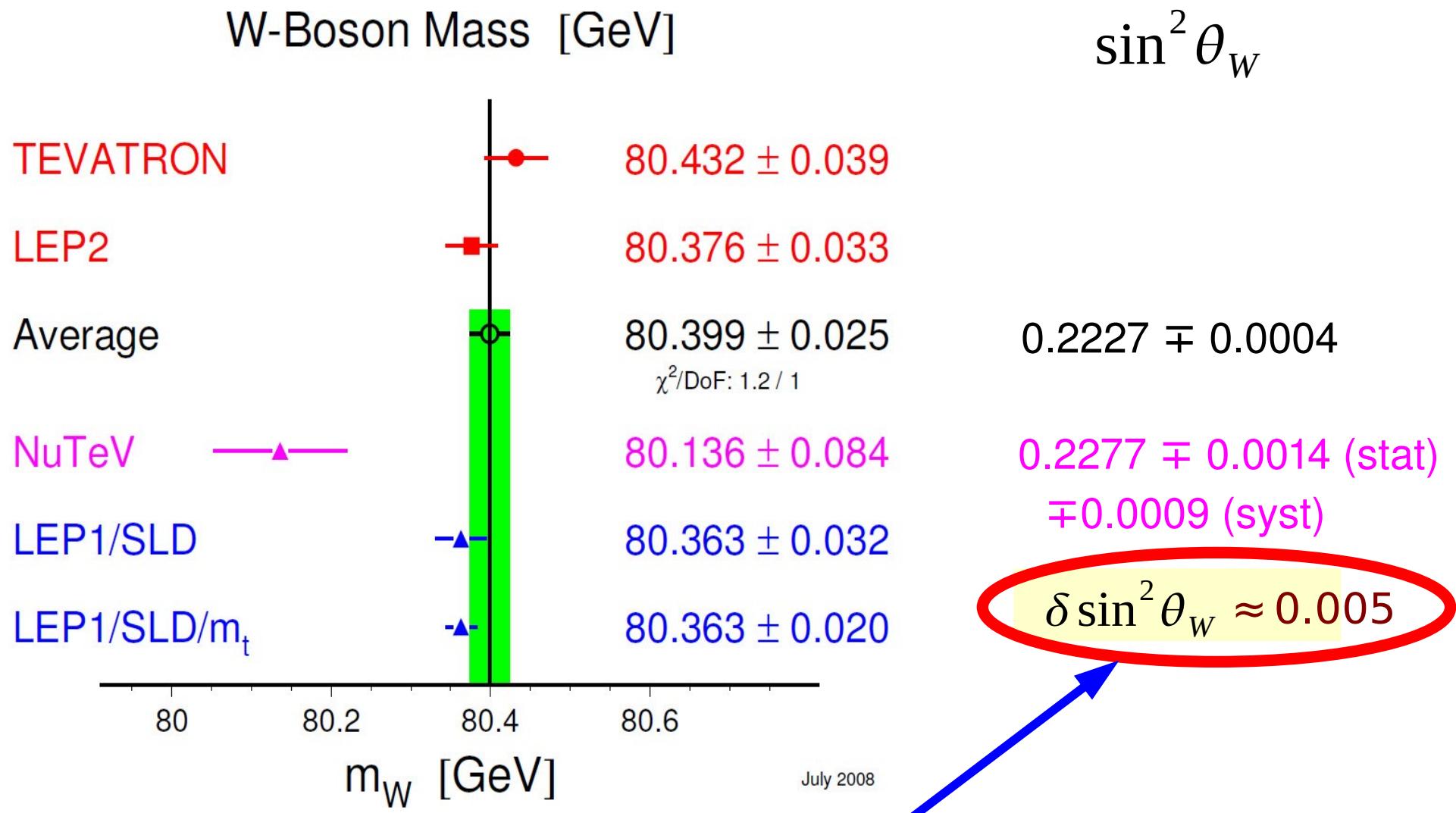
Electroweak radiative corrections to neutrino- nucleon scattering at NuTeV

Kwangwoo Park



PHENO09, May 11 2009

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



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

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

Existing Calculations

1. Bardin and Dokuchaeva (JINR-E2-86-260 (1986))
 - ▶ Not include full electroweak $O(\alpha)$ corrections.
 - ▶ **Massless** fermion approximation.
 - ▶ Used in NuTeV analysis.
2. Arbuzov, Bardin and Kalinovskaya.(JHEP **0506**, 078 (2005))
 - ▶ Include full electroweak $O(\alpha)$ corrections.
 - ▶ **Massless** fermion approximation.
3. Diener, Dittmaier and Hollik (Phys. Rev. D **69**, 073005, 2004
,Phys. Rev. D **72**, 093002 ,2005)
 - ▶ Include full electroweak $O(\alpha)$ corrections.
 - ▶ Higher order FSR, unv. 2-loop, γ induced precess
 - ▶ **Massless** fermion approximation
 - ▶ study the dependence on input-parameter scheme.

Motivation for our calculation

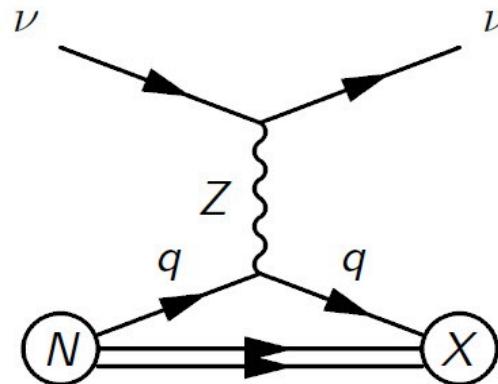
- ▶ Include full electroweak $O(\alpha)$ corrections.
- ▶ study the effect of fermion mass
- ▶ study the effect with realistic, experimental set-up

“Massless” / “Massive”

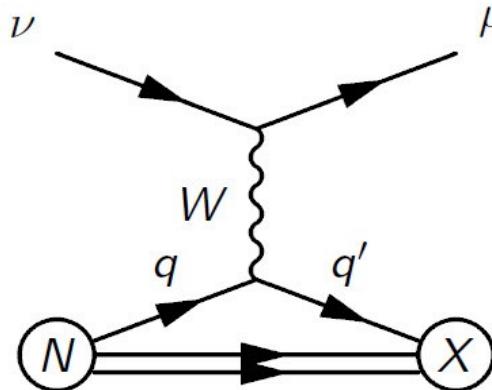
“Massless” : All fermion masses have only been used to regularize mass singularities, **otherwise neglected**.

“Massive” : Heavy fermion masses (muon, charm quark) have been taken into account **everywhere**.

W mass from νN scattering



< Neutral Current >



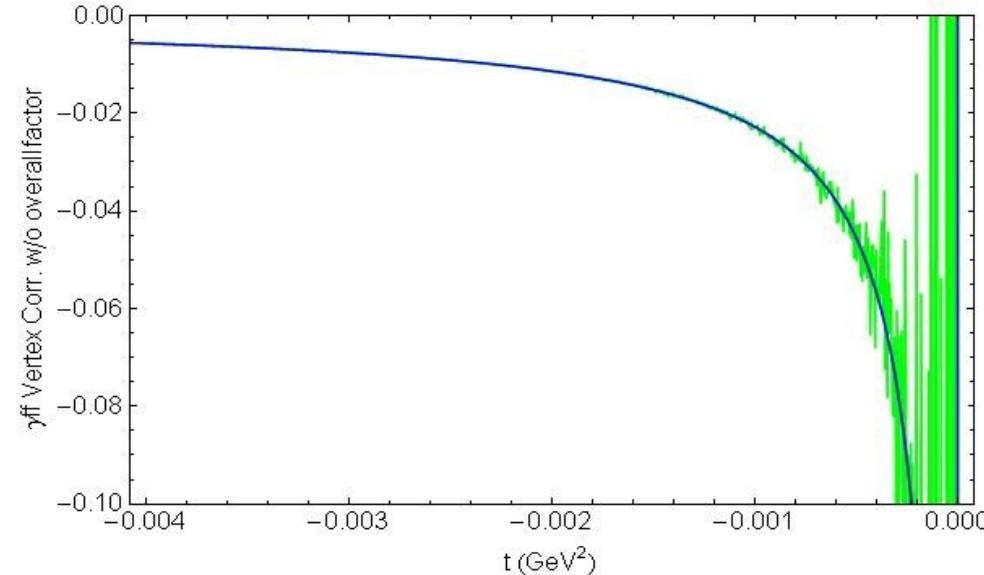
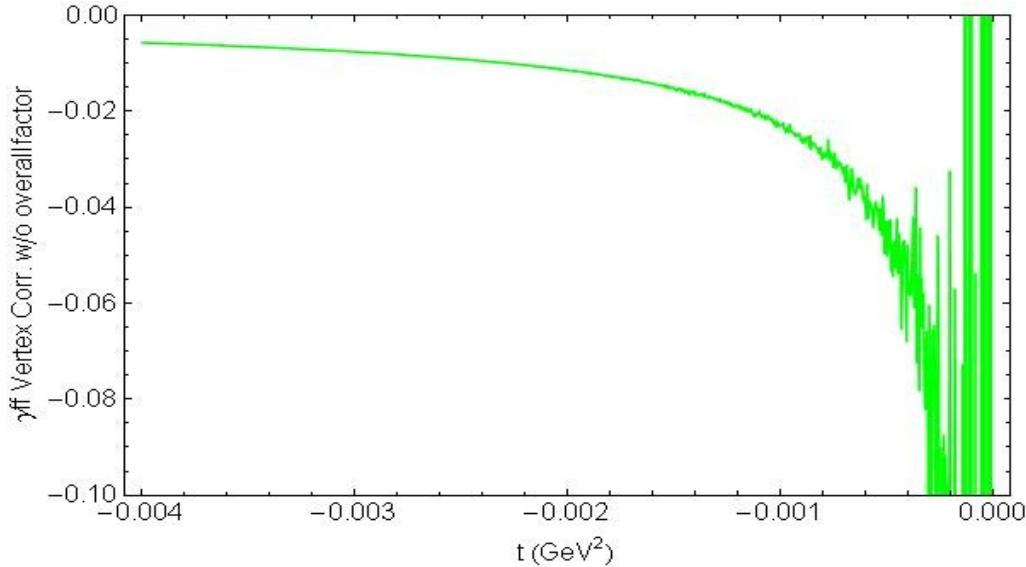
< Charged Current >

$$R = \frac{\sigma_{NC}^\nu(\nu N \rightarrow \nu X) - \sigma_{NC}^{\bar{\nu}}(\bar{\nu} N \rightarrow \bar{\nu} X)}{\sigma_{CC}^\nu(\nu N \rightarrow l X) - \sigma_{CC}^{\bar{\nu}}(\bar{\nu} N \rightarrow \bar{l} X)} = \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W \right)$$

- $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$ (On-shell scheme)
- Data(σ) + Theory(ρ) $\rightarrow \sin^2 \theta_W \rightarrow M_W$

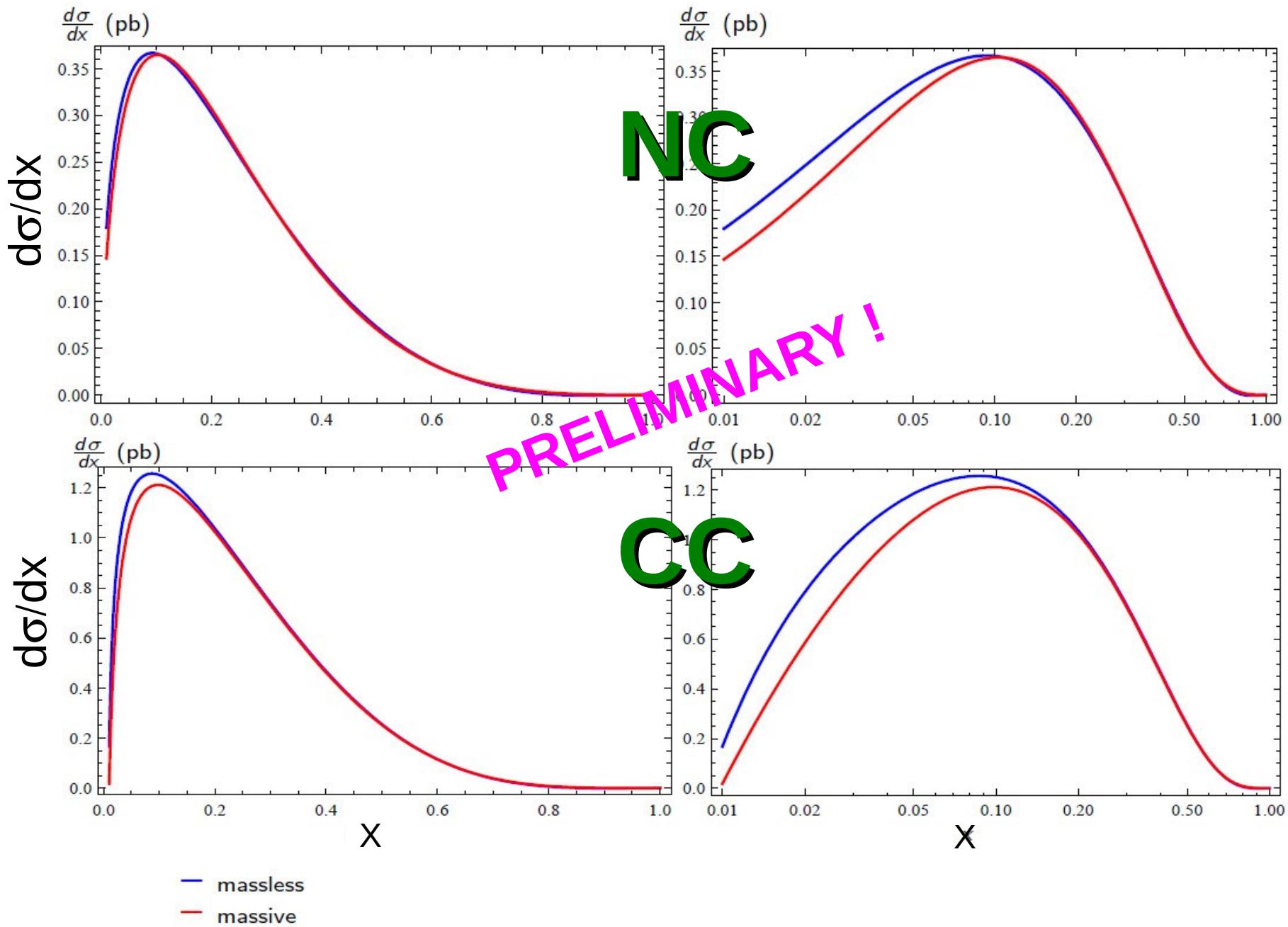
NuTeV G. P. Zeller et al., Phys. Rev. Lett. **88**, 091802 (2002)
 E. A. Paschos and L. Wolfenstein, Phys. Rev. **D7**, 91 (1973)

Numerical Instability

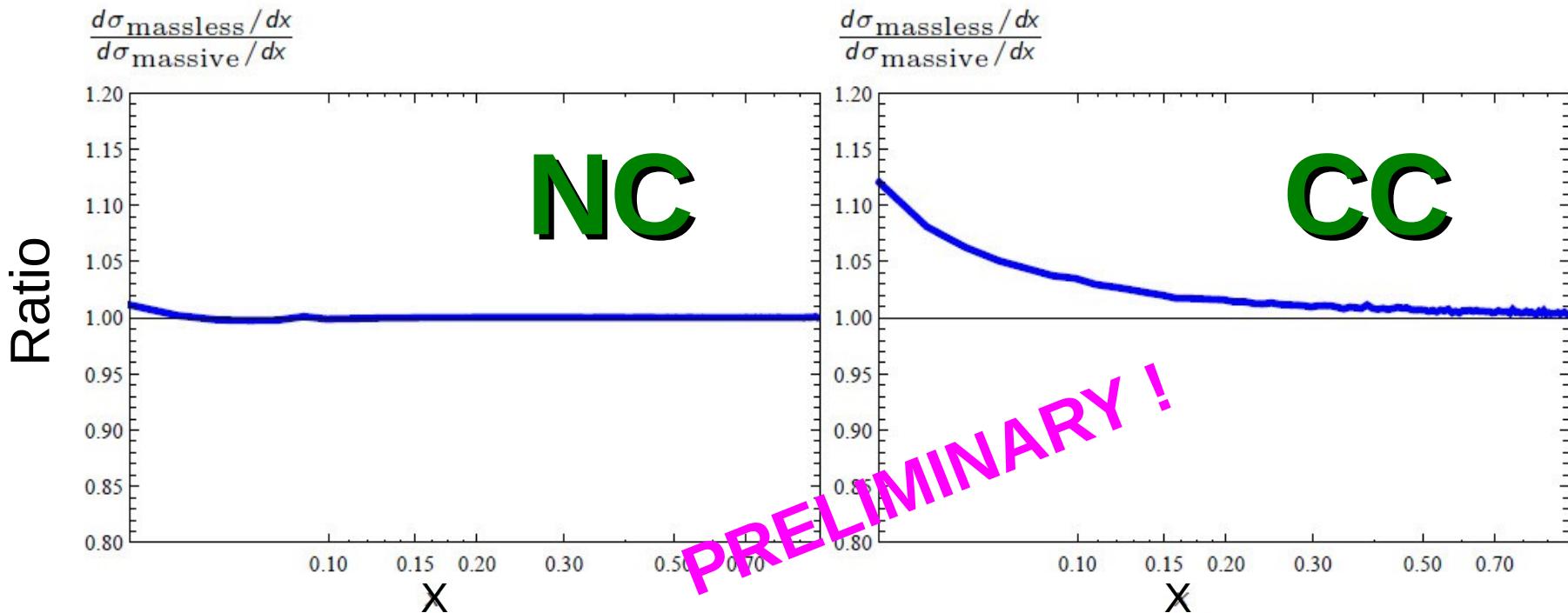


- The diagram in which photon is involved, has **numerical instability in small Q^2 ($=-t$)** due to t pole ($1/t$).
- We **expand those expression up to $O(t^3)$** to fix numerical instability.

Effect of Mass at small x



Numerical Results: massless vs massive



$$R = \frac{\sigma_{NC}^{\nu}(\nu N \rightarrow \nu X) - \sigma_{NC}^{\bar{\nu}}(\bar{\nu} N \rightarrow \bar{\nu} X)}{\sigma_{CC}^{\nu}(\nu N \rightarrow l X) - \sigma_{CC}^{\bar{\nu}}(\bar{\nu} N \rightarrow \bar{l} X)}$$
$$= \rho^2 \left(\frac{1}{2} - \sin^2 \theta_W \right)$$

Numerical Results: Other dependence

$\Delta \sin^2 \theta_W$ is sensitive to the choice of PDF, cuts, final photon treatment, isospin symmetry and so on.

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH I	0.31766	0.0582	-0.0758	-0.0082
BPW I	0.30638	0.0527	-0.0916	-0.0182
DDH III	0.31167	0.0668	-0.0365	-0.0142
DDH II	0.30455	0.0562	-0.0840	-0.0130
BPW II	0.30471	0.0527	-0.0877	-0.0183

 NuTeV Anomaly: $\delta \sin^2 \theta_W \approx 0.005$

BPW I, II: calculation by Baur, K. Park and Wackerlo

DDH I, II, III : calculation by Diener, Dittmaier and Hollik (Phys. Rev. D **69**, 073005 (2004,2005))

Definition of DDH I,II,III and Massless I,II

DDH(I): CTEQ4L, $y < 0.125$,

$$y = E_{had}^{LAB} / E_{\nu}^{LAB} = \frac{-\hat{S}}{\hat{t}}$$

DDH(II): MRST2004QED, $E_{had+phot}^{LAB} < 20$.

DDH(III): MRST2004QEDx(switted off $O(\alpha)$ corr.),
 $E_{had+phot}^{LAB} < 20$.

BPW(I): MRST2004QED, $y < 0.12$

BPW(II): MRST2004QED, $y < 0.22$

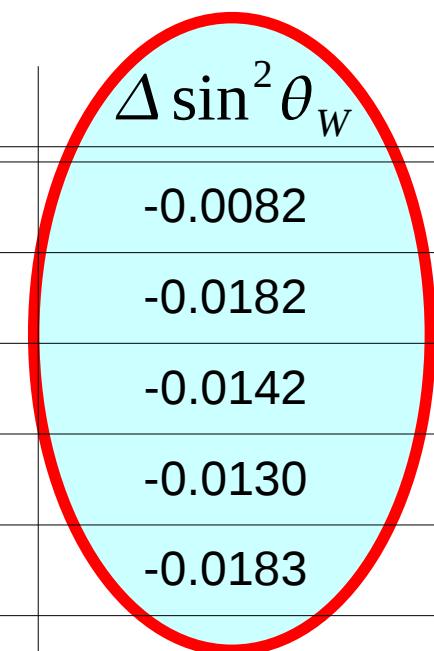
DDH: Diener, Dittmaier and Hollik (Phys. Rev. D **69**, 073005, 2004
, Phys. Rev. D **72**, 093002 ,2005)

BPW : Baur, Park and Wackerth (in preparation)

Numerical Results: Other dependence

$\Delta \sin^2 \theta_W$ is sensitive to the choice of PDF, cuts, final photon treatment, isospin symmetry and so on.

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH I	0.31766	0.0582	-0.0758	-0.0082
BPW I	0.30638	0.0527	-0.0916	-0.0182
DDH III	0.31167	0.0668	-0.0365	-0.0142
DDH II	0.30455	0.0562	-0.0840	-0.0130
BPW II	0.30471	0.0527	-0.0877	-0.0183

 NuTeV Anomaly: $\delta \sin^2 \theta_W \approx 0.005$

BPW I, II: calculation by Baur, K. Park and Wackerlo

DDH I, II, III : calculation by Diener, Dittmaier and Hollik (Phys. Rev. D **69**, 073005 (2004,2005))

Numerical Results: Other dependence

$\Delta \sin^2 \theta_W$ is sensitive to the choice of PDF, cuts, final photon treatment, isospin symmetry and so on.

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH I	0.31766	0.0582	-0.0758	-0.0082
BPW I	0.30638	0.0527	-0.0916	-0.0182
DDH II	0.31167	0.0668	-0.0365	-0.0142
DDH III	0.30455	0.0562	-0.0840	-0.0130
BPW II	0.30471	0.0527	-0.0877	-0.0183

Dependence on PDF and Isospin Symm.

$\Delta \sin^2 \theta_W$ is sensitive to the choice of PDF, cuts, final photon treatment, isospin symmetry and so on.

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH I	0.31766	0.0582	-0.0758	-0.0082
BPW I	0.30638	0.0527	-0.0916	-0.0182

DDH I : CTEQ4L,
y_{cut}=0.125 ,
Isospin symmetry.

BPW I: MRST2004QED ,
y_{cut}=0.12 ,
Isospin breaking.

(see also DDHII)

Numerical Results: Other dependence

$\Delta \sin^2 \theta_W$ is sensitive to the choice of PDF, cuts, final photon treatment, isospin symmetry and so on.

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH I	0.31766	0.0582	-0.0758	-0.0082
BPW I	0.30638	0.0527	-0.0916	-0.0182
DDH III	0.31167	0.0668	-0.0365	-0.0142
DDH II	0.30455	0.0562	-0.0840	-0.0130
BPW II	0.30471	0.0527	-0.0877	-0.0183

Dependence on photon treatment

DDH II :	MRST2004QED, Isospin breaking.	$E_{had + phot}^{LAB} < 20,$
BPW II:	MRST2004QED , Isospin breaking.	$E_{had}^{LAB} < 17.6,$
DDH (I*):	CTEQ4L Isospin symmetry.	$E_{had + phot}^{LAB} < 10,$

	R_o^ν	δR_{NC}^ν	δR_{CC}^ν	$\Delta \sin^2 \theta_W$
DDH II	0.30455	0.0562	-0.0840	-0.0130
BPW II	0.30471	0.0527	-0.0877	-0.0183
DDH(I)	0.31766	0.0582	-0.0758	-0.0082
DDH(I*)	0.31766	0.0589	-0.0842	-0.0118

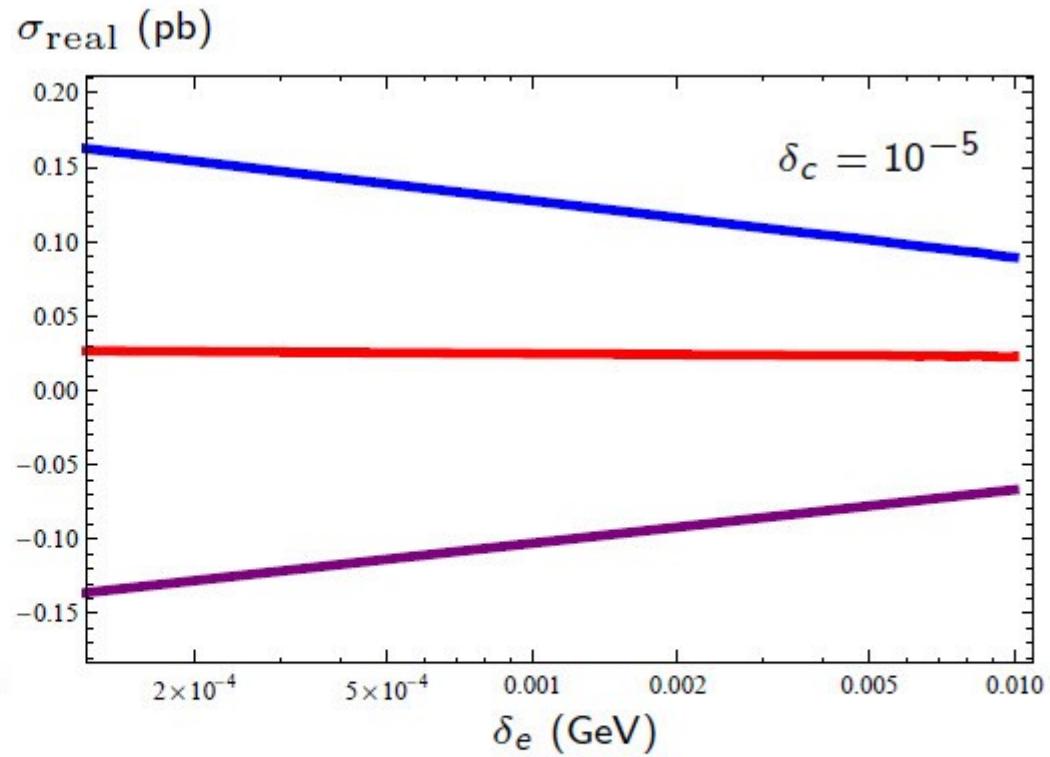
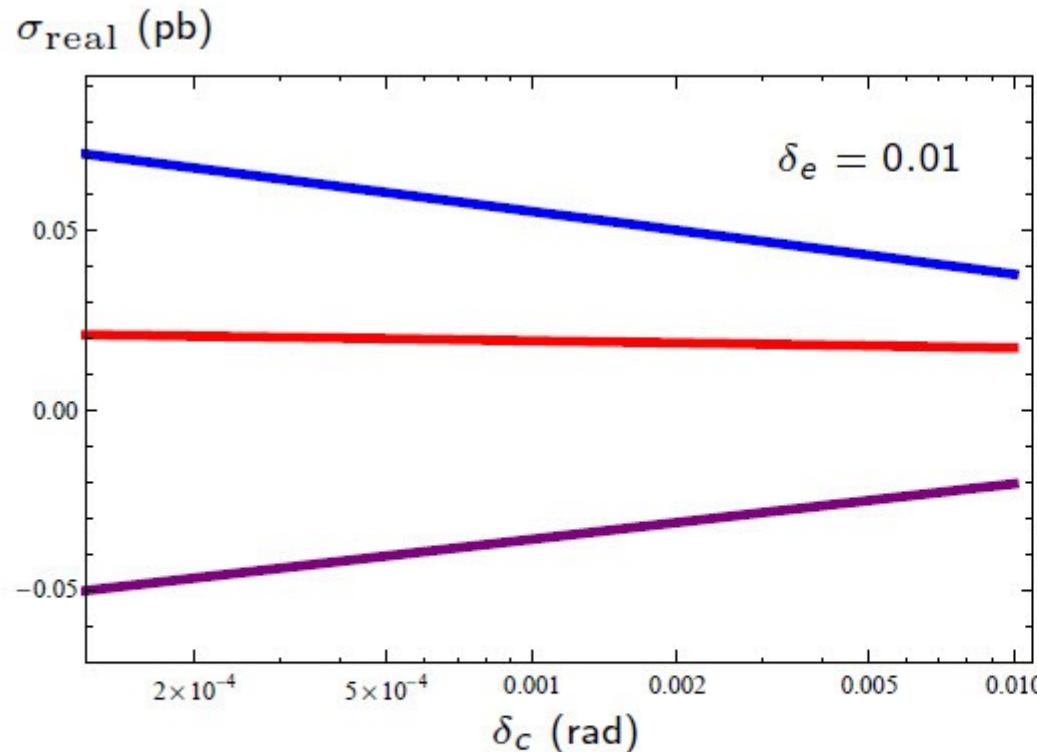
More realistic study is needed in coll. with NuTeV (in progress...)

Conclusion

- ▶ We calculated the complete electroweak $O(\alpha)$ 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**
- ▶ The detailed study of fermion mass effect is in progress. Also updated study on PDF uncertainty including isospin breaking effect will be available soon !
- ▶ Although more detailed studies are needed with more realistic setup, results from previous and this study shows that
 - Theoretical uncertainties due to EW corrections need to be carefully included into NuTeV analysis.
 - The effect of isospin breaking may be NOT negligible
 - An updated study of PDF uncertainty is necessary

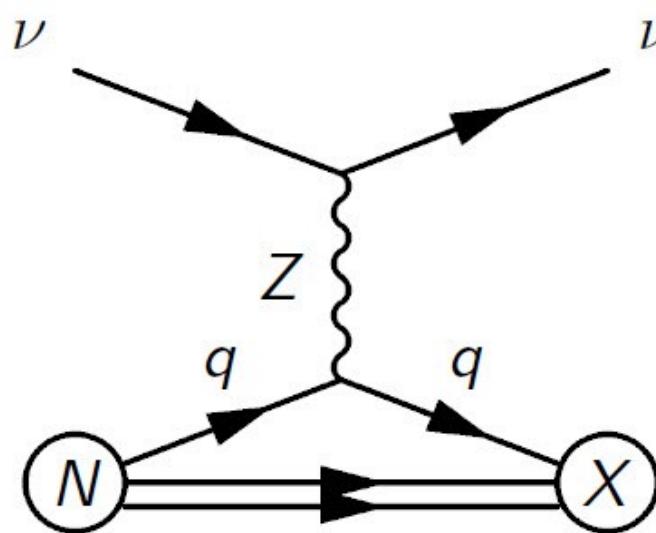
BackUp Slides

Numerical Results: Independence on phase space slicing parameters

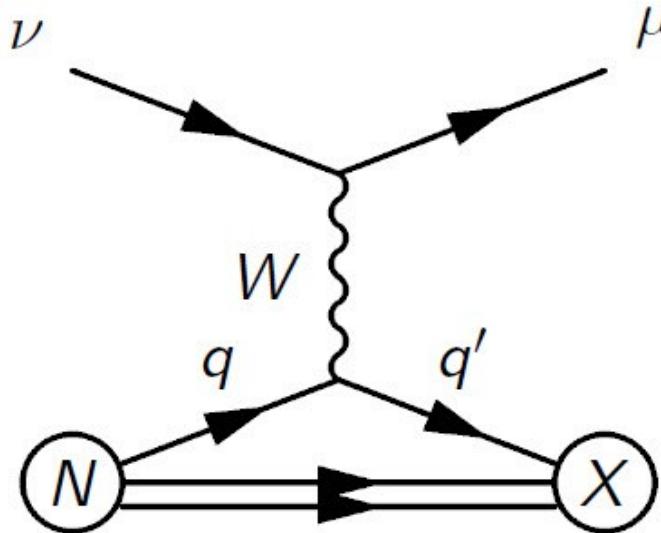


- finite($2 \rightarrow 3$)
- soft+coll.($2 \rightarrow 2$)
- finite+soft+coll.

Calculation: Leading Order



< Neutral Current >



< Charged Current >

- Cross section, σ can be derived from the multiplication of leptonic(L^μ) and hadronic(H_μ) currents
- L^μ and H_μ are function of fermion masses:

$\sigma_{NC} \sim L^\mu(m_\nu, m_\nu, \dots) H_\mu(m_\nu, m_\nu, \dots)$ — massive terms vanish (NC)

$\sigma_{CC} \sim L^\mu(m_\nu, m_\nu, \dots) H_\mu(m_\nu, m_\mu, \dots)$ — massive terms survive (CC)

Calculation: Mass effect

Consider self-energy correction:

- Two-point self-energy function:

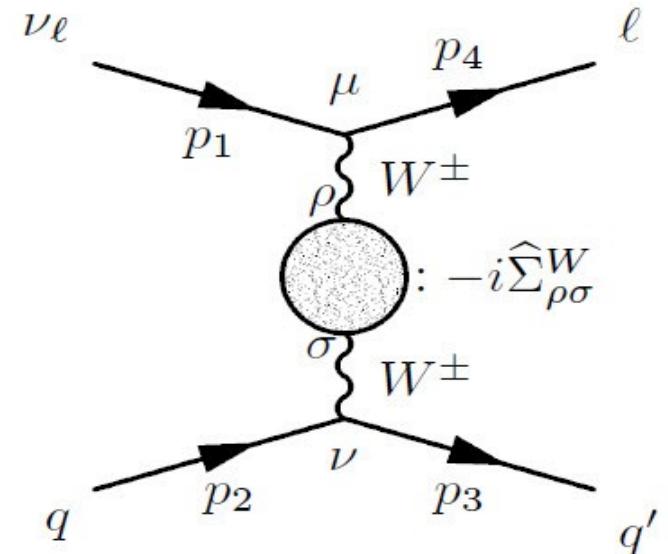
$$\hat{\Sigma}_{\rho\sigma}^W = \left(g_{\rho\sigma} - \frac{k_\rho k_\sigma}{k^2} \right) \hat{\Sigma}_T^W + \frac{k_\rho k_\sigma}{k^2} \hat{\Sigma}_L^W$$

- Contribution to cross section:

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

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

$$\alpha(0) = 1/137.03599911$$

$$M_Z = 91.1876 \text{ GeV}$$

$$m_e = 0.51099892 \text{ MeV}$$

$$m_u = 66 \text{ MeV}$$

$$m_c = 1.2 \text{ GeV}$$

$$m_t = 178 \text{ GeV}$$

$$V_{ud} = 0.9754$$

$$V_{cd} = 0.2205$$

$$M_W = 80.425 \text{ GeV}$$

$$M_H = 115 \text{ GeV}$$

$$m_\mu = 105.658369 \text{ MeV}$$

$$m_d = 66 \text{ MeV}$$

$$m_s = 150 \text{ MeV}$$

$$m_b = 4.3 \text{ GeV}$$

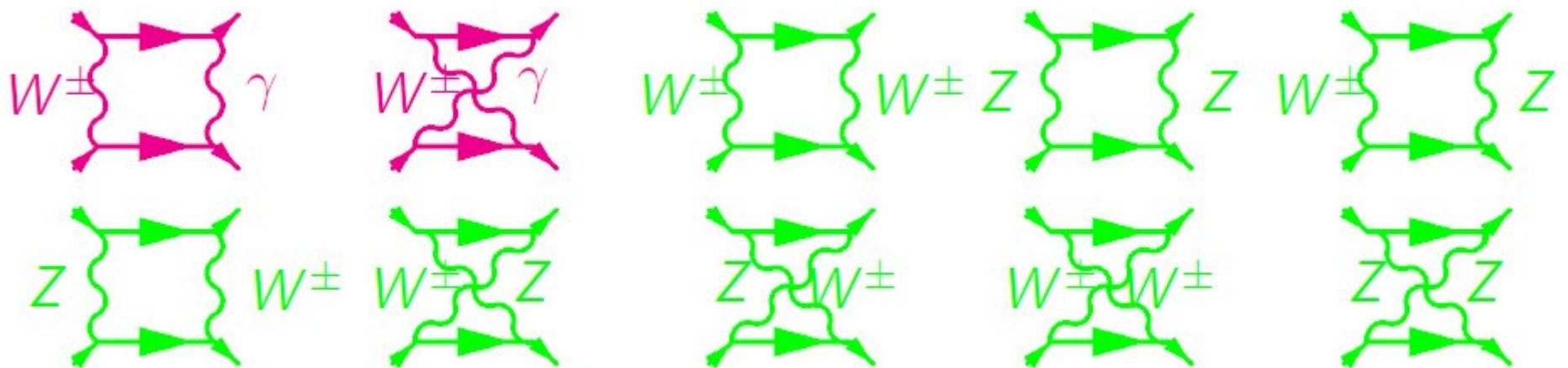
$$V_{us} = 0.2205$$

$$V_{cs} = 0.9754$$

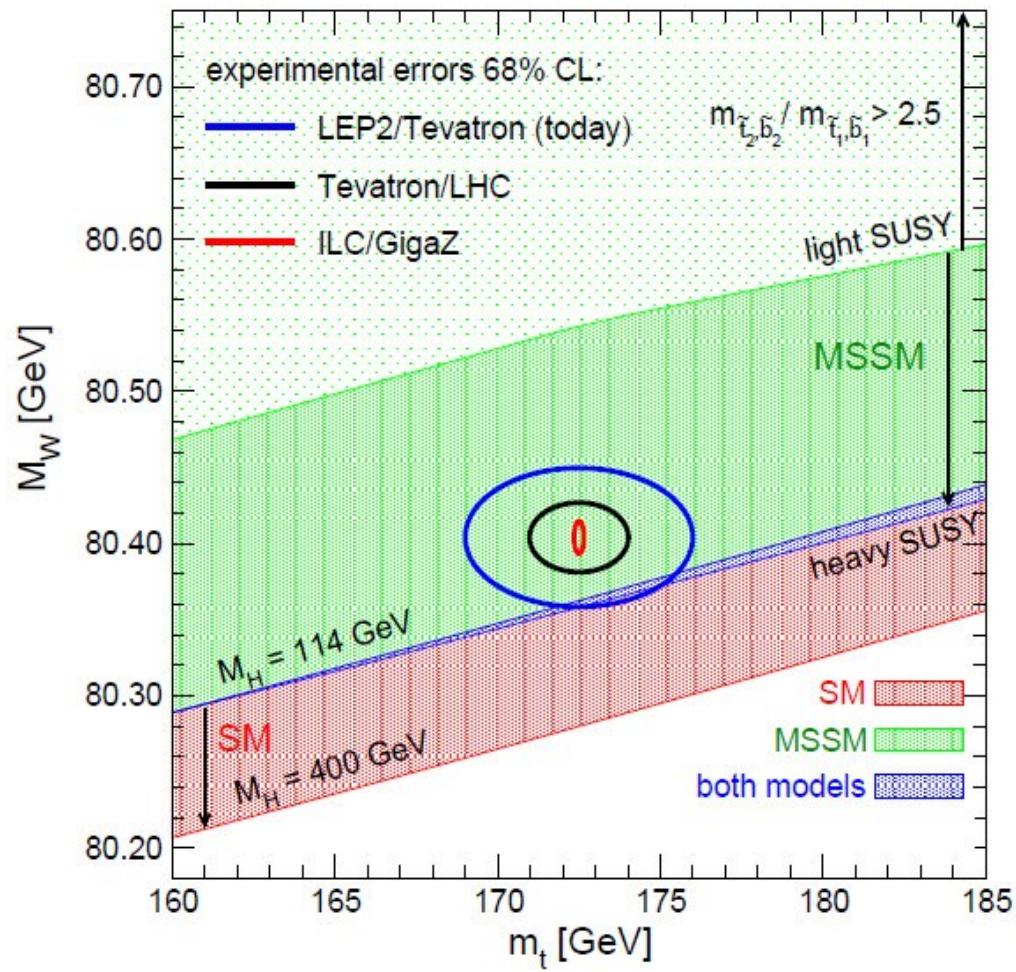
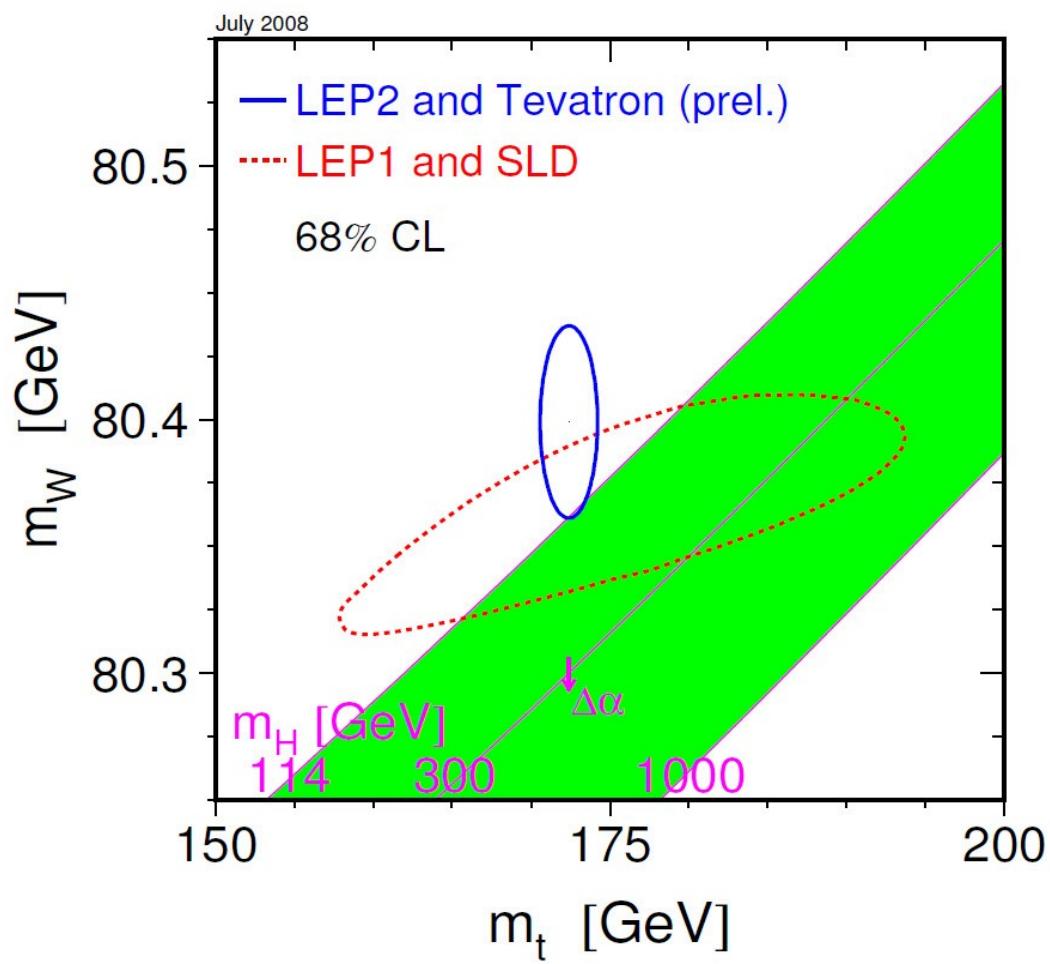
Existing Calculations I

1. Bardin and Dokuchaeva (JINR-E2-86-260 (1986))

- Not include full electroweak $O(\mathbb{R})$ corrections.
 - They did **include QED** but **not WEAK boxes**.



- Used in NuTeV analysis.



$$M_H = 84^{+34}_{-26} \text{ GeV}$$

LEP EWWG 2008(<http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2008>)
S. Heinemeyer et al., hep-ph/060417(www.ifca.unican.es/heinemey/uni/plots/)