BROOKHAVEN NATIONAL LABORATORY

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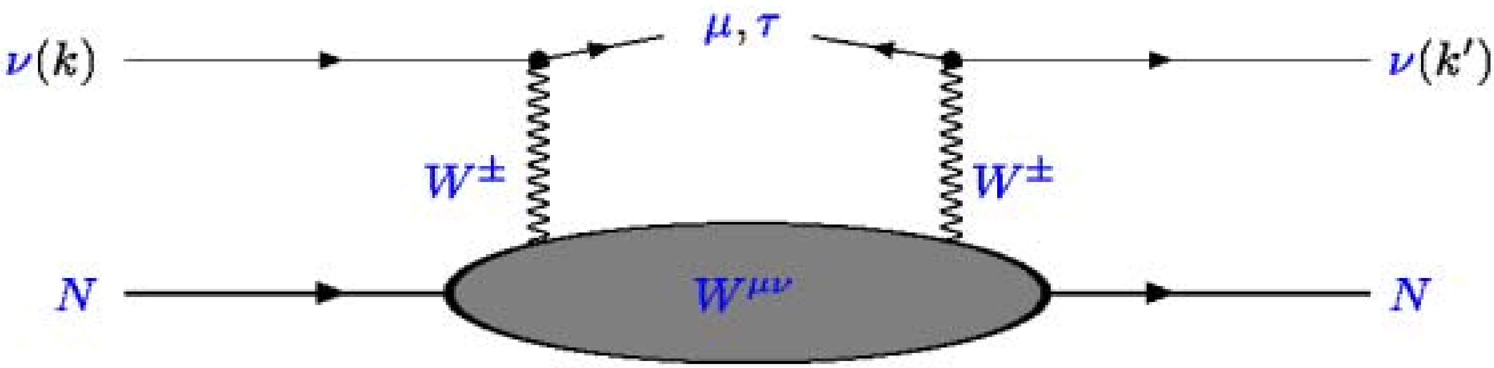
Mass Effects in Charged Current Scattering

- Collaboration with M.H. Reno (U. of Iowa):
  Tau Neutrino Deep Inelastic Charged Current Interactions
  Phys. Rev. D (2002)
- Title(s) say(s) it, and some more. Time is running, ...

Some theory to set the canvas ...

Neutrino Nucleon Scattering



$$d\sigma \propto L^{\mu\nu} W_{\mu\nu}$$

$$W_{\mu\nu} = \Im\left[i \int d^4x\, e^{iqx} \left\langle P \middle| T\, J^+_\mu(x) J_\nu(0) \middle| P \right\rangle \right]$$

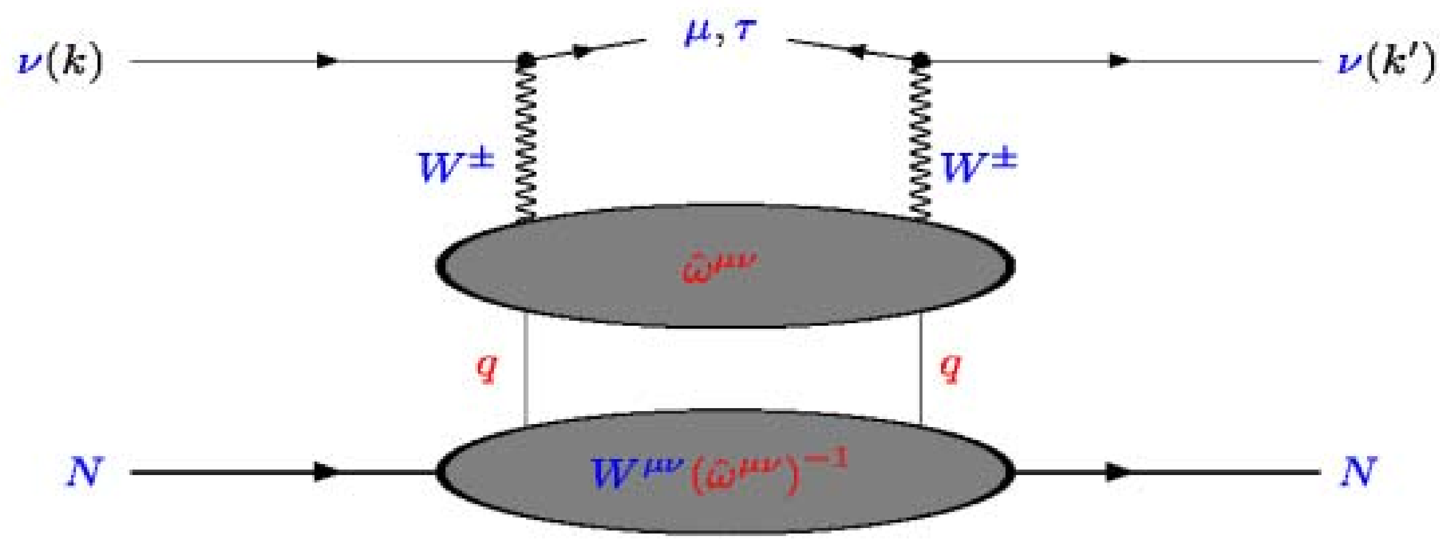
$$= \frac{1}{2} \int d^4x\, e^{iqx} \left\langle P \middle| J^+_\mu(x)\, \mathbf{1}\, J_\nu(0) \middle| P \right\rangle$$

$$\mathbf{1} = \sum_X | X \rangle \langle X |$$

$\sum_X$: Inclusive Sum covers

- (Quasi-)Elastic $| X \rangle = | N \rangle$
- Resonances / low multiplicity $| X \rangle = | N\pi \rangle$
- Continuum $| X \rangle = | multi-particle \rangle$

Deep Inelastic Scattering: *Factorization*...



$$W_{\mu\nu} = q(\mu) \otimes \hat{\omega}\left(\frac{Q}{\mu}, \alpha_s(\mu)\right) + O\left(\frac{1}{Q^2}\right)$$

...in the limit of light-cone dominance $Q^2 \equiv p_W^2 \to \infty$:

- operator product (twist) expansion (# of participating partons) of $W_{\mu\nu}$
- perturbative expansion (# of radiation vertices) of $\hat{\omega}_{\mu\nu}$

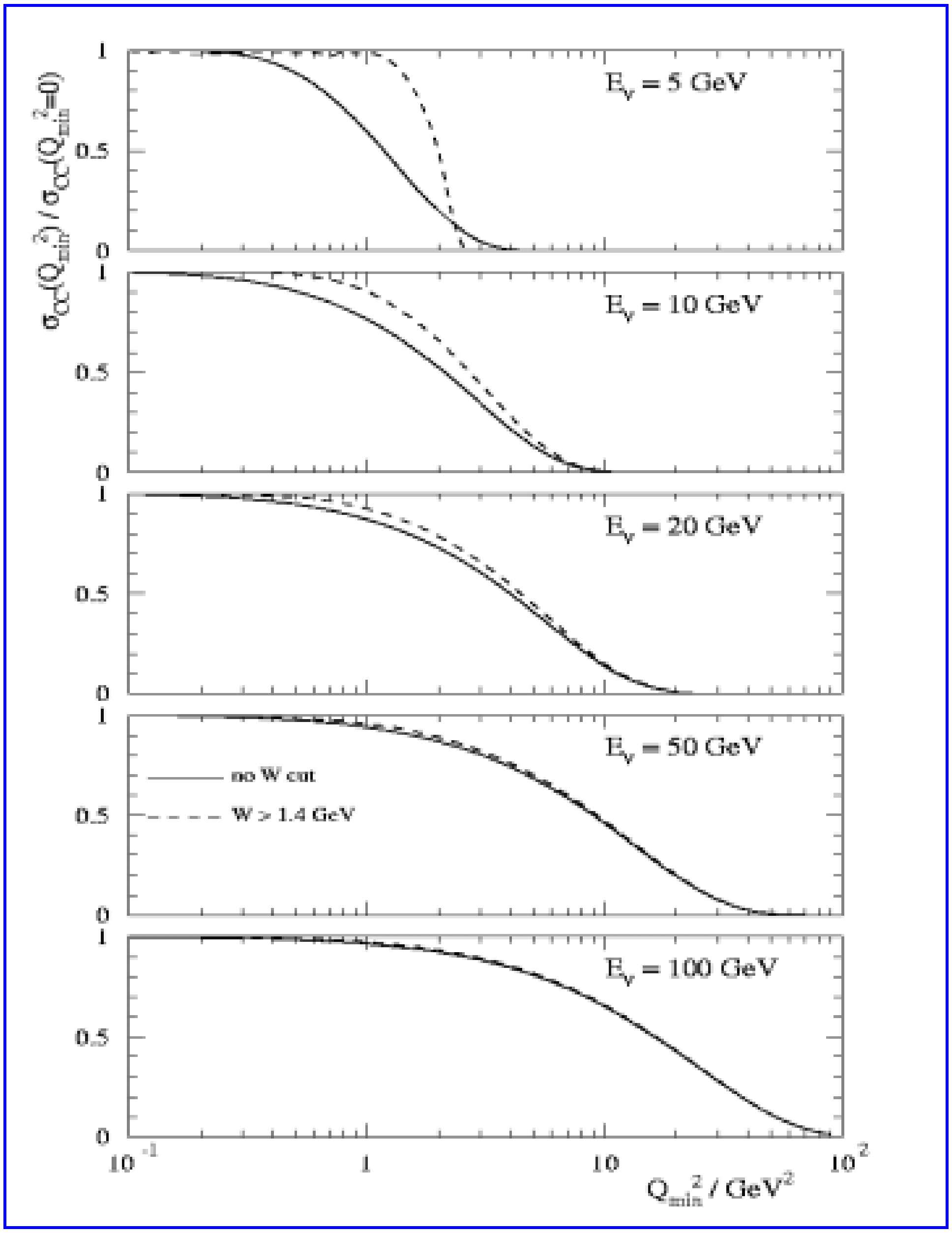
Comments:

- $Q^2 = O\left(1\,GeV^2\right)$:
  - perturbative $\alpha_s\left(Q^2\right)$
  - non-negligible/calculable $O\left(M^2/Q^2\right)$ (see results ...)
- cutting on Q^2 avoids higher twist / nonperturbative QCD
- cutting on $W^2(x_{Bj}, Q) \equiv (P_N + p_W)^2$ avoids resonances / elastic

  (formally enhanced higher twist effects as $x_{Bj} \to 1$)
- $\sum_X$ still includes resonant and elastic scattering:

  overlap-problem in $\sigma_{tot} = \sigma_{DIS\,\&\,res.\,\&\,el.}$

$\hookrightarrow$ $\sigma(\nu_\tau N \to \tau X)$ is a natural starting point

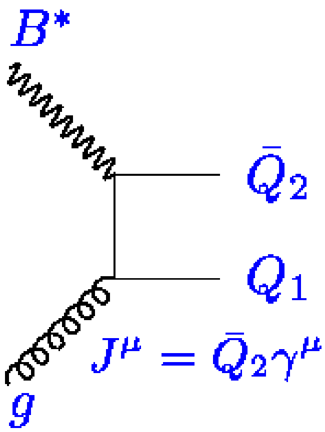


- as a theoretical playground because of a large perturbative DIS contribution from to the collinear cut-off effect of m_τ :

  $-p_W^2 \equiv Q^2 > O(m_\tau^2)$ at the $\nu_\tau \to \tau W$ emission vertex
- because of its relevance for τ appearance (even though this is a low energy workshop)

Charm Production with three partonic flavours {u,d,s}&gluons:

● Charm Production: NC $\leftrightarrow$ CC



$$J^\mu = \bar{Q}_2\gamma^\mu(V - A\gamma_5)Q_1$$

NC: $B = \gamma$

$Q_{1,2} = c$

$V = e_c;\ \ A = 0$

CC: $B = W$

$Q_1 = c;\ \ Q_2 = s$

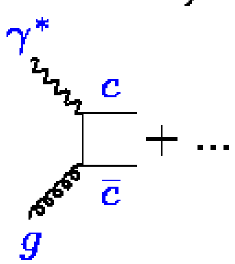
$V = A = 1$

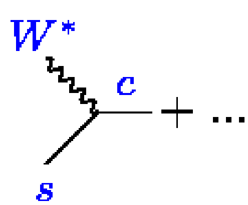
analogous, <u>but</u>: mass non-degeneracy

$\begin{pmatrix} u\text{: light} \\ d\text{: light} \end{pmatrix} \begin{pmatrix} c\text{: heavy} \\ s\text{: light} \end{pmatrix} \begin{pmatrix} t\text{: heavy} \\ b\text{: heavy} \end{pmatrix}$

$\ln m_c^2$: perturbative

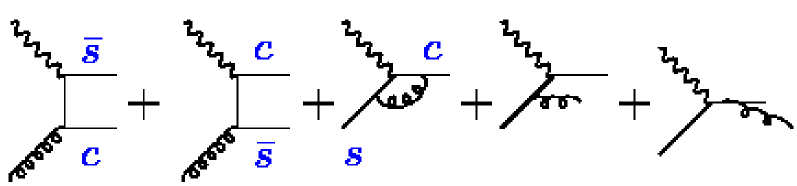
$\ln m_s^2$: <u>non</u>-pert.





$\mathcal{O}(\alpha_s^1) + \mathcal{O}(\alpha_s^2)$ LO + NLO !

$\mathcal{O}(\alpha_s^0) + \mathcal{O}(\alpha_s^1)$ LO + NLO ?



1^{st} $g \to c\bar{c}$ contb.: $\propto \ln Q^2/m_c^2$

NLO corrections to $s \to c$

$\rightarrow$ CC DIS: $\mathcal{O}(\alpha_s^1)$ <u>first reliable</u> order at high Q^2.

NLO and masses:

- $\sigma(\nu_\tau N \to [c]X)$: $m_\tau,\ M_N,\ m_c \neq 0$

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\ dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\left\{(y^2 x + \frac{m_\tau^2 y}{2E_\nu M_N})F_1^{W^\pm}\right.$$
$$+ \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\right] F_2^{W^\pm}$$
$$\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M_N}\right] F_3^{W^\pm}$$
$$\left. + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M_N^2 x} F_4^{W^\pm} - \frac{m_\tau^2}{E_\nu M_N} F_5^{W^\pm}\right\}$$

factorized pQCD for $\langle J^\mu J^\nu \rangle$:

$$W^{\mu\nu} = \int \frac{d\xi}{\xi}\ f(\xi,\mu^2)\ \hat\omega^{\mu\nu}|_{p^+=\xi P^+}$$

$$W^{\mu\nu} = \sum_i F_i\ T_i^{\mu\nu}(P,q,g) \quad \hat\omega^{\mu\nu} = \sum_i \mathcal{F}_i\ T_i^{\mu\nu}(p,q,g)$$

$$\mathcal{F}_i(x,Q^2) = q(\eta,\mu^2)\ (1-\delta_{i4}) + \mathcal{O}(\alpha_s)$$

(re-)scaling variables:

$$\eta = \frac{2x}{1+\rho} \quad \rho^2 \equiv 1 + \left(\frac{2M_N x}{Q}\right)^2 \quad \bar\eta = \eta(1+m_c^2/Q^2)$$

mixing of structure functions:

$$F_1 = \mathcal{F}_1 \quad F_2 = 2\ x\ \frac{\mathcal{F}_2}{\rho^2} \quad F_3 = 2\ \frac{\mathcal{F}_3}{\rho}$$

$$F_4 = \frac{(1-\rho)^2}{2\rho^2}\ \mathcal{F}_2 + \mathcal{F}_4 + \frac{1-\rho}{\rho}\ \mathcal{F}_5$$
$$F_5 = \frac{\mathcal{F}_5}{\rho} - \frac{(\rho-1)}{\rho^2}\ \mathcal{F}_2$$

Outlook:

- NLO target mass corrections for $F_{1,..,5}$ (incl. Mixing in the $F_{1,2}$ sector) from the OPE (equivalent to partons with k_T)
- NLO/mass corrections to NC/Paschos-Wolfenstein-relation

soon!

$F_{4,5}$ *revisited*

2 "new" structure functions F_4, F_5 (Albright & Jarlskog 75)

- AJ relation 1 $F_4 = 0$ is violated by M_N, $\mathcal{O}(\alpha_s)$, **not** by m_c (for $m_s = 0$)
- AJ relation 2 $F_2 - 2xF_5 = 0$ is violated by masses but holds to any $\mathcal{O}(\alpha_s^n)$ for $M_N = m_c = 0$ by "abelian" (single W exchange) gauge invariance

$$
\begin{aligned}
W_0 &= \varepsilon_0^{\mu}\varepsilon_0^{\nu} W_{\mu\nu} && (1)\\
W_s &= \left(\varepsilon_0^{\mu}\varepsilon_q^{\nu} + \varepsilon_q^{\mu}\varepsilon_0^{\nu}\right) W_{\mu\nu} && (2)\\
W_q &= \varepsilon_q^{\mu}\varepsilon_q^{\nu} W_{\mu\nu} && (3)\\
W_{\pm} &= \varepsilon_{\pm}^{\mu}\varepsilon_{\pm}^{\nu\,*} W_{\mu\nu} && (4)
\end{aligned}
$$

$$
\begin{aligned}
\varepsilon_{\pm}^{\mu} &= \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0) && (\mathit{transverse}) && (5)\\
\varepsilon_q^{\mu} &= \frac{q^{\mu}}{\sqrt{-q^2}} && (\mathit{scalar}) && (6)\\
\varepsilon_0^{\mu} &= \frac{(-q^2)k^{\mu} + (k\cdot q)q^{\mu}}{\sqrt{(-q^2)[(k\cdot q)^2]}} && (\mathit{longitudinal}) && (7)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{F}_1 &= \frac{1}{2}(W_+ + W_-) && (8)\\
\mathcal{F}_2 &= \frac{\lambda}{2}(W_+ + W_- + 2W_0) && (9)\\
\mathcal{F}_3 &= \mp\frac{1}{2}(W_+ - W_-) && (10)\\
\mathcal{F}_4 &= \frac{1}{2}(W_0 + W_q - W_s) && (11)\\
\mathcal{F}_5 &= \frac{1}{2}(W_+ + W_- + 2W_0 - W_s)\ . && (12)
\end{aligned}
$$

$$F_2 - 2xF_5 = xW_s \quad (13)$$

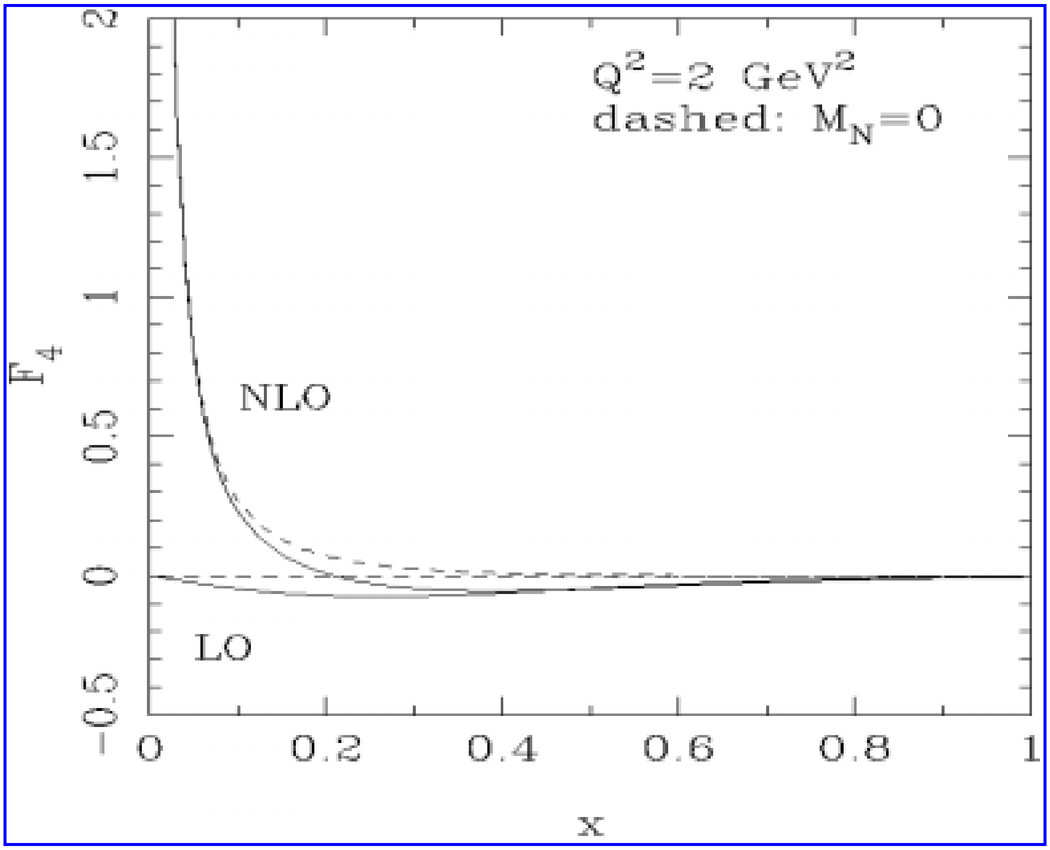
$$\mathcal{F}_4^c = \frac{k^{\mu}k^{\nu}}{Q^2} W_{\mu\nu} \quad (14)$$

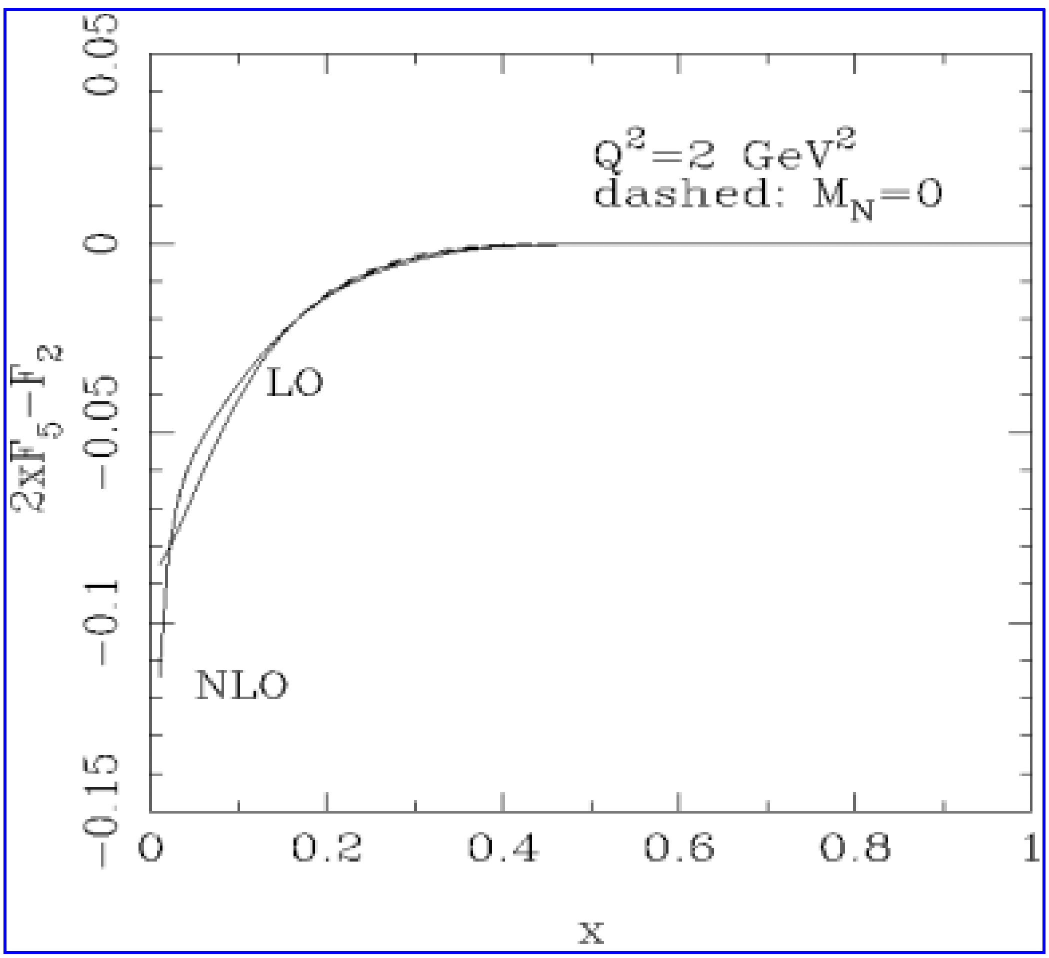
Comment:

OPE is not tied to perturbation theory, so (13)=0 should hold for the (equivalent) elastic form factors as well.

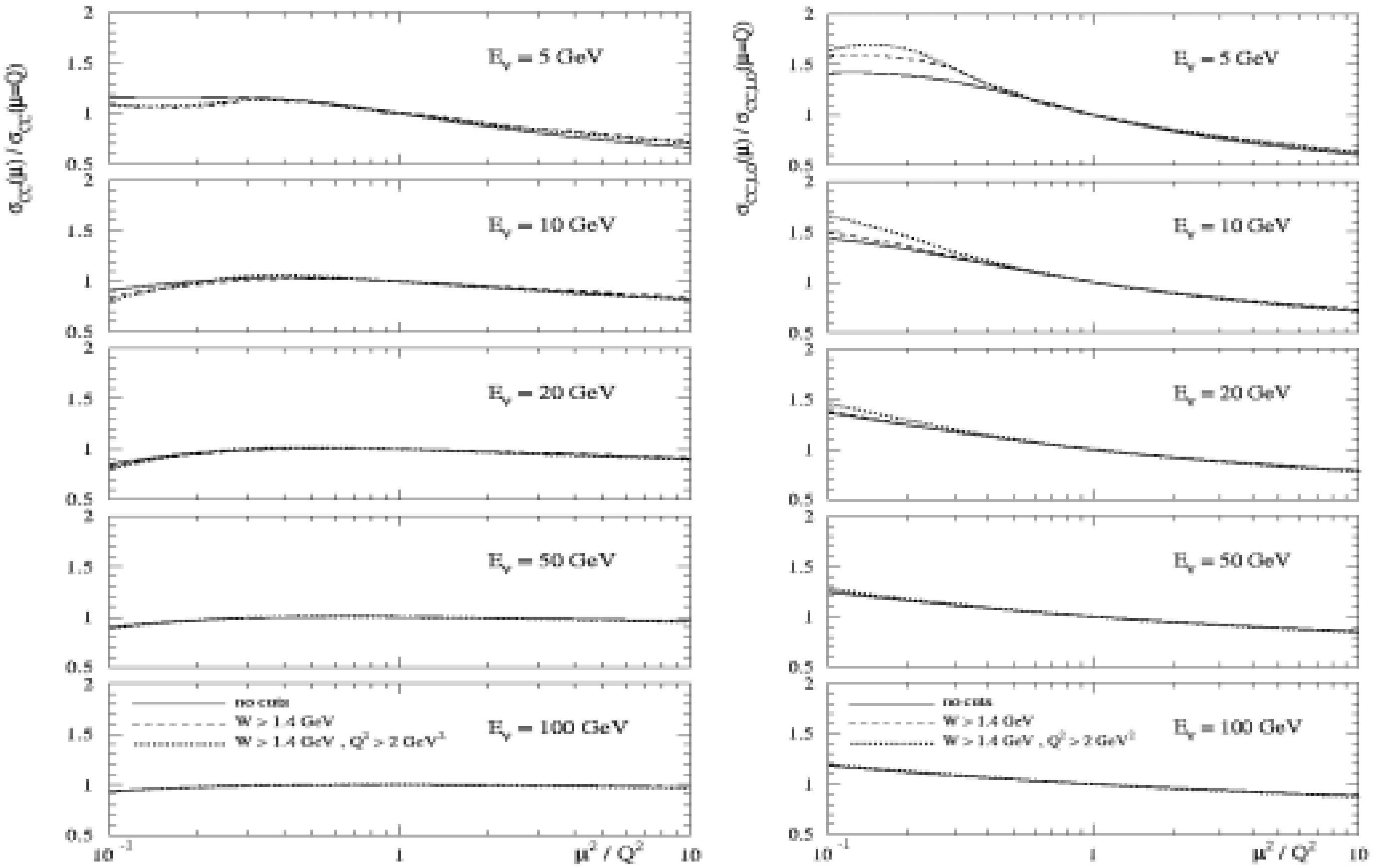
Results ...

Violation of the Albright&Jarlskog Relations



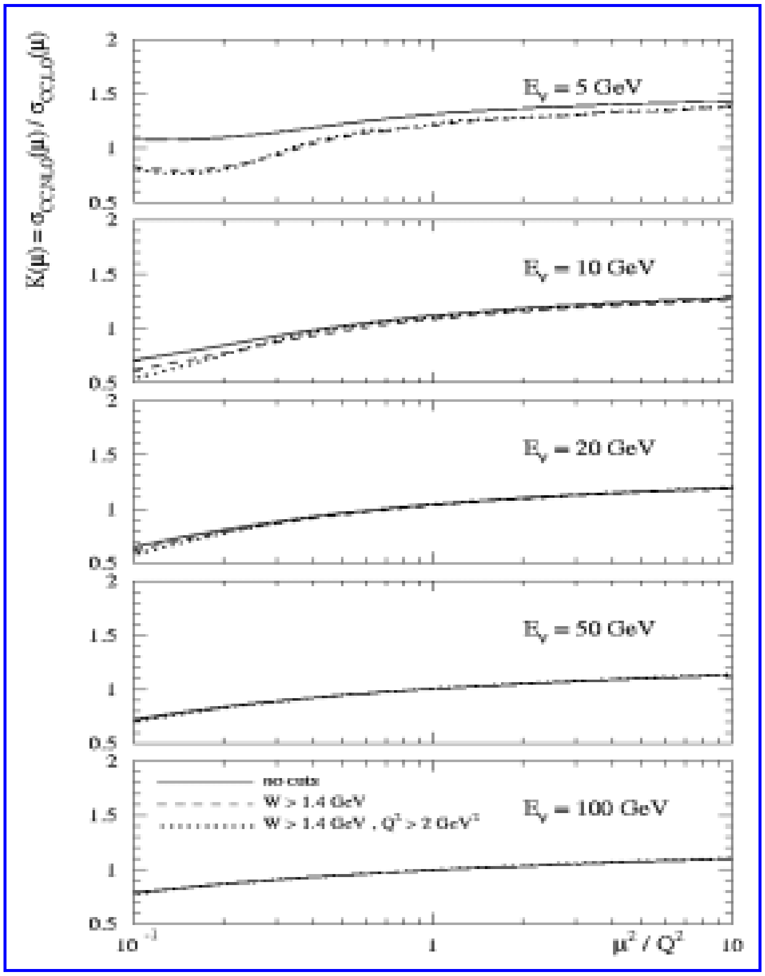


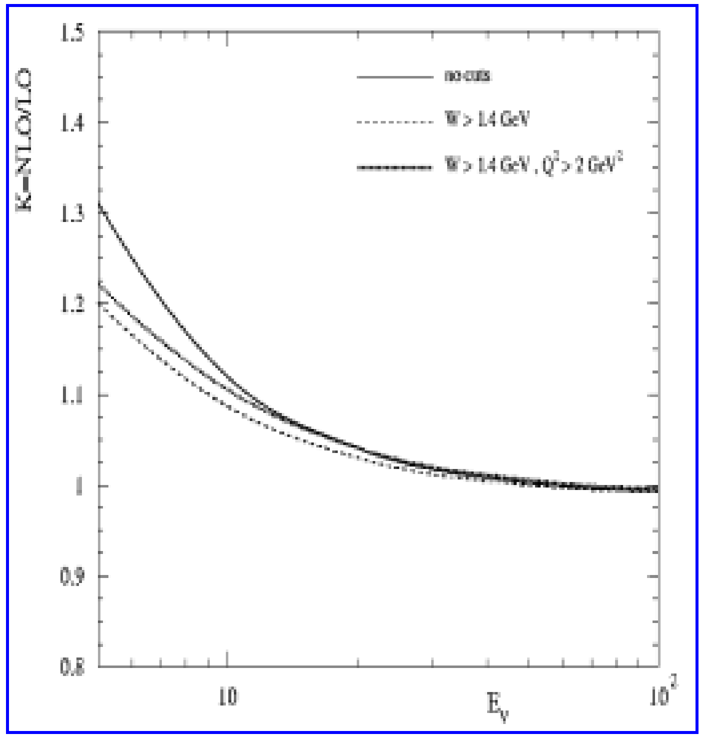
Scale dependence: $\sigma(\mu)/\sigma(\mu=Q)$



substantial improvement from NLO corrections

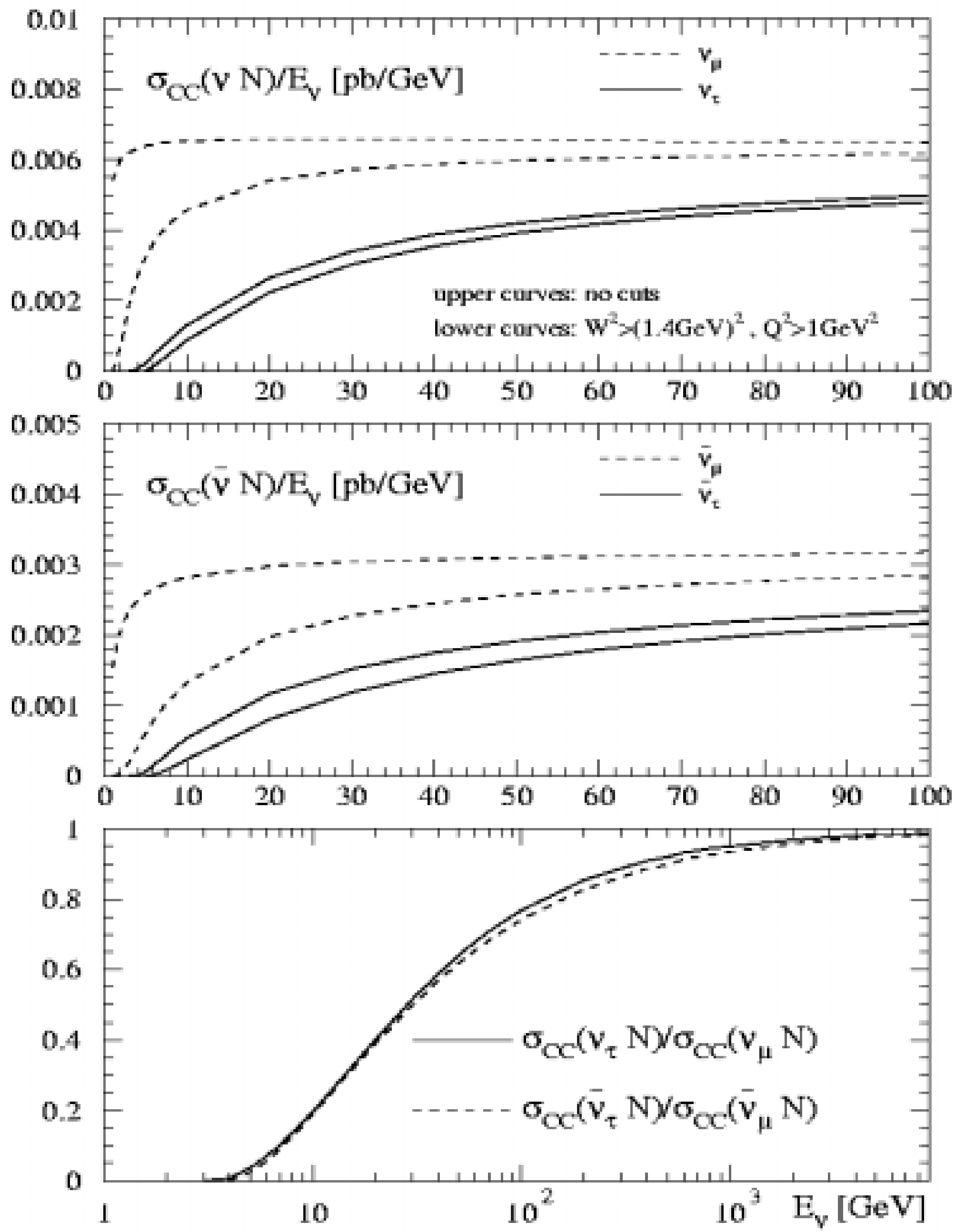
K-factor: NLO / LO





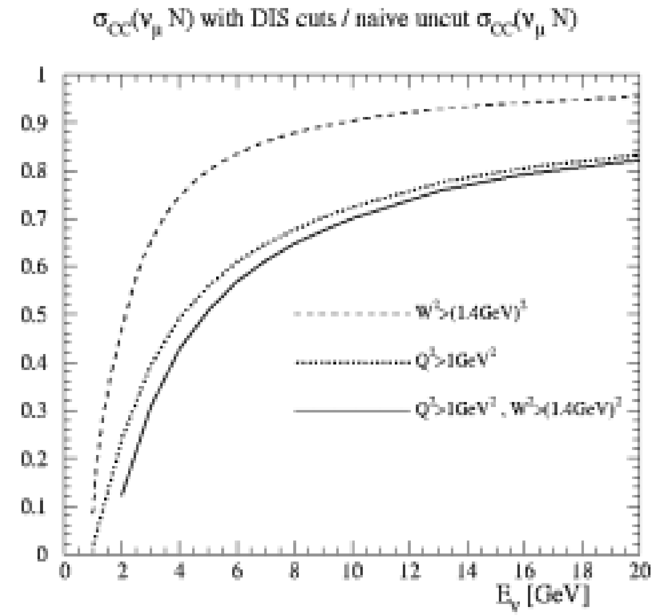
reasonably stable (but energy dependent); confirming canonical DIS choice $\mu = Q$

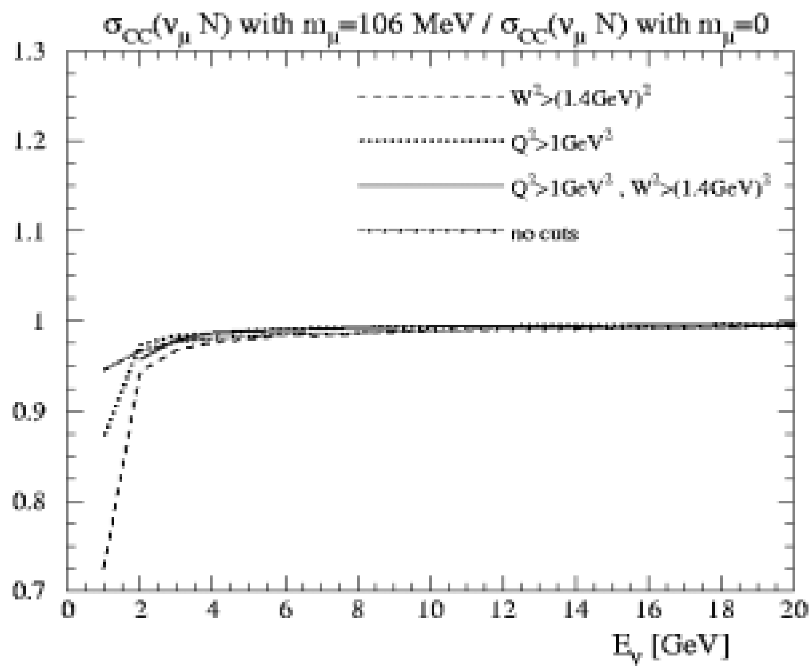
DIS cuts and/or lepton threshold in $\nu_{\tau,\mu}$ CC scattering



(*Prior to solving the overlap problem*)
What can we say about the scattering of muon neutrinos .... ?

- Reduction of *bona fide* DIS component
- Since $m_\tau \neq 0$ effects extend (at the 5% level) up to 1TeV(!), do $m_\mu \neq 0$ effects vanish only at (the equivalent) energy 3.5 GeV? (actually the scaling is not that simple ...)





- As to be expected, the *bona fide* DIS component becomes very small at low neutrino energies
- Muon mass corrections range within [5%;30%] at 1GeV but depend sensitively on DIS cuts
- A reliable quantitative statement will have to await the combination of deep inelastic scattering with resonant and quasi-elastic scattering (or an extended duality approach)

Conclusions / Outlook:

- **Tau neutrino (differential and integrated) CC DIS cross section at NLO including all mass effects (target mass effects in the collinear approximation) as:**
  - **a signal for tau appearance**
  - **a playground for the DIS component in neutrino scattering (of any neutrino flavour)**
- **NLO features:**
  - **stable under scale variations around** $\mu = Q$
  - **energy dependent K-factors reflecting 20%-30% corrections (depending on DIS cuts) at** $E_\nu = 5 GeV$ **to ~0% around** $E_\nu = 50 GeV$
  - **The uncertainties from scale variations and PDF-errors are very moderate.**
- **NC cross-sections and NLO target mass effects from the OPE approach (** $O(M^2/Q^2)$ **mixing in the** $F_{1,2}$ **sector) nearly finished (for e.g. Paschos-Wolfenstein type analyses at NLO)**
- **For low energies: Combination of DIS with resonant and quasi-elastic scattering (cuts, duality, ...?) and/or the inclusion of higher twist still to do.**
- **As long as this is unsolved we have no reliable quantitative statement on muon mass effects; but it seems they *can* be as large as 30% at low energy.**