# Radiative Corrections in CCQE $\nu N$ scattering

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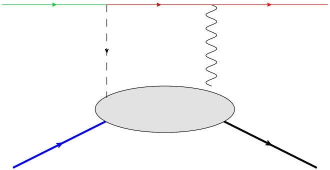
NuFact13

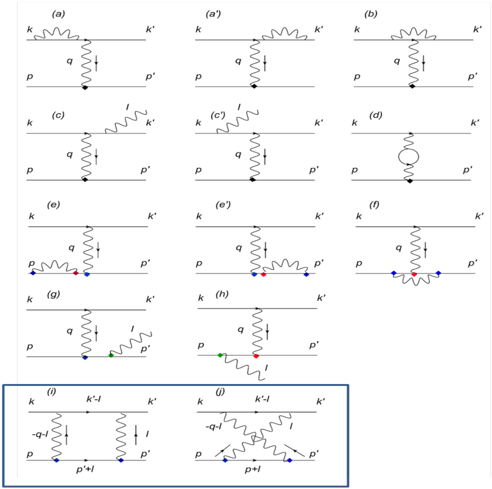
- $\nu_\mu \to \nu_e$: $\theta_{13}$ measurement and then CP violation parameter, in present and future neutrino experiments (e.g. T2K, NO$\nu$A).
-
  - $E_\nu \sim 1$ GeV.
  - Charged Current Quasi-Elastic (CCQE) Scattering: a dominant process
  - estimate of the systematic differences between $\nu_e N$ and $\nu_\mu N$ CCQE cross sections important for data analysis: Day, McFarland, PRD**86** (2012) 053003, also a talk by M. Day, **NuFact12**.
  - Are the Radiative Corrections (RC's) a potential source of difference between cross sections for $\nu_e$ and $\nu_\mu$ scattering?
    - Bremssthralung radiation via leading log formula: $\sim 10\%$ between $\nu_e$ and $\nu_\mu$, Day, McFarland, PRD**86** (2012) 053003).

  * $m_e \ll m_\mu$ : **electron radiates more than muon!**

- Two Boson Exchange Effect (TBE) in CCQE
- TBE effect intensively studied in the $ep$ scattering
  - Contribution from $\gamma\gamma$, $W^\pm\gamma$ and $Z_0\gamma$ box diagrams $\to$ hadronic model dependent;
  - **The TBE effect in CCQE interaction: is it important to consider?**



# $\alpha^3$ corrections: Born$\times\mathcal{O}(\alpha^2)$




1. $ep$ data analysis: the radiative corrections from: Mo and Tsai, Rev. Mod. Phys. **41** (1969) 205;

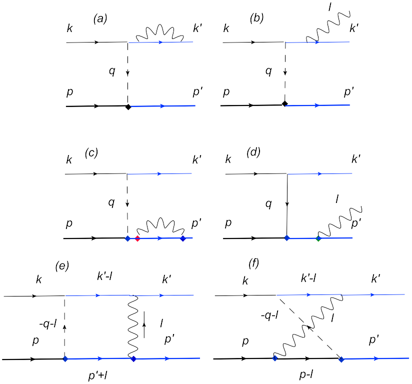
$$\begin{aligned} \sigma_R &\rightarrow \sigma_{1\gamma,R}(1+\delta_{rad.}) \\ \delta_{rad.} &= \delta_{ver.} + \delta_{prop.} \\ &+ \delta_{brem.}(soft.) \\ &+ \delta_{tpe}(soft) \end{aligned}$$

2. Re-Examinated by Maximon and Tjon, Phys. Rev. C **62** (2000) 054320.

| $E_e$ (GeV) | $Q^2$ (GeV$^2$) | RC (total) | Electron Leg Leg |
|---|---|---|---|
| 6.032 | 2.525 | $-25\%$ | $-24\%$ |
| 2.201 | 1.400 | $-25\%$ | $-22\%$ |
| 2.206 | 0.346 | $-22\%$ | $-21\%$ |

Table : Mo, Tsai, Rev. Mod. Phys. 41, 205 (1969) (elastic $ep$)

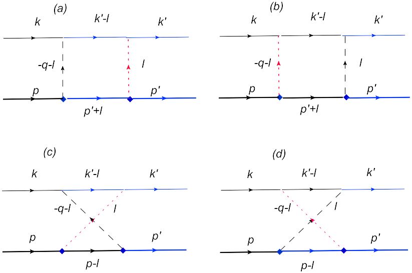
## Radiative Corrections in $\nu N$ Scattering




### Technical Remark:

- "Pure" lepton leg corrections: rather trivial to obtain;
- Model dependent part: hadronic part;
- Bremsstrahlung emission, one hast to take into account the detector properties the way of performing the measurement.

$Z_0 W$




additionally,

- Weak Vertex Corrections;
- Weak Propagator Self Energy Corrections;
- Vacuum Polarization;
- $\gamma$ emission by $W$;
- Separation of QED corrections in the case of $\nu q$ does not have sense; QED and Weak corrections stand gauge invariant set!

## Radiative Corrections in $\nu N$ Interactions

**$\beta$-decay, CCQE at the threshold scale (several MeV)**

- T. Kinoshita and A. Sirlin, PR113 (1959) 1652;
- A. Sirlin, NPB **71** (1974) 29;
- M. Fukugita and T. Kubota, Acta Phys. Polon. B **35** (2004) 1687.

* About $2\%$ (outer correction, Brem.+Self.+Extracted from vertex.), + About $(2.4\%$ (inner correction: Box Contribution, quark+impact of FF))

** Inner-Outer: a technical problem how to cancel UV divergences, which appear in propagator corrections.

- U. Raha, F. Myhrer and K. Kubodera, PRC **85** (2012) 045502;

**Bremsthralung Emission in CCQE in 1 GeV $\nu$ energy range.**

- A. Bodek, arXiv:0709.4004 [hep-ex]
- M. Day and K. S. McFarland, PRD**86** (2012) 053003. (relative effect between $\nu_e$ and $\nu_\mu$ of the order of $10\%$)

* De Rujula leading log formula applied for getting Brem. prediction $10\%$ of relative difference between $\nu_e$ and $\nu_\mu$.

**DIS**

- Kiskis, PRD8 2129, $\nu_\mu \to \mu^- + X$, RC$\sim$ $\pm 10\%$
- Barlow and Wolfram, (applied Kiskis) PRD20, 2198, $\nu_\mu \to \mu^- + X$ RC$\sim$ $\pm 20\%$
- De Rujula et al., NPB154, 394, Leading Log Approx, $\nu_\mu + p \to \nu_e + X$, RC$\sim$ $(-15\%, 10\%)$.
- A. Sirlin and W. J. Marciano, NPB**189** (1981) 442.
- H. Bohm, H. Spiesberger, NPB304, 749, DIS, $e^- p \to \nu_e + X$, RC of the order of$\sim$ $-20\%$ increasing with growing $x$, leptonic part (Leading log $-14\%$), $s = 10^5$ GeV, $\Delta E < 1$ GeV. , Adding hard photon Brem. contribution increases the total contribution.
- Arbuzow et al., JHEP06, 078, $\nu_\mu + q \to \mu^- + q'$, RS$\sim$ $(-1\%, 5\%)$ **but if $Q^2$ reconstructed only from leptonic part, several times larger**, applied for NOMAD.
- Notice the presence of the the hard and soft photon emission.

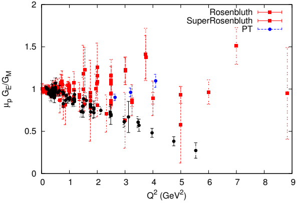
**Remark**

- In the case of the $\nu q$ scattering the calculations are complex but straightforward (Standard Model);
- $\beta$ decay, CCQE $\nu N$ interaction $\to$
  - Lepton leg rather obvious, fermion self energy, vertex and Bremsstrahlung corrections rather simple to take into account.
  - **Hadron leg: model dependent, in particular Two-Boson Exchange Correction.**

*Two Boson Exchange Effect in $ep$ and $\nu N$ Scattering*

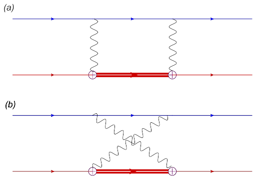
## TPE Effect in $ep$ Scattering

- Discrepancy between estimation of $G_{Ep}/G_{Mp}$ based on Polarization Transfer (PT) and Rosenbluth technique estimations.



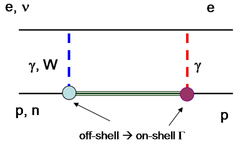

- CROSS SECTION data are consistent but one has to take into account normalization errors, Arrington, PRC**68** (2003) 034325;

- Inclusion, into Rosenbluth analysis, of the TPE effect (hard photon contribution) solved partially the problem. Blunden *et al.*, PRL**91** (2003) 142304, Chen *et al.* PRL **93** (2004) 122301.




- TPE effect in PV $ep$ scattering: $\Box_{\gamma Z^0}$ diagrams. Zhou, Kao and Yang, PRL **99** (2007) 262001, Tjon, Blunden and Melnitchouk, PRC **79** (2009) 055201.
- **What is the role of the TBE effect in CCQE $\nu N$ scattering?**

## TPE in $ep$ Scattering




- Quantum Field (QF) like approach:
  Blunden et al., PRL**91** (2003) 142304, PRC**72** (2005) 034612 ($\gamma\gamma$), Zhou et al.,PRC **81** (2010) 035208 ($Z^0\gamma$).
  - take the Nucleon, $\Delta(1232)$,..., to model hadronic intermediate state;
  - off-shell electro-weak $\longrightarrow$ on-shell nucleon vertices;
- Dominant contribution from Nucleon (elastic) state, Kondratyuk et al.PRL**95** (2005) 172503;
- Agreement (in low and intermediate $Q^2$ range) with **dispersion calculations** by Borisyuk and Kobushkin, PRC **78** (2008) 025208;

$$\delta_{TPE} = \frac{2\mathrm{Re}\left\{\mathcal{M}^*_{Born}\left(i\Box_{\gamma\gamma} - i\Box_{\gamma\gamma}(Mo-Tsai)\right)\right\}}{|\mathcal{M}_{Born}|^2}$$

- Let's apply above approach for predicting the TPE in CCQE.
- The same kinematical domain in $(s, t)$ plane as in the case of 1 GeV neutrinos.

**Remark**

Reasonable predictions of QF-like approach at low and intermediate $Q^2$ range. A model dependence for $Q^2 > 4$ GeV$^2$.

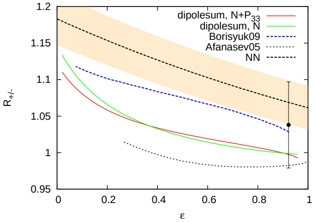



Figure : $R_{+/-} \approx 1 - 2\delta_{TPE}$, $Q^2 = 5$ GeV$^2$, K.M.G., arXiv:1306.5991.

## TPE in $ep$ Scattering

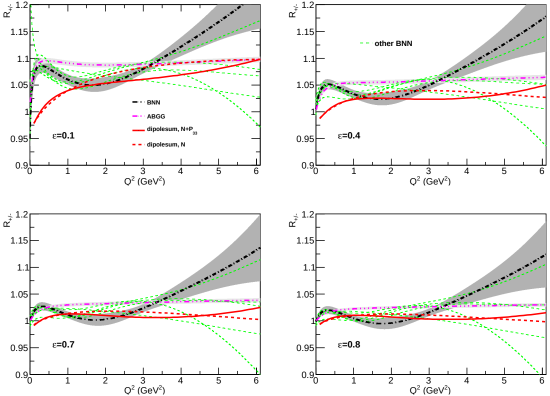
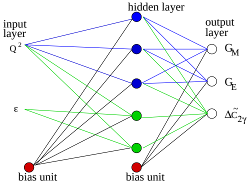


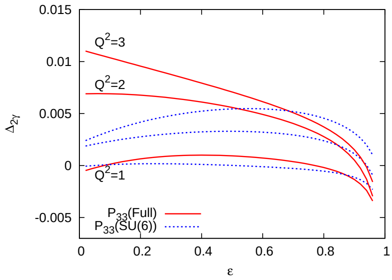

figure from K.M.G., arXiv:1306.5991

$$\varepsilon = \left[1 + 2\left(1 + \frac{Q^2}{4M_p^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right]^{-1},$$

- $R_{+/-} \approx 1 - 2\delta_{TPE}(2\gamma)$
- $\delta_{TPE}$ extracted from elastic $ep$ data $\rightarrow$ Bayesian Neural Network (BNN), **K.M.G. PRC 84, 034314**.
- * BNN breaks down below 1 GeV$^2$!
- Good quantitative agreement between QF-like approach and phenomenological extraction (by Bayesian Neural Network) for $Q^2 \in (1, 3)$ GeV $^2$



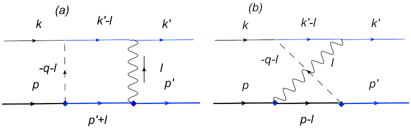
## $\Delta(1232)$ hadronic state




K.M.G., arXiv:1306.5991.

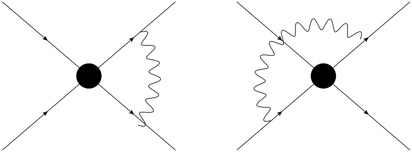
- Contribution from $\Delta(1232)$ negligible in the low $Q^2$ relevant for 1 GeV $\nu$.
- It is also model dependent!

## $\Box_{W\gamma}$ Contribution




If lack of form factors, it is UV finite!

$$\sim \int \frac{d^4 l}{(2\pi)^4} \frac{dl}{l^3}$$



If lack of form factors, it is UV (logarithmically) divergent!

$$\sim \int \frac{d^4 l}{(2\pi)^4} \frac{dl}{l}$$

1. TBE contribution corresponds to vertex correction in Fermi model.
2. TBE $\times$ Born Amplitude $\sim \alpha^3$ correction.

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}, \quad 4\pi\alpha \approx 0.09, \quad e^2 = g^2 \sin^2\theta_W$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}, \quad G_F = 1.16639 \times 10^{-5}\mathrm{GeV}^{-2}$$

$$\frac{g^2}{8} = M_W^2 \frac{G_F}{\sqrt{2}} \approx 0.05, \quad M_W = 80.385\mathrm{GeV}/c^2$$

## Born Amplitude

$\nu(k) + p(p) \to l^-(k') + n(p')$

$$
\begin{aligned}
i\mathcal{M}_{Born} &= i\frac{g^2\cos\theta_C}{8(t-M_W^2)} j^{cc}_\mu h^\mu_{cc}, \\
\frac{g^2}{8} &= M_W^2\frac{G_F}{\sqrt{2}} \approx 0.05
\end{aligned}
$$

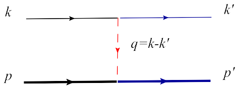
- Leptonic current:

$$j^\mu_{cc} = \overline{u}(k')\gamma^\mu(1-\gamma_5)u(k)$$

- **CCQE one-body hadronic current**:

$$h^\mu_{cc} = \overline{u}(p')\Gamma^\mu_{cc}(p'-p)u(p)$$

$$
\begin{aligned}
\Gamma^\mu_{cc}(q) &= \Gamma^\mu_p(q) - \Gamma^\mu_n(q) - \gamma_\mu\gamma_5 F_A(q) - \frac{q^\mu\gamma_5}{2M}F_P(q) \\
F_A(q) &= \frac{1.267}{(1-q^2/M_A^2)^2} \\
F_P(q) &= \frac{4M^2F_A(q)}{m_\pi^2 - q^2}
\end{aligned}
$$




$$\Gamma^\mu_{p,n}(q) = \gamma^\mu F_1^{p,n}(q) + \frac{i\sigma^{\mu\nu}q_\nu}{2M_{p,n}}F_2^{p,n}(q)$$

where

$$
\begin{aligned}
F_1^{p,n} &= \left(G_E^{p,n} + \tau_{p,n}G_M^{p,n}\right)/(1+\tau_{p,n}) \\
F_2^{p,n} &= \left(G_M^{p,n} - G_E^{p,n}\right)/(1+\tau_{p,n})
\end{aligned}
$$

$\tau_{p,n} = -q^2/4M_{p,n}^2.$

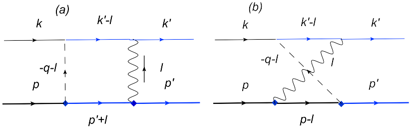
$$
\begin{aligned}
G_E^p(q^2) &= \frac{G_M^{p,n}(q^2)}{\mu_{p,n}} = \frac{\Lambda^4}{(q^2-\Lambda^2)^2} \\
G_E^n(Q^2) &= 0, \quad \Lambda = 0.84 \text{ GeV}
\end{aligned}
$$

## TBE in $\nu N$ Scattering

$i\Box^{\parallel}_{W+\gamma} = -\cos\theta_C e^2 g^2 I^{\parallel}_{W+\gamma}/8$ and
$i\Box^{\times}_{W+\gamma} = -\cos\theta_C e^2 g^2 I^{\times}_{W+\gamma}/8$, where

$$I^{\parallel}_{W+\gamma} = \int \frac{d^4 l}{(2\pi)^4} \frac{l^{\mu\nu} h^{\parallel}_{\mu\nu}}{D(p', M_p)} \qquad (1)$$

$$I^{\times}_{W+\gamma} = \int \frac{d^4 l}{(2\pi)^4} \frac{l^{\mu\nu} h^{\times}_{\mu\nu}}{D(-p, M_n)} \qquad (2)$$




$$l^{\mu\nu} = \overline{u}(k')\gamma^{\mu}(\hat{k}' - \hat{l} + m)\gamma^{\nu}(1-\gamma_5)u(k)$$

$$h^{\parallel}_{\mu\nu} = \overline{u}(p')\Gamma^{p}_{\mu}(-l)(\hat{p}' + \hat{l} + M_p)\Gamma^{cc}_{\nu}(q+l)u(p)$$

$$h^{\times}_{\mu\nu} = \overline{u}(p')\Gamma^{cc}_{\nu}(q+l)(\hat{p} - \hat{l} + M_n)\Gamma^{n}_{\mu}(-l)u(p)$$

$m$ denotes the lepton mass.

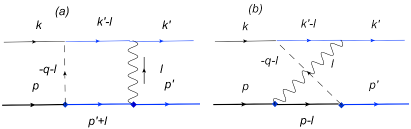
$$D_W(x, M_x) = [(q+l)^2 - M_W^2 + i\epsilon][l^2 + i\epsilon][(k'-l)^2 - m^2 + i\epsilon][(x+l)^2 - M_x^2 + i\epsilon].$$

$$\Delta_{TBE} = \mathrm{Re}\sum_{spin} \mathcal{M}^{*}_{Born}\left(\Box^{\parallel}_{W+\gamma} + \Box^{\times}_{W+\gamma}\right)$$

$$= \frac{g^4 e^2 \cos^2\theta_C}{16(M_W^2 - t)}\,\mathrm{Im}\underbrace{\sum_{spin}(j_\alpha h^\alpha)^*\left(I^{\parallel}_{W+\gamma} + I^{\times}_{W+\gamma}\right)}_{\diamondsuit}$$

- How to compute $\diamondsuit$?
- Take the trace (Numerator of loop integral);
- Reduce the numerator with the denominator as much as possible;
- Express in terms of 1-, 2-. 3- and 4- point scalar loop integrals t'Hooft, Veltman;
- Compute numerical values (photon mass $\mu$ introduced to regularize)

* FeynCalc and LoopTool library used for algebraical and numerical calculations.




- Both box amplitudes are ultraviolet (UV) finite, because the presence of the form factors;
- $i\square^{\|}_{\gamma W+}$ is infrared (IR) divergent;
- $i\square^{\times}_{\gamma W+}$ is IR finite, in the limit $l \to 0$ $i\square^{\times}_{W+\gamma}$ behaves as:

$$\mu_n \int \frac{dl l^3}{l^2\ k'\cdot l\ p'\cdot l}\left(\frac{\gamma^\mu l^2}{l^2 - 4M_n^2} + \sigma^{\mu\nu} l_\nu\right).$$

**Fraction of TBA Correction**

$$\delta^{\nu n}_{TBE} = \frac{\Delta^{\nu n}_{TBE} - \Delta^{\nu n}_{TBE}(\square^{\|}_{W+\gamma}, soft)}{\frac{1}{2}\sum_{spin}|\mathcal{M}_{Born}|^2}$$

$$d\sigma = d\sigma_{Born}(1+\delta_{TBE})$$

**Soft Contribution**

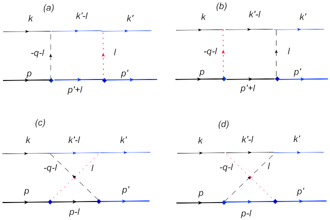
$$\int \frac{d^4}{(2\pi)^4 l}\frac{N(l\to 0)}{D(l)}$$

- $$\Delta^{\nu n}_{TBE}(\square^{\|}_{W+\gamma}, soft) = -8k'\cdot p' e^2|\mathcal{M}_{Born}|^2 \mathrm{Im} C_0,$$
- $C_0 \equiv C_0(m^2, M_p^2, s, m^2, 0, M_p^2)$ a scalar one-loop integral, see 't Hooft79

$$C_0 = \int \frac{d^4 l}{(2\pi)^4}\frac{1}{l^2[(k'-l)^2 - m^2][(p'+l)^2 - M_p^2]}$$

regularized by photon mass $1/l^2 \to 1/(l^2-\mu^2)$

## $WZ_0$ Box Contribution




- The weak vertex $\Gamma^{\mu}_{nc,p(n)}$ for $Z^0$ proton (neutron) coupling Alberico, Bilenky and Maieron, PR**358** (2002) 227,

$$\Gamma^{\mu}_{nc,p(n)} = \gamma^{\mu} F_1^{nc,p(n)} + \frac{i\sigma^{\mu\nu} q_{\nu}}{2M} \gamma^{\mu} F_2^{nc,p(n)} - \gamma^{\mu}\gamma_5 F_A^{nc,p(n)}$$

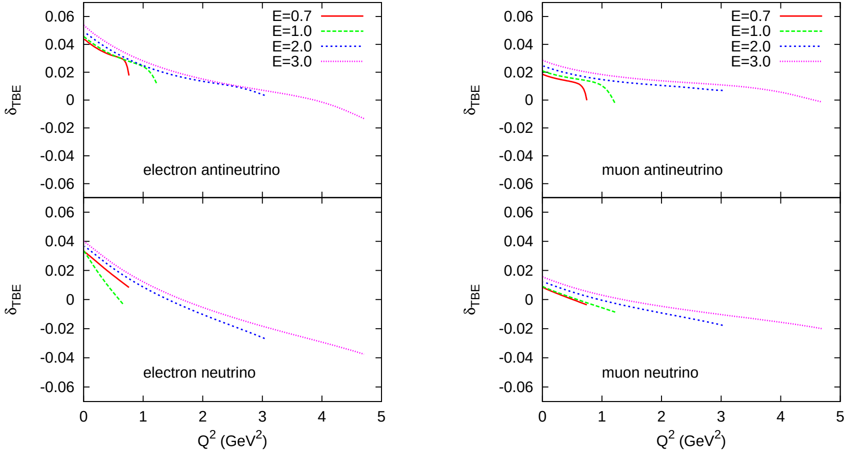
where

$$F_{1,2}^{nc,p(n)} = 1/2 \left[ \left(1 - 4\sin^2\theta_W\right) F_{1,2}^{p(n)} - F_{1,2}^{p(n)} \right],$$

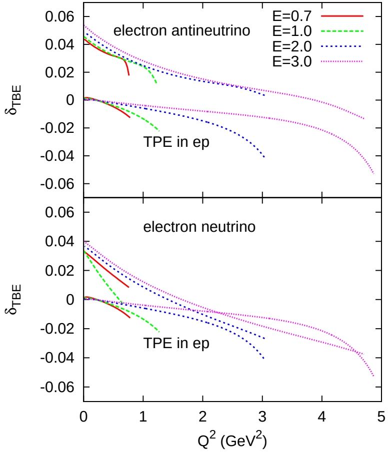
$$F_A^{nc,p(n)} = \pm F_A/2$$

- It is negligible in comparison to $W\gamma$ contribution.

## $Q^2$ dependence of TBE

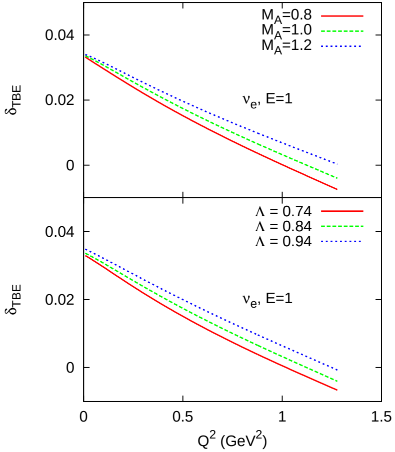


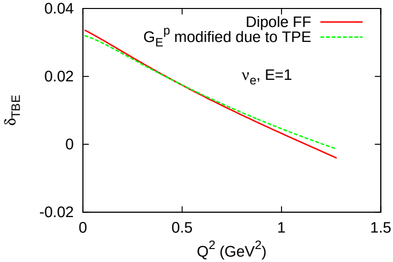
## TPE vs. TBE




- TPE and TBE effects are of comparable size!

## Parameter Dependence of TBE



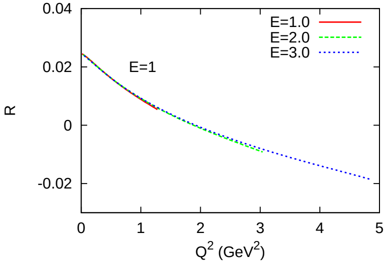




- Modification of the $G_{Ep}$ due to (TPE effect, Alberico, Bilenky, Giunti, K.M.G, PRC **79** (2009) 065204).

$$G_E^p(Q^2) = (-0.130\,Q^2 + 1.0022)G_M^p(Q^2)/\mu_p$$

- TBE weakly depends on the form factor parameters!

## $\nu_e$ vs. $\nu_\mu$

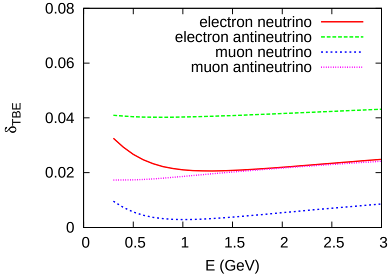



- The relative difference varies from $(2\%,\ -2\%)$

$$\mathcal{R}_\nu(Q^2) = \frac{\sigma_{Born}(\nu_e) + \sigma_{TBE}(\nu_e)}{\sigma_{Born}(\nu_\mu) + \sigma_{TBE}(\nu_\mu)} \left( \frac{\sigma_{Born}(\nu_e)}{\sigma_{Born}(\nu_\mu)} \right)^{-1} - 1$$

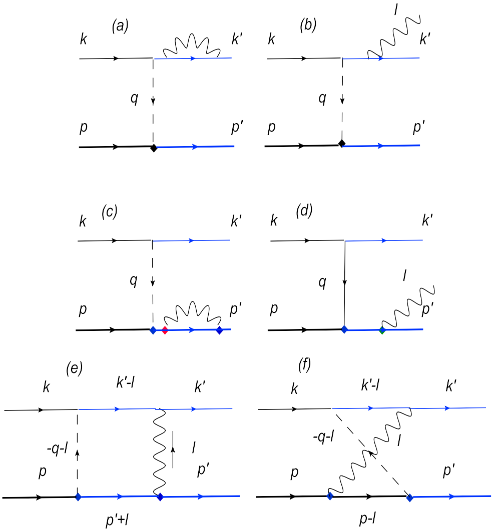
$$= \frac{1 + \delta_{TBE}(\nu_e)}{1 + \delta_{TBE}(\nu_\mu)} - 1 \approx \delta_{TBE}(\nu_e) - \delta_{TBE}(\nu_\mu),$$

## TBE in $\nu N$ Scattering




- The relative difference between $\sigma(\nu_e)$ and $\sigma(\nu_\mu)$, due to TBE, is of the order of $2\%$;
- TBE effect is negligible in the case of $\nu_\mu$ interactions.
- $G_F$ established from $\mu$ decay, hence, one should subtract the analogical $\Box_\mu$ contribution (Sirlin),
- at 20 MeV, $\delta_{TBE} - \Box_\mu \sim 0.032$
- outer correction (dominated by TBE prediction given by quark box diagrams in the massless limit) $\sim 0.024$ by M. Fukugita and T. Kubota, Acta Phys. Polon. B 35 (2004) 1687.

## QED-like only correction




Born$\times\mathcal{O}(\alpha^2) \sim \mathcal{O}(\alpha^3)$

- Minimal frame for validation of the calculations, only QED-like corrections;
- it allows to check the normalization, signs etc.
- lower bound for RC's corrections.

**Fermion Propagator Correction**

$$\delta_{Self.} = -\frac{\alpha}{\pi}\left\{\frac{9}{4} + \ln\frac{\mu}{m} + \ln\frac{\mu}{M_p} + \frac{1}{2}\left(\ln\frac{\Lambda_{UV}}{m} + \ln\frac{\Lambda_{UV}}{M_p}\right)\right\}.$$

## Cross Checks: Soft Bremsstrahlung

$$\nu(k) + n(p) \to l^-(k') + p(p') + \gamma(l)$$

$$i\mathcal{M}_{brem.} = i\mathcal{M}_{p',inel.} + i\mathcal{M}_{k',inel.}$$

$$i\mathcal{M}_{k',brem} = \overline{u}(k')(-ie)\gamma^\mu \epsilon^*_\mu(l) \frac{i(\hat{k'} + \hat{l} + m)}{(k'+l)^2 - m + i\epsilon} \times (\ldots, born)$$

soft photon approximation, in the numerator $l \to 0$, $l^2 \to 0$ in the denominator,

$$|i\mathcal{M}_{brem}|^2 = -e^2 \left[ \frac{m^2}{(k'\cdot l)^2} + \frac{M_p^2}{(p'\cdot l)^2} - \frac{2p'\cdot k'}{(p'\cdot l)(k'\cdot l)} \right] |\mathcal{M}_{born}|^2 \qquad (3)$$

$$d\sigma_{brem} \sim e^2 d\sigma_{Born} \left[ 2p'\cdot k' L_{p'k'} - m^2 L_{k'k'} - M_p^2 L_{p'p'} \right], \quad L_{xy} = \int_{|\mathbf{l}|<\varepsilon} \frac{d^3 l}{|\mathbf{l}|} \frac{1}{(x\cdot l)(y\cdot l)}$$

analytic formulas: 't Hooft79, Maximon00 (by Lorentz invariant scalars)

- IR divergent part of $L_{p'k'}$ cancels with IR singularity in TBE box diagrams.
- IR divergencies of $L_{p'p'}$ and $L_{k'k'}$ cancel with proton and electron (QED) self energy correction.

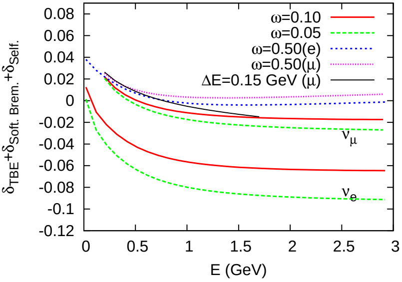
- $\epsilon$ is the maximal soft photon energy but in the frame **l** + **p'** = 0!

$$\Delta\epsilon = \underbrace{\eta}_{1+(E/M)(1-\cos\theta)} \quad \underbrace{\Delta E}_{\omega E'}$$

- $\Delta E = \omega E'$ is the detector acceptance.

* $\eta$ – expression for electron

## Soft Bremsstrahlung Emission




$$\sigma(E) = \sigma_{Born}(E)(1+\delta_{TBE}+\delta_{Brem.Soft.}+\delta_{Self.})$$

- TBE + Brem. + Self. is IR finite as it should be, UV divergence remains.
- It is the lower bound for RCs!
- It depends on the detector acceptance. Notice that it is divergent when $\omega \to 0$!
- TBE effect reduces the Soft Bremsstrahlung contribution!
- Adding hard Bremsstrahlung reduces the RCs (setting $\omega = 0.5$ mimic hard photon limit and it shows only the tendency, does not correctly model the hard photon emission).
- At low $E$ RC's($\nu_e$) $\to 3.8\%$, which agrees with the threshold estimates by Fukugita and Kubota, Acta. Phys. Polon. B35 (2004) 1687.
- A proper estimate of RC's depends on the detector properties and the way of reconstructing muon energy and $Q^2$.
- With hard photon emission the RC's tend to be on the percent level.

$$Bremsstrahlung\ Emission = \underbrace{\int_0^{\Delta E} \frac{d^3 l}{|\mathbf{l}|} \sigma_{Brem}(\nu N \to \nu P \gamma)}_{Soft(*)} + \underbrace{\sum_{\alpha=1}^{2} \int_{\Delta E}^{E^\alpha_{max}} \frac{d^3 l}{|\mathbf{l}|} \sigma_\alpha(\nu N \to \nu P \gamma)}_{Hard(**)}$$

## Summary

- TBE exchange correction to CCQE $\nu N$ scattering has been obtained.
- TBE is of comparable size as in the elastic $ep$ scattering.
- The averaged difference between TBE for $\nu_e$ and $\nu_\mu$ is of the order of $2\%$.
- QED set of corrections have been obtained. It gives the lower bound for RC's.
- TBE gives crucial contribution in total amount of RC's and it is necessary in order to reduces the Soft Bremsstrahlung correction.
- the proper inclusion of the RC's in the data analysis requires taking into account detector properties.
- Work in progress: calculations of the contribution from all diagrams required by gauge invariance;
- Confrontation with experiment: one should take into account the detector properties and the way of measurement of the particles, it seems to be not straightforward.
- **Let's include RS's corrections into NuWro Monte Carlo Generator.**