Radiative corrections to quasi-elastic neutrino-nucleon scattering

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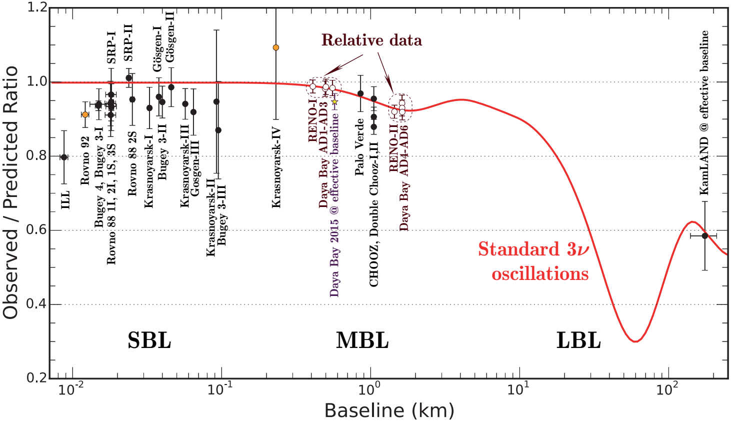
Outline

- Motivation
- Types of radiative corrections
- Magnitude of QED corrections
- Example: RC to ν DIS
- Preliminary results for LLA corrections
- RC to muon decay spectrum
- Remarks on higher-order corrections
- Estimates of theoretical uncertainties
- Outlook

Motivation

- The continuously increasing experimental precision due to higher statistics, modern detectors, and analysis techniques
- The general importance of the neutrino physics for understanding of the SM and going beyond it
- The progress in the methods of RC calculations
- Development of high-power computer tools (Monte-Carlo generators etc.)

Reactor antineutrino anomaly



The average ration $\mu = 0.943 \pm 0.023$ is significantly below 1

Figure from [D.V.Naumov, V.A.Naumov, D.S.Shkirmanov, Phys. Part. Nucl. '2017]

CERN Neutrino Platform (CENF)

The CERN Neutrino Platform is CERN's undertaking to foster and contribute to fundamental research in neutrino physics at particle accelerators worldwide, as recommended by the 2013 European Strategy for Particle Physics.

- Assist the various groups in their R&D phase (detectors and components) in the short and medium term and give coherence to a fragmented European Neutrino Community
- Provide to the community a test beam infrastructure (charged particles)
- Bring R&D at the level of technology demonstrators in view of major technical decisions
- Continue R&D on beam, as a possible base for further collaborations
- Support the short baseline activities (infrastructure & detectors)
- Support the long baseline activities (infrastructure & detectors)

CERN Neutrino Platform (CENF)

Involvement of CERN NP in current and future LBN experiments

Figure from [S. Bordoni, PoS(EPS-HEP2017)483]

Types of Radiative Corrections (RC)

Different classifications:

1) QED, QCD, (elecro)weak, mixed, . . .

2) improved Born approximation, one-loop, leading logs, higher orders etc.

3) leading order, next-to-leading order, NNLO, . . .

4) perturbative, re-summed, non-perturbative, . . .

5) virtual (loop) RC, soft photon emission, hard Bremsstrahlung, light pair creation, vacuum polarization, . . .

For quasi-elastic ν scattering on nuclei at E_ν $\sim$GeV we need at first
— nonperturbative effects of nucleon form factors
— one-loop QED corrections

Magnitude of QED RC

We have several small and large parameters in expansions:

- $\alpha/(2\pi) \approx 0.001$
- $(\alpha/(2\pi))^2 \approx 10^{-6}$
- $L \equiv \ln(E_e^2/m_e^2) \approx 16$ the large log for $E_e = 1$ GeV
- $(m_e^2/E_\nu^2) \ll 1$, but for μ and τ ...
- there can be other enhancement and suppression factors due to concrete experimental conditions

Knowing the experimental precision tag is crucial. E.g. for 1% precision tag we need to control all effects of the order of a few permille

Example: RC to ν DIS (I)

$$\nu_\mu \quad + \quad N \quad \longrightarrow \nu_\mu(\mu) \quad + \quad X$$

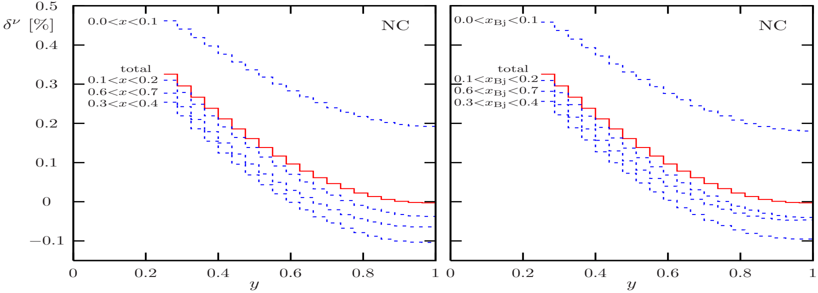
$$R^\nu = \frac{\sigma^\nu_{NC}(\nu_\mu N \to \nu_\mu X)}{\sigma^\nu_{CC}(\nu_\mu N \to \mu^- X)}$$

A.B. Arbuzov, D.Yu. Bardin, L.V. Kalinovskaya, Radiative Corrections to Neutrino Deep Inelastic Scattering Revisited, JHEP 06 (2005) 078

Calculation was done for the NOMAD experiment
motivated by the NuTeV anomaly in the NC/CC ratio

Example: RC to ν DIS (II)

Size of RC to neutral current DIS

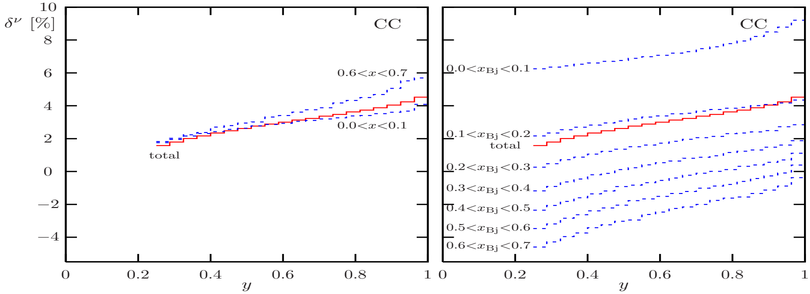


$$p_q^\mu = x P_N^\mu, \qquad x_{\mathrm{Bj}} = \frac{-(p_l - k_l)^2}{2 M_N E_{\mathrm{had+phot}}^{\mathrm{LAB}}}$$

N.B. No large logs here

Example: RC to ν DIS (III)

Size of RC to charged current DIS



N.B. Large logs dominate here: $(\alpha/\pi)\ln(Q^2/m_\mu^2)$

Preliminary results for LLA RC (I)

N.B. At the very beginning DGLAP evolution equations were first written for (scalar) QED. Later on they were extensively exploited in QCD. But QED DGLAP are very useful also to estimate the leading part of one-loop and higher-order QED radiative corrections.

LLA (LO) QED DGLAP:

[1] E.A.Kuraev and V.S.Fadin, On Radiative Corrections to e+ e- Single Photon Annihilation at High-Energy, Sov. J. Nucl. Phys. **41** (1985) 466 (758 citations)

[2] A.De Rujula, R.Petronzio, A.Savoy-Navarro, Radiative Corrections to High-Energy Neutrino Scattering, Nucl. Phys. B **154** (1979) 394 (177 citations)

NLO QED DGLAP:

[3] F.A.Berends, W.L. van Neerven, G.J.H.Burgers, Higher Order Radiative Corrections at LEP Energies, Nucl. Phys. B **297** (1988) 429

[4] A.Arbuzov, K.Melnikov, $O(\alpha^2 \ln(m_\mu/m_e))$ corrections to electron energy spectrum in muon decay, Phys. Rev. D **66** (2002) 093003.

Preliminary results for LLA RC (II)

The master formula for $\nu n \to ep$ in the NLO approximation:

$$\mathrm{d}\sigma(Q^2) = \int_{\bar{z}}^{1} \frac{\mathrm{d}z}{z} \left(\mathrm{d}\sigma^{(0)} \left(\frac{Q^2}{z} \right) + \mathrm{d}\bar{\sigma}^{(1)} \left(\frac{Q^2}{z} \right) + \mathcal{O}\left(\alpha^2 L^0\right) \right) \mathcal{D}_{ee}^{\mathrm{frg}}(z)$$

where $\mathrm{d}\bar{\sigma}^{(1)}$ is $\mathcal{O}(\alpha)$ correction with "massless electron" in $\overline{\mathrm{MS}}$ scheme

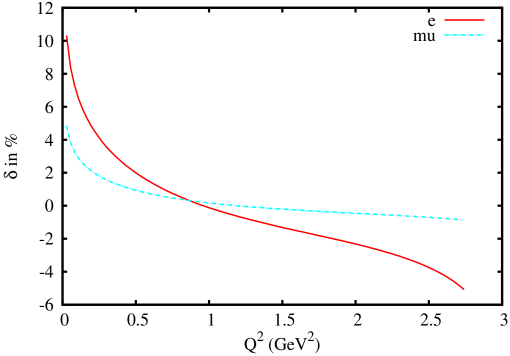
$\mathcal{D}_{ee}^{\mathrm{frg}}(z)$ is the QED fragmentation function $e \to e$

$$\begin{aligned} \mathcal{D}_{ee}^{\mathrm{frg}}(z) &= \delta(1-z) + \frac{\alpha}{2\pi} \left(\ln \frac{\Lambda^2}{m_e^2} - 1 \right) \left[\frac{1+z^2}{1-z} \right]_+ \\ &+ \frac{1}{2} \left(\frac{\alpha}{2\pi} \right)^2 \left(\ln \frac{\Lambda^2}{m_e^2} - 1 \right)^2 P^{\otimes 2}(z) + \ldots \end{aligned}$$

where Λ is the factorization scale, $\Lambda \sim E_e$

Preliminary results for LLA RC (III)

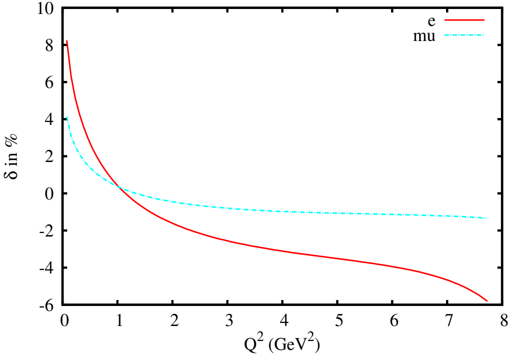
$E_\nu = 2$ GeV $\qquad \delta = \left[\dfrac{d\sigma^{\text{corrected}}}{d\sigma^{\text{Born}}} - 1\right] \cdot 100\%$



A simplified set of nucleon form factors was used for numerical calculations. Which one should be taken?

Preliminary results for LLA RC (IV)

$E_\nu = 5\ \mathrm{GeV}$ $\qquad \delta = \left[\dfrac{d\sigma^{\mathrm{corrected}}}{d\sigma^{\mathrm{Born}}} - 1\right] \cdot 100\%$



RC to muon decay spectrum

Nuclear beta decays yield $E_\nu \sim$ a few MeV. So effects of the order m_e/E_ν might be important even in $\mathcal{O}(\alpha)$

For the muon neutrino case m_μ/E_ν is typically not small at all

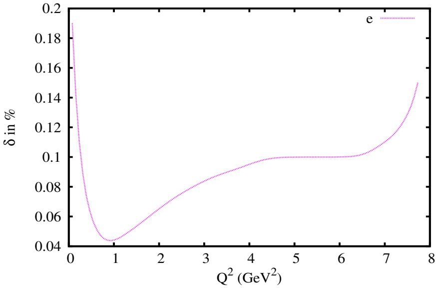
N.B. In most cases we get mass effects $\sim m_e^2/E_\nu^2$

Complete one-loop QED corrections with exact electron mass dependence to muon decay spectrum were computed first in [A.A. PLB' 2002]. Those results can be transformed into corrections to neutrino quasi-elastic scattering

$$\mu \to e + \bar{\nu}_e + \nu_\mu \ (\gamma) \longleftrightarrow \nu_e + n \to e + p \ (\gamma)$$

The work is in progress

Remarks on higher-order corrections



In higher orders we should estimate first the leading log effects of the order $\alpha^2 \ln(E^2/m_e^2)$. That is easy both for photonic and e^+e^- pair corrections

Typically, $\mathcal{O}\left(\alpha^2\right)$ pair RC are a few times less than $\mathcal{O}\left(\alpha^2\right)$ photonic ones, see e.g. A.A. JHEP'2001

Kinoshita–Lee–Nauenberg theorem

The large logs are singular if $m_e \to 0$. They are so-called mass singularities. But for sufficiently inclusive observables such mass singularities should cancel out in accord with the Kinoshita–Lee–Nauenberg theorem.

In practice (roughly speaking), the condition for the cancellation is the calorimetric registration of charged particles together with collinear photons which accompany them.

Another important principle for radiative corrections:

the more you cut — the more you get

i.e. corrections tend to increase for tight experimental cuts
or for "very exclusive" observables.

Estimates of theoretical uncertainties

For leading logs like in QCD we can estimate the uncertainty by variation of the energy scale under the large log: $L \to L \pm \ln(2)$.

But further reduction of the uncertainty will be (soon) reached by having the complete one-loop result plus leading-log higher order RC

Problem: form factors extracted from experiments might (in fact do) include a part of QED radiative corrections, if the RC have not been properly treated in the data analysis.

Outlook

1. Nowadays radiative corrections became relevant for many neutrino experiments

2. The size of RC crucially depend on the experimental set-up. There can't be a ready-to-use result for all cases

3. Leading log results for quasi-elastic ν_e and ν_μ scattering are presented

4. Double counting between QED RC and nucleon form factors should be excluded

5. Complete one-loop QED RC will be presented soon

6. Mass effects should be treated with care

7. Regions of max and min Q^2 deserve special treatment

8. Implementation of RC into a Monte-Carlo code have to be discussed