PARTICLE PHYSICS THEORY GROUP

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Particle Physics seeks to identify the elementary constituents of nature and to discover the fundamental forces acting between these constituents. Ordinary matter and non-gravitational interactions are described by the Standard Model which comprises two kinds of matter particles (quarks and leptons), three fundamental forces (the strong, electromagnetic and weak interactions) and the Higgs sector as the origin of mass via spontaneous symmetry breaking. The Standard Model constitutes a quantum field theory valid down to microscopic distances of the order of 10^{-18}m. The only Standard Model particle that escaped detection so far is the Higgs boson. The search for it is one of the most important endeavours at present and future collider experiments.

Quarks and leptons are grouped into three families (see Fig. 1). The first family contains the electron and the electrically neutral electron-neutrino as leptons as well as the up- and down-quarks. The protons and neutrons are built-up by up- and down-quarks and form atomic nuclei as strong-interaction bound states. The second family involves the muon and muon-neutrino as leptons and the strange- and charm-quark. The tau lepton and tau-neutrino joined by the bottom- and top-quark belong to the third family. The fundamental forces, i.e. the strong, electromagnetic and weak interactions, are mediated by the exchange of gauge bosons which are the basic carriers of the forces and observable as particles in collider experiments (see Fig. 1). The gauge boson of the electromagnetic interaction is the massless photon, while the massive W- and Z-bosons mediate the weak interaction with a very short range. Strong interactions are described by the exchange of gluons between the quarks as formulated in Quantum Chromodynamics (QCD).

The big success of the Standard Model in describing the experimental data relies crucially on precise calculations of quantum corrections to experimentally measured processes. An example for this is the work performed in the Theory Group on electroweak corrections to ν_μ-nucleon scattering measured in the NuTeV experiment, which determined the weak mixing angle, a basic parameter of electroweak interactions, with high accuracy. Electroweak interactions themselves can be tested in gauge-boson production at the LHC, a proton–proton collider currently built at CERN, and in electroweak processes at a future linear e^+e^- collider (LC). Owing to the high energies and rates available at these colliders a thorough analysis of these processes requires the extraction of the dominant parts of the electroweak corrections and the resummation of the corresponding higher-order contributions. This constitutes an important research direction within the Theory Group. Another major focus of the work of the Theory Group was the evaluation of precise predictions for various Higgs-boson production and decay processes, which will be used at the LHC and the LC to search for the Higgs boson and to study its properties.

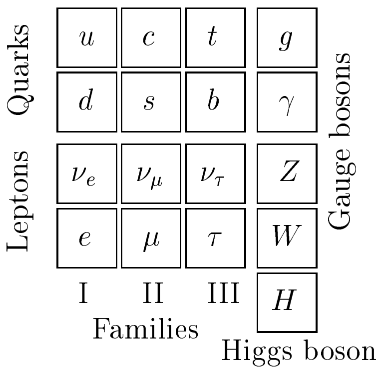

Figure 1: Particles of the Standard Model grouped into 3 families of quarks and leptons, the gauge bosons and the Higgs boson (see the text for more details).

The Standard Model has been tested with high accuracy at high energies, where the model can be treated perturbatively. At low energies, however, non-perturbative effects play a dominant role. This is reflected by the confinement effects of QCD which render it impossible to treat quarks and gluons as the basic degrees of freedom. The proper theoretical framework for low-energy processes is Chiral Perturbation Theory (ChPT) which is formulated in terms of the observed low-energy hadrons. Work in the Theory Group used ChPT to analyse K meson decays and the pion beta decay measured at PSI. This is important for a precise determination of the quark-mixing matrix elements, in particular, in the light of experimental indication that unitarity of the quark-mixing matrix may be violated. Another question of low-energy QCD studied in the Theory Group is the proper understanding of the structure functions of a confined system which are measured in deep-inelastic scattering experiments.

Despite its success, the Standard Model leaves several questions unanswered and suffers from various theoretical problems. Part of the latter are deeply routed in the Higgs sector and can be solved by the introduction of supersymmetry. Supersymmetry is a novel symmetry connecting bosons and fermions. For all particles of the Standard Model, it predicts supersymmetric partners, which have not yet been observed so far. The Theory Group performed calculations of quantum corrections to the production and decay processes of supersymmetric Higgs bosons and sfermions (the supersymmetric partners of the standard fermions) at the Tevatron, a running proton–anti-proton collider, the LHC and the LC.

The following contributions give more details on specific projects of the Theory Group. For a more complete overview of our work in 2003 see the list of publications and conference contributions.

ELECTROWEAK RADIATIVE CORRECTIONS TO HIGGS-BOSON PRODUCTION IN ELECTRON–POSITRON COLLISIONS

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One of the most important future challenges in particle physics is the understanding of the mechanism of electroweak symmetry breaking. In the Standard Model electroweak symmetry breaking is implemented via the Higgs–Kibble mechanism, which is responsible for the generation of particle masses and leads to the prediction of a physical scalar particle, the Higgs boson. The mass of the Higgs boson is expected to be in the range between the current lower experimental bound of $114.4\,\mathrm{GeV}$ and about $1\,\mathrm{TeV}$, above which the theory becomes inconsistent. The range below $200\,\mathrm{GeV}$ is favoured by electroweak precision data. While the LHC will find the Higgs boson in the full mass range up to $1\,\mathrm{TeV}$ if it exists, a complete investigation of the properties and interactions of the Higgs boson is only possible in the clean environment of an $\mathrm{e}^+\mathrm{e}^-$ collider.

At an $\mathrm{e}^+\mathrm{e}^-$ collider the two main Higgs-boson production mechanisms are Higgs-boson radiation off Z bosons, so-called Higgs-strahlung, and Higgs production via WW fusion. Both mechanisms are present in the reaction $\mathrm{e}^+\mathrm{e}^- \to \nu_l\bar{\nu}_l\mathrm{H}$ where l can be an e, μ, or τ. At a linear $\mathrm{e}^+\mathrm{e}^-$ collider with a center-of-mass energy of $500\,\mathrm{GeV}$ and an integrated luminosity of $500\,\mathrm{fb}^{-1}$, altogether of the order of 10^4 Higgs bosons can be produced per year [1]. This allows to measure the Higgs-production cross sections and thus the Higgs–gauge-boson couplings at the level of a few per cent. The top-quark Yukawa coupling can be investigated via the process $\mathrm{e}^+\mathrm{e}^- \to \mathrm{t\bar{t}H}$, which proceeds mainly through the emission of Higgs bosons off top quarks. For a light Higgs boson, a precision of about 5% is reachable. Consequently, adequate theoretical predictions have to take into account radiative corrections for these processes.

We have calculated the complete electroweak $\mathcal{O}(\alpha)$ radiative corrections to the single Higgs-boson production processes $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}$ and $\mathrm{e}^+\mathrm{e}^- \to \mathrm{t\bar{t}H}$ in the electroweak Standard Model. These calculations are among the most involved one-loop calculations that have been performed so far. The numerical evaluation is particularly complicated due to the presence of pentagon diagrams. Phase-space integration has been performed with Monte Carlo techniques.

Some illustrative results are shown in Figure 1 for the process $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}$. The corrections are typically of the order of 10%. They result from various contributions of this size which partially cancel each other. Therefore, precision analyses will require the inclusion of the full $\mathcal{O}(\alpha)$ corrections.

The electroweak corrections to the considered processes have been calculated in parallel by other groups. For both processes, our results agree with those of Ref. [4, 5] at the level of 0.1–0.2%, i.e. at the level of the integration errors. For $\mathrm{e}^+\mathrm{e}^- \to \mathrm{t\bar{t}H}$, there is also fair agreement with the results of Ref. [6], apart from the regions close to threshold and at high energies.

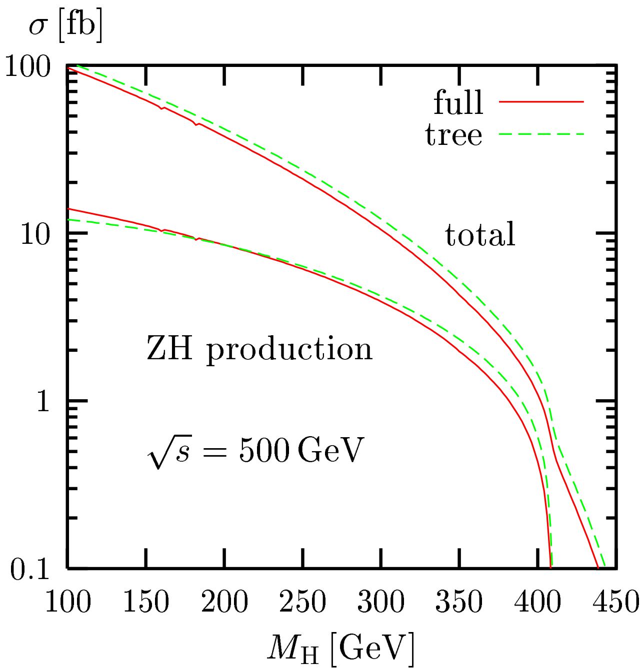

Figure 1: Cross section for $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}$ in lowest order and including the complete $\mathcal{O}(\alpha)$ electroweak corrections as a function of the Higgs-boson mass for $\sqrt{s} = 500\,\mathrm{GeV}$. Both the contribution of the Higgs-strahlung subprocess (ZH production) and the total contribution to the process $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\mathrm{H}$ are shown (taken from Ref. [2]).

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NEW PREDICTIONS FOR ELECTROWEAK $\mathcal{O}(\alpha)$ CORRECTIONS TO NEUTRINO–NUCLEON SCATTERING

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Deep-inelastic neutrino scattering $\nu_\mu N \to \mu X, \nu_\mu X$ has been analyzed in the NuTeV experiment [1] with a rather high precision. As a central result, the NuTeV collaboration has translated their measurements of the ratio of neutral to charged current neutrino-nucleon scattering cross sections into a value for the on-shell weak mixing angle, $\sin^2\theta_W = 1 - m_W^2/m_Z^2$, which can be viewed as independent (indirect) determination of the W- to Z-boson mass ratio. The NuTeV result on $\sin^2\theta_W$ is, however, about 3σ away from the result obtained from the global fit [2] of the Standard Model (SM) to the electroweak precision data.

As the electroweak radiative corrections have great influence on the NuTeV result and as the NuTeV analysis, so far, was relying on a single calculation only [3], we have, in a recent publication [4], performed a careful reanalysis of the $\mathcal{O}(\alpha)$ electroweak corrections to neutral current (NC) and charged current (CC) deep-inelastic neutrino scattering off an isoscalar target. The inclusion of higher-order quantum corrections induces a shift $\Delta\sin^2\theta_W$ to the value of the weak mixing angle as determined from the Born level relation between $\sin^2\theta_W$ and the neutrino-nucleon scattering cross sections.

Apart from a different set of parton density functions (PDFs) and input parameters the most important difference between our calculation and the result of Ref. [3] lies in the treatment of mass singularities due to collinear radiation of a photon from external charged particles. Initial-state mass singularities due to collinear photon radiation were subtracted from the real corrections with a suitably defined ($\overline{\mathrm{MS}}$) counterterm, as it is standard procedure in perturbative QCD and a standard set of leading-order parton densities was used in the numerical analysis. Our method of initial-state mass factorization is fundamentally different from the technique employed in Ref. [3] (denoted BD below), where the initial-state quark mass (m_q) dependence is left unsubtracted and $m_q = x\, m_N$, the scaled nucleon mass, is chosen for the initial-state mass value.

Unless the observable under consideration is inclusive enough with respect to final state radiation, the Kinoshita–Lee–Nauenberg (KLN) theorem states that there are also final state quark and (in the CC case) muon mass logarithms in the $\mathcal{O}(\alpha)$ corrections. Collinear safety is, in general, not guaranteed if phase-space cuts at the parton level are applied. In the NuTeV analysis an event is discarded unless the energy deposited in the calorimeter lies within certain bounds, which imposes a cut on the final-state particles' energies. We have implemented this final-state energy cut in three different ways in our theoretical analysis, namely by imposing it either (1) on the final-state quark alone, (2) on the final-state quark energy and the final-state real photon energy added together or (3) on the final-state quark energy and the final-state real photon energy added if the real photon is emitted within a cone of $5°$ (in the laboratory frame) around the final-state quark and otherwise on the final-state quark energy alone.

result of Ref. [3]			-114	
input parameters:	factorization scheme:	final-state energy cut: (1)	(2)	(3)
$G_F, \sin^2\theta_W$	$\overline{\mathrm{MS}}$	-90	-130	-94
$G_F, \alpha(0)$	$\overline{\mathrm{MS}}$	-95	-132	-99
$G_F, \sin^2\theta_W$	BD	-98	-138	-102
$G_F, \alpha(0)$	BD	-103	-139	-106

Table 1: Results for $\Delta\sin^2\theta_W \cdot 10^4$. We compare the prediction of Ref. [3] with ours in different input-parameter and initial-state mass factorization schemes and for different variants of final-state energy cut.

The relevant numerical result of Ref. [3] and a compilation of our results for $\Delta\sin^2\theta_W$ for different input-parameter and initial-state mass factorization schemes as well as different final-state energy cuts (labeled 1–3 as explained above) are shown in Table 1. The input parameter schemes labeled '$G_F, \sin^2\theta_W$' and '$G_F, \alpha(0)$' differ in the W-boson mass values (m_W) used to parameterize the SM. In the first case m_W is calculated from the Z-boson mass and $\sin^2\theta_W$ as quoted in Ref. [3] through the on-shell relation, in the second case it is obtained from iterative numerical solution of the next-to-leading order relation between the Fermi and the fine structure constant. Of course, this comparison of results can neither prove nor disprove the correctness of the results of Ref. [3]. However, the table suggests significant differences between their result and ours, no matter what final-state energy cut or what input-parameter or initial-state mass factorization scheme we chose. In any case, the variations in the corrections that are due to the different factorization schemes ($\overline{\mathrm{MS}}$ versus BD) and due to different ways of including the final-state photon in the hadronic energy in the final state can be as large as the accuracy in the NuTeV experiment, which is about $16 \cdot 10^{-4}$ in $\sin^2\theta_W$ and it can be concluded that in the light of such large uncertainties a reanalysis of the NuTeV data would be desirable.

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SEMILEPTONIC KAON DECAYS AND CKM UNITARITY

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One of the most prominent features of the Standard Model is the fact that the quark states undergoing charged current weak interactions are not the mass eigenstates. Interpretation of these weak interactions in terms of mass eigenstates necessitates the introduction of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The CKM matrix allows for transitions among the different quark flavours and accordingly modulates the strength of the weak interactions.

In the last years new high-precision experiments dedicated to the study of the CKM elements V_{ud} and V_{us} have been planned and gone into operation. For instance, the PIBETA Collaboration extracted $|V_{ud}|$ with high precision from a pion beta decay experiment at PSI. A series of experiments like E865, KLOE, CMD2 and NA48 is already taking data or going to take data from semileptonic kaon decays, $K \to \pi e^+ \nu_e$ (K_{e3}) and $K \to \pi \mu^+ \nu_\mu$ ($K_{\mu 3}$). One reason for this renewed interest in semileptonic kaon (pion) decays is the present $2.2\,\sigma$ deviation from unitarity obtained from the first row CKM elements:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0042 \pm 0.0019.$$

To match the expected experimental precision of about 1% or better, it is essential for a thorough theoretical analysis to account for electromagnetic radiative corrections in a systematic and unambiguous way. In a series of papers [1, 2, 3] we have studied radiative corrections to semileptonic kaon (pion) decays in the framework of Chiral Perturbation Theory (ChPT) with virtual photons and leptons. ChPT is the effective low-energy version of the Standard Model, and therefore optimally suited for a model independent examination of such meson decays. In particular, we have concentrated on the set-up of an experimentally viable definition of a (photon) inclusive infrared finite decay rate.

Besides phase-space and kinematical factors, the square root of the inclusive infrared safe decay rate $\Gamma(K_{e3(\gamma)})$ is given by a form factor at zero momentum transfer, $f_+^{K\pi}(0)$, times $|V_{us}|$. We calculated the form factors describing the decays $K^+ \to \pi^0 e^+ \nu_e$ and $K^0 \to \pi^- e^+ \nu_e$, and included isospin breaking corrections due to quark mass differences and electromagnetism at next-to-leading-order as well as next-to-next-to-leading-order corrections in the isospin symmetry limit. It should be noted that the value and uncertainty of the next-to-next-to-leading-order correction are still controversial and more work along these lines is needed to obtain a realistic estimate for the overall uncertainty. At the moment, we come up with a theoretical uncertainty in the extraction of $|V_{us}|$ which amounts to $\simeq 1\%$.

The present experimental status of $K^+ \to \pi^0 e^+ \nu_e$ and $K^0 \to \pi^- e^+ \nu_e$ decays and the information about $|V_{us}|$ contained in the data is summarized in Figure 1. Here, we choose to plot $|V_{us}|$ as obtained from data normalized to the $K^0\pi^-$ form factor. From the plot it is obvious that the situation is

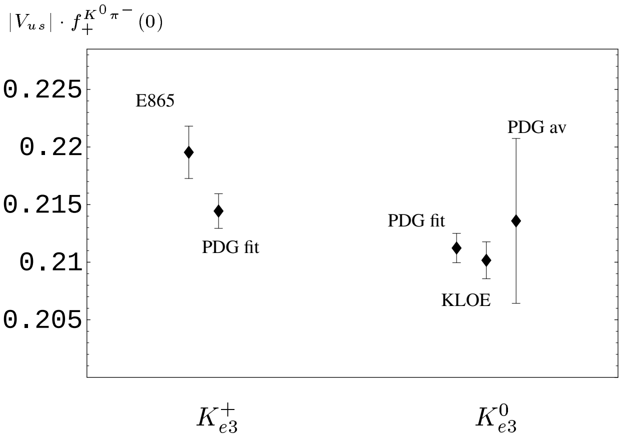

Figure 1: $|V_{us}| \cdot f_+^{K^0\pi^-}(0)$ from K_{e3} decay modes and various experimental sources. E865 and KLOE refer to recent measurements, where it should be stressed that the KLOE uncertainty is based on statistics only. 'PDG fit' and 'PDG av' refer to fits and averages from the Particle Data Group.

far from being clear and settled. Rather recently, the E865 experiment at Brookhaven measured an inclusive decay rate $\Gamma(K^+_{e3(\gamma)})$ which is about $2.3\ \sigma$ off the value quoted by the Particle Data Group. Hence, $|V_{us}|$ calculated from the new rate would be larger and the CKM discrepancy could be resolved:

$$|V_{us}| \quad = \quad 0.2238 \pm 0.0033.$$

However, one would have to face a discrepancy with what the Particle Data Group quotes. On the other hand, the preliminary new data from KLOE seem to confirm the old data but would not offer a solution to the unitarity problem. At present both new experiments are in disagreement with each other. Yet it is important to remember that the KLOE numbers can still change and indicate a problem in the old data.

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STRUCTURE FUNCTION OF A CONFINED SYSTEM

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The structure functions measured in deep inelastic lepton scattering provide important information about the nature and momentum distribution of the constituents of the target (quark and gluons in QCD). In a non-relativistic description the structure function for one particle is given by

$$S(q,\nu) \;=\; \sum\!\!\!\!\!\!\int_n \; \delta(\nu - (E_n - E_0)) \left| < n | e^{iq\cdot\hat{x}} | 0 > \right|^2$$

where the summation is over all discrete and continuum states which are excited by the probe. Here q, ν denote momentum and energy transfer and E_n the excitation energies of the target. Very often the confinement of quarks is described by using rising potentials which lead to a purely discrete spectrum. The simplest version is given by a harmonic oscillator potential whose structure function is a weighted sum of δ-functions. However, the observed structure functions are smooth due to hadronization and/or final state interactions. A number of recent theoretical studies have accounted for that by simply smearing out the δ-functions by a Breit-Wigner distribution with a constant width. This is not only *ad hoc* but also violates general properties of the structure function like its vanishing below the first (positive) excitation energy.

Thus a consistent quantum mechanical framework is needed which allows to treat couplings to unobserved degrees of freedom in a simple manner. For quasielastic scattering of electrons from nuclei Horikawa *et al.* [1] first have included multi-nucleon channels by employing an optical potential without violating the energy-weighted sum rules

$$\int_0^\infty d\nu \, \nu^n \, S\,(q,\nu) \;=\; \left(\frac{q^2}{2m}\right)^n \quad , \; n \;=\; 0,1 \; .$$

However, there exists a simpler treatment based on the description of dissipative quantum systems within the path integral formalism. This originates in the classic work of Feynman & Vernon and Caldeira & Leggett [2] who have modelled the coupling of the system to an environment ("bath") of $N(\to\infty)$ harmonic oscillators with a bilinear coupling. The path integral description of the system offers particular advantages since the bath oscillators can be integrated out exactly giving rise to a retarded two-time action for the single particle as in the polaron problem [3]. In addition, if this particle moves in a harmonic potential $V(x) = m\omega_0^2 \, x^2/2$ then the remaining path integral can also be done exactly. This approach allows for the consistent description of dissipative systems in a unitary quantum-mechanical framework and leads to a broadening (and a shift) of the δ-functions in the structure function of the confined system without violating the sum rules. It is also a very economical one: taking the simplest assumption for the properties of the bath oscillators (*Ohmic dissipation*) the damping is characterized by just *one* parameter γ.

Fig. 1 shows the results of a model calculation [4] for several momentum transfers and damping parameters. It is seen that the excitation of individual levels gradually moves

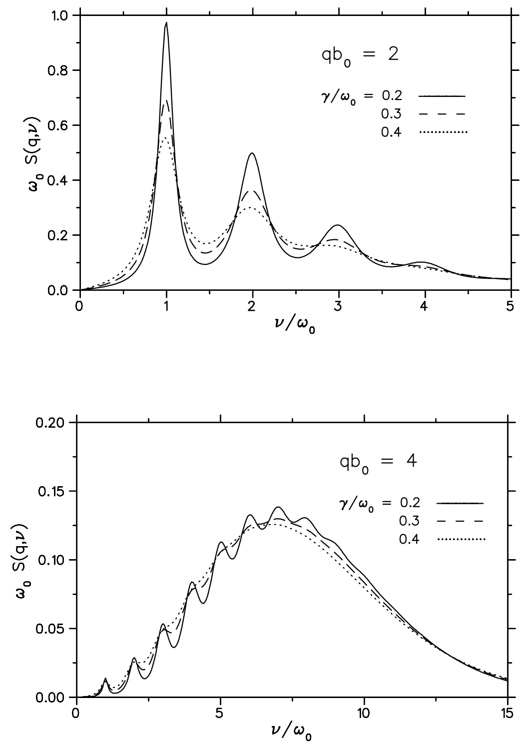

Figure 1: Structure function of the damped harmonic oscillator for different momentum transfers q and Ohmic damping parameters γ in units of the frequency ω_0 and the oscillator length b_0 of the undamped sytem.

into the broad structure of the quasi-elastic peak as the momentum transfer q increases.

Closer inspection reveals that the width of the n-th excited state is approximately $\Gamma_n \approx n\,\gamma$, a result already derived for some nuclear and mesoscopic models. However, the shape of the excited states is not an exact Breit-Wigner one: due to the unitary description of dissipation the structure function has the correct support, i.e. vanishes identically for negative excitation energies and the sum rules are conserved exactly.

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