Search for effects of new physics in electron-positron annihilation at the energies of existing and future accelerators

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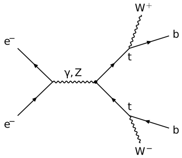
Session Particle Physics: Theory and Detectors

I. Search for effects beyond the Standard Model in electron-positron annihilation into the top quarks and their decay at energies of future colliders ILC, CLIC (Ivan Truten, Alexander Korchin).

Study of phenomena beyond the Standard model (SM) is one of the main directions nowadays. We will concentrate here on future e^+e^- colliders, e.g. CLIC or ILC.

One of motivations is the search for effects of *CP*-violation in the process $e^+e^- \to t\bar{t} \to b\bar{b}W^+W^-$:



– I.V. Truten, A.Yu. Korchin. *Energy correlation of bottom quarks from decays of top quarks in electron–positron annihilation.* J. Phys. G **49** (2022) 4, 045003.
– I.V. Truten, A.Yu. Korchin. *The top-quark polarization beyond the Standard Model in electron–positron annihilation.* Int. J. Mod. Phys. A **34** (2019) 12, 1950067.
– I.V. Truten, A.Yu. Korchin. *Energy and angular distributions of the bottom quark in the electron-positron annihilation $e^+e^- \to bW^+\bar{t}$.* Int. J. Mod. Phys. A **36** (2021) 02, 2150013.

$t\bar{t}\gamma$ and $t\bar{t}Z$ interactions

Contributions from beyond SM physics can be written as an effective vertex, describing interaction of the photon and Z-boson with the quarks, namely the top quarks. This interaction includes the SM contribution and "new physics" terms:

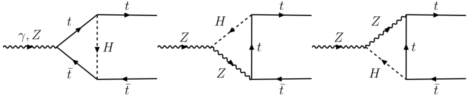
$$\Gamma^{\mu}_{t\bar{t}V} = -ie\bar{t}\left(\gamma^{\mu}(v_t^V - a_t^V\gamma_5) + \frac{1}{2m_t}\sigma^{\mu\nu}q_{\nu}(i\kappa^V - \tilde{\kappa}^V\gamma_5)\right)t.$$

where $V \equiv \gamma$, Z, and q is the four-momentum of photon or Z boson.
The terms proportional to couplings κ^V determine CP-even interaction, while the terms with $\tilde{\kappa}^V$ determine CP-odd interaction.

For the photon: the coupling κ^{γ} is the anomalous magnetic dipole moment and $\tilde{\kappa}^{\gamma}$ – electric dipole moment,
for the Z boson: κ^{z} – anomalous weak magnetic dipole moment and $\tilde{\kappa}^{z}$ – weak electric dipole moment.
The terms with $\tilde{\kappa}^{\gamma}$ and $\tilde{\kappa}^{z}$ are responsible for CP violation.
All these anomalous terms appear also in the dimension-6 terms in effective Lagrangian of SM.

One-loop model and Higgs couplings to top quarks

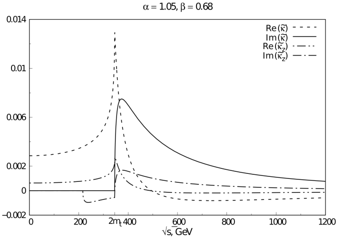
For an estimation of magnitude of couplings κ, κ_Z, $\tilde{\kappa}$ and $\tilde{\kappa}_Z$, we use one-loop corrections to the γtt and Ztt vertices:



To generate CP-violation effects, the Higgs boson interaction with t quarks is chosen

$$\mathcal{L}_{htt} = -\frac{m_t}{v}\, h\, \bar{t}\, (\alpha + i\, \beta\gamma_5)\, t\,,$$

α and β are real parameters ($\alpha = 1, \;\; \beta = 0$ correspond to SM). An example of dependence of real and imaginary part of $\tilde{\kappa}$ and $\tilde{\kappa}_Z$ on the e^+e^- energy:

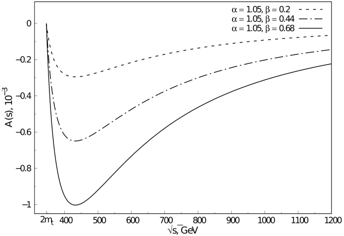


Observables for experiments

One of convenient observables is asymmetry of the bottom quark and antiquark energies

$$A(s) \equiv \int\int \frac{1}{\sigma_0} \frac{d^2\sigma}{d\varepsilon\, d\bar{\varepsilon}} \left[\theta(\varepsilon - \bar{\varepsilon}) - \theta(\bar{\varepsilon} - \varepsilon)\right] d\varepsilon\, d\bar{\varepsilon} = \frac{N_{E_b > E_{\bar{b}}} - N_{E_b < E_{\bar{b}}}}{N_{total}}$$

where ε is energy of the bottom quark, $\bar{\varepsilon}$ - energy of the antiquark and $\sigma_0 \equiv \sigma_{e^+e^- \to t\,\bar{t}}$ is the total cross section.
An example of this asymmetry is shown as a function of the invariant energy $\sqrt{s}$, for parameters α and β which are chosen within the limits obtained by the ATLAS and CMS collaborations.



Prospects: at present calculations with polarized electron and positron beams in the conditions of the future e^+e^- colliders are carried out.

II. Study of pion-nucleon resonances in electron-positron annihilation to a pair of nucleon-antinucleon and pion in conditions of experiments on detectors BELLE and BES III (Nikolai Merenkov, Gennadiy Gakh, Mykhailo Konchatnij).

The study of the elastic and different transition form factors in the time-like region is very important to understand hadrons as the composite systems of the strongly interacting quarks and gluons. The measurement of the exclusive hadron channels in the e^+e^- annihilation allows one to study the excited nucleon and hyperon states, such as Λ^*, Σ^* and Ξ^*. The corresponding experiments at the Beijing Electron-Positron Collider (BEPC) began about 20 years ago. Up to now, the N^* production from e^+e^- annihilations has been studied only around the charmonium region. We intend to investigate the reactions

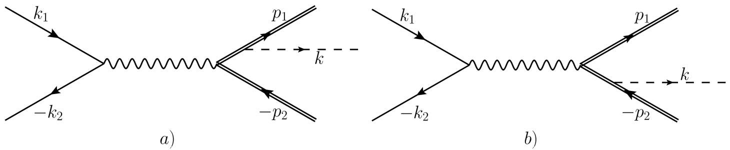
$$e^+ + e^- \to N + \bar{N} + \pi^0, \;\; N = p, \, n, \quad e^+ + e^- \to p + \bar{n} + \pi^-,$$

$$e^+ + e^- \to \bar{p} + n + \pi^+$$

and to account for the continuum (nonresonant) and resonance (with various vector resonances and excited baryons) contributions.

– G.I. Gakh, M.I. Konchatnij, N.P. Merenkov and E. Tomasi-Gustafsson, Phys. Rev. D **105**, 095029 (2022).

The continuum for the neutral pion reactions is defined by the diagrams



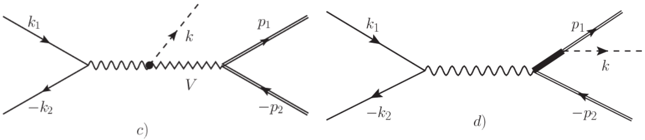
A key issue is the choice of the nucleon electromagnetic form factors in the time-like region, and one needs to use the data to fit various theoretical models of the form factors.

Here we use two parameterizations from the papers: F. Iachello and Q. Wan, Phys. Rev. C 69, 055204 (2004) and R. Bijker and F. Iachello, Phys. Rev. C 69, 068201 (2004), and calculated various double- and single differential distributions over the invariant variables, such as

$$s_1 = (k + p_1)^2,\ s_2 = (k + p_2)^2,\ t_1 = (k_1 - p_1)^2,\ t_2 = (k_2 - p_2)^2.$$

Resonant contribution for reactions with π^0

There are two types of the resonant contributions: with intermediate vector mesons (diagram c)) and with baryon resonances of different spins and parities (diagram d))



It can be expected that the low-mass vector mesons: ρ, ρ', ω, ϕ can give essential contribution at large values of the colliding energy.
The reason is that the decreasing strong form factors in the $V N \bar{N}$ vertex depends on invariant $s_{12} = (p_1 + p_2)^2$ for the diagram c), but not on $s = (p_1 + p_2 + k)^2$ as decreasing electromagnetic form factors in the $\gamma^* N \bar{N}$ vertex for the diagram d). At given s the variable s_{12} runs a wide range of values: $4M^2 < s_{12} < (\sqrt{s} - m)^2$, where $M\,(m)$ is the mass of nucleon (pion).
Prospects: the numerical estimation the resonant contribution implies quite large uncertainties in the underlying parameters, and the work in this direction is in progress.

III. Research into processes beyond leading order in perturbative QCD of production of bottom quark and antiquark in electron-positron annihilation at the ILC and CLIC energies (Volodymyr Kotlyar).

Aim of this stage of the project is to investigate:

- the mechanisms of charm and bottom quark production that come from processes beyond the leading order (LO) in perturbative QCD (pQCD);
- influence of parton showers on differential distributions and on correlation observables;
- the potentialities and the scope of the methods and models employed, in particular in pQCD and in hadronization of heavy quarks;
- to compute integral cross sections, differential distributions, and correlation observables for open and hidden flavor meson and baryons in electron-positron annihilation at the LHC, ILC, and CLIC energies.

Hard and soft QCD processes

The Monte Carlo simulation of the hard partonic processes is performed with the codes generated with
MadGraph5_aMC@NLO [R. Frederix et al. JHEP 11 (2021) 085].
The soft QCD processes, such as parton showers and fragmentation, or decay of unstable particles, are included with the help of
Pythia 8.3 event generator
[T. Sjöstrand.Comput. Phys. Commun. 246 (2020) 106910,
C. Bierlich et al. arXiv:2203.11601 [hep–ph]].

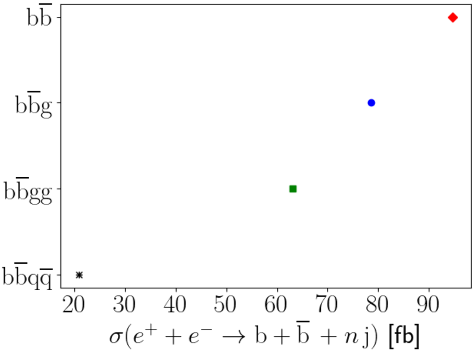
The hard processes are simulated for

$$\mathbf{e^+ + e^- \to Q + \overline{Q} + \mathit{n}\, j},$$

with n = 0, 1, and 2, Q being charm or bottom quark. In the case of Q =b , a jet "j" is gluon, u, d, c, s quarks or corresponding anti–quarks. Calculation for each process with n = 0, 1, and 2 are carried out at next–to–leading order of pQCD at one loop approximation, i.e. with inclusion of emission of real and virtual particles.

Bottom quark production in $e^+ + e^-$ collisions

Cross sections of partonic processes $\mathbf{e^+ + e^- \to b + \overline{b} + \mathit{n}\, j}$ at $\sqrt{s} = 1$ TeV



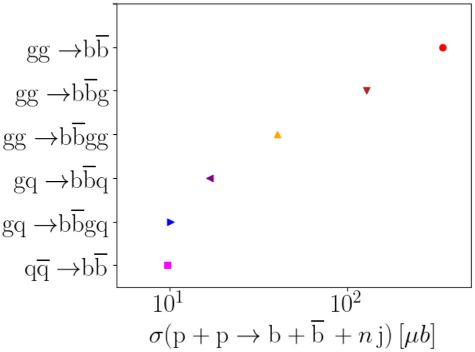
The cross sections σ are computed with value of minimal "jet" transverse momentum $p_{Tj} = 40$ GeV/c.

For p_{Tj} running from 20 up to 100 GeV/c renormalization scale uncertainties reduce from (+43%, -116%) down to (+4%, -13%) for the scale factor within range [1/2, 2].

The calculations confirm that pQCD correction are essential for the electroweak processes $e^+ + e^- \to Q + \overline{Q}$ of heavy quark production.

Bottom quark production in pp scattering

Cross sections of partonic processes $\mathbf{p} + \mathbf{p} \to \mathbf{b} + \overline{\mathbf{b}} + \boldsymbol{n}\,\mathbf{j}$ at $\sqrt{s} = 13$ TeV



Processes with gluons in the initial states give the dominant contributions. Heavy quark production, as known, is of interest for studying the gluon dynamics in the protons.

Comparison with the LHCb data for non–prompt J/ψ at 8 TeV ($p_{Tb} < 14$ GeV/c, 2.0 $< y <$ 4.5)

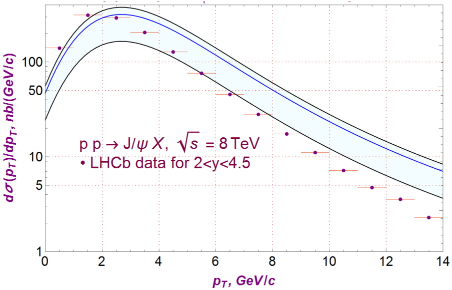
$$\sigma(pp \to J/\psi,\ LHCb) = 1.28 \pm 0.01 \pm 0.11\,\mu b$$

$$\sigma(pp \to J/\psi,\ calculated) = 1.69\,\mu b, (p_{TjMin} = 2GeV/c)$$

Scale variations are +19% and –48% in the scale factor envelope [1/2, 2],
PDF uncertainties are ±4.5%.

Bottom quark production in *pp* scattering

Hadronization of quarks is simulated with PYTHIA 8 employing the Lund string model. Non–prompt charmonia, in particular J/ψ, are created in decays of the B mesons.



The calculation are carried out with the partonic processes
$\mathbf{pp} \to \mathbf{Q\overline{Q}}$, $\mathbf{Q\overline{Q}j}$
with virtual and real emission processes.
The renormalization and factorization scale uncertainties are shown by the blue band.

Prospects: Dependence of σ on the minimal jet transverse momentum may be a source of additional uncertainties. Deviation of the computed from the experimental distributions indicates necessity of a more sophisticated treatment of soft QCD processes. We plan to use a new approach for hadronisation of multi-parton systems beyond the leading-colour approximation, that incorporates recent developments in the Lund string model.

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