Precision studies for particle-collider physics

In the phenomenology of accelerator experiments, it is essential to compare theoretical predictions and experimentally obtained distributions. Precision measurements enable access to quantum effects and thus validation if the theory is correct. So far, the so-called Standard Model (SM) of fundamental interactions describes data well. Otherwise, new interactions/particles are needed. Importantly, higher energies open a new window of opportunities as processes and states of higher masses become available. This is precisely the place where we operate: precision high-energy studies.

SM specifies a definite number of elementary particles. In 2012, the particle spectrum of SM was completed with the discovery of a scalar particle: the Higgs boson, found at the Large Hadron Collider (LHC) at CERN. The search for this elusive particle was guided by precise calculations derived in SM. Similarly, to recognise New Physics signatures, one must know even tiny quantum effects predicted by the Standard Model and the experimental setup. This knowledge provides a reference and a solid ground for further studies. After all, we are curious to know at the deeper level answers to the basic questions like: What is the origin of the Higgs boson, mass and flavour of particles? What is the source of dark matter? And ultimately, what is the origin of the Standard Model itself? These questions inspire basic research towards such issues as the evolution of the Universe with matter-antimatter asymmetry and CP violation effects, understanding the type of the electroweak phase transition or modelling composite models (presently known as elementary particles, they are not necessarily such when zoomed through high-energy quantum effects, they can reveal substructures).

Colliders are needed to answer questions on the origin and nature of objects in particle physics. The exploration of the multi-TeV scale at the LHC and planned colliders pertains to many such fundamental questions about how our Universe came to be and its further evolution. In collider studies, simulations of theoretical processes and verification of new ideas and models are possible using Monte Carlo (MC) event generators. The Krakow particle physics IFJ PAN and UJ groups involved in the project have specialised in constructing such tools for decades. The Krakow MC generators such as KKMC, BHLUMI, BHWIDE, PHOTOS and TAUOLA are widely used since the LEP (Large Electron-Positron) experiment at CERN in the 1980s–2000s. In the present project, this legacy will be solidified towards frontier studies in the context of the ongoing (LHC, Belle II) and future (e.g. HL-LHC, FCC, ILC, CLIC) particle colliders. The Katowice particle theory group will strengthen these efforts, adding knowledge on calculating higher-order quantum corrections (a.k.a. "loops") for Feynman diagrams, which involve a wealth of massive particles (meaning many parameters and evaluation of highly complicated loop integrals).

Proper merging MC event generators with precise, subtle perturbative quantum corrections is critical for successfully studying feeble theoretical effects at any present or future collider.

The project will investigate many higher-order quantum electrodynamics (QED) and electroweak (EW) corrections, and MC simulations of the processes considered at present or needed at future colliders. We will consider, among others, the MC event generator KKMC implementing the $e^+e^- \to HZ \to 4f$ ("Higgs factory") and $e^+e^- \to \gamma\gamma$ (luminosity) processes and τ-lepton decays with hadron and multiphoton effects. New Z-decay higher-order results for decay widths and EW observables will be added to the EW libraries, and non-standard dark matter and heavy neutrino effects will be simulated and tested.

The research undertaken is complex and will be performed in cooperation with scientists from Germany, Hungary, Switzerland, Ukraine, the UK and the USA. In this way, also Katowice and Krakow particle physics groups will be strengthened considerably by working in a demanding international environment, gaining experience to sustain a high level of basic research studies.

The team includes both theorists and experimenters.