HEP Theory Group Activities: Third Quarter 2016

The Theory Group continued its activities in a broad range of subjects, with emphasis on hadron collider phenomenology, Higgs, top-quark and quarkonium physics, as well as on fundamental processes. Examples of these works are the following:

Production of Weak Gauge bosons in Association with jets

In arXiv:1602.05612, Boughezal and Petriello performed a detailed comparison of next-to-next-to-leading order (NNLO) QCD predictions for the $W+$jet and $Z+$jet processes with 7 TeV experimental data from ATLAS and CMS. They observed excellent agreement between theory and data for most studied observables, which span several orders of magnitude in both cross section and energy. For some observables, such as the HT distribution, the NNLO QCD corrections are essential for resolving existing discrepancies between theory and data.

In arXiv:1602.06965, Boughezal and Petriello presented a detailed phenomenological study of W-boson production in association with a jet through next-to-next-to-leading order (NNLO) in perturbative QCD. Fiducial cross sections and differential distributions for both 8 TeV and 13 TeV LHC collisions were presented, as were results for both the inclusive one-jet bin and the exclusive one-jet bin. Two different event selection criteria were considered: a general selection with standard cuts used in experimental analyses, and a boosted selection that focuses on high transverse momentum jets. They discussed the higher-order corrections in detail and identified for which observables and phase space regions the QCD perturbative expansion is under good theoretical control, and where additional work is needed. For most distributions and phase space regions the QCD perturbative expansion exhibits good convergence after the inclusion of the NNLO corrections.
In arXiv:1602.08140, Boughezal and Petriello presented a detailed phenomenological study of Z-boson production in association with a jet through next-to-next-to-leading order (NNLO) in perturbative QCD. Fiducial cross sections and differential distributions for both 8 TeV and 13 TeV LHC collisions were presented. They studied the impact of different parton distribution functions (PDFs) on predictions for the Z+jet process. Upon inclusion of the NNLO corrections, the residual scale uncertainty is reduced such that both the total rate and the transverse momentum distributions can be used to discriminate between various PDF sets.

NRQCD Factorization in Quarkonium Production

This project was described in detail in the reports for the first and second quarters of FY2016. It is being carried out by Geoff Bodwin, Hee Sok Chung (CERN), U-Rae Kim (Korea University), June-Haak Ee (Korea University), and Jungil Lee (Korea University). It involves the calculation of a two-loop test of NRQCD factorization for heavy-quarkonium production. In the last quarter, the Mellin-Barnes representation was used to carry out the diagrammatic parameter integrals. Here, new methods had to be devised that make use of $\alpha$ parameters and the Cheng-Wu parameter theorem, as standard methods lead to divergent parameter integrals. The next step in the calculation is to use the method of Kausk to extract the soft-pole contributions and to make an asymptotic expansion in powers of the eikonal-line momentum squared. It is hoped that the latter expansion will simplify the Mellin-Barnes integrals so that they are analytically tractable.

Using Maxwell’s Equations to Constrain the Magnetic Field

This work, which is being carried out by Geoff Bodwin and Hee Sok Chung (CERN), was described in detail in the report for the second quarter of FY2016.

During the last quarter, it was noticed that the RMS deviation of the magnetic field data from the fits is about an order of magnitude larger than the field-measurement uncertainty. It is conjectured that more harmonics are needed in the theoretical expression in order to eliminate this discrepancy. However, there is a limit to the number of harmonics that can be used with a given number of data points because, if too many harmonics are used, the
fitting problem becomes under constrained. Methods are being explored to circumvent this difficulty, including using an interpolating function to generate “fake” data points and using Padé approximants to improve the convergence of harmonic series.

Discussions are also ongoing with the $g - 2$ experimental group with the aim of using the theoretical results for the radial magnetic-field component to check Hall-probe measurements of that component.

**Single Top Quark Production at NNLO in QCD**

During the April - June quarter of 2016, Ed Berger and Argonne postdoc Jun Gao finished a complete calculation at next-to-next-to-leading-order (NNLO) in perturbative quantum chromodynamics (QCD) of single top quark production at Large Hadron Collider energies. A paper describing this work was posted to the archives as arXiv:1606.08463 and submitted for journal publication. They were joined in this work by Hua-Xing Zhu (MIT) and C. P. Yuan (MSU). Theirs are the first fully differential NNLO predictions of t-channel single top quark production and decay at the LHC. Since it combines QCD corrections for production and decay, their calculation offers a realistic simulation at NNLO for leptonic top-quark decay in single top-quark production. The differential nature the calculation allows imposition of phase space selections on final state objects, as done in the experiments. ATLAS experimenters have already expressed significant interest in these results.

**Charm-quark production in deep-inelastic scattering at NNLO in QCD**

A complete calculation at next-to-next-to-leading-order (NNLO) in perturbative quantum chromodynamics (QCD) of charm-quark production in deep-inelastic scattering of a neutrino from a nucleon was described in a previous quarterly report. A paper describing this work, posted to the archives as arXiv:1601.05430, was published in Physical Review Letters 116 (2016) no.21, 212002. Ed Berger and Argonne postdoc Jun Gao were joined in this work by Chong Sheng Li, and Ze Long Liu (Peking University, Beijing) and Hua Xing Zhu (MIT). Theirs is the first complete NNLO calculation of QCD corrections to charm-quark production in weak charged-current deep inelastic scattering. The calculation
is based on a phase space slicing method and uses fully-differential Monte Carlo integration.

**Enhancing the Higgs Associated Production with a Pair of Top-Quarks**

The combined analysis of the Higgs data from the ATLAS and CMS experiments has revealed an apparently significant excess in the production of Higgs bosons in associations of top-quark pairs. This may be associated with an enhancement of the top-quark Yukawa coupling with respect to its Standard Model value. Wagner, in collaboration with Prof. Badziak, from Warsaw University pointed out that in a wide class of models reminiscent of type-II Two-Higgs-Doublet Models (2HDM) the signal of the Higgs produced in association with a top-antitop quark pair ($t\bar{t}h$) and decaying into gauge bosons can be significantly larger than the Standard Model (SM) prediction without violating any experimental constraints. The crucial feature of these models is enhanced (suppressed) Higgs coupling to top (bottom) quarks and existence of light colored particles that give negative contribution to the effective Higgs coupling to gluons resulting in the gluon fusion rates in the gauge boson decay channels close to SM predictions. They demonstrated this mechanism in the next-to minimal supersymmetric extension of the Standard Model (NMSSM), with light stops and show that $t\bar{t}h$ signal in the $WW$ decay channel can be two times larger than the SM prediction, as suggested by the excesses observed by ATLAS and CMS. This can only be achieved if the MSSM-like Higgs boson masses are in the range of 160 to 300 GeV, what can be tested in the next run of the LHC. This article, arXiv:1602.06198, is now published in JHEP 1605 (2016) 123.

**A Second Peak in Diphoton (or Diboson) Resonances**

The recent observation of a diphoton resonance at the CMS and ATLAS experiments at the LHC, at an invariant mass of about 750 GeV, have motivated theoretical work on the study of diboson resoances. A resonant diphoton peak can be explained by gluon fusion production of a new neutral scalar which subsequently decays into a pair of photons. Loop-induced couplings of the new scalar to gluons and photons should be mediated by particles carrying color and electric charge. Wagner and Low, in collaboration with M. Carena and Argonne postdocs Ismail and Huang, pointed out that, if the loop particles
hadronize before decaying, their bound states will induce a second peak in the diphoton invariant mass spectrum near twice their mass. Using the recently reported 750 GeV excess as a benchmark, they discussed implications of this second peak for resonance searches at the LHC. The second peak could be present for resonances in the gg and Z? channels, or even in the WW and ZZ channels for a pseudo-scalar resonance, where the couplings are mediated by new loop particles. This article, arXiv:1606.06733, appeared recently and has been submitted for publication to JHEP.

**Heavy-stoponium-heavy-Higgs diphoton rate**

As stressed above, excesses in measurements by the Atlas and CMS collaborations of the diphoton have stimulated a great deal of theoretical work. Scenarios have been put forward to explain the excesses that involve a heavy stop-antistop bound state (stoponium). Other scenarios involve a heavy Higgs boson. Both of these approaches tend to produce cross sections times branching fractions to diphotons that are too small to account for the observed excesses. It has been conjectured that the combination of a stoponium state and a heavy Higgs boson near the stop-antistop threshold might lead to an enhanced diphoton rate.

Geoff Bodwin, Hee Sok Chung (CERN), and Carlos Wagner have been exploring this possibility. They have used the effective field theory NRQCD to account for the stop-antistop interactions, which must be resummed near threshold. They have also developed a formalism that accounts fully for mixing between the heavy Higgs boson and the stop-antistop system near threshold. Preliminary results indicate that, contrary to expectations, mixing effects near threshold reduce the diphoton rate when the stop has a narrow width, of order 0.1 MeV.

The mechanisms that reduce the rate are different for weak stop-antistop-Higgs coupling than for strong stop-antistop-Higgs coupling. In the weak-coupling case, the reduction in rate occurs because mixing broadens the stoponium peak. In the strong-coupling case, the reduction in rate occurs for two reasons: (1) the mixing shifts the Higgs mass away from the threshold region, where threshold form factors would produce an enhancement; (2) the mixing renormalizes the Higgs propagator near threshold, effectively reducing the strengths of the Higgs couplings to photons and gluons. A paper describing these results is in progress.