HEP Theory Group Activities : First 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 :

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

During the September - December quarter of 2014, Ed Berger and Argonne postdoc Jun Gao finished a 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. A paper describing this work was posted to the archives as arXiv:1601.05430 and submitted for journal publication in January 2016. They 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. In all current analyses which include charm-quark production data in neutrino DIS, the hard-scattering cross sections are calculated only at next-to-leading order (NLO). Approximate NNLO results are available for case of very large momentum transfer. However, for neutrino DIS experiments, the typical momentum transfer is small and the exact charm-quark mass dependence must be kept. The calculation is based on a phase space slicing method and uses fully-differential Monte Carlo integration. It maintains the exact mass dependence and all kinematic information at the parton level. The NNLO corrections can change the cross sections by up to 10% depending on the kinematic region considered. Their results show that the NLO predictions underestimate the perturbative uncertainties owing to accidental cancellations at that order. Their calculation is an important ingredient for future global analyses of parton distribution functions at NNLO in QCD, especially for extracting the

strange quark PDFs. The results can also be used to correct for acceptance in experimental analyses. In their paper, they show comparisons of their results with data from the NuTeV and NOMAD collaborations, indicating that once the NNLO corrections are included slightly higher strangeness PDFs are preferred in the low-x region than those based on a NLO analysis.

Fragmentation Contributions to Prompt , χ_c, and $\psi(2S)$ Hadroproduction

This work, carried out by Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee (Korea University), U-Rae Kim (Korea University), Kuang-Ta Chao (Peking University), and Yan-Qing Ma (Maryland University, Peking University), was described in detail in the first quarterly report of FY15. During the last quarter, a paper describing these results (arXiv:1509.07904) was accepted for publication in Physical Review D.

Precise Predictions for $H \to V\,\gamma$

This work, carried out by Geoff Bodwin, Hee Sok Chung, Jungil Lee (Korea University), and June-Haak Ee (Korea University), was described in detail in the report for the third quarter of FY15. During the last quarter, numerical calculations were completed. These involved the use of a novel method to perform resummations of large logarithms of p_T^2/m_Q^2 in the quarkonium light-cone distribution amplitudes at next-to-leading logarithmic (NLL) accuracy. In addition, a new method was devised to estimate uncertainties in the Higgs decay rates, which depend in a highly nonlinear way on the uncertainties in the fundamental input parameters and, so, are not amenable to a conventional Gaussian error analysis. A paper describing this work is in progress.

NRQCD Factorization in Quarkonium Production

During this quarter, work was begun by Geoff Bodwin, Hee Sok Chung, Jungil Lee (Korea University), and June-Haak Ee (Korea University) on a calculation of two-loop contributions to the fragmentation function for a heavy $Q\bar{Q}$ pair in a color-octet state to fragment into a heavy $Q\bar{Q}$ pair in a color-singlet state. This computation is a state-of-the-art

theoretical test of the NRQCD factorization conjecture for inclusive heavy-quarkonium production. That conjecture is the basis for most modern computations of heavy-quarkonium production. The two-loop fragmentation computation was carried out several years ago by Nayak, Qiu, and Sterman, who used light-cone variables. Their computation confirms the NRQCD factorization conjecture, but is very complicated and has never been checked. The aim of the present work is to carry out the two-loop calculation covariantly and to use scaling properties of the Feynman-parameter representation and a zero-mass asymptotic expansion for light-like propagators in the Mellin-Barnes representation to simplify the computation. It is hoped that a sufficient simplification can be achieved to generalize the result to higher loop orders.

W-boson production in association with a jet at next-to-next-to-leading order in perturbative QCD

In arXiv:1504.02131, Boughezal and Petriello, in collaboration with the PhD student Chris Focke, presented the complete calculation of W-boson production in association with a jet in hadronic collisions through next-to-next-to-leading order in perturbative QCD. To cancel infrared divergences they introduced a new subtraction method that exploits the fact that the N-jettiness event-shape variable fully captures the singularity structure of QCD amplitudes with final-state partons. This method holds for processes with an arbitrary number of jets, and is easily implemented into existing frameworks for higher-order calculations. They presented initial phenomenological results for W+jet production at the LHC. The NNLO corrections are small and lead to a significantly reduced theoretical error, opening the door to precision measurements in the W+jet channel at the LHC. This work was accepted for publication in Phys. Rev. Lett.

N-jettiness soft function at next-to-next-to-leading order

In arXiv:1504.02540, Boughezal and Petriello presented a general framework for the calculation of soft functions for $SCET_I$ observables through next-to-next-to-leading order (NNLO) in the strong coupling constant. As an example of their formalism they showed how it can be used to obtain the complete NNLO soft function for the N-jettiness event

shape variable. They presented numerical results for two examples with phenomenological impact: the one-jettiness soft function for both electron-proton and proton-proton collisions. This work was accepted for publication in Phys. Rev. D.

Z-boson production in association with a jet at NNLO in perturbative QCD

In arXiv:1512.01291, Boughezal and Petriello presented the first complete calculation of Z-boson production in association with a jet in hadronic collisions through next-to-next-to-leading order in perturbative QCD. This computation uses their recently-proposed N-jettiness subtraction scheme to regulate the infrared divergences that appear in the real-emission contributions. They presented phenomenological results for 13 TeV proton-proton collisions with fully realistic fiducial cuts on the final-state particles. The remaining theoretical uncertainties after the inclusion of their result are at the percent-level, making the Z+jet channel ready for precision studies at the LHC Run II. Other work based on the N-jettiness subtraction method as well as phenomenological studies are in progress.

Precision Higgs Physics and the Next-to-Minimal Supersymmetric Model

Continuing the previous work on two Higgs Doublet Models and the Minimal Supersymmetric Standard Model, Wagner, in collaboration with staff member Ian Low, and Marcela Carena, Howard Haber and Nausheen Shah, studied the conditions under which the lightest CP-even Higgs particle in the Next-to-Minimal Supersymmetric Standard Model looks Standard-Model like. The Next-to-Minimal Supersymmetric extension of the Standard Model (NMSSM) with a Higgs boson of mass 125 GeV can be compatible with stop masses of order of the electroweak scale, thereby reducing the degree of fine-tuning necessary to achieve electroweak symmetry breaking. Moreover, in an attractive region of the NMSSM parameter space, corresponding to the "alignment limit" in which one of the neutral Higgs fields lies approximately in the same direction in field space as the doublet Higgs vacuum expectation value, the observed Higgs boson is predicted to have Standard-Model-like properties. Wagner and collaborators derived analytical expressions for the alignment conditions and show that they point toward a more natural region of

parameter space for electroweak symmetry breaking, while allowing for perturbativity of the theory up to the Planck scale. Moreover, the alignment limit in the NMSSM leads to a well defined spectrum in the Higgs and Higgsino sectors, and yields a rich and interesting Higgs boson phenomenology that can be tested at the LHC. They also discussed the most promising channels for discovery and present several benchmark points for further study. This article, arXiv:1510.09137, was submitted to the arXiv in October and it is now in press in Phys. Rev. D.

Probing the electroweak phase transition at the LHC

The origin of the matter-antimatter asymmetry is one of the most important questions in high energy physics and cosmology. It is well known that this asymmetry may originate from processes occuring at the barrier of the expanding bubbles after the electroweak phase transition. For this to occur, the phase transition must be strongly first order.

Wagner, in collaboration with Argonne postdoc P. Huang, and two University of Chicago students, A. Joglekar and B. Li, studied the correlation between the value of the triple Higgs coupling and the nature of the electroweak phase transition. They used an effective potential approach, including higher order, non-renormalizable terms coming from integrating out new physics. They showed that if only the dimension six operators are considered, large positive deviations of the triple Higgs coupling from its Standard Model (SM) value are predicted in the regions of parameter space consistent with a strong first order electroweak phase transition (SFOEPT). They also showed that at higher orders sizable and negative deviations of the triple Higgs coupling may be obtained, and the sign of the corrections tends to be correlated with the order of the phase transition. They also considered a singlet extension of the SM, which allows us to establish the connection with the effective field theory (EFT) approach and analyze the limits of its validity. Furthermore, we study how to probe the triple Higgs coupling from the double Higgs production at the LHC. They showed that selective cuts in the invariant mass of the two Higgs bosons should be used, to maximize the sensitivity for values of the triple Higgs coupling significantly different from the Standard Model one. This article, arXiv:1512.00068 was submitted to the arXiv in December, and was submitted for publication in Phys. Rev. D. early this year.

The Higgs sector in heavy Supersymmetry with explicit CP-violation

Wagner, in collaboration with M. Carena, J. Ellis, J.S. Lee and A. Pilaftsis works towards a further upgrade of their CPsuperH code for the computation of Higgs properties in supersymmetry with explicit CP-violation phases. They introduced and explore new heavy Higgs scenarios in the Minimal Supersymmetric Standard Model (MSSM) with explicit CP violation, which have important phenomenological implications that may be testable at the LHC. For soft supersymmetry-breaking scales M˙S above a few TeV and a charged Higgs boson mass M˙H+ above a few hundred GeV, new physics effects including those from explicit CP violation decouple from the light Higgs boson sector. However, such effects can significantly alter the phenomenology of the heavy Higgs bosons while still being consistent with constraints from low-energy observables, for instance electric dipole moments. To consider scenarios with a charged Higgs boson much heavier than the Standard Model (SM) particles but much lighter than the supersymmetric particles, they revisited previous calculations of the MSSM Higgs sector. They computed the Higgs boson masses in the presence of CP violating phases, implementing improved matching and renormalization group (RG) effects, as well as two-loop RG effects from the effective two-Higgs Doublet Model (2HDM) scale M˙H+ to the scale M˙S. They also illustrated the possibility of non-decoupling CP-violating effects in the heavy Higgs sector using new benchmark scenarios named CPX4LHC. This article, arXiv:1512.00437 was submitted to the arXiv in December and it is already acccepted for publication in JHEP.