HEP Theory Group Activities : Fourth Quarter 2014

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 :

Broken Flavor Symmetry and Higgs Boson Physics

During the July - September quarter of 2014, Ed Berger and collaborators continued their studies of the relationship of broken electroweak symmetry and broken flavor symmetry. Their paper, "Higgs-flavon mixing and LHC phenomenology in a simplified model of broken flavor symmetry", arXiv:1406.6054 [hep-ph], has been published in Phys. Rev. D **90**, 076004 (2014). Berger spoke about this work at ICHEP2014 in Valencia, Spain in July. The written version of his presentation, entitled "Higgs boson physics and broken flavor symmetry – LHC phenomenology", has been prepared for publication in the Proceedings. The minimal new particle content of their model of broken gauged flavor symmetry includes a scalar flavon φ, a gauge singlet under the SM; a heavy fermion T partner of the top quark; and a neutral top-phiilc gauge boson Z_T.

An extra $U(1)$ gauge symmetry is a popular extension of the standard model (SM). In most cases, the Z' boson is assumed to couple with the light quarks or charge leptons of the SM. While flavor-non-universal Z' bosons have been considered, the Z' is usually assumed to couple to at least one of the SM light fermions. On the other hand, the top quark, as the heaviest particle in the SM, might be the most sensitive particle to new physics. The top-philic Z' boson present in the model of broken flavor symmetry couples only to the top-quark at tree level. In their first paper, Berger and collaborators focused on the modifications of Higgs boson production and decay properties introduced by this model and on flavon phenomenology at the LHC, notably the flavon production cross section and the decay modes $\varphi \to hh$ and $\varphi \to ZZ$. In a new paper now in partial draft form, Berger and collaborators concentrate on the LHC phenomenology of the top-philic gauge boson of the

model. The signals for light ($m_{Z'} < 2m_t$) and heavy ($m_{Z'} > 2m_t$) Z''s are treated separately.

Double Logarithms in $e^+e^- \to J/\psi + \eta_c$ at the B Factories

As was described in the previous quarterly report, G. Bodwin and H.S. Chung, in collaboration with J. Lee (Korea University), carried out an analysis of double logarithms of Q^2/m_c^2 in the cross section for $e^+e^- \to J/\psi + \eta_c$. These logarithms are important numerically at B-factory energies. A paper describing these results (arXiv:1406.1926) has been accepted for publication in Physical Review D.

Relativistic Corrections to $H \to V\,\gamma$

G. Bodwin, H.S. Chung, F. Petriello, J. Lee (Korea University), J.H. Ee (Korea University) have completed a calculation of relativistic corrections to Higgs-boson decays to J/ψ or $\Upsilon(1S)$ plus a photon. Details of this work were given in the previous quarterly report. The inclusion of relativistic corrections reduces the theoretical uncertainty for the decay $H \to J/\psi + \gamma$ by about a factor of three—opening the door to higher-precision measurements of the $Hc\bar{c}$ coupling. A paper describing these results (arXiv:1407.6695) was written during this reporting period. After the completion of this paper, Bodwin *et al.* learned that the ATLAS Collaboration is about to measure the processes $H \to \Upsilon(2S) + \gamma$ and $H \to \Upsilon(3S) + \gamma$. Calculations of the rates for these additional processes were carried out. A new version of arXiv:1407.6695 that includes these new results is in preparation.

Quark Fragmentation into $Q\bar{Q}$ Pairs

The calculation of leading-power (LP) contributions to quarkonium production at hadron colliders requires, among other ingredients, the fragmentation functions for a quark (q) into a heavy quark-antiquark ($Q\bar{Q}$) pair. Here, q can be either a light quark or a heavy quark. Calculations of the fragmentation functions into unpolarized color-singlet and color-octet $Q\bar{Q}$ pairs already exist in the literature. However, the fragmentation functions into polarized $Q\bar{Q}$ pairs are needed in order to calculate LP contributions to polarized quarkonium production.

During this reporting period, G. Bodwin, Hee Sok Chung, Jungil Lee (Korea Univer-

sity), and U-Rae Kim (Korea University) carried out calculations of both the polarized and unpolarized fragmentation functions for a quark fragmenting into color-singlet and color-octet $Q\bar{Q}$ pairs. These new calculations confirmed calculations in the literature for the case of unpolarized color-singlet $Q\bar{Q}$ pairs, which has a nonzero fragmentation function only when $q = Q$, and for the case of color-octet $Q\bar{Q}$ pairs when $q \neq Q$. In addition, the fragmentation function to unpolarized color-octet $Q\bar{Q}$ pairs when $q = Q$ was calculated for the first time. This calculation involves a tricky interference contribution that arises from the interchange of identical heavy quarks in the final state. The new calculations of fragmentation functions into polarized $Q\bar{Q}$ pairs will facilitate the program to calculate LP contributions to polarized quarkonium production at the Tevatron and the LHC. Details of this program were given in the last quarterly report. A paper describing these results is in progress.

Higgs production in association with a jet at NNLO in QCD

In Higgs boson studies at the LHC, final states containing one jet are major contribution to the total event rate, and their understanding is crucial for improved determinations of the Higgs boson properties.

Boughezal and Petriello took a major step toward improving SM predictions for Higgs boson distributions by providing a next-to-next-to-leading order (NNLO) calculation of Higgs production in association with a jet in the gluon-fusion channel. They first provided results for the gluon-channel in an earlier paper, and they now completed the calculation for the missing quark-gluon channel and therefore can provide the full hadronic result for this process. A paper with the corresponding results will appear in the next quarterly report period. The phenomenological impact of this result spans all Higgs search channels. In the WW final state it refines the division of the signal prediction into exclusive zero-jet, one-jet and inclusive two-jet bins,and can be used to improve the resummation of the jet-veto logarithms that accompany this division. In all final states it can be used to more accurately re-weight the Higgs p_T distribution obtained from Monte Carlo. It will allow for the comparison of the measured differential distributions from LHC Run II to the most precise SM theory to more accurately probe the mechanism of electroweak symmetry breaking.

Jet vetoes for Higgs production at future hadron colliders

One of the major goals of the LHC in the next few years is the precision study of the properties of the Higgs particle. This requires precise experimental measurements coupled with an accurate modeling of the signal and background on the theory side. Unfortunately the discovery of the Higgs does not answer all the open questions which may require energies beyond those accessible at the LHC. In particular, precise tests of Higgs couplings to Standard Model particles, the self-coupling of the Higgs and the structure of its potential may require a future higher-energy proton-proton collider. The past year has seen a growing interest in the physics of a possible Future Hadron Collider (FHC). It is a candidate to continue exploration of the energy frontier once the LHC program is complete in roughly 20 years from now.

Since higher scattering energies will be probed, this will lead to increasingly stringent cuts on QCD radiation that produces spurious jets in addition to those contained in signal processes. The large logarithms in question take the form $L = \log(Q/p_{cut})$, where Q is the hard scale of the considered process and p_{cut} is the scale of the cut on QCD radiation. At a FHC, Q will signicantly increase. The role of resummation of these large logarithms L will become more central at future machines.

Boughezal in collaboration with the postdocs Xiaohui Liu and Ye Li and the student Chris Focke studied Higgs boson production in exclusive jet bins at possible future 33 and 100 TeV proton-proton colliders. They compared the cross sections obtained using fixed-order perturbation theory with those obtained by also resuming large logarithms induced by the jet-binning in the gluon-fusion and associated production channels. The central values obtained by the best-available fixed-order predictions differ by $10 - 20\%$ from those obtained after including resummation over the majority of phase-space regions considered. Additionally, including the resummation dramatically reduces the residual scale variation in these regions, often by a factor of two or more. They further showed that in several new kinematic regimes that can be explored at these high-energy machines, the inclusion of resummation improvement is mandatory. This work has been published in the Physical Review D journal.

Precision Higgs Measurements and Searches for Non-Standard Higgs Bosons at the LHC

In this quarter Wagner, in collaboration with staff member Low, Carena, Haber and Shah returned to the question of obtaining a Higgs bosons with Standard Model-like couplings in two Higgs doublet models, that he worked on at the end of 2013. In collaboration with Fermilab staff member Carena, UC Professor Haber, Argonne staff member Low and Michigan University postdoc Shah he concentrated in the two Higgs doublet model obtained at low energies in supersymmetric extensions of the Standard Model.

Precision measurements of the Higgs boson properties at the LHC provide relevant constraints on possible weak-scale extensions of the Standard Model (SM). In the context of the Minimal Supersymmetric Standard Model (MSSM) these constraints seem to suggest that all the additional, non-SM-like Higgs bosons should be heavy, with masses larger than about 400 GeV. This article shows that such results do not hold when the theory approaches the conditions for "alignment independent of decoupling", where the lightest CP-even Higgs boson has SM-like tree-level couplings to fermions and gauge bosons, independently of the non-standard Higgs boson masses. The combination of current bounds from direct Higgs boson searches at the LHC, along with the alignment conditions, have a significant impact on the allowed MSSM parameter space yielding light additional Higgs bosons. In particular, after ensuring the correct mass for the lightest CP-even Higgs boson, we find that precision measurements and direct searches may soon be able to probe the region of non-SM-like Higgs boson with masses below the top quark pair mass threshold of 350 GeV and low to moderate values of $\tan\beta$.

To reach this conclusion Wagner and collaborators made a detailed study of the production cross section and decay branching ratios of the non-standard Higgs bosons in the case that the supersymmetric particles are heavy and also in the case that they are light, and demonstrated an interesting complementarity between the tests of this model arising from precision Higgs measurements and those coming from direct searches for non-standard Higgs bosons. The result of this work has been summarized in the article arXiv:1410.4969.

Endpoint in the invariant mass distribution of leptons at CMS

Wagner and Argonne postdoc Peisi Huang worked on the interpretation of an excess in the dilepton invariant mass distribution observed by the CMS collaboration. The excess is interesting since it presents an endpoint, which is characteristic of scenarios in which a heavy neutral particle decays into a pair of leptons and a light neutral particle. In the simplest cases, the endpoint measures the mass difference between the heavy neutral particle and the light one. The events include two hard jets, which are characteristic of the presence of a heavier color particle. The heavier neutral particle proceeds from decays of this color particle.

Wagner and Huang presented two scenarios in the Minimal Supersymmetric Extension of the Standard Model (MSSM) that can lead to an explanation of the excess in the invariant mass distribution of two opposite charged, same flavor leptons, and the corresponding edge at an energy of about 78 GeV, recently reported by the CMS collaboration. In both scenarios, s-bottoms are pair produced, and decay to neutralinos and a b-jet. The heavier neutralinos further decay to a pair of leptons and the lightest neutralino through on-shell s-leptons or off-shell neutral gauge bosons. These scenarios are consistent with the current limits on the s-bottoms, neutralinos, and s-leptons. Assuming that the lightest neutralino is stable they discussed the predicted relic density as well as the implications for Dark Matter direct detection. They also showed that consistency between the predicted and the measured value of the muon anomalous magnetic moment may be obtained in both scenarios. Finally, they defined the signatures of these models that may be tested at the 13 TeV run of the LHC. The result of this work has been summarized in the article arXiv:1410.4998.