HEP Theory Group Activities : Second 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.

Fragmentation Contributions to Prompt J/ψ, 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 summarizing this work was published as Phys. Rev. D **93**, no. 3, 034041 (2016).

Precise Predictions for

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 reports for the third quarter of FY15 and the first quarter of FY16. During the current quarter, a paper on this work was written (arXiv:1603.06793).

NRQCD Factorization in Quarkonium Production

This project, carried out by Geoff Bodwin, Hee Sok Chung, Jungil Lee (Korea University), and June-Haak Ee (Korea University), involves the calculation of a two-loop test of NRQCD factorization for heavy-quarkonium production. It was described in detail in the report for the first quarter of FY2016. During the current quarter, progress was

made in expressing the phase-space integral in a compact, covariant form, and expressions were obtained in terms of Feynman parameter integrals. In addition, strategies were devised for extracting the soft pole and making an asymptotic expansion in the invariant momentum squared of the light-like eikonal (Wilson) line that appears in the definition of the quarkonium fragmentation function.

Using Maxwell's Equations to Constrain the $g-2$ Magnetic Field

A precise determination of the magnetic field in the ring for Muon $g-2$ Experiment at Fermilab is a crucial ingredient in the measurements that are planned for that experiment. To date, the experiment has measured the magnitude of the magnetic field at many points in the beam region, but not the direction of the field. In order to compute the effects of the magnetic field on the beam, one needs a smooth function that is fitted to the measurements of magnitude of the magnetic field, and one also needs information about the direction of the field. This directional information could be particularly important in reducing systematics in the planned measurement of the muon electric dipole moment.

From Maxwell's equations, if follows that the divergence and curl of the magnetic field both vanish in the region of zero current. Then, one can express the magnetic field as the gradient of a potential that satisfies Laplace's equation. This fact can be used to constrain the fits to the measurements of the magnitude of the magnetic field, thereby improving the quality of the fits and also providing information about the direction of the magnetic field.

Geoffrey Bodwin and Hee Sok Chung have begun a project to use this constraint from Maxwell's equations in making fits to the measurements of the magnitude of the magnetic field. The strategy is to express the magnetic potential in terms of the solutions of Laplace's equation in toroidal coordinates, which are well matched with the geometry of the $g-2$ ring. The solutions, toroidal harmonics, can be expressed in terms of sines and cosines of the azimuthal angle and the poloidal angle and in terms of half-integer Legendre functions of the cosh of the radial coordinate.

A straightforward minimization of the χ^2 of the fit is not practical, as the size of the expression for χ^2 grows linearly with the number of data points (about 37000) and involves the square root of a polynomial with a number of terms that grows as the square of the number of fit parameters (about 10000^2). However, one can simplify the problem by taking

the approximation of expanding toroidal-harmonic expression for the magnitude of the magnetic field through linear order in the deviations from the average value of the field. Then, the toroidal-harmonic expression for the magnitude of the magnetic field is linear in the fit parameters, and the number of terms in the expression for χ^2 does not grow with the number of data points. In the linear approximation, the fitting problem becomes a linear-algebra problem that can be solved in less than eight hours on a typical workstation. Preliminary results suggest that the linear approximation is valid at the level of 0.1 ppb. Furthermore, it is systematically improvable by making use of an iterative method in which computing times grow only linearly with the number of iterations.

Preliminary fits to the data show an RMS deviation from the data of about 6 ppm. These preliminary fits indicate that the previously unknown radial and azimuthal components of the magnetic field, averaged over the azimuthal angle, are typically about 10^{-5} times the vertical component.

Discussions are ongoing with the $g-2$ experimental group to refine this work and to identify further computations that will help to support the experimental effort.

T-channel Single Top-Quark Production and Decay at NNLO in QCD

Ed Berger and Argonne postdoc Jun Gao made substantial progress on their fully differential next-to-next-to-leading order calculation of t-channel single top-quark production and decay at the LHC. They anticipate releasing a publication shortly. They are focusing on the fiducial cross sections at the LHC at 13 TeV. The next-to-next-to-leading order corrections can reach the level of -6% for the total cross sections. The effects are more pronounced in various differential distributions. Moreover, the hard scale variations are reduced to the level of a percent. Their results can be used to improve the measurements of the single-top quark production cross sections and the top quark electroweak couplings at the LHC.

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, 2015, and is now published in Phys. Rev. D 93, 2016, 055049.

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 had been published in JHEP 1602 (2016) 123.

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. Wanger, 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 (tth) 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 tth 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.