HEP Theory Group Activities : Third Quarter 2013

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 :

Study of flavor violating W' at the LHC

Ed Berger, Hao Zhang, and Zack Sullivan report a new study of the collider phenomenology of the flavor-changing W' model in Argonne report ANL-HEP-PR-13-40, to be submitted to Physical Review D. Their new fit to the Tevatron top-quark forward-backward asymmetry and $t\bar{t}$ inclusive cross section includes higher-order loop effects in the effective interaction. The higher order correction changes the best fit value of the effective coupling as a function of the W' mass. The consistency of the model is checked against the shape of the $t\bar{t}$ invariant mass distribution. The authors use these updated W' parameters to compute the expected contributions from $W't$ associated production and, for the first time, $W'W'$ pair production at the LHC. They do a full Monte Carlo simulation of the $t\bar{t}X$ final state, including interference between the tW' induced $t\bar{t}j$ process and the standard model $t\bar{t}j$ process. They show that the jet multiplicity distribution in $t\ \bar{t}$ jet production at 8 TeV constrains the W' model severely.

Searches for $t\bar{t}$ plus Missing Energy Signatures at the LHC

Radja Boughezal and Markus Schulze have studied the pair production of scalar top-quark partners decaying to a top-quark pair plus large missing energy at the LHC, a signature which appears in numerous models that address outstanding problems at the TeV-scale. In all experimental searches so far performed, the signal process was modeled with leading-order kinematics, and was normalized to an inclusive higher-order prediction for stable stops. The severe experimental search cuts require a description which combines production and decay dynamics for a realistic final state. An exact next-to-leading order (NLO) QCD analysis was not performed, nor were NLO QCD corrections considered in the decay of the top partner, or in the decay of

the top quark. Boughezal and Schulze have done this at NLO in QCD for the first time. They found large, kinematic-dependent QCD corrections that differ dramatically depending upon the observable under consideration, potentially impacting the search for and interpretation of these states. Their new results are crucial to assist in both the search for and eventual interpretation of the underlying model assuming discovery. This work has been accepted for publication in PRL. In their previous analysis, Boughezal and Schulze have studied the pair production of scalar top-quark partners decaying to a top-quark pair plus large missing energy at the LHC, where the top decays semi-leptonically. They are currently performing a detailed analysis that compares the results of several simulation tools: leading-order matrix elements, next-to-leading order matrix elements in production and decay as well as spin correlations, leading-order plus parton shower simulations currently used in experimental studies, and finally a merged sample. Their analysis for the stop case is extended to include the di-leptonic channel which has also been searched for experimentally. In addition to that, they are studying similar effects due to the production and decay of a fermionic top partner that is motivated by the littlest Higgs model.

The polarization of a top-quark can be sensitive to new physics beyond the standard model. E. Berger and collaborators proposed a novel method to measure top-quark polarization, based on the charged lepton energy fraction in top-quark decay, and illustrated the method with a detailed simulation of top-quark pairs produced in supersymmetric top squark pair production. They showed that the lepton energy ratio distribution that they define is very sensitive to the top-quark polarization but insensitive to the precise measurement of the top-quark energy. This work is summarized in "Measurement of the Top Quark Polarization in Top Pair plus Missing Energy Events", arXiv:1305.7266, the written version of the invited talk presented by Hao Zhang at the 48th Rencontres de Moriond "QCD and High Energy Interactions", La Thuile, Italy, March 9 – 16, 2013. It is scheduled to be published in the Proceedings.

Motivated by the prospects of finding light stops at the LHC, Ian Low has been also working on polarization issues in the stop searches at this collider.

Higgs Boson Production

Boughezal, Petriello and Schulze have provided the differential cross-section for Higgs boson production in gluon fusion in association with a hadronic jet at next-to-next-to-leading order (NNLO) in perturbative QCD. This result is urgently needed in order to reduce the theoretical uncertainties hindering a precise extraction of the Higgs properties at the LHC. Currently, the theoretical errors in the one-jet bin comprise one of the largest systematic errors in Higgs analyses at the LHC, particularly in the WW final state. They have shown explicitly how to employ known soft and collinear limits of scattering amplitudes to construct subtraction terms for NNLO computations. The NNLO QCD corrections significantly reduce the residual scale dependence of the cross-section. The computational method that they described in their paper is applicable to the calculation of NNLO QCD corrections to any other $2 \to 2$ process at a hadron collider. This work has been recently accepted for publication in JHEP. As a first step, Boughezal, Petriello and Schulze have shown results for the gg channel in their first publication. While this channel is the dominant one, the quark channels will be essential for achieving precise results for the Higgs + jet cross-section. Boughezal, Petriello and Schulze are currently working on the quark channels.

Boughezal and Petriello co-authored the Handbook of LHC Cross Sections Volume III on Higgs properties. This document is available as arXiv:1307.1347. Boughezal contributed a study of Higgs plus jet production through NNLO in QCD for the gluon-fusion chapter of the report. She provided initial theoretical predictions for the 8 TeV LHC run that reduced the residual theoretical errors on Higgs production in association with a jet. This is expected to have an important impact on the $H \to WW$ analysis. Petriello contributed a study of the resummation of large logarithms in Higgs production induced by the experimental division of the signal into bins of exclusive jet multiplicity. This resummation was found to reduce the theoretical error in the one-jet bin by approximately 25%.

C. Wagner also co-authored the Handbook of LHC Cross Sections quoted before. His contribution is related to new benchmarks for the study of MSSM Higgs bosons. The MSSM provides a very rich Higgs structure, including two

CP-even Higgs, a CP-odd and a charged Higgs bosons. Searches for the standard and non-standard Higgs bosons depend on their decay and production rates, which depend on their masses, the value of $\tan\beta$ and the radiative effects which depend on the supersymmetric mass parameters. C. Wagner, in collaboration with M. Carena, S. Heinemeyer, O. Stal and G. Weiglein, defined benchmarks for searches of the Higgs bosons in the MSSM, which contain different interesting scenarios, and which can serve as a guidance for future searches at the LHC. Apart from scenarios that lead to interesting modifications of the SM-like Higgs phenomenology, they also analyzed the sensitivity of the searches to heavy Higgs decays into light charginos and neutralinos, and to decays of the form $H \to hh$.

Liu and Petriello resummed a class of large Sudakov logarithms affecting Higgs boson production in the exclusive one-jet bin at the LHC. They extended previous results by calculating the full one-loop soft function for this process, which extends the accuracy of the resummation to include the leading three logarithmic corrections at each order in the QCD coupling constant. They matched this result to the next-to-leading order cross section and present a detailed numerical study assuming realistic LHC cuts. Careful attention was paid to the matching procedure, and to the theoretical uncertainties induced by residual scale variation. The matched NLL′+ NLO cross section has significantly smaller uncertainties than the fixed-order result, and can be used to alleviate the theoretical errors hindering current Higgs analyses at the LHC. This work was accepted for publication in PRD, and discussions are ongoing with experimentalists in both ATLAS and CMS regarding how to incorporate these theoretical improvements into the current analyses.

Measuring the Higgs Couplings to Heavy Quarks via the Decays $H \to V\,\gamma$

G. Bodwin and F. Petriello have begun a calculation, in collaboration with Northwestern University experimentalists S. Stoynev and M. Velasco, of the rates for the rare decays $H \to V\,\gamma$, where V denotes a quarkonium vector meson, such as the J/ψ or the $\Upsilon(1S)$. The quarkonium state subsequently decays to l^+l^-, yielding a clean experimental signature for this process. The decay $H \to J/\psi + \gamma$ is particularly interesting because it provides a means

to measure the $H\bar{c}c$ coupling, which would otherwise be inaccessible at the LHC.

These decays proceed through two channels: (1) an indirect channel, in which the Higgs decays to a real photon and a virtual photon through a top-quark loop or a W loop, with subsequent decay of the virtual photon to the quarkonium; (2) a direct channel, in which the Higgs decays to a Q and a $\bar{Q}$, which evolve into a quarkonium, radiating a photon in the process. Quantum interference between the two production channels enhances the sensitivity of the decay rate to the $H\bar{Q}Q$ coupling and potentially allows the $H\bar{c}c$ coupling to be constrained directly by a measurement of the branching ratio for $H \to J/\psi\,\gamma$. Deviations from SM predictions for the $H\bar{Q}Q$ couplings can lead to large shifts in the branching ratios that can either be observed or constrained by a measurement of the $H \to V\,\gamma$ branching ratio. It had previously been expected that only third-generation Higgs-quark couplings would be accessible to measurements at the LHC. Since the decay modes $H \to V\,\gamma$ can be accessed only with high statistics, the possibility of using them to measure the $H\bar{c}c$ coupling motivates a high-luminosity run of the LHC.

The $H \to V\,\gamma$ decay modes will also play an important role at future high-luminosity e^+e^- machines. Measurements of the $H\bar{c}c$ and $H\bar{b}b$ couplings via the direct decays $H \to \bar{c}c$, $\bar{b}b$ leave the overall signs of the couplings undetermined. This ambiguity is resolved by the quantum interference that is present in the decays $H \to V\,\gamma$, providing us with important additional information about the properties of the Higgs.[1]

Higgs Boson Signatures

Although current Higgs data at the Large Hadron Collider is compatible with a SM Higgs signal, the current uncertainties are large enough to allow the presence of new physics, leading to a modification of the relevant couplings governing the Higgs production and decay rates. A few months ago, Low and Wagner analyzed the general properties that new particles must fulfill in order to modify the Higgs diphoton decay rate. This information was used by C. Wagner, in collaboration with M. Carena, S. Gori, N. Shah and L.T. Wang to study the possible modifications of the bottom, gluon and

[1]This feature of the $H \to V\,\gamma$ decay modes was pointed out by Heather Logan.

tau couplings to the SM-like Higgs in scenarios where there is not only a light stau but also a light stop in the spectrum. It was shown that sizable modifications of the Higgs production and decay rates may be obtained, which can be tested at the next run of the LHC. Searches for the light stops and light staus were also analyzed in channels not previously considered. C. Wagner gave a talk at the ATLAS SUSY working group, whose members decided to perform the corresponding search analyses.

C. Wagner, in collaboration with his student, A. Joglekar and Argonne-UIC postdoc, P. Schwaller studied the supersymmetric extension of a model they proposed in which the standard model lepton sector is extended to include vector-like leptons, which lead to modifications of the Higgs diphoton rate. Problems of vacuum stability are avoided by this extension. This model also leads to the presence of a neutral stable particles that are good Dark Matter candidates. In a previous work, the authors demonstrated that there are regions of parameters in which the proper relic density may be obtained. The supersymmetric extension leads to two or three different stable particles and they are now performing an analysis of the relic density in this richer system. A general way of obtaining the number of Dark Matter particles in the presence of Z_2 symmetries was also derived with P. Schwaller and is being written.

Low studied constraints on masses and couplings of new scalars and fermions that can be derived from 5% to 10% deviations in the Higgs digluon and diphoton partial widths. To reduce theoretical uncertainties, he presented next-to-leading order QCD corrections to the Higgs-to-digluon coupling for scalars and fermions in arbitrary representations of SU(3)c color group, by applying the low-energy Higgs theorems at two-loop order. As a by-product he provided a new value for NLO QCD corrections to the top squark contributions to digluon decays that differs from existing literature.

Factorization in Quarkonium Production

G. Bodwin made further progress in understanding NRQCD factorization for inclusive quarkonium production. It was found that violations of factorization are suppressed by a factor $\alpha_s(m_c)$ relative to the factorized expression.

Light Sbottoms and Precision Electroweak Data

In collaboration with L.T. Wang, and Brian Batell, C. Wagner has been working on the possibility of having sbottoms with masses which are close to the bottom mass, and analyzing their effects in precision electroweak data and searches at the LHC. When produced in high energy collisions, such a sbottom will decay to a bottom quark and a very soft LSP, leaving a signature which is diffifficult to distinguish from direct bottom quark production. He demonstrated that this scenario can resolve some of the discrepancies in the bottom quark precision electroweak observables , and is furthermore consistent with all past collider data. Even though R-parity is conserved, supersymmetric phenomenology at the LHC can be dramatically altered, with bottom quark-rich final states instead of large missing energy. This work makes connection with related work done at the Argonne HEP Theory group a decade ago.

Snowmass Contributions

Boughezal and Petriello contributed to the QCD Working Group Report of the 2013 Snowmass Community Planning exercise. Boughezal studied the theoretical predictions for Higgs production at future 33 TeV and 100 TeV proton-proton colliders. Petriello was a convener of the QCD working group and is an editor of this report. He also contributed a study of the scaling of jet-veto logarithms with collider energy in proton-proton collisions. Boughezal and Petriello will be co-authors of the report when it appears.

Petriello co-authored a study of electroweak corrections at high-energy colliders as part of the 2013 Snowmass Community Planning exercise. This document is available as arXiv:1308.1430. He studied the interplay between higher-order QCD and electroweak corrections at a 33 TeV proton-proton collider. He found an interesting effect in the lepton pseudorapidity distributions at high invariant masses. This may have an effect on extractions of parton distributions at a 14 TeV LHC.

During this period, G. Bodwin began writing a Snowmass White Paper on Quarkonium Physics in collaboration with E. Braaten (Ohio State University), E. Eichten (Fermilab), S. Olsen (Seoul National University),

T. Pedlar (Luther College), and J. Russ (Carnegie-Mellon University). The White Paper focuses on issues in quarkonium production and spectroscopy and highlights opportunities for dramatic progress in those areas at the Intensity and Energy Frontiers. Work on this project is in progress.

Fundamental Processes

With T Curtright, Cosmas Zachos has completed an extensive paper [arXiv:1304.0429] on umbral correspondences, intended to serve as a sourcebook to intensity and cosmic frontier applications. Umbral calculus is emerging as the leading framework providing systematic solutions of ubiquitous difference equations (illustrated with umbral counterparts of the Airy, Kummer, and Whittaker equations, and umbral maps of solitons for the Sine-Gordon, Korteweg–de Vries, and Toda systems) permitting glimpses of discrete structures at very short distances, at cosmic scales, as well as GUT texture problems. The article is under consideration for the inaugural issue of a new journal.

The book of C Zachos, T Curtright, and D Fairlie, "A Concise Treatise on Quantum Mechanics in Phase Space" is in the final stages of production by World Scientific Publishers.

Abstract work on neutrinos and umbral structures in fundamental processes has also been carried out by Cosmas Zachos and collaborators.

International Quarkonium Workshop in Beijing

The Quarkonium Working Group (QWG) held the 9th International Workshop on Heavy Quarkonium at IHEP in Beijing, April 22-26, 2013. This Workshop, which was attended by about 150 experts in quarkonium physics, covered topics in quarkonium production, decay, spectroscopy, standard-model measurements, physics beyond the standard model, and quarkonium in media (heavy-ion collisions). G. Bodwin played an important role in organizing the workshop, both as a convener of the QWG and as a convener of the production section. In addition, he gave an invited plenary talk on "Factorization in Inclusive Quarkonium Production" and participated in a round-table discussion on "Higher-Order Corrections, Matrix-Element Ex-

tractions, and Factorization in Quarkonium Production."

Annual DoE Review of the U.S. Lattice QCD Effort

G. Bodwin was a reviewer for the annual DoE review of the Lattice Quantum Chromodynamics Project (LQCD-ext), which was held at Thomas Jefferson National Accelerator Facility, May 9–10, 2013.