HEP Theory Group Activities : Fourth 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, Zack Sullivan, and Hao Zhang completed a paper with the title "LHC and Tevatron constraints on a W' model interpretation of the top quark forward-backward asymmetry". The paper was posted to the archives as arXiv:1309.7110 and was submitted to Physical Review D.

In this paper they investigate a model with right-handed coupling of a W' boson to the first and third quark generations. They fit for values of the coupling constant V'_{td} consistent with Tevatron data on the observed anomalously large top-quark forward-backward asymmetry and the $t\bar{t}$ cross section as a function of the W' mass. Their theoretical expressions include higher-order W' loop corrections whose contributions diminish the required best fit value of the coupling strength compared to previous LO fits.

Given the model and their determination of its parameters, Berger, Sullivan and Zhang then investigate the consequences at the LHC. For masses of the W' below 400 GeV, their previous comparison to early ATLAS data excluded all relevant values of V'_{td} based on cross section rate. For larger masses, the predicted broader width of the W' requires other strategies, and they focus on the multiplicity distribution of jets accompanying a $t\bar{t}$ pair in the full 8 TeV CMS data sample. In the W' model, processes such as associated tW' production and $W'W'$ pair production, with $W' \to \bar{t}d$, contribute to the $t\bar{t} + \mathrm{n}j$ final state along with standard model QCD production of $t\bar{t} + \mathrm{n}j$.

Berger, Sullivan and Zhang simulate all $t\bar{t} + \mathrm{n}j$ processes including the interference between the SM $t\bar{t}$+nj process and inclusive tW' associated production, as well as contributions from the $W'^{+}W'^{-}$ channel. They examine the entire mass range $200 < m_{W'} < 1100$ GeV. Their simulation includes parton fragmentation and hadronization from PYTHIA6.4 and

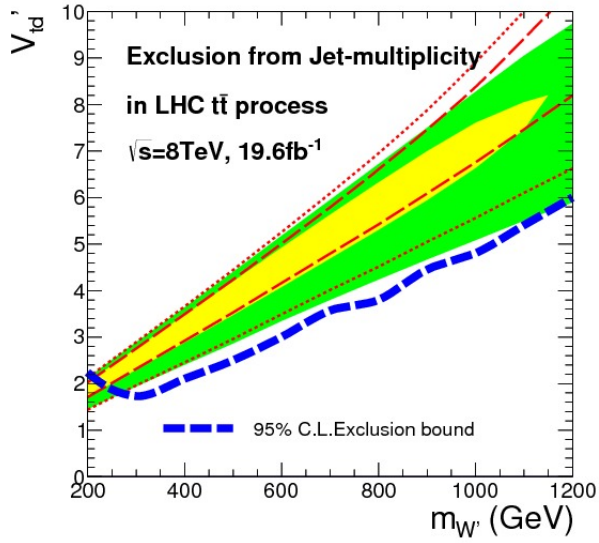

FIG. 1: The 95% exclusion bound in the parameter space of V'_{td} vs $m_{W'}$ from χ^2/d.o.f fits to the LHC jet-multiplicity distribution in the inclusive $t\bar{t}X$ process at 8 TeV. The (blue) dashed line is the 95% exclusion bound. The shaded regions show the values of V'_{td} obtained from fits to Tevatron data on $\sigma_{t\bar{t}}$ and A^t_{FB} as a function of the W' mass. Values of χ^2 in the light-shaded (yellow) region remain less than 1. Values of χ^2 in the dark-shaded (green) region are not greater than the SM χ^2. The results without NLO contributions are also shown. In the region between the (red) dashed lines χ^2 is not greater than 1, and in the region between the (red) dotted lines χ^2 is not greater than the SM χ^2.

a detector simulation using the PGS code. They compare their resulting jet multiplicity distribution with data from the CMS collaboration. Interference plays a quantitatively significant role, altering the expected cross sections and exclusion bounds.

The essential conclusions of the study are shown in Fig.1. Within the mass range $200 < m_{W'} < 1100$ GeV, values of V'_{td} large enough to accommodate the forward backward asymmetry observed at the Tevatron are incompatible with a good fit to the jet multiplicity distribution at the LHC.

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. In a subsequent work that appeared in arXiv:1309.2316, they performed a detailed study for this final state, presenting results for both scalar and fermionic top-quark partners in the semi-leptonic and dileptonic decay modes of the top quarks. They compared the results of several simulation tools: leading-order matrix elements, next-to-leading order matrix elements, leading-order plus parton shower simulations, and merged samples that contain the signal process with an additional hard jet radiated. They found that predictions from leading-order plus parton shower simulations can significantly deviate from NLO QCD or LO merged samples and do not correctly model the kinematics of the $t\bar{t} + E_{Tmiss}$ signature. They are therefore not a good framework for modeling this new physics signature. On the other hand, the acceptances obtained with a merged sample of the leading-order process together with the radiation of an additional hard jet are in agreement with the NLO predictions. They also demonstrated that the scale variation of the inclusive cross section, plus that of the acceptance, does not accurately reflect the uncertainty of the cross section after cuts, which is typically larger. In addition, they showed the importance of including higher-order QCD corrections when using kinematic distributions to determine the spin of the top-quark

partner.

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 $H \to V\,\gamma$

This work by G. Bodwin and F. Petriello, in collaboration with Northwestern University experimentalists S. Stoynev and M. Velasco, which was described in the report for the second quarter of 2013, has now been completed. It was found that, owing to the interference between the direct and indirect channels, the $H\bar{c}c$ coupling can be measured in a high-luminosity run of the LHC. If the $H\bar{c}c$ coupling deviates from its Standard Model value by a factor of 2, then the $H \to J/\psi\,\gamma$ rate can shift by 100% or more. In the case of $H \to \Upsilon\,\gamma$,

there is almost complete destructive interference between the direct and indirect amplitudes at the Standard Model value of the $H\bar{b}b$ coupling. Consequently, if the $H\bar{b}b$ deviates from its Standard Model value by a factor of 2, the rate can shift by a factor 1000 or more.

This work has been submitted to the arXiv (arXiv:1306.5770) and has been published in Phys. Rev. D **88**, 053003 (2013).

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 year ago, Low and Wagner analyzed the general properties that new particles must fulfill in order to modify the Higgs diphoton decay rate. This provided new insight into the findings of Wagner, working in collaboration with M. Carena, S. Gori, N. Shah, who had shown that light staus can lead to large modifications of the Higgs decay rate into diphotons. This information was used by C. Wagner, who in the second quarter of this year worked in collaboration with M. Carena, S. Gori, N. Shah and L.T. Wang to study the possible modifications of the bottom, gluon and 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. This work is now published in JHEP **1308** (2013) 087. Wagner related study of the supersymmetric generalization of the vector-like leptons, performed in the same quarter, is also published in JHEP **1307** (2013) 046.

Quite recently, Wagner in collaboration with B. Batell and S. Jung concentrated on the possible quantum effects of light charginos on the Higgs phenomenology. Wagner analyzed the possible corrections to the Higgs $h\gamma\gamma$ and $h\gamma Z$ couplings, and showed that significant modifications may be obtained for charginos that are below the naive LEP bound of 100 GeV can significantly affect these couplings. However, if the charginos are lighter than 100 GeV, more dramatic alterations to these couplings are possible as a consequence of the rise of the one loop form factor. For example, the diphoton signal strength can be enhanced by as much as 70% compared to the Standard Model value. Wagner and collaborators scrutinized in detail the existing LEP, Tevatron, and LHC searches and present a scenario

in which a very light chargino with a mass as light as half the Higgs mass is hidden at LEP and is allowed by all direct collider constraints and electroweak precision tests. The scenario has a sneutrino LSP with a macroscopic decay length of order 10 to 100 cm. Furthermore, they outlined potential search strategies to test this scenario at the LHC. This work has been submitted to the arXiv (arXiv:1309.2297) and is being submitted for publication in Phys. Rev. **D**.

Wagner and Low studied the condition of alignment, which may exist in models with an extended Higgs sector. In the alignment limit the lightest CPeven Higgs boson mimics the Standard Model Higgs. This limit is commonly associated with the decoupling limit, where all non-standard scalars are signicantly heavier than the Z boson. However, alignment can occur irrespective of the mass scale of the rest of the Higgs sector. In their work, Wagner and Low, in collaboration with M. Carena and N. Shah, discussed the general conditions that lead to "alignment without decoupling", therefore allowing for the existence of additional non-standard Higgs bosons at the weak scale. The values of $\tan\beta$, the ratio of the two Higgs vacuum expectation values, for which this happens were derived in terms of the effective Higgs quartic couplings in general two-Higgs-doublet models as well as in supersymmetric theories, including the MSSM and the NMSSM. Moreover, they studied the information encoded in the variations of the SM Higgs-fermion couplings to explore regions in the m_A-$\tan\beta$ parameter space which are difficult to test via direct searches for non-standard Higgs bosons. This work was submitted to the arXiv very recently, arXiv:1310.2248.

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.

Resummation of Large Logarithms in Quarkonium Production at the LHC

G. Bodwin and H.-S. Chung, in collaboration with J. Lee (Korea University), have begun a calculation aimed at summing the large logarithms of p_T^2/m_c^2 that appear in quarkonium-production cross sections at the LHC. These resummations are needed in order to make reliable predictions for cross sections at the the unprecedentedly large values of p_T that are accessible at the LHC. The calculations are done by making use of the fragmentation approximation, which is valid for p_T^2 much larger than the quarkonium mass. It is thought that the fragmentation contributions may dominate the complete NLO calculations at values of p_T that are only a few times the quarkonium mass. This hypothesis will be tested as a by-product of the resummation calculation. If it is correct, then it could be used to simplify the analysis of quarkonium productions rates and polarizations for a variety of process at large p_T. Such simplified analyses could allow one to devise more stringent tests of NRQCD factorization, which is the current state-of-the-art model for quarkonium production and could lead to new insights into the dominant quarkonium-production mechanisms.

Light Sbottoms and Precision Electroweak Data

In collaboration with L.T. Wang, and Brian Batell, 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 difficult 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, and will be soon submitted to the arXiv.

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. Boughezal and Petriello have also co-authored the Computing for Perturbative QCD Report of the 2013 Snowmass, which appeared recently in arXiv:1309.3598.

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 the second quarter of 2013, 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. This 42-page white paper has now been completed and has been submitted to the arXiv (arXiv:1307.7425). These same authors contributed sections on quarkonium physics to the Snowmass reports on Quark Flavor Physics at the Intensity Frontier and QCD at the Energy Frontier.

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 appeared in the inaugural issue of a new journal, Front. Physics 1 (2013) 15.

The book of C Zachos, T Curtright, and D Fairlie, "A Concise Treatise on Quantum Mechanics in Phase Space". has been proofread and in press (World Scientific Publishers.

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