HEP Theory Group Activities : **Second 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. Examples of these works are the following :

Top Quark Rapidity Asymmetries and Top-Quark Polarization

Ed Berger and collaborators continued their studies of the forward-backward asymmetries A^t_{FB} and A^ℓ_{FB} in the top quark t rapidity distribution and in the rapidity distribution of charged leptons ℓ from top quark decay. These asymmetries are observed at the Tevatron proton-antiproton collider, and a charge asymmetry A_C is seen in proton-proton collisions at the Large Hadron Collider (LHC). E. Berger, in collaboration with Argonne postdoctoral fellow Hao Zhang and former postdoctoral fellows Qing-Hong Cao and Chuan-Ren Chen, provided expectations for A_C at the LHC based first on simple extrapolations from the Tevatron results, and second based on new physics models that can explain the Tevatron asymmetries. They also examined the relationship of the two asymmetries A^t_{FB} and A^ℓ_{FB}, and they showed their connection through the $(V - A)$ spin correlation between the charged lepton and the top quark with different polarization states. Furthermore, they showed that the ratio of the two asymmetries provides independent insight into the physics interpretation of the top quark asymmetry. Considering the value of the measurement of both asymmetries, they concluded that a model which produces more right-handed than left-handed top quarks is suggested by the present Tevatron data.

E. Berger and collaborators produced further work in this direction, which has appeared in "Top Quark Polarization and the Search for New Physics", arXiv:1301.5053¡http://arxiv.org/abs/1301.5053, the written version of the invited talk Ed Berger presented at Beyond the Standard Model of Particle Physics, Quy Nhon, Vietnam, July 15 – 21, 2012. It will be published in the Proceedings.

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 recently 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 includes also the di-leptonic channel, which has also been considered by the LHC experimental collaborations. In addition, they are studying similar effects due to the production and decay of a fermionic top partner.

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.

In arXiv:1303.4405, 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.

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. In particular, as Carlos Wagner and collaborators showed in previous 2012 publications, this enhancement could be accommodated in the Minimal Supersymmetric Standard Model (MSSM) with highly mixed light staus. Furthermore, I. Low, C. Wagner, in collaboration with M. Carena, from Fermilab, S. Gori from the University of Chicago and N. Shah from the University of Michigan, revisited the issue of vacuum instabilities induced by large mixing in the stau sector, including ffeffects of a radiatively-corrected tau Yukawa coupling. In arXiv:1303.4414, 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 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.

In arXiv:1303.2969 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 3 different stable particles and they are now performing an analysis of the relic density in this richer system.

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. In arXiv:1302.7033, 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 $H \to hh$.

Ian Low has been working on constraints on new physics from precision measurements of loop-induced Higgs couplings.

Quarkonium Production

During this period, G. Bodwin submitted a CMS Analysis Note (with Carlos Lourenço) on Studies of Quarkonium Hadroproduction in pp Collisions at 8 TeV: A Physics Case for Data Parking. The Analysis Note has had a major impact on the allotted bandwidth for quarkonium data at CMS. Also during this period, G. Bodwin prepared a conference proceeding (with U-Rae Kim and Jungil Lee) on Order-v^4 Relativistic Corrections to Gluon Fragmentation into $^3S_1$ Quarkonium (arXiv:1301.3532).

G. Bodwin made further progress in understanding NRQCD factorization for inclusive quarkonium production. The factorization issue was seen to be related to the dipole conjecture of Becher and Neubert for the soft anomalous dimension.

Formal Physics

Abstract work on neutrinos and umbral structures in fundamental processes has also been carried out by Cosmas Zachos and collaborators. 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 second edition of a book on phase-space, substantially expanded and now titled "A Concise Treatise on Quantum Mechanics in Phase Space" has been submitted to Imperial Press and is currently under production.