HEP Theory Group Activities : First 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 :

Study of flavor violating W' at the LHC

Ed Berger, Hao Zhang, and Zack Sullivan concluded and published their study "LHC and Tevatron constraints on a W' model interpretation of the top quark forward-backward asymmetry". The paper was issued as Argonne preprint ANL-HEP-PR-13-40 (arXiv:1309.7110) and published in Physical Review D **88**, 114026 (2013) (December 13, 2013). Berger, Zhang, and Sullivan investigate a model with right-handed coupling of a W' boson to the first and third quark generations, and fit Tevatron data to determine values of the coupling constant V'_{td} consistent with the observed anomalously large top-quark forward-backward asymmetry and the $t\bar{t}$ cross section as a function of W' mass. Their theoretical expressions include higher-order W' loop corrections. Given the model and their determination of its parameters, they then investigate the consequences at the LHC, focussing 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 $t\bar{t}+\mathrm{n}j$. They simulate all $t\bar{t}+\mathrm{n}j$ processes including the interference between the SM $t\bar{t}+\mathrm{n}j$ process and inclusive tW' associated production; as well as contributions from the $W'^{+}W'^{-}$ channel. The simulation includes parton fragmentation and hadronization and a detector simulation. They compare their resulting jet multiplicity distribution with data from the CMS collaboration. Within the mass range $200 < m_{W'} < 1100$ GeV, they conclude that values of V'_{td} large enough to accommodate the asymmetry observed at the Tevatron are incompatible with a good fit to the jet multiplicity distribution at the LHC.

There are other new physics models proposed for the top-quark anomaly at the Tevatron. Many of them are disfavored or highly constrained by LHC data and other

direct or indirect experiments. The difficulties encountered in constructing models of new physics that can simultaneously accommodate the Tevatron asymmetry and LHC observables motivate renewed inquiry into the standard model QCD expectations against which the data are compared. We look forward to the next stage of fully differential NNLO calculations of $t\bar{t}$ production and decay that should be incorporated into the understanding of experimental acceptances, and allow for a full NLO prediction of the asymmetry after cuts.

Combining Resummed Higgs Predictions Across Jet Bins

Experimental analyses often use jet binning to distinguish between different kinematic regimes and separate contributions from background processes. To accurately model theoretical uncertainties in these measurements, a consistent description of the jet bins is required. In arXiv:1312.4535 Boughezal and Petriello, in collaboration with the postdoc Xiaohui Liu, presented a complete framework for the combination of resummed results for production processes in different exclusive jet bins, focusing on Higgs production in gluon fusion as an example. They have extended the resummation of the Higgs + 1-jet cross section into the challenging low transverse momentum region, lowering the uncertainties considerably. They provided combined predictions with resummation for cross sections in the Higgs + 0-jet and Higgs + 1-jet bins, and gave an improved theory covariance matrix for use in experimental studies. They estimated that the relevant theoretical uncertainties on the signal strength in the Higgs to WW analysis are reduced by nearly a factor of 2 compared to the current value.

Disentangling radiative corrections using high-mass Drell-Yan at the LHC

Future measurements of the Drell-Yan spectrum at a 14 TeV LHC will access an even larger kinematic range than what has been so far probed. Along with this larger phase space comes an increased sensitivity to a host of effects. In addition to QCD corrections through next-to-next-to-leading order (NNLO), electroweak Sudakov corrections become increasingly more important at high- energy colliders. Photon-initiated corrections also increase in importance at high energies, as has been recently emphasized for both Drell-Yan and W-pair production processes. The ATLAS collaboration has performed detailed studies showing the importance of these effects for a host of measurements in the Drell-Yan channel. One view

of these corrections is that they represent additional sources of theoretical uncertainty which must be sufficiently controlled in order to perform interesting measurements. Sufficient understanding of electroweak (EW) corrections and photon-initiated processes, in addition to the usual QCD corrections, will be needed to interpret these measurements. The experimental control over the Drell-Yan channel allows such theoretical effects to be precisely validated before being applied to other processes.

In arXiv:1312.3972, Boughezal and Petriello presented a detailed numerical study of lepton-pair production via the Drell-Yan process above the Z-peak at the LHC. Their results consistently combine next-to-next-to-leading order QCD corrections and next-to-leading order electroweak effects, and included the leading photon-initiated processes using a recent extraction of the photon distribution function. They focused on the effects of electroweak corrections and of photon-photon scattering contributions, and demonstrated which kinematic distributions exhibit sensitivity to these corrections. They showed that a combination of measurements allows these effects to be disentangled and separately determined.

Higgs alignment in two Higgs doublet models and in SUSY extensions.

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, arXiv:1310.2248, will be published in JHEP.

Computation of the Higgs Mass at higher loops in the MSSM

In supersymmetric models, very heavy stop squarks introduce large logarithms into the computation of the Higgs boson mass. Although it has long been known that in simple cases these logs can be resummed using effective field theory techniques, it is technically easier to use fixed-order formulas, and many public codes implement the latter. Wagner, in collaboration with his student Gabriel Lee and his former student Patrick Draper calculated three- and four-loop NNLL corrections to the Higgs mass and compare the fixed order formulas numerically to the resummed results in order to estimate the range of SUSY scales where the fixed-order results are reliable. They found that the four-loop result may be accurate up to a few tens of TeV. They showed an accidental cancellation between different three-loop terms, which persists to higher scales and becomes more effective with the inclusion of higher radiative corrections. One of the consequence of their analysis is that results in the literature based on partial three-loop calculations, and which include only one of the two canceling terms overestimate the Higgs mass. Wagner and collaborators presented analytic expressions for the three- and four-loop corrections in terms of Standard Model parameters and provide a complete dictionary for translating parameters between the SM and the MSSM and the MS and DR renormalization schemes. This article was submitted to the arXiv just before Christmas, arXiv:1312.5743, and will be sent for publication in Phys. Rev. D.

Resummation of Large Logarithms in Quarkonium Production at the LHC

As was described in the previous quarterly report, G. Bodwin and H.-S. Chung, in collaboration with J. Lee and U-Rae Kim (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. (Please see the previous quarterly report for further discussion.)

During the last quarter, Mathematica and Fortran codes were written to carry out the resummation. In constructing the resummation code, Bodwin and collaborators tried various combinations of integration variables in order to determine the most efficient choice. They also devised a method to deal numerically with a sharp peaking in the evolved fragmentation

functions near $z = 1$. The peaking grows worse as the amount of evolution becomes small, resulting in singular distributions in z in the no-evolution limit. The method of Bodwin and collaborators, which makes use of subtractions at $z = 1$, deals with both the problem of computing the convolution over z accurately and the problem of taking the inverse Mellin transform of the moment-space fragmentation function accurately.

Bodwin and collaborators performed numerous checks of the code by making comparisons with fixed-order expressions in the small-evolution region, by using model parton distributions with exact, analytic moment-space expressions, and by testing that the resulting fragmentation functions satisfy the momentum sum rule.

Preliminary results indicate that the fragmentation approximation already reproduces the full NLO calculations in the ${}^3S_1$ and ${}^3P_J$ color-octet channels well at $p_T = 20$ GeV, but that the fragmentation approximation is valid for the ${}^1S_0$ color-octet channel only at much higher values of p_T. The resummation corrections appear to be small in the ${}^3S_1$ color-octet channel (of order -10% at $p_T = 20$ GeV), but large in the ${}^3P_J$ color-octet channel (of order -50% at $p_T = 20$ GeV). The contribution of light-quark fragmentation to J/ψ production appears to be small in comparison with the contribution of gluon fragmentation to J/ψ production. The effects of light-quark-gluon mixing in the evolution appear to be small in comparison with the effects of purely gluonic evolution.

Production running of the resummation calculation is about to commence.

Constraints on a Light Sbottom

Wagner, L.T. Wang, and Brian Batell, investigated the phenomenological viability of a very light bottom squark, with a mass less than half of the Z boson mass. They showed that these models are strongly constrained by the contribution to precision electroweak data and Higgs signal strength measurement induced by the decays of the Z and Higgs bosons to light sbottom pairs are, respectively. These constraints are complementary to direct collider searches, which depend in detail on assumptions regarding the superpartner spectrum and decays of the sbottom. In particular, if the lightest sbottom has a mass below about 15 GeV, compatibility with these measurements is possible only in a special region of parameter space in which the couplings of the lightest sbottom to the Z and Higgs are suppressed. In this region, the second sbottom is predicted to be lighter than

about 300 GeV and can also be searched for directly at the LHC. Wagner and collaborators also surveyed relevant collider searches for canonical scenarios with a bino, gravitino, or singlino LSP in the compressed and stealth kinematic regimes and provide suggestions to cover remaining open regions of parameter space. This article, arXiv: 1312.2590, appeared recently and has been submitted for publication in JHEP.

Abstract Developments.

C Zachos with T Curtright (U of Miami) have submitted an extensive paper on Branched Hamiltonians and Supersymmetry [arXiv:1311.6147], in which they introduce several such Hamiltonians, in the context of quantum mechanics, as recently advocated by Shapere and Wilczek, one of which is, perhaps surprisingly, supersymmetric.

Such Hamiltonians, with broad applications to quantum cosmology, condensed matter, and quantum field theory, typically result from Legendre-transforming Lagrangians whose velocity dependence is not convex, which invariably leads to a Riemann surface phase-space structure, with multiply-branched (but still self-adjoint) Hamiltonians, and probes interesting topological issues.

Based on their past work, they invent a new class of models where analytic results can be obtained; one of them possesses a pair of Hamiltonians that comprise a supersymmetric quantum mechanical system, considered in substantial detail, to illuminate two-worlds theory. After outlining a gaussian model whose branches lie on a compact, closed momentum manifold with coalescing cusps at finite momentum, as a preliminary step in the search for a supersymmetric model with similar properties, they introduce the new double-valued Hamiltonians, one of which has the canonical structure of a supersymmetric pair of Hamiltonians. They survey the spectral and boundary condition linkages involved across the respective branches for this supersymmetric model, in a uniform framework, by utilizing the eigenstate-linking supercharge ladder operators (but which are not Grassmann and which do not commute with the two Hamiltonians).

These particular branched Hamiltonians are nevertheless paired by supercharges into a uniform Darboux isospectral system, in the same Hilbert space; and yet they are inexorably separated, in some analogy to fermionic and bosonic sectors, as the respective dynamical intervals only connect at $p = \infty$. Applications of this system are currently being developed.