HEP Theory Group Activities : Second Quarter 2015

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 :

Axial vector meson production

Ed Berger and collaborator Jean-Louis Basdevant of l'Ecole Polytechniquec in Paris continued their investigations of axial-vector meson production in high energy hadronic scattering. As reported previously, their paper entitled "The twofold emergence of the a_1 axial vector meson in high energy hadronic production" was posed to the archives in January 2015, as arXiv:1501.04643 [hep-ph]. A shortened version will appear in Physical Review Letters. To quote one of the referees "Nice job!". This work was motivated by the high statistics COMPASS collaboration results at CERN showing that the isospin $I = 1$ spin-parity $J^{PC} = 1^{++}$ $a_1(1260)$ resonance could be split into two states: $a_1(1260)$ decaying into an S-wave $\rho\pi$ system, and $a_1'(1420)$ decaying into a P-wave $f_0(980)\pi$ system. Berger and Basdevant analyzed the reaction by incorporating their previous treatment of resonant re-scattering corrections in the Drell-Deck forward production process (e.g., "Unitary Coupled-Channel Analysis of Diffractive Production of the a_1 Resonance," Phys. Rev. D **16**, 657 (1977)). Their new results show that the COMPASS results are consistent with the existence of a single axial-vector a_1 resonance. The characteristic structure of the production process, which differs in the two orbital angular momentum states, plays a crucial role in this determination. This resonance produces two peaks at different locations in the two channels, with a rapid increase of the phase difference between their amplitudes arising mainly from the structure of the production process itself, and not from a dynamical resonance effect. In addition, the Berger-Basdevant analysis clarifies questions related to the mass, width, and decay rates of the a_1 resonance.

Fragmentation Contributions to Quarkonium Photoproduction

The J/ψ photoproduction cross section, differential in p_T, has been measured by the H1 collaboration at values of p_T up to about 10 GeV. At values of p_T that are significantly greater than the J/ψ mass, one would expect nonrelativistic QCD (NRQCD) factorization to hold. Nevertheless, NRQCD factorization calculations through NLO typically overshoot the data considerably when NRQCD long-distance matrix elements (LDMEs) from fits to the J/ψ hadroproduction cross sections and polarizations are used.

In the case of hadroproduction, Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee and U-Rae Kim (Korea University), recently computed additional leading power (LP) fragmentation contributions that go beyond NLO. (See previous quarterly reports for an account of this calculation.) It was found that these LP fragmentation contributions are large and that they lead, for the first time, to a prediction of near-zero J/ψ polarization, in agreement with the CDF and CMS data.

The large size of the LP fragmentation contributions in J/ψ hadroproduction motivates a computation of the corresponding LP fragmentation contributions to J/ψ photoproduction. Such a calculation was carried out during the last quarter by Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee and U-Rae Kim. That calculation makes use of a new computation of the quark fragmentation functions, which was described in the previous quarterly report, to compute the quark-fragmentation contribution, which is much more important in photoproduction than in hadroproduction. Preliminary results indicate that the LP fragmentation contributions to J/ψ photoproduction are small numerically in comparison with the NLO corrections. Therefore, these contributions do not resolve the discrepancy between theory and experiment, and a significant puzzle remains. A paper describing these results is in preparation.

Fragmentation Contributions to Quarkonium Production at the LHC

This work by Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee and

U-Rae Kim (Korea University), was described in previous reports. The corresponding publication in Phys. Rev. Lett. **113**, no. 2, 022001 (2014) was cited prominently in the March 2014 CERN Courier article "CMS head towards solving a decades-long quarkonium puzzle."

Quark Fragmentation into Pairs

This work by Geoff Bodwin and Hee Sok Chung, in collaboraton with Jungil Lee and U-Rae Kim (Korea University), was described in the previous quarterly report. During the current reporting period, a paper presenting these results (arXiv:1412.7106) was accepted for publication in Physical Review D.

Updated NNLO QCD predictions for the weak radiative B-meson decays

In arXiv:1503.01789, Boughezal and collaborators performed an updated analysis of the inclusive weak radiative B-meson decays in the Standard Model, incorporating all the available results for the $\mathcal{O}(\alpha_s^2)$ and lower-order perturbative corrections that have been calculated after 2006. New estimates of non-perturbative effects were taken into account, too. For the CP- and isospin-averaged branching ratios, they found $B_{s\gamma} = (3.36 \pm 0.23) \times 10^{-4}$ and $B_{d\gamma} = 1.73^{+0.12}_{-0.22} \times 10^{-5}$, for $E_\gamma > 1.6$ GeV. These results remain in agreement with the current experimental averages. Normalizing the sum of these branching ratios to the inclusive semileptonic branching ratio, Boughezal and collaborators obtain $R_\gamma = (B_{s\gamma} + B_{d\gamma})/B_{cl\nu} = (3.31 \pm 0.22) \times 10^{-3}$. A new bound from $B_{s\gamma}$ on the charged Higgs boson mass in the two-Higgs-doublet-model II reads $M_{H^+} > 480$ GeV at 95%C.L.

Jet vetoes for Higgs production at future hadron colliders

One of the major goals of the LHC in the next few years is the precision study of the properties of the Higgs particle. This requires precise experimental measurements coupled

with an accurate modeling of the signal and background on the theory side. Unfortunately the discovery of the Higgs does not answer all the open questions which may require energies beyond those accessible at the LHC. In particular, precise tests of Higgs couplings to Standard Model particles, the self-coupling of the Higgs and the structure of its potential may require a future higher-energy proton-proton collider.

The ATLAS measurement of the exclusive Z+1-jet cross section shows a surprising agreement with fixed-order predictions in the kinematic region expected to be dominated by large jet-veto logarithms. In arXiv:1501.01059, Boughezal in collaboration with the PhD student Chris Focke and the postdoc Xiaohui Liu have identified the explanation for this effect. The jet-isolation criterion implemented by ATLAS allows dijet events where an energetic jet is collinear to a final-state lepton. This process contains a giant K-factor arising from the collinear emission of a Z-boson from the dijet configuration which overwhelms the effect of the jet-veto logarithms. Boughezal and collaborators provided numerical results for 7 TeV, 8 TeV and 14 TeV LHC collisions that demonstrate the interplay between the jet-veto logarithms and the giant K-factor in the theoretical prediction. In addition, they have suggested an alternate isolation criterion that removes the giant K-factor and allows for a direct test of the jet-veto resummation framework in the Z+1-jet process.

The past year has seen a growing interest in the physics of a possible Future Hadron Collider (FHC). It is a candidate to continue exploration of the energy frontier once the LHC program is complete in roughly 20 years from now. Since higher scattering energies will be probed, this will lead to increasingly stringent cuts on QCD radiation that produces spurious jets in addition to those contained in signal processes. The large logarithms in question take the form $L = \log(Q/p_{cut})$, where Q is the hard scale of the considered process and p_{cut} is the scale of the cut on QCD radiation. At a FHC, Q will signicantly increase. The role of resummation of these large logarithms L will become more central at future machines.

Boughezal in collaboration with the postdocs Xiaohui Liu and Ye Li and the student Chris Focke studied Higgs boson production in exclusive jet bins at possible future 33 and 100 TeV proton-proton colliders. They compared the cross sections obtained using fixed-order perturbation theory with those obtained by also resuming large logarithms induced by the jet-binning in the gluon-fusion and associated production channels. The central values obtained by the best-available fixed-order predictions differ by $10-20\%$ from those obtained

after including resummation over the majority of phase-space regions considered. Additionally, including the resummation dramatically reduces the residual scale variation in these regions, often by a factor of two or more. They further showed that in several new kinematic regimes that can be explored at these high-energy machines, the inclusion of resummation improvement is mandatory. This work has been published in the Physical Review D journal.

Hadronic production of W and Z bosons at large transverse momentum

The production distributions of massive electroweak gauge bosons, W's and Z's, can be sensitive to new physics beyond the standard model (SM), either because new states in extensions of the SM may decay into W and Z bosons, or because the lepton distributions from SM W and Z decay are important backgrounds for high-energy lepton signatures in new physics models. Moreover, W and Z boson production serve as tests of perturbative quantum chromodynamics (QCD) calculations, and data on their distributions are important in the determination of the parton distribution functions. Among measurements of W and Z production, precise cross sections at large transverse momentum p_T hold particular interest. In a recent paper "Hadronic production of W and Z bosons at large transverse momentum" posted to the archives as arXiv:1503.08836 [hep-ph], Ed Berger and Argonne postdoc Jun Gao, along with external collaborators Zhong-Bo Kang (Los Alamos), Jian-Wei Qiu (Brookhaven), and Hao Zhang (UC Santa Barbara), introduce a modified factorization formalism in quantum chromodynamics for hadronic production of W and Z bosons at large p_T. When p_T is much larger than the invariant mass Q of the vector boson, this new factorization formalism systematically resums the large fragmentation logarithms, $\alpha_s^m \ln^m(p_T^2/Q^2)$, to all orders in the strong coupling α_s. Using their modified factorization formalism, they calculate the next-to-leading order (NLO) predictions for W and Z boson production at high p_T and provide predictions for the CERN Large Hadron Collider and at a future 100 TeV proton-proton collider. Their NLO results are about 5% larger in normalization, and they show improved convergence and moderate reduction of the scale variation compared to the NLO predictions derived in a conventional fixed-order perturbative expansion.

Rare exclusive decays of the Z-boxon

The realization that first- and second-generation Yukawa couplings can be probed by decays of the Higgs boson to a meson in association with a photon has renewed interest in such rare exclusive decays. Frank Petriello, in collaboration with Ting-Chung Huang presented a detailed study of the rare Z-boson processes $Z \to J/Psi + \gamma$, $Z \to \Upsilon + \gamma$ and $Z \to \varphi + \gamma$. that can serve as benchmarks for the analogous Higgs-boson decays. We include both direct-production and fragmentation contributions to these decays, and consider the leading QCD corrections and the relativistic corrections to the J/Ψ and Υ processes. They presented numerical predictions for the branching ratios that include a careful accounting of the theoretical uncertainties.

Precision Higgs Measurements and Searches for Non-Standard Higgs Bosons at the LHC

Wagner, in collaboration with Fermilab staff member Carena, UC Professor Haber, Argonne staff member Low and Michigan University postdoc Shah, concentrated in the two Higgs doublet model obtained at low energies in supersymmetric extensions of the Standard Model. The combination of current bounds from direct Higgs boson searches at the LHC, along with the alignment conditions, have a significant impact on the allowed MSSM parameter space yielding light additional Higgs bosons. In particular, after ensuring the correct mass for the lightest CP-even Higgs boson, they found that precision measurements and direct searches may soon be able to probe the region of non-SM-like Higgs boson with masses below the top quark pair mass threshold of 350 GeV and low to moderate values of $\tan\beta$.

To reach this conclusion Wagner and collaborators made a detailed study of the production cross section and decay branching ratios of the non-standard Higgs bosons in the case that the supersymmetric particles are heavy and also in the case that they are light, and demonstrated an interesting complementarity between the tests of this model arising from precision Higgs measurements and those coming from direct searches for non-standard

Higgs bosons. The result of this work has recently apperared in Phys. Rev. D **91**, no. 3, 035003 (2015).

Endpoint in the invariant mass distribution of leptons at CMS

Wagner and Huang, a joint Argonne/UofC postdoc, presented two scenarios in the Minimal Supersymmetric Extension of the Standard Model (MSSM) that can lead to an explanation of the excess in the invariant mass distribution of two opposite charged, same flavor leptons, and the corresponding edge at an energy of about 78 GeV, recently reported by the CMS collaboration. In both scenarios, s-bottoms are pair produced, and decay to neutralinos and a b-jet. The heavier neutralinos further decay to a pair of leptons and the lightest neutralino through on-shell s-leptons or off-shell neutral gauge bosons. These scenarios are consistent with the current limits on the s-bottoms, neutralinos, and s-leptons. Assuming that the lightest neutralino is stable they discussed the predicted relic density as well as the implications for Dark Matter direct detection. They also showed that consistency between the predicted and the measured value of the muon anomalous magnetic moment may be obtained in both scenarios. Finally, they defined the signatures of these models that may be tested at the 13 TeV run of the LHC. The result of this work has recently appeared in Phys. Rev. D **91**, no1, 015014 (2015) . The scenarios presented by Wagner and Huang are now being used as benchmarks for searches for sbottoms at ATLAS and CMS.

CP-odd component of the lightest neutral Higgs boson in the MSSM

The Higgs sector of the Minimal Supersymmetric Extension of the Standard Model may be described with a two Higgs doublet model with properties that depend on the soft supersymmetry breaking parameters. For instance, flavor independent CP-violating phases associated with the gaugino masses, the squark trilinear mass parameters and the Higgsino mass parameter μ may lead to sizable CP-violation in the Higgs sector. Constraints on this possibility come from direct searches for non-standard Higgs bosons, precision measurements on the lightest neutral Higgs properties, including its mass, and electric dipole moments.

In a recent article, Wagner and University Chicago student Bing Li discussed these constraints within the MSSM. They showed that the values of the stop left-right mixing parameter that maximize the lightest CP-even Higgs mass lead to a suppression of the dominant loop contribution to the CP-odd component of the lightest Higgs boson. Since for stop masses of order of the TeV scale, stop mixings close to the ones that maximize m_{H_1} are necessary in order to obtain SM-like Higgs masses of order of the one observed experimentally, the measured Higgs mass puts a significant constraint on the possible values of the H_1 CP-odd component. Moreover, they showed that large H_1 CP-odd components lead necessarily to a significant increase of the width of the lightest neutral Higgs decay into bottom quarks. Since the width of $H_1 \to b\bar{b}$ is the dominant decay width of H_1, this increase leads also to a significant modification of the branching ratio of the decays of H_1 to gauge bosons, what leads to a further constraint into large H_1 CP-odd components. This article appeared in [arXiv:1502.02210 [hep-ph]] and has recently been published in Phys. Rev. D **91**, 095019 (2015).

Program Chair, March and April General Meetings of the American Physical Society

In his roles as a member of the Program Committee of the American Physical Society and Chair of the Invited Paper sessions for the Forum on International Physics (FIP), Ed Berger organized the 5 FIP invited paper sessions: 2 for the March 2 - 6, 2015 meeting in San Antonio, Texas, and 3 for the April 11 - 14 meeting in Baltimore, Maryland. In March, the focus of the sessions is "Condensed Matter Physics in Latin America", with invited speakers from Argentina, Brazil, Colombia, and Mexico. In April, the focus is "Models of International Partnership", with invited speakers reporting on the organization and management of successful international collaborative efforts in astrophysics, particle physics, nuclear physics, and gravity research.