# HEP Theory Group Activities : Fourth 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

Following publication of their paper "Peak locations and relative phase of different decay modes of the $a_1$ axial vector resonance in diffractive production", arXiv:1504.05955, in Physical Review Letters **114**, 192001 (2015), Ed Berger and collaborator Jean-Louis Basdevant of l'Ecole Polytechnique have focussed on the $a_1$ produced in the decay of the $\tau$ heavy lepton: $\tau \to \pi\pi\pi\nu_\tau \to a_1\nu_\tau$, with the goal of providing a consistent description of both the hadronic data and the $\tau$ decay data. Very high statistics data on $e^+e^- \to \tau \to 3\pi\nu_\tau$ have been published by the CLEO, ALEPH, and BELLE collaborations. The understanding of these $\tau$ data requires coping with a substantial component of the $3\pi$ system in which no pair of pions is in a P-wave, in other words a non-$\pi\rho$ component. This research is well-along and a publication is anticipated before the end of 2015. Related to this research, Berger presented an invited talk, "Production Dynamics of the $a_1$ Axial Vector Meson", at HADRON 2015, XVI International Conference on Hadron Spectroscopy, Newport News, VA, September 13 –18, 2015.

## Topphilic $Z_T$ Boson in Broken Flavor Symmetry

Ed Berger and former Argonne postdoctoctoral fellow Hao Zhang are continuing their studies of the relationship of broken electroweak symmetry and broken flavor symmetry. Their first paper, "Higgs-flavon mixing and LHC phenomenology in a simplified model

of broken flavor symmetry", arXiv:1406.6054 [hep-ph], was published in Phys. Rev. D **90**, 076004 (2014). The minimal new particle content of their model of broken gauged flavor symmetry includes a scalar flavon $\varphi$, a gauge singlet under the SM; a heavy fermion $T$ partner of the top quark; and a neutral topphiilc gauge boson $Z_T$. An extra $U(1)$ gauge symmetry is a popular extension of the standard model (SM). In most cases, the $Z'$ boson is assumed to couple with the light quarks or charge leptons of the SM. While flavor-non-universal $Z'$ bosons have been considered, the $Z'$ is usually assumed to couple to at least one of the SM light fermions. On the other hand, the top quark, as the heaviest particle in the SM, might be the most sensitive particle to new physics. The topphilic $Z_T$ boson present in the model of broken flavor symmetry couples only to the top-quark at tree level. In a new paper now in partial draft form, Berger and Zhang are now investigating neutral topphilic gauge boson $Z_T$ production at the LHC by tagging SM top quarks at large $p_T$, an interestingly knotty problem in its own right. They aim to post a paper to the archives before the end of the calendar year.

**Fragmentation Contributions to Quarkonium Photoproduction**

This work, carried out by Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee (Korea University) and U-Rae Kim (Korea University), was described in the previous quarterly report. During the current reporting period, a paper on this work (arXiv:1504.06019 [hep-ph]) was accepted for publication in Physical Review D.

**Fragmentation Contributions to Prompt , $\chi_c$, and $\psi(2S)$ Production**

This work, carried out by Geoff Bodwin and Hee Sok Chung, in collaboration with Jungil Lee (Korea University), U-Rae Kim (Korea University), Kuang-Ta Chao (Peking University), and Yan-Qing Ma (Maryland University, Peking University), was described in detail in the first quarterly report of FY15. It extends an earlier analysis of leading-power fragmentation contributions to $J/\psi$ hadroproduction to the cases of $\chi_c$ and $\psi(2S)$ hadroproduction. The computation of $J/\psi$ rates includes contributions from feeddown

from the $\chi_c$ and $\psi(2S)$ states. Good fits to the Tevatron and LHC cross section data were obtained. The NRQCD long-distance matrix elements (LDMEs) that were obtained from these fits have been used to make predictions for the prompt $J/\psi$, $\chi_c$, and $\psi(2S)$ polarizations. These predictions are in good agreement with the LHC data. During the last quarter, a detailed paper describing these results was written and submitted to the arXiv (arXiv:1509.07904) and to Physical Review D.

**Precise Predictions for $H \to V\,\gamma$**

This work, carried out by Geoff Bodwin, Hee Sok Chung, Jungil Lee (Korea University), and June-Haak Ee (Korea University), was described in detail in the previous quarterly report. During the last quarter, novel methods were devised to achieve a numerically accurate resummation of large logarithms of $p_T^2/m_Q^2$ in the quarkonium light-cone distribution amplitudes through next-to-leading logarithmic (NLL) accuracy. It is expected that this work will be completed during the next quarter.

***W*-boson production in association with a jet at next-to-next-to-leading order in perturbative QCD**

In arXiv:1504.02131, Boughezal and Petriello, in collaboration with the PhD student Chris Focke, presented the complete calculation of W-boson production in association with a jet in hadronic collisions through next-to-next-to-leading order in perturbative QCD. To cancel infrared divergences they introduced a new subtraction method that exploits the fact that the N-jettiness event-shape variable fully captures the singularity structure of QCD amplitudes with final-state partons. This method holds for processes with an arbitrary number of jets, and is easily implemented into existing frameworks for higher-order calculations. They presented initial phenomenological results for W+jet production at the LHC. The NNLO corrections are small and lead to a significantly reduced theoretical error, opening the door to precision measurements in the W+jet channel at the LHC. This work was accepted for publication in Phys. Rev. Lett.

**$N$-jettiness soft function at next-to-next-to-leading order**

In arXiv:1504.02540, Boughezal and Petriello presented a general framework for the calculation of soft functions for $SCET_I$ observables through next-to-next-to-leading order (NNLO) in the strong coupling constant. As an example of their formalism they showed how it can be used to obtain the complete NNLO soft function for the N-jettiness event shape variable. They presented numerical results for two examples with phenomenological impact: the one-jettiness soft function for both electron-proton and proton-proton collisions. This work was accepted for publication in Phys. Rev. D.

**Higgs Boson Production in Association with a Jet at Next-to-Next-to-Leading Order**

In arXiv:1504.07922, Boughezal and Petriello presented precise predictions for Higgs boson production in association with a jet. Their calculation is accurate to next-to-next-to-leading order (NNLO) QCD in the Higgs Effective Field Theory and uses the sector-improved residue subtraction to remove the infra-red singularities. It includes all relevant phenomenological channels and describes fully-differential observables as well as total cross sections for the LHC. Their NNLO predictions reduced the unphysical scale dependence by more than a factor of two and enhanced the total rate by about twenty percent compared to NLO QCD predictions. Their results demonstrate for the first time satisfactory convergence of the perturbative series. This work was accepted for publication in Phys. Rev. Lett.

**Higgs boson production in association with a jet using jettiness subtraction**

In arXiv:1505.03893, Boughezal and Petriello in collaboration with the graduate student Chris Focke, used their recently proposed jettiness-subtraction scheme to provide the complete calculation of Higgs boson production in association with a jet in hadronic collisions through next-to-next-to-leading order in perturbative QCD. This method exploits the observation that the N-jettiness event-shape variable completely describes the singularity structure of QCD when final-state colored particles are present. Their result constitutes the

first complete NNLO computation for Higgs production with a final-state jet in hadronic collisions. It is in agreement with their recent computation of the gg and qg partonic initial states based on sector-improved residue subtraction. They presented phenomenological results for both fiducial cross sections and distributions at the LHC. This work was accepted for publication is Phys. Lett. B.

**Hadronic production of $W$ and $Z$ bosons at large transverse momentum**

The recent paper "Hadronic production of $W$ and $Z$ bosons at large transverse momentum", arXiv:1503.08836 [hep-ph], by 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) was published this quarter in Phys. Rev. D **91**, 113001 (2015). In this paper, the authors 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 $\alpha_s$. Using their modified factorization formalism, they are currently undertaking the calculation of inclusive top quark production at very large transverse momentum.

**Same-Sign Dilepton Excesses and Light Top Squarks**

Wagner has continued his analysis of anomalous events containing bottom quarks and leptons. Following his analysis with Argonne postdoc Peisi Huang of the edge in the dilepton invariant mass distribution observed by CMS, published recently in Phys. Rev. D91 (2015), 015014, Wagner has now concentrted on the excess in same-sign dilpeton production in association with bottom-quarks at the LHC. Indeed, Run 1 data of the Large Hadron Collider (LHC) contain excessive events in the same-sign dilepton channel with b-jets and missing transverse energy (MET), which were observed by five separate analyses from ATLAS and CMS collaborations. Wagner and Low, in collaboration with Argonne postdocs Huang and Ahmed, showed that these events could be explained by direct production of top squarks (stops) in supersymmetry. In particular, a right-handed

stop with a mass of 550 GeV decaying into 2 top-quarks, 2 W bosons, and MET could fit the observed excess without being constrained by other direct search limits from Run 1. We propose kinematic cuts at 13 TeV to enhance the stop signal, and estimate that stops could be discovered with 40 $fb^{-1}$ of integrated luminosity at Run 2 of the LHC, when considering only statistical uncertainties. This work was submitted to the arXiv in late July, arXiv:1507.01601, and it has been accepted for publication in Physical Revew D.

**Computation of the MSSM lightest CP-even Higgs Mass at Higher Loops.**

Two years ago, Wagner, in collaboration with his former student Gabriel Lee, and Patrick Draper (a former student and currently a postdoc at UCSB), studied analytically a resummation of the radiative corrections to the Higgs Mass in the MSSM up to four loop orders, and compared it with numerical results which provide a resummation to all orders in perturbation theory. The convergence of the resummed result at the four loop order is quite good and does not depart from the numerical results by more than 1 to 2 GeV even if the stops are as heavy as 30 TeV in mass. Large variations with respect to the two-loop order results, and some three-loop order ones were obtained at these high stop masses. In particular, Wagner and collaborators showed that there is a high degree of cancellation between the dominant and subdominant three and four loop contributions, what invalidates previous results in the literature in which only the dominant three loop effects were considered. This article was submitted to the arXiv at the end of 2013 and it is now published in Phys. Rev. D. **89** (2014) 5, 055023.

The above described computation of the Higgs mass was limited to the case in which the heavy MSSM Higgs bosons had masses comparable to the squark and gluino masses. There was great interest in the theoretical and experimental community in extending such results to the case in which the non-standard Higgs bosons could be light, with masses of the order of the Standard Model like Higgs mass. Recently Wagner, in collaboration with Gabriel Lee, performed such a computation. They used a generic two Higgs doublet model as an effective theory below the supersymmetry breaking scale and considered the coupled renormalization group evolution of the seven quartic couplings to obtain the low energy predictions for the Higgs masses and mixing angles. For intermediate values of the non-

standard Higgs bosons masses, they considered the transition from the two Higgs doublet model description to a Standard Model Higgs one at energy scales below the heavy Higgs masses, and recovered their previous results when the CP-odd Higgs mass equal the stop and sbottom masses. Wagner and Lee compared their results with previous ones in the literature and explained the origin of the differences between different existing results in the literature. Their work served as a basis for their contribution to an internal note of the LHC Higgs working group [1], and it was recently submitted to the arXiv:1508.00576 and it has been accepted for publication in Phys. Rev. D.

---

[1] https://cds.cern.ch/record/2039911/files/LHCHXSWG-2015-002.pdf