Final Technical Report

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Title: Heavy Quarks, QCD, and Effective Field Theory

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I. INTRODUCTION

The research supported by this OJI award is in the area of heavy quark and quarkonium production, especially the application Soft-Collinear Effective Theory (SCET) to the hadronic production of quarkonia. SCET [1–8] is an effective theory which allows one to derive factorization theorems and perform all order resummations for QCD processes. Factorization theorems allow one to separate the various scales entering a QCD process, and in particular, separate perturbative scales from nonperturbative scales. The perturbative physics can then be calculated using QCD perturbation theory. Universal functions with precise field theoretic definitions describe the nonperturbative physics. In addition, higher order perturbative QCD corrections that are enhanced by large logarithms can be resummed using the renormalization group equations of SCET. The goal of my OJI-supported research was to apply SCET to the physics of heavy quarks, heavy quarkonium, and similar particles.

The research supported by the OJI award led to seven publications [9–15] and two published conference proceedings [16, 17]. The main results of the research were:

• Factorization and Resummation for J/ψ Photoproduction

In Ref. [15], my collaborators and I used SCET to derive a factorization theorem and resummed cross section for the photoproduction of J/ψ near the kinematic endpoint. The resummed cross section resolves discrepancies between fixed-order Non-Relativistic QCD (NRQCD) calculations of J/ψ production via the color-octet mechanism and experimental data. This was also the first factorization theorem derived using SCET that exhibited a nonperturbative function that has since come to be known as a "beam function". Beam functions are ubiquitous in high energy collider cross sections with kinematic restrictions on the final state and have come under a great deal of investigation in recent years [18–25].

• Equivalence of Zero-bin and Soft Subtractions

Any approach to factorization attempts to cleanly separate energetic light-like collinear modes from soft modes. In perturbative calculations one runs the risk of double counting these modes because the kinematic regimes in which the two degrees of freedom are defined can overlap. In traditional QCD approaches to factorization, the double counting was removed by dividing certain matrix elements by vacuum matrix elements of soft wilson lines. In SCET, the double counting was implemented by a procedure called the "zero-bin" subtraction [26]. In Refs. [13, 14], A. Idilbi and I demonstrated the equivalence of these two approaches in a two-loop calculation of the quark form factor and a one-loop analysis of deep inelastic scattering in the limit $x \to 1$. We also completed a nonperturbative argument for their equivalence.

• Nonperturbative Charming Penguin Contributions (NPCP) to Isospin Asymmetries in B Meson Decays.

In Ref. [12], my collaborators and I performed an SCET analysis of isospin asymmetries in $B \to V\gamma$ where V is a vector meson. Anomalously large asymmetries were observed in $B \to \rho\gamma$ while the asymmetries were observed to be small in $B \to K^*\gamma$. We included $O(1/m_b)$ corrections and $O(\alpha_s v)$ NPCP effects and found the latter could account for the large isospin asymmetries. We also suggested experimental tests of this explanation for the asymmetries.

• **Color-Octet Scalar (COS) Bound States (Octetonium) at the LHC**

Many models of new physics contain heavy particles carrying color charge. Recently, models with heavy color-octet scalars (COS) have come under enhanced scrutiny because this is essentially the unique addition to the Standard Model scalar sector which is consistent with the principal of Minimal Flavor Violation [27]. In Ref. [11], C. Kim and I studied the production and decay of bound states of COS which we called octetonium. We argued the production of octectonium would give clean signals in hadron colliders, and therefore would be a promising way to search for COS as well as put more stringent constraints on their existence. My collaborators and I also used to SCET to derive factorization theorems and resummed cross sections for the production of single COS [9] as well as octetonium [10].

While I was funded by the OJI award, I was also supported by the Lattice and Effective Field Theory (L/EFT) group grant. I co-authored eight published eight papers [28–35], two conference proceedings [36, 37], and one unpublished preprint [38] that were not directly related to the subject of my OJI grant. These papers developed an effective theory for the $X(3872)$ as a molecular bound state of $D^0\bar{D}^{*0} + c.c.$ mesons [28, 29, 31], studied non-relativistic conformal field theories and their application to cold trapped atoms [30], developed effective theories with heavy quark-diquark symmetry for the study of doubly heavy baryons [32–34], explored the experimental consequences of a nonstandard Lorentz violating, $SIM(2)$ invariant neutrino mass [38], and studied the effects of twisted boundary conditions on the quark condensate in the epsilon regime of chiral perturbation theory [35]. A detailed description of these projects can be found in the L/EFT group continuation progress reports.

During funding period, the OJI award was used to support my summer salary and travel costs. It also was used to support two postdocs, Dr. Ahmad Idilbi and Dr. Chul Kim, and one graduate student, Dr. Jie Hu. Dr. Ahmad Idilbi is currently a postdoc at the University of Regensberg, Germany. Dr. Chul Kim is currently a faculty member at Seoul National University of Science and Technology, Seoul, Korea. Dr. Hu is a faculty member at Capitol Normal University in Beijing, China.

Another important professional activity I undertook during this project period was to serve as lead organizer for an international conference on "Heavy Quarkonium and Related Heavy Quark States", at the European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Trento, Italy, from August 11-31, 2006. For more information, see http://www.phy.duke.edu/ mehen/ECT/.

In the next section I give a more detailed description of the research projects completed during the period of my OJI award.

II. COMPLETED WORK

A. Photoproduction of J/ψ

S. Fleming (U. of Arizona), A. Leibovich (Pittsburgh U.), and T. Mehen (Duke U.)

Our current understanding of the production of heavy quarkonia is based on Non-Relativistic Quantum Chromodynamics (NRQCD) [39, 40]. This theory formulates the calculation of quarkonium production cross sections as a double expansion in α_s and v. The short-distance cross section for the production of a heavy quark-antiquark pair ($Q\bar{Q}$) in a particular color and spin configuration is calculable in perturbative QCD. The hadronization of that $Q\bar{Q}$ into the final state quarkonium is described by long-distance NRQCD matrix elements whose scaling in v can be estimated. Of crucial importance are the existence of color-octet mechanisms, in which the $Q\bar{Q}$ are produced in a color-octet state in the short-distance process. These mechanisms must be included if decay and production calculations are to be free of infrared divergences, and are also needed to account for the observed J/ψ production cross section at the Tevatron.

A long standing problem in quarkonium production has been the role of color-octet production mechanisms in the photoproduction of J/ψ. A crucial test of the NRQCD factorization theorem is verifying the universality of the color-octet matrix elements which enter into a variety of different J/ψ production processes. Early fixed order calculations [41] of J/ψ photoproduction revealed that inclusion of color-octet mechanisms gives an unwanted enhancement of the cross section near the kinematic endpoint. The kinematic endpoint is defined by $z \to 1$, where $z = E/E_{\rm max}$ where E is the J/ψ energy and $E_{\rm max}$ is the maximum possible energy. The fixed order calculation of Ref. [41] suggests a glaring failure of the NRQCD factorization formalism for J/ψ photoproduction.

In Ref. [15], we use NRQCD and SCET to derive a factorization theorem and resummed cross section for J/ψ photoproduction in the $z \to 1$ limit. This calculation simultaneously resums large logarithms in perturbation theory as well as effects that are included in a non-perturbative distribution function called a shape function. An important point of our paper is that while resummation of either perturbative or nonperturbative corrections leads to a softer J/ψ spectrum in the limit $z \to 1$, the effect of the two combined dramatically suppresses the cross section in the $z \to 1$ region. Our results are compatible with experimental data.

An important result of Ref. [15] is that the NRQCD color-octet matrix elements (COME) extracted in that paper were smaller than those extracted from a LO analysis of J/ψ production at the Tevatron by almost an order of magnitude. Later analysis of Tevatron data using higher order calculations of J/ψ production yielded values of COME that were closer to those estimated in Ref. [15].

Another important result of the photoproduction paper was the discovery of a new non-perturbative function called a beam function. The factorization theorem of Ref. [15] consists of a hard matching coefficient, a soft function that contains gluons that have small energy in the J/ψ rest frame, and a non-perturbative function, called a jet function in Ref. [15] but now commonly referred to as a beam function. The beam function can be further factorized into a matching coefficient that contains large logarithms at an intermediate scale, and a conventional parton distribution function (PDF). Later work in Ref. [25] demonstrates that these functions arise generically in collider cross sections whenever the final state is not completely inclusive. For example, if one considers the Drell-Yan process with a restriction that the final state to have no central jets, then the factorization theorem involves beam functions rather than conventional PDFs. In recent years, several papers have appeared [18–25] in which the beam functions play an important role.

B. Equivalence of Soft and Zero-Bin Subtractions

A. Idilbi and T. Mehen (Duke U.)

In factorization theorems, a QCD cross section is expressed as a convolution of matrix elements which are characterized by one of the scales appearing the process. For instance, our factorization theorem for $e^+e^- \to J/\psi + X$ near the endpoint [43] contains a hard coefficient, which describes the short distance production of a $c\bar{c}$ pair that captures the physics at the highest energy scale in the process ($\sqrt{s}$), a soft function, which describes the hadronization of the J/ψ and contains all partons which have low energy ($\sim \Lambda_{\rm QCD}$) in the J/ψ rest frame, and a jet function, which describes the jet of hard partons against which the J/ψ is recoiling in the endpoint region. The final state jet has invariant mass $\sim \sqrt{s}\sqrt{1-x} \gg \Lambda_{\rm QCD}$. The partons in the jet have momenta scaling as $(p^+, p^-, p^\perp) \sim \sqrt{s}(1, \lambda^2, \lambda)$ where $\lambda \sim \sqrt{1-x} \sim \sqrt{\Lambda_{\rm QCD}/\sqrt{s}}$, and are described by SCET collinear modes. The partons in the soft function have momenta scaling as $(p^+, p^-, p^\perp) \sim \Lambda_{\rm QCD}$ and are described by the soft modes in SCET.

When actually calculating the collinear matrix elements, one could in principle use hard cutoffs to separate the collinear modes from the soft modes in the evaluation of loop and phase space integrals. However, this would be very tedious to implement in practice because it makes the calculations much more complicated and requires the introduction of regulators which violate gauge invariance. In actual calculations of collinear matrix elements, one makes approximations relevant to the collinear regime and integrates over all of momentum space. This procedure then raises the issue of how one prevents double counting of the soft region in collinear and soft matrix elements.

Within the framework of SCET, double counting is avoided by performing "zero-bin" subtractions on collinear matrix elements [26]. In traditional approaches to QCD factorization, the double counting problem is dealt with by dividing or convolving collinear matrix elements with certain matrix elements of eikonal, or soft, Wilson lines. Lee and Sterman give an argument as to why the two methods are equivalent in Ref. [42].

In Ref. [14], we carefully compare the two approaches to avoiding double counting. We emphasize that there are certain restrictions on the choice of IR regulator used in calculating matrix elements in order for the equivalence to hold. We perform a one-loop calculation of the quark form factor to show that the two methods are equivalent if dimensional regularization (DR) is used to regulate both infrared (IR) and ultraviolet (UV) divergences. Our calculation is the first SCET matching calculation to be done in this way. The ability to perform matcing calculations using DR to regulate both IR and UV will greatly simplify future calculations in SCET. Previous analyses use other regulators which can raise difficulties. For example, regulating the IR by taking external particles off-shell spoils factorization properties of the theory and can make evaluation of loop integrals more difficult. We were also able to verify the equivalence for the case of the quark form factor in an abelian theory to two-loop order.

The paper also reanalyzed the factorization theorem for deeply inelastic scatttering (DIS) as $x \to 1$ (where x is the Bjorken variable). This process has been analyzed by many SCET collaborations and there is no consensus on the proper SCET derivation of the factorization theorem in this case [44–47]. In our work, we recover the classic factorization theorem of Sterman for this process. Moreover, our work uses DR to regulate all IR divergences in the evaluation of the soft, jet, and parton distribution functions. Therefore we can directly verify that the SCET factorization theorem reproduces the IR behavior of QCD at lowest non-trivial order (one-loop). Properly implementing the zero-bin subtractions in the jet function and parton distribution function is essential. Our analysis is the first SCET analysis of DIS in the endpoint region which handles this aspect of the calculation properly. Furthermore, the zero-bin subtractions are essential to obtain the correct anomalous dimension for the jet function, which is critical for obtaining the correct resummed formulae for the cross section. This analysis greatly clarifies the proper SCET analysis of endpoint factorization in DIS.

In Ref. [13] we complete the two-loop analysis of the heavy quark form factor in the nonabelian theory. We also completed the argument for the equivalence of the zero-bin subtraction and convolution with soft Wilson lines initiated by Lee and Sterman. Essentially, the argument of Lee and Sterman is that the zero-bin modes (the modes which overlap the soft and collinear regions) can be removed from the collinear Wilson line by a field redefinition similar to the field redefinition that decouples soft from collinear modes in SCET. The argument relied on an assumption about a certain factorization property of the collinear Wilson lines, which we were able to prove. This work this definitively established the equivalence of the two approaches to avoiding double counting.

C. Heavy Colored Particle Production at the LHC

A. Idilbi, C. Kim, and T. Mehen (Duke U.)

Many extensions of the Standard Model (SM) have scalar particles that also carry color. The couplings of colored scalars are highly constrained by flavor physics and generically they are expected to be quite heavy. However, if suitable restrictions on the Yukawa couplings to SM quarks are imposed, the bounds on the scalar masses can be surprisingly weak. If one imposes Minimal Flavor Violation (MFV) [48, 49], then the colored scalars must be electroweak doublets as well as color-octets [27]. As a consequence of MFV, the COS couple most strongly to the third generation of quarks, greatly weakening bounds on their masses. A completely model-independent bound on the mass of the COS, m_S, found in Ref. [50] is $m_S \geq 100$ GeV, where m_S is the COS mass. Clearly one would like to improve existing bounds on m_S and propose new means of detecting them at the LHC.

In Ref. [11], C. Kim and I proposed searching for bound states of COS which we called octetonium. These bound states are formed as resonances in gluon-gluon fusion and can decay to pairs of electroweak bosons, such as $\gamma\gamma$ or W^+W^-. Ref. [11] calculated tree level cross sections for the production and decay of octetonium and showed that for m_S in the range 100 - 500 GeV, the octetonium produce a resonant cross section in $pp \to \gamma\gamma$ that will be visible above the SM background for this process at the LHC. Thus, searches in this channel would either greatly improve existing bounds on COS or discover new physics.

Higher order QCD corrections from initial- and final-state radiation can greatly impact leading order predictions for the cross section. In Refs. [9, 10], SCET was used to derive factorization theorems for COS production and resum these corrections to all-orders. The factorization theorems and the resummed cross sections are similar to well known results for Drell-Yan and Higgs production, but there is an added complication due to the presence of colored particles in the final state. In Ref. [9], we considered single COS production and showed that resummation can enhance the cross section by a factor of 2-3, depending on the mass of the COS. In Ref. [10], we considered the pair production of COS. In this case there is an added complication near threshold due to the exchange of Coulomb gluons between the slowly moving COS pair. These corrections can be resummed to all orders using the QCD Coulomb Greens function and they are responsible for the octetonium resonance. This allowed us to provide resummed results for the total cross section for COS as well as for the resonant cross section for octetonium decaying to $\gamma\gamma$.

D. Nonperturbative Charming Penguin Contributions to Isospin Asymmetries in Radiative B Decays

C. Kim (Duke U.), A. Leibovich (Pittsburgh U.), and T. Mehen (Duke U.)

Recent experimental data on the radiative decays $B \to V\gamma$, where V is a light vector meson, find negligible isospin violation in $B \to K^*\gamma$ while isospin asymmetries in $B \to \rho\gamma$ are of order 20%, with large uncertainties. The purpose of Ref. [12] was to see if the anomalously large isospin violation in $B \to \rho\gamma$ can be accounted for in the Standard Model or required new physics. Using SCET, we calculate isospin asymmetries in these radiative B decays up to $O(1/m_b)$ and $O(v\alpha_s)$, where the $O(v\alpha_s)$ contributions come from nonperturbative charming penguins (NPCP). The NPCP comes from a loop diagram with a $c\bar{c}$ pair. Near the kinematic threshold, $2m_c$, the $c\bar{c}$ can interact strongly and nonperturbative effects not accounted for by a perturbative evaluation of the loop diagram can be important. These size of the effects can be estimated using NRQCD and they are found to be suppressed by only $O(v\alpha_s)$ relative to the leading loop diagram. Our fit to the experimental data indicates that NPCP can give large contributions which are crucial for accommodating the large difference in the observed isospin asymmetries. This explanation for the large isospin asymmetry can be tested in further experiments. If the isospin asymmetries are large and the NPCP is the source of these asymmetries, then we predict the CP asymmetries in $B \to \rho\gamma$ to be of order 10-30% and the right-handed polarized decay rates in $B \to V\gamma$ to be larger than expected.

III. GRADUATE STUDENTS

Graduate Student	Entered Program	Joined Group	Mentor	Graduated
Jie Hu	2002	2003	Mehen	2008

Jie Hu finished her thesis then 2008, then took a postdoctoral position at Hong Kong Science and Technology University. In 2012 she became a faculty member at Capital Normal University, Beijing, China.

CONFERENCE ORGANIZER

1. “Heavy Quarkonium and Related Heavy Quark States”, (lead organizer) European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Trento, Italy, 8/11/2007-8/31/2007.

INVITED TALKS

1. “Charmed Exotics and the X(3872)”, Quark Confinement and the Hadron Spectrum IX, Universidad Complutense de Madrid, Madrid, Spain, 9/3/2010.

2. “X(3872) Decays in X-EFT”, VII Latin American Symposium on Nuclear Physics and Applications, Santiago, Chile, 12/17/2009.

3. “Phenomenology of Color Octet Scalars at the LHC”, Perimeter Institute, Waterloo, Canada,10/23/09.

4. “Effective Field Theories and Multiple Scales in Quantum Physics”, Center for Theoretical and Mathematical Sciences Workshop, Duke University, Durham, NC, 9/11/2009.

5. “Hadronic Molecules”, 19th Int. Conference on Few-Body Physics, U. Bonn, Germany, 9/2/2009.

6. “X(3872) Decays to Quarkonia in X-EFT”, Physikzentrum, Bad Honneff, Germany 8/11/2009.

7. “XEFT and X(3872) Decays to Quarkonia”, Kavli Institute for Theoretical Physics, Beijing, China, 8/4/2009.

8. “Resummation in Heavy Particle Production”, Berkeley Workshop on Early LHC Physics, LBNL, Berkeley, CA, 5/7/09.

9. “Non-Relativistic Conformal Field Theory and Trapped Cold Atoms”, Yale University, New Haven, CN, 3/23/2009.

10. “Effective Field Theory and Strongly Interacting System: from Charmed Hadrons to Cold Atoms”, Department Colloquium, University of Arizona, Tucson, AZ, 2/29/2008.

11. “New Applications of Non-Relativistic EFT’s with Large Scattering Lengths: X(3872) and Trapped Cold Atoms”, University of Arizona, Tucson, AZ, 2/28/2008.

12. “New Application of Non-Relativistic EFT’s with Large Scattering Lengths: X(3872) and Trapped Cold Atoms”, Argonne National Lab, Chicago, IL, 3/11/2008.

13. “Non-Relativistic Conformal Field Theory and Trapped Cold Atoms”, North Carolina State University, Raleigh, NC, 12/7/2007.

14. “Effective Field Theory and Strongly Interacting System: from Charmed Hadrons to Cold Atoms”, Department Colloquium, UNC-Wilmington, Wilmington, NC, 11/30/2007.

15. “New Application of Non-Relativistic EFT’s with Large Scattering Lengths: X(3872) and Trapped Cold Atoms”, University of Maryland, College Park, MD, 10/24/2007.

16. “Pion Interactions in the $X(3872)$”, Massachusetts Institute of Technology, Boston, MA, 4/4/2007.

17. “On the Equivalence of Soft and Zero-Bin Subtractions”, Massachusetts Institute of Technology, Boston, MA, 2/14/2007.

18. “New Charmed Resonances and Effective Field Theory”, Massachusetts Institute of Technology, Boston, MA, 2/28/2007.

19. “New Charmed Resonances and Effective Field Theory”, Caltech, Pasadena, CA, 1/8/2007.

20. “Heavy Quark-Diquark Symmetry and χPT for Doubly heavy Baryons”, Yale University, New Haven, CN, 12/12/2006.

21. “QCD, Effective Field Theory, and Charmed Hadrons”, Physics Department Colloquium, Virginia Tech, Blacksburg, VA, 11/17/2006.

22. “Heavy Quark-Diquark Symmetry and χPT for Doubly Heavy Baryons”, Joint Meeting of the Pacific Region Particle Physics Communities, Honolulu, HI, 10/20/2006.

23. “Heavy Quark-Diquark Symmetry and χPT for Doubly heavy Baryons”, 5th International Workshop on Chiral Dynamics, Chapel Hill, NC, 9/21/2006.

PUBLICATIONS

1. “Pair Production of Color-Octet Scalars at the LHC ”, A. Idilbi, C. Kim and T. Mehen, Phys. Rev. D **82**, 075017 (2010).

2. “Factorization and Resummation for Single Color-Octet Scalar Production at the LHC”, A. Idilbi, C. Kim and T. Mehen, Phys. Rev. D **79**, 114016 (2009).

3. “Color-Octet Scalar Bound States at the LHC”, C. Kim and T. Mehen, Phys. Rev. D **79**, 035011 (2009).

4. “Nonperturbative Charming Penguin Contributions to Isospin Asymmetries in Radiative B Decays”, C. Kim, A. Leibovich, and T. Mehen, Phys. Rev. D **78**, 054024 (2008).

5. “Demonstration of the Equivalence of Soft and Zero-Bin Subtractions”, A. Idilbi and T. Mehen, Phys. Rev. D **76**, 094015 (2007).

6. “On the Equivalence of Soft and Zero-Bin Subtractions”, A. Idilbi and T. Mehen, Phys. Rev. D **75**, 114017 (2007).

7. “Resummation of Large Endpoint Corrections to Color-Octet J/ψ Photoproduction”, S. Fleming, A. Leibovich and T. Mehen, Phys. Rev. D **74**, 114004 (2006).

PUBLISHED PROCEEDINGS

1. “Octetonium at the LHC”, Chul Kim and Thomas Mehen, Proceedings of the 17th International Conference on Supersymmetry and the Unification of Fundamental Interactions (SUSY 09), Boston, MA, June 5-10, 2009.

2. “J/ψ photo-production at large Z in soft collinear effective theory”, S. Fleming, A. Leibovich, and T. Mehen, presented at Ringsberg Workshop on New Trends in HERA Physics 2005, Ringberg Castle, Tegernsee, Germany, Oct. 2-7, 2005.

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