1. Res. Assoc. Ilmo Sung

Dr. Sung's research is rooted in QCD and related gauge theories, with an emphasis on the infrared structure of perturbative amplitudes. It can be cast in two (overlapping) categories: i) developing factorization and resummation formalisms to understand properties in non-abelian gauge theories that appear in higher order calculations, and ii) studying how these interesting properties can be used directly or indirectly to discover physics beyond the standard model (BSM) in collider experiments.

A. *Applications of Perturbative QCD for Discovering Physics BSM*

(a) Color Flow for Extracting Properties in BSM

Dr. Sung's work in this category is based on the following connection between QCD and BSM at hadron colliders like the Tevatron and the LHC: QCD serves both to make predictions for signals of new physics and their backgrounds. This implies that applying QCD techniques for analyzing signals of new physics may provide new avenues to extract properties in physics beyond the standard model. Following this approach, in a paper [1] Dr. Sung developed a method to determine the color SU(3) gauge content of BSM resonances from new physics signals by investigating the pattern of soft gluon radiation into specified regions of a detector. This work illustrates the use of energy flow, treated by perturbative QCD and factorization, as a tool to analyze properties of new physics. This allowed the prediction of the distribution of soft gluon radiation into a rapidity region of a detector, reflecting the gauge content of heavy resonances. The results, in general, predict more radiation for singlet than for octet resonances. Especially, for spin-1 resonance production, the work showed a quite large difference in radiation into a rapidity gap region from color singlet and octet resonances. In a paper [2], this idea was extended to identify Higgs particles from QCD backgrounds where Higgs are color singlet while QCD jets carry colors, leading to a distinguished difference. Also several projects related to color flow and substructure of high p_T jets are work in progress.

(I. Sung)

(b) Substructure of High p_T Jets

The above work is focused on the role of soft gluon radiation. In Refs. [2–4], we used the collinear enhancement in perturbative QCD amplitudes to distinguish products of highly-boosted massive particle decay from QCD jets whose collinear structure is described by a factorized jet function. At the LHC, events with highly-boosted massive particles such as top, W, Z and Higgs may be a key ingredient for the discovery of physics beyond the standard model. In many decay channels, these particles would be identified as high-p_T jets, and any such signal of definite mass must be disentangled from a large background of QCD jets. We showed that this background far exceeds such signals, and relying solely on jet mass as a way to reject QCD background from signal would probably not suffice in most cases. For the solution to this problem, we found that jets from QCD are characterized by different patterns of intrajet energy flow compared to highly-boosted heavy particle decays. Based on this observation, we introduced several event shapes that could be used to disentangle signals from backgrounds.

(L. Almeida (CEA), G. Perez, S. Lee (Weizmann), G. Sterman (YITP, Stony Brook), I. Sung)

B. *Developing Factorization and Resummation Formalisms in Non-Abelian Gauge Theories*

(a) Soft Anomalous Dimension Matrices

Understanding the higher-loop infrared structure of gauge theories caused great enthusiasm in recent years. Infrared poles in higher loop calculations are organized by anomalous dimension matrices for color mixing through soft gluon exchange. In papers [5, 6] with Mitov and Sterman, we studied the soft anomalous dimension matrix for massive external particles. We used an analysis in Euclidean space, showing that the contributions to these matrices from diagrams that link three massive Wilson lines do not vanish in general. This differs from the pattern found with massless external lines in Ref. [7], where the authors discovered that massless soft anomalous dimension matrices at two loops are proportional to their one-loop values. We, however, found that, at ninety degrees in the center of mass, the massive anomalous dimension matrix also restores the proportionality to their one-loop value.

In a paper [8], we provided a recursive diagrammatic prescription for the exponentiation of gauge theory amplitudes involving products of Wilson lines and loops. This construction generalizes the concept of webs, originally developed for eikonal form factors and cross sections with two eikonal lines, to general soft functions in QCD and related gauge theories. The arguments in this paper apply to arbitrary paths for the lines. This graphical exponentiation also has potential applications in the phenomenological treatment of cross sections. Because the underlying structure is fundamentally nonperturbative, webs have been used to organize the structure of power corrections due to soft radiation for Drell-Yan and related cross sections. The work in the massless soft anomalous dimension matrix for massless external lines at higher order is in preparation.

(A. Mitov (CERN), G. Sterman (YITP, Stony Brook) and I. Sung)

C. *Infrared Safe Observable in 3D Gauge Theory*

The classic analysis of Kinoshita and of Lee and Nauenberg showed that total transition probabilities remain finite in fully massless theories because the zero-mass limit does not violate unitarity in perturbation theory. Infrared safe quantities such as jet cross sections and energy correlation functions are generalizations of this analysis to less inclusive observables, and have been used successfully in QCD. To define an observable that is IR safe in massless super-renormalizable theories such as QED in $(2+1)$ dimensions or ϕ^3 theory in four dimensions, we need a detailed study of IR structures. Since these theories contain different IR structures from QCD, and which are more severe than in QCD, we may expect that new prescriptions may be necessary to get rid of IR sensitivity.

(I. Sung)

D. *New Approach to Flavor and Grand Unified Theory*

In a paper [9], we constructed an anomaly-free extension of the left-right symmetric model, where the maximal flavor group is gauged and anomaly cancellation is guaranteed by adding new vector-like fermion states. We addressed the question of the lowest allowed flavor symmetry scale consistent with data. Because of the mechanism recently pointed out by Grinstein et al., tree-level flavor changing neutral currents turn out to play a very weak constraining role. The same occurs, in this model, for electroweak precision observables. In the case where discrete parity symmetry is present at the TeV scale, this constraint implies lower bounds on the mass of vector-like fermions and flavor bosons of 5 and 10 TeV, respectively. However, these limits are weakened under the condition that only $SU(2)_R \times U(1)_{B-L}$ is restored at the TeV scale, but not parity. For example, assuming the SU(2) gauge couplings in the ratio $g_R/g_L \approx 0.7$ allows the above limits to go down by half for both vector-like fermions and flavor bosons. This model provides a framework for accommodating neutrino masses and, in the parity symmetric case, provides a solution to the strong CP problem. The bound on the lepton flavor gauging scale is somewhat stronger because of Big Bang Nucleosynthesis constraints. We argue, however, that the applicability of these constraints depends on the mechanism at work for the generation of neutrino masses. In an on-going project, we have been studying a grand unification of this model based on the gauge group $SU(5)_L \times SU(5)_R$ where the gauge flavor symmetry reduces to only a vector $SU(3)_H$ due to anomaly cancellation.

D. Guadagnoli (Orsay, LPT), R. Mohapatra (Maryland) and I. Sung)

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[1] I. Sung, Phys. Rev. D **80**, 094020 (2009) [arXiv:0908.3688 [hep-ph]].
[2] L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung, Phys. Rev. **D82**, 054034 (2010). [arXiv:1006.2035 [hep-ph]].
[3] L. G. Almeida, S. J. Lee, G. Perez, G. Sterman, I. Sung and J. Virzi, Phys. Rev. D **79**, 074017 (2009) [arXiv:0807.0234 [hep-ph]].
[4] L. G. Almeida, S. J. Lee, G. Perez, I. Sung and J. Virzi, Phys. Rev. D **79**, 074012 (2009) [arXiv:0810.0934 [hep-ph]].
[5] A. Mitov, G. Sterman and I. Sung, Phys. Rev. D **79**, 094015 (2009) [arXiv:0903.3241 [hep-ph]].
[6] A. Mitov, G. F. Sterman, I. Sung, Phys. Rev. **D82**, 034020 (2010). [arXiv:1005.4646 [hep-ph]].
[7] S. M. Aybat, L. J. Dixon and G. Sterman, Phys. Rev. Lett. **97**, 072001 (2006) [arXiv:hep-ph/0606254]; S. M. Aybat, L. J. Dixon and G. Sterman, Phys. Rev. D **74**, 074004 (2006) [arXiv:hep-ph/0607309].
[8] A. Mitov, G. Sterman, I. Sung, Phys. Rev. **D82**, 096010 (2010). [arXiv:1008.0099 [hep-ph]].
[9] D. Guadagnoli, R. N. Mohapatra, I. Sung, JHEP **1104**, 093 (2011). [arXiv:1103.4170 [hep-ph]].