Research Statement

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Research Experience

My main field of research has been focused on nonrelativistic effective field theories. It involves two fronts: nonrelativistic EFTs for atomic systems and nonrelativistic QCD (NRQCD) factorization. For atomic systems, we treat the atomic system with nonrelativistic EFT. We then examine the asymptotic behavior of the wave-functions near origin with operator product expansion (OPE) [1–3]. I also studied the NRQCD factorization of fully-heavy tetraquark production: we factorized the fragmentation function of fully-heavy tetraquark production via the NRQCD factorization approach, derived the short-distance coefficients (SDCs) for it, and obtained phenomenological results with diquark and tetraquark wave-functions at the origin [4]. Apart from these EFT-related works, I also participated in the study on meson-meson scattering in the context of 't Hooft model, a model based on the large-N_c limit of 1+1-dimensional QCD [5].

Atomic wave-functions near origin

Our motivation originated from the fact that the wave-functions of relativistic wave equations (i.e. Klein-Gordon equation or Dirac equation) diverge at the origin. Intuitively, as wave-functions approaching the origin, it would probe the short distance behavior of the system that was never the intent of the corresponding wave equation. It is our goal to utilize nonrelativistic EFTs and OPE to study this near-origin asymptotic behavior of wave-functions.

To describe the atom in a field-theoretical way, we adopt a natural combination of EFTs in this case: we use nonrelativistic QED (NRQED) to describe electrons, and nucleus with a heavy nucleus effective theory (HNET) to describe the nucleus. HNET takes the idea of heavy quark effective theory (HQET), except that the basic degree-of-freedom for HNET is the nucleus, not heavy quarks. Despite the terminology, HNET is exactly the same as HQET at the leading order in mass. This form of EFT for atoms has been proposed for decades. However, unlike previous studies, we will not go further into pNRQED, as what we are probing is the physics near the hard scale of the EFT, and it is much natural to discuss OPE involving fields than nonlocal potential.

The central idea is to employ OPE to separate the short-distance behavior where the divergence happens from the long-distance one. As we know, the atomic wave-function, in terms of fields, is the matrix element of nonlocal electron fields and nucleus field, sandwiched by vacuum and the atom state. We take the nonlocal composite field operators of electrons and nucleus and expand it into products of SDCs and local operators with OPE. It comes as a surprise to us that if we ignore relativistic corrections (thus only taking leading order from NRQED), the SDC at order-α reproduces the renown Kato's cusp relation in atomic physics [1]. Considering the leading relativistic corrections, the SDC at order-α^2 matches the logarithmic divergence of the wave-function [2, 3]. Furthermore, we resumed all leading logarithms with the renormalization group equation, and the result agrees with what comes out of the wave-function.

NRQCD factorization for fully-heavy tetraquark

Very recently, a fully-charmed tetraquark candidate, namely the X(6900), was discovered at LHCb. In light of this discovery, we decided to tread upon the production mechanism of fully-heavy tetraquark with NRQCD factorization. Although studies on multiquark states have been actively engaging in recent decades, there's rarely any development regarding the production mechanism of fully-heavy tetraquarks. The main obstacle is the nonperturbative nature of tetraquarks, especially for inclusive production processes. However, for fully-heavy systems, the effect of light quarks and gluons popping out of the vacuum is highly suppressed by the heavy quark masses. Therefore, it is reasonable to claim the leading Fock state to be only composed of four valence quarks. The heavy quark masses also allow clear scale separation for NRQCD factorization to work.

For tetraquark inclusive production at LHC, the cross section can be factorized into the convolution of parton distribution functions (PDFs), partonic cross section and fragmentation function (FF). The leading contribution comes from the partonic process $gg \to gg$. Then, one of the produced gluons would fragment into a tetraquark via gluon FF. As we already have the PDFs and partonic cross section, we are left with the FF undetermined. Similar to quarkonium production, we assume the FF can be further factorized into the product of SDCs and NRQCD long-distance matrix elements (LDMEs). The NRQCD operators forming the LDMEs are determined with assumptions on the quantum numbers of the final state tetraquark. However, there was not much information about X(6900) other than its mass and the fact that it arose from di-J/ψ spectrum. The latter dictates its C-parity to be even. For the sake of simplicity, we only discuss S-wave tetraquarks, which means there is no orbital motion between any of the quarks/anti-quarks at all. We constructed all leading order NRQCD local operators that are allowed by these conditions. With heavy quarks, vacuum saturation approximation is also applied, which limits the inclusive final states to be only a single gluon. We then matched the SDCs with free four-quark states. The factorization formula is now complete, and to obtain the cross section, we need the value of the LDMEs from lattice QCD.

As an attempt to the value of the production cross section, however, we used diquark and tetraquark wave-functions at the origin to obtain the value of the LDMEs. Furthermore, we also dropped the $\mathbf{6} \otimes \bar{\mathbf{6}}$ component of the tetraquark. As a result, we obtained the p_T distributions of the inclusive fully-heavy tetraquark production. We also tried to obtain the total cross sections and event numbers at HL-LHC. However, due to the limitation of our factorization, we can not approach the small p_T region, which contributes to most parts of the total cross section.

Meson-meson scattering in 1+1 dimension

The notorious nonperturbative nature of QCD in 3+1 dimension has been a major roadblock for decades. While there are some nonperturbative methods on the market, such as lattice QCD, QCD sum rules and large-N_c expansion, they all have their limitations. Even with lattice QCD, the most reliable nonperturbative method, subjects like light-cone distributions or finite temperature QFT are still mostly out of reach. In 1+1 dimension, however, the theory is much simpler to solve. There is neither gluon degree-of-freedom nor spin, angular momentum or transverse momentum in 1+1 dimension. As proposed by 't Hooft in 1973, in 1+1-dimensional QCD, the meson wave-function can be obtained by applying large-N_c expansion in light-cone gauge. In 1+1 dimension, the effect of gluon presents as a static potential. As a result, there are rigorously only planar diagrams, thus the so-called "rainbow approximation" is exact. One can solve the Dyson-Schwinger equation to obtain the dressed quark propagator, then solve the Bethe-Salpeter equation for $q\bar{q}$ pair to obtain the mass eigenvalues and wave-functions of the mesons. The latter equation is exactly the celebrated 't Hooft equation.

Having the wave-functions of the mesons opens up lots of opportunities to investigate the nonperturbative properties of QCD. Some tried to search for indications of tetraquarks in the meson-meson scattering amplitudes. Among those, Batiz et al. claimed to have found Breit-Wigner-like line shape in the amplitudes. The goal of our work is to examine such a conclusion.

In order to obtain the meson-meson scattering amplitudes, we can again use the Bethe-Salpeter equation to derive the vertex function between meson and $q\bar{q}$ pair. Then it is straightforward to get the scattering amplitudes. It is worth noting that Batiz et al. failed to distinguish the outgoing and incoming quark for the meson vertex, and they missed the gluon-exchanging diagrams. We eventually calculated the scattering amplitudes numerically, and we found no evidence of tetraquark or Breit-Wigner-like structure. We concluded that the structure indicating the presence of tetraquarks can not be found at leading order of large-N_c expansion, and the near-threshold enhancements we observed in our numerical results are merely kinematic effects.

Future Plans

During my postdoctoral period, I would like to

References

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