QCD Effects in High Energy Processes

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In this talk, some important QCD effects in Higgs physics, supersymmetry and top physics, as well as the factorization and resummation techniques in QCD are reviewed.

Keywords: QCD; Higgs; supersymmetry; top; factorization and resummation.

1. QCD effects in Higgs physics

The Higgs boson is essential in the Standard Model (SM) for explaining the electroweak symmetry breaking and the origin of the mass of the fermions. Beyond the SM, we may also have different variations of the SM Higgs boson, viz. Two Higgs doublet model (2HDM)\(^1\), 3HDM\(^2\), triplet\(^3\), SUSY\(^4\), little\(^5\) and fat\(^6\) Higgs bosons etc. However none of them have yet been observed. Thus the search for Higgs bosons becomes a primary goal of next generation colliders.

Before the Higgs is found, we may ask some questions like: (1) Is there any fundamental scalar field in nature? (2) What kind of Higgs might be found? All these questions may be answered at the next generation colliders. And QCD effects play an important role in answering the above questions because they will affect Higgs production and decay at next generation colliders.

1.1. The SM Higgs at Hadron Colliders

\( gg \rightarrow H \): Gluon fusion is the dominant production mode for the Higgs boson at hadron colliders. The NLO QCD corrections were calculated years ago and found to be large\(^7\). Since then the NNLO QCD corrections were done, which contains: (1) Two-loop corrections to the H-g-g vertex in Ref.\(^8\), (2) Soft-plus-virtual gluon corrections in Ref.\(^9\), and (3) Two-to-three body processes contributions in Ref.\(^10\).

The calculations show that the NNLO corrections significantly reduced the renormalization and factorization scales dependence.

For this production channel, for \( 100\text{GeV} \leq m_H \leq 140\text{GeV} \), \( H \rightarrow \gamma\gamma \) is the most important decay mode for searching for the Higgs boson. To thoroughly analyze the signal and the background, \( gg \rightarrow \gamma\gamma \) has been calculated at the NLO level in Ref.\(^11\).

Also, the effect of the jet veto on \( gg \rightarrow H \) has been studied at the NLO level in Ref.\(^12\). The jet veto reduces both the total cross section and the size of the higher-order QCD corrections.
Although rates for these production channels are small, the final states have distinctive signatures. At the LHC, the \( t\bar{t}H \) channel can complement \( WH \) associated production for \( m_H \leq 130 \text{GeV} \). Beyond the SM, the \( b\bar{b}H \) channel may be more important since the \( b\bar{b}H \) coupling can be enhanced, for example, in the MSSM the vertex can be enhanced by \( \tan \beta \).

The NLO QCD corrections to \( pp(\bar{p}) \rightarrow t\bar{t}H \) have been calculated in Ref. 13, which increase the LO total cross sections and significantly reduce the scale dependence of the LO results. The NLO QCD corrections to \( pp(\bar{p}) \rightarrow b\bar{b}H \) were also done in Ref. 14 and the partly SUSY-QCD corrections to \( pp(\bar{p}) \rightarrow b\bar{b}H \) were examined in Ref. 17 in the special case for convenience that the relevant sparticles are heavy, well above TeV scale.

Due to the ability to tag the b quark in the final state, the processes of the Higgs boson production associated with b quark(s) are promising. So these production channels may be more important since the \( bbH \) coupling can be enhanced beyond the SM. For inclusive Higgs production, the LO process is \( b\bar{b} \rightarrow H \). And in its NLO QCD calculations, due to the smallness of the b quark mass, large logarithms \( \log(Q^2/m_b^2) \) might arise from phase space integration in the four-flavor-number scheme and the convergence of the perturbative expansion can be improved by summing the collinear logarithms to all orders by the introduction of evolved b quark parton distributions with an appropriate factorization scale, as analyzed in Ref. 18: Since in the collinear limit \( d\sigma/dt \sim 1/t \), one can observe that the collinear limit here is about \( \sqrt{-t} < m_H/4 \). Thus the collinear logarithm that is generated at NLO is therefore approximately \( \ln(m_h/4\mu_F) \), rather than \( \ln(m_h/\mu_F) \), leading to the fact that the factorization scale for the \( 1/\ln(m_h/m_b) \) correction should be chosen to be of order \( \mu_F \approx m_h/4 \) in order to sum the collinear logarithm into the parton distribution function and thus the results obtained in the bottom parton picture can be in good agreement with those for the gluon-initiated production process. However there are still many open questions concerning the introducing of bottom densities, and due to the limited space, for more discussions please see for example Ref. 19.

Moreover, if at least one high-\( p_T \) b quark is required to be observed, the leading partonic process is \( gb \rightarrow bH \). The relevant NLO QCD calculations were done in Ref. 18,21 and the SUSY-QCD corrections in Ref. 22.

The weak-boson fusion process is expected to provide crucial information on Higgs boson couplings at the LHC. The NLO QCD calculations have been done23. Since then the QCD corrections to jet correlations in this channel have been done24 and are shown to be modest, of the order of from 5% to 10% in most cases, but reaching 30% occasionally, and the scale uncertainties range from the order of 5% or less for distributions to below 2% for the Higgs boson cross section in typical weak-boson fusion search regions.
1.2. The SM Higgs at Linear Colliders

\( e^+e^- \rightarrow t\bar{t}H \): Although the production rate is small, it has a distinctive signature and can potentially be used to measure the relevant Yukawa coupling. The NLO QCD corrections were done in Ref.\(^\text{25}\) and found to enhance the total cross sections by a factor of roughly 1.5 at \( \sqrt{s} = 500\text{GeV} \).

\( \gamma\gamma \rightarrow t\bar{t}H \): An \( e^+e^- \) LC can also be designed to operate as a \( \gamma\gamma \) collider. Thus \( e^+e^- \rightarrow \gamma\gamma \rightarrow t\bar{t}H \) offers another approach to probe the Higgs boson and the relevant Yukawa coupling in addition to \( e^+e^- \rightarrow t\bar{t}H \). The NLO QCD corrections were done in Ref.\(^\text{26}\) and can reach 34.8% at \( \sqrt{s} = 800\text{GeV} \).

1.3. The MSSM Higgs at Hadron Colliders

The Higgs sector of MSSM, which is the special case of the 2HDM, is of particular theoretical interest, and contains five physical Higgs bosons: two neutral CP-even bosons \( h^0 \) and \( H^0 \), one neutral CP-odd boson \( A^0 \), and two charged bosons \( H^\pm \). The \( h^0 \) is the lightest, with a mass \( m_{h^0} \leq 140 \text{ GeV} \) when including the radiative corrections\(^\text{27}\) and is a SM-like Higgs boson especially in the decoupling region \((m_{A^0} \gg m_Z^0)\). The other four are non-SM-like, and the discovery of them may give the direct evidence of MSSM. It has been shown in Ref.\(^\text{28,29}\) that the \( h^0 \) boson of MSSM cannot escape detection at the CERN LHC and that more than one neutral Higgs particle can be found in a large area of the supersymmetry (SUSY) parameter space.

Many higher order QCD corrections to Higgs bosons production have been performed, for example, \( pp \rightarrow (\text{pseudo})\text{scalar Higgs bosons at NNLO in Ref.}\(^\text{31}\)\). Note that for large values of \( \tan\beta \) the bottom loop contribution to \( pp \rightarrow \text{pseudo-scalar Higgs bosons} \) is dominant. It is necessary to point out that the NNLO corrections to this process have been obtained only in the infinite top mass limit and are not applicable for large values of \( \tan\beta \) so that one has to rely on the full NLO results of the last 2 papers of Ref.\(^\text{17}\). The effects of SUSY-QCD in hadronic Higgs production at NNLO in Ref.\(^\text{22}\) and the NLO QCD corrections to Higgs plus 1 or 2 high \( P_T \) final bottom quark(s) production in Ref.\(^\text{15,19}\) and Ref.\(^\text{14,15,33}\) respectively.

For charged Higgs production, the NLO QCD and SUSY-QCD corrections to \( gb \rightarrow tH^- \), which is the primary charged Higgs boson production channel at the LHC, were done in Ref.\(^\text{37}\) and Ref.\(^\text{35}\) respectively. The size of the QCD corrections are quite large and can reach 80%. The NLO QCD and SUSY-QCD corrections to \( bb \rightarrow W^+H^- \) were done in Ref.\(^\text{40}\) and Ref.\(^\text{37}\) respectively. The ones to \( bb \rightarrow H^+H^- \) were done in Ref.\(^\text{38}\).

In Ref.\(^\text{39}\) and Ref.\(^\text{40}\), the QCD and SUSY-QCD effects on neutral Higgs bosons pair production through \( q\bar{q} \) annihilation, \( gg \) fusion and \( bb \) annihilation were calculated, respectively. In Ref.\(^\text{41}\) the NLO QCD and SUSY-QCD corrections to \( A^0Z^0 \) associated production were calculated. For a cross check, both the dimensional regularization scheme and the dimensional reduction scheme were used to organize the calculations which yielded the same NLO rates in Ref.\(^\text{40,41}\) The NLO
corrections can either enhance or reduce the total cross sections, but it generally significantly reduces the dependence of the total cross sections on the renormalization/factorization scale. The uncertainty of the total cross sections, due to the parton distribution function uncertainties, was also studied in Ref. \cite{40, 41}, and it was found that the NLO QCD corrections do not reduce the PDF uncertainty.

### 1.4. The MSSM Higgs at Linear Colliders

At the linear colliders, the NLO (SUSY)QCD corrections to $e^+e^- \rightarrow t\bar{t}H(b\bar{b})$ were done in Ref. \cite{42}. The QCD corrections significantly increase the total cross sections for $\sqrt{s} = 500$GeV. The SUSY QCD effects generally are very moderate (say 10%) and under control. The NLO QCD corrections to $e^+e^- \rightarrow tbH^-$ were done in Ref. \cite{43}. After resumming the large logarithmic corrections that arise in the on-mass-shell scheme of quark mass renormalization by adopting the modified minimal-subtraction scheme, the convergence behavior of the perturbative expansion is improved. The NLO QCD corrections lead to a significant reduction of the theoretical uncertainties due to scheme and scale dependences.

### 2. QCD effects in SUSY

As stated above, the MSSM is one of the most interesting new physics models beyond the SM. It was devised to solve the hierarchy problem and has the celebrated feature of gauge coupling unification, and can naturally provide a candidate for dark matter. The direct search for SUSY particles is one of the primary tasks of the current and future colliders. As in the case of Higgs searches, QCD effects are essential for the theoretical evaluation of the production cross sections and decay rates. They could also be important for distinguishing SUSY breaking scenarios. In the following we review the works on the QCD corrections to the production cross sections of SUSY particles at hadron colliders and linear colliders.

For QCD corrections, the most difficult cases for two particle final states are colored particle pair production at hadron colliders. These have been done at next-to-leading order for squark pair production, gluino pair production, and squark-gluino production \cite{44}. The top squark pair production was calculated in Ref. \cite{45}. For processes involving one colored final state, the associated production of gluinos and gauginos was calculated with QCD corrections and SUSY QCD corrections \cite{46, 47}. The associated production of top squark and chargino was accomplished \cite{48} with both QCD and SUSY QCD corrections. For the colorless final states, the NLO corrections to slepton pair production and gaugino pair production are presented in Ref. \cite{49}. In R-parity violating supersymmetric models, SUSY particles need not be produced in pairs. Single top squark production was considered \cite{50}. The production of a top squark and a lepton was calculated in Ref. \cite{51}. The production of a single slepton was calculated in Ref. \cite{52, 53}.

In general, the QCD corrections enhance the total cross sections by 10-90%. More importantly, the higher order corrections reduce the renormalization and fac-
torization scale dependence by a factor of 3 to 4, which render the results more stable and reliable. The remaining scale dependence, typically at a level of 10-15%, serves as an estimate of the theoretical uncertainty.

At linear colliders, the situation is much simpler, since now only colored final states receive QCD corrections. In fact, since the gluinos do not participate in electroweak interactions, the only possible two-body final state at tree level is squark pair production. The QCD and SUSY QCD corrections to this process at e+e− colliders are presented in Ref. 55. The complementary results in photon-photon collision are calculated in Ref. 56. For three-body final states, the QCD and SUSY QCD corrections to squark-squark-gluon production and quark-squark-gluino production have been described in Ref. 57. In general, at linear colliders, the QCD corrections are positive and dominant over other ones at low colliding energy (e.g. 500-1000 GeV).

3. QCD effects in top physics

3.1. Top quark decay and Single top production

The one-loop QCD corrections to top quark decay were calculated years ago.58 There were some recent works studying the QCD effects on the top quark decay, for example, two loop calculation techniques,59 polarized top quark decay,60 decay distributions,61 and SUSY-QCD effects in top quark rare decay within a most general framework.62 However, we only discuss the top quark production in the following and mostly focus on recent developments. We first review the SM processes of single top production. At hadron colliders, single top quarks can be produced within the SM in three different channels, and the corresponding NLO QCD effects have been completed: the s-channel W∗ production,63 the t-channel W-exchange mode,64 and through tW− production.65 Later, a new NLO calculation for fully differential single-top-quark final states also were obtained.66 This calculation is performed using phase space slicing and dipole subtraction methods, and the dipole subtraction method calculation retains the full spin dependence of the final state particles. Recently, there have been several works combining the decay effects on the production processes.67 In order to confront theory with experimental data, where kinematical cuts are necessary in order to detect a signal, it is crucial to accurately model event topologies of single top quark events. Ref.67 calculated the differential cross sections for on-shell single top quark production. The complete NLO calculations including both the single top quark production and decay have been done. In these calculations, the narrow width approximation was adopted in order to link top quark production with its consequent decay and various kinematic distributions are examined both with and without top quark decay at NLO.

Ref.67 calculated the NLO QCD effects on single top production at an eγ collider. Within new physics beyond the SM, some works studied single top FCNC production at ILC68 and HERA69, as well as hadron colliders (LHC).70 The results at the LHC can be as large as a few pb, and may supply a powerful probe...
for the details of the SUSY FCNC couplings. Moreover, the QCD corrections to
single top quark production induced by model-independent FCNC couplings have
been investigated by two groups. The NLO results increase the experimental
sensitivity to the anomalous couplings, and vastly reduce the dependence of the
total cross sections on the renormalization/factorization scale at the Tevatron Run
II, which leads to increased confidence in predictions based on these results..

3.2. Top Pair production

In the SM, QCD corrections to the total cross sections for top quark pair production
at the Tevatron and LHC are known very well. Since then authors obtained:
\( p_T \) and \( y \) spectra; double-differential spectra; resummation at LL level and NLL
level. Recent developments (include the soft-gluon corrections at NNLO) can be seen
from Ref. The state of art at present is: the soft NNLO corrections to the total
top quark cross section and top transverse momentum distributions in hadron-

hadron collisions with new soft NNNLL terms and some virtual terms, including all
soft-plus-virtual factorization and renormalization scale terms. It was found that
these new subleading corrections greatly diminish the dependence of the cross sec-
tion on the kinematics and on the factorization/renormalization scales.

During the past few years, spin correlations in top pair production have been
studied at various colliders:

1. Hadron colliders. The NLO QCD effects on the hadronic production of \( t\bar{t} \)
quarks in a general spin configuration have been computed and also the dilepton
angular correlation coefficients \( C \) that reflect the degree of correlation between the
t and \( \bar{t} \) spins. These results for the Tevatron show that the scale and in particular
the PDF uncertainties in the prediction of the dileptonic angular distribution must
be reduced before \( t\bar{t} \) spin correlations can be used in a meaningful way to search
for relatively small effects of new interactions that are, for example, not distin-
guished by violating parity or CP invariance. And the LHC may turn top quark
spin correlations into a precision tool for the analysis of \( t\bar{t} \) events.

2. Polarized photon colliders. A variety of spin observables have been cal-
culated for the process \( \gamma\gamma \rightarrow t\bar{t}X \) up to order \( \alpha^2\alpha_s \), especially the NLO QCD
contributions to the fully differential cross section with intermediate top quark pair
production at a photon collider.

Moreover, Ref. studied the NLO QCD effects in \( VV \rightarrow tt \) at the ILC. They
found that QCD corrections can be quite substantial, so that they need to be taken
into account when studying \( t\bar{t} \) production. Recently, a first paper on NLO QCD
corrections to \( gg \rightarrow t\bar{t}g \) became available. We also should mention the works on
the interference between production and decay at Linear Colliders.

SUSY-QCD effects on top quark production at \( e^+e^- \) and photon-photon colli-
ders were studied in Ref. and Ref. respectively. Strong supersymmetric quantum
effects on top quark production as well as supersymmetric QCD parity noncon-
servation in top quark pairs at the Tevatron were studied in Ref. 83. Ref. 84 studied the one-loop supersymmetric QCD corrections arising from squarks and gluino to top quark pair production by gg fusion at the LHC in the MSSM, and found that the corrections to the hadronic cross section amount to a few percent. $O(\alpha_s)$ QCD Corrections to spin correlations in $e^-e^+ \rightarrow t\bar{t}$ process at the NLC and SUSY-QCD at $e^+e^-$ colliders (including spin correlations) can be found in Ref. 85.

4. Factorization and Resummation

The QCD factorization theorems are essential for the perturbative calculations of physical observables in high energy processes involving hadrons. Historically, the development of the factorization theorems as well as the resummation techniques was based on the analysis of the conventional perturbative QCD Feynman diagrams. Recently, the soft-collinear effective theory (SCET) was proposed, which provides a natural framework to deal with the infrared and collinear structure of the QCD theory. The factorization theorems and the resummation formulas were re-derived in this framework.

4.1. The pQCD approach

The QCD resummation formalism was developed about two decades ago by Dokshitzer, Diakonov and Troian (DDT) in the double leading logarithm approximation (DLLA). In order to resum the sub-leading logarithms, transverse momentum conservation must be imposed. This was achieved by performing Fourier transform to impact parameter ($b$) space. Based on previous work, Collins, Soper and Sterman showed that all the large logarithms can be systematically resummed. Their results are often referred to as the CSS formalism. Besides the $b$-space formalism, it has been shown that some of the sub-leading logarithms can also be resummed directly in $q_T$ space (for transverse momentum distribution). Their results are consistent with the $b$-space results up to NNLL level.

After the invention of the resummation formalism, it has been applied to a large variety of physical processes, including $q_T$ resummation and/or threshold resummation for vector boson production, Higgs boson production and many other processes. The accuracy of the calculations have been considerably improved, partly because higher order terms are included, and partly because of the progress on the non-perturbative parametrization. We will only review the recent works here.

Most recently, Moch, Vermaseren and Vogt completed the calculation of the three loop splitting functions, which enables one to extract one of the third order coefficients for the resummation formula. Utilizing this result, two groups independently worked out the $\mathcal{N}^3LL$ threshold resummation for Drell-Yan process and Higgs boson production.

The progresses on the non-perturbative functions are also significant. Landry, Brock, Nadolsky and Yuan presented a global fit of the non-perturbative parameters based on their parametrization. They showed that all the available data is in
good agreement with the theoretical predictions, which is strong evidence for the universality of the non-perturbative function. Kulesza and Stirling\(^9\) investigated the form of the non-perturbative parametrization in both \(b\)-space and \(q_T\)-space, and discussed the theoretical errors in the resummed Higgs \(q_T\) distribution arising from the non-perturbative contribution. They proposed to use \(\Upsilon\) production data to study the non-perturbative contribution in processes with two gluons in the initial state. Qiu and Zhang\(^9\) proposed an extrapolation method using conditions of continuity, which Berger and Qiu\(^9\) used to present a NNLL prediction for the Higgs boson \(q_T\) distribution.

There are also improvements of the resummation formula in recent years. The original formula involves process-dependent form factors and coefficient factors. Catani, de Florian and Grazzini\(^9\) presented a new universal form, in which the process dependence is embodied in a single perturbative factor. Bozzi, Catani, de Florian and Grazzini gave a NNLL prediction for the Higgs boson production based on the above formula. Ji, Ma and Yuan\(^9\) proposed a factorization and resummation formalism in terms of the transverse momentum dependent parton distributions. Berge, Nadolsky, Olness and Yuan\(^9\) discussed the transverse momentum resummation with small-\(x\) effects taken into account.

The application of the transverse momentum resummation to other processes include: gauge boson pair production, single stop production, polarized \(W\) and \(Z\) production at RHIC, \(\Upsilon\) production\(^9\), and single slepton production\(^9\).

Given the formula for the transverse momentum resummation and the threshold resummation, one natural question is whether the two effects can be combined. This was achieved as the so-called joint resummation. The predictions have been worked out for Drell-Yan process, Higgs boson production as well as top quark pair production\(^9\).

### 4.2. SCET approach

SCET was proposed in Ref.\(^9\) as a systematic framework for the study of processes involving highly energetic quarks and gluons. In this section we review only a few key points of SCET and its application to hard processes.

SCET separates the contributions from different energy scales by introducing fields with well-defined momentum scaling. These modes must reproduce the IR behavior of the full theory of QCD. We make use of two theories: SCET\(_I\) and SCET\(_II\), defined in terms of a small scaling parameter \(\lambda\). The fields in SCET\(_I\) include: (1) collinear quarks \(\xi_n\) and gluons \(A_n\) with momenta \(p_c \sim Q(\lambda^2,1,\lambda)\); (2) usoft quarks \(q_us\) and gluons \(A_us\) with momenta \(p_us \sim Q(\lambda^2,\lambda^2,\lambda^2)\). In SCET\(_II\), the corresponding fields are: (1) collinear modes with momenta \(p_c \sim Q(\lambda^4,1,\lambda^2)\); (2) soft modes \(q_s, A_s\) with momenta \(p_s \sim Q(\lambda^2,\lambda^2,\lambda^2)\). Here and below we use the light-cone notation \(p = (n \cdot p, \bar{n} \cdot p, p_\perp)\), defined in terms of light-cone vectors \(n\) and \(\bar{n}\) satisfying \(n^2 = \bar{n}^2 = 0\) and \(n \cdot \bar{n} = 2\).

Through integrating out the hard \(\sim Q^2\) fluctuations from the full QCD, we get
SCET\textsubscript{I}, and by further integrating out the jets with $\sim Q^2\lambda^2$ fluctuations, SCET\textsubscript{II} can be obtained. This two-step matching can be represented by QCD $\rightarrow$ SCET\textsubscript{I} $\rightarrow$ SCET\textsubscript{II}.

The interactions between the SCET fields are described by the SCET Lagrangians. For the theory describing usoft and collinear fields, the Lagrangian can be written as\textsuperscript{99}

$$L_{\text{SCET}} = L_{\xi\xi} + L_{cg} + L_{q\xi}. $$

The Lagrangian can be expanded in $\lambda$. At leading order in $\lambda$, $L_{q\xi}$ does not contribute, and the collinear quark Lagrangian is

$$L_{\xi\xi} = \bar{\xi}n\left\{n\cdot iD_{us} + gn\cdot A_n + i\nabla_\perp e\frac{1}{n\cdot iD_e}i\nabla_\perp\right\}\frac{\bar{n}}{2}n\xi,$$

with $iD_{us}^\mu = i\partial^\mu + gA_{us}^\mu$. The explicit form of $L_{cg}$ can be found in Ref.\textsuperscript{100}.

Comparing with the full theory of QCD, an advantage of the SCET is the factorization of usoft and collinear degrees of freedom at leading order in $\lambda$. Since the usoft gluons couple to collinear quarks and gluons only through a term $n\cdot A_{us}$, its effects can be absorbed into a Wilson line $Y_n[n\cdot A_{us}]$ by a field redefinition:

$$\xi_n = Y_n[n\cdot A_{us}]\xi^{(0)}_n, \quad A_n^\mu = Y_n A_n^{(0)\mu}Y^\dagger_n,$$

$$Y_n[n\cdot A_{us}] \equiv \text{P exp}\left(i\int_{-\infty}^{x} ds n\cdot A_{us}(ns)\right).$$

The new collinear fields $\xi_n^{(0)}$ and $A_n^{(0)}$ do not couple to the usoft gluon field $A_{us}$, which now appears only through the Wilson line $Y[n\cdot A_{us}]$. This provides a convenient approach to SCET\textsubscript{II}\textsuperscript{101}.

The applications of SCET to the phenomenology of B decay have been discussed by many authors\textsuperscript{102}a. Here we only summarize its applications to the high energy hard processes. For these processes SCET naturally realizes the proof of factorization. The matching and running procedure automatically separates the process-dependent Wilson coefficients and universal quantities in the effective theory, and resums the large logarithms that may be invalid in the perturbative expansion using the renormalization group equation directly.

The first investigation was made in Ref.\textsuperscript{103}, where the factorization theorem for various hard processes are proved. Then the enhanced nonperturbative effects in Z decays as $T \rightarrow 1$ to hadrons was discussed in the framework of SCET\textsuperscript{104}, and Ref.\textsuperscript{105} discussed the resummation for the deep inelastic scattering as $x \rightarrow 1$. The author of Ref.\textsuperscript{106} performed the threshold resummation for Drell-Yan process as $z \rightarrow 1$ in SCET and the transverse momentum resummation for Drell-Yan process as $Q_T \rightarrow 0$ using SCET was given in Ref.\textsuperscript{107}.

\textsuperscript{a}For further details we refer to the talk of Bauer in this proceeding.
Furthermore, SCET provides a convenient method to classify and parameterize the factorizable and nonfactorizable terms beyond the leading order in $\lambda$. Therefore SCET is a good framework for discussing processes with soft and collinear particles, and its applications are still developing.

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