Factorization and resummation for jet processes

Dingyu Shao[1]

[1]Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

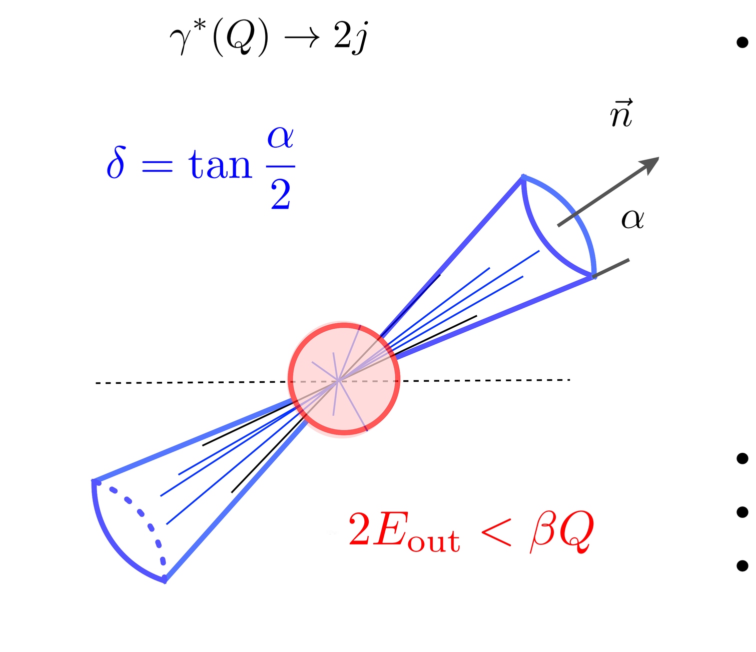
UNIVERSITÄT BERN

AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

Introduction

Jets not only display the behaviour of QCD over a wide range of energy scales, from hard colliding energy to the hadronization energy, but also contain important signatures of exotic physics, such as top quarks or particles beyond the SM. In particular, jet substructure observables are playing a central role in a large number of analyses at the LHC. Most of the theoretical discussion on these aspects has taken place in the context of Monte Carlo (MC) simulation studies. However, MC analysis is not always good enough, and it is difficult to extract the key characteristics of individual methods and reveal the relations between them. With this motivation, it is imperative to understand jet observables from the first principles QCD.

Sterman-Weinberg dijet cross section

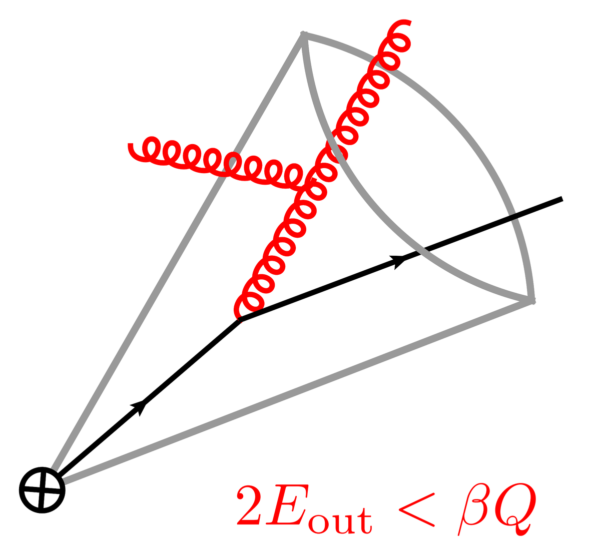


- Jet cross sections are the most important class of observables. Such cross section were introduced in a seminal paper by Sterman and Weinberg [1]

$$\frac{\sigma(\beta,\delta)}{\sigma_0} = 1 + \frac{\alpha_s C_F}{4\pi}\left(-16\ln\delta\ln\beta - 12\ln\delta + c_0\right)$$

- Infrared finite, but problems for small β, δ
- Large logarithms spoil perturbative expansion
- Scale choice: Q? Qβ? Qβδ? Qδ?

Non-global logarithms in jet observables



Jet observables involve non-global logarithms(NGLs) because they are insensitive to emissions inside the cone.

$$\alpha_s^2 C_F C_A \pi^2 \ln^2\beta$$

These types of logarithm can not be described in the usual resummation formula.

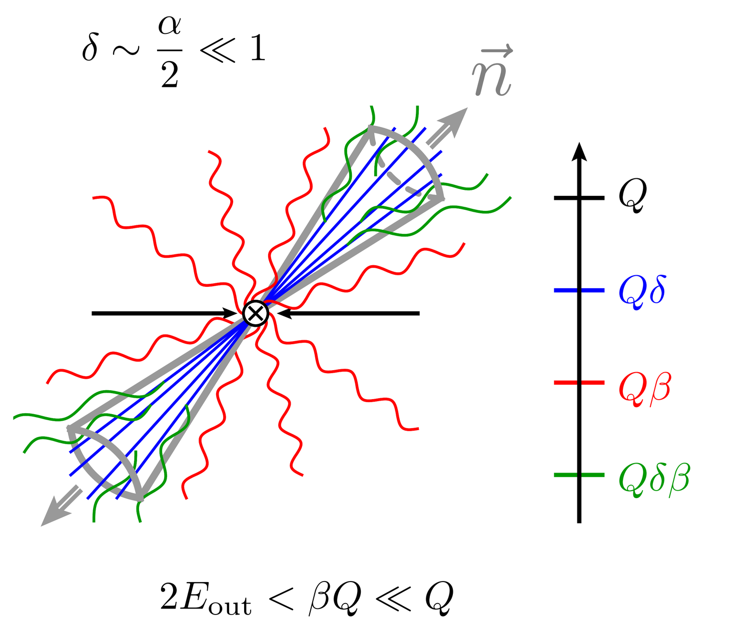
Leading Logarithms(LL) resummation:

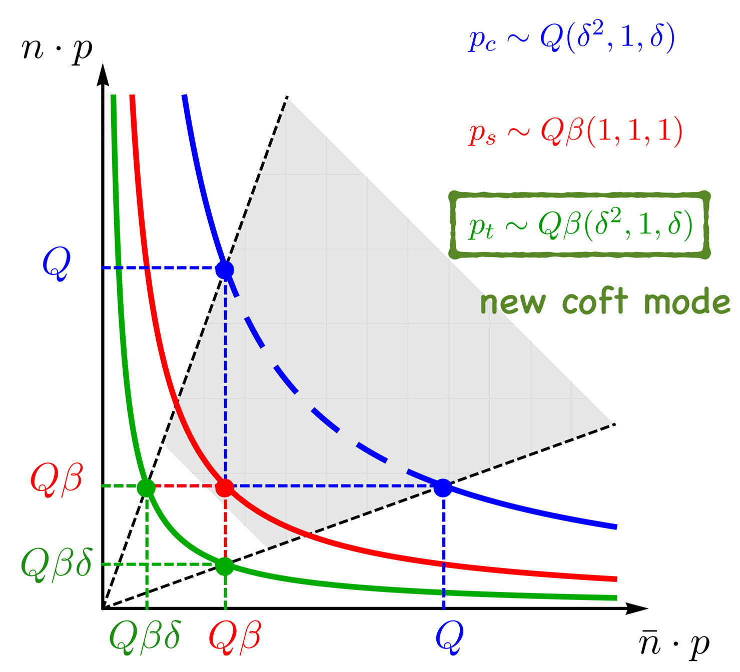
- Dasgupta-Salam dipole shower [2]
- Banfi-Marchesini-Smye equation [3]

No all-order factorization formula

Effecitve Field Theory for SW jet process

In Ref.[4] we constructed a new effective field theory(EFT) which fully factorizes non-global jet observables for the first time. Analysing SW jet processes in EFT, we find that in addition to soft and collinear fields their description requires degrees of freedom that are simultaneously soft and collinear to the jets. These collinear-soft(coft) particles can resolve individual collinear partons, leading to a complicated <u>**multi-Wilson-line structure**</u> of the associated operators at higher orders.





Factorization formula

Laplace transformation

$$\tilde{\sigma}(\tau,\delta) = \int_0^\infty d\beta\, e^{-\beta/(\tau e^{\gamma}_E)}\frac{d\sigma(\delta)}{d\beta}$$

integration over angles

$$\widetilde{\sigma}(\tau,\delta) = \sigma_0\, H(Q)\, \widetilde{S}(Q\tau)\left[\sum_{m=1}^{\infty}\left\langle \mathcal{J}_m(Q\delta) \otimes \widetilde{\mathcal{U}}_m(Q\delta\tau)\right\rangle\right]^2$$

color trace

hard function

Jet function

Soft function

Coft function

<u>**Multi-Wilson-line structure**</u>: Coft radiation resolves the colours and directions of individual energetic collinear patrons ⟶ infinite summation, nontrivial convolution between jet and coft function

First all order factorization theorem for non-global observable. Achieves full scale separation!

Fixed-order expansion

The factorization formula can be justified order by order in perturbation theory. We calculate all ingredients up to NNLO and expand our factorisation formula to two loop order. At the NLO, we can check our results analytically, and at the NNLO we check them numerically.

One-loop expansion:

Hard	$\Delta\sigma_h = \frac{\alpha_s C_F}{4\pi}\sigma_0\left(\frac{\mu}{Q}\right)^{2\epsilon}\left(-\frac{4}{\epsilon^2}-\frac{6}{\epsilon}-16+\frac{7\pi^2}{3}\right)$
Collinear	$\Delta\sigma_{c+\bar{c}} = \frac{\alpha_s C_F}{4\pi}\sigma_0\left(\frac{\mu}{Q\delta}\right)^{2\epsilon}\left(\frac{4}{\epsilon^2}+\frac{6}{\epsilon}+16-\frac{5\pi^2}{3}+c_0\right)$
Soft	$\Delta\sigma_s = \frac{\alpha_s C_F}{4\pi}\sigma_0\left(\frac{\mu}{Q\beta}\right)^{2\epsilon}\left(\frac{4}{\epsilon^2}-\pi^2\right)$
Coft	$\Delta\sigma_{t+\bar{t}} = \frac{\alpha_s C_F}{4\pi}\sigma_0\left(\frac{\mu}{Q\delta\beta}\right)^{2\epsilon}\left(-\frac{4}{\epsilon^2}+\frac{\pi^2}{3}\right)$

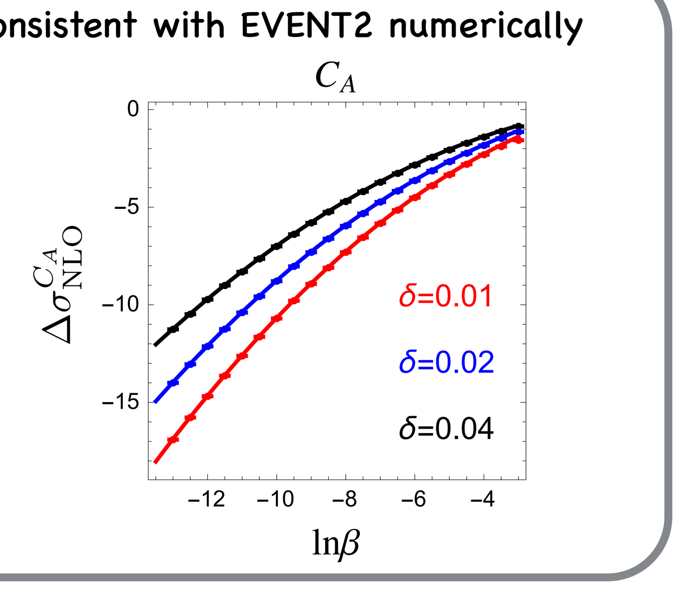
$$\Delta\sigma^{\rm tot} = \frac{\alpha_s C_F}{4\pi}\sigma_0\left(-16\ln\delta\ln\beta - 12\ln\delta + c_0\right)$$

Consistent with NLO SW dijet cross section

Two-loop expansion ($C_F C_A$ structure):

$$\Delta\sigma^{C_A}_{\rm NLO} = \left(\frac{\alpha_s}{2\pi}\right)^2 C_F C_A\left[\left(\frac{44\ln\beta}{3}+11\right)\ln^2\delta - \frac{2\pi^2}{3}\ln^2\beta + \left(\frac{8}{3}-\frac{31\pi^2}{18}-4\zeta_3-6\ln^2 2-4\ln 2\right)\ln\beta + \left(\frac{44\ln^2\beta}{3}+\left(-\frac{268}{9}+\frac{4\pi^2}{3}\right)\ln\beta - \frac{57}{2} + 12\zeta_3 - 22\ln 2\right)\ln\delta + c_2^A\right]$$

Consistent with EVENT2 numerically



Resummation

- In order to manifest the NGLs resummation property. We choose δ~O(1), then the collinear direction vanish and the dijet process only involve hard and soft modes. The resumed cross section is given by

$$\sigma(\beta,\delta) = \sum_{l=2}^{\infty}\left\langle \boldsymbol{\mathcal{H}}_l(\{\underline{n}\},Q,\delta,\mu_h) \otimes \sum_{m\geq l}\boldsymbol{U}^S_{lm}(\{\underline{n}\},\delta,\mu_s,\mu_h)\,\hat{\otimes}\,\boldsymbol{\mathcal{S}}_m(\{\underline{n}\},Q\beta,\delta,\mu_s)\right\rangle$$

- All the large logs are resumed by renoramlizaion group(RG) evolution factor. Infinity hard and soft operators are mixed under RG renormalisation.

One-loop anomalous dimension:

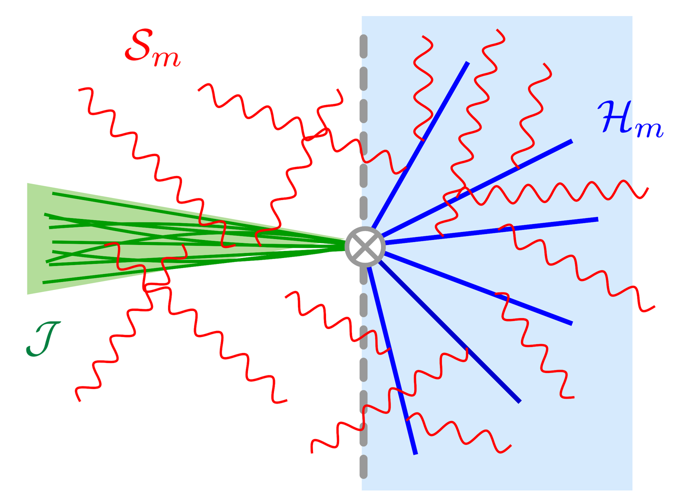
$$\boldsymbol{V}_m = \boldsymbol{\Gamma}^{(1)}_{m,m} = 2\sum_{(ij)}\left(\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,L} + \boldsymbol{T}_{i,R}\cdot\boldsymbol{T}_{j,R}\right)\int\frac{d\Omega(n_k)}{4\pi}W^k_{ij}\left[\Theta^{n\bar{n}}_{\rm in}(k) + \Theta^{n\bar{n}}_{\rm out}(k)\right]$$

$$\boldsymbol{R}_m = \boldsymbol{\Gamma}^{(1)}_{m,m+1} = -4\sum_{(ij)}\boldsymbol{T}_{i,L}\cdot\boldsymbol{T}_{j,R}\,W^{m+1}_{ij}\,\Theta^{n\bar{n}}_{\rm in}(n_{m+1})\,.$$

- Resummation accuracy can be improved systematically., e.g. two-loop anomalous dimension and one-loop matching conditions.

Light jet mass distribution

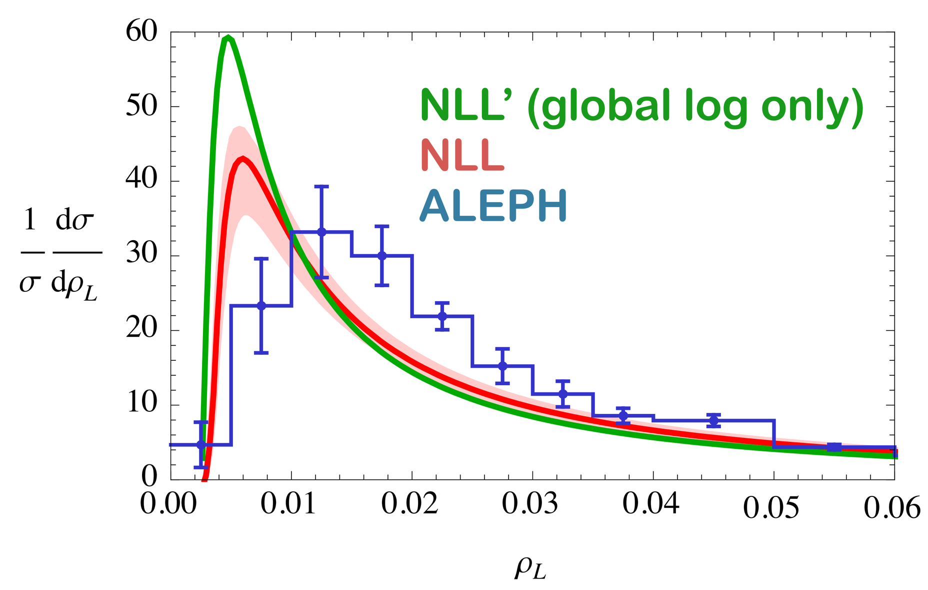
Many collider observables suffer from NGLs not captured by standard resummation techniques. Classic examples are the light-jet mass event shape in the limit of small mass As an application of our jet EFT, in Ref.[5] we studied facotirzatioin and resummation for light jet mass distribution.



Factorization formula:

$$\frac{d\sigma}{dM_L^2} = \sum_{i=q,\bar{q},g}\int_0^\infty d\omega_L\, J_i(M_L^2 - Q\,\omega_L)\sum_{m=1}^{\infty}\left\langle \boldsymbol{\mathcal{H}}^i_m(\{\underline{n}\},Q) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\},\omega_L)\right\rangle$$

- NLL resummation results:
  - Contribution from NGLs are sizeable. Including NGLs leads to better agreement with data.
- further improvement:
  - N^2LL? Non-perturbative effects?
  - Superleading logarithms at hadron colliders?



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