Heavy quark jet substructure

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Probing substructure of QCD jets

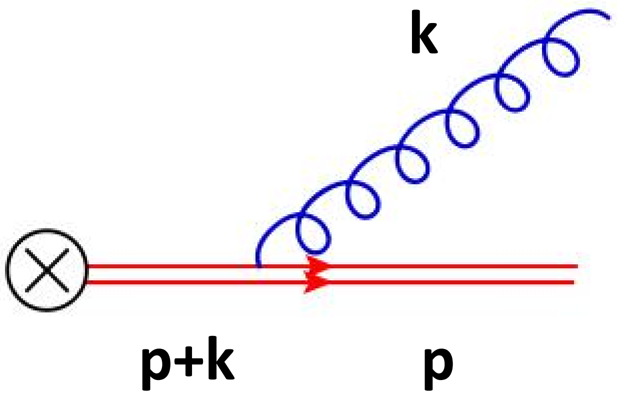
- Jet substructure observables allow us a deeper understanding of QCD dynamics in a jet and are designed to uncover specific features of a jet.

- Significant progress for analytical calculation of massless/light parton jets.

The goal is to understand the radiation pattern of a heavy quark initiated jet and compute jet substructure observables on them

- A significant step towards utilizing b quark jets as hard probes of the QGP medium in heavy ion collisions.

The radiation from a heavy quark



$$\sim \frac{E_q}{(p+k)^2 - m_q^2 + i0} = \frac{1}{2k^0\left(1-\sqrt{1-\frac{m_q^2}{E_q^2}}\mathrm{Cos}\,\theta\right)}$$

$$\approx \frac{1}{k^0\left(\theta^2 + \frac{m_q^2}{E_q^2}\right)}$$

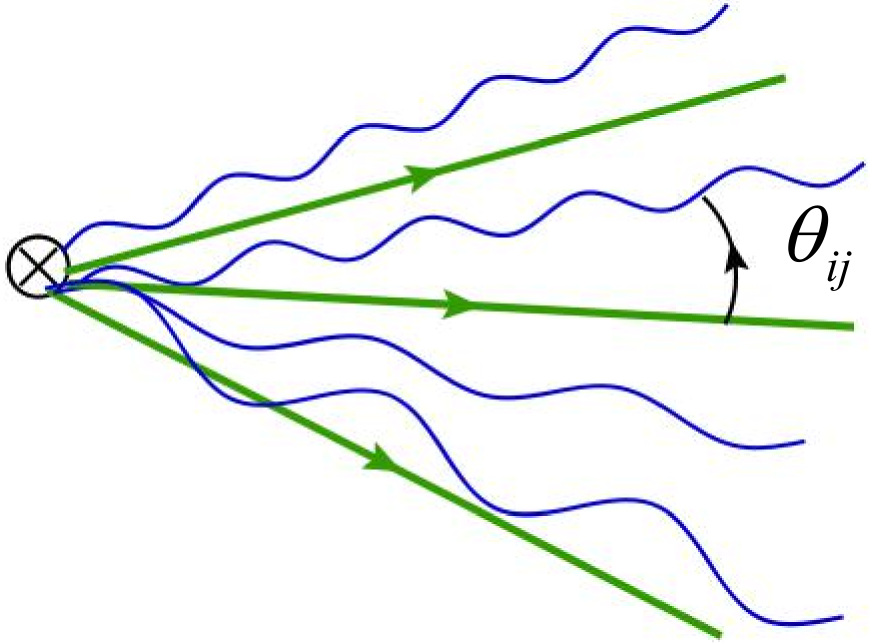
Phase space integral

$$\int \frac{dk^0}{k^0} \int \frac{\theta d\theta}{\theta^2 + \frac{m_q^2}{E_q^2}}$$

- The soft singularity still exists but the collinear singularity is cut-off by the quark mass
- the heavy quark does not like to radiate collinear modes

- Mass dependence of the jet manifests itself through the angle $\theta_{HQET} = \frac{m_q}{E_q}$

A prototype measurement of correlations between particle momenta on the whole jet.

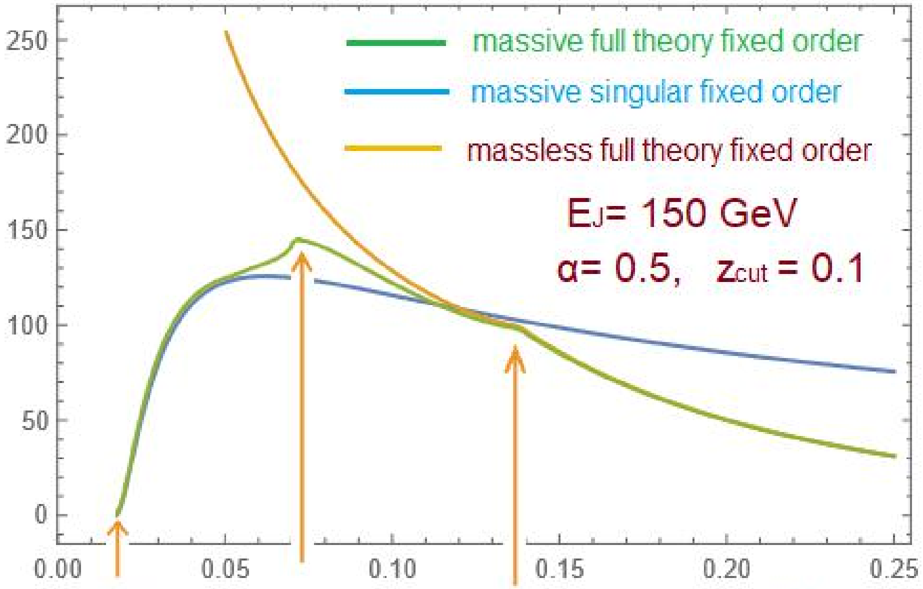


$$e_2^{(\alpha)} = \frac{1}{E_J^2} \sum_{i,j \in J} E_i E_j \theta_{ij}^{\alpha}$$

$$z_i \equiv \frac{E_i}{E_J}, \qquad \theta_{ij}^2 \equiv \frac{2p_i \cdot p_j}{E_i E_j},$$

Implement Soft-drop grooming to mitigate the effects of MPI and pile-up

Fixed order cross section



Real contribution

$$\frac{\alpha_s}{2\pi}C_F\left(\frac{4}{\alpha e_2^{(\alpha)}}\ln\left(\frac{e_2^{(\alpha)}}{e_{2,min}^{(\alpha)}}\right)-\frac{2}{e_2^{(\alpha)}}\left(1-\left(\frac{e_{2,min}^{(\alpha)}}{e_2^{(\alpha)}}\right)^{2/\alpha}\right)\right)$$

$$e_{2,min}^{(\alpha)}\sim z_{cut}\left(\frac{m}{E_J}\right)^{\alpha}$$

Virtual contribution

$$\sim\delta(e_2^{(\alpha)})\left(\ln^2\frac{E_J}{m},\ln\frac{E_J}{m}\right)$$

$e_{2,min}^{(\alpha)}$ $(m/E_J)^{\alpha}$ z_{cut} $e_2^{(\alpha)}$ ⟶

Develop an EFT to resum large logs in e_2 and m

Factorization in SCET, HQET

- Heavy Quark carries a large fraction of the jet energy $E_q/E_J \sim 1$.

- Dominant contribution to $e_2^{(\alpha)}$ when one of (i, j) is the heavy quark.

$$e_2^{(\alpha)} \sim \sum_i \frac{E_i}{E_J} \theta_{iq}^{\alpha} = \sum_i z_i \theta_{iq}^{\alpha}$$

Constraints

- $$\theta \geq \theta_{HQET} \sim \frac{m}{E_q} \sim \frac{m}{E_J}$$
- $$z_i = \frac{E_i}{E_J} \geq z_{cut}$$
- $$e_2^{(\alpha)} \sim \sum_i z_i \theta_{iq}^{\alpha} \geq e_{2,\min}^{(\alpha)} \sim z_{cut} \left(\frac{m}{E_J} \right)^{\alpha}$$

EFT modes for $e_2^{(\alpha)} << z_{cut} << 1$

$$e_2^{(\alpha)} \sim z\theta^\alpha$$

- Jet boundary mode $\theta \sim 1$

$$z \sim e_2^{(\alpha)} << z_{cut}$$

- Radiation sensitive to jet boundary does not contribute to the measurement

$$e_2^{(\alpha)} \sim z\theta^{\alpha}$$

- Mode sensitive to soft- drop : $z \sim z_{cut}$

$$\theta_{cs} \sim \left(\frac{e_2^{(\alpha)}}{z_{cut}}\right)^{1/\alpha} > \theta_{HQET}$$

$$p \sim z_{cut} E_J \left(1, \theta_{cs}^2, \theta_{cs}\right)$$

Collinear-Soft mode

$$e_2^{(\alpha)} \sim z\theta^{\alpha}$$

- Mode insensitive to Soft-drop

$$z \quad \sim \quad 1 \qquad \Rightarrow \theta_c \sim \left(e_2^{(\alpha)}\right)^{1/\alpha}$$

$$\theta_c > \theta_{HQET} \Rightarrow e_2^{(\alpha)} > \left(\frac{m}{E_J}\right)^{\alpha} = \left(\theta_{HQET}\right)^{\alpha}$$

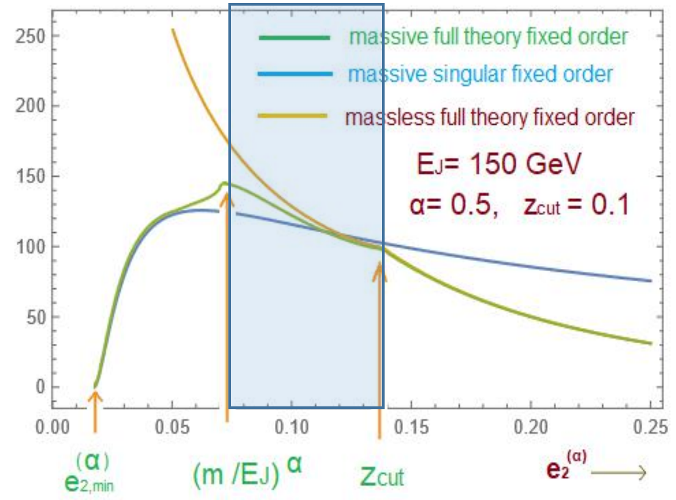
$$p \sim E_J\left(1, \theta_c^2, \theta_c\right)$$

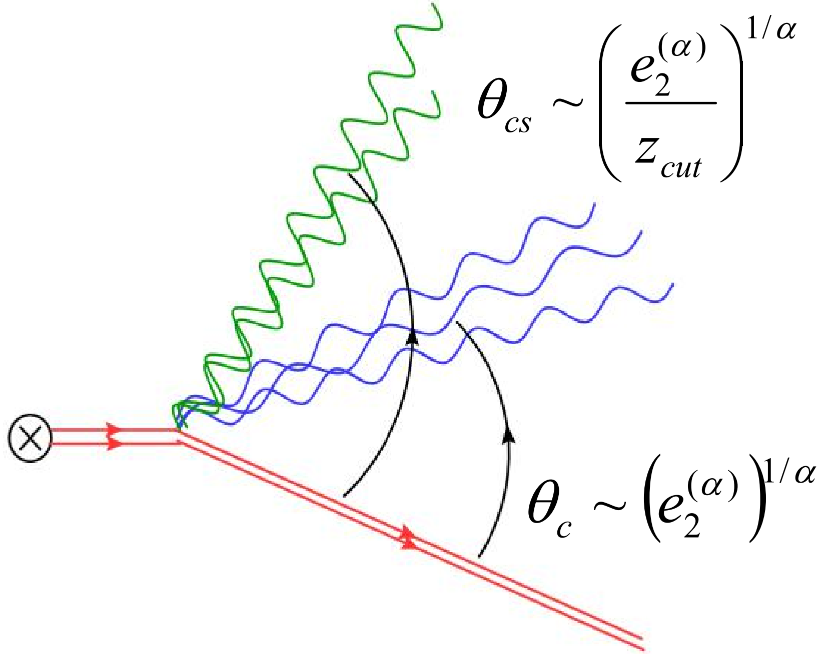
Collinear mode

Factorization for $e_2^{(\alpha)} > \left(\frac{m}{E_J}\right)^{\alpha} = \theta_{HQET}^{\alpha}$

$$\frac{d\sigma}{de_2^{\alpha}} = \sigma_0(E_J) S_G(E_J z_{cut}) S_c(E_J z_{cut}, e_2^{(\alpha)}) \otimes J(e_2^{(\alpha)})$$

- S_G: jet boundary soft function
- S_c: Collinear soft function
- J: Massless SCET jet function





$$e_2^{(\alpha)} \sim z\theta^\alpha$$

$$\theta_c < \theta_{HQET} \Rightarrow e_2^{(\alpha)} < \left(\frac{m}{E_J}\right)^\alpha$$

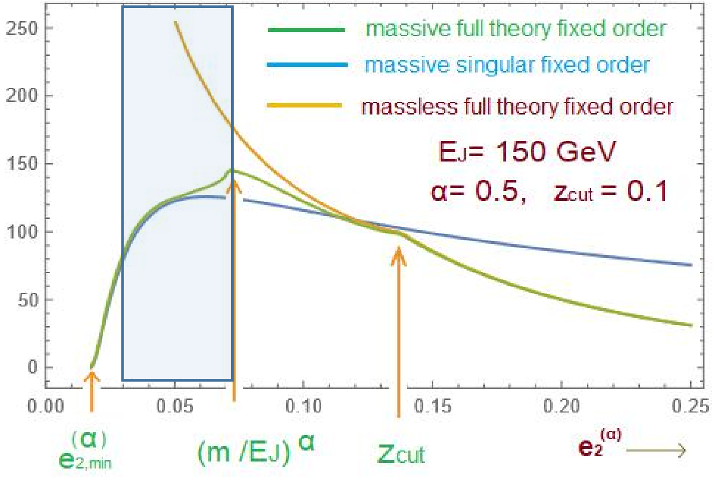
z~ 1 is not allowed

θ is set by θ_{HQET} $\quad \Rightarrow z \sim \dfrac{e_2^{(\alpha)}}{\theta_{HQET}^\alpha} > z_{cut}$

$$p \sim \frac{e_2^{(\alpha)}}{\theta_{HQET}^\alpha} E_J \left(1, \theta_{HQET}^2, \theta_{HQET}\right)$$

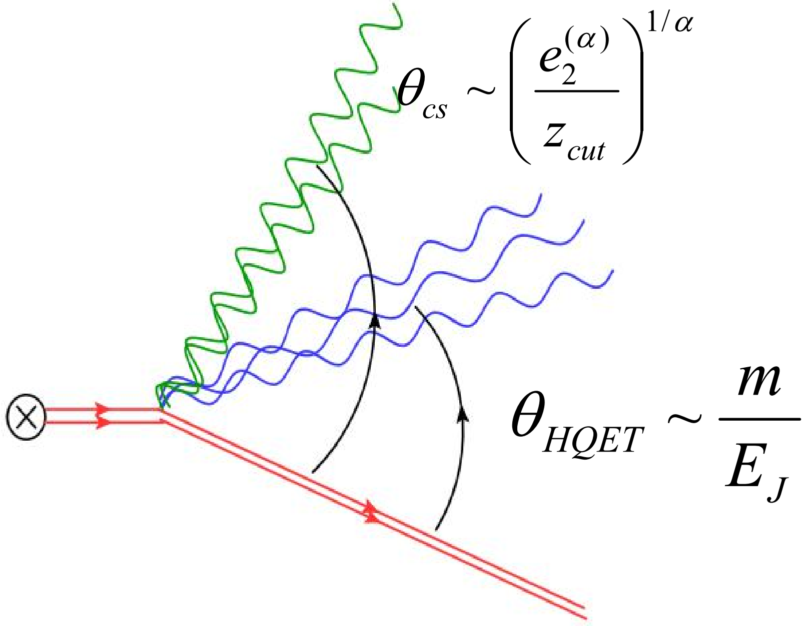
ultra-collinear mode of HQET

Factorization for $e_{2,\min}^{(\alpha)} < e_2^{(\alpha)} < \left(\frac{m}{E_J}\right)^{\alpha}$



$$\frac{d\sigma}{de_2^{\alpha}} = \sigma_0(E_J) S_G(E_J z_{cut}) H(m) S_c(E_J z_{cut}, e_2^{(\alpha)}) \otimes B_+(e_2^{(\alpha)}, m)$$

- $S_G(E_J z_{cut})$: jet boundary soft function
- $H(m)$: HQET matching coefficient
- $S_c(E_J z_{cut}, e_2^{(\alpha)})$: Collinear soft function
- $B_+(e_2^{(\alpha)}, m)$: Boosted HQET jet function



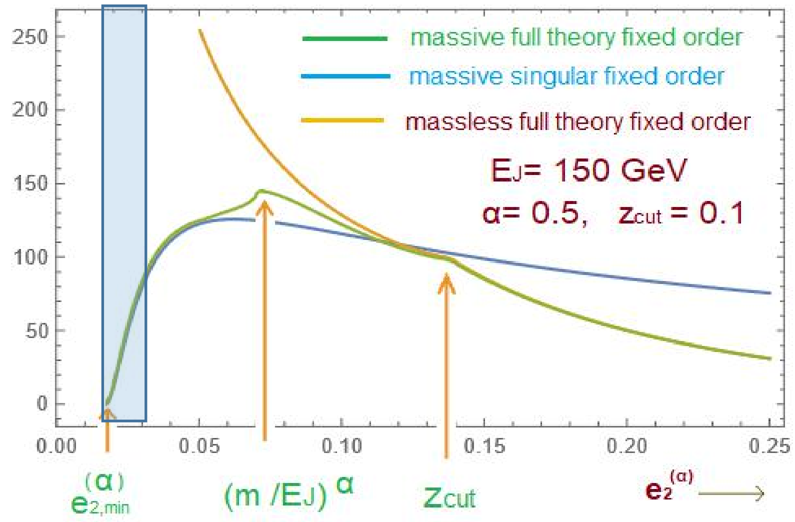
Factorization for $e_2^{(\alpha)} \sim e_{2,\min}^{(\alpha)}$

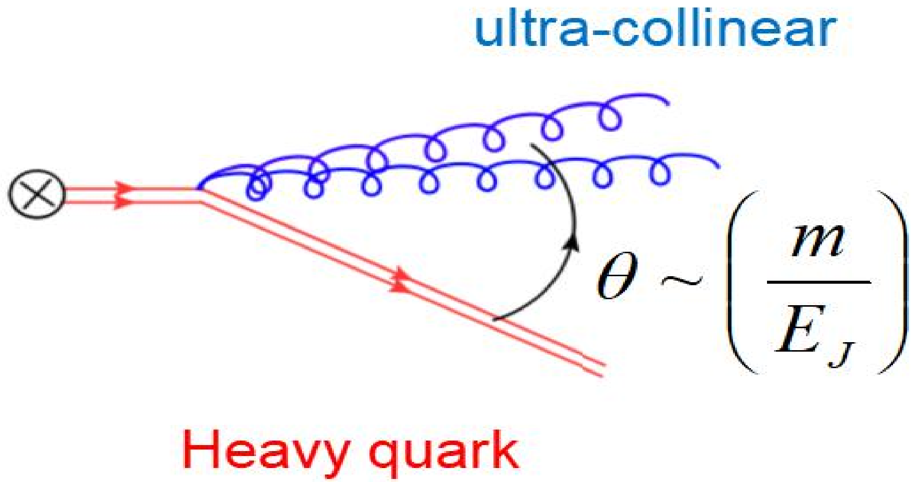
$$\frac{d\sigma}{de_2^{\alpha}} = \sigma_0(E_J) S_G(E_J z_{cut}) H(m) B_+^{SD}(e_2^{(\alpha)}, m, z_{cut})$$

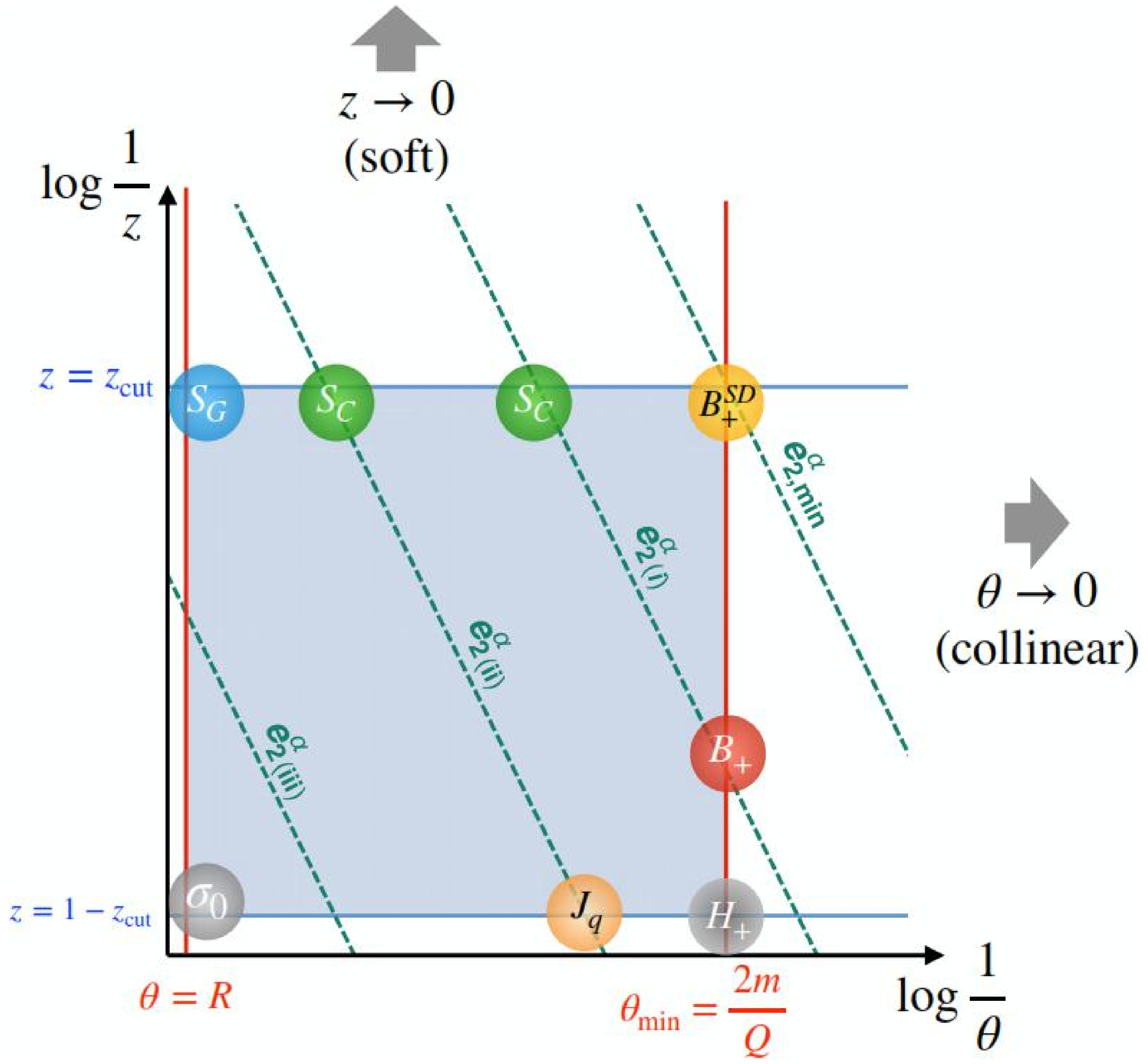
jet boundary soft function

HQET matching coefficient

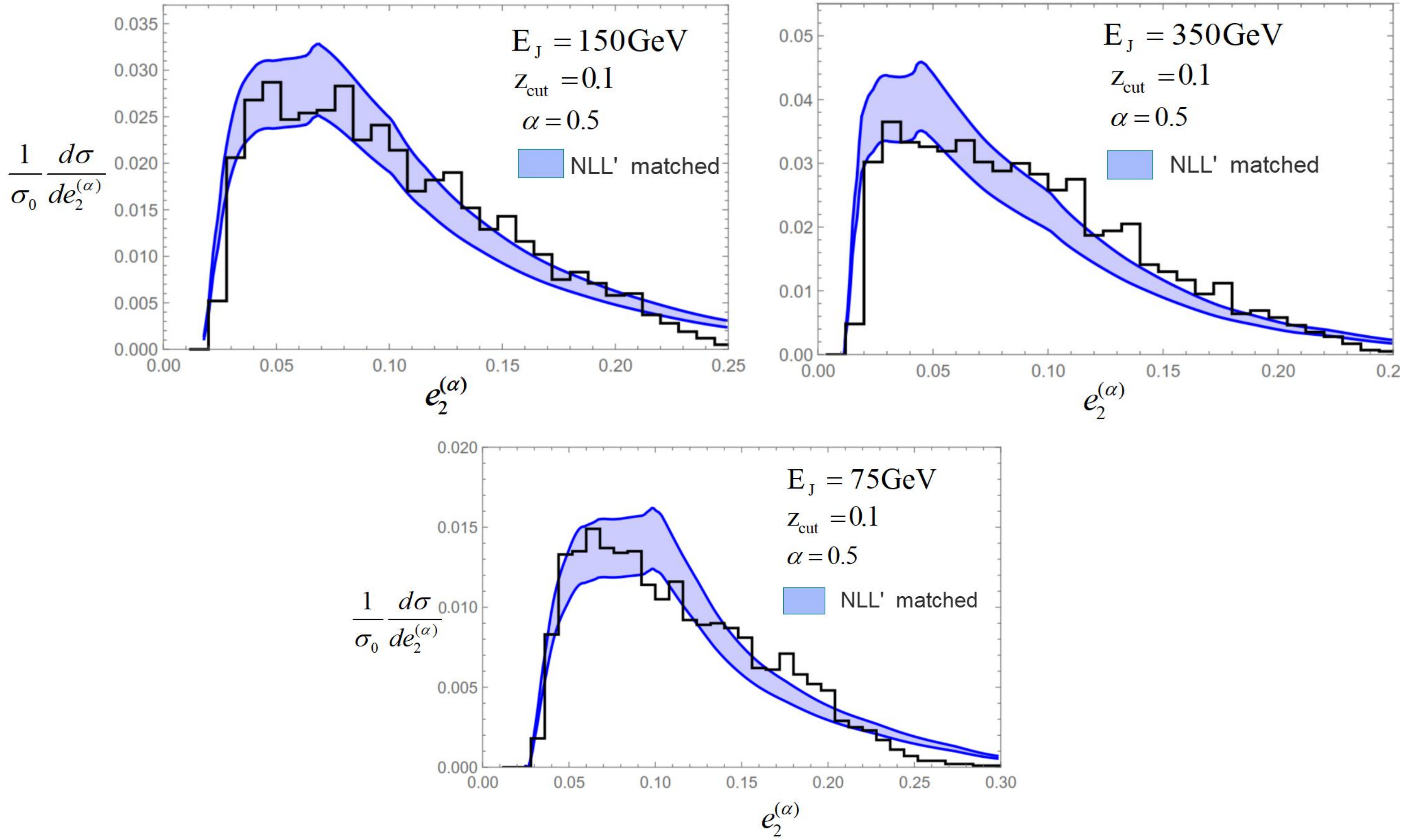
Soft-drop contrained Boosted HQET jet function





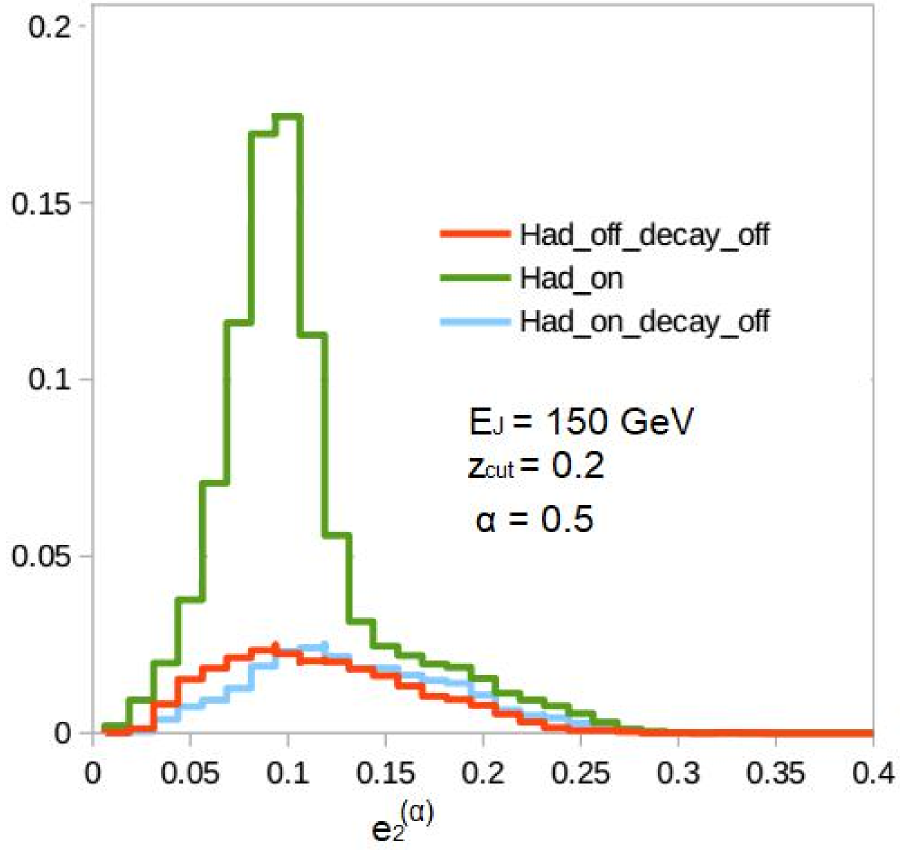


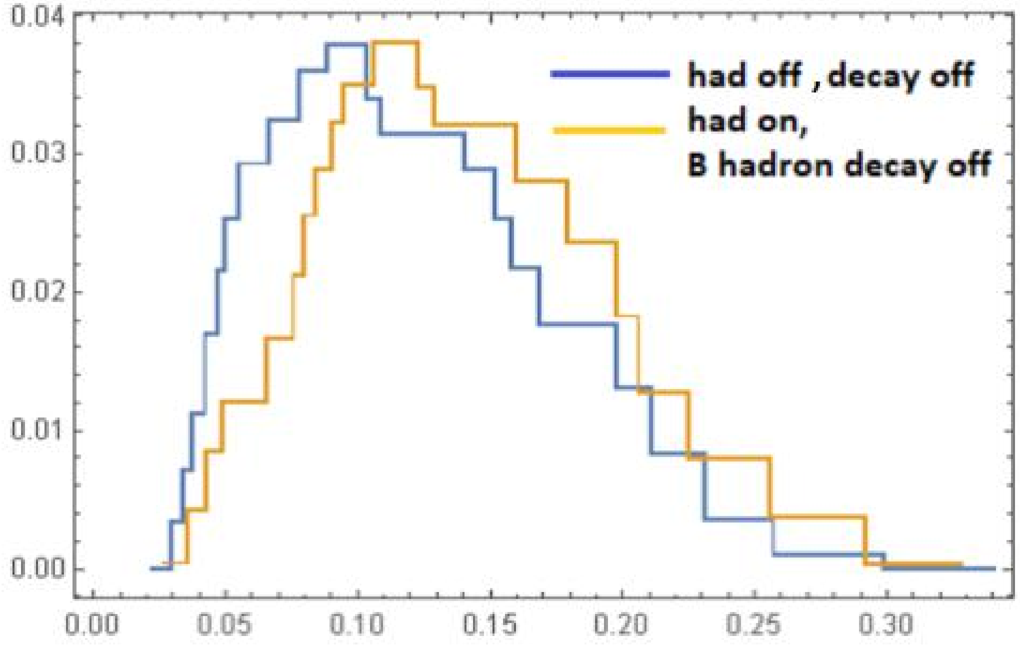
Phase Space for factorization



$E_J = 150$GeV
$z_{cut} = 0.1$
$\alpha = 0.5$
NLL' matched
$\frac{1}{\sigma_0}\frac{d\sigma}{de_2^{(\alpha)}}$
$e_2^{(\alpha)}$
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.00
0.05
0.10
0.15
0.20
0.25
$E_J = 350$GeV
$z_{cut} = 0.1$
$\alpha = 0.5$
NLL' matched
$e_2^{(\alpha)}$
0.00
0.01
0.02
0.03
0.04
0.05
0.00
0.05
0.10
0.15
0.20
0.2
$E_J = 75$GeV
$z_{cut} = 0.1$
$\alpha = 0.5$
NLL' matched
$\frac{1}{\sigma_0}\frac{d\sigma}{de_2^{(\alpha)}}$
$e_2^{(\alpha)}$
0.000
0.005
0.010
0.015
0.020
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Non-perturbative effects



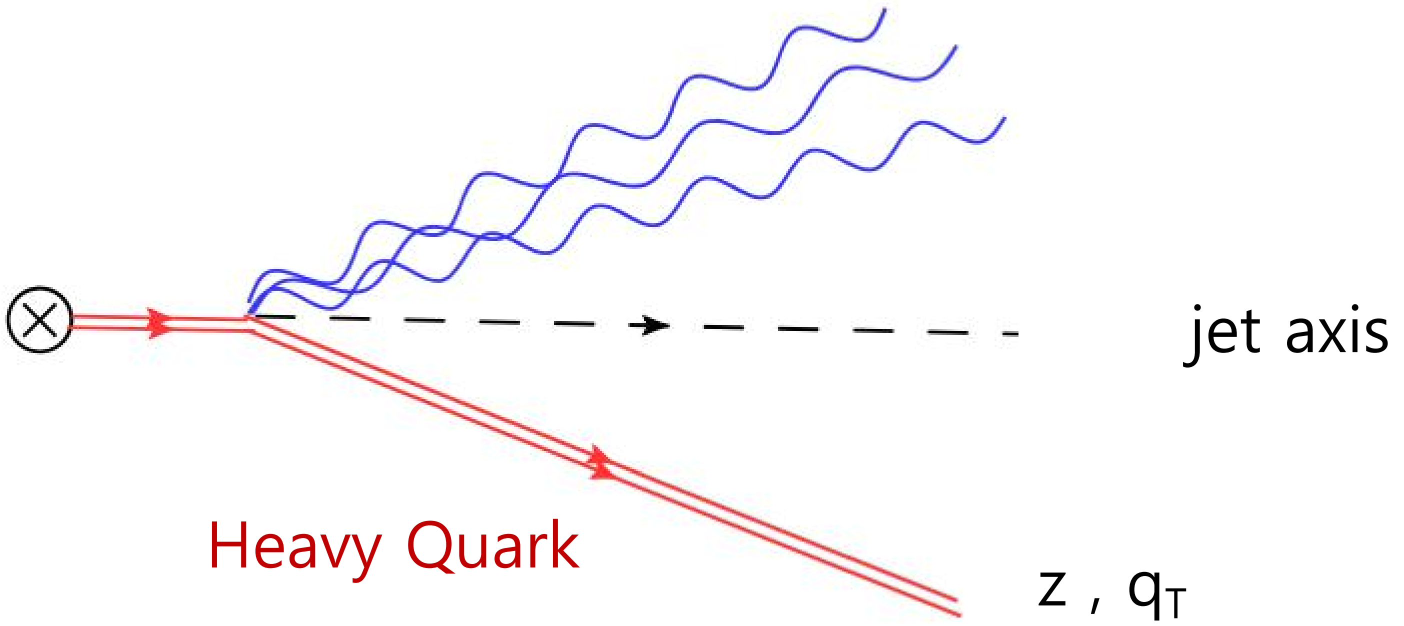


Transverse spectrum at threshold

- Measure properties of the heavy hadron in the groomed jet.

$$\theta_{HQET} << (1-z) \sim z_{cut} << 1$$

$$\theta_{HQET} \sim \frac{m}{E_q} \sim \frac{m}{E_J}$$



$$q_\perp \sim m(1-z) \sim m z_{cut} << m$$

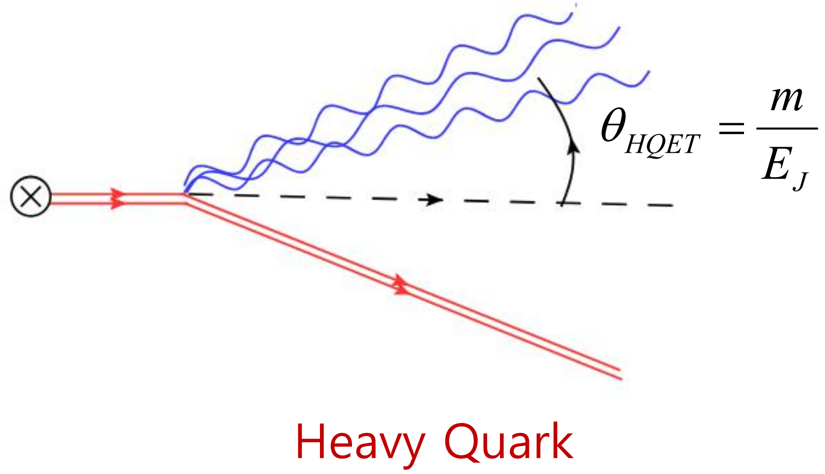
$$p \sim (1-z)E_J(1, \theta^2_{HQET}, \theta_{HQET})$$ ultra-collinear HQET mode

$$\frac{d\sigma}{dz d^2 q_\perp} = \sigma_0(E_J) S_G(E_J z_{cut}) H(m) B_+(q_\perp, (1-z), m)$$

jet boundary soft function

HQET matching coefficient

Boosted HQET jet function



$$E_J(1-z) >> q_\perp >> m(1-z)$$

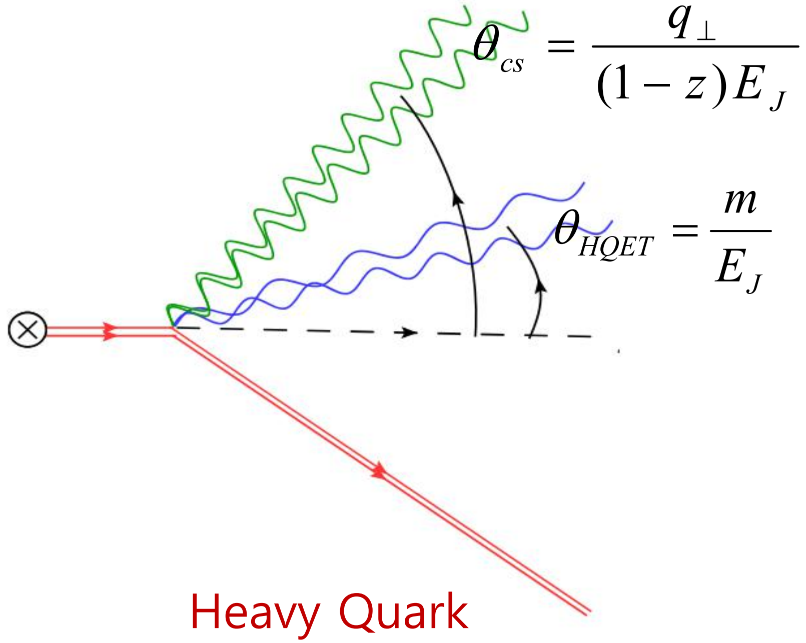
$$\frac{d\sigma}{dz d^2 q_\perp} = \sigma_0(E_J) S_G(E_J z_{cut}) H(m) S_c(E_J z_{cut}, q_\perp, 1-z) \otimes B_+(1-z, m, z_{cut})$$

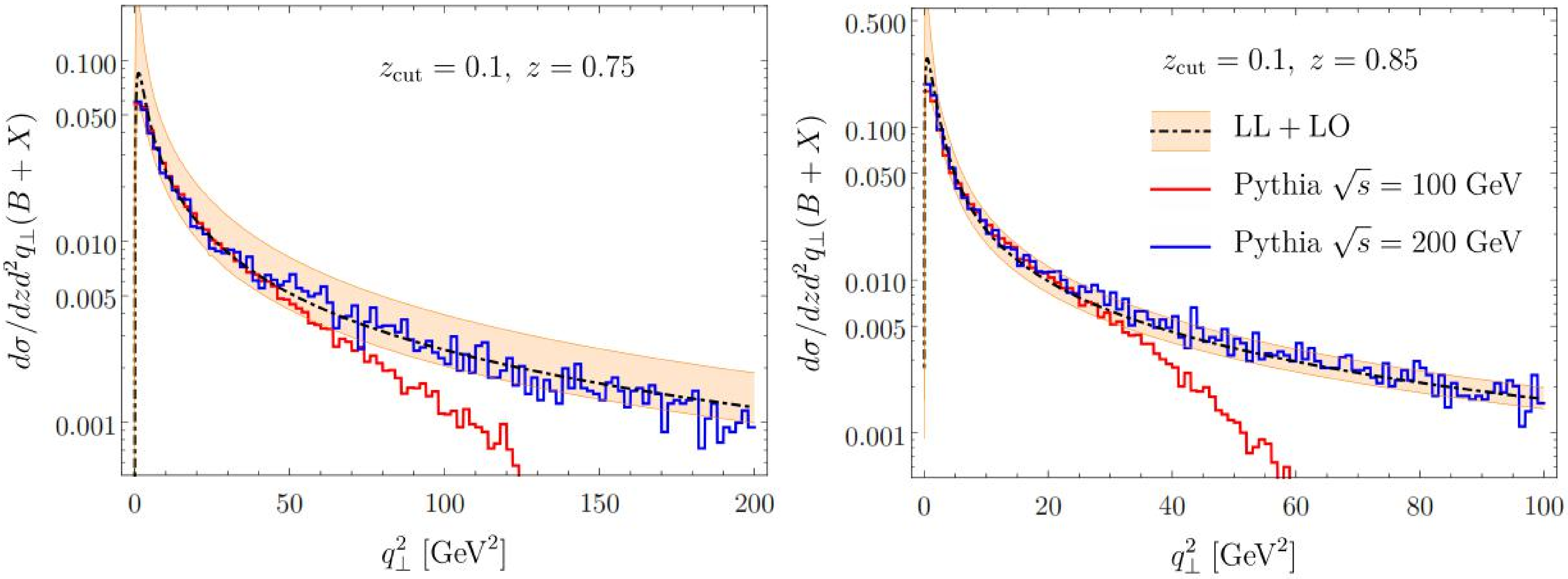
$S_G(E_J z_{cut})$: jet boundary soft function

$H(m)$: HQET matching coefficient

$S_c(E_J z_{cut}, q_\perp, 1-z)$: Collinear soft function

$B_+(1-z, m, z_{cut})$: Boosted HQET jet function





Shape is independent of the hard scale (jet energy) for $q_\perp << E_J(1-z)$

Summary

- A comprehensive study of heavy quark initiated groomed jets using SCET and HQET effective field theories.

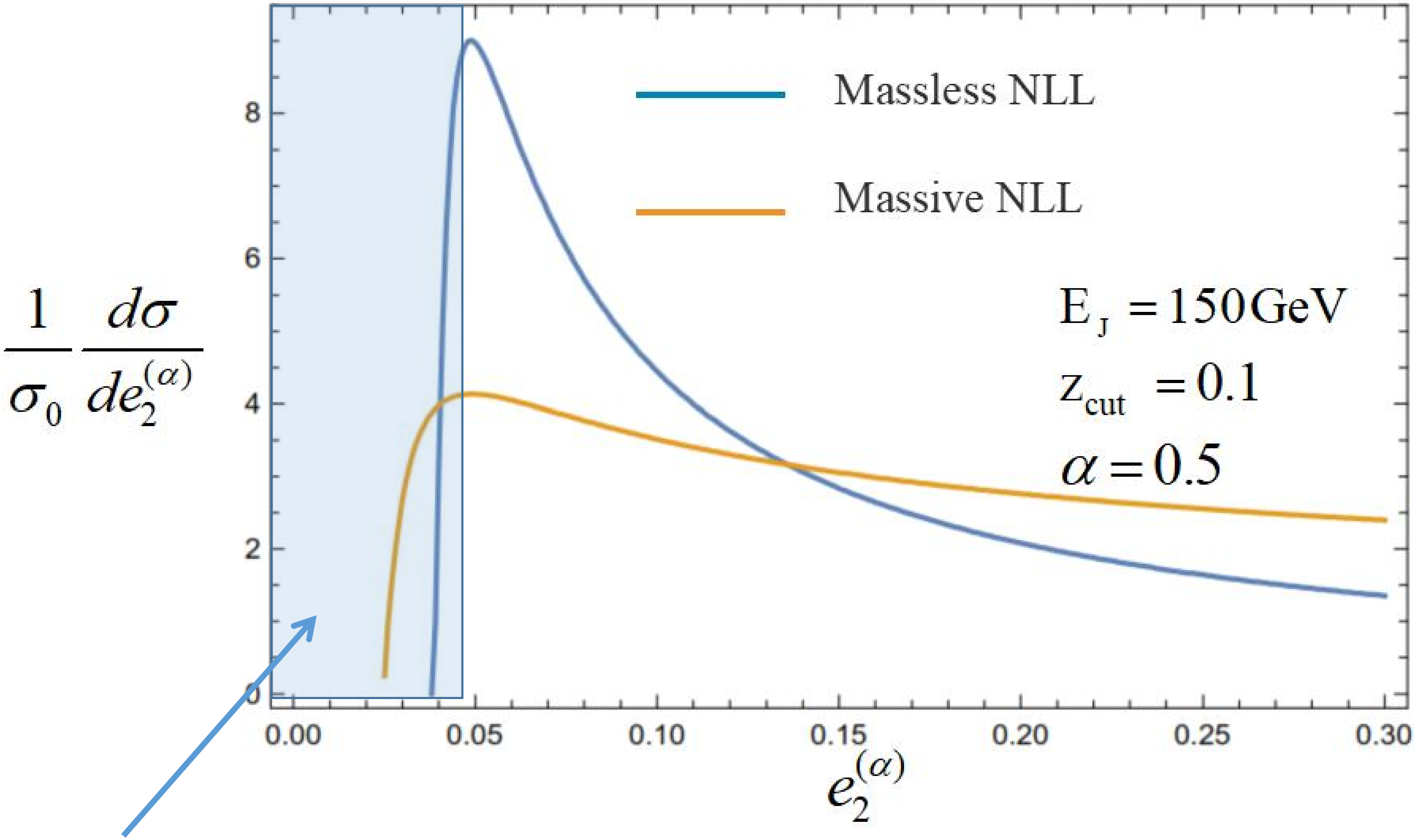
- Two classes of observables considered:

1. Energy correlators
2. Transverse spectrum of a single heavy hadron at threshold

A template for studying medium effects in QGP

Implement these types of b jet observables in the medium

Extras



Non-perturbative effects need to be included