Heavy Quark Jet Substructure

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Outline

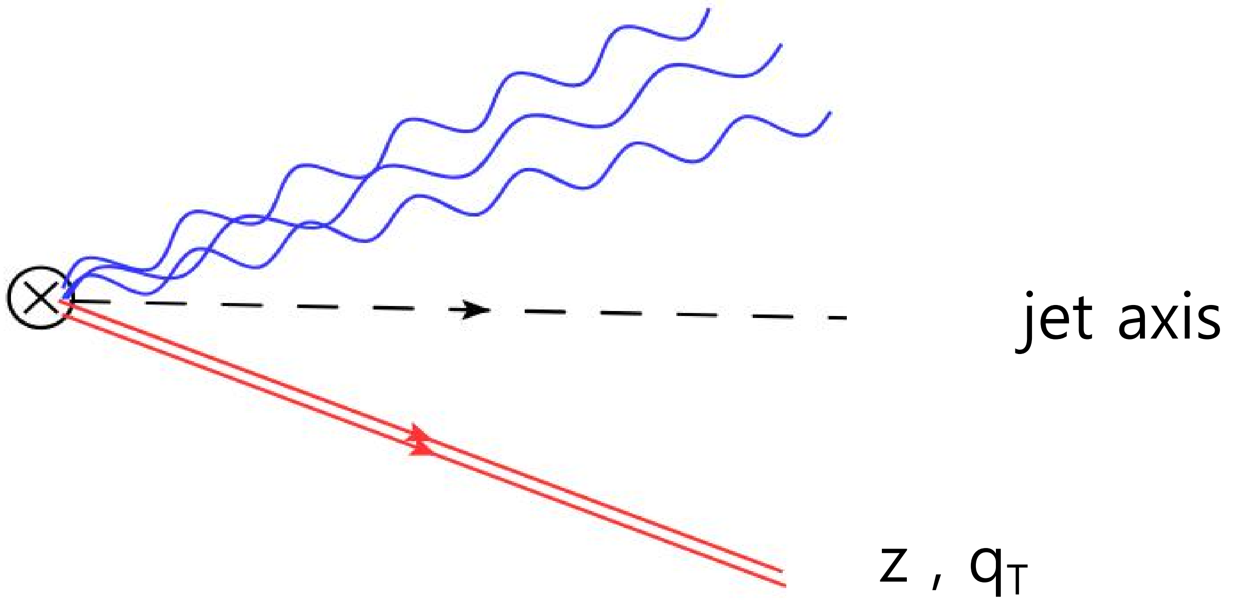
- Jet substructure observables for heavy quark initiated groomed jets
- Analytical computations using EFT's for heavy quark jet observables

    1. Groomed Jet shapes

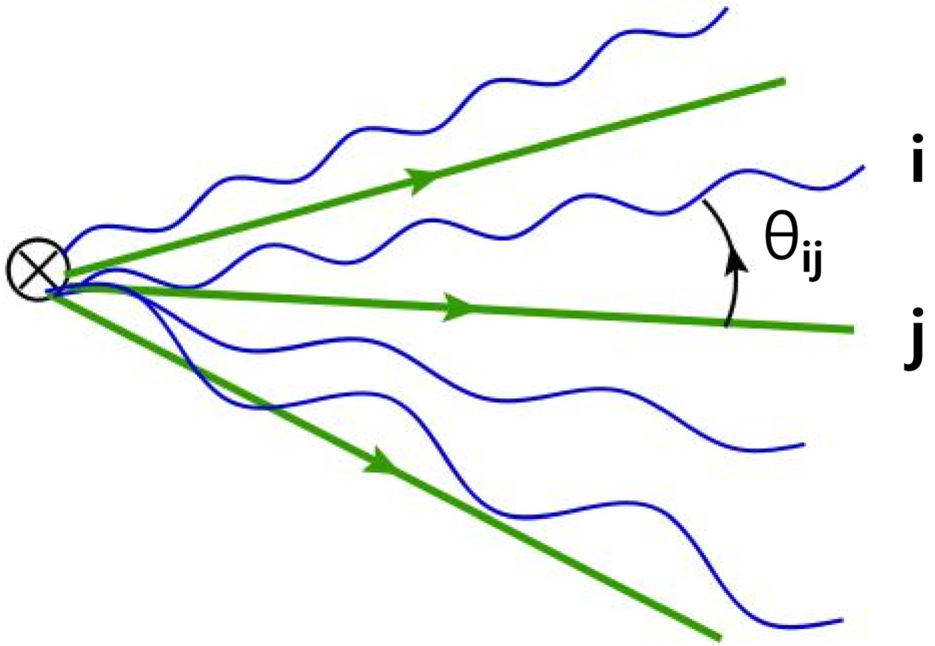
    2. Measuring properties of an identified heavy hadron

Jet substructure : Unravelling the pattern of radiation in a jet

- Measure properties of an identified particle in the jet.



- Measure correlations between particle momenta on the whole jet.



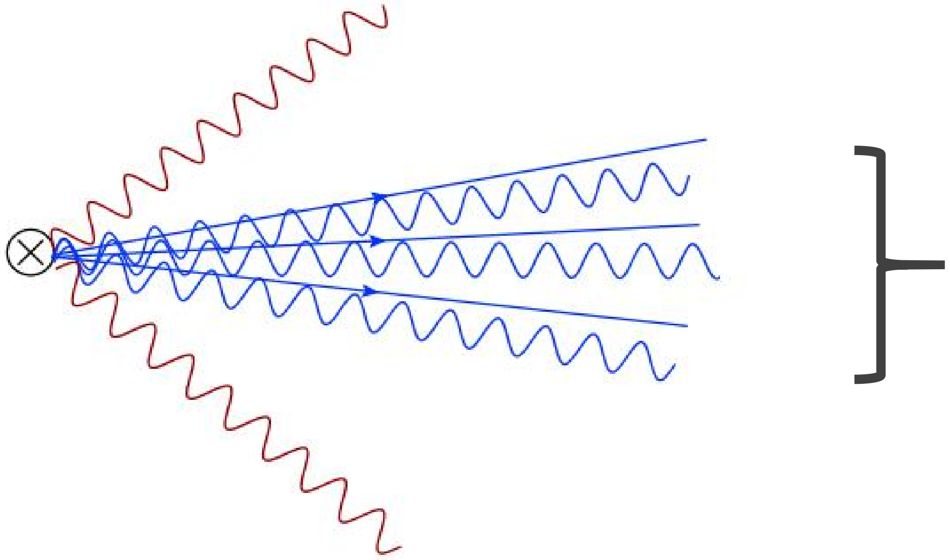
Two point Energy Correlators

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

Soft Drop Jet Grooming

- Mitigate the effects of Non-Gobal logarithms and MPI by removing wide angle soft radiation

$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{cut}$$



Observable only sensitive to collinear radiation

Energy Correlators for heavy quark jets

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

- Definition of θ used for $e^+ e^-$ collisions

$$\theta_{ij} = \frac{2 p_i \bullet p_j}{E_i E_j}$$

- 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

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

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

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

Collinear mode

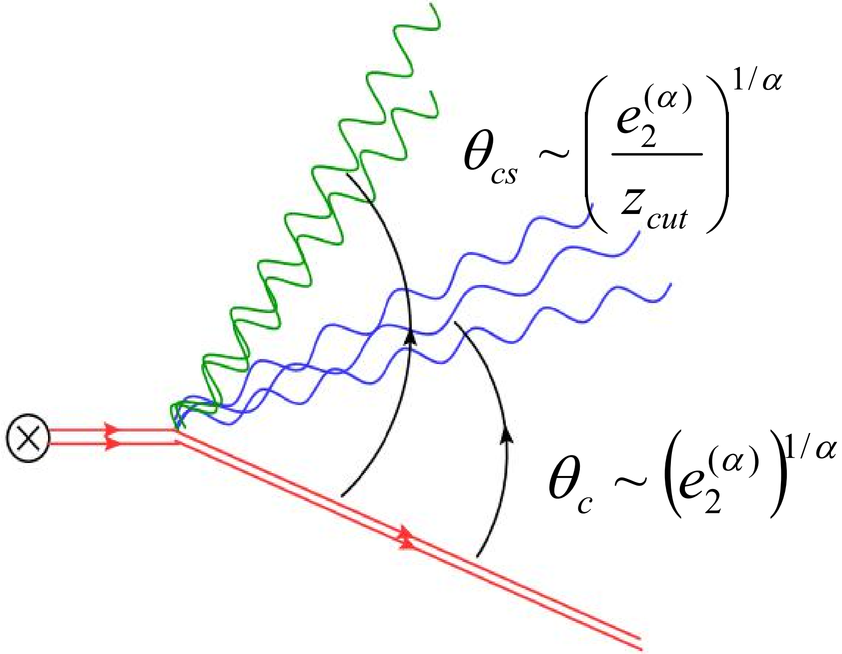
Factorization for $e_2^{(\alpha)} > \left(\frac{m}{E_J}\right)^{\alpha} = \theta_{HQET}^{\alpha}$

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

jet boundary soft function

Collinear soft function

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} $\Rightarrow z \sim \frac{e_2^{(\alpha)}}{\theta_{HQET}^{\alpha}} > z_{cut}$

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

ultra-collinear mode of HQET

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

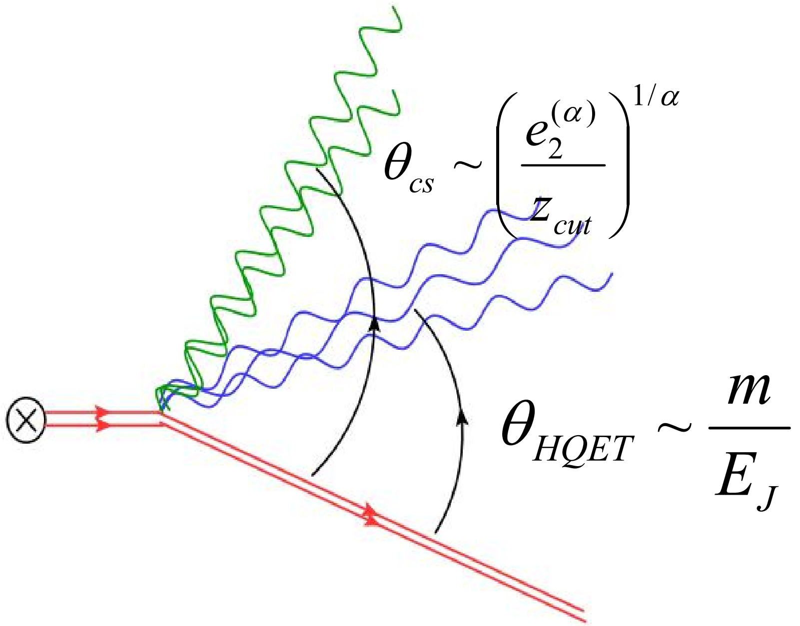
$$\frac{d\sigma}{de_2^{\alpha}} = \sigma_0(E_J) S_G(E_J z_{cut}) H(m) S_c(E_J z_{cut}, e_2^{(\alpha)}) \otimes B_+(e_2^{(\alpha)}, m)$$

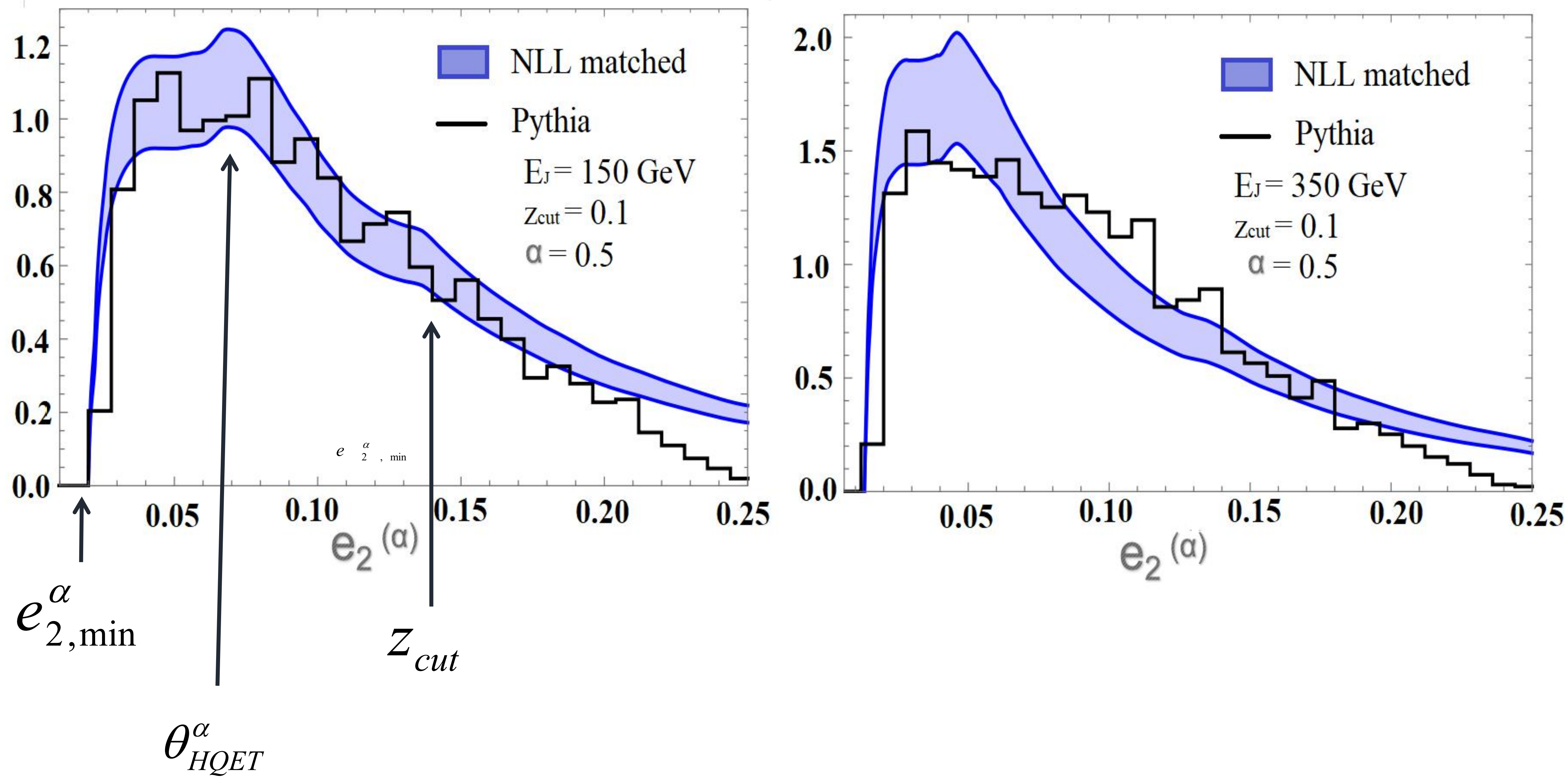
$S_G(E_J z_{cut})$: jet boundary soft function

$H(m)$: HQET matching coefficient

$S_c(E_J z_{cut}, e_2^{(\alpha)})$: Collinear soft function

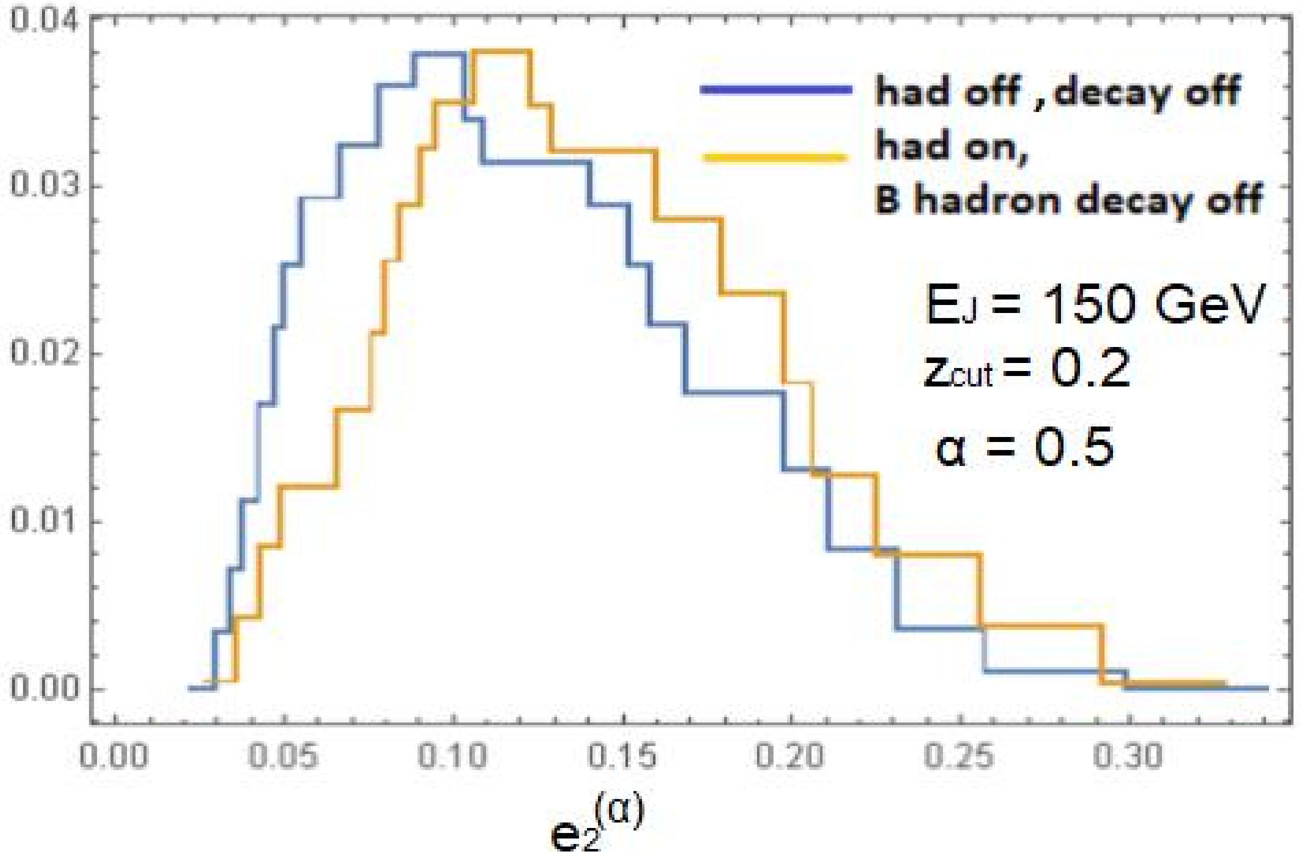
$B_+(e_2^{(\alpha)}, m)$: Boosted HQET jet function





NLL matched
Pythia
$E_J = 150$ GeV
$z_{cut} = 0.1$
$\alpha = 0.5$
$e_2^{(\alpha)}$
NLL matched
Pythia
$E_J = 350$ GeV
$z_{cut} = 0.1$
$\alpha = 0.5$
$e_2^{(\alpha)}$
$e^{\alpha}_{2,\min}$
θ^{α}_{HQET}
z_{cut}

Non-perturbative effects



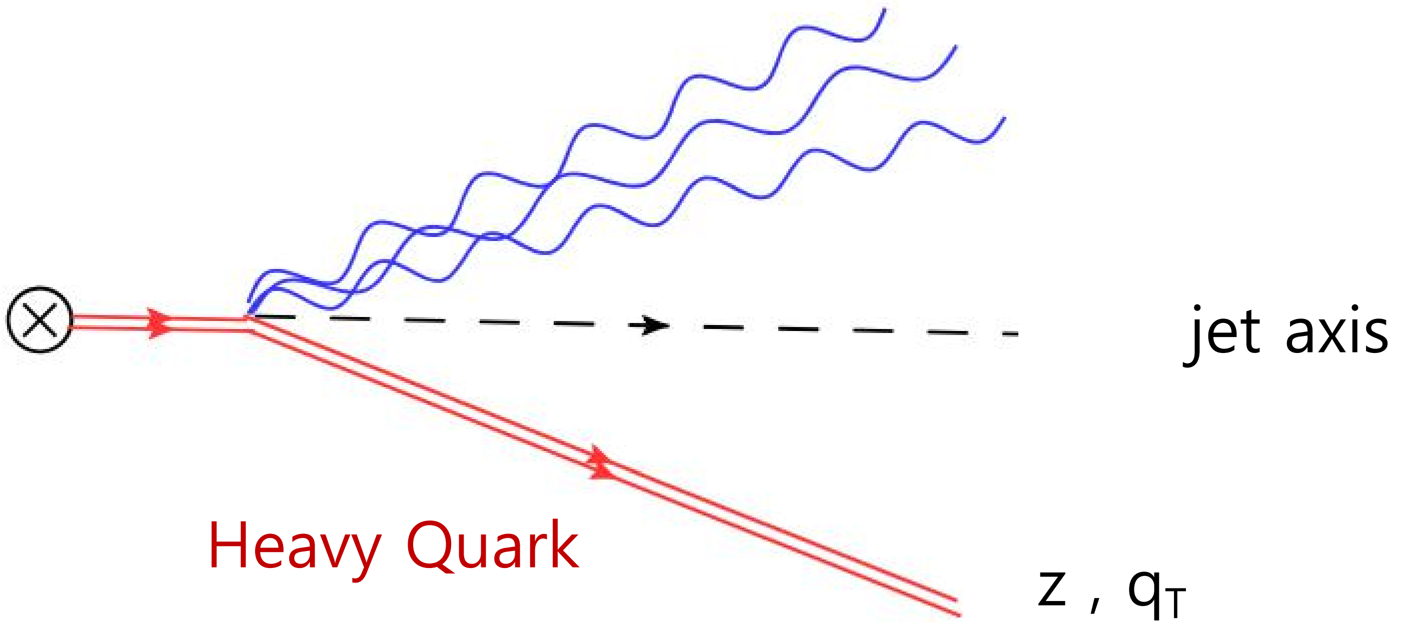
$$e_{2,avg}^{(\alpha)} = e_{2,avg}^{(\alpha),pert} + \frac{\theta_{HQET}^{\alpha}}{m} A(\alpha)$$

$A(\alpha) = 0.5$ GeV for α =0.5

Transverse spectrum at threshold

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

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



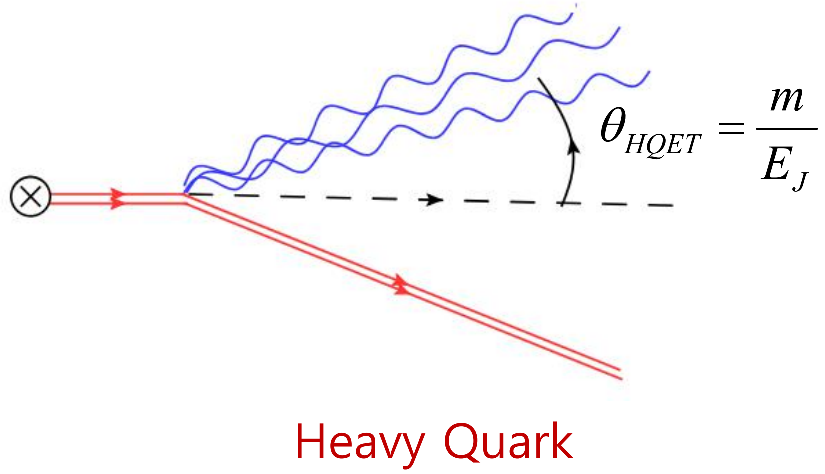
$$q_\perp \sim m(1-z) \sim m z_{cut} << m$$

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

ultra-collinear HQET mode

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

- $S_G(E_J z_{cut})$: jet boundary soft function
- $H(m)$: HQET matching coefficient
- $B_+(q_\perp, (1-z), m)$: Boosted HQET jet function



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

$$p \sim (1-z)E_J(1, \theta_{HQET}^2, \theta_{HQET})$$

ultra-collinear HQET mode

$$p \sim (1-z)E_J(1, \theta_{cs}^2, \theta_{cs})$$

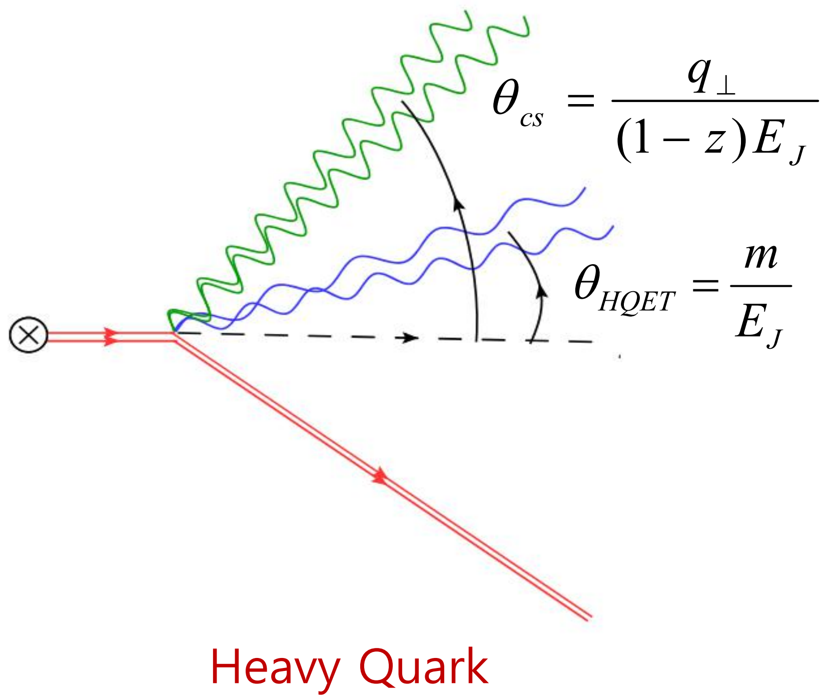
Collinear-Soft mode

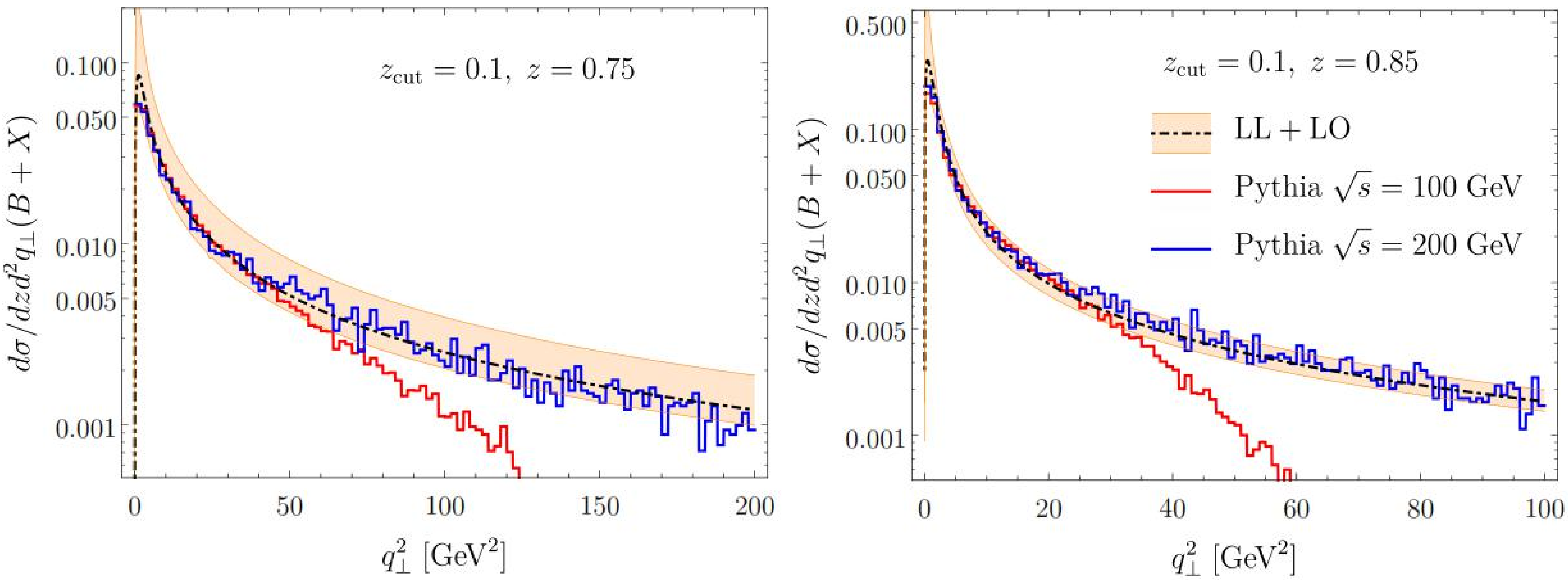
$$\theta_{cs} = \frac{q_\perp}{(1-z)E_J} >> \theta_{HQET}$$

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

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

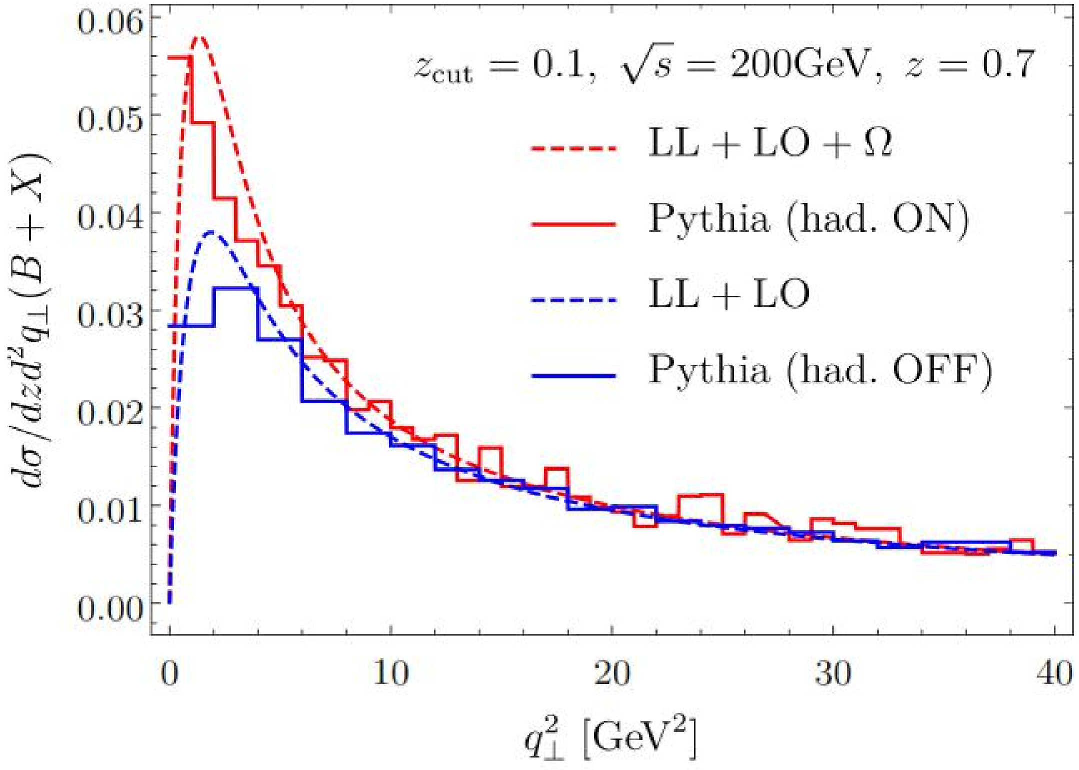
- $S_G(E_J z_{cut})$: jet boundary soft function
- $H(m)$: HQET matching coefficient
- $S_c(E_J z_{cut}, q_\perp, 1-z)$: Collinear soft function
- $B_+(1-z, m)$: Boosted HQET jet function





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

Non-perturbative effects



$$\frac{d\sigma}{d^2 q_\perp dz} = \frac{d\sigma}{d^2 q_\perp dz} \otimes F(z)$$

$$F(z) = \delta\left((1-z) - \frac{\Omega}{m} \right)$$

- A simple shift in the value of z

Summary

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

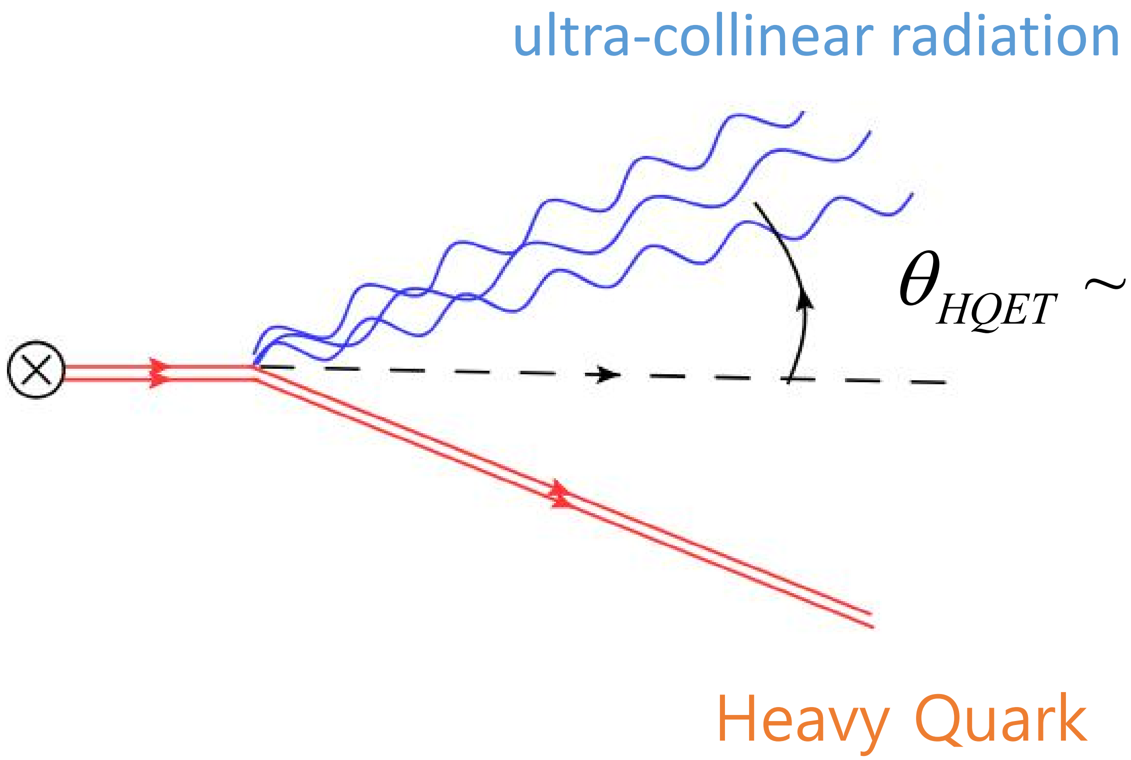
- Two classes of observables considered:

  Energy correlators

  Transverse spectrum of a single heavy hadron at threshold

- Useful for studying TMD physics of heavy quarks
- A template for studying medium effects in QGP

(Boosted) Heavy Quark Effective Theory



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

$$p \sim \Gamma \frac{E_q}{m}\left(1, \theta_{HQET}^2, \theta_{HQET}\right)$$

$$\Gamma << m$$

is the IR scale of the EFT imposed by measurement