# *Extracting a Short Distance Top Mass with Light Grooming*

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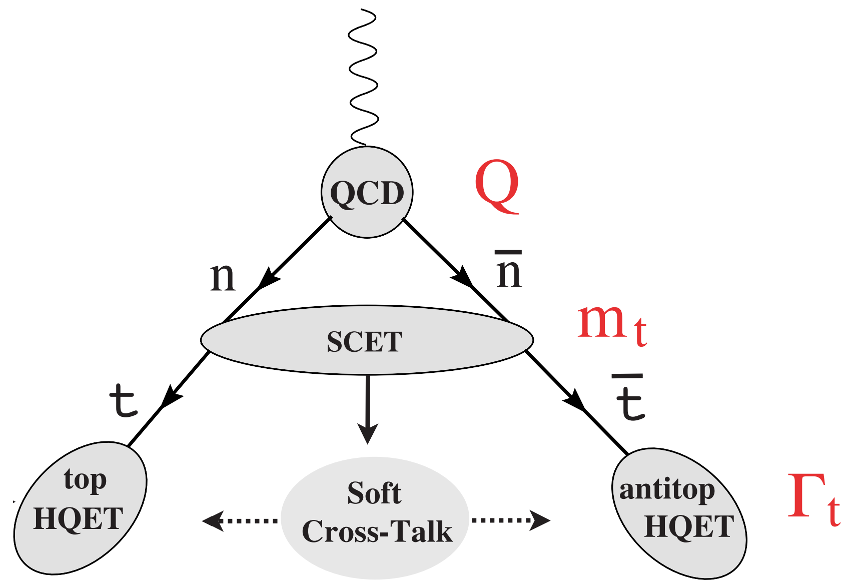
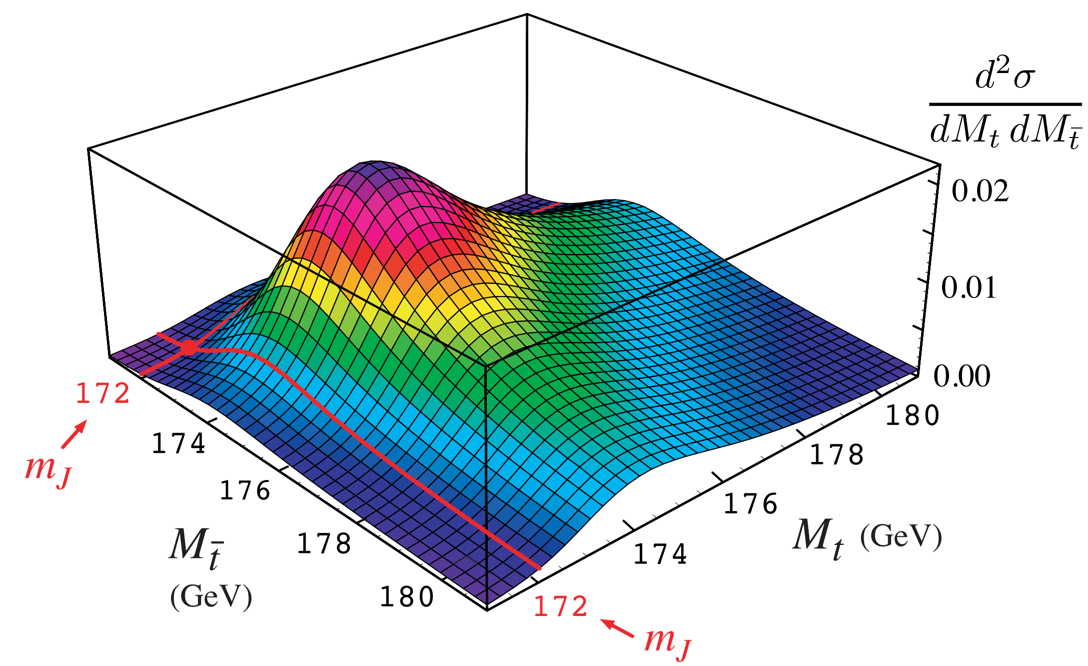
# Top Mass from Boosted Top Jet Distributions

(Fleming, Hoang, SM, Stewart, 2007)

$$e^+e^- \to t\bar{t}X$$




Hard modes integrated out

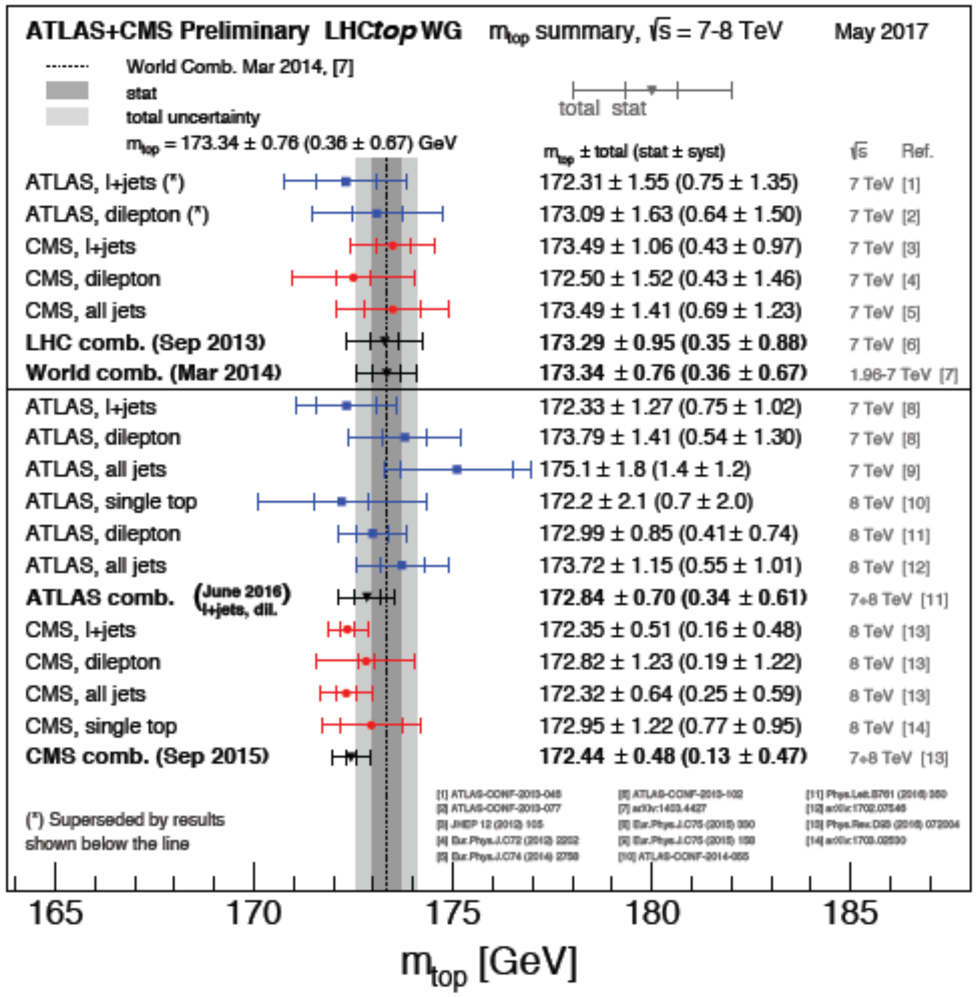
"Hard" collinear modes integrated out

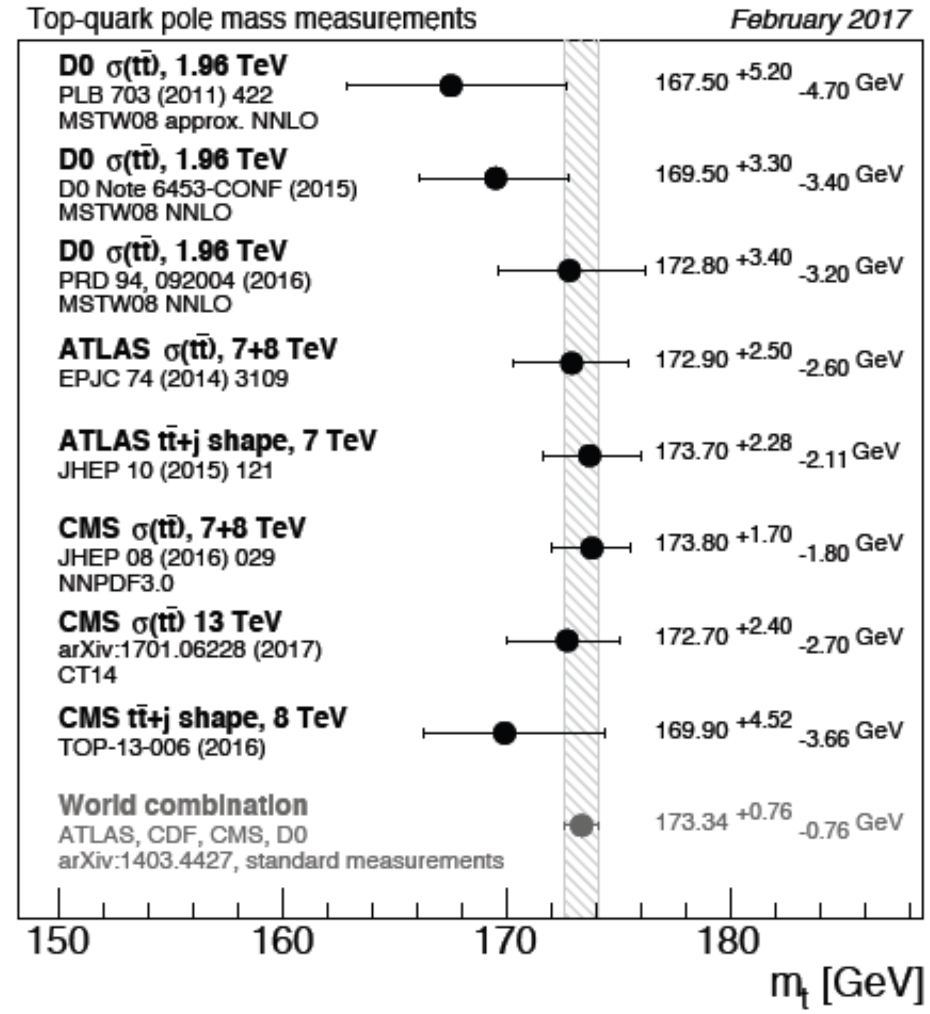
Evolution and decay of top quarks close to mass shell

Soft cross-talk

$$\frac{d\sigma}{dM_t^2\,dM_{\bar{t}}^2} = \sigma_0\, H_Q(Q,\mu_m) H_m\left(m_J, \frac{Q}{m_J}, \mu_m, \mu\right)$$

$$\times \int d\ell^+ d\ell^- B_+\left(\hat{s}_t - \frac{Q\ell^+}{m_J}, \Gamma_t, \mu\right) B_-\left(\hat{s}_{\bar{t}} - \frac{Q\ell^-}{m_J}, \Gamma_t, \mu\right) S(\ell^+, \ell^-, \mu)$$




- Most precise top mass extractions come from direct reconstruction techniques

$$m_t^{\rm MC} = 172.44(49){\rm GeV}({\rm CMS})$$
$$m_t^{\rm MC} = 172.84(70){\rm GeV}({\rm ATLAS})$$
$$m_t^{\rm MC} = 174.34(64){\rm GeV}({\rm Tevatron})$$

- Additional 0.5 ~ 1 GeV uncertainty from relating Monte Carlo mass parameter $m_t^{\rm MC}$ to a well-defined top mass renormalizaton scheme.

# Factorization for Boosted Tops at Hadron Colliders

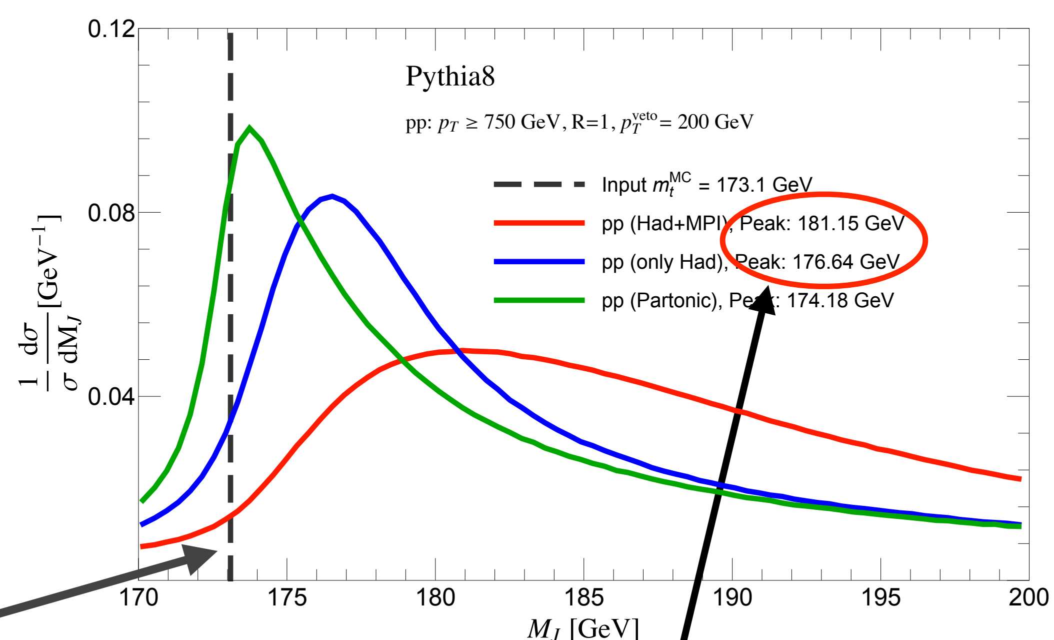
(Hoang, SM, Pathak, Stewart)

$$\frac{d^2\sigma}{dM_{J1}^2 dM_{J2}^2 d\mathcal{T}^{\rm cut}} = {\rm tr}\big[\hat{H}_{Qm}\hat{S}(\mathcal{T}^{\rm cut}, R, \ldots)\otimes F\big]\otimes J_B \otimes J_B \otimes \mathcal{I}\mathcal{I} \otimes f\, f$$

Hard function — Soft function — Top HQET jet functions (identical to lepton collider!) — ISR — PDFs

- Jet mass spectrum is quite sensitive to contamination:

**Effect of UE/MPI**

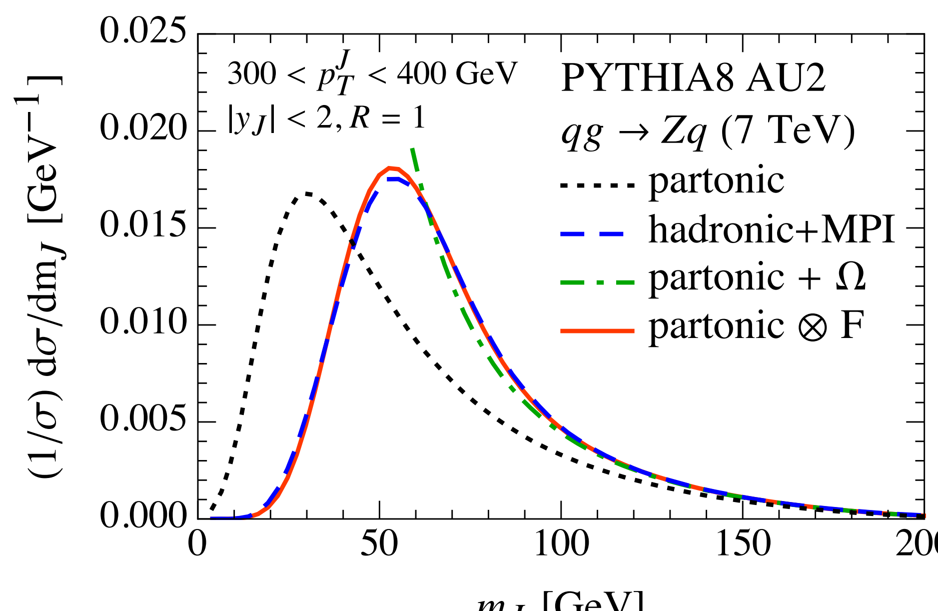



Input mass in Pythia
$m_t$ = 173.1 GeV

Significant contamination

- Same soft model for hadronization can describe UE

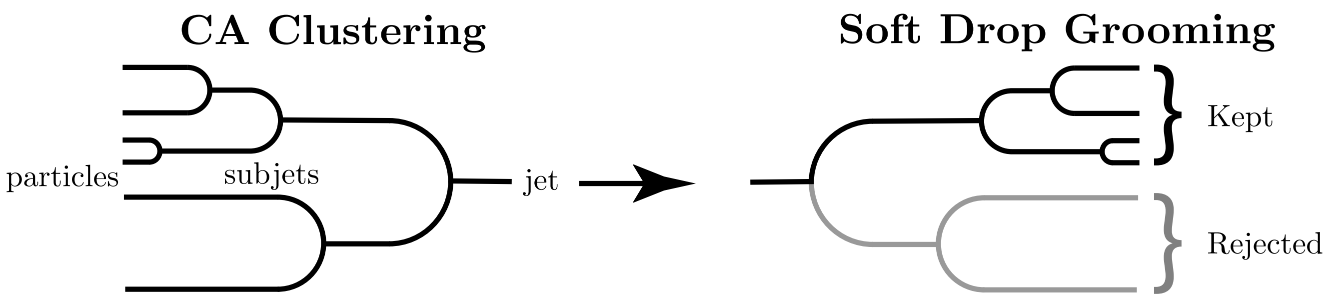
(Stewart, Tackmann, Waalewijin)

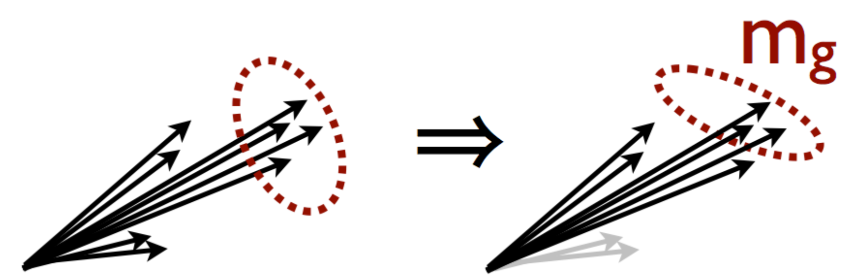


# Soft Drop

(Larkoski, Marzani, Soyez, Thaler, 2014)

- Soft drop grooming reduces sensitivity of the jet mass spectrum to soft contamination.

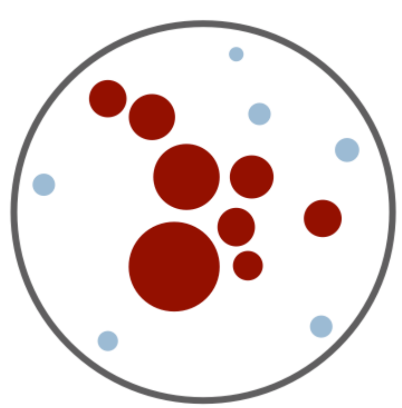


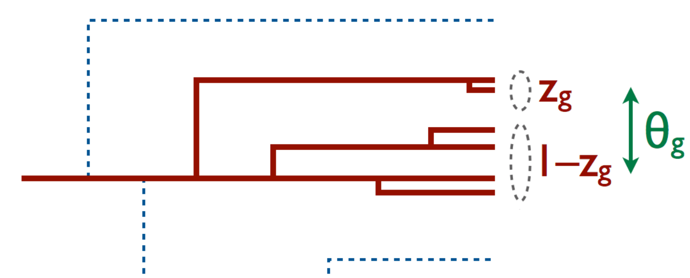

$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

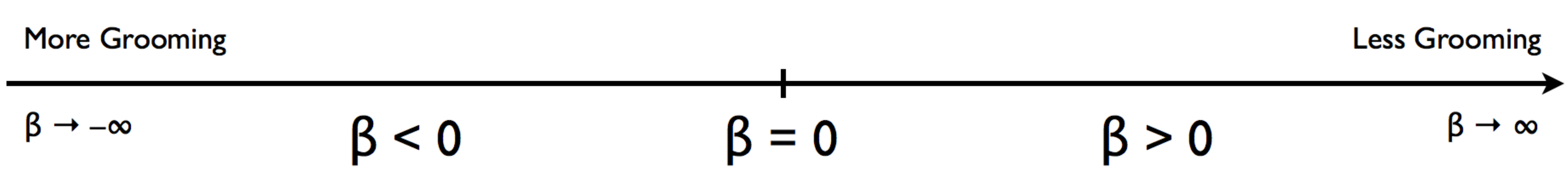
$$z > z_{\rm cut}\ \theta^{\beta}$$

## Groomed jet



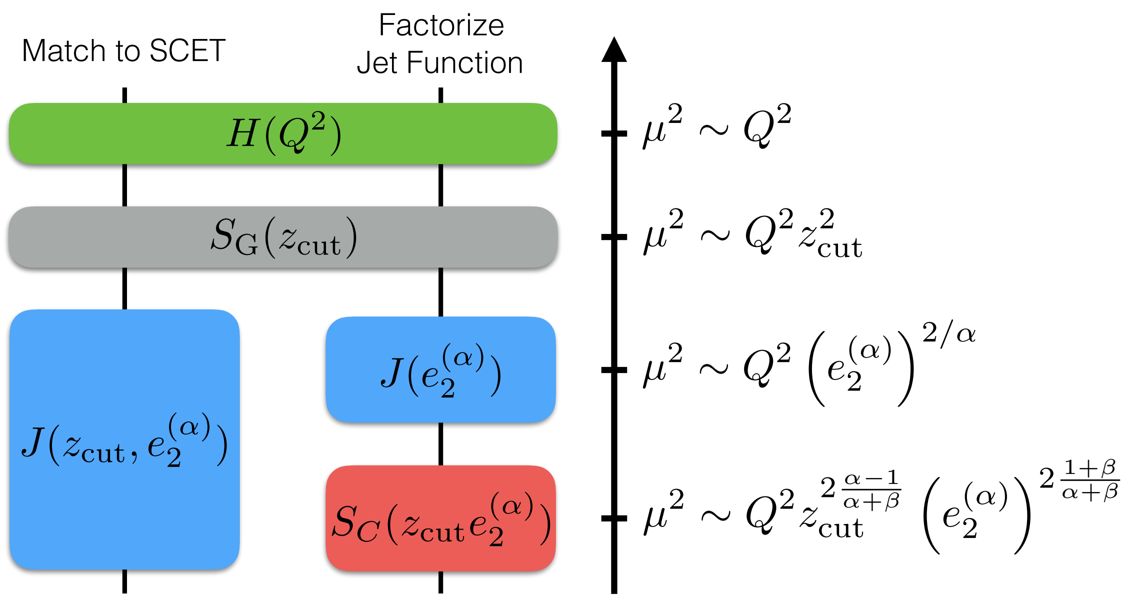
## Groomed Clustering tree

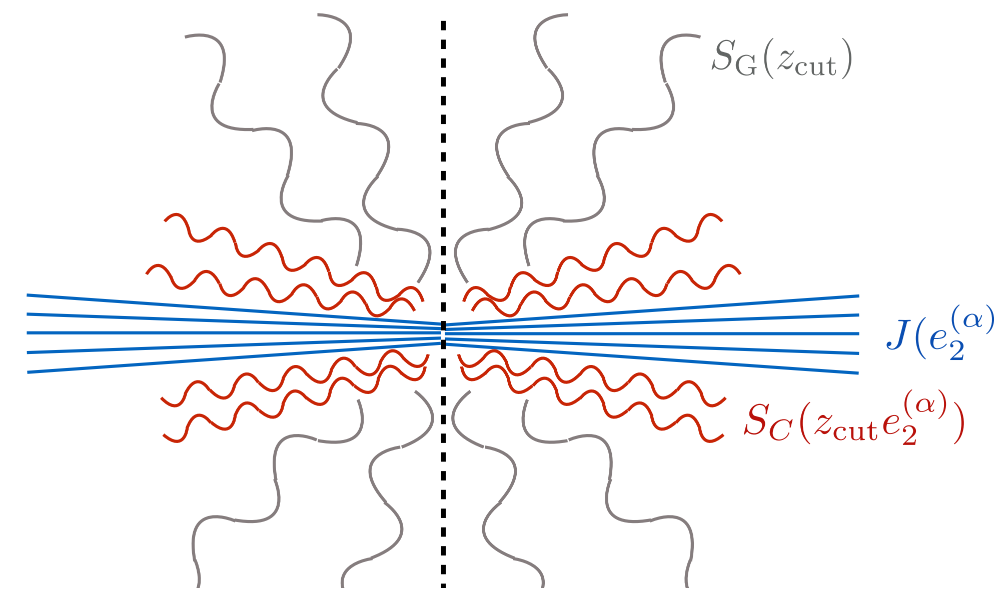


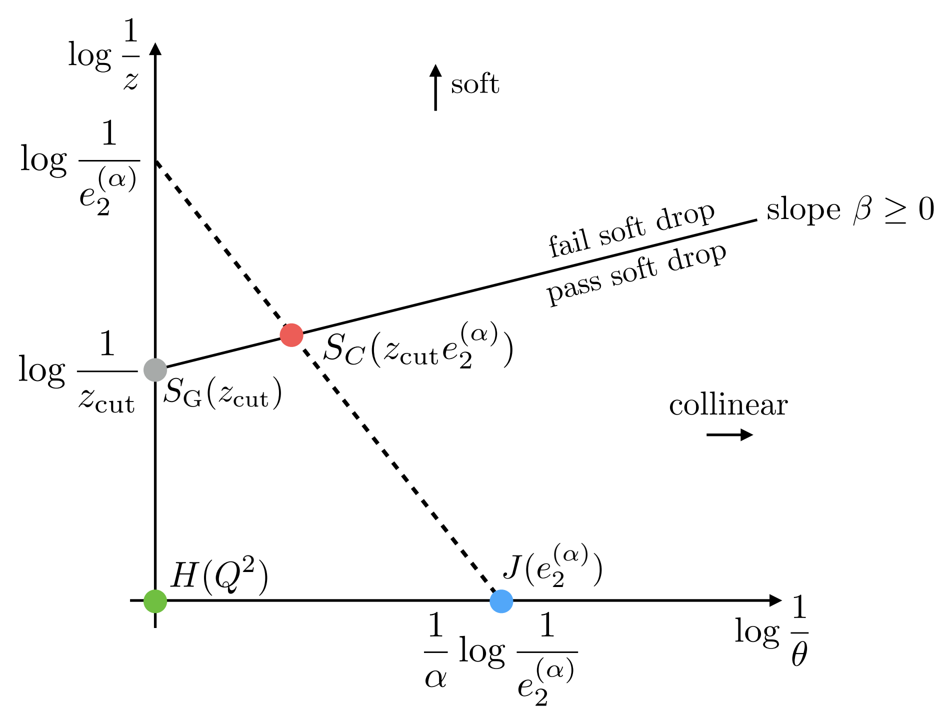



# Soft Drop Factorization

(Fyre, Larkoski, Schwartz, Yan, 2016)




- Factorization

$$\frac{d^2\sigma}{de_{2,L}^{(\alpha)}\, de_{2,R}^{(\alpha)}} = H(Q^2) S_G(z_{cut}) \left[S_C(z_{cut} e_{2,L}^{(\alpha)}) \otimes J(e_{2,L}^{(\alpha)})\right] \left[S_C(z_{cut} e_{2,R}^{(\alpha)}) \otimes J(e_{2,R}^{(\alpha)})\right]$$

- Wide angle soft radiation groomed away
- No non-global logs

# Non-Perturbative Effects in Groomed Massless Jet Spectrum

(See talk by A. Pathak)

Perturbative Coefficient of shift term

Perturbative Coefficient of Boundary term

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\circledcirc}\frac{d}{dm_J^2}\left(C_1(m_J^2, Q, z_{\rm cut}, \beta)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\right) + \frac{\Upsilon_1^\kappa(\beta)}{Q}\,C_2(m_J^2, Q;\, z_{\rm cut}, \beta)\,\frac{d\hat\sigma_\kappa}{dm_J^2}$$

Non-perturbative "shift" term

Non-perturbative "Boundary" term

- Lessons learned:
  - Non-perturbative effects are tied to the perturbative branching history of the jet
  - Two types of non-perturbative effects: "shift correction" and "boundary correction"

- "Shift": contribution from the jet mass from NP radiation kept in the groomed jet

- "Boundary": Modification of the soft drop test on a perturbative subjet in the presence of NP radiation

# NLL Factorization of Groomed Massless Jet Spectrum

- At NLL, at leading order in the OPE, the factorization for the groomed massless jet distribution can be written as:

Global soft function

Jet Function

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \sum_{\kappa=q,g} D_\kappa(\Phi_J, z_{\rm cut}, \beta, \mu) \int_0^\infty d\ell^+ J_\kappa\big(m_J^2 - Q\,\ell^+, \mu\big)$$

Collinear-Soft Function

$$\times \int_0^\infty dk\, S_c^\kappa\Big[\big(\ell^+ - C_1(m_J^2, Q)\,k\big) Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\Big]$$

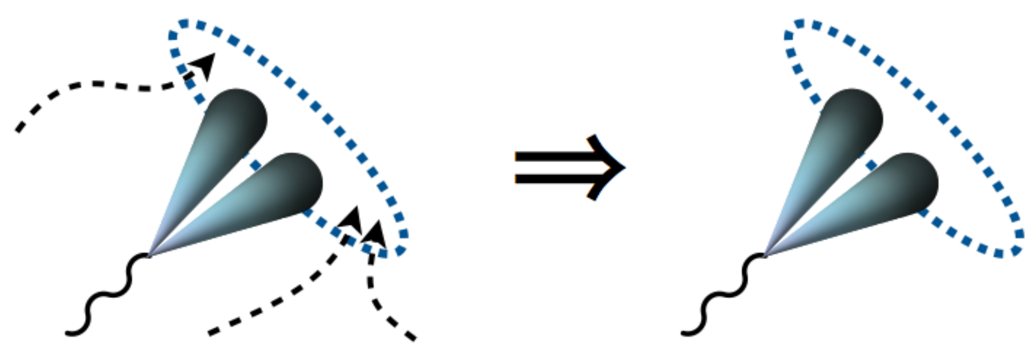
$$\times \left(1 - Q\,k\,\frac{dC_1(m_J^2,Q)}{dm_J^2} + \frac{\Upsilon_1^\kappa(\beta)}{Q} C_2(m_J^2, Q)\right) F_{\oplus}^\kappa(k)$$

Boundary correction

shape function (encode $\Omega_1$ here)

- NP effects are not simply described by a shape function at this order.

# Groomed Top Jet Mass Distribution




(Hoang, SM, Pathak, Stewart arXiv: 1708.02586, v1)

“Decay” Factorization

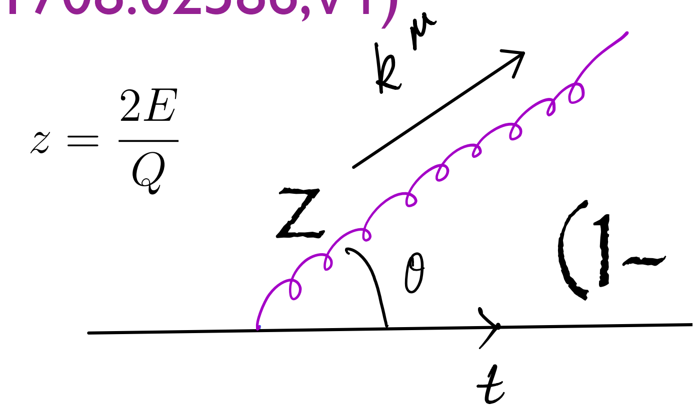
“High-pT” Factorization

update →

Single Factorization Formula

# Top Jet Mass with Soft Drop

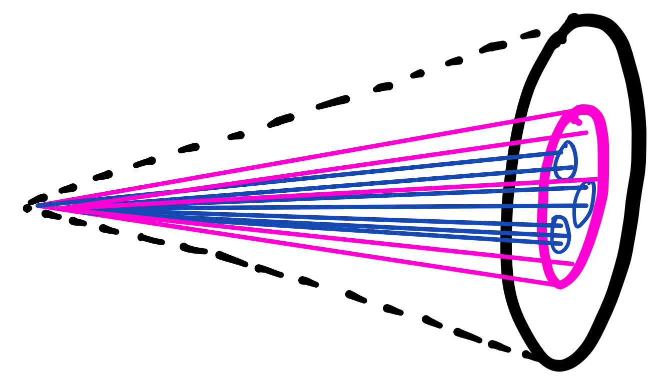
(Hoang, SM, Pathak, Stewart arXiv: 1708.02586,v1)




- We implement soft drop grooming of top jets with three main objectives:

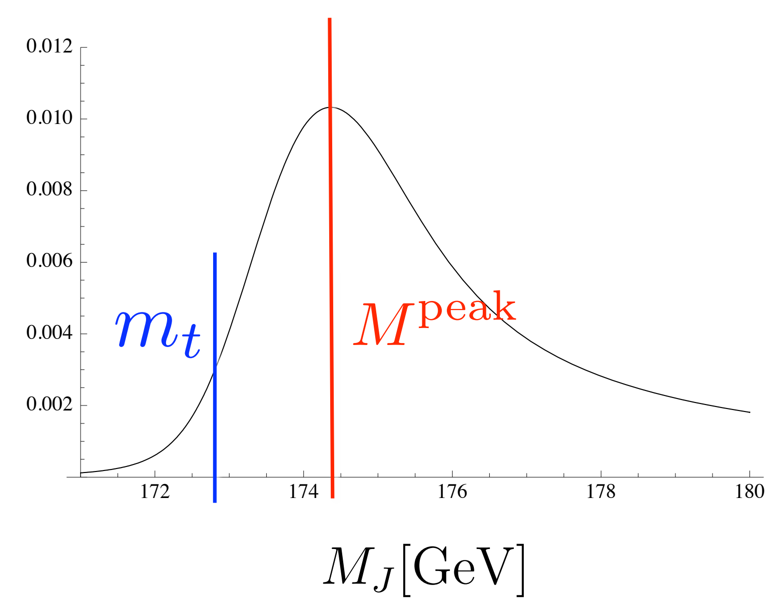
  - Remove most of the soft contamination from the top jet
  - Retain the top decay products within the final groomed jet
  - Leave the top mass scheme information unaffected

$$z > z_{\rm cut}\, \theta^{\beta}$$



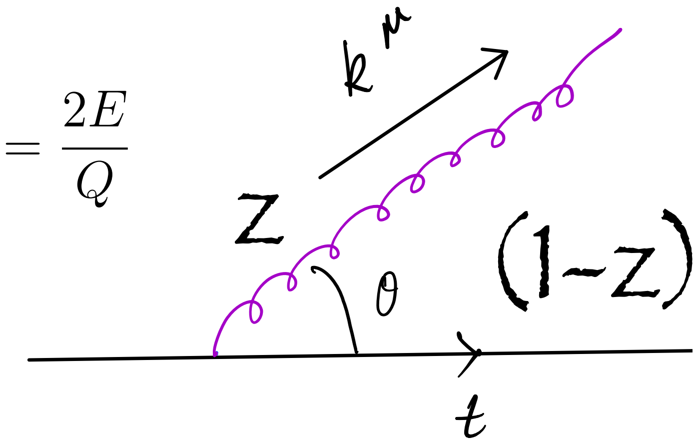
- The peak region of the groomed top jet mass spectrum gives enhanced sensitivity to the top mass:

$$\hat{s} \equiv \frac{M_J^2 - m_t^2}{m_t} \sim \Gamma_t \ll m_t$$

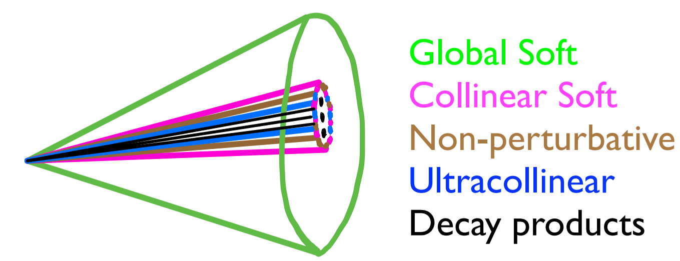


# Light Grooming Region

$$z = \frac{2E}{Q}$$




$$k_j^\mu = (k^+, k^-, k_\perp) = (E(1-\cos\theta), E(1+\cos\theta), k_\perp)$$

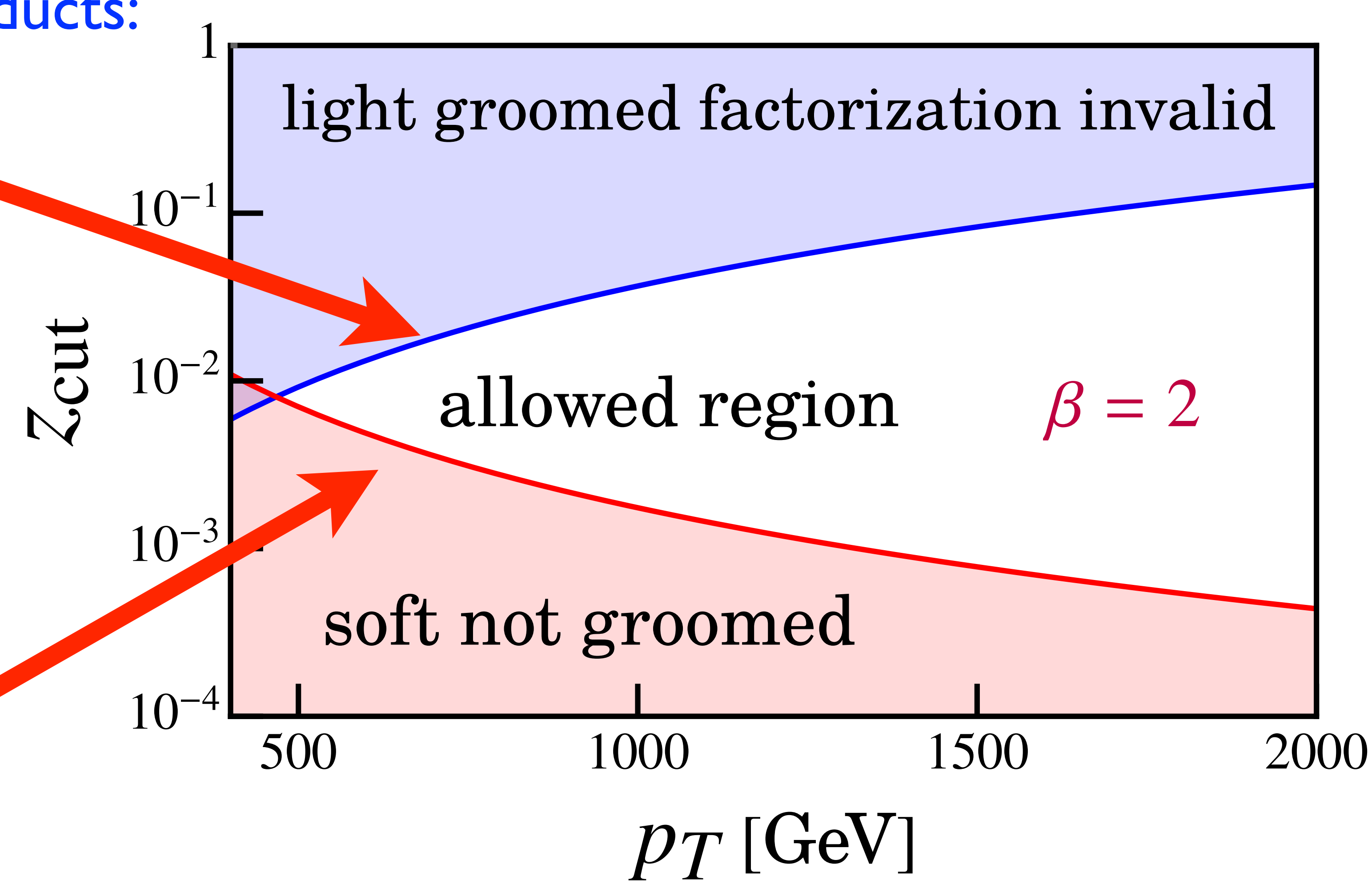



- We use a more restrictive light grooming region that simplifies the theoretical framework:
  - Simplified treatment of decay products:

$$\frac{\Gamma_t}{h^2 m_t}\left(\frac{Q}{2 h m_t \cosh\eta_J}\right)^{\beta} \gtrsim z_{\rm cut}$$

  - Decoupling the effects of energetic collinear radiation in the top jet from wider-angle soft radiation:

$$z_{\rm cut}^{\frac{1}{2+\beta}} \gg \frac{1}{2}\left(\frac{\Gamma_t}{m_t}\frac{4m_t^2}{Q^2}\frac{1}{\cosh^\beta\eta_J}\right)^{\frac{1}{2+\beta}}$$



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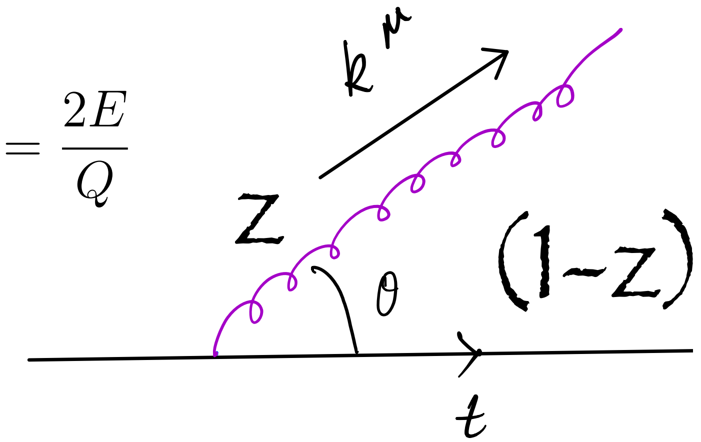


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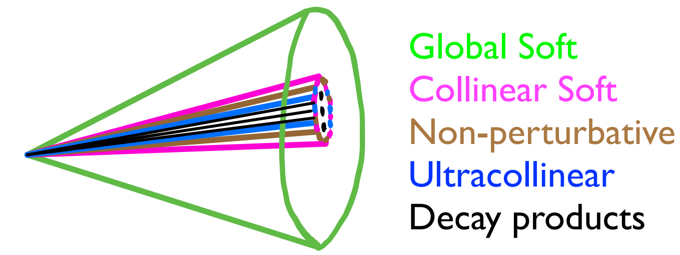


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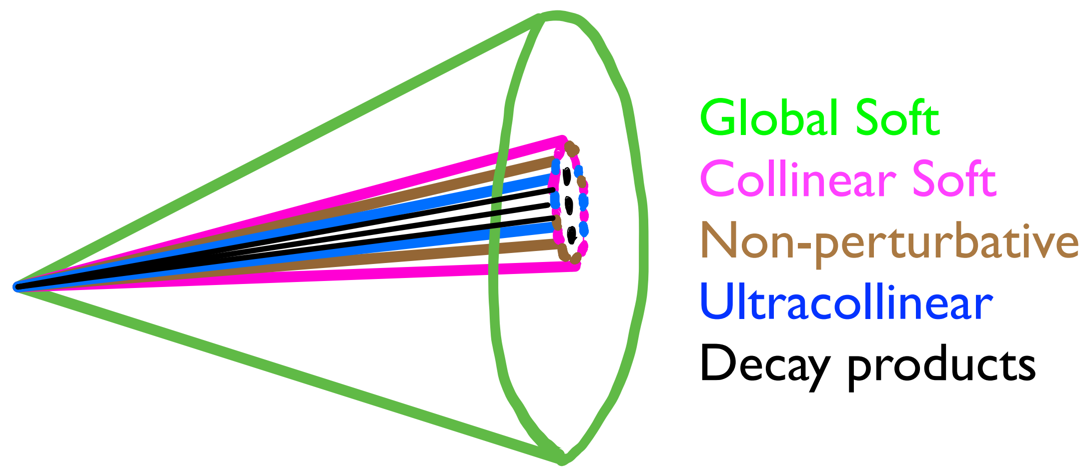
$$z_{\rm cut} \simeq 0.01$$

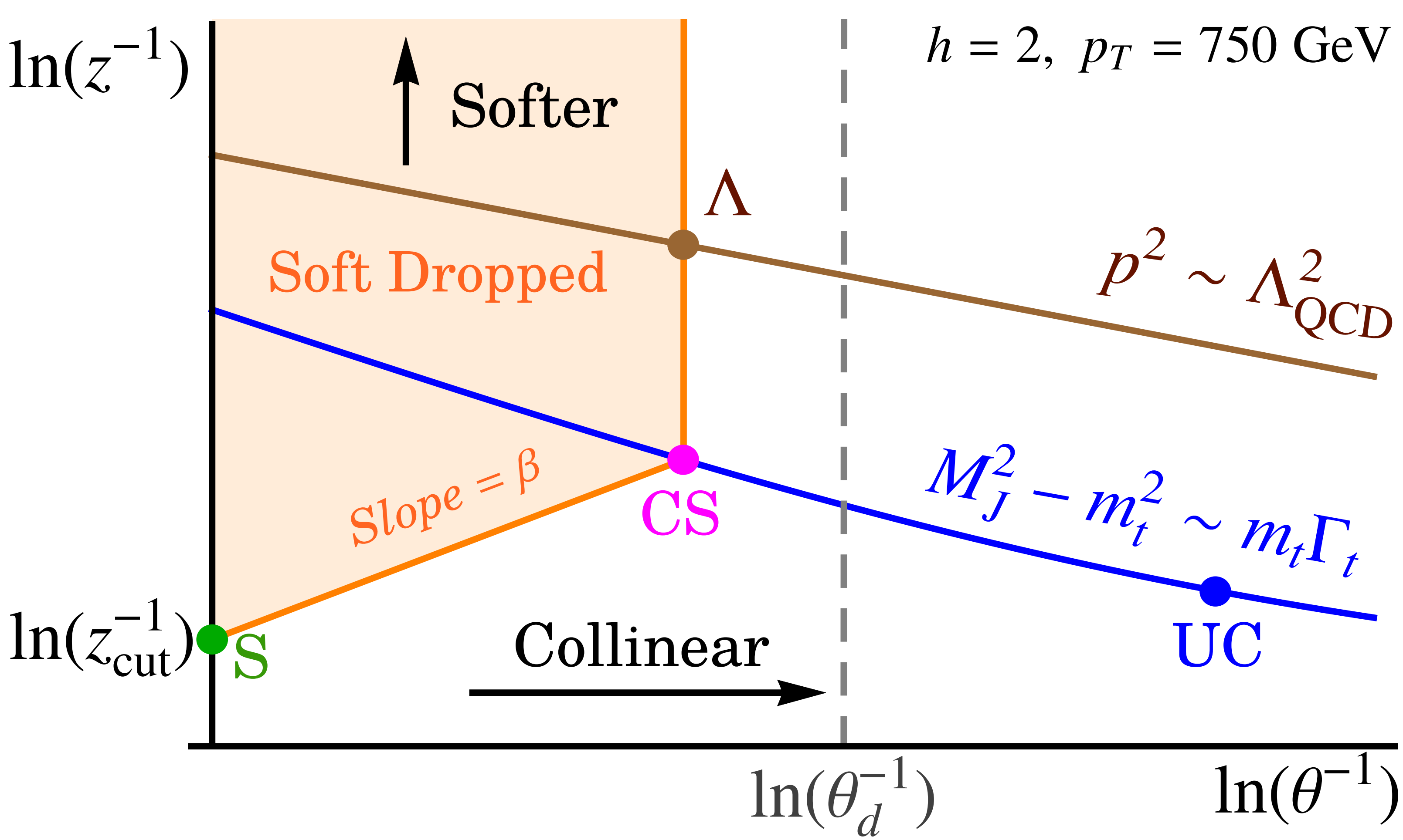
"Light Grooming"

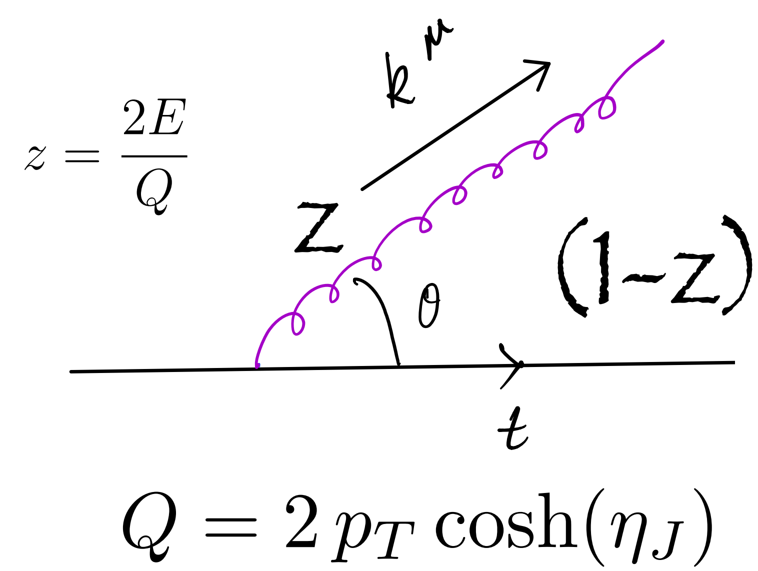
# Effective Theory Modes

- Soft Drop (SD) and Peak Region constraints determine the relevant effective theory modes:

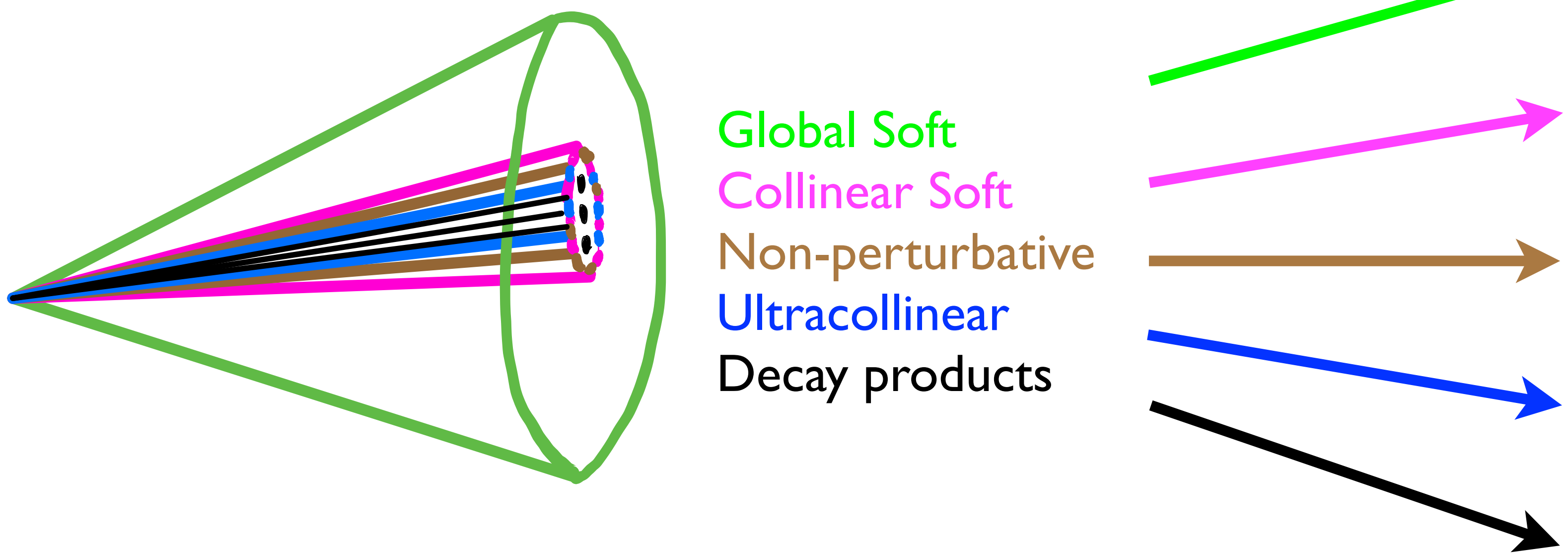



- The relevant effective theory modes:



# Effective Theory Modes: Momentum Scalings




$$p_{S_G} \sim \frac{z_{\rm cut} Q}{2}(1,\, 1,\, 1)$$

$$p^\mu_{\rm cs} \sim \Gamma_t \frac{Q}{m}(\lambda^2,\, \eta^2,\, \lambda\,\eta)$$

will be discussed later

$$p^\mu_{\rm uc} \sim \Gamma_t \frac{Q}{m}(\lambda^2,\, 1,\, \lambda)$$

$$p^\mu_d \sim m\left(\frac{hm}{Q},\, \frac{Q}{hm},\, 1\right)$$

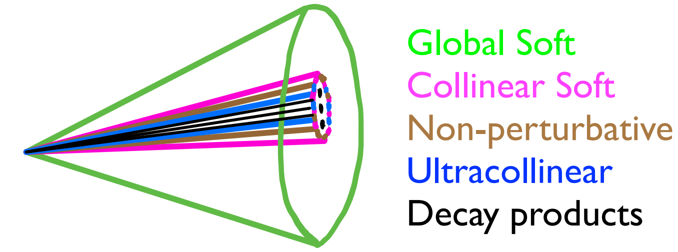
- Expansion parameters:

$$\lambda = \frac{m}{Q} \quad , \qquad \eta \equiv \left[\left(\frac{2m}{Q}\right)^{\beta} z_{\rm cut} \frac{m}{\Gamma_t}\right]^{\frac{1}{\beta+2}}$$

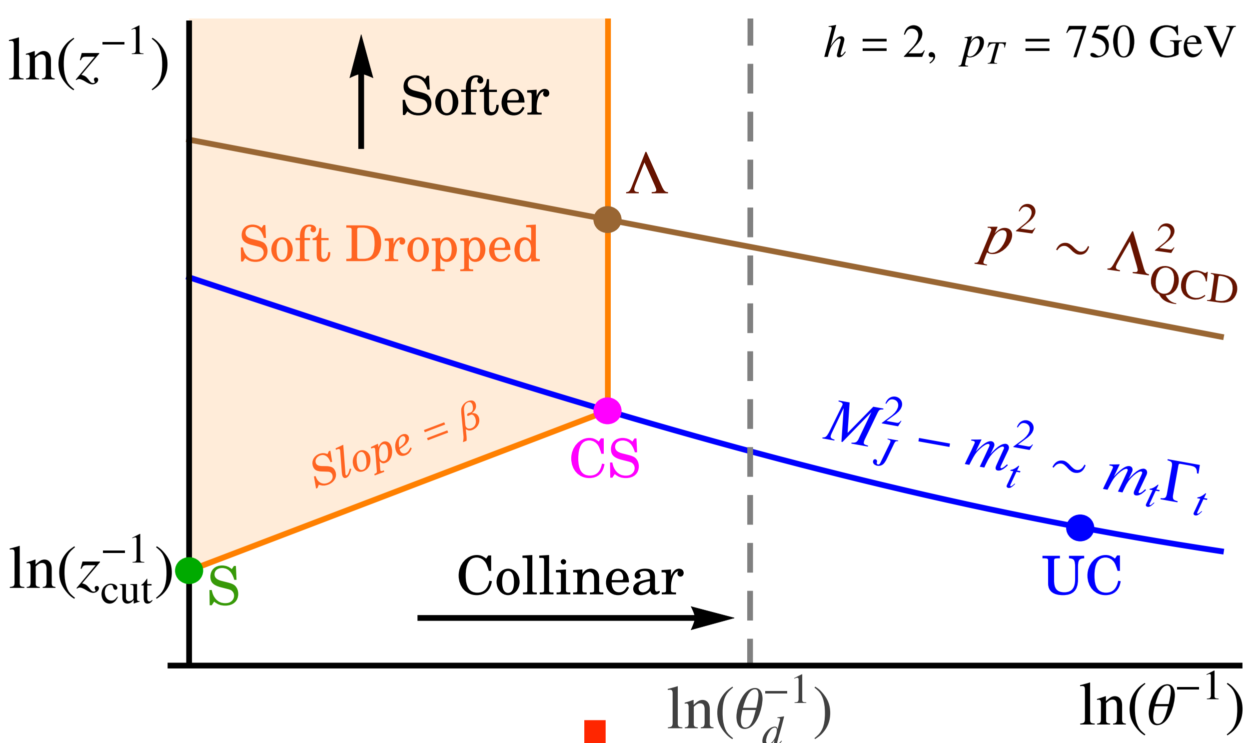
- Hierarchy of expansion parameters

$$1 \gg \eta \gg \lambda$$

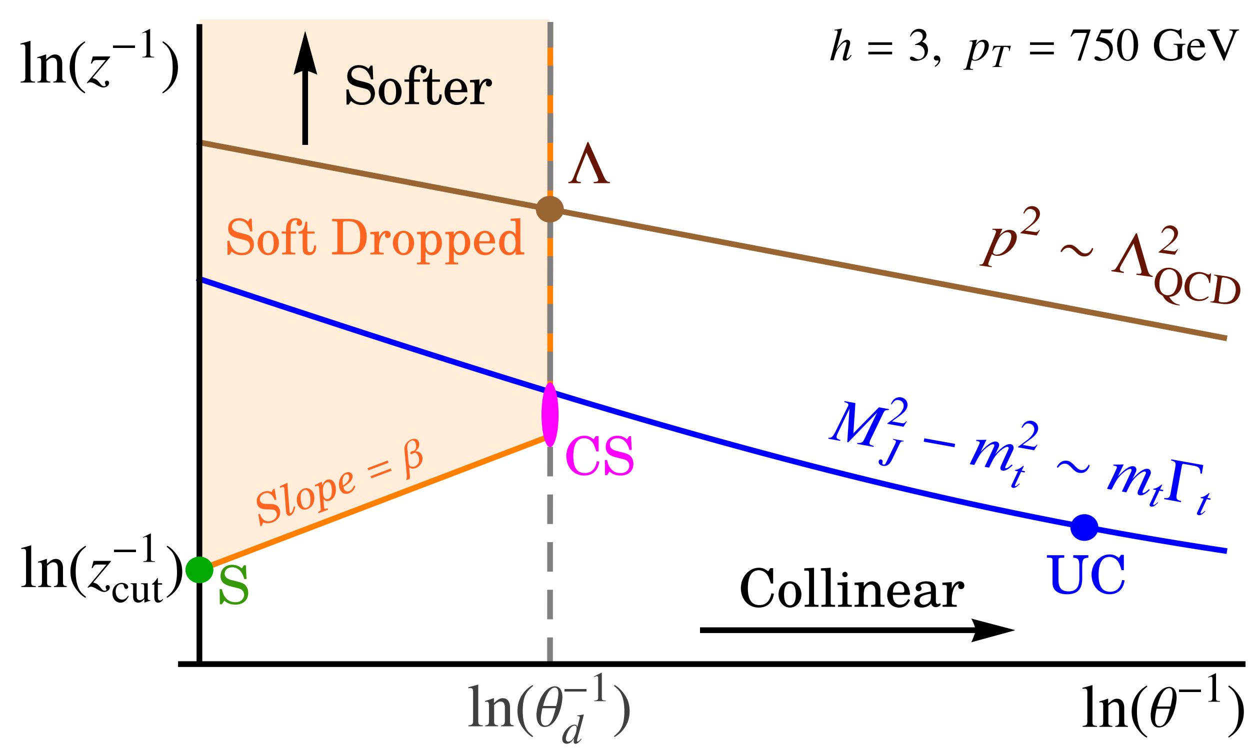
# Factorization with Soft Drop (SD)




- Two possibilities for the termination of soft drop:
  - SD could terminate on a collinear-soft (CS) subjet
  - SD could terminate on a subjet containing top decay products

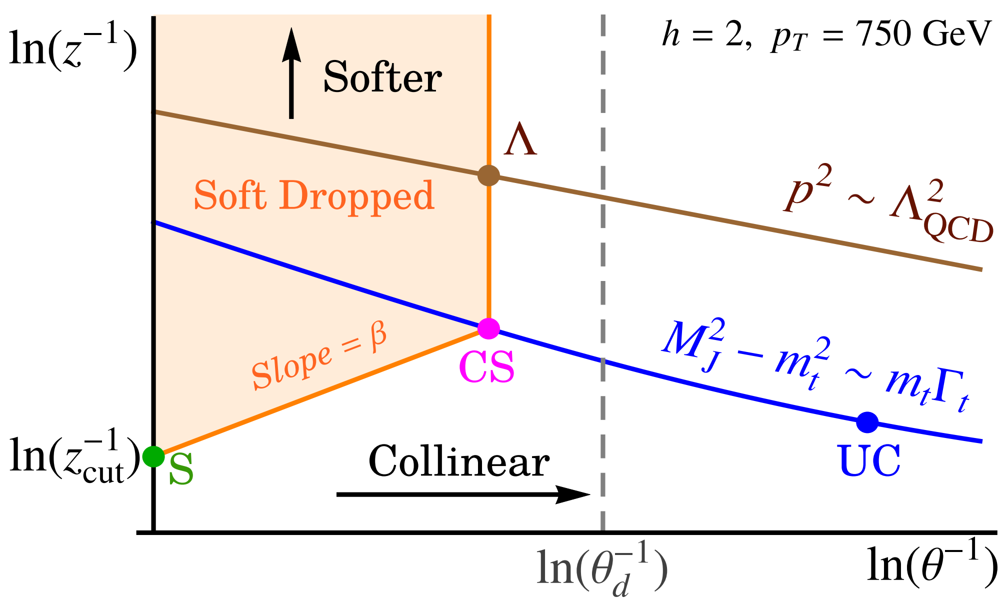


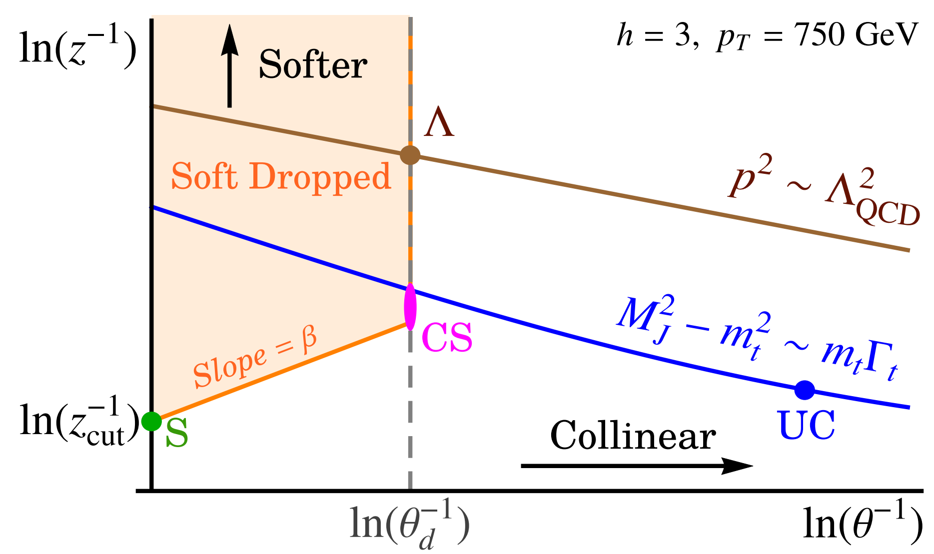

Soft Drop stops
on CS subjet




Soft Drop stops
on top decay product subjet

# Generalized Collinear-Soft function



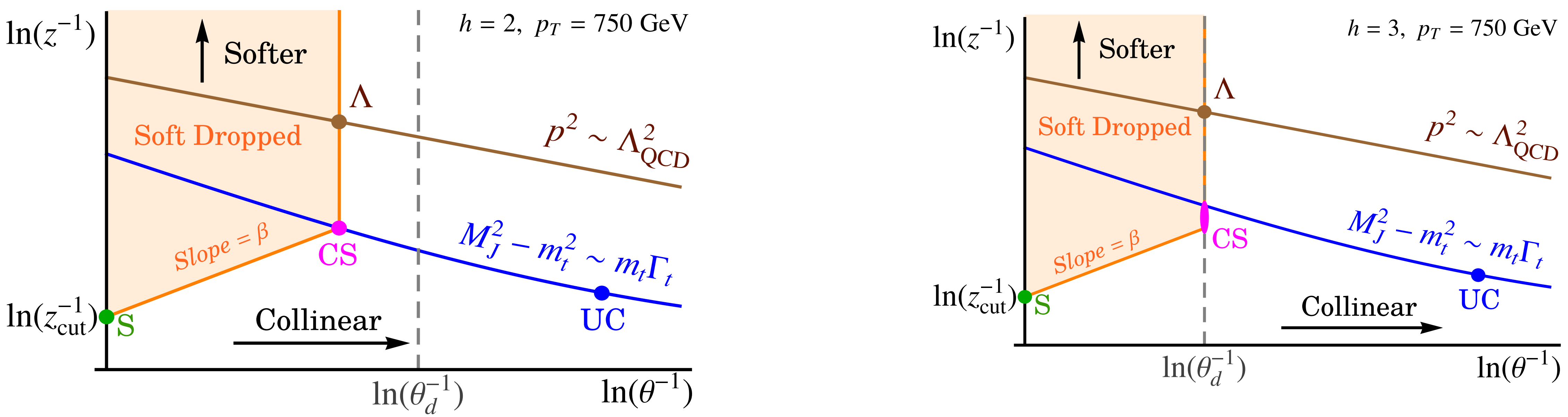

- Collinear-Soft function must compare the angles of the CS and decay subjets:

$$S_C^{(d)}(\ell,\beta,\theta_d,\mu) = S_C^q(\ell,\beta,\mu) - \frac{\alpha_s(\mu)C_F}{(\beta+2)\pi}\frac{2^{\beta+3}}{Q_{\rm cut}\theta_d^{\beta+2}}\mathcal{L}_1\left(\frac{\ell}{Q_{\rm cut}}\frac{2^{\beta+2}}{\theta_d^{\beta+2}}\right)\Theta\left[\frac{Q_{\rm cut}\theta_d^{\beta+2}}{2^{\beta+2}} - \ell\right]$$

Extra term from $\theta_{cs}$ vs $\theta_d$ comparison

No large logs in the light grooming region

# Generalized Collinear-Soft function

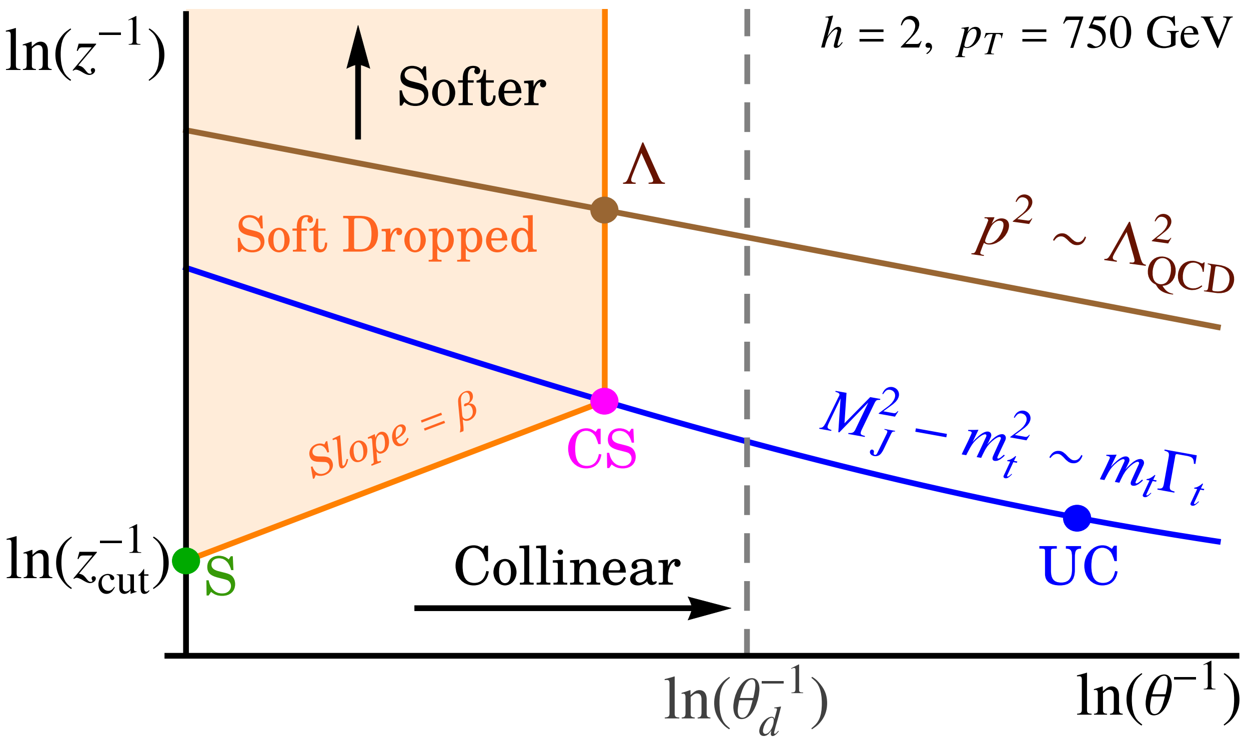


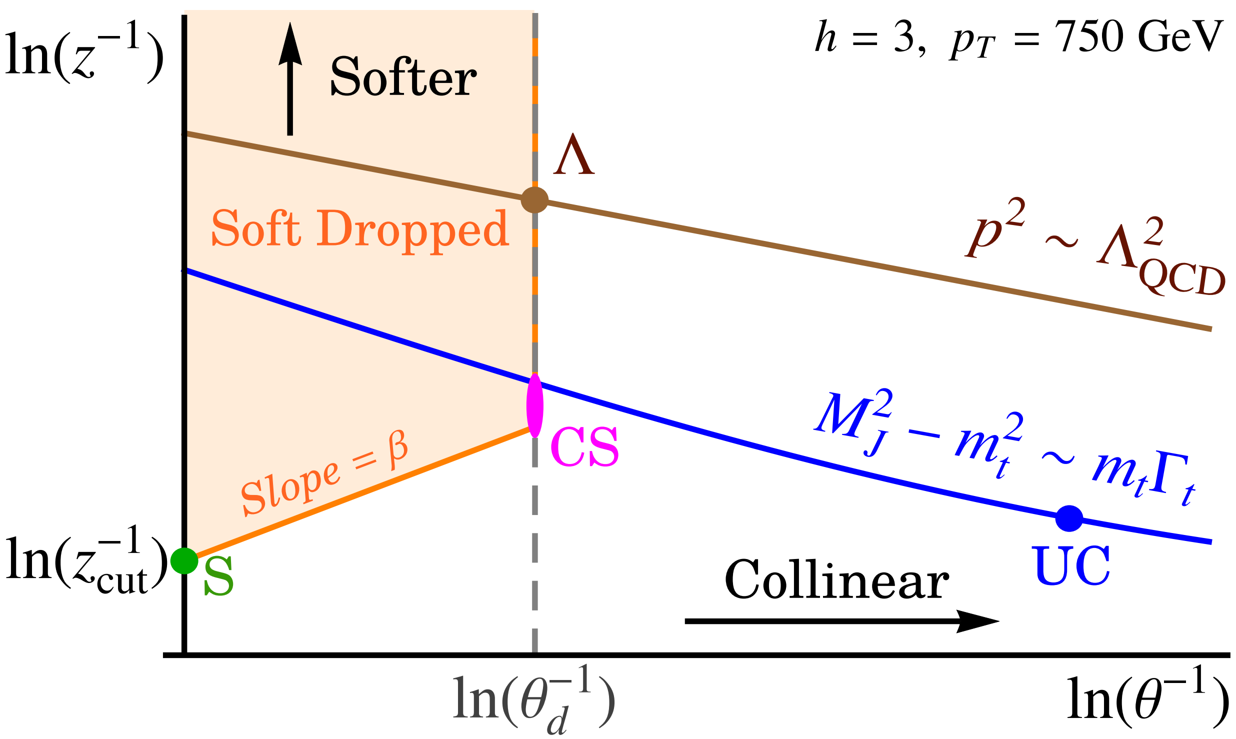

- At NLL, the same perturbative collinear-soft function can be used as in the mass groomed jet case:

$$S_C^{(d)}(\ell, \beta, \theta_d, \mu)\Big|_{\rm NLL} = S_C^q(\ell, \beta, \mu)\Big|_{\rm NLL}$$

- However, we will see that the NP part of the collinear-soft function must still know information about the decay products.

# Combining "High-pT" & "Decay" Factorization



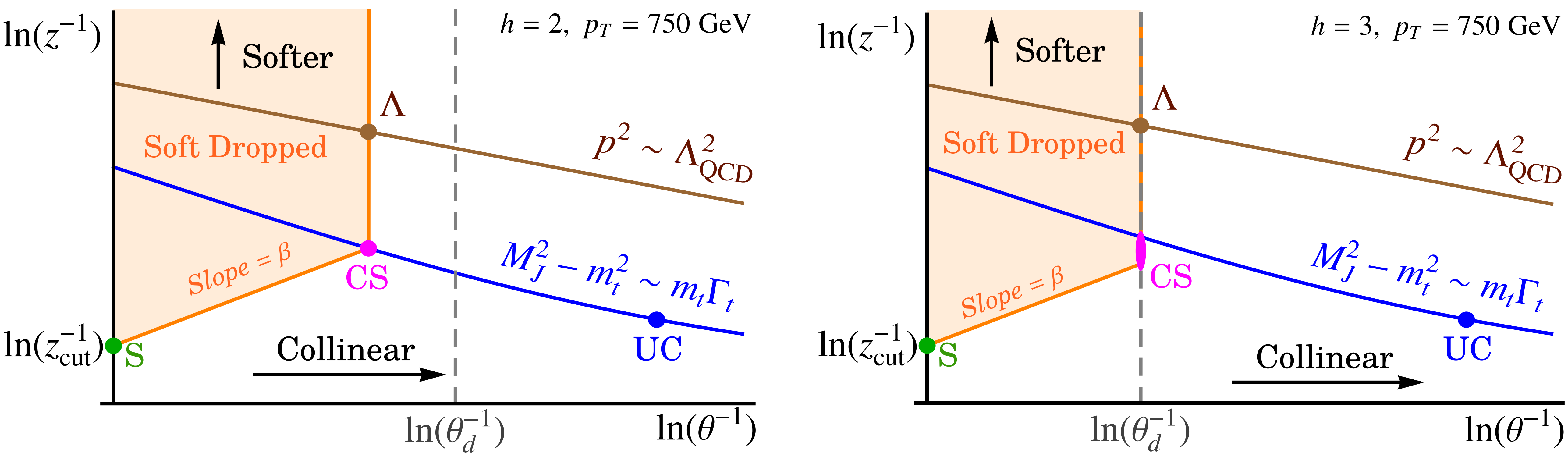




$$\frac{d\sigma}{dM_J} \sim N \otimes S_c(M_J) \otimes J(M_J)$$

Collinear Soft Function must know about decay products to compare:

$$\theta_{cs} \text{ vs } \theta_d$$

# Combining "High-pT" & "Decay" Factorization




$$\frac{d\sigma}{dM_J} \sim N \otimes S_c(M_J) \otimes J(M_J)$$

Collinear Soft Function must know about decay products to compare:

$$\theta_{cs} \text{ vs } \theta_d$$

Jet function must communicate information on $\theta_d$ to the collinear-soft function

# Top BHQET Jet function

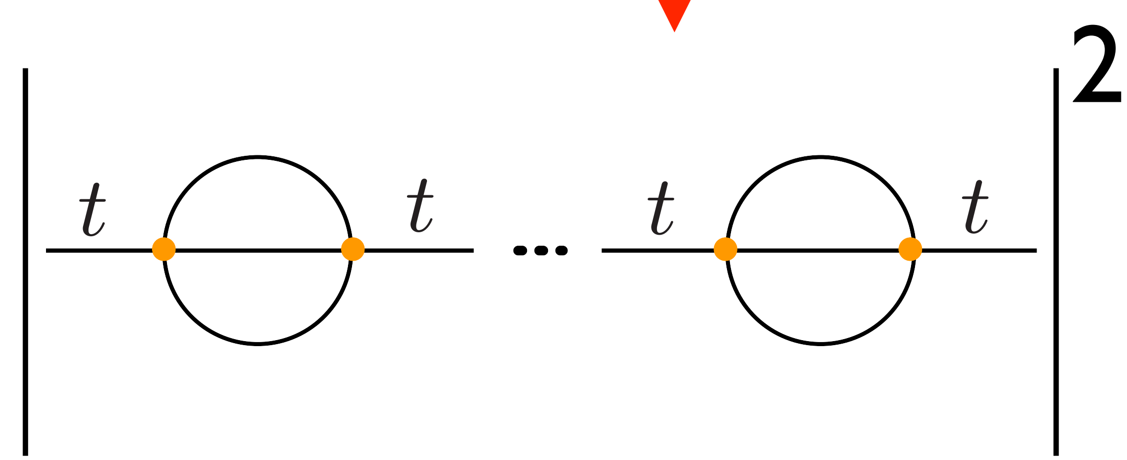
- The unstable BHQET top jet function can be defined in terms of a convolution of the stable top BHQET function and a Breit Wigner:

$$J_B(\hat{s}_t, \Gamma_t, \delta m, \mu) = \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}' \, J_B(\hat{s}_t - \hat{s}', \delta m, \mu) \frac{\Gamma_t}{\pi\left(\hat{s}'^{\,2} + \Gamma_t^2\right)}$$

Unstable top jet function

Stable top jet function

Breit Wigner



# Differential Top BHQET Jet function

- Similarly, we define a stable BHQET top jet function, that is fully differential in the top decay phase space by cutting across one of the "bubbles":

Top Decay Product phase space

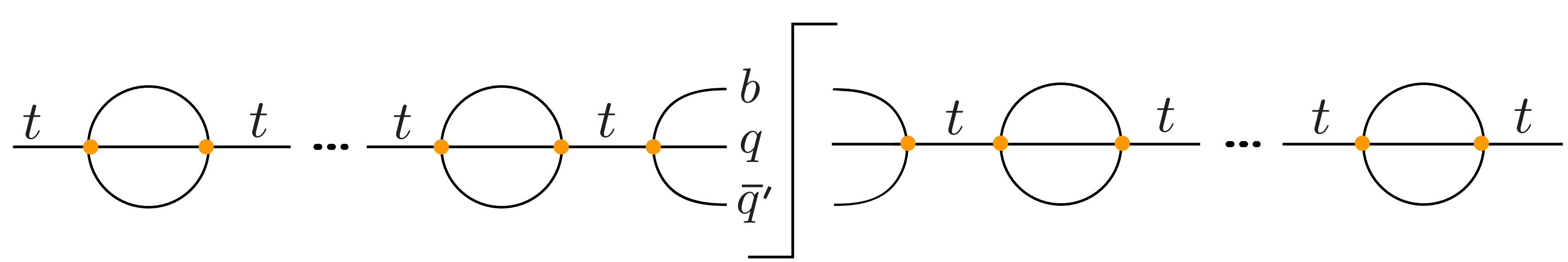
$$J_{D_t}\left(\hat{s}_t, \Phi_d, \frac{m}{Q}, \delta m, \mu\right) = \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}'_t \, J_B^{\Gamma_t=0}(\hat{s}_t - \hat{s}'_t, \delta m, \mu) D_t\left(\hat{s}'_t, \Phi_d, \frac{m}{Q}\right)$$

Stable Differential top jet function

Stable top jet function

$$= \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)} \, d_t\left(\Phi_d, \frac{m_t}{Q}\right)$$

$$d_t\left(\Phi_d, \frac{m_t}{Q}\right) = \frac{1}{\Gamma_{t\to bq\bar{q}'}} \frac{d\Gamma_{t\to bq\bar{q}'}}{d\Phi_d}$$



# Differential Top Jet function

- The unstable BHQET top jet function can be defined in terms of a convolution of the stable top BHQET function and

Top Decay Product phase space

$$J_{D_t}\left(\hat{s}_t, \Phi_d, \frac{m}{Q}, \delta m, \mu\right) = \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}_t'\, J_B^{\Gamma_t=0}(\hat{s}_t - \hat{s}_t', \delta m, \mu) D_t\left(\hat{s}_t', \Phi_d, \frac{m}{Q}\right)$$

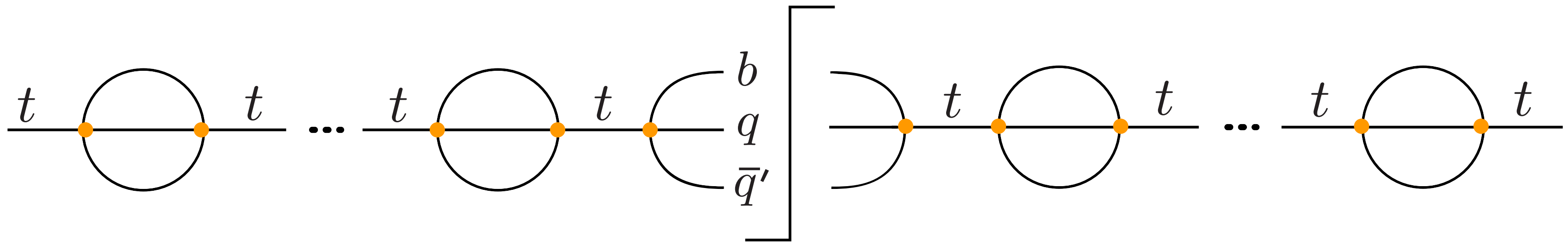
Stable Differential top jet function

Stable top jet function

$$= \frac{\Gamma_t}{\pi(\hat{s}'^{\,2} + \Gamma_t^2)}\, d_t\left(\Phi_d, \frac{m_t}{Q}\right)$$

$$d_t\left(\Phi_d, \frac{m_t}{Q}\right) = \frac{1}{\Gamma_{t\to bq\bar{q}'}} \frac{d\Gamma_{t\to bq\bar{q}'}}{d\Phi_d}$$

Passes decay subjet angle information to the collinear-soft function for comparison



# Differential Top Jet function

$$J_{D_t}\left(\hat{s}_t, \Phi_d, \frac{m}{Q}, \delta m, \mu\right) = \int_{-\infty}^{\hat{s}_t} \mathrm{d}\hat{s}_t' \, J_B^{\Gamma_t=0}(\hat{s}_t - \hat{s}_t', \delta m, \mu) D_t\left(\hat{s}_t', \Phi_d, \frac{m}{Q}\right)$$

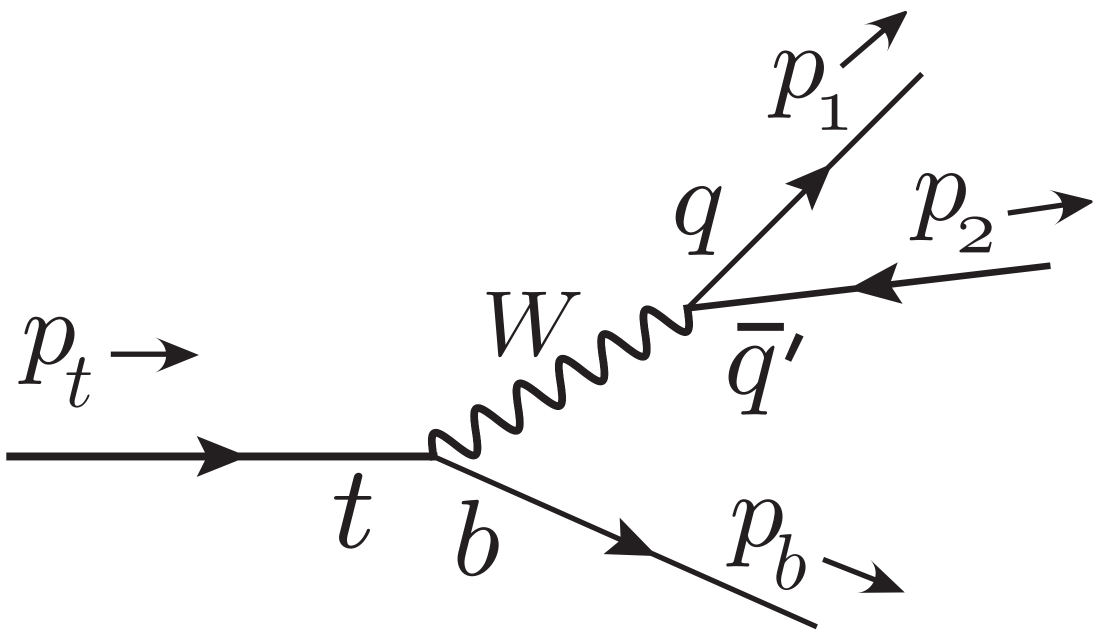
Stable Differential top jet function

Stable top jet function

- Recover the standard inclusive unstable top BHQET function:

$$J_B(\hat{s}_t, \Gamma_t, \delta m, \mu) = \int \mathrm{d}\Phi_d \, J_{D_t}\left(\hat{s}_t, \Phi_d, \frac{m}{Q}, \delta m, \mu\right)$$

# Top Decay: Phase Space & Subjet Angle




- Decay subjet angle:

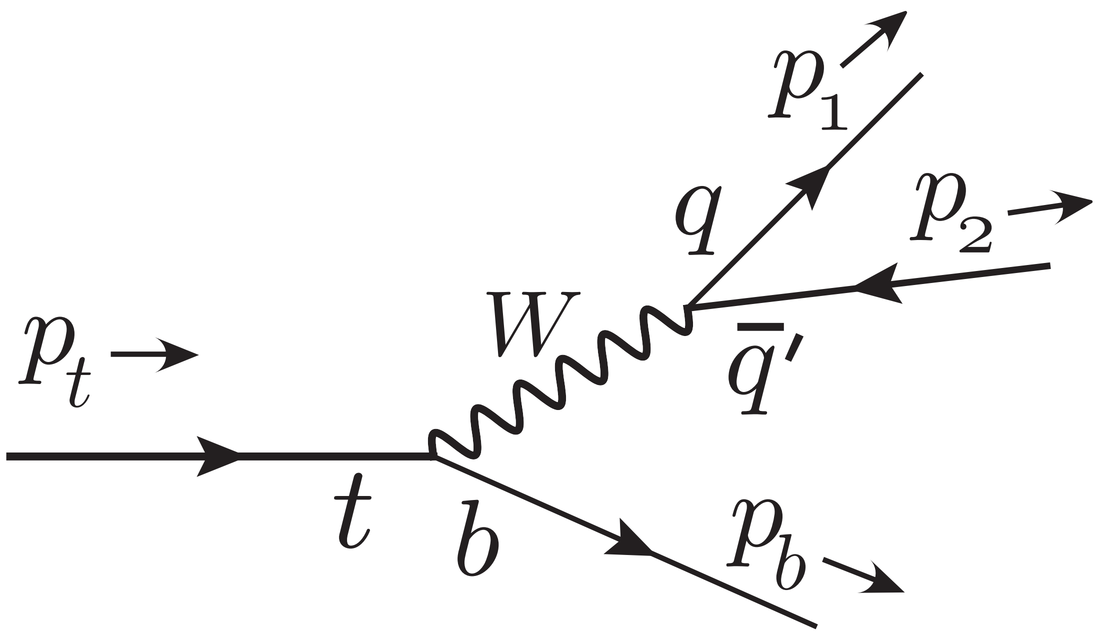
$$\tilde{\theta}_{xy} = \min\left(\tilde{\theta}_{q\bar{q}'}, \tilde{\theta}_{qb}, \tilde{\theta}_{\bar{q}'b}\right)$$

$$\theta_d \equiv \max\left(\tilde{\theta}_{(xy)t}, \tilde{\theta}_{zt}\right)$$

- Top decay subjet momentum scaling:

$$p_d^\mu \sim m\left(\frac{hm}{Q}, \frac{Q}{hm}, 1\right) \longrightarrow h(\theta_d) = \frac{Q}{m}\sqrt{\frac{1-\cos\theta_d}{1+\cos\theta_d}} = \frac{Q}{m}\tan\frac{\theta_d}{2}$$

# Top Decay Subjet Angle



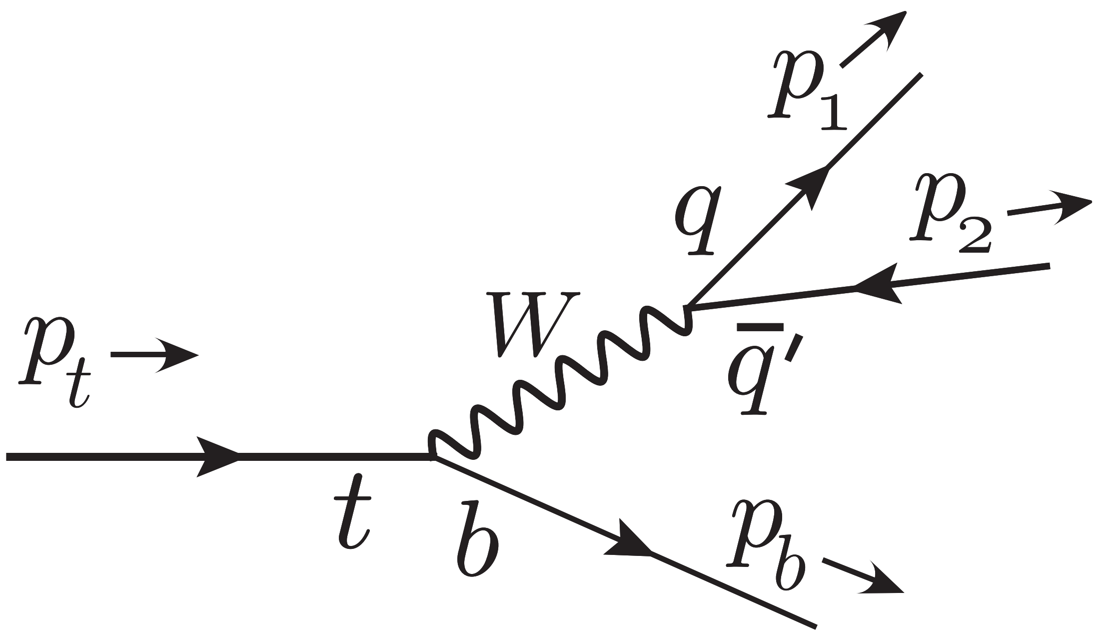

$$d_t\left(\Phi_d, \frac{m_t}{Q}\right) = \frac{1}{\Gamma_{t\to bq\bar{q}'}} \frac{d\Gamma_{t\to bq\bar{q}'}}{d\Phi_d}$$

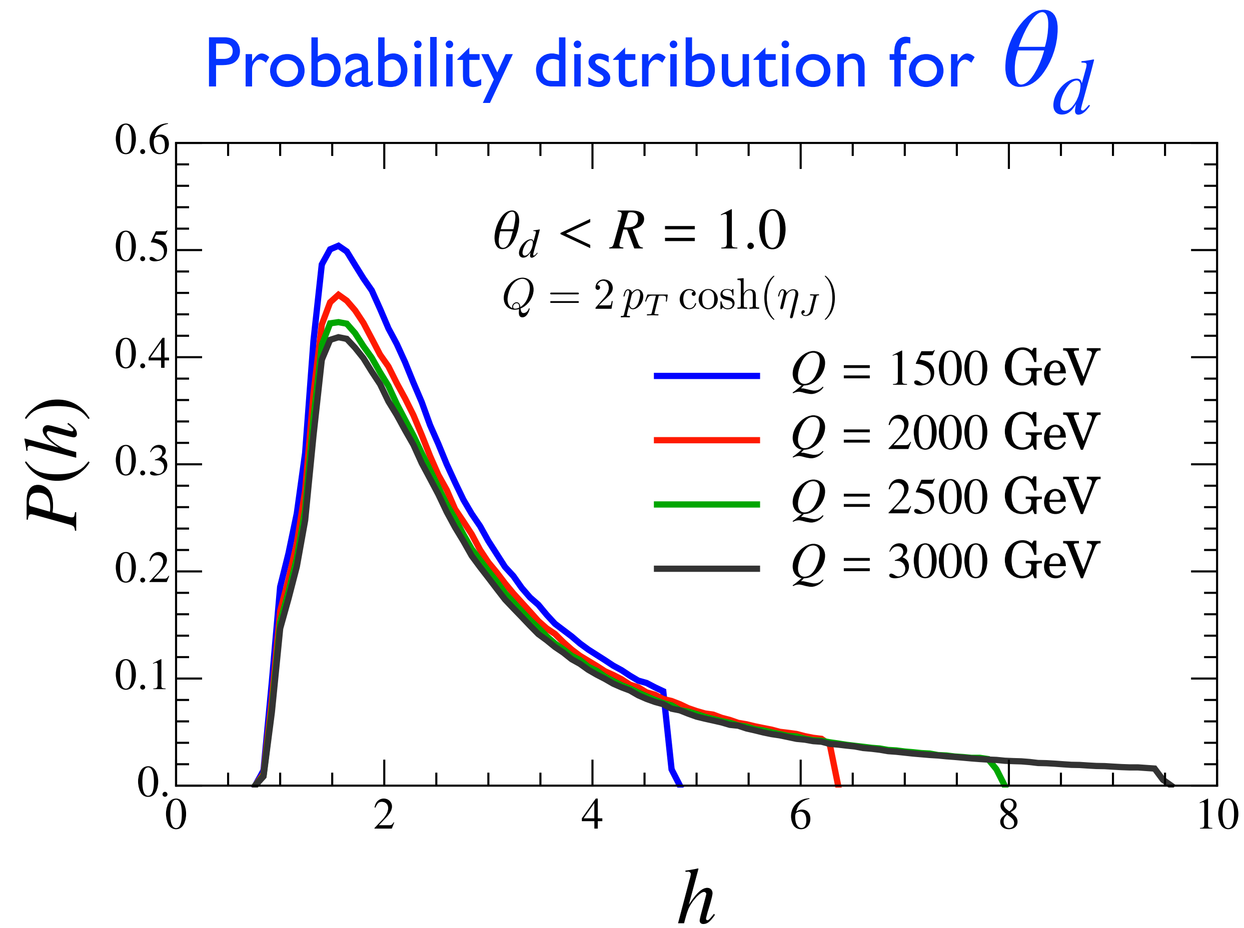
$$P\left(\tilde{h}, \frac{m_t}{Q}\right) = \int_{\mathcal{J}} d\Phi_d \, d_t\left(\Phi_d, \frac{m_t}{Q}\right) \delta\left(\tilde{h} - h(\Phi_d, \frac{m_t}{Q})\right)$$

- Top decay subjet momentum scaling:

$$p_d^\mu \sim m\left(\frac{hm}{Q}, \frac{Q}{hm}, 1\right) \longrightarrow h(\theta_d) = \frac{Q}{m}\sqrt{\frac{1-\cos\theta_d}{1+\cos\theta_d}} = \frac{Q}{m}\tan\frac{\theta_d}{2}$$

# Top Decay Subjet Angle




$$d_t\left(\Phi_d, \frac{m_t}{Q}\right) = \frac{1}{\Gamma_{t\to bq\bar{q}'}} \frac{d\Gamma_{t\to bq\bar{q}'}}{d\Phi_d}$$

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- Top decay subjet momentum scaling:

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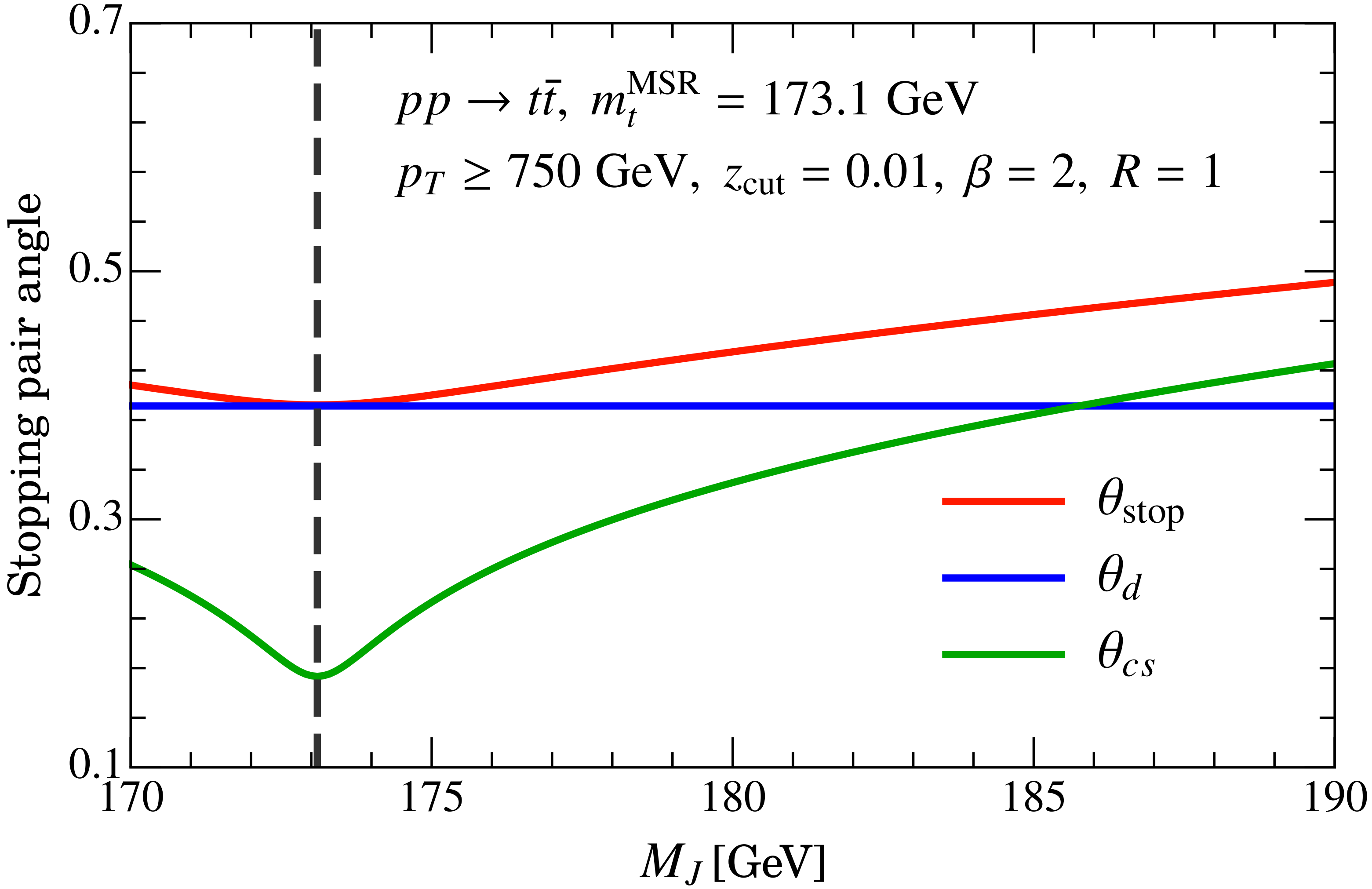


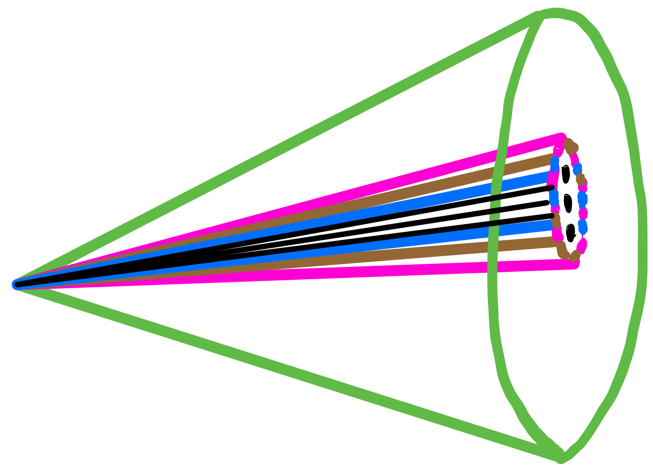

Soft Drop stops on a decay subjet most of the time!

$$\theta_{\rm stop} = 2 \int d\tilde{h}\, P\Big(\tilde{h}, \frac{m_t}{Q}\Big) \times \max\Big\{\arctan\Big(\frac{m_t}{Q}\,\tilde{h}\Big),\ C_1\big(M_J^2 - m_t^2, Q, z_{\rm cut}, \beta\big)\Big\}$$

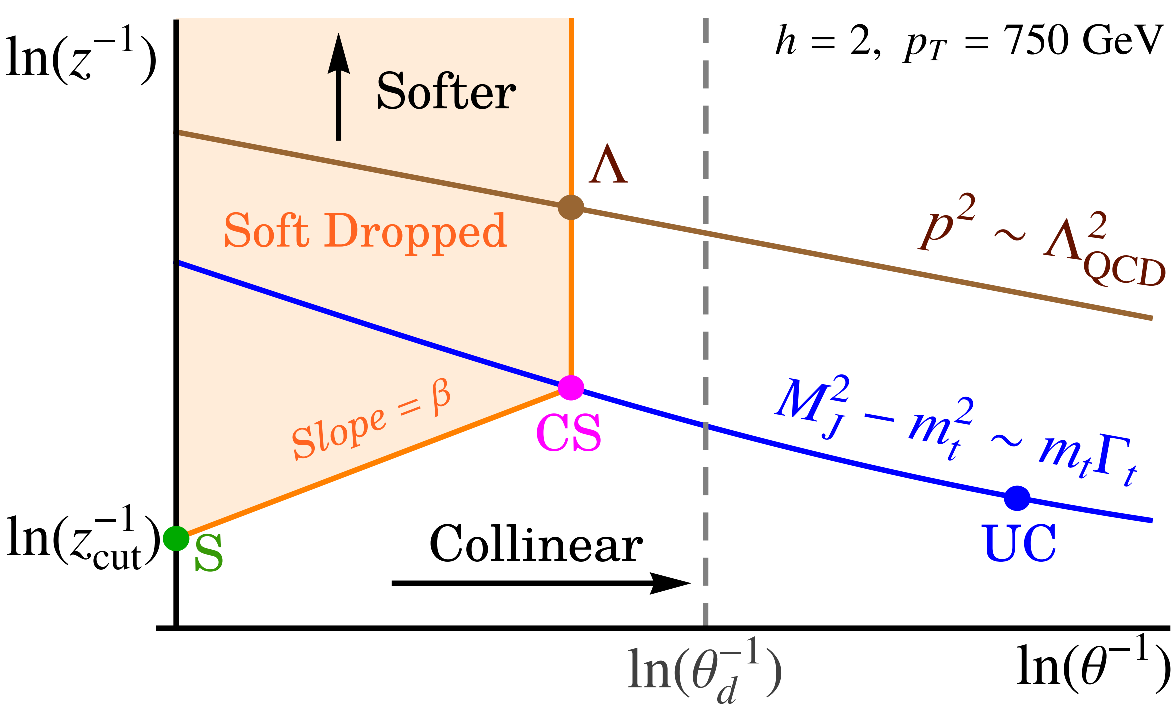
$\downarrow$ $\theta_d$ $\qquad$ $\downarrow$ $\theta_{cs}$ → (See talk by A. Pathak)

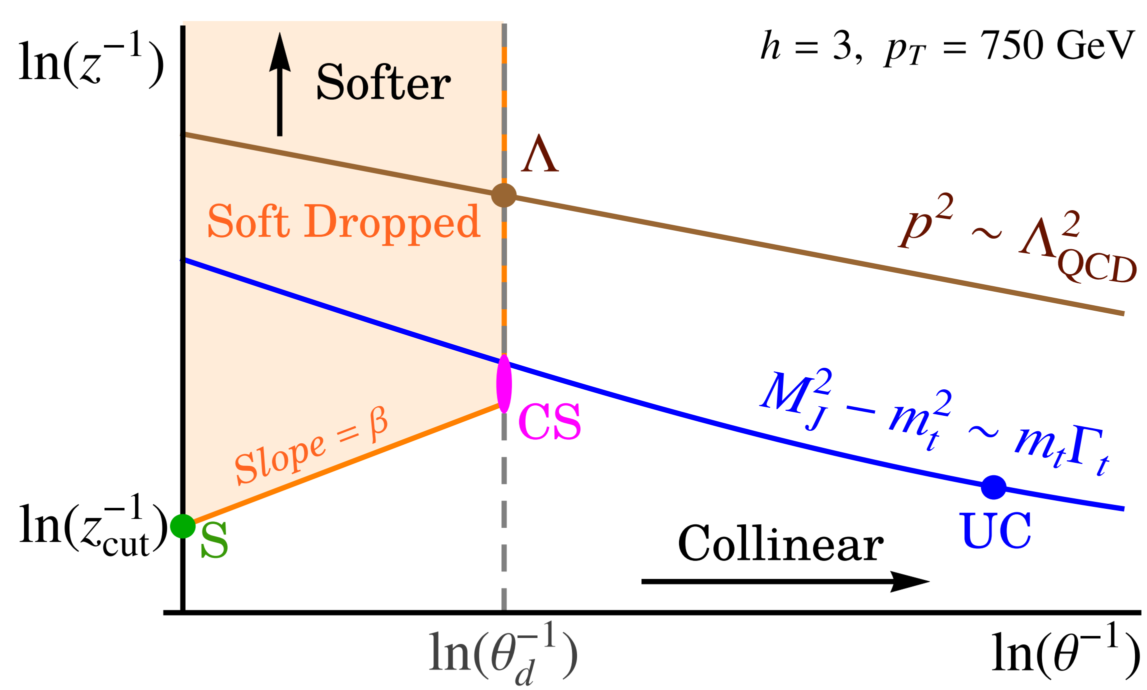
# Non-Perturbative Effects

# Non-Perturbative Effects




- Non-perturbative effects for the groomed jet mass spectrum depend on the perturbative branching history.




- Dominant non-perturbative modes:

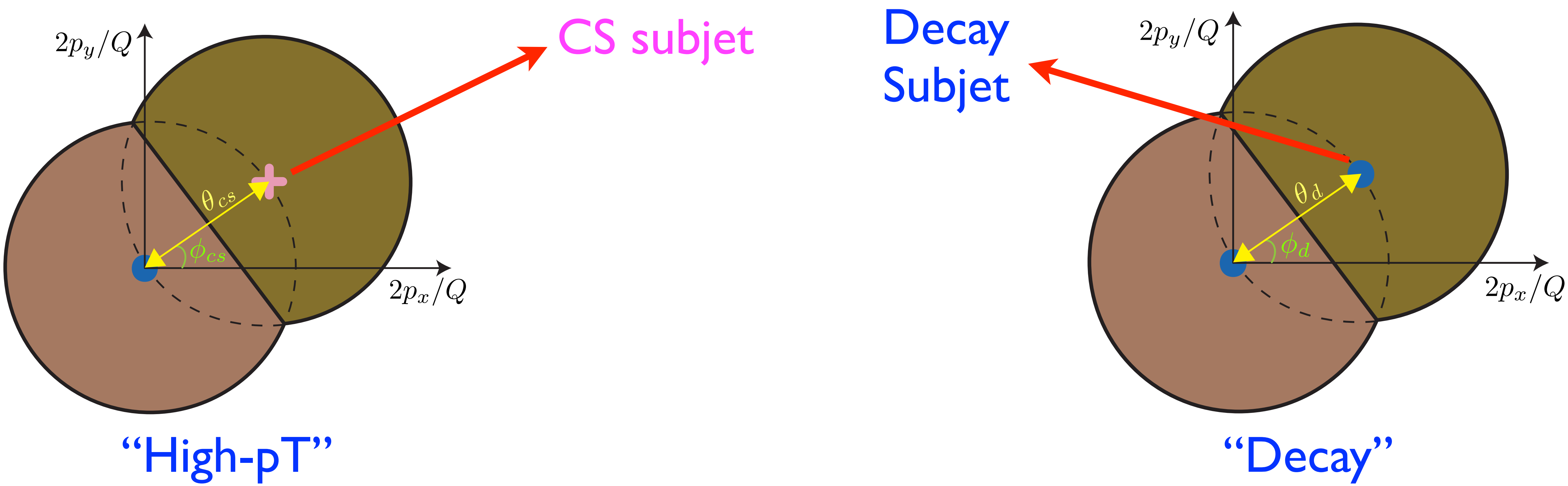
$$p_\Lambda^\mu \sim \frac{2\Lambda_{\rm QCD}}{\theta_{\rm CS}}\left(\frac{\theta_{\rm CS}^2}{4}, 1, \frac{\theta_{CS}}{2}\right)$$

$$p_\Lambda^\mu \sim \frac{2\Lambda_{\rm QCD}}{\theta_d}\left(\frac{\theta_d^2}{4}, 1, \frac{\theta_d}{2}\right)$$

# Non-Perturbative "Shift" Correction

- "Shift": contribution from the jet mass from NP radiation kept in the groomed jet

- Catchment area for NP radiation clustered in with the final soft drop stopping pair of subjets:

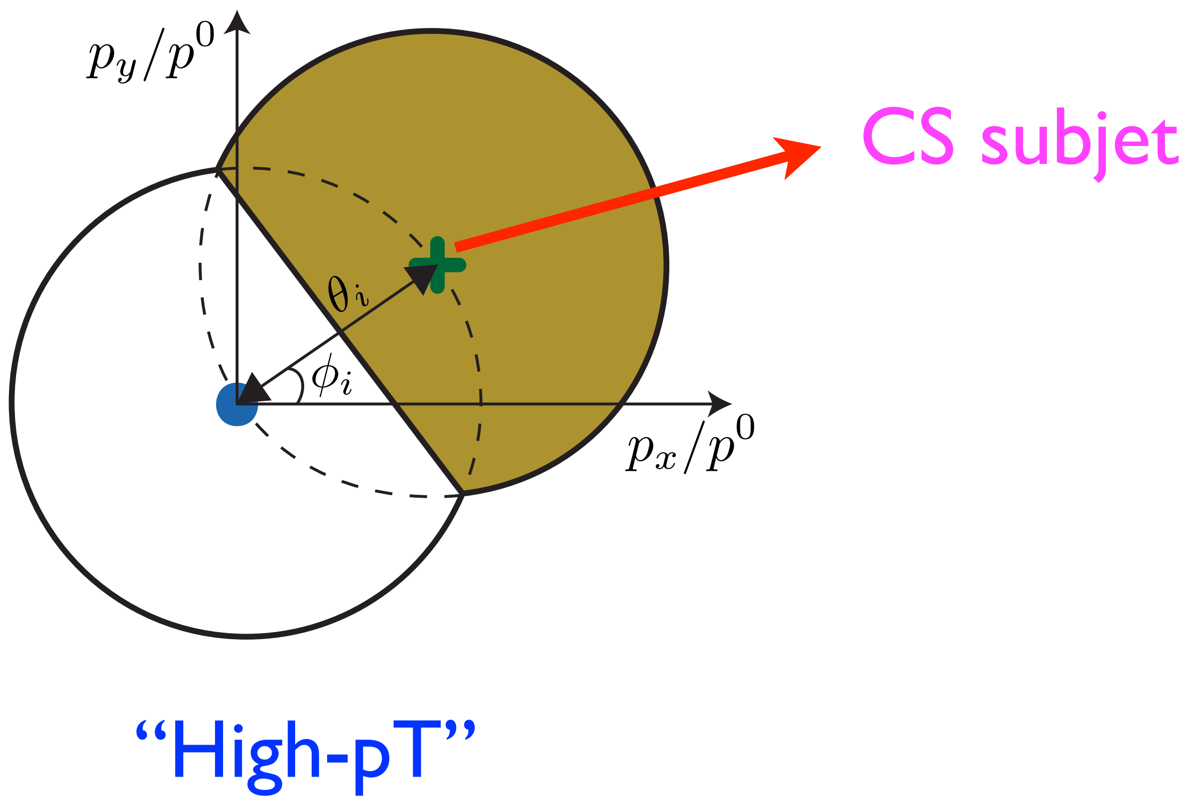



$$p_\Lambda^\mu \sim \frac{2\Lambda_{\rm QCD}}{\theta_{\rm CS}}\left(\frac{\theta_{\rm CS}^2}{4}, 1, \frac{\theta_{CS}}{2}\right) \qquad p_\Lambda^\mu \sim \frac{2\Lambda_{\rm QCD}}{\theta_d}\left(\frac{\theta_d^2}{4}, 1, \frac{\theta_d}{2}\right)$$

$\theta_{CS}$ *vs* $\theta_d$

Determines NP radiation captured!

# Non-Perturbative "Boundary" Correction



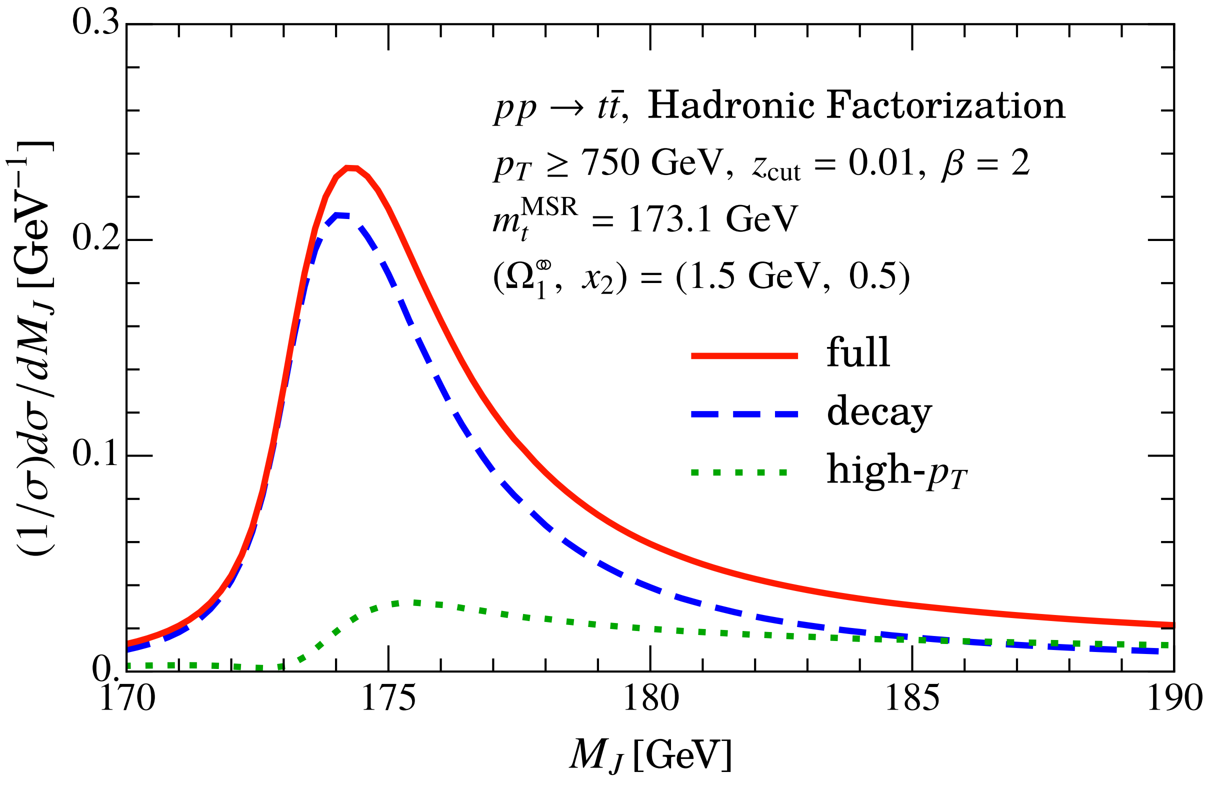

- "Boundary correction" ONLY affects the "high-pT" case. Due to the much larger energy of the "decay" subjet, the NP effect on soft drop is suppressed.

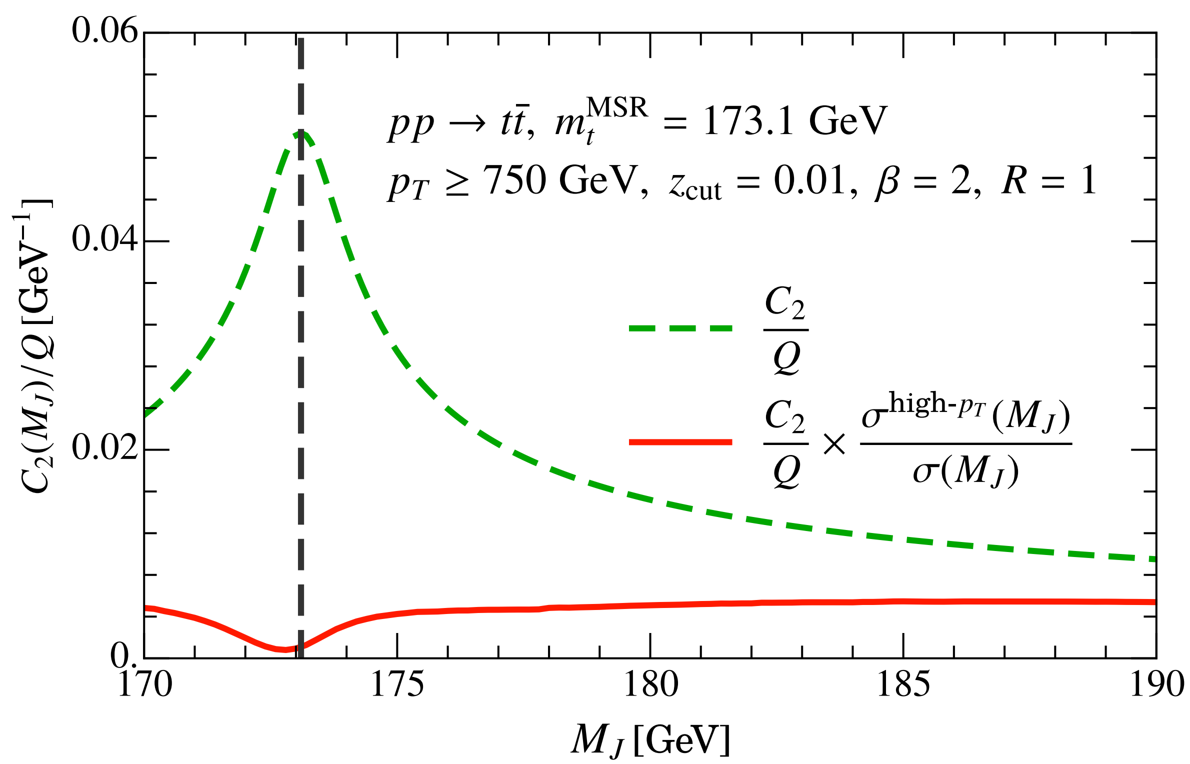
# Non-Perturbative Effects in the Collinear-Soft function

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega_{1\kappa}^{\varpi}\,\frac{d}{dm_J^2}\left(C_1(m_J^2, Q, z_{\rm cut}, \beta)\,\frac{d\hat\sigma_\kappa}{dm_J^2}\right) + \frac{\Upsilon_1^\kappa(\beta)}{Q}\,C_2(m_J^2, Q;\, z_{\rm cut}, \beta)\,\frac{d\hat\sigma_\kappa}{dm_J^2}$$

Boundary term only present for "High-pT" case

- The top jet mass spectrum in the peak region is dominated by the "decay" contribution. Thus, boundary term effect can be neglected!



# Factorization Formula

Global soft function

$$\frac{d\sigma^{\rm NLL}(\Phi_J)}{dM_J} = N(\Phi_J, z_{\rm cut}, \beta, \mu) \int d\tilde{h}\; P\Big(\tilde{h}, \frac{m_t}{Q}\Big)$$

Decay angle distribution

BHQET top jet function

$$\times \int d\ell^+ J_B\Big(\hat{s}_t - \frac{Q\ell^+}{m_t}, \delta m, \Gamma_t, \mu\Big) \int dk^+ F^q_{\otimes}(k^+)$$

shape function

Collinear-Soft Function

$$\times\, S^q_C\bigg[\bigg(\ell^+ - \max\Big\{C_1(m_t\hat{s}_t), \frac{m_t\tilde{h}}{Q}\Big\}k^+\bigg) Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\bigg]$$

Comparison of CS and decay subjet Angles

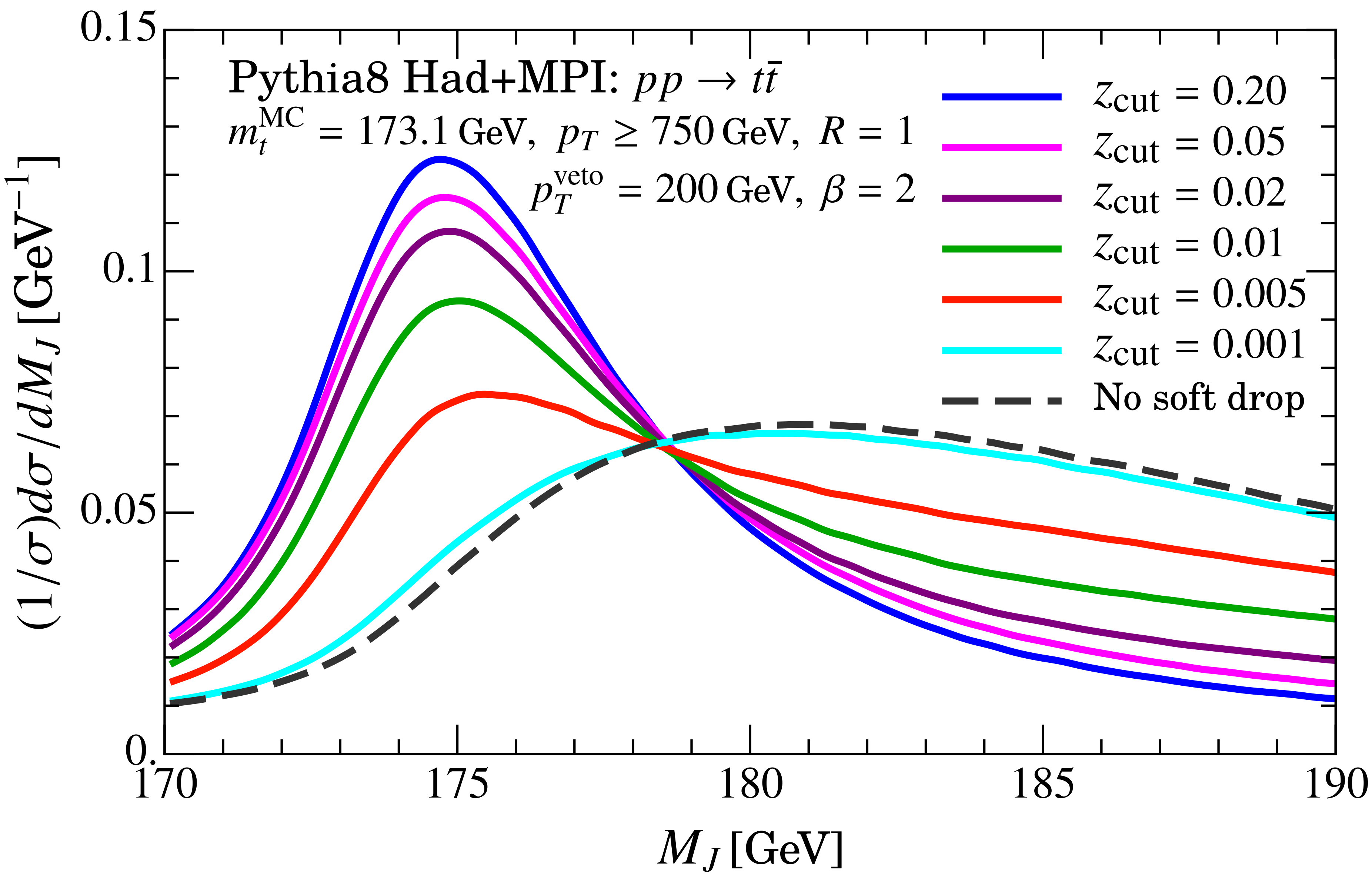
$$\times \bigg(1 - \Theta\Big(C_1(m_t\hat{s}_t) - \frac{m_t\tilde{h}}{Q}\Big)\frac{Q}{m_t}k^+\frac{dC_1(m_t\hat{s}_t)}{d\hat{s}_t}\bigg)$$

- Can still encode leading power correction in a more sophisticated shape function, unlike for massless jets.

# Plots

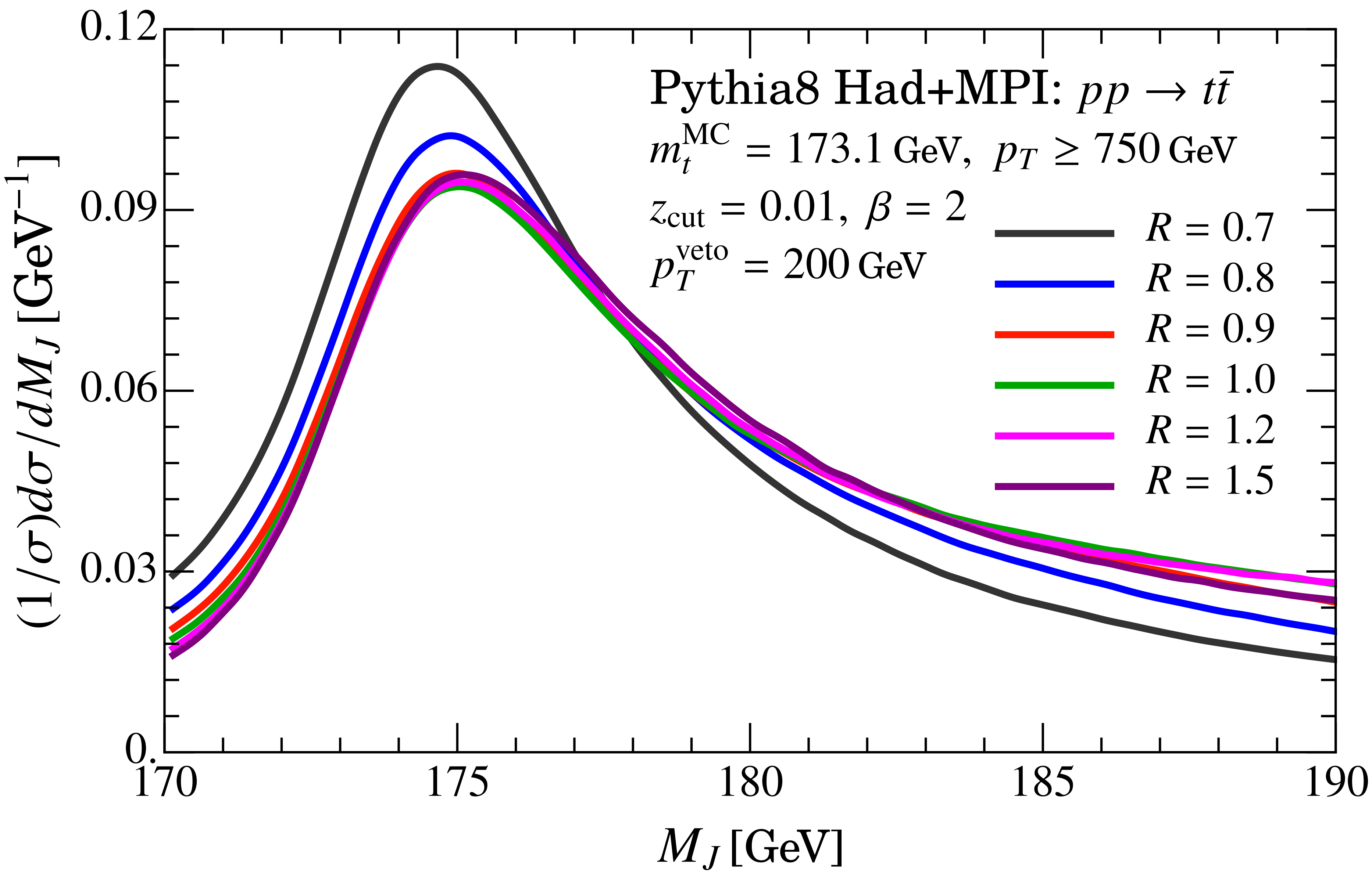
(Hoang, SM, Pathak, Stewart arXiv: 1708.02586)

# zcut Dependence



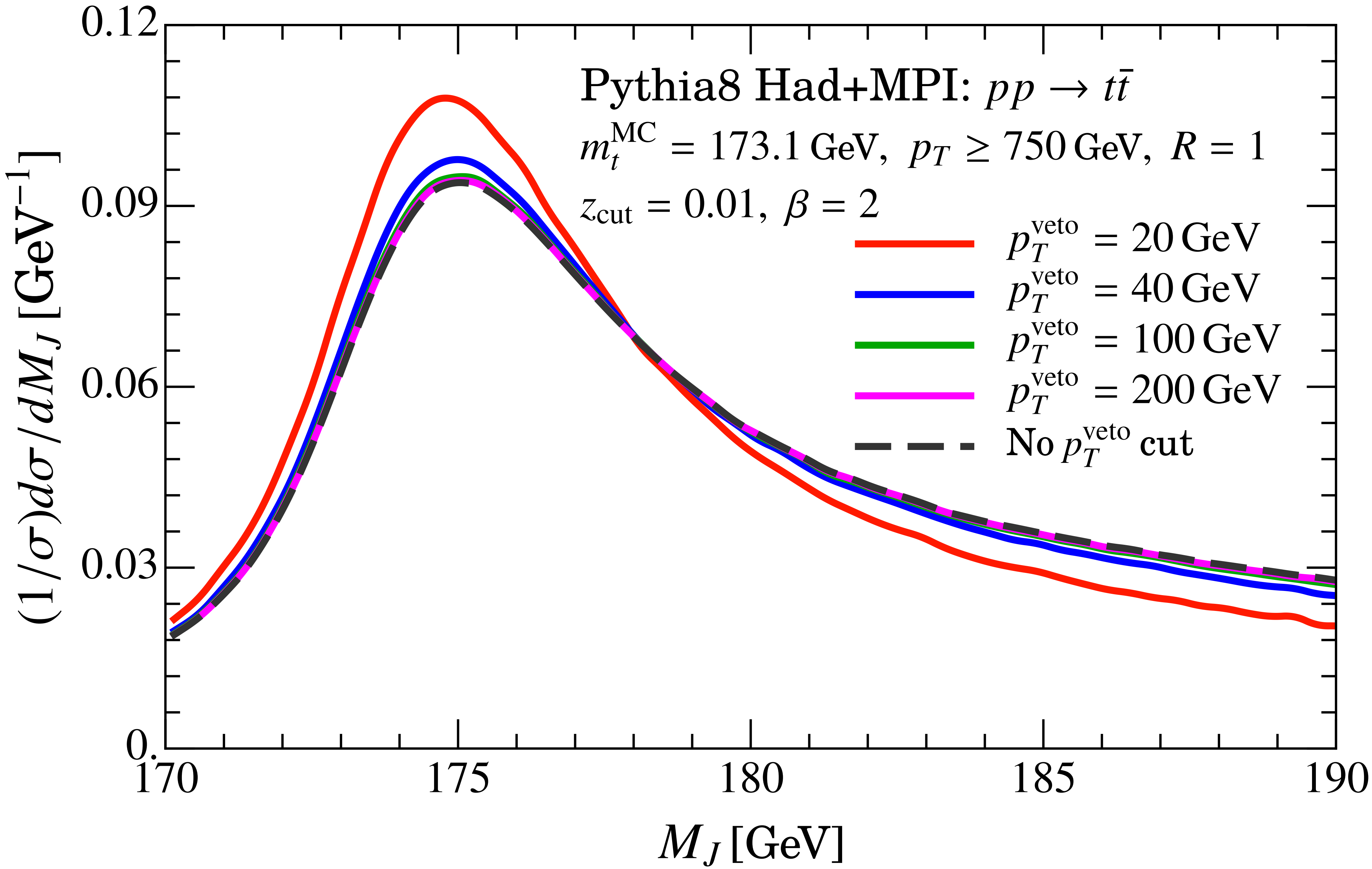

- Light grooming region effective in removing contamination
- For more aggressive grooming, SD stops on decay subjects. Thus, peak position remains stable since decay products are always kept (unlike massless case).

# Jet Radius Dependence




- Groomed top jet mass spectrum is independent of the original top jet radius for $R \gtrsim 0.9$

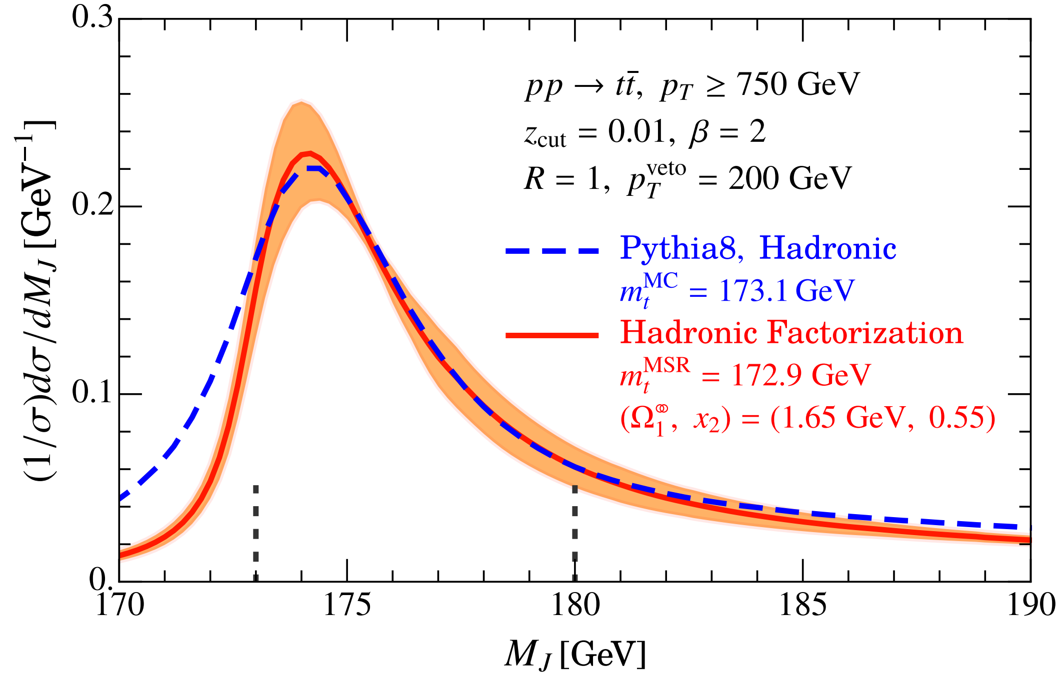
# pT-Veto Dependence

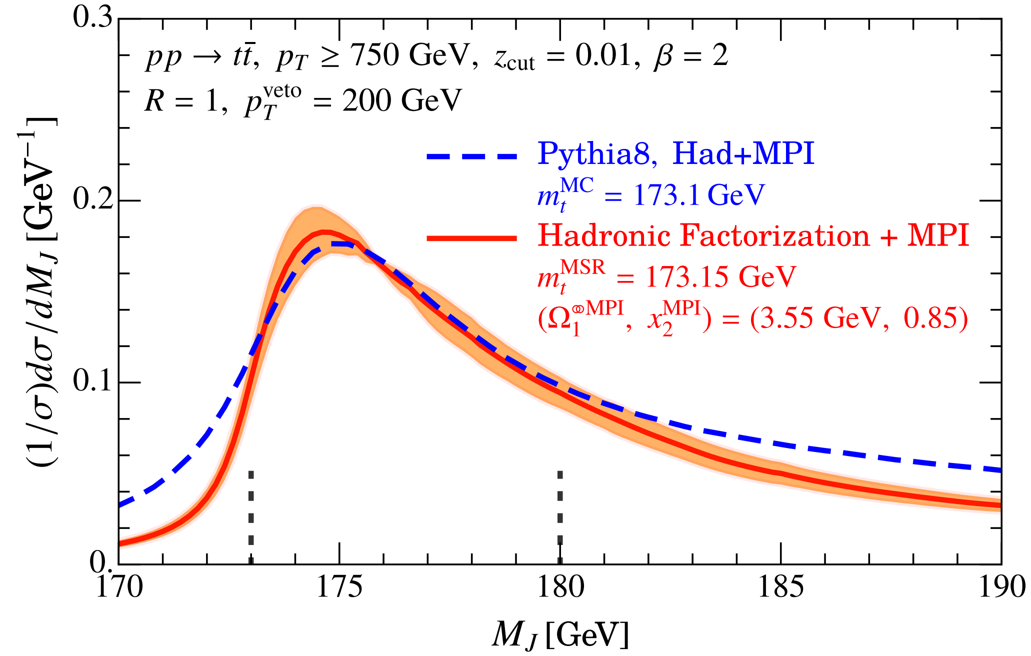


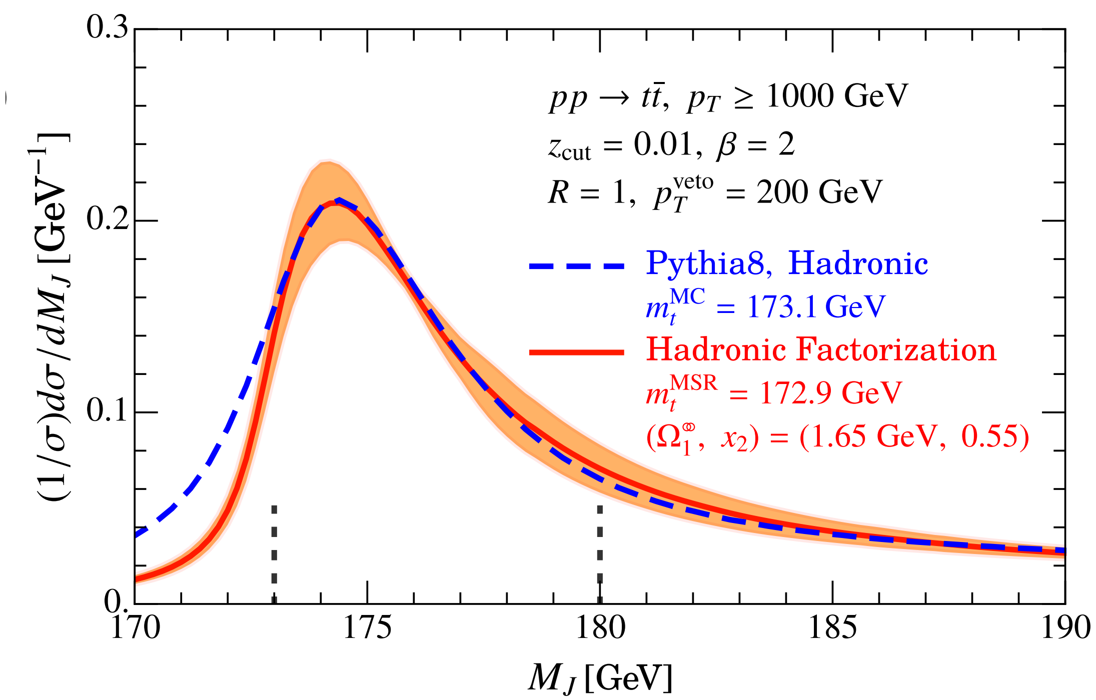

- Groomed top jet mass spectrum is independent of jet veto on additional jets for $p_T^{\rm veto} \gtrsim 50\,{\rm GeV}$

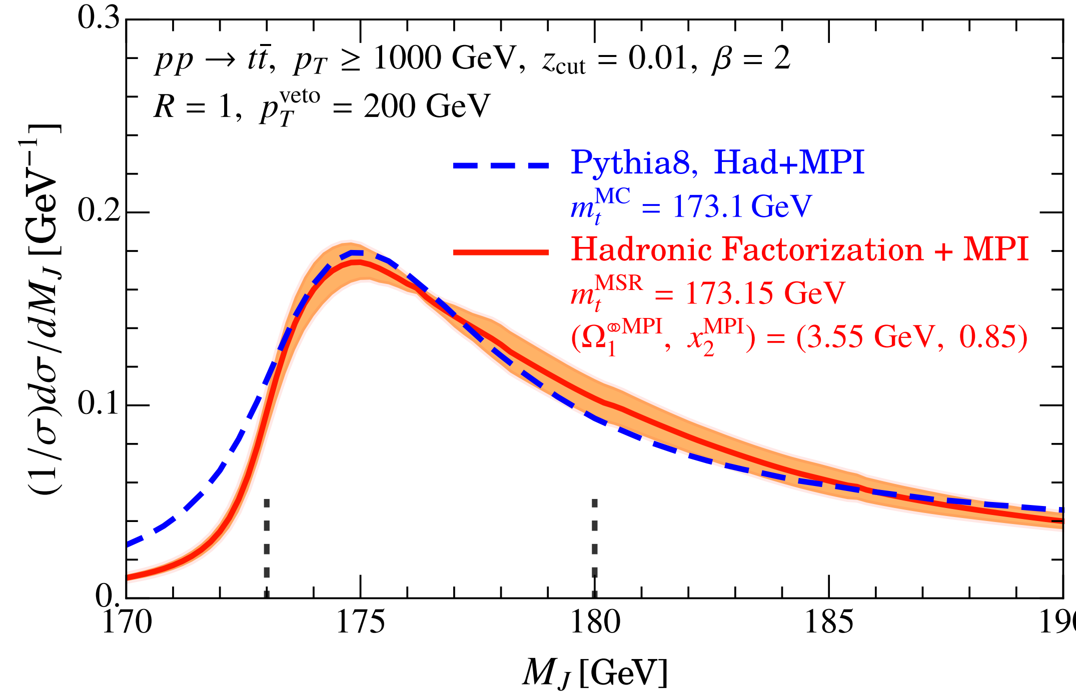
# Had

# Had+ MPI




- MPI effects are well-described through a shift in the shape function parameters, just like in the ungroomed case:

$$\Omega_n^{\circledcirc} \to \Omega_n^{\circledcirc \rm MPI}$$

# Conclusions

- New factorization framework for the groomed top jet mass distribution in the peak region that allows for the a short distance top mass extraction.

- Soft Drop can terminate on top decay products, requiring a more careful treatment of top decay dynamics compared to the ungroomed case.

- The new factorization framework provides a unified treatment of the two possibilities: (i) soft drop terminates on a collinear-soft subjet (ii) soft drop terminates on subjet containing top decay products

- Novel dependence in the factorization formula on a perturbative decay distribution P(h).

- Unlike the case of massless groomed jets, non-perturbative effects can be treated with a standard shape function analysis.

- MPI effects are well described through a shift in the shape function moment, just like in the ungroomed case.