Collinear Drop

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Based On: Yang-Ting Chien & IS (in progress) [1906.xxxxx]

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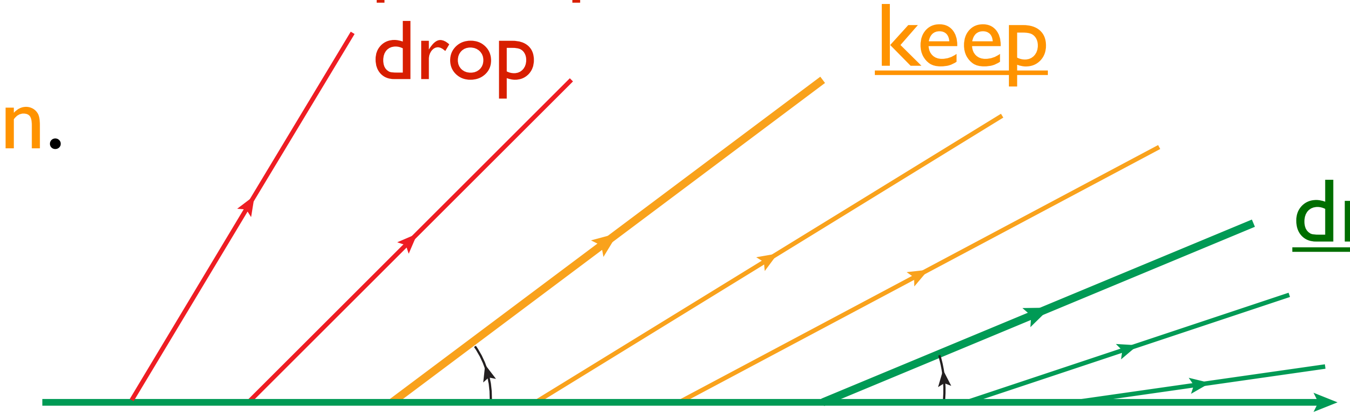
Collinear Drop:

- Class of observables that do not depend on energetic collinear radiation in a jet.
- Puts focus on soft radiation.



Motivation:

- Test treatment of perturbative soft radiation in Monte Carlo Sim.
- More sensitive to hadronization. Provide new tests for hadronization models by comparing to collinear drop data.
- Can be made sensitive or insensitive to underlying event/MPI
- Study color charge and correlations (eg. quark vs. gluon vs. Z, connection to rest of event, ...)
- Provide a probe for jet quenching and medium effects in heavy-ion collisions

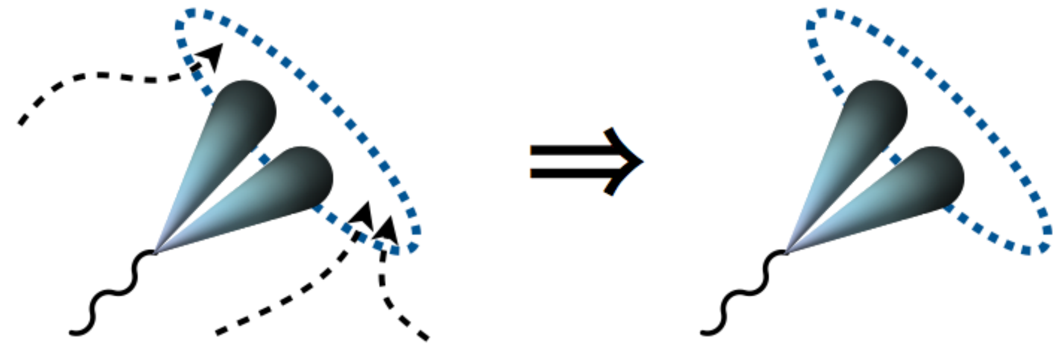
Outline

- Jet Substructure, Soft Drop grooming
- Factorization for Soft Drop Jet Mass
- Collinear Drop (CD) - exploring soft phase space in jets
- Partonic Factorization & NLL Resummation with SCET
- Analysis of CD using MC simulations and SCET
- Conclude

Jet Substructure

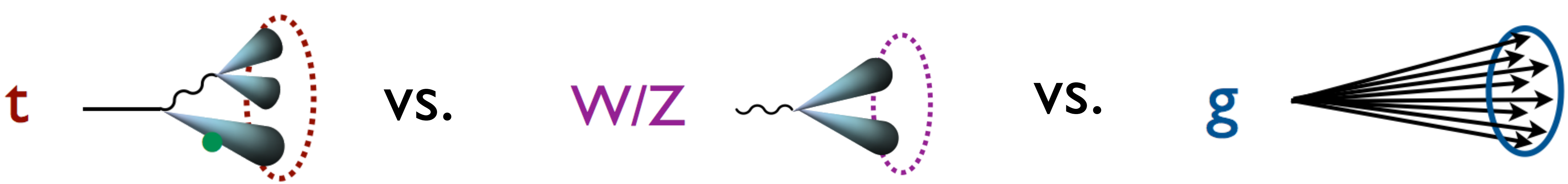
- grooming jets

  remove soft contamination from jets



- tagging subjets

  boosted particles have collimated decay products



- collinear drop

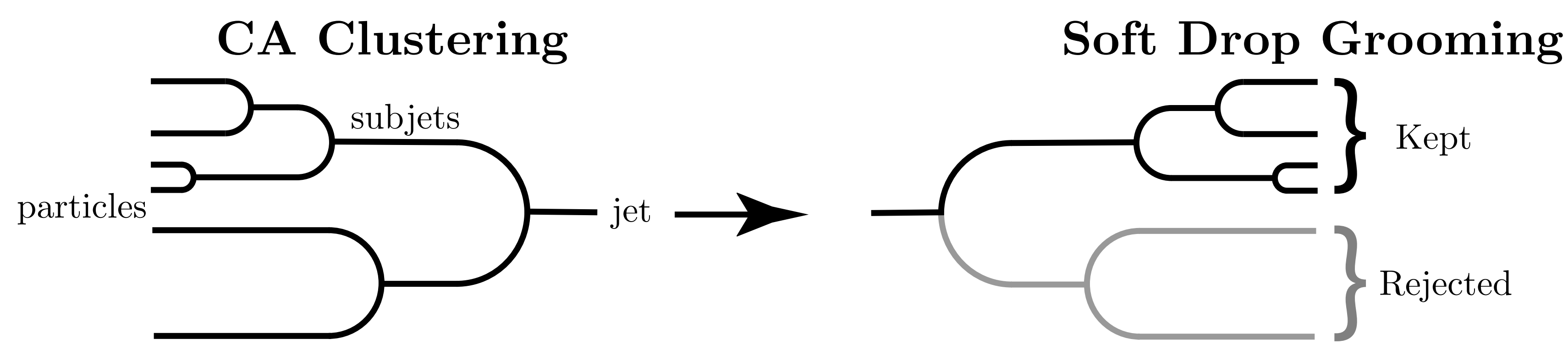
Soft Drop Grooming

Larkoski, Marzani, Soyez, Thaler (1402.2657)

(generalization of mMDT: Butterworth et.al., Dasgupta et.al.)

Recluster jet with CA

Groom soft radiation



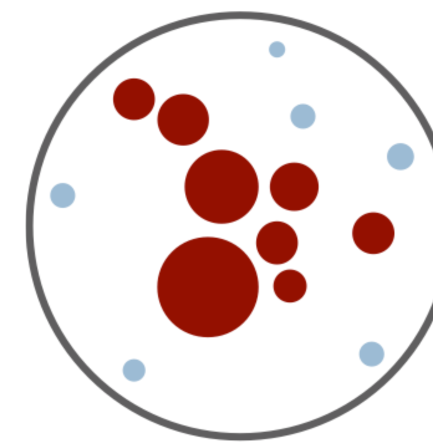
Groomed Clustering Tree

test for subjets:

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

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

Groomed Jet



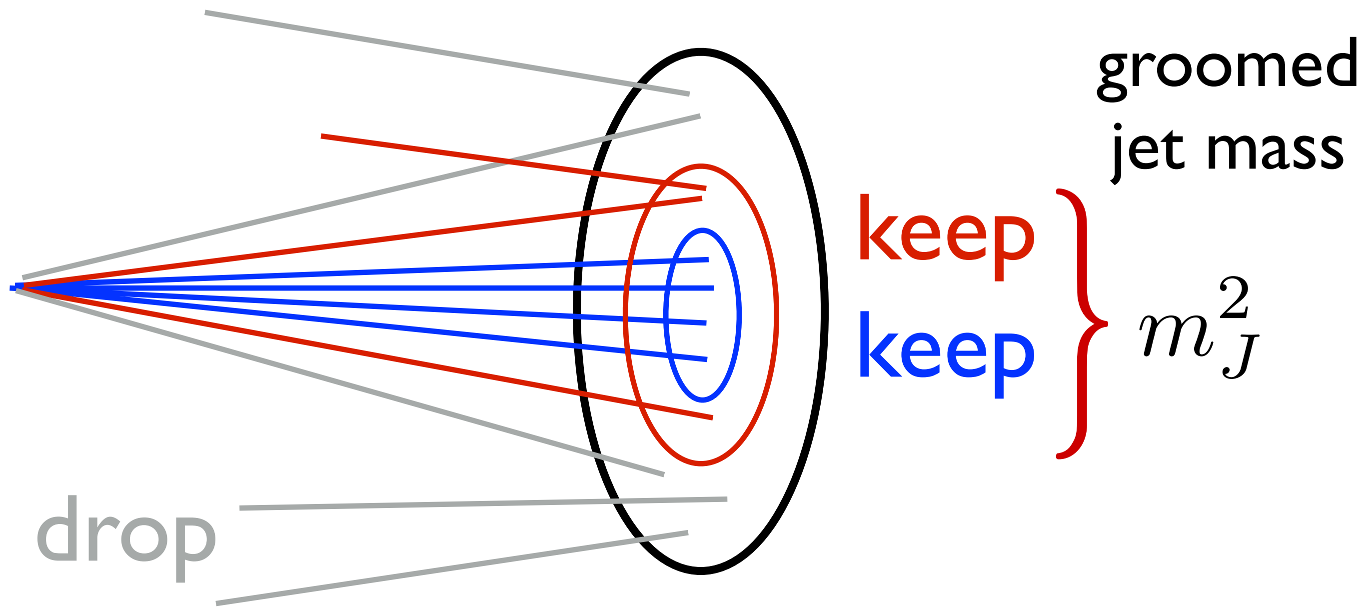
two grooming parameters

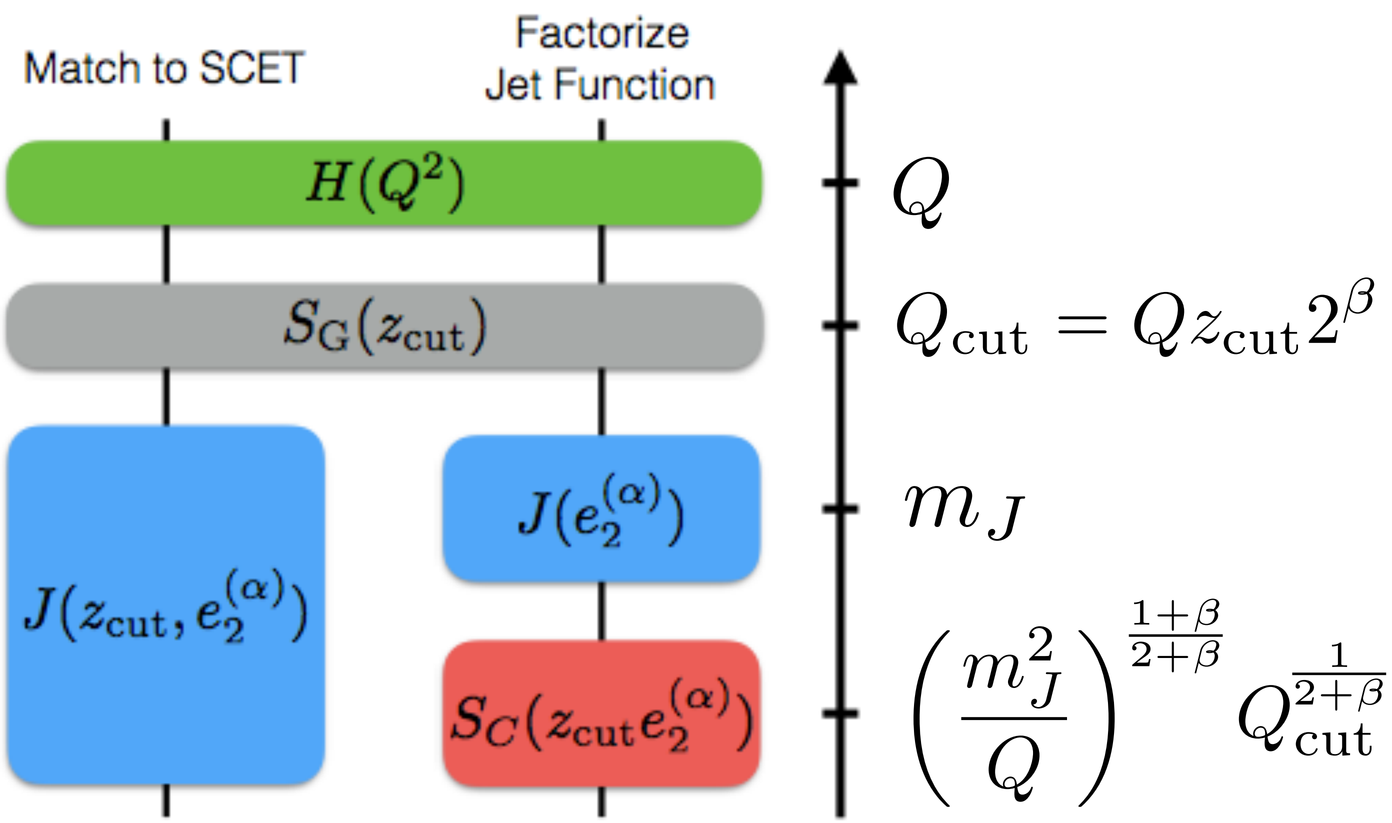
β : more grooming ⟶ less grooming ($\beta = 0$, $\beta > 0$)

z_{cut} : less grooming ⟷ more grooming ($z_{\text{cut}} = 0.1$, $z_{\text{cut}} = 0.2$)

Soft Drop Factorization

Frye, Larkoski, Schwartz, Yan (1603.09338)



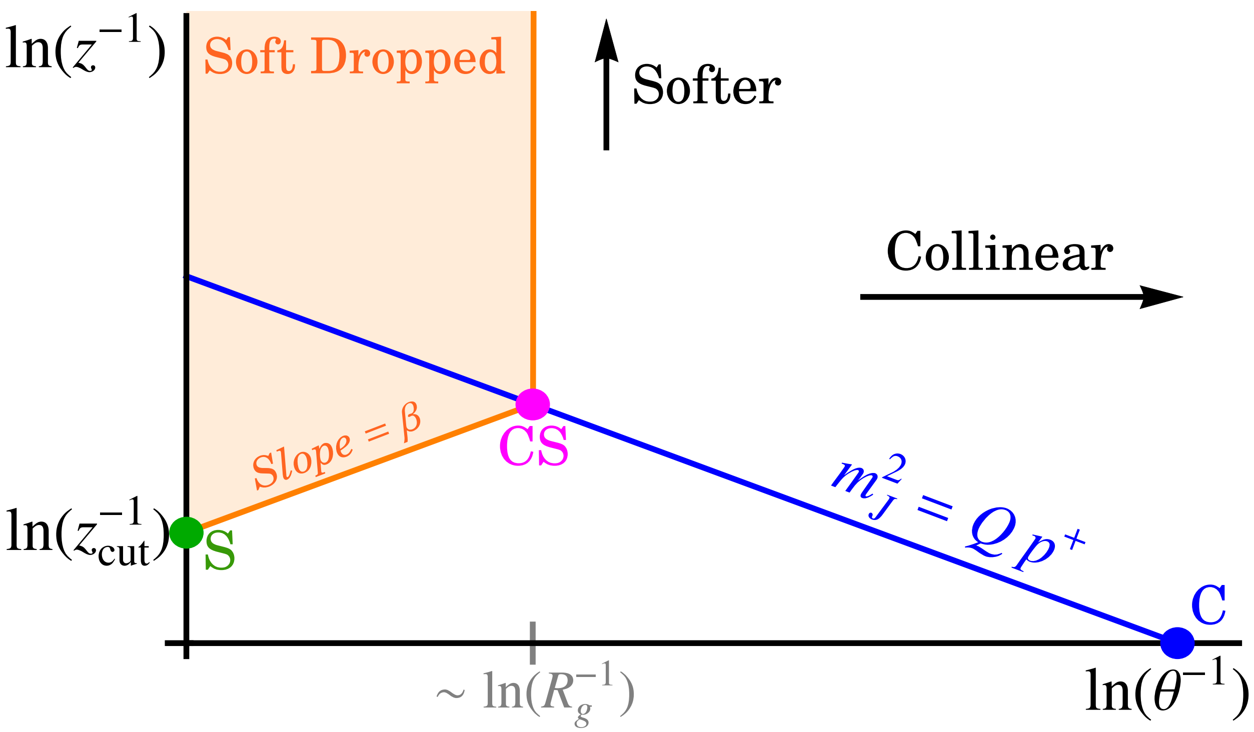


sum large logs from ratios of scales

isolates measurement from rest of event

Soft Drop Factorization

Frye, Larkoski, Schwartz, Yan (1603.09338)



- Single scale in Collinear-Soft function
- No non global logarithms for the spectrum
- Enables NNLL, … precision

$$\frac{d\sigma}{dm_J^2} = \sum_{i=q,g} \underbrace{N_i(\Phi_J, z_{\rm cut}, \beta, R, \mu)} \; \underbrace{P_i^{\rm SD}(m_J^2, Q, z_{\rm cut}, \beta, \mu)}$$

normalization, contains $S_G(Qz_{\rm cut}, \beta, R, \mu)$

soft drop jet mass spectrum

$$P_i^{\rm SD} = Q_{\rm cut}^{\frac{1}{1+\beta}} \int dk^+ \; J_i\left(m_J^2 - Qk^+, \mu\right) \; S_{Ci}\left(k^+ Q_{\rm cut}^{\frac{1}{1+\beta}}, \beta, \mu\right)$$

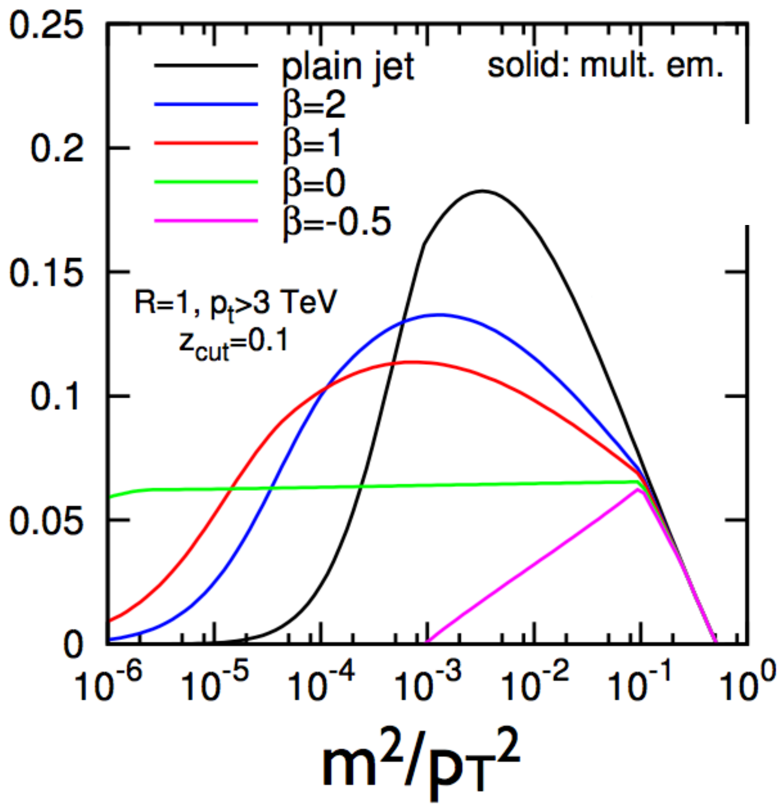
Jet function

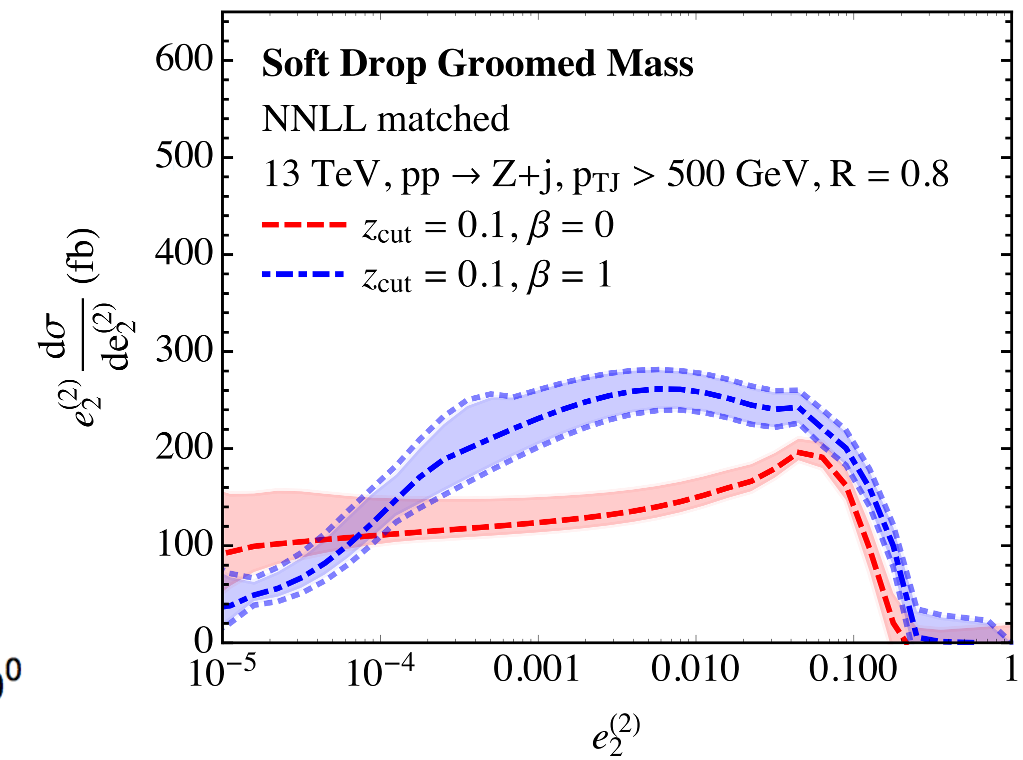
Collinear-Soft function

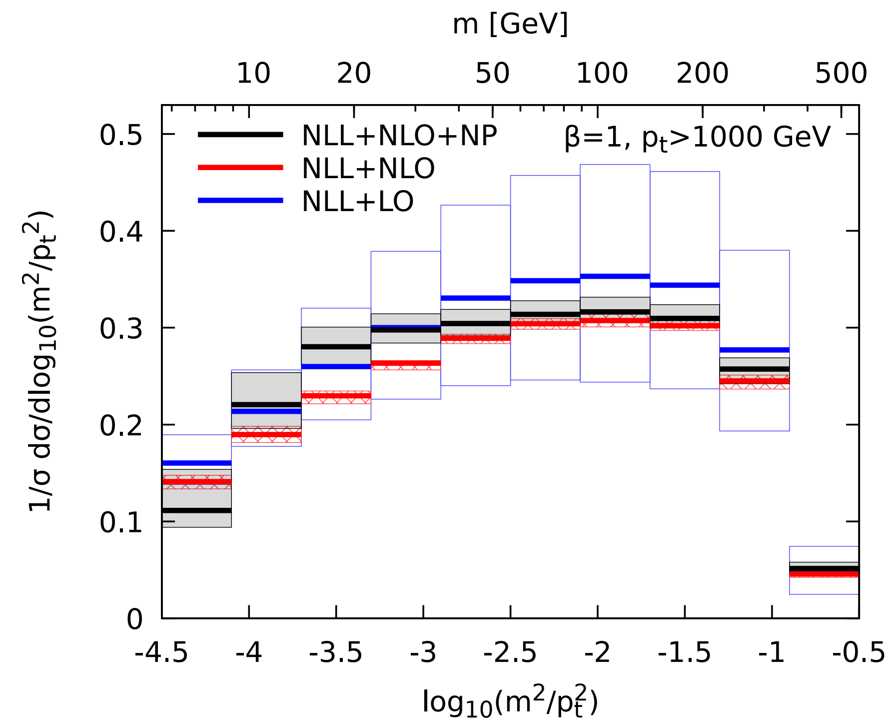
$$\frac{m_J^2}{Q^2} \ll z_{\rm cut} \ll 1$$

$$Q_{\rm cut} = Q z_{\rm cut} 2^\beta$$

Soft Drop Jet Mass







Pert. QCD at mLL

NNLL+LO

NLL+NLO

Larkoski, Marzani, Soyez, Thaler 2014

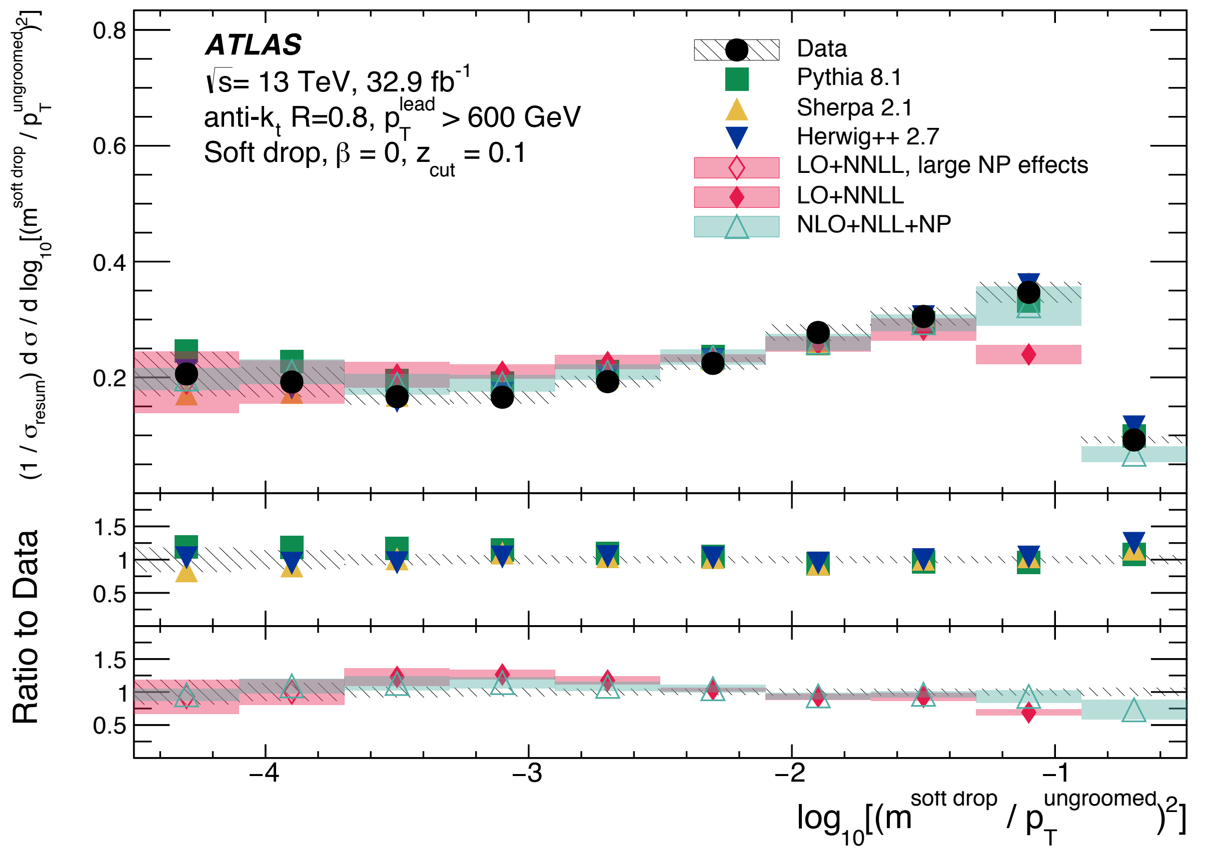
Frye, Larkoski, Schwartz, Yan 2016

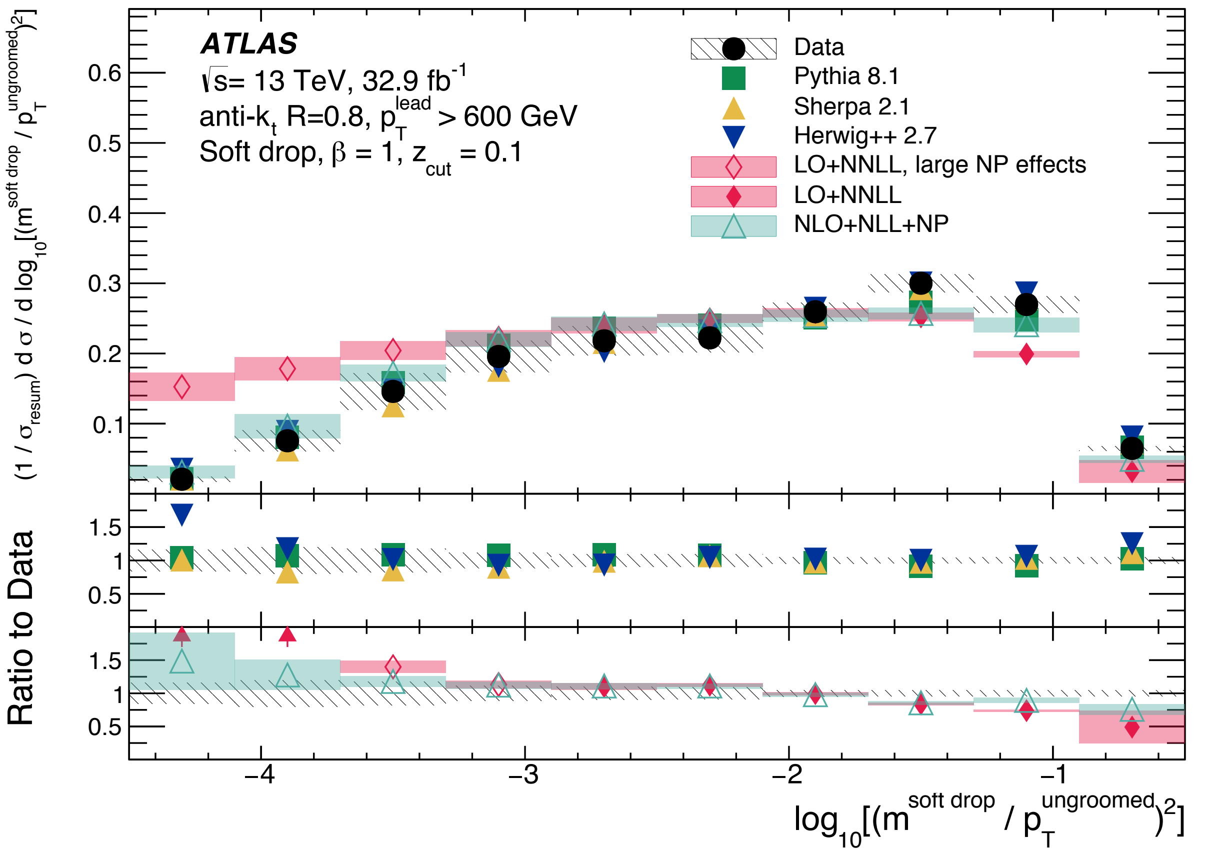
Marzani, Schunk, Soyez 2017

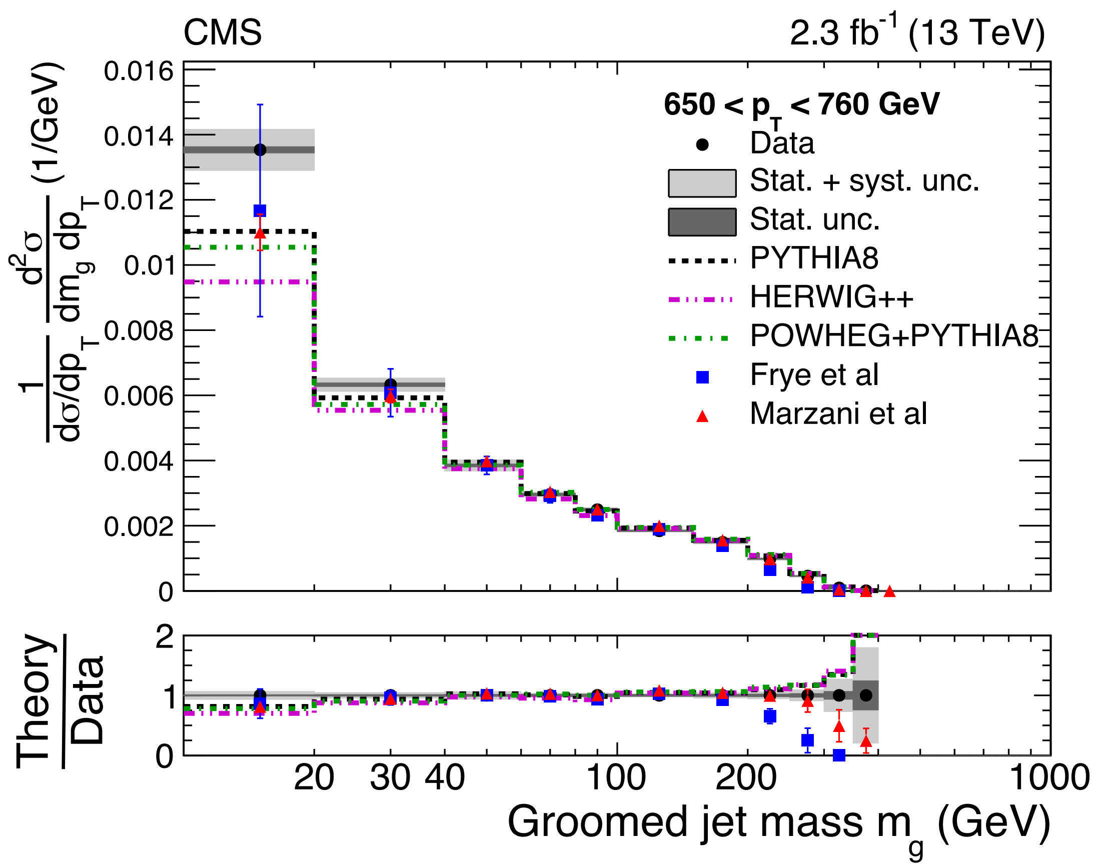
Also: Kang, Liu, Lee, Ringer 2018, Baron, Marzani, Theeuwes 2018

Comparison with Measurements

ATLAS 1711.08341





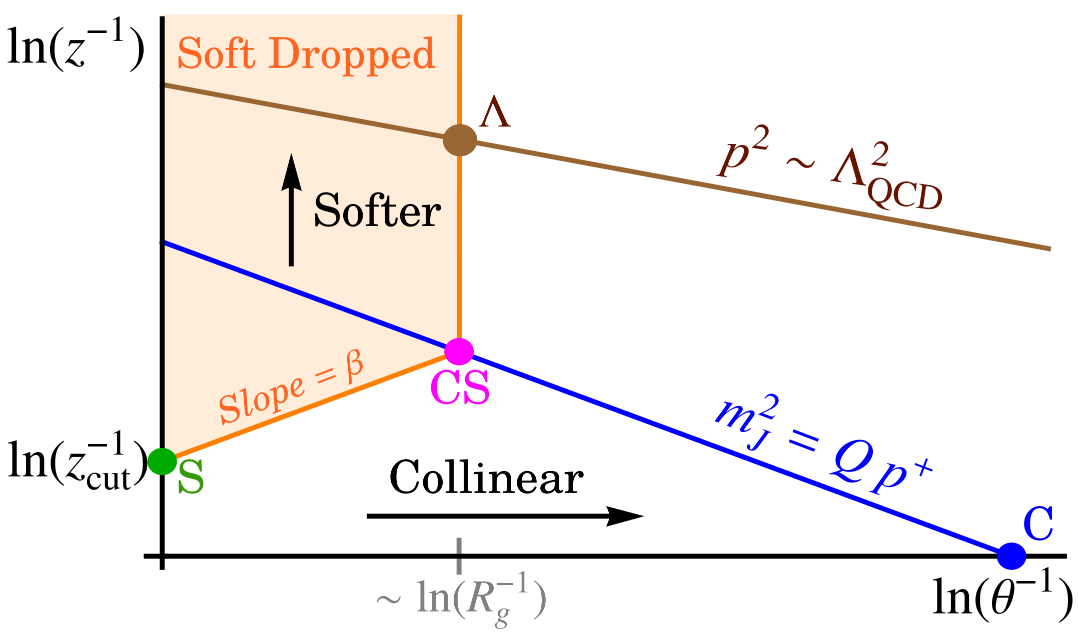


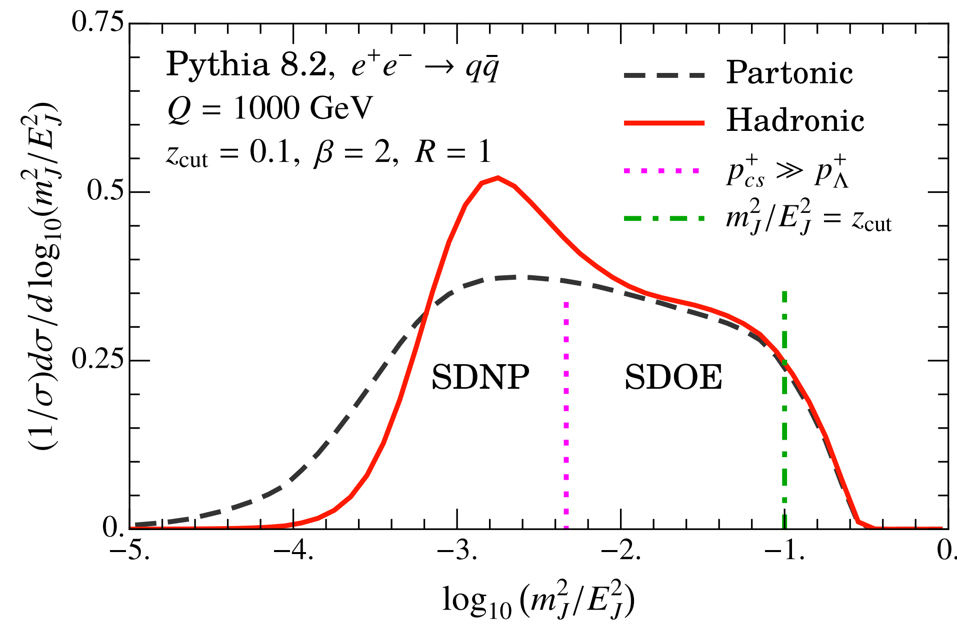
CMS 1807.05974

Nonperturbative Corrections to Soft Drop Jet Mass

Hoang, Mantry, Pathak, Stewart 1906.xxxxx

Focus on the region where the soft drop stopping subjet is perturbative:
Soft drop operator expansion region(SDOE)





Consider the perturbative modes in the EFT and determine the leading nonperturbative mode in the SDOE region: $\frac{Q\Lambda_{\rm QCD}}{2m_J^2}\left(\frac{4m_J^2}{Q^2 z_{\rm cut}}\right)^{\frac{1}{2+\beta}} \ll 1$

Derive the leading power corrections to the partonic cross section:

- 3 universal hadronic parameters (indep. of zcut, beta, R, Q, and mJ)
- Perturbatively calculable Matching coefficients.
- LL resummation of matching coefficients in the coherent branching formalism

$$\frac{d\sigma_\kappa^{\rm had}}{dm_J^2} = \frac{d\hat\sigma_\kappa}{dm_J^2} - Q\,\Omega^{\infty}_{1\kappa}\frac{d}{dm_J^2}\left(C_1^\kappa(m_J^2, Q, \tilde z_{\rm cut}, \beta, R)\frac{d\hat\sigma_\kappa}{dm_J^2}\right) + \frac{Q(\Upsilon^\kappa_{1,0} + \beta\Upsilon^\kappa_{1,1})}{m_J^2} C_2^\kappa(m_J^2, Q, \tilde z_{\rm cut}, \beta, R)\frac{d\hat\sigma_\kappa}{dm_J^2}$$

see talks by A.Pathak:

Tues. blackboard - theory
Fri. 2pm - MC analyses

Collinear Drop

Demand that contributions from collinear region are at least exponentially suppressed

Examples:

1) jet algorithm based

eg. groom jet twice and take complement

$$O_{\rm CD} = O\big[\{{\rm jet}_{{\rm SD}_1}\} \setminus \{{\rm jet}_{{\rm SD}_2}\}\big]$$

$$O_{\rm CD} = O_{{\rm SD}_1} - O_{{\rm SD}_2}$$

soft drop 1 & soft drop 2 ← stronger grooming

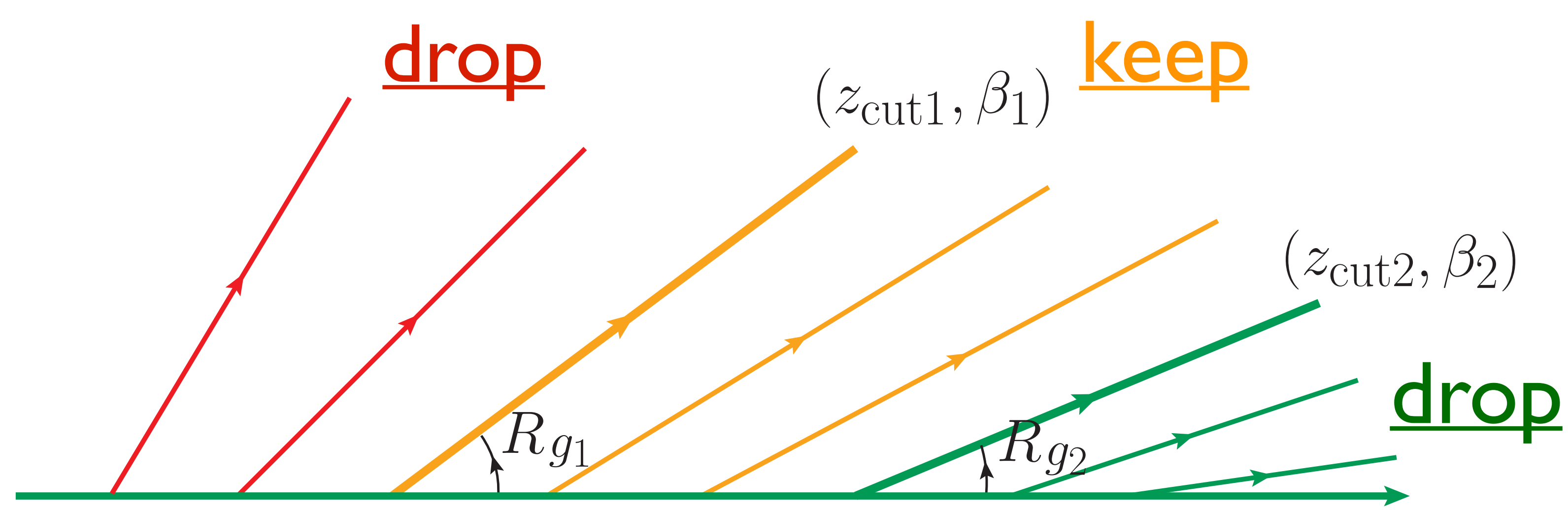
$(z_{\rm cut1}, \beta_1)$ $(z_{\rm cut2}, \beta_2)$

- $\beta_1 = \beta_2, \quad z_{\rm cut1} < z_{\rm cut2}$
- $\beta_1 > \beta_2, \quad z_{\rm cut1} = z_{\rm cut2}$
- $\beta_1 > \beta_2, \quad z_{\rm cut1} < z_{\rm cut2}$, ...

CD jet mass:

$$\Delta m^2 = m^2_{{\rm SD}_1} - m^2_{{\rm SD}_2}$$

(trivially generalizes to other observables)

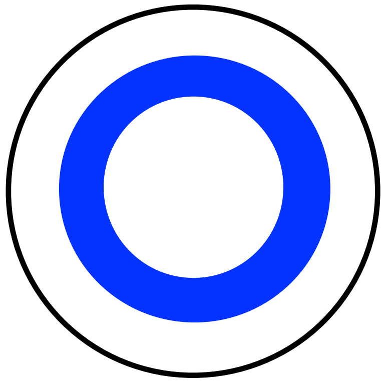


Collinear Drop

Demand that contributions from collinear region are at least exponentially suppressed

Examples:

2) jet shape based



eg. energy fraction in an angular region

for e^+e^- collisions: $\tau_\omega = \sum_{i\in\text{jet}} z_i\ \omega(\theta_i, \theta_0)\,,$ where $z_i = \frac{E_i}{E_{\text{jet}}}$

for pp collisions: $\tau_\omega = \sum_{i\in\text{jet}} z_i\ \omega(\Delta R_i, \theta_0)\,,$ where $z_i = \frac{p_{Ti}}{p_T^{\text{jet}}}$

collinear drop: $\omega(\theta \le \theta_0, \theta_0) \simeq 0$

suppress wide angle radiation if desired: $\omega(\theta \to R, \theta_0) \simeq 0$

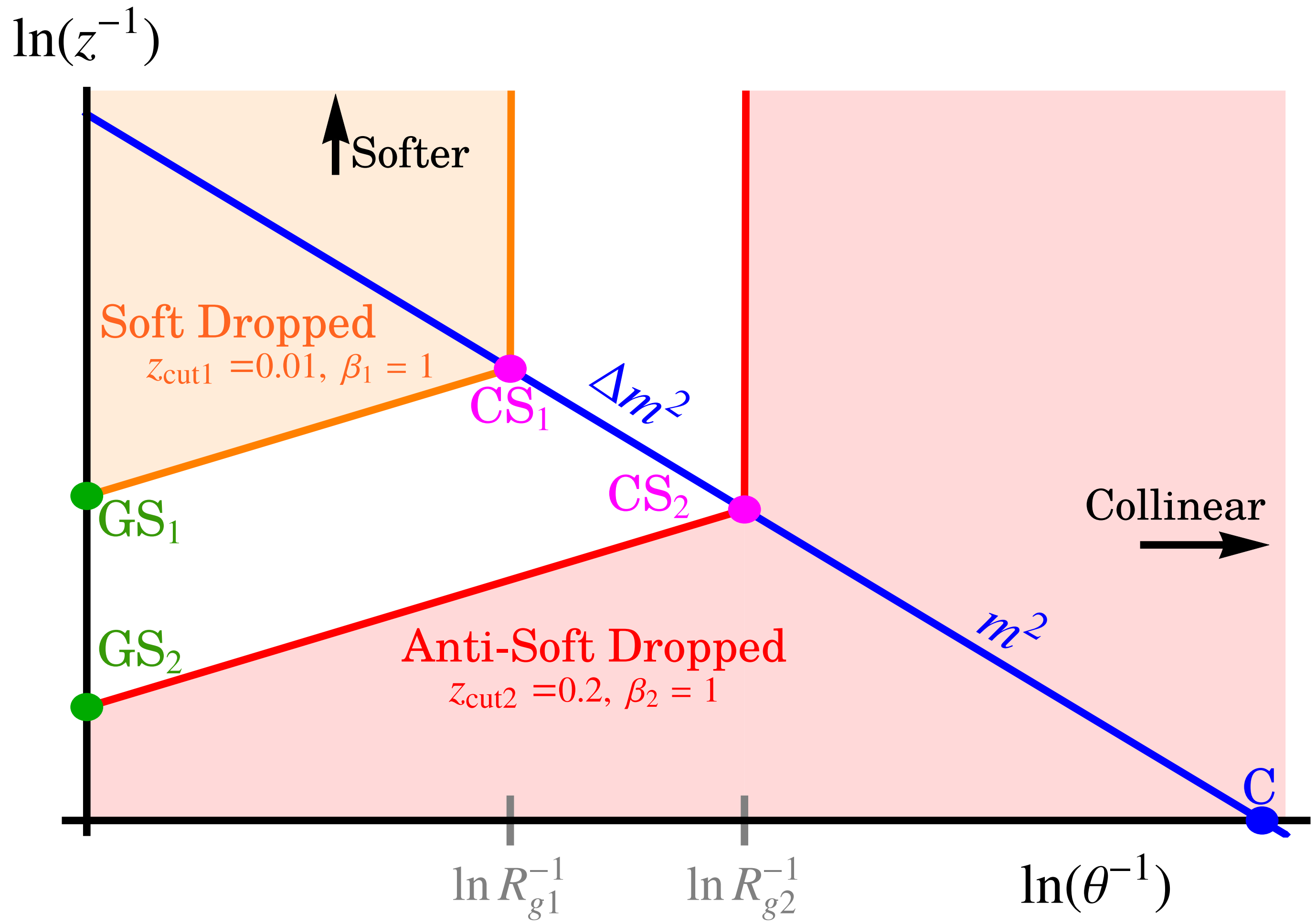
(can make various choices for ω , and trivially generalizes to other observables)

Not CD: large α angularity, (1-T)-(C/6) , ... have polynomial angular suppression

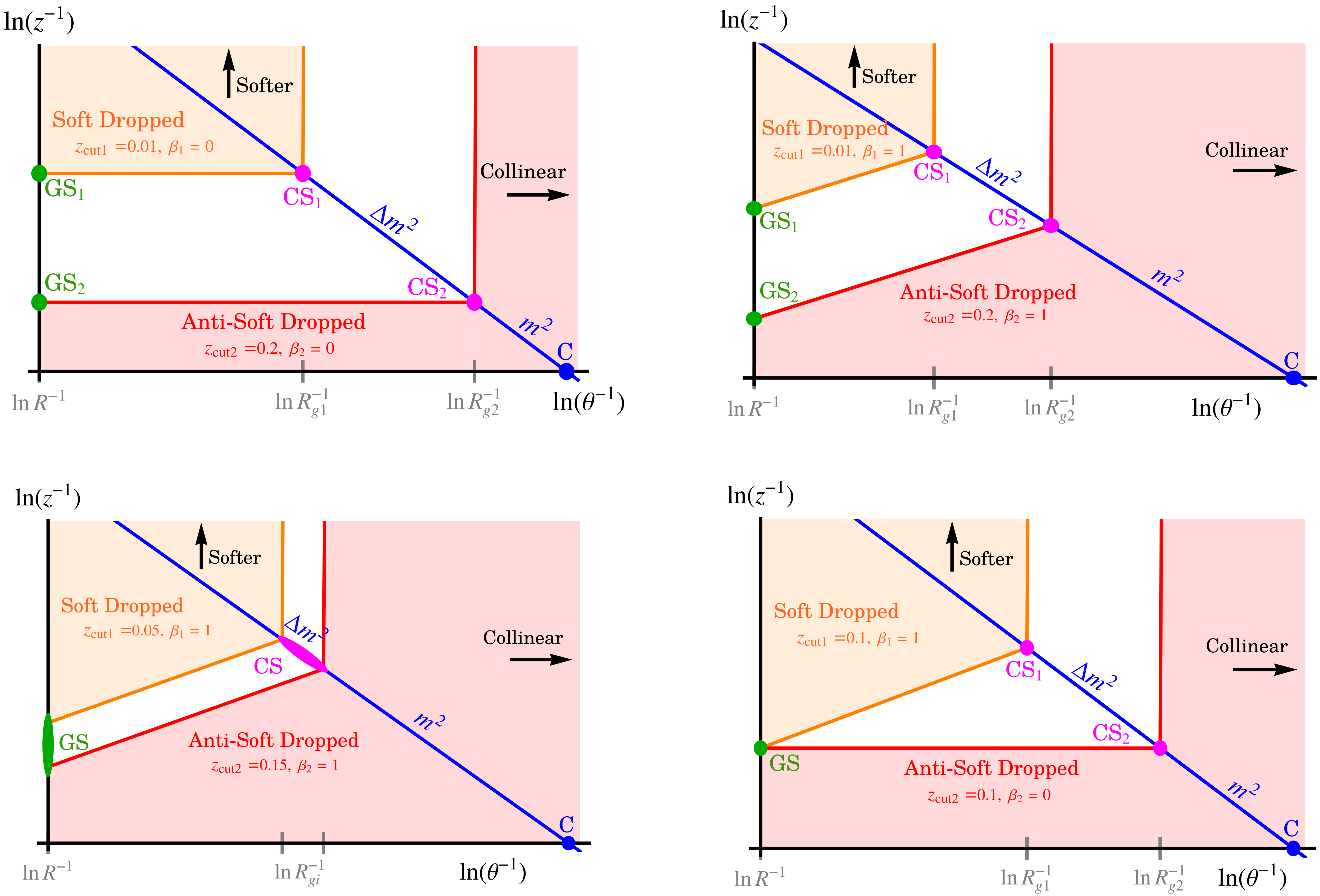
Focus on first example with two Soft Drops

$$\Delta m^2 = m^2_{\mathrm{SD}_1} - m^2_{\mathrm{SD}_2}$$

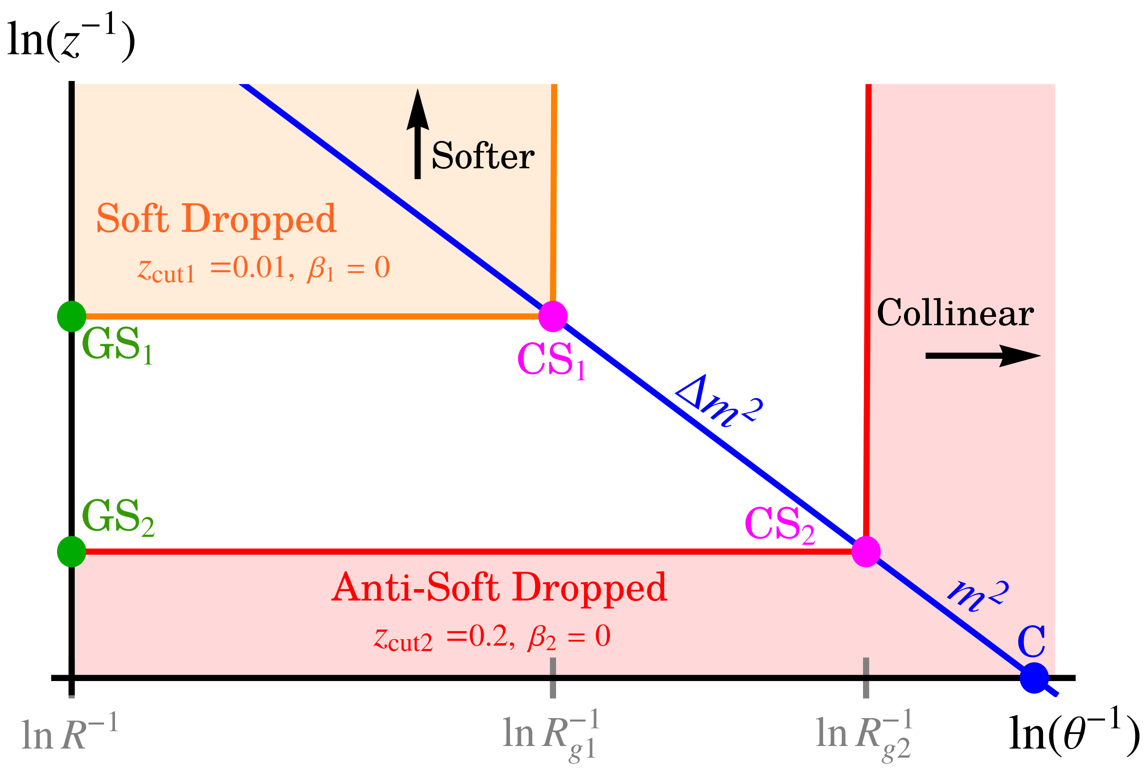
$(z_{\mathrm{cut}1}, \beta_1)$ $(z_{\mathrm{cut}2}, \beta_2)$

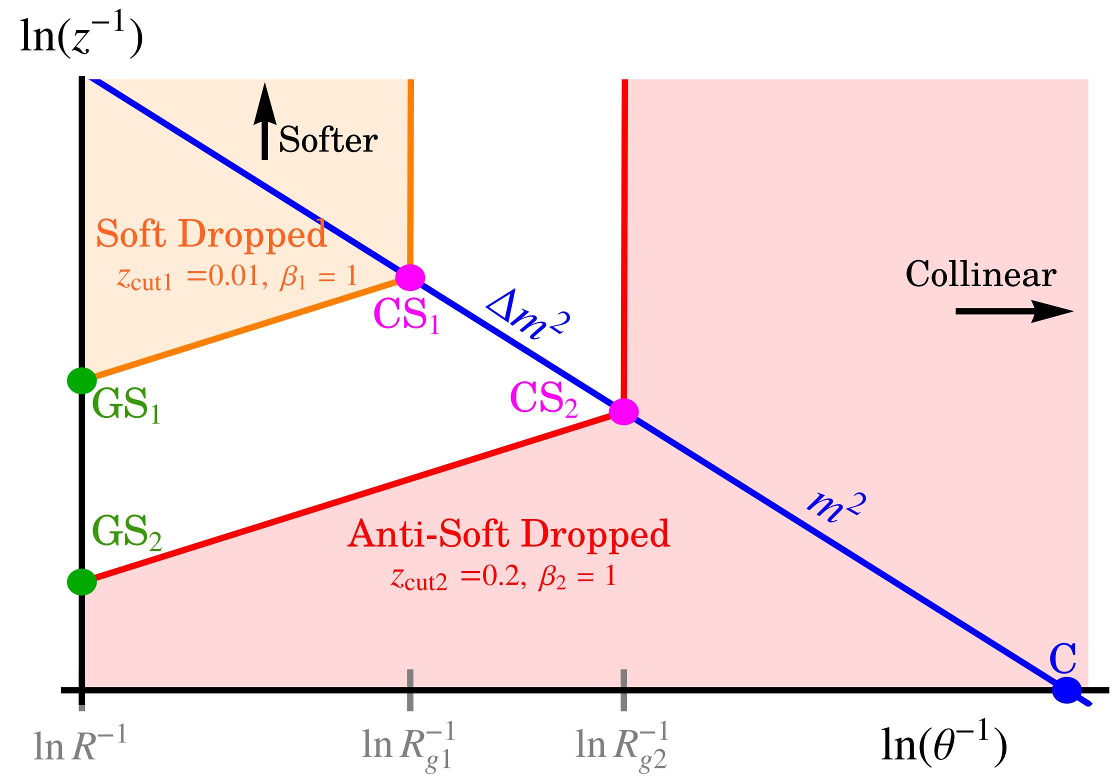


Choose a Region of Soft Phase Space

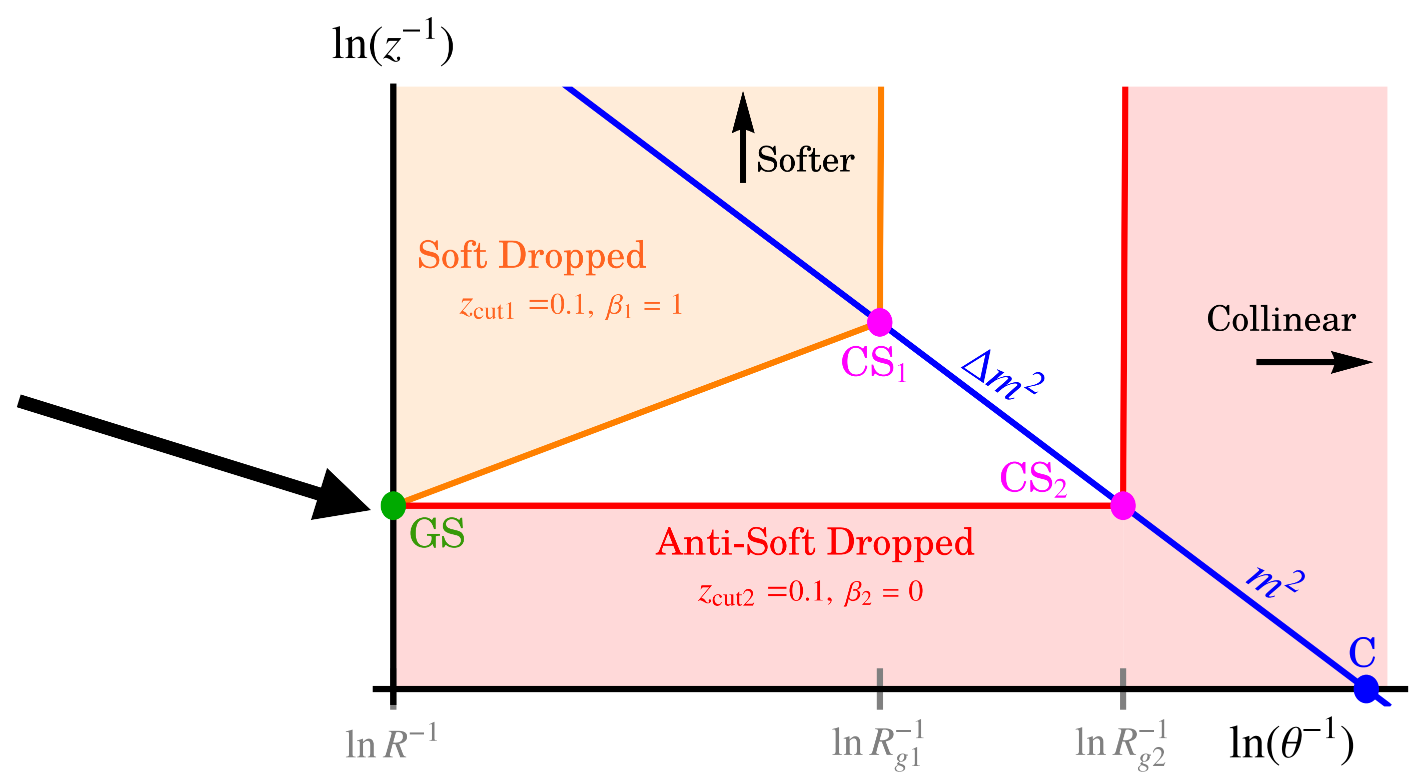


Choose a Region of Soft Phase Space

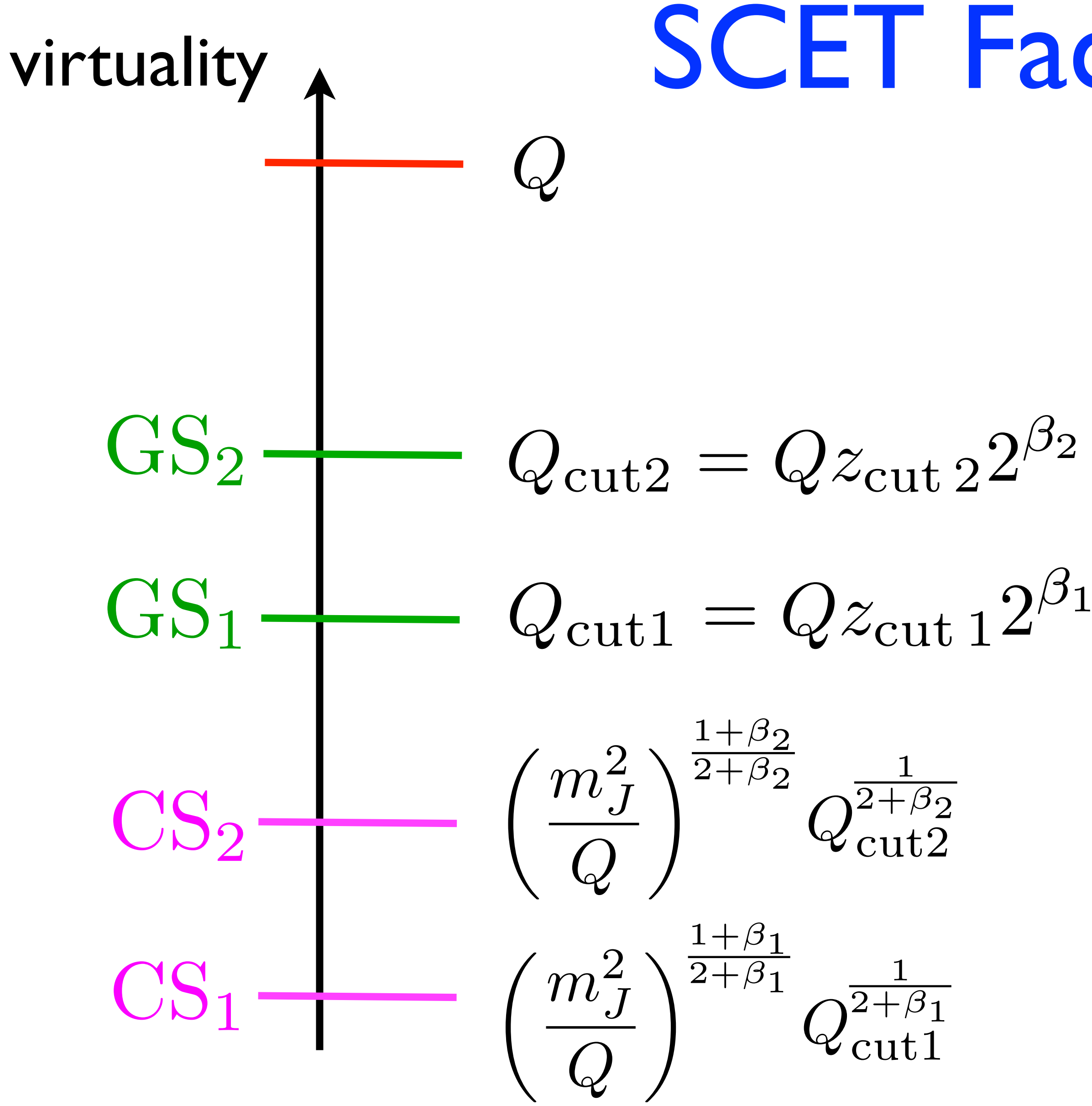


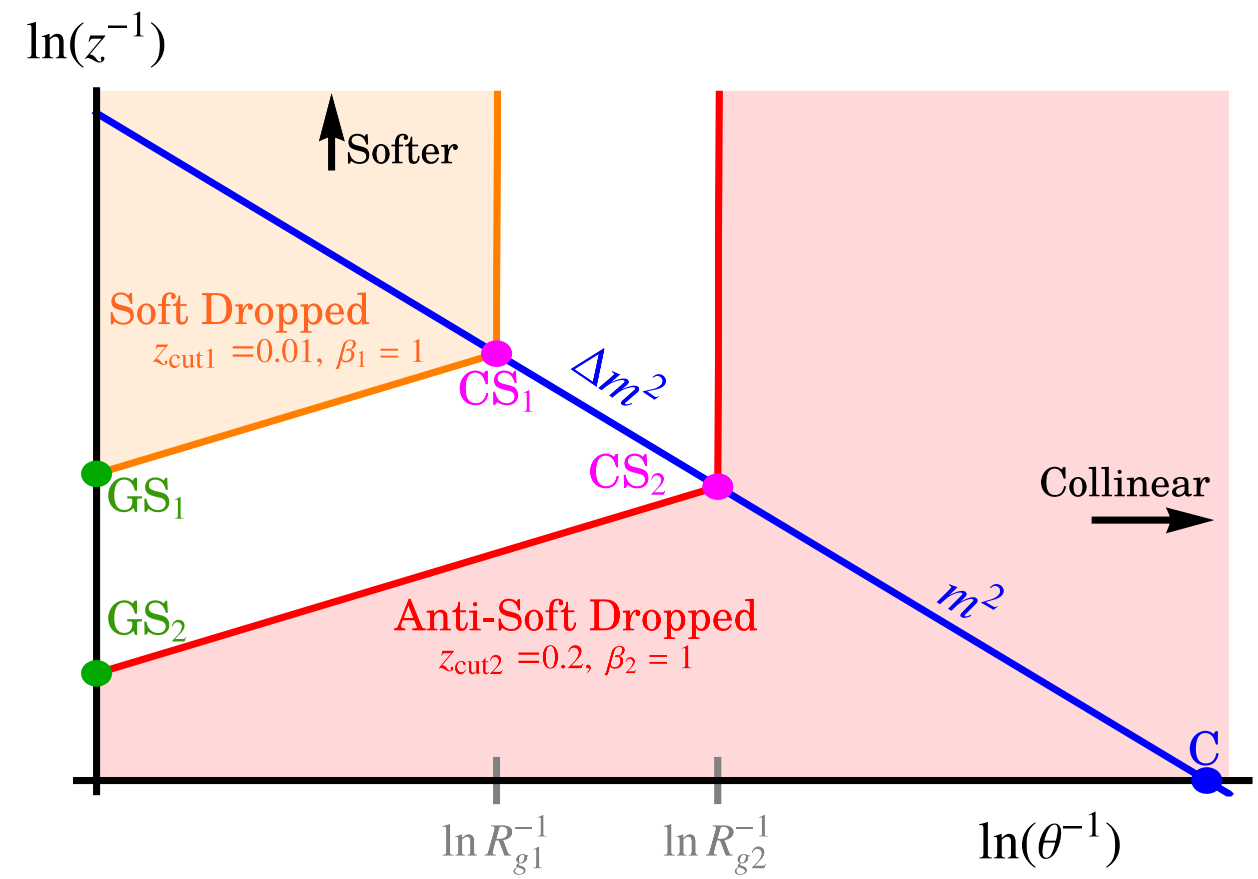


“pinched case” provides extra suppression for wide angle soft radiation



SCET Factorization (partonic)





<u>Single emission:</u>

$$\Delta m^2 \frac{d\sigma^{(\alpha_s)}}{d\Delta m^2} = \frac{\alpha_s(\mu) C_i}{\pi} \ln\left[\frac{z_{\mathrm{cut}\,2}^{\frac{2}{2+\beta_2}}}{z_{\mathrm{cut}\,1}^{\frac{2}{2+\beta_1}}}\left(\frac{\Delta m^2}{(p_T R)^2}\right)^{\frac{\beta_2}{2+\beta_2}-\frac{\beta_1}{2+\beta_1}}\right]$$

double logs cancel when $\beta_1 = \beta_2$

true for full resummed result (“NLL” is actually LL for this case)

SCET Factorization (partonic)

virtuality

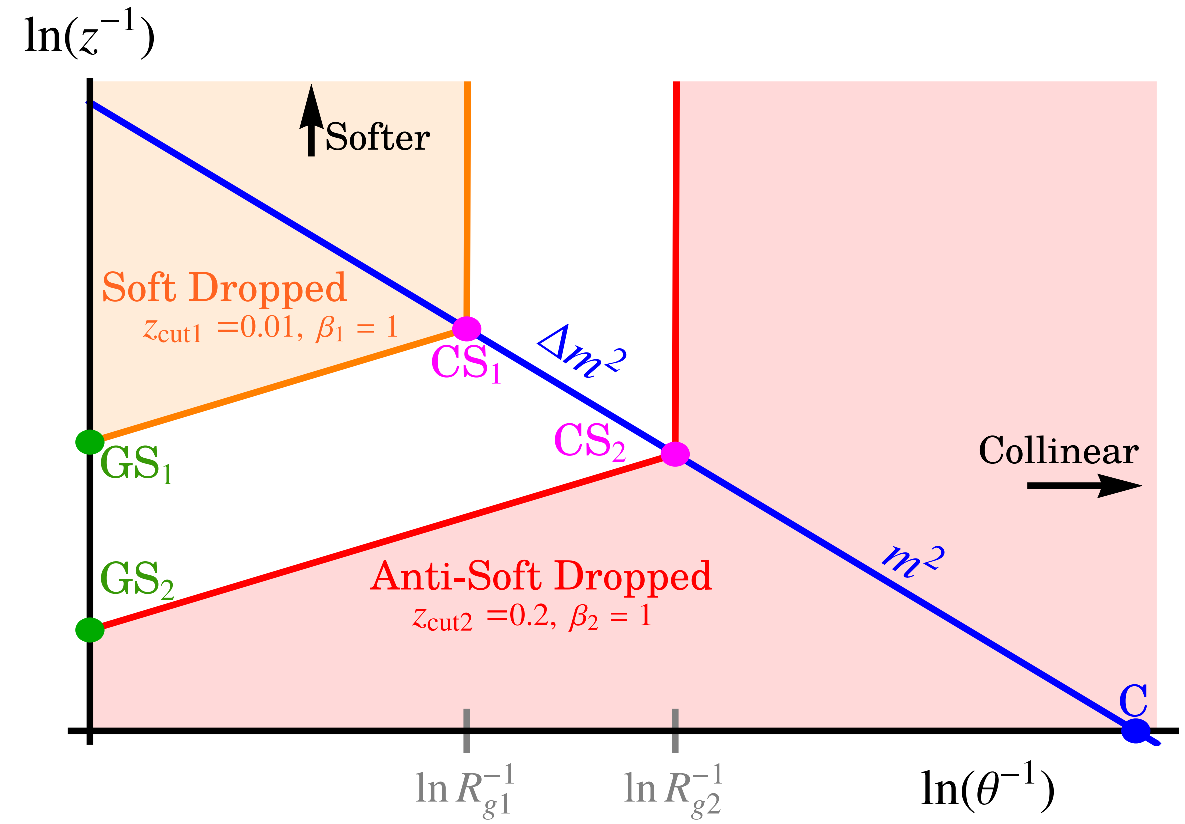
Q

GS$_2$ $\quad \mu_{gs2} = Q_{\text{cut2}} = Q z_{\text{cut}\,2} 2^{\beta_2}$

GS$_1$ $\quad \mu_{gs1} = Q_{\text{cut1}} = Q z_{\text{cut}\,1} 2^{\beta_1}$

CS$_2$ $\quad \mu_{cs2} = \left(\frac{m_J^2}{Q}\right)^{\frac{1+\beta_2}{2+\beta_2}} Q_{\text{cut2}}^{\frac{1}{2+\beta_2}}$

CS$_1$ $\quad \mu_{cs1} = \left(\frac{m_J^2}{Q}\right)^{\frac{1+\beta_1}{2+\beta_1}} Q_{\text{cut1}}^{\frac{1}{2+\beta_1}}$



$$\frac{d\sigma}{d\Delta m^2} = \sum_{j=q,g} \underbrace{N_j^{\text{CD}}(\Phi_J, R, z_{\text{cut}\,i}, \beta_i, \mu)}_{H_j^{\text{CD}}(\Phi_J, R)\, S_{Gj}(Q_{\text{cut}\,1}, \beta_1, \mu)\, \bar{S}_{Gj}(Q_{\text{cut}\,2}, \beta_2, \mu)} P_j^{\text{CD}}(\Delta m^2, Q, z_{\text{cut}\,i}, \beta_i, \mu)$$

GS$_1$ GS$_2$

product is RG invariant (unlike Soft Drop)

$$P_j^{\text{CD}} = Q_{\text{cut1}}^{\frac{1}{1+\beta_1}} Q_{\text{cut2}}^{\frac{1}{1+\beta_2}} \int dk_1^+ dk_2^+\, \delta(\Delta m^2 - Qk_1^+ - Qk_2^+)\, S_{Cj}\left(k_1^+ Q_{\text{cut1}}^{\frac{1}{1+\beta_1}}, \beta_1, \mu\right) D_{Cj}\left(k_2^+ Q_{\text{cut2}}^{\frac{1}{1+\beta_2}}, \beta_2, \mu\right)$$

CS$_1$ CS$_2$

Resummation

Simple to derive for fully hierarchical case:

$$P_j^{\rm CD} = \exp\left[-\frac{2(2+\beta_1)}{1+\beta_1}C_j K(\mu_{cs1},\mu) + \frac{2(2+\beta_2)}{(1+\beta_2)}C_j K(\mu_{cs2},\mu)\right]\left[\frac{Q_{\rm cut1}^{\frac{1}{1+\beta_1}}\,\mu_{cs2}^{\frac{2+\beta_2}{1+\beta_2}}}{Q_{\rm cut2}^{\frac{1}{1+\beta_2}}\,\mu_{cs1}^{\frac{2+\beta_1}{1+\beta_1}}}\right]^{2C_j\,\omega(\mu_{cs1},\mu)}$$
$$\times \exp\left[\omega_{S_{Ci}}(\mu_{cs1},\mu) + \omega_{D_{Ci}}(\mu_{cs2},\mu)\right]\,\widetilde{D}_{Ci}\big(\partial_\eta,\beta_2,\alpha_s(\mu_{cs2})\big)$$
$$\times \widetilde{S}_{Ci}\left(\partial_\eta + \ln\frac{Q_{\rm cut1}^{\frac{1}{1+\beta_1}}\,\mu_{cs2}^{\frac{2+\beta_2}{1+\beta_2}}}{Q_{\rm cut2}^{\frac{1}{1+\beta_2}}\,\mu_{cs1}^{\frac{2+\beta_1}{1+\beta_1}}},\beta_1,\alpha_s(\mu_{cs1})\right)\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}\,\frac{1}{\Delta m^2}\left(\frac{\Delta m^2\,Q_{\rm cut2}^{\frac{1}{1+\beta_2}}}{\mu_{cs2}^{\frac{2+\beta_2}{1+\beta_2}}\,Q}\right)^{\eta}\Bigg|_{\eta=2C_j\,\omega(\mu_{cs1},\mu_{cs2})}.$$

$$N_j^{\rm CD}(\Phi_J,R,\tilde{z}_{{\rm cut}\,i},\beta_i,\mu_{gs1},\mu_{gs2},\mu) = H_j^{\rm CD}(\Phi_J,R)S_{Gj}(Q_{\rm cut1},\beta_1,\mu_{gs1})\bar{S}_{Gj}(Q_{\rm cut2},\beta_2,\mu_{gs2})$$
$$\times \exp\left[\frac{2C_j}{1+\beta_1}K(\mu_{gs1},\mu) - \frac{2C_j}{1+\beta_2}K(\mu_{gs2},\mu)\right]\exp\left[\omega_{S_{Gi}}(\mu_{gs1},\mu) + \omega_{\bar{S}_{Gi}}(\mu_{gs2},\mu)\right]$$

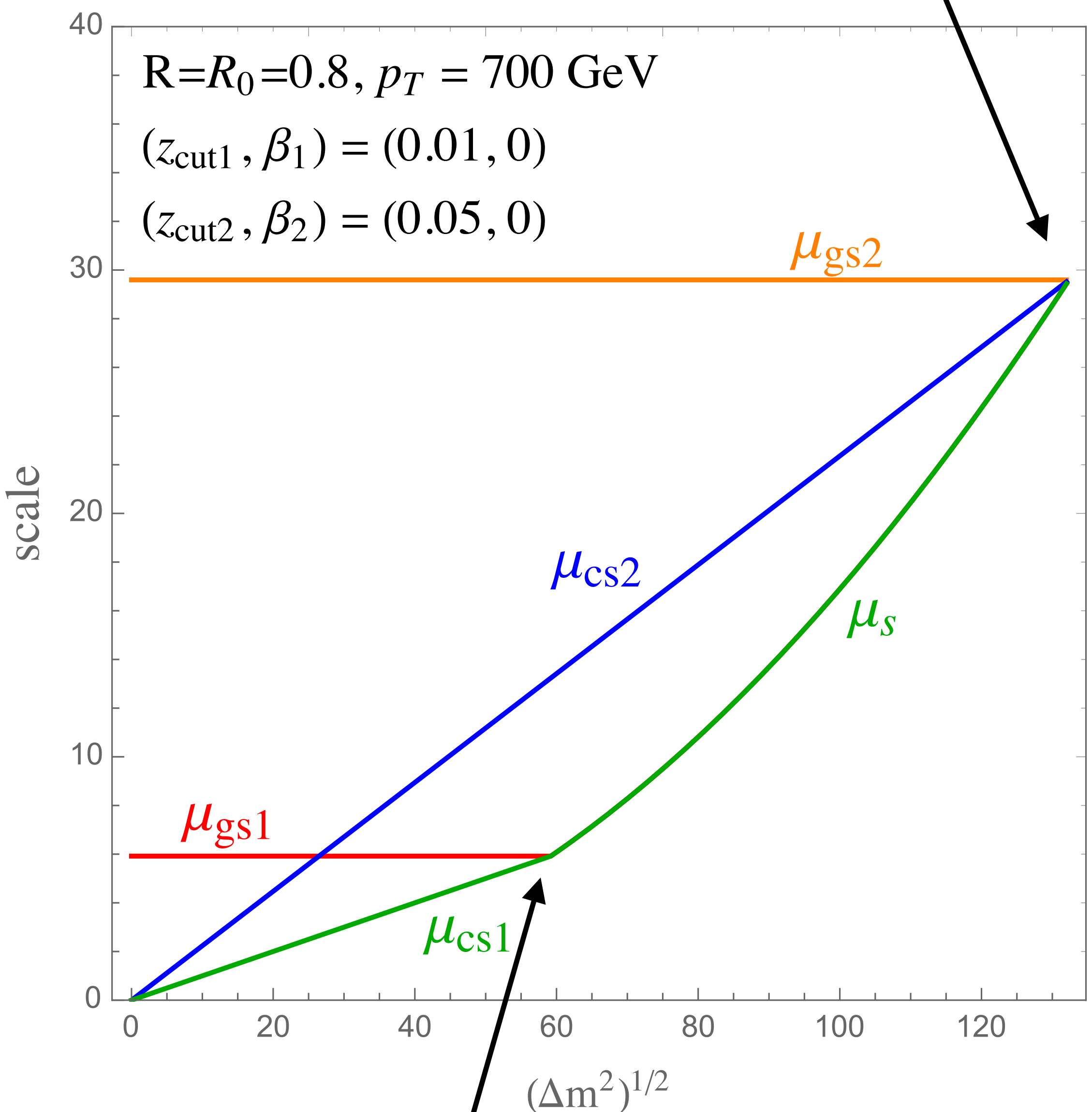
Up to NLL this same formula smoothly gives the non-hierarchical cases

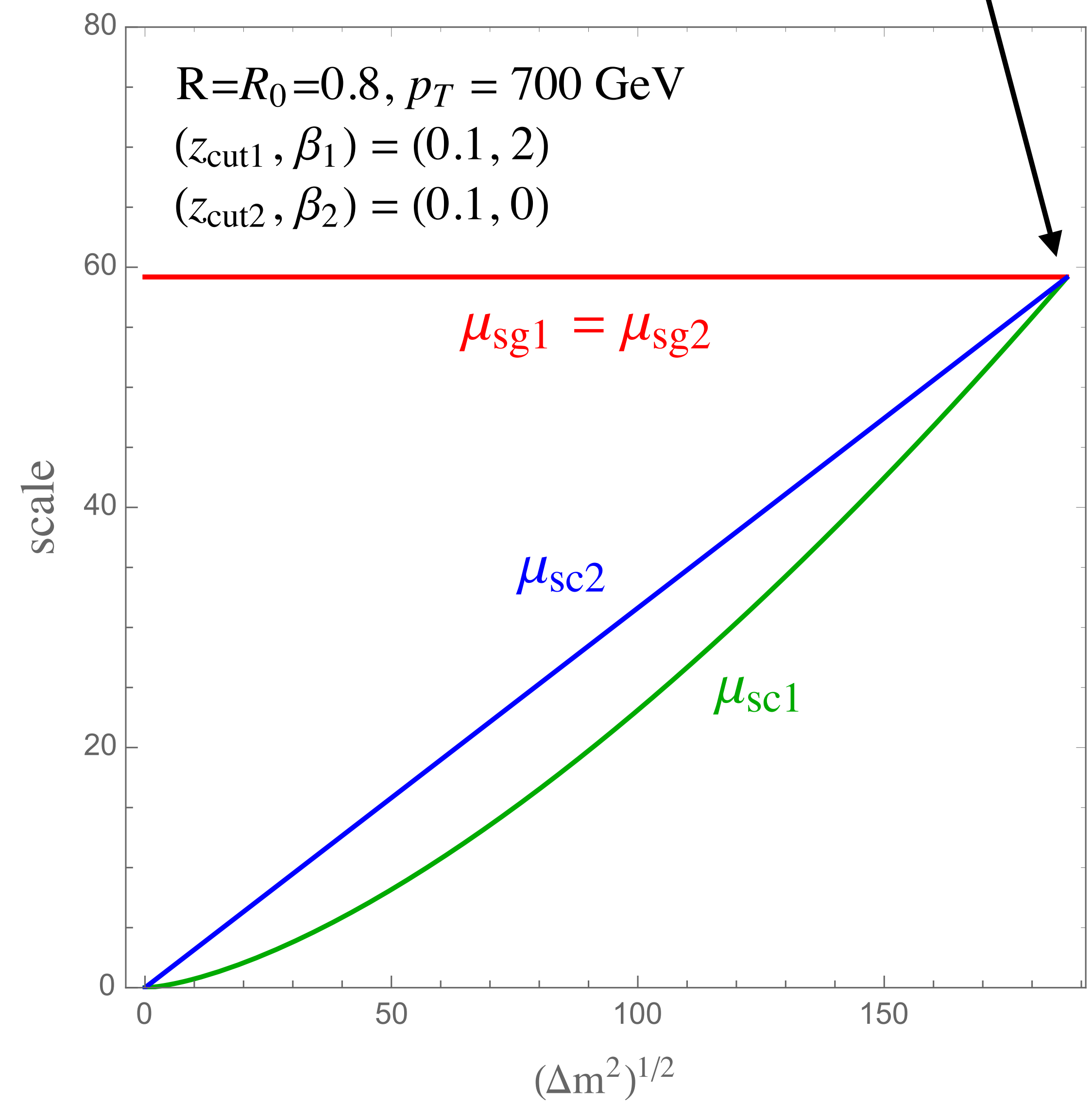
Only consider NLL here

Transitions & Endpoints

Collinear Drop endpoint: $\frac{\Delta m^2}{p_T^2 R^2} = z_{\rm cut2}$

Same in "pinched" case





Soft drop no longer active

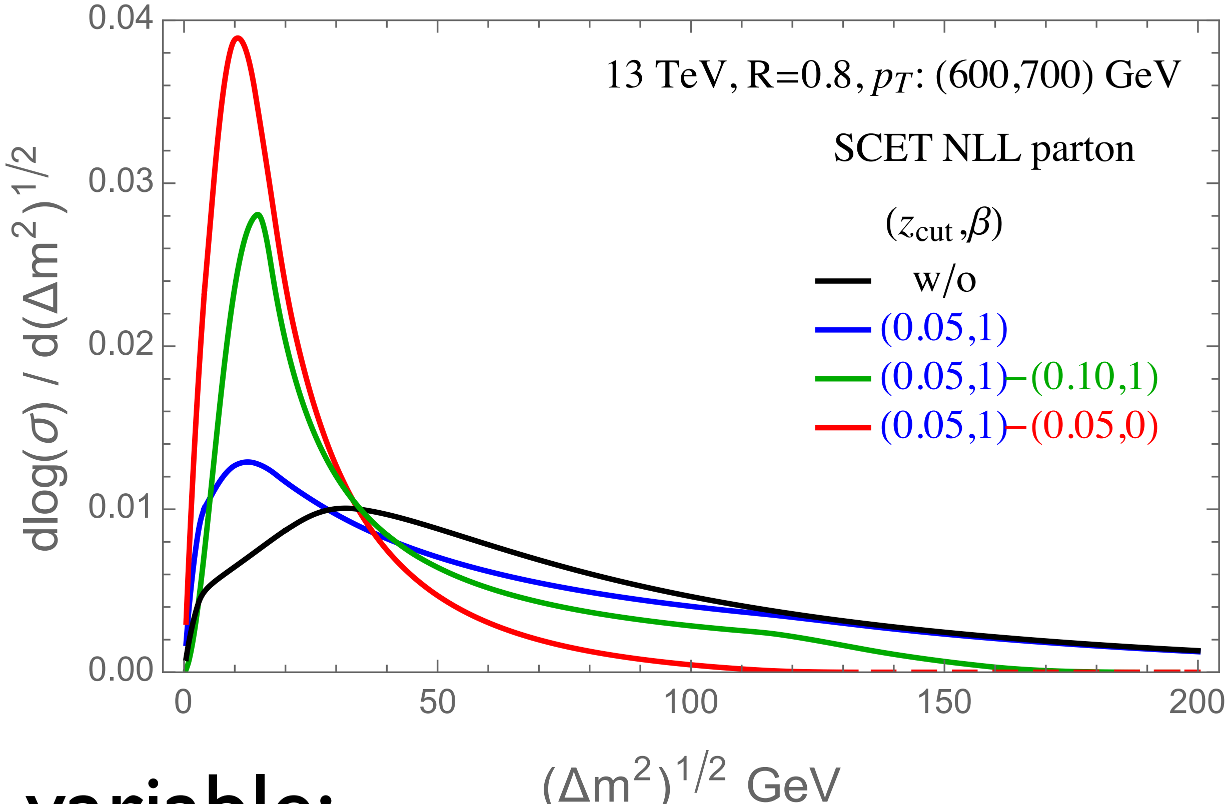
$$\frac{\Delta m^2}{p_T^2 R^2} \geq z_{\rm cut1}$$

Look at

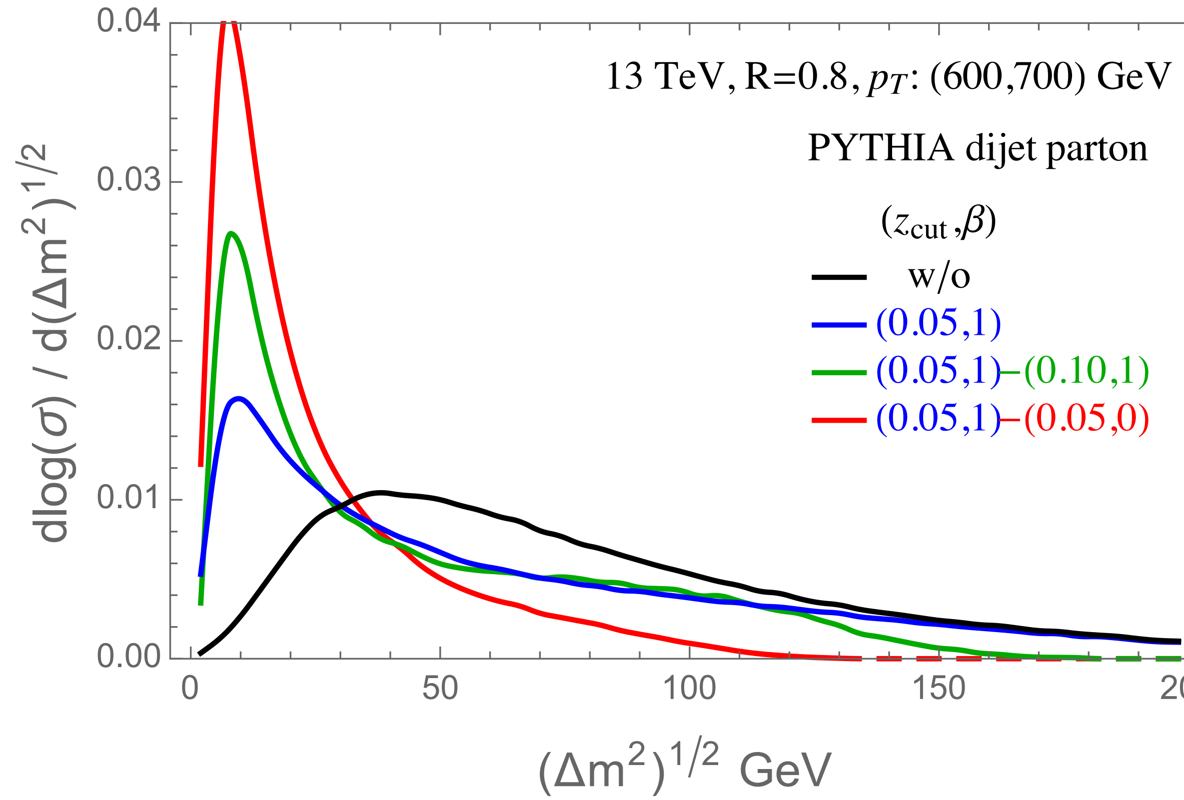
$$pp \longrightarrow \mathrm{dijet}$$

Collinear Drop vs. Soft Drop vs. Ungroomed

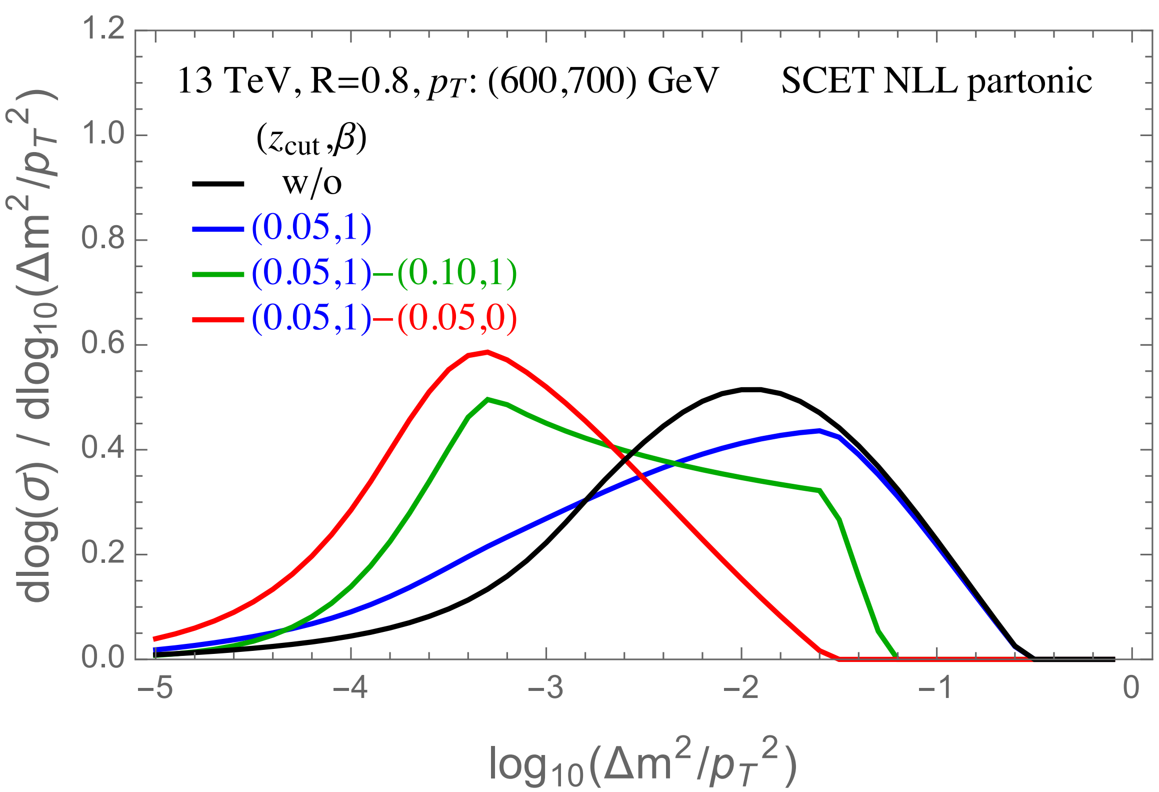
SCET

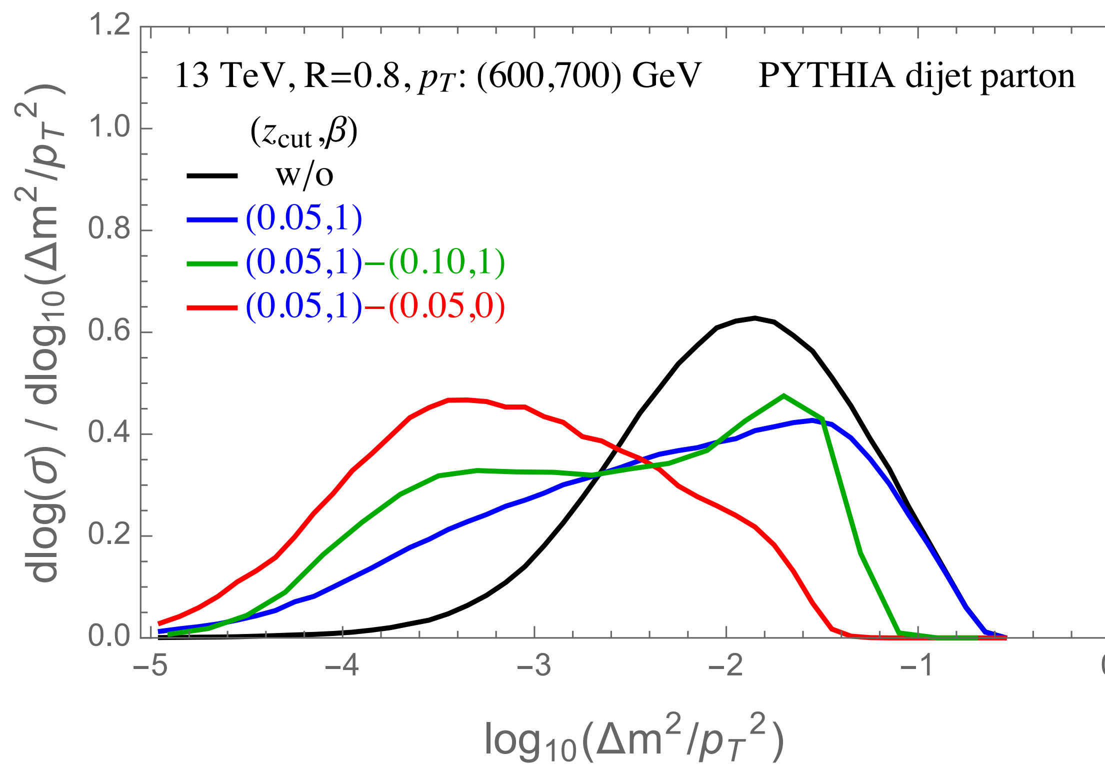


Pythia 8.223



log variable:

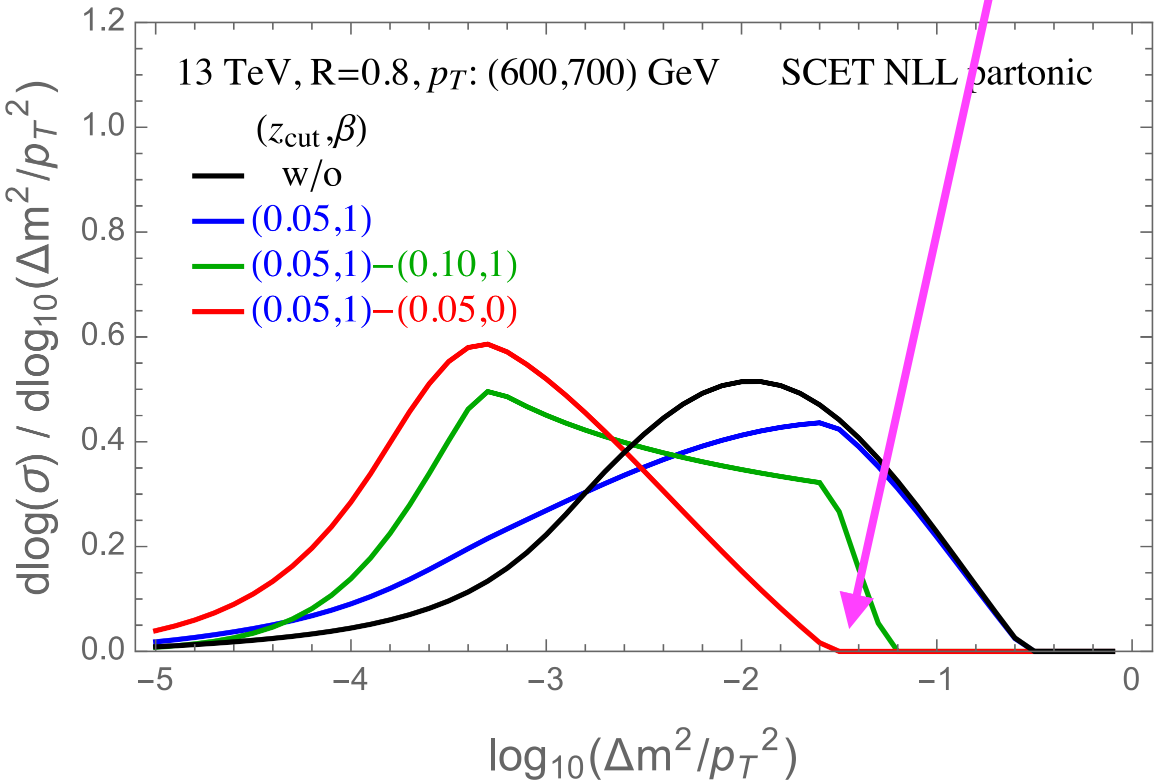


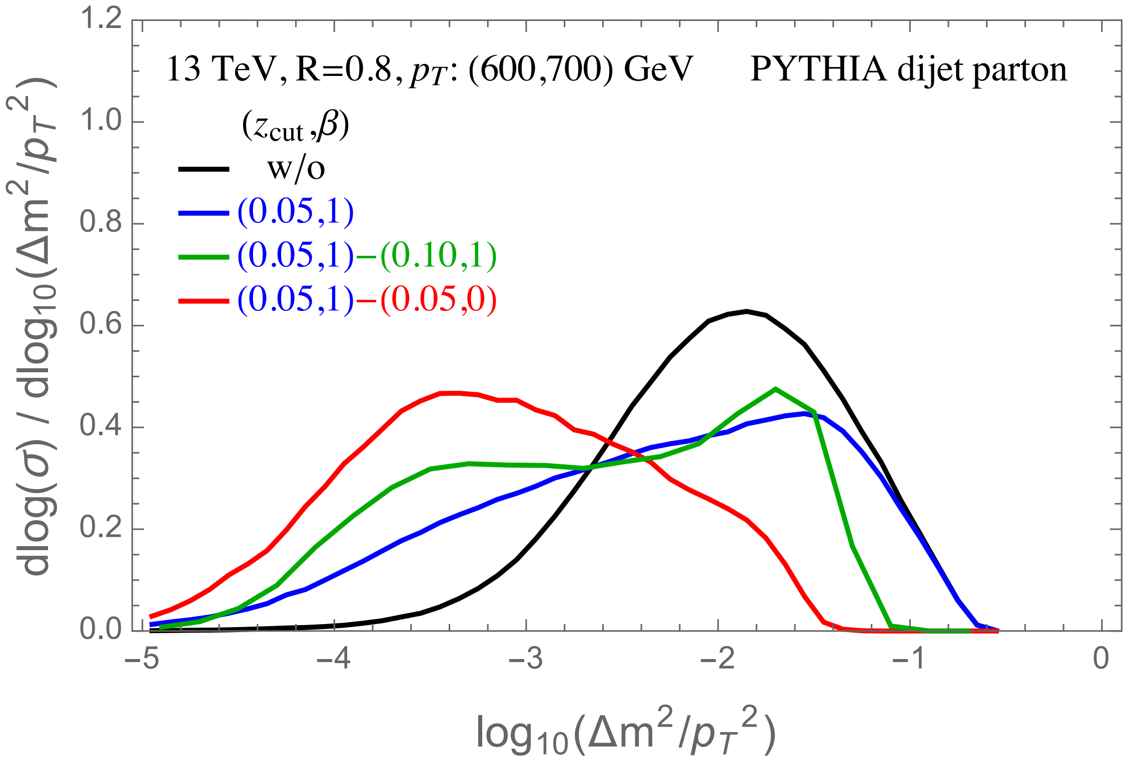


Collinear Drop vs. Soft Drop vs. Ungroomed

Tunable Collinear Drop endpoint: $\frac{\Delta m^2}{p_T^2 R^2} = z_{\text{cut2}}$

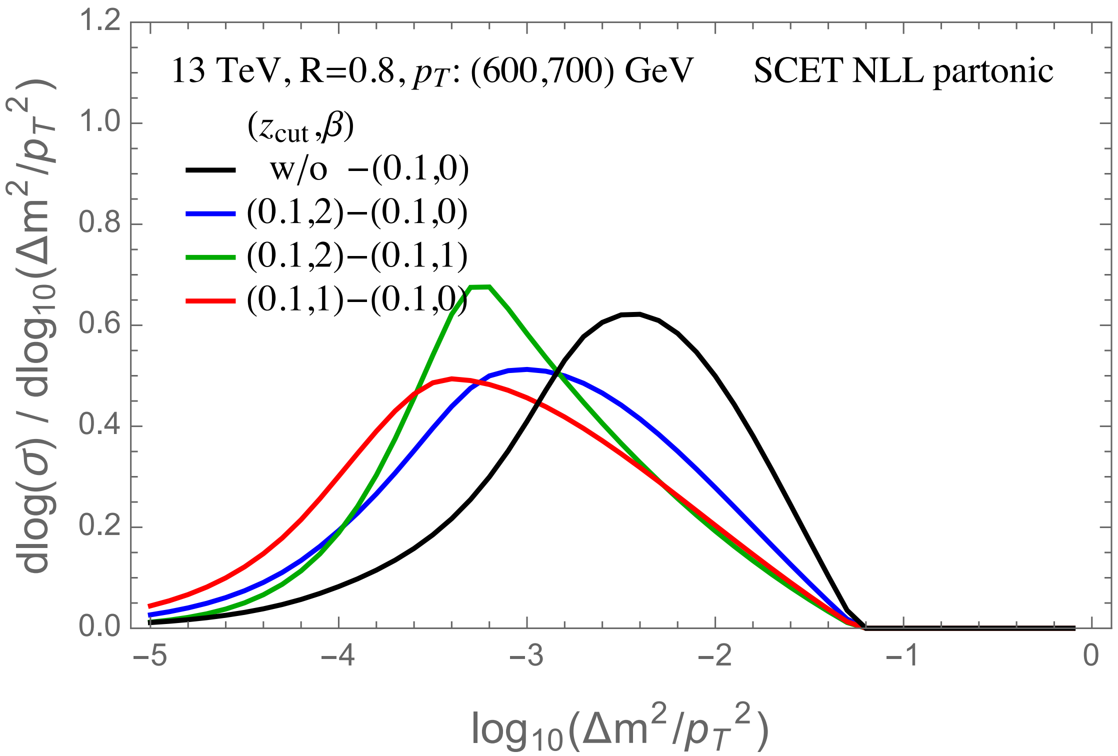
<u>log variable:</u>

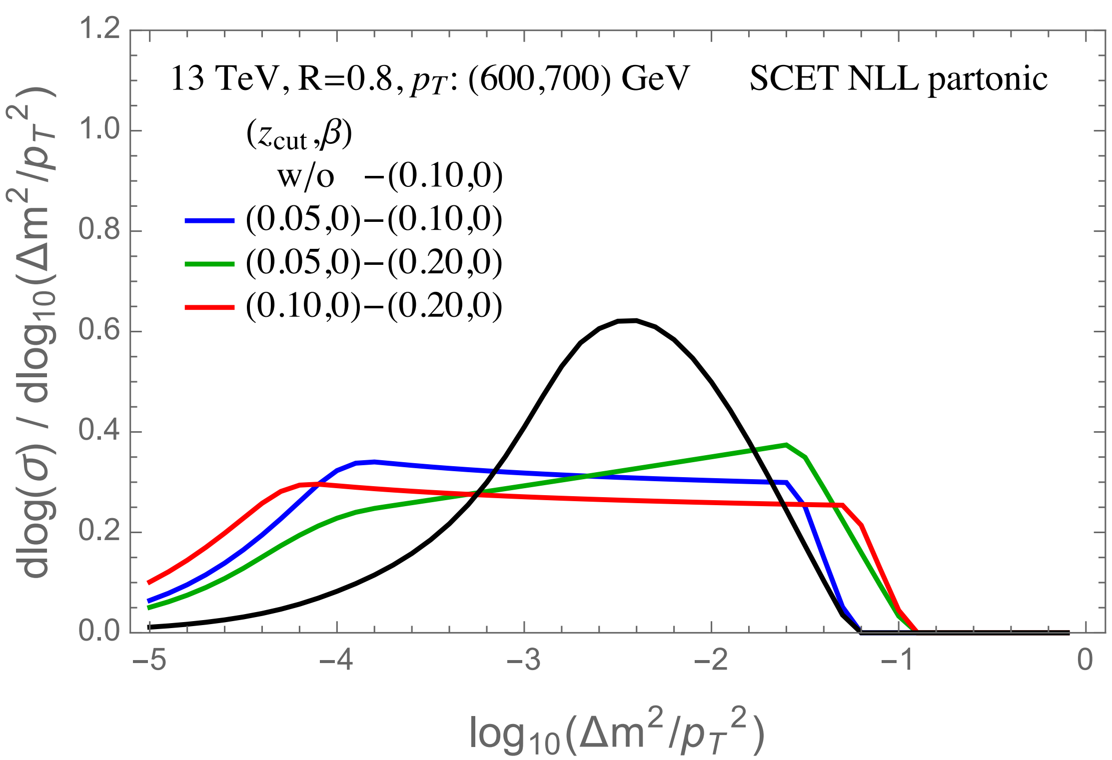




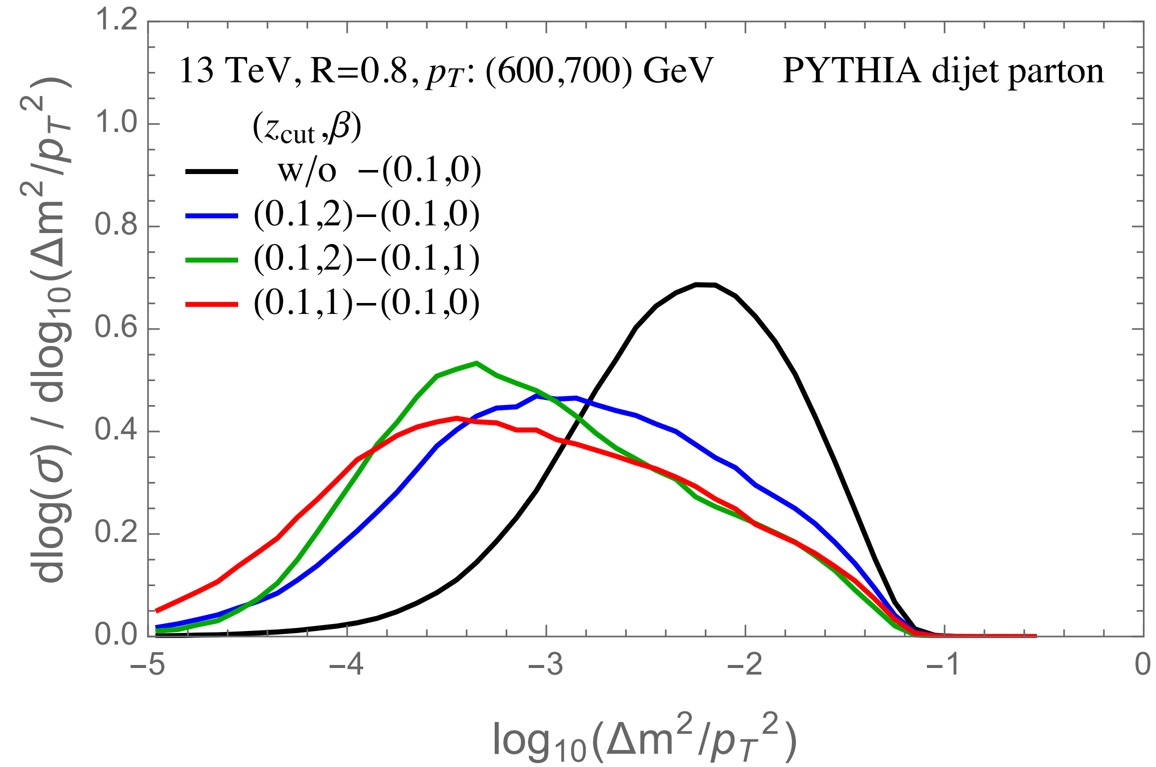
Collinear Drop Spectra

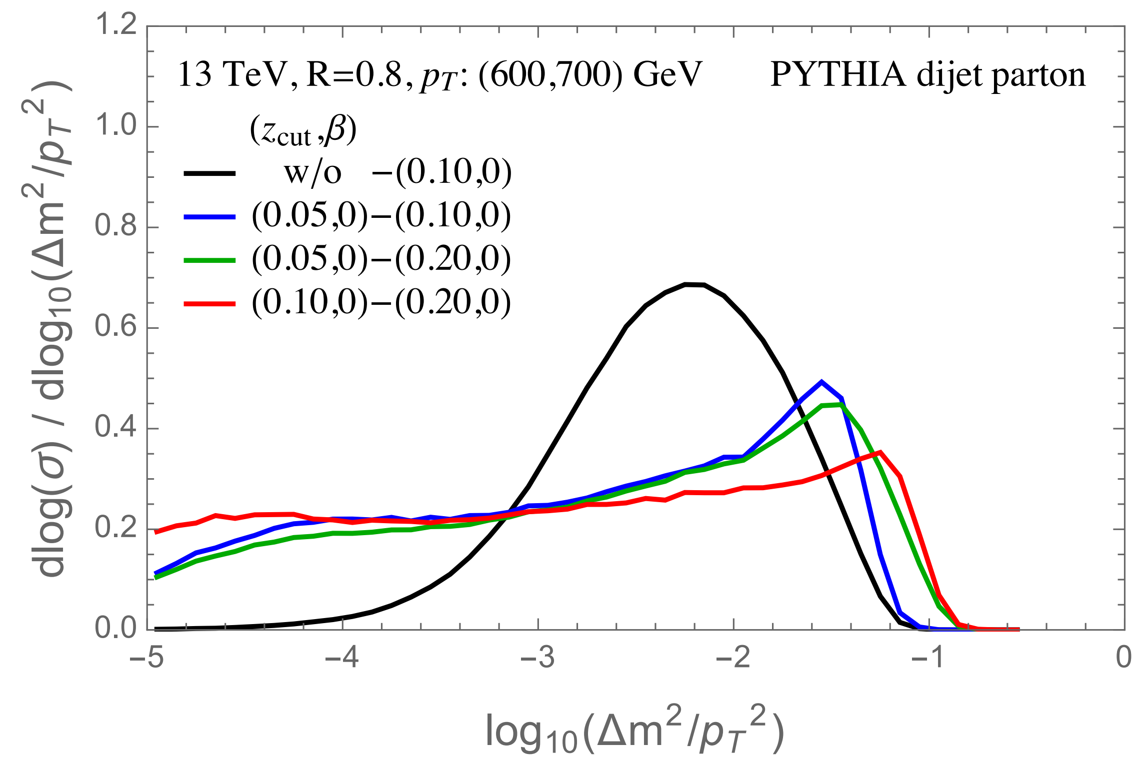
SCET





Pythia



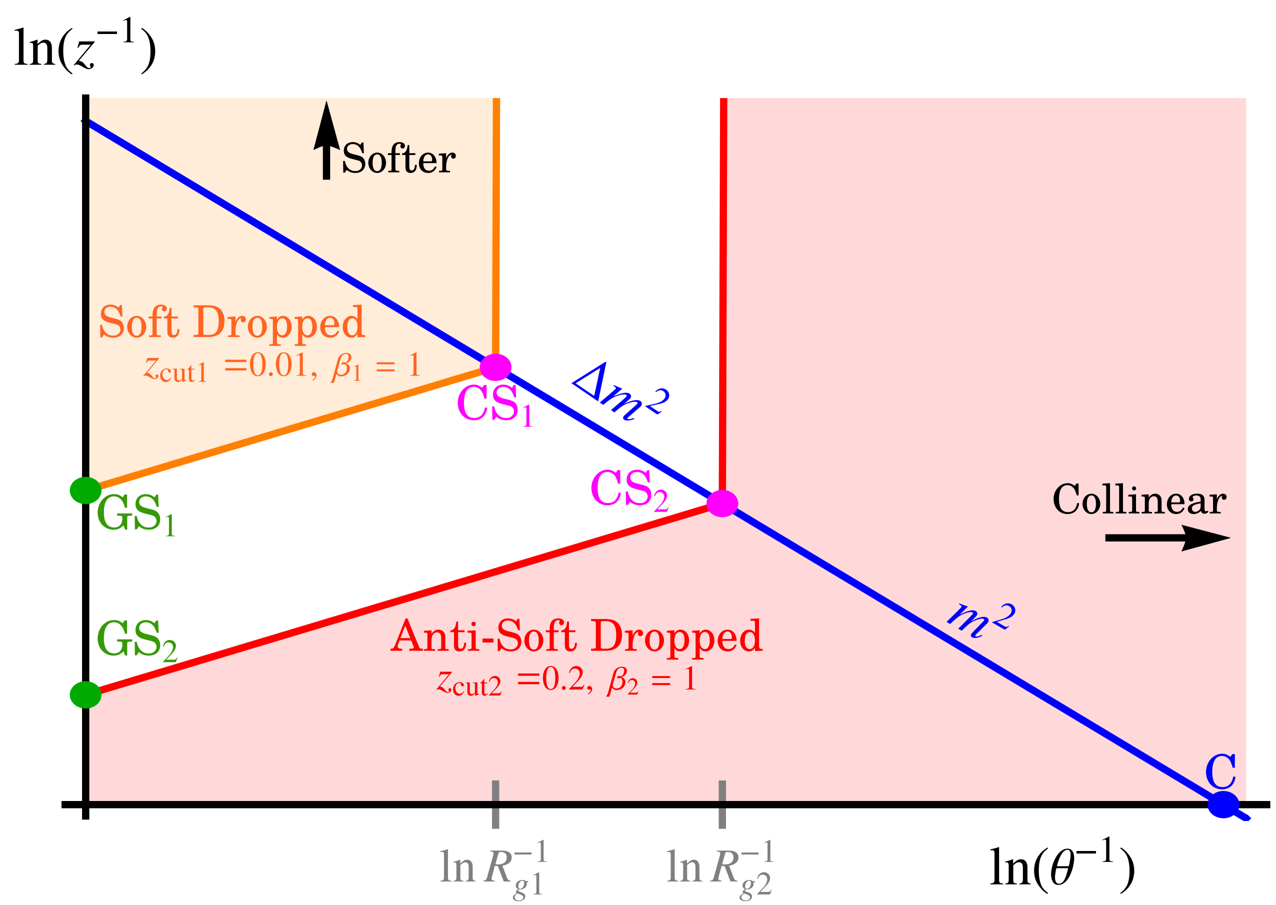


Endpoint of Evolution & Nonperturbative region (SCET, compared to MC)

Stop SCET evolution at $\mu_0 \sim 1\,\mathrm{GeV}$

as $\Delta m^2 \to 0$ take $\mu_{cs2} \to \mu_0$
$\mu_{cs1} \to \mu_0$

CD has a non-trivial contribution in $\Delta m^2 \simeq 0$ bin



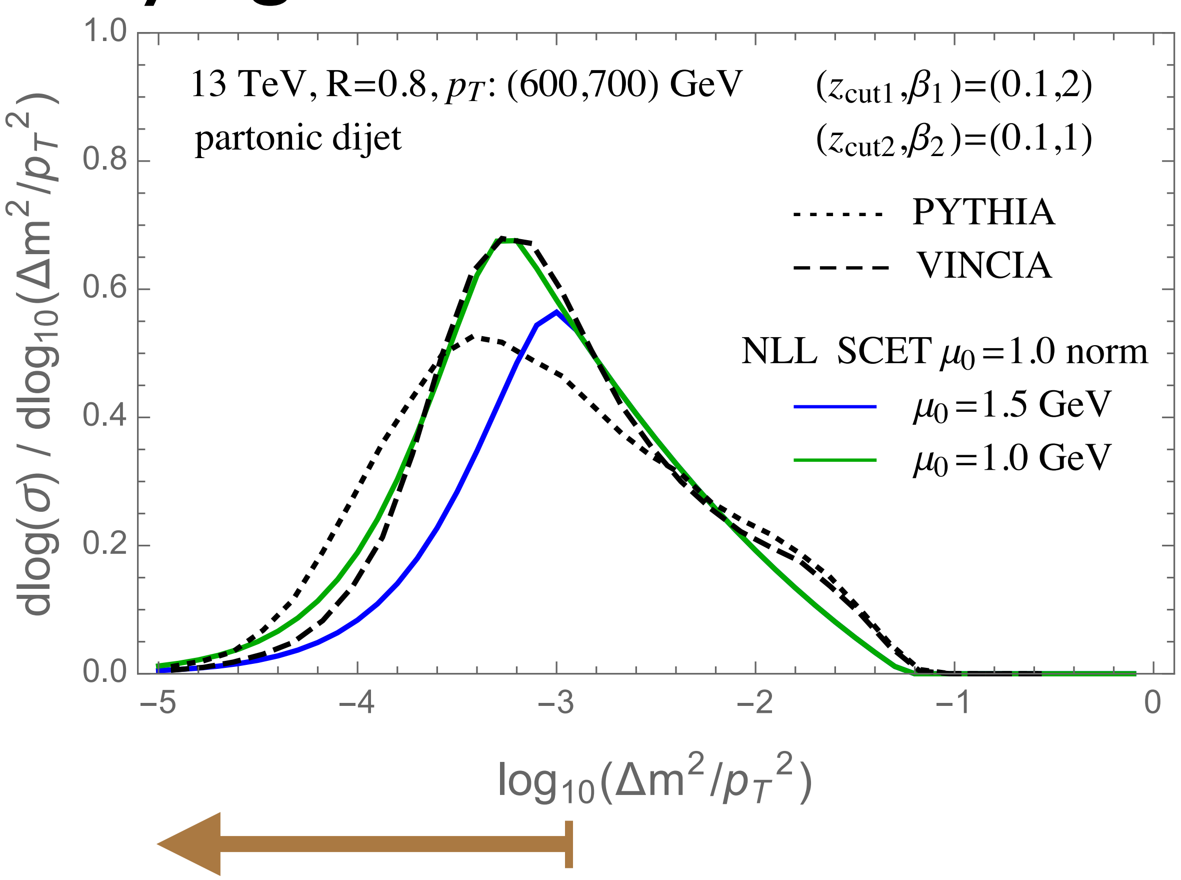
Endpoint of Evolution & Nonperturbative region (SCET, compared to MC)

Stop SCET evolution at $\mu_0 \sim 1\,\mathrm{GeV}$

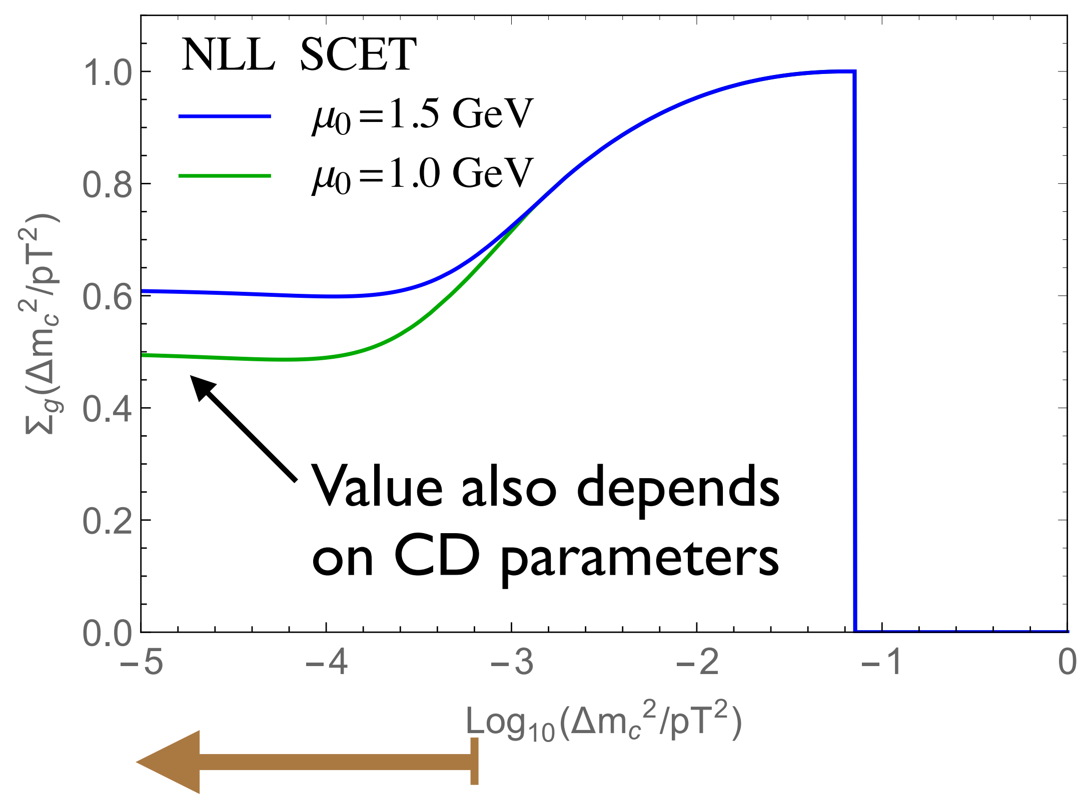
as $\Delta m^2 \to 0$ take $\mu_{cs2} \to \mu_0$
$\mu_{cs1} \to \mu_0$

CD has a non-trivial contribution in $\Delta m^2 \simeq 0$ bin

varying the cutoff:

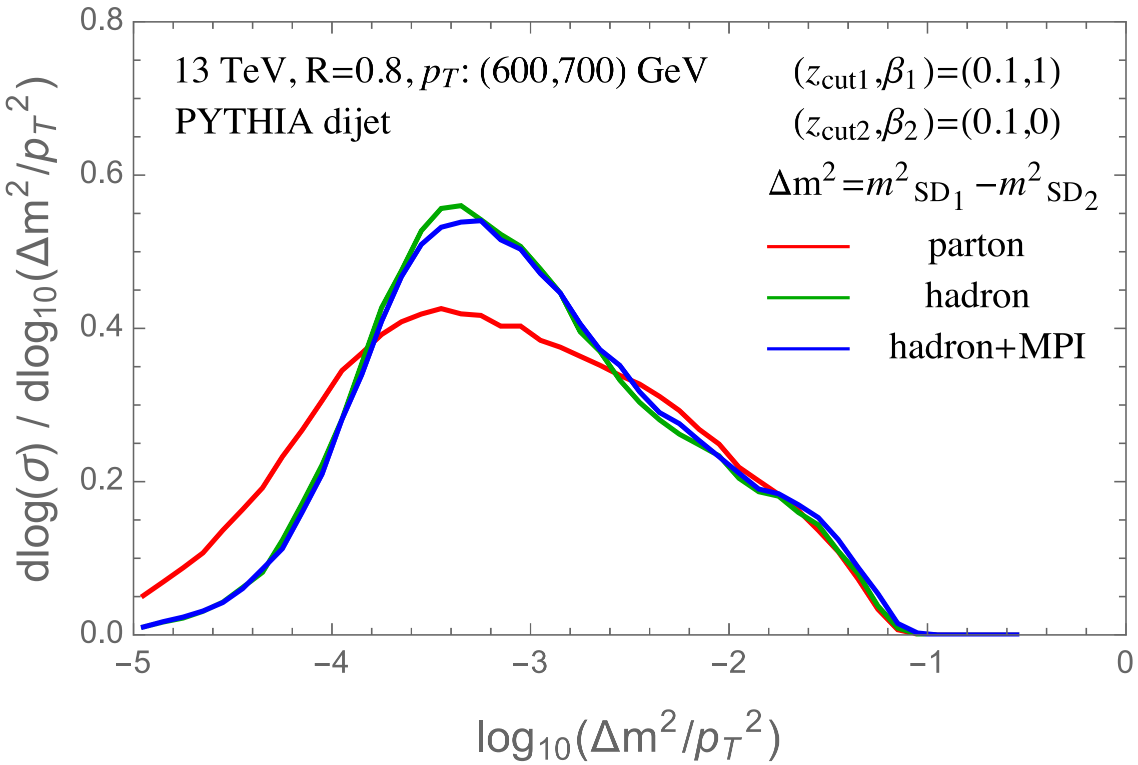


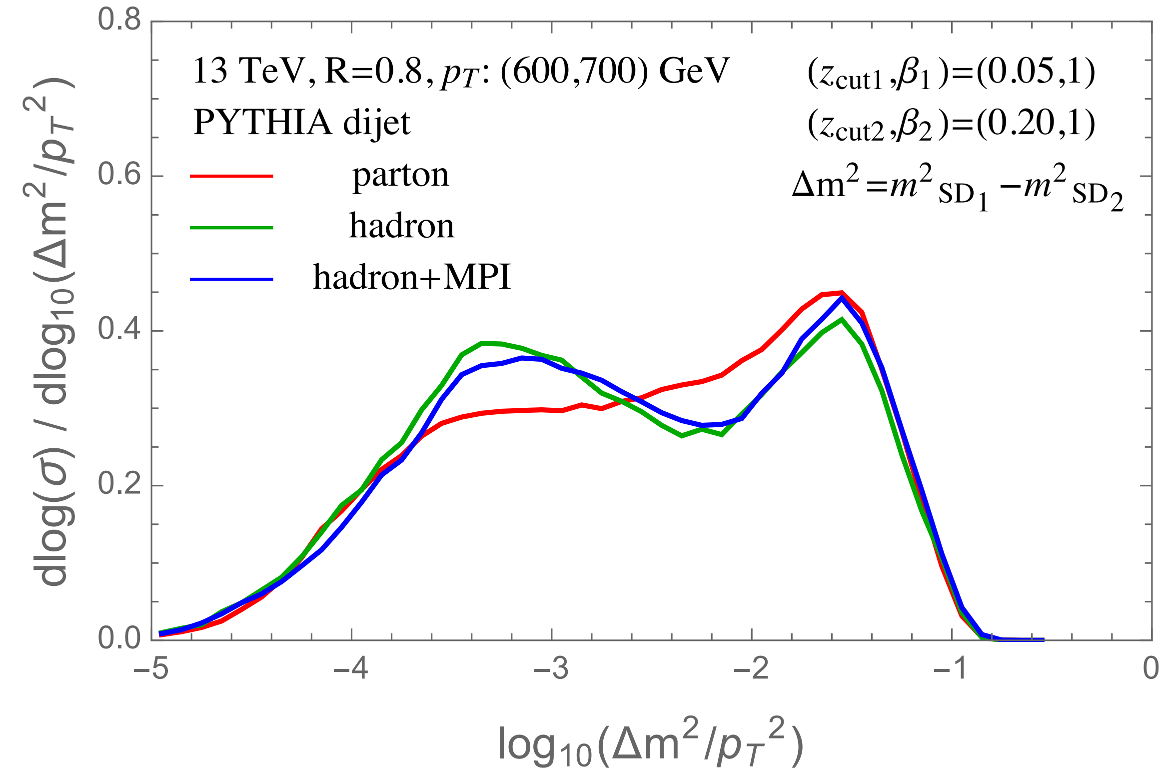
$$\Sigma(\Delta m_c^2) = \int_0^{\Delta m_c^2} d(\Delta m^2)\ \frac{d\sigma}{d\Delta m^2}$$



region more sensitive to NP effects / hadronization

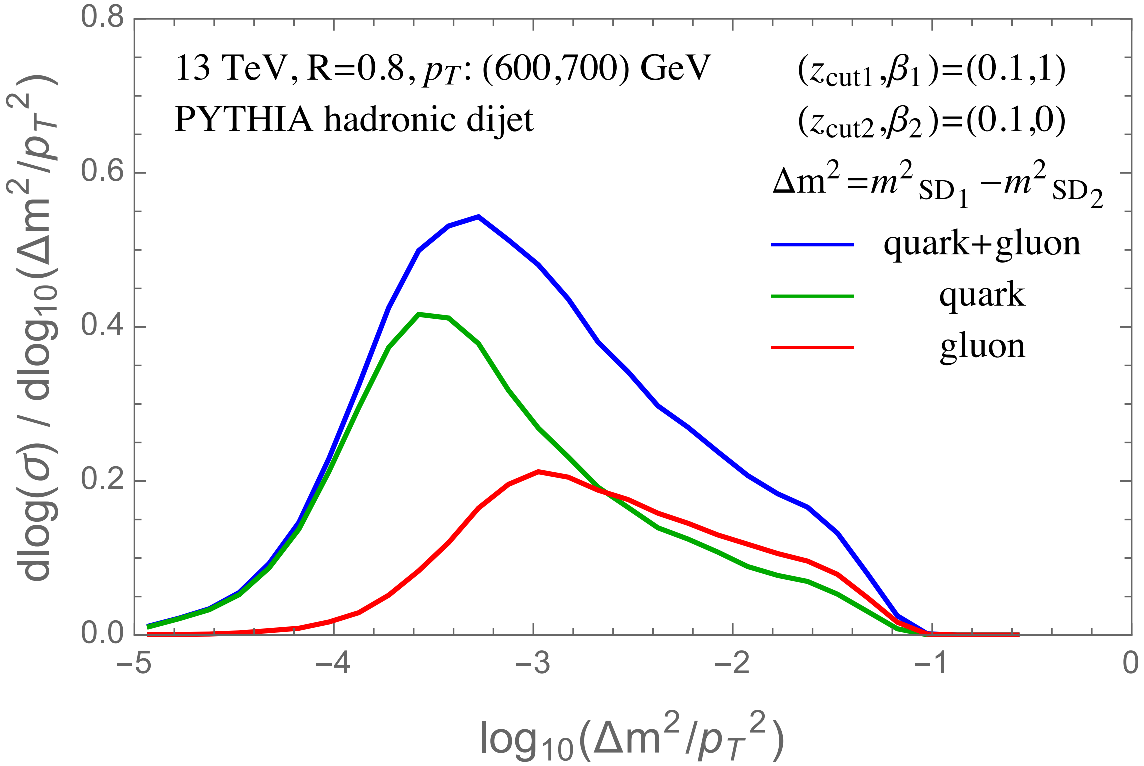
Sensitivity to Hadronization & MPI (MC)

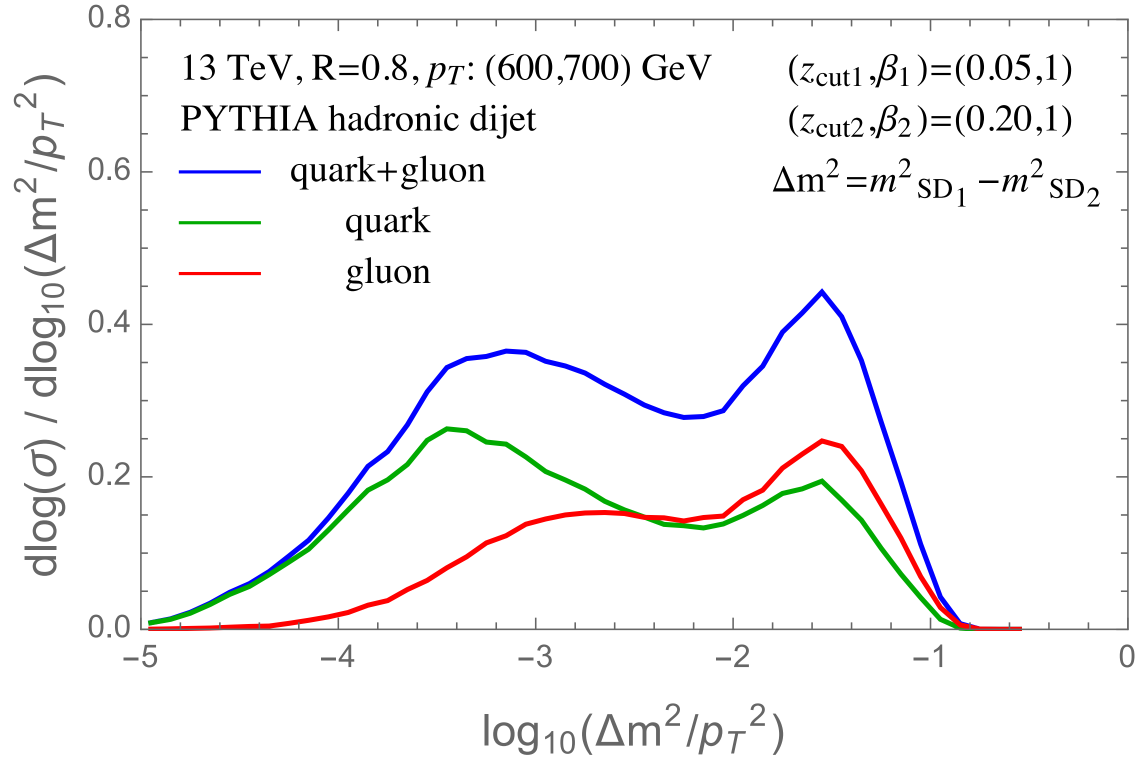




- Interesting hadronization corrections
- Soft Drop grooming protects against large MPI effects

Quark and Gluon Components for Dijet

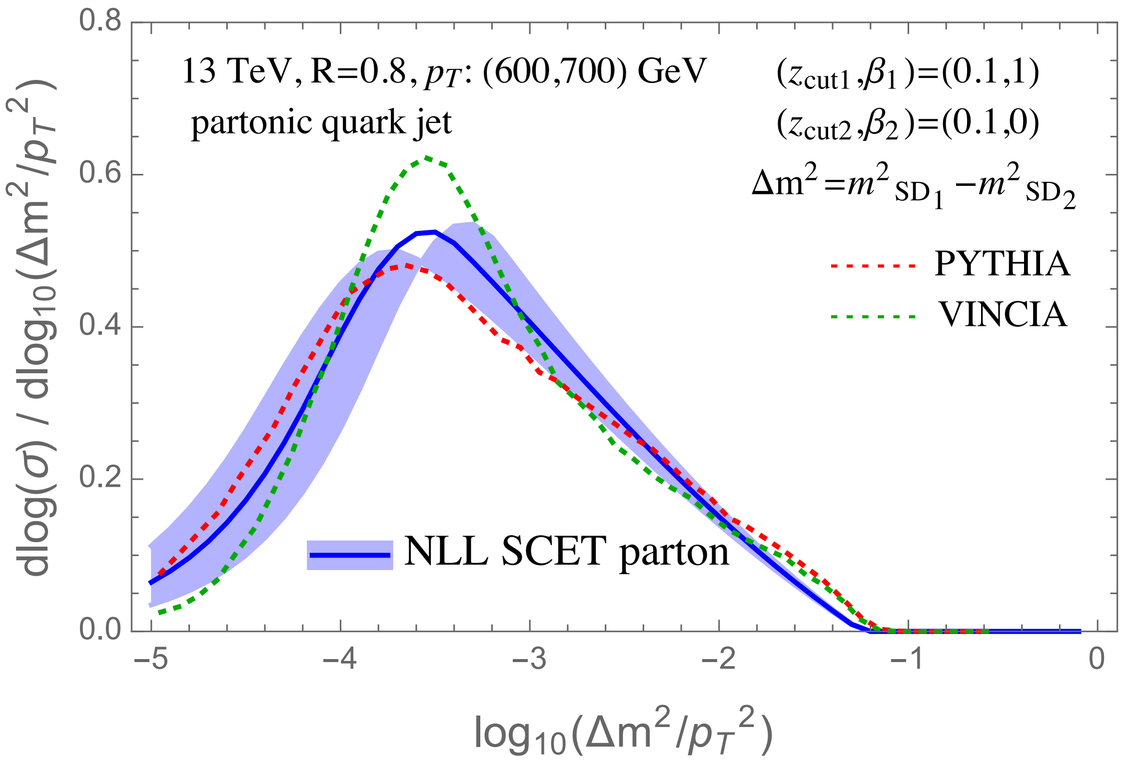


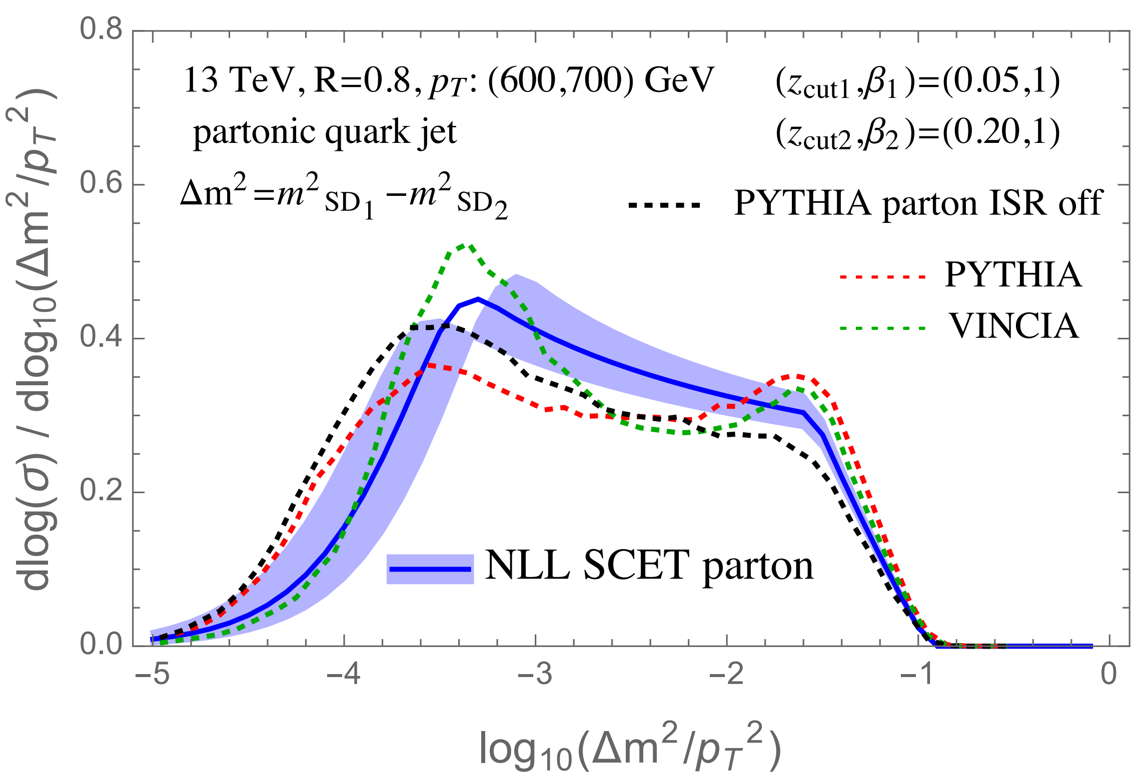


- Quark and Gluon peak in different regions

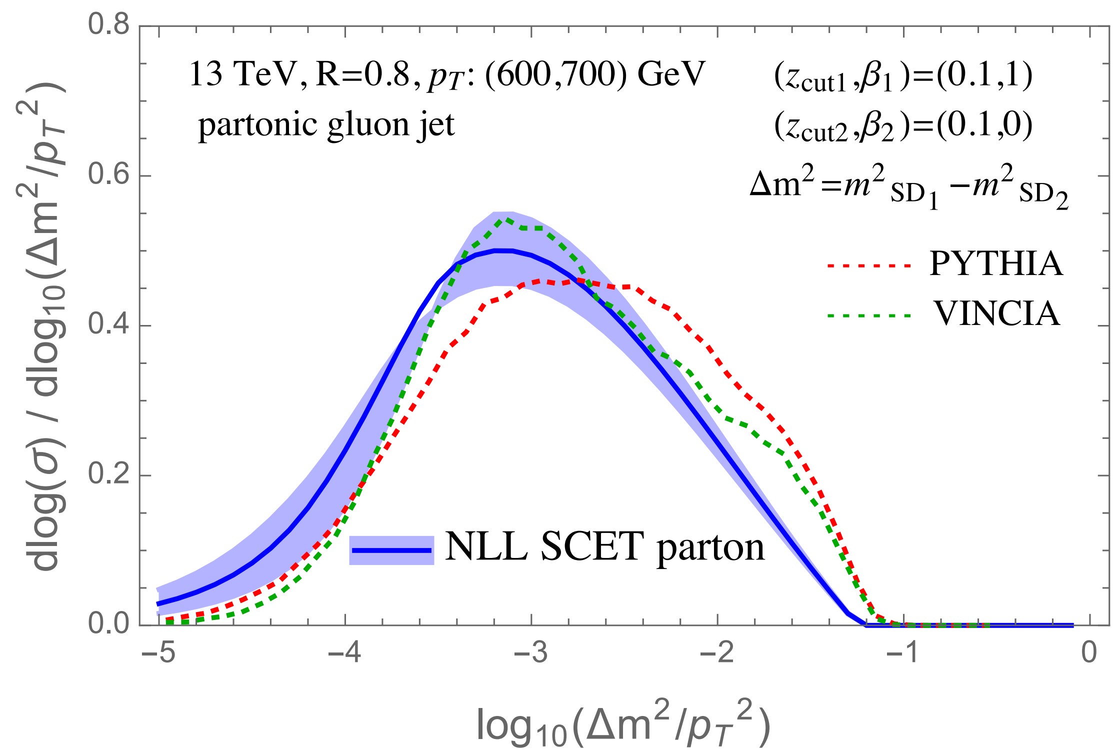
Comparison SCET & partonic MC

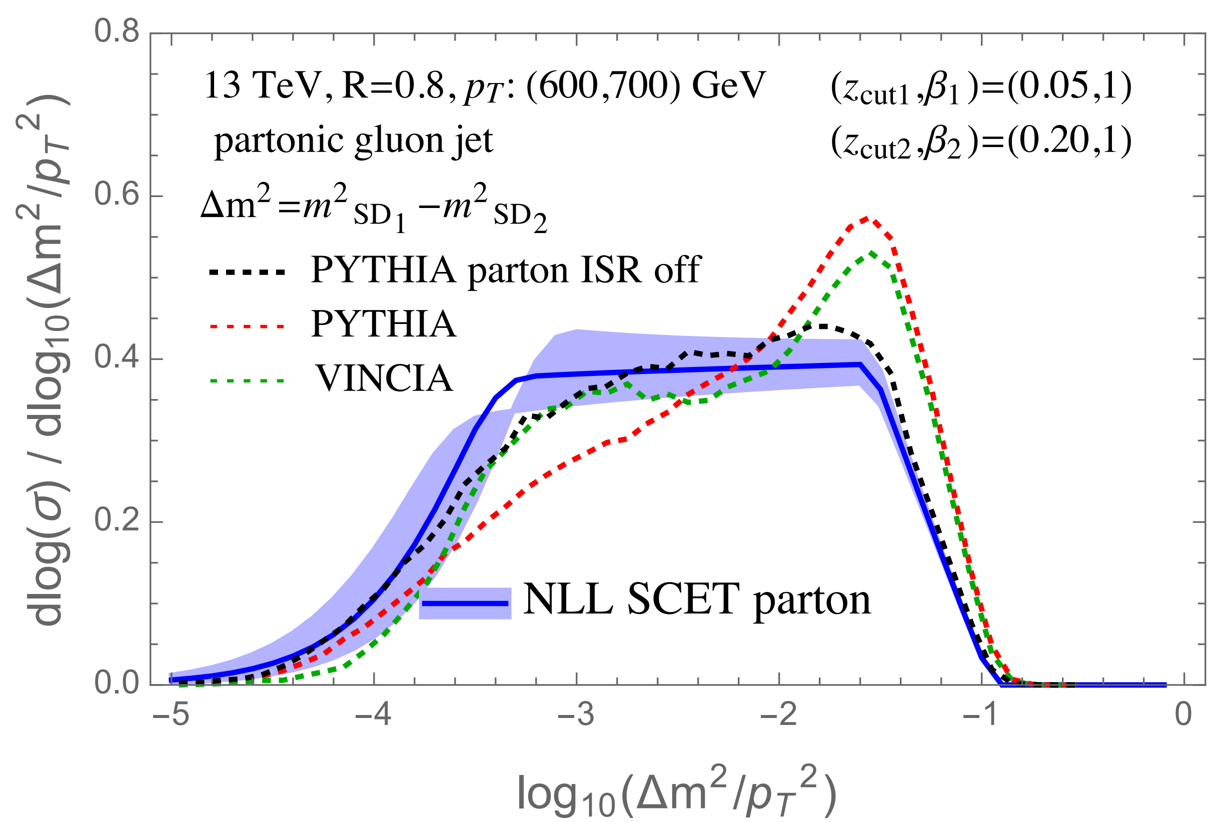
<u>quark</u>



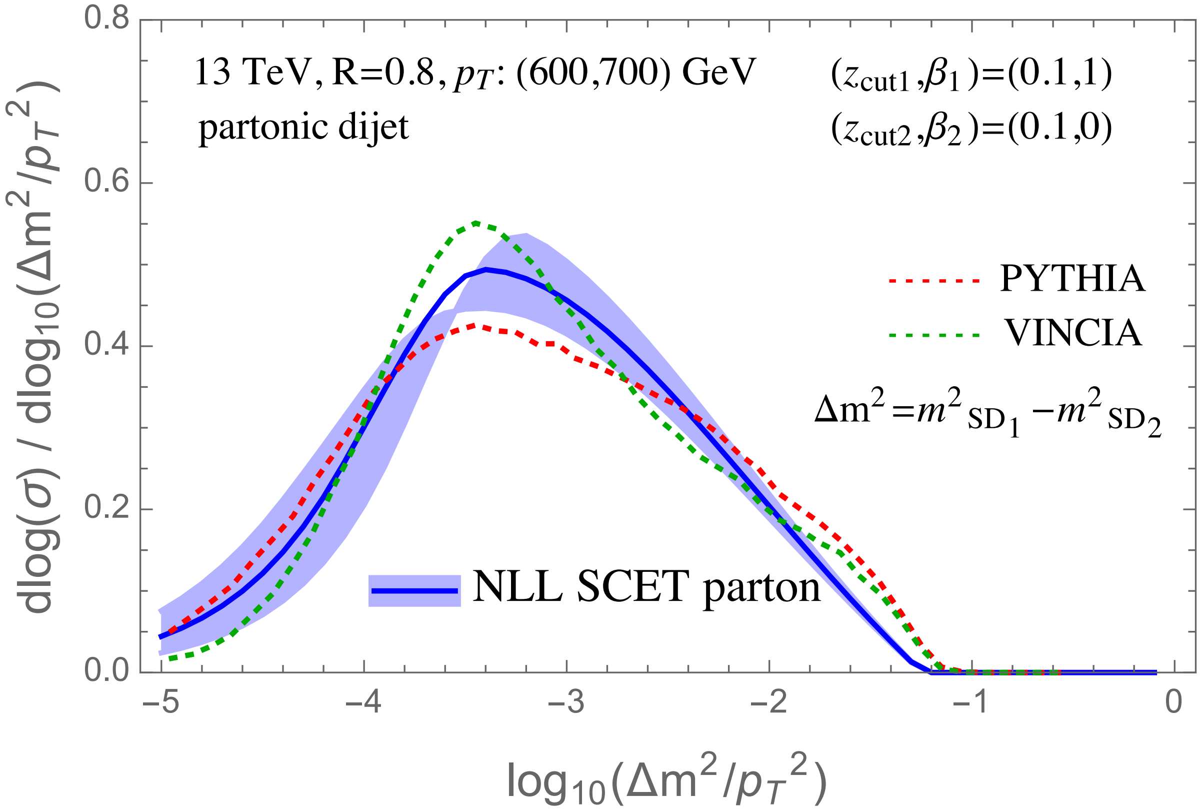


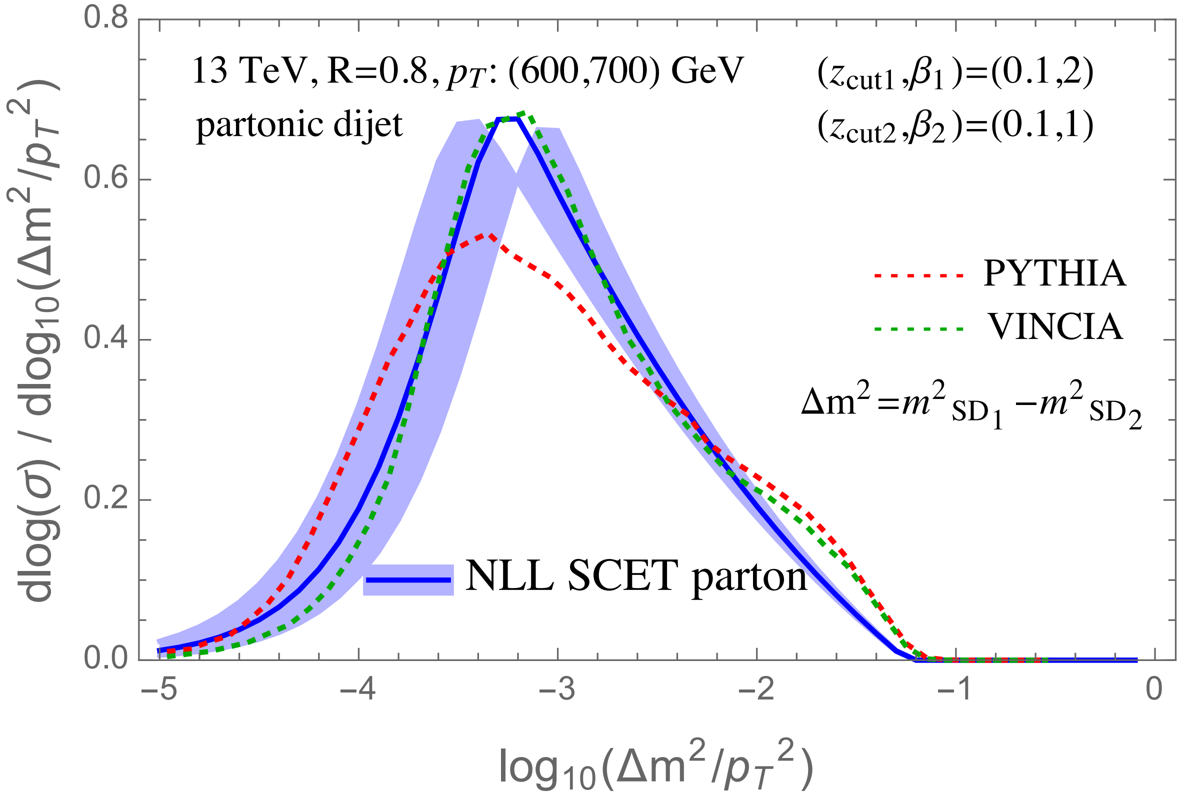
<u>gluon</u>

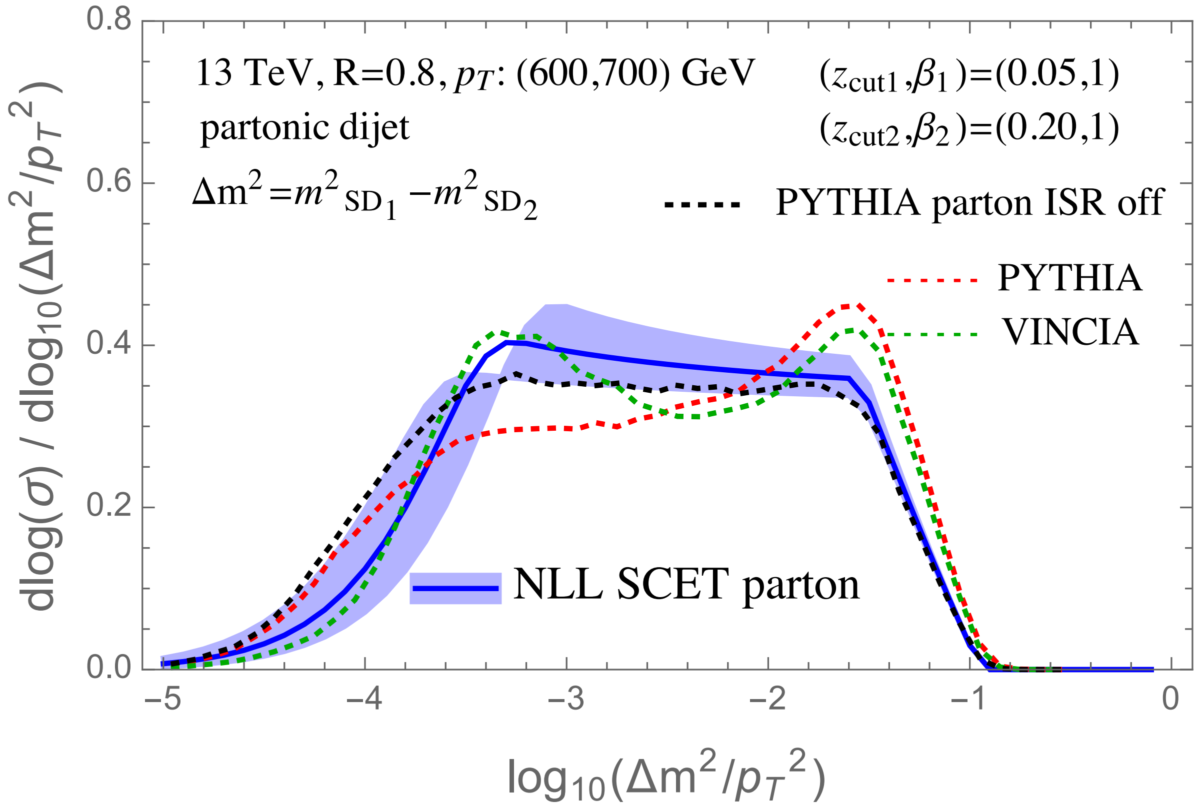




Comparison SCET vs. MC (dijet)







Summary:

- Collinear Drop: direct probe for soft (& collinear-soft) radiation
- Tool for MC, testing softer momentum regions in the shower and hadronization models
- Interesting observable for color correlations (quark vs. gluon, ISR)

Future:

- Improve partonic SCET predictions (NNLL+NLO)
- Universality for hadronization? (extend Soft Drop results)
- Study slices through soft phase space with other Collinear-Drop observables (eg. angularities)
- Add Herwig. Systemize the study of various features.