Collinear Drop

Yang-Ting Chien

MIT Center for Theoretical Physics

March 27, 2019
SCET2019, UC San Diego

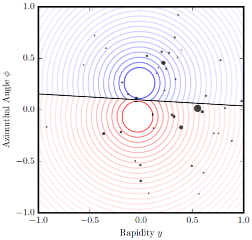
In collaboration with Iain Stewart, to appear soon

M.S.: Are you dropping all the radiation? Y.-T.C.: No.

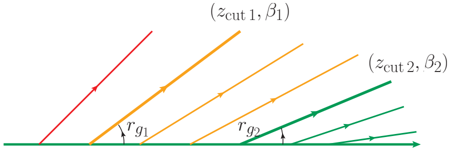
Collinear Drop: veto energetic, collinear particles

- Understanding soft QCD is the goal
- Monte Carlo accuracy limited by soft radiation and hadronization modeling
- Want to directly probe soft physics by disentangling hard components of jets
- Specific examples:
  (i) multiple soft drop
  (ii) telescoping deconstruction
  (iii) flattened angularity

(ii) Telescoping deconstruction (1803.03589)



(i) Two soft-drop settings $z_{\text{cut1}} < z_{\text{cut2}}, \beta_1 \geq \beta_2$



(iii) Flattened angularity

$$\tau_\omega = \sum_{i \in \text{jet}} z_i \, \omega(\theta_i)$$

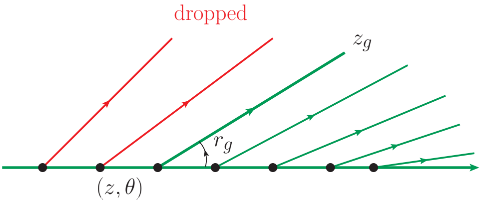
Suppress collinear and wide-angle radiation

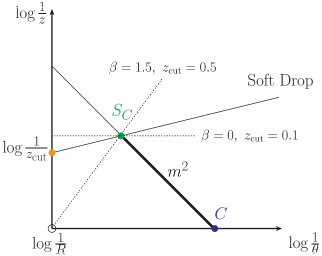
$$\omega(\theta) \to 0 \,, \quad \theta \to 0, R$$

Outline

- Soft drop and collinear drop
- Analytic and Monte Carlo studies
- Conclusions

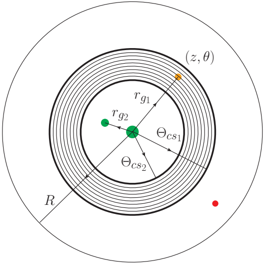
Soft Drop

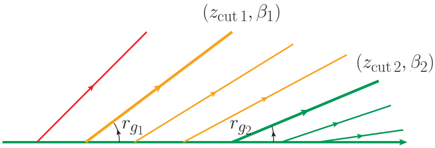




- Tree-based procedure to drop soft radiation (Larkoski, Marzoni, Soyez, Thaler, 1402.2657)
  - Recluster a jet using C/A algorithm: angular ordered tree
  - For each branching, consider the p_T of each branch and the angle θ between branches
  - Soft drop condition: drop the soft branch if $z < z_{\rm cut}\ \theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - $(z_{\rm cut}, \beta)$ parameterize the operation on jet

Collinear Drop using soft drop + anti soft drop





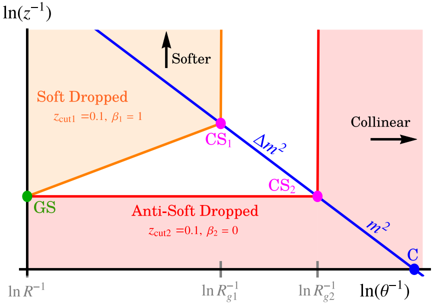
- $\Delta m^2 = m^2_{\mathrm{SD}_1} - m^2_{\mathrm{SD}_2}$ probes the mass of the soft radiation within the “ring"
- Phase space constraints on the kinematics of soft emissions,

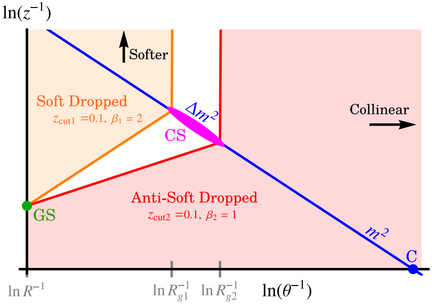
$$z\theta^2 \approx \frac{\Delta m^2}{E_J^2}\,, \qquad z_{\mathrm{cut}\,1}\left(\frac{\theta}{R}\right)^{\beta_1} \lesssim z \lesssim z_{\mathrm{cut}\,2}\left(\frac{\theta}{R}\right)^{\beta_2}$$

- Two collinear-soft modes emerge from the phase space boundaries

$$p_{cs_i} \sim \left(E_J z_{\mathrm{cut}\,i}\left(\frac{\Delta m^2}{E_J^2 R^2 z_{\mathrm{cut}\,i}}\right)^{\frac{\beta_i}{2+\beta_i}}, \frac{\Delta m^2}{E_J}, \sqrt{\Delta m^2 z_{\mathrm{cut}\,i}}\left(\frac{\Delta m^2}{E_J^2 R^2 z_{\mathrm{cut}\,i}}\right)^{\frac{\beta_i}{2(2+\beta_i)}}\right) = E_{cs_i}\left(1,\ \Theta^2_{cs_i},\ \Theta_{cs_i}\right)$$

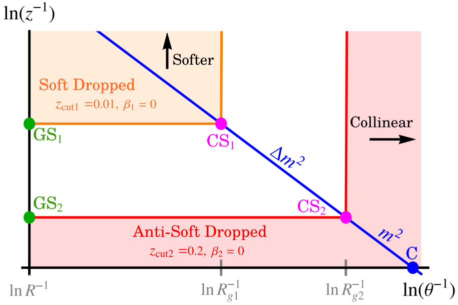
Factorization of Δm^2





- Two examples:
  - fixed $z_{\rm cut}$ and varying β (ATLAS 13 TeV data: $z_{\rm cut} = 0.1$, $\beta = 0, 1, 2$. 1711.08341)
  - fixed β and varying $z_{\rm cut}$
- Identify relevant soft-collinear effective theory modes by corners of phase space boundaries

Factorization of Δm^2



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Factorization and resummation of Δm^2

- Factorization of Δm^2

$$\frac{d\sigma}{d\Delta m^2} = \sum_{i=q,g} N_i(\mu) J^{\mathrm{SD}}_{\mathrm{un},i}(z_{\mathrm{cut}\,2}, \beta_2, \mu) S^{\mathrm{CD}}_i(\Delta m^2, z_{\mathrm{cut}\,i}, \beta_i, \mu)$$

- If two soft-drop conditions are hierarchically separated, collinear-soft sector can be further factorized

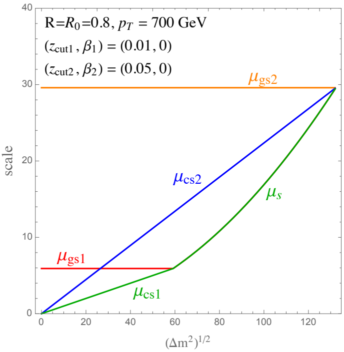
$$S^{\mathrm{CD}}_i(\Delta m^2, \mu) = \int dk_i D_{C_2,i}(k_2, \mu) S_{C_1,i}(k_1, \mu) \delta(\Delta m^2 - 2E_J(k_1 + k_2))$$

- Factorization expression allows us to resum Δm^2 using renormalization group techniques

RG evolution and anomalous dimensions

- Characteristic scales: $\mu_{sc_i} = \sqrt{\Delta m^2 z_{\text{cut}\,i}}\left(\frac{\Delta m^2}{(E_J R)^2 z_{\text{cut}\,i}}\right)^{\frac{\beta_i}{2(2+\beta_i)}}$, $\mu_{sg_i} = E_J R z_{\text{cut}\,i}$

$$\frac{d\tilde{S_C}(\nu,\mu)}{d\ln\mu} = \Gamma_{S_C}(\mu)\tilde{S_C}(\nu,\mu)\ , \quad \text{where } \tilde{S_C}(\nu,\mu) = \int dk \exp\Big(-\frac{2E_J\nu k}{e^{\gamma_E}}\Big)S_C(k,\mu)$$



$$\Gamma_{S_{G_1},i} = \frac{2}{1+\beta_1}C_i\gamma_{\text{cusp}}\ln\frac{\mu}{E_J R z_{\text{cut}\,1}} + \gamma^{S_{G_1},i}$$

$$\Gamma_{S_{G_2},i} = \frac{2}{1+\beta_2}C_i\gamma_{\text{cusp}}\ln\frac{\mu}{E_J R z_{\text{cut}\,2}} + \gamma^{S_{G_2},i}$$

$$\Gamma_{S_{C_1},i} = \frac{2+\beta_1}{1+\beta_1}C_i\gamma_{\text{cusp}}\ln\frac{z_{\text{cut}\,1}^{\frac{2}{2+\beta_1}}}{\nu^{\frac{2+2\beta_1}{2+\beta_1}}\mu^2(E_J R)^{\frac{2\beta_1}{2+\beta_1}}} - 2\gamma^{S_{C_1},i}$$

$$\Gamma_{D_{C_2},i} = -\frac{2+\beta_2}{1+\beta_2}C_i\gamma_{\text{cusp}}\ln\frac{z_{\text{cut}\,2}^{\frac{2}{2+\beta_2}}}{\nu^{\frac{2+2\beta_2}{2+\beta_2}}\mu^2(E_J R)^{\frac{2\beta_2}{2+\beta_2}}} - 2\gamma^{D_{C_2},i}$$

$$\Gamma_{S_i^{\text{CD}}} = \Gamma_{S_{C_1},i} + \Gamma_{D_{C_2},i} \qquad \text{RG consistency}$$

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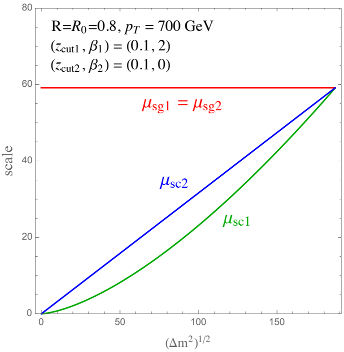

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$$\Gamma_{S_i^{\mathrm{CD}}} = \Gamma_{S_{C_1},i} + \Gamma_{D_{C_2},i} \qquad \text{RG consistency}$$

Resummed Δm^2

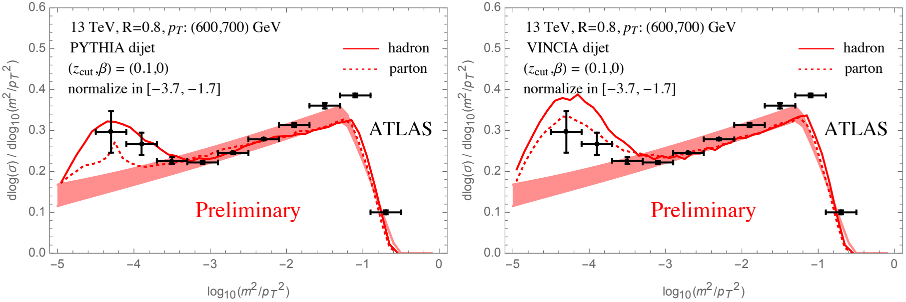
- Large logarithms of $\Delta m^2/E_J^2$ are resummed using RG evolution

$$
\begin{aligned}
& S_i^{\rm CD}(\Delta m^2,\mu) \\
= \quad & \exp\left[2\frac{2+\beta_1}{1+\beta_1}C_iS(\mu_{sc_1},\mu) - 2\frac{2+\beta_2}{1+\beta_2}C_iS(\mu_{sc_2},\mu) + 2A_{S_{C_1,i}}(\mu_{sc_1},\mu) + 2A_{S_{C_2,i}}(\mu_{sc_2},\mu)\right] \\
& \left[\frac{z_{\rm cut\,1}^{\frac{1}{1+\beta_1}}}{z_{\rm cut\,2}^{\frac{1}{1+\beta_2}}}\frac{\mu_{sc_2}^{\frac{2+\beta_2}{1+\beta_2}}}{\mu_{sc_1}^{\frac{2+\beta_1}{1+\beta_1}}}\frac{(E_JR)^{\frac{1}{1+\beta_1}}}{(E_JR)^{\frac{1}{1+\beta_2}}}\right]^{\eta_{sc_1}}\tilde{D}_{C_2,i}(\partial\eta,\mu_{sc_2})\tilde{S}_{C_1,i}(\partial\eta+\ln\frac{z_{\rm cut\,1}^{\frac{1}{1+\beta_1}}}{z_{\rm cut\,2}^{\frac{1}{1+\beta_2}}}\frac{\mu_{sc_2}^{\frac{2+\beta_2}{1+\beta_2}}}{\mu_{sc_1}^{\frac{2+\beta_1}{1+\beta_1}}}\frac{(E_JR)^{\frac{1}{1+\beta_1}}}{(E_JR)^{\frac{1}{1+\beta_2}}},\mu_{sc} \\
& \frac{1}{\Delta m^2}\left(\frac{\Delta m^2 z_{\rm cut\,2}^{\frac{1}{1+\beta_2}}}{\mu_{sc_2}^{\frac{2+\beta_2}{1+\beta_2}}(E_JR)^{\frac{\beta_2}{1+\beta_2}}}\right)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}
\end{aligned}
$$

where $\eta_{sc_1} = 2C_iA_\Gamma(\mu,\mu_{sc_1})$ and $\eta = 2C_iA_\Gamma(\mu_{sc_2},\mu_{sc_1})$. $S(\mu_1,\mu_2)$ and $A(\mu_1,\mu_2)$ are RG evolution kernels.

$$
\begin{aligned}
S(\mu_1,\mu_2) &= -\int_{\alpha_s(\mu_1)}^{\alpha_s(\mu_2)} d\alpha\,\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}\int_{\alpha_s(\mu_1)}^{\alpha}\frac{d\alpha'}{\beta(\alpha')} \\
A_i(\mu_1,\mu_2) &= -\int_{\alpha_s(\mu_1)}^{\alpha_s(\mu_2)} d\alpha\,\frac{\gamma^i(\alpha)}{\beta(\alpha)}\,, \qquad A_\Gamma(\mu_1,\mu_2) = -\int_{\alpha_s(\mu_1)}^{\alpha_s(\mu_2)} d\alpha\,\frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)}
\end{aligned}
$$

Validation with soft drop: turning off collinear drop



- Grooming-ungrooming transition happens at $\log_{10}(R^2 z_{\rm cut})$, treated by EFT merging
- Soft drop reduces nonperturbative effects
- Band corresponds to next-to-leading log (NLL) SCET calculation with uncertainty estimated by scale variation. Previous work: Larkoski et al '16, Marzani et al '17, Kang et al '18
- Analytic calculation agrees with Pythia partonic simulation: collinear physics dominates

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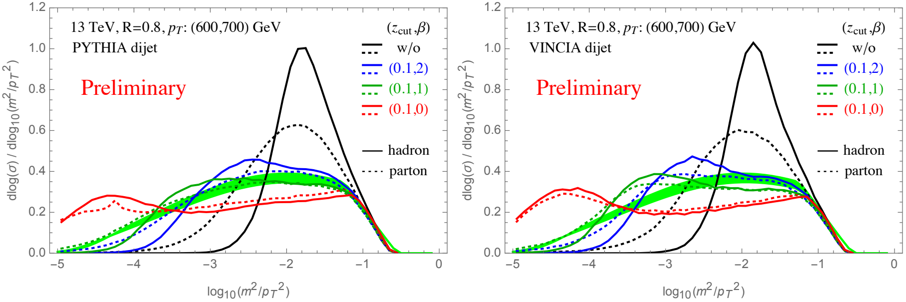

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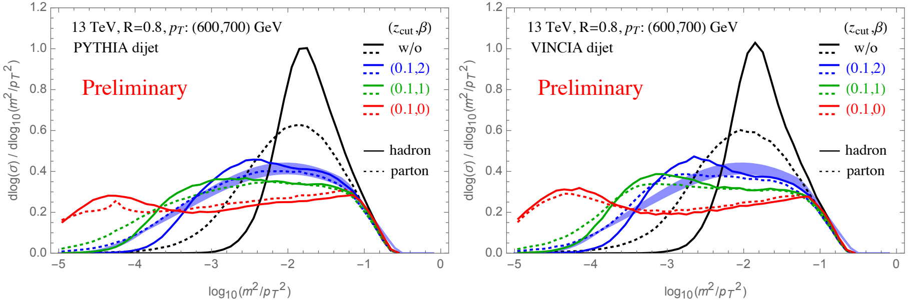

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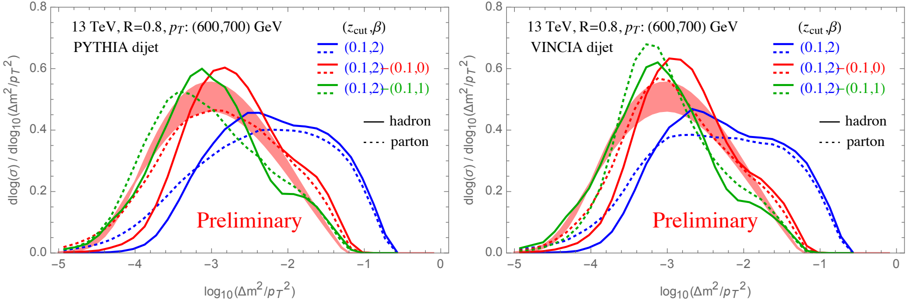
Collinear Drop results



- New and different observables
- $\Delta m^2 = m^2_{\mathrm{SD}_1} - m^2_{\mathrm{SD}_2}$ labeled by $(z_{\mathrm{cut}_1}, \beta_1) - (z_{\mathrm{cut}_2}, \beta_2)$
- Increase sensitivity to soft radiation and nonperturbative hadronization
- New hadronization features in Pythia simulation appear
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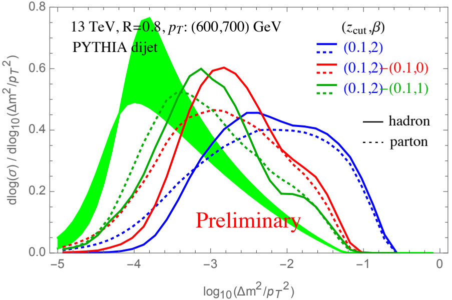

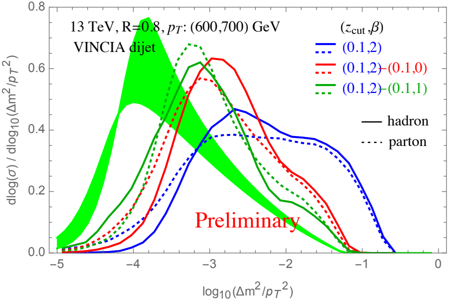

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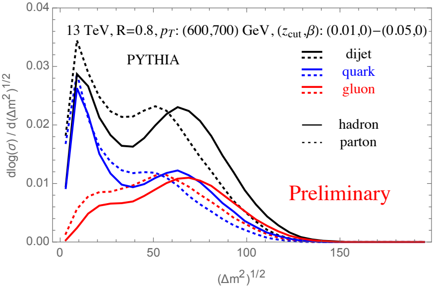
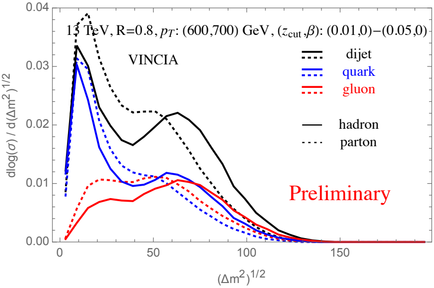
Quark gluon discrimination





- Decompose total leading dijet into quark jet and gluon jet components
- Enhance the difference between quark jets and gluon jets: promising observable for improving quark-gluon discrimination
- Nonperturbative effects enhance the features of quark and gluon peaks in mixed jet samples

Conclusions

- We propose to use collinear-drop observables to directly probe soft physics and color flows in jets
  - for probing soft radiation contributions
  - for testing Monte Carlo simulations
  - for tagging hard probes (color-singlet jet isolation, 1711.11041)
  - for determining hadronization corrections
  - for studying perturbative-nonperturbative transition
  - for probing QCD medium in heavy ion collisions (1803.03589)
- Factorization expression of a specific collinear drop observable is derived in SCET which allows us to resum logarithmically-enhanced contributions
- Future work: detailed studies of hadronization and jet quenching using collinear drop observables