Telescoping Deconstruction

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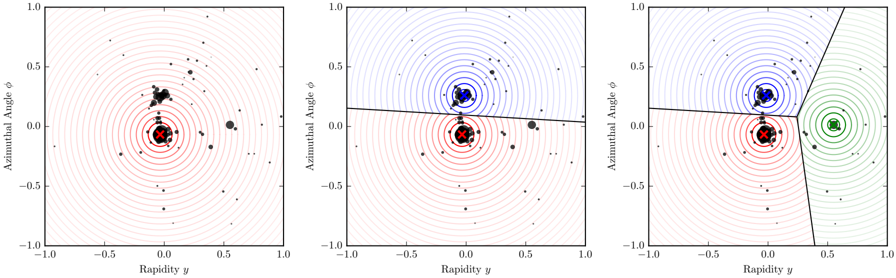
with A. Emerman, S.-C. Hsu, S. Meehan, Z. Montague, E. Metodiev, P. Komiske, R. Elayavalli
and I. Stewart, 1711.11041, 1803.03589 and work in progress

Outline

- Telescoping deconstruction (TD): what, why and how
  - boosted W (Z, Higgs), top, quark v.s. gluon tagging
  - collinear QCD splitting
  - jet spectroscopy of QGP (*not* covered in this talk)
- SCET calculation of δm^2
  - “collinear-drop = (soft-drop)-drop"
  - W “isolation"
- Conclusions

Telescoping deconstruction: a subjet expansion

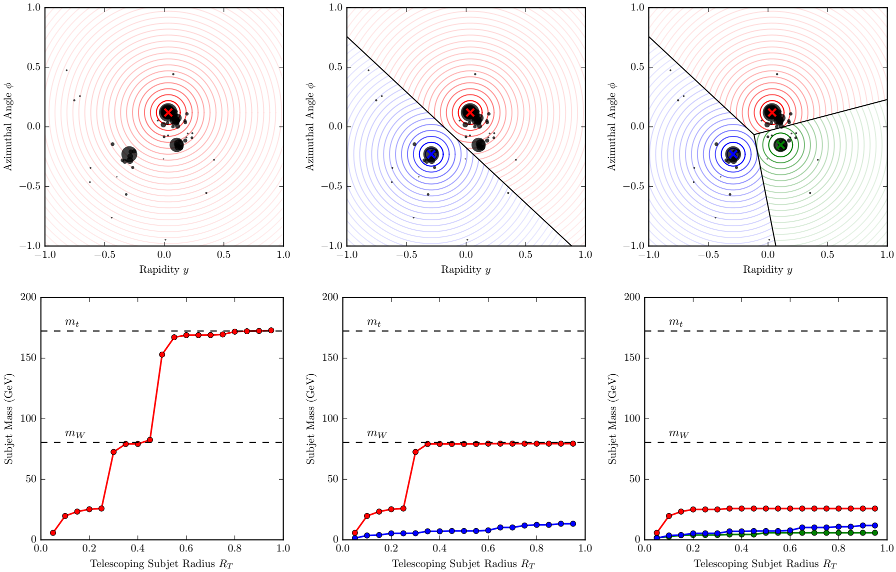
- A systematic framework for studying aspects of jet formation
- $\sum_N N$-subjet (TN): ordered by the number N of exclusively reconstructed subjets
- Procedures:
  - Identify dominant energy flow directions using N soft recoil-free axes
  - Reconstruct subjets around the axes with multiple subjet radii R_T
  - Transverse momenta and masses of subjets together with axis directions form TD obervables: subjet kinematics



Physics of TD observables

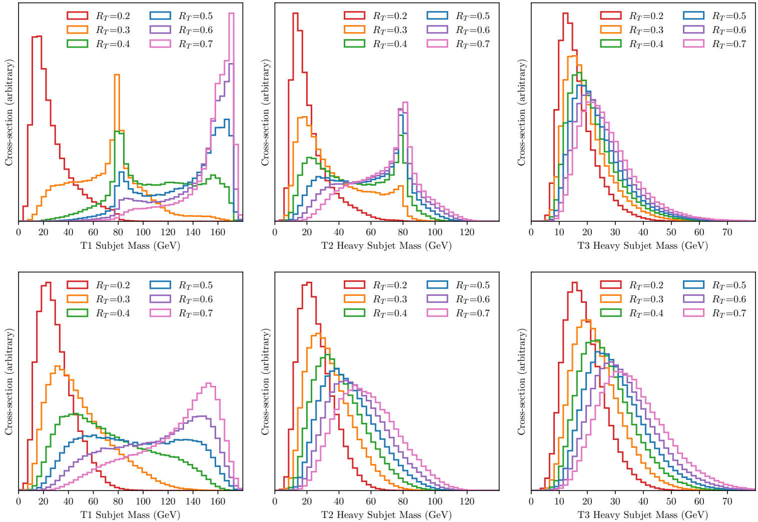
- TD observables fall into two categories
  - subjet *topology*: energy flow directions and subjet transverse momenta
  - subjet *substructure*: subjet mass
- Features
  - Completeness: capture relevant physics information
  - Simplicity: using simple, physically-meaningful observables
  - Analyticity: as close to perturbative expansion and parton shower as possible
- Examples: boosted W and top tagging, and quark gluon discrimination

Subjet masses of a top jet



Heavy subjet mass distribution

- Top (top row) v.s. QCD (bottom row)

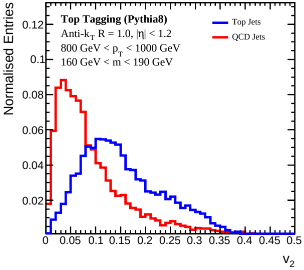


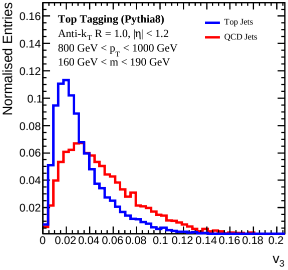
Variability

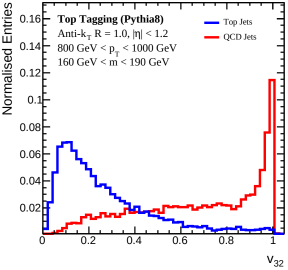
- The variation of the invariant masses $m_N(R_T)$ of the sum of N subjets can be quantified by the *variability*, motivated by the Qjet volatility (Ellis et al).

$$v_N = \frac{\sigma(\{m_N(R_T)\})}{\langle\{m_N(R_T)\}\rangle}$$

- In the case of top tagging, we also consider $v_{N2} = v_N/v_2$ for $N = 3, 4$ to optimize the variability performance, motivated by the N-subjettiness (Thaler et al) and energy correlation function (Larkoski et al) ratios.

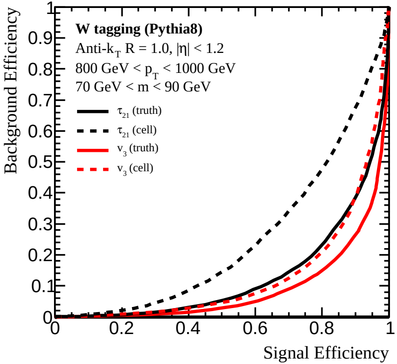


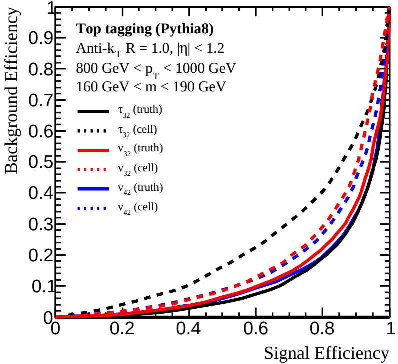




Variability in W and top tagging

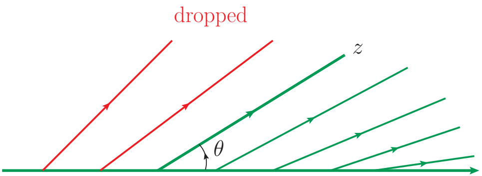
- v_3 and v_{42} have excellent performance and are robust against substructure smearing, which is meant to destroy the N-prong structure
- Manifestation of W isolation due to its color-singlet nature
  - A dominant feature over the two-prong structure

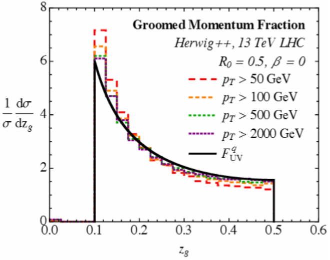




QCD subjet distribution in soft drop

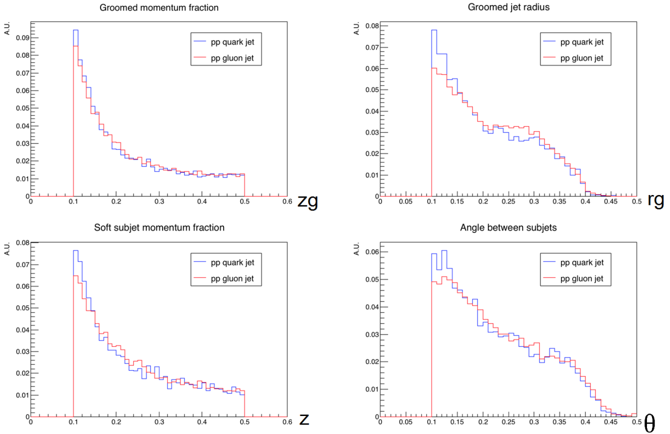
- Soft Drop: a tree-based procedure to drop soft radiation (Larkoski et al)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\ \theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
- z_g: the momentum fraction of the soft branch. r_g: the angle between the branches



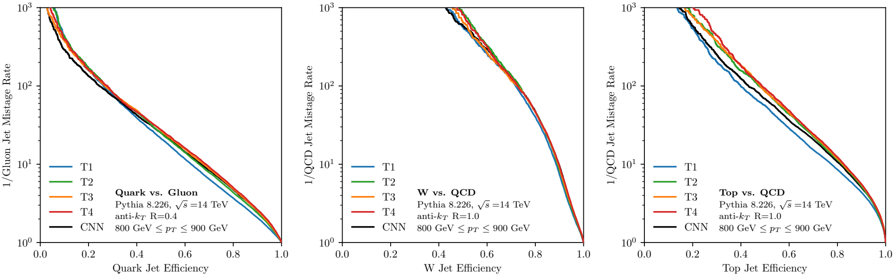


Soft drop and telescoping subjet topology

- Variable subjet radius according to the angles among axes
- Soft-drop $\{z_g, r_g\}$ and TD $\{z, \theta\}$ both capture the collinear QCD splitting function



Optimal performances in multivariate analysis



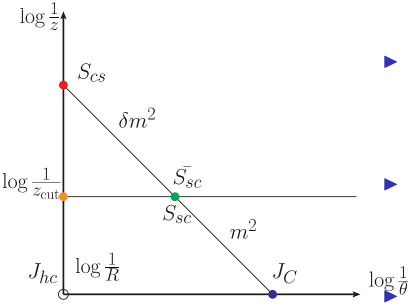
- Tagging performance can be captured in a ROC curve plotting the inverse of the background mistag rate at different signal efficiencies
- TN performances converge quickly to optimal performance
- TD faithfully represents jet information

Analytic TD

- Understand the rich jet information TD can reveal analytically
- A simpler observable capturing variability: $\delta m^2 = m_1^2 - m_2^2$
  - $m^2(R) - m^2(r)$ where $R > r$
  - $m^2(\text{ungroomed}) - m^2(\text{groomed})$
  - $m^2(\text{sd1}) - m^2(\text{sd2})$ where sd2 is more aggressive than sd1.
- $m_1^2 = P_c^2 + 2P_c \cdot P_{s_1}\ , \quad m_2^2 = P_c^2 + 2P_c \cdot P_{s_2}$
  - $\delta m^2 = 2P_c \cdot (P_{s_1} - P_{s_2})$
  - collinear drop: measuring the projection of dropped soft radiation
- δm^2 probes the soft radiation and is directly sensitive to jet flavors and color flows

Power counting for δm^2

- Consider the case of $\delta m^2 = m^2(\text{ungroomed}) - m^2(\text{sd})$, where the soft-drop parameters are $\beta = 0, z_{\text{cut}} = 0.1$. Non-global logs are not addressed in this talk



- In-jet global soft mode

$$p_s = E_J z_{cut}(1, R^2, R), \text{ with } \mu_s = E_J R z_{cut}$$

- Soft-collinear mode (Frye et al)

$$p_{sc} = (E_J z_{cut}, \frac{\delta m^2}{2E_J}, \sqrt{\frac{z_{cut}\delta m^2}{2}}), \text{ with } \mu_{sc} = \sqrt{\frac{z_{cut}\delta m^2}{2}}$$

- C-soft mode (Ellis et al)

$$p_{cs} = (\frac{\delta m^2}{2E_J R^2}, \frac{\delta m^2}{2E_J}, \frac{\delta m^2}{2E_J R}), \text{ with } \mu_{cs} = \frac{\delta m^2}{2E_J R}$$

- $\mu_s \gg \mu_{sc} \gg \mu_{cs}, \delta m^2 \approx m^2$

Factorization of δm^2

- Factorization of soft-drop jet mass (Frye et al)

$$J^{\not{s}}(m^2,\mu) = \int dp^2 dk J(p^2,\mu) S^{\not{s}}(k,R,z_{cut},\mu)\delta(m^2 - p^2 - 2E_J k)$$

  where $S^{\not{s}}(k,R,z_{cut},\mu) = S_C(k,R,z_{cut},\mu)S_G(R,z_{cut},\mu)$

- With the measurement of δm^2, the in-jet global soft sector is constrained and needs to be refactorized

$$S_G(R,z_{cut},\mu) \to S(k_1,R,z_{cut},\mu) = \int dk_2 dk_3 S_{in}(k_2,R,\mu)\overline{S_C}(k_3,R,z_{cut},\mu)\delta(k_1 - k_2 - k_3)$$

  where $\overline{S_C}$ is the complement of S_C (similarly Lee et al)

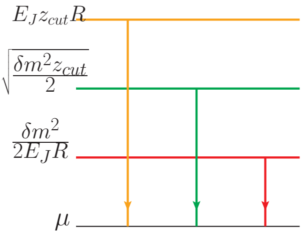
- Soft-drop jet mass is integrated out and gives soft-drop unmeasured jet function

$$\frac{d\sigma}{d\delta m^2} = \frac{J^{sd}_{un}(\mu)S(\frac{\delta m^2}{2E_J},R,z_{cut},\mu)}{J_{un}(\mu)} = \frac{S(\frac{\delta m^2}{2E_J},R,z_{cut},\mu)}{S_G(R,z_{cut},\mu)}\ , \quad \text{RG invariant}$$

Anomalous dimensions and RG evolution

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

$$\frac{d\tilde{S}(\nu,\mu)}{d\ln\mu} = \gamma(\mu)\tilde{S}(\nu,\mu)\ , \quad \text{where } \tilde{S}(Q^2,\mu) = \int dk \exp\left(-\frac{2E_J}{Q^2 e^{\gamma_E}}\right) S(k,\mu)$$



$$\begin{aligned}
\gamma_{S_G}(\mu) &= 2C_i\Gamma_{cusp}\ln\frac{\mu}{2E_J z_{cut}\tan\frac{R}{2}} + \gamma^s \\
\gamma_{S_{\overline{S_C}}}(\mu) &= -2C_i\Gamma_{cusp}\ln\frac{Q^2 z_{cut}}{\mu^2} + \gamma_c^s \\
\gamma_{S_{in}}(\mu) &= 2C_i\Gamma_{cusp}\ln\frac{Q^2}{\mu 2E_J\tan\frac{R}{2}} + \gamma_{in}^s \\
\gamma_{S_G}(\mu) &= \gamma_{S_{in}}(\mu) + \gamma_{S_{\overline{S_C}}}(\mu)
\end{aligned}$$

Resummed and fixed-order δm^2 (preliminary)

- At $\mathcal{O}(\alpha_s)$,

$$\frac{d\sigma}{d\delta m^2} = \frac{\alpha_s C_i}{\pi \delta m^2} \ln \frac{z_{cut} E_J^2 R^2}{\delta m^2}\,, \qquad \left(\text{or } \ln \frac{z_{cut1}}{z_{cut2}},\ \ln \frac{R^2}{r^2} \text{ for different versions of } \delta m^2\right)$$

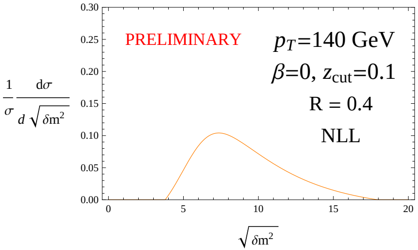
- At NLL,

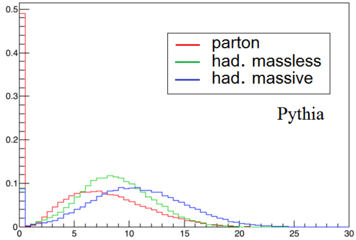
$$\begin{aligned}\frac{d\sigma}{d\delta m^2} &= \exp\Big[2C_i S(\mu_{cs},\mu_{sc}) + 2C_i S(\mu_{sc},\mu_s) + 2A_s(\mu_{sc},\mu_s) + 2A_s(\mu_{cs},\mu_s)\Big] \\ &\times \left(\frac{\mu_{sc}^2}{\mu_s \mu_{cs}}\right)^{-2C_i A_\Gamma(\mu_{cs},\mu_{sc})} \left(\frac{\mu_s}{2E_J z_{cut} \tan\frac{R}{2}}\right)^{-2C_i A_\Gamma(\mu_{cs},\mu_s)} \frac{1}{\delta m^2 S_G(\mu_s)} \\ &\tilde{\tilde{S}}_C(\partial\eta,\mu_{sc}) \tilde{S}_{in}\left(\partial\eta + \ln\frac{\mu_{sc}^2}{\mu_{cs}(2E_J z_{cut}\tan\frac{R}{2})},\mu_{cs}\right) \left(\frac{\delta m^2 z_{cut}}{\mu_{sc}^2}\right)^{\eta} \frac{e^{-\gamma_E \eta}}{\Gamma(\eta)}\end{aligned}$$

where $\eta = -2C_i A_\Gamma(\mu_{cs},\mu_{sc})$. $S(\mu_1,\mu_2)$ and $A(\mu_1,\mu_2)$ are RG evolution kernels.

Plots

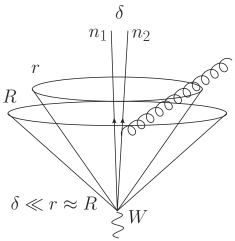
- Non perturbative contributions can be significant
- $\delta m^2 = 0$: no radiation removed by soft-drop





SCET of W isolation

- In the boosted regime, $\delta \approx m_W/p_T \ll 1$, $n_1 \approx n_2 \approx n$, $n_1 \cdot n_2 \approx \delta^2/2$
- Consider $\delta m^2 = m^2(R) - m^2(r)$ where $\delta \ll r \approx R$



- At $\mathcal{O}(\alpha_s)$,

$$\frac{d\sigma}{d\delta m^2} = \delta^2 \frac{\alpha_s C_F}{\pi \delta m^2} \frac{R^2 - r^2}{R^2 r^2} \text{ , power suppressed by } \delta^2$$

- Resummed results: stayed tuned

Conclusions

- Telescoping deconstruction is a systematic framework for jet studies
- W isolation is identified as a dominant feature of boosted W jets
- δm^2 for QCD jets is resummed at NLL
- Wide angle radiation around W jets is power-suppressed (or boost-suppressed) by m_W/p_T
- Future studies: non-perturbative contributions, NGLs (Dingyu's talk), understand from multi-differential cross section (Lisa's talk)