Telescoping **D**econstruction and **C**ollinear **D**rop

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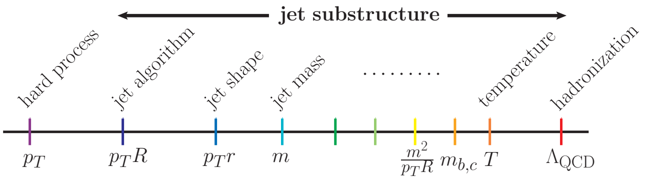
In collaboration with A. Emerman, S.-C. Hsu, S. Meehan, Z. Montague (arXiv:1711.11041)
R. Elayavalli (arXiv:1803.03589), and I. Stewart (to appear soon)

The goal of heavy ion jet substructure studies



Relate precise jet modifications to medium properties

- Determine, between the hard scattering scale and Λ_{QCD}, where medium scales come in and how the medium affects all the jet substructure observables
  - observable = contribution 1 + contribution 2 + contribution 3 + ...
- Determine how the medium respond to jets
- Determine the medium properties from jet modifications: a challenging inverse problem
- Precision and/or completeness is the key

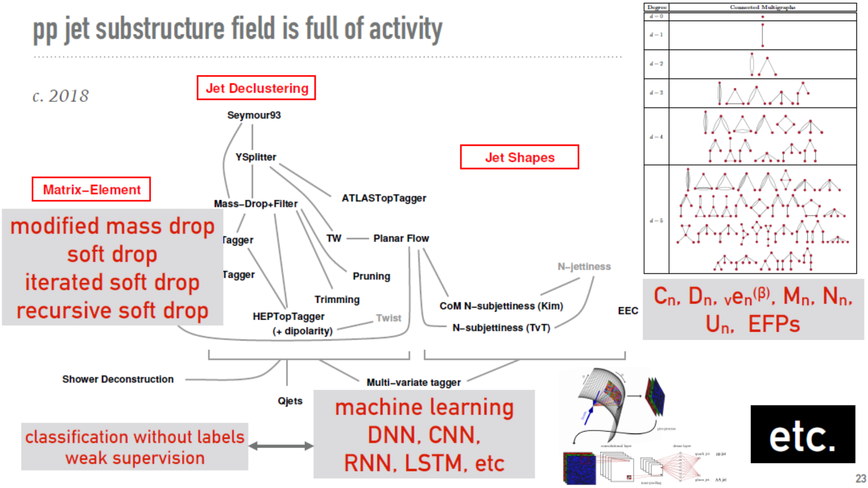
What is the next substructure observable to consider? (G. Salam, QM18)

Jet structure observables

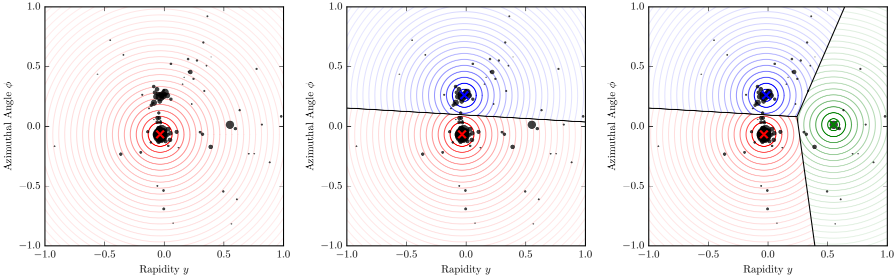
fragmentation function	$D(z) = \left\langle \sum_{i \in \mathrm{jet}} \delta(z - p_{ti}/p_{t,\mathrm{jet}}) \right\rangle_{\mathrm{jets}}$	
differential jet shape	$\rho(r) = \frac{1}{p_\perp^{\mathrm{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)},$	
girth ≡ broadening	$g = \frac{1}{\ldots}$ $\ldots_{kJ},$	
jet mas	$m^2 = \left(\sum_{i \in (\mathrm{sub})\mathrm{jet}} p_i^\mu \right)^2$	
z_g, ΔR_{12}	$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$	

Is this a sufficiently informative set of observables?

We have a lot/an infinite number of observables (G. Salam, QM18)



Telescoping Deconstruction: a complete subjet fragmentation basis



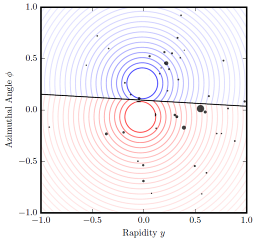
- A fixed-order N subjet expansion with subjet kinematics (p_T, y, ϕ, m)
  - identify dominant energy flow directions using N soft recoil-free axes
  - reconstruct subjets around the axes with multiple subjet radii R_T
  - TD obervables represent *subjet topology* and *subjet substructure*
- Closely related to perturbative expansion and parton shower picture

arXiv:1803.03589

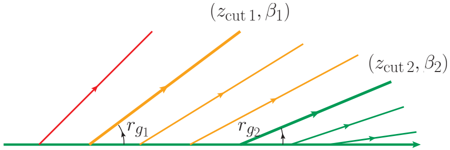
Collinear Drop: veto energetic, collinear particles

- Understanding soft QCD is the goal
- Monte Carlo accuracy limited by soft radiation and hadronization modeling
- Heavy ion medium scale is low
- Want to *directly* probe soft physics by disentangling hard components of jets
- Implementation examples: (i)TD, (ii)soft drop and (iii)flattened angularity

(i) TD



(ii) Two soft-drop settings $z_{\mathrm{cut}1} < z_{\mathrm{cut}2}$, $\beta_1 \geq \beta_2$



(iii) Flattened angularity

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

Suppress collinear and wide-angle radiation

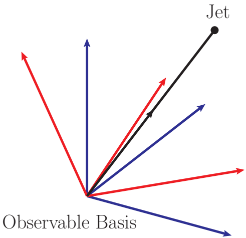
$$\omega(\theta) \to 0\,, \quad \theta \to 0, R$$

With I. Stewart, to appear soon

Use quark and gluon jets to probe heavy ion collisions

$$\begin{tikzcd}
\text{quark jets in pp} \arrow[r, leftrightarrow, "\text{discrimination}"] \arrow[d, leftrightarrow, "\text{quenching}"'] & \text{gluon jets in pp} \arrow[d, leftrightarrow, "\text{quenching}"] \\
\text{quark jets in AA} \arrow[r, leftrightarrow, "\text{discrimination}"'] & \text{gluon jets in AA}
\end{tikzcd}$$

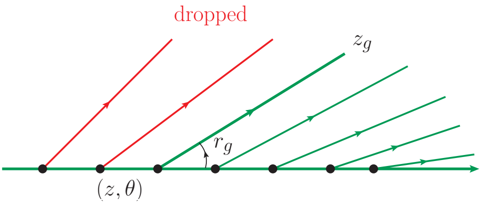
- Classify quark jets and gluon jets in pp and AA
- Different multivariate techniques suit different jet representations
  - list of physics-motivated observables
  - unbiased and raw input
  - complete basis and expansion
- Modern computation power and deep learning tools help benchmark jet feature identification

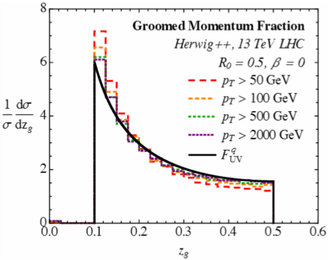


Outline

- Telescoping deconstruction
  - collinear QCD splitting
  - heavy ion jet modification
  - W, top, quark v.s. gluon classification
- Collinear drop
  - designed for soft physics studies
  - color singlet jet isolation
- Conclusions

QCD subjet distribution in soft drop





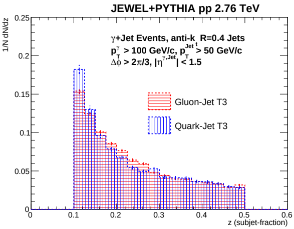
- Tree-based procedure to drop soft radiation (Larkoski et al)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\ \theta^{\beta}$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$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

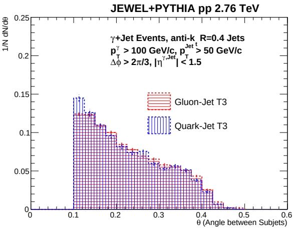
Telescoping subjet topology (z, θ)

arXiv:1803.03589

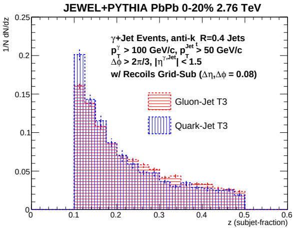
- Enhancement of soft, wide angle radiation in AA (simulated with Jewel (Zapp et al))

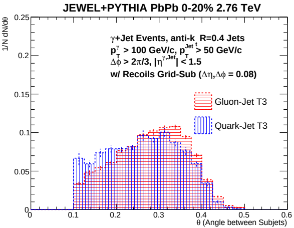
z θ





pp





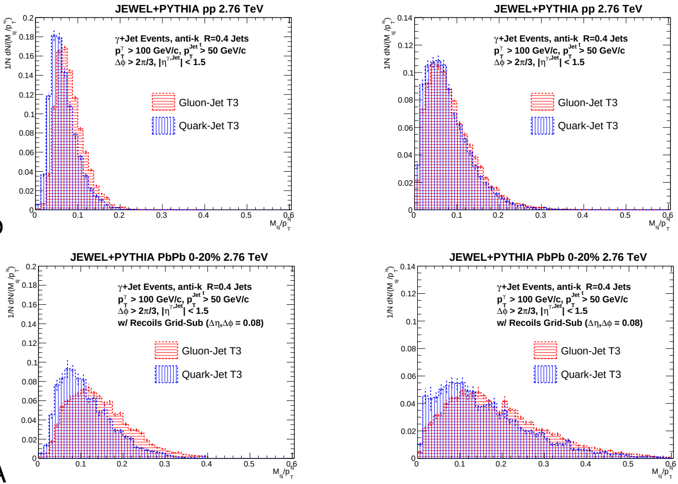
AA

Telescoping subjet substructure m

- Reveal subjet flavor dependence in first splitting $q \to qg$ and $g \to gg$ using $m^{\rm sub}/p_T^{\rm sub}$

Hard Subjet

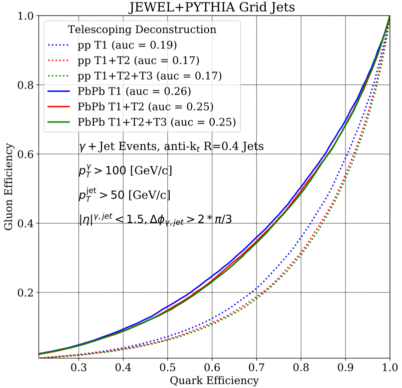
Soft Subjet

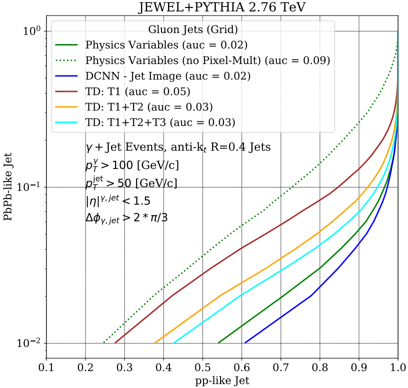


pp

AA

Quark gluon jet classification in pp and AA

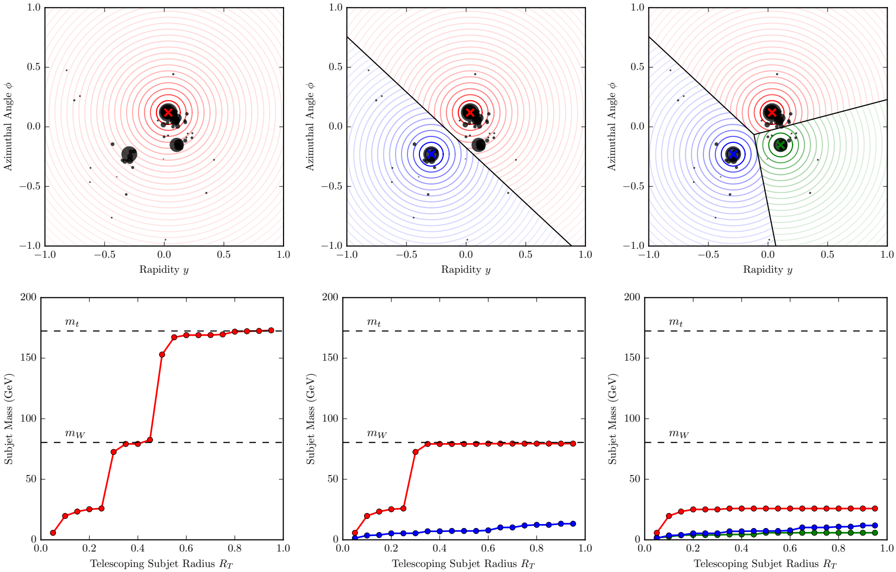




- Quark/gluon discrimination performance drops in JEWEL-simulated AA collisions
- Information contained in subleading subjets is washed out
- Pixel multiplicity is the dominant feature distinguishing pp and AA jets

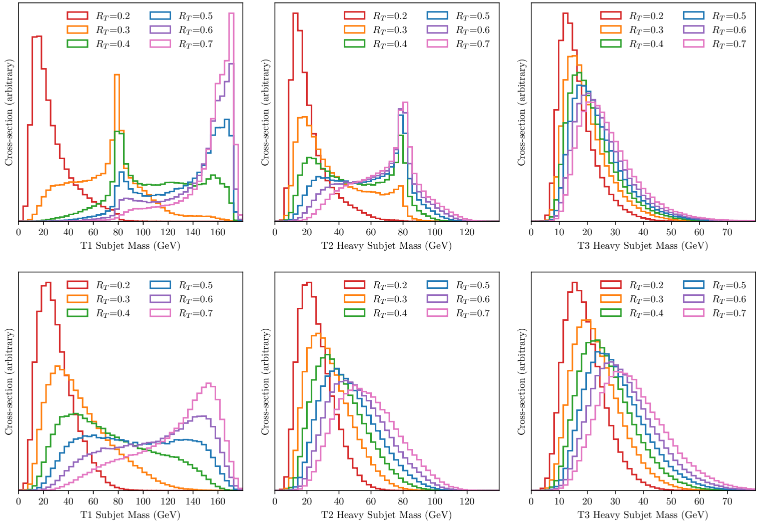
Subjet masses of a top jet

arXiv:1803.03589

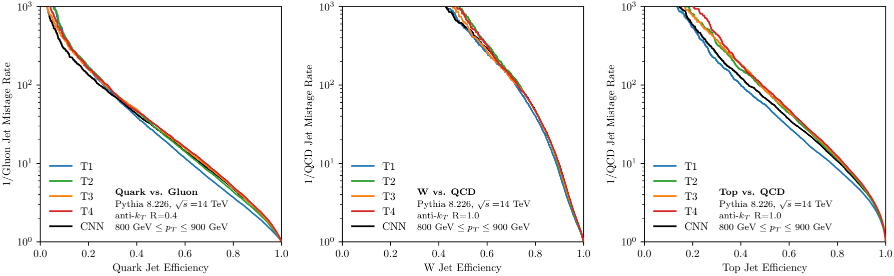


Heavy subjet mass distribution

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

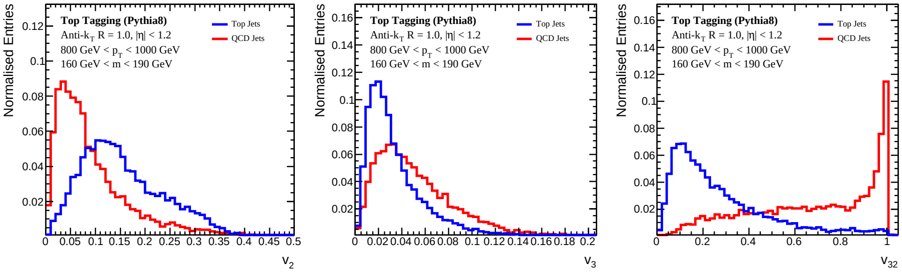


Good performances in multivariate analysis



- TN performances converge quickly to optimal performance
- TD faithfully represents jet information: a practical proof

Variability



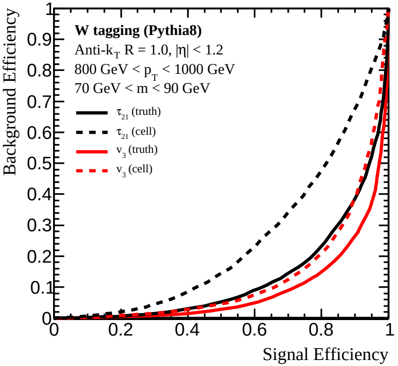
- The variation of the invariant masses $m_N(R_T)$ of the sum of N subjets can be quantified by the *variability*, motivated by the Qjet volatility (Ellis et al).

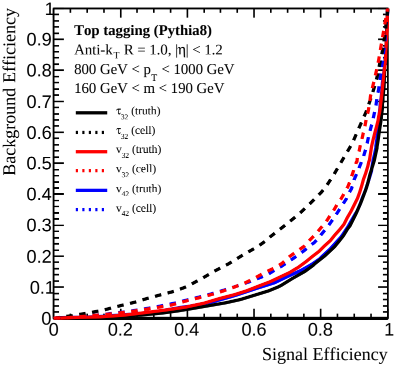
$$v_N = \frac{\sigma(\{m_N(R_T)\})}{\langle\{m_N(R_T)\}\rangle}$$

- For top tagging, we 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.

arXiv:1711.11041

Variability in *W* and top tagging

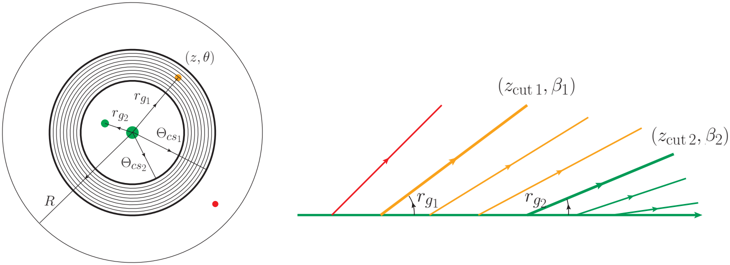




- v_3 and v_{42} have good performance and are robust against substructure smearing, which is meant to destroy the N-prong structure
- Manifestation of W jet isolation due to its color-singlet nature
  - A dominant feature over the two-prong structure
  - Net color charge: leading-order contribution in multipole expansion

Collinear drop

One example of a CD observable can be constructed using a Soft Drop + an Anti Soft Drop



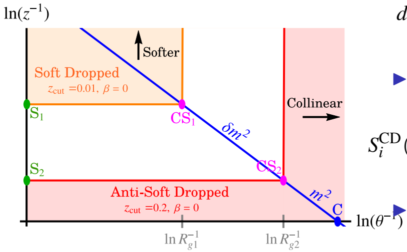
- Consider $\delta m^2 = m^2_{\text{SD}_1} - m^2_{\text{SD}_2}$ to quantify the radiation distribution within the “ring"
  - TD version: $\delta m^2 = m^2(r_2) - m^2(r_1)$ where $r_2 > r_1$ (BOOST2015)
  - Difference of angularities, event shapes are not CD observables
- Contributions from collinear radiation to soft-drop jet mass cancel

$$m^2_{\text{SD}_\text{i}} \sim p_c^2 + 2E_J n\cdot p_{cs_i}\ , \qquad \delta m^2 \sim 2E_J n\cdot (p_{cs_1} - p_{cs_2})$$

- Phase space constraints on the kinematics of soft emissions,

$$z\theta^2 \approx \frac{\Delta m^2}{E_J^2}\ , \qquad z_{\text{cut }1}\left(\frac{\theta}{R_0}\right)^{\beta_1} \lesssim z \lesssim z_{\text{cut }2}\left(\frac{\theta}{R_0}\right)^{\beta_2}$$

Factorization and resummation of δm^2 using SCET

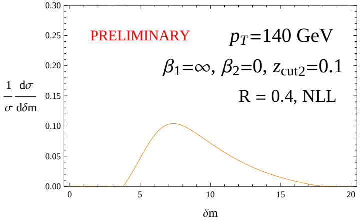


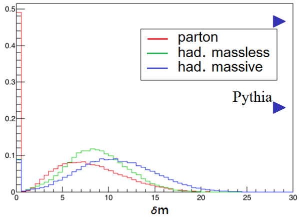
$$\frac{d\sigma}{d\delta m^2} = \sum_{i=q,g} N_i(\mu) J^{\rm SD}_{{\rm un},i}(z_{{\rm cut}\,2},\beta_2,\mu) S_i^{\rm CD}(\delta m^2, z_{{\rm cut}\,i},\beta_i,\mu)$$

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

$$S_i^{\rm CD}(\delta m^2,\mu) = \int dk_i \overline{S_{C_2,i}}(k_2,\mu) S_{C_1,i}(k_1,\mu)\delta(\delta m^2 - 2E_J(k_1+k_2))$$

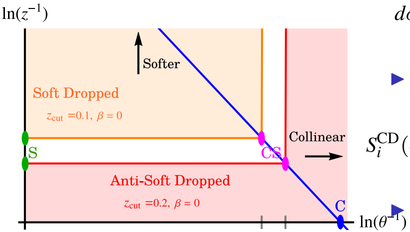
- Using SCET renormalization group techniques we can resum δm^2





- Massless hadrons are constructed using the p-scheme
- Significant hadronization correction is seen. Addressed in future work.

Factorization and resummation of δm^2 using SCET



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

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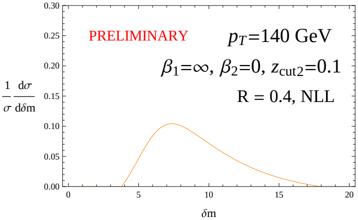

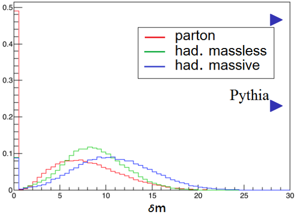

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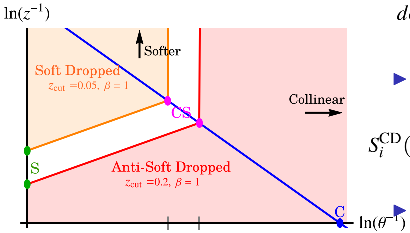

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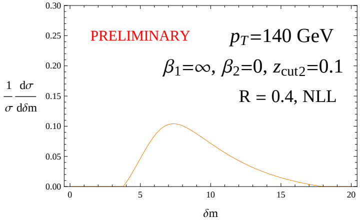

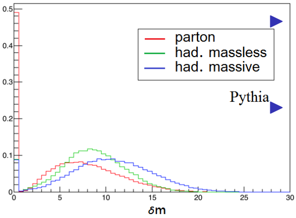

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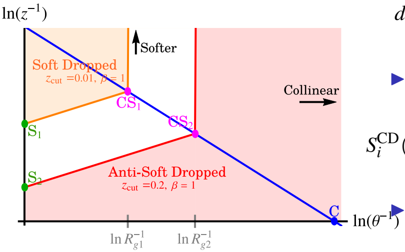

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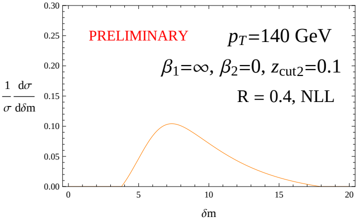

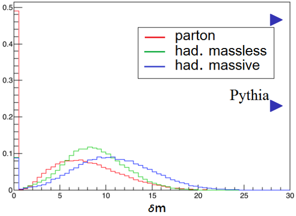

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Resummed expression

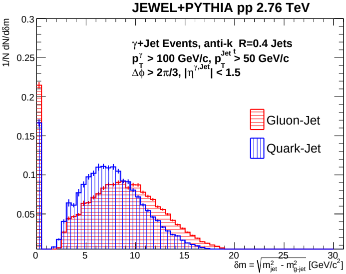
- The formula that entered the plots

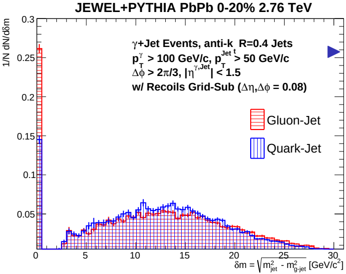
$$
\begin{aligned}
& S_i^{\rm CD}(\delta m^2,\mu) \\
= \quad & \exp\Big[2\frac{2+\beta}{1+\beta}C_iS(\mu_{sc_1},\mu) - 2\frac{2+\beta}{1+\beta}C_iS(\mu_{sc_2},\mu) + 2A_{S_{C_1},i}(\mu_{sc_1},\mu) + 2A_{S_{C_2},i}(\mu_{sc_2},\mu)\Big] \\
& \left[\left(\frac{z_{\rm cut\,1}}{z_{\rm cut\,2}}\right)^{\frac{1}{1+\beta}}\left(\frac{\mu_{sc_2}}{\mu_{sc_1}}\right)^{\frac{2+\beta}{1+\beta}}\right]^{\eta_{sc_1}}\overline{\tilde{S}_{C_2,i}}(\partial\eta,\mu_{sc_2})\tilde{S}_{C_1,i}\Big(\partial\eta+\ln\left(\frac{z_{\rm cut\,1}}{z_{\rm cut\,2}}\right)^{\frac{1}{1+\beta}}\left(\frac{\mu_{sc_2}}{\mu_{sc_1}}\right)^{\frac{2+\beta}{1+\beta}},\mu_{sc_1}\Big) \\
& \frac{1}{\delta m^2}\left(\frac{\delta m^2 z_{\rm cut\,2}^{\frac{1}{1+\beta}}}{\mu_{sc_2}^{\frac{2+\beta}{1+\beta}}\mu_{J_R}^{\frac{\beta}{1+\beta}}}\right)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}\;,\;\text{where}
\end{aligned}
$$

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

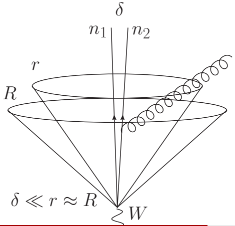
- $\eta_{sc_1} = 2C_iA_\Gamma(\mu,\mu_{sc_1})$ and $\eta = 2C_iA_\Gamma(\mu_{sc_2},\mu_{sc_1})$

Collinear-drop in heavy ion and W jet isolation





- Quark/gluon jet difference disappearing in JEWEL-simulated AA collisions



- In the boosted regime, $\delta \approx m_W/p_T \ll 1$
- At $\mathcal{O}(\alpha_s)$,

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

- Key feature of W jets: zero net color charge

Conclusions

- Telescoping deconstruction is a systematic framework for jet studies
  - An organization principle suited for energy/color flow studies
- Collinear-drop class of observables allows one to directly probe soft physics in Jets
  - studying hadronization in/quenching of jets and testing MC
  - studying the effect of the jet on the soft medium in heavy ion
  - discrimination studies
- Heavy ion jet modification can be comprehensively studied as a classification problem
- W/Z jet isolation is identified as a novel and dominant feature of W/Z jets