

Possible jet measurements at EIC

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Outline

- ▶ Brief overview of jet substructure
- ▶ Telescoping deconstruction: complete jet basis
 - ▶ collinear QCD splitting
 - ▶ heavy ion jet modification
 - ▶ quark v.s. gluon classification
- ▶ Collinear drop: designed for soft physics studies
- ▶ Conclusions and suggestive recommendations

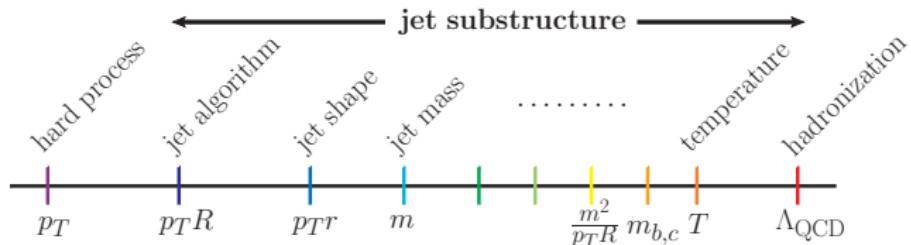
Jets are bundles of hadrons

- ▶ Complete hadron structure
 - ▶ EIC directly probes *existing* nucleon and nucleus
 - ▶ A complimentary study: *production* of hadrons
- ▶ Jets of hadrons are produced in hard processes, through *parton shower* and *hadronization*
 - ▶ Both are constructively described by *models* to some extent
 - ▶ "Breaking of color strings" is at similar level of "quark model" of hadrons
- ▶ pQCD calculations are useful and can be improved order-by-order, but we still need to know how partons turn into hadrons
- ▶ Ultimately we need to know all the hadron structure to understand how they are formed

Many outstanding problems

- ▶ Some open questions (obviously non-exhaustive):
 - ▶ Relating partonic quantum numbers to jet observables and hadrons
 - ▶ Color flow, connection, reconnection
 - ▶ Underlying event (multi-parton interaction), initial state radiation, beam (remnant)
 - ▶ Hadronization
 - ▶ Collective behavior seen in pp , pA and AA
 - ▶ Apparent jet quenching in AA , but not in pp and pA with current precision
 - ▶ ...

The goals of jet substructure studies



- ▶ Examine QCD dynamics between the hard scattering scale and Λ_{QCD} through jet substructure
 - ▶ Why jets if the goal is at Λ_{QCD} ?
 - ▶ Non-perturbative physics affects *all* jet substructure observables
 - ▶ Study parton-to-hadron transition for *arbitrary* partonic states allowed in QCD
- ▶ Precision and/or completeness is the key
- ▶ EIC allows *precision* QCD studies. That's why I am (everyone here is) very excited!

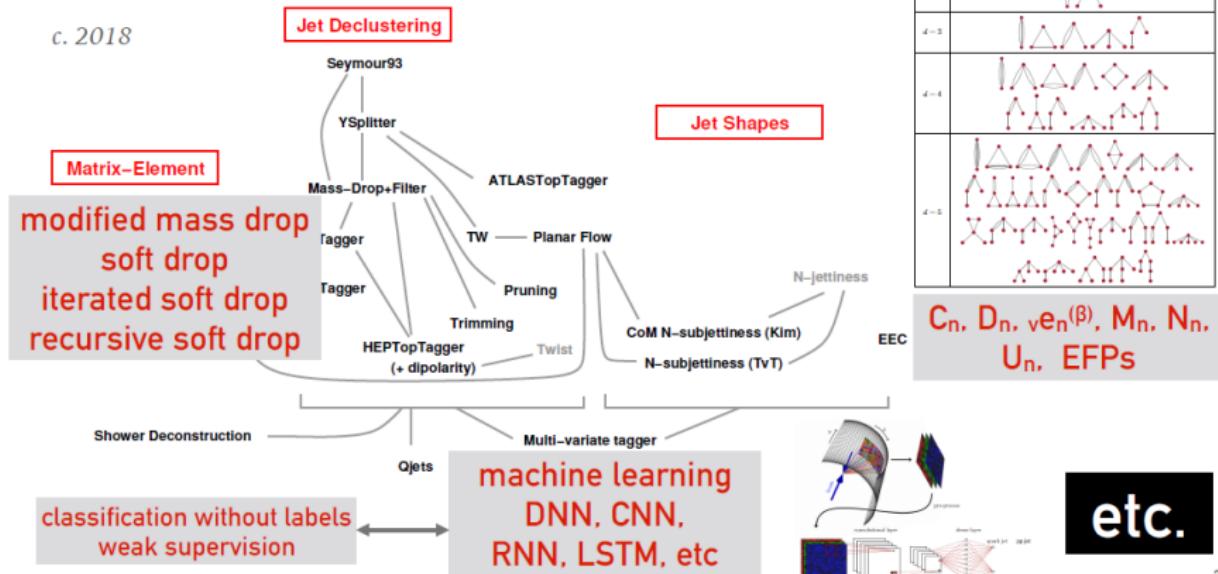
Jet observable zoo

- ▶ Jet and beam kinematics (energy and direction) is the high-scale observable
 - ▶ differential jet and hadron cross sections are the first observables to measure
 - ▶ excellent reference momentum from electron kinematics: correlation between jet/hadron kinematics and electron kinematics, or (Q^2, x)
 - ▶ electron-jet transverse momentum imbalance (energy loss)
 - ▶ electron-jet angular decorrelation (jet broadening)
- ▶ Average jet substructure
 - ▶ radial energy profile
- ▶ Jet and beam substructure distribution
 - ▶ mass, angularity, radial moment, energy correlation function...
 - ▶ hadron fragmentation in transverse and longitudinal directions
 - ▶ in general, a function of hadron *energy and angle*
 - ▶ energetic particles tend to be collinear
 - ▶ soft particles can extend to wide angle
- ▶ Compare ep to eA to quantify the nuclear effect on jets

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

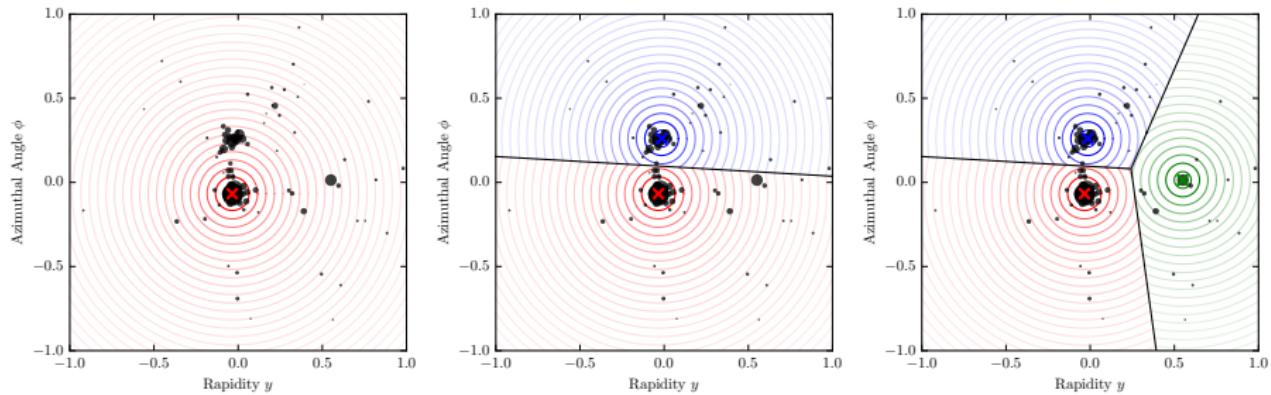
pp jet substructure field is full of activity

c. 2018



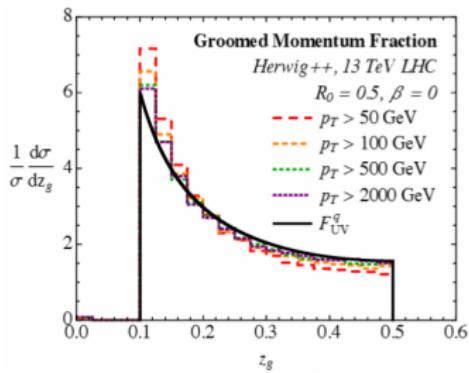
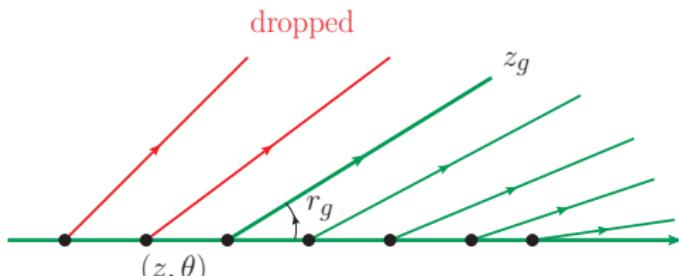
- ▶ What specific physics can each observable probe?
- ▶ Need an organization principle of jet observables and a strategy for physics goals

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 observables represent *subjet topology* and *subjet substructure*
- ▶ Closely related to perturbative expansion and parton shower picture
- ▶ Two dominant energy flows at EIC: beam and struck quark-jet. With higher Q^2 multi-jet events may open up.

QCD subjet distribution in soft drop

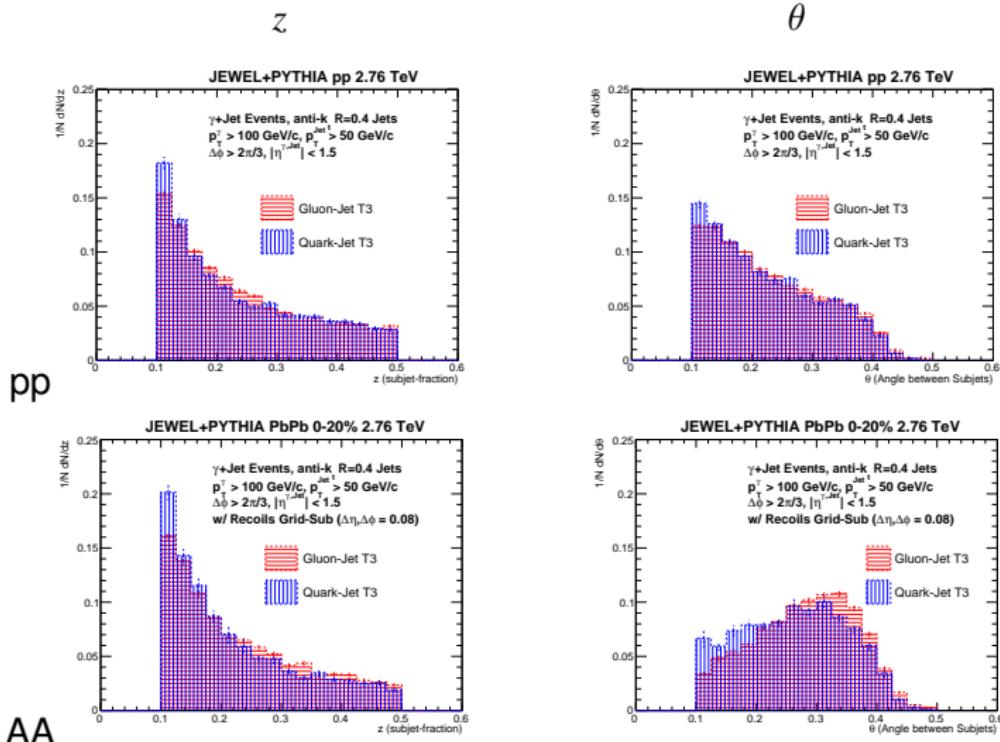


- ▶ Tree-based procedure to remove soft radiation (Larkoski et al)
 - ▶ Recluster a jet using C/A algorithm: angular ordered
 - ▶ For each branching, consider the p_T of each branch and the angle θ
 - ▶ Drop the soft branch if $z < z_{cut} \theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}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

Telescoping subjet topology (z, θ)

arXiv:1803.03589

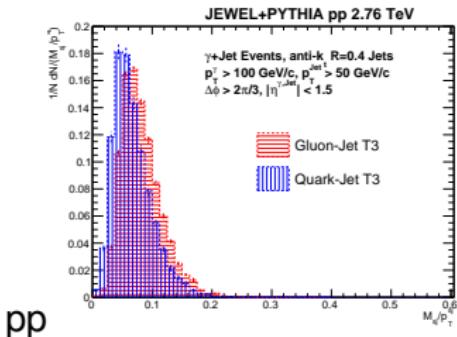
- Enhancement of soft, wide angle radiation in AA (simulated with Jewel (Zapp et al))



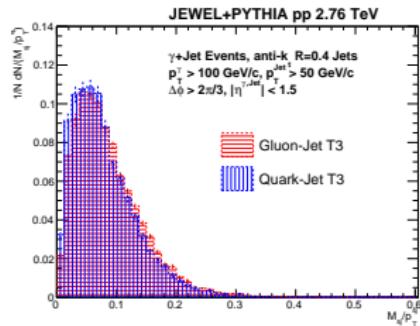
Telescoping subjet substructure m

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

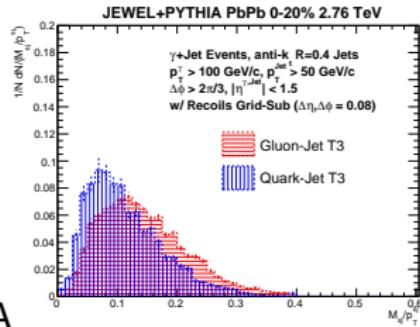
Hard Subjet



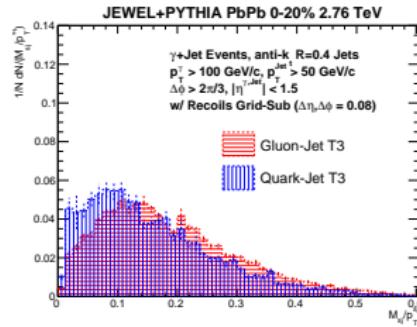
Soft Subjet



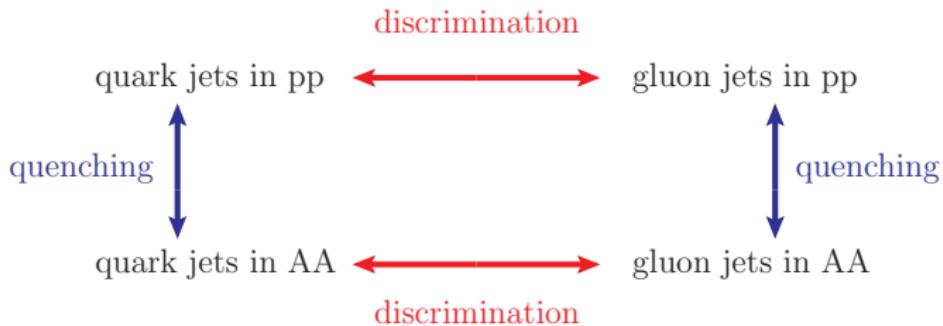
pp



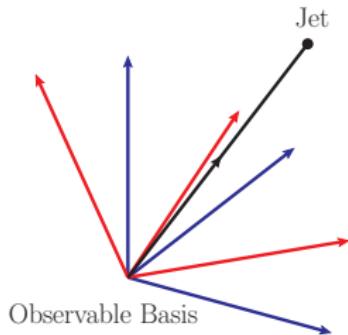
AA



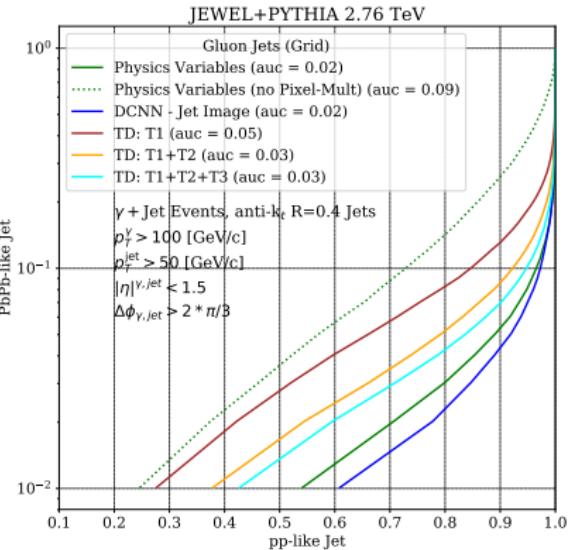
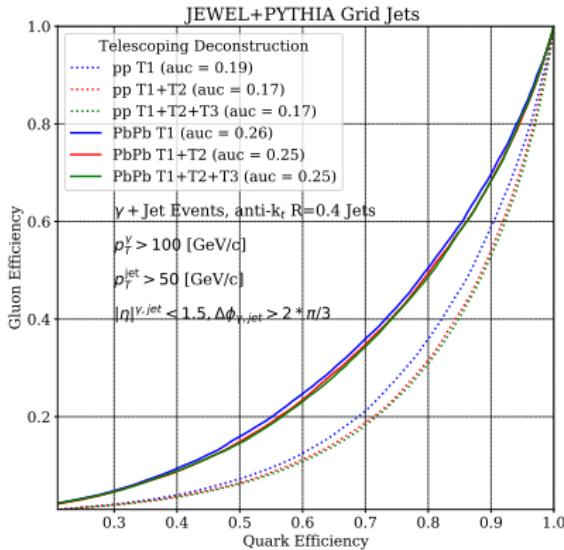
Classification of quark and gluon jets



- ▶ 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



Quark gluon jet classification in pp and AA

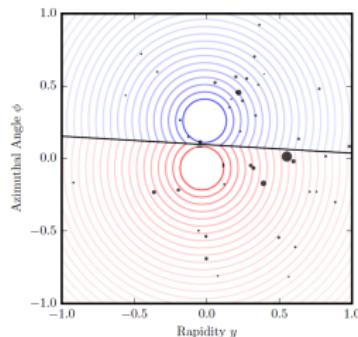


- ▶ Quark/gluon discrimination performance drops in JEWEL-simulated AA collisions
- ▶ Information contained in subleading subjets is washed out
- ▶ Pixel multiplicity is the dominant feature distinguishing pp and AA jets

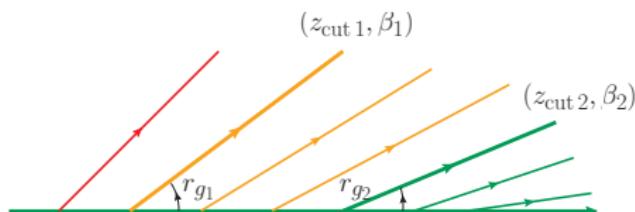
Collinear drop: veto energetic, collinear particles

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

(i) Telescoping deconstruction



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



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

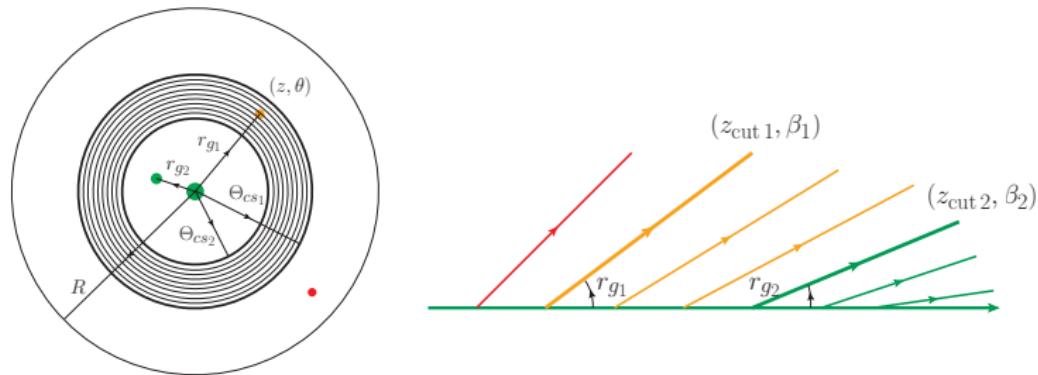
Suppress collinear and wide-angle radiation

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

With I. Stewart, to appear soon

Collinear drop from soft drop

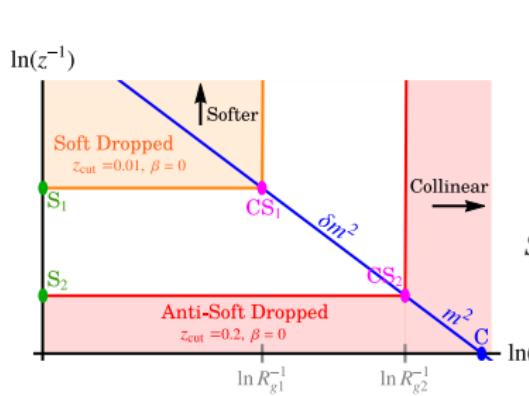
One example of a CD observable can be constructed using a Soft Drop + an Anti Soft Drop



- ▶ Consider $\delta m^2 = m_{SD_1}^2 - m_{SD_2}^2$ to quantify the radiation distribution within the “ring”
- ▶ Contributions from collinear radiation to soft-drop jet mass cancel
$$m_{SD_i}^2 \sim p_c^2 + 2E_J n \cdot p_{cs_i}, \quad \delta m^2 \sim 2E_J n \cdot (p_{cs_1} - p_{cs_2})$$
- ▶ Phase space constraints on the kinematics of soft emissions,

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

Factorization of δm^2 using Soft-Collinear Effective Theory

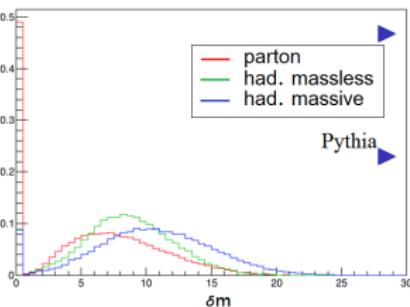
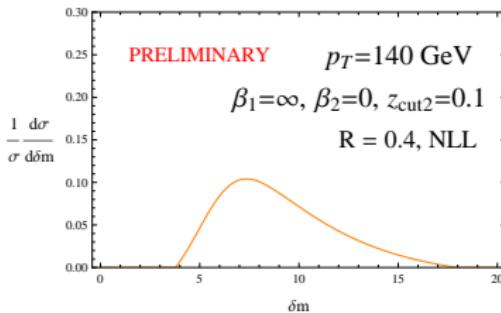


$$\frac{d\sigma}{d\delta m^2} = \sum_{i=q,g} N_i(\mu) J_{un,i}^{\text{SD}}(z_{\text{cut } 2}, \beta_2, \mu) S_i^{\text{CD}}(\delta m^2, z_{\text{cut } i}, \beta_i, \mu)$$

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

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

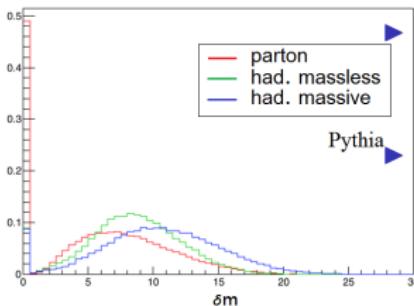
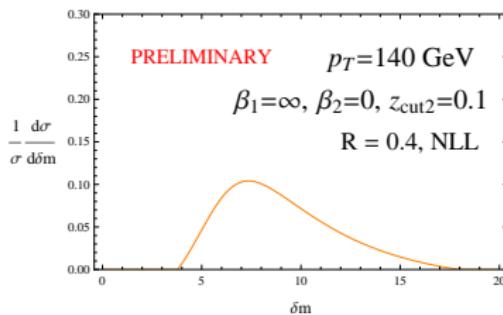
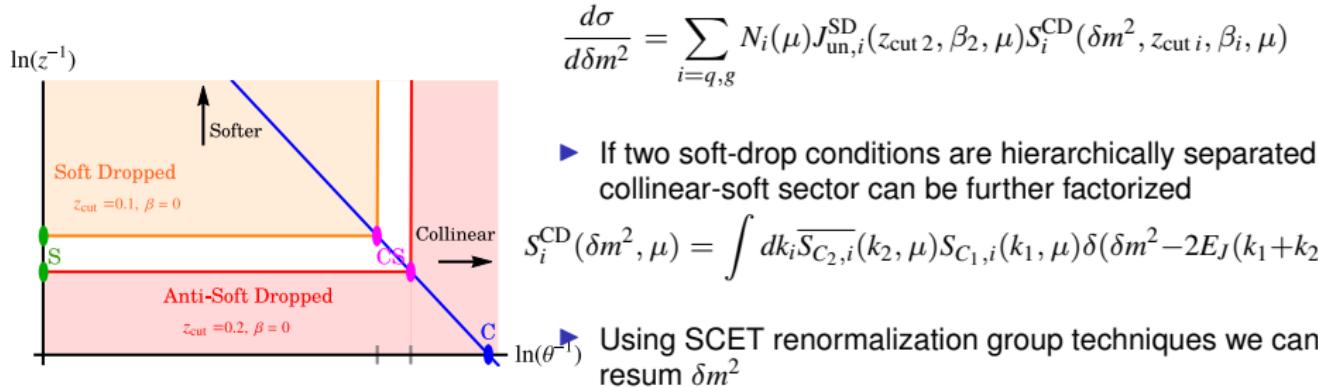
Using SCET renormalization group techniques we can resum δm^2



Massless hadrons are constructed using the p -scheme

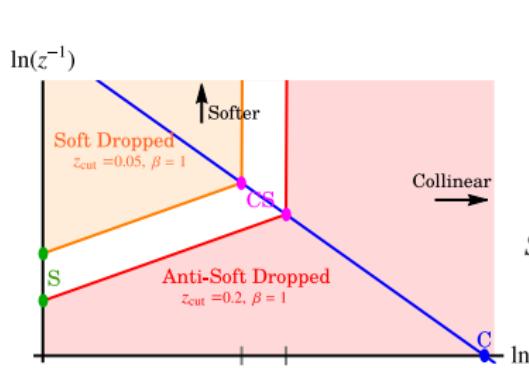
Significant hadronization correction is seen.
Addressed in future work.

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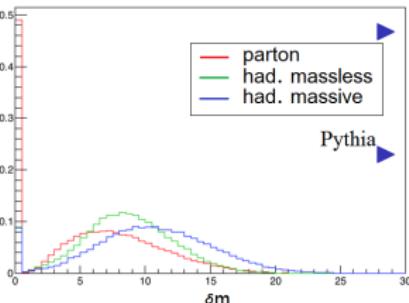
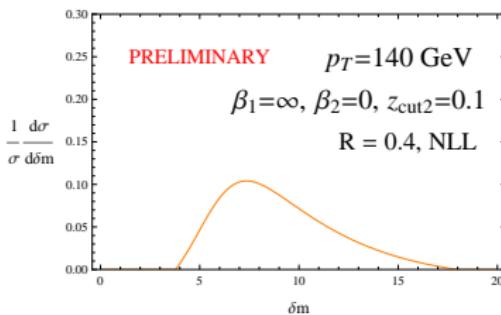


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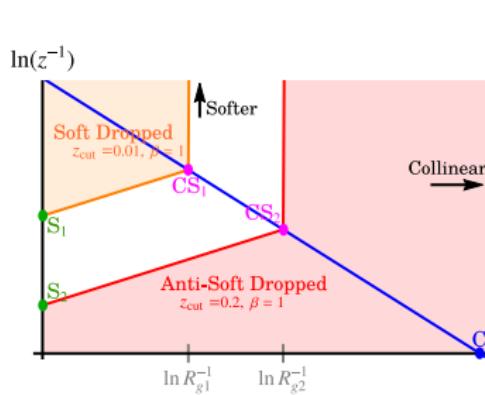
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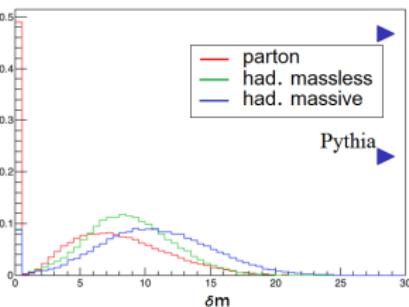
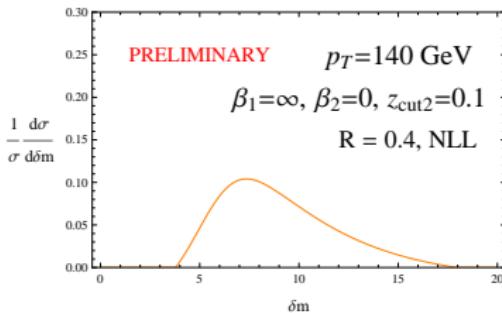


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Perturbative resummation expression

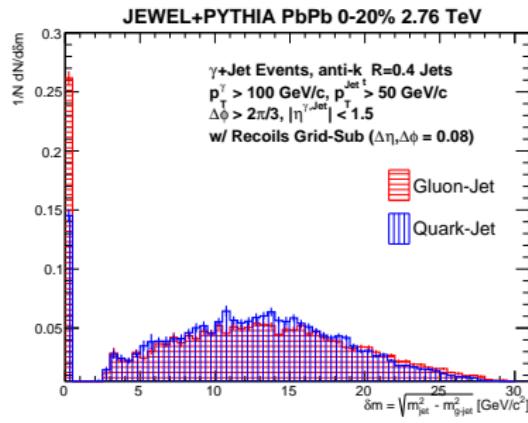
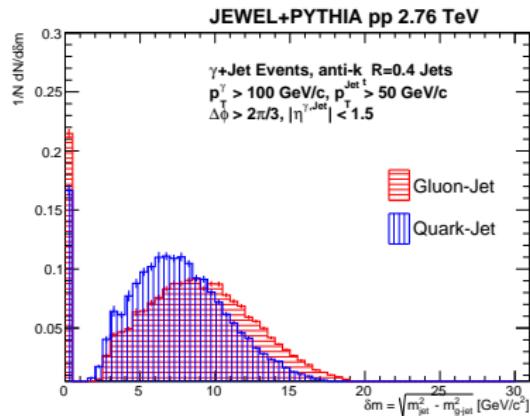
- The formula that entered the plots

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

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

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

Collinear-drop in heavy ion application



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

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 and soft physics in jets and testing MC
- ▶ Nuclear effects on jets can be comprehensively studied as a classification problem

Suggestions

- ▶ With the capability of GPD study using forward regions, it may be worth extending to beam studies
 - ▶ Hadronization of beam remnant
 - ▶ Effects from beam remnant to jets
- ▶ More exclusive jet measurements
 - ▶ Design jet observables to carve out specific QCD phase space
- ▶ Exploit observable correlations
 - ▶ among jet observables
 - ▶ PDFs and jets
 - ▶ beam and jets
 - ▶ hadron and jets
 - ▶ ...
- ▶ Let's keep the discussions going!