Precision Jet Substructure using Soft Collinear Effective Theory

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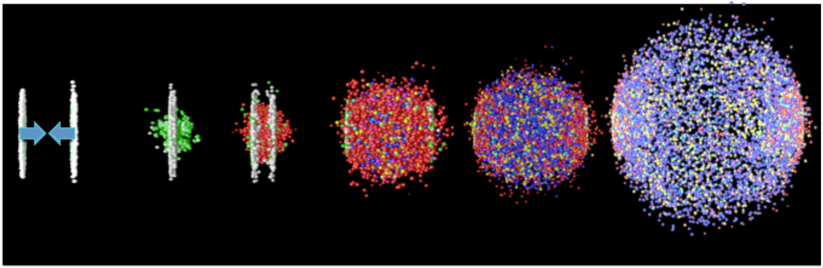
with Ivan Vitev (PRL 119, 112301 (2017)) and Iain Stewart (to appear soon)

Outline

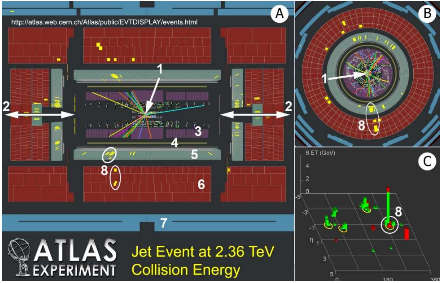
- Jets
  - hard probes of quark-gluon plasma
  - precision jet substructure and grooming
  - Soft Collinear Effective Theory (SCET)
- Hard and soft jet substructure
  - splitting function and subjet distribution
  - groomed jet mass with small jet radius
- Conclusion

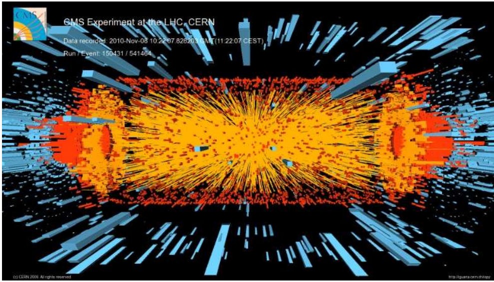
The creation of the Quark Gluon Plasma (QGP)

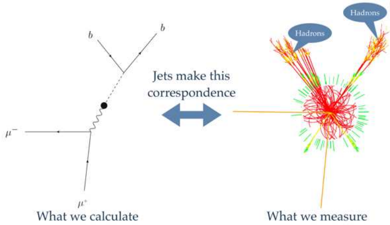
- A hot and dense medium is created during heavy ion collisions
  - The medium quickly thermalizes and allows a hydrodynamic description of its spacetime evolution, eventually turning into soft hadrons
  - Energetic jets are also produced abundantly in the medium



Jets and QCD

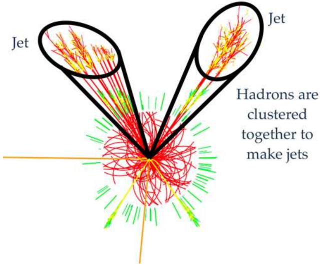


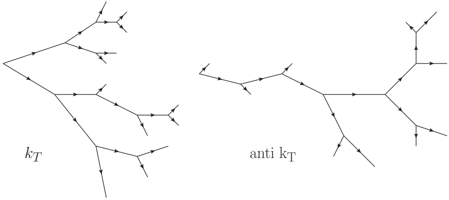




- Jets are collimated particles observed at high energy colliders
- They are manifestations of underlying partons and defined using jet algorithms with radius R
- Jet physics gets the richest in heavy ion collisions
- Thousands of particles are produced and the underlying event backgrounds are enormous

Jet algorithm



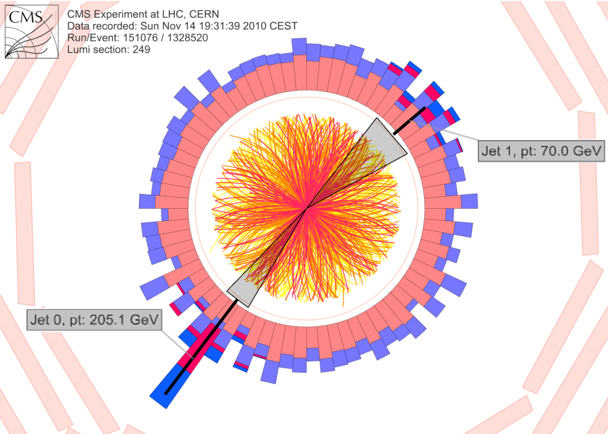


$\beta = 1$: k_T $\quad \beta = 0$, C/A $\quad \beta = -1$, anti-k_T

- Jet clustering algorithms merge pairs of closest particles until the angular resolution R
- The distance d_{ij} between particles i and j is defined as $d_{ij} = \min(p_{ti}^{2\beta}, p_{tj}^{2\beta})\Delta R_{ij}^2/R^2$

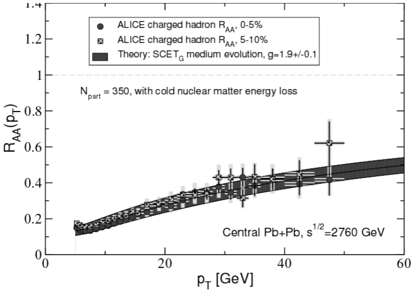
Jets are quenched and modified in heavy ion collisions

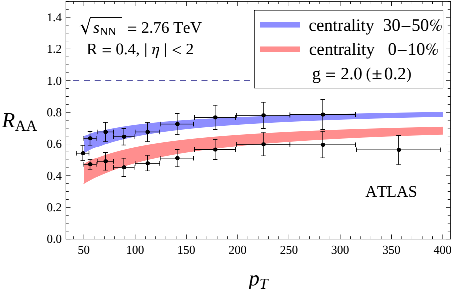
- Jets are not only embedded in an enormous underlying event background but also significantly modified
- Because of the huge background, one needs to do both background subtraction and jet grooming and measure jets with small radii ($0.2 < R < 0.4$)
- Dramatic suppression of jets and momentum imbalance is observed



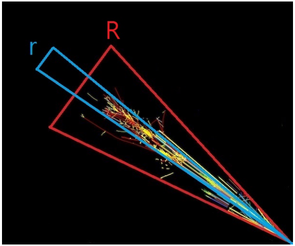
Hadron and jet cross section suppression

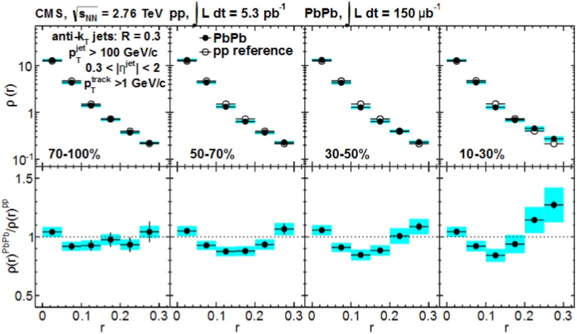
- $R_{AA} < 1$ is the ratio of the cross sections in AA and pp collisions





Jet spectroscopy of the QGP





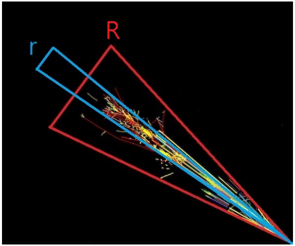
$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{Ti}}{\sum_{r_i<R} E_{Ti}}$$

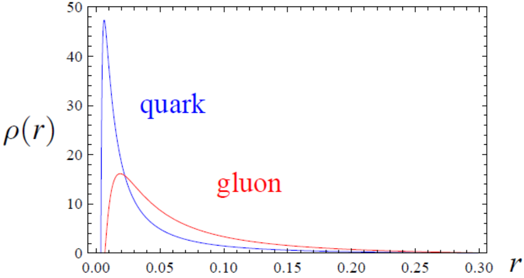
$$\langle\Psi\rangle = \frac{1}{N_J}\sum_J^{N_J}\Psi_J(r,R)$$

$$\rho(r) = \frac{d\langle\Psi\rangle}{dr}$$

- Jets have become essential tools to probe the quark-gluon plasma produced in heavy ion collisions
- One typically evaluates the observable modification by the ratio of the curves in AA and pp collisions $\frac{\mathcal{O}^{AA}}{\mathcal{O}^{pp}}$
- With detailed understanding of jets and their structures we can relate their modifications to the medium properties: the need of precise jet substructure studies

Jet substructure calculation and resummation





- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n), \ n = 1, \ldots, \infty$ need to be resummed
- Sensitive to the partonic origin of jets and the quark/gluon jet fraction

QCD and effective field theory

Systematically decompose QCD radiations

- Resolve jets at different energy scales
    - A jet is not simply a parton but with sequential branching and splitting
    - Substructure measurements allow us to study the jet formation mechanism at various energy scales
- The dominant contributions to jet observables come from radiations which are
    - Energetic, *collinear*
    - *Soft*, ubiquitous (not necessarily collinear)
- Power counting by systematically defining *collinearity* and *softness*

Resummation and effective field theory

THE BASIC IDEA

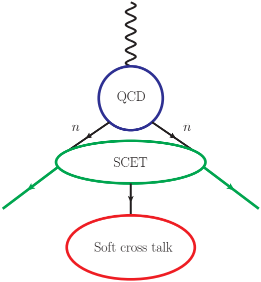
- Logarithms of *scale ratios* appear in perturbative calculations
  - Logarithms become large when scales become hierarchical

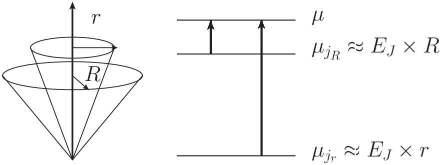
$$\log \frac{r}{R} = \log \frac{\text{scale 1}}{\text{scale 2}}$$

- In effective field theories, logarithms are resummed using renormalization group evolution between characteristic scales
  - To resum *all* the logarithms we need to identify *all* the relevant scales in EFT

Resummation using Soft-Collinear Effective Theory (SCET)

- Effective field theory techniques are most useful when there is hierarchy between characteristic energy scales
- SCET factorizes physical degrees of freedom in QCD by a systematic expansion in power counting
    - Match SCET with QCD at the hard scale by integrating out the hard modes
    - Integrating out the off-shell modes gives collinear Wilson lines which describe the collinear radiation
    - The soft sector is described by soft Wilson lines along the jet directions





Renormalization group evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

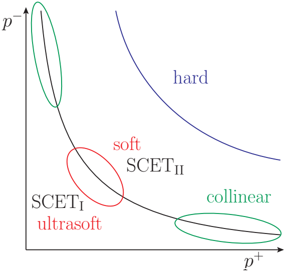
(Chien et al 1405.4293)

Power counting in SCET

- The scaling of modes in lightcone coordinates $(\bar{n}\cdot p, n\cdot p, p_\perp)$ where $n = (1,0,0,1)$ and $\bar{n} = (1,0,0,-1)$:

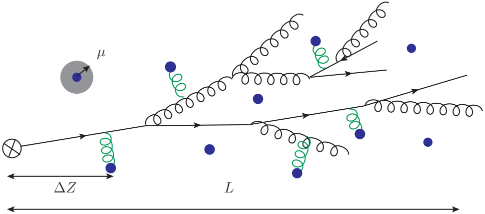
$$p_h : E_J(1,1,1),\ p_c : E_J(1,\lambda^2,\lambda) \text{ and } p_s : E_s(1,R^2,R)$$

  - E_J is the hard scale which is the energy of the jet
  - λ is the **power counting** parameter ($\lambda < R$)
  - $E_J\lambda$ is the jet scale which is significantly lower than E_J
  - The relevant soft scales depend on observables
- QCD $= \mathcal{O}(\lambda^0) + \mathcal{O}(\lambda^1) + \cdots$ in SCET
  - Leading-power contribution in SCET is a very good approximation

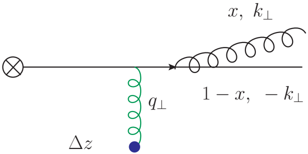


Multiple scattering in a medium and QCD bremsstrahlung

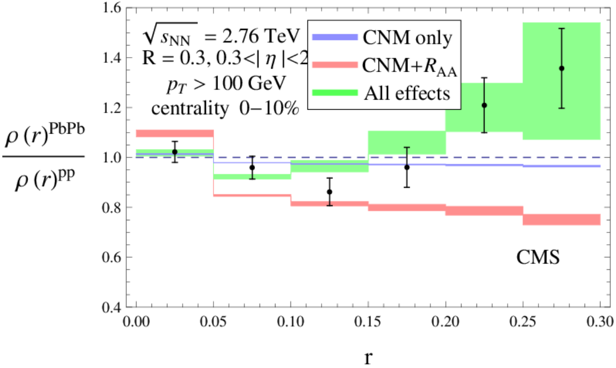
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ



- Jet-medium interaction using SCET with background Glauber gluon fields $\mathrm{SCET_G}$ (Glauber-collinear: Majumder et al, Vitev et al. Glauber-soft: work in progress)
- Leading-order medium induced splitting functions $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ were calculated using $\mathrm{SCET_G}$ (Vitev et al)



First quantitative understanding of jet shape modification



- Cold nuclear matter effect is negligible
- Jet quenching increases the quark jet fraction
- Jet-by-jet the shape is broadened
- Chien et al 1509.07257 and CMS data 1310.0878

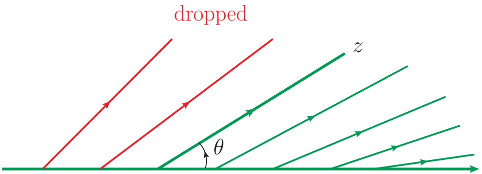
How do we isolate physics and distinguish jet quenching models?

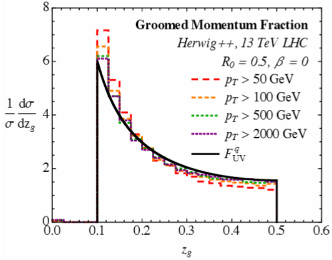
- Jets are multi-scaled objects with rich information about the physics across the entire energy spectrum
- Jet observables have different sensitivities to physics at different energy scales
- Through a series of jet measurements we can map out the whole jet formation history
- Whether the model relies on the low scale physics corresponds to two rough pictures of jet quenching
    - Yes. Parton showers are not affected much until the later stages. The medium depletes the partons out of the jet
    - No. The medium effects open up more channels in the jet formation process, all the way from the hard process through hadronization
- Can we test the two pictures and the role of medium response?
    - We are able to dissect radiations and pick out the components of interest
    - The idea: come up with an observable as insensitive to low scale physics as possible
    - The tool: jet grooming

Jet grooming is actually artificial jet quenching

- It is a controlled way to remove soft radiation
- How does a jet quenching model confront with jet grooming?
    - Do they add up or interfere?

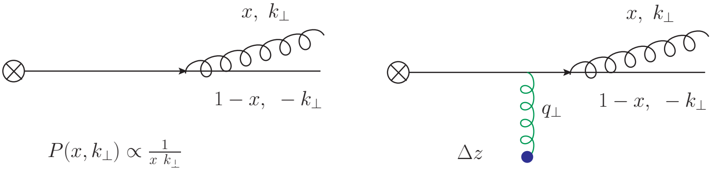
Groomed momentum fraction z_g





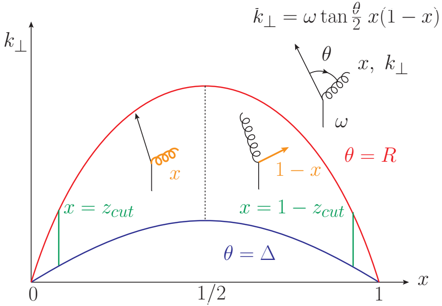
- Soft Drop: a tree-based procedure to drop soft radiation (Larkoski et al 1402.2657)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^{\beta}$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - CMS used $\beta = 0$, $z_{cut} = 0.1$, $R = 0.4$, $\Delta R_{12} > \Delta = 0.1$ and measured z_g
- z_g: the momentum fraction of the soft branch. r_g: the angle between the branches

z_g and splitting functions



- In vacuum, the soft branch kinematics is closely related to the Altarelli-Parisi splitting function
- In the medium, the bremsstrahlung component modifies the soft branch kinematics

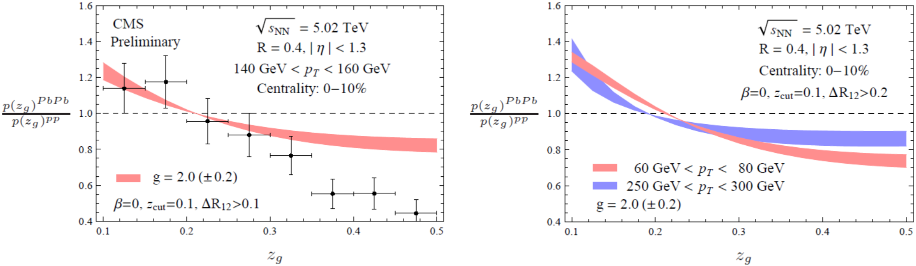
Analysis of z_g



- The partonic phase space is constrained by R (jet algorithm), Δ (jet selection) and z_{cut} (jet grooming)
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution
$$\mathcal{P}_{i\to jl}(x,k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x,k_\perp) + \mathcal{P}^{med}_{i\to jl}(x,k_\perp)$$
- The distributions of z_g and r_g are calculated ($\overline{\mathcal{P}}(x) = \mathcal{P}(x) + \mathcal{P}(1-x)$)

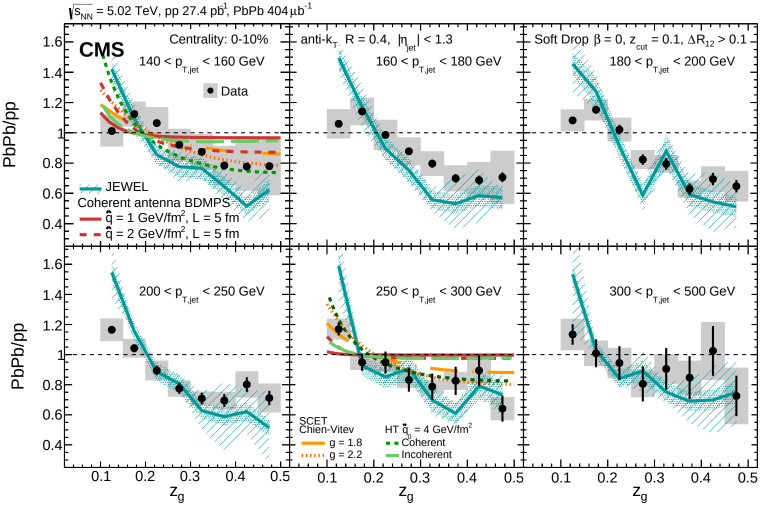
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g,k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x,k_\perp)}\,, \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x)\overline{\mathcal{P}}_i(x,k_\perp(r_g,x))}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x,k_\perp)}$$

Theory calculation of z_g



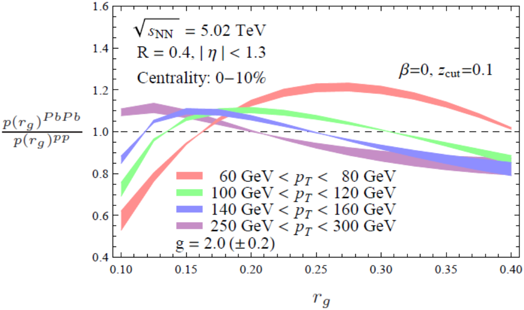
- The medium enhances the small z_g and suppresses the large z_g regions, and the effect becomes smaller for higher p_T jets
- Cutting on the angle between branches selects a special subset of the jet sample
  - Jets with a two prong structure not typical for QCD jets
  - The scale of this subjet branching is high: hard jet substructure

Theory calculation of z_g



- Quantitatively agreeing with the CMS data

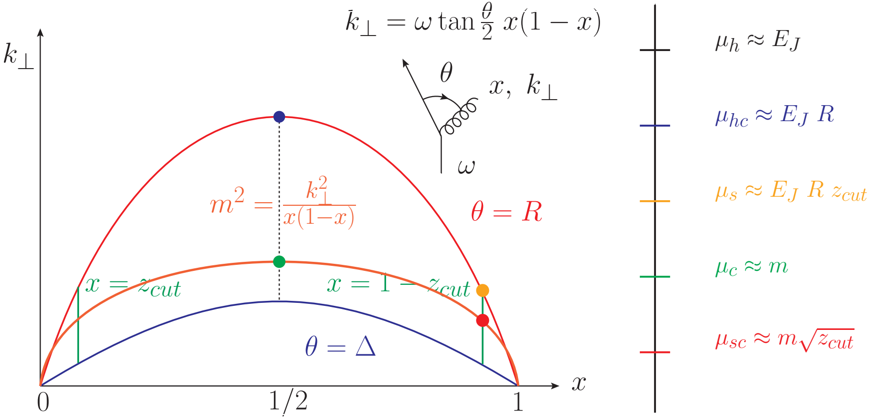
Theory prediction for r_g



- The subjet angular distribution will reveal the nature of QCD bremsstrahlung
- It will be a direct probe of the medium scale
- The next step is the groomed jet mass

Groomed jet mass

- Invariant mass of soft-dropped jet: $m^2 = (\sum p_i)^2$
- Factorization in SCET



Power counting of modes

- Factorization and resummation:
- **In-jet soft** mode

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

- **Collinear** mode

$$p_c = (E_J, \frac{m^2}{E_J}, m), \text{ with } \mu_j = m$$

- **Soft-collinear** mode respecting the measurement $x\theta^2 \sim m^2/E_J^2$ and jet grooming $z_{cut} \sim x(\theta/R)^{-\beta}$

$$p_{sc} = (E_J z_{cut}\left(\frac{m}{E_J R\sqrt{z_{cut}}}\right)^{\frac{2\beta}{2+\beta}}, \frac{m^2}{E_J}, m\sqrt{z_{cut}}\left(\frac{m}{E_J R\sqrt{z_{cut}}}\right)^{\frac{\beta}{2+\beta}}), \text{ with } \mu_{sc} = m\sqrt{z_{cut}}\left(\frac{m}{E_J R\sqrt{z_{cut}}}\right)^{\frac{\beta}{2+\beta}}$$

- **Hard collinear** mode from pure jet reconstruction

$$p_{j_R} = E_J(1, R^2, R), \text{ with } \mu_{j_R} = E_J R$$

Groomed jet mass function

- The process-independent groomed jet mass function $J_M^{\not{s}}(m^2, \mu)$ captures all the soft-collinear radiation inside jets ($i = q, g$)

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

where $S_i^{\not{s}}(k, R, z_{cut}, \mu) = S_i^C(k, R, z_{cut}, \mu) S_i^{IN}(R, z_{cut}, \mu)$

- Medium-induced splitting functions are used to calculate the modification of $J_M^{\not{s}}(m^2, \mu)$. At $\mathcal{O}(\alpha_s)$,

$$J_M^{i\not{s}}(m^2, \mu) = \sum_{j,k} \int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x, k_\perp) \delta(m^2 - M^2(x, k_\perp)) \Theta_{\text{alg.}} \Theta_{\not{s}}$$

$M^2(x, k_\perp) = \frac{k_\perp^2}{x(1-x)}$, $\Theta_{\text{k}_\text{T}} = \Theta(E_J R x(1-x) - k_\perp)$, $\Theta_{\not{s}} = \Theta(E_J R x(1-x) \left(\frac{x}{z_{cut}}\right)^{1/\beta} - k_\perp)$.

- The full jet mass distribution can be calculated by weighing the groomed jet mass functions with jet cross sections

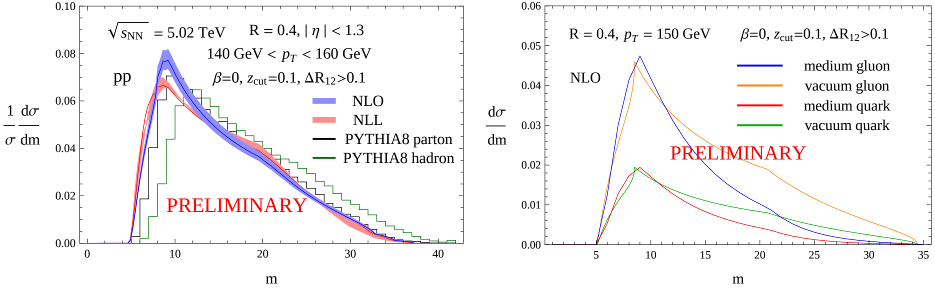
$$\frac{d\sigma}{dm^2} = \sum_{i=q,g} \int_{PS} dp_T dy \frac{d\sigma^i}{dp_T dy} P_i^{\not{s}}(m^2, \mu), \text{ where } P_i^{\not{s}}(m^2, \mu) = \frac{J_M^{i\not{s}}(m^2, \mu)}{J_{un}^i(\mu)}$$

Resummed groomed jet mass function

- Each function is calculated at 1-loop and depends on a single scale
- $P_i^{\not{s}}(m^2,\mu)$ is manifestly renormalization group invariant. Logs are resummed using the RG evolution of each function.

$$\begin{aligned}
& P_i^{\not{s}}(m^2,\mu) \\
= \quad & \exp\Big[2\frac{2+\beta}{1+\beta}C_iS(\mu_{sc},\mu_s) - 4C_iS(\mu_j,\mu_s) + 2C_iS(\mu_{j_R},\mu_s) + 2A_{J_i}(\mu_j,\mu_{j_R}) + 2A_{S_i}(\mu_{sc},\mu_{j_R})\Big] \\
& \times\Bigg(\frac{\mu_j^2 z_{cut}^{\frac{1}{1+\beta}}}{\mu_{sc}^{\frac{2+\beta}{1+\beta}}\,(2E_J\tan\frac{R}{2})^{\frac{\beta}{1+\beta}}}\Bigg)^{2C_iA_\Gamma(\mu_s,\mu_{sc})}\Bigg(\frac{2E_J\tan\frac{R}{2}}{\mu_{j_R}}\Bigg)^{2C_iA_\Gamma(\mu_s,\mu_{j_R})}\frac{S_i^{IN}(\mu_s)}{m^2J_{\rm un}^i(\mu_{j_R})} \\
& \tilde{J}_i(\partial\eta,\mu_j)\tilde{S}_i^C\Bigg(\partial\eta + \ln\frac{\mu_j^2 z_{cut}^{\frac{1}{1+\beta}}}{\mu_{sc}^{\frac{2+\beta}{1+\beta}}\,(2E_J\tan\frac{R}{2})^{\frac{\beta}{1+\beta}}},\mu_{sc}\Bigg)\Bigg(\frac{m^2}{\mu_j^2}\Bigg)^{\eta}\frac{e^{-\gamma_E\eta}}{\Gamma(\eta)}
\end{aligned}$$

Preliminary results



- The $\Delta R_{12} > 0.1$ cut cuts out the Sudakov peak and eliminates the quark/gluon difference
- The lower and upper limits of jet mass are essentially dictated by kinematics. r_g and jet mass are highly correlated
- The medium lowest-order perturbative contribution enhances the small mass region
- Hard splitting can "shield" inner soft radiations from being soft-dropped
- Soft contributions (anything softer: modification of subjets, pp smearing, etc) and hadronization effects are still under examination

Conclusion

- What we have learned: flavor dependence of jet quenching and the role of quark/gluon jet fraction in jet substructures
- Subjet distribution provides an opportunity to test the modification of hard splitting within jets
- Groomed jet mass is resummed with small radius, and the medium lowest-order perturbative contribution enhances the small mass region (preliminary)
- Effective field theory techniques allow systematically improvable jet quenching studies