Splitting Functions and Jet Mass Distributions in Heavy Ion Collisions

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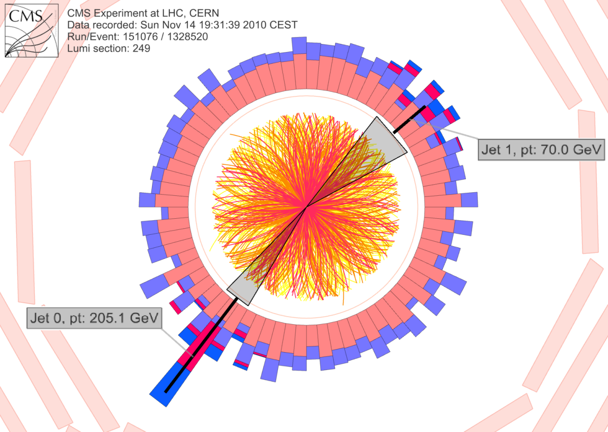
Outline

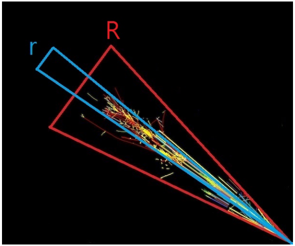
- Heavy ion jet physics
  - jet quenching and jet modification
  - the necessity and utility of jet grooming
- Hard and soft jet substructure
  - splitting function
  - groomed jet mass with small jet radius
- Conclusion and outlook

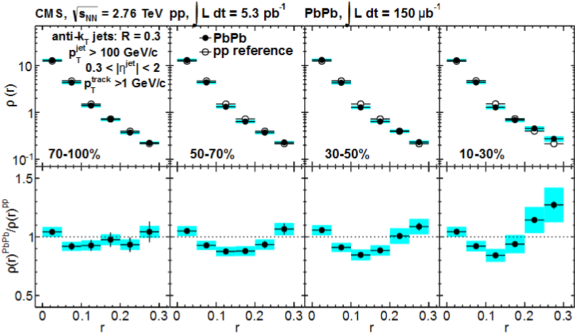
Jets are "quenched" and modified in heavy ion collisions

- 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



Jet spectroscopy of the QGP





$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

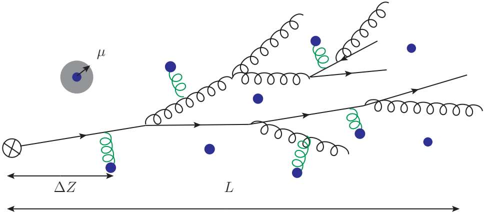
$$\langle\Psi\rangle = \frac{1}{N_J}\sum_{J}^{N_J}\Psi_J(r,R)$$

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

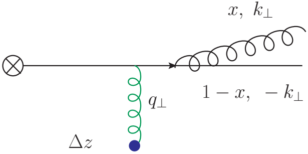
- Jets have become essential tools to probe the quark-gluon plasma produced in heavy ion collisions
- One typically evaluates the observable modification by the ratio of the curves in AA and pp collisions $\frac{\mathcal{O}^{AA}}{\mathcal{O}^{pp}}$
- With detailed understanding of jets and their structures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

Multiple scattering in a medium and QCD bremsstrahlung

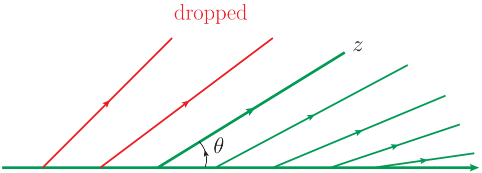
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ

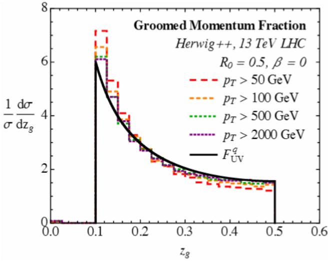


- Jet-medium interaction using SCET with background Glauber gluon fields (Glauber-collinear: Majumder et al, Vitev et al. Glauber-soft: work in progress with Iain and Patrick)
- Leading-order medium induced splitting functions $\mathcal{P}^{med}_{i\to jl}(x, k_\perp)$ were calculated using $\mathrm{SCET_G}$ (Vitev et al, and also for heavy quarks)
- How can we directly test the QCD splitting functions?



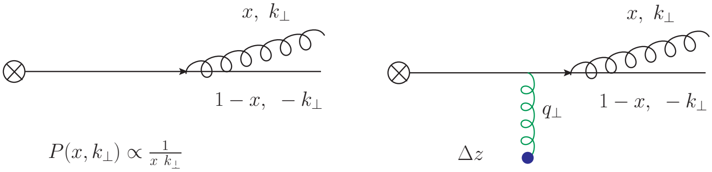
Groomed momentum fraction z_g





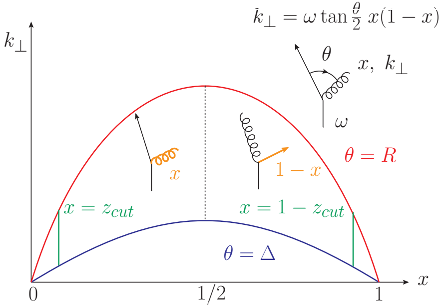
- Soft Drop: a tree-based procedure to drop soft radiation
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^\beta$, where $z = \frac{\min(p_{T,1},p_{T,2})}{p_{T,1}+p_{T,2}}$
  - 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 is closely related to the subjet fragmentation within jets (Lin's talk)

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



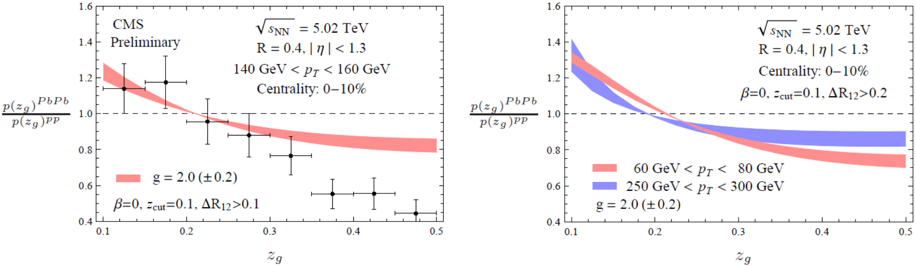
- The partonic phase space is constrained by R (jet algorithm), Δ (jet selection) and z_{cut} (jet grooming)
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

$$\mathcal{P}_{i\to jl}(x, k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x, k_\perp) + \mathcal{P}^{med}_{i\to jl}(x, k_\perp)$$

- The distributions of z_g and r_g are calculated ($\overline{\mathcal{P}}(x) = \mathcal{P}(x) + \mathcal{P}(1-x)$)

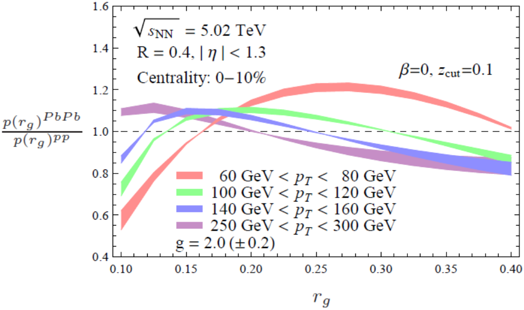
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g, k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x, k_\perp)}\ , \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x) \overline{\mathcal{P}}_i(x, k_\perp(r_g, x))}{\int_{z_{cut}}^{1/2}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

Theory calculation of z_g



- The medium enhances the soft branches, and the effect becomes smaller for higher p_T jets
- Qualitatively expected and quantitatively surprising (CMS is reanalyzing the data because of a systematic bias we pointed out. Stay tuned)
- 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 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 to measure the groomed jet mass (CMS measurement in progress. Charged jets done by ALICE)

Power counting of modes for groomed jet mass (Larkoski et al squeezed)

- 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 $z_{cut} \sim x(\theta/R)^{-\beta}$

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

  it becomes the c-soft mode $(m^2/E_J R^2, m^2/E_J, m^2/E_J R)$ when $\beta \to \infty$, and R independent when $\beta \to 0$

- Hard collinear mode from pure jet reconstruction

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

- We first consider the case where

$$\mu_{j_R} \gg \mu_s \gg \mu_j \gg \mu_{sc}$$

Groomed jet mass function

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

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

where $S_i^{\not{g}}(k, R, z_{cut},\mu) = S_i^C(k, R, z_{cut},\mu) S_i^{IN}(R, z_{cut},\mu)$. caveat: non-global logs of $\log z_{cut}$?

- Medium-induced splitting functions are used to calculate the modification of $J_M^{\not{g}}(m^2,\mu)$. At leading order,

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

$$M^2(x, k_\perp) = \frac{k_\perp^2}{x(1-x)},\ \Theta_{\mathrm{k_T}} = \Theta(E_J R x(1-x) - k_\perp),\ \Theta_{\not{g}} = \Theta(E_J R x(1-x)\left(\frac{x}{z_{cut}}\right)^{1/\beta} - k_\perp).$$

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

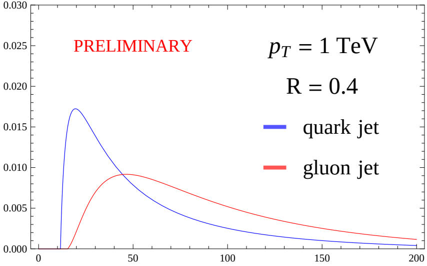
$$\frac{d\sigma}{dm^2} = \sum_{i=q,g}\int_{PS} dp_T dy \frac{d\sigma^i}{dp_T dy} P_i^{\not{g}}(m^2,\mu),\ \text{where } P_i^{\not{g}}(m^2,\mu) = \frac{J_M^{i\not{g}}(m^2,\mu)}{J_{un}^i(\mu)}$$

Resummed groomed jet mass function (preliminary)

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

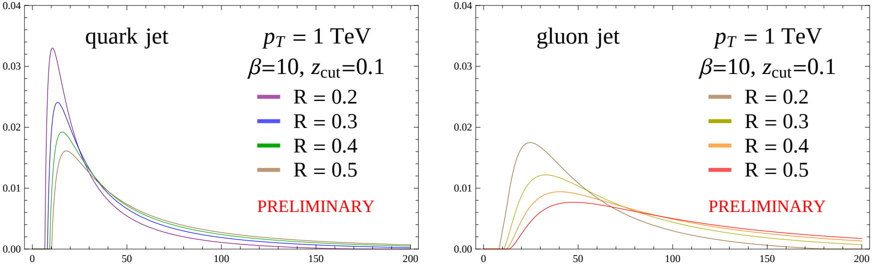
$$
\begin{aligned}
& P_i^{\not g}(m^2,\mu) \\
= \quad & \exp\Big[2\frac{2+\beta}{1+\beta}C_i S(\mu_{sc},\mu_s) - 4C_i S(\mu_j,\mu_s) + 2C_i S(\mu_{j_R},\mu_s) + 2A_{J_i}(\mu_j,\mu_{j_R}) + 2A_{S_i}(\mu_{sc},\mu_{j_R})\Big] \\
& \times\Big(\frac{\mu_j^2 z_{cut}^{\frac{1}{1+\beta}}}{\mu_{sc}^{\frac{2+\beta}{1+\beta}}(2E_J\tan\frac{R}{2})^{\frac{\beta}{1+\beta}}}\B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

Preliminary results



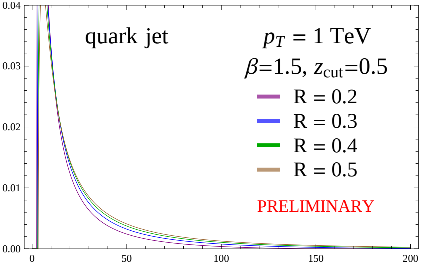
- gluon jets are fatter than quark jets (plot shows $\beta \to \infty$)

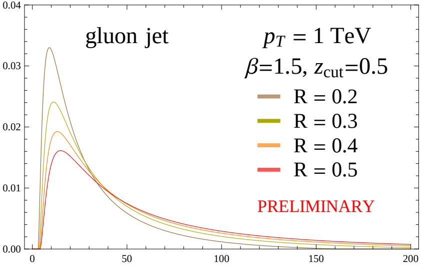
Preliminary results



- Plots show the R dependence for mildly groomed jets

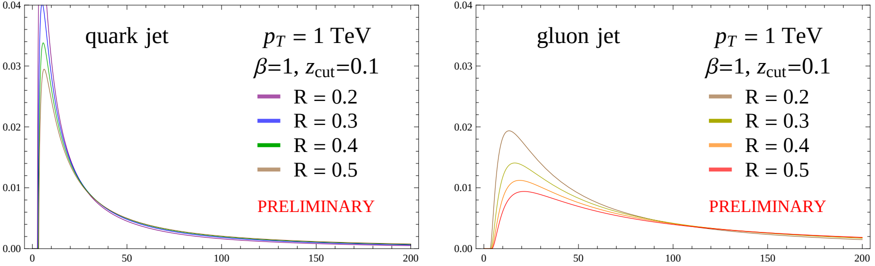
Preliminary results





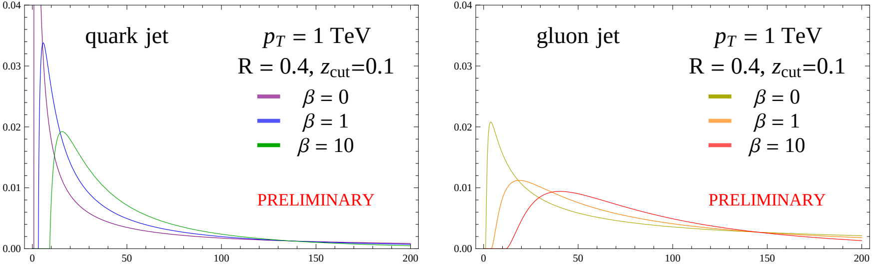
- Plots show the R dependence for more aggressively groomed jets

Preliminary results



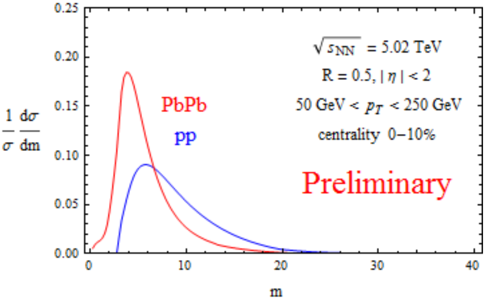
- Plots show the R dependence for groomed jets approaching $\beta = 0$
- Need non-singular terms in the tail region

Preliminary results



- Plots show the β dependence
- Again, need non-singular terms in the tail region

Preliminary results



- In the medium the jet mass shifts to smaller values. Plot shows the $\beta \to \infty$ case.
- Another powerful observable to test jet quenching models

Conclusion and outlook

- Subjet distribution provides an opportunity to test the modification of hard splitting within jets
- Groomed jet mass is resummed with small radius
- To-do 1: include non-singular terms and non-perturbative contributions
- To-do 2: explore other scale hierarchies
- To-do 3: study the $\beta : 0 \to \infty$ transition
- To-do 4: phenomenological comparisons
- To-do 5: check the calculations of medium modifications
- Stay tuned!