Confronting Jet Quenching with Jet Grooming:

Splitting Function and Jet Mass Distribution in Heavy Ion Collisions

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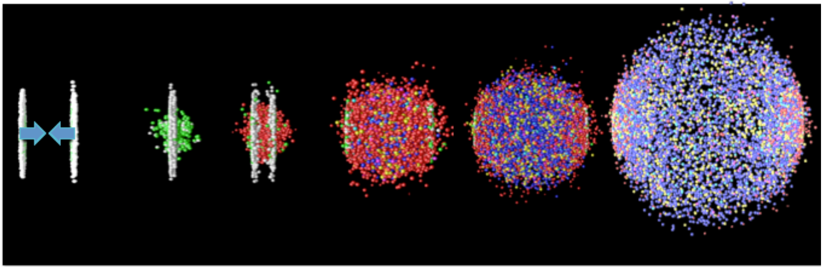
Outline

- Heavy ion jet physics
  - hard probes of quark-gluon plasma
  - jet quenching and jet modification
  - the necessity and utility of jet grooming
- Hard and soft jet substructure
  - splitting function and subjet distribution
  - groomed jet mass with small jet radius
- Conclusion and outlook

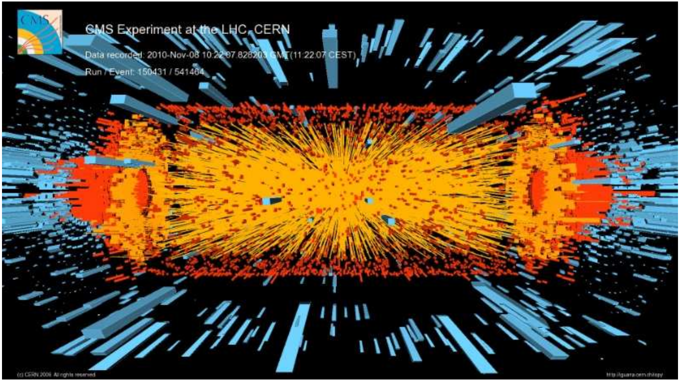
The creation of the Quark Gluon Plasma (QGP)

- A hot and dense medium is created during the collision
  - 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



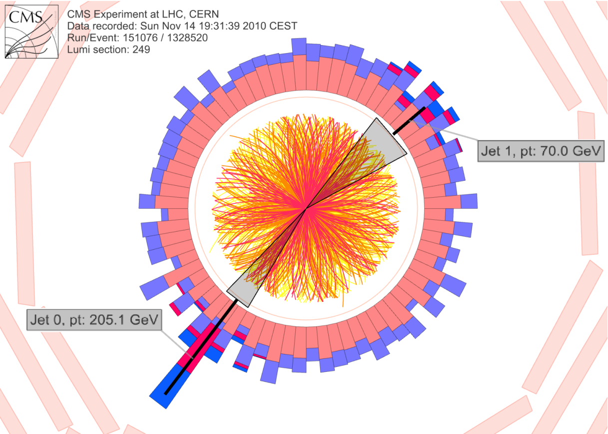
Jet physics gets the richest in heavy ion collisions

- Thousands of particles are produced and the underlying event backgrounds are enormous



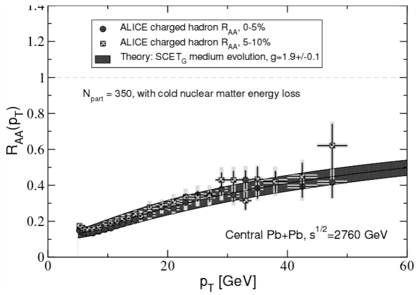
Jets are "quenched" and modified in heavy ion collisions

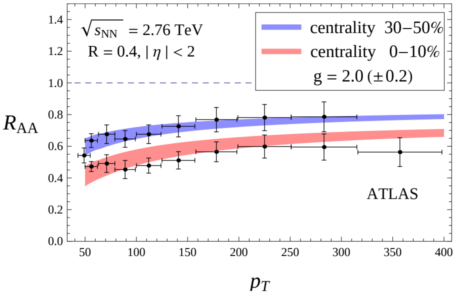
- Jets are not only embedded in an enormous underlying event background but also significantly modified
- Because of the huge background, one needs to do both background subtraction and jet grooming and measure jets with small radii $(0.2 < R < 0.4)$
- Dramatic suppression of jets and momentum imbalance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



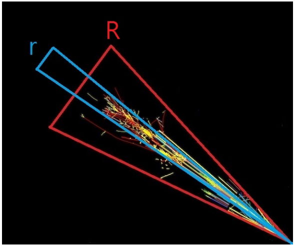
Hadron and jet cross section suppression

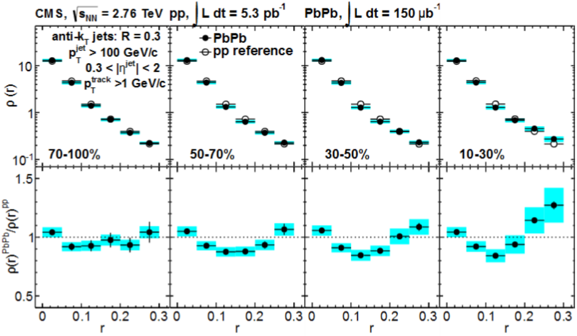
- $R_{AA} < 1$ is the ratio of the cross sections in AA and pp collisions





Jet spectroscopy of the QGP





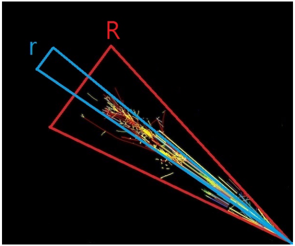
$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{Ti}}{\sum_{r_i<R} E_{Ti}}$$

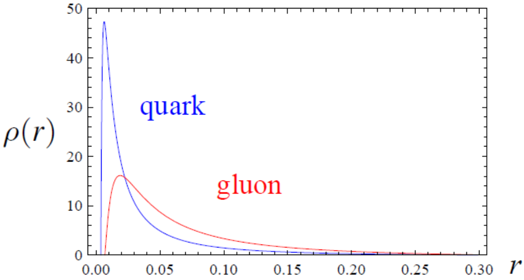
$$\langle\Psi\rangle = \frac{1}{N_J}\sum_J^{N_J}\Psi_J(r,R)$$

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

- 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

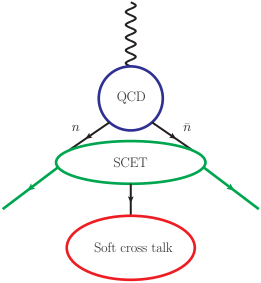


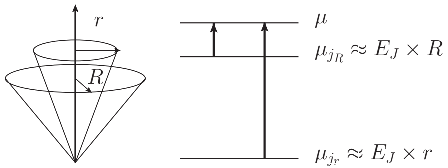


- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n)$ need to be resummed
- Sensitive to the partonic origin of jets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

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



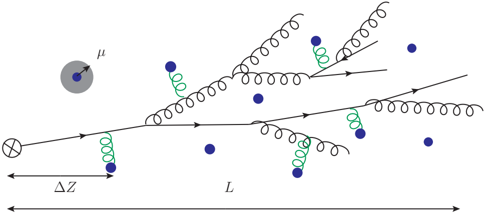


Renormalization group evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

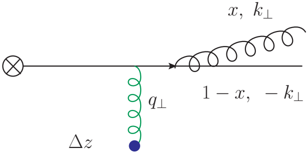
(Chien et al 1405.4293)

Multiple scattering in a medium and QCD bremsstrahlung

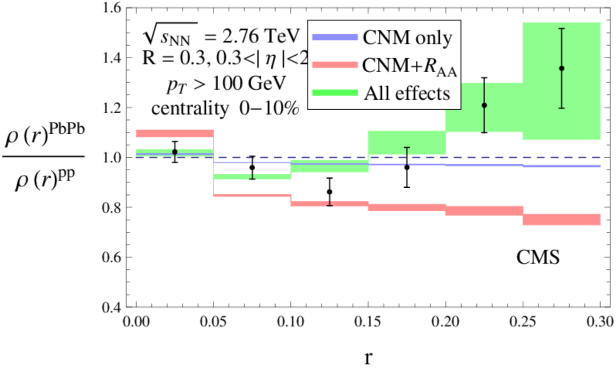
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ



- 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

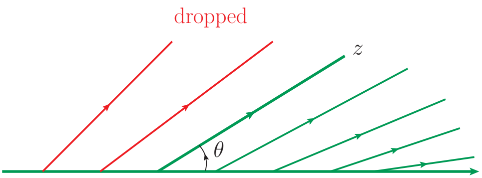
How do we isolate physics and distinguish jet quenching models?

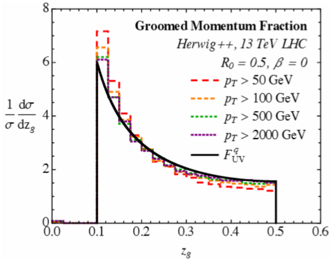
- Jets are multi-scaled objects with rich information about the physics across the entire energy spectrum
- Jet observables have different sensitivities to physics at different energy scales
- Through a series of jet measurements we can map out the whole jet formation history
- Whether the model relies 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?

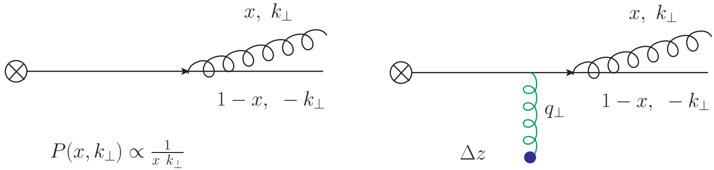
Groomed momentum fraction z_g





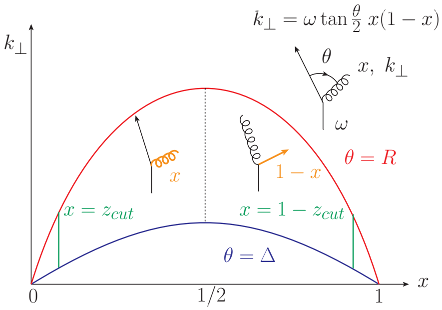
- Soft Drop: a tree-based procedure to drop soft radiation (Larkoski et al1402.2657)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - 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 (Chien et al 1608.07283)



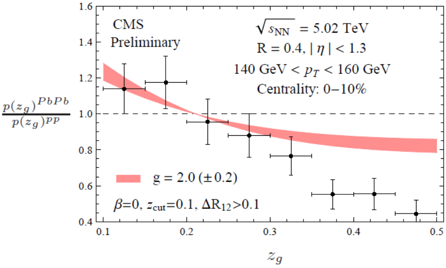
- The partonic phase space is constrained by R (jet algorithm), Δ (jet selection) and z_{cut} (jet grooming)
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

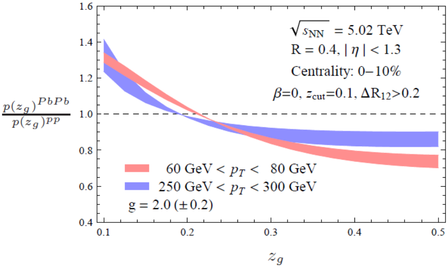
$$\mathcal{P}_{i\to jl}(x, k_\perp) = \mathcal{P}^{vac}_{i\to jl}(x, k_\perp) + \mathcal{P}^{med}_{i\to jl}(x, k_\perp)$$

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

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

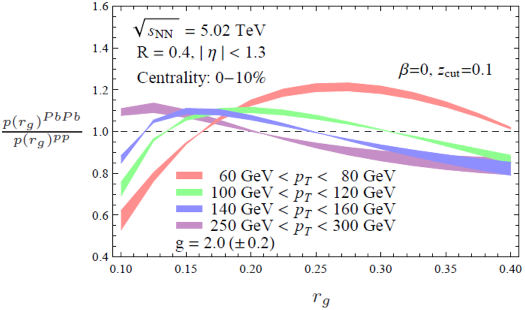
Theory calculation of z_g





- The medium enhances the soft branches, and the effect becomes smaller for higher p_T jets
- Qualitatively expected and quantitatively surprising (CMS is updating the data (CMS-HIN-16-006) soon. 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 coming out. Ungroomed charged jets done by ALICE)

Power counting of modes for groomed jet mass (work in progress)

- Factorization in SCET (Larkoski et al 1603.09338 "in jets"):
- **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 $J_M^{\not{g}}(m^2,\mu)$ captures all the soft-collinear radiation inside jets ($i=q,g$)

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

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

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

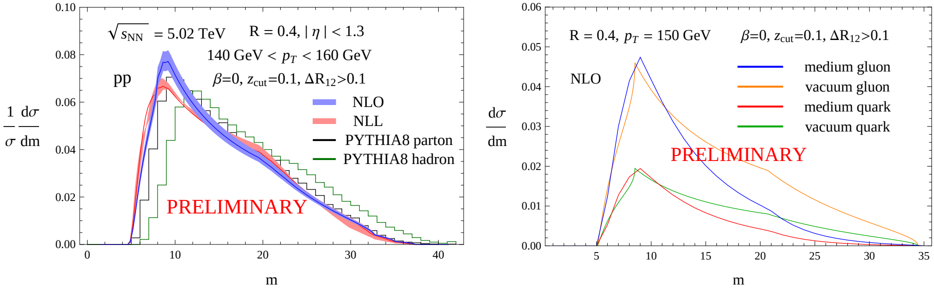
$$J_M^{i\not{g}}(m^2,\mu)=\sum_{j,k}\int_{PS}dxdk_\perp\mathcal{P}_{i\to jk}(x,k_\perp)\delta(m^2-M^2(x,k_\perp))\Theta_{\text{alg.}}\Theta_{\not{g}}$$

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

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

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

Preliminary results



- The $\Delta R_{12} > 0.1$ cut cuts out the Sudakov peak
- The lower and upper limits of jet mass are essentially dictated by kinematics. r_g and jet mass are highly correlated
- The medium perturbative contributions enhance small mass region
- Soft contributions and hadronization 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 enhances the small mass region (preliminary)
- Design specific grooming procedure along the physics goal of jet quenching studies
- Stay tuned for the jet mass calculation with different soft drop parameters ($\beta = 1.5$, $z_{cut} = 0.5$)!