Groomed Jet Substructures in Heavy Ion Collisions

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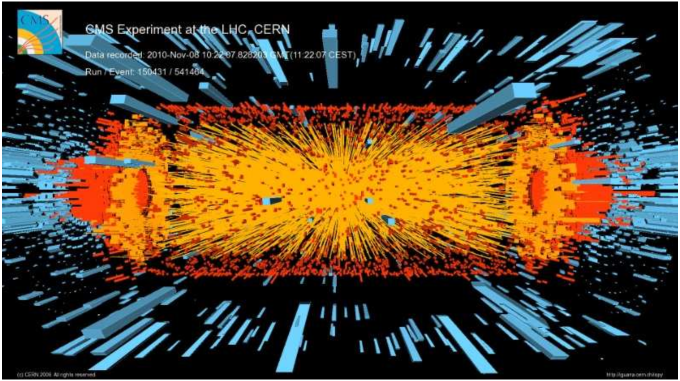
with Ivan Vitev (1608.07283, to be published in PRL) and Iain Stewart (170s.oooon)

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 discussion

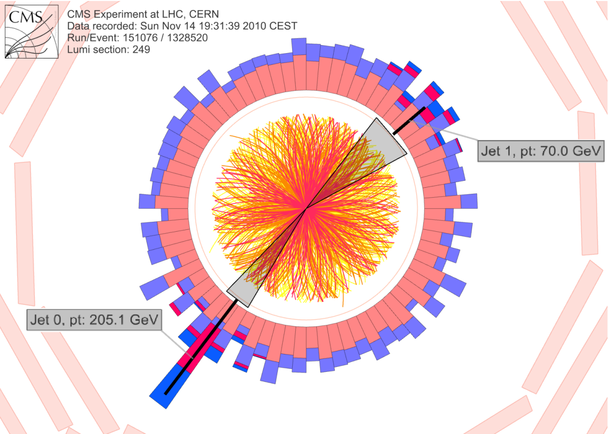
Jet physics gets the richest in heavy ion collisions

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

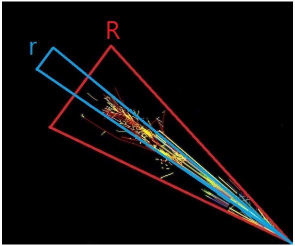


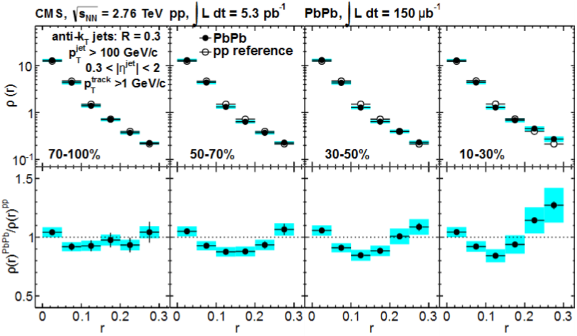
Jets are "quenched" and modified in heavy ion collisions

- 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



Jet spectroscopy of the QGP





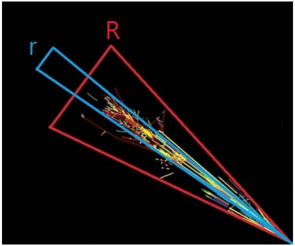
$$\Psi_J(r) = \frac{\sum_{r_i<r} E_{Ti}}{\sum_{r_i<R} E_{Ti}}$$

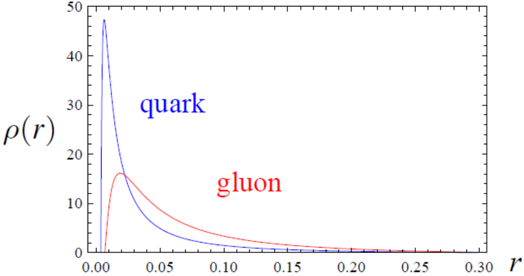
$$\langle\Psi\rangle = \frac{1}{N_J}\sum_J^{N_J} \Psi_J(r,R)$$

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

- 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

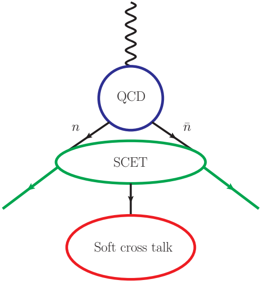


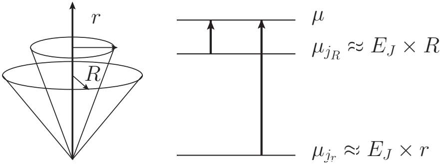


- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n), \ n = 1, ..., \infty$ need to be resummed
- Sensitive to the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



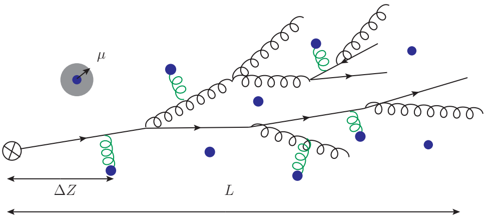


Renormalization group evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

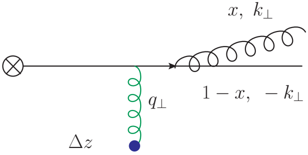
(Chien et al 1405.4293)

Multiple scattering in a medium and QCD bremsstrahlung

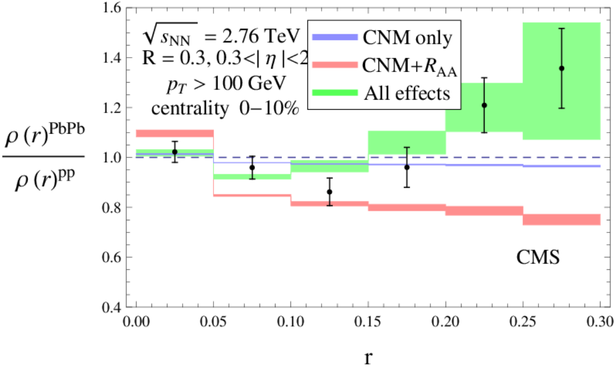
- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between multiple characteristic scales:
  - Debye screening scale μ
  - Parton mean free path λ
  - Radiation formation time τ



- 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

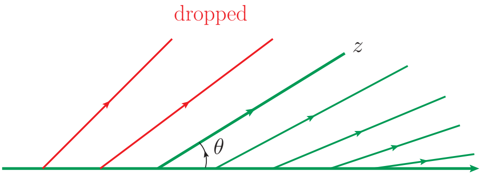
How do we isolate physics and distinguish jet quenching models?

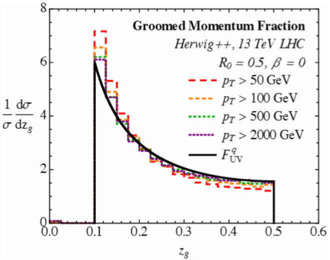
- Jets are multi-scaled objects with rich information about the physics across the entire energy spectrum
- Jet observables have different sensitivities to physics at different energy scales
- Through a series of jet measurements we can map out the whole jet formation history
- Whether the model relies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

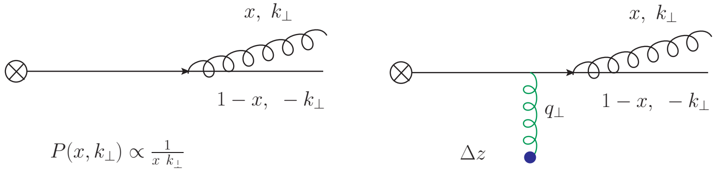
Groomed momentum fraction z_g





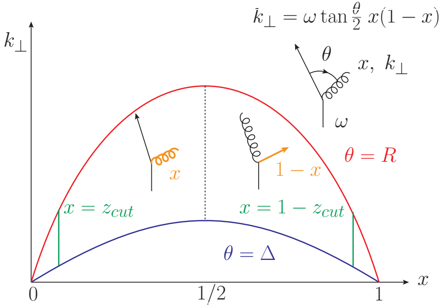
- Soft Drop: a tree-based procedure to drop soft radiation (Larkoski et al 1402.2657)
  - Recluster a jet using C/A algorithm: angular ordered
  - For each branching, consider the p_T of each branch and the angle θ
  - Drop the soft branch if $z < z_{cut}\,\theta^\beta$, where $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}}$
  - 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 (Chien and Vitev 1608.07283, to be published in PRL)



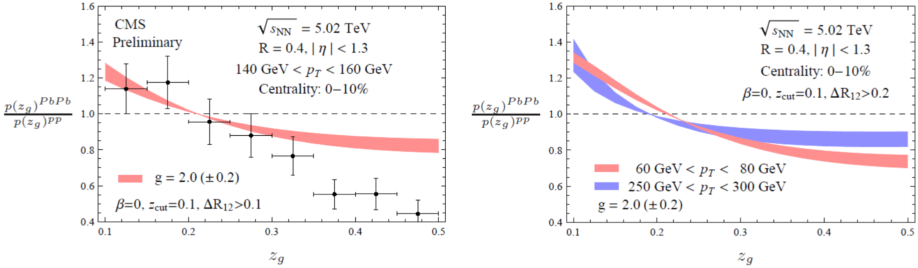
- The partonic phase space is constrained by R (jet algorithm), Δ (jet selection) and z_{cut} (jet grooming)
- At leading order, the $1 \to 2$ branching probability directly affects the subjet distribution

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

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

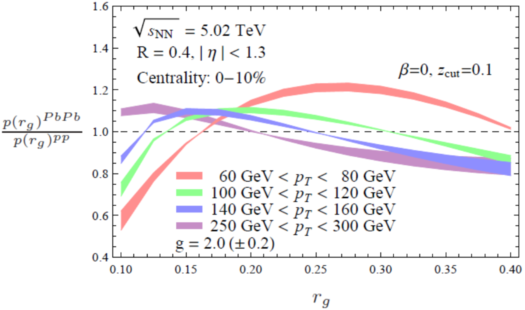
$$p_i(z_g) = \frac{\int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(z_g,k_\perp)}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta}^{k_R} dk_\perp \overline{\mathcal{P}}_i(x,k_\perp)}\,, \qquad p_i(r_g) = \frac{\int_{z_{cut}}^{1/2} dx\, p_T x(1-x) \overline{\mathcal{P}}_i(x,k_\perp(r_g,x))}{\int_{z_{cut}}^{1/2}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

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
- Quantitatively agreeing with the CMS data! (see Yi's talk for the updated data)
- 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

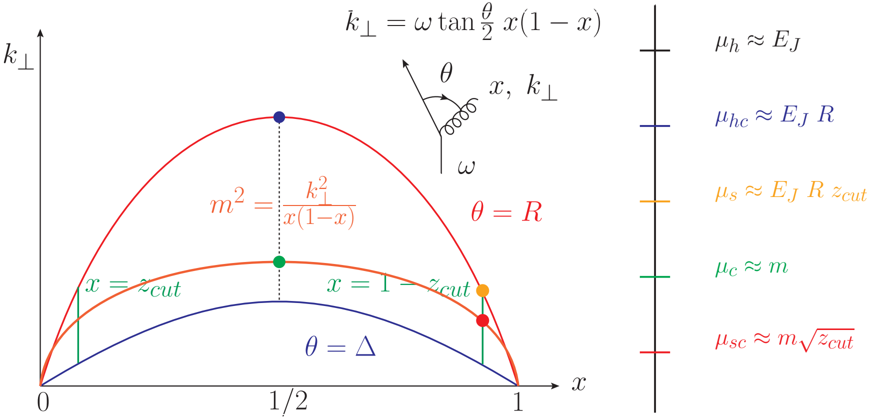
Theory prediction for r_g



- 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 the groomed jet mass (See Yi's talk. Ungroomed charged jets done by ALICE)

Groomed jet mass (work in progress)

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



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

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

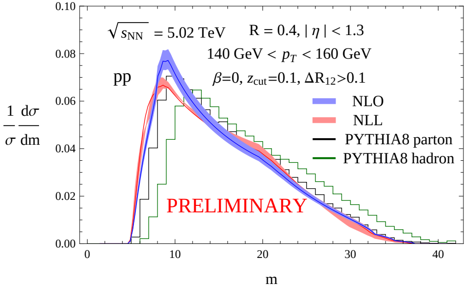
$$J_M^{i\not{g}}(m^2,\mu)=\sum_{j,k}\int_{PS} dx dk_\perp \mathcal{P}_{i\to jk}(x,k_\perp)\delta(m^2-M^2(x,k_\perp))\Theta_{\text{alg.}}\Theta_{\not{g}}$$

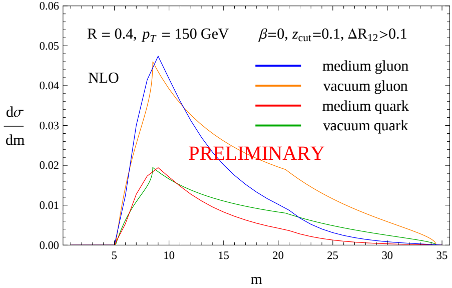
$M^2(x,k_\perp)=\frac{k_\perp^2}{x(1-x)}$, $\Theta_{\mathrm{k_T}}=\Theta(E_J Rx(1-x)-k_\perp)$, $\Theta_{\not{g}}=\Theta(E_J Rx(1-x)\left(\frac{x}{z_{cut}}\right)^{1/\beta}-k_\perp)$.

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

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

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)
- Design specific grooming procedure along the physics goal of jet quenching studies

Discussion

- How do we understand the broadening effect seen in the jet shape? My answer: rely on soft, wide angle radiation
- How do we understand the z_g modification? My answer: rely on enhancing the small z_g and suppressing the large z_g regions
- The expectation of r_g: still not disentangled from the small z_g region
- How special is the groomed jet mass distribution? The large mass region forces us to study large z_g and large r_g region: the first time going beyond the "energy loss paradigm"