

Towards the Understanding of Jet Substructures and Cross Sections in Heavy ion Collisions using Soft-Collinear Effective Theory

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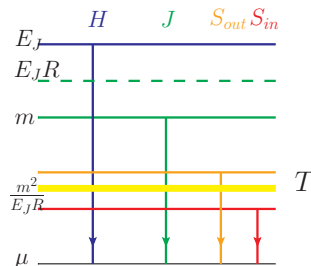
Outline

- Hard Probes with jets
 - Precision jet substructure calculations
 - The need of resummation
- Soft-Collinear Effective Theory (SCET)
 - Factorization theorem
 - Renormalization group evolution
 - Medium modification by Glauber interactions
- Results and conclusions

Resolving jets and the QGP with jet substructure

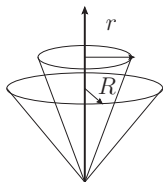
Jet quenching is a multi-scale problem

- The strong suppression of hadron and jet cross sections has been observed more than a decade ago
- Many models exploit the idea of parton energy loss and can explain the data
- However, it has been clear that more differential and correlated measurements are needed to distinguish various jet formation mechanisms
- Jet substructure can resolve jets at different energy scales
- It can also separate final-state, jet-medium interactions from initial state effects
- The interference between jets and the medium is an even more complicated multi-scale problem



Effective field theory techniques are extremely useful

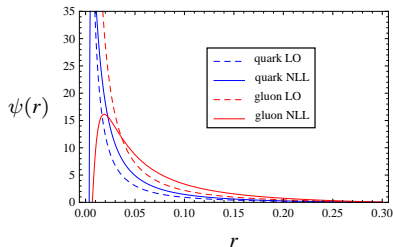
Jet shape (Ellis, Kunszt, Soper)



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

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

$$\psi(r, R) = \frac{d\langle \Psi \rangle}{dr}$$



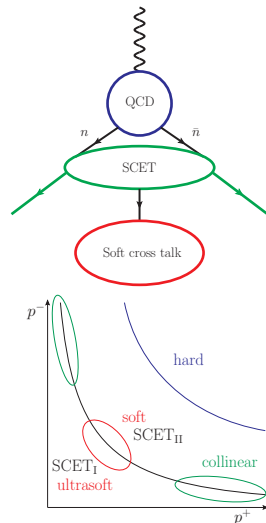
- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R$ ($m \leq 2n$) need to be resummed

The necessity of resummation for jet substructure calculations

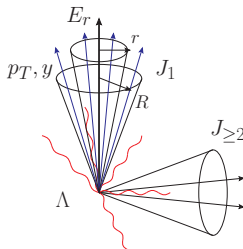
Soft-Collinear Effective Theory (SCET)

- Effective field theory techniques are useful whenever there is clear scale separation
- SCET separates 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
- At leading power, soft-collinear decoupling leads to the factorization of cross sections

SCET factorizes a complicated, multi-scale problem into multiple simpler, single-scale problems



Jet shape factorization theorem (Chien et al)



- The factorization theorem for the differential cross section of the production of N jets with p_{Ti} , y_i , the energy E_r inside the cone of size r in one jet, and an energy cutoff Λ outside all the jets is the following,

$$\frac{d\sigma}{dp_{Ti}dy_i dE_r} = H(p_{Ti}, y_i, \mu) J_1^{\omega_1}(E_r, \mu) J_2^{\omega_2}(\mu) \dots S_{1,2,\dots}(\Lambda, \mu)$$

- For the differential jet rate

$$\frac{d\sigma}{dp_{Ti}dy_i} = H(p_{Ti}, y_i, \mu) J_1^{\omega_1}(\mu) J_2^{\omega_2}(\mu) \dots S_{1,2,\dots}(\Lambda, \mu)$$

- $H(p_{Ti}, y_i, \mu)$ describes the hard scattering process at high energy
- $J_1^{\omega_1}(E_r, \mu)$ describes the probability of having the amount of energy E_r inside the cone of size r
 - X_c is constrained within jets by the corresponding jet algorithm
- $S_{1,2,\dots}(\Lambda, \mu)$ describes how soft radiation is constrained in measurements

Factorization theorem simplifies dramatically and has a product form

Jet shape factorization theorem (Chien et al)

The averaged energy inside the cone of size r in jet 1 is the following,

$$\langle E_r \rangle_\omega = \frac{1}{\frac{d\sigma}{dp_{Ti}dy_i}} \int dE_r E_r \frac{d\sigma}{dp_{Ti}dy_i dE_r} = \frac{H(p_{Ti}, y_i, \mu) J_{E,r_1}^{\omega_1}(\mu) J_2^{\omega_2}(\mu) \dots S_{1,2,\dots}(\Lambda, \mu)}{H(p_{Ti}, y_i, \mu) J_1^{\omega_1}(\mu) J_2^{\omega_2}(\mu) \dots S_{1,2,\dots}(\Lambda, \mu)} = \frac{J_{E,r_1}^{\omega_1}(\mu)}{J_1^{\omega_1}(\mu)}$$

- $J_{E,r}^\omega(\mu) = \int dE_r E_r J^\omega(E_r, \mu)$ is referred to as the **jet energy function**
- Huge cancelation between the hard, unmeasured jet and soft functions
 - The jet shape is insensitive to the details of the underlying hard scattering process as well as the other part of the event
- The integral jet shape, averaged over all jets, is the following

$$\langle \Psi \rangle = \frac{1}{\sigma_{\text{total}}} \sum_{i=q,g} \int_{PS} dp_T dy \frac{d\sigma}{dp_T dy} \Psi_\omega^i, \text{ where } \Psi_\omega = \frac{J_{E,r}(\mu)/J(\mu)}{J_{E,R}(\mu)/J(\mu)} = \frac{J_{E,r}(\mu)}{J_{E,R}(\mu)}$$

The jet shape is within the class of collinear observables and is relatively insensitive to the soft radiation

Scale hierarchy and renormalization group evolution

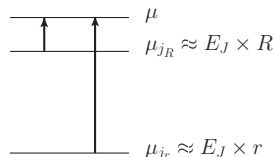
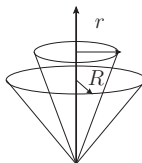
$$\frac{dJ_{E,r}^q(r, R, \mu)}{d \ln \mu} = \left[-C_F \Gamma_{\text{cusp}} \ln \frac{\omega^2 \tan^2 \frac{R}{2}}{\mu^2} - 2\gamma_{J^q} \right] J_{E,r}^q(r, R, \mu)$$

$$\frac{dJ_{E,r}^g(r, R, \mu)}{d \ln \mu} = \left[-C_A \Gamma_{\text{cusp}} \ln \frac{\omega^2 \tan^2 \frac{R}{2}}{\mu^2} - 2\gamma_{J^g} \right] J_{E,r}^g(r, R, \mu)$$

- $\langle E_r \rangle_\omega$ and Ψ_ω are renormalization group invariant

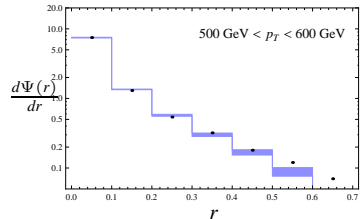
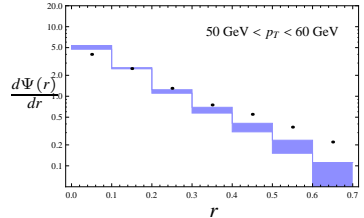
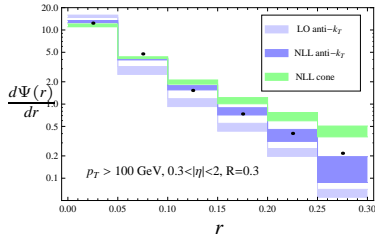
$$\Psi_\omega = \frac{J_{E,r}(\mu)}{J_{E,R}(\mu)} = \frac{J_{E,r}(\mu_{j_r})}{J_{E,R}(\mu_{j_R})} U_J(\mu_{j_r}, \mu_{j_R})$$

- Identify the natural scale μ_{j_r} to eliminate large logarithms in $J_{E,r}(\mu_{j_r})$
- The RG evolution kernel $U_J(\mu_{j_r}, \mu_{j_R})$ resums the large logarithms



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

Baseline jet shape calculations

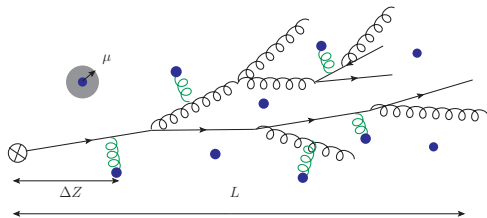


- Compare with pp data at 2.76 and 7 TeV
- Bands are theory uncertainties estimated by varying μ_{j_r} and μ_{j_R}
- The shape difference for jets reconstructed using different algorithms is significant
- In the region $r \approx R$, higher fixed order calculations and power corrections are more prominent

- For low p_T jets, power corrections have significant contributions

Multiple scattering in a medium

- Coherent multiple scattering and induced bremsstrahlung are the qualitatively new ingredients in the medium parton shower
- Interplay between several characteristic scales:
 - Debye screening scale μ
 - Parton mean free path λ
 - Radiation formation time τ
- From thermal field theory and lattice QCD calculations, an ensemble of quasi particles with debye screened potential and thermal masses is a reasonable parameterization of the medium properties

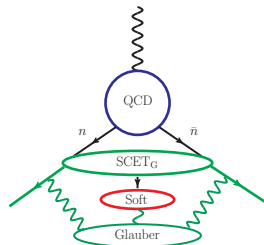


$$\frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q_{\perp}} = \frac{\mu^2}{\pi(q_{\perp}^2 + \mu^2)^2}$$

Parton splitting and induced bremsstrahlung interfere in the jet formation

SCET with Glauber gluons (SCET_G)

- Glauber gluon is the relevant mode for medium interactions
- SCET_G was extended from SCET (Idilbi et al, Vitev et al)
- Glauber gluons are generated from the colored charges in the QGP providing transverse momentum transfer
- Given a medium model, we can use SCET_G to consistently couple the medium to jets



- The jet shape can be directly calculated using the splitting functions

$$J_{E,r}^i(\mu) = \sum_{j,k} \int_{PS} dx dk_{\perp} \left[\frac{dN_{i \rightarrow jk}^{vac}}{dx d^2 k_{\perp}} + \frac{dN_{i \rightarrow jk}^{med}}{dx d^2 k_{\perp}} \right] E_r(x, k_{\perp})$$

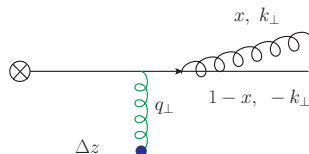
- The medium induced splitting functions are calculated numerically using SCET_G with the Bjorken-expanded hydrodynamic QGP model

SCET_G provides a consistent framework to incorporate the medium modification and the resummation for jet substructure calculations

Medium-induced splitting

- The hierarchy between τ and λ determines the degree of coherence between multiple scatterings

$$\tau = \frac{x \omega}{(q_{\perp} - k_{\perp})^2} \quad \text{v.s.} \quad \lambda$$



- Medium induced splitting functions in SCET_G (Ovanesyan et al)

$$\frac{dN_{q \rightarrow qg}^{med}}{dx d^2 k_{\perp}} = \frac{C_F \alpha_s}{\pi^2} \frac{1}{x} \int_0^L \frac{d\Delta z}{\lambda} \int d^2 q_{\perp} \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_{\perp}} \frac{2k_{\perp} \cdot q_{\perp}}{k_{\perp}^2 (q_{\perp} - k_{\perp})^2} \left[1 - \cos \left(\frac{(q_{\perp} - k_{\perp})^2 \Delta z}{x \omega} \right) \right]$$

- $\frac{dN^{med}}{dx d^2 k_{\perp}} \rightarrow \text{finite as } k_{\perp} \rightarrow 0$: the Landau-Pomeranchuk-Migdal effect

Large angle bremsstrahlung takes away energy, resulting in jet energy loss and the modification of jet shapes

Jet shapes in heavy ion collisions

- Jet shapes get modified through the modification of jet energy functions

$$\Psi(r) = \frac{J_{E,r}^{vac} + J_{E,r}^{med}}{J_{E,R}^{vac} + J_{E,R}^{med}} = \frac{\Psi^{vac}(r) J_{E,R}^{vac} + J_{E,r}^{med}}{J_{E,R}^{vac} + J_{E,R}^{med}}$$

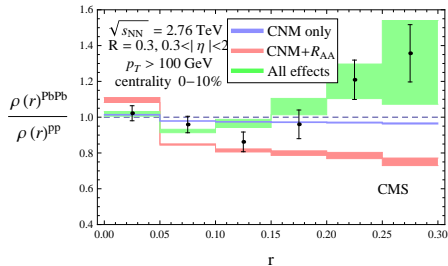
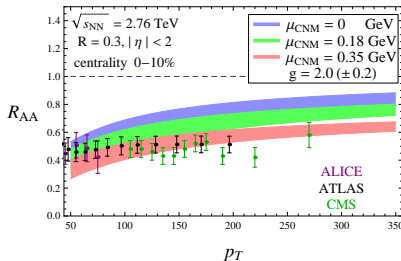
- Large logarithms in $\Psi^{vac}(r) = J_{E,r}^{vac}/J_{E,R}^{vac}$ have been resummed
- There are no large logarithms in $J_{E,r}^{med}$ due to the LPM effect
- The RG evolution of medium-modified jet energy functions is unchanged
- However, with the use of small R 's in heavy ion collisions, there is significant jet energy loss which leads to the suppression of jet production cross sections
- Jet-by-jet shapes are averaged with the jet cross sections

$$\frac{1}{\langle N_{bin} \rangle} \frac{d\sigma_{CNM}^k}{d\eta dp_T} = \sum_{ijX} \int dx_1 dx_2 f_i^A(x_1, \mu_{CNM}) f_j^A(x_2, \mu_{CNM}) \frac{d\sigma_{ij \rightarrow kX}}{dx_1 dx_2 d\eta dp_T}$$

$$\left. \frac{1}{\langle N_{bin} \rangle} \frac{d\sigma_{med}^i}{d\eta dp_T} \right|_{p_T} = \left. \frac{1}{\langle N_{bin} \rangle} \frac{d\sigma_{CNM}^i}{d\eta dp_T} \right|_{\frac{p_T}{1-\epsilon_i}} \frac{1}{1-\epsilon_i}$$

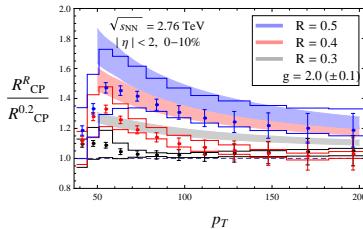
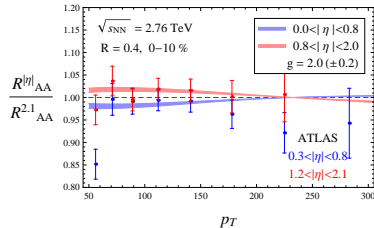
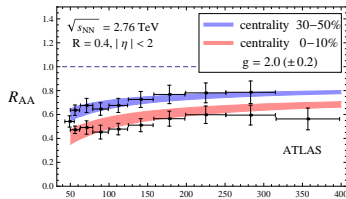
- Cold nuclear matter effects are characterized by μ_{CNM}

Results



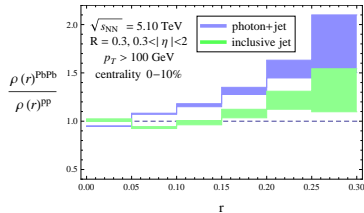
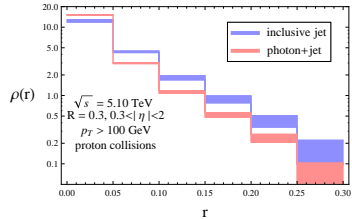
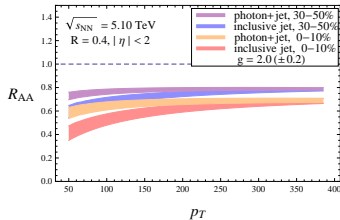
- The plots are the ratios between the jet cross sections and differential jet shapes in lead-lead and proton-proton collisions
- Jet shapes are insensitive to cold nuclear matter effects
- Jet shape modifications are due to the following two effects
 - **Gluon jets are more suppressed which increases the quark jet fraction**
 - **Jet-by-jet the shape is broadened**

Results



- The plots show the dependence of jet cross section suppressions on centrality, jet rapidity and jet radius

Results



- Predictions for jet shapes and cross sections at 5 TeV for inclusive and photon-tagged jets

Conclusions

- Jet substructure in proton and heavy ion collisions can be calculated within the same framework
 - Promising agreement with data and phenomenological applications
 - Stay tuned before Hard Probes 2016 for jet fragmentation function, jet mass distribution and the splitting function
- Physics understanding as of ICHEP 2016:
the modification of jet substructure is a combination of cross section suppression and jet-by-jet broadening
- Heavy ion jet physics as of ICHEP 2016:
Precision jet substructure studies in heavy ion collisions has been initiated and we are entering the golden age