Theory of Hard Probes in PbPb Collisions

Jet Substructures and Cross Sections using Soft-Collinear Effective Theory

Yang-Ting Chien

Los Alamos National Laboratory, Theoretical Division, T-2
LHC Theory Initiative Fellow, MIT Center for Theoretical Physics

June 15, 2016
LHCP 2016, Lund, Sweden

JHEP 1412 (2014) 061 and JHEP 1605 (2016) 023

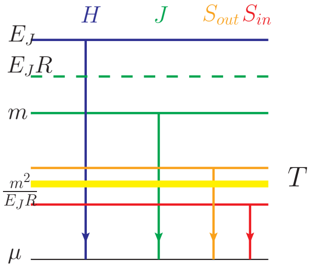
Outline

- 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

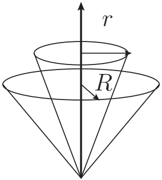
Jet quenching is a multi-scale problem

- 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 cross sections are not sufficient 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

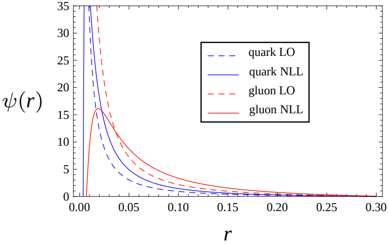
Jet shape (Ellis, Kunszt, Soper)



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

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

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



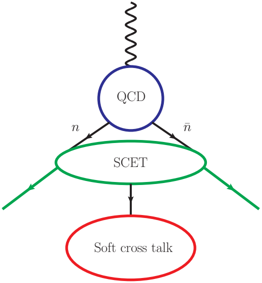
- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R \ (m \leq 2n)$ need to be resummed

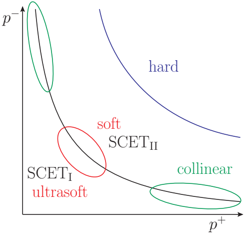
The necessity of resummation for jet substructure calculations

Soft-Collinear Effective Theory (SCET)

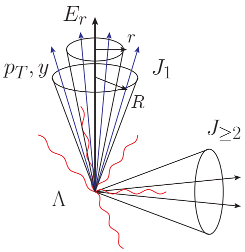
- Effective field theory techniques are useful whenever there is clear scale separation
- SCET separates physical degrees of freedom in QCD by a systematic expansion in power counting
    - Match SCET with QCD at the hard scale by integrating out the hard modes
    - Integrating out the off-shell modes gives collinear Wilson lines which describe the collinear radiation
    - The soft sector is described by soft Wilson lines along the jet directions
- Soft-collinear decoupling holds at leading power in the Lagrangian, which makes the factorization theorems of cross sections manifest

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,

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

- For the differential jet rate

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

- $H(p_{Ti}, y_i, \mu)$ describes the hard scattering process at high energy
- $J_1^{\omega}(E_r, \mu)$ 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
- $S_{1,2,\ldots}(\Lambda, \mu)$ 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,

$$\langle E_r\rangle_\omega = \frac{1}{\frac{d\sigma}{dp_{T_i}dy_i}}\int dE_r E_r \frac{d\sigma}{dp_{T_i}dy_i dE_r} = \frac{H(p_{T_i},y_i,\mu)J^{\omega_1}_{E,r_1}(\mu)J^{\omega_2}_2(\mu)\dots S_{1,2,\dots}(\Lambda,\mu)}{H(p_{T_i},y_i,\mu)J^{\omega_1}_1(\mu)J^{\omega_2}_2(\mu)\dots S_{1,2,\dots}(\Lambda,\mu)} = \frac{J^{\omega_1}_{E,r_1}(\mu)}{J^{\omega_1}_1(\mu)}$$

- $J^{\omega}_{E,r}(\mu) = \int dE_r E_r J^{\omega}(E_r,\mu)$ 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

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

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

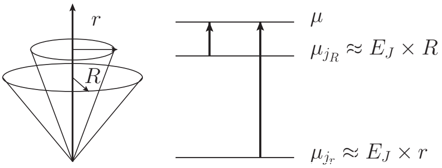
Scale hierarchy and renormalization group evolution

$$\frac{dJ^q_{E,r}(r,R,\mu)}{d\ln\mu} = \left[-C_F\Gamma_{\rm cusp}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^q}\right]J^q_{E,r}(r,R,\mu)$$
$$\frac{dJ^g_{E,r}(r,R,\mu)}{d\ln\mu} = \left[-C_A\Gamma_{\rm cusp}\ln\frac{\omega^2\tan^2\frac{R}{2}}{\mu^2} - 2\gamma_{J^g}\right]J^g_{E,r}(r,R,\mu)$$

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

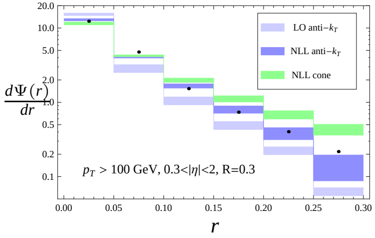
$$\Psi_\omega = \frac{J_{E,r}(\mu)}{J_{E,R}(\mu)} = \frac{J_{E,r}(\mu_{j_r})}{J_{E,R}(\mu_{j_R})}U_J(\mu_{j_r},\mu_{j_R})$$

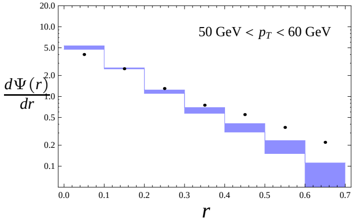
- Identify the natural scale μ_{j_r} to eliminate large logarithms in $J_{E,r}(\mu_{j_r})$
- The RG evolution kernel $U_J(\mu_{j_r},\mu_{j_R})$ resums the large logarithms

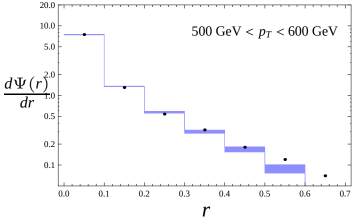


RG evolution between μ_{j_r} **and** μ_{j_R} **resums** $\log\mu_{j_r}/\mu_{j_R} = \log r/R$

Baseline jet shape calculations





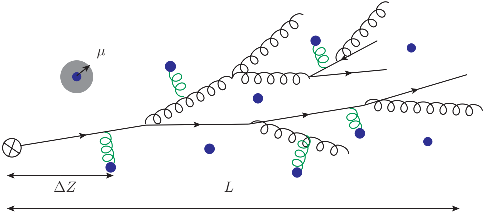


- Compare CMS *pp* data at 2.76 and 7 TeV
- Bands are theory uncertainties estimated by varying μ_{j_r} and μ_{jR}
- The shape difference for jets reconstructed using different algorithms is significant
- In the region $r \approx R$, higher fixed order calculations and power corrections are more prominent

- 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



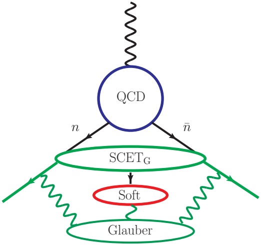
- From thermal field theory and lattice QCD calculations, an ensemble of quasi particles with debye screened potential and thermal masses is a reasonable parameterization of the medium properties

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

Parton splitting and induced bremsstrahlung interfere in the jet formation

SCET with Glauber gluons ($\mathrm{SCET_G}$)

- Glauber gluon is the relevant mode for medium interactions
- $\mathrm{SCET_G}$ 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 $\mathrm{SCET_G}$ to consistently couple the medium to jets



- Because of the collinear nature, the jet shape can be calculated using only the splitting functions

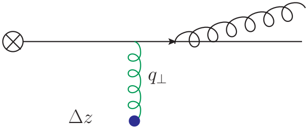
$$J^{i}_{E,r}(\mu) = \sum_{j,k} \int_{PS} dx dk_\perp \left[\frac{dN^{vac}_{i\to jk}}{dx d^2 k_\perp} + \frac{dN^{med}_{i\to jk}}{dx d^2 k_\perp} \right] E_r(x, k_\perp)$$

The medium induced splitting functions are calculated numerically using $\mathrm{SCET_G}$ with the Bjorken-expanded hydrodynamic QGP model

Landau-Pomeranchuk-Migdal effect

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

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



  - $\tau \gg \lambda$: destructive interference
  - $\tau \ll \lambda$: Bethe-Heitler incoherence limit

- Medium induced splitting functions in $\mathrm{SCET_G}$ (Ovanesyan et al)

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

- $\frac{dN^{med}}{dxd^2k_\perp} \to$ finte as $k_\perp \to 0$: the LPM effect
  - $\frac{dN^{vac}}{dxd^2k_\perp} \to \frac{1}{k_\perp}$ as $k_\perp \to 0$

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

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

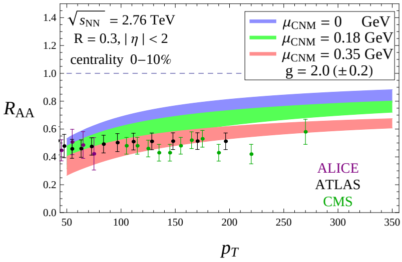
  - Large logarithms in $\Psi^{vac}(r) = J^{vac}_{E,r}/J^{vac}_{E,R}$ have been resummed
  - There are no large logarithms in $J^{med}_{E,r}$ due to the LPM effect
  - The RG evolution of medium-modified jet energy functions is unchanged
- However, with the use of small R's in heavy ion collisions, there 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

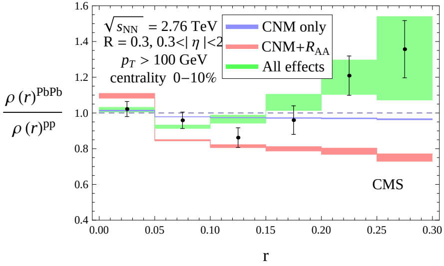
$$\frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^k_{\rm CNM}}{d\eta dp_T} = \sum_{ijX} \int dx_1 dx_2 f^A_i(x_1, \mu_{\rm CNM}) f^A_j(x_2, \mu_{\rm CNM}) \frac{d\sigma_{ij\to kX}}{dx_1 dx_2 d\eta dp_T}$$

$$\frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^i_{med}}{d\eta dp_T}\bigg|_{p_T} = \frac{1}{\langle N_{\rm bin}\rangle} \frac{d\sigma^i_{\rm CNM}}{d\eta dp_T}\bigg|_{\frac{p_T}{1-\epsilon_i}} \frac{1}{1-\epsilon_i}$$

  - Cold nuclear matter effects are characterized by $\mu_{\rm CNM}$

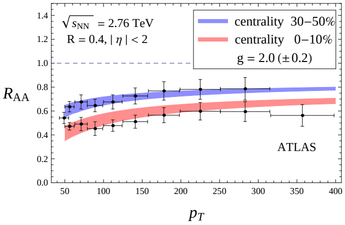
Results

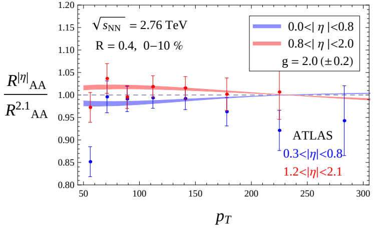


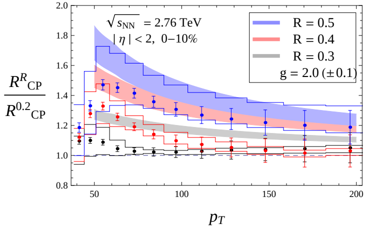


- The plots are the ratios between the jet cross sections and differential jet shapes in lead-lead and proton-proton collisions
- Jet shapes are insensitive to cold nuclear matter effects
- Jet shape modifications are due to the following two effects
  - **Gluon jets are more suppressed which increases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

Results

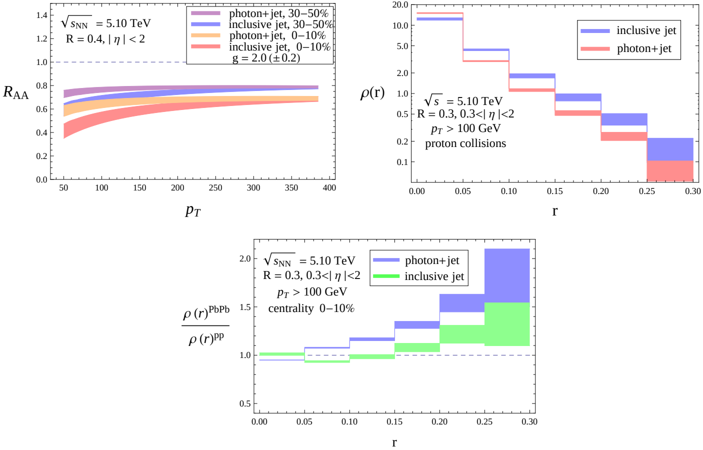






- The plots shows the dependence of jet cross section suppressions on centrality, jet rapidity and jet radius

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 pA and AA jet fragmentation function and jet mass distribution
- Take-home message: **the modification of jet substructure is a combination of cross section suppression and jet-by-jet broadening**