Jet Substructures and Cross Sections in Proton and Heavy Ion Collisions

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References: JHEP 1412 (2014) 061, arXiv:1509.07257, arXiv:1512.06851 and work in progress

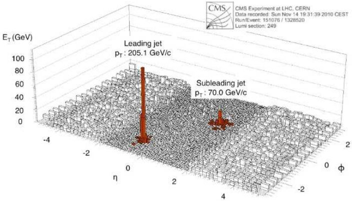
Outline

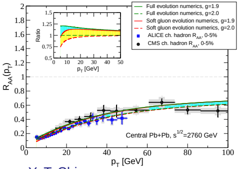
- Heavy ion collisions compared to proton collisions
  - Quark-gluon plasma (QGP)
  - Hard Probes with jets
  - Precision jet modification studies
- Resummation using Soft-Collinear Effective Theory (SCET)
  - Factorization theorem
  - Renormalization group evolution
- Medium Modification using SCET with Glauber gluons ($\mathrm{SCET_G}$)
  - Medium induced splitting functions
- Results

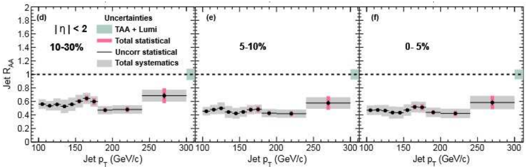
Jet quenching in heavy ion collisions

- Hard probes of the QGP: the study of how various hard processes are affected by the presence of the medium. Traditionally,
  - J/ψ and charged hadron suppression
    – Debye screening and energy loss
    – $R_{AA} = \frac{\sigma_{AA}}{\langle N_{coll} \rangle \; \sigma_{pp}} < 1$
  - jet quenching and dijet asymmetry

- Initial and final state energy loss can both contribute to the suppression of cross sections
- Kinematics of charged particles and jets contain limited information about the QGP
- How to disentangle the hot QGP from the cold nuclear matter effects?

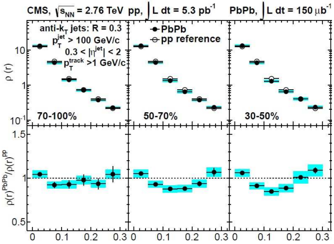


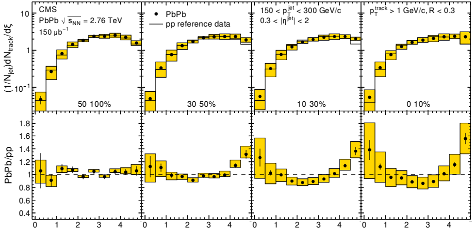




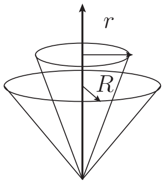
Jet modifications

- Jet substructure contains more information about the QGP
- Isolate final state effects
  - jet shape: how energies are distributed in r
  - jet fragmentation function: how particles are distributed in z (or $\ln 1/z$)
  - Jet X modification factor: X_{AA}/X_{pp}





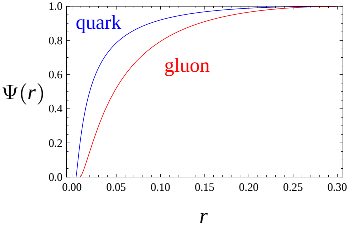
Jet shape, a classic jet substructure observable (Ellis, Kunszt, Soper)

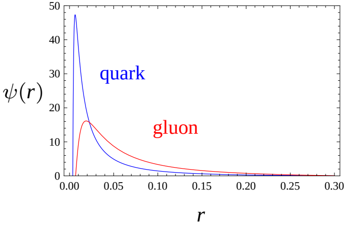


$$\Psi_J(r,R) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

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

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

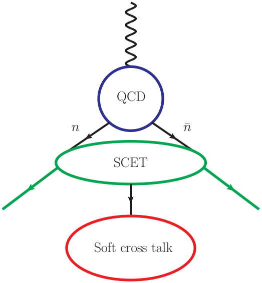




- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breaks down at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R$ $(m \le 2n)$ need to be resummed

Soft-Collinear Effective Theory (SCET)

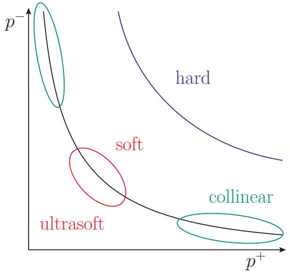
- Effective field theory techniques are most useful when there is clear scale separation
- SCET separates physical degrees of freedom in QCD by a systematic expansion in power counting
  - Match SCET with QCD at the hard scale by integrating out the hard modes
  - Integrating out the off-shell modes 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 leads to the factorization theorems of cross sections

Power counting in SCET

- The scaling of modes:
  $p_h : Q(1,1,1)$, $p_c : Q(1,\lambda^2,\lambda)$ and $p_s : Q(\lambda,\lambda,\lambda)$
- Q is at the hard scale which is the energy of the jet
- λ is the power counting parameter ($\lambda \approx m_J/Q$)
- QCD $= \mathcal{O}(\lambda^0) + \mathcal{O}(\lambda^1) + \cdots$ in SCET
- $Q\lambda$ is the jet scale which is significantly lower than Q



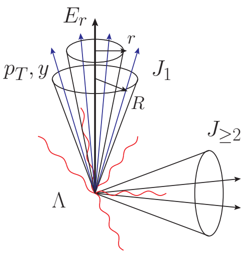
- Jet shapes have dominant contributions from the collinear sector

$$\Psi(r) = \frac{E_c^{<r} + E_s^{<r}}{E_c^{<R} + E_s^{<R}} = \frac{E_c^{<r}}{E_c^{<R}} + \mathcal{O}(\lambda)$$

  – Soft contributions are power suppressed
  – For high p_T and narrow jets, power corrections are small and the leading power contribution is a very good approximation of the full QCD result

Factorization theorem for jet shapes in proton collisions (Chien et al)

- Without loss of generality, we demonstrate the calculation in e^+e^- collisions since the initial state radiation in proton collisions contributes as power corrections



- The factorization theorem for the differential cross section of the production of N jets with $p_{T\,i}$, 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,

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

- For the differential jet rate (without measuring E_r)

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

- $J_1^{\omega}(E_r, \mu) = \sum_{X_c} \langle 0|\bar{\chi}_\omega(0)|X_c\rangle\langle X_c|\chi_\omega(0)|0\rangle \delta(E_r - \hat{E}^{<r}(X_c, \text{algorithm}))$
  - X_c is constrained within jets by the corresponding jet algorithm
  - the energy outside jets is power suppressed
- The factorization theorem has a product form instead of a convolution

Factorization theorem for jet shapes (continued)

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

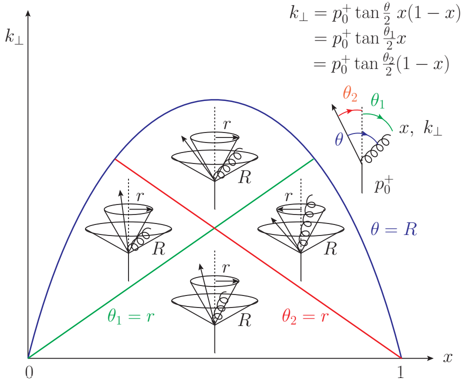
$$\langle E_r \rangle_\omega = \frac{1}{\frac{d\sigma}{dp_{T\,i}dy_i}} \int dE_r E_r \frac{d\sigma}{dp_{T\,i}dy_i dE_r} = \frac{H(p_{T\,i}, y_i, \mu) J^{\omega_1}_{E,r_1}(\mu) J^{\omega_2}_2(\mu) \ldots S_{1,2,\ldots}(\Lambda, \mu)}{H(p_{T\,i}, y_i, \mu) J^{\omega_1}_1(\mu) J^{\omega_2}_2(\mu) \ldots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

- $J^{\omega}_{E,r}(\mu) = \int dE_r E_r J^{\omega}(E_r, \mu)$ is referred to as the jet energy function
- Nice cancelation between the hard, unmeasured jet and soft functions
- The integral jet shape, averaged over all jets, is the following

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

  - ratio of sums equals weighted ratios (not sum of ratios)
  - $\frac{a_1+a_2+\ldots}{b_1+b_2+\ldots} = \frac{1}{\sum_i b_i}\left(b_1 \frac{a_1}{b_1} + b_2 \frac{a_2}{b_2} + \ldots\right)$
- Using the collinear SCET Feynman rules, the jet energy function $J_{E,r}(\mu)$ and its anomalous dimension are calculated at $\mathcal{O}(\alpha_s)$ for both quark jets and gluon jets

Jet energy function



- $J^{\omega}_{E,r}(\mu) = \sum_{X_c} \langle 0|\bar{\chi}_\omega(0)|X_c\rangle\langle X_c|\chi_\omega(0)|0\rangle \hat{E}^{<r}(X_c)$
- At $\mathcal{O}(\alpha_s)$, the phase space integrals in the jet energy function calculations are illustrated
- The axis is fixed and along the jet direction

Renormalization group evolution

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

- The anomalous dimensions of the jet energy functions are

$$\gamma_{J^q} = -3C_F\ , \qquad \gamma_{J^g} = -\beta_0 = -\frac{11}{3}C_A + \frac{4}{3}T_F n_f$$

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

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

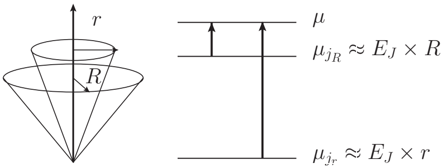
- Identify the natural scale μ_{j_r} to eliminate large logarithms in $J_{E,r}(\mu_{j_r})$
- The RG evolution kernel $U_J(\mu_{j_r},\mu_{j_R})$ resums the large logarithms

Natural scales

- The quark jet energy function at $\mathcal{O}(\alpha_s)$ is the following

$$\frac{2}{\omega} J^q_{E,r} = \frac{\alpha_s C_F}{2\pi} \Big[\frac{1}{2} \ln^2 \frac{\omega^2 \tan^2 \frac{r}{2}}{\mu^2} - \frac{3}{2} \ln \frac{\omega^2 \tan^2 \frac{r}{2}}{\mu^2} - 2 \ln X \ln \frac{\omega^2 \tan^2 \frac{r}{2}}{\mu^2} + 2 - \frac{3\pi^2}{4} + 6X - \frac{3}{2} X^2 - \Big(\frac{1}{2} X^2 - 2X^3 + \frac{3}{4} X^4 + 2X^2 \log X \Big) \tan^2 \frac{R}{2} \Big] \,, \text{ where } X = \frac{\tan \frac{r}{2}}{\tan \frac{R}{2}} \approx \frac{r}{R}$$

- The scale $\mu_{j_r} = \omega \tan \frac{r}{2} \approx E_J \times r$ eliminates large logarithms in $J^q_{E,r}$ at $\mathcal{O}(\alpha_s)$



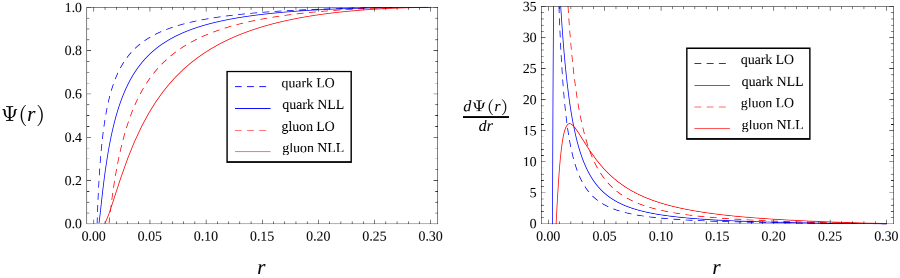
RG evolution between μ_{j_r} and μ_{j_R} resums $\log \mu_{j_r}/\mu_{j_R} = \log r/R$

Resummed jet energy functions

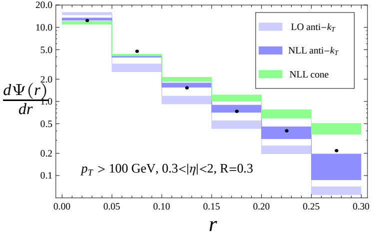
- $\log r/R$ are resummed using the RG kernels in SCET ($i = q, g$)

$$\Psi^i_\omega(r,R) = \frac{J^{iE}_r(r,R,\mu_{j_r})}{J^{iE}_R(R,\mu_{j_R})} \exp[-2\,C_i\,S(\mu_{j_r},\mu_{j_R}) + 2\,A_{J^i}(\mu_{j_r},\mu_{j_R})] \left(\frac{\mu^2_{j_r}}{\omega^2 \tan^2\frac{R}{2}}\right)^{C_i\,A_\Gamma(\mu_{j_R},\mu_{j_r})}$$

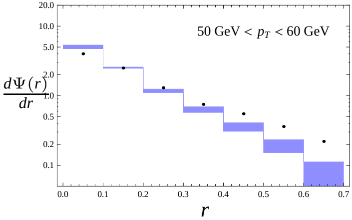
$$S(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha \frac{\Gamma_{\rm cusp}(\alpha)}{\beta(\alpha)} \int_{\alpha_s(\nu)}^{\alpha} \frac{d\alpha'}{\beta(\alpha')}, \quad A_X(\nu,\mu) = -\int_{\alpha_s(\nu)}^{\alpha_s(\mu)} d\alpha \frac{\gamma_X(\alpha)}{\beta(\alpha)}$$

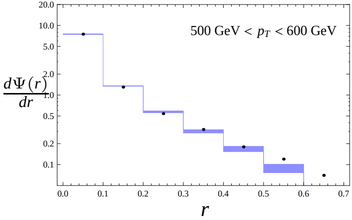


Comparison with the CMS data at 2.76 and 7 TeV



- The difference for jets reconstructed using different jet algorithms is of $\mathcal{O}(r/R)$
- Bands are theory uncertainties estimated by varying μ_{j_r} and μ_{j_R}
- In the region $r \approx R$ we may need higher fixed order calculations and include power corrections





- NLL, anti-k_T, $R = 0.7$
- For low p_T jets, power corrections have significant contributions

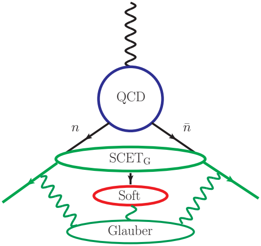
Jet shapes in heavy ion collisions

- More generally, the jet energy function can be calculated from integrating the splitting functions over appropriate phase spaces. At the leading-order splitting,

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

- The medium induced splitting functions are calculated numerically using SCET_G with realistic hydrodynamic QGP models

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



- The Glauber region of phase space is the other relevant mode
- $\mathrm{SCET_G}$ was constructed from SCET bottom up (Idilbi et al, Vitev et al)
  - Glauber gluon momentum scales as $p_G : Q(\lambda^2, \lambda^2, \lambda)$
  - Glauber gluons are off-shell modes providing momentum transfer transverse to the jet direction
  - Glauber gluons are treated as background fields generated from the colored charges in the QGP
- In principle, Glauber gluons interact with both the collinear and the soft modes
- However, jet shapes have dominant contributions from the collinear sector so the Glauber-collinear interaction is the most relevant

Jet shapes in heavy ion collisions (continued)

- 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

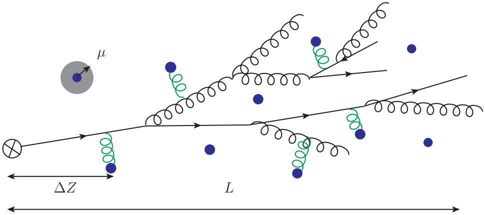
$$\frac{d\sigma^k}{d\eta dp_T} = \langle N_{\rm bin}\rangle \sum_{ijX} \int dx_1 dx_2 f_i^A(x_1,\mu) f_j^A(x_2,\mu) \frac{d\sigma_{ij\to kX}}{dx_1 dx_2 d\eta dp_T}$$

$$\left.\frac{d\sigma^i_{AA}}{d\eta dp_T}\right|_{p_T} = \left.\frac{d\sigma^i_{pp}}{d\eta dp_T}\right|_{\frac{p_T}{1-\epsilon_i}} \frac{1}{1-\epsilon_i}$$

  - With cold nuclear matter effects in nuclear parton distributions

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



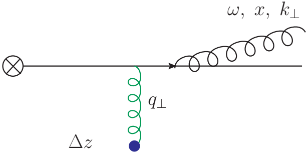
- From thermal field theory and lattice QCD calculations, an ensemble of quasi particles with debye screened potential and thermal masses is a reasonable parameterization of the medium properties

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

Landau-Pomeranchuk-Migdal effect

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

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



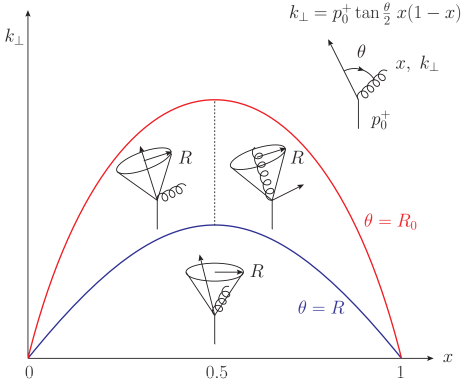
  - $\tau \gg \lambda$: destructive interference
  - $\tau \ll \lambda$: Bethe-Heitler incoherence limit

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

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

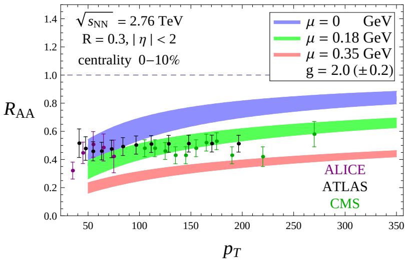
- $\frac{dN^{med}}{dxd^2k_\perp} \to$ finite as $k_\perp \to 0$: the LPM effect
  - $\frac{dN^{vac}}{dxd^2k_\perp} \to \frac{1}{k_\perp}$ as $k_\perp \to 0$
- Large angle bremsstrahlung takes away energy, resulting parton energy loss

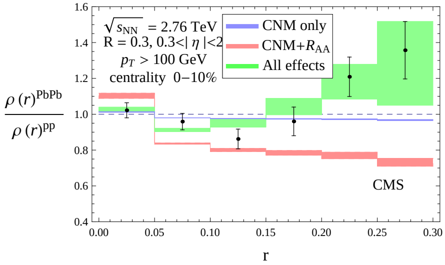
Jet energy loss



- For a parton shower constrained within radius R_0 ($\mathcal{O}(1)$), the averaged energy outside the leading anti-k_T jet of size R is the jet energy loss
  - The jet axis is not necessarily along the original parton direction

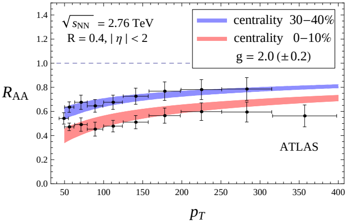
Results

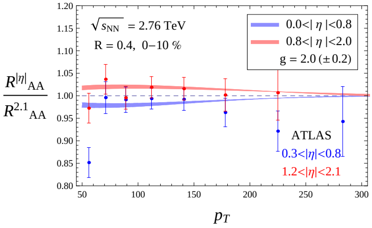


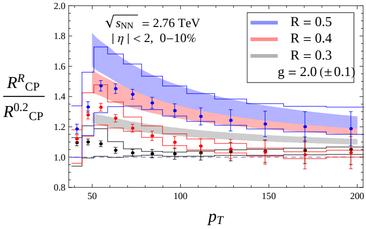


- The plots are the ratios between the jet cross sections and differential jet shapes in lead-lead and proton collisions
- Jet shapes are insensitive to cold nuclear matter effects
- Gluon jets are more suppressed which increases the quark jet fraction
- Jet-by-jet the shape is broadened

Results

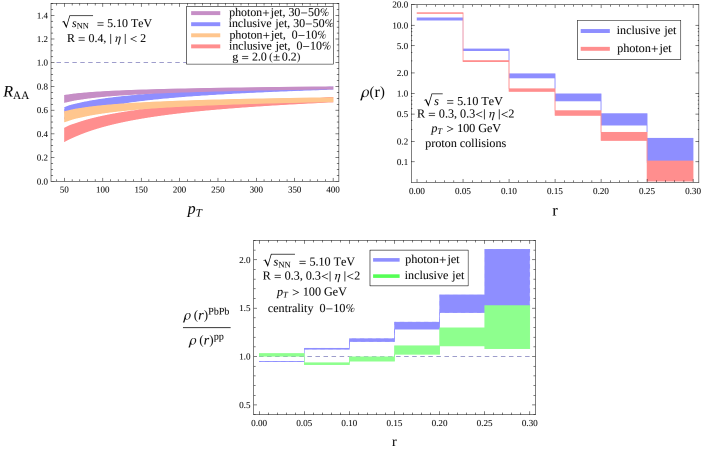






- The plots shows the dependence of jet cross section suppressions on centrality, jet rapidity and jet radius

Results

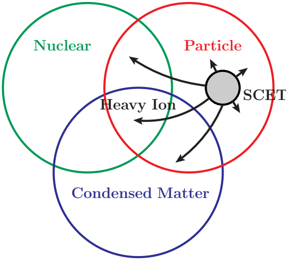


- Predictions for jet shapes and cross sections at 5 TeV for inclusive and photon-tagged jets

Conclusions and outlooks

- Jet shapes in proton and heavy ion collisions are calculated within the same framework
  - Promising agreement with data and phenomenological applications
- The modification of jet shapes is a combination of cross section suppression and jet-by-jet broadening
- Work in progress and future work
  – Calculate jet fragmentation function modifications
  – Construct SCET at finite temperature
  – Modification of other jet substructure observables more sensitive to soft physics

Conclusions and outlooks



- The physics of heavy ion collisions is a multi-disciplinary subject
- The study of jet quenching is a unique opportunity to probe non-perturbative QCD physics with perturbative objects
- SCET can make important contributions in these new territories!