Jet energy loss and modifications in heavy ion collisions

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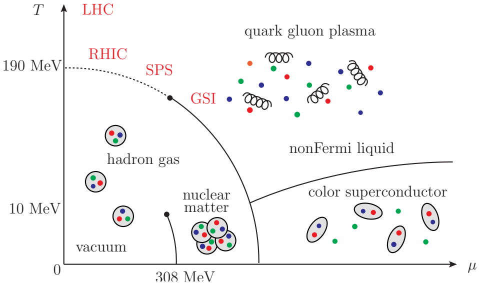
Outline

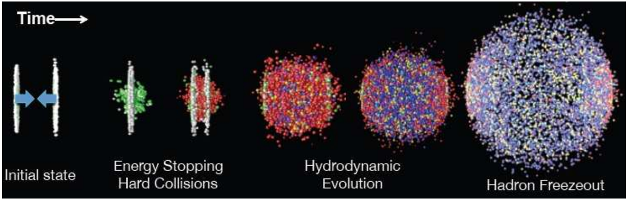
- Heavy ion collisions and parton multiple scattering
- Jet quenching
  - Jet shape resummation and modifications
  - Jet energy loss
- Beyond jet substructure: subjet structure and subjet substructure
- Conclusions and outlooks

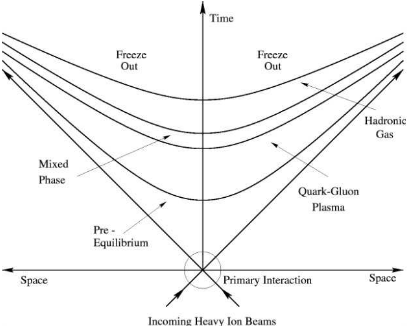
Heavy ion collisions and QCD phase diagram



- The study of heavy ion collisions is part of the program of determining the QCD phase diagram
- RHIC and the LHC probe the QCD deconfinement transition and the properties of the quark-gluon plasma

Spacetime picture of heavy ion collisions



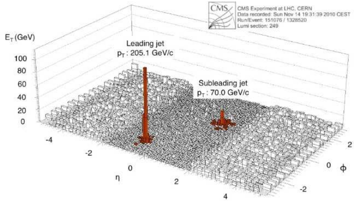


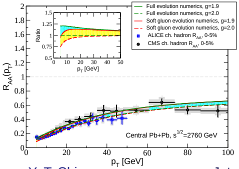
- Nuclei are highly Lorentz contracted
  - Radius of $Pb \sim 7$ fm
- Due to multiple scattering, a hot, deconfined phase is formed
  - Asymmetric for $b \neq 0$
- The medium quickly thermalizes (< 0.2 fm) and allows a hydrodynamic description of its spacetime evolution
- Occasionally, some hard process occurs in the medium

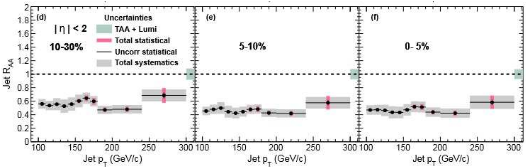
Jet quenching

- 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 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?

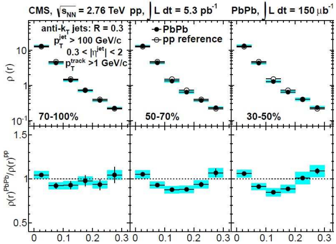


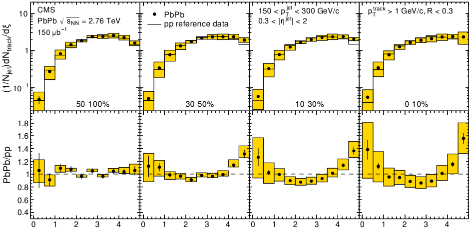




Jet modifications

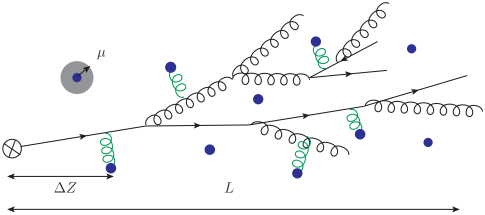
- Jet substructure contains more information about the QGP
- Isolate final state effects
  - jet shape: how energies are distributed in r
  - jet fragmentation function: how particles are distributed in z (or $\ln 1/z$)
  - Dijet momentum balance restoration (more later)
  - Jet X modification factor: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





Multiple scattering

- 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



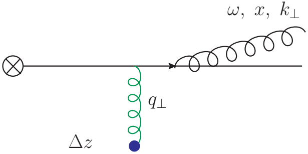
- From thermal field theory and lattice QCD calculations, an ensemble of quasi particles with debye screened potential and thermal masses is a reasonable parameterization of the medium properties

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

Landau-Pomeranchuk-Migdal effect

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

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

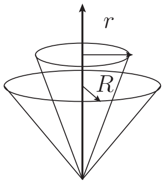


  - $\tau \gg \lambda$: destructive interference
  - $\tau \ll \lambda$: Bethe-Heitler incoherence limit
- Medium induced splitting functions calculated using $\mathrm{SCET_G}$ (Ovanesyan et al)

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

- $\frac{dN^{med}}{dxd^2k_\perp} \to 0$ 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

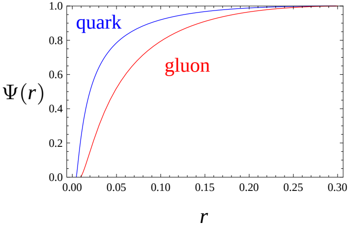
Jet shape, a classic jet substructure observable (Ellis, Kunszt, Soper)

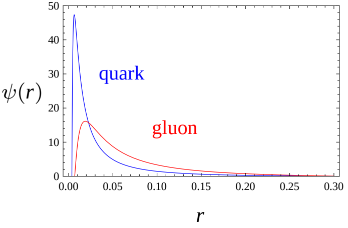


$$\Psi_J(r,R) = \frac{\sum_{r_i<r} E_{T\,i}}{\sum_{r_i<R} E_{T\,i}}$$

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

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



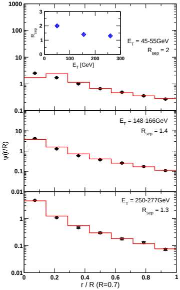


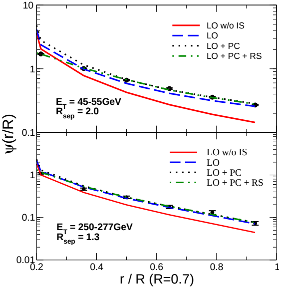
- Jet shapes probe the averaged energy distribution inside a jet
- The infrared structure of QCD induces Sudakov logarithms
- Fixed order calculation breakdowns at small r
- Large logarithms of the form $\alpha_s^n \log^m r/R$ $(m \le 2n)$ need to be resummed

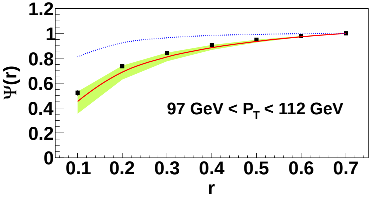
Jet shape resummation using pQCD (Seymour, Vitev et al, and Yuan et al)

In proton collisions,

- pQCD calculation with a parameter R_{sep}: effective angular separation in the leading-order parton splitting
- Resummation using the modified leading logarithmic approximation
- Initial state radiation and power corrections are discussed
- Jet shapes are quite different for jets reconstructed using the iterative cone algorithm and the clustering algorithm



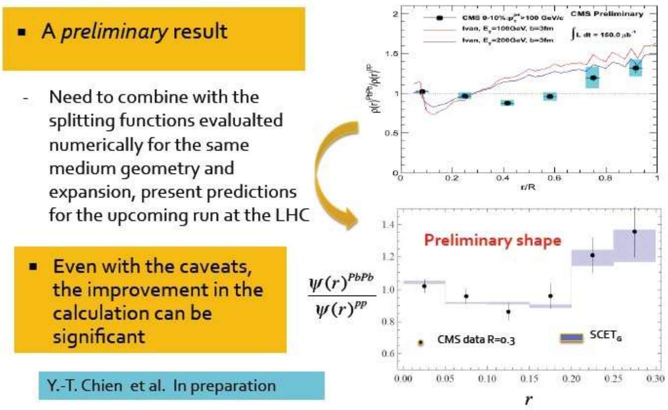




Jet shape modifications using pQCD and energy loss (Vitev et al)

In heavy ion collisions,

- Jet shape modifications are not well described by the energy loss formalism
- We will improve the calculation using effective field theory techniques



Power counting

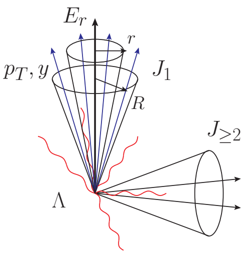
- Jet shapes have dominant contributions from the collinear sector

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

  - Soft contributions are power suppressed
  - Glauber gluons don't contribute to the energy measurement
  - 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
- The jet shape is a collinear observable

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

Jet energy function

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

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

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

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

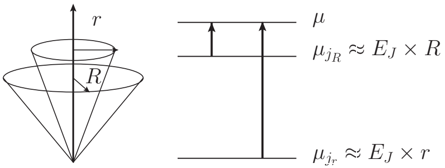
- Identify the natural scale μ_{j_r} to eliminate large logarithms in $J_{E,r}(\mu_{j_r})$
- The RG evolution kernel $U_J(\mu_{j_r},\mu_{j_R})$ resums the large logarithms

Natural scales

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

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

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



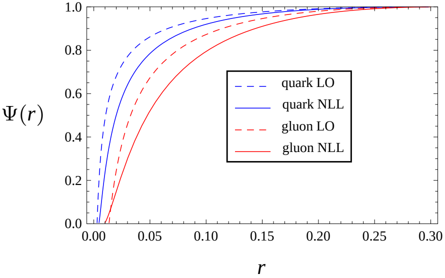
RG evolution between μ_{j_r} and μ_{j_R} resums $\log\mu_{j_r}/\mu_{j_R} = \log r/R$

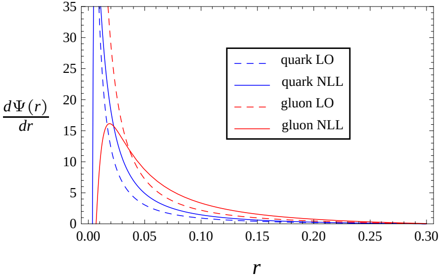
Resummed jet energy functions

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

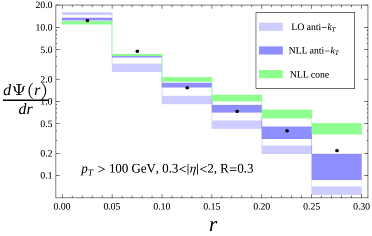
$$\Psi^i_\omega(r,R) = \frac{J_r^{iE}(r,R,\mu_{j_r})}{J_R^{iE}(R,\mu_{j_R})} \exp[-2\,C_i\,S(\mu_{j_r},\mu_{j_R}) + 2\,A_{J^i}(\mu_{j_r},\mu_{j_R})] \left(\frac{\mu_{j_r}^2}{\omega^2 \tan^2 \frac{R}{2}}\right)^{C_i\,A_\Gamma(\mu_{j_R},\mu_{j_r})}$$

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

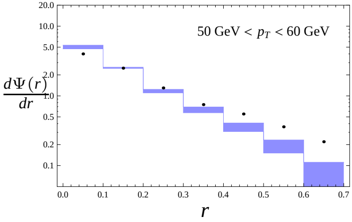


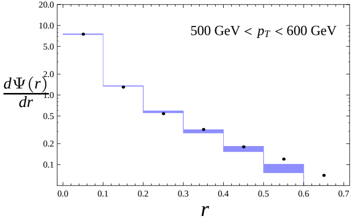


Comparison with the CMS data at 2.76 and 7 TeV



- 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,

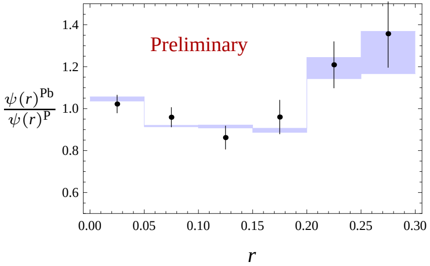
$$J^i_{E,r}(\mu) = \sum_{j,k} \int_{PS} dx dk_\perp \left[\frac{dN^{vac}_{i\to jk}}{dx d^2k_\perp} + \frac{dN^{med}_{i\to jk}}{dx d^2k_\perp} \right] E_r(x, k_\perp)$$

- The medium induced splitting functions are calculated numerically using $\mathrm{SCET_G}$ with realistic hydrodynamic QGP models
- 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

Preliminary result for jet shape modifications



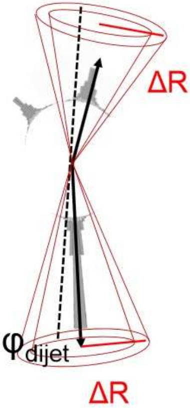
- The plot is the ratio between the differential jet shapes in lead-lead and proton collisions for jets with $p_T > 100$ GeV and $|y| < 1$
- The data is for the centrality bin between $30 - 50\%$

Jet energy loss

- Jet shapes and jet energy loss are highly correlated
  - Jet shapes probe the energy distribution inside jets
  - Jet energy loss describes the amount of energy outside jets
- A consistent theory of jets should be able to describe jet shapes and jet energy loss at the same time
  - The previous calculation assumes that the energy outside jets is power suppressed, which is no longer valid
- There is no jet energy loss if R is big enough
  - With jet energy loss, R should in some sense be small
- For small-radius jets, the parton-jet correspondence is less clear
  - In the $R \to 0$ limit, every particle is a jet

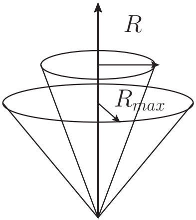
Dijet momentum imbalance

- The momentum imbalance of the leading two jets are mostly due to the third hard emission
- Jet energy loss in heavy ion collisions makes the dijet momentum imbalance even more significant
- At CMS, telescoping jets with a larger jet radius R_{max} restores the lost energy
    - lost energy carried by low p_T particles at wide angles



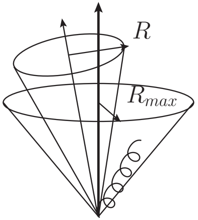
Jet energy loss using jet energy functions

- The first attempt using the existing framework: use R_{max} to constrain the collinear radiation or parton shower, and identify the subcone of size R as the jet
  - Limitation: restricted to cone jets
  - Caveat: Not all jets are the center subcone of a parton shower



Beyond jet substructure: subjet structure and subjet substructure

- Given a jet with radius R_{max} (assumed to be large), what is the averaged energy inside its leading anti-k_T subjet of size R?
    - Algorithm dependence in the subjet definition
    - The leading subjet axis is not necessarily along the original fat jet axis
    - Work in progress: subjet kinematics, subjet energy functions and subjet shapes



Preliminary result for subjet energy functions

$$J^{q,sub}_{E,R_{max}}(\mu) = J^{q}_{E,R_{max}}(\mu) - \frac{\alpha_s}{2\pi} C_F \Big((\frac{3}{4} - 4\ln 2) \ln \frac{\tan\frac{R}{2}}{\tan\frac{R_{max}}{2}} + \frac{37}{64}(\tan^2 \frac{R_{max}}{2} - \tan^2 \frac{R}{2}) \Big) \Big]$$

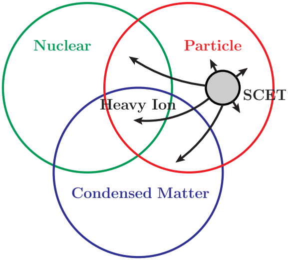
$$\begin{aligned} J^{g,sub}_{E,R_{max}}(\mu) = J^{g}_{E,R_{max}}(\mu) \quad & - \quad \frac{\alpha_s}{2\pi} \Big(\Big[C_A(\frac{43}{48} - 4\ln 2) - T_F n_f \frac{7}{24} \Big] \ln \frac{\tan\frac{R}{2}}{\tan\frac{R_{max}}{2}} \\ & + \quad \Big[C_A \frac{521}{960} + T_F n_f \frac{17}{240} \Big] (\tan^2 \frac{R_{max}}{2} - \tan^2 \frac{R}{2}) \Big) \Big] \end{aligned}$$

- Coefficients reproducing arXiv:1411.5182 (Dasgupta et al) at $\mathcal{O}(\alpha_s)$
- Single logarithms need to be resummed

Conclusions and outlooks

- Jet shapes in proton and heavy ion collisions are calculated within the same framework
  - Promising agreement with data and phenomenological applications
- To calculate jet shapes and jet energy loss consistently, the previous framework needs to be extended
  - Subjet structure and subjet substructure being investigated
- Work in progress and future work
  – Check the numerics of jet shape modifications
  – Making predictions for the LHC Run-2 (paper in preparation)
  – Calculate jet fragmentation function modifications
  – Construct SCET at finite temperature
  – Study the quenching of photon-tagged jets
  – 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!