Jet Substructure for Quark Gluon Plasma at colliders

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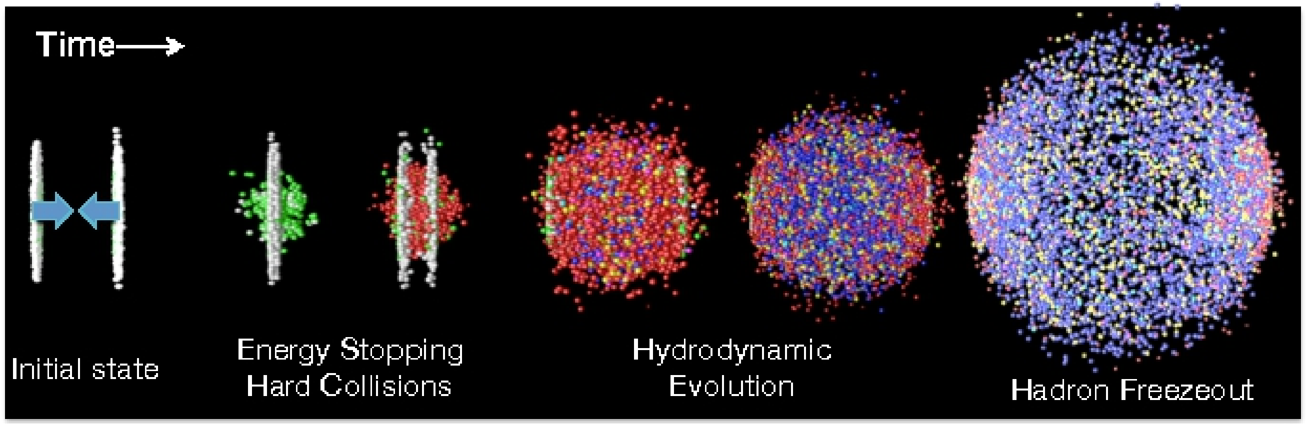
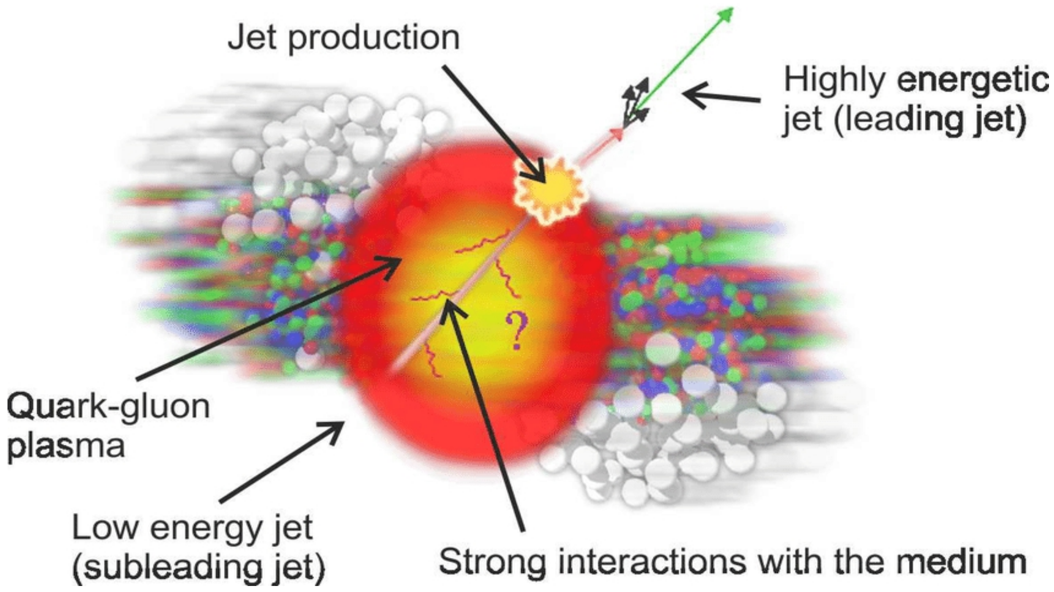
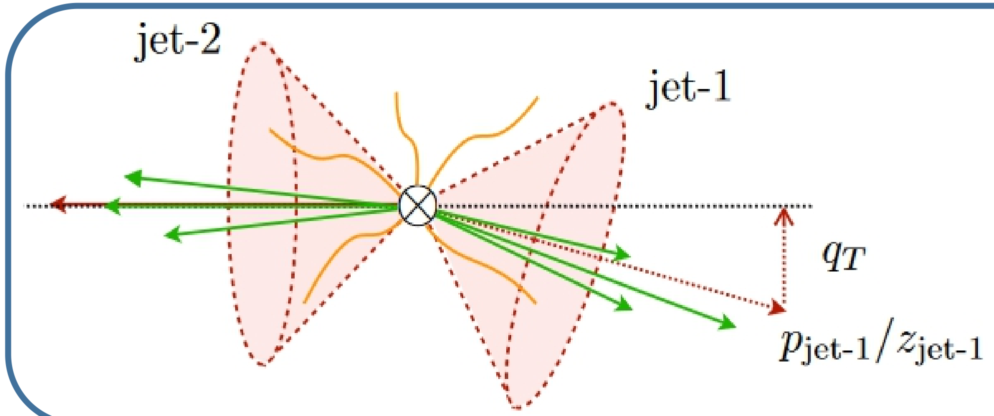


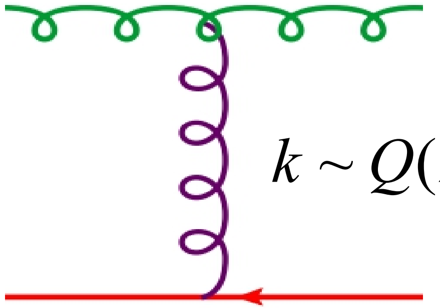




1. Identify dijets R~1 and groom to remove soft hadrons.
2. Measure transverse momentum imbalance between jets.
3. Measure jet mass in each groomed jet

Can we derive a factorization formula for jet substructure observables with a clear separation of physics at different scales

An EFT in the forward scattering regime



$p_s \sim Q(\lambda,\lambda,\lambda)$ QGP is a thermal bath made of **soft** partons (T~λQ <<Q)

$k \sim Q(\lambda,\lambda^2,\lambda)$ Forward scattering mediated by virtual **Glauber** partons

$p_c \sim Q(1,\lambda^2,\lambda)$ The jet is made up of highly energetic massless **collinear** partons

$n^\mu \equiv (1,0,0,1)$

$\bar{n}^\mu \equiv (1,0,0,-1)$

$p^\mu \equiv (\bar{n}\cdot p, n\cdot p, \vec{p}_\perp)$

Soft Collinear Effective Theory : An effective QCD Lagrangian at leading power in λ~T/Q

$$L_{QCD} = L_c + L_s + L_G + O(\lambda^2) \equiv L_{SCET} + L_G + O(\lambda^2)$$

I. Rothstein, I. Stewart, JHEP 1608 (2016) 025

Measurement and dynamical scales lead to a more involved factorization

$$Q \gg Qz_{cut} \gg q_T \sim T \sim Q\sqrt{e} \gg m_D \geq \Lambda_{QCD}$$

Hard scale; Grooming scale; transverse imbalance; QGP temperature; jet mass; medium induced gluon mass

$$L_{IR} = \{L_c^n + L_s + L_{cs}^n + L_{sc}^n + n \leftrightarrow \bar{n}\} + L_G^{ns} + O(\lambda^2) \equiv L_{SCET} + L_G$$

Jets as Open Quantum systems

- Treat the jet as an open quantum system interacting with a bath (via Glaubers)
- Write an evolution equation for the factorized reduced density matrix of the jet.

$$\rho(t)=\int_0^t dt_1\int_0^t dt_2 e^{-i(H_{SCET}+H_G)t}\mathrm{O}_{\mathrm{hard}}(t_1)\rho(0)\mathrm{O}^{+}_{\mathrm{hard}}(t_2)e^{i(H_{SCET}+H_G)t}$$

QGP density matrix

$$\rho(0)=\left|e^+e^-\right\rangle\left\langle e^+e^-\right|\otimes\rho_B$$

We assume ρ_B is time independent and intially unentangled from the partons(here $e^+ e^-$)that form dijets via a hard interaction.

- H_G prevents factorization of Soft physics from the collinear
- Factorization needs to be proven order by order in the H_G expansion

$$\Sigma(t)=Tr[\rho(t)M]_{t\to\infty}=\Sigma^{(0)}(t)+\Sigma_b^{(1)}(t)+\Sigma_a^{(1)}(t)+O(H_G^3)$$

reduced density matrix with measurement

Vacuum evolution

Virtual interaction with medium

Real interaction with medium

Factorization for the density matrix

Leading order : Vacuum evolution

$$\Sigma^{(0)} = V \times H(Q,\mu) \times S(\vec{q}_T;\mu) \otimes_{q_T} \mathcal{J}_n^{\perp}(e_n, Q, z_{cut}, \vec{q}_T;\mu) \otimes_{q_T} \mathcal{J}_{\bar{n}}^{\perp}(e_{\bar{n}}, Q, z_{cut}, \vec{q}_T;\mu)$$

4 D volume

hard function

Soft function

$$S^{\perp}_{sc,n}(Qz_{cut}, \vec{q}_T) \times S_{cs,i}(e_n, Qz_{cut}) \otimes_{e_n} J_n(e_n, Q)$$

Soft colllinear

Collinear Soft

Jet

Using RG evolution of the factorized functions allows us to resum large logarithms in ratio of scales

Next to leading order: Medium evolution

$$\Sigma_a^{(1)} = V \times |C_{qq}|^2 H(Q,\mu) S(\vec{q}_T) \otimes_{q_T} S_{sc,\bar{n}}(\vec{q}_T) \otimes_{q_T} S_{sc,n}(\vec{q}_T) \otimes_{e_n} CS_n(Qz_{cut}, e_n) \otimes_{e_n}$$
$$\otimes_{q_T} \tilde{J}_n(e_n, q_T) J_{\bar{n}}(e_{\bar{n}}) \otimes_{e_{\bar{n}}} CS_{\bar{n}}(e_{\bar{n}})$$

$$\int \frac{d^4k}{(2\pi)^4 k_\perp^4} D_>^{AB}(k) \delta^2(q_T - \vec{k}_\perp) \int d^4x \int d^4y e^{i(x-y)\cdot k} \{J_n^{AB}(e_n, x, y)\}$$

Correlator of soft operators in the medium

Modified jet function

Contains large logarithms in the gluon mass m_D that are not resummed by RG evolution -> Match to an EFT at scale m_D

Master Evolution equation

$$P(e_n, e_{\bar{n}}, \vec{q}_T) \equiv \frac{d\sigma(t)}{de_n de_{\bar{n}} d^2\vec{q}_T} = \mathcal{N}\frac{\Sigma(t)}{V}$$

Relate the factorized density matrix to the jet substructure cross section

Taking the limit t → 0 yields an evolution equation for the differential cross section

$$\partial_t P(e_n, \vec{q}_T)(t) = -RP(e_n, \vec{q}_T) + P(e_n, \vec{q}_T) \otimes_{q_T} K(q_T) + F(q_T, e_n)$$

Solution in impact parameter space

$$\frac{d\sigma}{de_n d\vec{q}_T}(t) = \int d^2\vec{r}_\perp e^{i\vec{r}_\perp\cdot\vec{q}_T}\left\{\left[V(e_n, \vec{r}_\perp) + \tilde{g}(e_n, \vec{r}_\perp)\right]e^{(-R+\tilde{K}(\vec{r}_\perp))t} - \tilde{g}(e_n, \vec{r}_\perp)\right\}$$

Cross section as a function of medium propagation time

Vacuum cross section

Thermal correlators in the medium

Medium induced cross section

The solution resums mutiple interactions of the jet partons with the medium in the Markovian approximation.

Summary and Future directions

Summary

- An EFT for jet substructure in heavy ion collisions
- Resums large logarithms of scales using factorization
- Resums multiples interactions of the jet with the medium in the Markovian approximation

Future directions

- A phenomenological prediction including nuclear pdf's.
- Match to EFT at the scale m_D to resum new medium induced logartihms.
- Extend formalism to jets initiated by heavy quarks.
- Relax assumption for time independence of medium density matrix.