Jet Substructure for heavy ion collisions.

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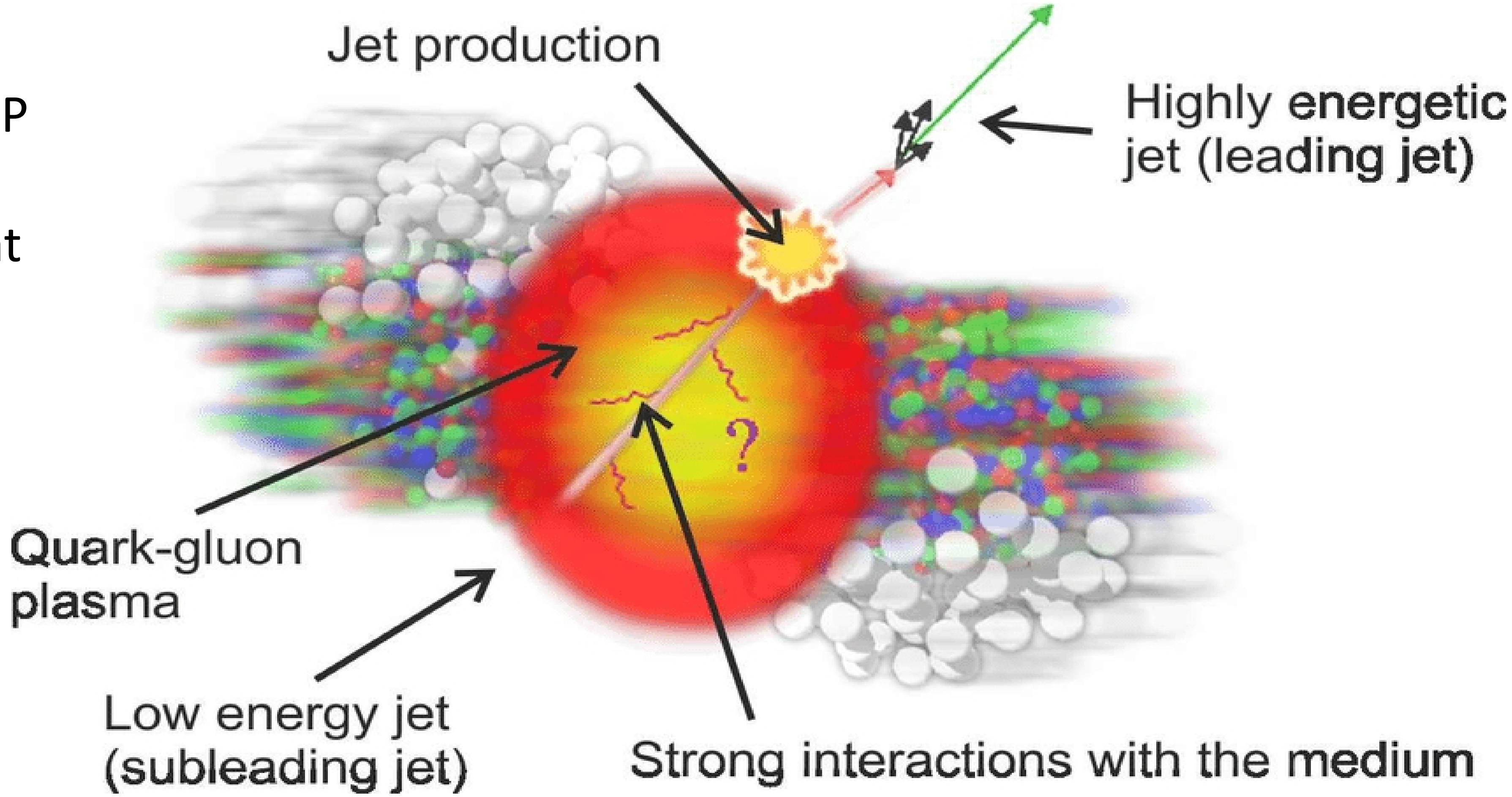
Based on

JHEP 20 (2020) 024, Xiaojun Yao, V.V
arXiV 2010.00028, V.V
arXiV 2101.02225 V.V.

Quark Gluon Plasma at colliders

- Few events in the QGP background produce energetic partons that evolve into back to back jets

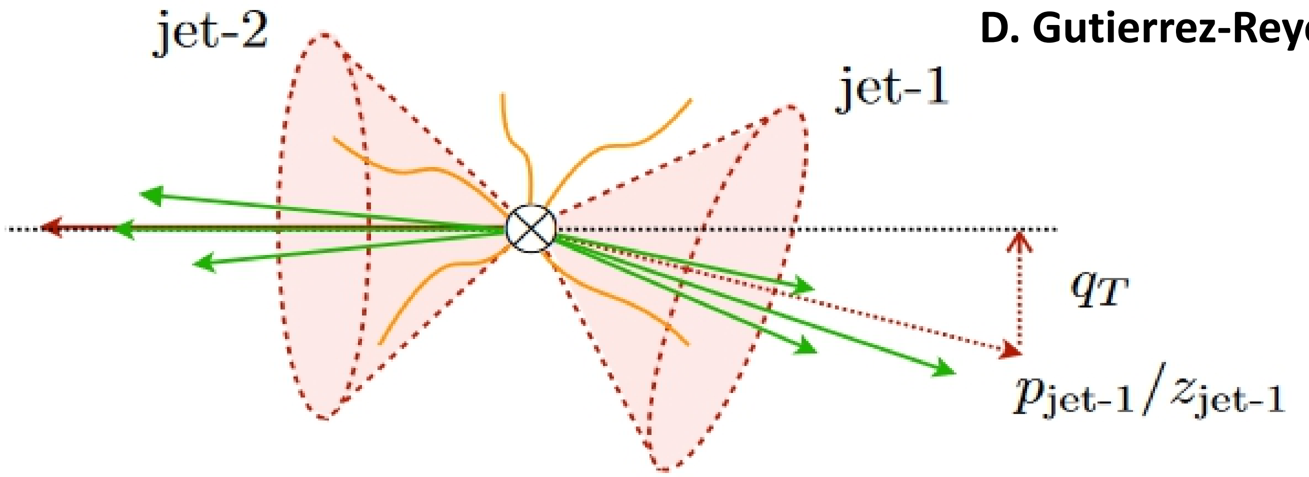
- Jet energy $E_J >> T$: Temperature of the QGP



- **How is the jet modified as it travels through the medium?**

The observable

D. Gutierrez-Reyes, Y. Makris, V. V, I. Scimemi, L. Zoppi JHEP 08 (2019) 161



$$\frac{d\sigma}{de_1 de_2 d^2 q_T}$$

- Identify Dijet events with large radius jets R~1.
- Groom the jets to remove soft radiation : Removes soft contamination from the cooling QGP.

Measure the transverse momentum imbalance between the two groomed jets .

$$\vec{q}_T = \frac{\vec{p}_{t,jet1}}{z_{jet1}} + \frac{\vec{p}_{t,jet2}}{z_{jet2}}$$

Impose a jet mass measurement on each groomed jet

$$e_{jet} = \frac{\left(\sum_{j \in jet} p_j\right)^2}{E_{jet}}$$

An Effective Field theory approach to Heavy Ion physics

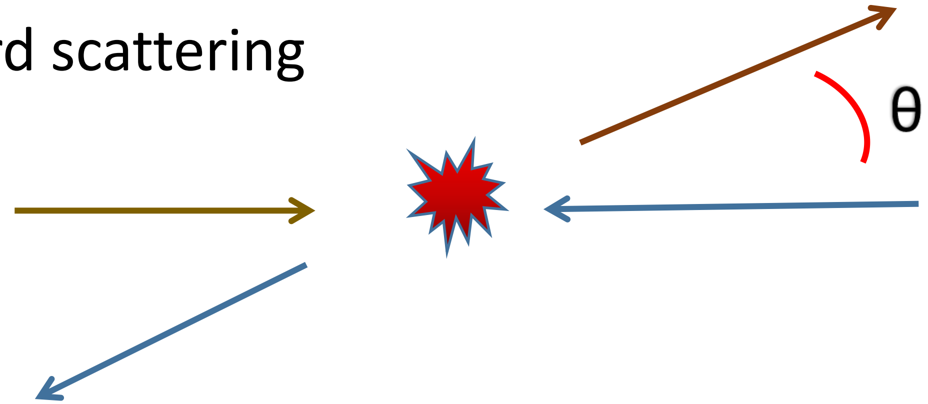
Can we borrow tools from jet substructure computations for pp collisions and systematically derive factorization formulas for jet sub-structure in heavy ion collisions?

↓

An Effective Field theory for jet propagation in the QGP medium

An EFT in the forward scattering regime

2->2 Forward scattering



In the limit $\theta \to 0$

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{\theta^4}$$

- Develop an EFT formalism for forward scattering of a jet in QGP with λ= θ<<1 as the expansion parameter.
- Step I : Identify the degrees of freedom that describe our system
- The jet is made up of highly energetic massless partons moving along the light-cone

$$p_c \sim Q(1, \lambda^2, \lambda)$$

- QGP is a thermal bath made of soft partons (T~ θQ <<Q)

$$p_s \sim Q(\lambda, \lambda, \lambda)$$

Light-Cone co-ordinates

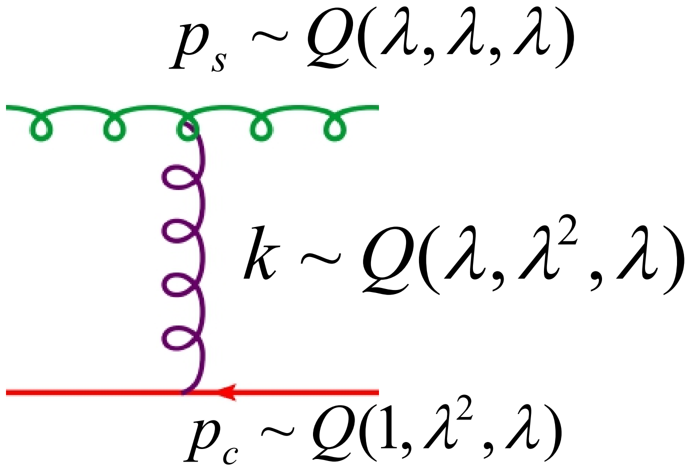
$$n^\mu \equiv (1,0,0,1) \quad \bar{n}^\mu \equiv (1,0,0,-1)$$

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

An EFT in the forward scattering regime

Step II: Write down an effective Lagrangian for the degrees of freedom

Forward interaction between soft and collinear modes is mediated by off-shell Glauber modes



Soft Collinear Effective Theory : An effective QCD Lagrangian at leading power in λ

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

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

- L_c: Interactions among Collinear partons
- L_s: Interactions among soft partons
- L_G: Soft Collinear forward interactions mediated by the Glauber mode

$$L_G \sim O_{cs}^{qq} = O_n^{q\alpha} \frac{1}{P_\perp^2} O_S^{q\alpha}$$

$$O_n^{q\alpha} = \bar{\chi}_n W_n T^\alpha \frac{\bar{n}}{2} W_n^+ \chi_n$$

$$O_S^{q\alpha} = \bar{\psi}_s S_n T^\alpha \frac{n}{2} S_n^+ \psi_s^n$$

EFT for jet substructure in QGP

How does the EFT apply to our system?

Physical scales that describe the system

Kinematic scales :

- Jet energy **Q**
- QGP temperature **T**

Measurement scales:

- Transverse momentum imbalance **qT**
- Jet mass **e**
- Grooming parameter $\mathbf{z_{cut}}$

Dynamical or emergent scales:

- Strong dynamics scale : Λ_{QCD}
- Induced Gluon Mass : $m_D \sim gT$
- Inverse interaction time of system and medium g^2T

In this talk

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

Weak coupling regime

EFT for jet substructure in QGP

Additional degrees of freedom of our EFT

$p_s^\mu \sim Q(\lambda_s, \lambda_s, \lambda_s)$ $\lambda_s = q_T / Q \sim \theta \sim T / Q$ Soft

$p_n^\mu \sim Q(1, \lambda_c^2, \lambda_c)$ $\lambda_c = \sqrt{e}$ Collinear

$p_{sc,n}^\mu \sim Q z_{cut}(1, \lambda_{sc}^2, \lambda_{sc})$ $\lambda_{sc} = \frac{q_T}{Q z_{cut}}$ Soft-Collinear

$p_{cs,n}^\mu \sim Q z_{cut}(1, \lambda_{cs}^2, \lambda_{cs})$ $\lambda_{cs} = \sqrt{\frac{e}{z_{cut}}}$ Collinear Soft

$$\lambda_s \sim \lambda_c \sim \theta$$

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

- Only the collinear mode talks to the medium(soft mode) via the Glauber Lagrangian which breaks factorization.

Jets as Open Quantum systems

How do we describe the evolution of a jet as it traverses a region of the QGP?

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

QGP density matrix

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

We assume ρ_B is time independent and intially unentagled from the partons that are involved in the hard interaction.

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

Factorization for the density matrix

- The Glauber Hamiltonian prevents us from factorizing the Soft physics from the collinear to all orders in perturbation theory

- Factorization needs to be proven order by order in the Glauber operator insertion

$$\Sigma(t) = Tr[\rho(t)M]_{t\to\infty}$$

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

Vacuum evolution

Single Real interaction with medium

Single Virtual 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

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

Soft colllinear

Collinear Soft

Jet

- A manifest separation of scales !
- Using RG evolution of the factorized functions allows us to resume large logarithms in ratio of scales

Factorization for the density matrix

Next to Leading order: Quadratic Glauber insertion

4 D volume

hard function

Collinear Soft

Soft colllinear

$$\Sigma_a^{(1)} = V \times |C_{qq}|^2 H(Q,\mu) J_{\bar{n}}(e_{\bar{n}}) \otimes_{e_n} CS_{\bar{n}}(Qz_{cut}, e_{\bar{n}}) S_{sc,n}(Qz_{cut}, \vec{q}_T) \otimes_{q_T} S_{sc,\bar{n}}(Qz_{cut}, \vec{q}_T)$$
$$\otimes_{q_T} \int d^4x \int d^4y \, S^{AB}(\vec{q}_T, \{x_\perp, x^-\}, \{y_\perp, y^-\}) J_n^{AB}(e_n, x, y) \otimes_{e_n} CS_n(Qz_{cut}, e_n)$$

Soft function in QGP background

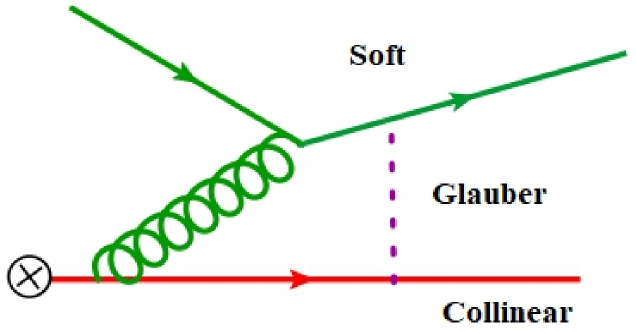
Jet function in QGP background

- Ignore back reaction of soft radiation on subsequent jet-medium interactions -> Valid when the time scale for soft radiation is much smaller than formation time of QGP

$$S^{AB} \rightarrow S \otimes_{q_T} S_G^{AB}$$

Vacuum Soft function

Medium soft function



Factorization for the density matrix

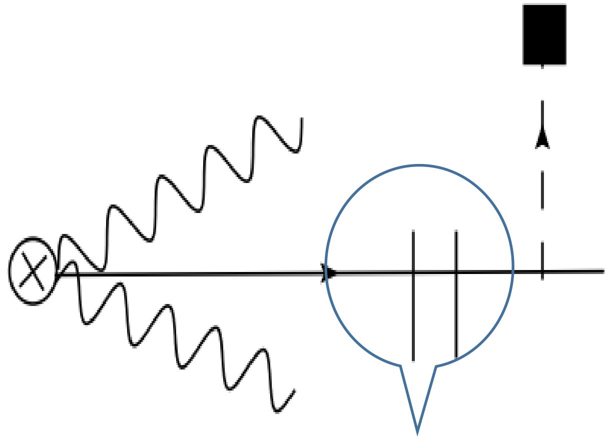
Next to Leading order: Quadratic Glauber insertion

Three time scales that characterize the system,

1. **t_e ~ 1/T** : Correlation time in the bath :Time scale over which coherence is lost in the QGP bath

2. **t** : Time of propagation of the jet in the medium

3. **t_l** : Emergent time scale of jet-medium interaction: A leading order calculation gives $t_l \sim 1/(T\,\alpha_s)$



Pinch singularity in the feynman integral

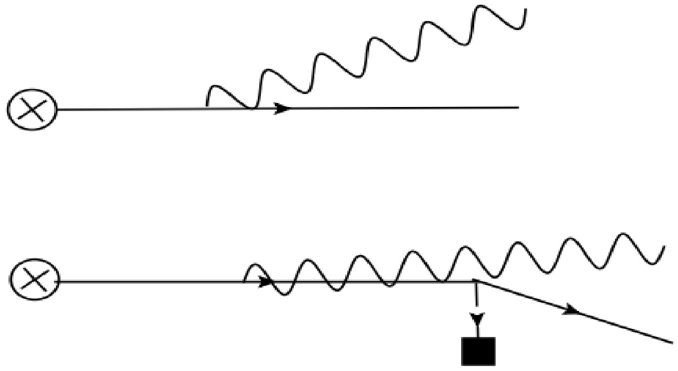
For weak coupling and $t \geq t_l >> t_e$: Expand further in $\lambda \sim t_e/t_l$ while keeping dominant contribution from 't/t_l' enhanced diagrams :

Partons created in the jet (and subsequent shower) go on-shell before interacting with the medium

Medium modified jet function

$$J_n^{(1)}(e_n, \vec{k}_\perp) = J_n^{(1)}(e_n) + J_n^M(e_n, k_\perp, m_g)$$

vacuum jet function



$$J_n^M = \frac{\alpha_s C_F}{2\pi(e_n + y)} \left\{ -2(e_n + y) \frac{\ln \frac{M^2 y(e_n+y)}{e_n^3}}{\sqrt{e_n^2 + 4M^2 y}} + \left\{ \frac{e_n^2}{(e_n + y)^2} + \frac{e_n}{e_n + y} - 4 \right\} \ln \frac{e_n(e_n + y)}{M^2 y} \right\}$$

$$M = \frac{2m_D}{Q}, \qquad y = \frac{4k_\perp^2}{Q^2}$$

UV finite, medium induced term

- Anomalous dimension is the same as the vacuum jet function
- **Logarithms in the gluon mass are NOT resummed by the present EFT formulation : Match to EFT at the scale m_D**

Evolution equation

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

Taking the limit t $\rightarrow$ 0 yields an evolution equation for the differential cross section

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

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

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. (‘t’ enhanced terms)

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.

THANKS