Jet Substructure for heavy ion collisions.

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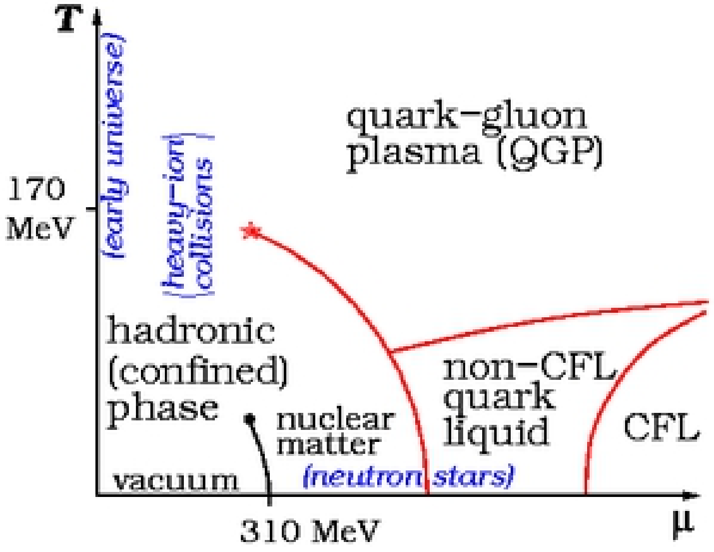
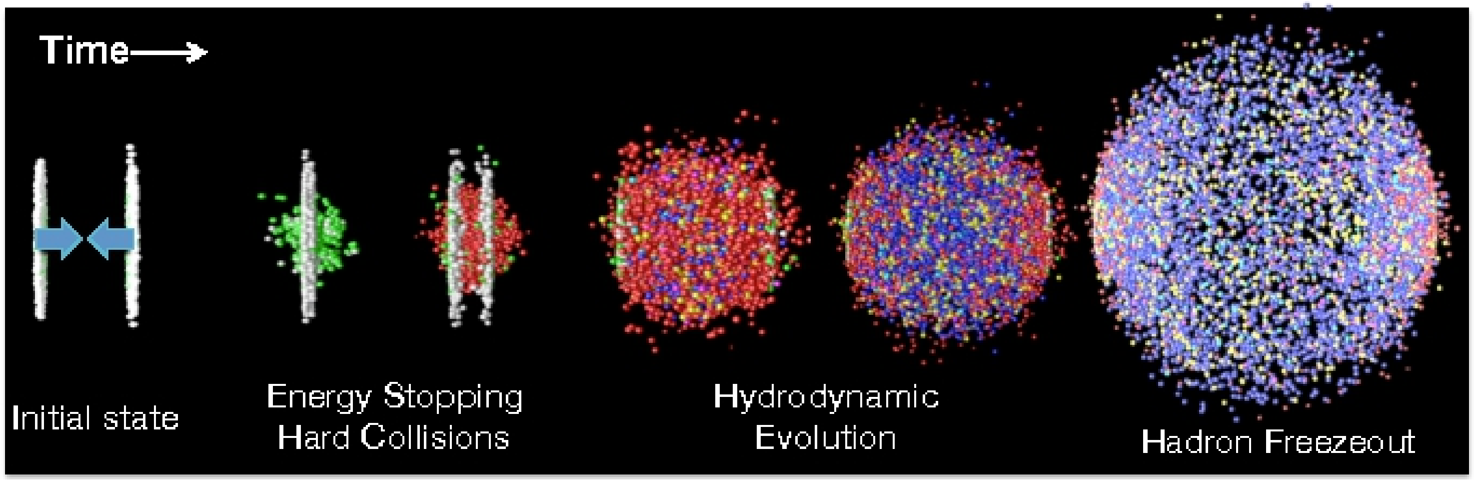
Based on

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

Quark Gluon Plasma at colliders



QCD phase diagram

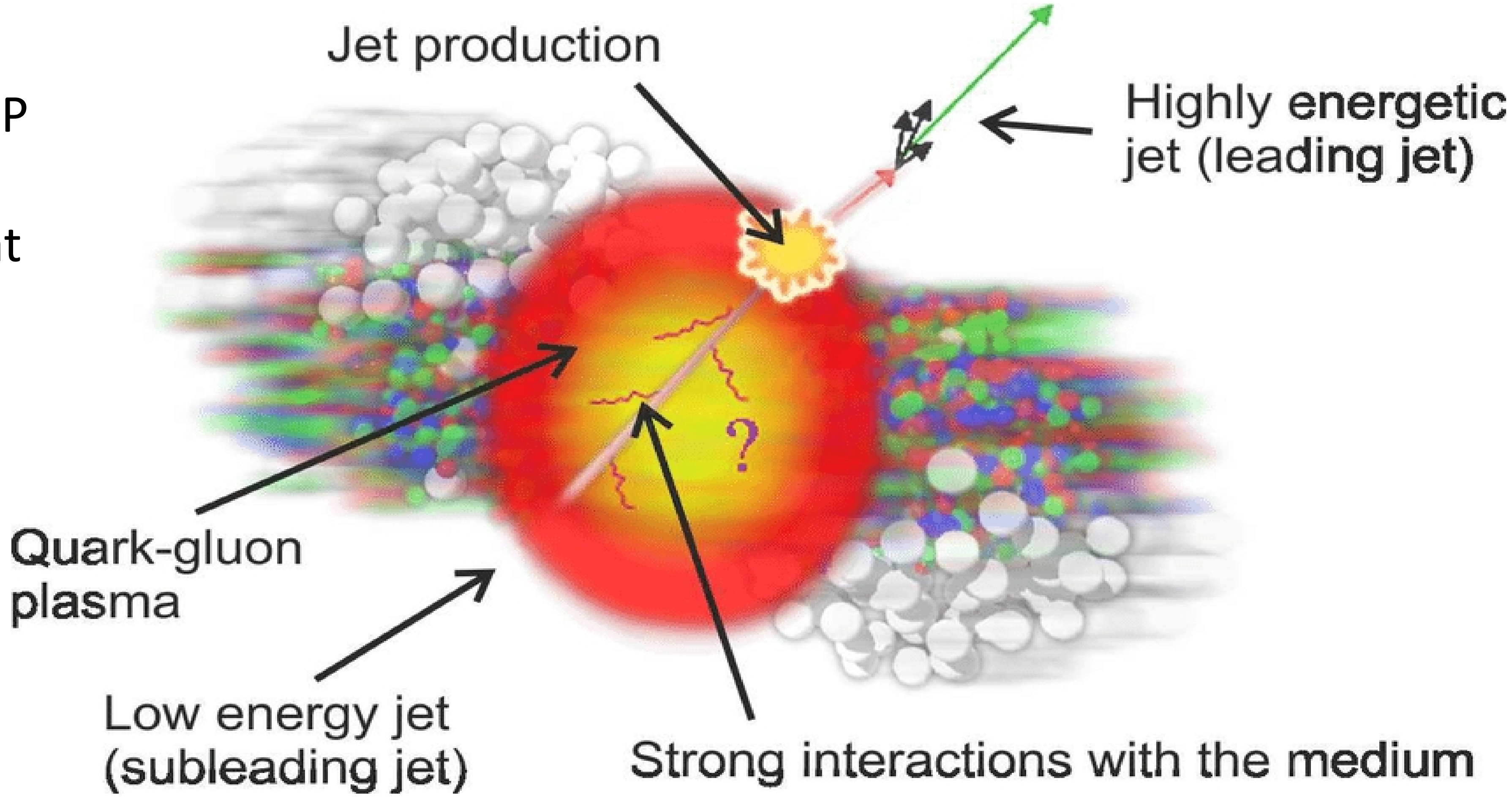


Formation of QGP in Heavy Ion collisions

QGP: A soup of free quarks and gluons created in the early universe and recently at Heavy Ion colliders

Quark Gluon Plasma at colliders

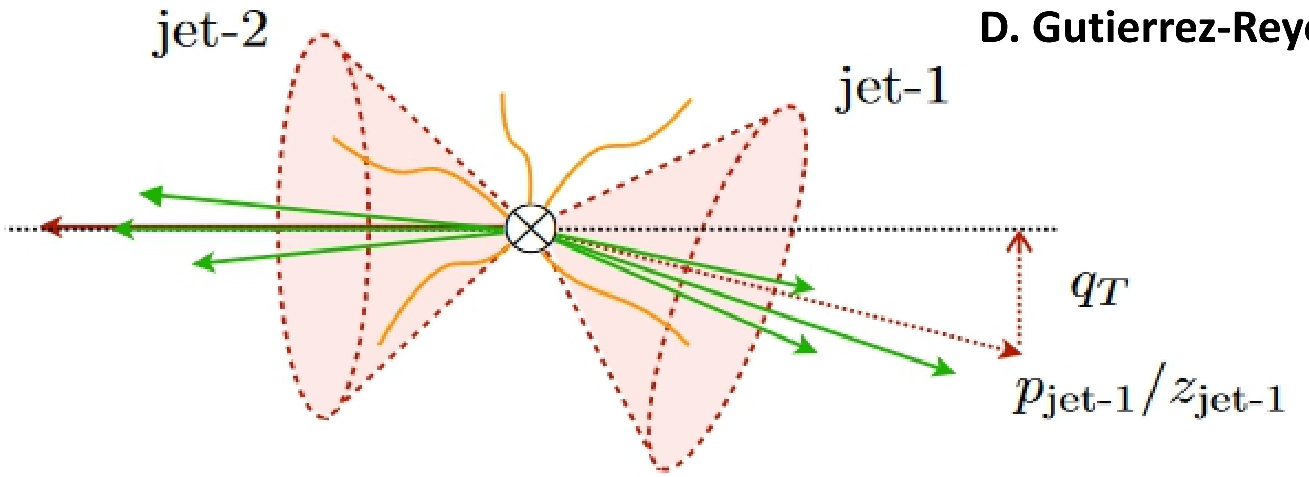
- Few events in the QGP background produce energetic partons that evolve into back to back jets



- **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 .

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

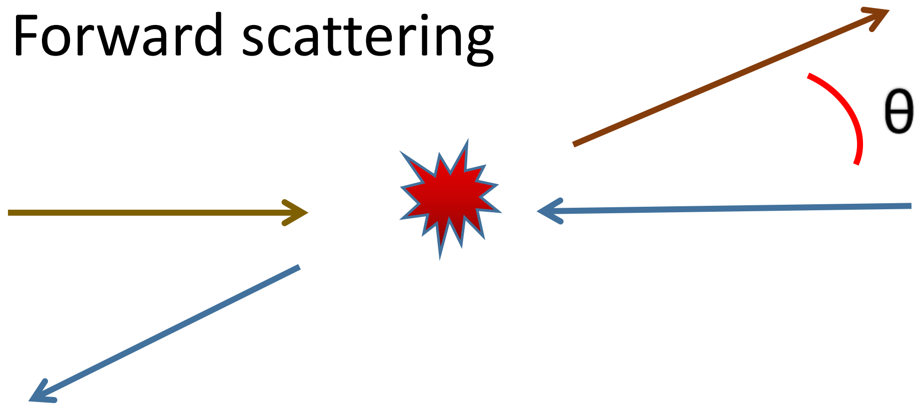
Impose a jet mass measurement on each groomed jet

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

An Effective Field theory 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.
- 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

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

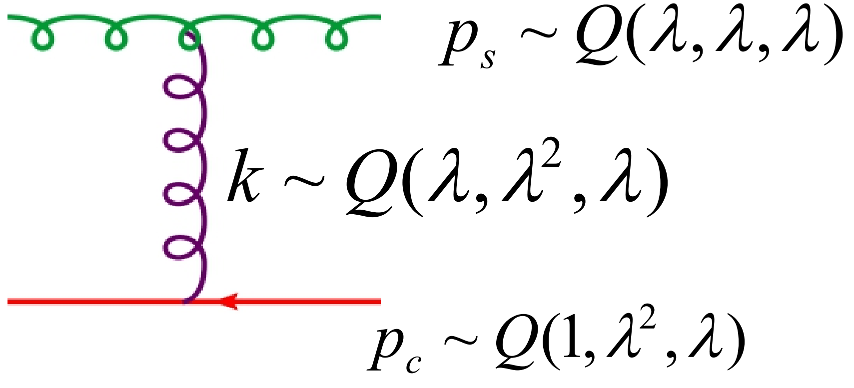
$$p^\mu \equiv (\bar{n} \cdot p, n \cdot p, \vec{p}_\perp)$$

An EFT in the forward scattering regime

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

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

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



Interactions among Collinear partons

Interactions among soft partons

Effective Soft Collinear forward interactions mediated by the Glauber mode

- The Glauber interaction breaks factorization between the Soft and Collinear sectors

EFT for jet substructure in QGP

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 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

Factorize the physics at different scales within SCET

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

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

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

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

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

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

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

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

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

Soft colllinear

Collinear Soft

Jet

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

Factorization for the density matrix

Next to Leading order: Quadratic Glauber insertion

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

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

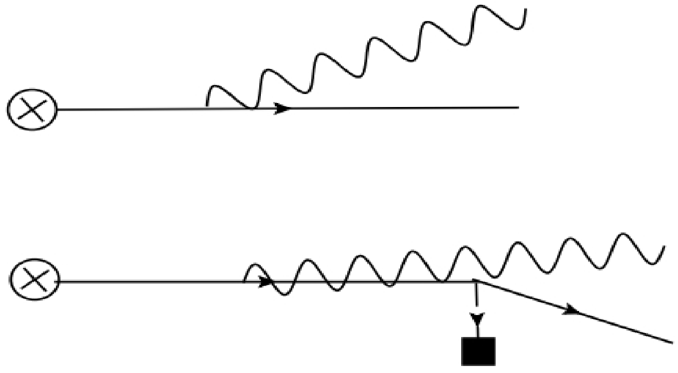
Correlator of soft operators in the medium

Modified jet function

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**

Markovian approximation

- Till now, we have considered a single interaction of the jet with the medium.
- This can be used to resum multiple interactions treating them as independent scattering events -> Markovian approximation

Between two interactions, the environment loses any memory of interaction with the jet.

coherence time of the environment (t_e) << time scale of the interaction with system (t_I)

$t_e \sim 1/T$

$t_I \sim 1/(T\,\alpha_s)$

So for a weak coupling regime, the Markovian approximation holds.

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 → 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.

Summary and Future directions

Summary

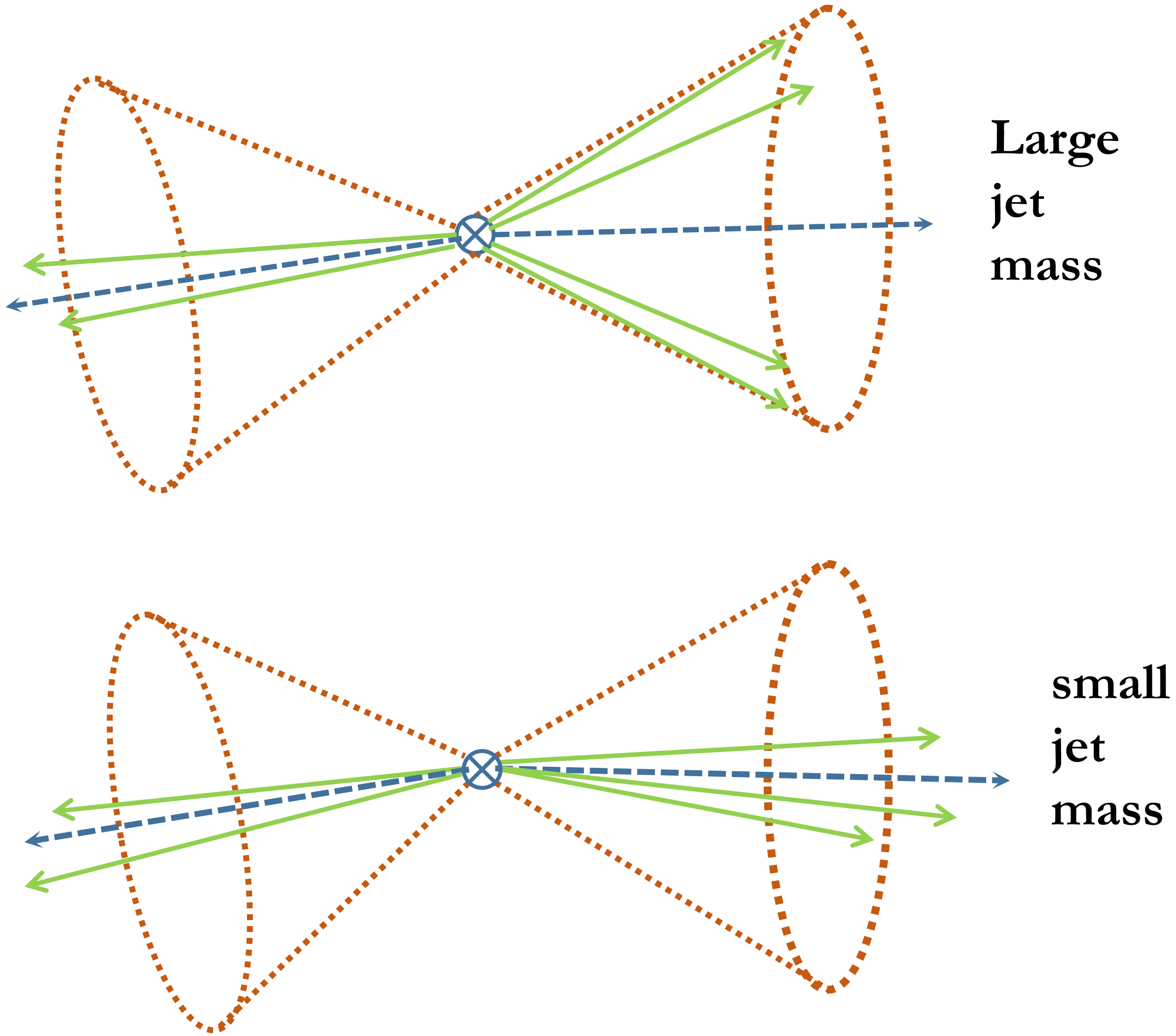
- An EFT for jet substructure in heavy ion collisions
- Resums large logarithms of scales using factorization
- Resums multiples interactions of the jet with the medium in the Markovian approximation

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

The observable



- Impose a jet mass measurement on groomed jet to ensure radiation collimated along the jet axis

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

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

Leading order : Vacuum evolution

$$S(\vec{q}_T) = \frac{1}{N_R}\mathrm{tr}\langle X_S|\mathcal{T}\left\{e^{-i\int_0^\infty dt' H_S(t')}S_{\bar{n}}^\dagger S_n(0)\right\}\rho_{QGP}\bar{\mathcal{T}}\left\{e^{-i\int_0^\infty dt' H_S(t')}S_n^\dagger S_{\bar{n}}(0)\right\}\delta^2(\vec{q}_T - \mathcal{P}_\perp)|X_S\rangle$$

If the time scale for Soft emissions off the intial hard quark is much smaller than the formation time for the medium, then

$$S(\vec{q}_T) = S_V(q_T)\mathrm{Tr}[\rho_{QGP}]$$

vacuum soft function

Evolution equation

Integro-differential Evolution equation can be solved in impact parameter space.

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

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