Probing Quark Gluon Plasma with jets

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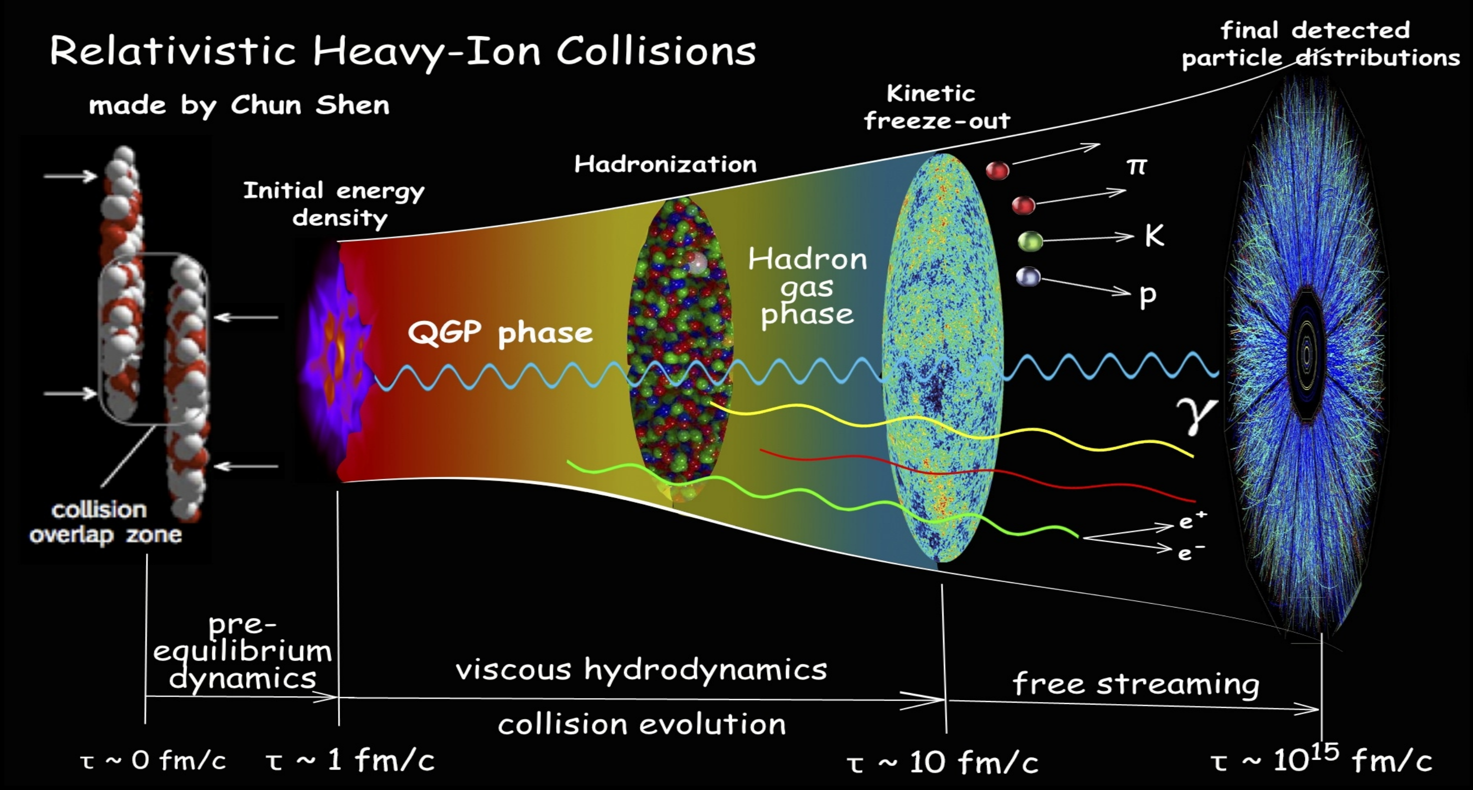
2010.00028,   V.V
2101.02225   V.V
2105.XXXXX ,V.V

1.

Physics of Heavy Ion Collisions



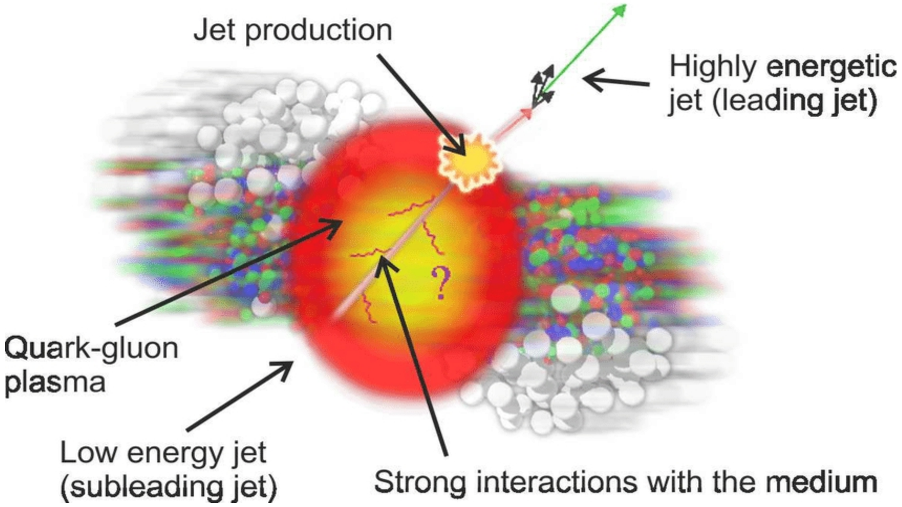
c.o.m energy per
nucleon pair
200 GeV - 2.76 TeV

QGP temperature
200 - 1000 MeV

Using QCD Jets to probe the QGP

- QGP phase exists for a very small time-> Using external probes (like an electron in DIS) is unfeasible

- Look for natural probes that appear in HIC



Few events produce energetic partons that evolve into back to back jets : A natural X ray for the QGP!

Modification of the jet substructure compared to pp collisions :

$$R_{AA} = \frac{\left.\frac{d\sigma}{d\phi}\right|_{HIC}}{\left.\frac{d\sigma}{d\phi}\right|_{pp}}$$

What is a good jet substructure observable in HIC environment?

Jet substructure observables in HIC

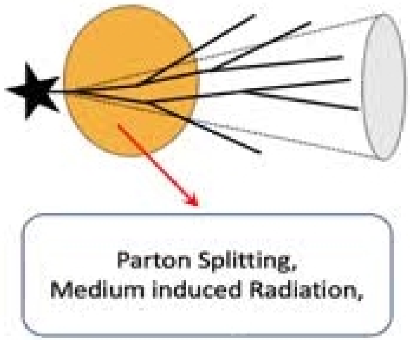
Heavy ion collisions are messy environments!

- Work with groomed jets for clean measurement.

$$E_J\, z_{cut} \sim E_J >> T \quad : \text{Energy scale of the QGP}$$

Jet substructure observables in HIC

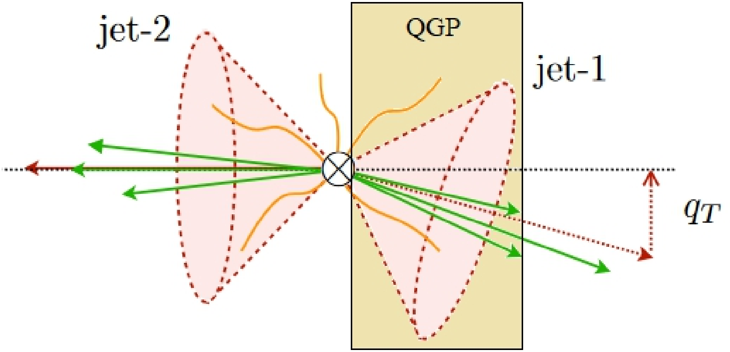
- Choose an observable insensitive to **jet selection bias***:



- The same hard event leads to jets with different {pT, R} in pp vs HIC .
- Energy/pT leaks out due to interaction with medium near the edge of the jet-> Jet Quenching
- Cannot directly compare jet substructure modification for the same hard event with a given R, pT cut.
- Solution :Any observable that is insensitive to edge of the jet radiation
  Added advantage -> No NGLs

*** 2009.03316, 1907.11248 K. Rajagopal et.al.**
1907.12301 D. Pablos

The Observable



$$\frac{d\sigma(e_n, e_{\bar{n}})}{d^2 q_T}$$

- Measure the transverse momentum imbalance between the two groomed jets (R ~1) in the small q_T regime.

- Measure the groomed jet mass (cumulative)

$$m_D << \sqrt{e_i} E_J \sim q_T \sim \mathrm{T} << E_J z_{cut} \sim E_J$$

Debye screening mass ~ gT

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

Given the enormous success of factorization in probing hadron structure..

Can we do the same for the QGP in HIC ?

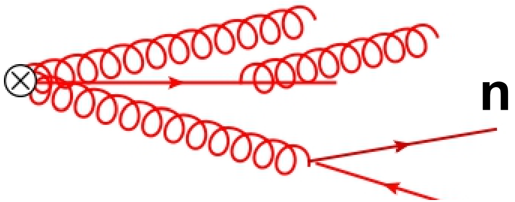
a. Derive factorization for jet observables in HIC.

b. Give a universal observable independent operator definition of the medium structure in analogy with PDF/TMDPDF for Hadrons.

An EFT within SCET

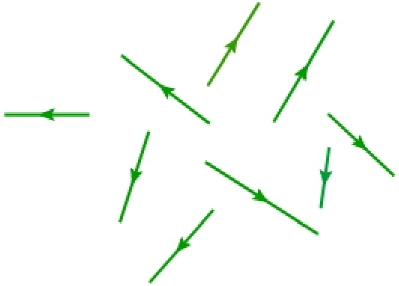
- The jet is made up of collinear partons

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



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

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



- Interaction between d.o.f s is dominated by forward scattering θ <<1

$$\lambda \sim \theta \leq \frac{T}{E_J} \sim \frac{q_T}{E_J} \sim \sqrt{e_i}$$

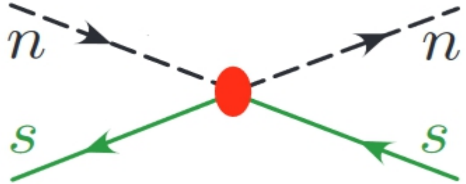
EFT for jet substructure in HIC

- The forward interaction between the Collinear and Soft modes is mediated by the Glauber mode.

$$L_{QCD} = L_c + L_s + L_G + O\left(\lambda^2\right) \qquad p_G \sim Q(\lambda, \lambda^2, \lambda)$$

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

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



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

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

How this EFT compares with previous formulations

Off shell Glauber mode is integrated out instead of the QGP degrees of freedom

Consequences

Manifestly Gauge invariant operators

Factorization formulas for observables can be derived rigorously

Factorization leads to Rapidity Divergences not observed in earlier EFTs

Treat QGP as a background Glauber field ($SCET_G$)

G. Ovanesyan and I. Vitev, JHEP 1106, 080 (2011)

G. Ovanesyan and I. Vitev, Phys. Lett. B 706, 371 (2012)

Y. T. Chien and I. Vitev, JHEP 1605, 023 (2016)

Jets as open quantum systems

QGP density matrix

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

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

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

$$O_{hard} = J_\mu^{SCET} L^\mu$$

- 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 H_G (but all order in H_{SCET})

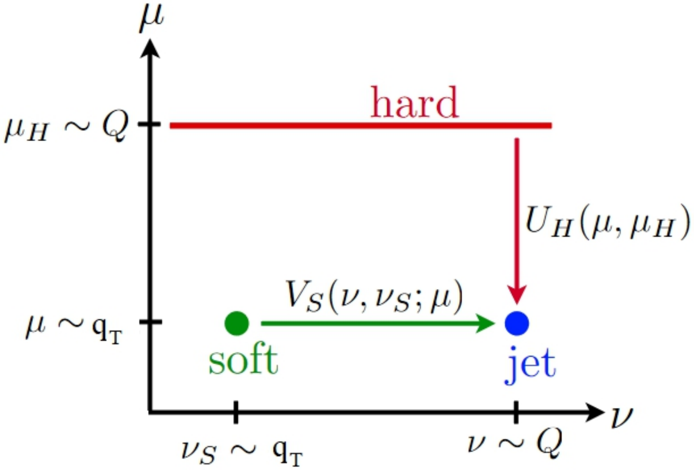
$$\Sigma(t) = Tr[\rho(t)M] = \underbrace{\Sigma^{(0)}(t)}_{O(H_G^0)} + \underbrace{\Sigma^{(1)}(t)}_{O(H_G^1)} + \underbrace{\Sigma^{(2)}(t)}_{O(H_G^2)} + \ldots$$

Factorization for reduced density matrix

Leading order ($H_G^{(0)}$): Vacuum evolution

$$\Sigma^{(0)}(q_T, e_n, e_{\bar{n}}) = \underbrace{V}_{\text{4 D Volume}} \times \underbrace{H(Q,\mu)}_{\text{hard function}} \underbrace{S(\vec{q}_T;\mu,\nu)}_{\text{Soft function}} \otimes_{q_T} \underbrace{\mathcal{J}_n^{\perp}(e_n, Q, z_{cut}, \vec{q}_T;\mu,\nu)}_{\text{Jet}} \otimes_{q_T} \mathcal{J}_{\bar{n}}^{\perp}(e_{\bar{n}}, Q, z_{cut}, \vec{q}_T;\mu,\nu)$$

- Using RG evolution in μ, ν allows us to resum large logarithms in q_T/Q, e_i



Factorization for reduced density matrix

Next to Leading order ($H_G^{(2)}$)

- Three time scales that characterize the system-medium interaction,

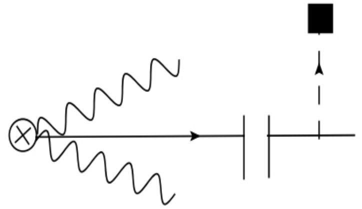
$t_e \sim 1/T$
Relaxation time of the bath :Time scale over which coherence is lost in the QGP bath

t
Time of propagation of the jet in the medium

$t_l \sim 1/(T\, \alpha_s(k_T))$
Emergent time scale of jet evolution in the medium

- For **$t \gg t_e$**, Dominant contribution comes from "**t/t_l**" enhanced terms,
- Partons go on-shell before interacting with the medium

- Assumption : The QGP bath is homogeneous over the length scale($\sim 1/k_T$) probed by a single jet-medium interaction .



Factorization for reduced density matrix

Next to Leading order $(H_G^{(2)})$

$$\Sigma^{(2)}(\vec{q}_T, e_n, e_{\bar{n}}) = t \times |C_G|^2 \Sigma^{(0)}(\vec{q}_T, e_n, e_{\bar{n}}) \otimes_{q_T} \int d^2k_\perp S^{AB}_{\rm Med}(k_\perp) \mathcal{J}^{AB}_{n,{\rm Med}}(e_n, \vec{q}_T, \vec{k}_\perp)$$

jet propagation time in medium

hard function

Vacuum density matrix

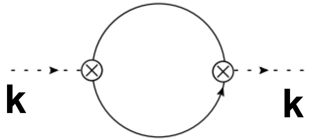
Medium structure function

Medium Jet function

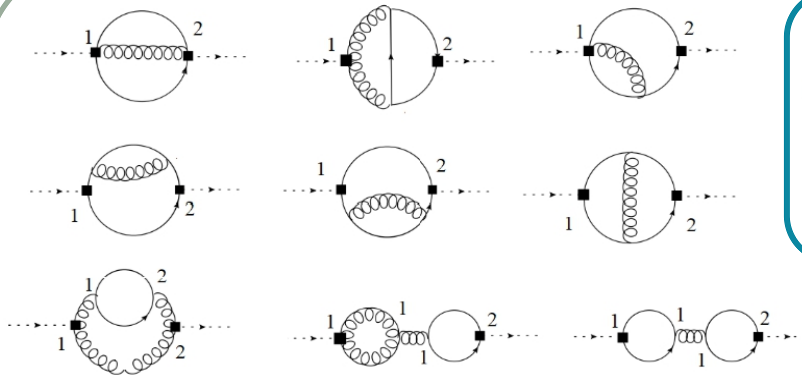
$$S^{AB}_{\rm Med}(k_\perp) = 2(2\pi)^3 \frac{1}{k_\perp^2} \int \frac{dk^-}{2\pi} \int d^4x e^{-ik\cdot x} \langle X_S | O^A_S(x) \rho_B O^B_S(0) | X_S \rangle$$

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

Renormalization for Soft correlator in a thermal medium



$$\frac{\delta^{AB}}{k_\perp^2}\int d^2p_\perp \int_0^\infty dp^+ \left\{ n_F\left(\left|\frac{p^+}{2}+\frac{p_\perp^2}{2}\right|\right)\left[1-n_F\left(\left|\frac{p^+}{2}+\frac{(\vec{p}_\perp+\vec{k}_\perp)^2}{2p^+}\right|\right)\right]\right\}$$



One loop corrections in the thermal medium using Real Time formalism

$$\nu\frac{d}{d\nu}S(\vec{k}_\perp) = \frac{\alpha_s N_c}{\pi^2}\int d^2q_\perp\left(\frac{S(\vec{q}_\perp)}{(\vec{q}_\perp-\vec{k}_\perp)^2} - \frac{k_\perp^2 S(k_\perp)}{2q_\perp^2(\vec{q}_\perp-\vec{k}_\perp)^2}\right)$$

BFKL equation

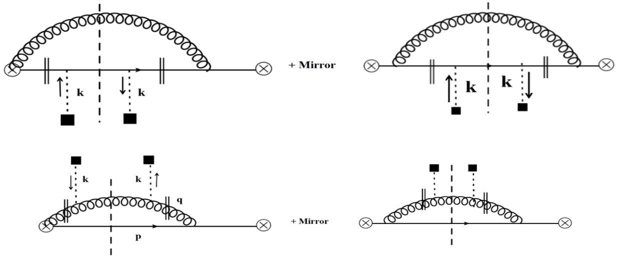
$$\mu\frac{d}{d\mu}S(\vec{k}_\perp) = -\frac{\alpha_s\beta_0}{\pi}$$

Running of the QCD coupling

$$\mu \sim k_\perp$$

Renormalization for the medium jet function

Elastic collision with medium



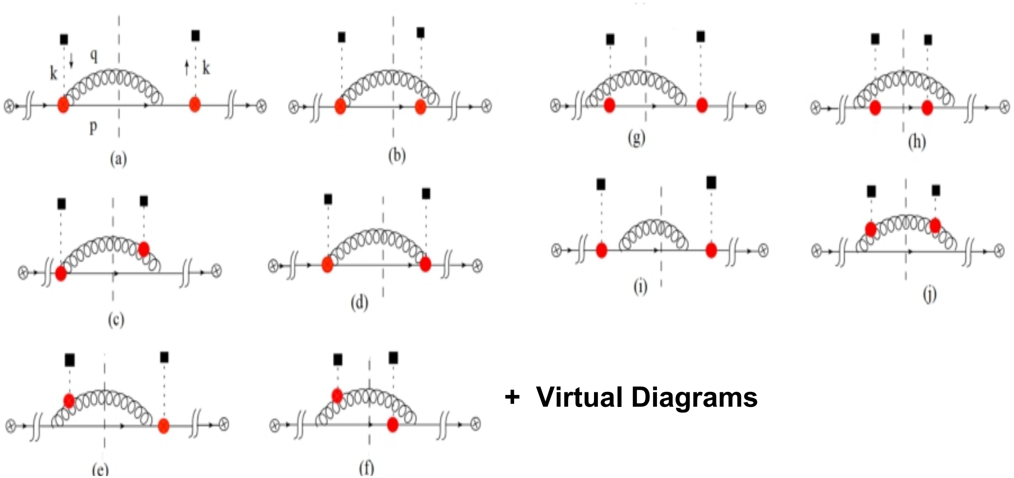
$$J(k_\perp) \propto \frac{(k_\perp^2/Q^2)\alpha_s}{(e_n + k_\perp^2/Q^2)} \ln \frac{e_n}{(m_D^2/Q^2)}$$

UV finite IR sensitive logarithm

⇩

Requires matching to EFT at $\sim m_D$

Medium induced Bremsstrahlung



+ Virtual Diagrams

$$\nu \frac{d}{d\nu} J(\vec{k}_\perp) = -\frac{\alpha_s N_c}{\pi^2} \int d^2 q_\perp \left(\frac{J(\vec{q}_\perp)}{(\vec{q}_\perp - \vec{k}_\perp)^2} - \frac{k_\perp^2 J(k_\perp)}{2q_\perp^2 (\vec{q}_\perp - \vec{k}_\perp)^2} \right)$$

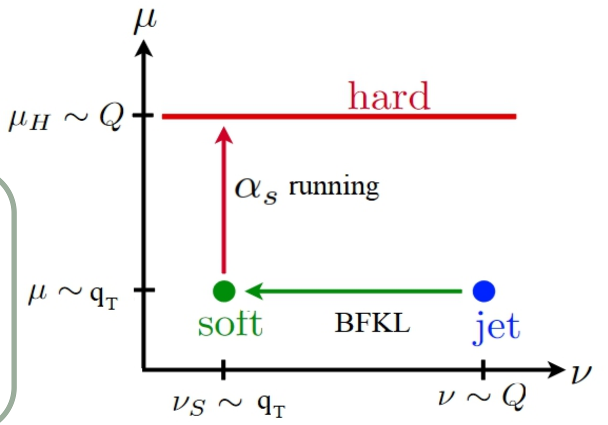
BFKL equation

Solution for the RG equations

Solution for rapidity RGE -> Solution for the BFKL equation

$$J(\mu,\nu_f,k_\perp,\vec{q}_{T_n}) = \sum_{n=-\infty}^{\infty}\int_{a-i\infty}^{a+i\infty}\frac{d\gamma}{2\pi^2 i}k_\perp^{2(\gamma-1)}q_{Tn}^{2(\gamma^*-1)}e^{in(\phi_k-\phi_{q_{Tn}})}e^{-\frac{\alpha_s(\mu)N_c}{\pi}\chi_{n,\gamma}\ln\frac{\nu_f}{Q}}$$

Can be solved numerically using Saddle point approximation



Running the soft function in μ

$$S(k_\perp,\nu\sim k_\perp,\mu\sim Q) = S(k_\perp,\nu\sim k_\perp,\mu\sim k_\perp)e^{-\int_{k_\perp}^{Q}d\ln\mu\frac{\alpha_s(\mu)\beta_0}{\pi}}$$

Master Equation

$$\Sigma(\vec{q}_T, e_n, e_{\bar{n}}, t) = \Sigma^{(0)}(\vec{q}_T, e_n, e_{\bar{n}})(1 - Rt) + t \int d^2p_\perp K_{\text{Med}}(p_\perp)\Sigma^{(0)}(\vec{p}_\perp + \vec{q}_T, e_n, e_{\bar{n}}) + O(H_G^3)$$

$$\mathrm{K}_{\text{Med}}(p_\perp) = \int \frac{d^2k_\perp}{(2\pi)^4} S_G^{\text{resum}}(k_\perp) J^{\text{Resum}}(Q, z_{cut}, \vec{p}_\perp, k_\perp)$$

$$R = \int d^2p_\perp K_{\text{Med}}(p_\perp)$$

Taking the limit t $\rightarrow 0$ yields an evolution equation for **multiple incoherent medium-jet interactions**

$$P(\vec{q}_T) \equiv \frac{d\sigma(t)}{d^2\vec{q}_T} = \mathcal{N}\frac{\Sigma(t)}{V}$$

$$\partial_t P(\vec{q}_T)(t) = -RP(\vec{q}_T) + P(\vec{q}_T) \otimes_{q_T} K_{\text{Med}}(\vec{q}_T)$$

Introduce time dependence in S_G to account for inhomogeneity of the medium over length scales >> 1/kT

$$\partial_t P(\vec{q}_T)(t) = -R(\mathrm{t})\, P(\vec{q}_T, \mathrm{t}) + P(\vec{q}_T, \mathrm{t}) \otimes_{q_T} K_{\text{Med}}(\vec{q}_T, \mathrm{t})$$

Master Equation

Evolution equation can be solved in impact parameter space.

$$\frac{d\sigma}{d^2q_T}(t, e_n, e_{\bar{n}}) = \int d^2\vec{b}e^{i\vec{b}\cdot\vec{q}_T}\sigma^{\text{vac}}(\vec{b}, e_n, e_{\bar{n}}) \times e^{\int_0^t d\bar{t}\left(-R(\bar{t})+K_{\text{Med}}(\vec{b},\bar{t})\right)}$$

Cross section as a function of medium propagation time

Factorized and resummed Vacuum cross section

Factorized and resummed medium kernel

- Resums mutiple interactions of the jet partons with the medium accounting for leading 't' enhanced terms to all orders taking into account medium inhomogeneity.
- Systematic higher order corrections to R (multiple coherent Glauber exchanges) allow us to go beyond the independent scattering paradigm : **arXiV 2101.02225 V.V.**

What do we learn from this analysis

- Careful selection of jet observables is necessary in messy HIC environment to make sensible comparisons with pp.
- It is possible to derive a factorization formula for jet observables assuming medium homogeneity over certain scales (~ 1/kT)
- The information about the medium properties is encoded in a soft correlator which has both UV and rapidity divergences.
- A coherent interaction of the jet with the medium is captured by the BFKL equation.
- Multiple incoherent jet-medium interactions with an inhomogeneous medium(>>1/kT) are captured by a Lindblad type evolution equation.

Stay tuned for the numerics!

Open Questions

- A phenomenological prediction including nuclear pdf's.
- Match to the EFT at scale m_D account for medium induced IR logarithms
- Extend formalism to jets initiated by heavy quarks-> PHENIX and sPHENIX
- Apply this formalism for jet propagation in cold nuclear matter (EIC)?

THANKS!