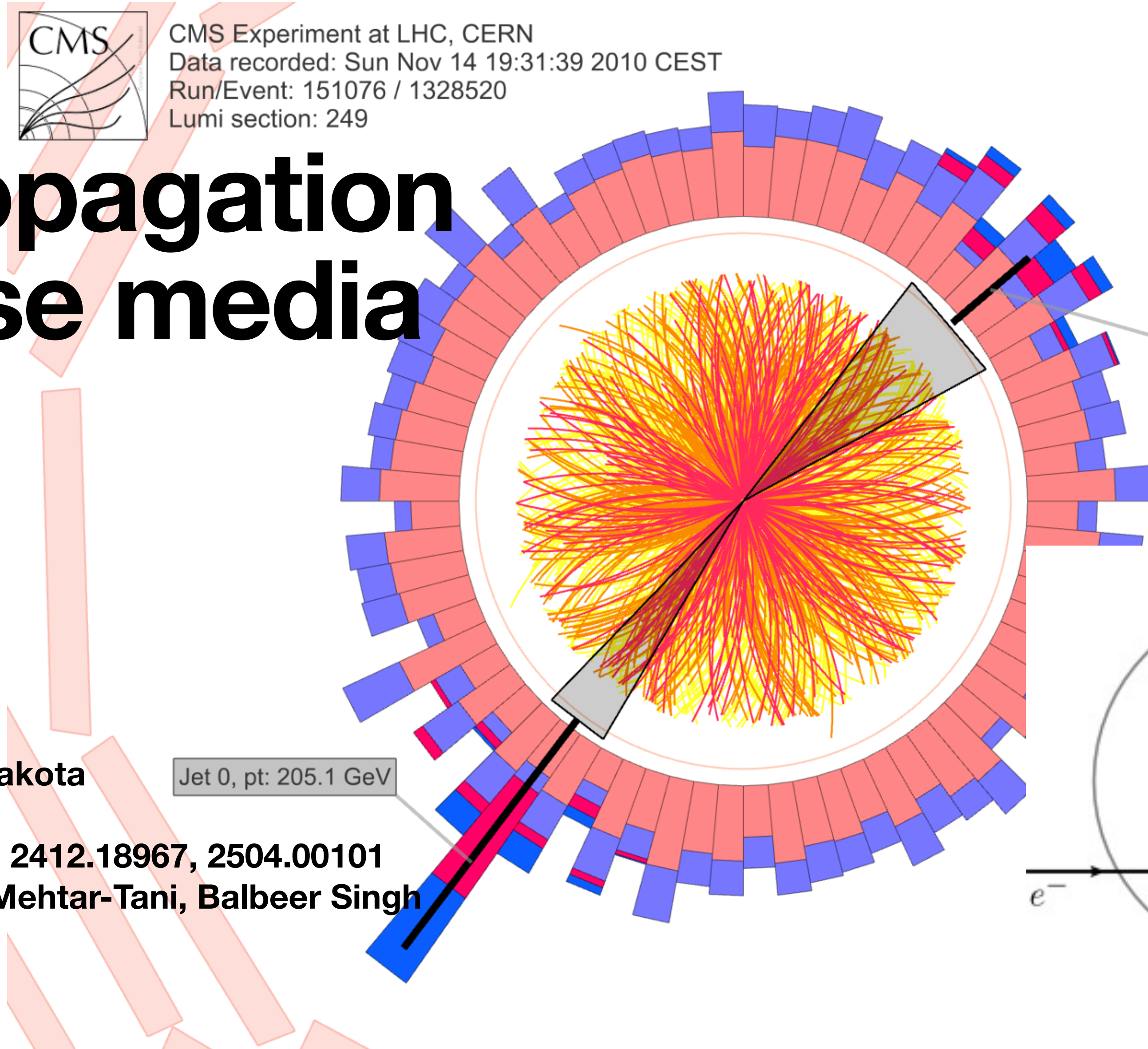
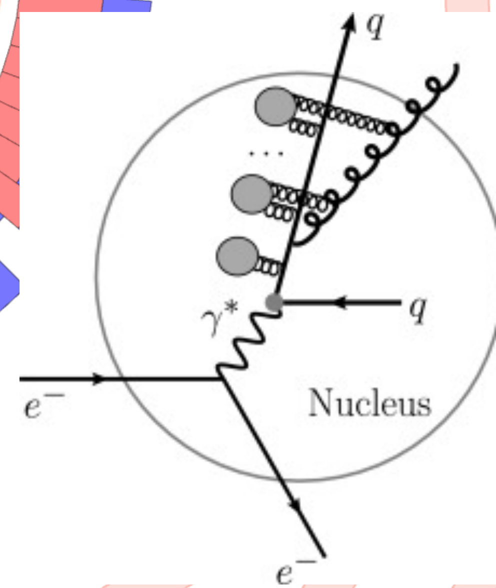
Jet propagation in dense media

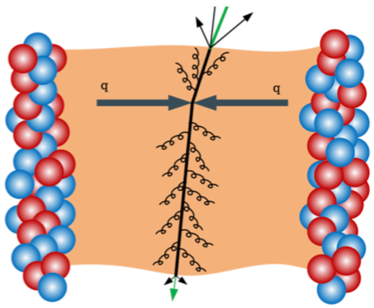




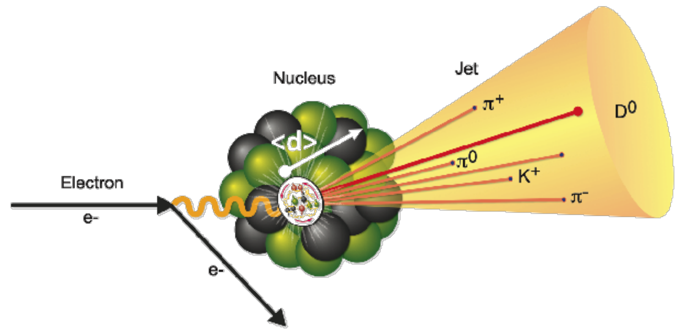
Varun Vaidya,
University of South Dakota

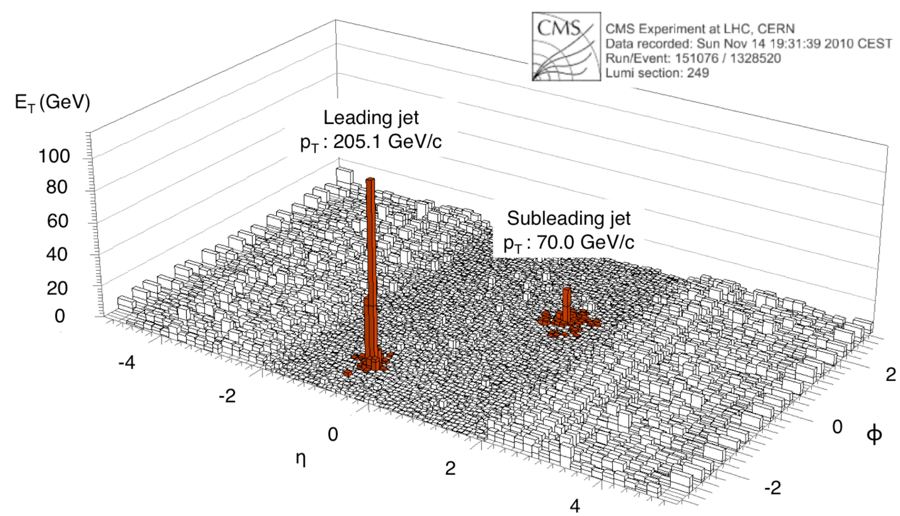
on 2409.05957, 2412.18967, 2504.00101
Felix Ringer, Yacine Mehtar-Tani, Balbeer Singh

Jets in a Nuclear medium



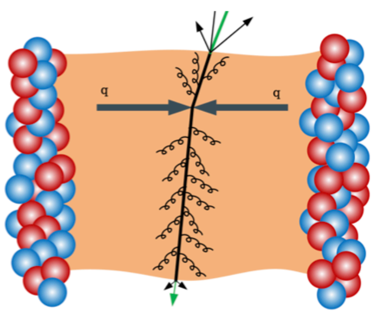
A+A





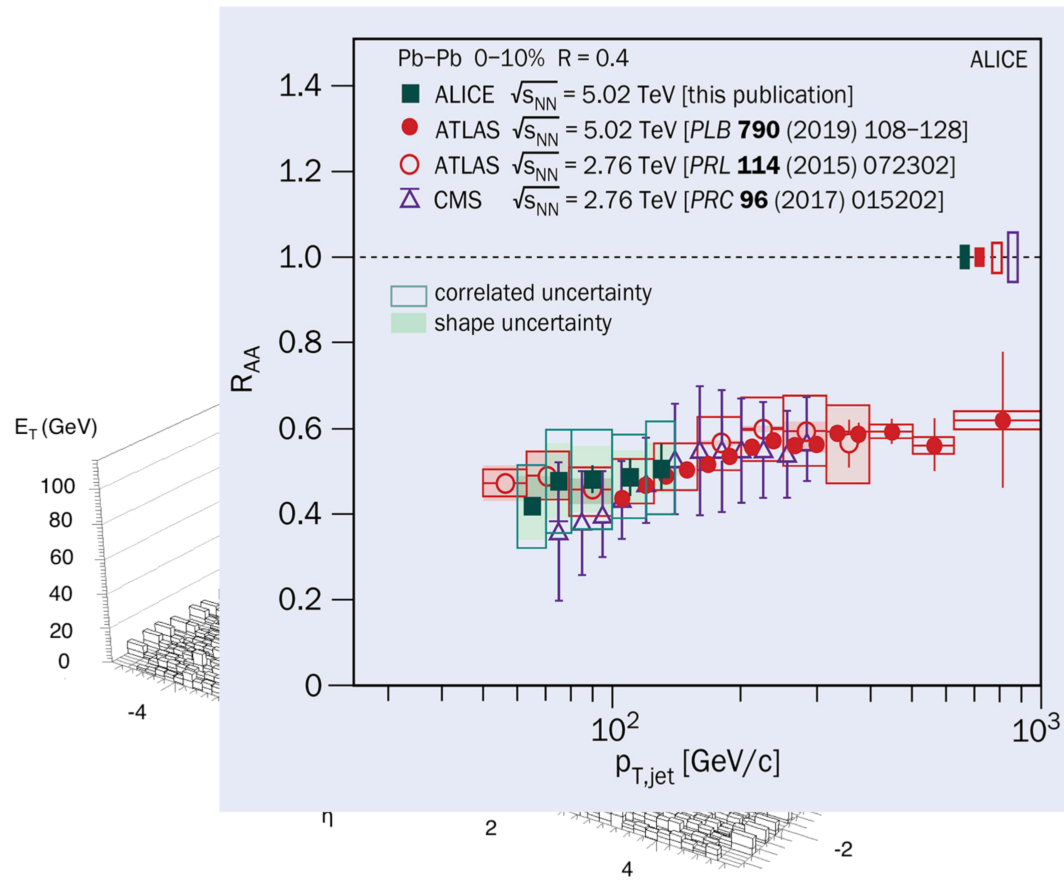
- We can use the jet to access the microscopic structure of the strongly coupled Nuclear medium.
- How does the jet evolve in the medium?

Jets lose energy and are "Quenched"

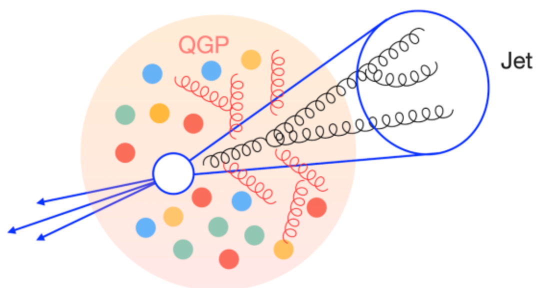


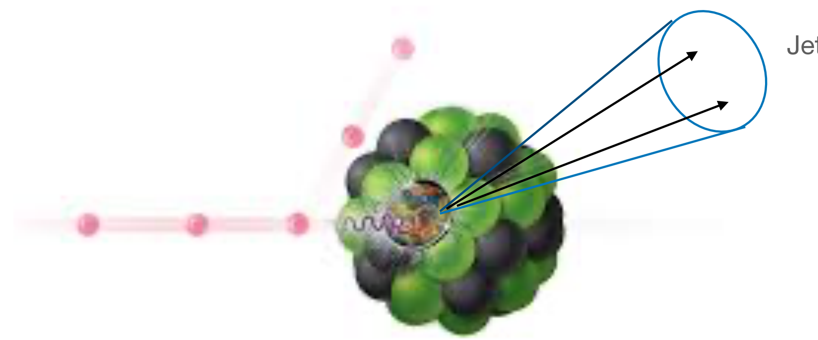
A+A

- We can use the jet to access the microscopic structure of the strongly coupled medium.
- How does the jet evolve in the medium?



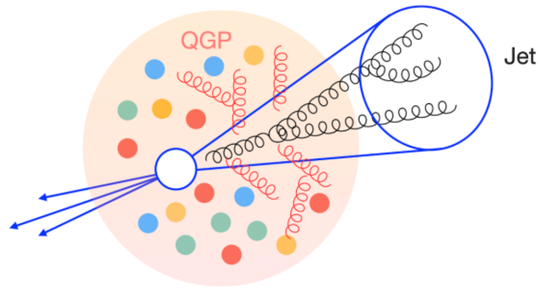
Poking a nuclear blob

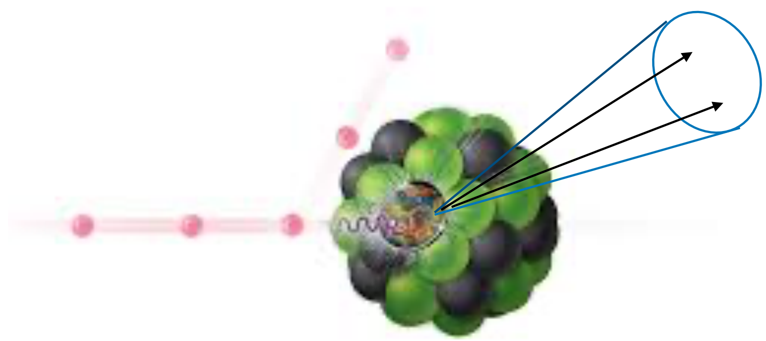




- This is NOT a new problem in nuclear physics
- A high energy probe scattering off a strongly coupled target.
- We rely on **Factorization.**

Key questions for jet production and evolution in medium



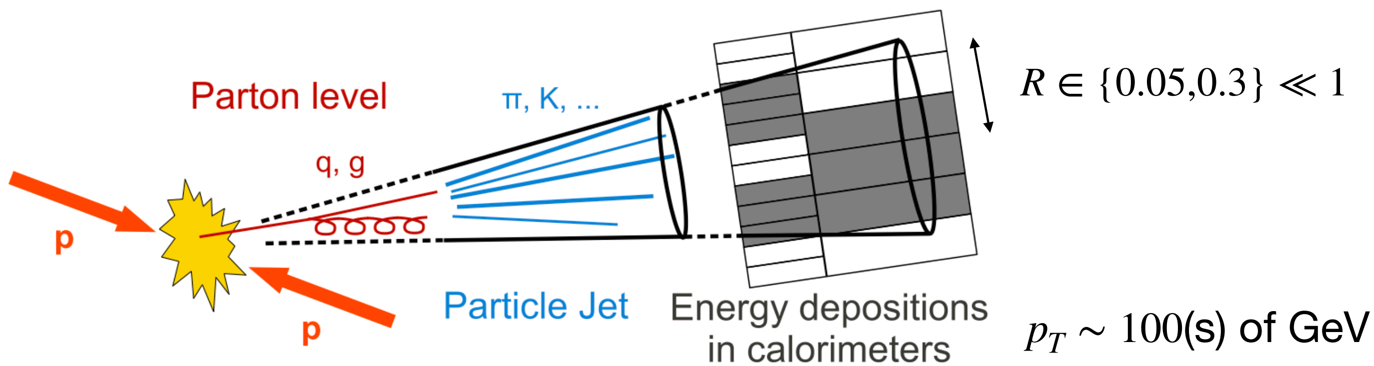


- **Separate** the **perturbative physics** from the non-perturbative by scale
- **Parameterize** the **non-perturbative physics** in terms of Gauge invariant operators.

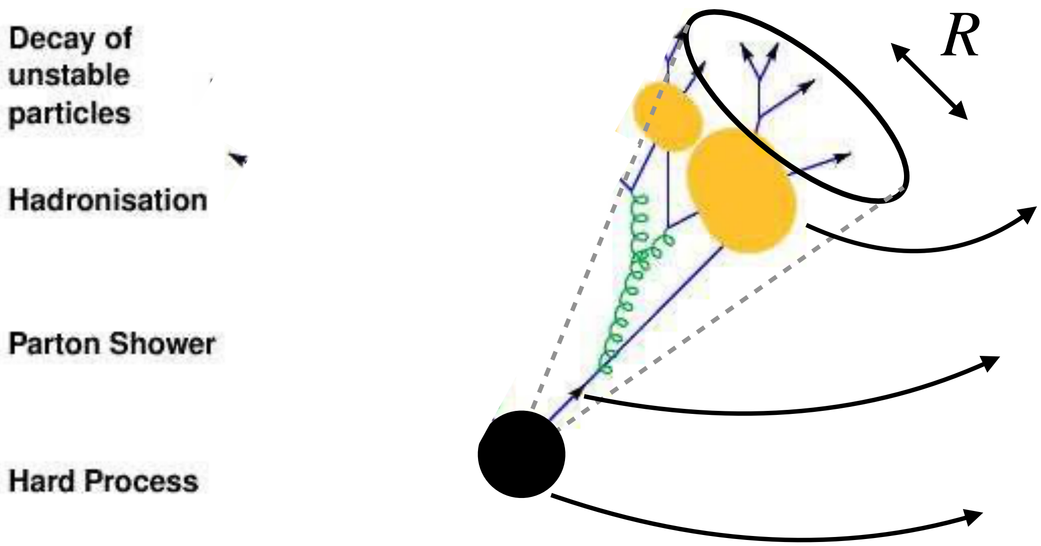
  Prove (disprove) universality of non-perturbative physics across jet observables → **Universality** gives **predictive power** !

1

Anatomy of a vacuum jet



Physical picture



		LHC	EIC
$p^2 \sim \Lambda^2_{\text{QCD}}$		100(s) MeV	100(s) MeV
$p^2 \sim (p_T R)^2$	**Jet Scale**	10(s) GeV	Few GeV
$p^2 \sim p_T^2$	**Hard Scale**	100(s) GeV	10(s) GeV

$$\lambda_1 = R, \quad \lambda_2 = \frac{\Lambda_{QCD}}{p_T R} \rightarrow$$ **A sequence of two EFTs**

The factorized probe

$$\frac{d\sigma^{pp\to \mathrm{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^1 \frac{dx_a}{x_a} f_a(x_a,\mu) \int_{x_b^{\min}}^1 \frac{dx_b}{x_b} f_b(x_b,\mu)$$

Physics at scale Λ_{QCD}

$$\times \int \frac{dz}{z} H(z, x_a, x_b, \mu) \; J_c(z, p_T, R, \mu) \qquad + O(R^2) + O\left(\frac{\Lambda_{QCD}^2}{(p_T R)^2}\right)$$

Hard function at p_T

Jet function at $p_T R$

The semi-inclusive jet function in SCET and small radius resummation for inclusive jet production

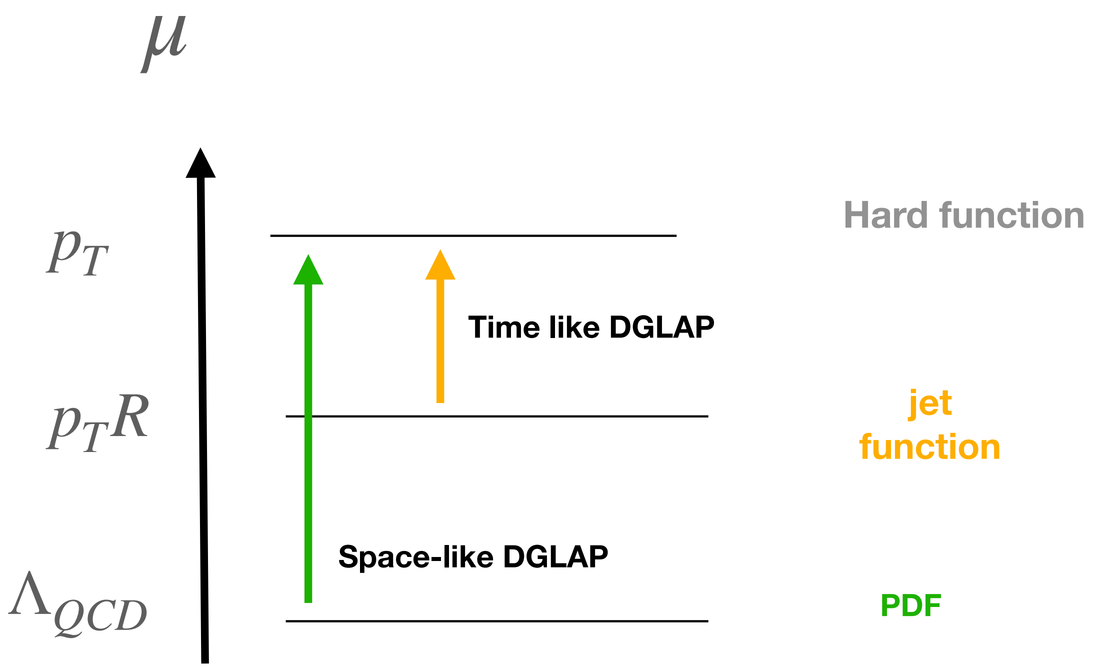
Zhong-bo Kang, Felix Ringer and Ivan Vitev
JHEP 10 (2016) 125

$\longrightarrow$

Updated version

K. Lee. and I.Moult 2410.01902

RG Flow



μ
p_T
$p_T R$
Λ_{QCD}
Time like DGLAP
Space-like DGLAP
Hard function
jet
function
PDF

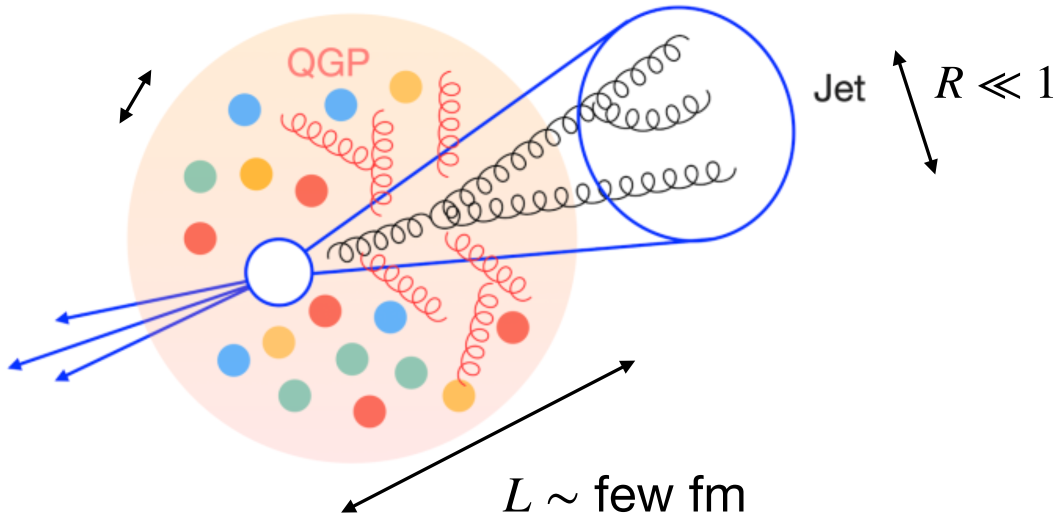
2

Introducing the QGP/Nuclei

New medium scales

color screening length

$\frac{1}{m_D}$



jet p_T

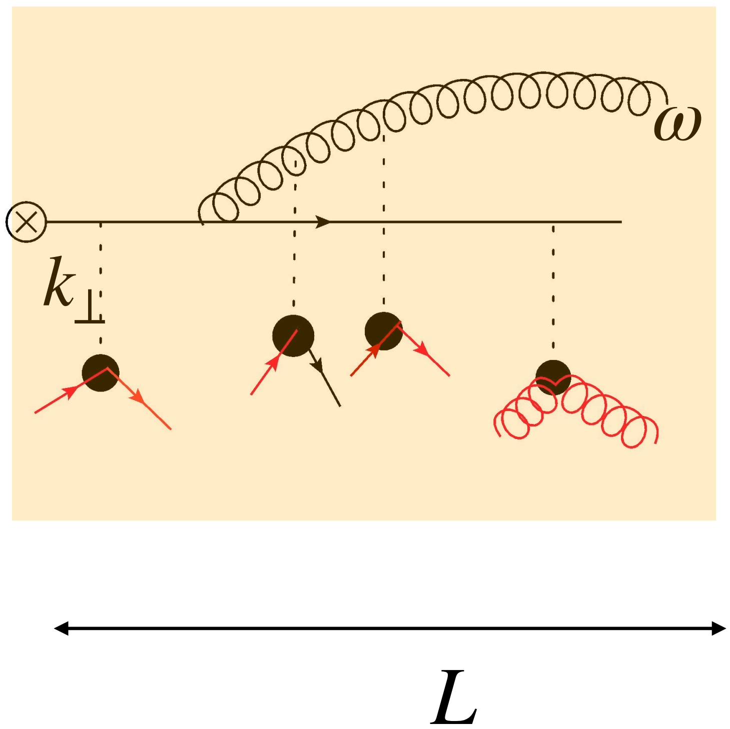
$p_T R$

Λ_{QCD}, T, m_D

- Avg QGP temperature T $\sim 200 - 300$ MeV

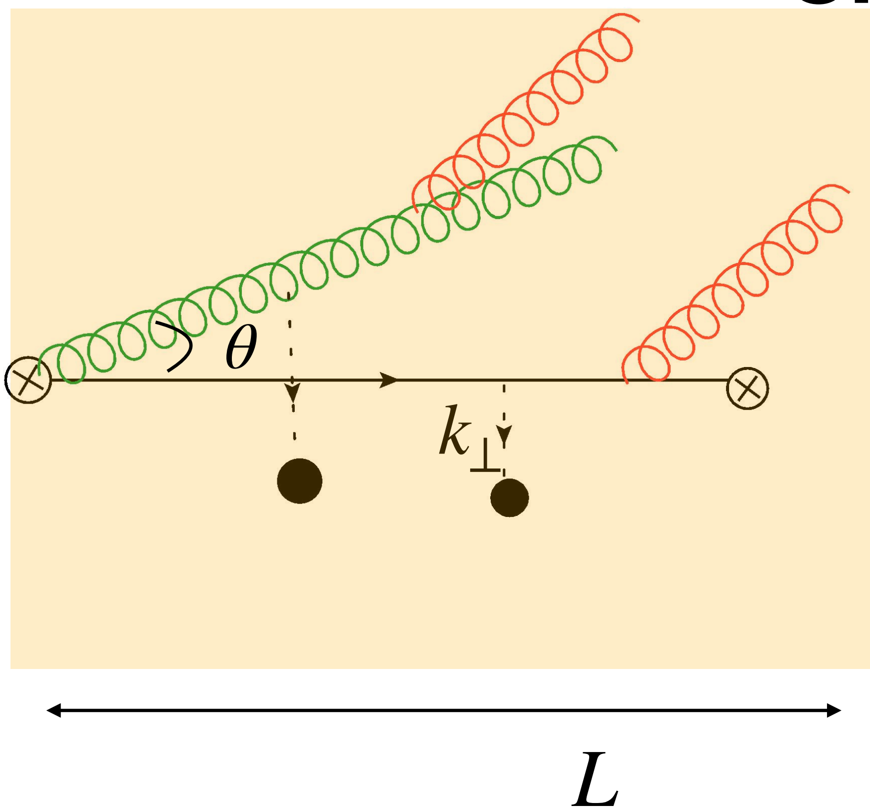
The jet interacts multiple times with the medium → Open quantum system
There are other emergent scales which arise.

Parton in the medium



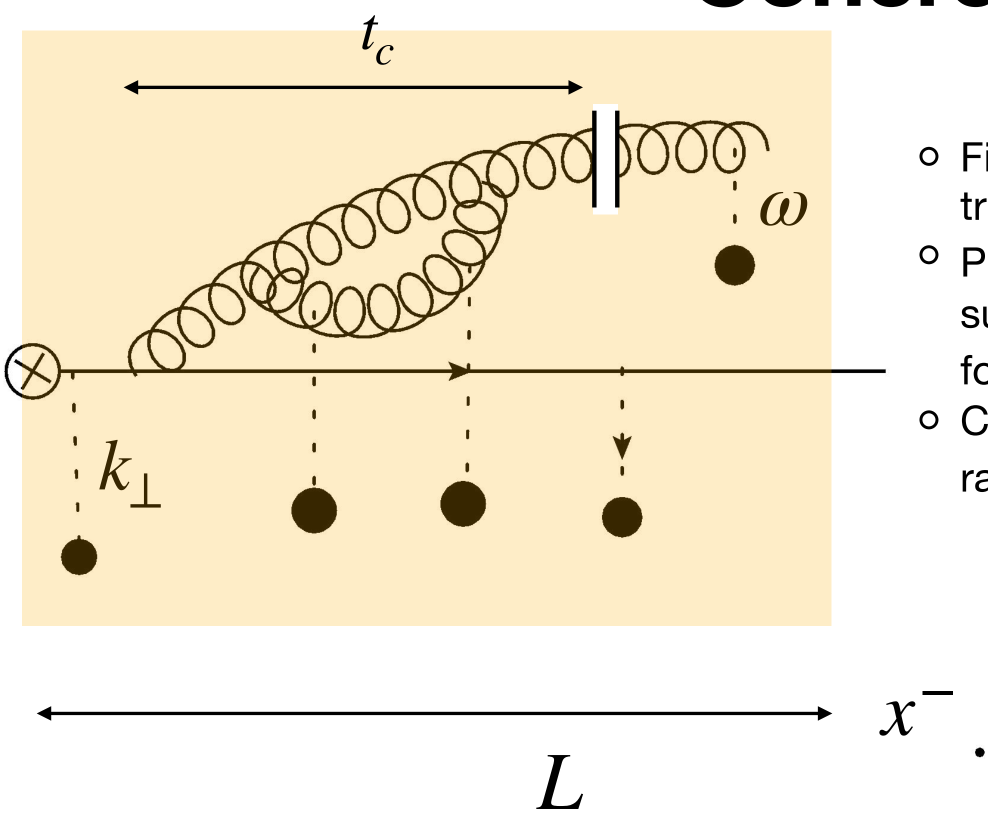
- $Q_{\text{med}} \rightarrow$ Total average transverse kick per parton $\geq m_D$
- For a dense medium, perturbative?

Critical angle



- Critical angle of the medium $\theta_c \sim \dfrac{1}{Q_{\text{med}} L}$
- Energetic partons separated by $\theta \gg \theta_c$ act as independent sources of medium induced radiation

Coherence time



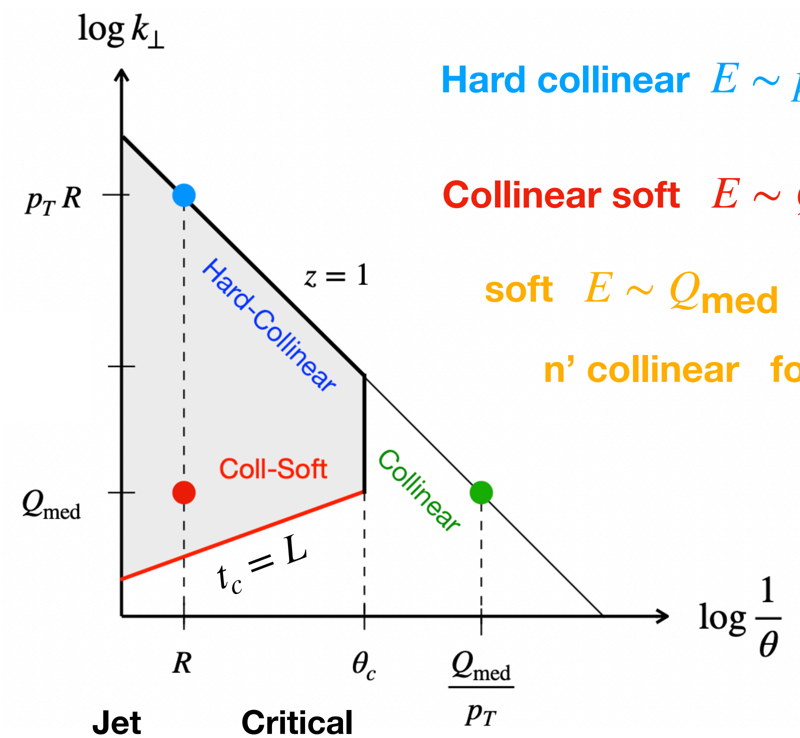
- Finite medium length breaks translational invariance .
- Phase factor ~ $\exp\{iLp^+\}$ strongly supresses medium induced radiation for $Lp^+ \ll 1 \rightarrow$ LPM Effect
- Characterized by the coherence time of radiation $t_c = 1/p^+$

Jet physics at the EIC

Case 1 : $Q_{\text{med}} \leq 1$**GeV** $\rightarrow$ **Non-perturbative scale**

Vacuum Jet scale

Typical medium transverse kick



Jet Radius **Critical Angle**

Hard collinear $E \sim p_T, \ \theta \sim R$

Collinear soft $E \sim Q_{\text{med}}/R, \ \theta \sim R$

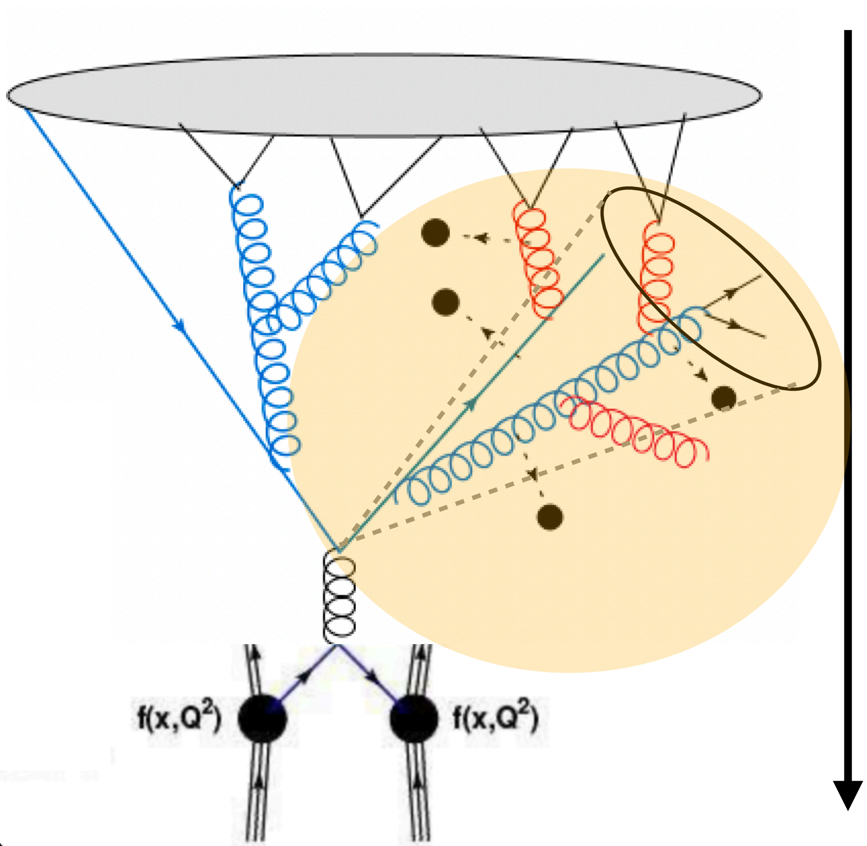
Jet degrees of freedom

soft $E \sim Q_{\text{med}}$ **for QGP**

n' collinear for EIC

Medium

The hierarchy of scales



$\sqrt{p^2} \sim m_D \sim \Lambda_{\text{QCD}} \sim \sqrt{Q^2_{\text{med}}}$ 100(s) MeV

$\sqrt{p^2} \sim p_T R \sim p_T \theta_c$ Few GeV

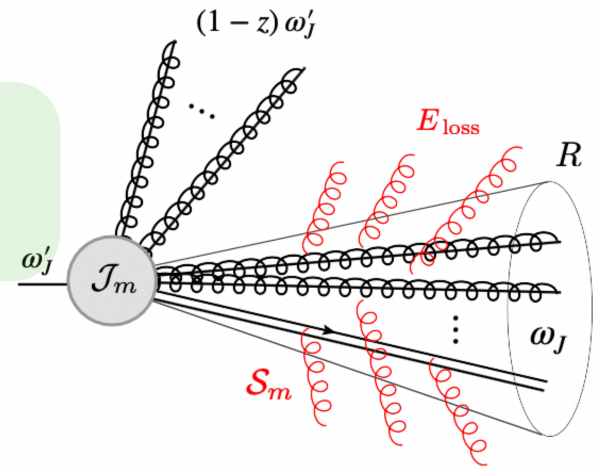
$\sqrt{p^2} \sim p_T$ 10(s) GeV

The EFT picture*

$$\frac{d\sigma^{AA\to \mathrm{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)$$

$$\times\int\frac{dz}{z}H(z,x_a,x_b,\mu)$$

Hard process $\to$ Wilson coeff at p_T



$$\times\int_{\omega_J}^{\frac{\omega_J}{z}}d\omega_J'\int d\epsilon\,\delta(\omega_J'-\omega_J-\epsilon)\sum_{m=1}^{\infty}\langle\mathcal{J}_{i\to m}(\omega_J',\mu,\theta_c)\otimes_\theta S_m(\epsilon,\mu)\rangle + O(R^2) + O\left(\frac{Q_{\mathrm{med}}}{p_T R}\right)^2$$

Create m prongs $\to$ Wilson coeff at $p_T R$

Medium induced energy loss function

Exactly same structure as factorization for Non-Global logs*!

* V. Vaidya et. al. , arXiV: 2409.05957

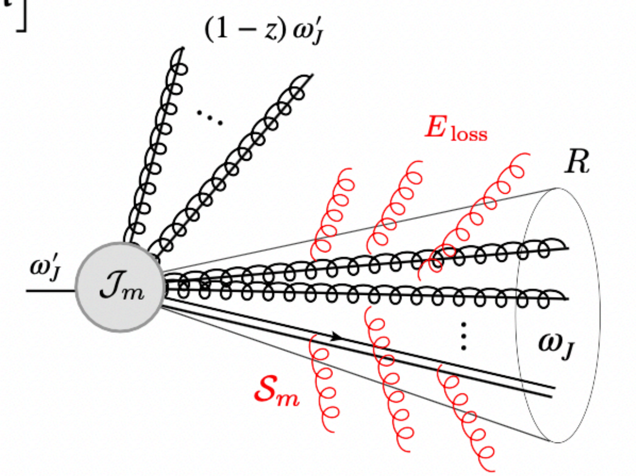
*T. Becher et. al, Phys. Rev. Lett. 116, 192001

The medium energy loss function

$$\mathcal{S}_m(\{\underline{n}\},\epsilon) \equiv \mathrm{Tr}\Big[U_m(n_m)...U_1(n_1)U_0(\bar{n})\rho_M U_0^\dagger(\bar{n})U_1^\dagger(n_1)...U_m^\dagger(n_m)\mathcal{M}\Big]$$

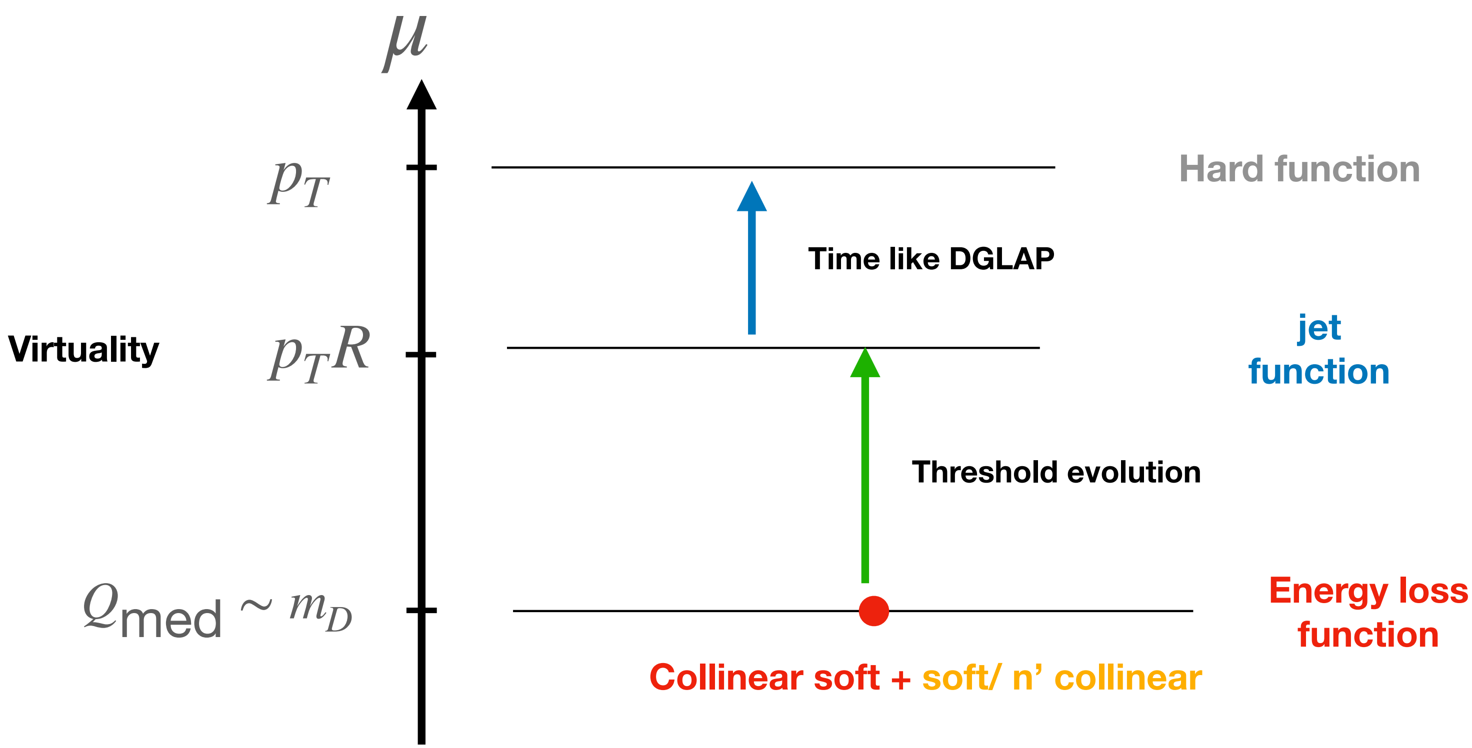
Correlator of m Wilson lines sourced by m subjet prongs.

$$U(n) \equiv \mathcal{P}\exp\left[ig\int_0^{+\infty} \mathrm{d}s\, n\cdot A_{\mathrm{cs}}(sn)\right]$$



Each function is a distinct non-perturbative function that needs to be extracted from experiment.
No description in terms of a jet quenching parameter $\hat{q}$.

Medium Jet RG Flow : Dilute medium



Jet physics at the EIC

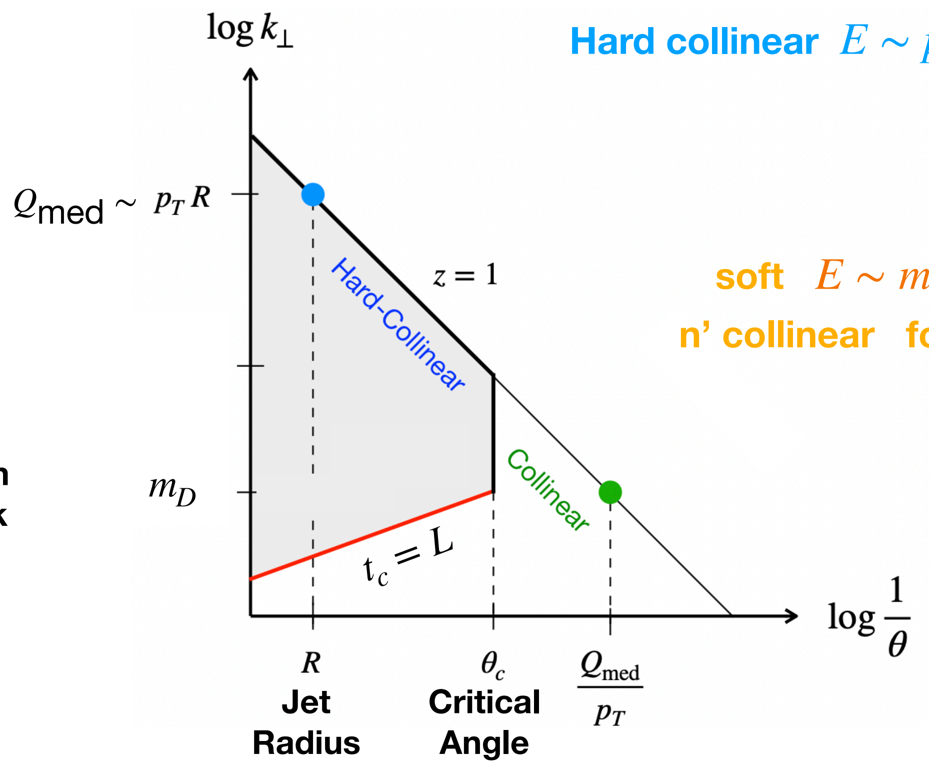
Case 2: $Q_{\text{med}} \gg m_D \sim p_T R \rightarrow$ **Perturbative scale**

Hard collinear $E \sim p_T,\ \theta \sim R$ } Jet degrees of freedom

soft $E \sim m_D$
n' collinear for EIC } Medium

Vacuum Jet scale

Typical medium transverse kick



The factorized probe

$$\frac{d\sigma^{pp\to\text{jet}X}}{dp_T d\eta} = \frac{2p_T}{s}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)$$

Physics at scale Λ_{QCD}

$$\times\int\frac{dz}{z}H(z,x_a,x_b,\mu)\;J_c(z;p_TR\sim Q_{\text{med}},\mu,m_D)\quad+O(R^2)$$

Hard function at p_T

Jet function at p_TR

A further factorization is needed to completely separate the non-perturbative physics at the scale m_D

An EFT within SCET

- Interaction between d.o.f s is dominated by forward(small angle) scattering mediated by the Glauber mode.

An effective field theory for forward scattering and factorization violation
I. Rothstein, I. Stewart, JHEP 1608 (2016) 025

$$L_{QCD} = L_{n,coll} + L_{n',coll} + L_{Glauber} + O(x^2)$$
$$\equiv L_{SCET} + L_G$$

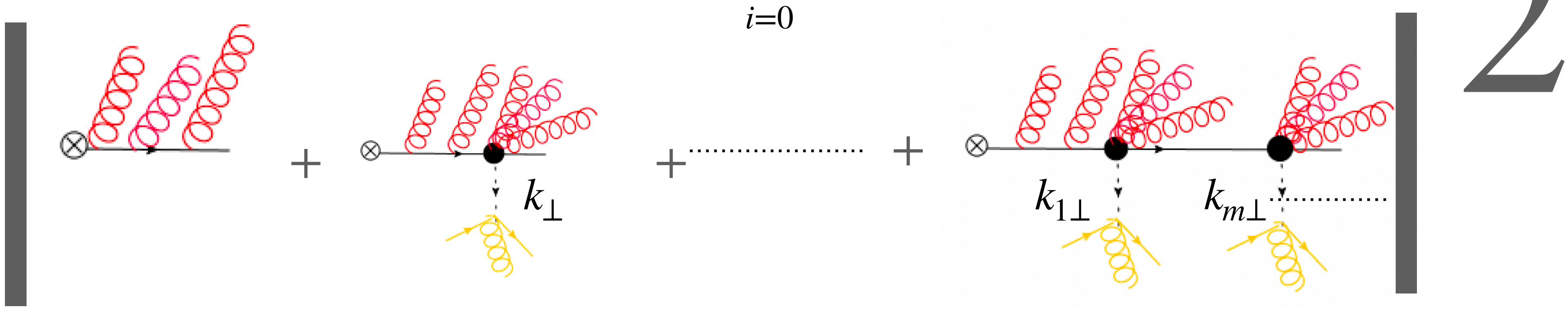
$$O_n^{q\alpha} = \bar{\chi}_n W_n T^\alpha \frac{\bar{n}}{2} W_n^+ \chi_n$$

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

Gauge invariant building block

Looking inside the jet function

$$J_c(p_T R, m_D, \mu) = \sum_{i=0}^{\infty} \bar{\mathcal{J}}_i(n, p_T R, m_D, \mu)$$



Assuming successive interactions happen with color uncorrelated partons

$$\bar{\mathcal{J}}_0(n, p_T R, \mu) + \int d^2k_\perp \bar{\mathcal{J}}_1(n, p_T R, k_\perp, \mu, \nu)\, \mathcal{B}(k_\perp, \mu, \nu) + \cdots\cdots \prod_{i=1}^{m} \int d^2k_{i\perp} \mathcal{B}(k_{i\perp}, \mu, \nu)\, \bar{\mathcal{J}}_m(n, p_T R, k_{1\perp}, \ldots k_{m\perp}, \mu, \nu)$$

Vacuum jet function + **All order collinear radiation with Single medium interaction** + ... **m medium interactions**

Single medium interaction

$$\int d^2k_\perp \mathcal{J}_1(n, p_T R, k_\perp, \mu, \nu) \;\; \mathcal{B}(k_\perp, \mu, \nu)$$

Single medium interaction

$$\mathcal{B}(k_\perp, \mu, \nu) \equiv \int d^2 r_\perp e^{i\vec{k}_\perp \cdot \vec{r}_\perp} \langle O^A_{n'}(r_\perp) \rho_M \; O^A_{n'}(0) \rangle$$

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

A gauge invariant operator definition → Wightman correlator at LO

$$\frac{d}{d\ln\nu}\mathcal{B}(k_\perp, \mu, \nu) = \int d^2u_\perp K_{BFKL}(k_\perp, u_\perp)\mathcal{B}(u_\perp, \mu, \nu)$$

$$\frac{d}{d\ln\mu}\mathcal{B}(k_\perp, \mu, \nu) = -\frac{\alpha_s \beta_0}{\pi}\mathcal{B}(k_\perp, \mu, \nu)$$

$\mathcal{J}_1(n, \epsilon, k_\perp, \nu)$ → **obeys BFKL evolution in ν. DGLAP in μ**

Broadening with Multiple interactions

$$\mathcal{J}_1^{(1)} = \int d^2\mathbf{p} F(\mathbf{p}, R, m_D) P(\mathbf{p}, R, m_D)$$

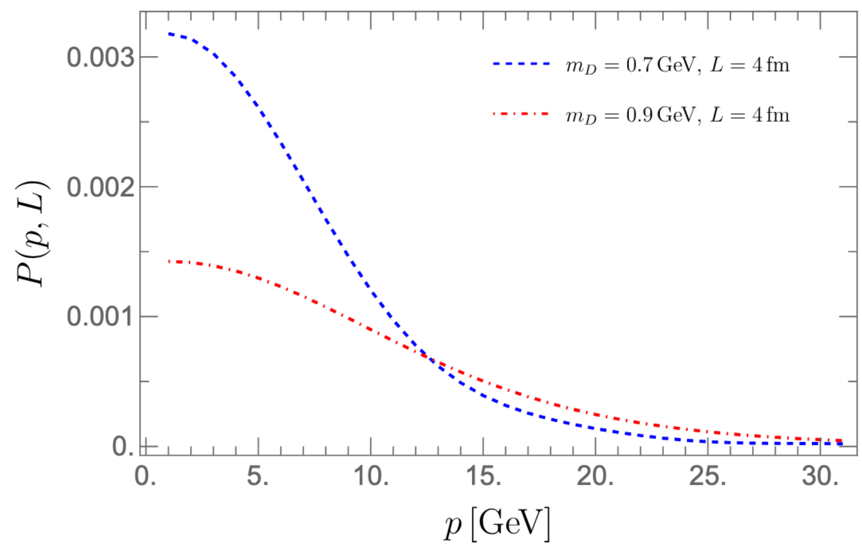
Probability of parton production

Probability distribution of broadening

$$\langle |\mathbf{p}| \rangle \sim Q_{\text{med}} \gg m_D$$

An emergent perturbative scale that depends on medium density and interaction strength

$$P(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\hat{q}}$$



One important difference, there is possibility of the gluon splitting to happen at low transverse momentum $m_D \ll Q_{\text{med}}$ $\rightarrow$ The vacuum gluon production can be non-perturbative.

$\hat{q}$ is insufficient to fully parameterize the non-perturbative physics $\rightarrow$ How do we further factorize?

*** V. Vaidya et. al. , arXiV: 2412.18967**

Epilogue

- Quantitative precision in a non-perturbative medium requires us to adopt an effective field theory framework.
- A factorization formula for jet propagation that explicitly isolates physics at widely separated scales.
- Distinct structure for dense/dilute medium.

Still to be done …

- Factorization for gluon production mechanism in dense medium $\rightarrow$ Will lead to a complete parameterization of non-perturbative physics.