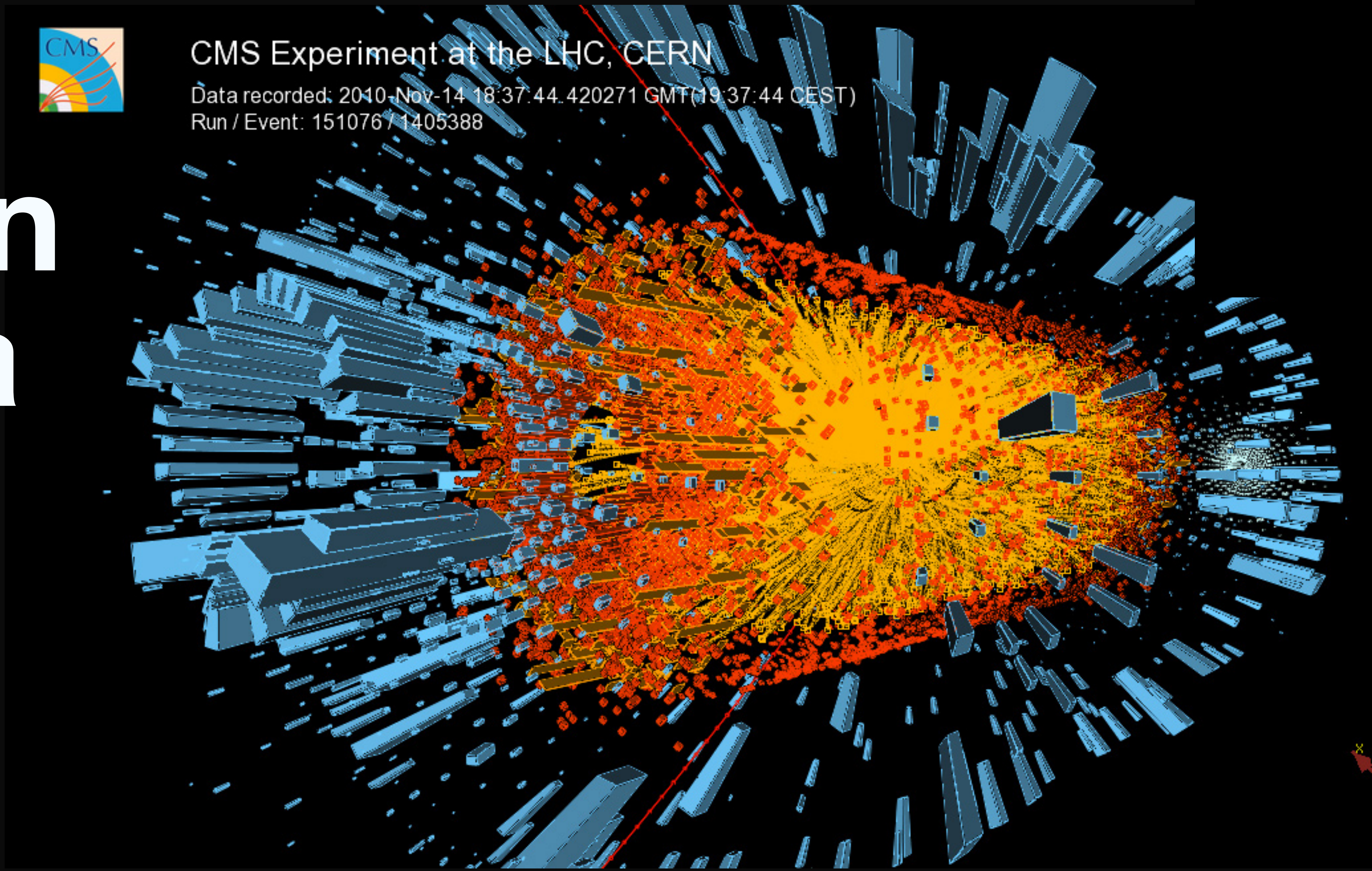
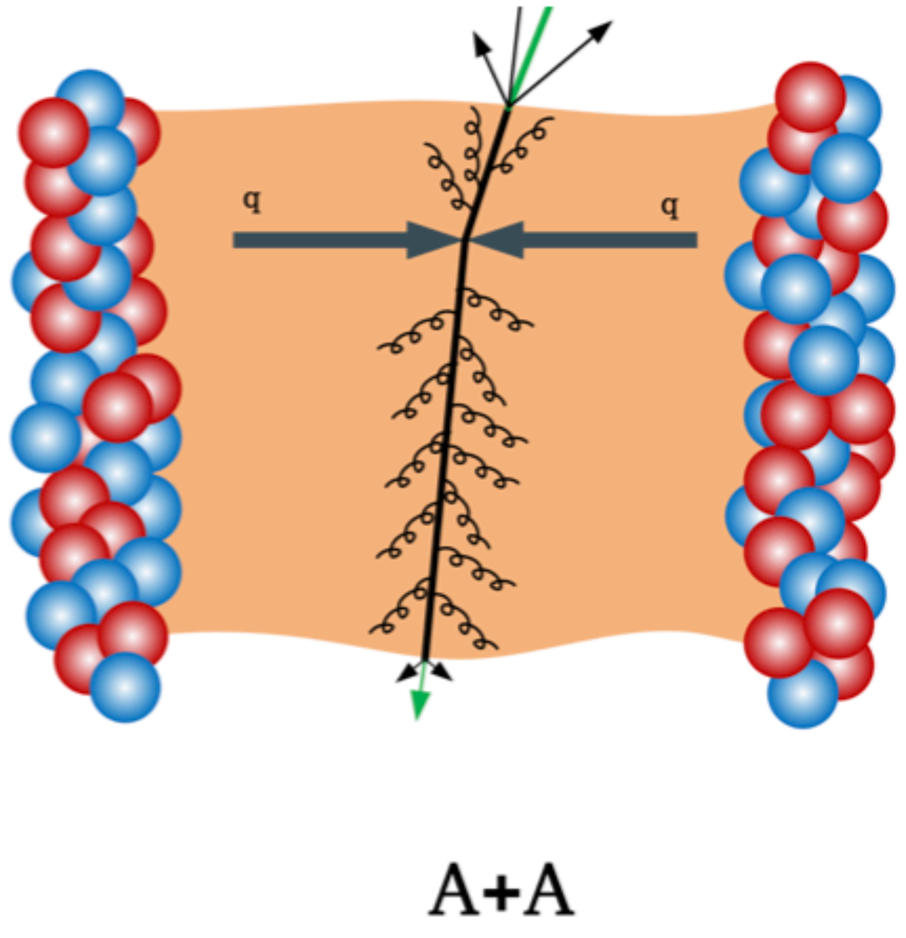
Jet propagation in dense media

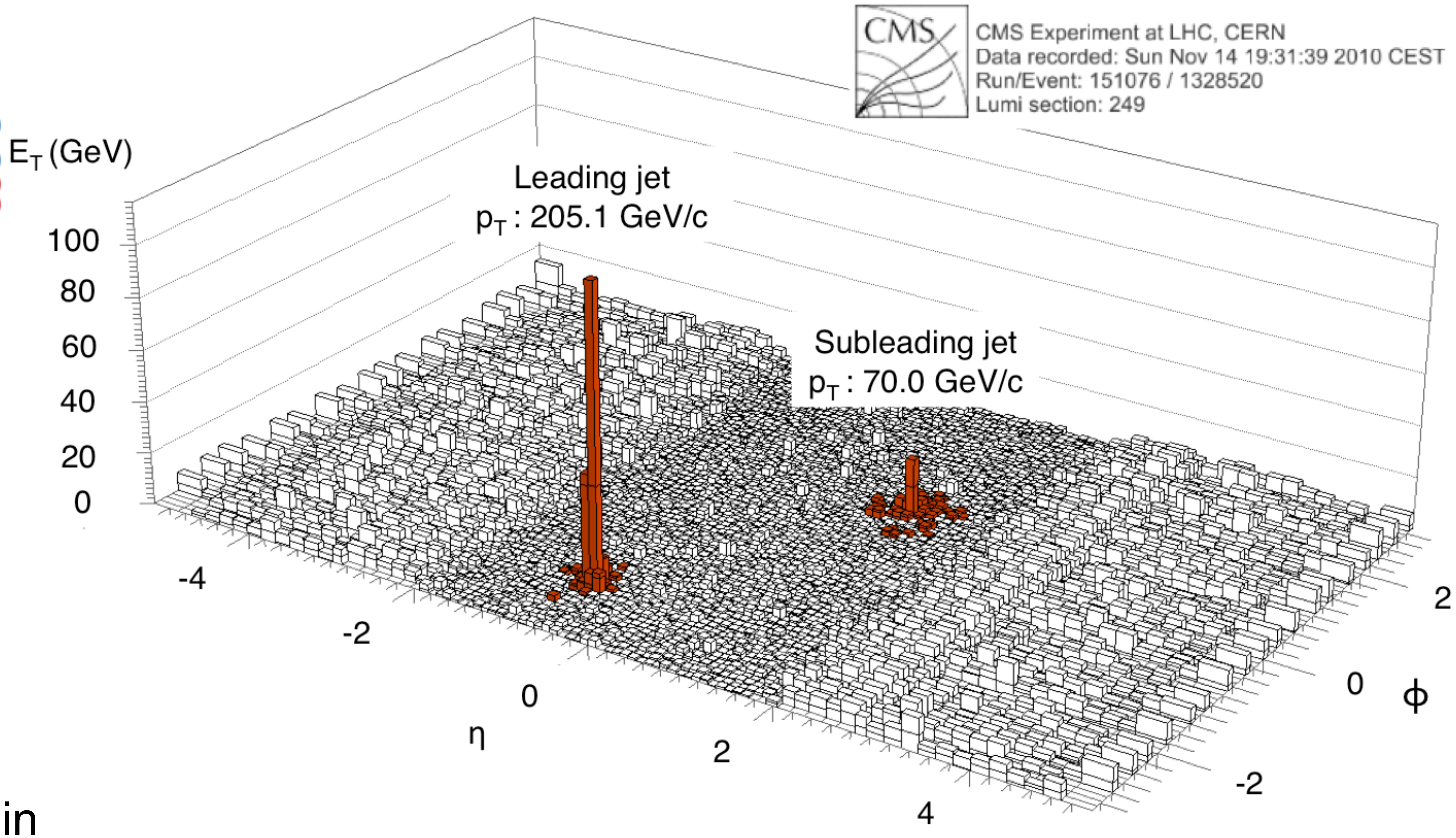


Varun Vaidya,
University of South Dakota

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

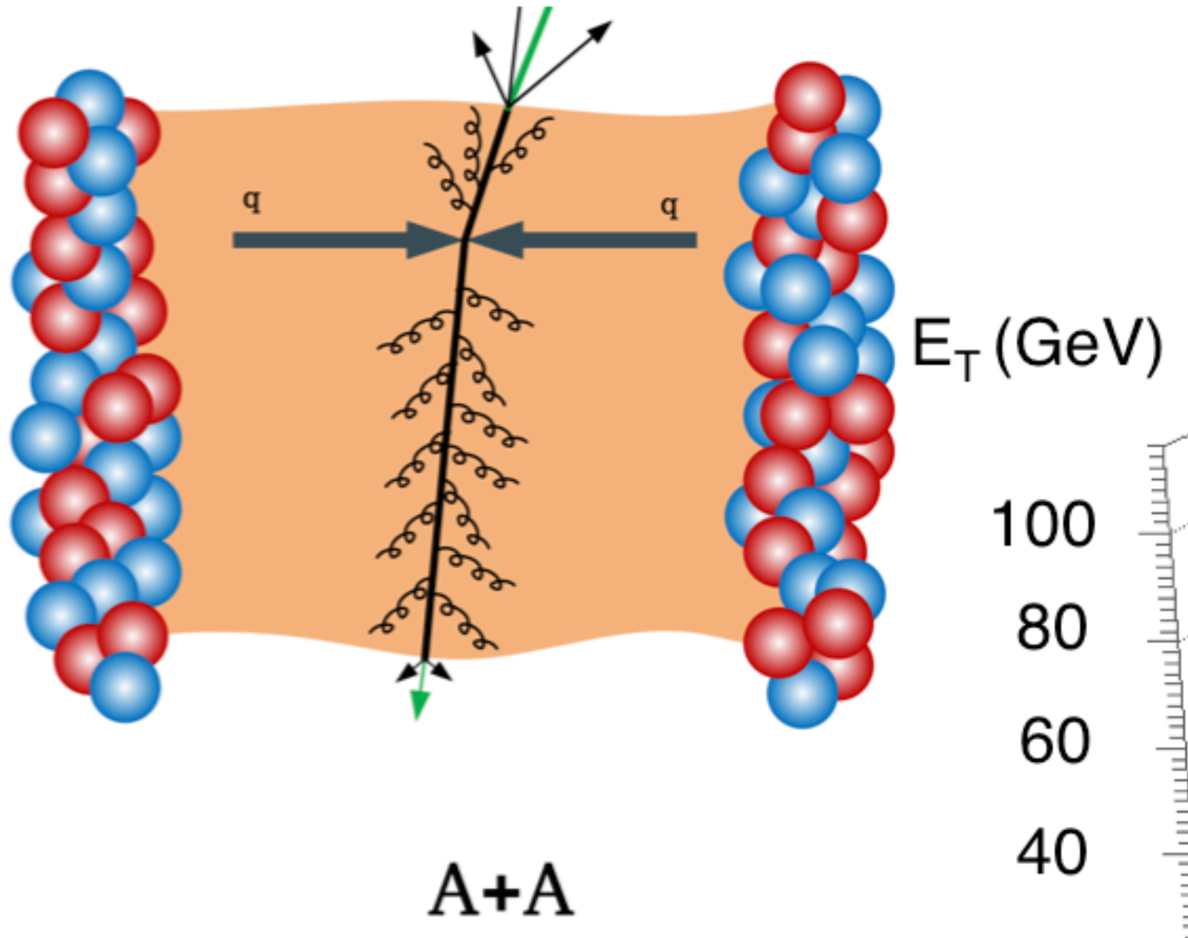
Jets lose energy and are "Quenched"

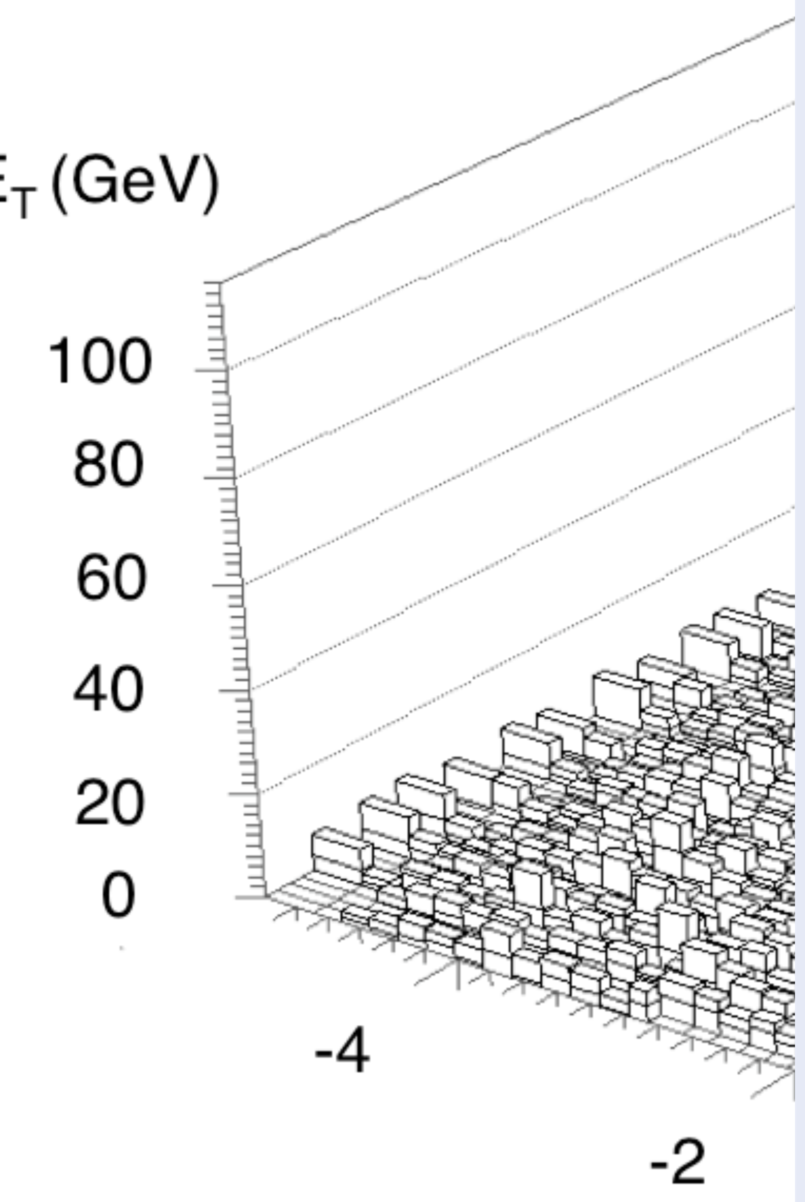


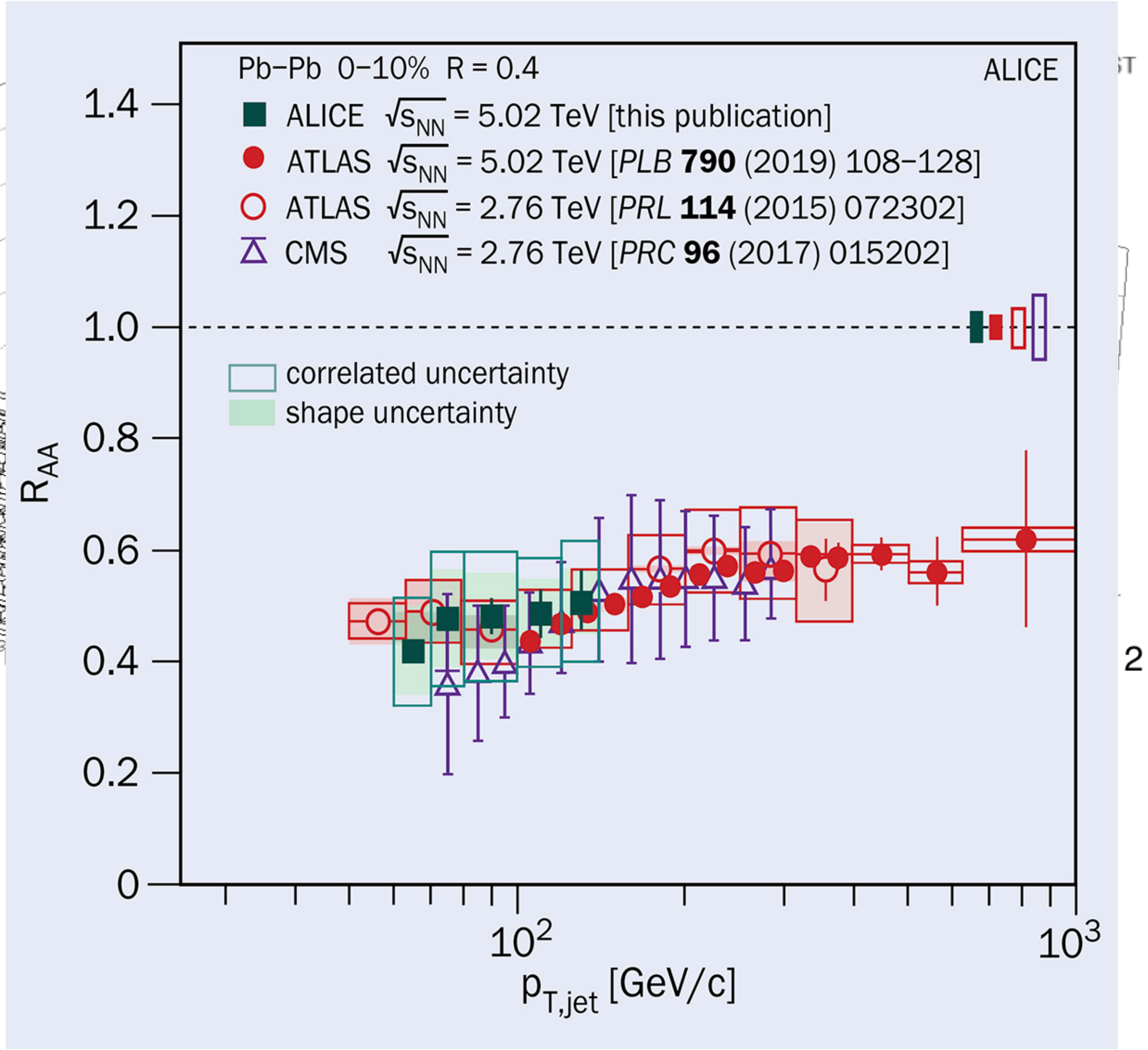


- We can use the jet to access the microscopic structure of the strongly coupled QGP.
- How does the jet evolve in the medium?

Jets lose energy and are "Quenched"

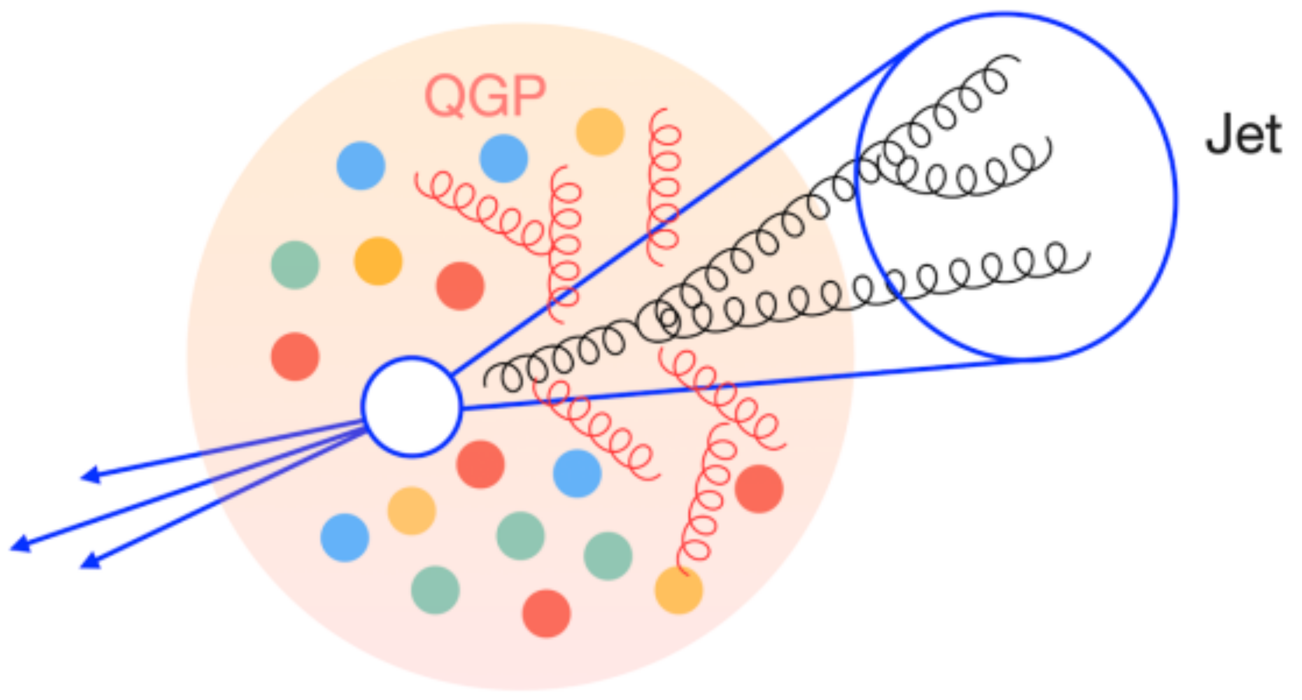


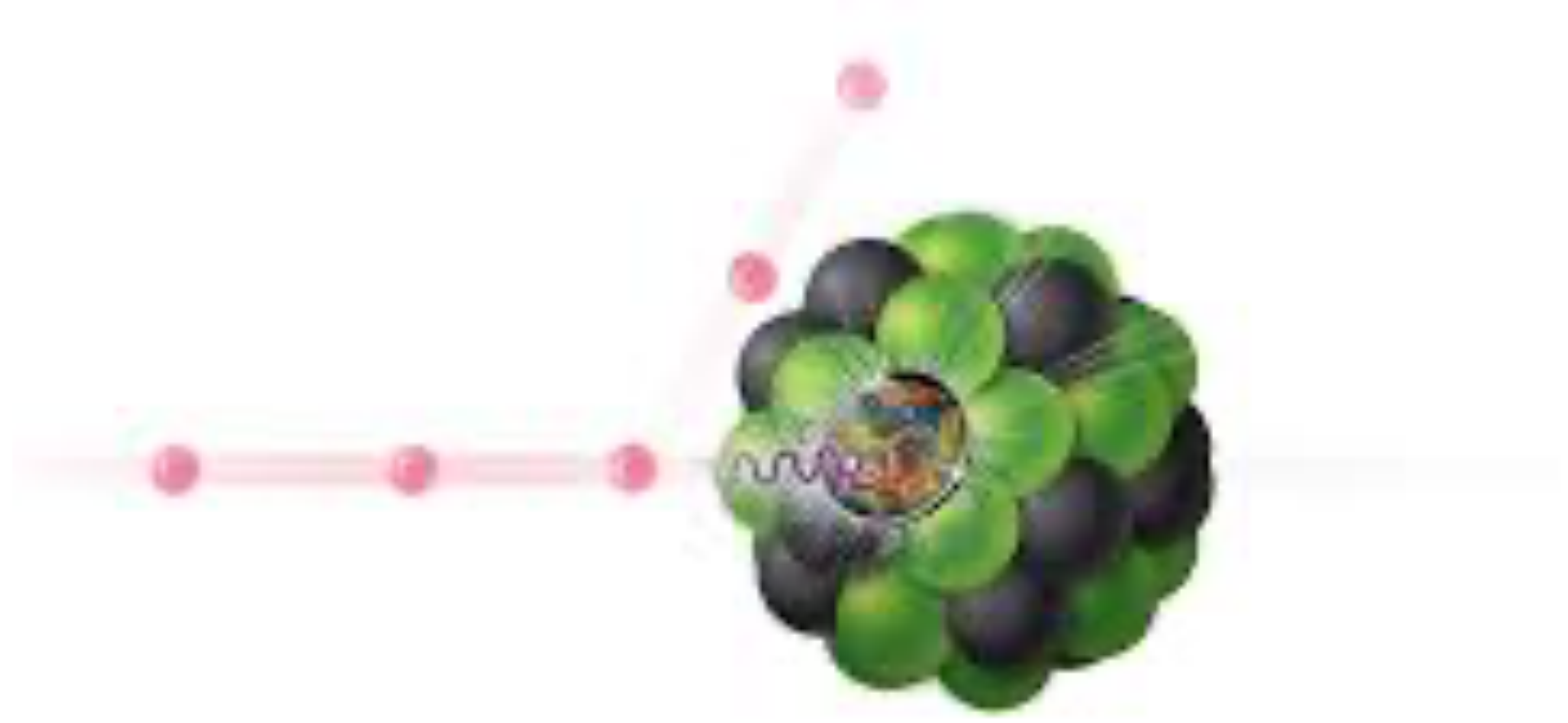




- We can use the jet to access the microscopic structure of the strongly coupled QGP.
- How does the jet evolve in the medium?

Poking a nuclear blob

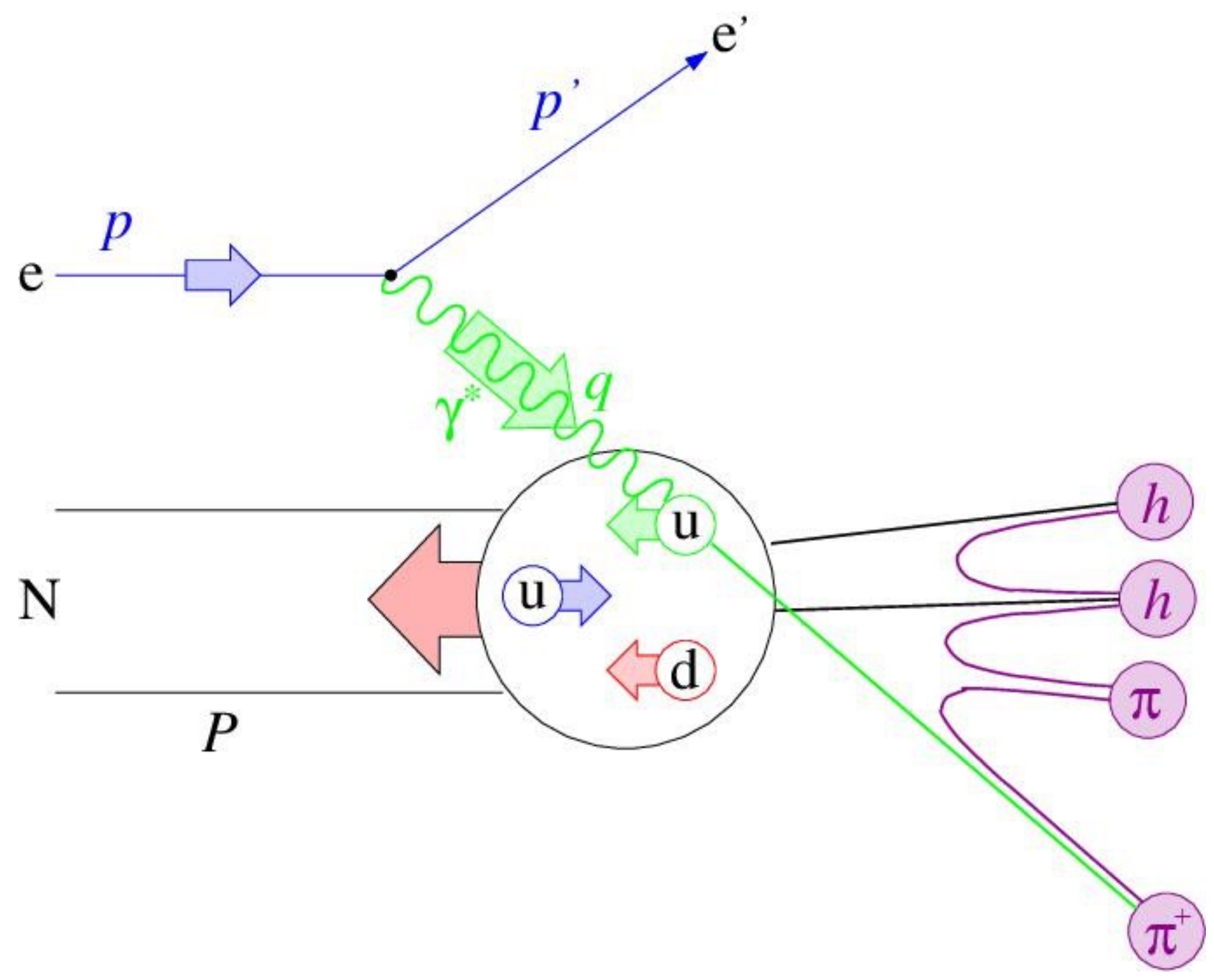




- This is NOT a new problem in nuclear physics
- A high energy probe scattering off a strongly coupled target.
- We rely on **Factorization.**

An familiar example

Factorization relies on separation of scales in an EFT sense



Photon virtuality Q $\rightarrow$ UV scale

Hadron Mass Λ_{QCD} $\rightarrow$ IR scale

$$\lambda = \frac{\Lambda_{\mathrm{QCD}}}{Q} \rightarrow$$ Power counting parameter

An EFT description of DIS

Effective description at Λ_{QCD}

$$\frac{d\sigma}{dQ^2dx} = \boxed{H(Q^2,\mu,x)}\otimes\boxed{\sum_{i\in q} e_i^2 f_i(x,\mu)} + O\left(\frac{\Lambda_{QCD}}{Q}\right)^2$$

Perturbatively calculable **Hard function**

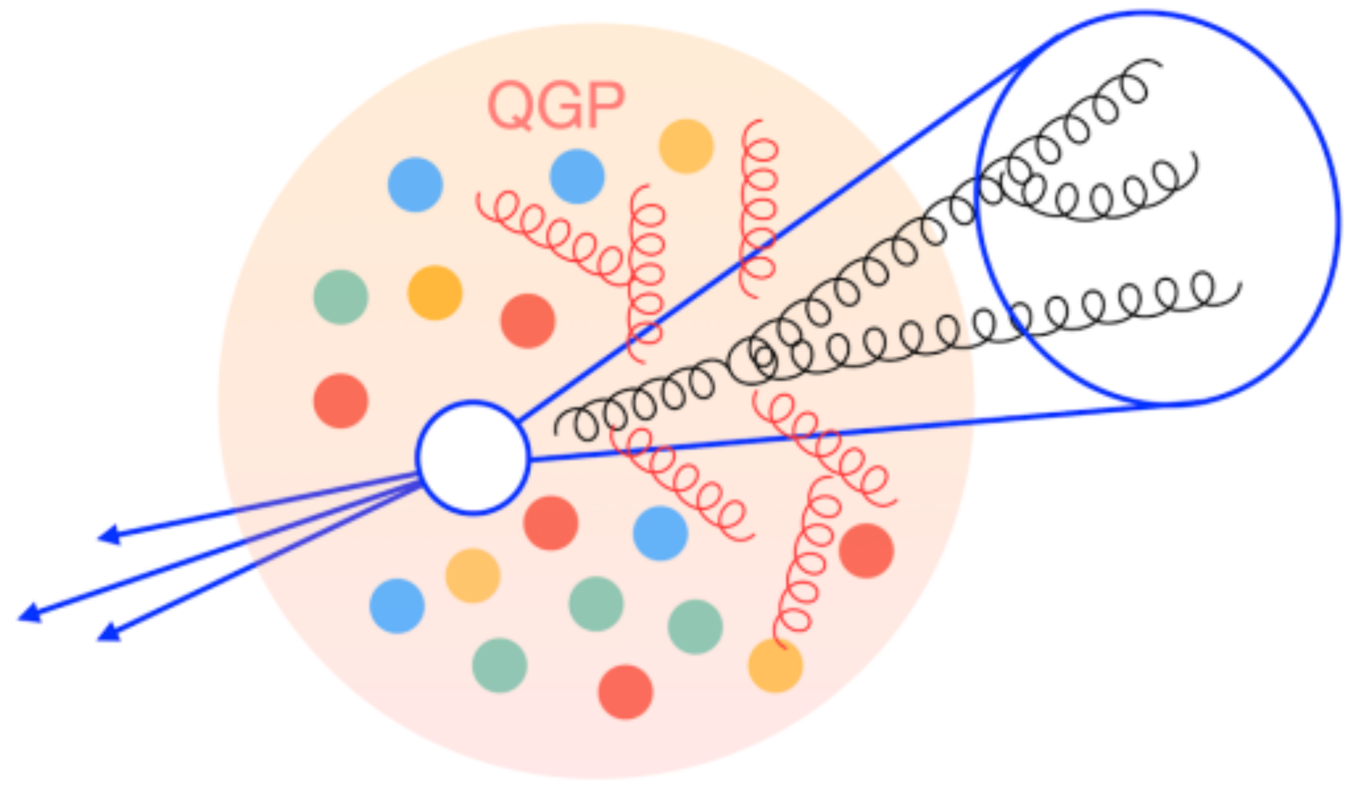
Non-perturbative **Parton Distribution function**

Wilson co-efficient

Effective operator → isolates the universal microscopic physics

- **Factorization allows us to prove universality → predictive power**

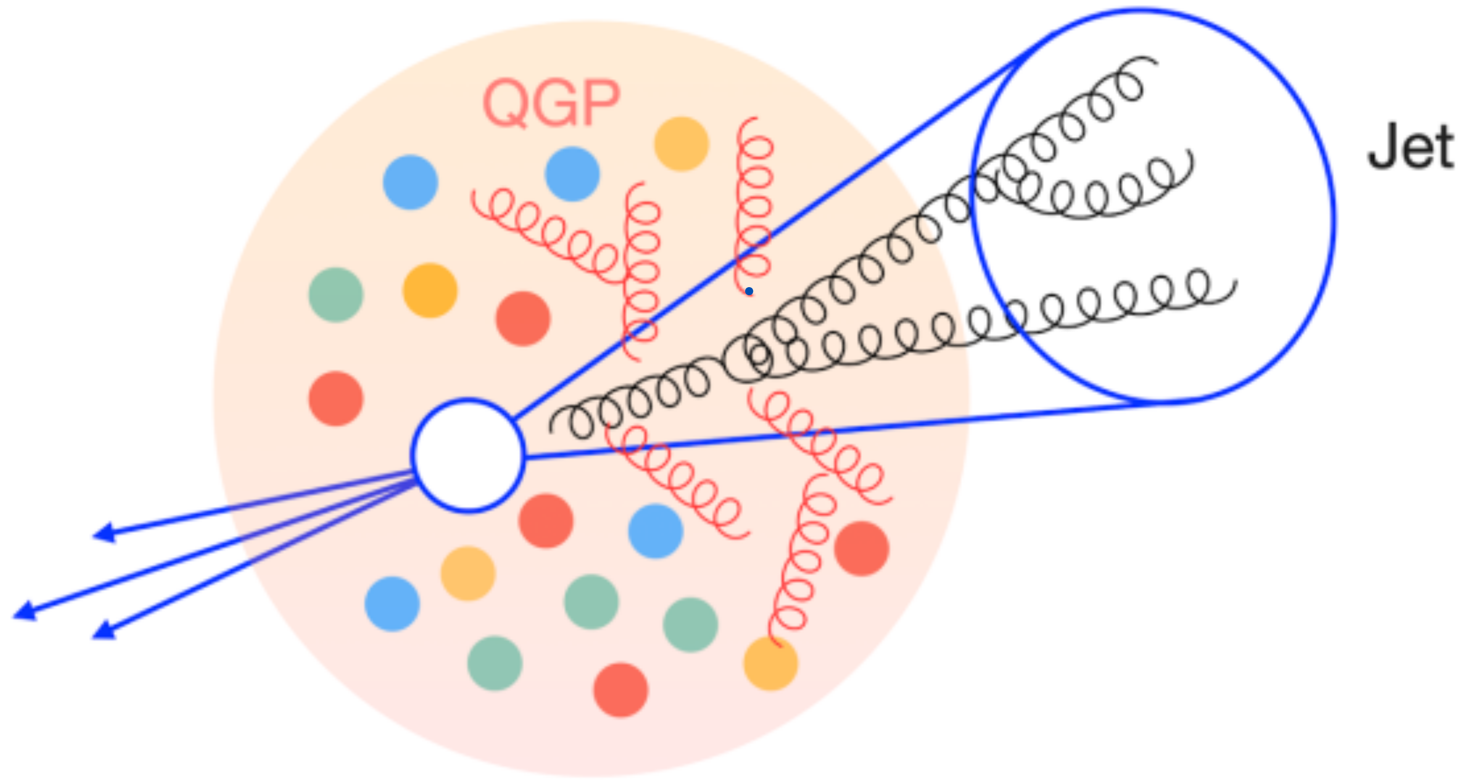
Key questions for jet evolution in QGP



- **Separate** the **perturbative physics** from the non-perturbative by scale
- **Parameterize** the **non-perturbative physics** in terms of Gauge invariant operators → e.g the PDF in DIS, Drell Yan, Higgs production etc.
- **Prove** (disprove) universality of non-perturbative physics across jet observables → **Universality** gives **predictive power** !

Goal of this talk

- Can we factorize jet evolution in Quark Gluon plasma by scale?



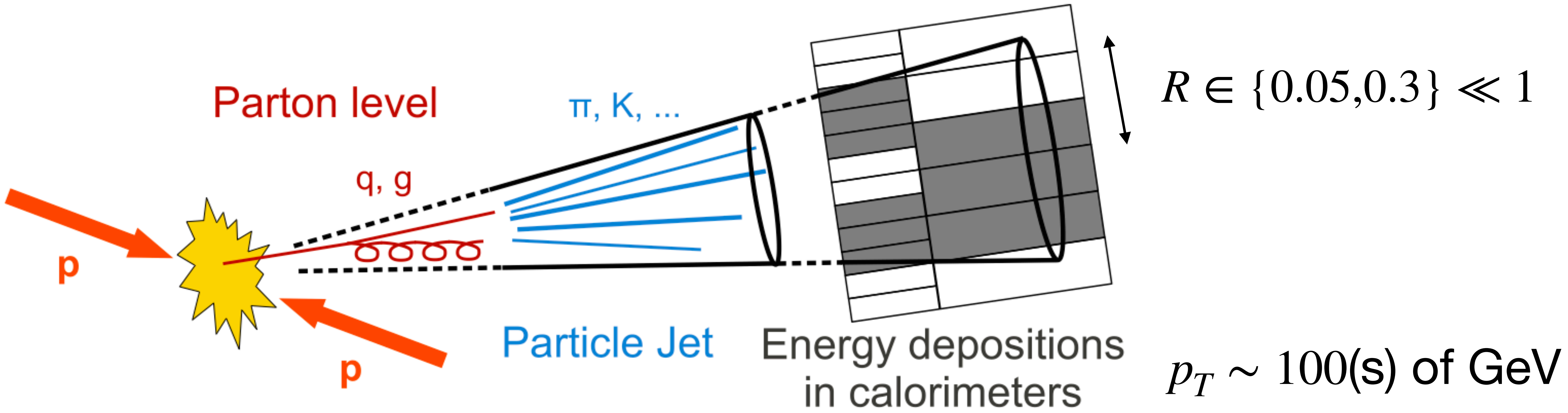
- Focus of this talk → inclusive jet production.

- Same framework extended* to jet substructure observables → EEC

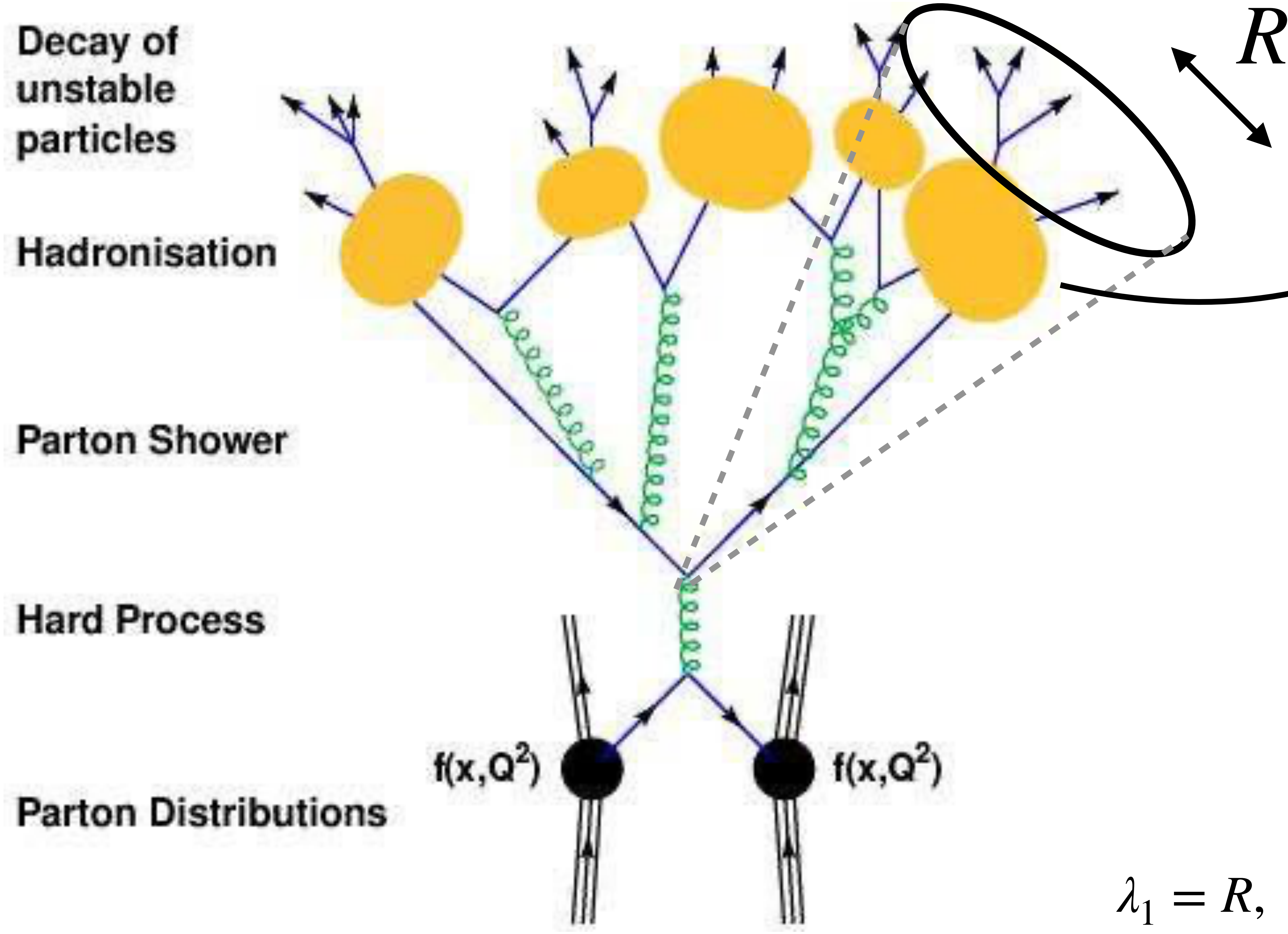
* V. Vaidya et. al. 2408.02753

Chapter 1

Anatomy of a vacuum jet



Physical picture



$p^2 \sim \Lambda^2_{\mathrm{QCD}}$ 100(s) MeV

$p^2 \sim (p_T R)^2$ **Jet Scale** 10(s) GeV

$p^2 \sim p_T^2$ **Hard Scale** 100(s) GeV

$\lambda_1 = R, \quad \lambda_2 = \dfrac{\Lambda_{QCD}}{p_T R} \to$ **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}

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

Hard function at p_T

Jet function at p_TR

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

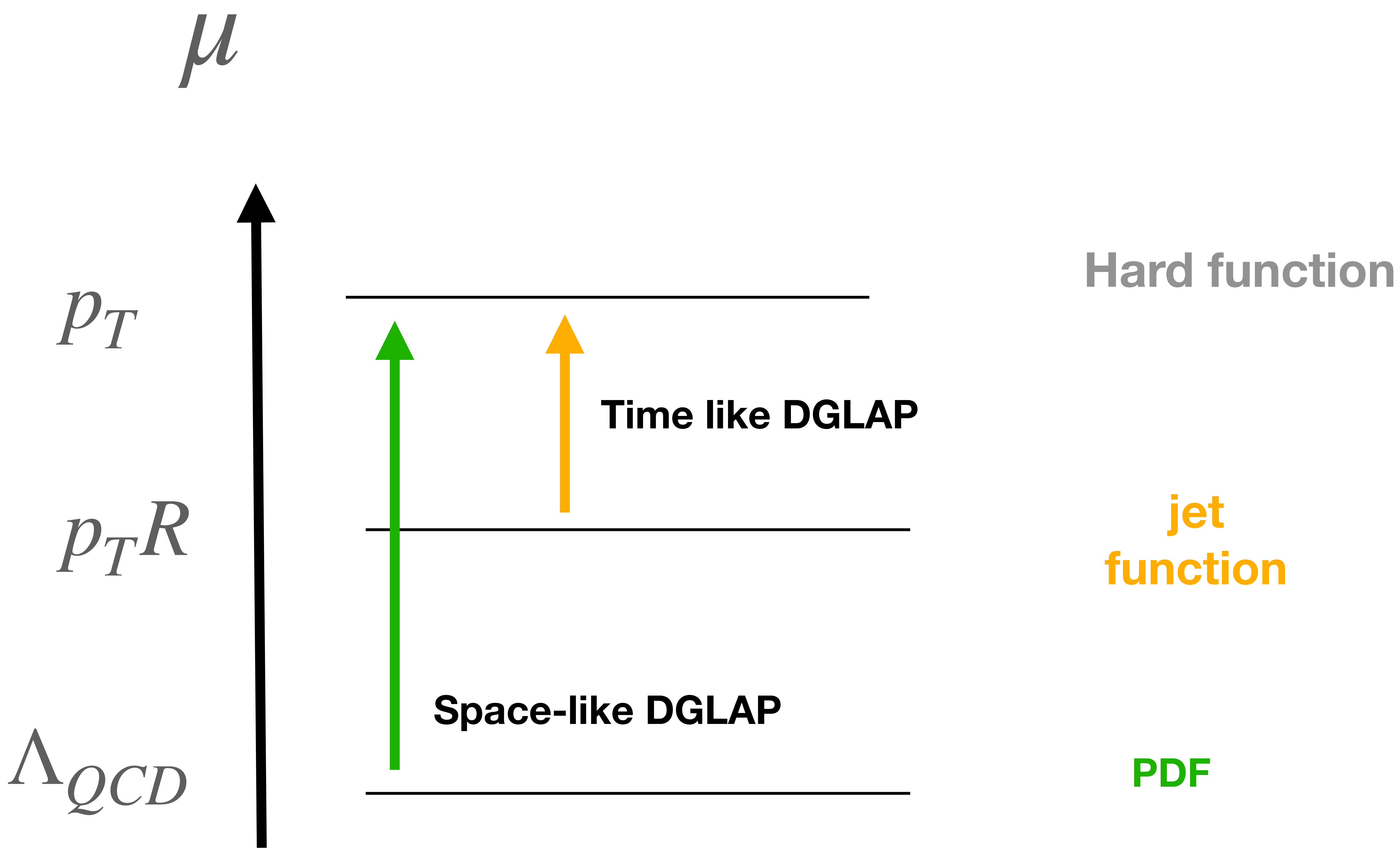
Zhong-bo Kang, Felix Ringer and Ivan Vitev
JHEP 10 (2016) 125

$\longrightarrow$

Updated version

K. Lee. and I.Moult 2410.01902

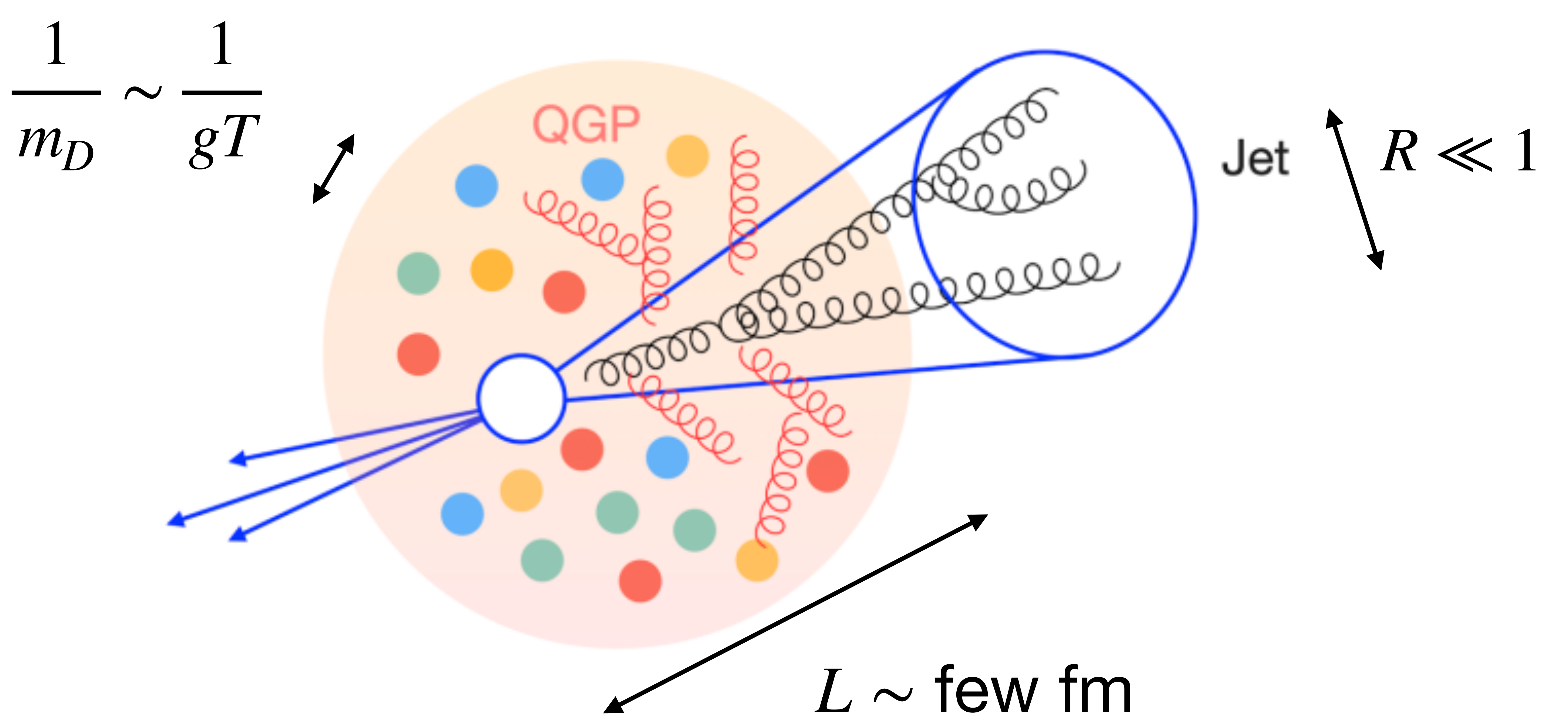
RG Flow

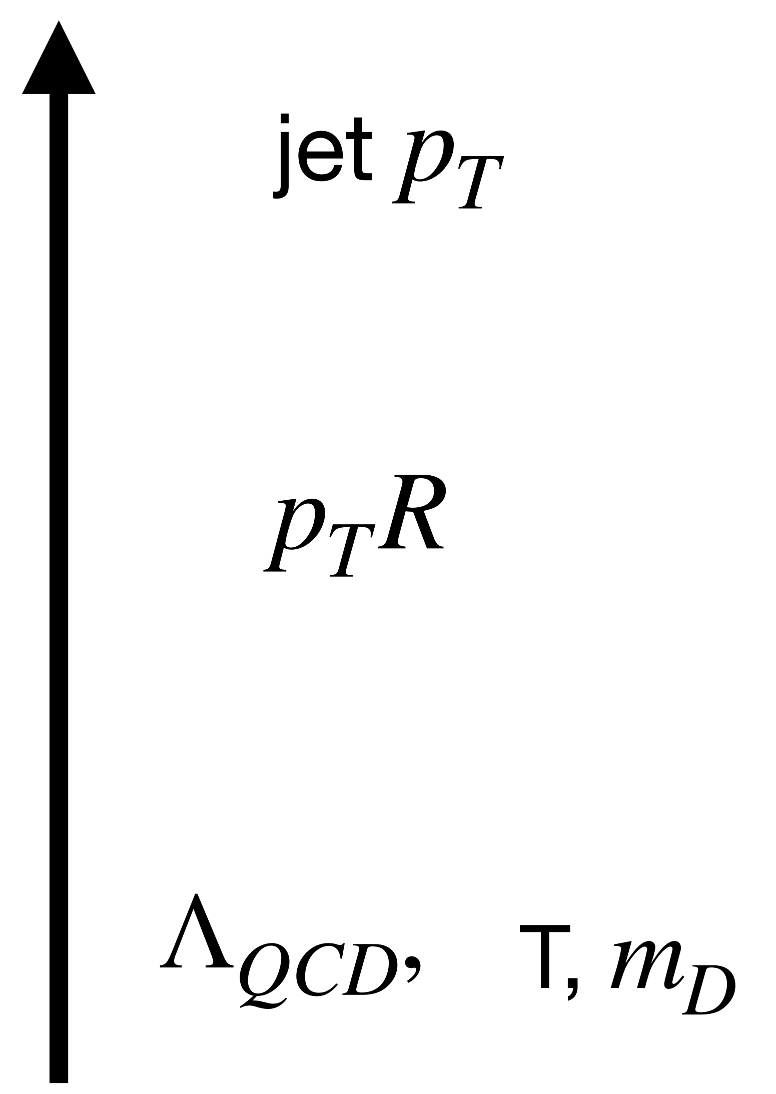

μ
p_T
$p_T R$
Λ_{QCD}
Time like DGLAP
Space-like DGLAP
Hard function
jet
function
PDF

Chapter 2

Introducing the QGP/Nuclei

New medium scales

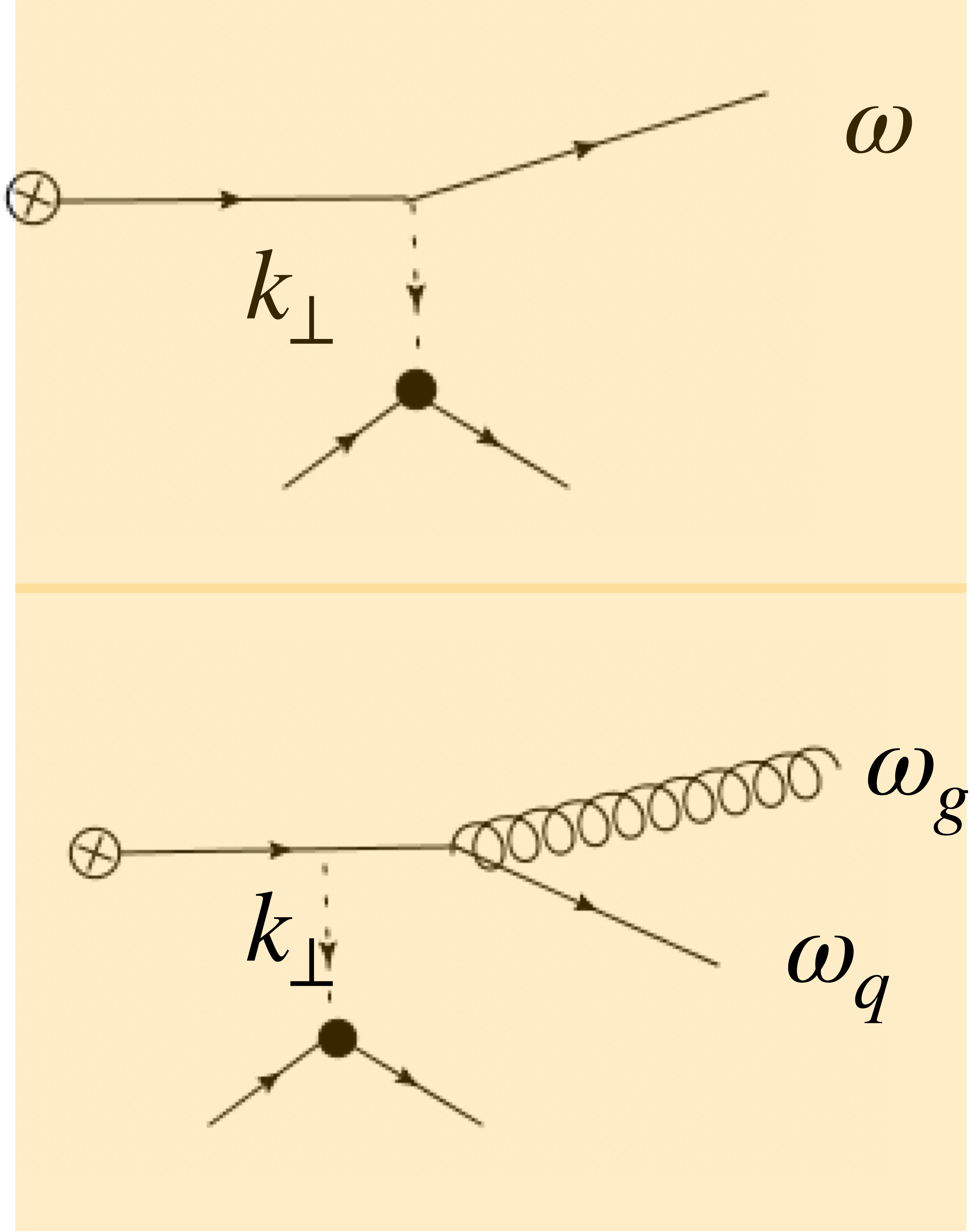




- QGP temperature T $\sim 300 - 800$ MeV

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

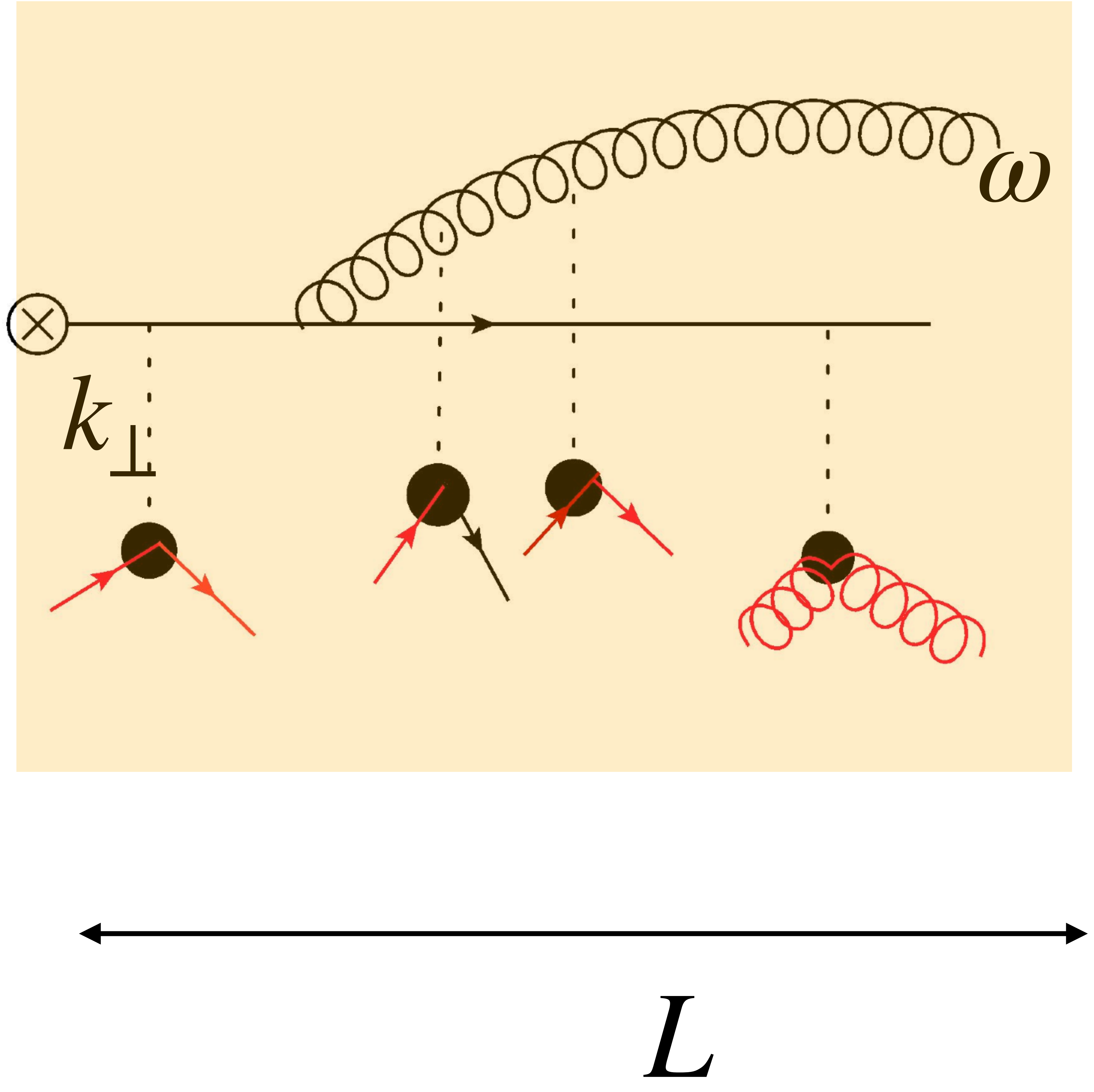
Parton in the medium



Coulomb like instantaneous "**Glauber**" gluon exchange ~$\dfrac{1}{k_\perp^2 + m_D^2}$

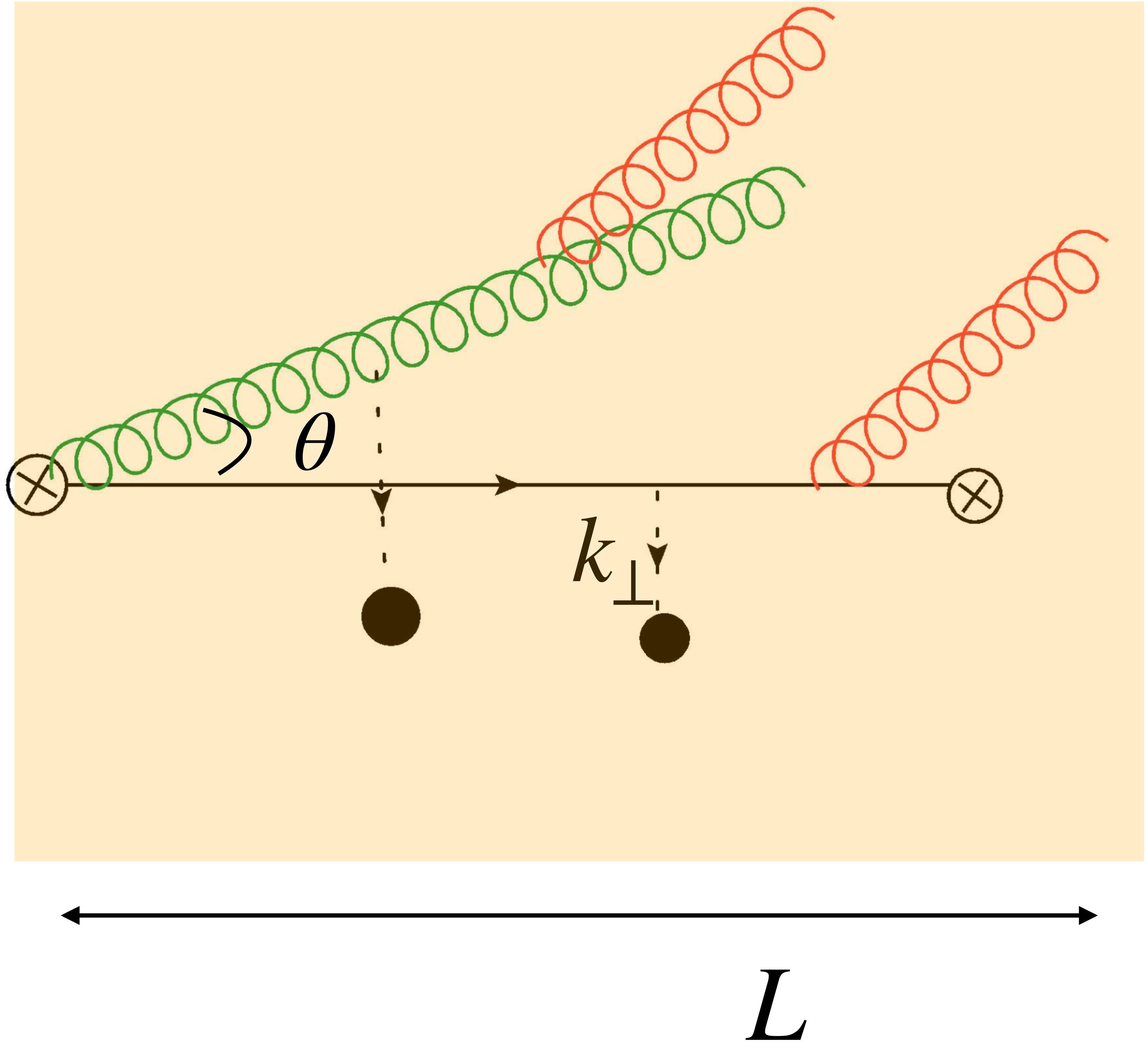
- In a single exchange, typical $k_\perp \sim m_D$,
- Angle of deflection $\theta \sim \dfrac{k_\perp}{\omega} \ll 1$

Multiple interactions



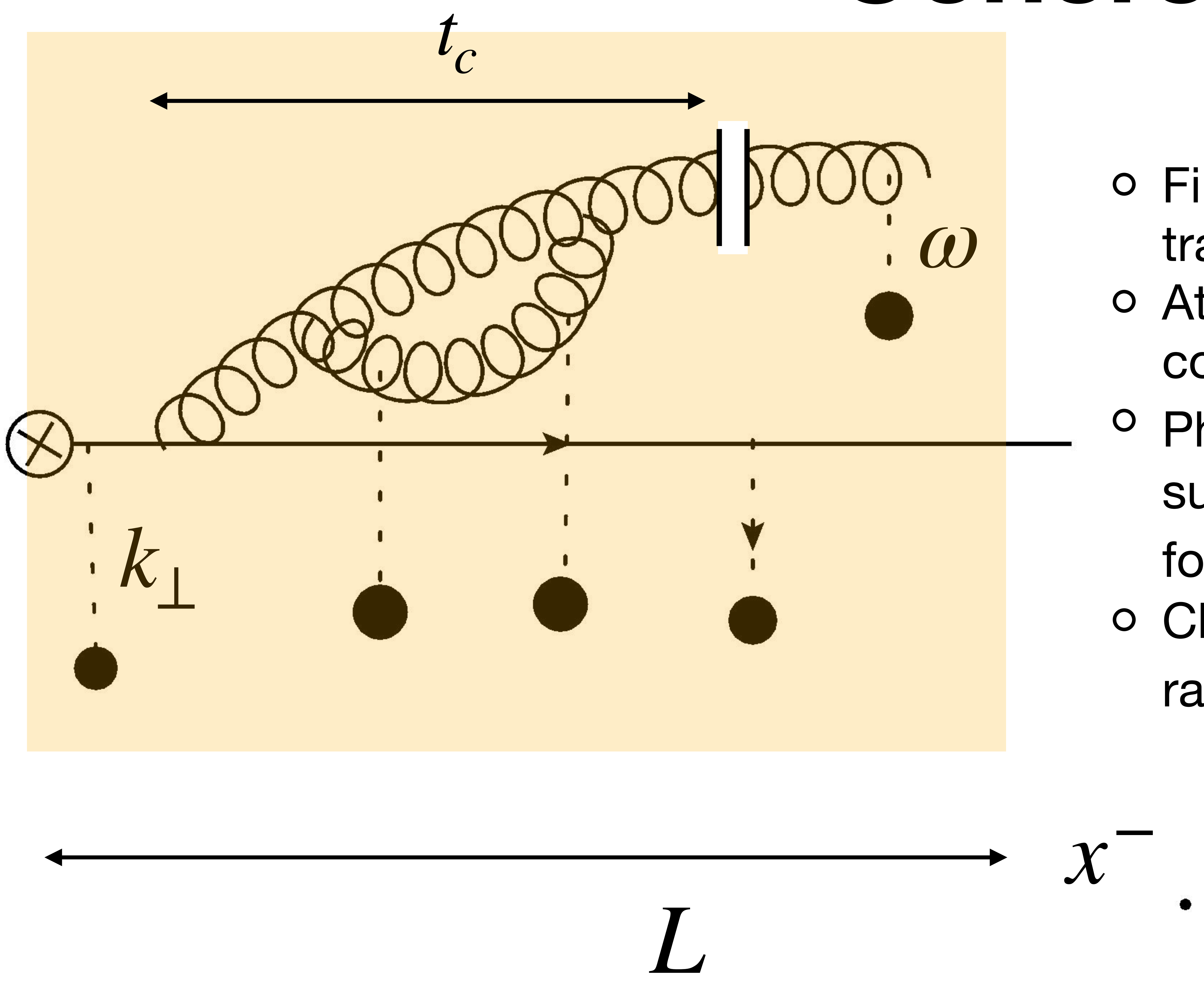
- $Q_{\text{med}} \rightarrow$ Total average transverse kick per parton $\geq m_D$
- For a dense medium, perturbative?

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

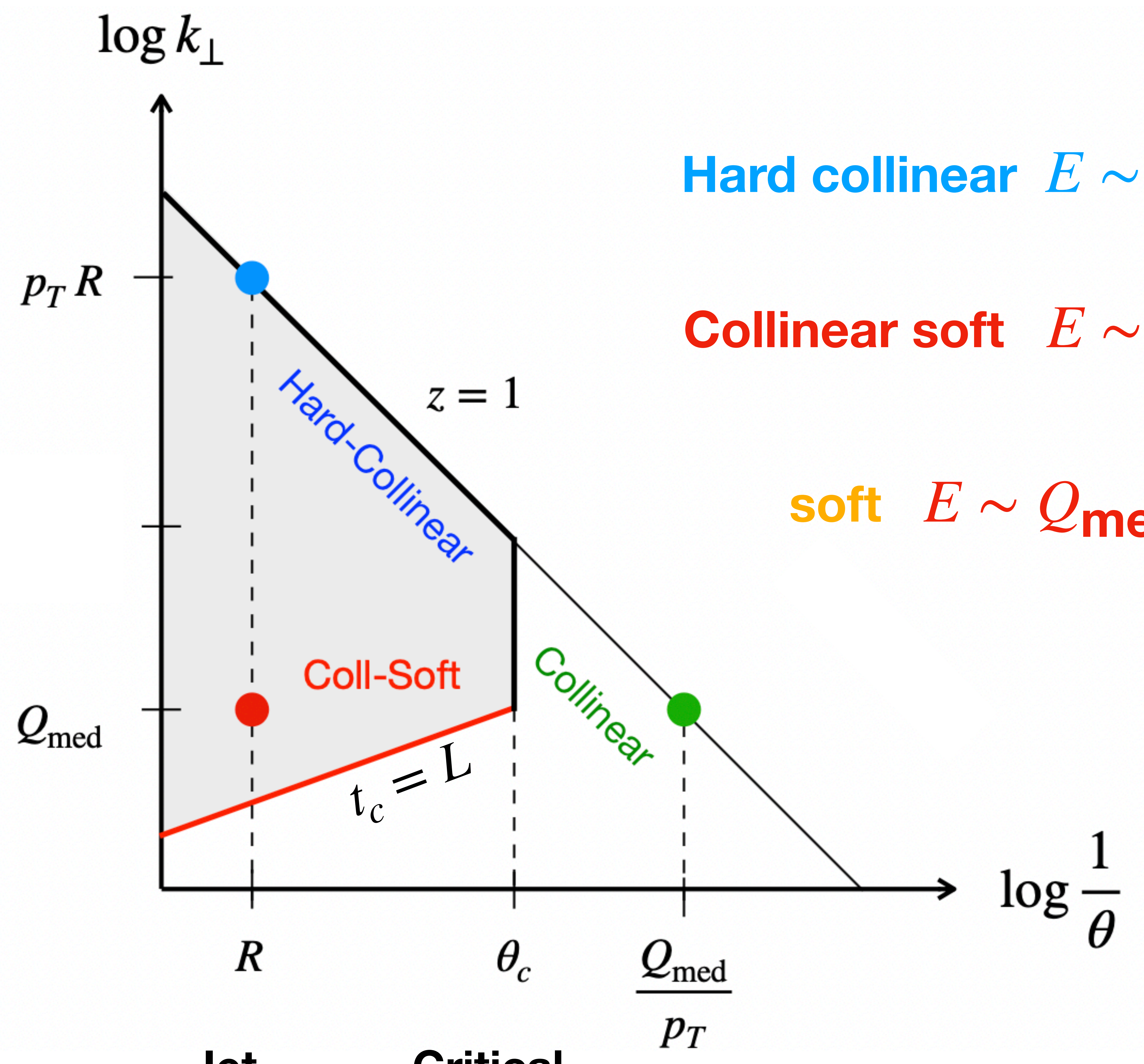


- Finite medium length breaks translational invariance .
- At the Glauber vertex „+ ” is not conserved
- Phase factor ~ $\exp\{iLp^+\}$ strongly supresses medium induced radiation for $Lp^+ \ll 1 \to$ LPM Effect
- Characterized by the coherence time of radiation $t_c = 1/p^+$

Putting it all together

Vacuum Jet scale

Typical medium transverse kick



Jet Radius

Critical Angle

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

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

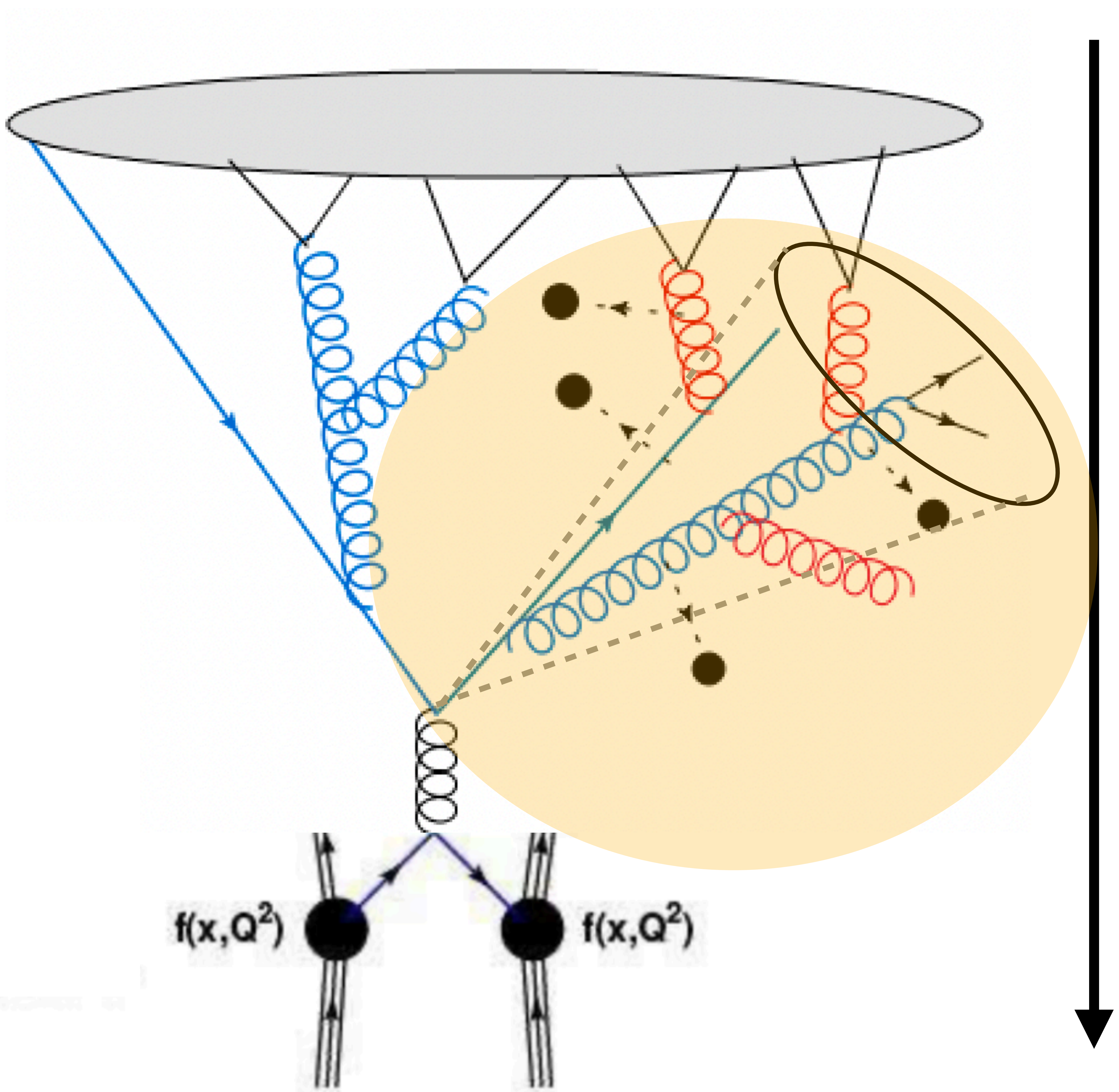
Jet degrees of freedom

soft $E \sim Q_{\textbf{med}}$

Medium

We assume $\theta_c \sim R$ for the rest of this talk

The hierarchy of scales



$p^2 \sim m_D^2 \sim \Lambda^2_{\text{QCD}}$ 100(s) MeV

$p^2 \sim Q^2_{\text{med}}$?

$p^2 \sim (p_T R)^2 \sim (p_T \theta_c)^2$ 10(s) GeV

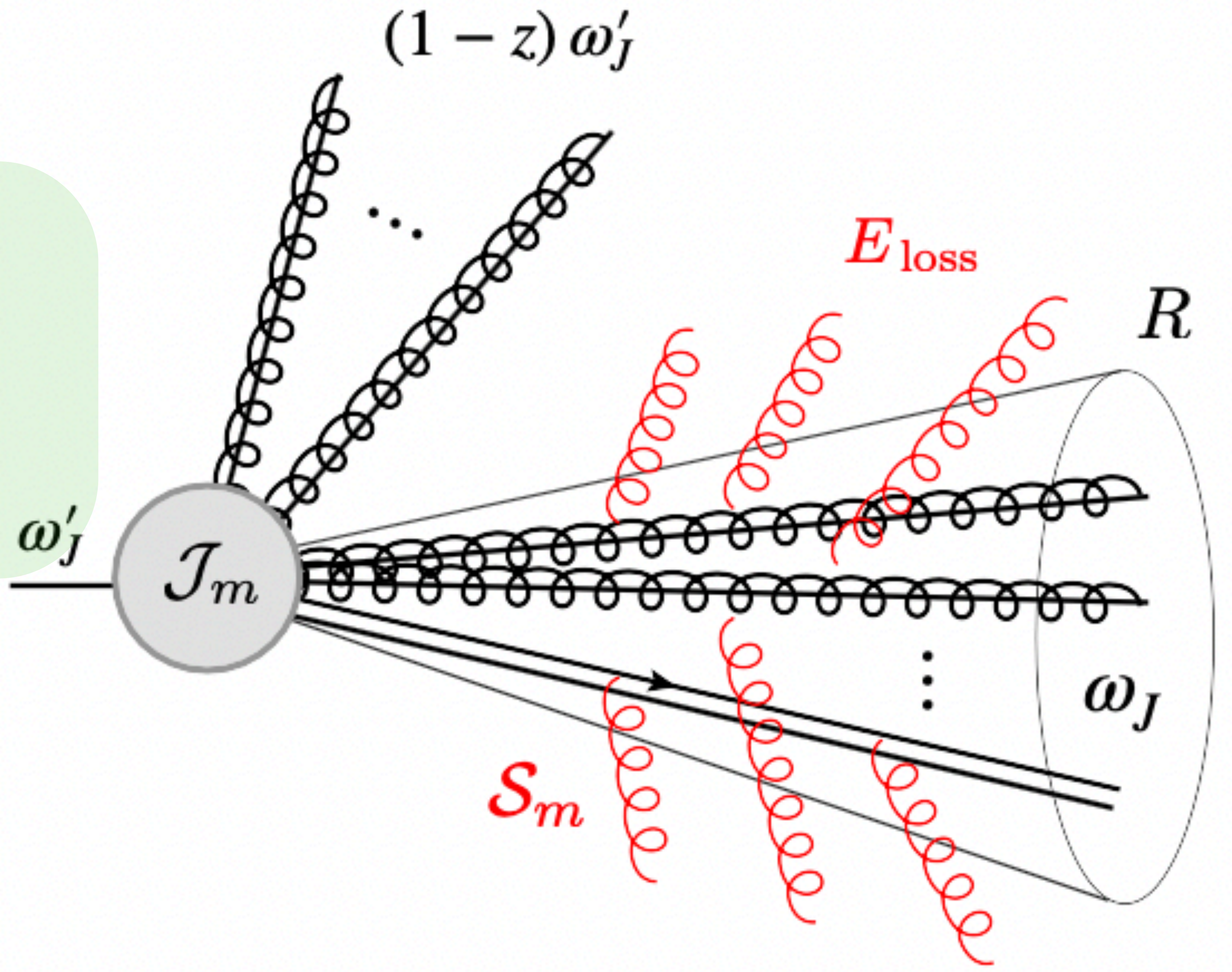
$p^2 \sim p_T^2$ 100(s) GeV

The EFT picture*

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

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

Hard process $\rightarrow$ Wilson coeff at p_T



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

Create m prongs $\rightarrow$ 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**

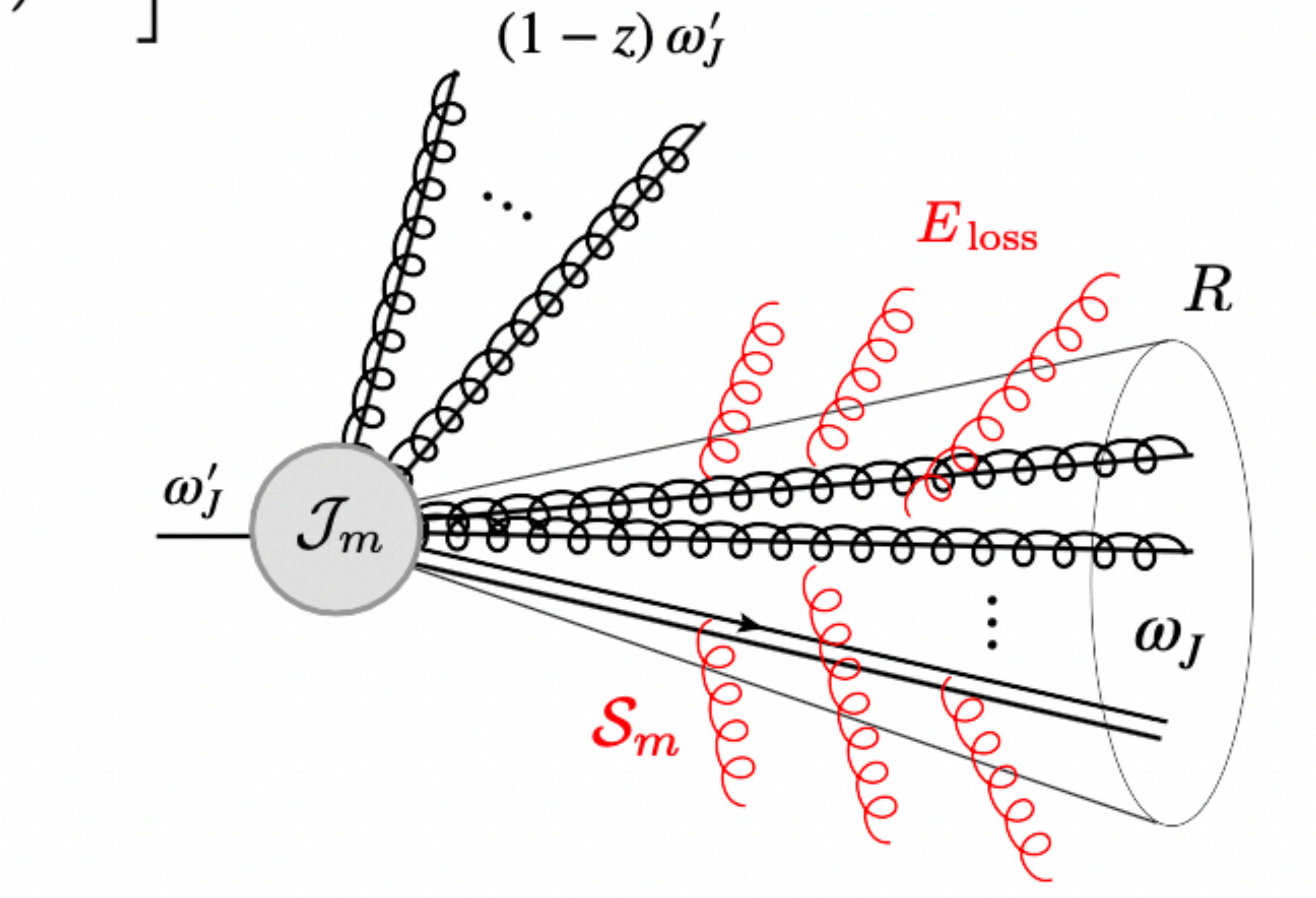
***T. Becher et. al, Phys. Rev. Lett. 116, 192001**

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.

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

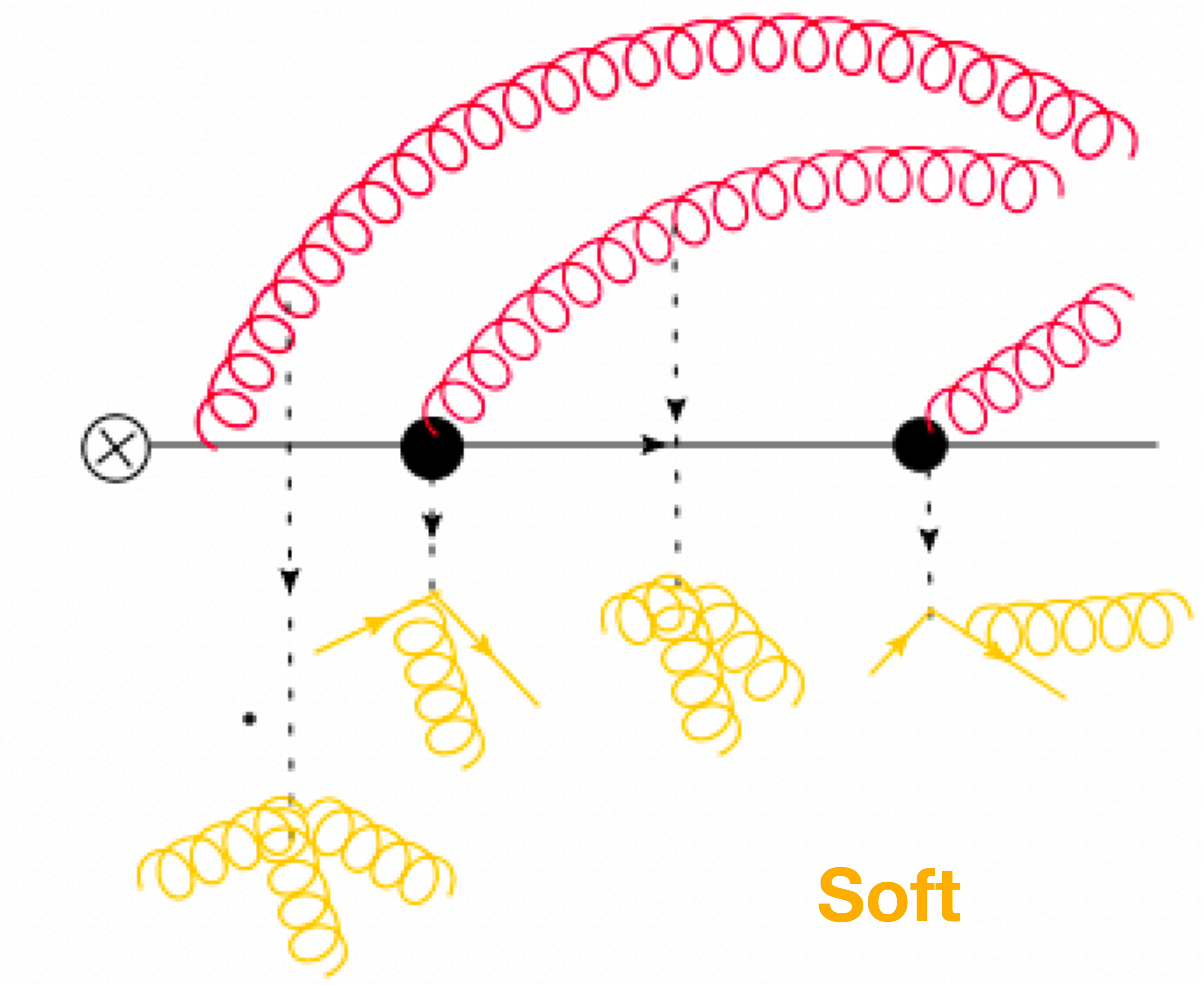


The medium scale Q_{med} is hidden and can only be seen through an explicit calculation → An emergent scale

Chapter 3
Separating the medium from the jet

Looking inside a single prong S_1

Collinear Soft



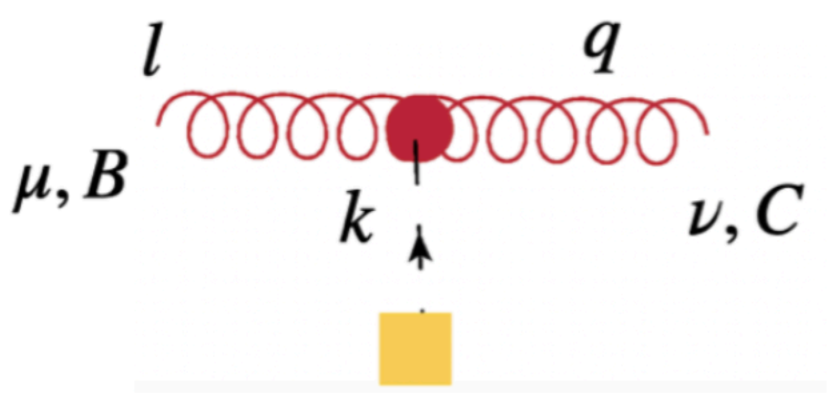
Derived from
I. Rothstein, I. Stewart, JHEP 1608 (2016) 025

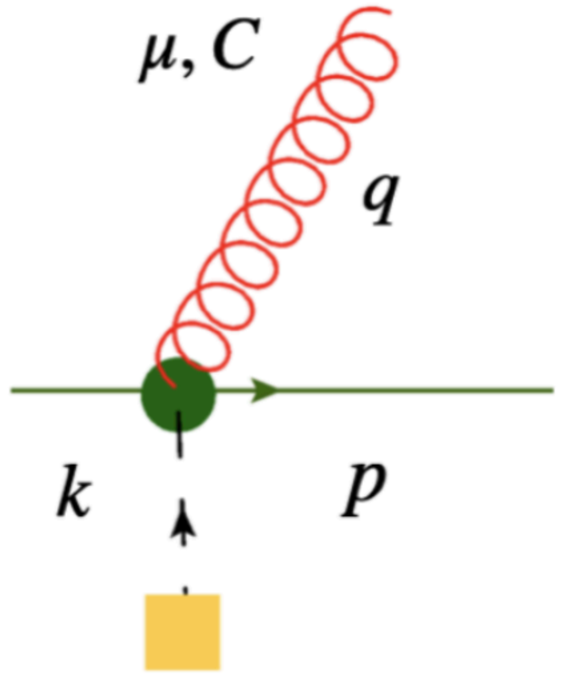
$$\mathcal{S}_1 = \text{Tr}\left[U(n)U(\bar{n})\mathcal{M}U^\dagger(\bar{n})U^\dagger(n)\right]$$

$$\int H dt = \int dt \left[H_{cs} + H_s + H_G^{cs-s}\right] + \int ds \mathcal{O}_{c-s}(sn)$$

Forward Scattering of CS off Soft

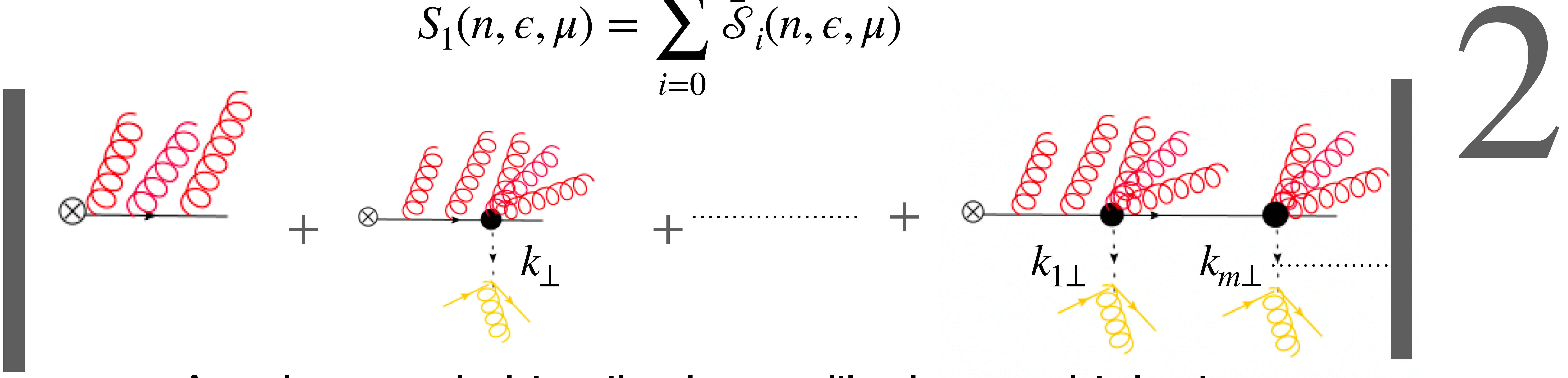
Medium induced
CS radiation along world
line of hard prong





Single prong physics

$$S_1(n,\epsilon,\mu) = \sum_{i=0}^{\infty} \bar{\mathcal{S}}_i(n,\epsilon,\mu)$$

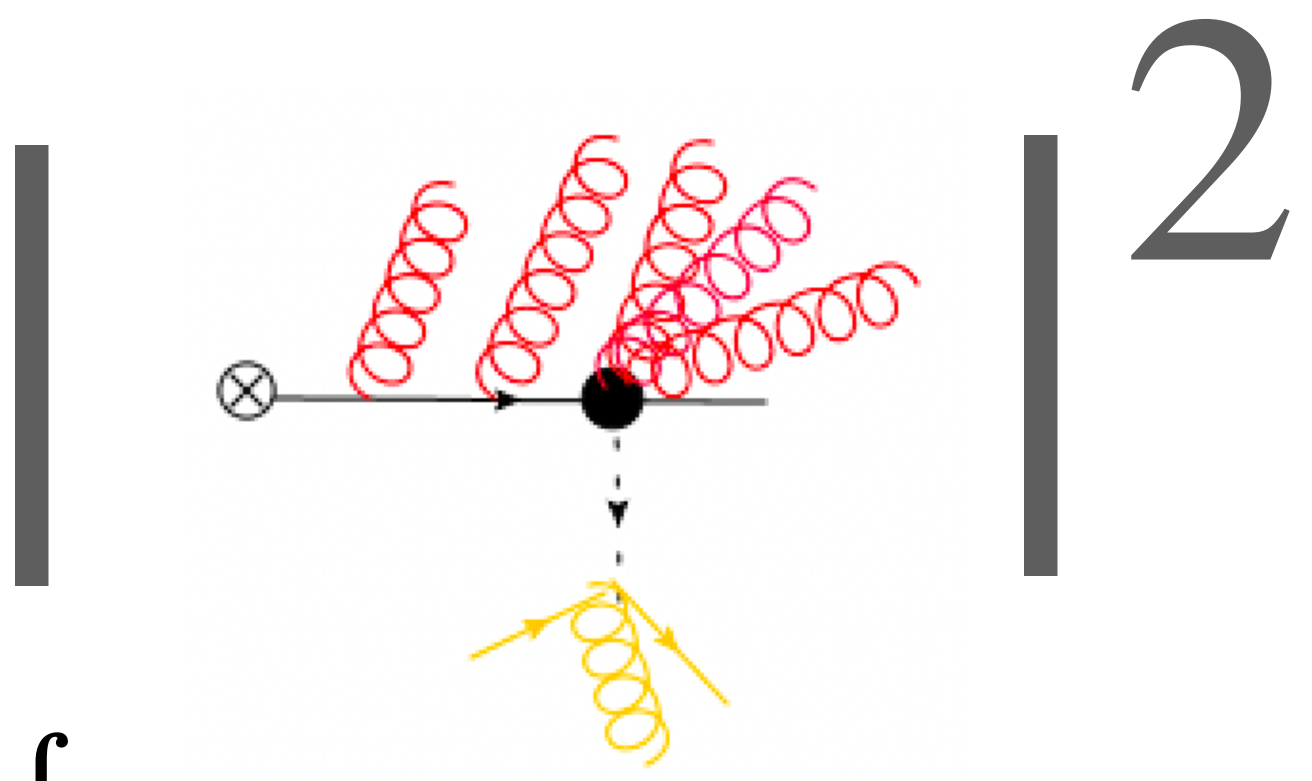


Assuming successive interactions happen with color uncorrelated partons

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

All order Vacuum cs radiation (Threshold) + **All order CS + Soft radiation with Single medium interaction** + ... **m medium interactions**

Single interaction



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

Single medium interaction

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

$$O_S^{q\alpha} = \overline{\psi}_s S_n T^\alpha \frac{\not{n}}{2} S_n^+ \psi_s^n$$

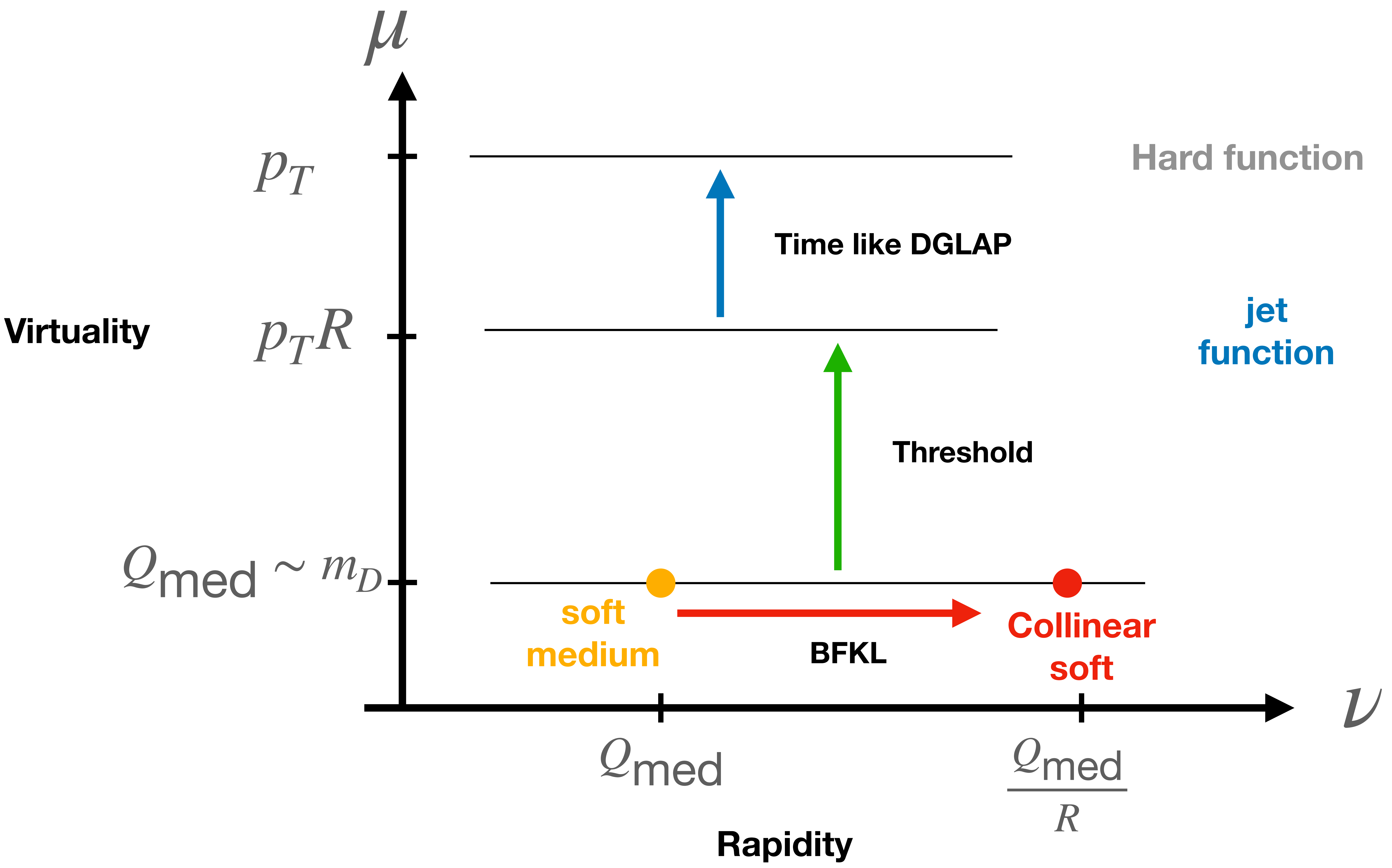
A gauge invariant operator definition → Wightman correlator at LO

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

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

$\mathcal{S}_1(n,\epsilon,k_\perp,\nu)$ → **GLV at LO, obeys BFKL evolution in ν. Threshold resummation in μ**

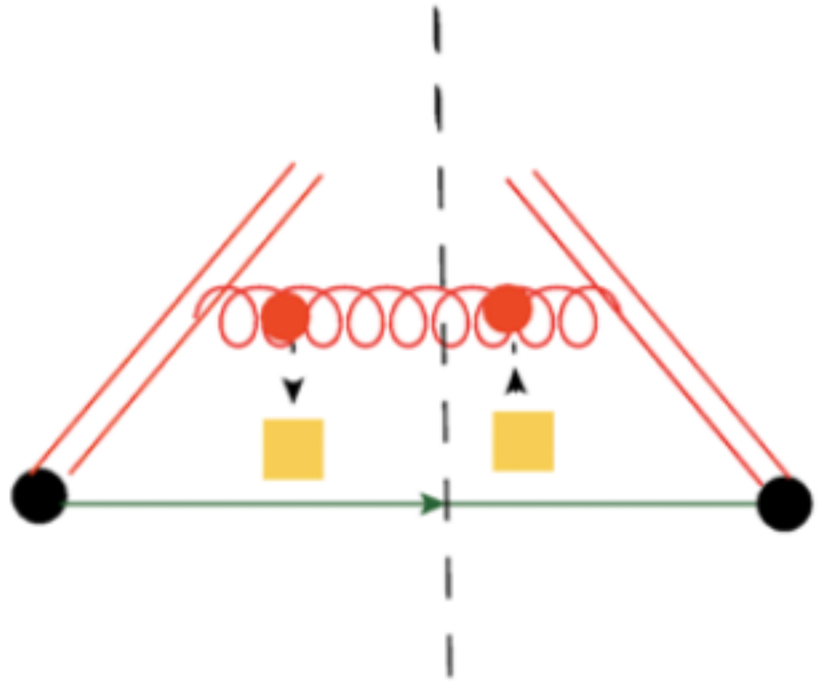
Medium Jet RG Flow : Dilute medium



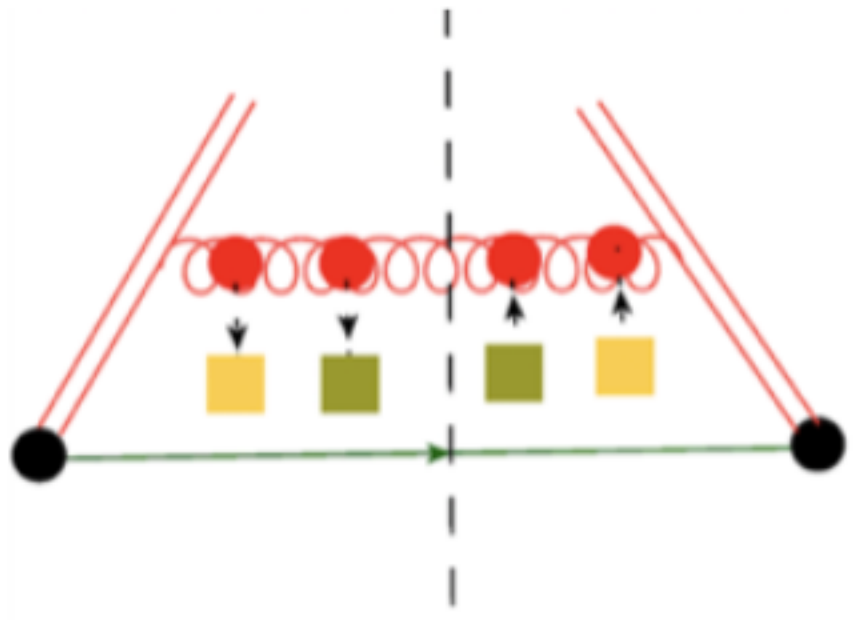
Multiple interactions

$$\mathcal{S}_1 = \mathrm{Tr}\left[U(n)U(\bar{n})\mathcal{M}U^{\dagger}(\bar{n})U^{\dagger}(n)\right]$$

Broadening for vacuum induced and medium induced radiation in Markovian approximation (ignore quantum interference)

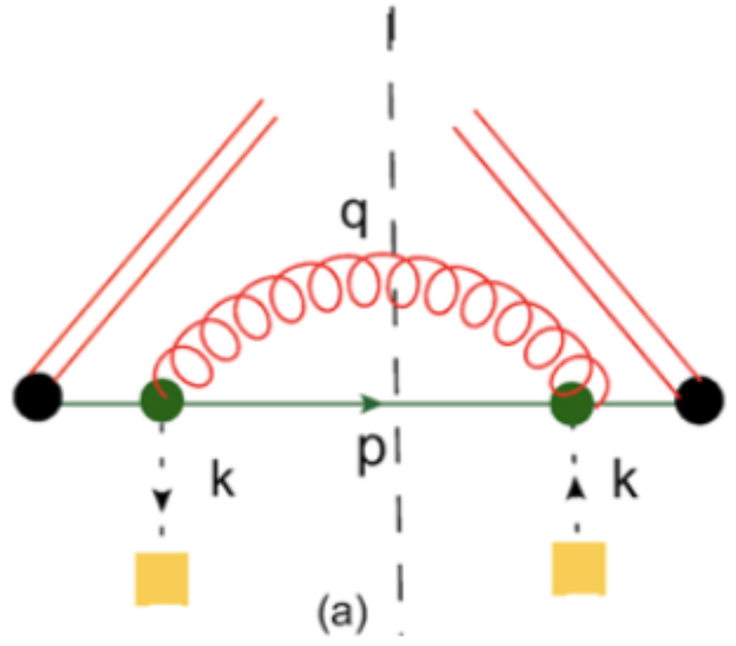


+

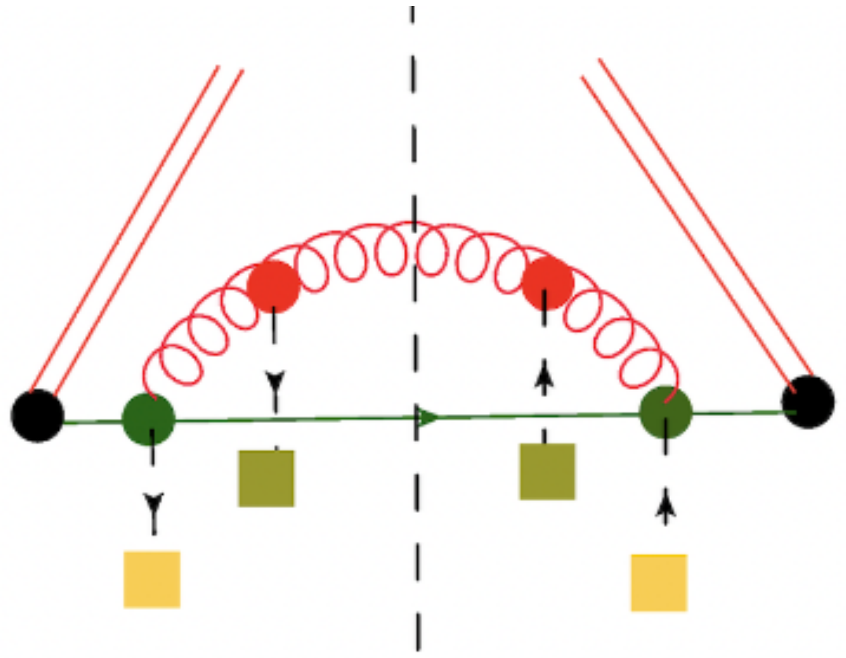


+ . . . . .

Broadening of vacuum radiation



+



+ . . . . .

Broadening of medium induced radiation

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

Multiple interactions

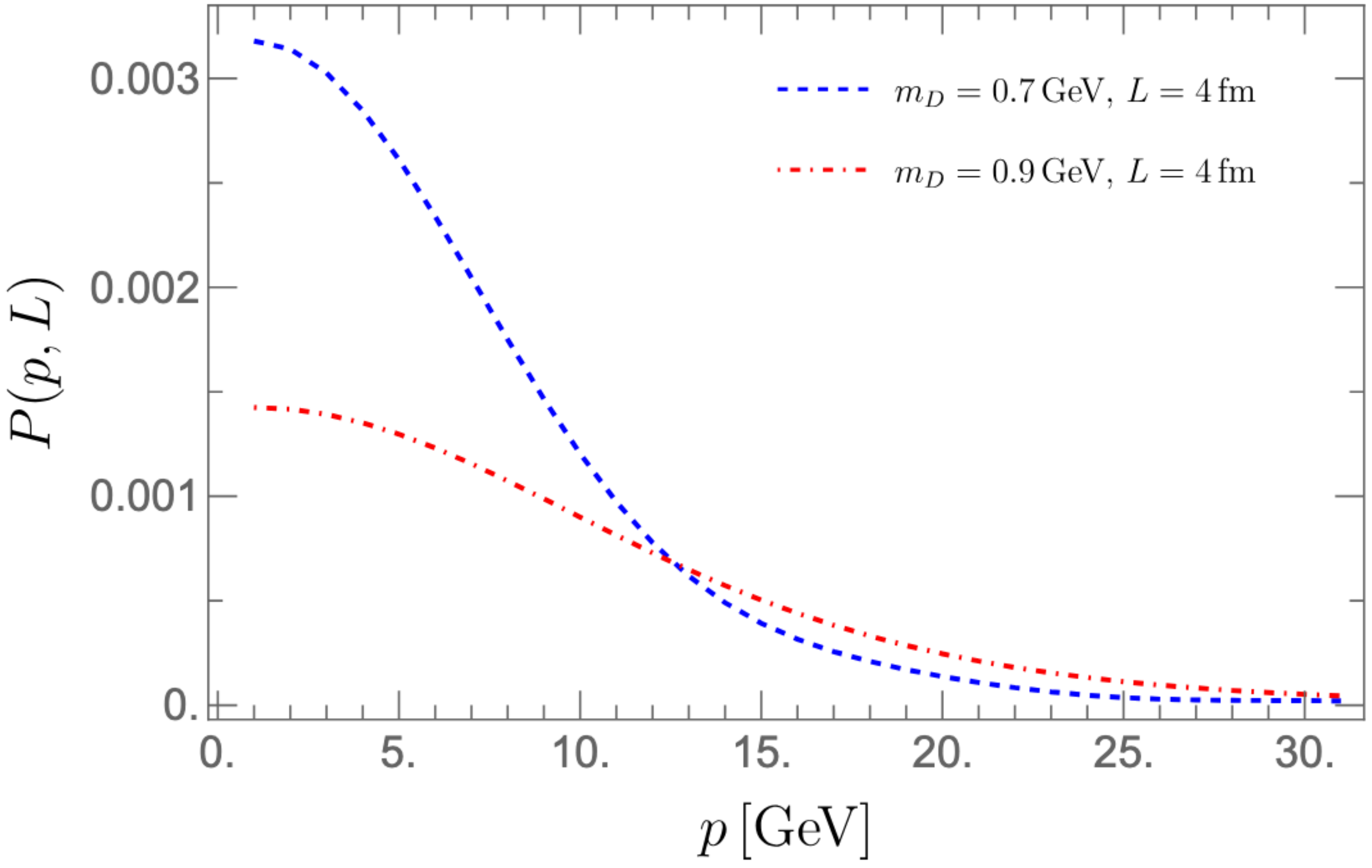
$$\mathcal{S}_1^{(1)} = \int d^2\mathbf{p} F(\mathbf{p}, R, m_D) P(\mathbf{p}, R, m_D)$$

Probability of gluon 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



A further factorization for complete separation of non-perturbative physics

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

Implications of the emergent scale

- The emergence of a perturbative scale implies that **forward scattering is insufficient,**

- **Hard scattering** of collinear soft **contributes** at the same order in power counting

  So we need to go back and include hard scattering of cs in the EFT framework if we want to describe a dense medium

- **Gluon broadening encoded through two non -perturbative operator matrix elements that depend on the jet radius R**

$$P(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\Phi(\mu, m_D, R)} \times e^{-L\int \frac{d\xi}{\xi} C(\mathbf{b}, R, \xi, \mu) Y(\xi, m_D)} + O\left(\frac{m_D^2}{Q^2_{\text{med}}}\right)$$

Encodes multiple forward (small x) scattering
Obeys BFKL evolution

Encodes multiple hard (large x) scattering
Obeys DGLAP evolution

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

The overlap region and $\hat{q}$

$$P(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\Phi(\mu, m_D, R)} \times e^{-L\int \frac{d\xi}{\xi} C(\mathbf{b}, R, \xi, \mu) Y(\xi, m_D)} + O\left(\frac{m_D^2}{Q^2_{\text{med}}}\right)$$

Encodes multiple forward (small x) scattering
Obeys BFKL evolution

Encodes multiple hard (large x) scattering
Obeys DGLAP evolution

The overlap region between large and small x physics is the Double logarithmic limit.

$$P_{\text{overlap}}(\mathbf{p}, L) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{-|\mathbf{b}|^2 L\hat{q}} + O\left(\frac{m_D^2}{Q^2_{\text{med}}}\right)$$

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

Epilogue

- Quantitative precision in a non-perturbative QGP medium requires us to adopt an effective field theory framework.

- A factorization formula for jet quenching that explicitly isolates physics at widely separated scales.

- A new parameterization of gluon broadening in the medium going beyond $\hat{q}$.

Still to be done …

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

  - Computation of mutiple prongs to see explicit emergence of θ_c.

  - Relax Markovian approximation include quantum interference effects from finite medium length.

Thank You