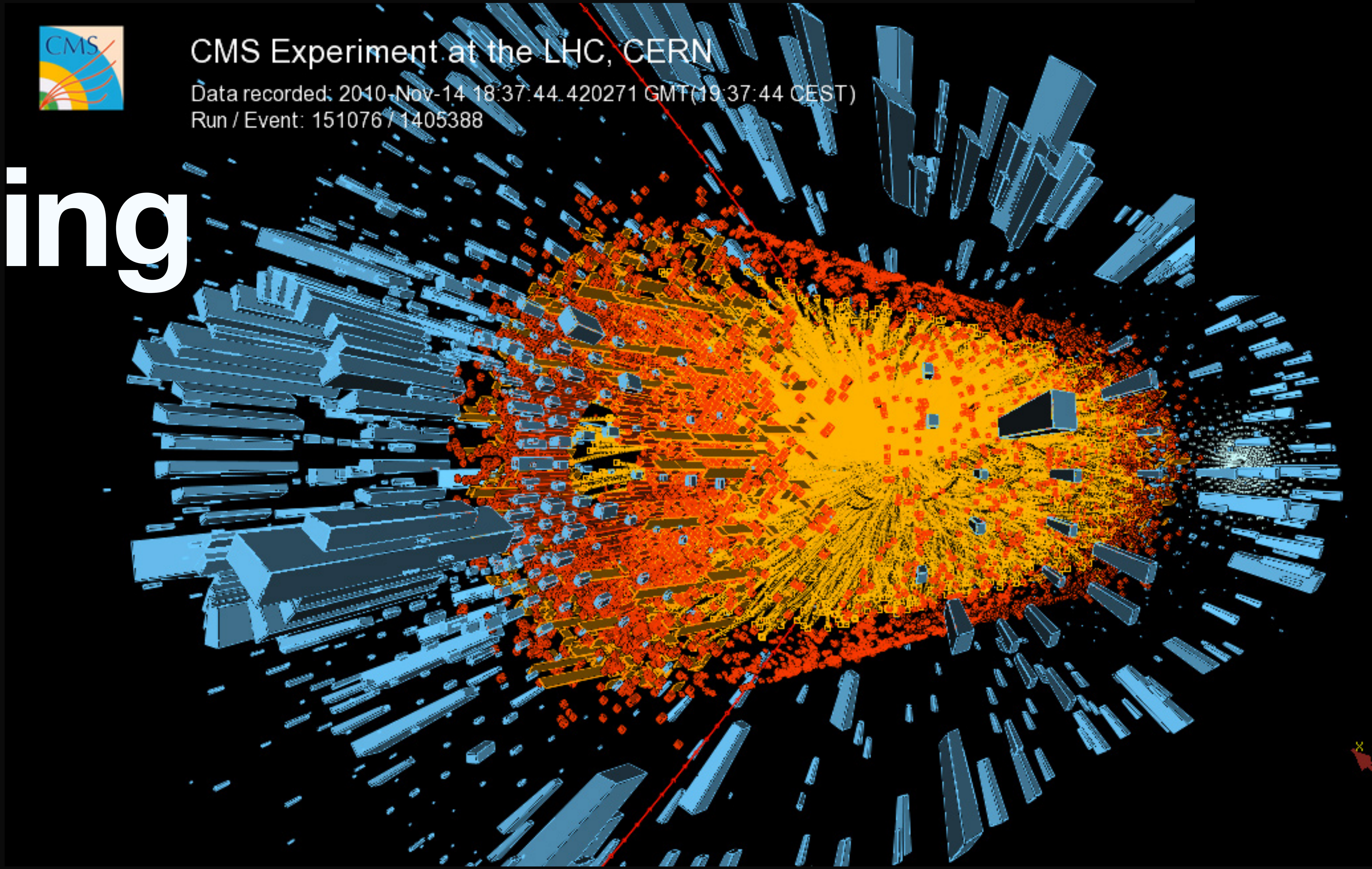
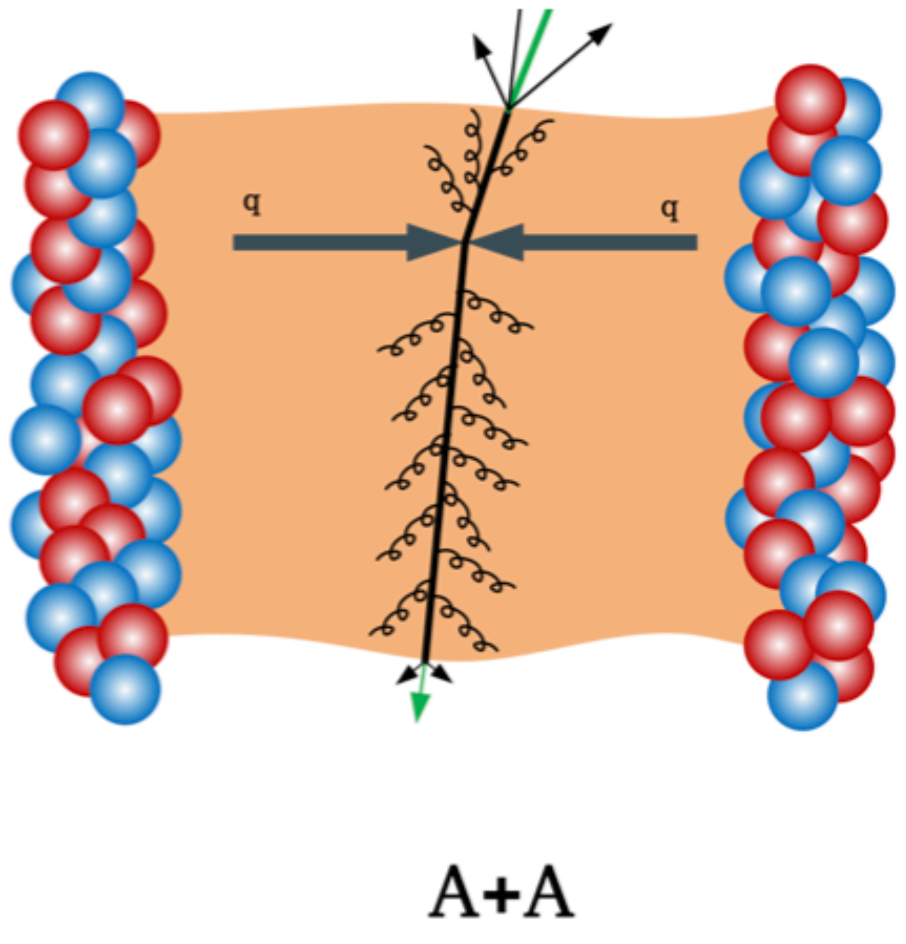
Power counting to jet quenching

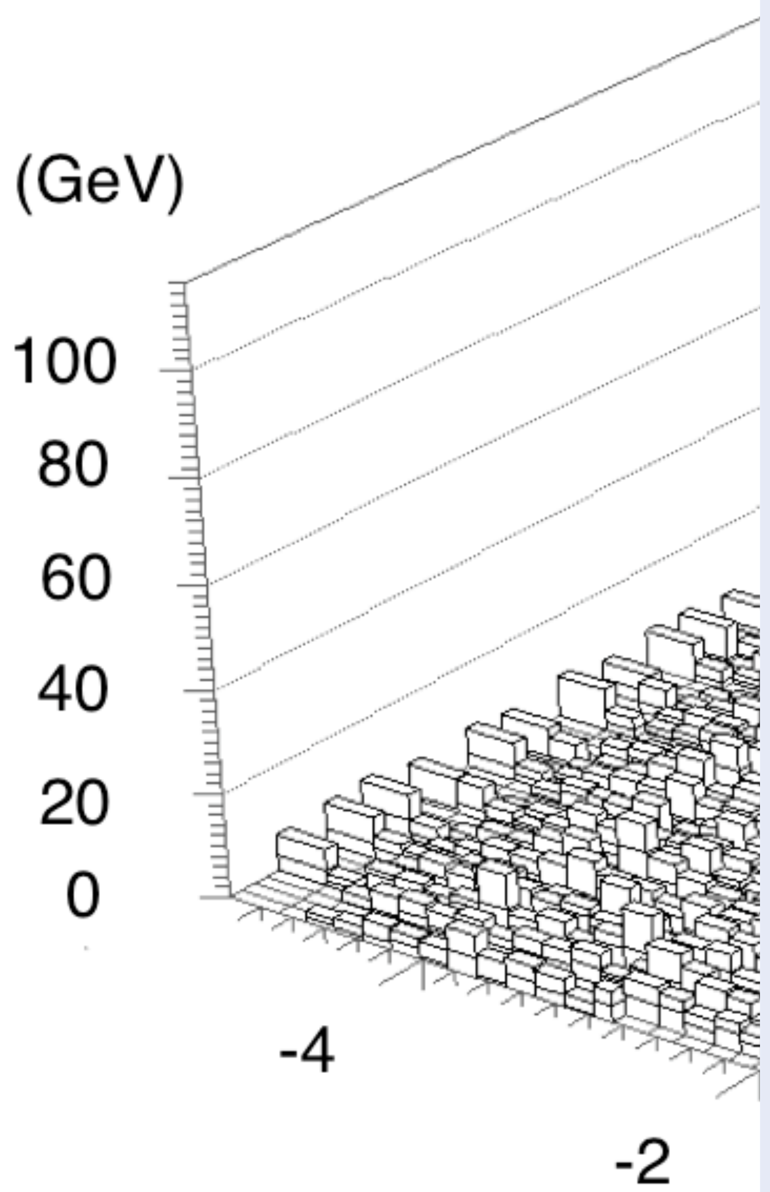


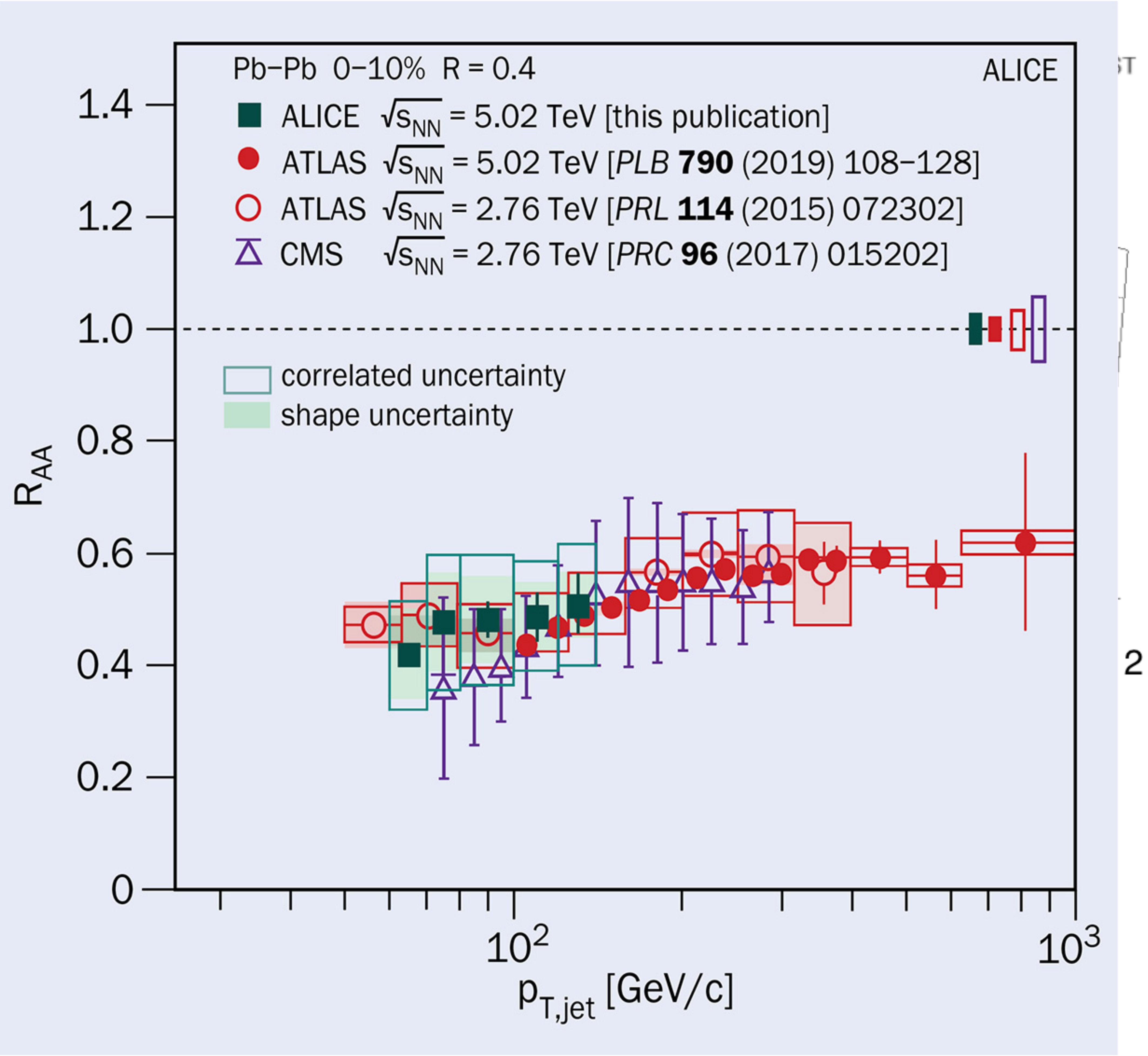
Varun Vaidya,
University of South Dakota

based on 2408.XXXX
Felix Ringer, Yacine Mehtar-Tani, Balbeer Singh

Jets lose energy and are "Quenched"

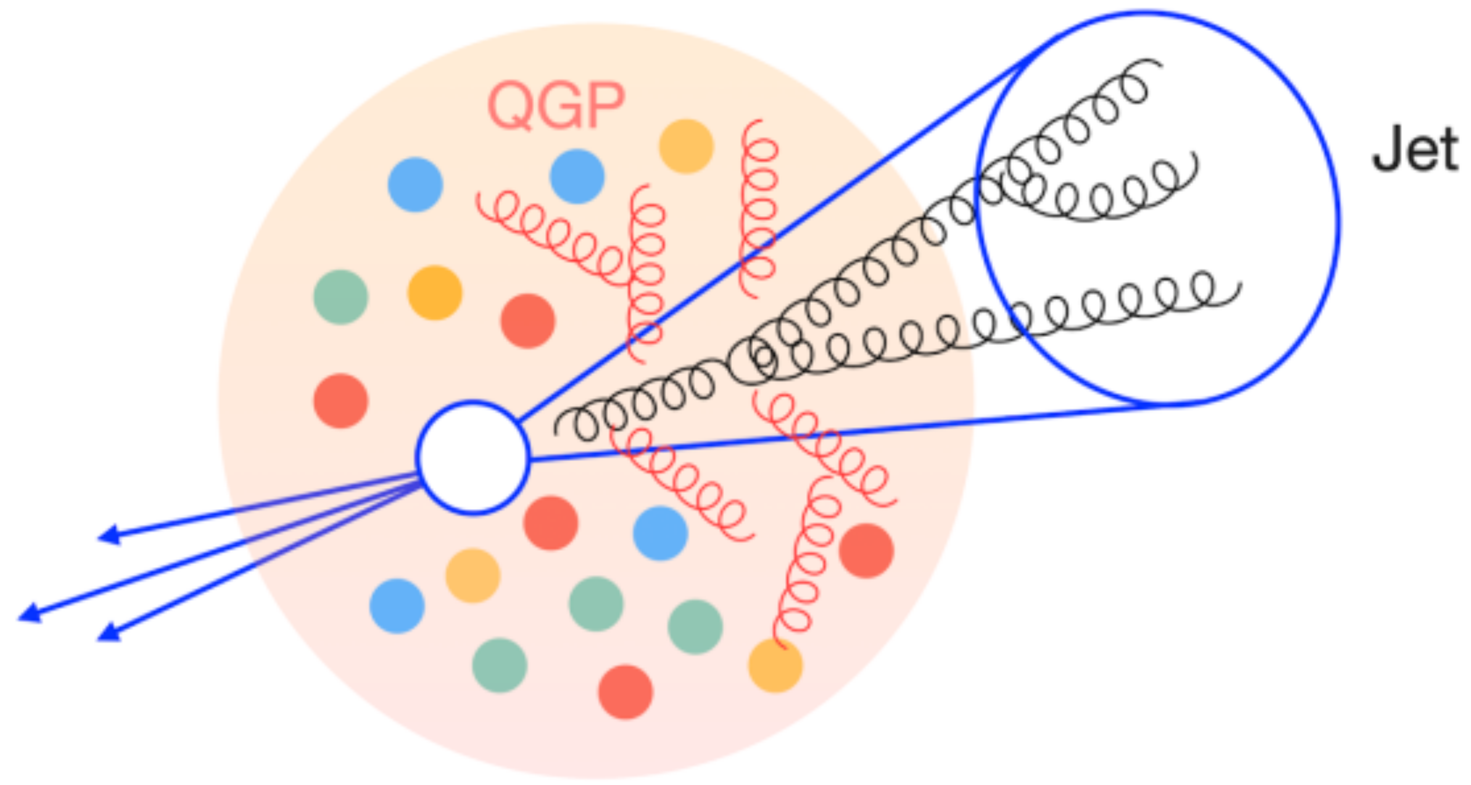






- We can use the jet to access the microscopic structure of the strongly coupled QGP.

Key questions for jet evolution in QGP

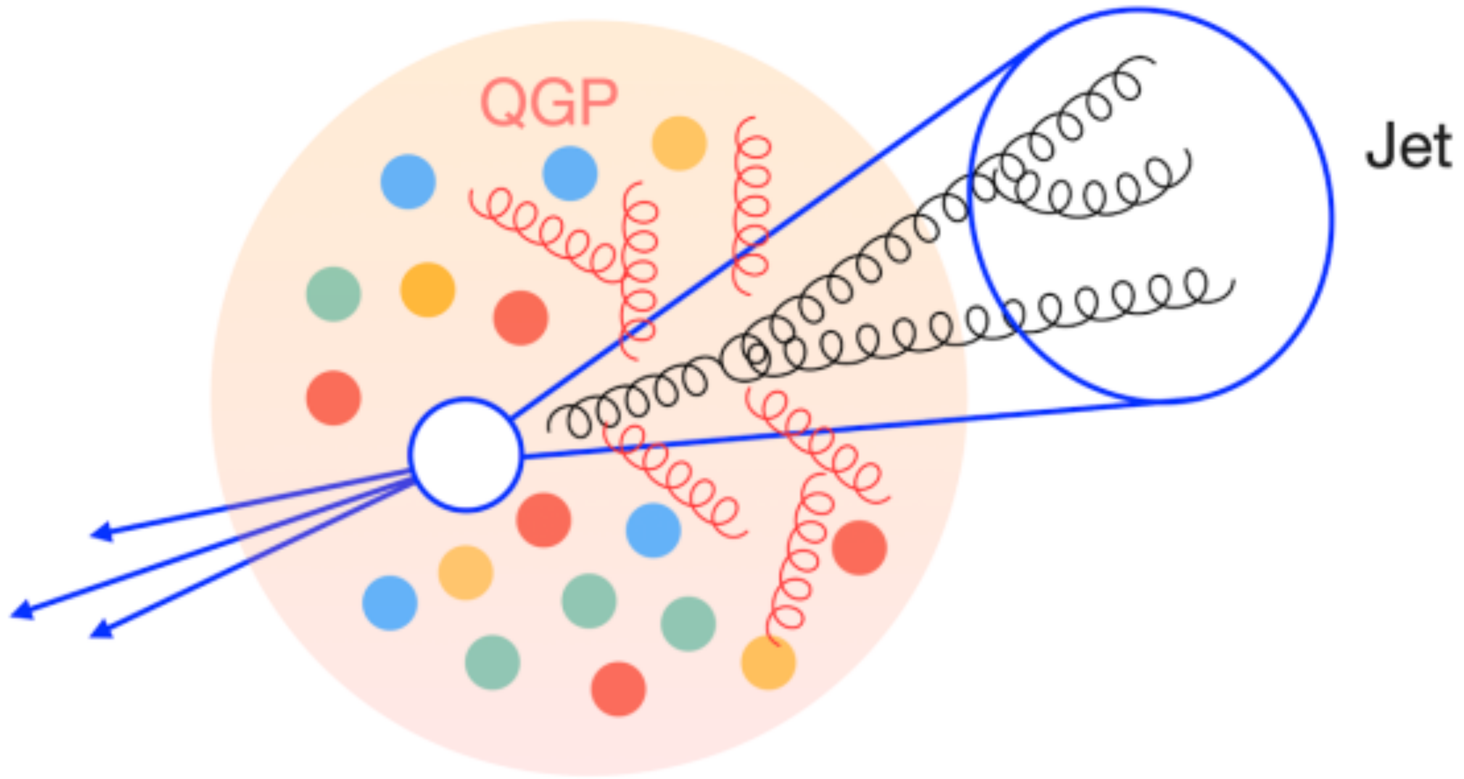


- **Separate** the **perturbative physics** from the non-perturbative by scale
- **Parameterize** the **non-perturbative physics** in terms of Gauge invariant operators → e.g the PDF in DIS, Drell Yan, Higgs production etc.
- **Prove** (disprove) universality of non-perturbative physics across jet observables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

We rely on EFT approach to factorization → Explicitly separate physics at widely separated scales to all orders in α_s.

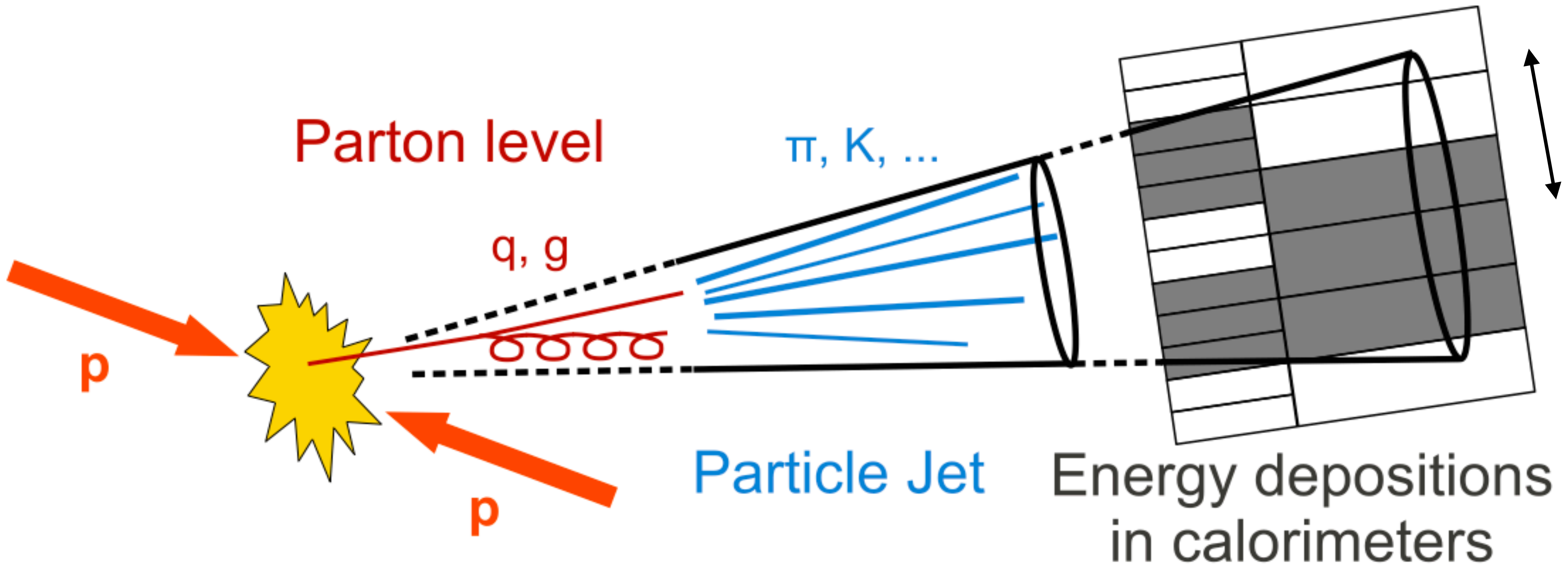
Goal of this talk

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



Chapter 1

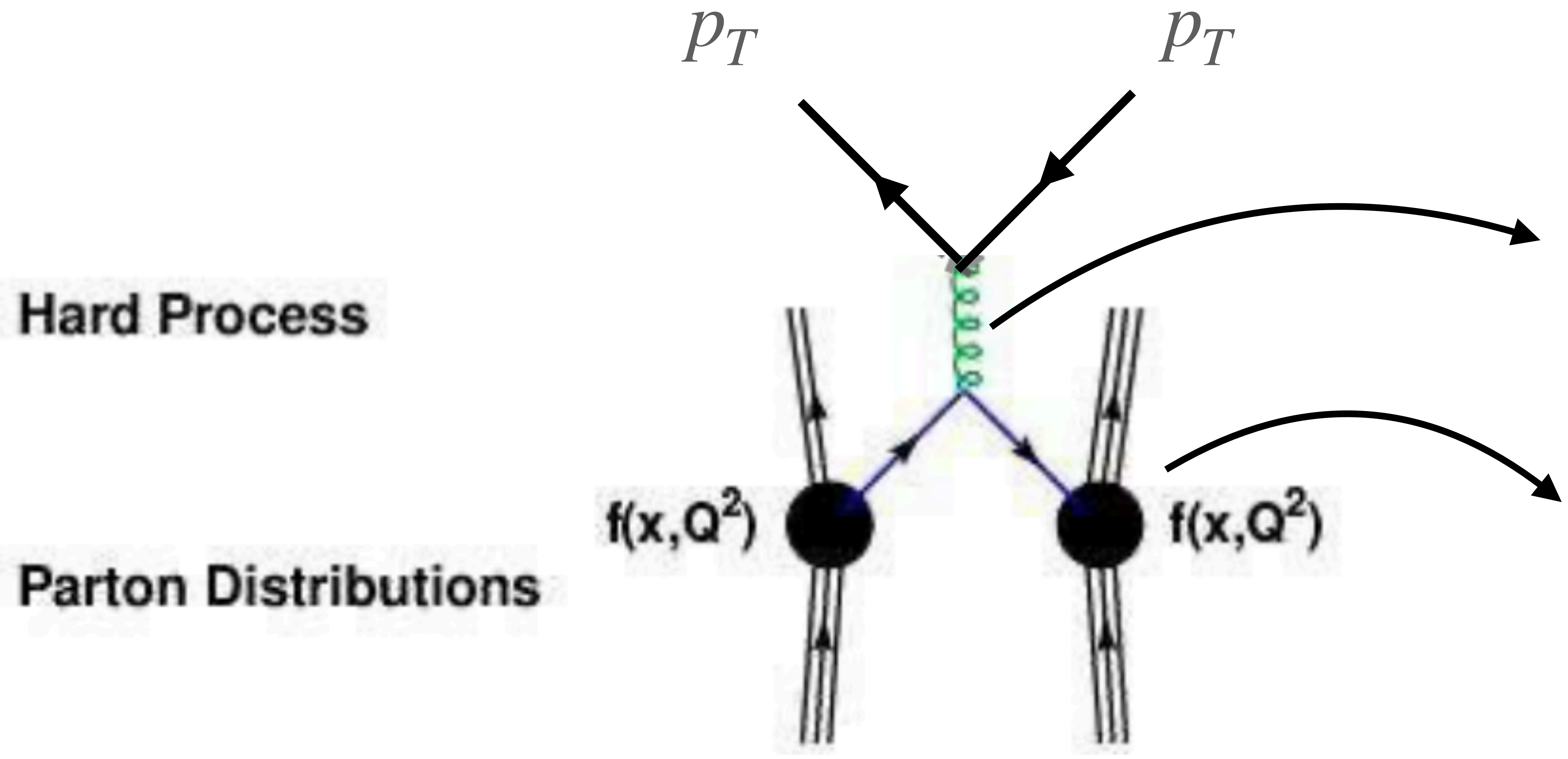
Anatomy of a vacuum jet



$R \in \{0.05, 0.3\} \ll 1$

$p_T \sim 100$(s) of GeV

Tree level



$p^2 \sim p_T^2$ **Hard Scale**

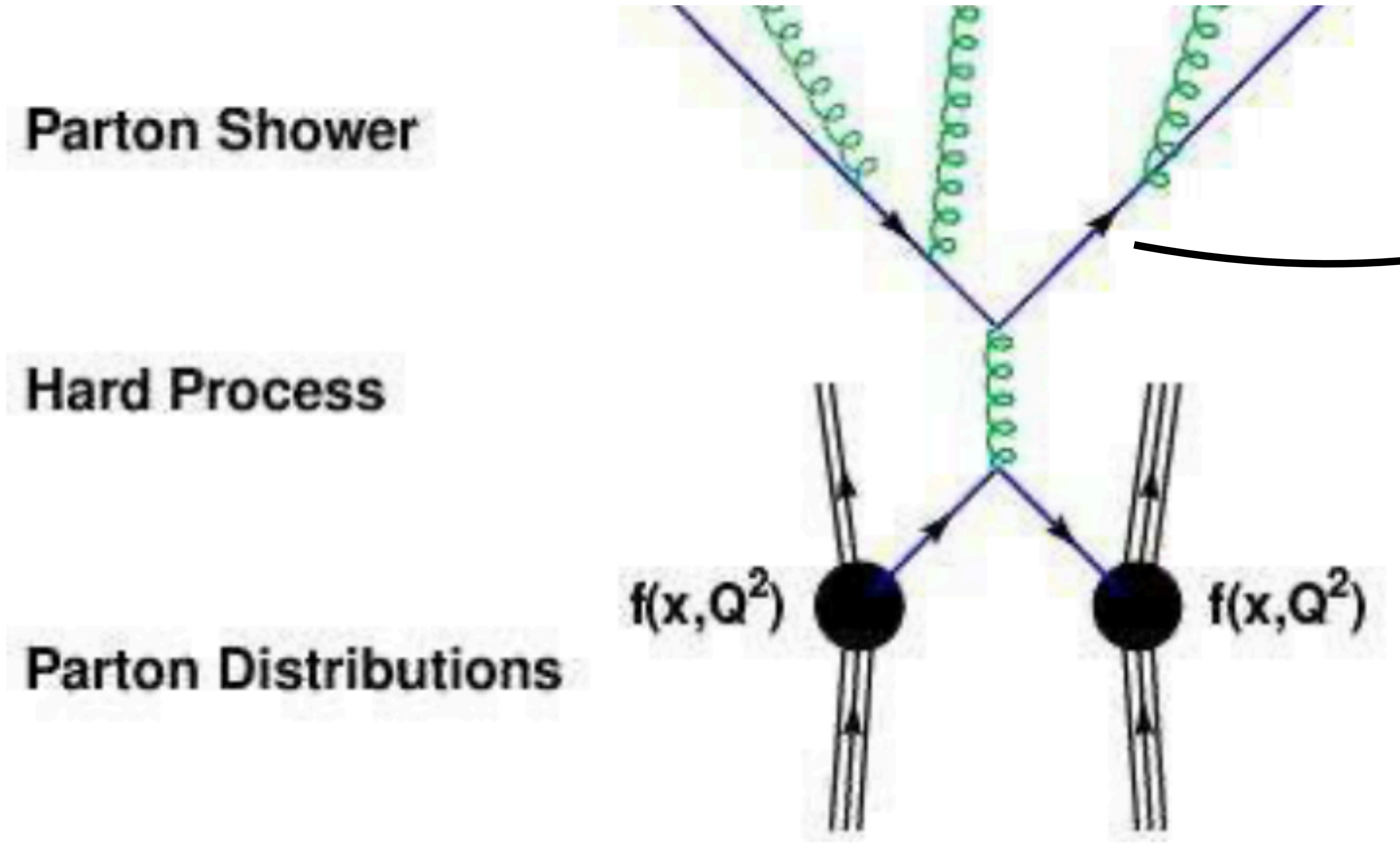
$p^2 \sim \Lambda_{\text{QCD}}^2$

The parton shower

- Parton splittings preferentially happen at small angles →“ collinear”
- Selecting events with a jet of radius R sets the angular scale for collinear splittings.

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

Hard collinear

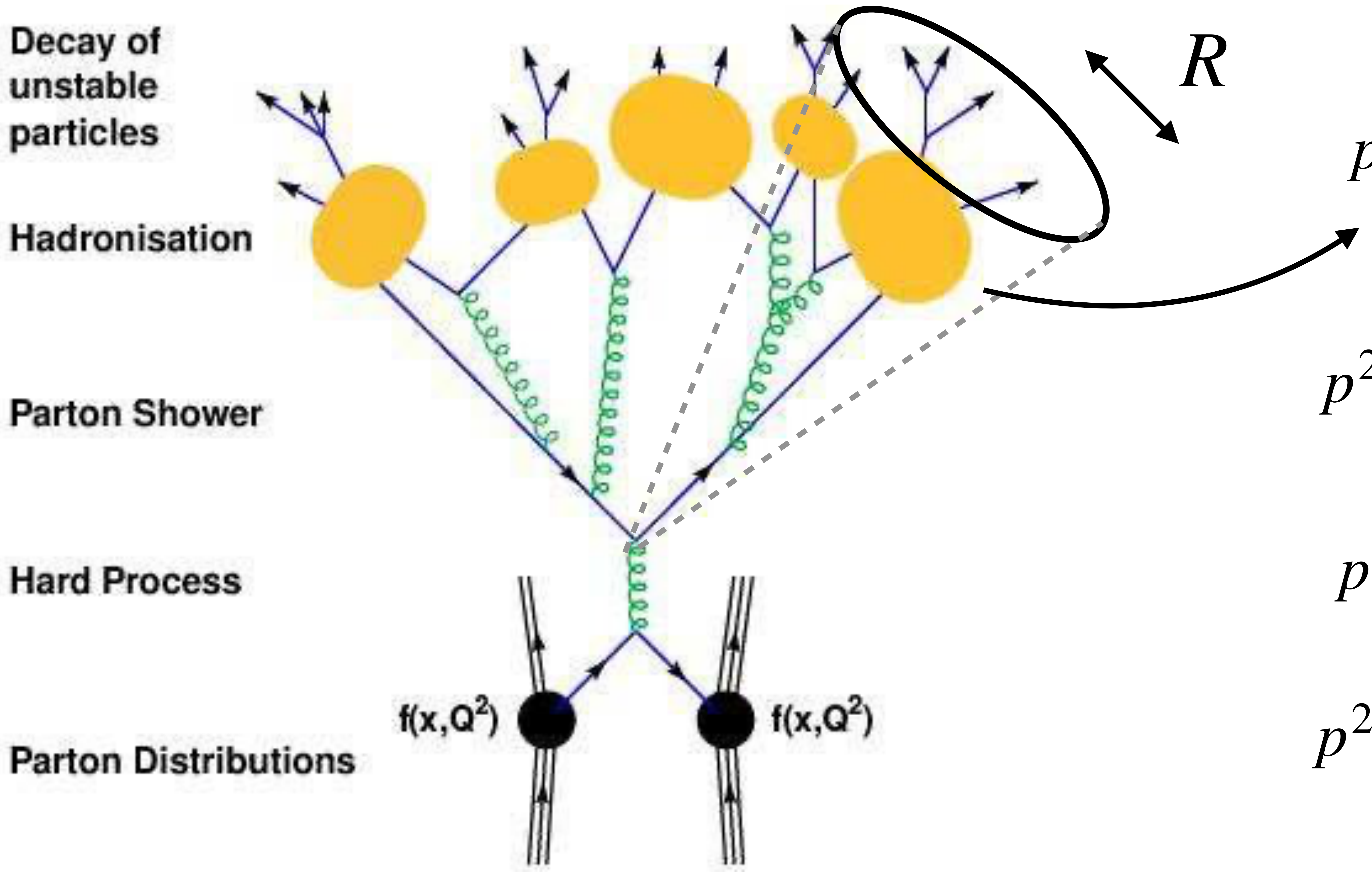


$p^2 \sim (p_T R)^2$ **Jet Scale**

$p^2 \sim p_T^2$ **Hard Scale**

$p^2 \sim \Lambda^2_{\rm QCD}$

Hadronization



$p^2 \sim \Lambda^2_{\mathrm{QCD}}$

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

$p^2 \sim p_T^2$ **Hard Scale**

$p^2 \sim \Lambda^2_{\mathrm{QCD}}$

A separation of scales

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

Physics at scale Λ_{QCD}

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

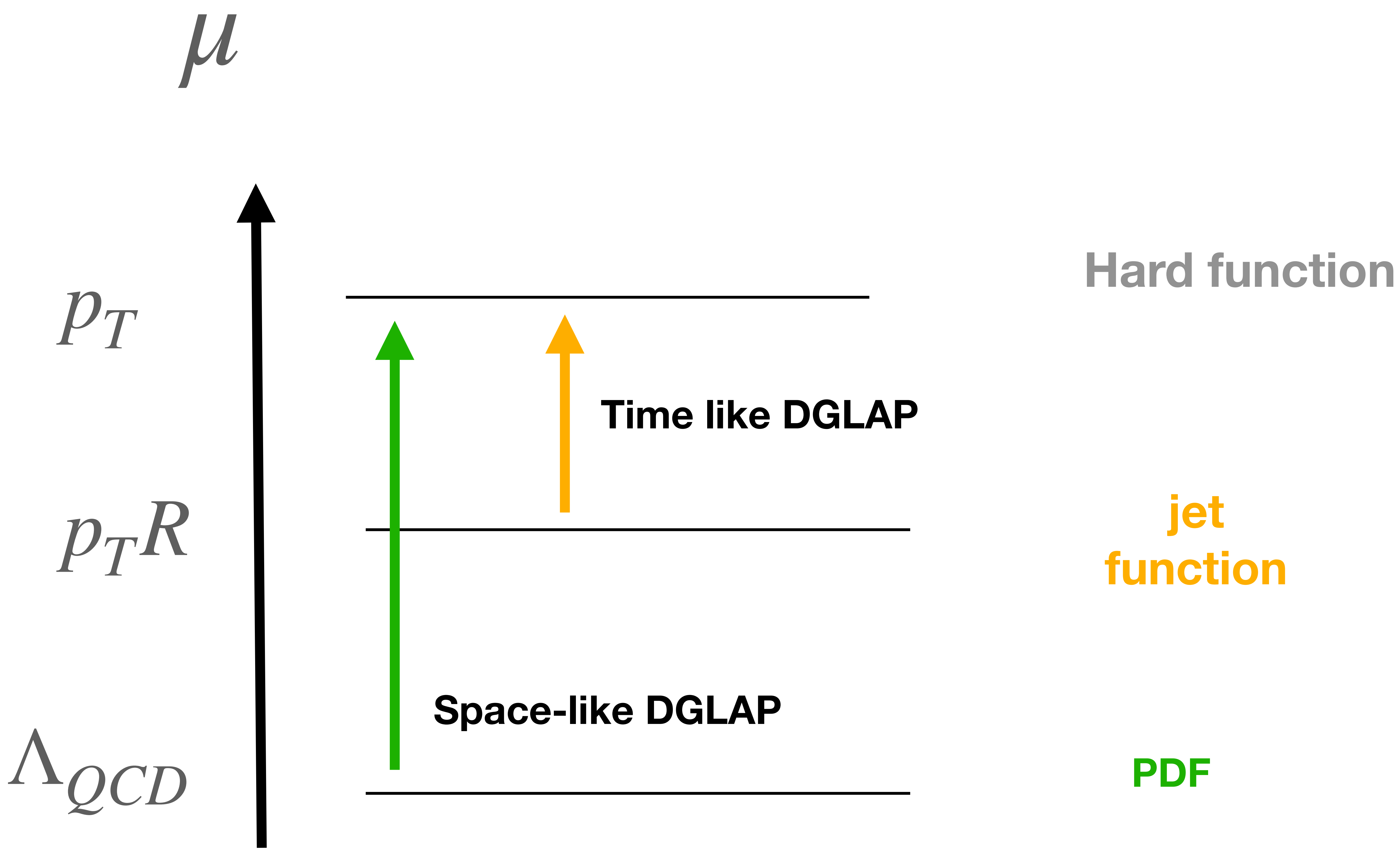
Hard function at p_T

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

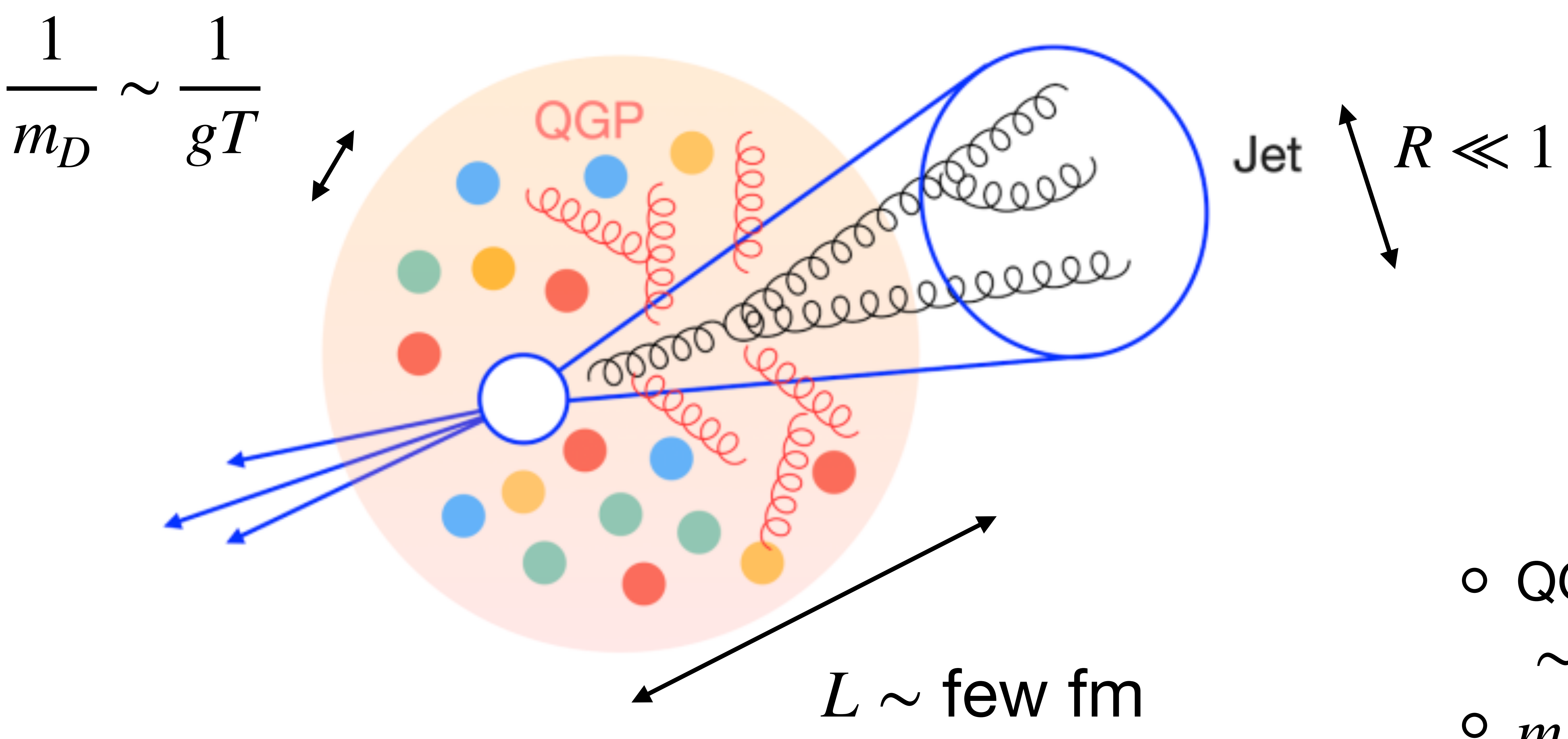
RG Flow


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

Chapter 2

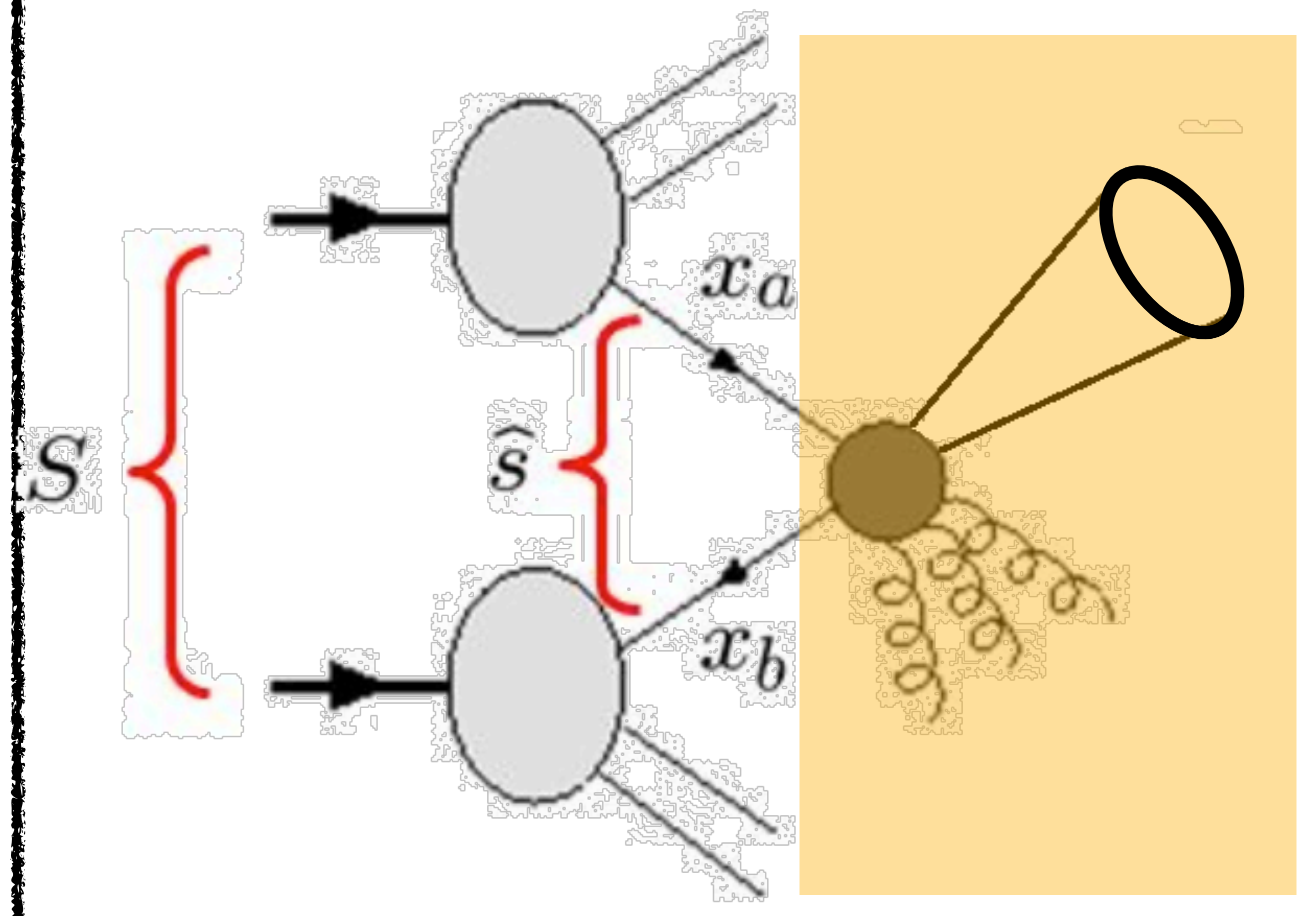
Introducing the QGP medium

New medium scales



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

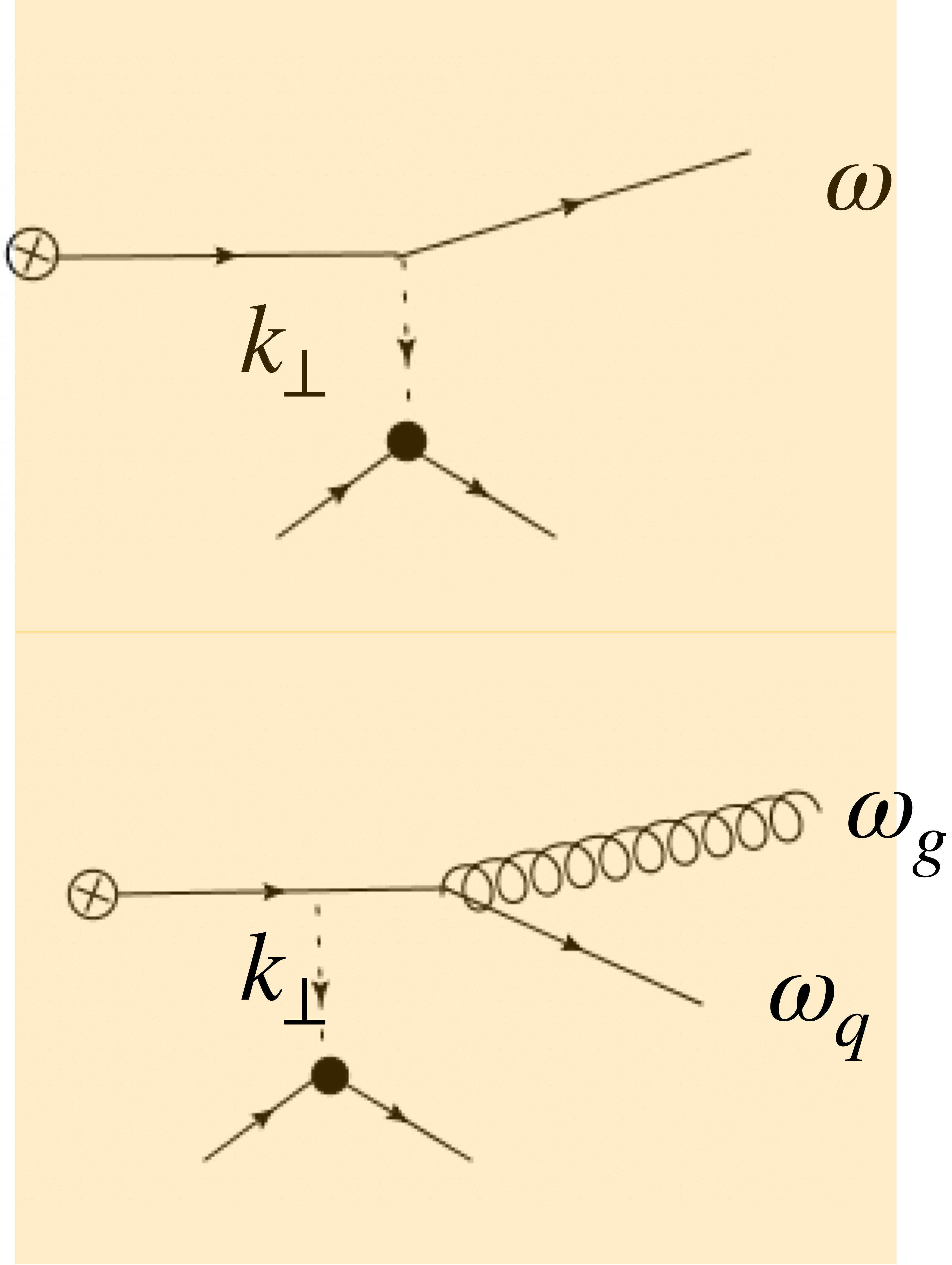
The basic hierarchy



QGP/Nucleus

jet p_T	→	perturbative ~ 100(s) of GeV
$p_T R$	→	perturbative ~ 10(s) of GeV
Λ_{QCD}, T, m_D	→	non-perturbative ~ 100s of MeV

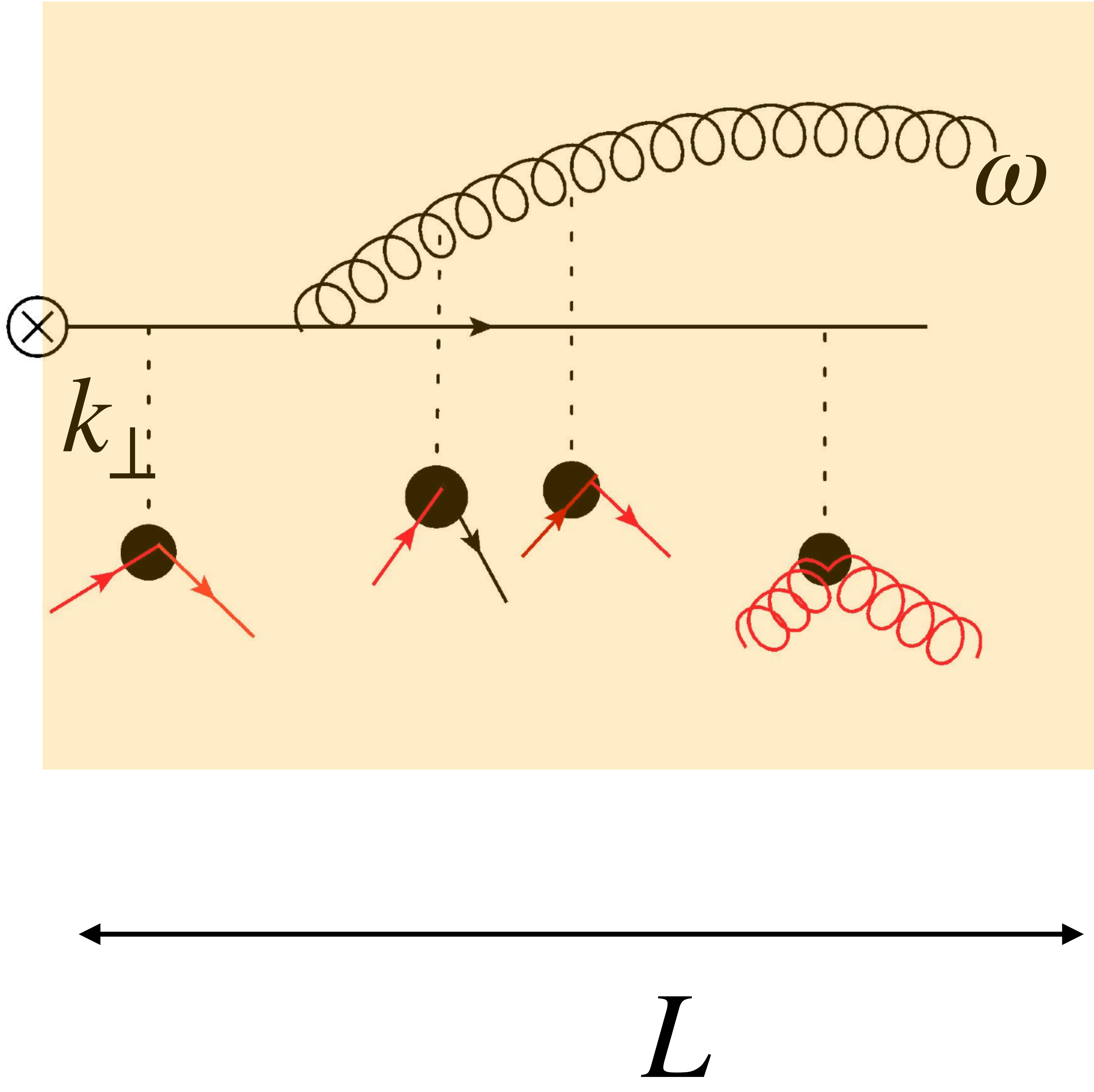
Parton in the medium



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

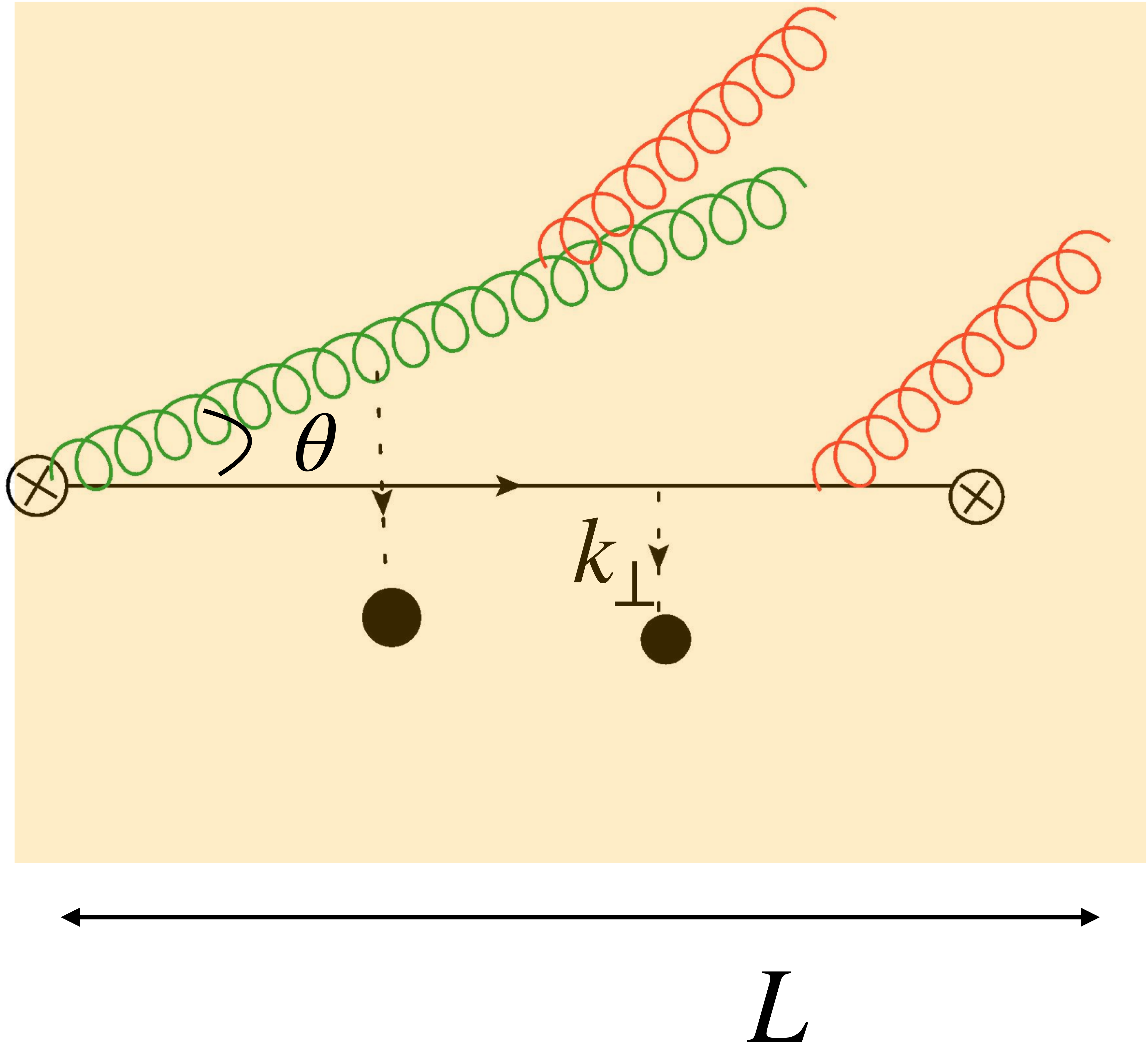
- Elastic forward scattering
- Medium induced radiation
- Typical $k_\perp \sim m_D$,
- Angle of deflection $\theta \sim \frac{k_\perp}{\omega} \ll 1$
- An EFT with θ as the expansion parameter →

Multiple interactions



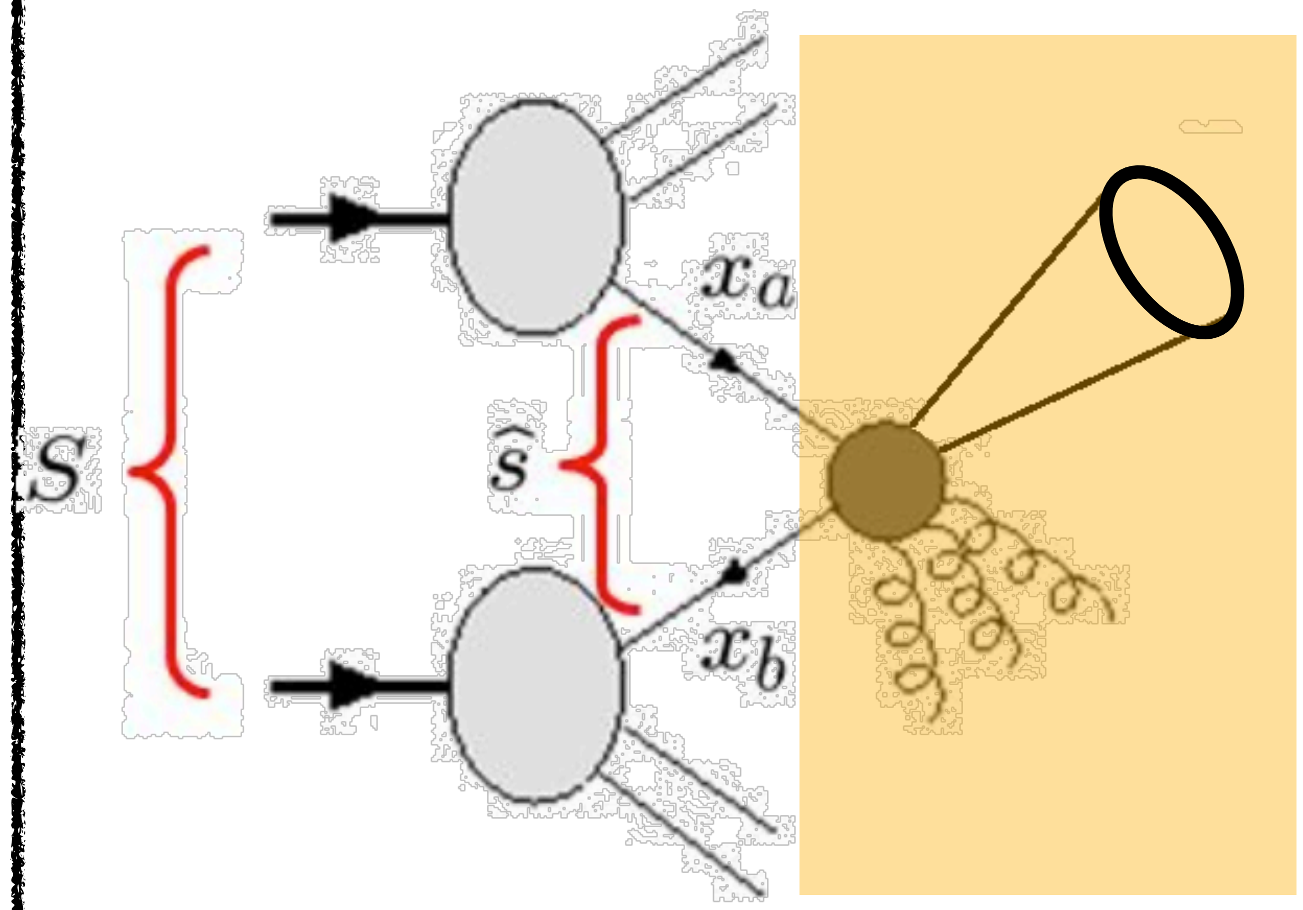
- Q_{med} → Total average transverse kick per parton $\geq m_D$
- For a dense medium, perturbative?

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

The updated hierarchy



QGP/Nucleus

jet p_T	→	perturbative ~ 100(s) of GeV
$p_T R,\ p_T \theta_c$	→	perturbative ~ 10(s) of GeV
Q_{med}	→	perturbative/non-perturbative ~ 1- few GeV
Λ_{QCD}, T, m_D	→	non-perturbative ~ 100s of MeV

Chapter 3

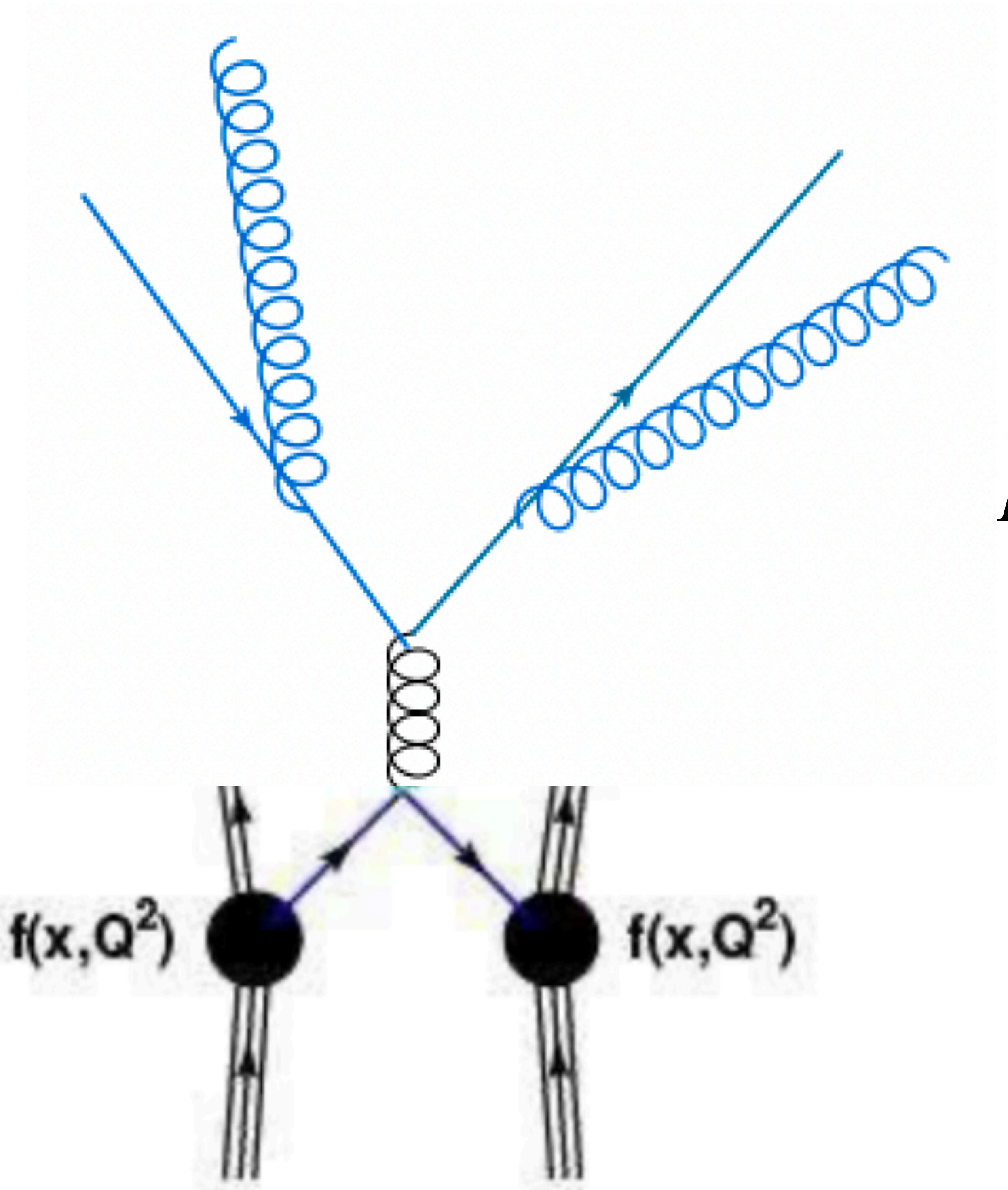
Jet propagation in the medium

The physical picture

Parton shower

Hard Process

Parton Distributions

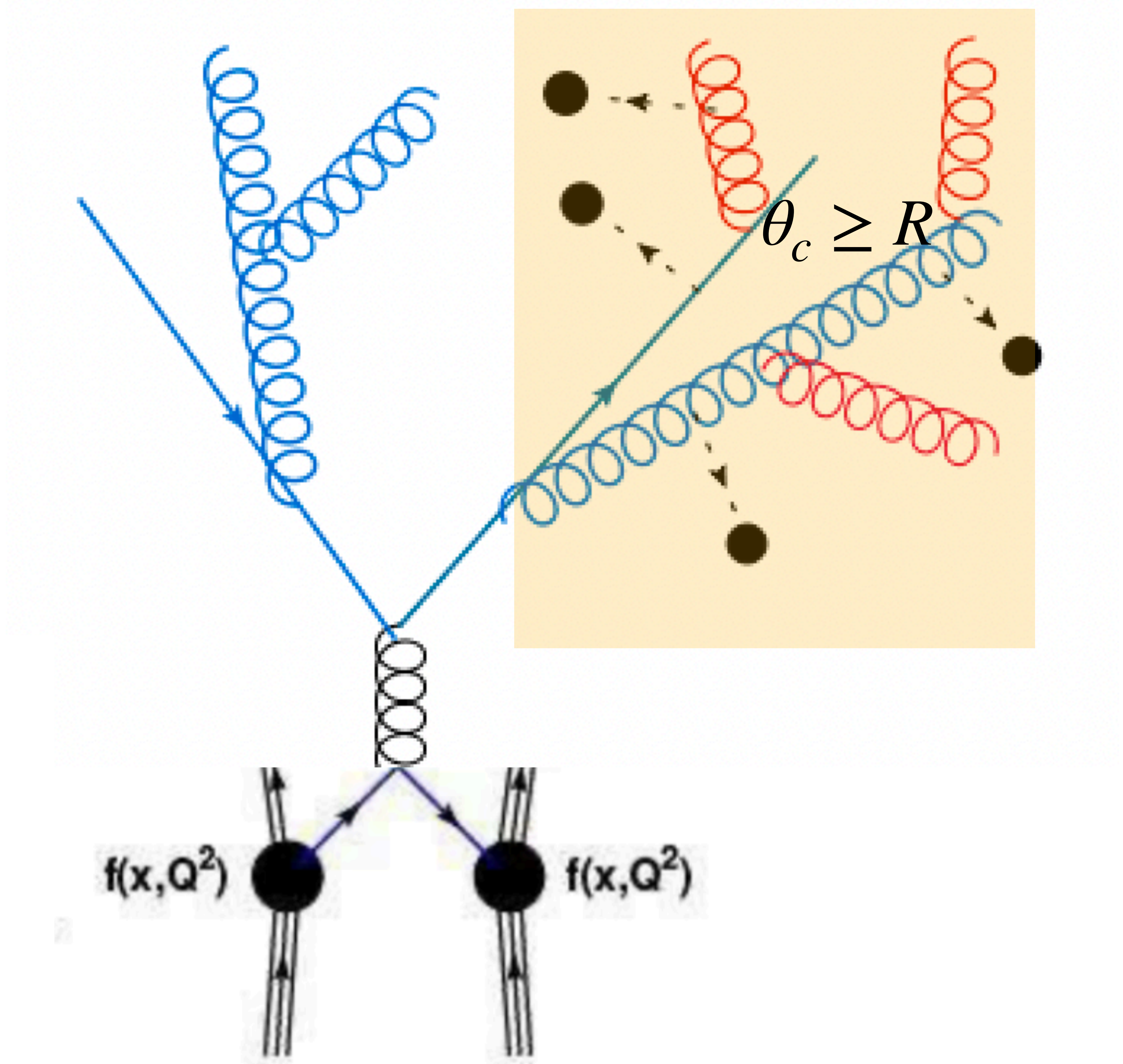


$p^2 \sim (p_T R)^2$ **Jet Scale** **Hard collinear** $E \sim p_T,\ \theta \sim R$

$p^2 \sim p_T^2$ **Hard Scale**

- The hard process and parton shower for scales $\sim p_T R$ remain unaffected by the medium

The physical picture



$p^2 \sim Q^2_{\text{med}}$ **Medium Scale**

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

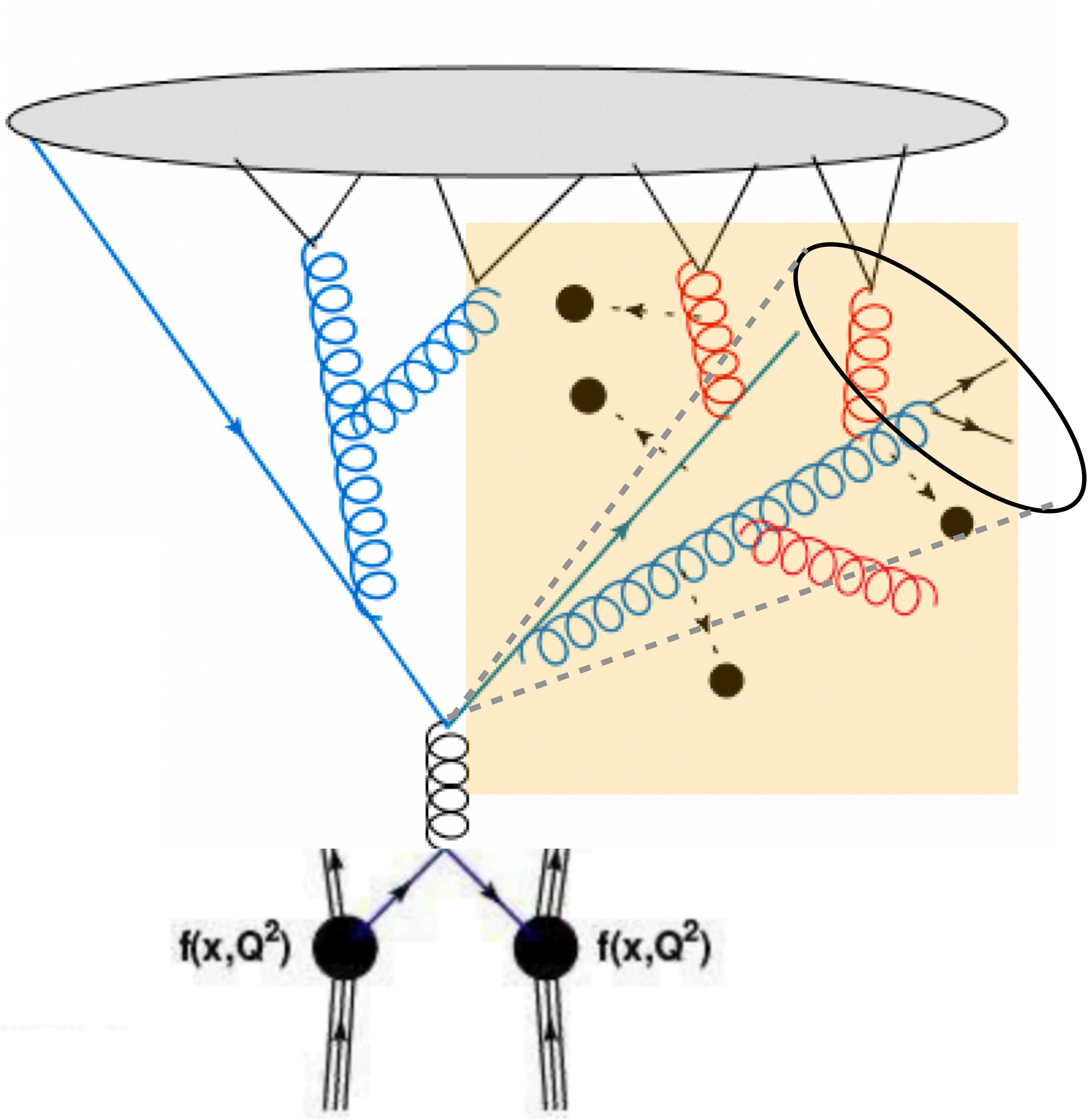
$p^2 \sim (p_T R)^2$ **Jet Scale**

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

$p^2 \sim p_T^2$ **Hard Scale**

- Each hard collinear parton separated by θ_c acts as a source for collinear soft radiation at virtuality $\sim Q^2_{\text{med}}$

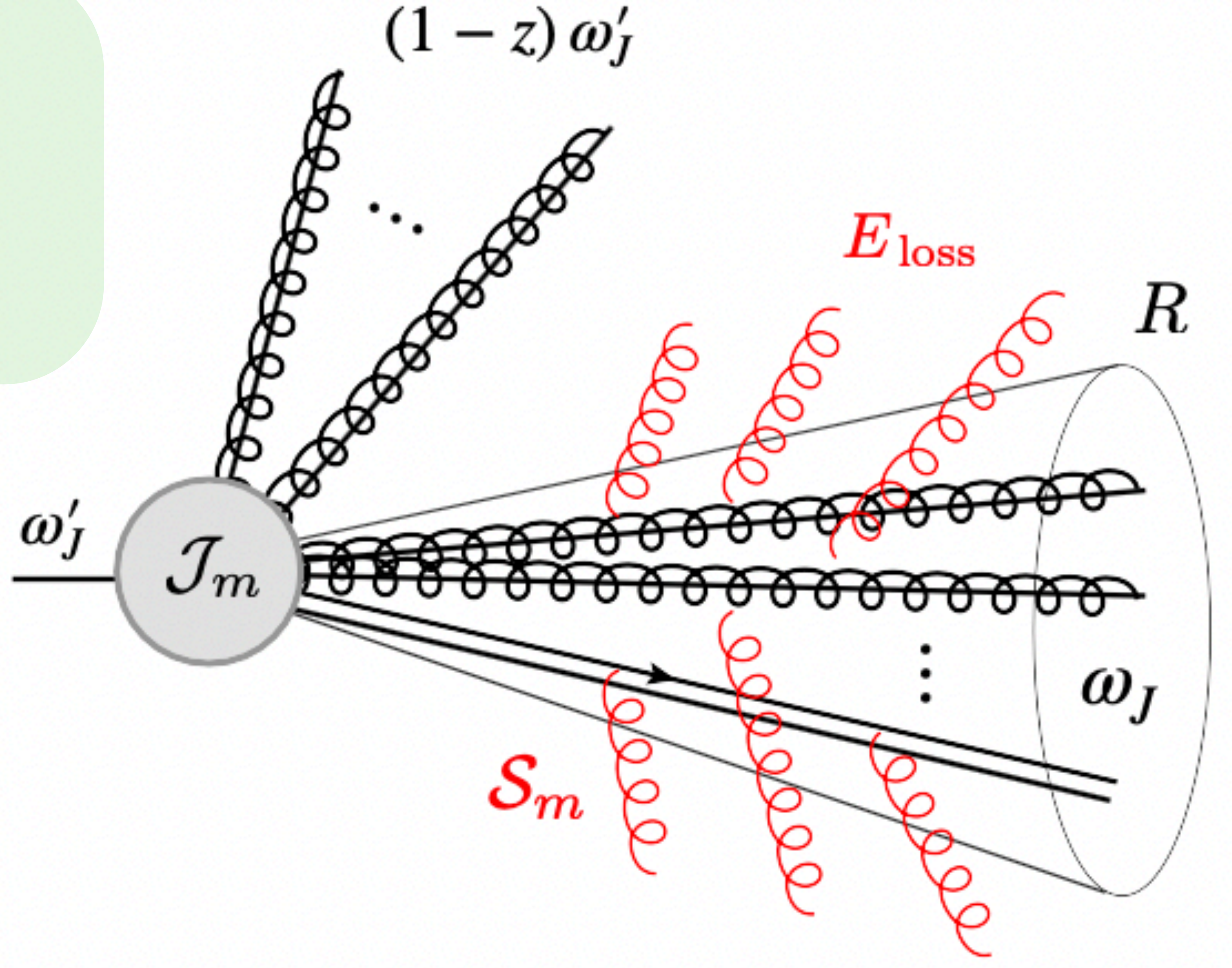
The physical picture



$p^2 \sim \Lambda^2_{\text{QCD}}$	**Hadronization**	
$p^2 \sim Q^2_{\text{med}}$	**Medium Scale**	**collinear soft**
$p^2 \sim (p_T R)^2$	**Jet Scale**	**Hard collinear**
$p^2 \sim p_T^2$	**Hard Scale**	**Hard radiation**

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 → Wilson coeff at p_T

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

Create m prongs → Wilson coeff at $p_T R$

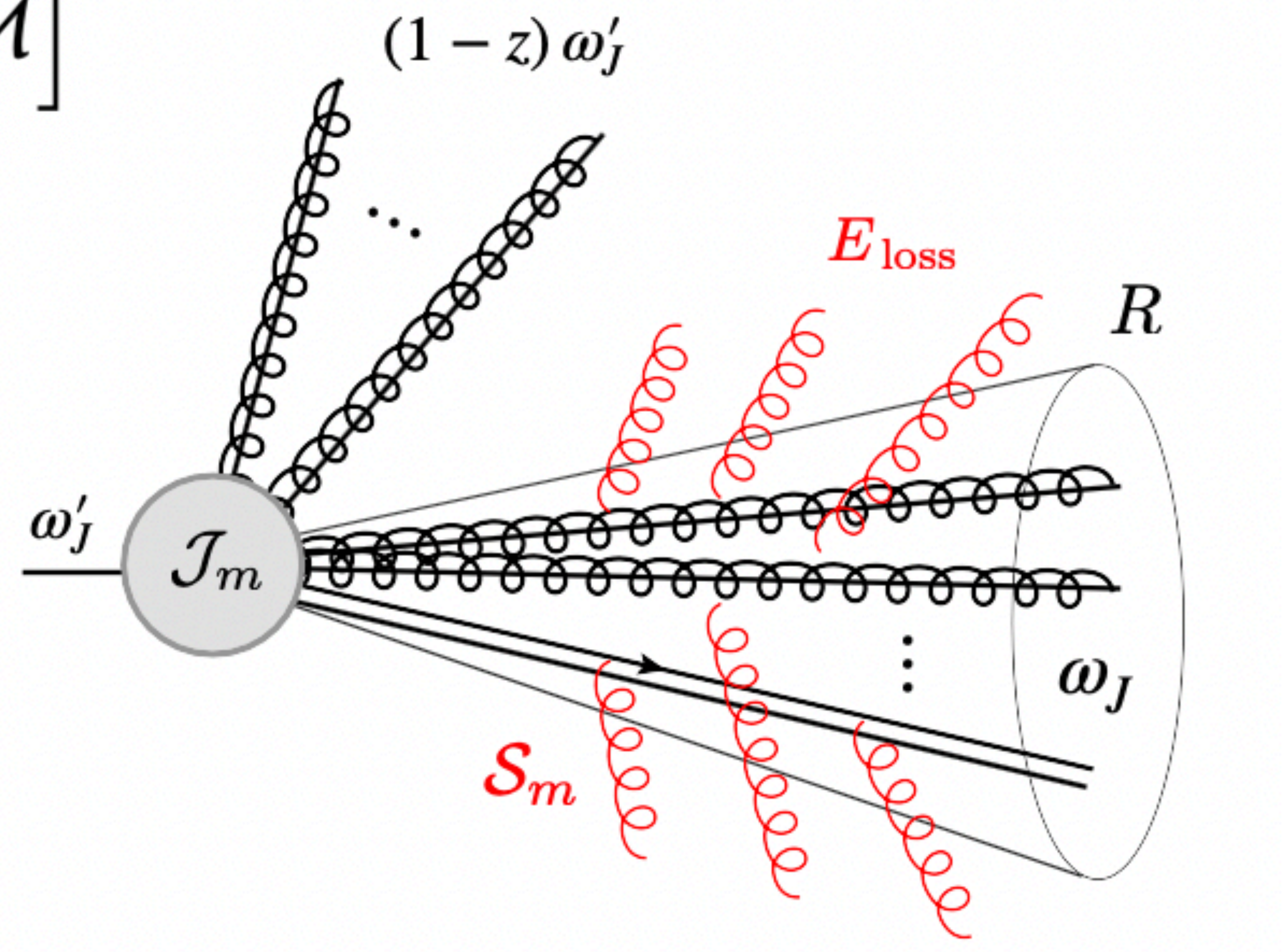
Medium induced energy loss function

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

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

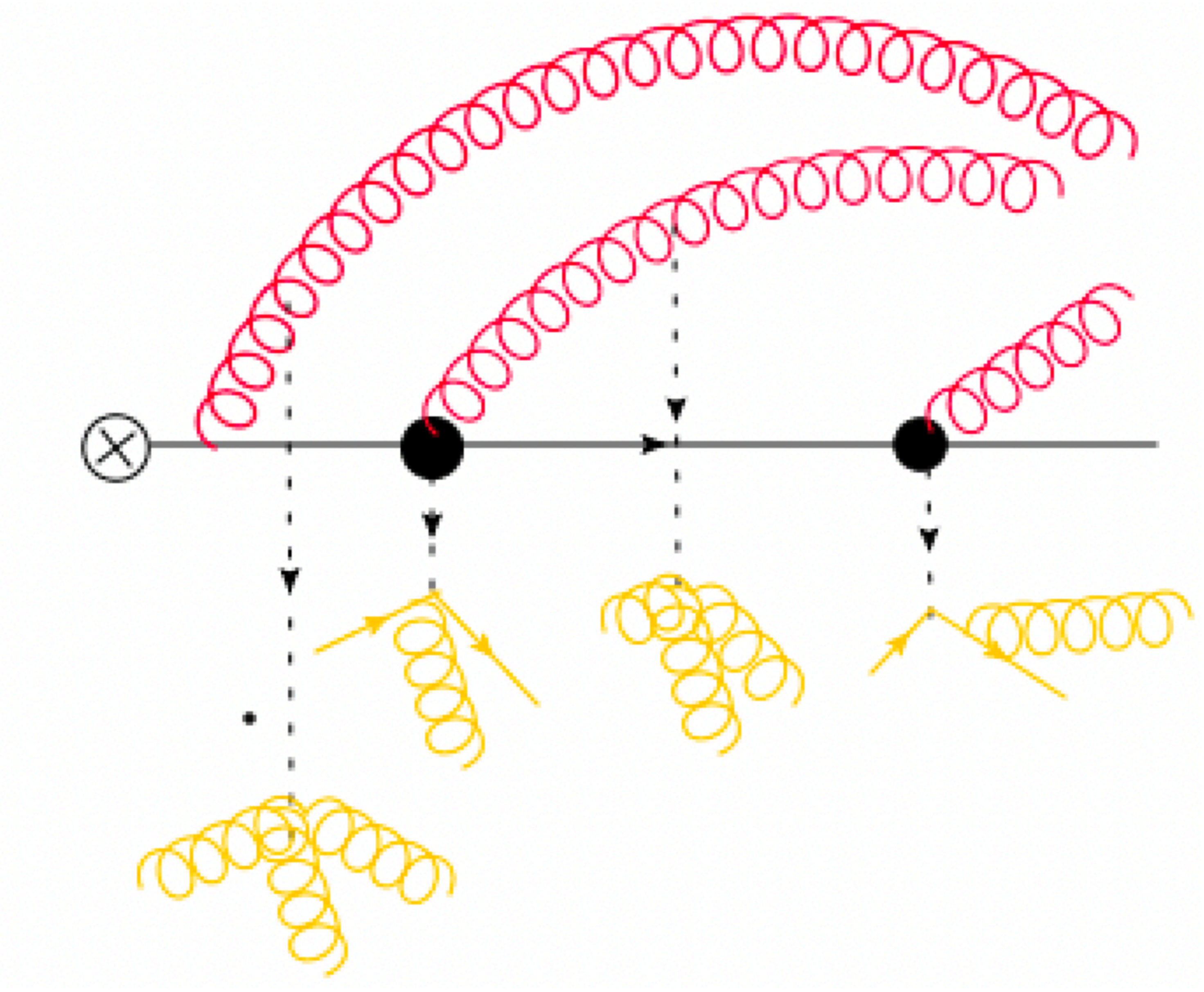


Chapter 4

Separating the medium from the jet

Looking inside a single prong S_1

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



$E \sim Q_{\text{med}}/R\,,\;\; p^2 \sim Q^2_{\text{med}} \to$ **Collinear Soft**

Medium partons and dynamics

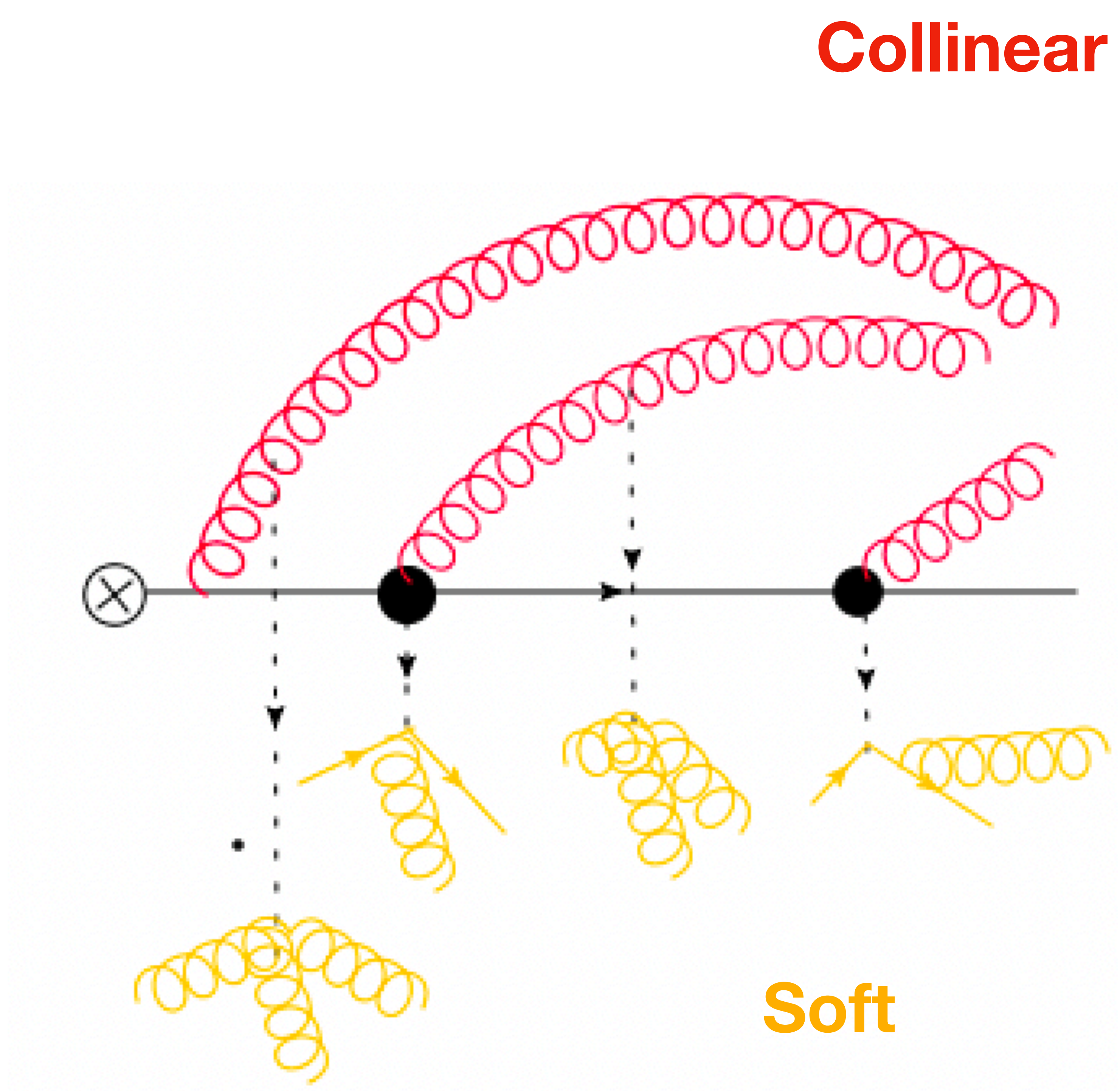
$E \leq Q_{\text{med}}\,,\;\; p^2 \sim Q^2_{\text{med}} \to$ **Soft**

A separation in rapidity

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

Defines an effective action for CS, S d.o.f at leading power in the scattering angle θ

Looking inside a single prong S_1

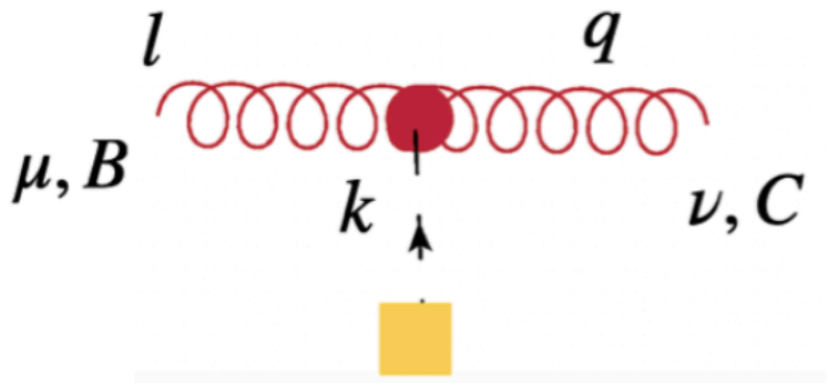


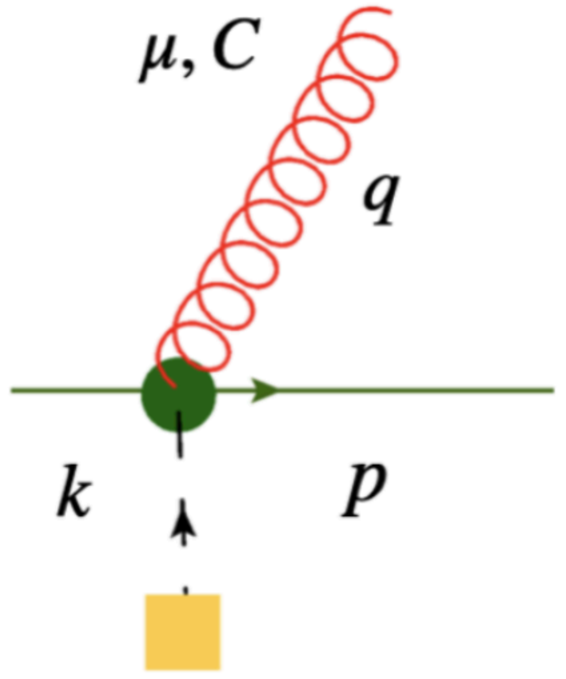
$$\mathcal{S}_1 = \mathrm{Tr}\Big[U(n)U(\bar{n})\mathcal{M}U^\dagger(\bar{n})U^\dagger(n)\Big]$$

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

Forward Scattering of CS off Soft

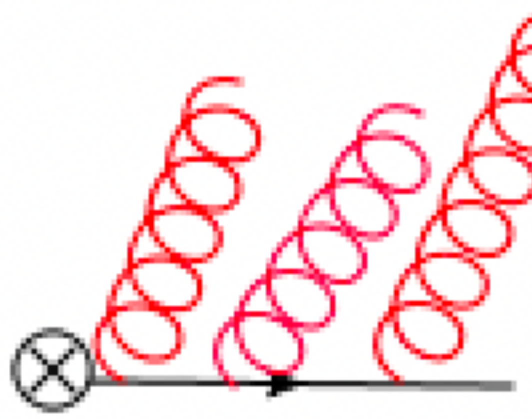
Medium induced CS radiation along world line of hard prong



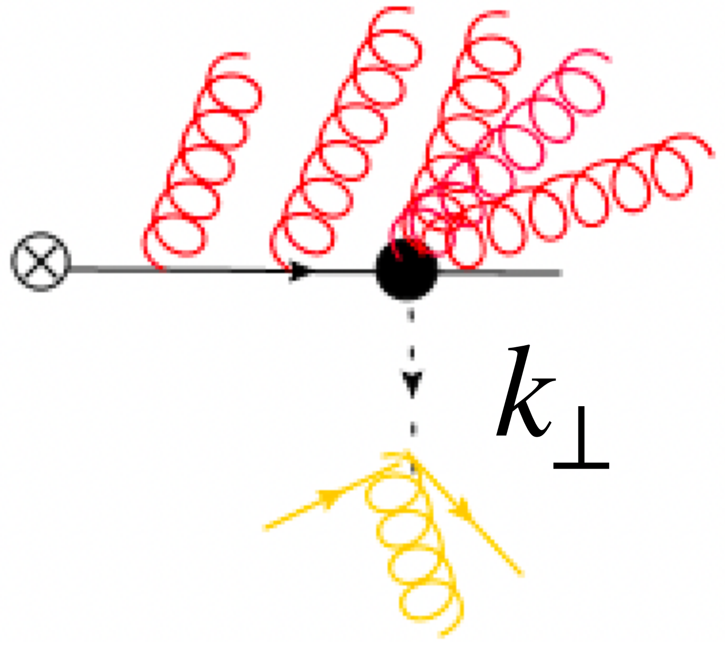


Single prong physics

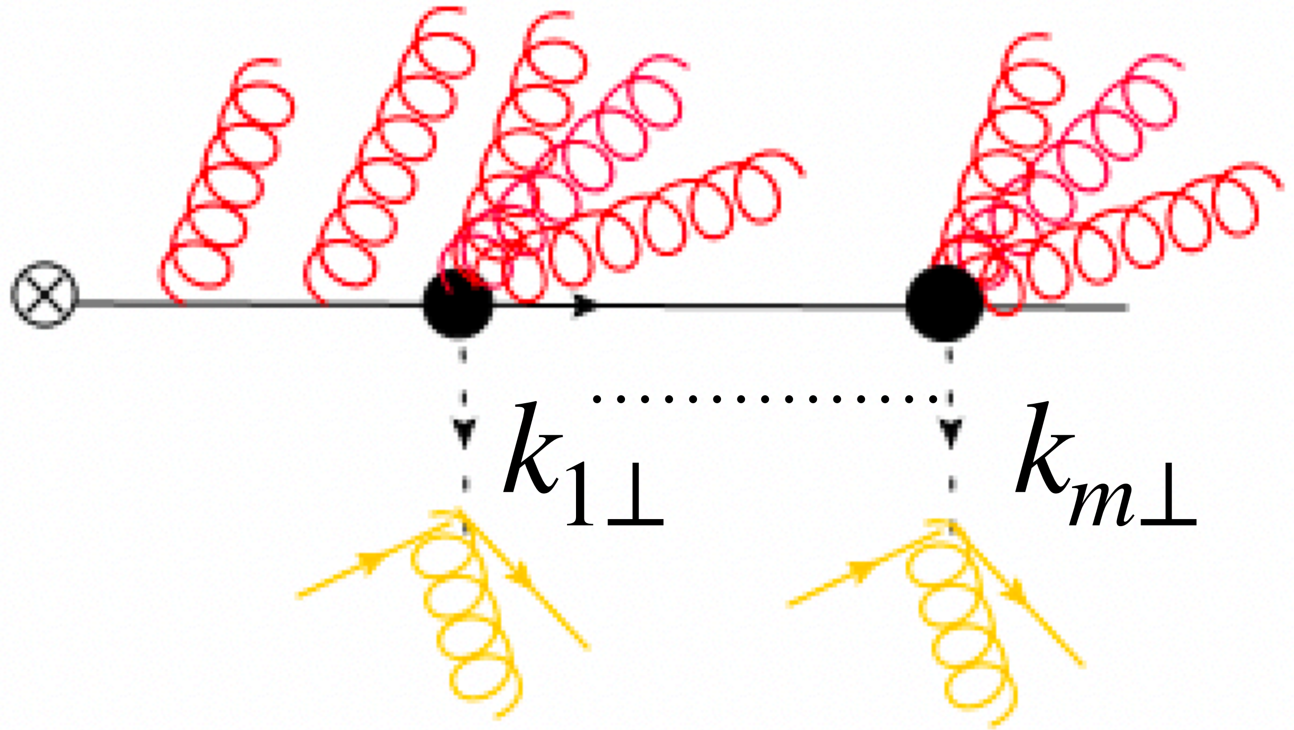
$$S_1(n,\epsilon,\mu) = \sum_{i=0}^{\infty} \bar{\mathcal{S}}_i(n,\epsilon,\mu)$$



$+$



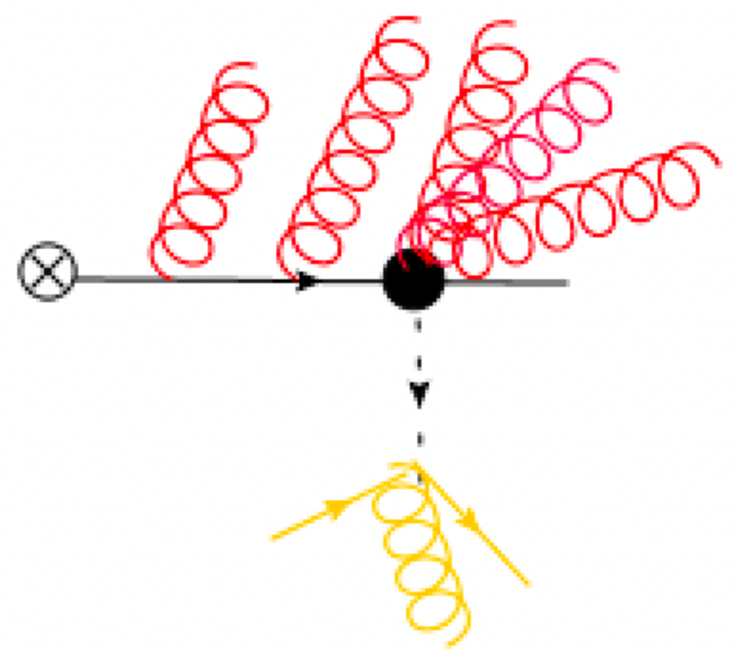
$+ \cdots\cdots\cdots\cdots +$



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

All order Vacuum cs radiation + **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

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

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

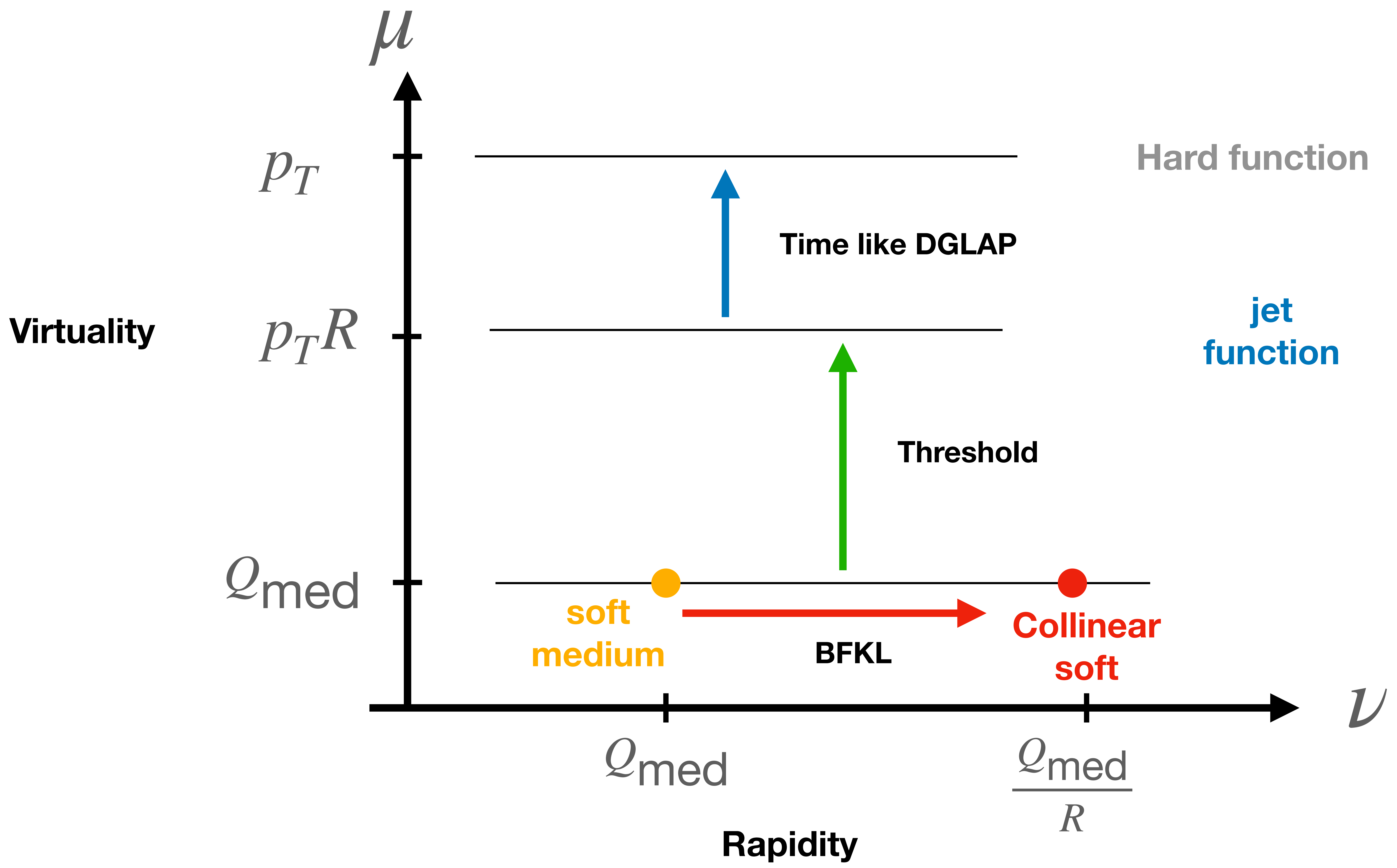
A gauge invariant operator definition → Wightman correlator at LO

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

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

$\mathcal{S}_1(n,\epsilon,k_\perp,\nu)$ → **Soft limit of GLV at LO, obeys BFKL evolution in ν**

Medium Jet RG Flow



Epilogue

p_T $p_T R$ Q_{med}

$$\frac{d\sigma}{dp_T d\eta} \sim f \otimes f \otimes H \otimes \mathcal{J} \otimes \left(S_0 + \int d^2k_\perp \mathcal{S}_1 \mathcal{B} + \ldots . \right)$$

Nuclear PDF

Perturbative

Observable dependent

Universal medium physics

Q_{med} Non Perturbative?

Emergent Q_{med} scale?
Further matching to T?

Thank You

Back up

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

$$L_{QCD} = L_{collinear} + L_{soft} + L_{Glauber} + O(x^2)$$
$$\equiv L_{SCET} + L_G$$

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

$$O_S^{q\alpha} = \overline{\psi}_s S_n T^\alpha \frac{n}{2} S_n^+ \psi_s^n$$
$$O_n^{q\alpha} = \overline{\chi}_n W_n T^\alpha \frac{\overline{n}}{2} W_n^+ \chi_n$$

Gauge invariant building blocks

A single hard prong

$p^2 \sim (p_T R)^2$ $\qquad$ $p^2 \leq Q^2_{\text{med}}$

$$J_i(z, \omega_J, \mu) = \int_{\omega_J}^{\frac{\omega_J}{z}} d\omega_J' \int d\epsilon \delta(\omega_J' - \omega_J - \epsilon) \mathscr{J}_{i\to 1}(n, \omega_J', \mu) \otimes_{\theta_n} S_1(n, \epsilon = (1-z)\omega_J', \mu) + \ldots$$

For a quark jet

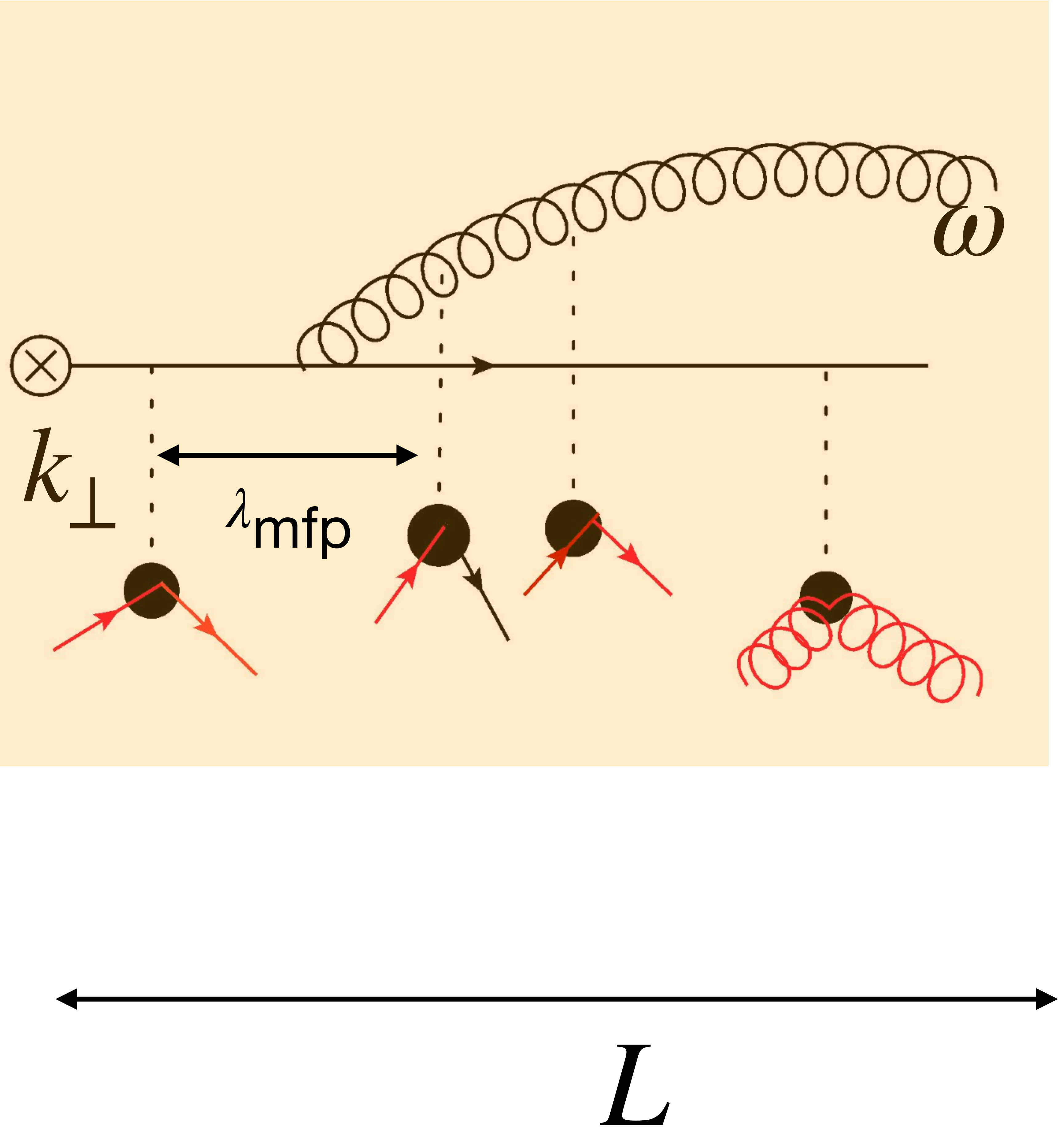
$$\gamma^{qq}_{\mathscr{J}_{q\to 1}} = \delta(1-z)\frac{\alpha_s C_F}{2\pi}\left(4\ln\frac{\mu^2}{\omega_J^2 R^2} + 3\right) - \frac{\alpha_s C_F}{\pi}(1+z)$$

$$\gamma^q_{S_1} = -\delta(1-z)\frac{4\alpha_s C_F}{2\pi}\ln\frac{\mu^2}{\omega_J^2 R^2} + \frac{\alpha_s C_F}{2\pi}\frac{4}{(1-z)_+}$$

$$\gamma^{qq}_{\mathscr{J}_{q\to 1}} + \gamma^q_{S_1} = P_{qq}$$ ➡ **Consistency of factorization**

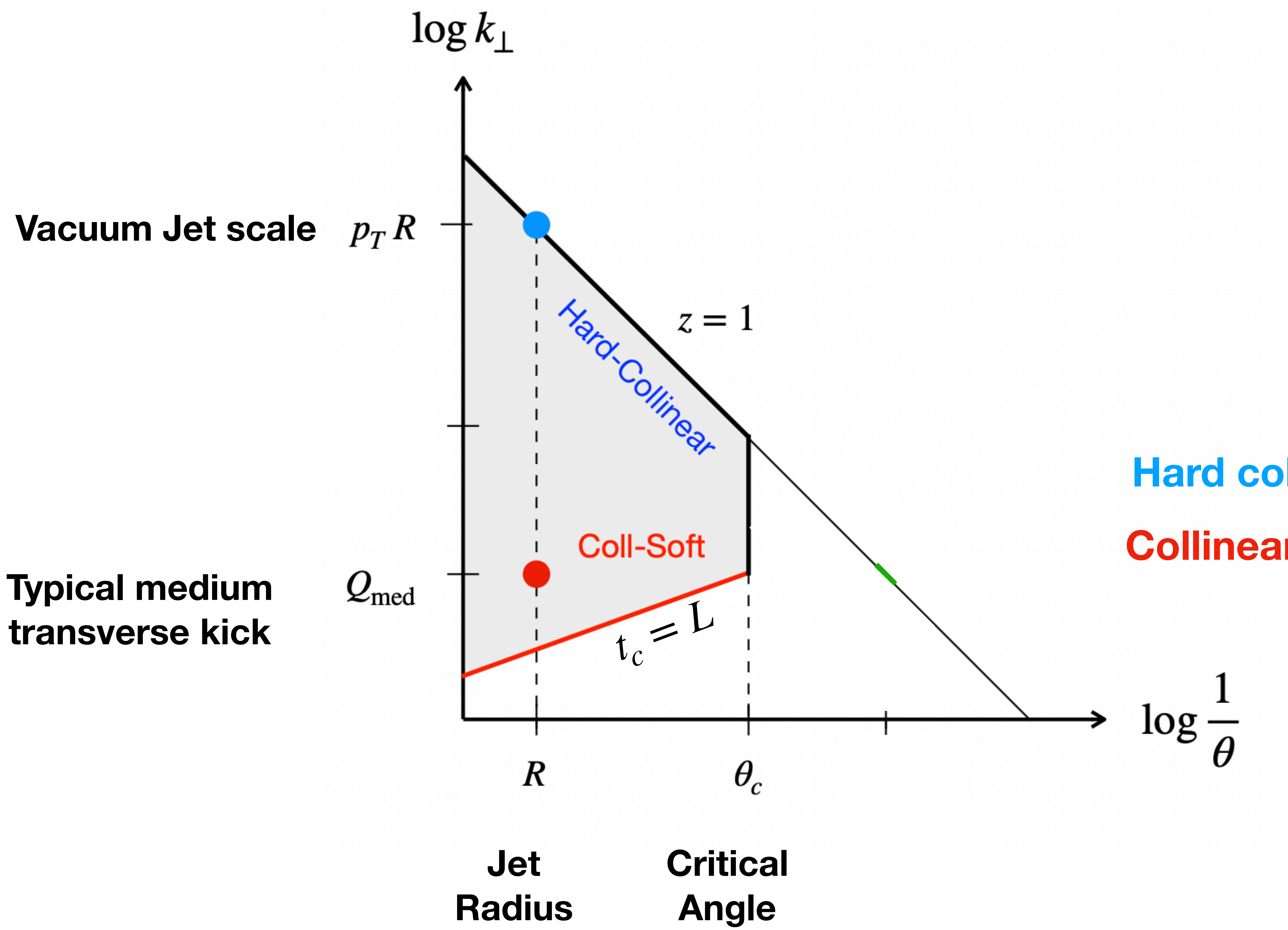
RG running leads to a resummation of threshold $\ln(1-z)$

The mean free path



- Mean free path of a jet → average distance between successive interactions → emergent scale.
- Dilute medium $\lambda_{\text{mfp}} \gg L$
- Dense medium $\lambda_{\text{mfp}} \leq L$
- Asumption : $\lambda_{\text{mfp}} \gg \frac{1}{m_D}$ → Successive interactions with color uncorrelated medium partons

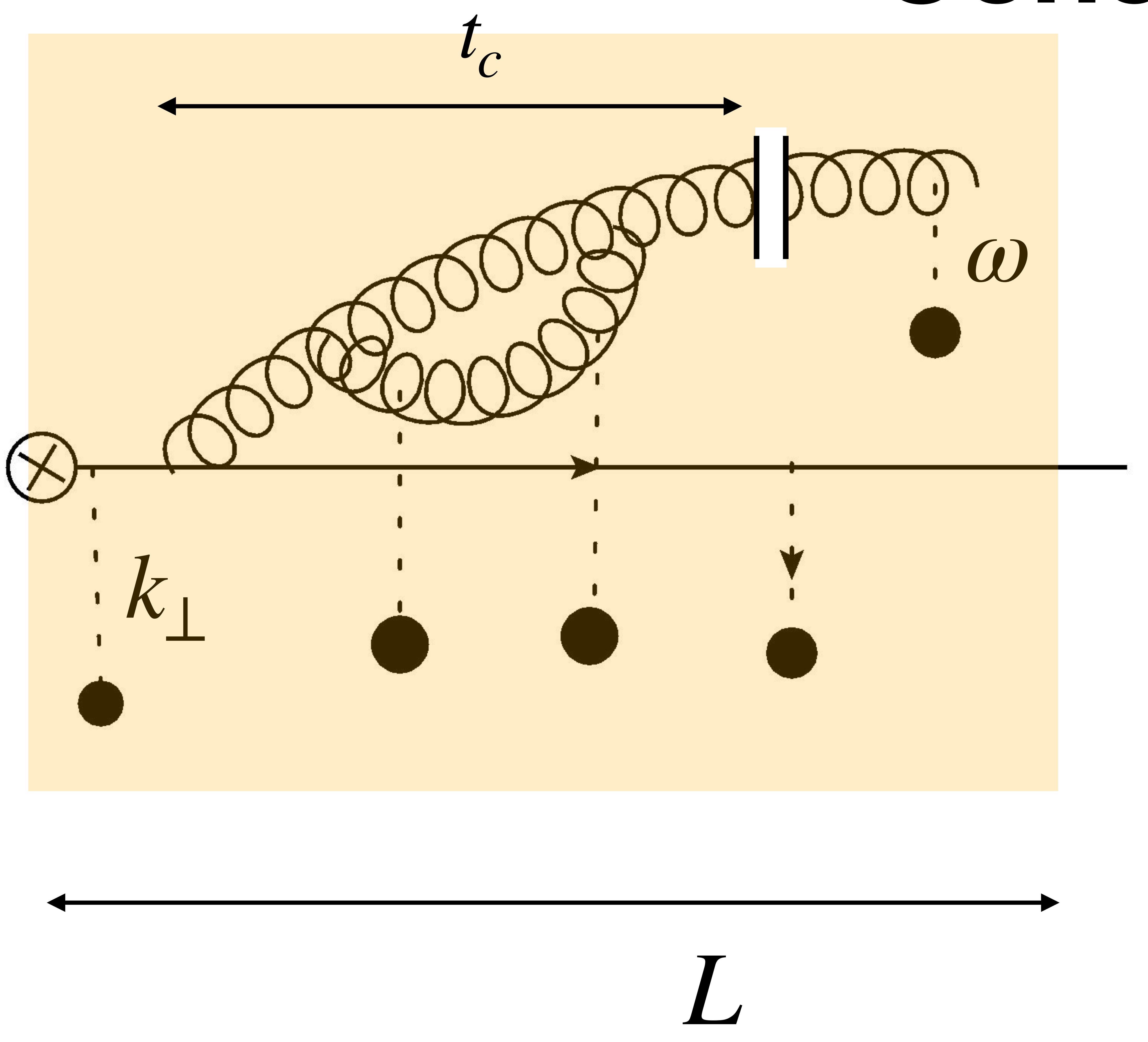
Putting it all together



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

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

Coherence time



- Quantum coherence time of radiated parton $t_c \sim \dfrac{\omega}{q_\perp^2}$
- No quantum interference for $t \gg t_c$
- $t_c \gg L$, strong quantum interference → LPM suppression

•

Soft Collinear Effective Theory(SCET)

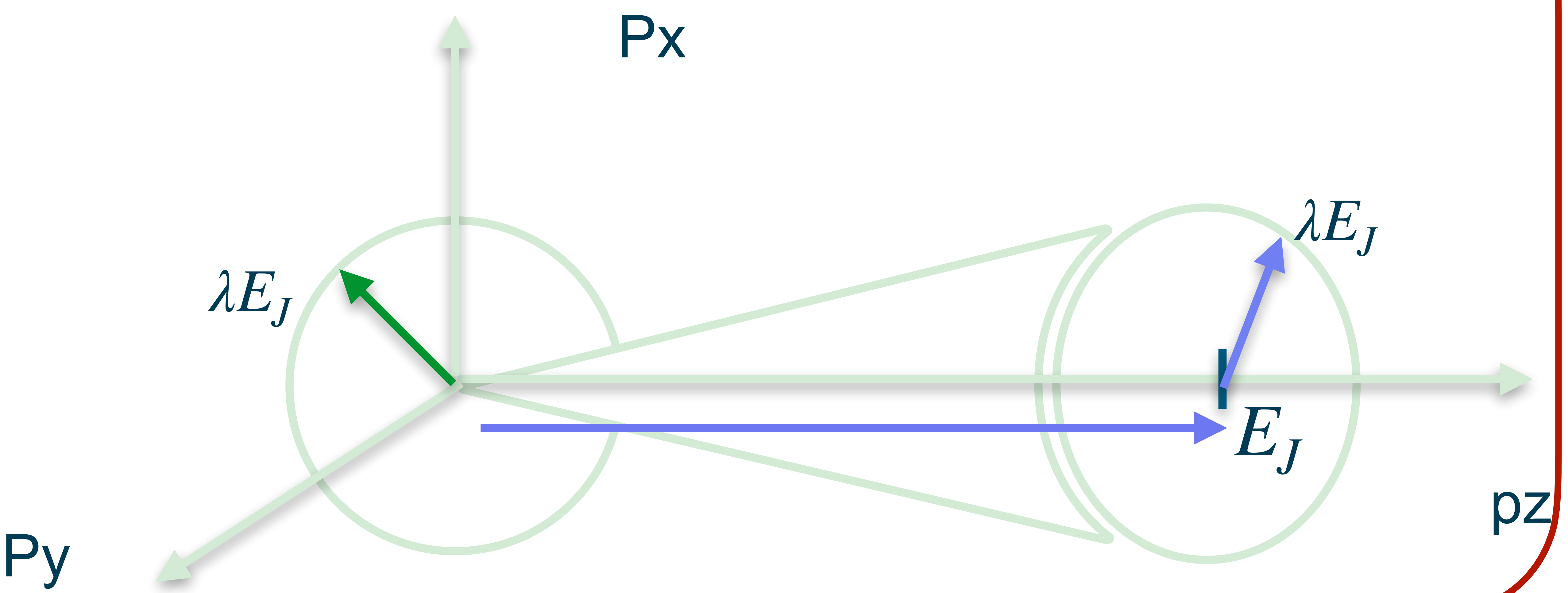
Step 1 : Identify the relevant degrees of freedom.

- The jet is made up of collinear partons

$$p_c \sim \frac{p_T R}{x}\left(1, x^2, x\right)$$

- QGP is a bath made of soft partons

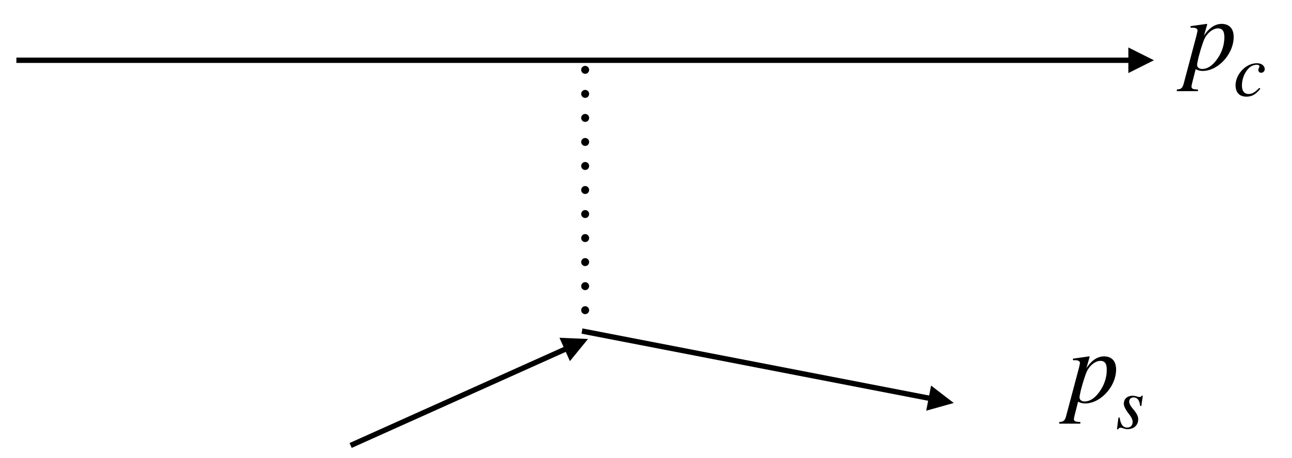
$$p_s \sim \frac{p_T R}{x}(x, x, x)$$



Step 2: Write down an effective Lagrangian at leading power in x(expansion parameter)

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

$$L_{QCD} = L_{collinear} + L_{soft} + L_{Glauber} + O(x^2)$$



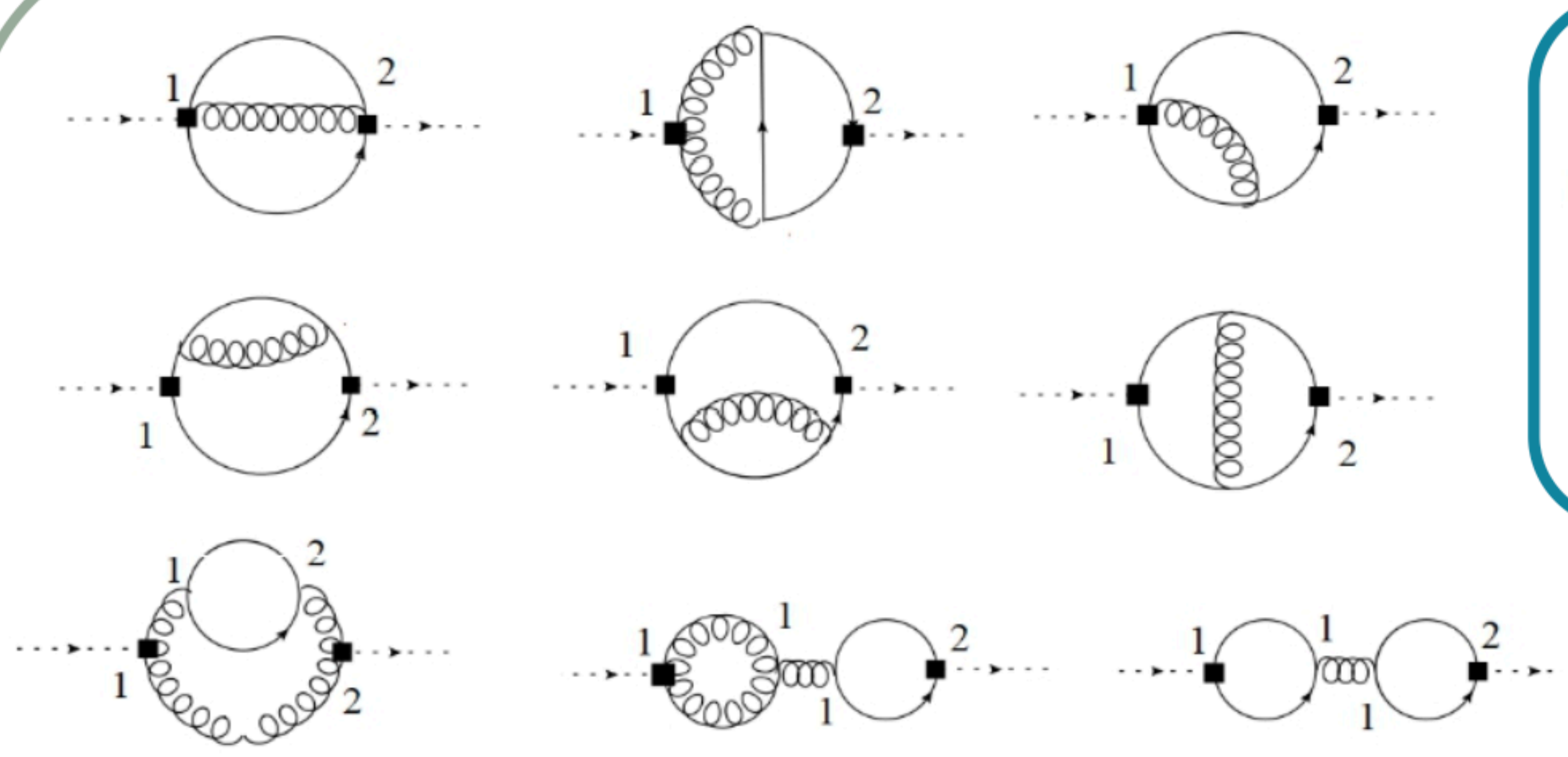
Tree level Glauber exchange

The medium TMDPDF

$$S^{AB}_{\text{med}}(k_\perp) = \frac{1}{k_\perp^2}\int \frac{dk^-}{2\pi}\int d^4x e^{-ik\cdot x}\text{Tr}\left[O^A_S(x)O^B_S(0)\rho_{QGP}\right]$$

Model independent and universal !

- SCET Operator version of color source density function ρ^A in the CGC



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

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

Running of the QCD coupling

$$\mu \sim k_\perp$$