Open quantum system approach to jets in heavy-ion collisions

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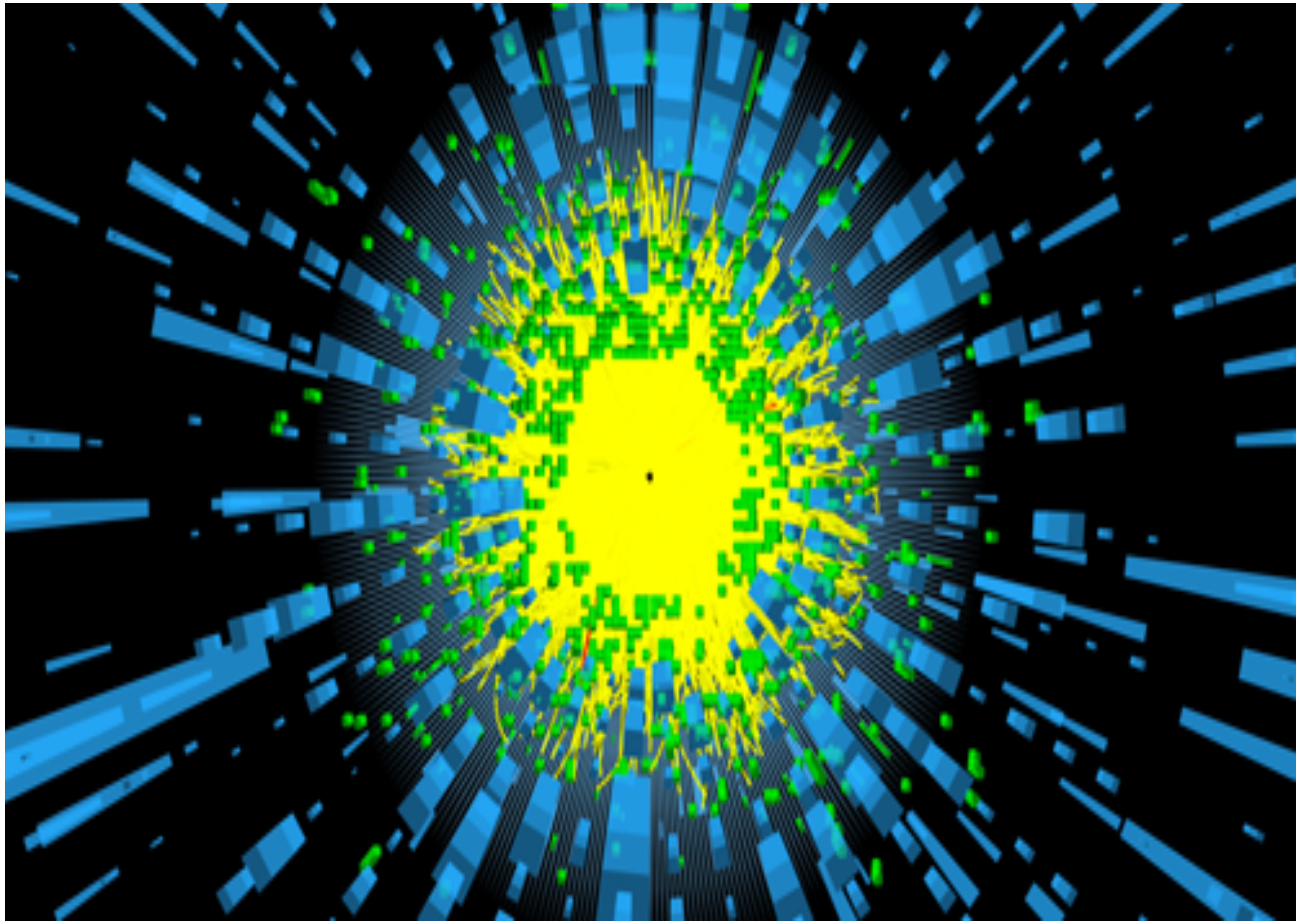
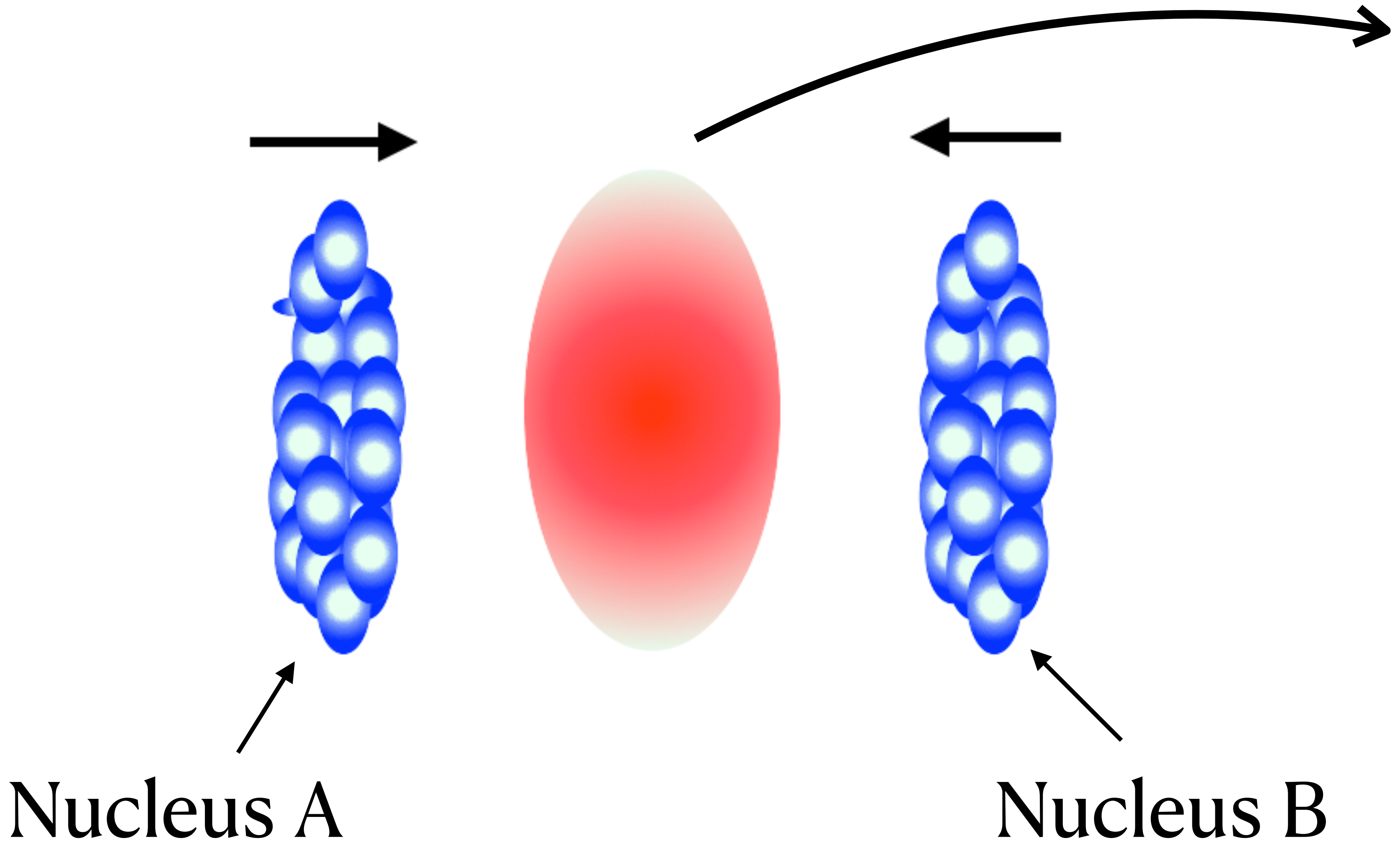


Open Quantum Systems: Dissipative Dynamics from Quarks to the Cosmos

1-12 December 2025, INT Seattle

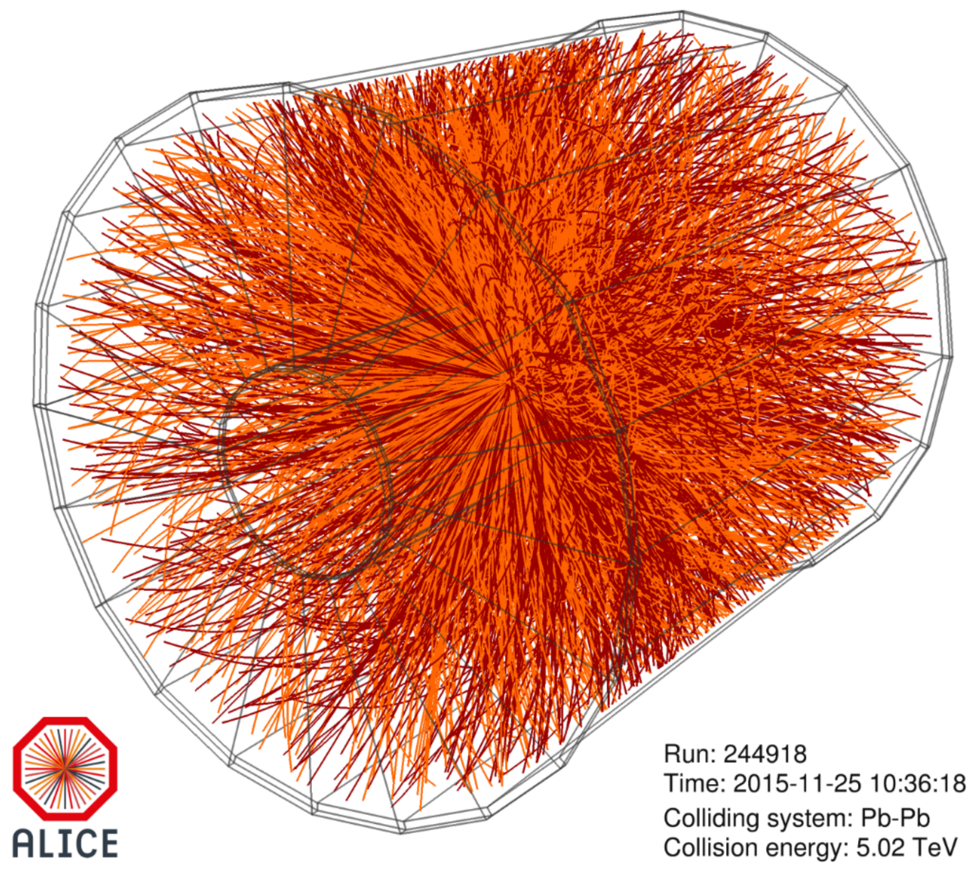
Heavy-ion collision

Collision of two heavy nuclei (Pb, Au) at ultra-relativistic energies $\sqrt{s} = 5.02$ TeV/A



Strongly interacting (deconfined) short lived medium of quark and gluon

Conditions similar to early universe just after the big bang



Final state

What do we learn from these massive collisions?

Properties of nuclear matter at extreme conditions

Phase transitions in strongly interacting gauge theories

Dynamics of many-body QCD interactions

Bulk properties in strong interacting gauge theories

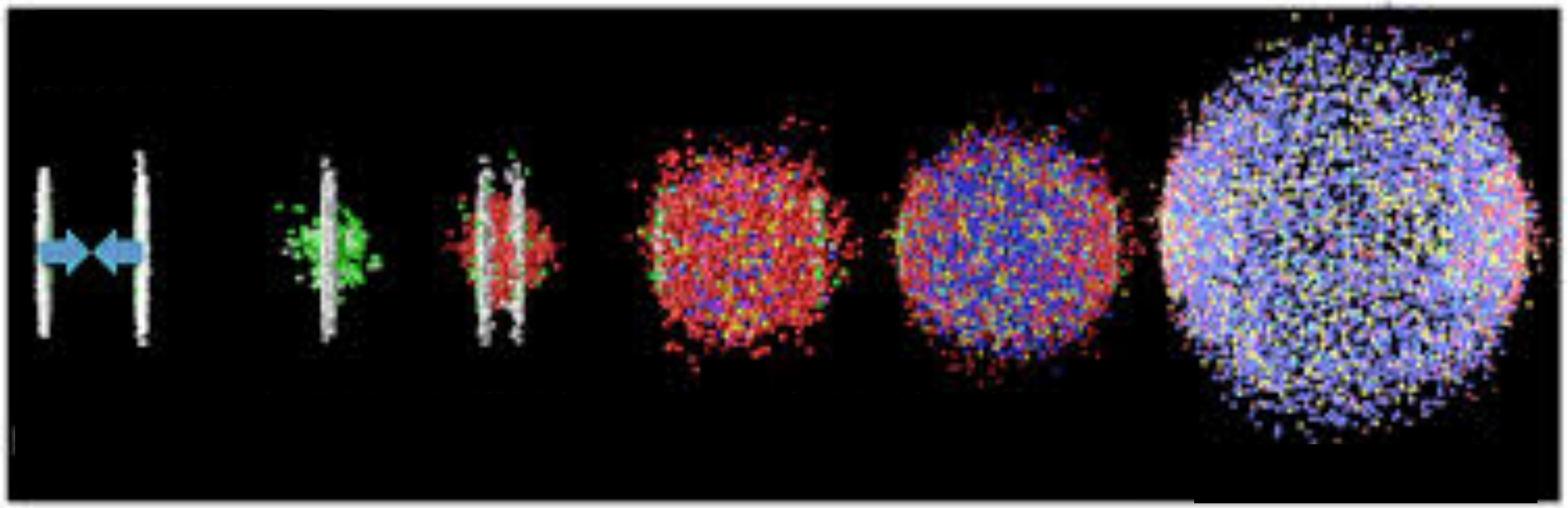
Energy transport in strongly interacting systems

Heavy-ion collision

Before showering enormous number of particles at the detectors the event undergoes many stages

$\tau_{\text{therm}} = 0.6\,\text{fm} \quad T_{\text{i}} \sim 500\,\text{MeV} \qquad T_{\text{f}} \sim 200\,\text{MeV}$

Increasing time direction



Initial state

Hard scattering processes

Hydrodynamic expansion

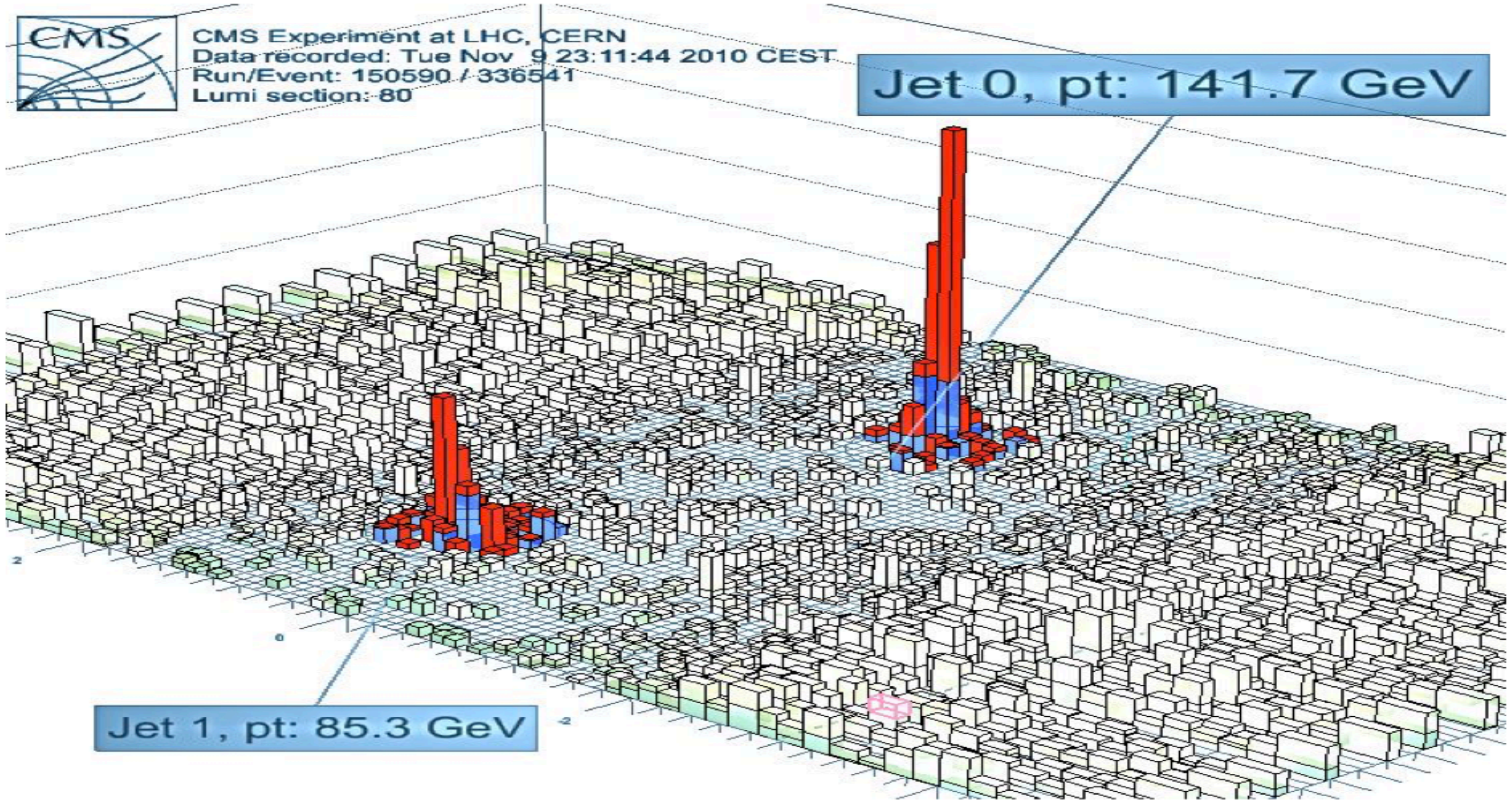
Hadron freezeout

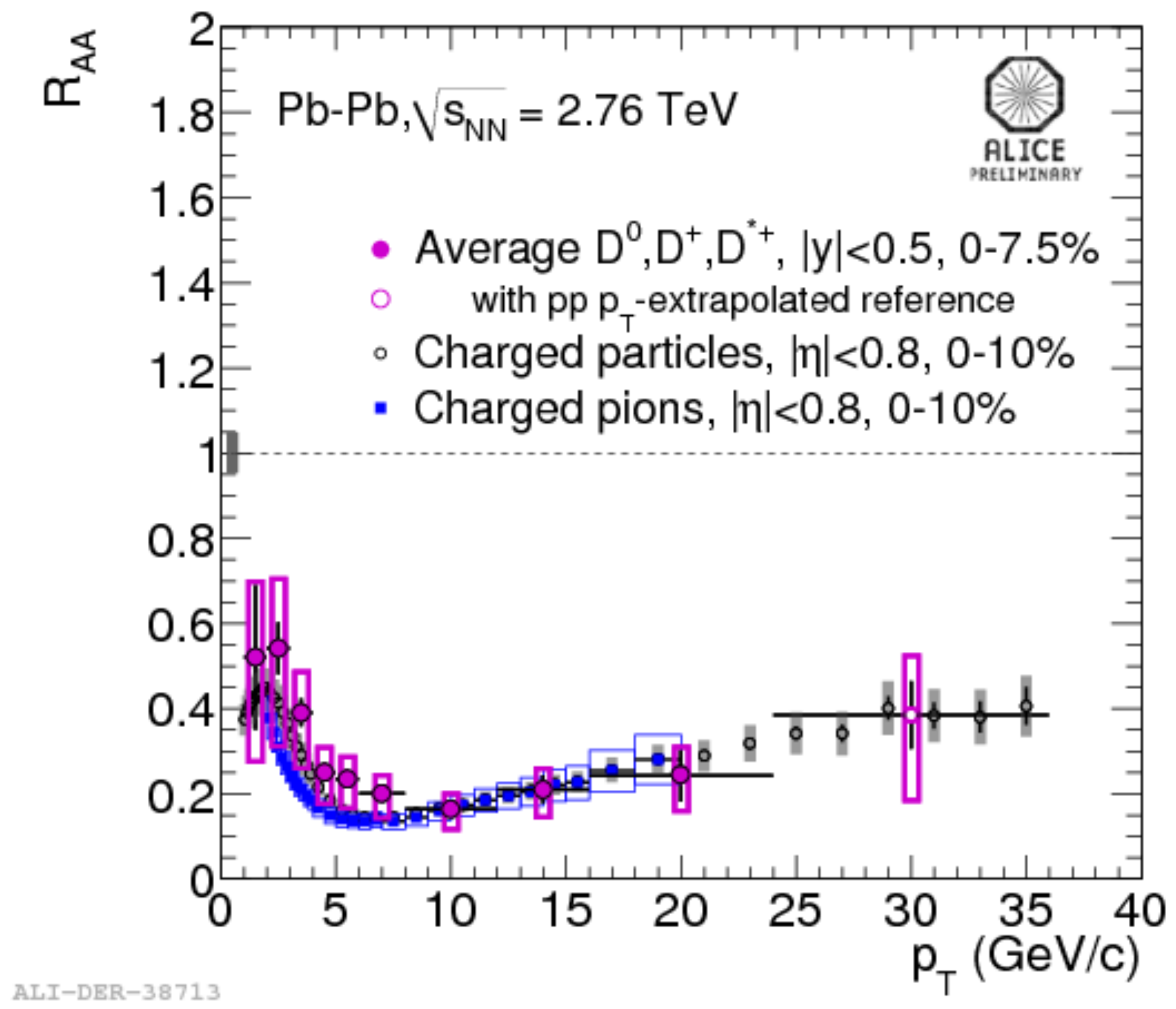
Detectors

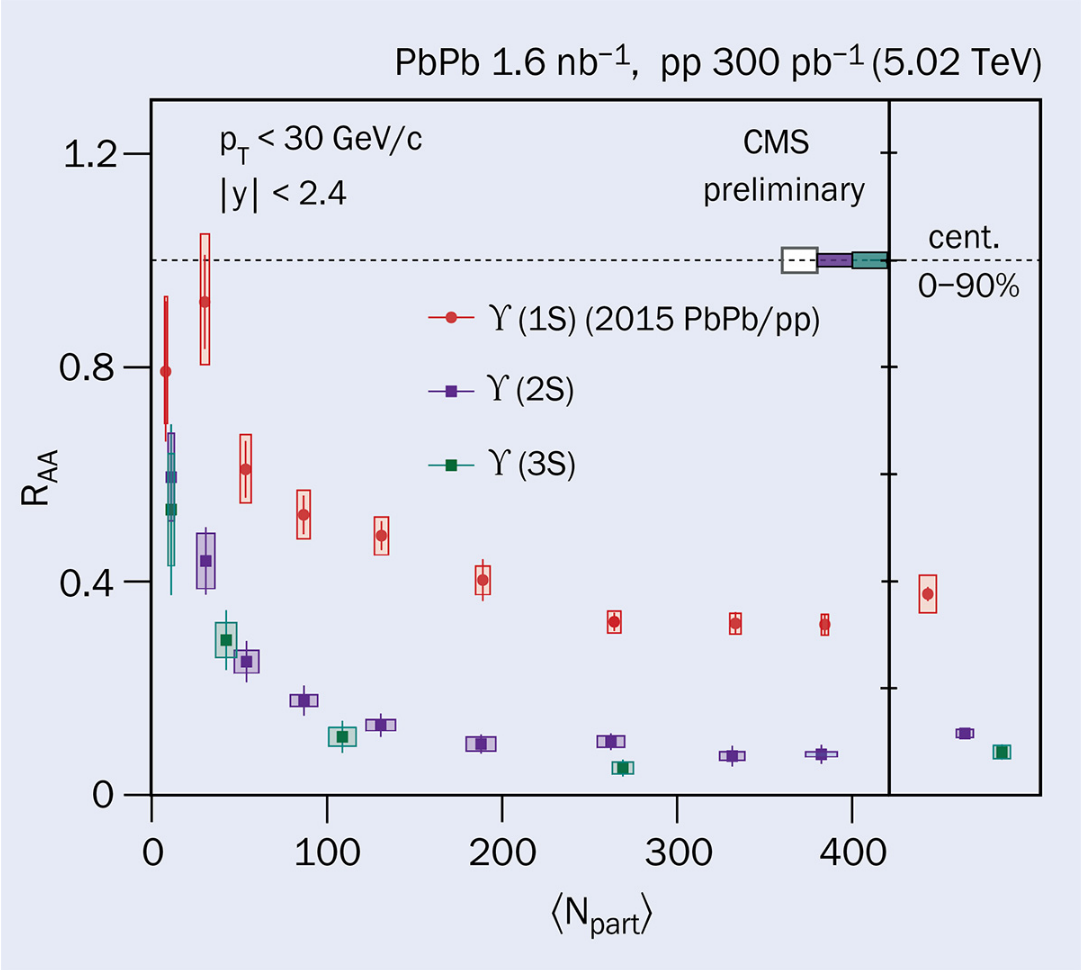
Observable modification in HICs

Compare the relevant particle yield with proton-proton baseline

$$R_{AA} = \frac{\sigma_{AA}}{\sigma_{pp}}$$ Nuclear modification factor

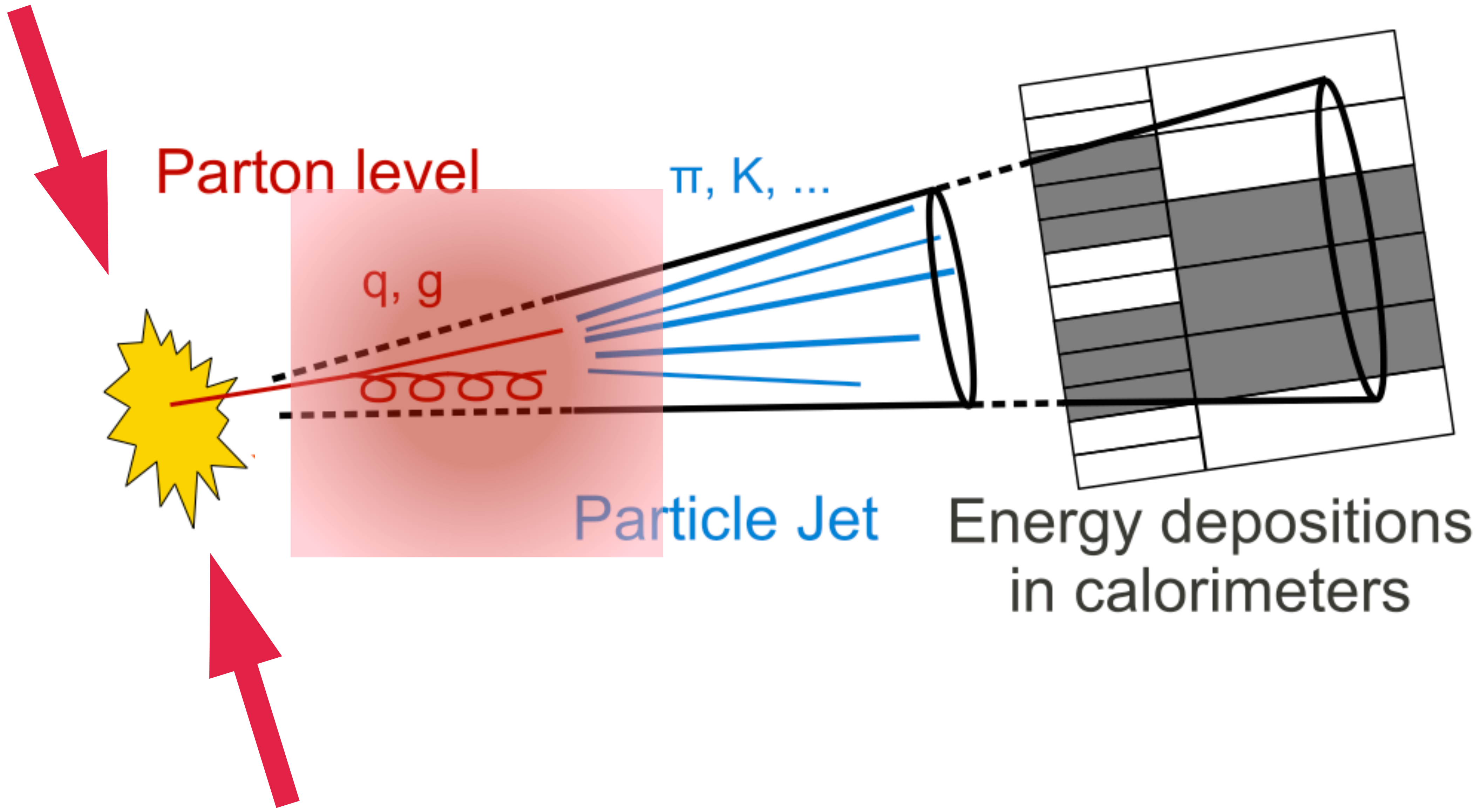






Seems straightforward task but quite challenging in practice!

QGP properties with jets



Jets are collimated sprays of hadrons at the detectors

Defined by jet reconstruction algorithms with parameters jet radius and transverse momentum with p_T beam axis

Jets are one of the important probe to study many-body QCD interactions and emergent phenomena at extreme conditions

Jets are produced during the hard scattering events at the initial stages of the collision and evolve all the way from from perturbative hard scale $\sim p_T \equiv \mathcal{O}(100)$ GeV to non-perturbative hadronization $\Lambda_{\text{QCD}} \sim 200$ GeV scale and retain the imprints of various stages medium evolution

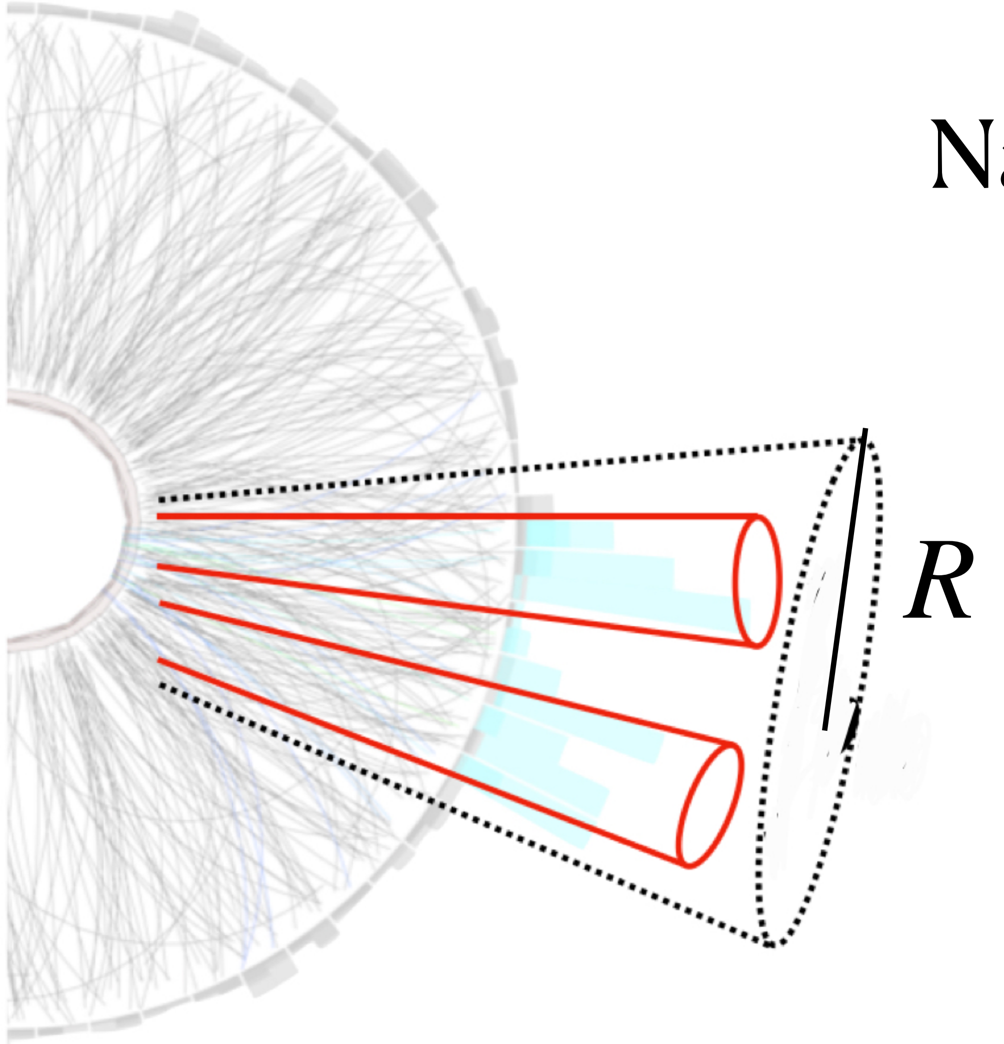
Offers exciting opportunities to study energy loss, color coherence dynamics in the medium and hadronization mechanisms in heavy-ion collision scenarios.

Two jet observables

I will focus on two measurements and switch between these two wherever needed for interpretation

Jet production cross-section in heavy ion collisions. Measurement is jet radius R

Correlations of energetic final state particles inside the jet, I.e., **energy correlators**



Narrow jet approximation

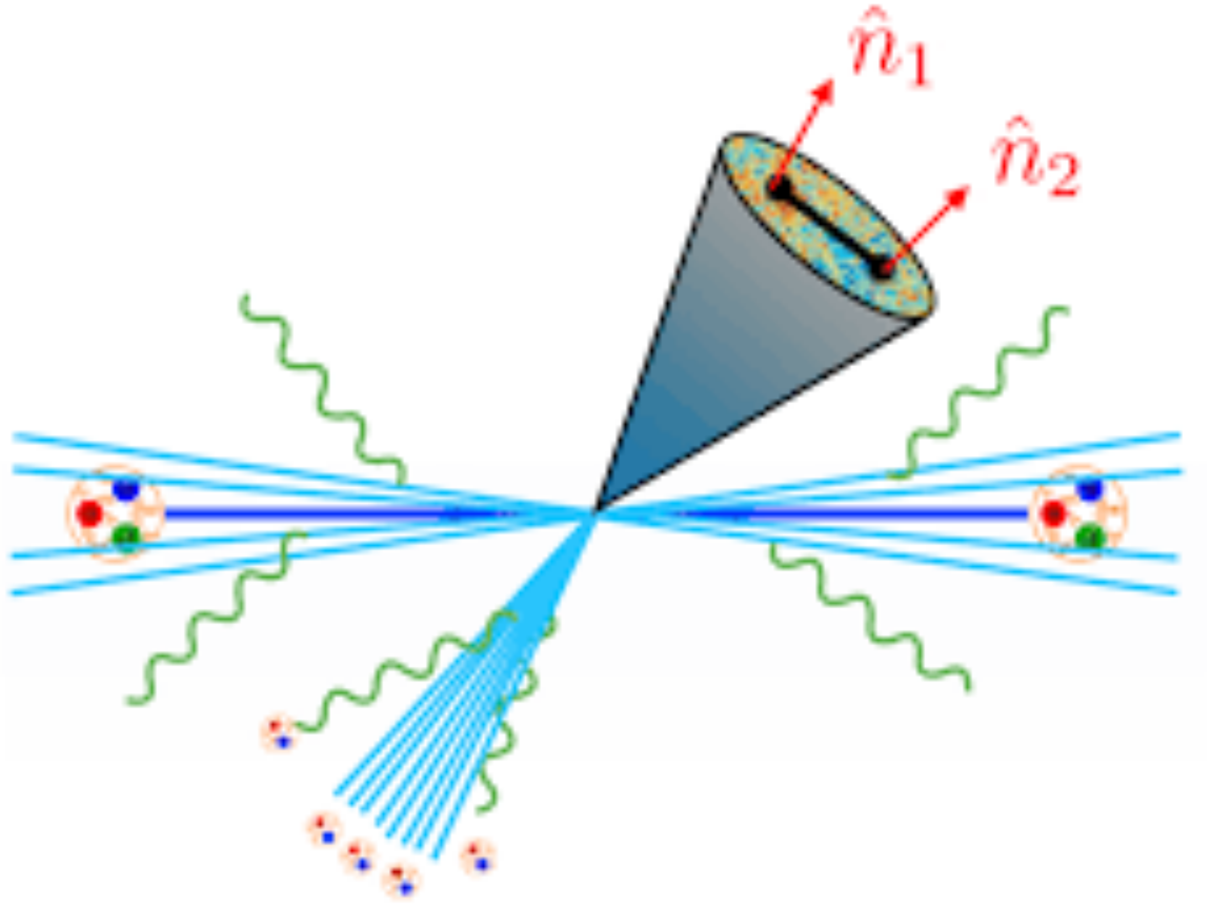
$$R \ll 1$$

$$p_T \sim \mathcal{O}(100)\,\text{GeV}$$

$$p_T \gg P_T R$$

Scales p_T, $p_T R$

$$\frac{d\sigma}{d\chi} = \sum_{ij} \int d\sigma \frac{E_i E_j}{Q^2} \delta(\theta^2 - \chi)$$



Collinear limit

$$\sqrt{\chi} \ll 1$$

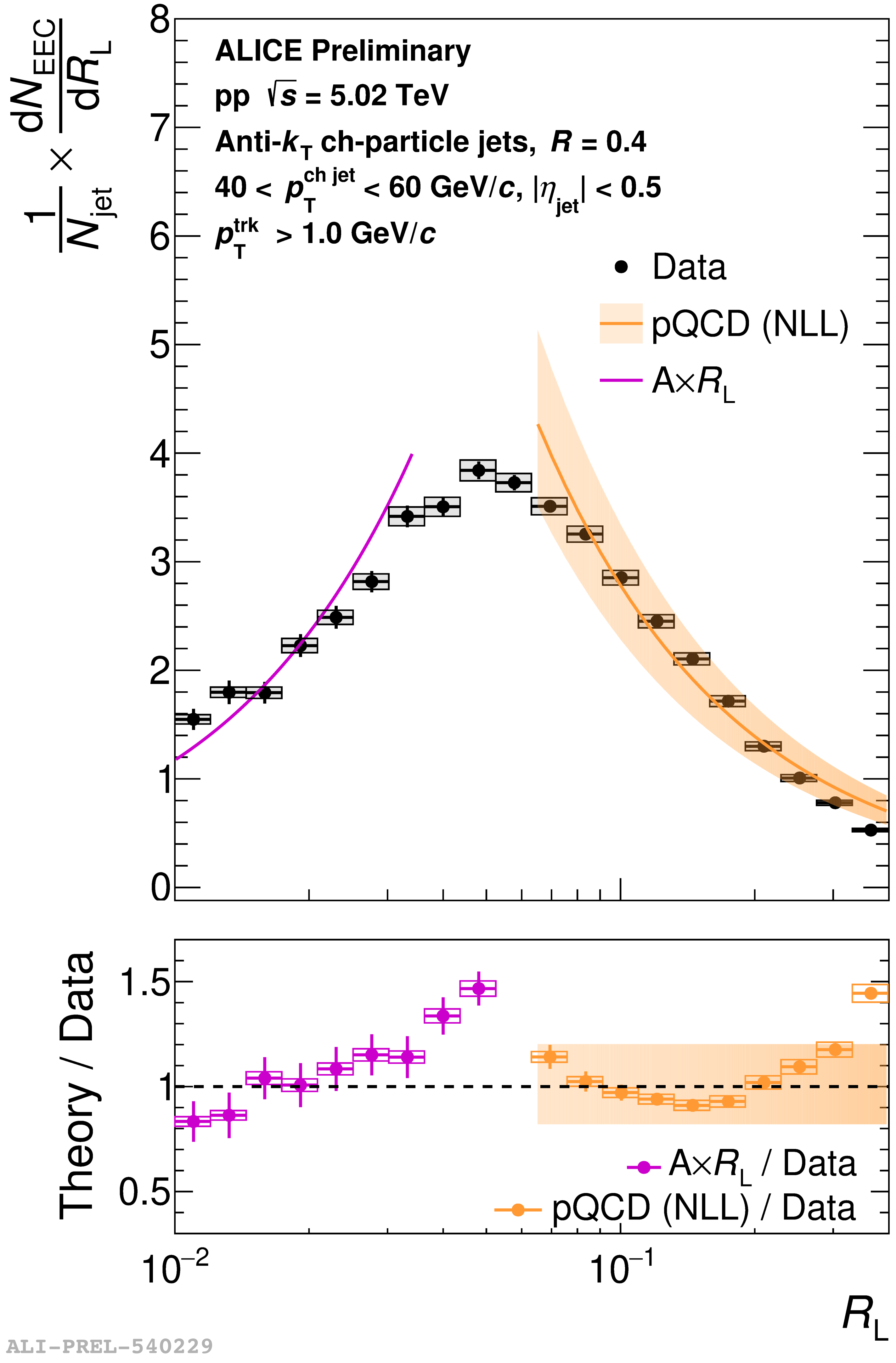
$$p_T \sim \mathcal{O}(100)\,\text{GeV}$$

$$p_T \gg P_T \sqrt{\chi}$$

$$Q \sim \mathcal{O}(P_T)$$

Measurement χ, scales $p_T, p_T\sqrt{\chi}$

Energy correlators



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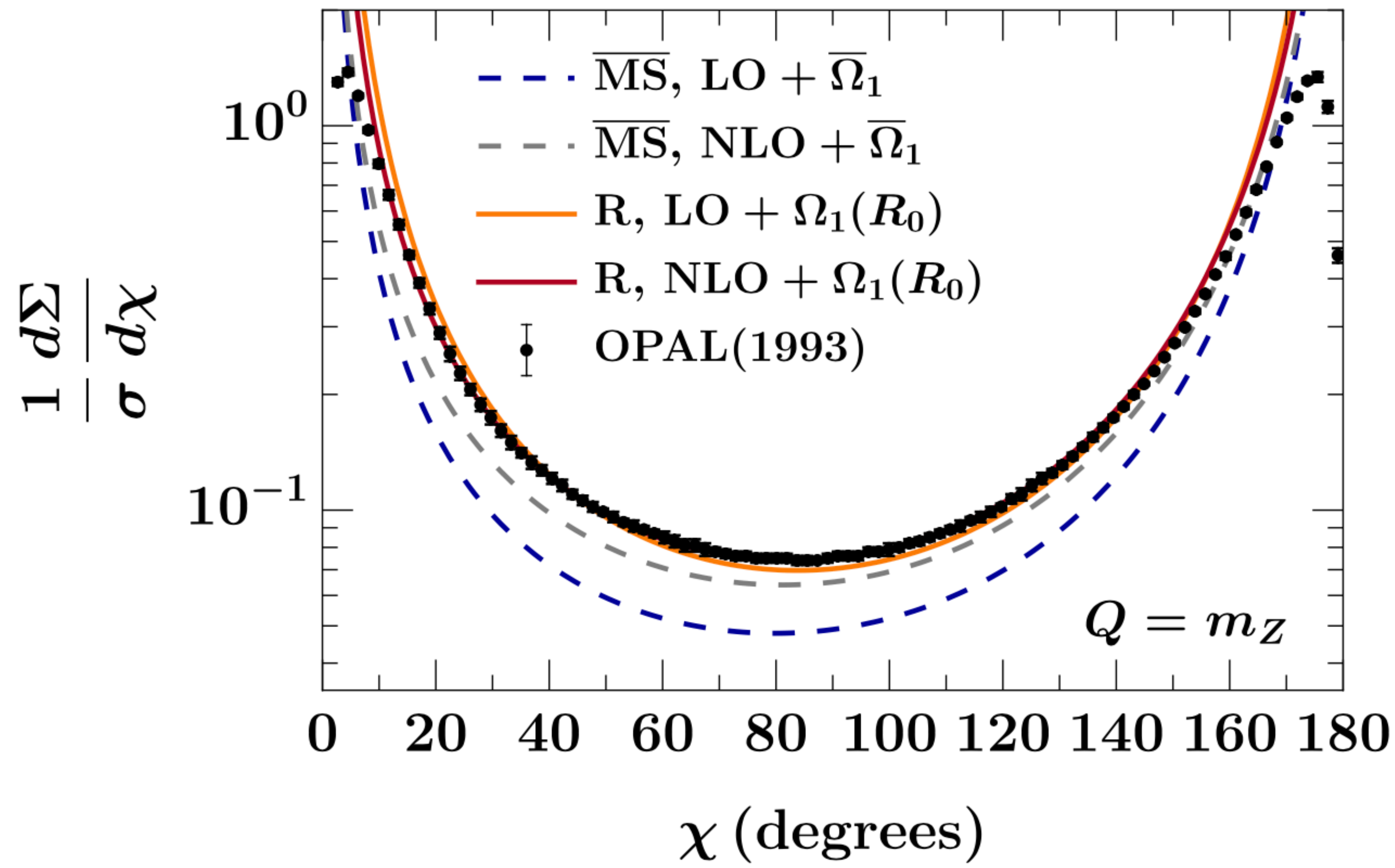
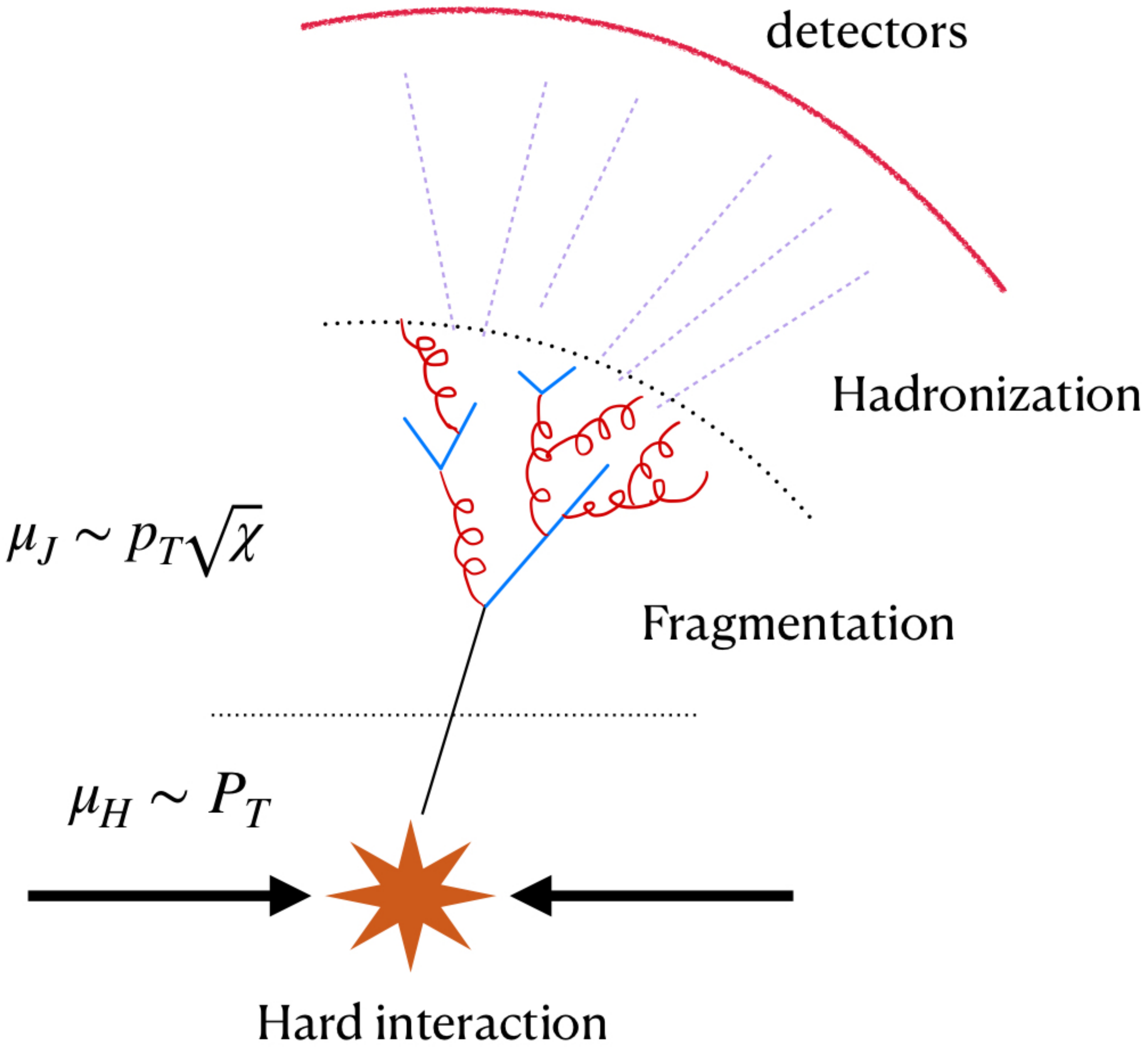
Two distinct scaling behaviours

Impressive agreement with data with leading non-perturbative effects



Schindler, Stewart, Sun '23

Jets in proton-proton collision



Production scale

μ_H ⟷

μ_J ⟷

Jet scale

Hard interaction produces high-energetic jet initiating partons

Fragmentation produces showers of partons, i.e., quarks and gluons which eventually confine and produce hadrons

Hadronization is non-perturbative effective effects and captured by shape functions

In vacuum there are only two scales associated with production and measurements on final state particles

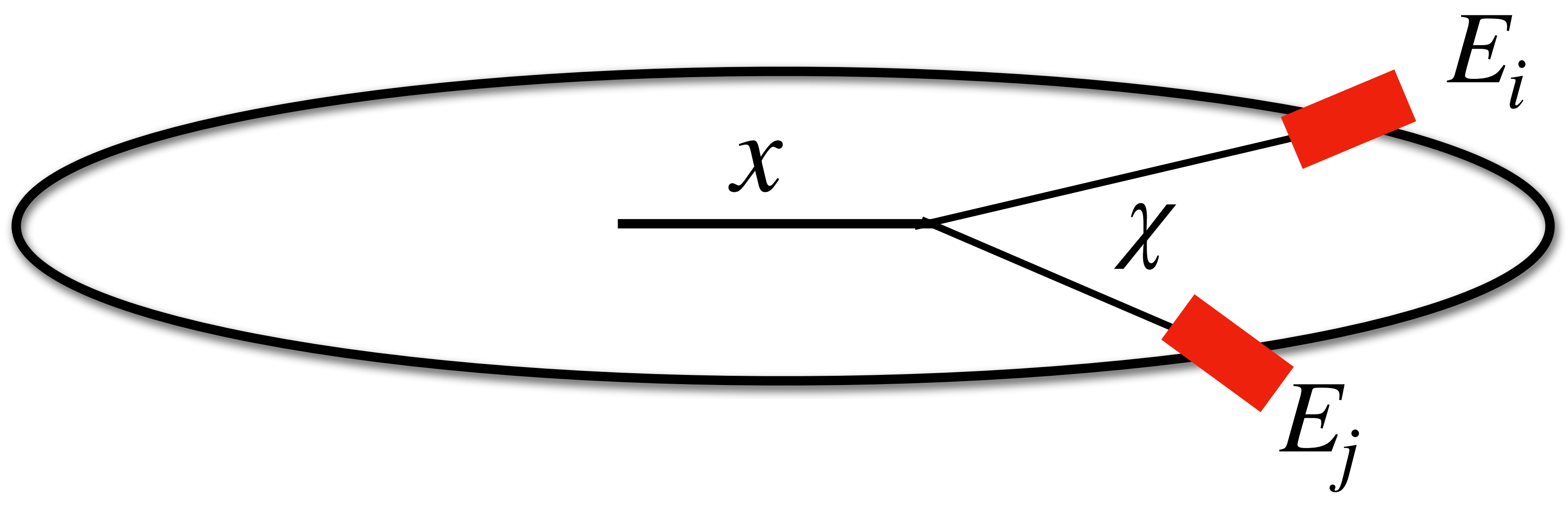
Factorization in proton-proton collision

Jets in vacuum: Only production p_T and measurement scales $p_T R$ or $p_T\sqrt{\chi}$

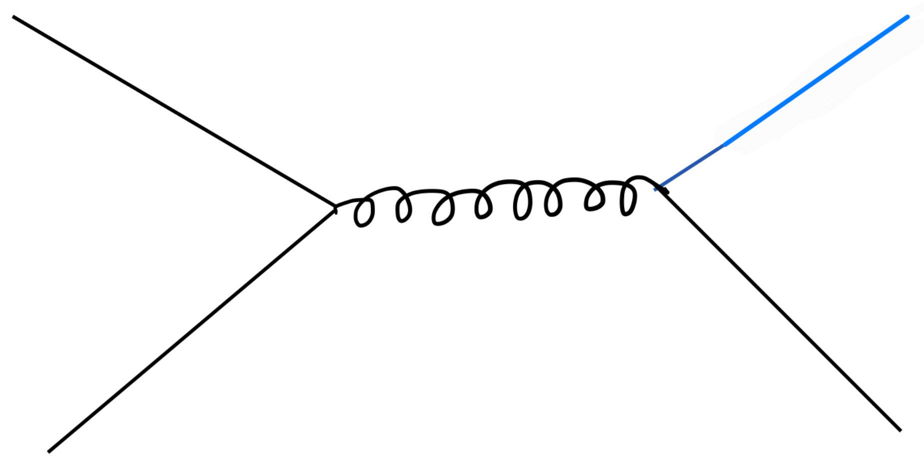
$$\frac{1}{\sigma_0}\frac{d\sigma}{d\chi} = \sum_{i\in\{q,\bar{q},g\}} \int dx x^2 H_i(xQ,\mu)\, J_i(xQ,\chi,\mu)$$

hard function   Jet function

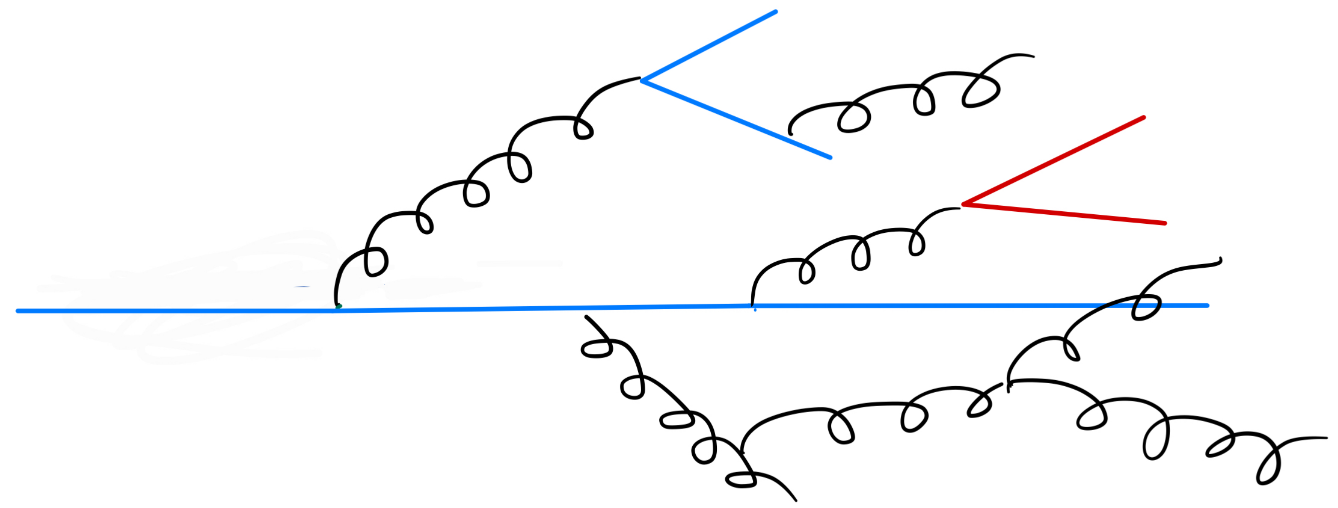
μ is factorization scale



Hard function describes the production of jet initiating parton



Production mechanism



Subsequent evolution of jet

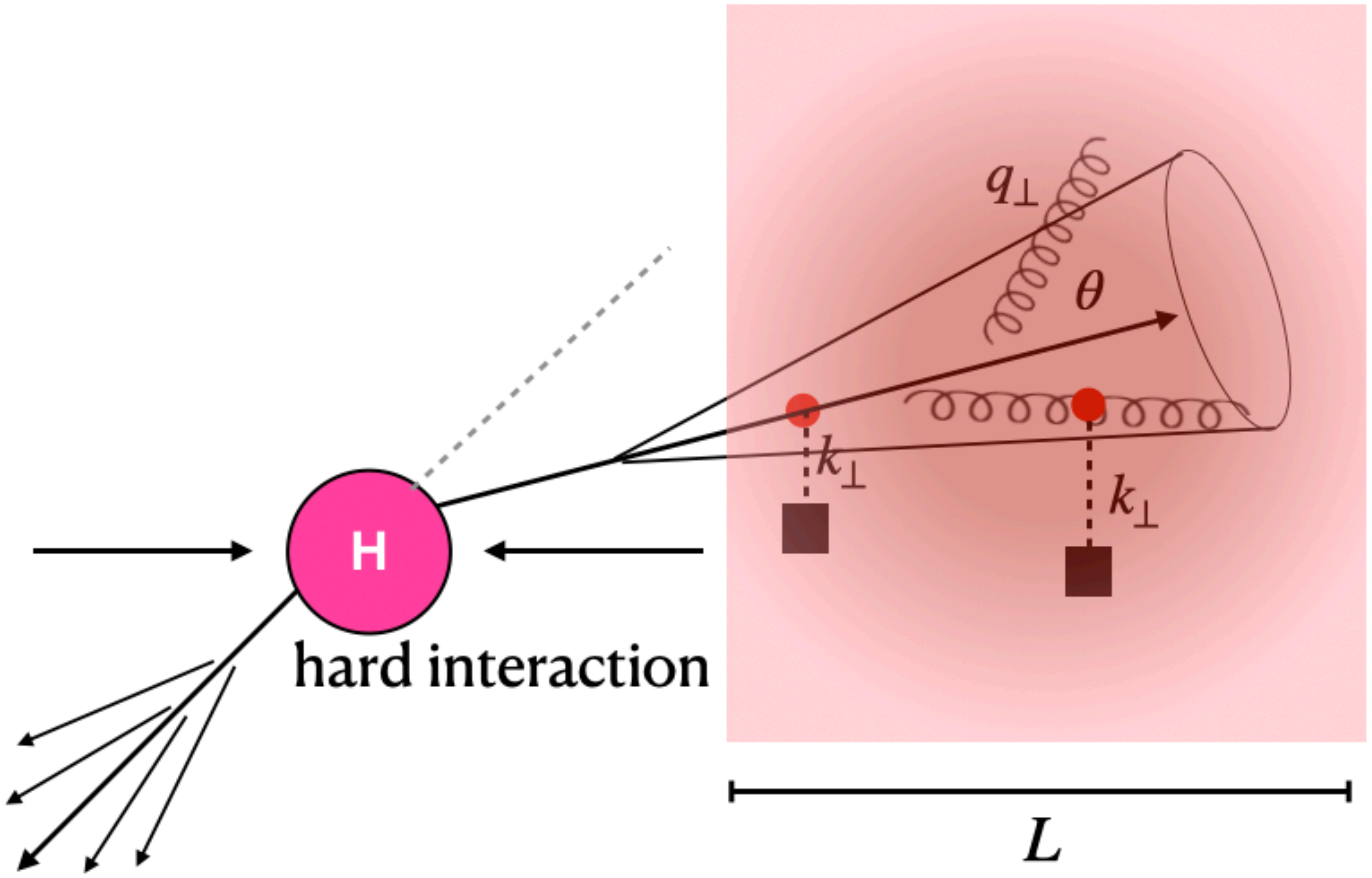
Jet function describes its subsequent evolution in vacuum

Hard function does not depend on the measurement imposed on final state particles

High precision calculations have been performed for simpler systems proton-proton and electron-positron collisions

Jet propagation in medium

Presence of medium introduces many direct and indirect scales



$l_{\text{mfp}} \to$ mean free path

$T \sim m_D \to$ medium temperature

$t_f \sim \frac{\omega}{q_\perp^2} \to$ formation time

Direct scales

$\hat{q} \to$ jet quenching parameter

$\theta_c \sim \frac{1}{\sqrt{\hat{q}L^3}} \to$ critical angle

emergent scales

Scale hierarchy: $\mu_H \gg \mu_J \gg \gg T \sim m_D \gg \Lambda_{QCD}$

Emergent scales appear in the relevant phase space within the EFT set up

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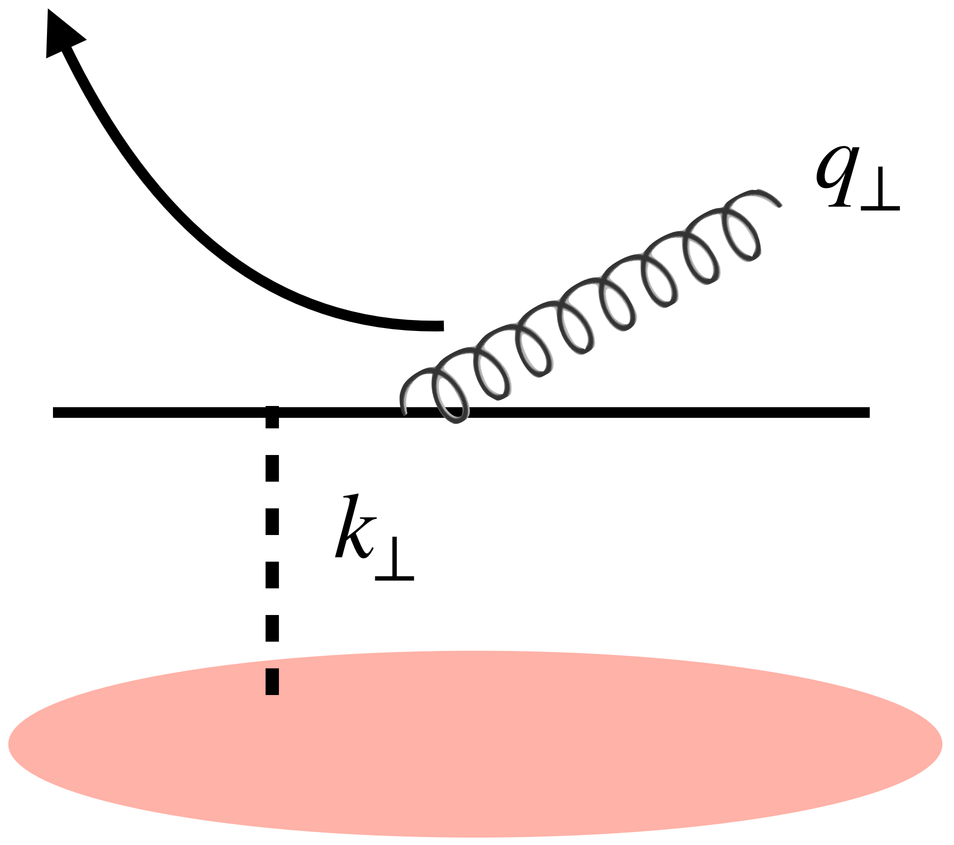
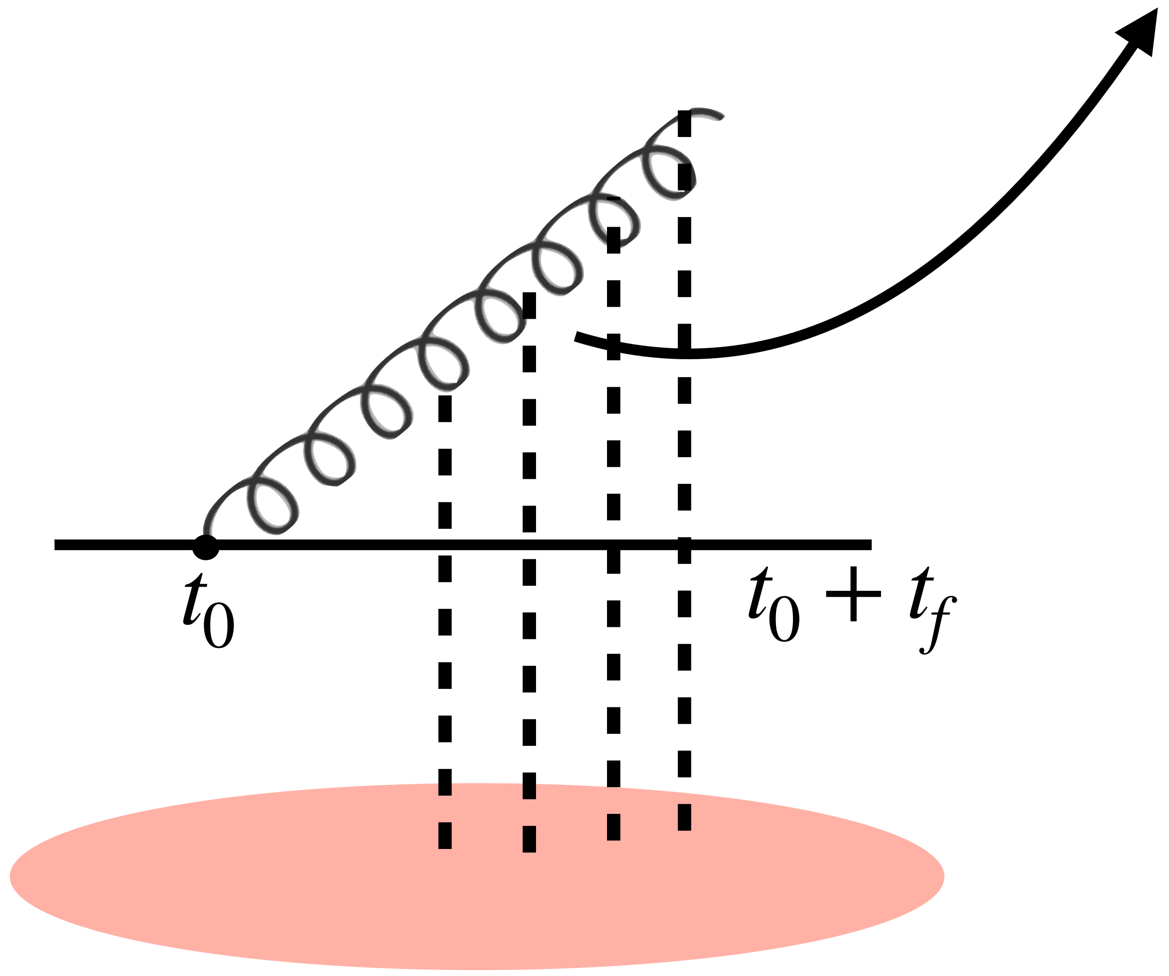
Jet propagation in medium

Due to additional medium-induced radiations jet looses energy to the medium

Medium induced radiation



Broadening of medium induced radiation



Incoherent scatterings: $\tau_f \leq l_{\mathrm{mfp}}$

Coherent scatterings: $\tau_f > l_{\mathrm{mfp}}$

$$\frac{dq_\perp^2}{dt} = \hat{q}$$ Transverse broadening

$$t = \tau_f \equiv L$$

$$q_\perp = Q_{,\mathrm{med}} \equiv \sqrt{\hat{q}L}$$ Saturation scale

Energetic parton propagation direction

Single scattering

$k_\perp \sim m_D \sim T$

Multiple scattering

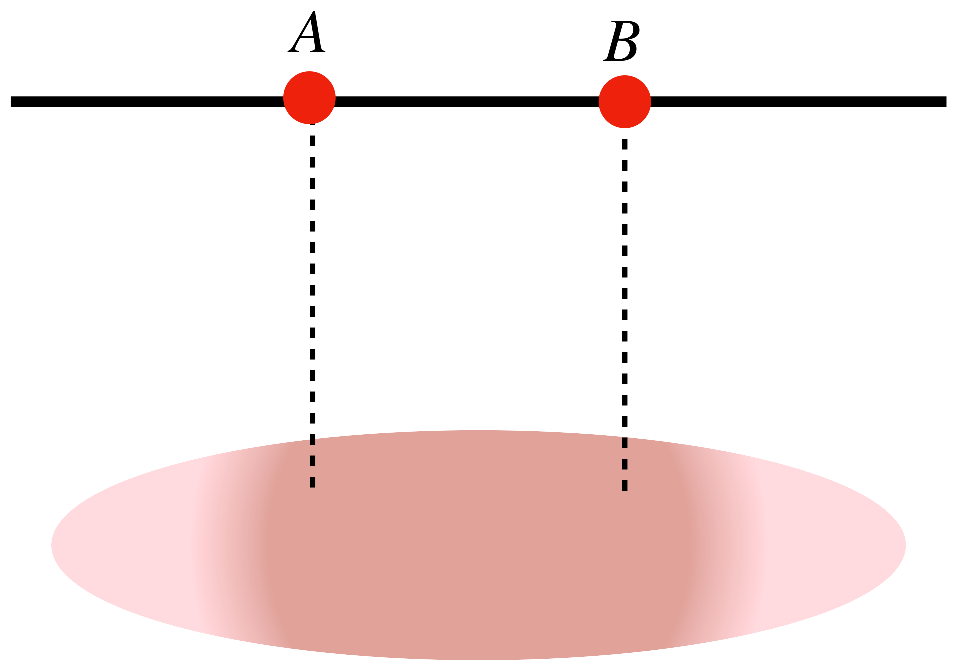
$k_\perp \sim \sqrt{\hat{q}L} \equiv$ Maximum transverse momentum transferred

Glauber interaction give small transverse kick to the jet parton and do not capture collisional energy loss

In medium parton shower

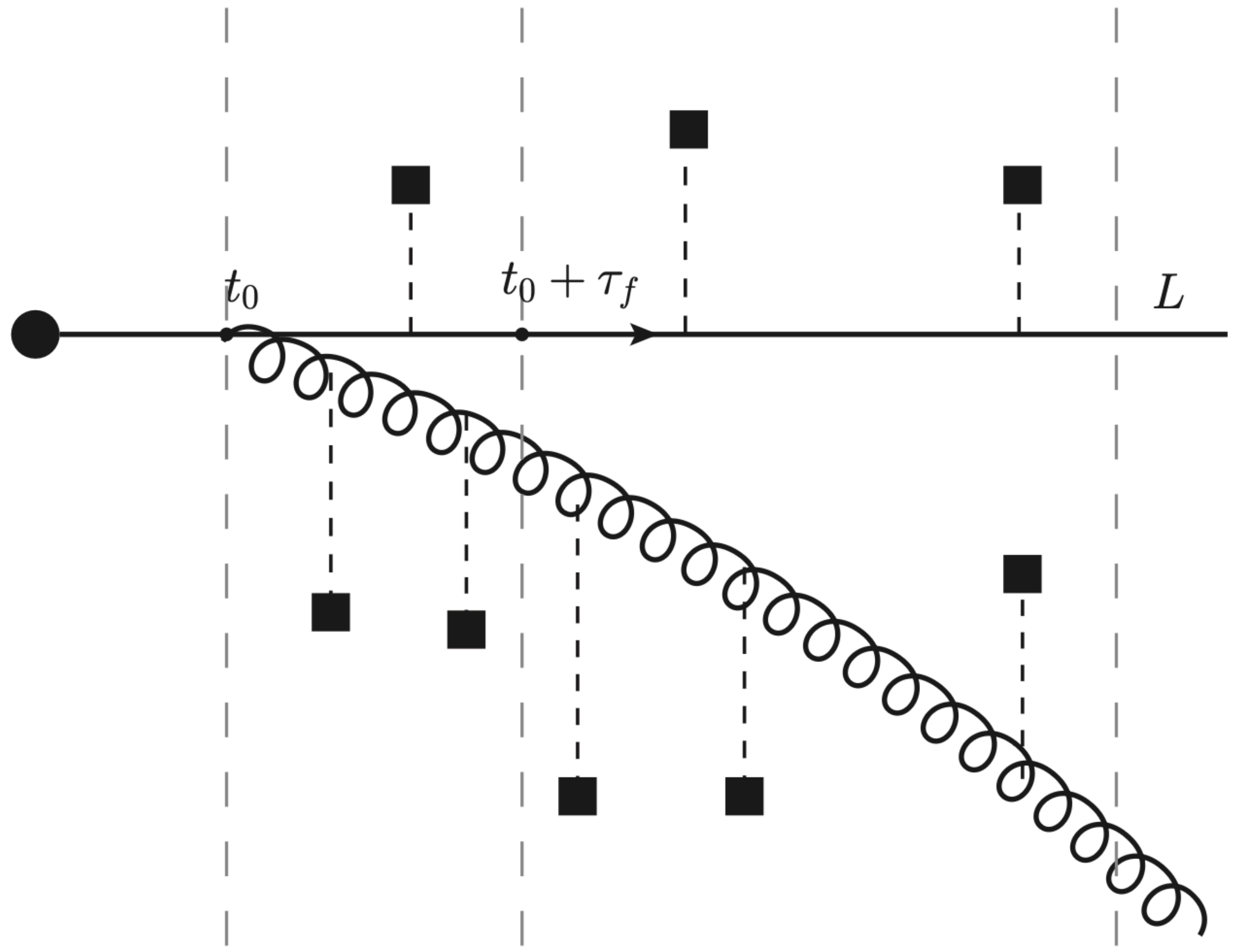
Multiple scatterings between jet and the medium can suppress gluon emission rate, LPM effect

Two consecutive scatterings leads to a phase factor known as LPM phase



$\sim e^{i(p_A^+ - p_B^+)x^-}$

LPM phase factor



Energetic parton propagation direction

$p^+ = \frac{p_\perp^2}{p^-}$

x^- runs all the way to the length of the medium

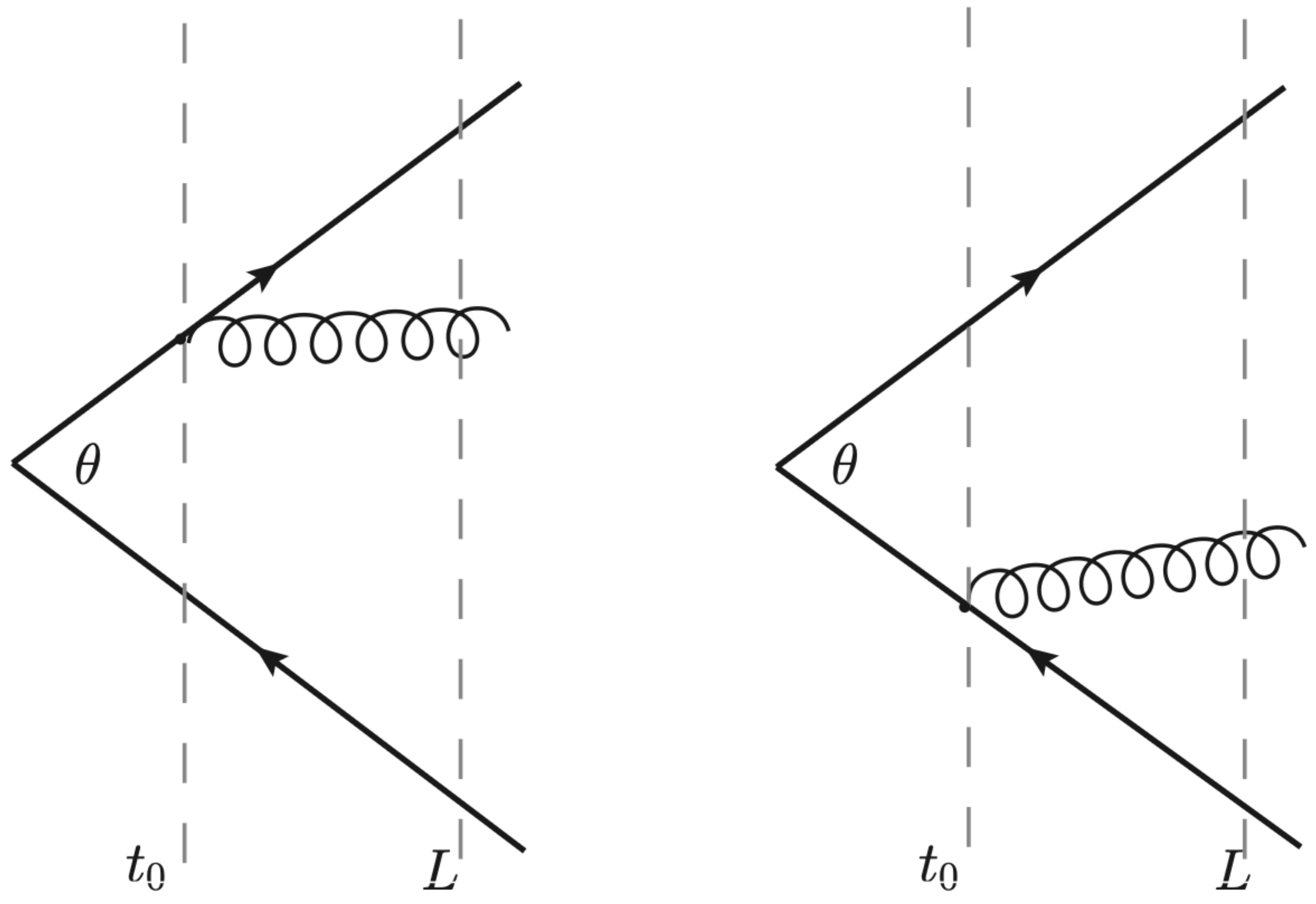
Radiation suppression: $\tau_f > L$

p^- is the energy of energetic partons

$l_{\text{mfp}} < \tau_f < L$ LPM effect is important and contribute to broadening

In medium parton shower

Interference between multiple jet partons can can have interference in the transverse direction, color (de)coherence, θ_c



$\theta_c \sim \frac{1}{\sqrt{\hat{q}L^3}}$ → critical angle

$\theta > \theta_c$: Interference between the two prongs vanishes

Two prongs are independent source of radiation

Probing this scale is one of the major ongoing efforts at heavy-ion collision experiments

Hierarchy between jet radius R and θ_c

$R \leq \theta_c$, only one color source of medium induced radiation

$R > \theta_c$, multiple color sources of medium induced radiation

A wish list for jets in HICs

- Can we derive a similar factorization formula for observables in HIC ?
- Can we separate out universal non-perturbative physics from the perturbative one ?
- Can we systematically improve computation/accuracy for jets in HIC ?
- Can we compute anomalous dimensions for jets in HIC ?
- Can we relax model dependence ?
- Time based evolution of jet?

⋮

We attempt to answer some of these questions using EFT and open quantum system framework

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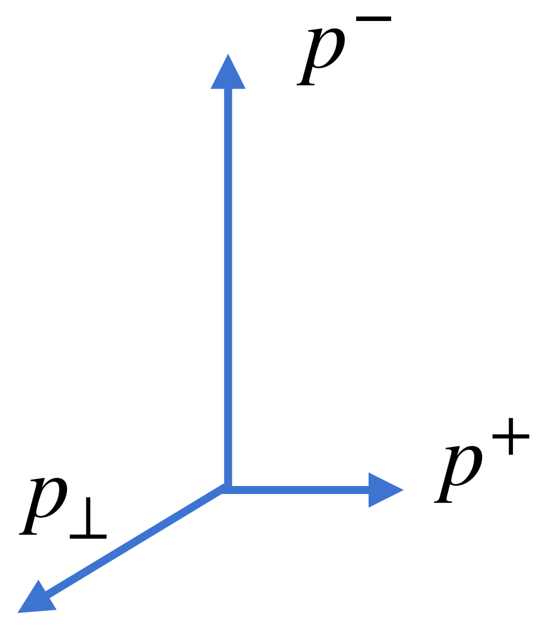
Soft Collinear Effective Theory (SCET)

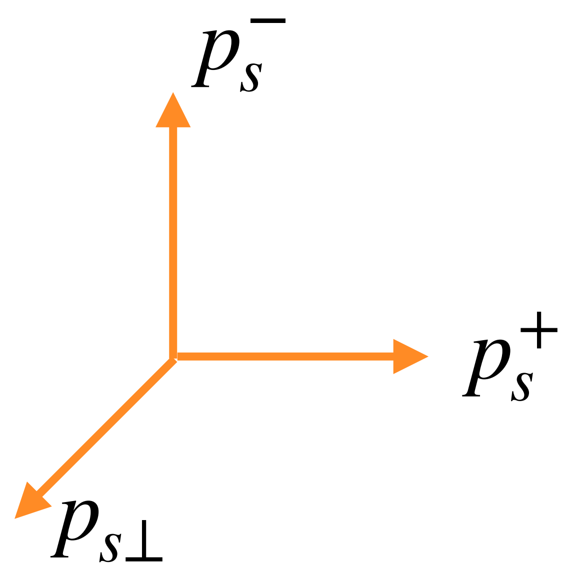
SCET is an EFT of QCD designed to study collinear and soft radiations

collinear: Boosted along jet direction

soft : No preferred direction

Leading power Lagrangian for any process





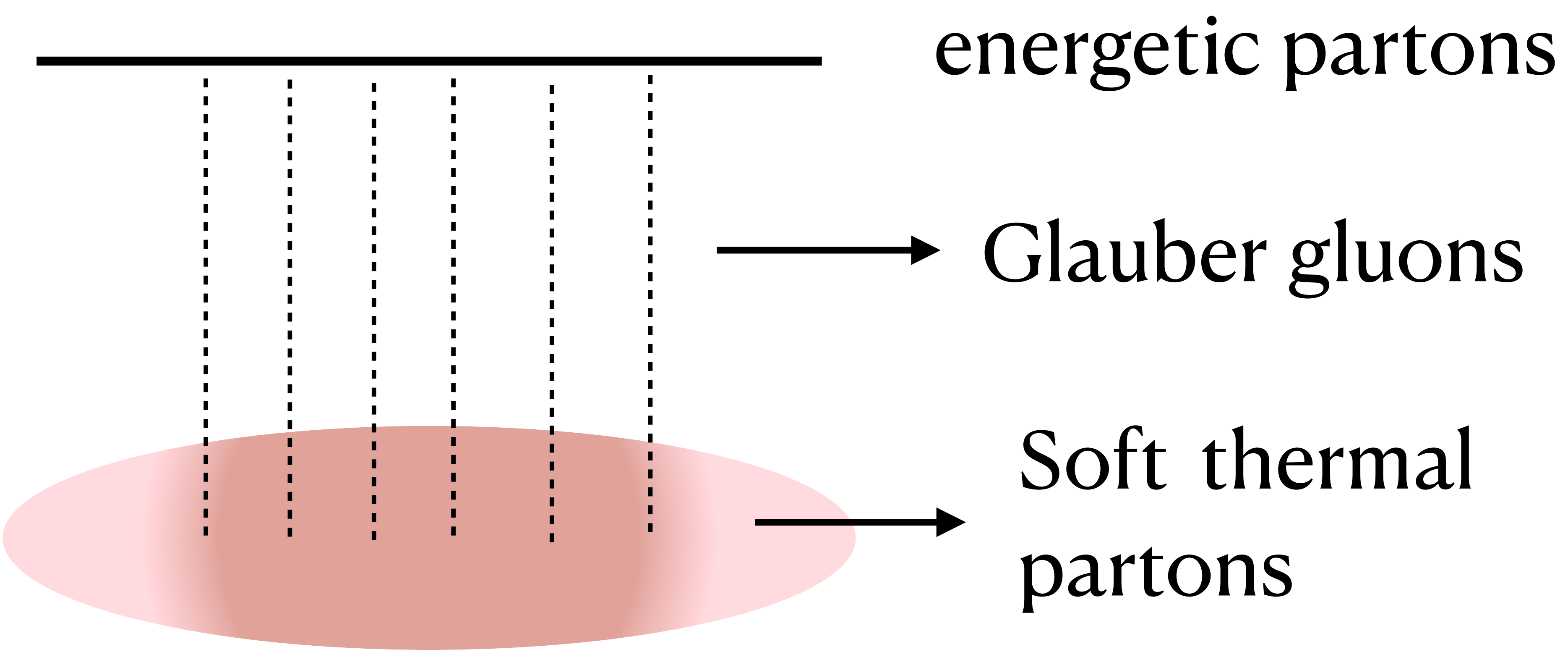
$$\mathscr{L}_{\rm SCET}^{\rm hardscatter} = \sum_K C_K \otimes O_K(\xi_n, A_n, \psi_s, A_s)$$

$$\mathscr{L}_{\rm SCET}^{0} = \mathscr{L}_s(\psi_s, A_s) + \sum_{n_i} \mathscr{L}_{n_i}^{0}(\xi_{n_i}, A_{n_i}) + \mathscr{L}_G(\xi_{n_i}, A_{n_i}, \psi_s, A_s)$$

Medium Jet Interaction

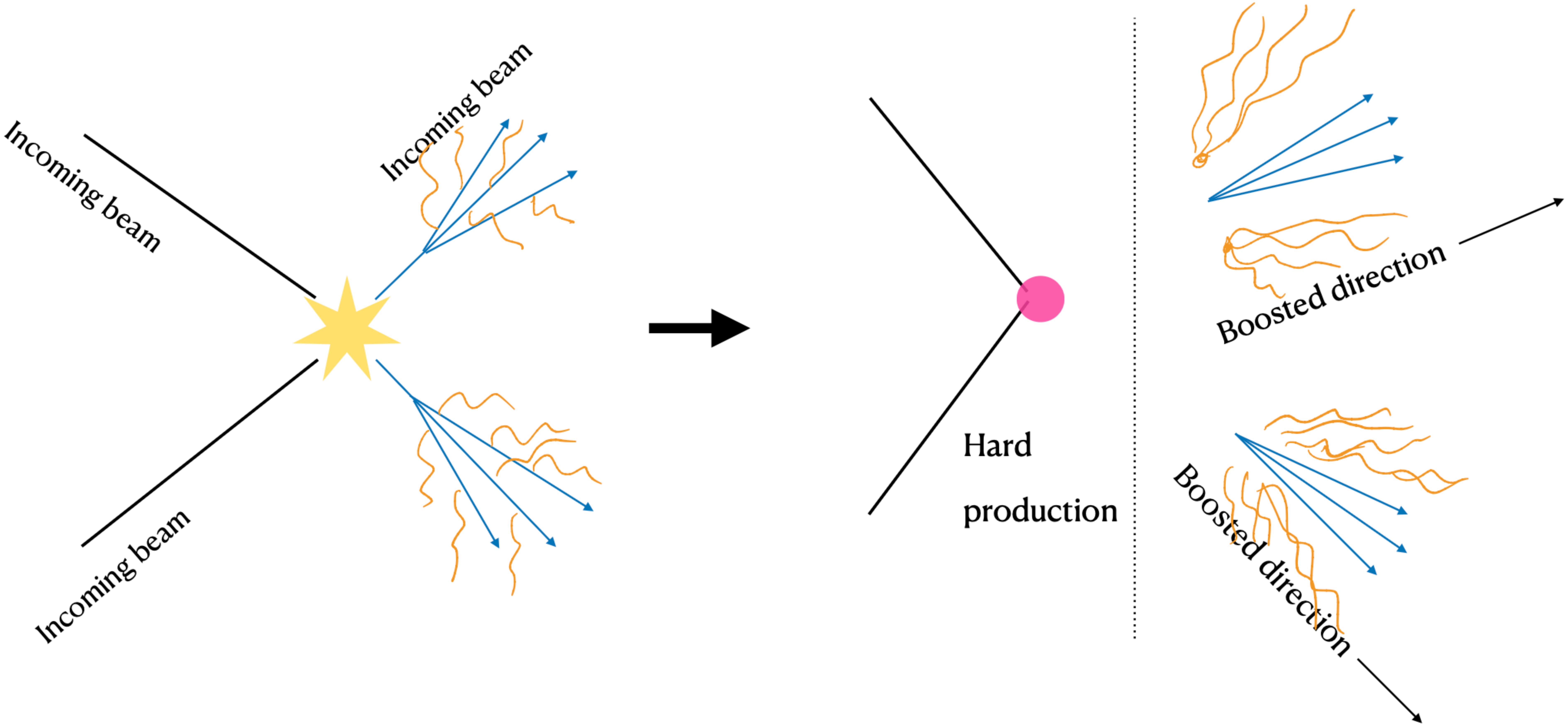
Short distance physics of virtuality $p^2 \sim Q^2$ is integrated out

Glaubers are off-shell modes and mediate interactions between collinear and soft partons



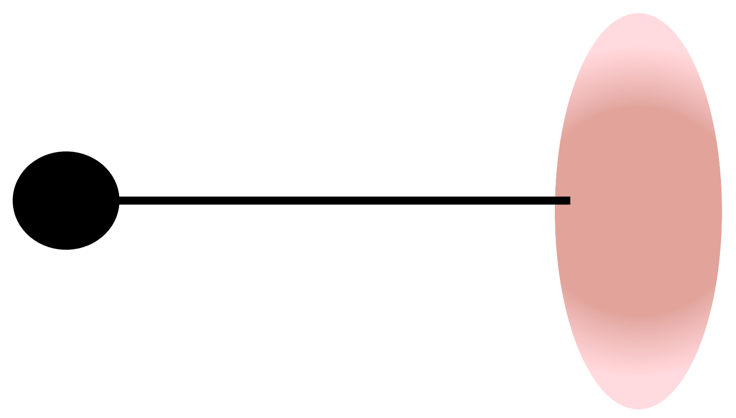
Soft Collinear Effective Theory (SCET)

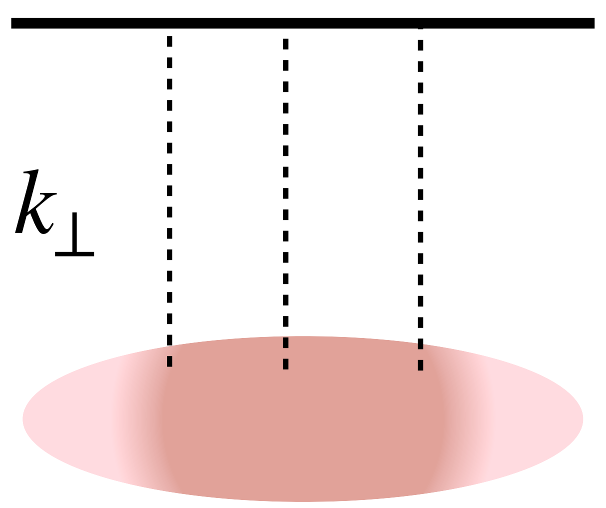
Long distance physics is factored out into collinear and soft modes in the SCET lagrangian

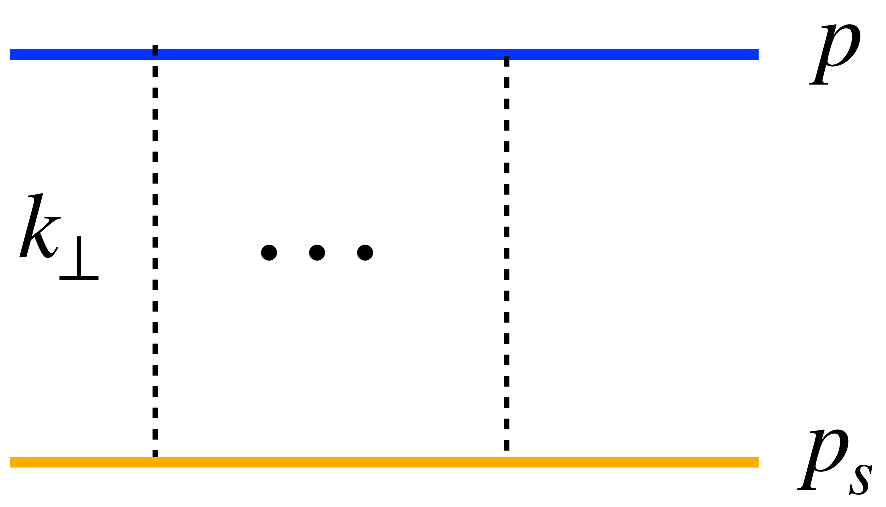


Each sector in the lagrangian contribute to different mechanism associated to jet production and evolution

EFT modes







Jets : collinear mode $p_c \sim Q(1, \lambda^2, \lambda)$

Medium : soft mode $p_s \sim Q(\lambda, \lambda, \lambda)$ with $Q\lambda = Q_{\text{med}}$

Transverse momentum scaling of c mode is fixed by the measurement $p_{c\perp} = Q\sqrt{\chi}, \lambda = \sqrt{\chi}$

Glauber : Scale such that interaction should not change the off-shellness of collinear or soft modes $k \sim Q(\lambda, \lambda^2, \lambda)$

Region I : $Q \gg Q\sqrt{\chi} \sim Q_{\text{med}} = [2-3]$ GeV for $\hat{q} = [1-2]\text{GeV}^2\text{fm}^{-1}$ and $L = 5$ fm

Region II : $Q \gg Q\sqrt{\chi} \gg Q_{\text{med}}$, two stage EFT

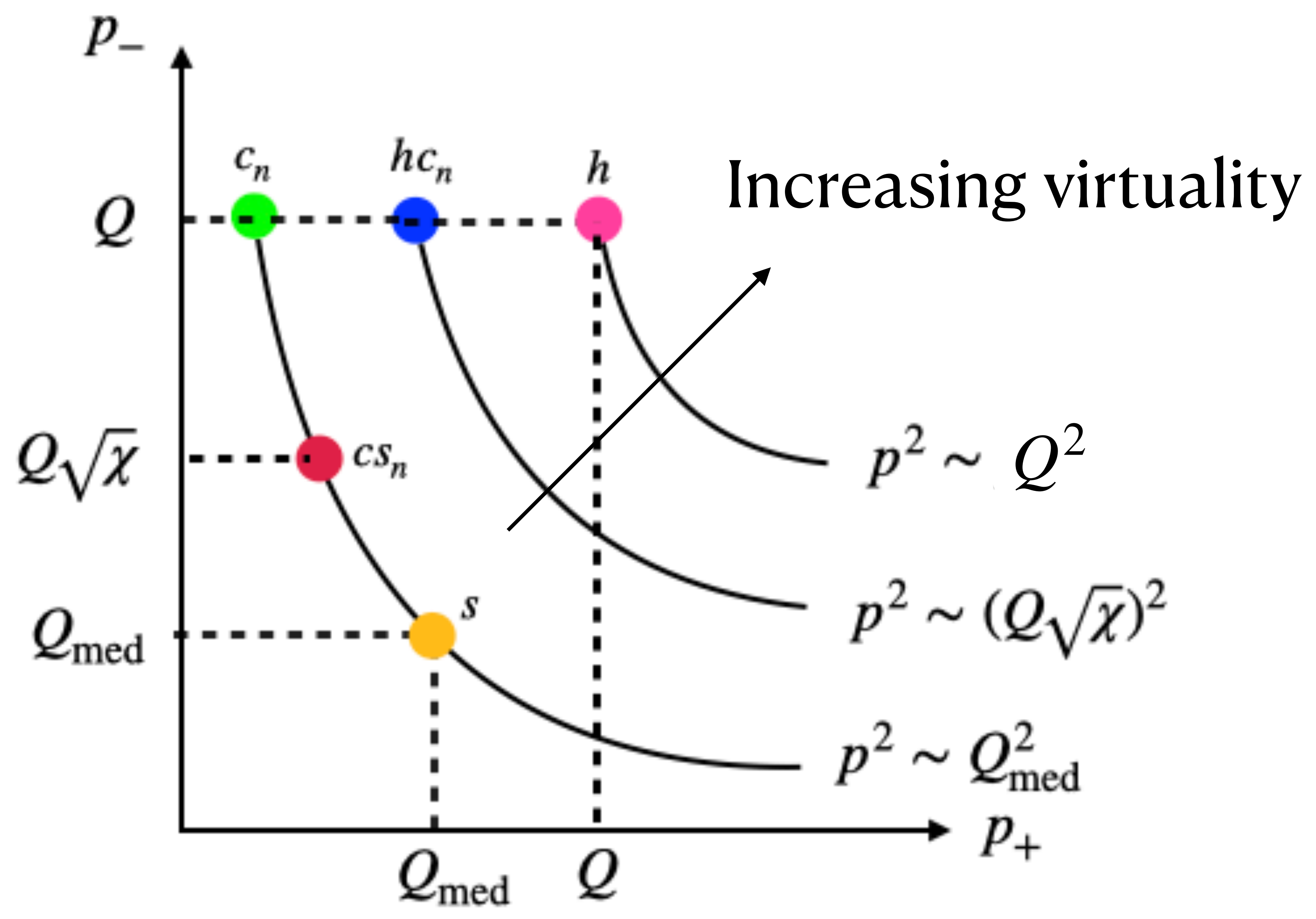
cs modes are also collinear modes but softer than collinear modes but energy larger than medium partons

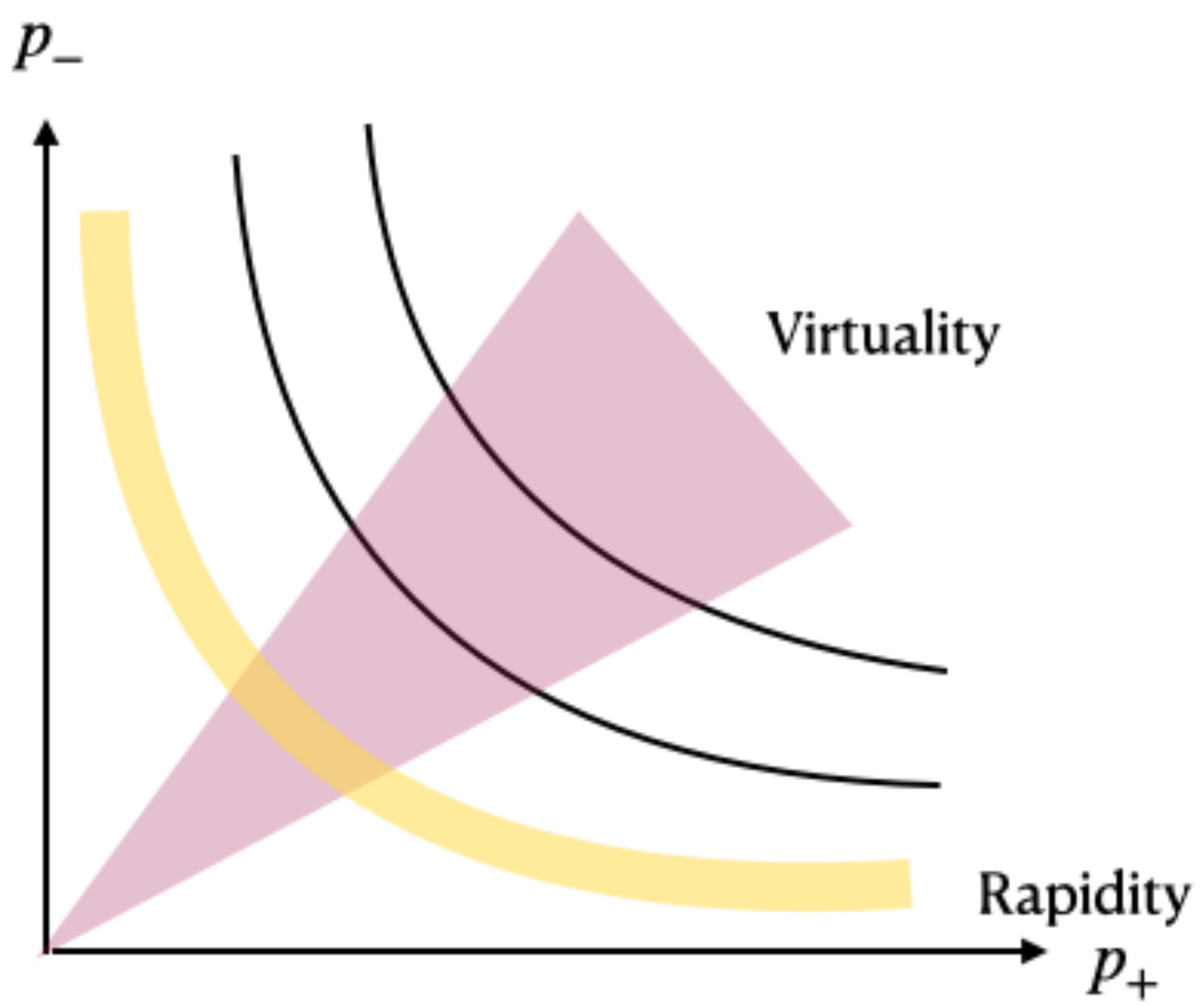
Medium induced emissions : collinear soft $p_{cs} \sim Q_{\text{med}}\left(\frac{1}{\sqrt{\chi}}, \sqrt{\chi}, 1\right)$

EFT modes

Soft and collinear soft modes sits on same mass hyperbola

Hard collinear modes and generated during vacuum evolution of the jet



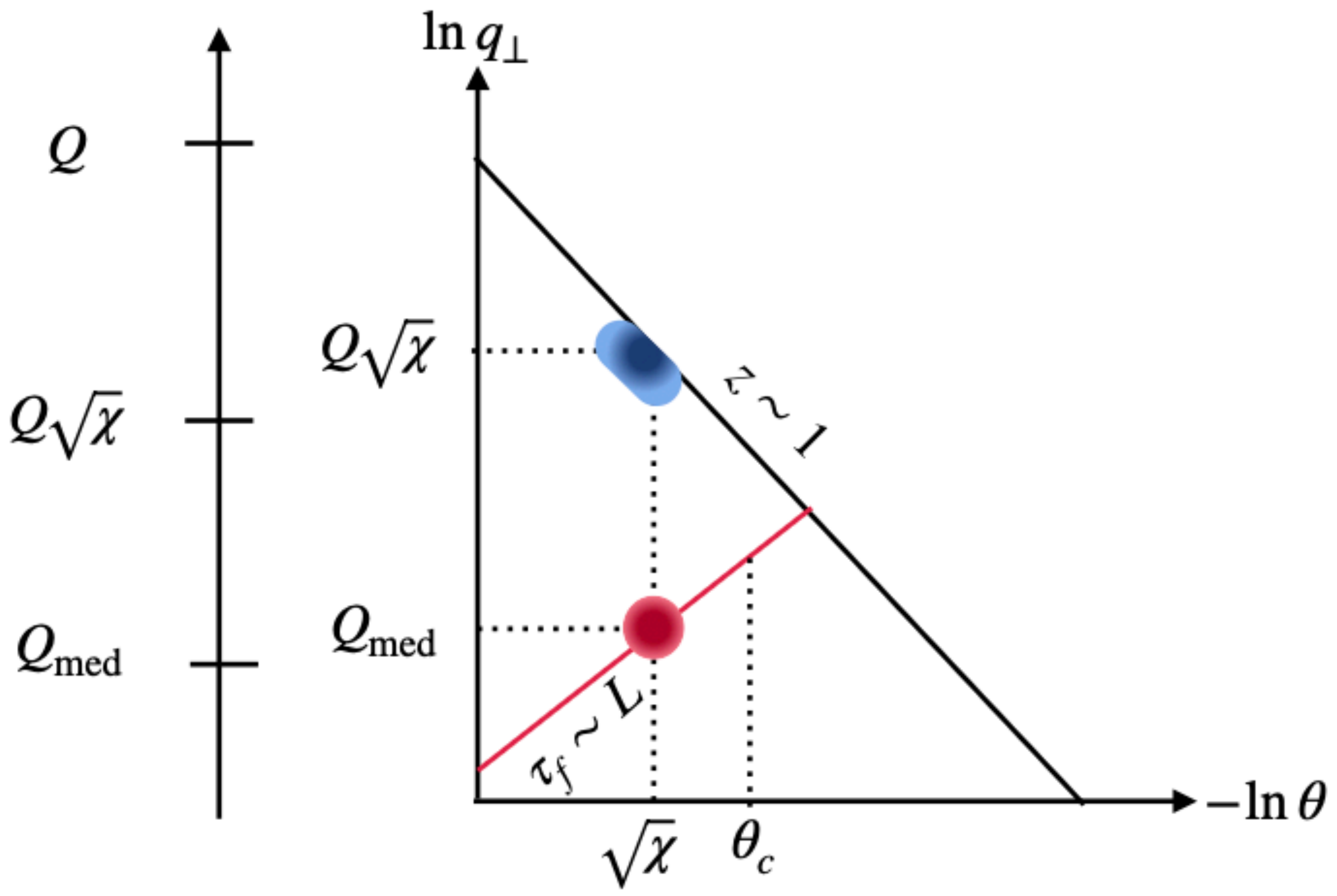


Non-trivial running in both virtuality and rapidity, DGLAP and BFKL

Lund plane representation

Intercepts of lines give relevant mode and its scaling

Emissions with formation time larger than the medium length are suppressed



$$\tau_f \sim \frac{1}{q_\perp \theta} \sim \frac{1}{z p_T \theta^2}$$

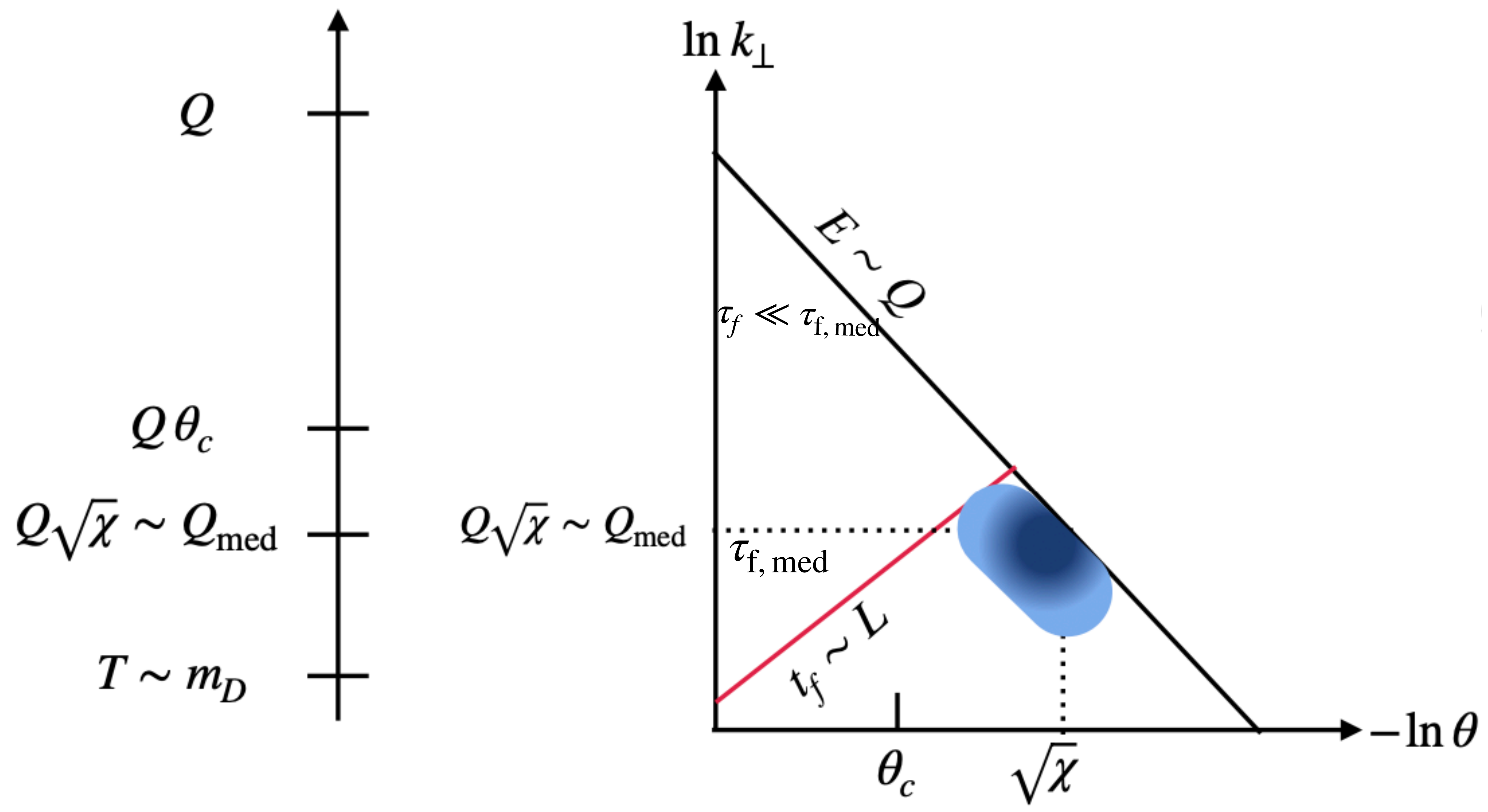
1. Hard emissions are generated during vacuum emissions
2. Medium induced emissions are generated through scattering processes of jet and medium parton and have transverse momentum $Q_{\rm med}$
3. Emissions with $\theta < \theta_c$ are not resolved by the medium
4. There can be medium induced emissions with $\tau_f \gg L$

2408.02753

Lund plane representation

Intercepts of lines give relevant mode and its scaling

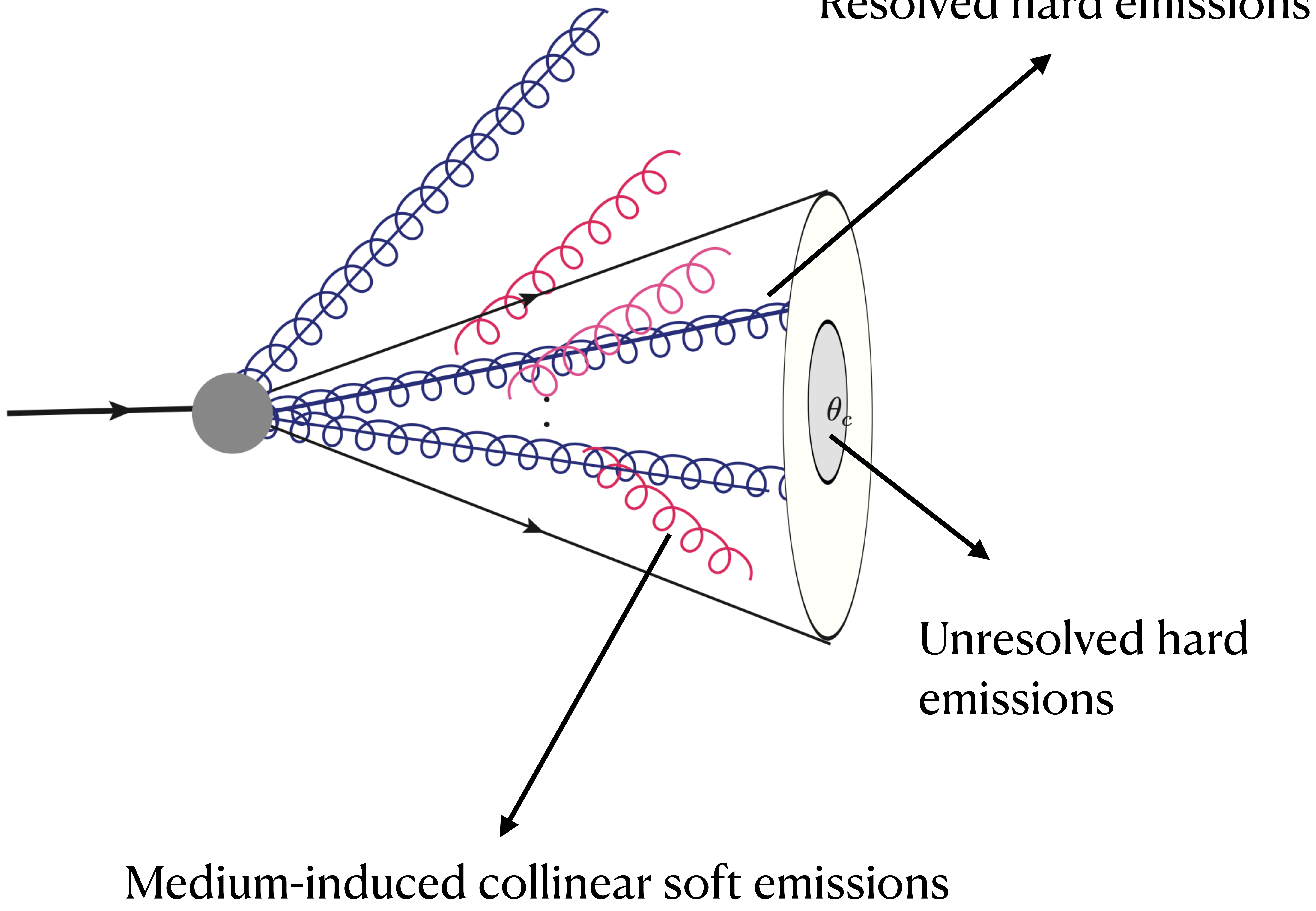
Emissions with formation time larger than the medium length are not resolved by the medium



Emissions out the medium are not resolved so do not contribute to the measurement

Emissions with short formation time can be generated by a very large momentum transfer from the medium. However such interactions are suppressed by tail of the potential

In-medium jet evolution



In-medium jet evolution

1. Hard interaction creates jet initiating parton

↓

2. Initial vacuum emissions generates hard collinear modes

↓

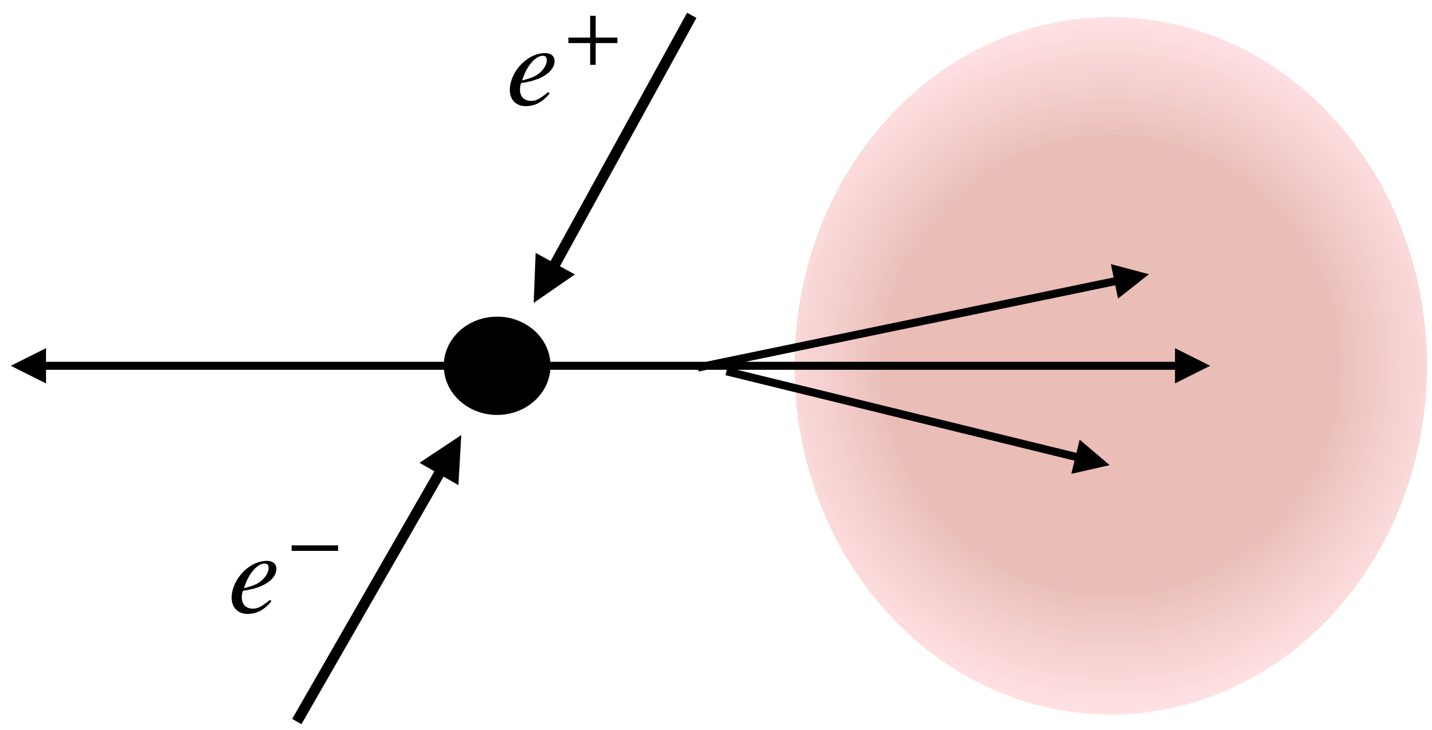
3. Hard collinear modes interact with medium and produce collinear soft modes

Both hard collinear and collinear soft modes contribute to the measurement imposed on final state particles

Jet as open quantum system

1. Factorized total initial density matrix

$$\rho(0) = |e^+e^-\rangle\langle e^+e^-| \otimes \rho_M(0)$$



2. Time evolution of the jet is defined through system density matrix evolution

$$\rho(t) = e^{-iHt}\rho(0)e^{iHt}$$

Lindblad equation with Markovian approximation can be derived from here.

$$H = H_n + H_s + H_G + C(Q)l^\mu j_\mu \equiv H_S + \underbrace{\mathcal{O}_H}$$

$$j^\mu = \bar{\chi}_n\gamma^\mu\chi_n$$

Hard interaction

For broadening of a single energetic quark in medium

2305.10476 **2004.11403**

3. Hard operator creates hard scattering event that produces the jet

$$\frac{d\sigma}{d\chi} = \lim_{t\to\infty}\mathrm{Tr}[\rho(t)\mathcal{M}] = \underbrace{|C(Q)|^2} L_{\mu\nu}\lim_{t\to\infty}\int d^4x d^4y e^{iq\cdot(x-y)}\mathrm{Tr}[e^{-iH_St}j^\mu(x)\rho(0)\mathcal{M}j^\nu(y)e^{iH_St}]$$

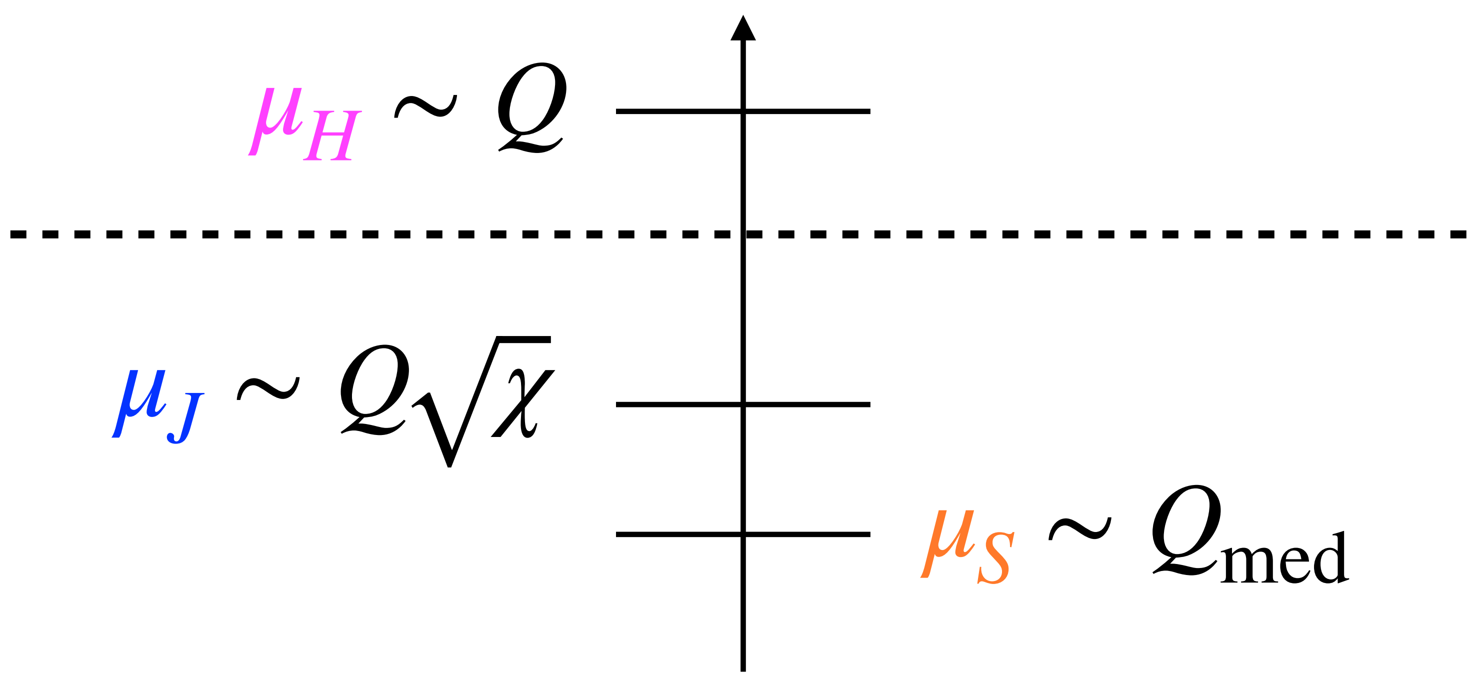
Hard matching Wilson coefficient

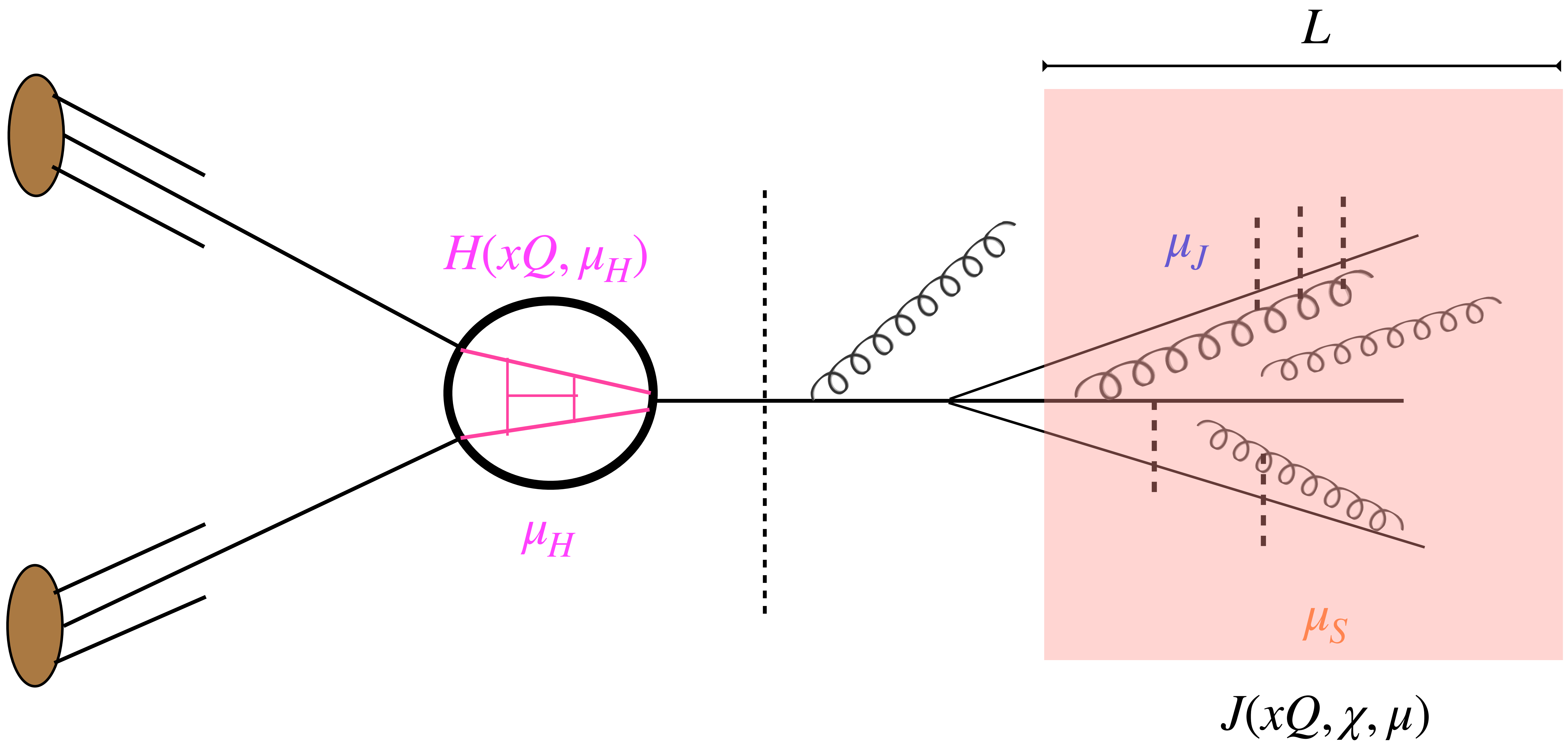
Factorizing differential cross-section

- OPE for factorizing hard scales

$$\frac{d\sigma}{d\chi} = \sum_{i\in\{q,\bar{q},g\}} \int dx x^2 H_i(xQ,\mu)\, J_i(xQ,\chi,\mu)$$

- At this stage $J(xQ,\chi,\mu)$ contains both vacuum and medium physics





Soft scale depends only on the Glauber momentum which is transferred to the jet by the medium

Region I : $Q \gg Q\sqrt{\chi} \sim Q_{\text{med}}$

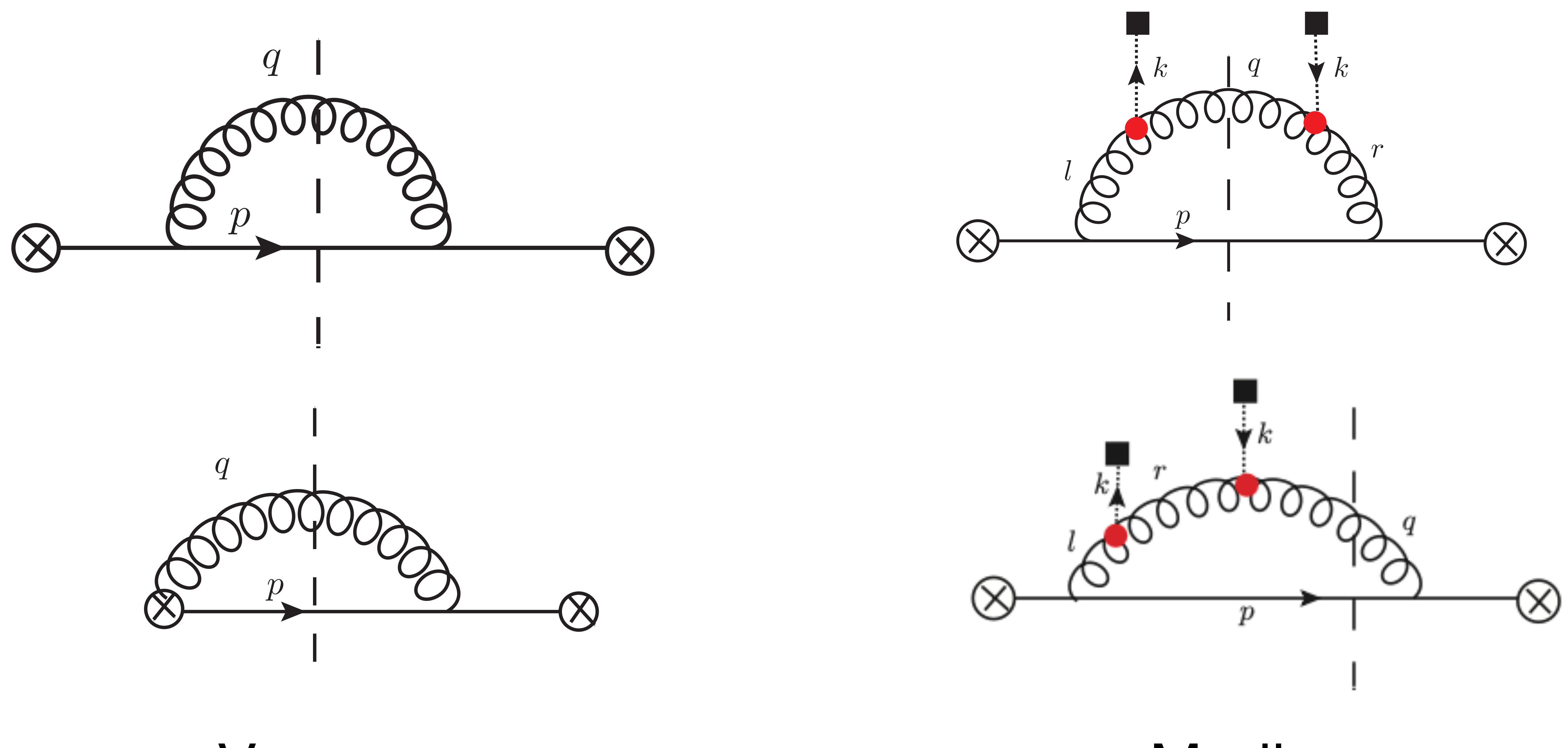
$$J_q(\chi) = \frac{1}{2N_c}\sum_X \mathrm{Tr}\Big[\rho_E(0)\frac{\bar{n}}{2}e^{iH_{ns}t}\,\underbrace{\bar{\mathbf{T}}\Big\{e^{-i\int_0^t dt' H_{G,I}(t')}\chi_{n,I}(0)\Big\}}_{\text{Glauber interaction}}\,\mathscr{M}\,|X\rangle\langle X|\,\underbrace{\mathbf{T}\Big\{e^{-i\int_0^t dt' H_{G,I}(t')}\bar{\chi}_{n,I}(0)\Big\}}_{\text{Glauber interaction}}\,e^{-iH_{ns}t}\Big]$$

2004.11381

With order by order expansion in Glauber Hamiltonian we can separate vacuum emissions from medium induced jet dynamics

$$J_q(\omega,\chi) = \underbrace{J_{q0}(\omega,\chi)}_{\text{vacuum}} + \underbrace{J_{q2}(\omega,\chi;L) + \ldots}_{\text{medium induced}}$$

$$H_G = 8\pi\alpha_s \sum_{i,j\in q,g}\int d^3\mathbf{y}\,\mathcal{O}_n^{ia}(\mathbf{y})\frac{1}{\mathcal{P}_\perp^2}\mathcal{O}_s^{ja}(\mathbf{y})$$



Medium induced jet function

$$J_q(\chi) = \frac{1}{2N_c} \sum_X \mathrm{Tr}\left[\rho_E(0) \frac{\bar{n}}{2} e^{iH_{ns}t} \int_0^t dt' H_{G,I}(t') \chi_{n,I}(0) \mathscr{M} \, |X\rangle\langle X| \int_0^t dt' H_{G,I}(t') \bar{\chi}_{n,I}(0) e^{-iH_{ns}t}\right] + c.c.$$

Collinear and soft operators act on their corresponding states so can be separated $|X\rangle = |X_n\rangle \otimes |X_s\rangle$

$$J_{q2}(\chi; L) = L \int \frac{d^2 k_\perp}{(2\pi)^2} \mathbf{J}_{q2}(\chi, k_\perp, L) \otimes \mathbf{B}(k_\perp)$$

Production of medium induced emissions

Depends on measurement and medium properties

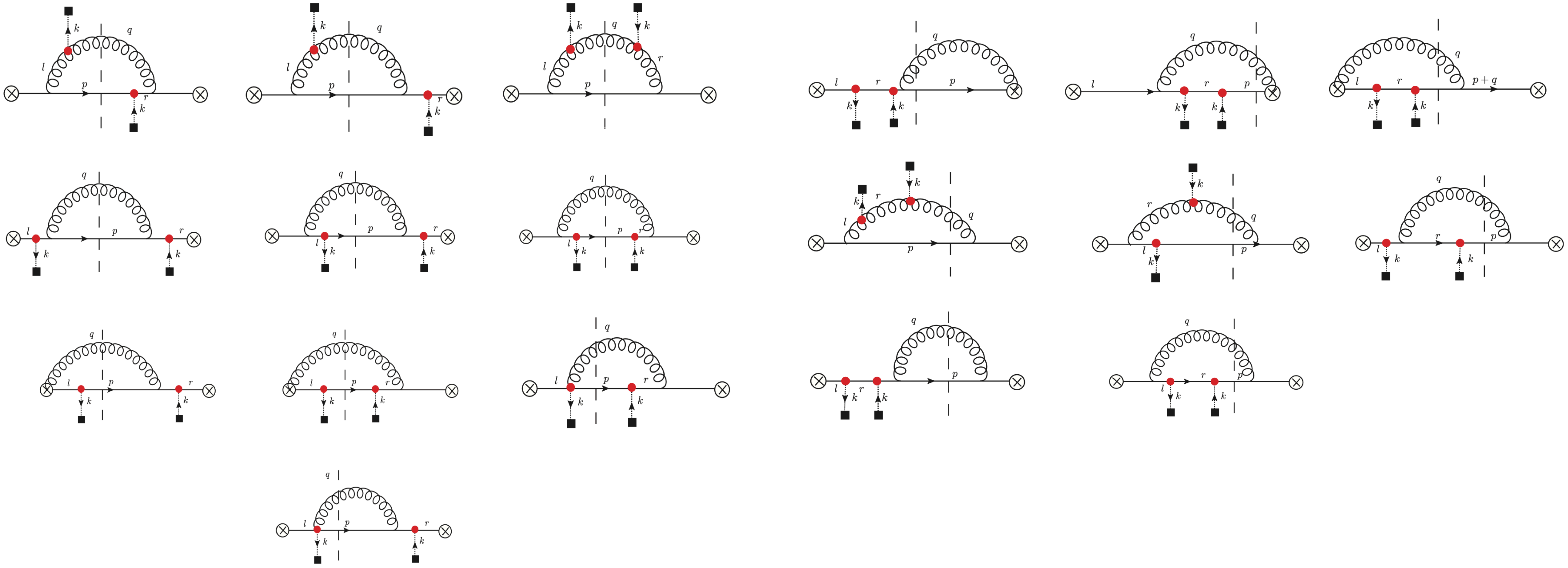
Medium correlator

Depends only on medium properties

Allows for dynamic treatment of the medium through medium correlation function

Medium induced jet function : NLO

Single and double Glauber insertions for NLO jet function

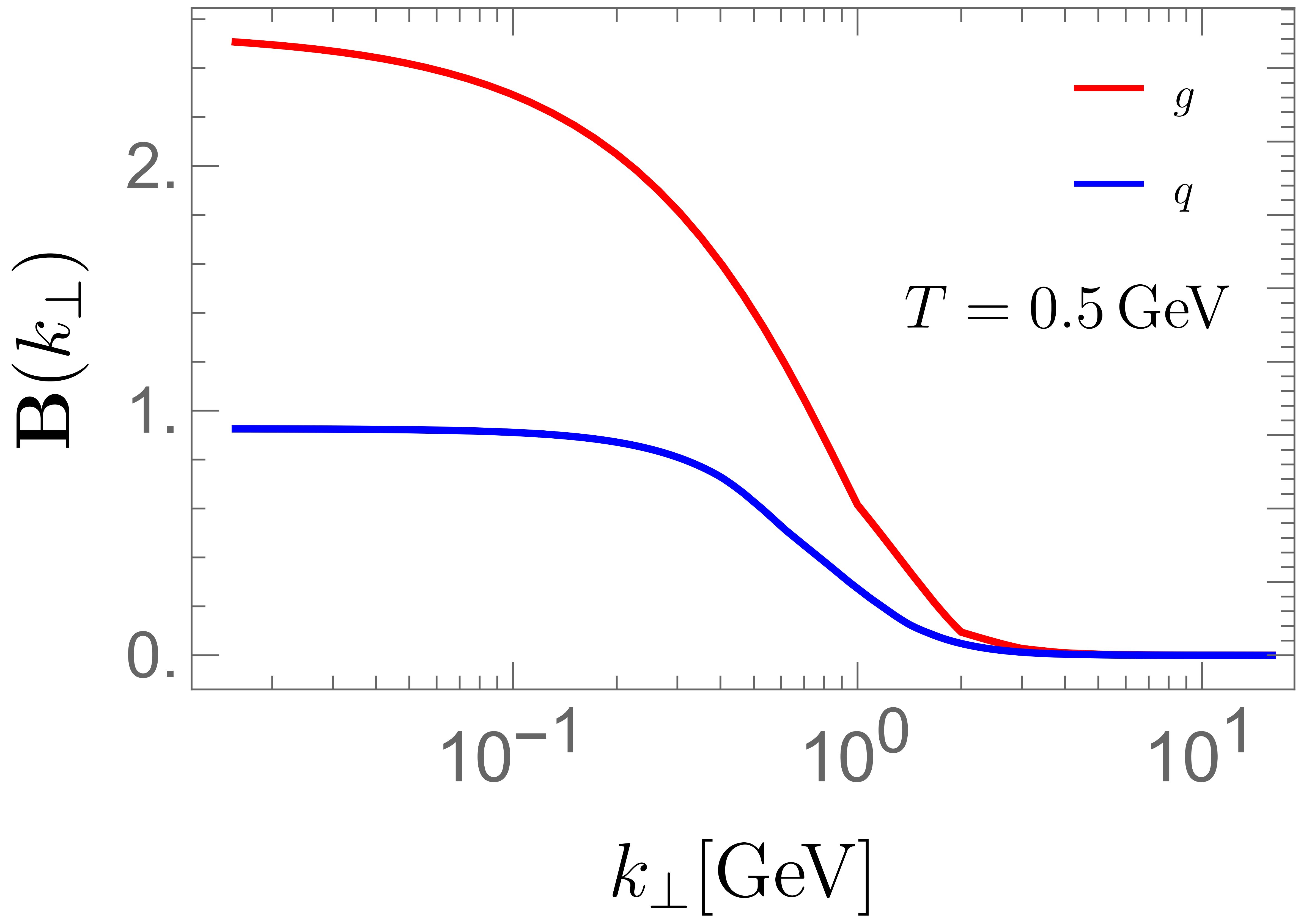


No UV divergence in the jet function.

Medium correlator

Medium correlator can be obtained from thermal expectation of soft operators in the medium

$$\mathbf{B}(k) = \int d^4r\, e^{ik\cdot r} \langle \rho_E O_s^a(r) O_s^a(0) \rangle$$



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At leading order it has $\dfrac{1}{(k_\perp^2 + m_D^2)^2}$ behavior

m_D is Debye screening mass and appears from soft loop corrections of Glauber propagator

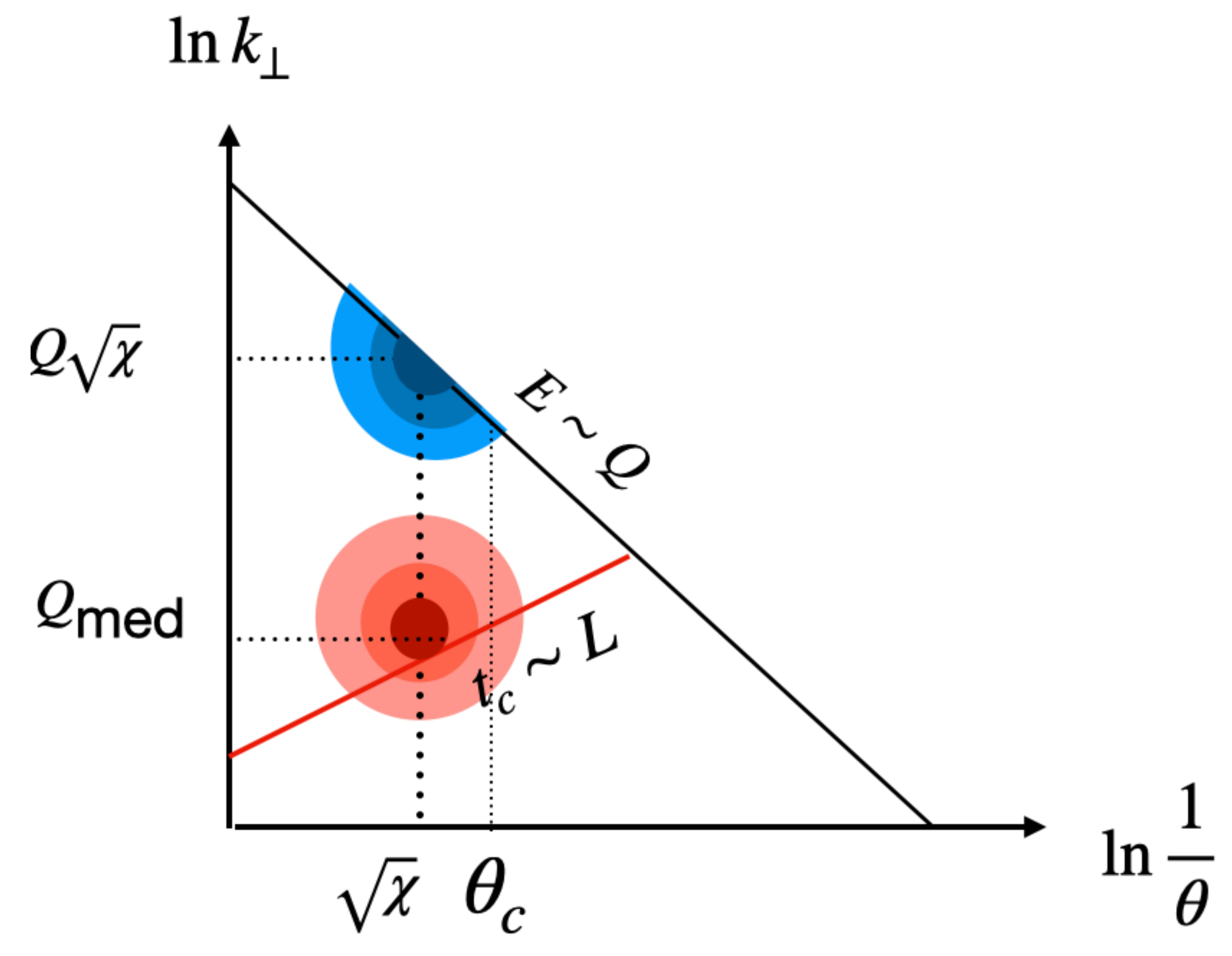
Interactions with very hard transverse momentum transfer from the medium to the jet are suppressed by the tail part

For most of the interaction jet partons get soft transverse kick from the medium partons

Region II : $Q \gg Q\sqrt{\chi} \gg Q_{\text{med}}$

- Refactorize the jet function to match the EFT to lower virtuality

$$J_i = J_{i0}(\omega,\chi,\mu) + \sum_{m=1}^{\infty}\sum_{j=1}^{m} \underbrace{\mathcal{J}^{j}_{i\to m}(\{\underline{m}\},\theta_c,\omega,\mu)}_{\text{Matching function}} \otimes_\theta \underbrace{\mathcal{S}_{m,j}(\{\underline{m}\},\chi,\mu)}_{\text{Collinear soft subjet function}}$$



Matching function describes the production of m resolved hard partons from initial parton i

Collinear soft function describes the production of medium induced emissions from m resolved hard partons

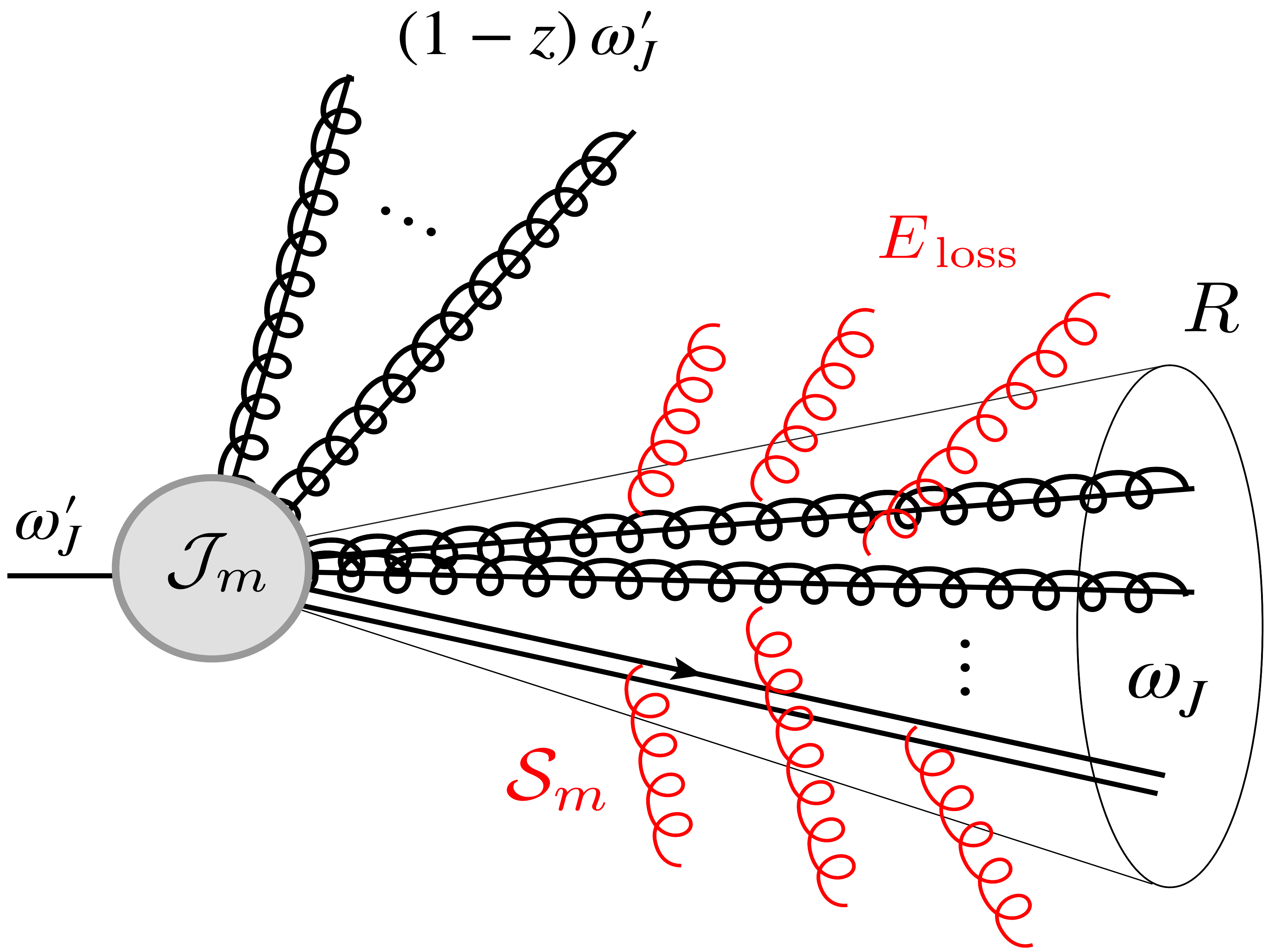
Matching function requires computing the jet function in full theory at one side and similarly at the other end with low virtuality

Collinear soft function

Collinear soft emissions are factored out in terms of Wilson lines that are attached to hard collinear modes

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

$$U(n) \equiv \mathbf{P}\exp\left[ig\int_0^{+\infty} ds\, n\cdot A_{\rm cs}(sn)\right]$$



$U(n)$ is collinear soft Wilson lines that contributes to both the energy loss and measurement imposed on final state particles

collinear soft Wilson lines are attached to each hard collinear mode along the direction n_i

Jet function : Next to leading order

For $R \ll 1$ and $\theta_c \sim R$ only one emission is resolved by the medium

First term for medium induced radiation, i.e., single subjet case

$$J_{q1} = \mathcal{J}_{i\to 1}(\theta_c, \omega, \mu)\, \mathcal{S}_1(\chi, \mu)$$

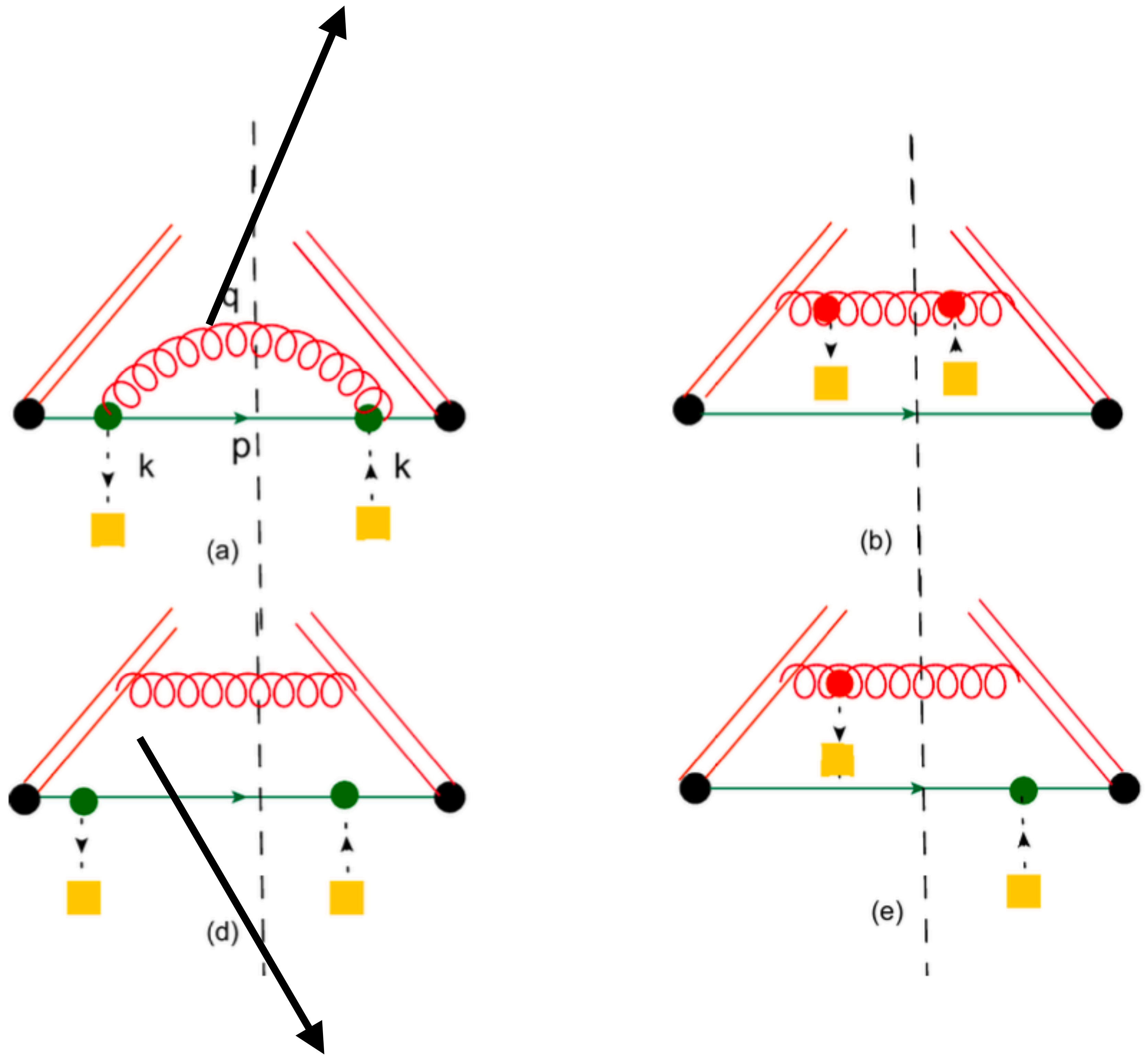
Matching function is sensitive to coherence angle but requires at least two subjet

See Varun's talk

$$\mathcal{S}_1(\chi) = L \int \frac{d^2k_\perp}{(2\pi)^3} \mathbf{S}_1(\chi, k_\perp; L) \otimes \mathbf{B}(k_\perp)$$

$$\mathbf{S}_{q2}(\chi, \omega, k_\perp) = \frac{4C_F N_c g^2 L}{\pi} \int \frac{dz}{z} \int \frac{d^2q_\perp}{(2\pi)^2} \underbrace{\frac{\vec{q}_\perp \cdot \vec{k}_\perp}{\vec{q}_\perp^{\,2} \vec{\kappa}_\perp^{\,2}}}_{\vec{\kappa}=\vec{q}_\perp - \vec{k}_\perp} \Bigg(1 - \underbrace{\frac{z\omega}{\vec{\kappa}_\perp^{\,2} L} \sin\Big[\frac{L\vec{\kappa}^2}{z\omega}\Big]}_{\text{LPM}}\Bigg) \mathcal{M}$$

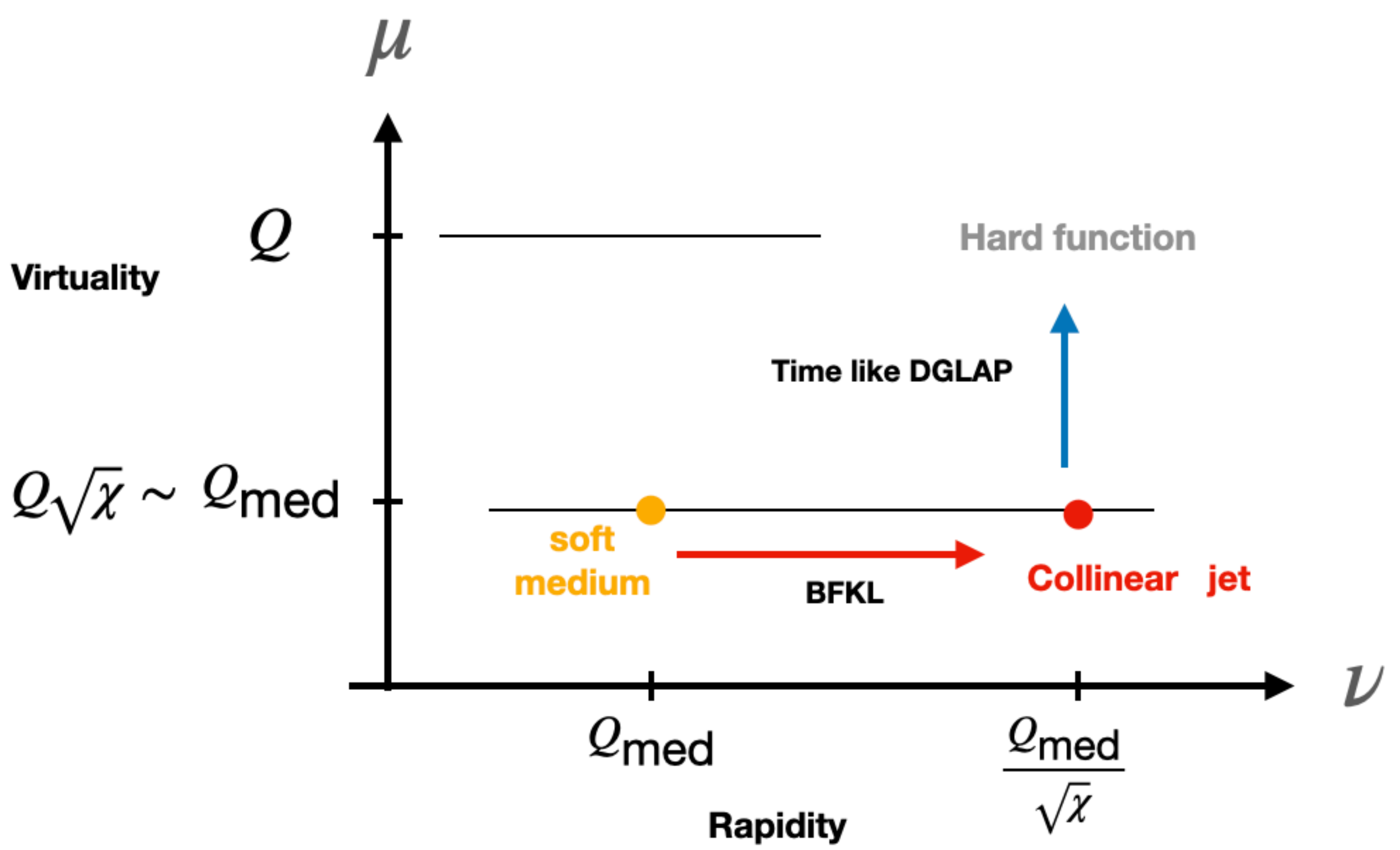
Medium induced collinear soft emissions

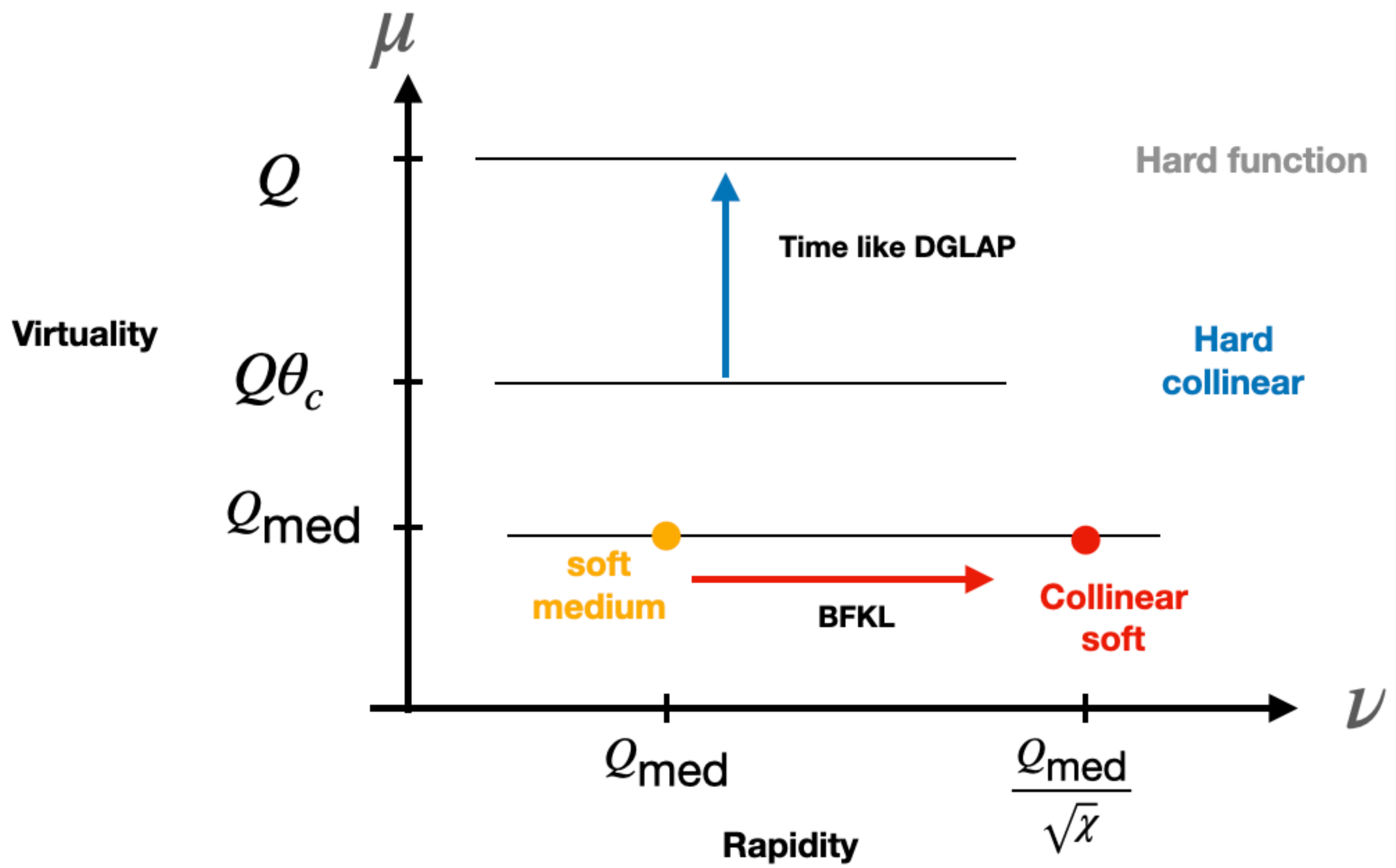


Collinear soft emission from vacuum Wilson lines

Beyond fixed order

- Medium function obeys BFKL, therefore, from RG consistency collinear-soft jet function also obeys BFKL evolution equation





- Natural scales for each functions are provided by the logs appearing in the functions

BFKL resummation

- From RG consistency the jet function obeys BFKL evolution equation

$$\nu \frac{d\mathbf{S}_1^{(1)}(k_\perp,\nu)}{d\nu} = -\frac{\alpha_s(\mu)N_c}{\pi^2}\int d^2l_\perp\left[\frac{\mathbf{S}_1^{(1)}(l_\perp,\nu)}{(\vec{l}_\perp-\vec{k}_\perp)^2} - \frac{k_\perp^2\mathbf{S}_1^{(1)}(k_\perp,\nu)}{2l_\perp^2(\vec{l}_\perp-\vec{k}_\perp)^2}\right]$$

Resummed jet function for two point energy correlator

$$\mathbf{S}_{1,\mathrm{R}}^{(1)}(k_\perp,\mu,\nu_f) = \int d^2l_\perp \mathbf{S}_1^{(1)}(l_\perp,\mu,\nu_0)\int\frac{d\nu}{2\pi}k_\perp^{-1+2i\nu}l_\perp^{-1-2i\nu}e^{in(\phi_k-\phi_l)}e^{-\frac{\alpha_s(\mu)N_c}{\pi}\chi(n,r)\log\frac{\nu_f}{\nu_0}}$$

Scale for jet function

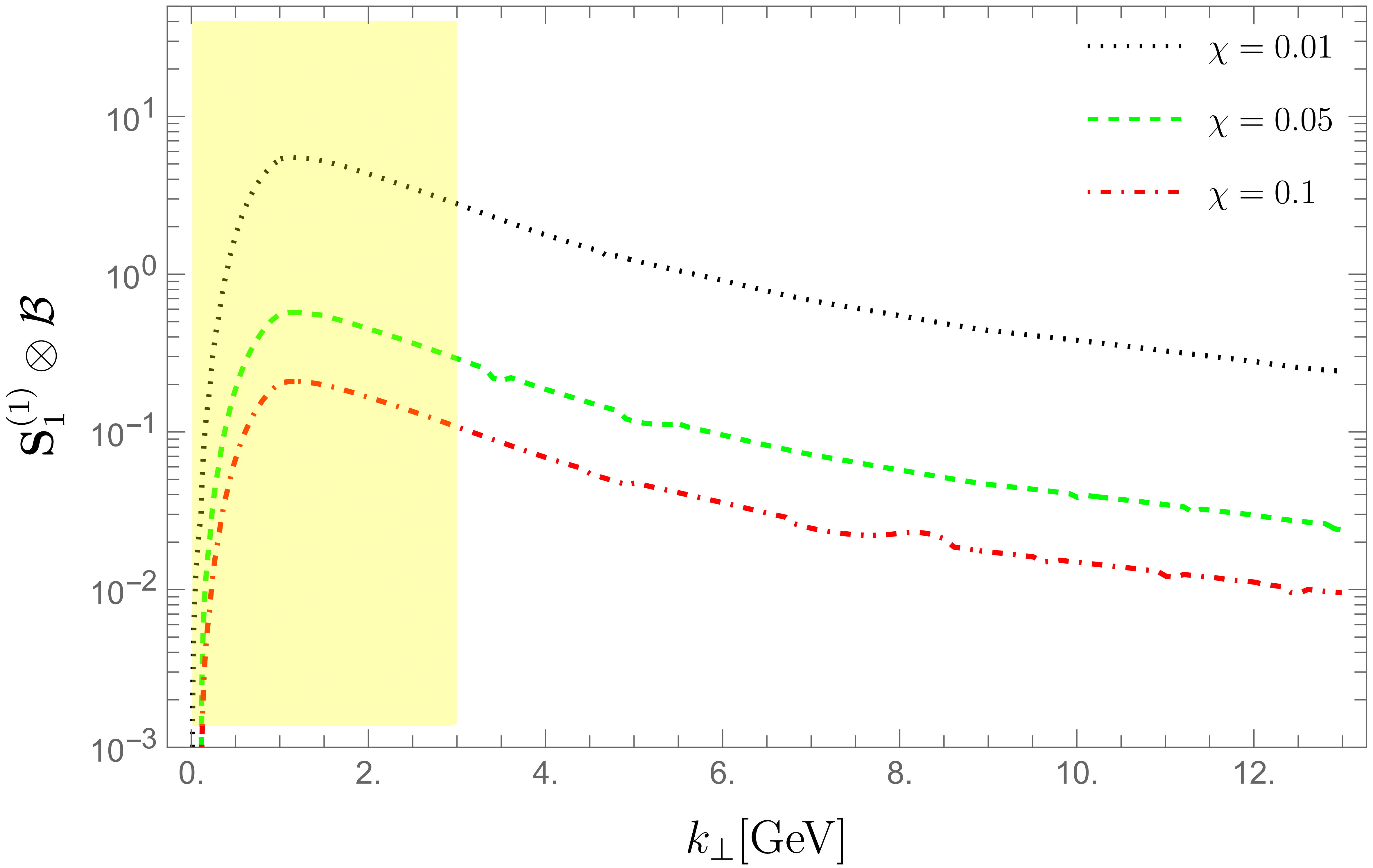
$$\nu_0 \sim \frac{Q_{\mathrm{med}}}{\sqrt{\chi}}$$

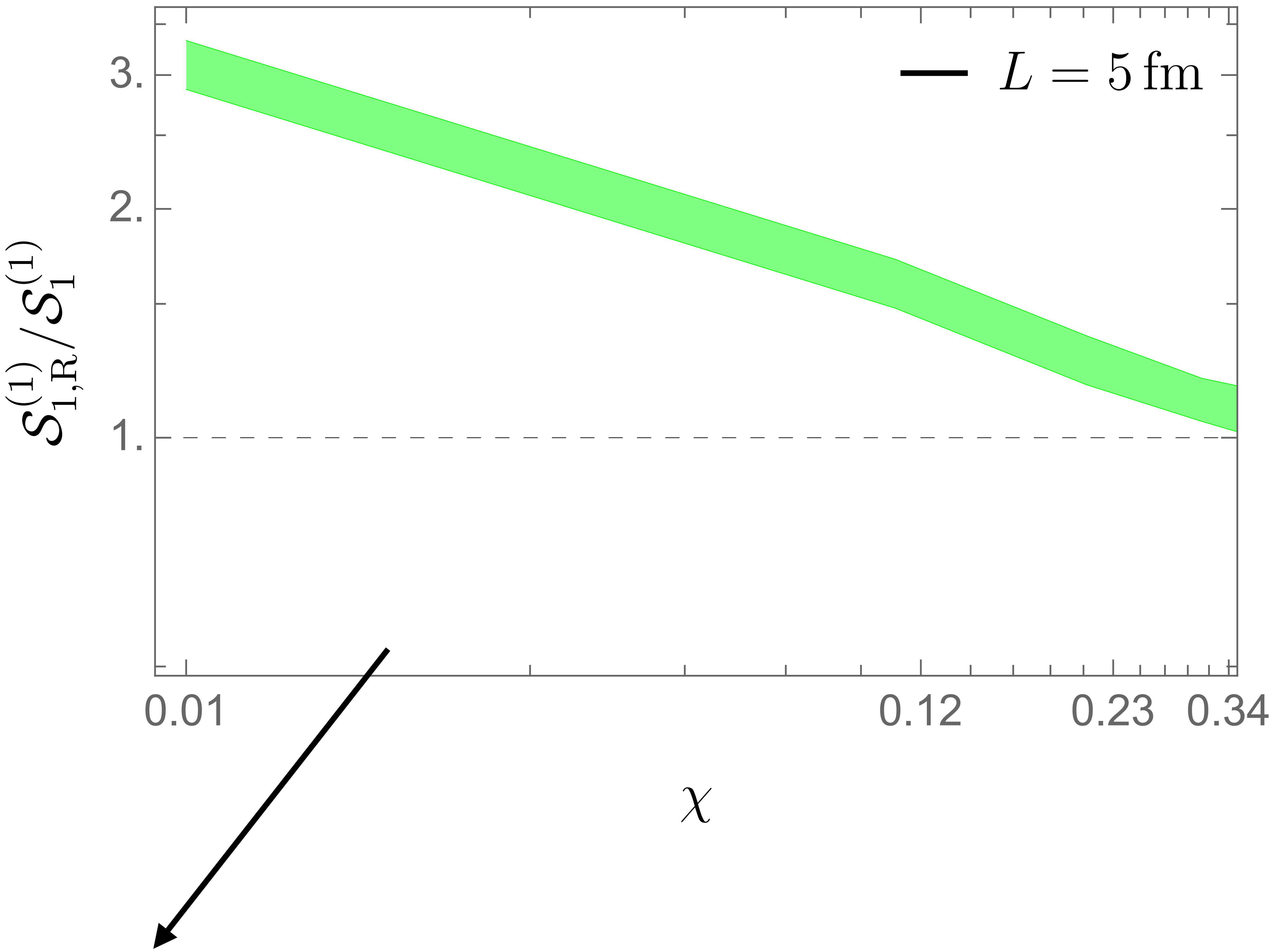
Medium scale $\nu_f \sim Q_{\mathrm{med}}$

- Resums $\sim \alpha_s \log\sqrt{\chi}$ terms which are relevant in small χ limit

Impact of resummation

Collinear soft emissions are factored out in terms of Wilson lines that are attached to hard collinear modes



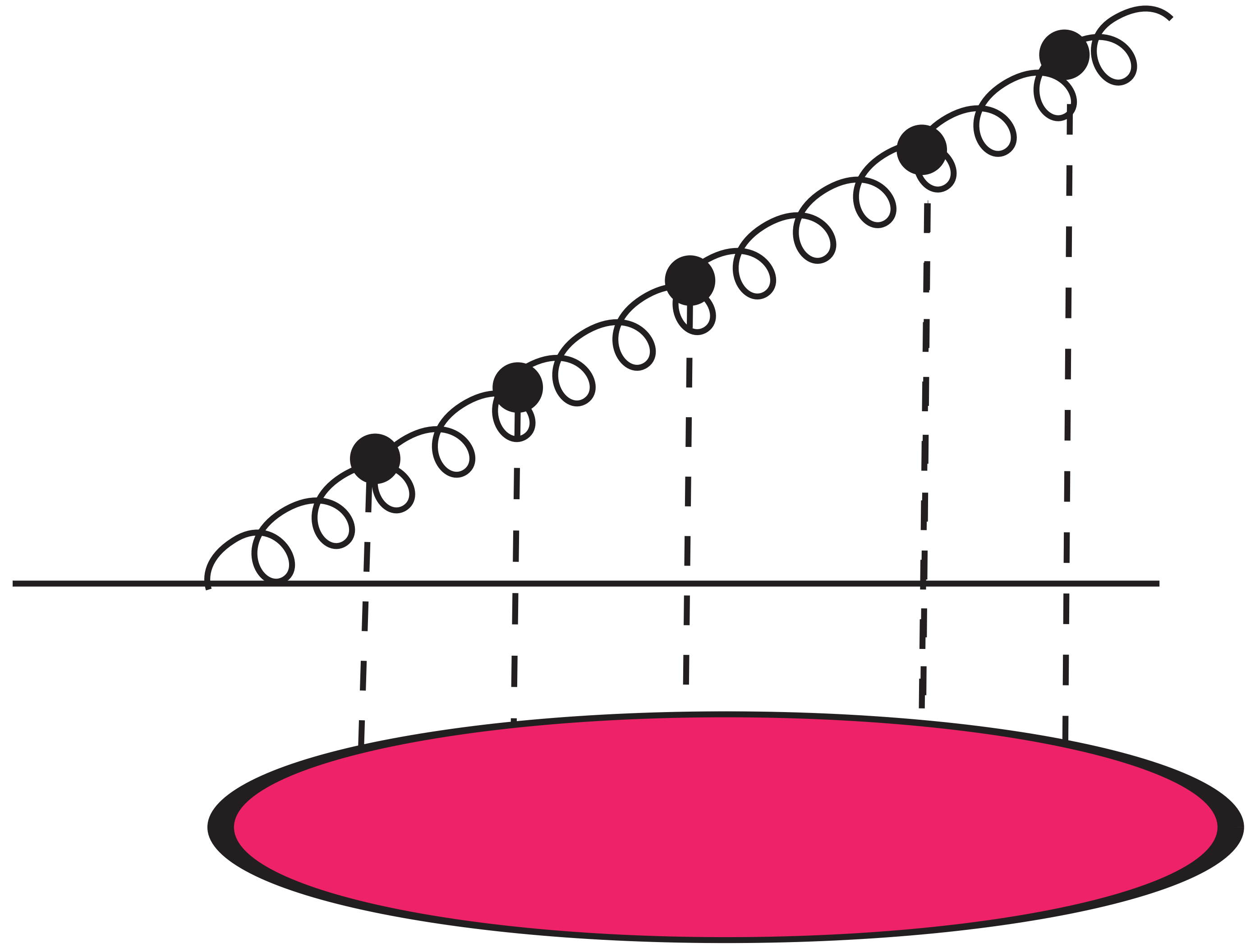


BFKL resummed jet function for two point energy correlator

All order factorization

Multiple scatterings are important and gives rise to broadening

$$p_T \gg p_T R \gg Q_{\text{med}} > T > \Lambda_{QCD}$$



We want to find out how large Q_{med} can be due to multiple scatterings of jet and medium partons

Q_{med} is average momentum transferred to the jet by the medium during coherent multiple scatterings

$$J_i(z, \omega_J, \mu) = \int_0^1 dz' \int_0^\infty d\epsilon_L \, \delta(\omega_J' - \omega_J - \epsilon_L) \sum_m \prod_{j=2}^m \int \frac{d\Omega(n_j)}{4\pi} \mathcal{J}_{i\to m}\left(\{\underline{n}\}, z', \omega_J' = \frac{z'\omega_J}{z}, \mu, \mu_{cs}\right) \mathcal{S}_m(\{\underline{n}\}, \epsilon_L, \mu_{cs})$$

Number of subjets

Denotes subjet directions such that $n_i \cdot n_j = R$

Jet function NLO : arbitrary number of interactions

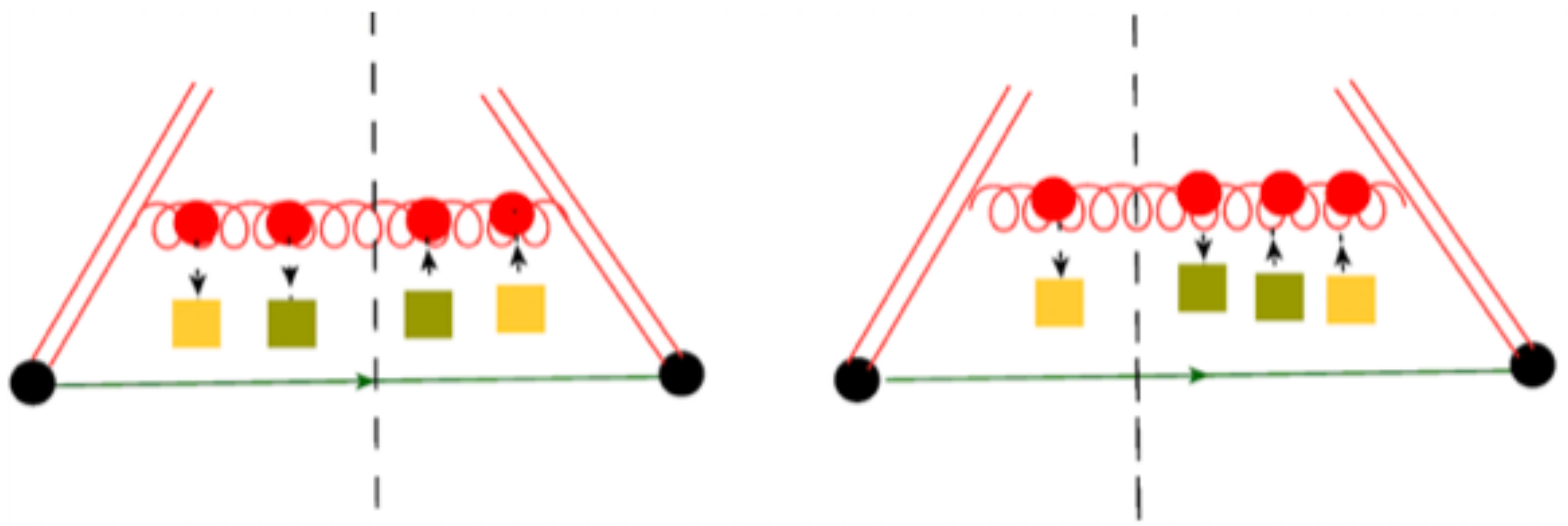
$$\mathcal{S}_1^{(n)}(\epsilon_L,\mu) = |\,C_G\,|^{2n}\left[\prod_{i=1}^{n}\int_0^L \mathrm{d}x_i^-\Theta(x_i^- - x_{i+1}^-)\int \frac{\mathrm{d}^2k_i}{(2\pi)^3}\mathbf{B}(k_{i\perp},\mu,\nu',x_i^-)\right]\mathbf{S}_1^{(n)}(\epsilon_L;k_{1\perp},\ldots,k_{n\perp};x_1^-,\ldots x_n^-;\nu')$$

Number of Glauber insertions

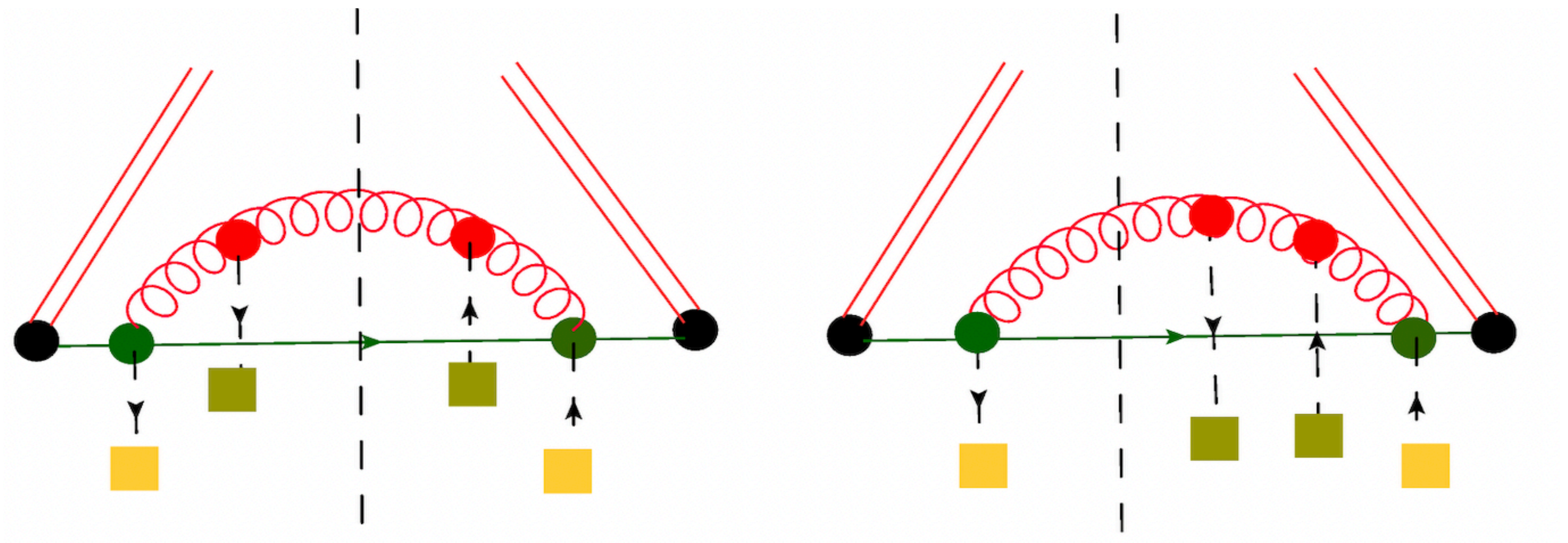
Path ordering of interactions

Production of collinear soft emissions

Broadening of vacuum emission



Broadening of medium induced emission



The factorization formula assumes that medium correlators are not correlated beyond the scattering length

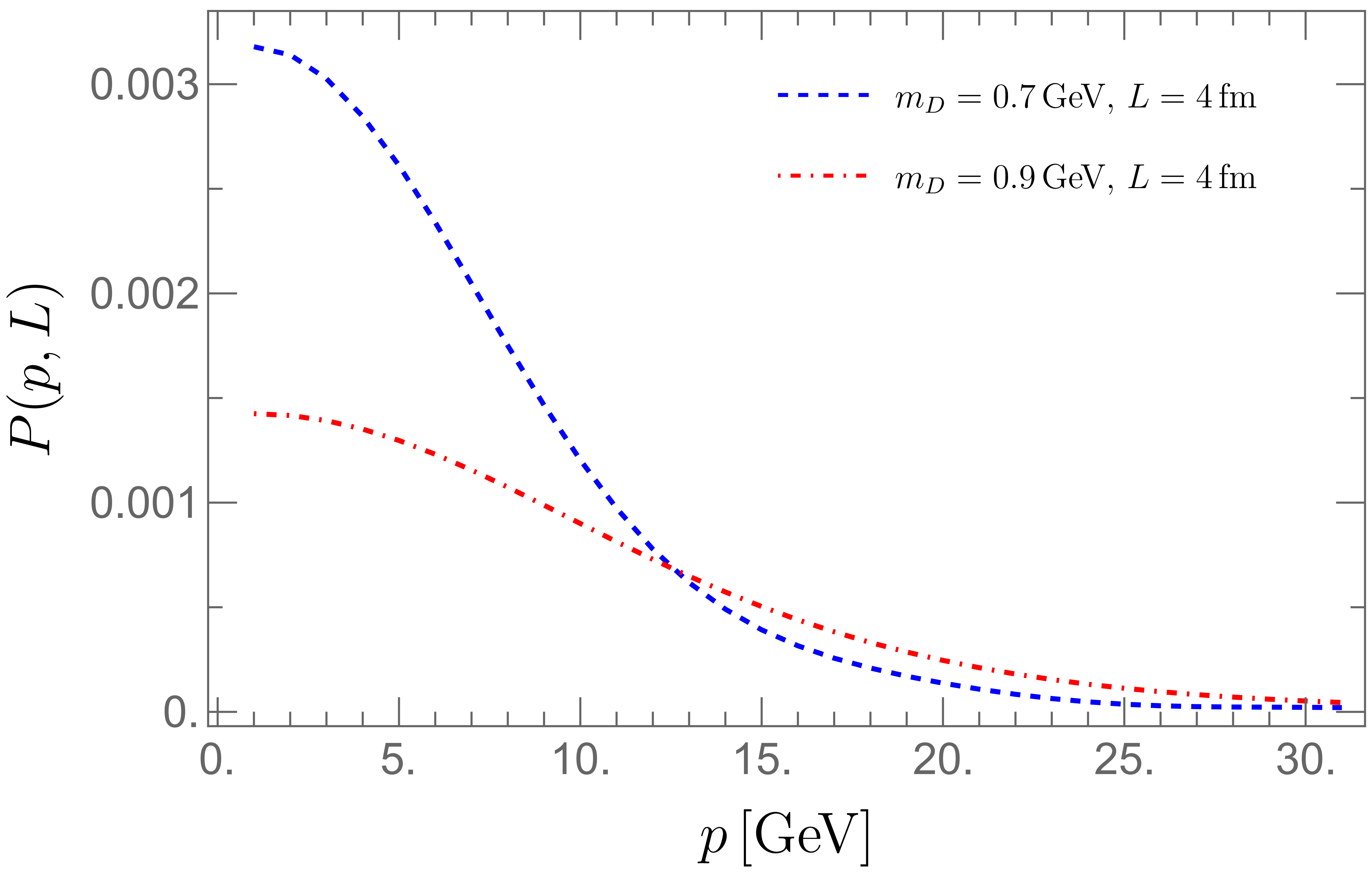
Vacuum emissions can happen very early in time

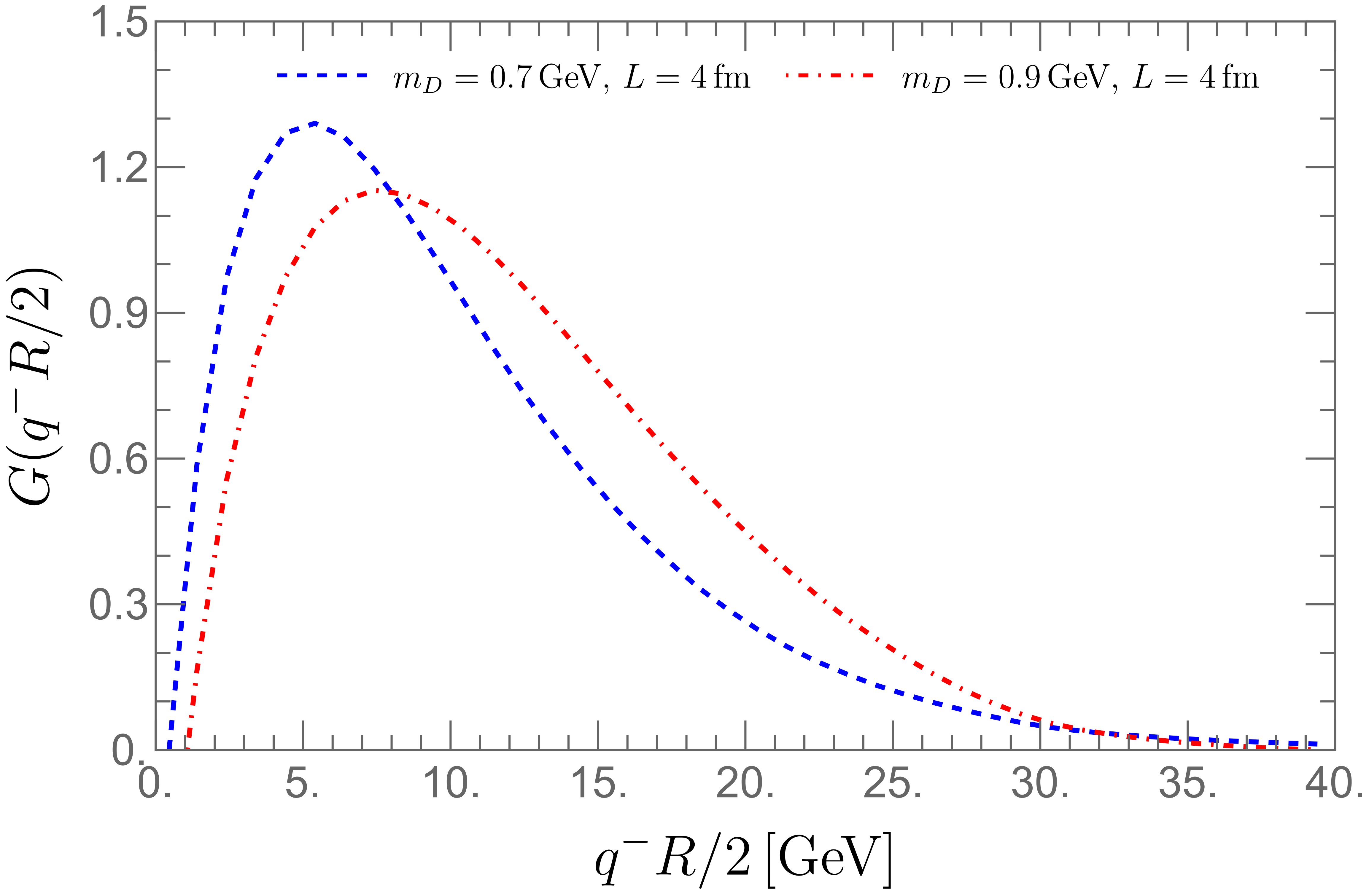
Vacuum emissions have very short formation time compared to medium induced emissions

Emergent perturbative scale

Multiple scatterings lead to larger momentum transfer from medium to jet parton

B.S. and V.Vaidya, 2412.18967





Peak in the distribution provides an estimate for the emergent scale $Q_{\rm med}$ through multiple scattering

Exact value of the emergent scale depends on medium properties and parameters

Summary and outlook

1. Factorization allows for resummation and a systematic improvement of theoretical calculations

2. Open quantum system and EFT combination allows for a dynamical treatment of medium as well

3. Factorization allows for separation of perturbative physics and universal non-perturbative physics

outlook:

1. Higher order perturbative calculations are needed for better accuracy and to see the scale for color coherence dynamics

2. To account for non-linear evolutions such as BK and JIMWLK multiple scatterings with LPM contributions are needed

3. Time evolution of jets in heavy-ion collision will allow to systematically incorate initial state jet evolution and hydrodynamic expansion of the medium

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Thank you