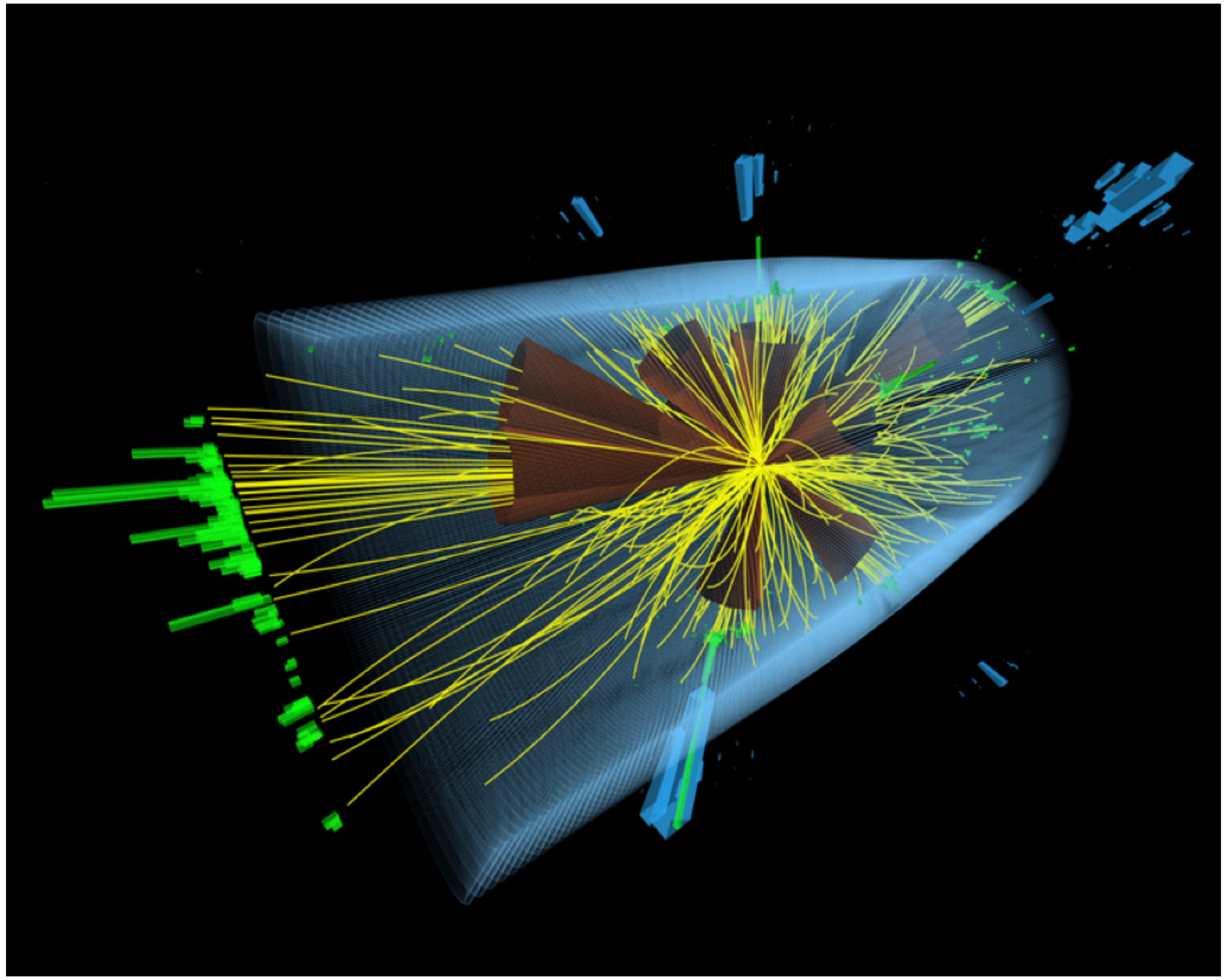
Exploiting ν dependence of projected energy correlators in HICs



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Based on works: 2408.02753, 2503.20019, $25XX.XXXX$

New opportunities in particle and nuclear physics with energy correlators, C3NT China

Energy correlators

What are energy correlators?

Observables that characterize angular structure of energy flow in high-energy particle collisions.

Defined via correlations of energy depositions in detectors.

$$\text{EEC}(\chi) = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\cos\chi - \hat{n}_i \cdot \hat{n}_j\right)$$

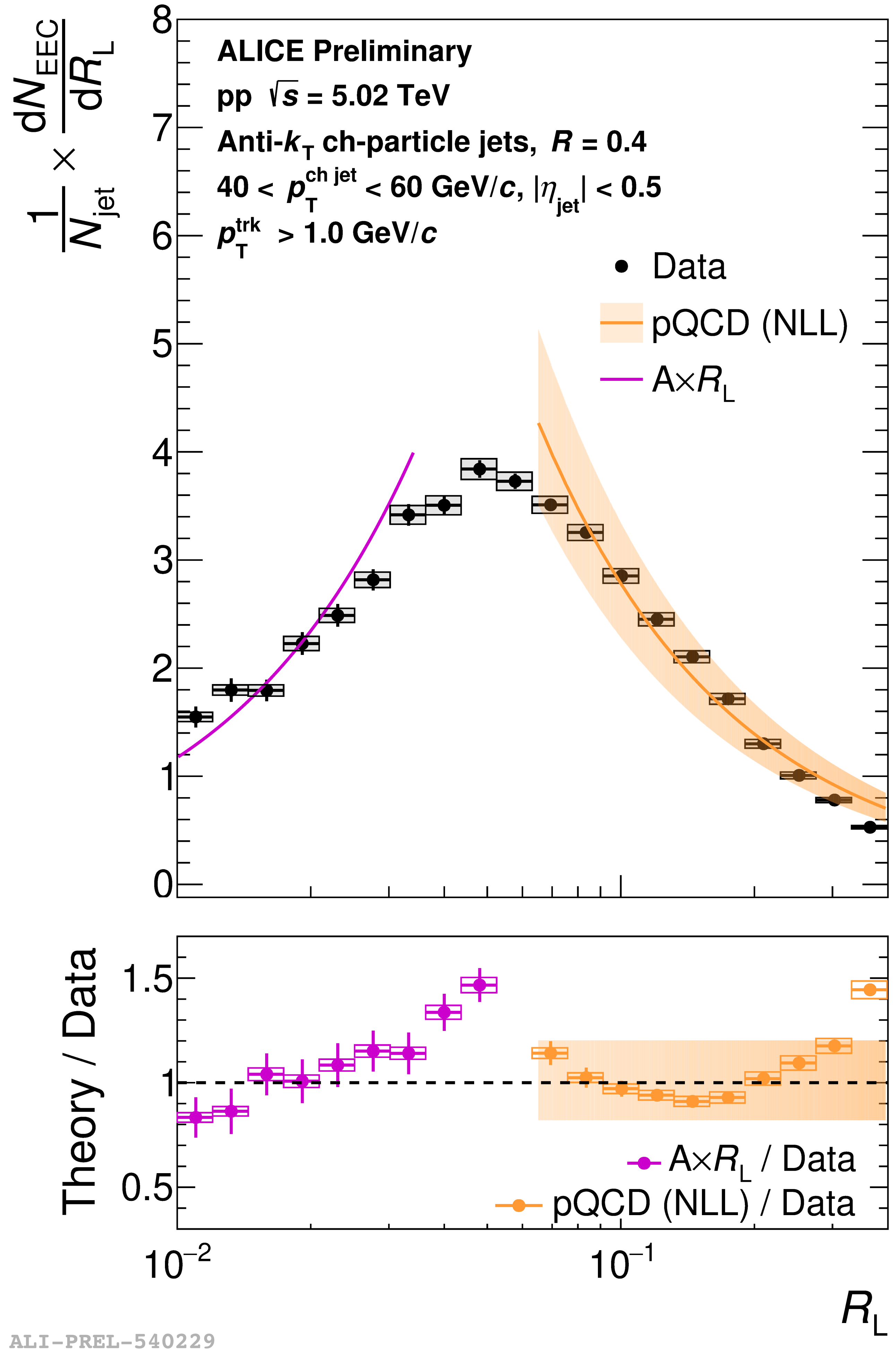
N-point projected energy correlators **2004.11381**

$$\text{PENC}(\chi) \equiv \frac{\mathrm{d}\sigma^{[N]}}{\mathrm{d}\chi} = \sum_M \int \mathrm{d}\sigma_X \Bigg[\sum_{1\le b_1 \le M} \mathscr{W}_1^{[N]}(b_1)\,\delta(\chi) + \sum_{1\le b_1 < b_2 \le M} \mathscr{W}_2^{[N]}(b_1, b_2)\delta(\chi - \Delta R_{b_1,b_2}) + \ldots$$

$$+ \sum_{1\le b_1 <..< b_M = N} \mathscr{W}_M^{[N]}(b_1, .., b_M)\,\delta(\chi - \max\{\Delta R_{b_1,b_2}, .., \Delta R_{b_{M-1,M}}\})\Bigg]$$

ν-correlators (PEνC) are defined by analytic continuation of PENC with $N \to \nu$

Energy correlators



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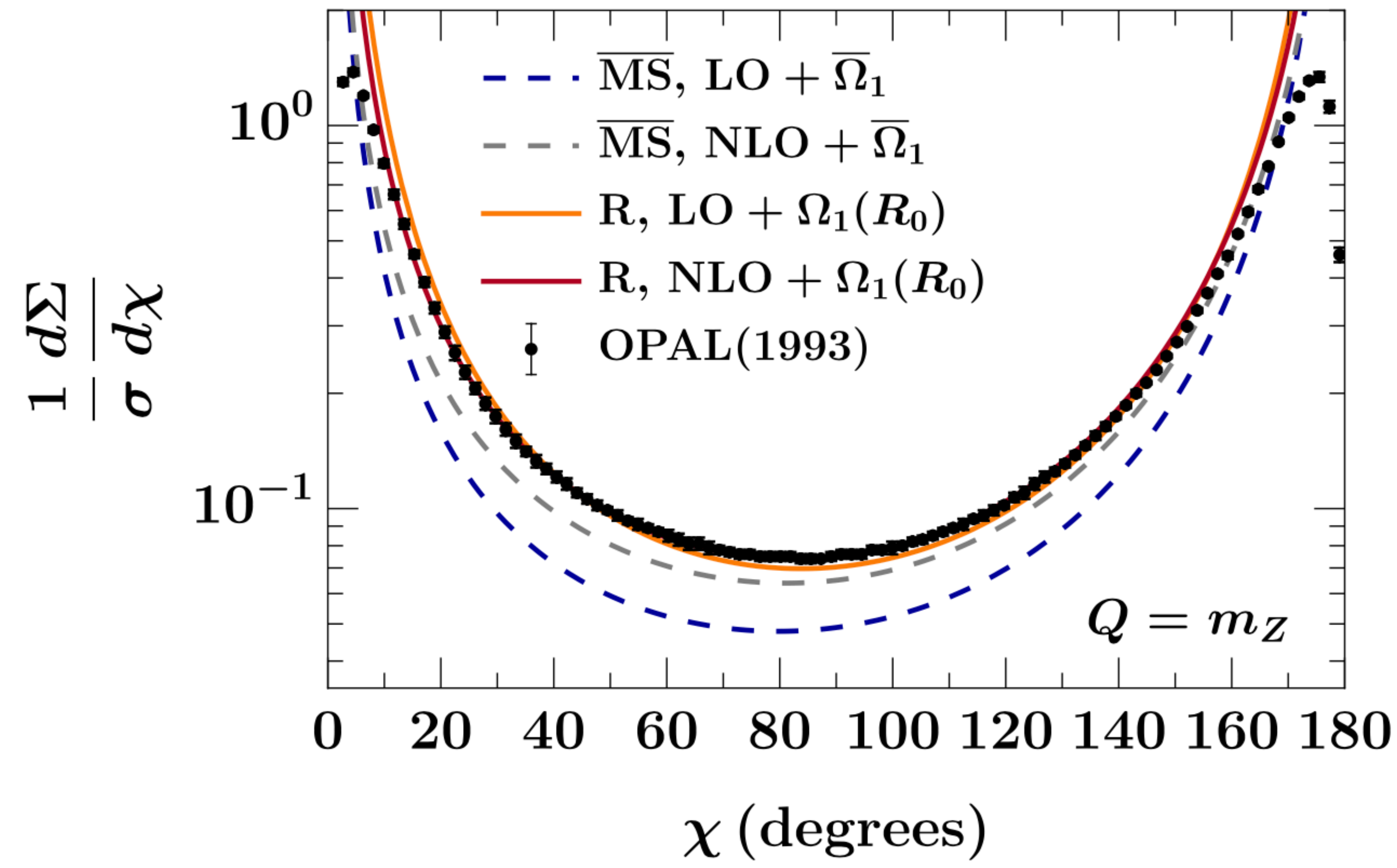
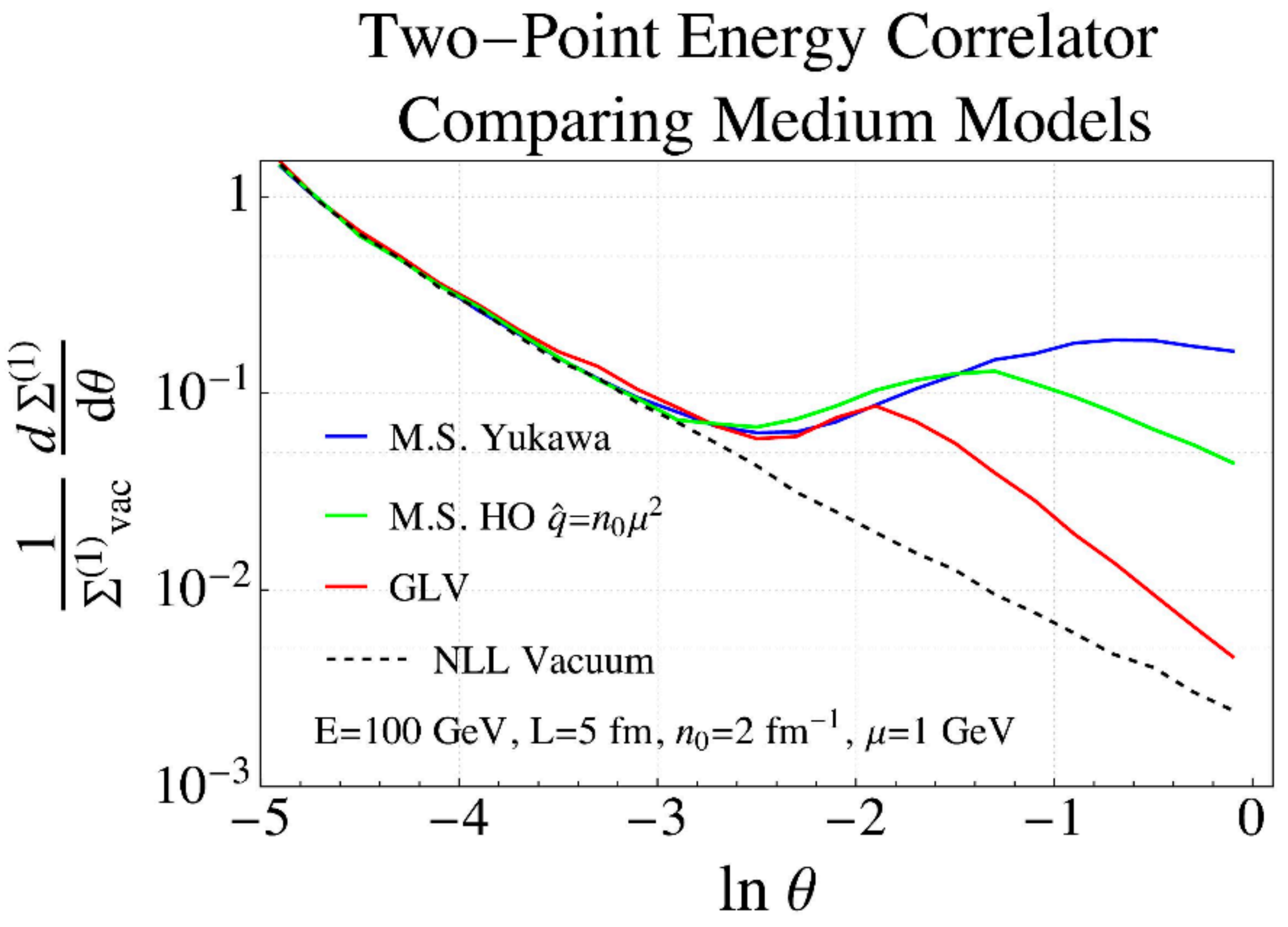
Two distinct scaling behaviours

Impressive agreement with data with leading non-perturbative effects

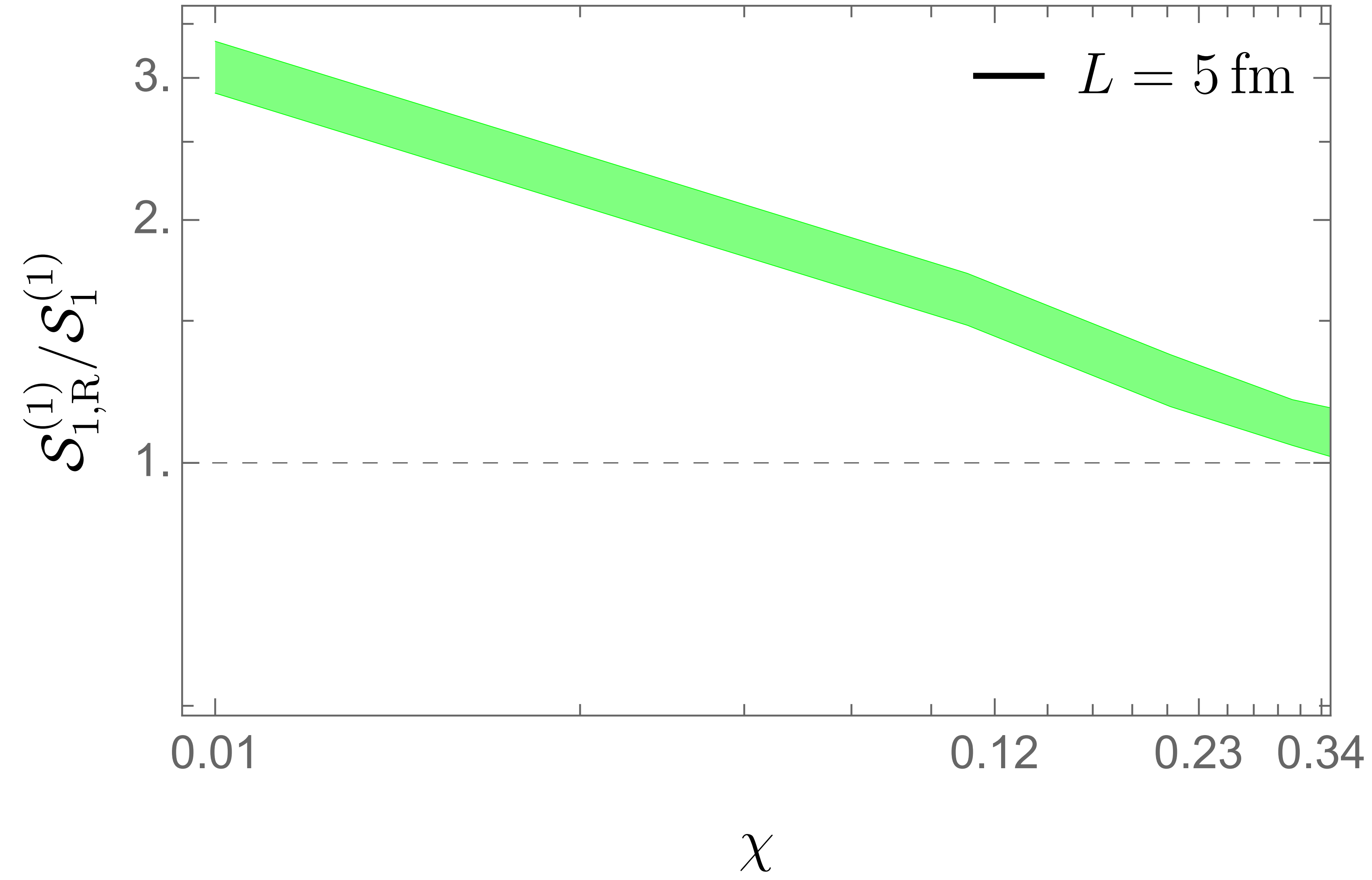


Schindler, Stewart, Sun '23

Energy correlator in HIC



2312.12527



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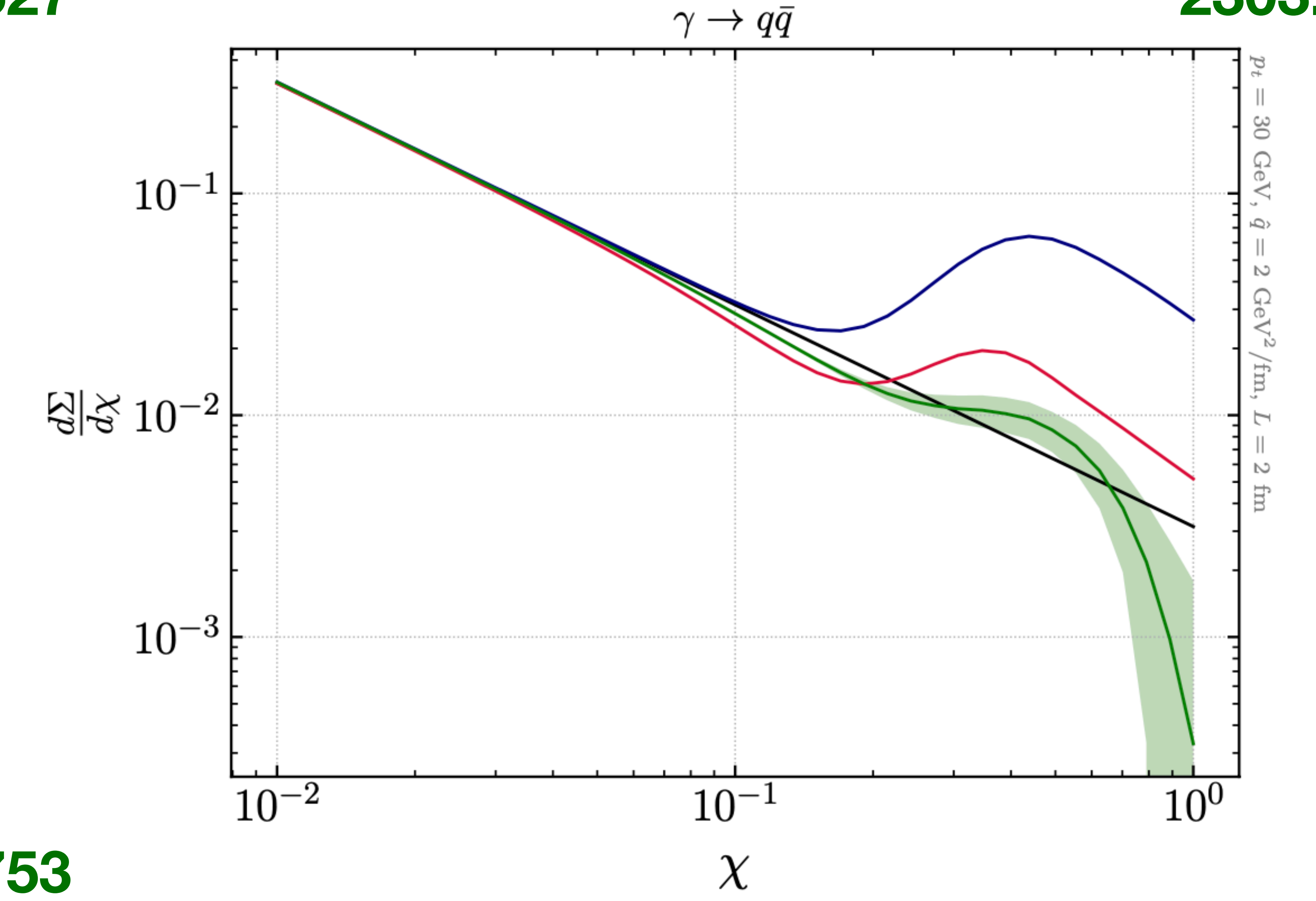


2303.03413

Selection bias 2409.07514

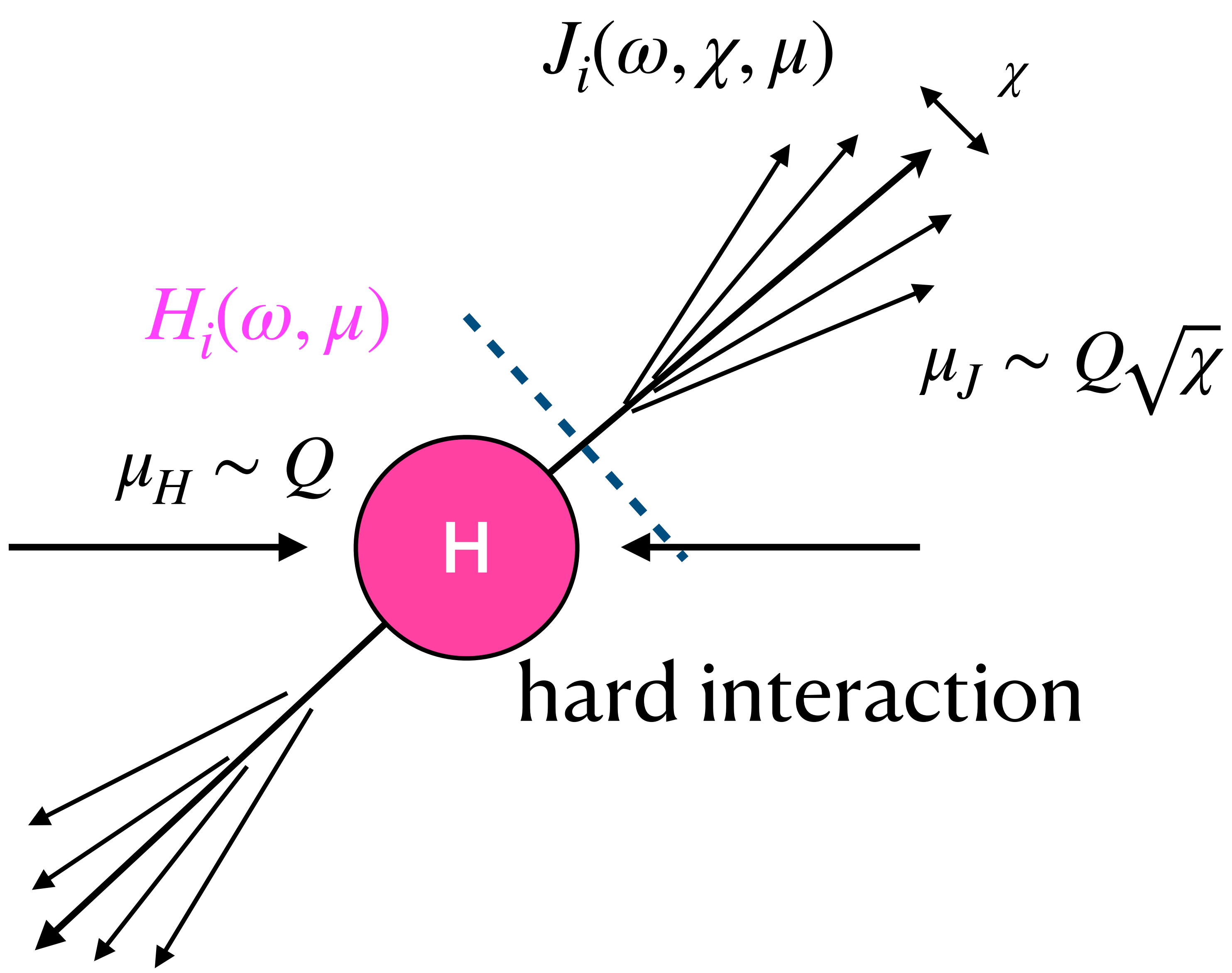
Medium response (wakes) 2407.13818

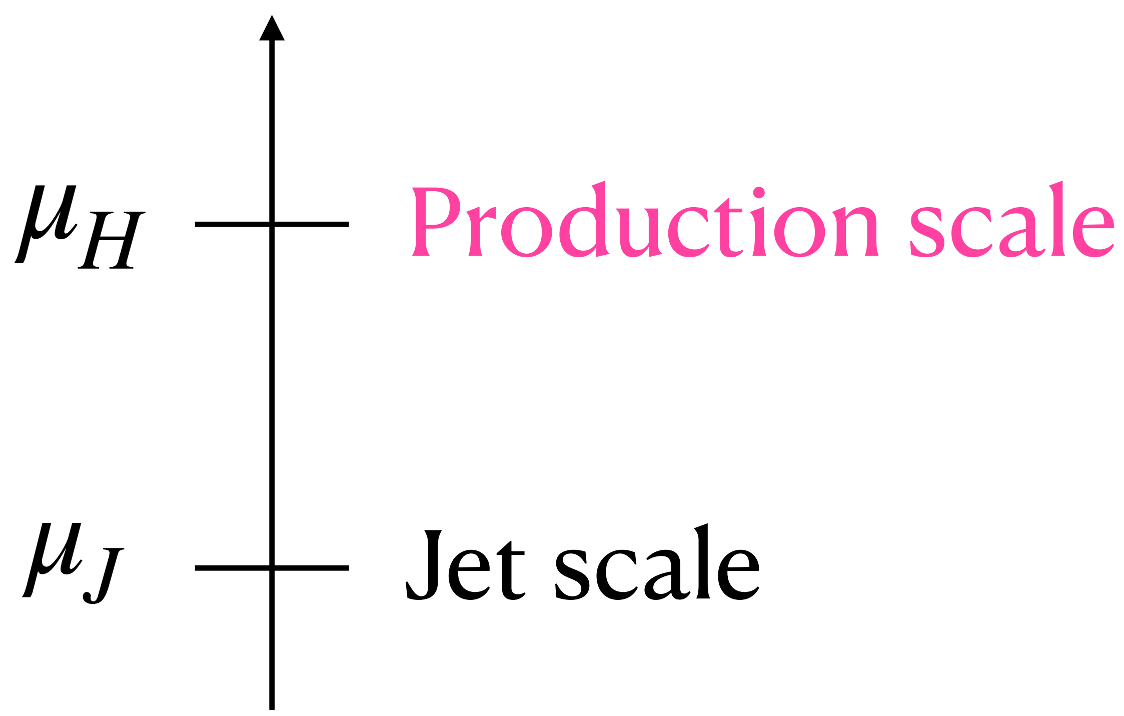
Heavy flavour jets 2307.15110

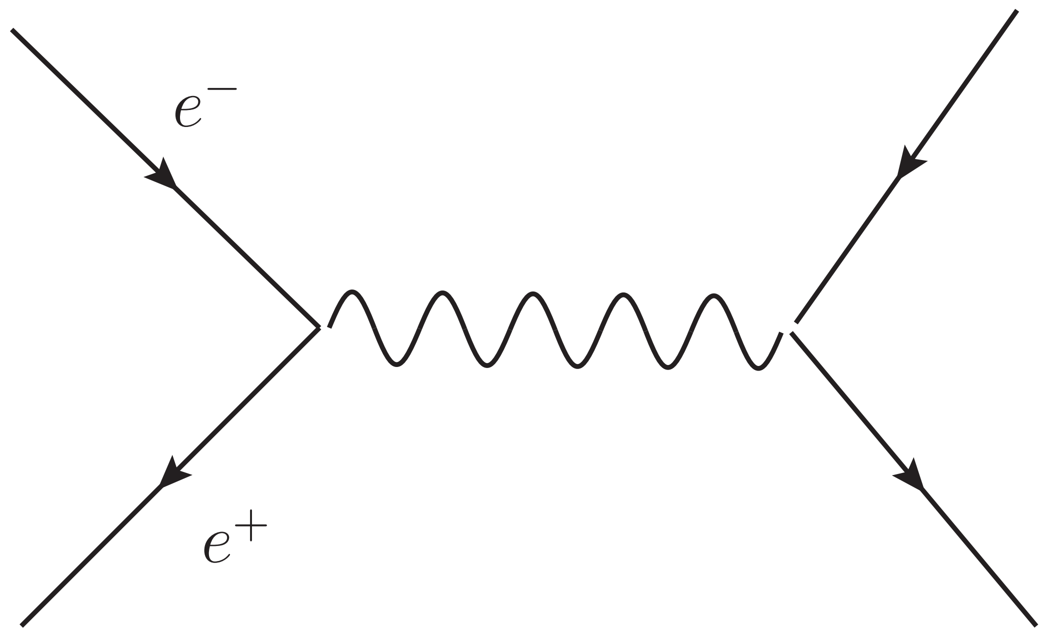
Projected higher point 2503.13603

Projected ν-correlators 2503.20019

Jet in vacuum







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

hard function Jet function

Hard function describes the production of jet initiating parton

Jet function describes subsequent evolution

$$J_q^{[\nu]}(\omega, \chi, \mu) = \frac{1}{2N_c} \sum_{X_n} \mathrm{Tr}\left[\frac{\bar{n}}{2} \langle 0 | \chi_n(0) \mathscr{M}^{[\nu]} | X_n \rangle \langle X_n | \bar{\chi}_n(0) | 0 \rangle \right]$$

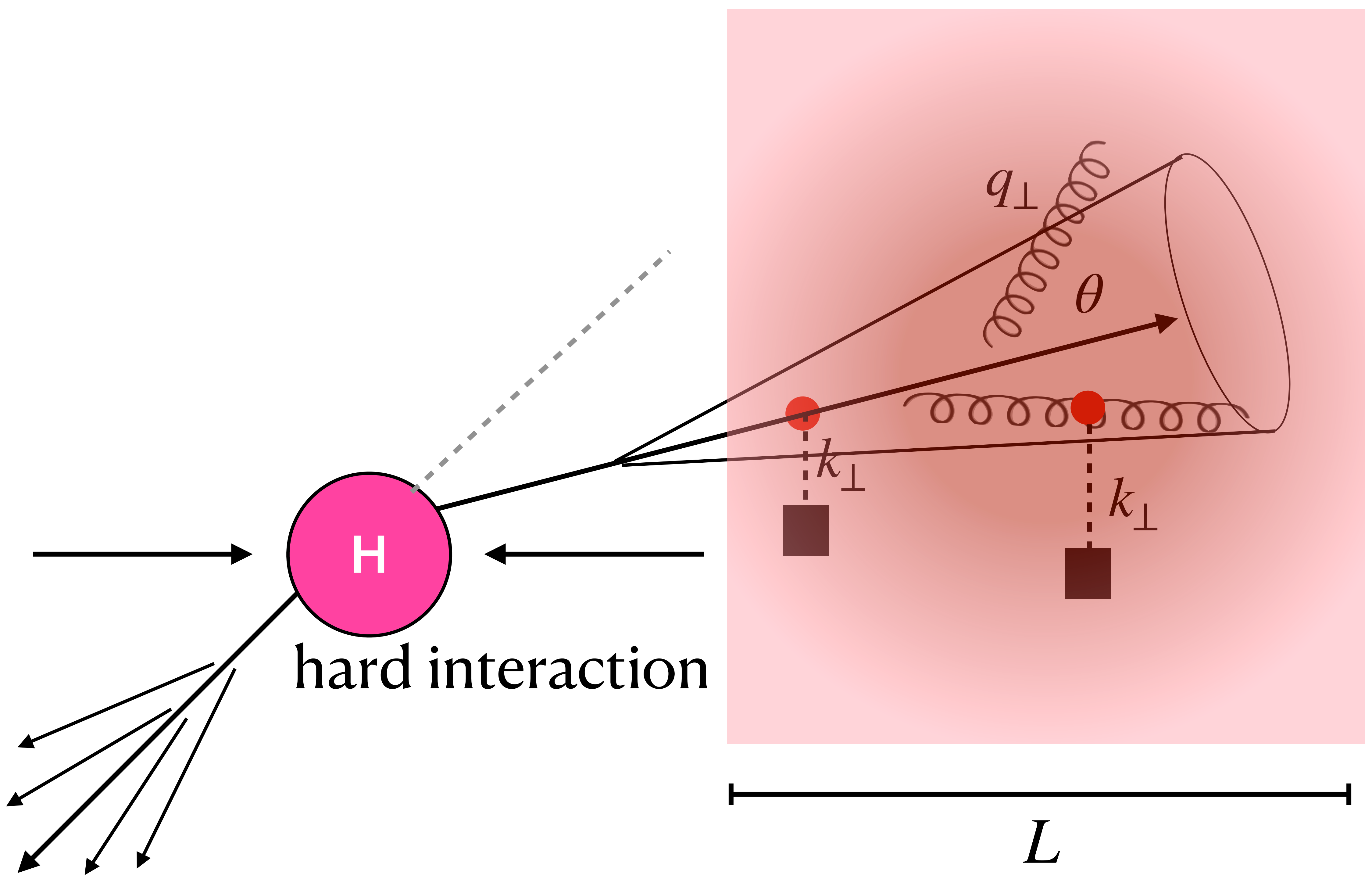
$\chi_n \rightarrow$ collinear quark operator

2004.11381

Jet evolution in a medium

Encounters multiple emergent and direct scales $T \sim m_D,\ L,\ \tau_f,\ \hat{q},\ \theta_c, \ldots$

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



$T \sim m_D$ → medium temperature

$\hat{q}$ → jet quenching parameter

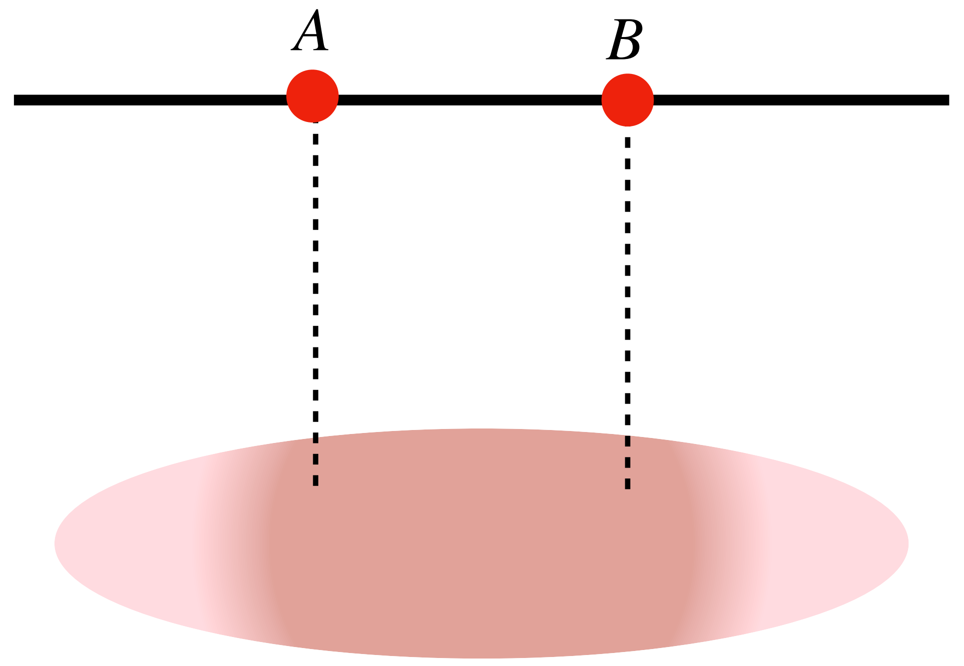
$\tau_f \sim \dfrac{q_\perp^2}{\omega}$ → formation time

ℓ_{mfp} → mean free path of jet

$\theta_c \sim \dfrac{1}{\sqrt{\hat{q}L^3}}$ → coherence angle

Dynamic scales

Interactions with the medium parton trigger medium-induced emissions

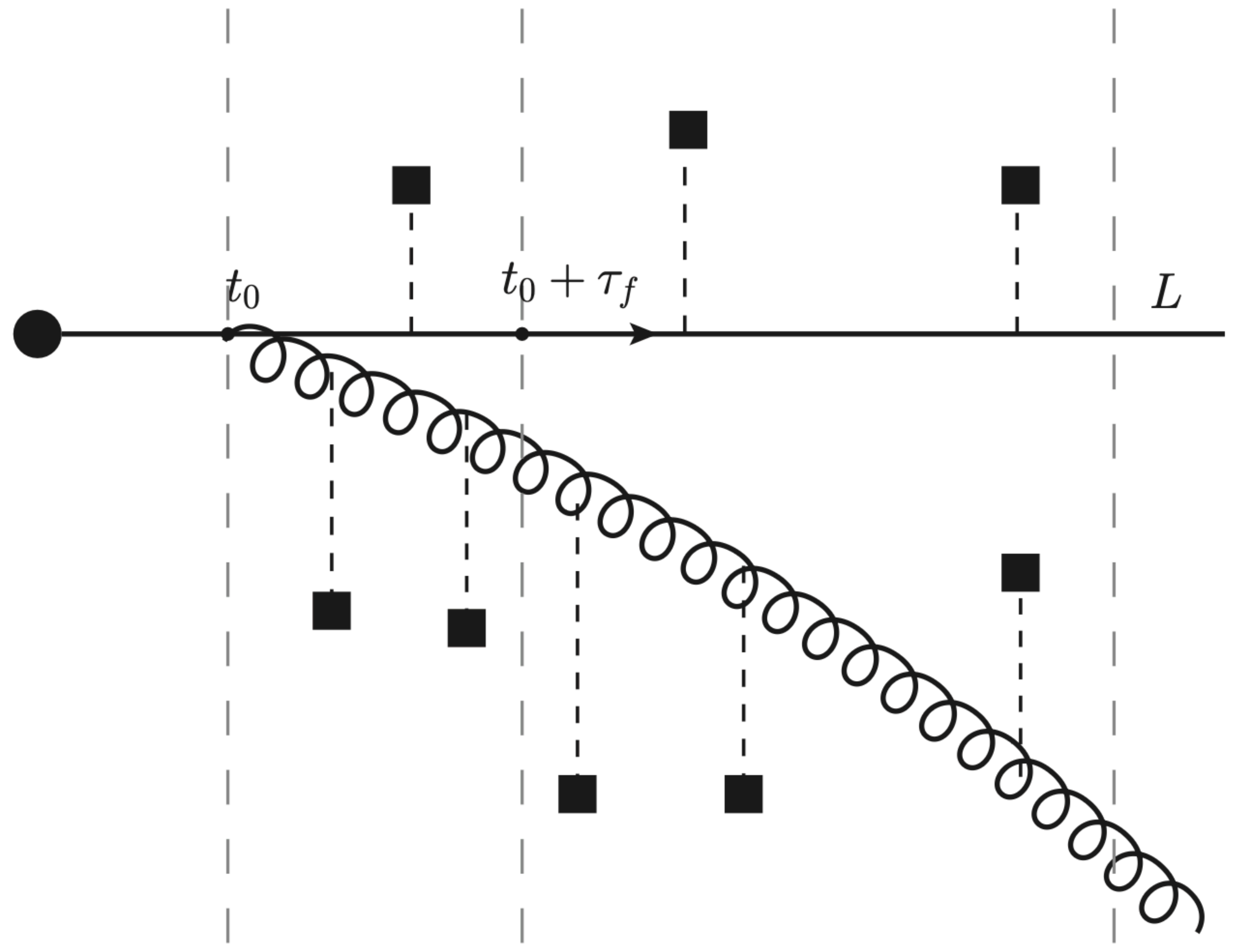


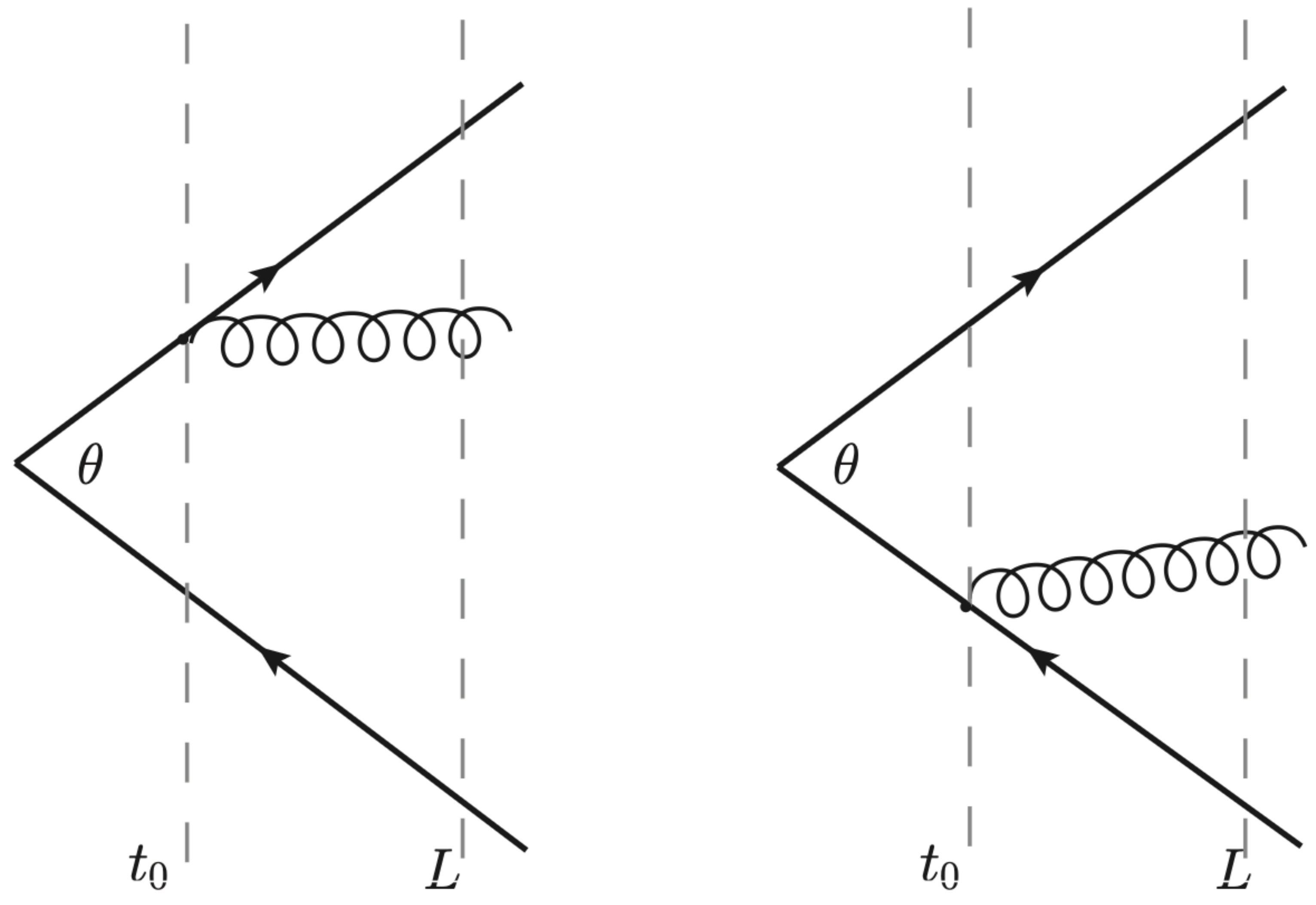
$\sim e^{i(p_A^+ - p_B^+)x}$

In medium parton shower

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

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





I will restrict to single scattering and NLO hence the relevant scales are τ_f and L

Jet-medium interaction involves both jet and medium dynamics and requires a systematic approach to incorporate them

EFT modes

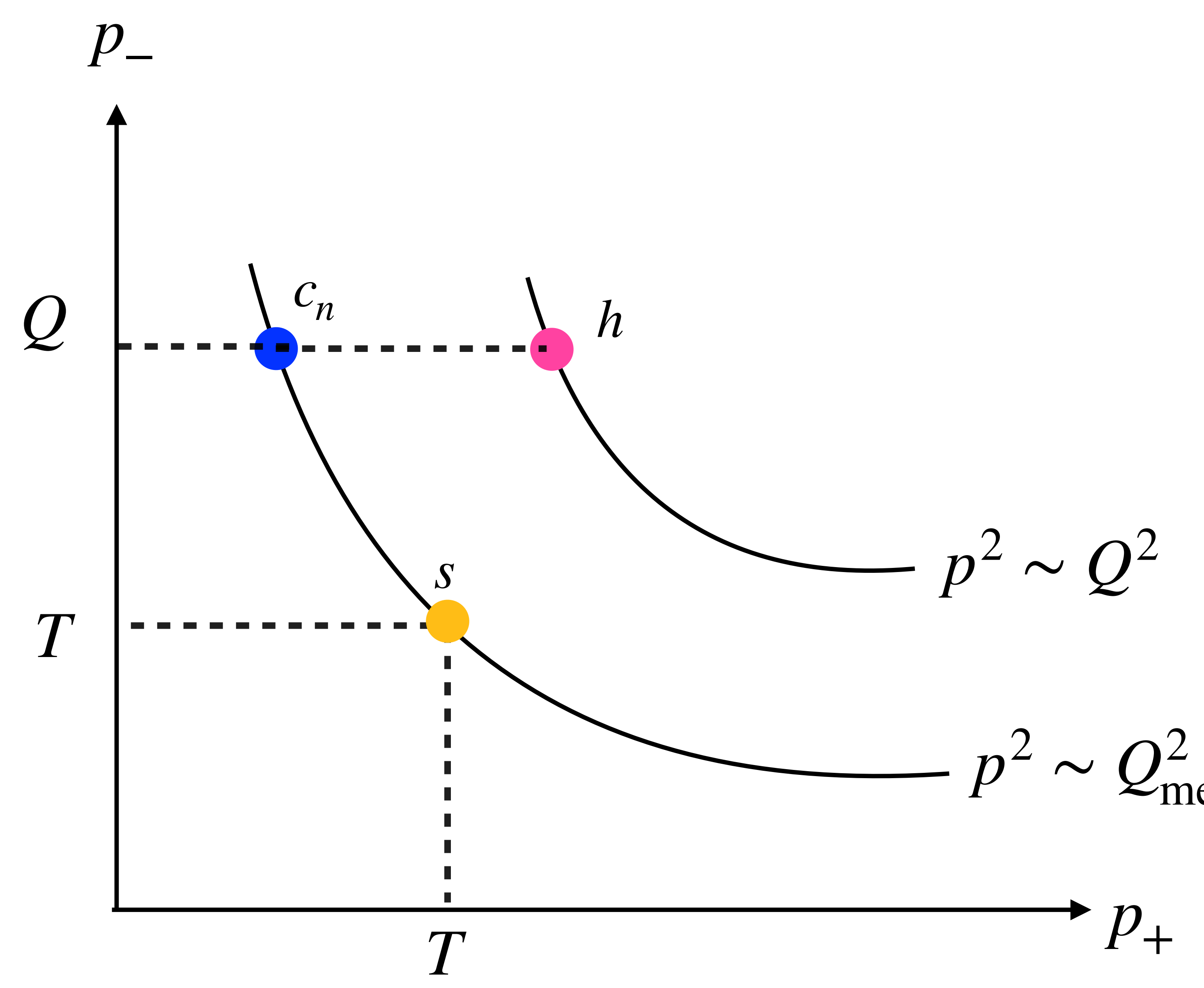
In the EFT set-up we separate jet and medium dynamics in terms of momentum scaling of particles

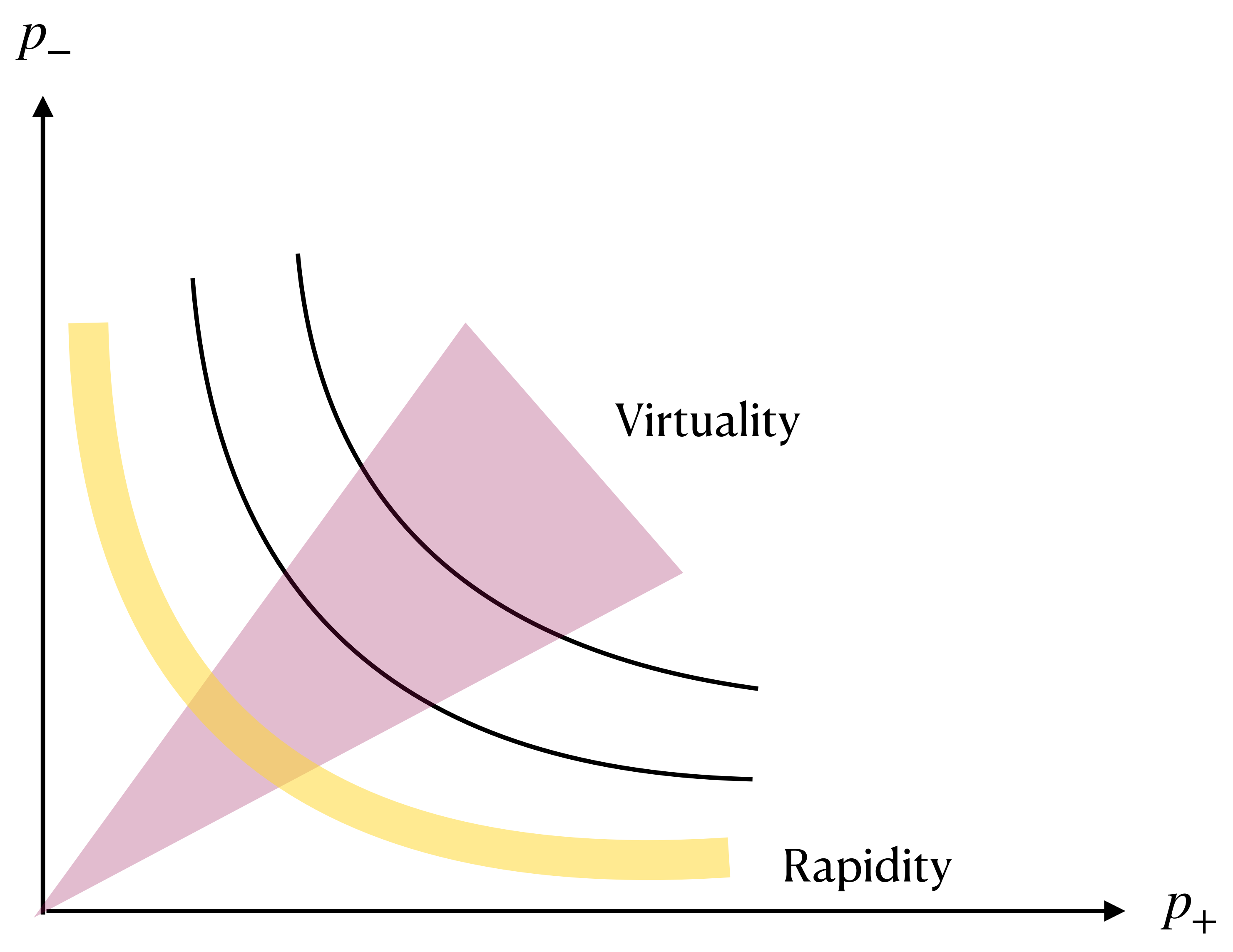
Medium : soft mode $p_s \sim Q(\lambda, \lambda, \lambda)$ $\quad p^\mu = (p^-, p^+, p_\perp)$

Thermal partons have energy of the order of temperature of the plasma $Q\lambda \sim T \equiv Q_{\text{med}}$

Jet : collinear mode $p_c \sim Q(1, \lambda^2, \lambda)$ $\quad$ Exchange Glauber modes $p_G \sim Q(\lambda, \lambda^2, \lambda)$

Off-shell mode scale such that the interaction should not change the off-shellness of collinear or soft modes





$$\mathcal{L}_{\text{SCET}} = \mathcal{L}_c^{(0)} + \mathcal{L}_s^{(0)} + \mathcal{L}_G^{(0)}$$

$$\mathcal{L}_G^{ns} = C_G(\mu) \sum_{i \in \{q,g\}} \mathcal{O}_{ns}^{ij}$$

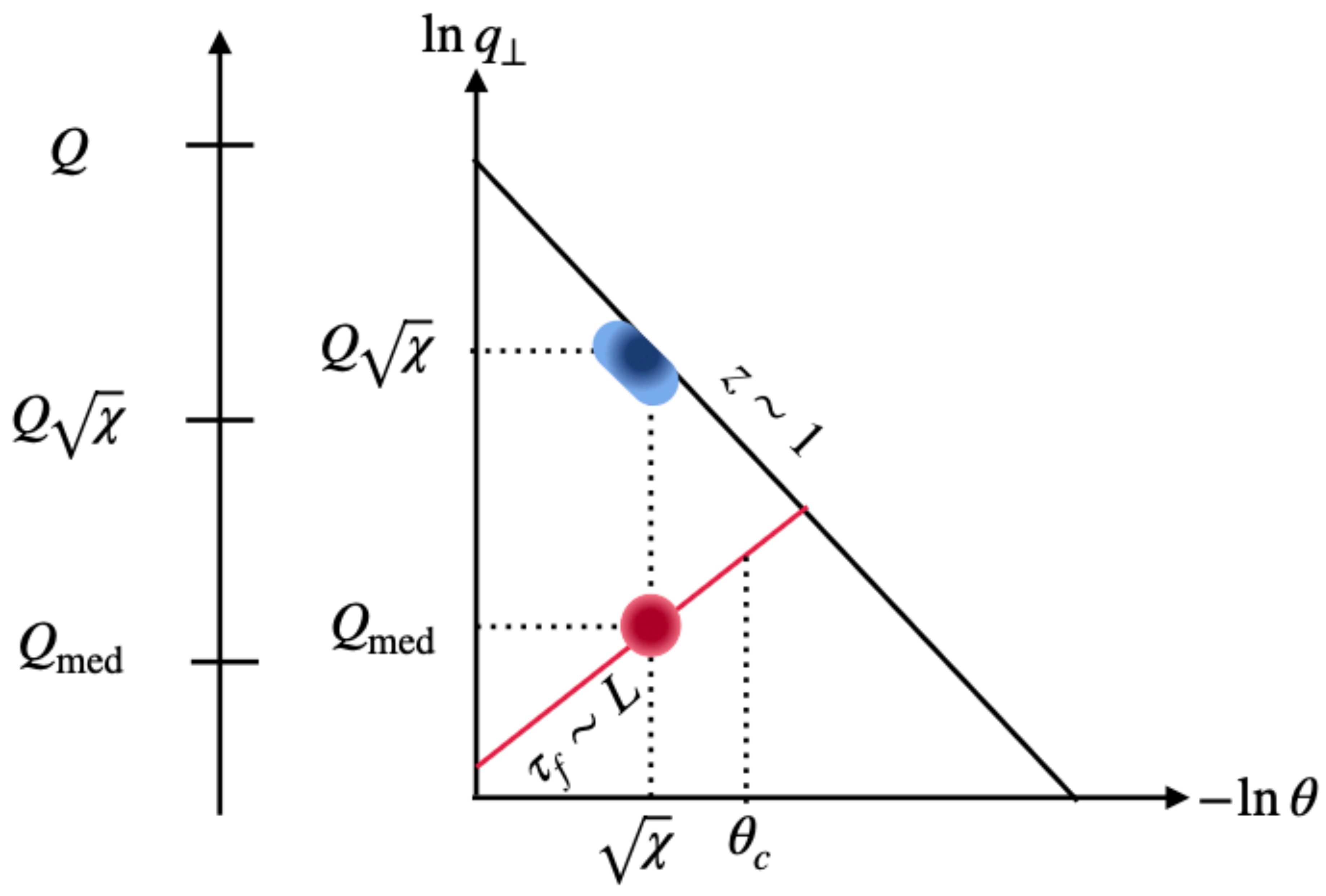
$$\mathcal{O}_{ns}^{ij} = \mathcal{O}_n^{ib} \frac{1}{P_\perp^2} \mathcal{O}_s^{jb}$$

Mode with virtuality $\gg Q_{\text{med}}$ can be factored out $\quad$ See Varun's talk

Lund plane representation

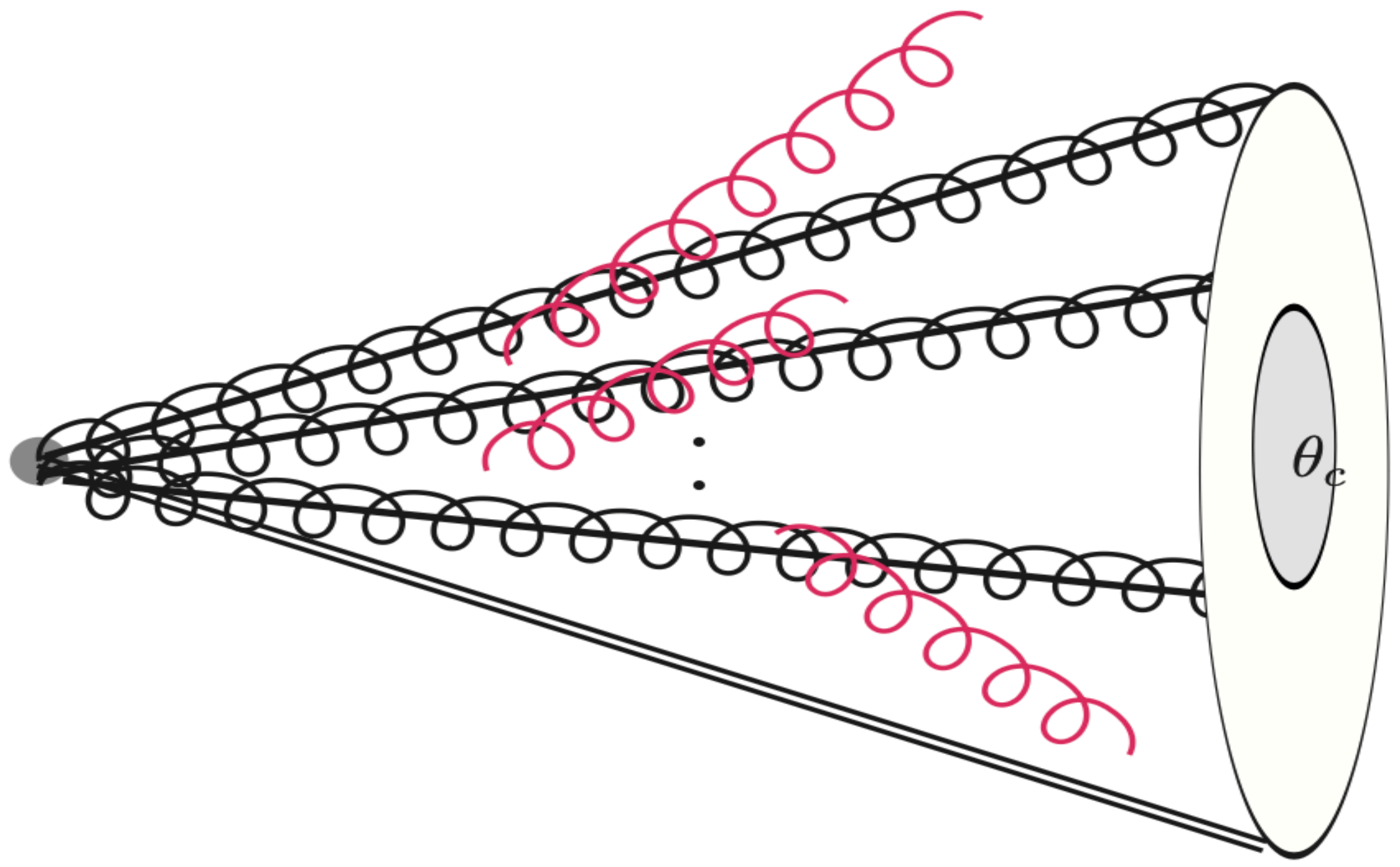
Intercepts of lines give relevant mode and its scaling

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 $\tau_f \gg L$



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Jet as an open quantum system

Step1: Factorized total initial density matrix

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

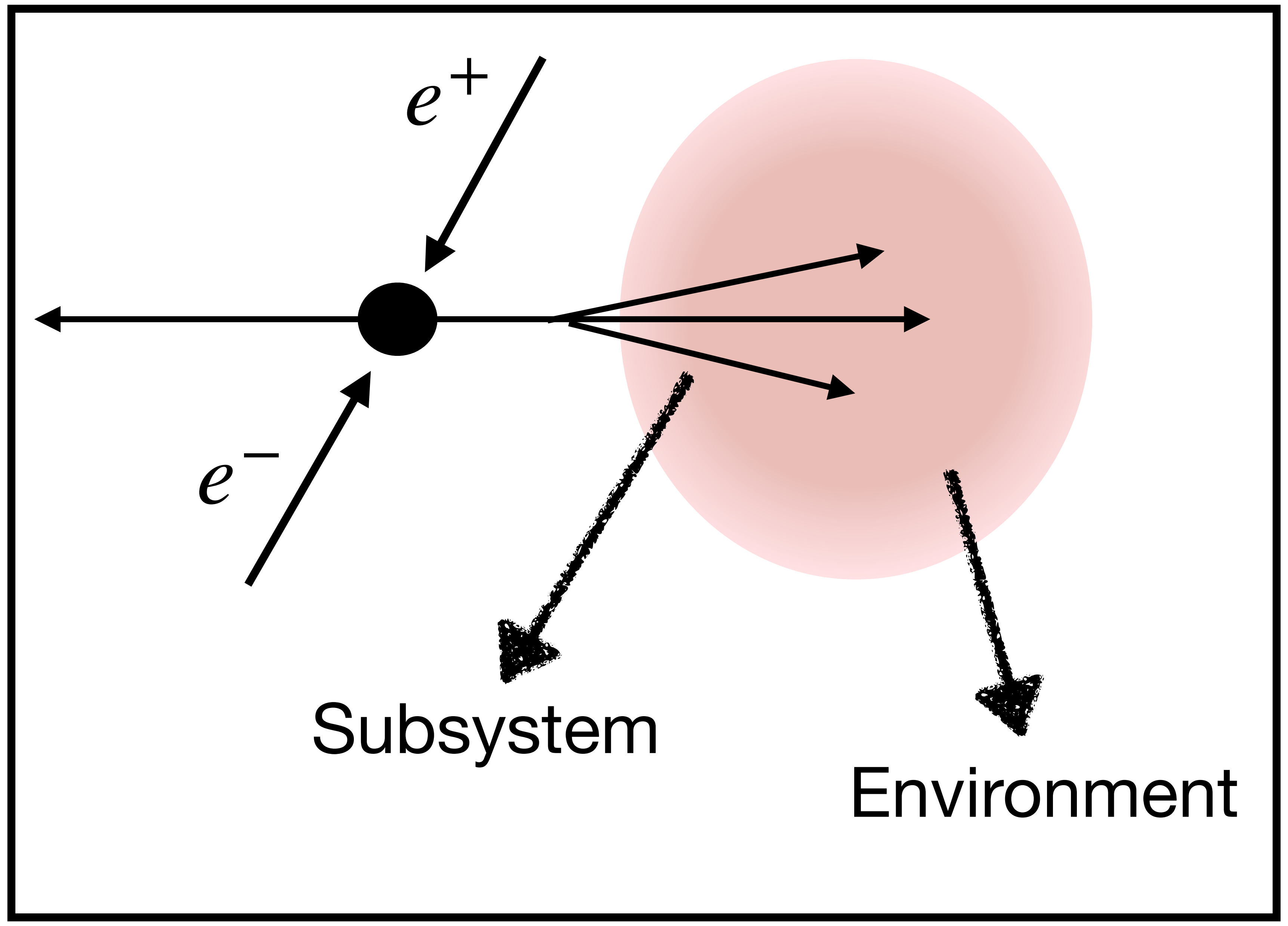
Step2: Time evolution of the jet through total density matrix

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

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

Hard interaction

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



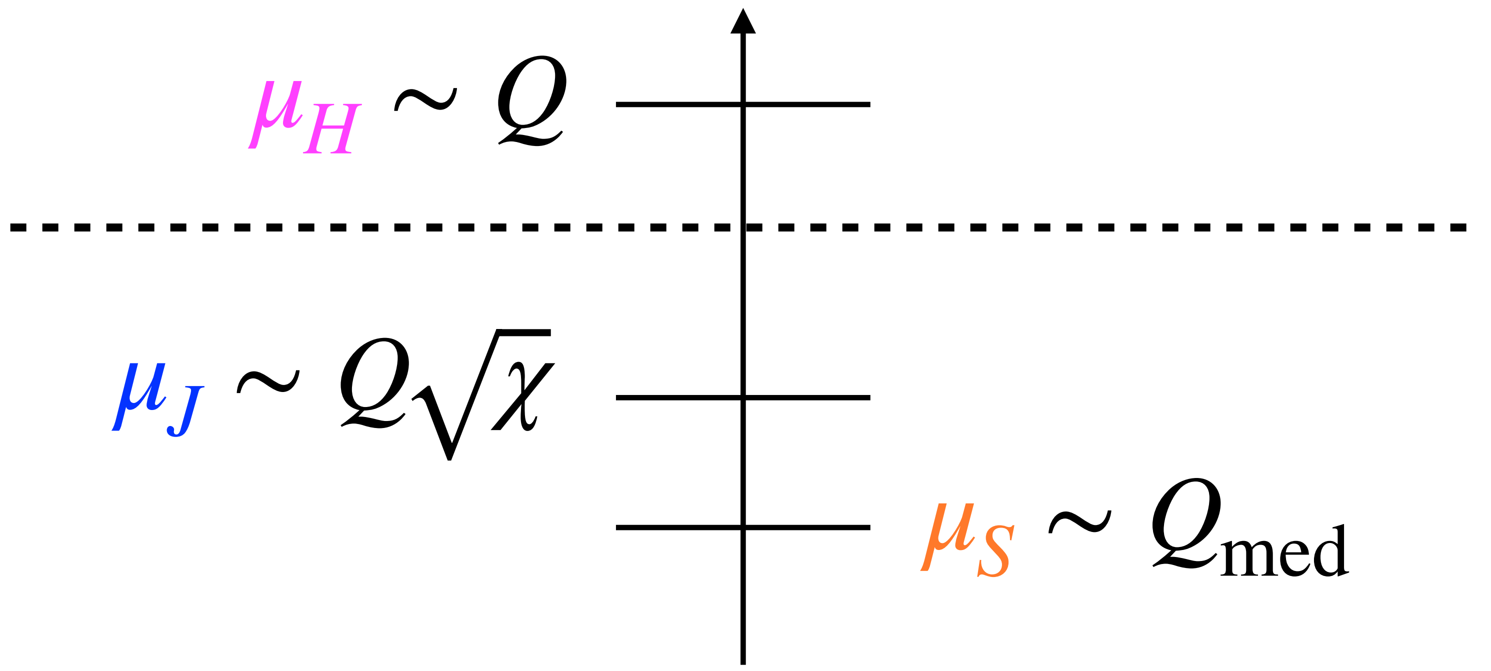
Step3: Solve it!

Hard operator creates hard scattering event that produces the jet

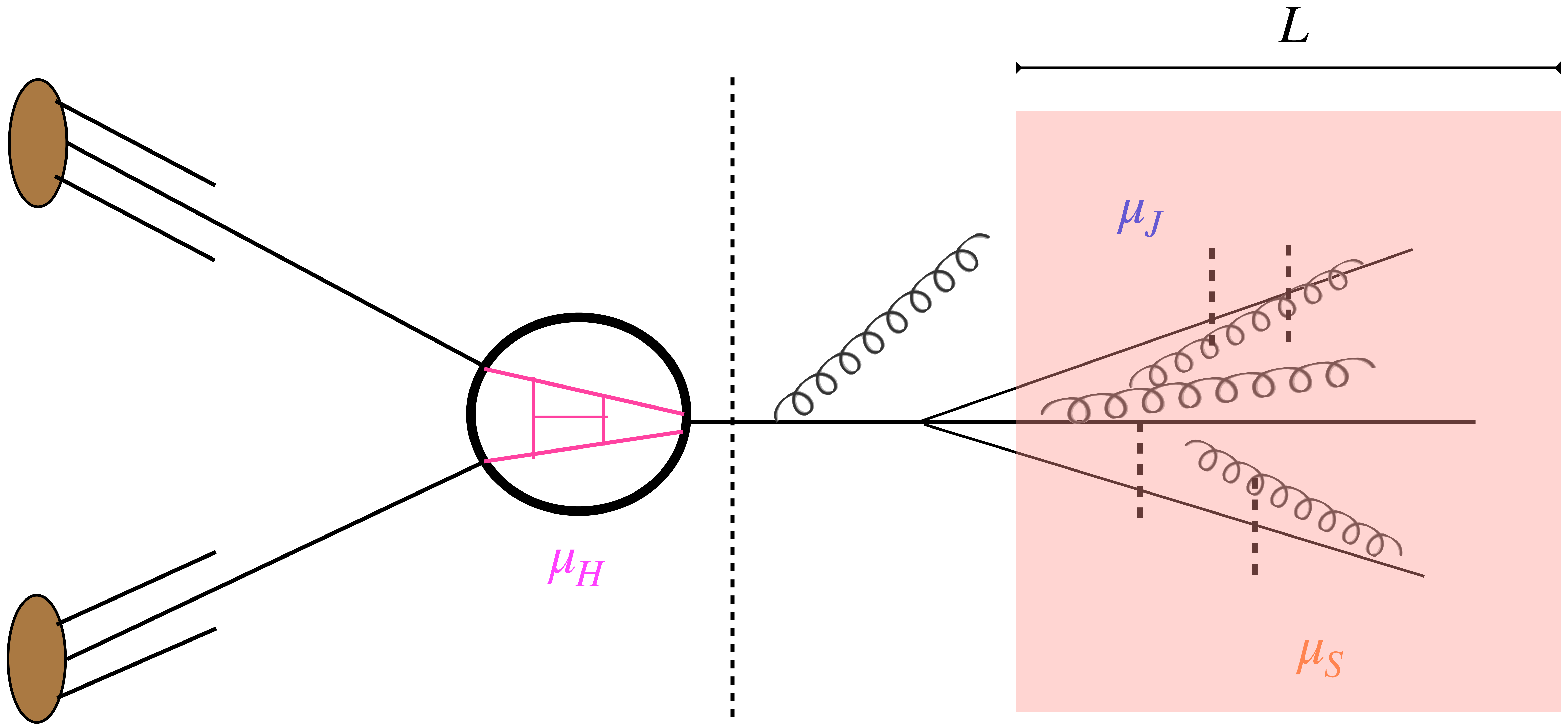
$$\frac{d\sigma^{[\nu]}}{d\chi} = \lim_{t\to\infty} \mathrm{Tr}[\rho(t)\mathcal{M}] = |C(Q)|^2 L_{\alpha\beta} \lim_{t\to\infty} \int d^4x d^4y e^{iq\cdot(x-y)} \mathrm{Tr}[e^{-iH_st} j^\alpha(x)\rho(0)\mathcal{M}^\nu j^\beta(y) e^{iH_st}]$$

Factorization for energy correlators

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



$J(\omega, \chi, \mu)$ contains both vacuum and medium jet dynamics



Initial state effects can be incorporated through nuclear parton distribution functions or parton distribution function in pp collision

Factorization for energy correlators

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

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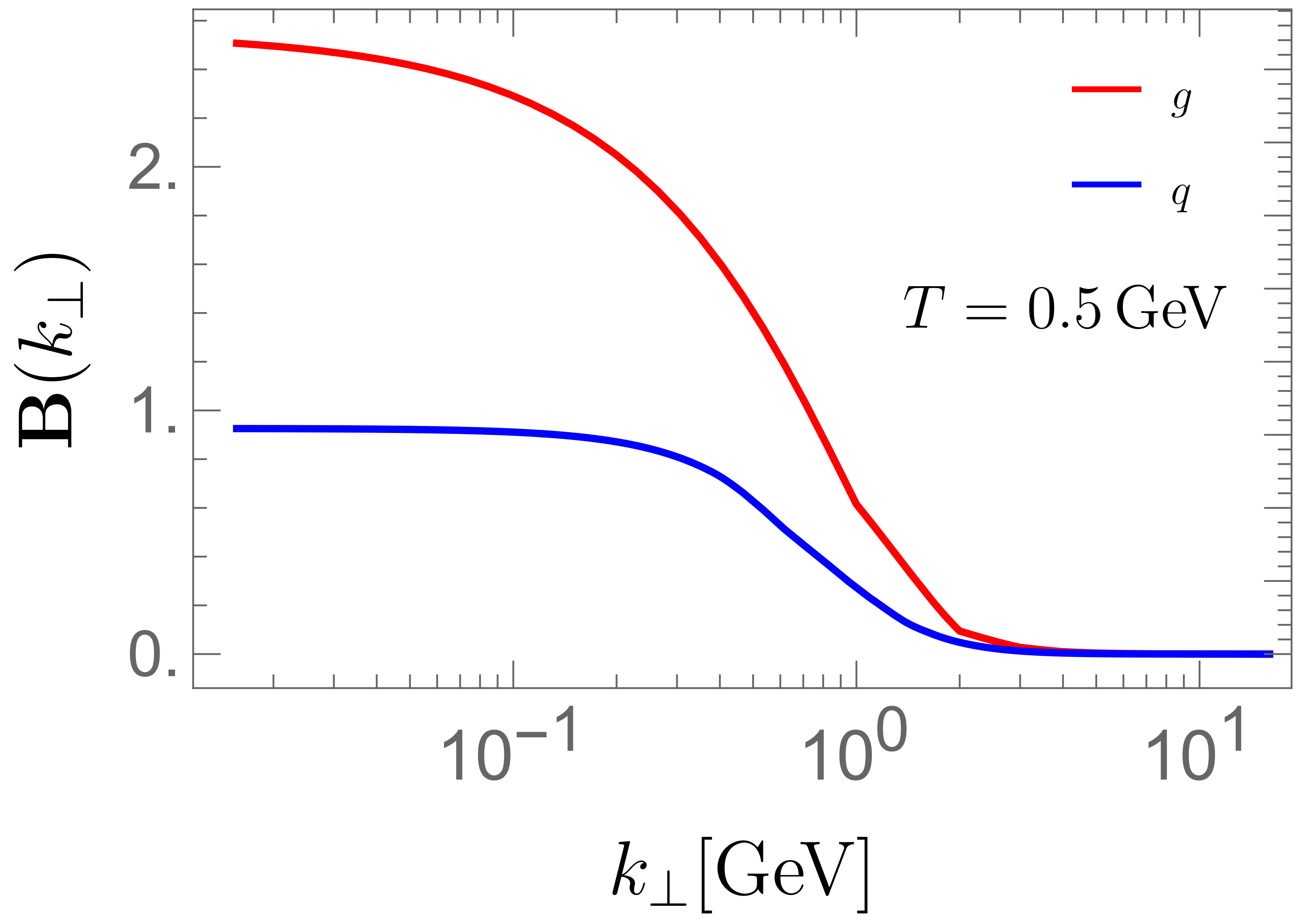
With order by order expansion in Glauber Hamiltonian we can separate vacuum emissions from medium induced jet dynamics

$$J_q^{[\nu]}(\omega,\chi) = \underbrace{J_{q0}^{[\nu]}(\omega,\chi)}_{\text{vacuum}} + \underbrace{J_{q2}^{[\nu]}(\omega,\chi;L) + \dots}_{\text{medium induced}}$$

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

Allows for dynamic treatment of the medium



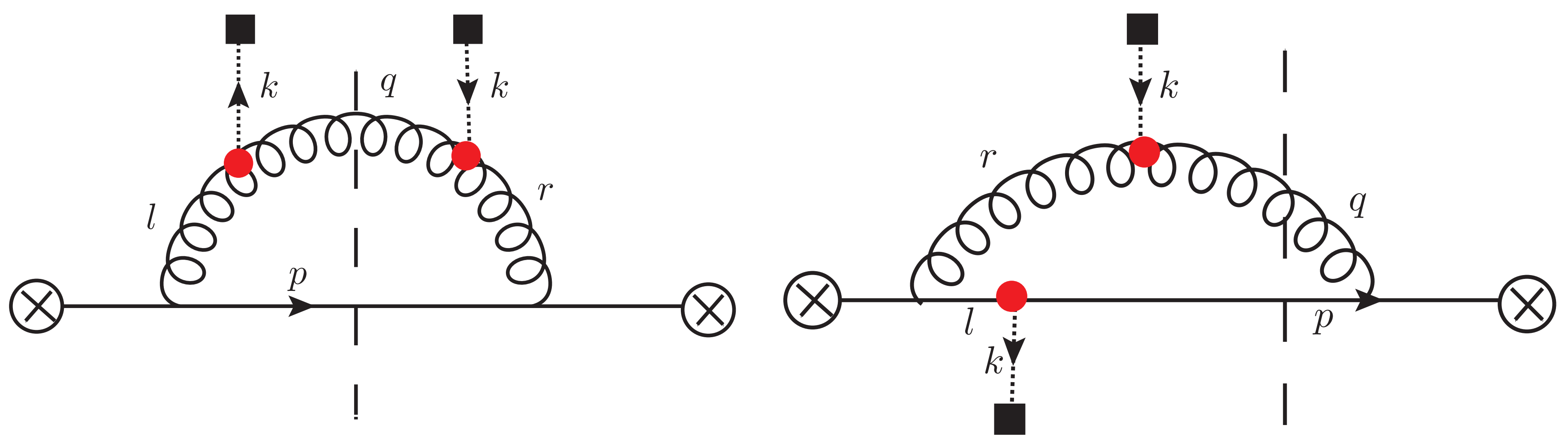
$$\mathbf{B}(k) = \int d^4r\, e^{ik\cdot r}\langle\rho_E O_E^a(r)O_E^a(0)\rangle$$

Medium induced jet function

$$\mathbf{S}^{[\nu]}_{q2}(\chi,\omega,k_\perp) = \underbrace{\mathbf{S}^{[\nu]}_{qR}(\chi,\omega,k_\perp)}_{\text{real emission}}\ \mathscr{M}^{[\nu]} + \underbrace{\left[\mathbf{S}^{[\nu]}_{qR}(\chi,\omega,k_\perp) - \overbrace{\mathbf{S}^{[\nu]}_{qV}(\chi,\omega,k_\perp)}^{\text{virtual}}\right]\delta(\chi)}_{=0}$$

$$\boxed{\mathscr{M}^{[\nu]} = (z^\nu - \nu z)\,[\delta(\chi) - \delta(\chi-\theta^2)]}$$

$$\mathbf{S}^{[\nu]}_{qR}(\chi,\omega,k_\perp) = \mathbf{S}^{[\nu]}_{qRR}(\chi,\omega,k_\perp) - \mathbf{S}^{[\nu]}_{qVR}(\chi,\omega,k_\perp)$$

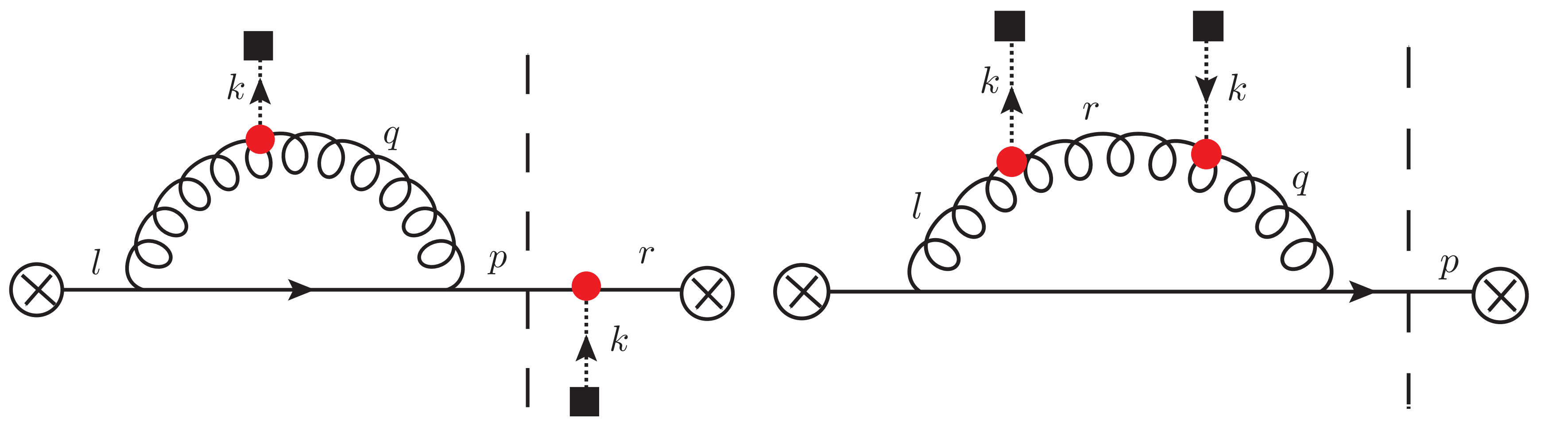


Real diagrams contribute to both contact term and finite χ terms

Virtual diagrams contribute to contact term only

Real and virtual contributions cancel against each other

$$\mathbf{S}^{[\nu]}_{qV}(\chi,\omega,k_\perp) = \mathbf{S}^{[\nu]}_{qRV}(\chi,\omega,k_\perp) - \mathbf{S}^{[\nu]}_{qVV}(\chi,\omega,k_\perp)$$



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

In-medium jet function: A case study

For the case $\tau_f \ll L$

$$J^{[\nu]}(\chi) \approx -\frac{\bar{\alpha} g^4 T^3 (5+4\nu)}{(\nu+2)\pi^4}\frac{L}{\chi^2\omega^2} + \frac{\bar{\alpha} g^4 T^3 \nu L}{\pi^4 \omega\, m_D \chi^{3/2}} + \mathcal{O}\left(\frac{m_D^2}{\chi\omega^2}\right)$$

For the case $\tau_f \geq L$

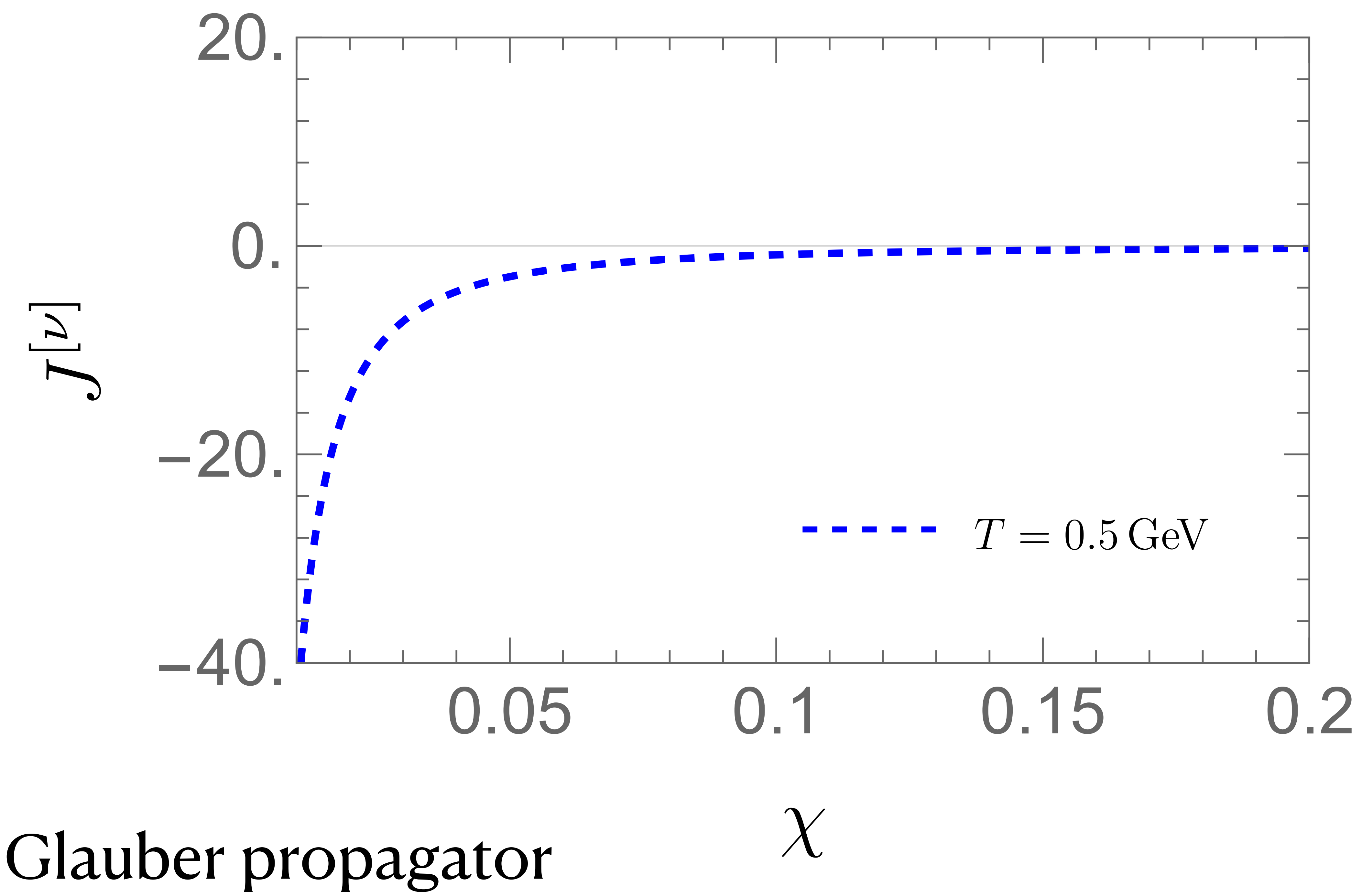
$$J^{[\nu=0]}(\chi) \approx -\frac{\bar{\alpha} g^4 T^3}{\pi^4 m_D^4 L \chi^2}\log(\chi\omega L) + \mathcal{O}(1/\chi L^2 m_D^2)^3$$

Distinct behaviour in two limiting cases

For smaller ν values jet function saturates

Scaling behaviour in vacuum

$$J_0^{[\nu]}(\chi) \propto \frac{1}{\chi} \qquad J_0^{[\nu]}(\chi) \propto \frac{1}{\chi^{1-\gamma(\nu+1)}}$$



Debye screening mass appears through soft loop contributions in Glauber propagator

Leading scaling behaviour is enhanced compared to vacuum jet function

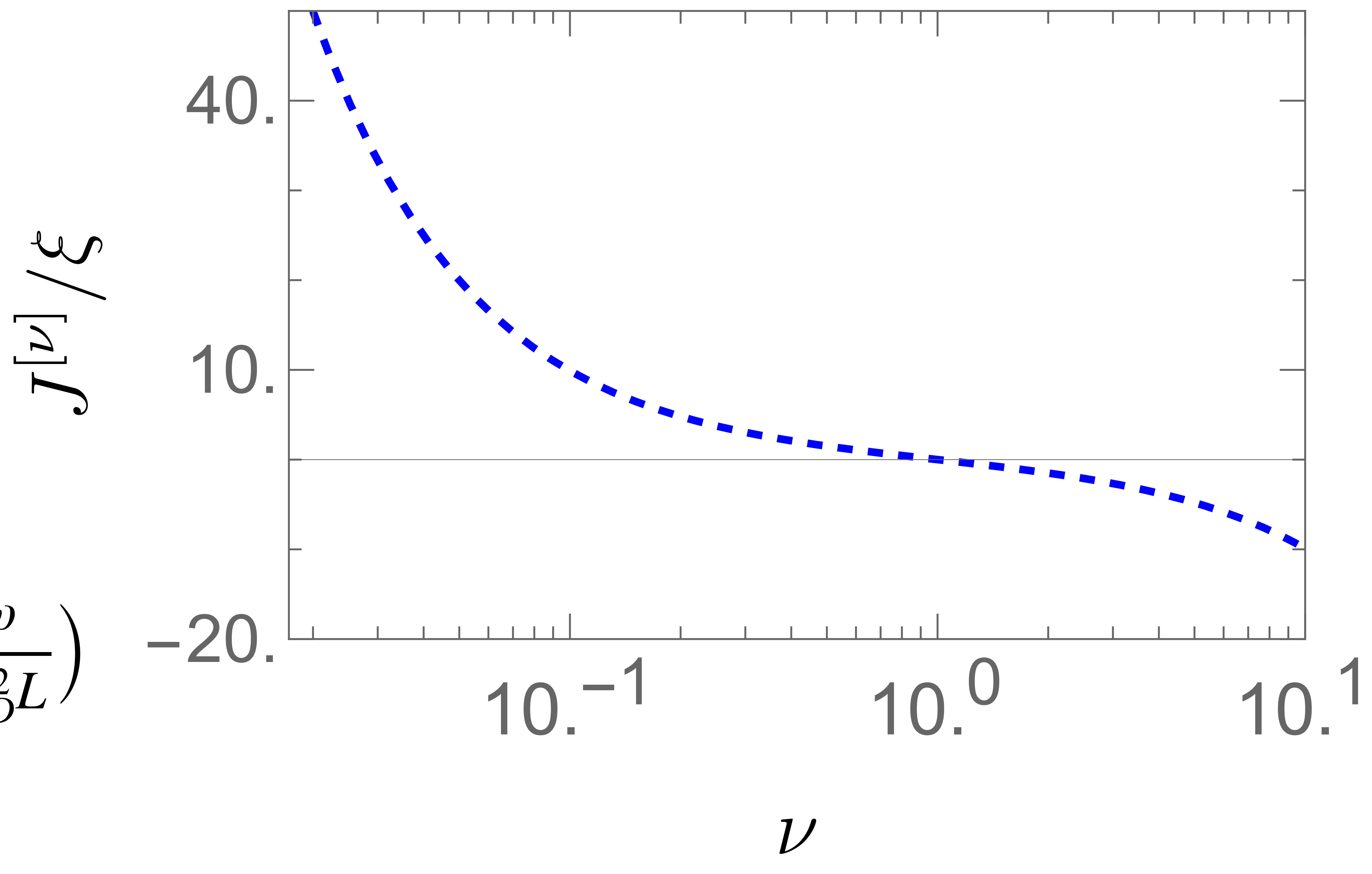
Contact term

For the case $\tau_f \ll L$

$$J^{[\nu]}(\chi = 0) \approx \frac{g^4 T^3 L}{m_D^2}\left[\frac{1}{\nu} - \nu\right]\delta(\chi) = \xi\left[\frac{1}{\nu} - \nu\right]\delta(\chi)$$

For the case $\tau_f \geq L$

$$J^{[\nu=0]}(\chi = 0) \approx -\frac{g^4 T^3 L^2}{\omega}\left[2 + \log\left(\frac{\omega}{m_D^2 L}\right)\right]\delta(\chi) + \mathcal{O}\left(\frac{\omega}{m_D^2 L}\right)$$



Contact terms are enhanced by the length of the medium

Contact term depends only on the medium properties in $\tau_f \ll L$ limit

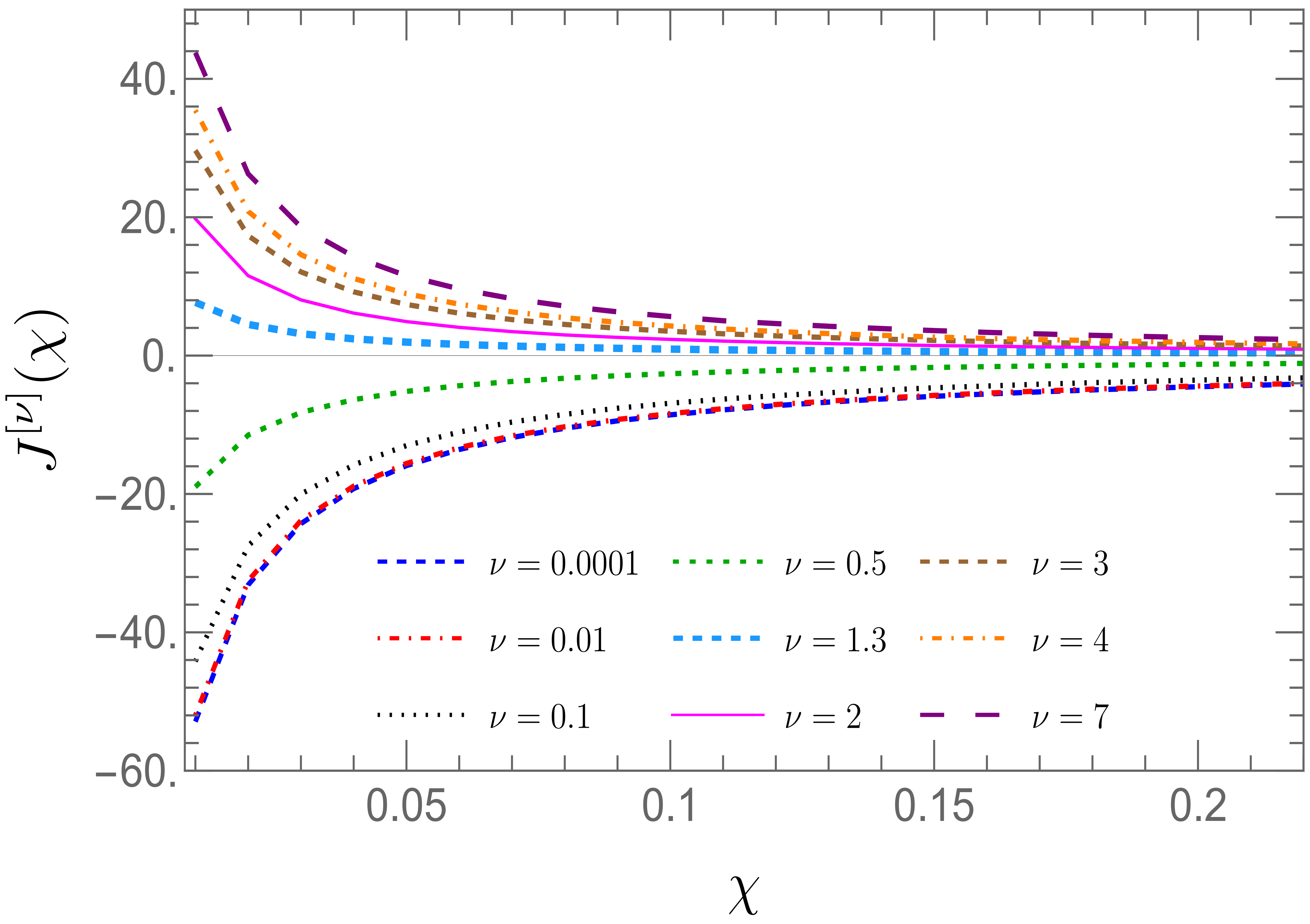
For $\tau_f \geq L$ jet function has strong dependence on the length of the medium

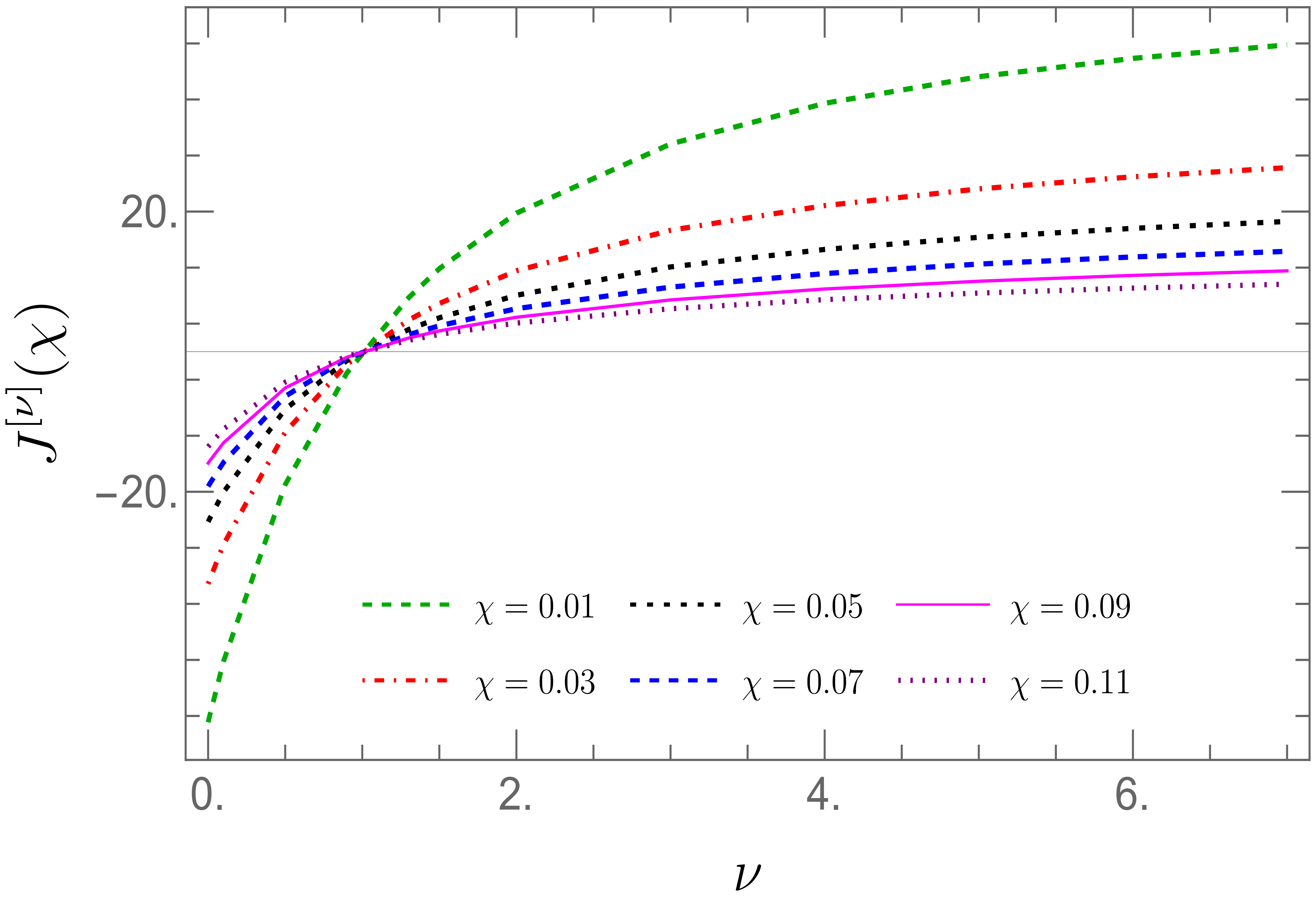
Medium induced jet function

Small ν point energy correlators are more sensitive to large angle radiations

For small ν values correlators saturate at $\nu = 0.01$

$L = 5\,\text{fm}$





ν-correlator ratios

$$\mathbf{S}_R^{[\nu]}(\chi, k_\perp) = \frac{1}{\pi k_\perp}\sqrt{\frac{\pi}{14\zeta(3)\bar{\alpha}Y}}e^{(a_p-1)Y}\int d^2 l_\perp \frac{\mathbf{S}^{[\nu]}(\chi, l_\perp)}{l_\perp}e^{-\frac{\log^2(k_\perp/l_\perp)}{14\zeta(3)\bar{\alpha}Y}} \qquad Y = \log(\nu_0/\nu_f)$$

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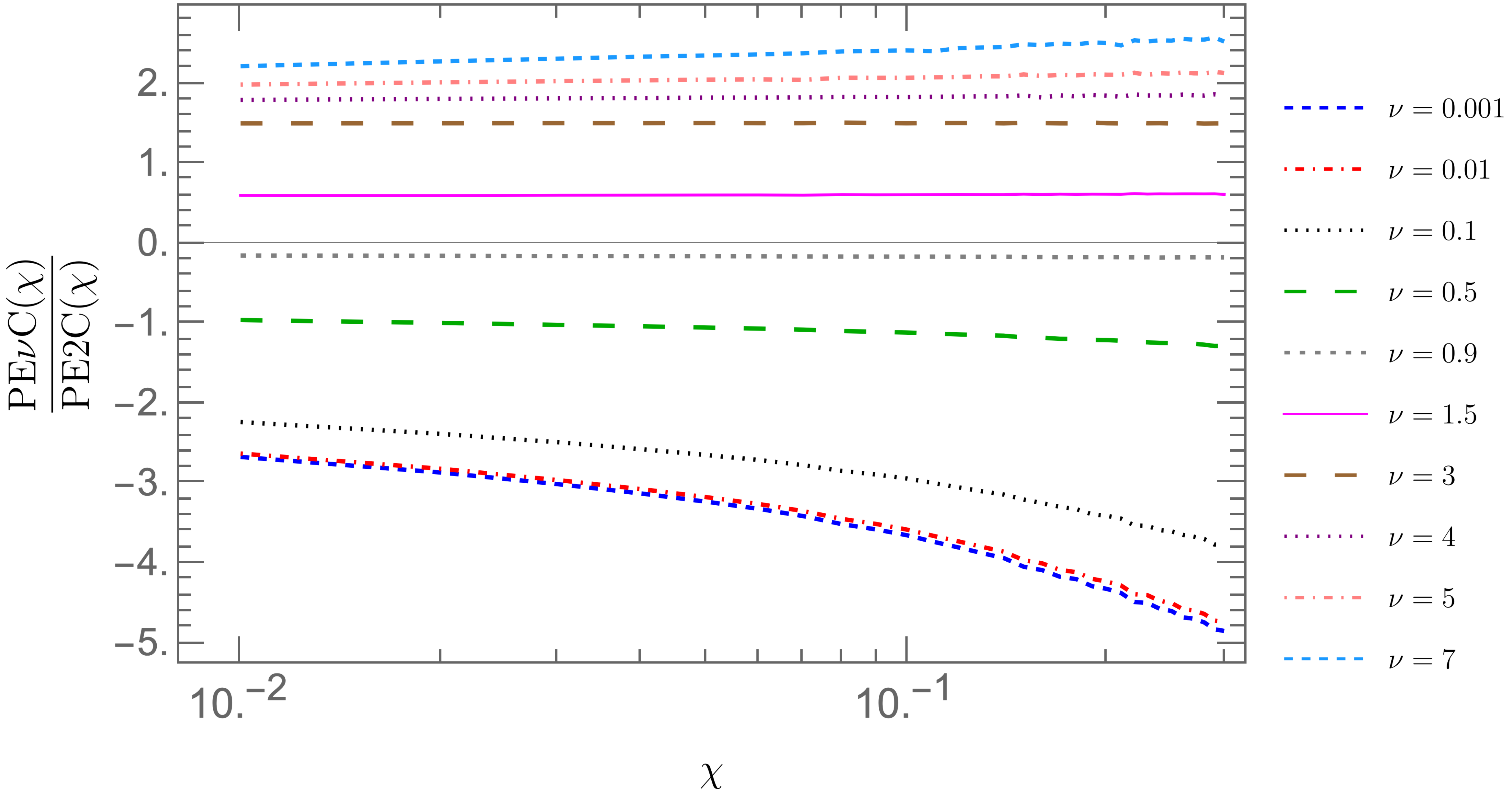
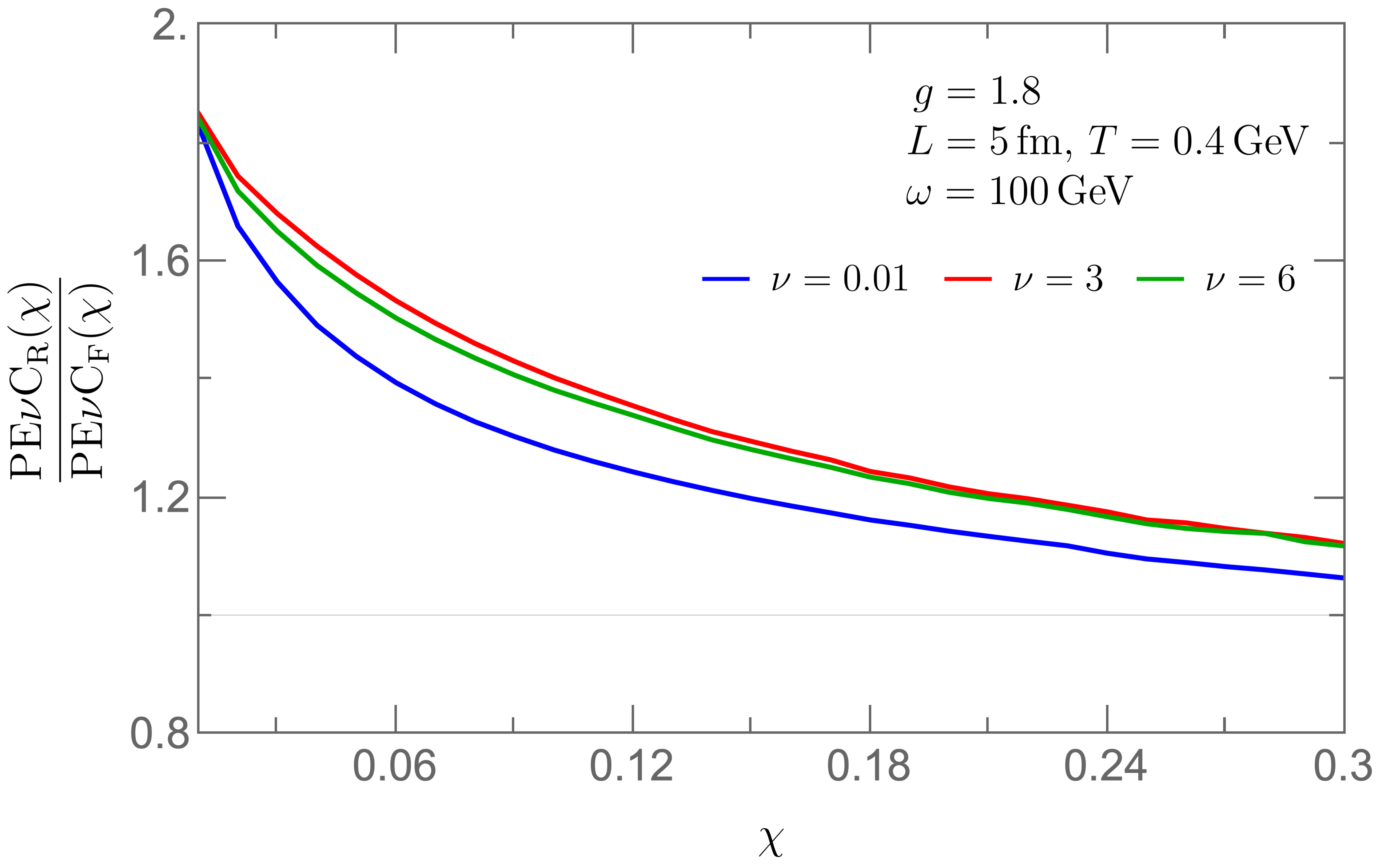
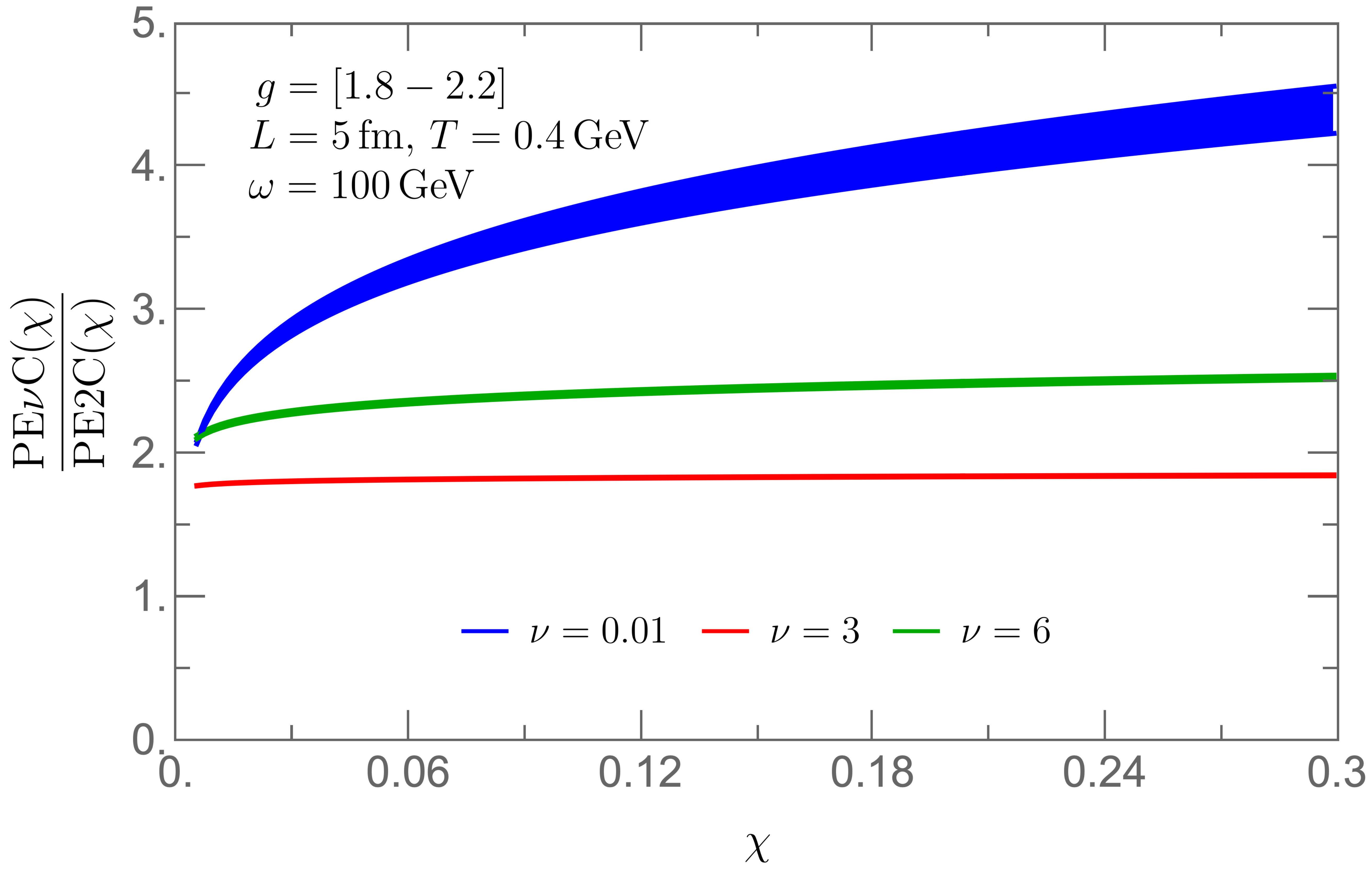




$\nu < 1$ has stronger scaling behaviour compared to $\nu > 1$

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

Scaling behaviour of ν-correlators



Power law fit for ratios

$$\frac{\text{PE}\nu\text{C}}{\text{PE2C}} \propto a\chi^b$$

For L=4 fm, T=0.5 GeV

$$\left.\frac{\text{PE}\nu\text{C}}{\text{PE2C}}\right|_{\nu=0.01} \propto \chi^{0.18}$$

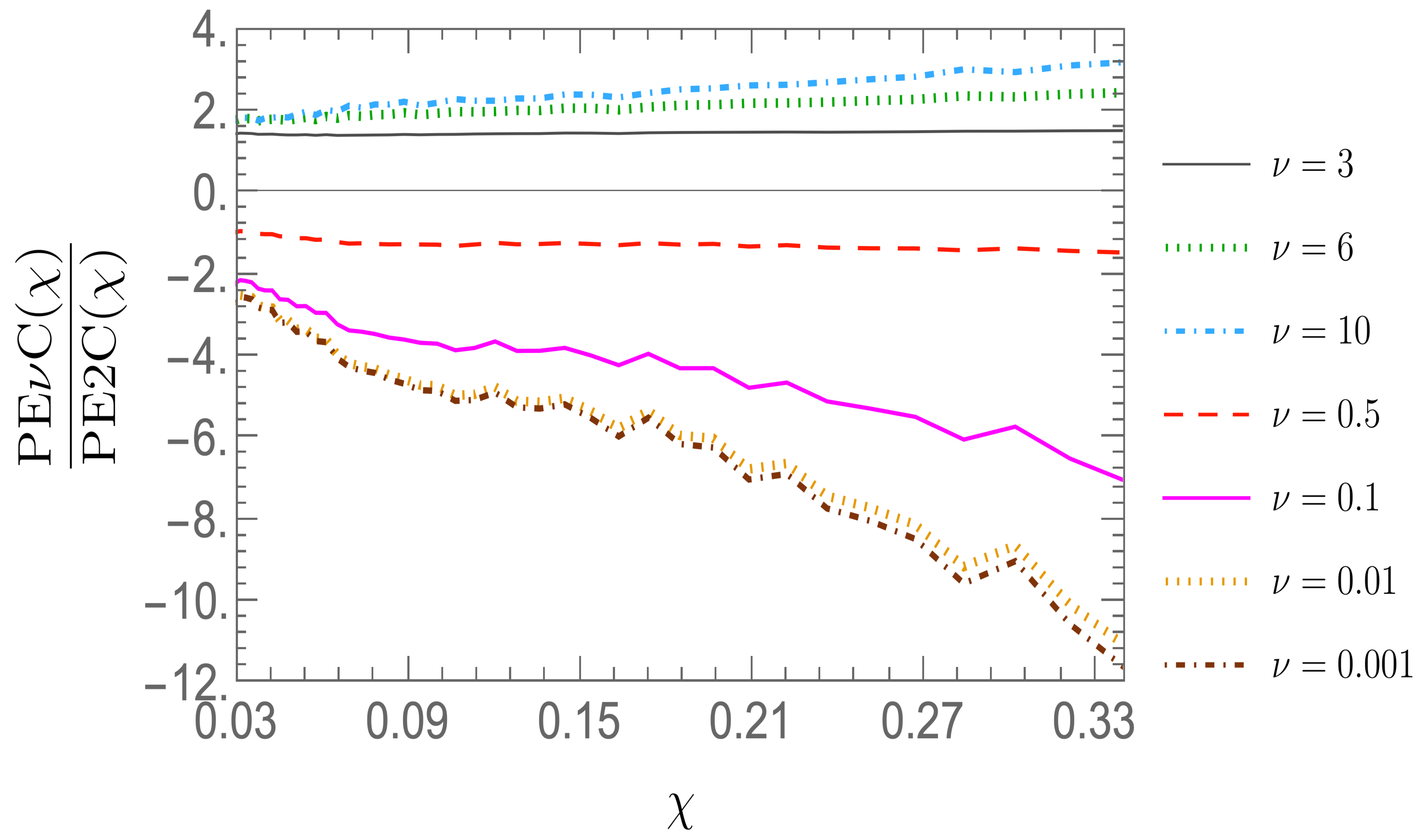
$$\left.\frac{\text{PE}\nu\text{C}}{\text{PE2C}}\right|_{\nu=3} \propto \chi^{0.0095}$$

$$\left.\frac{\text{PE}\nu\text{C}}{\text{PE2C}}\right|_{\nu=6} \propto \chi^{0.042}$$

$\nu < 1$ has stronger scaling behaviour compared to $\nu > 1$

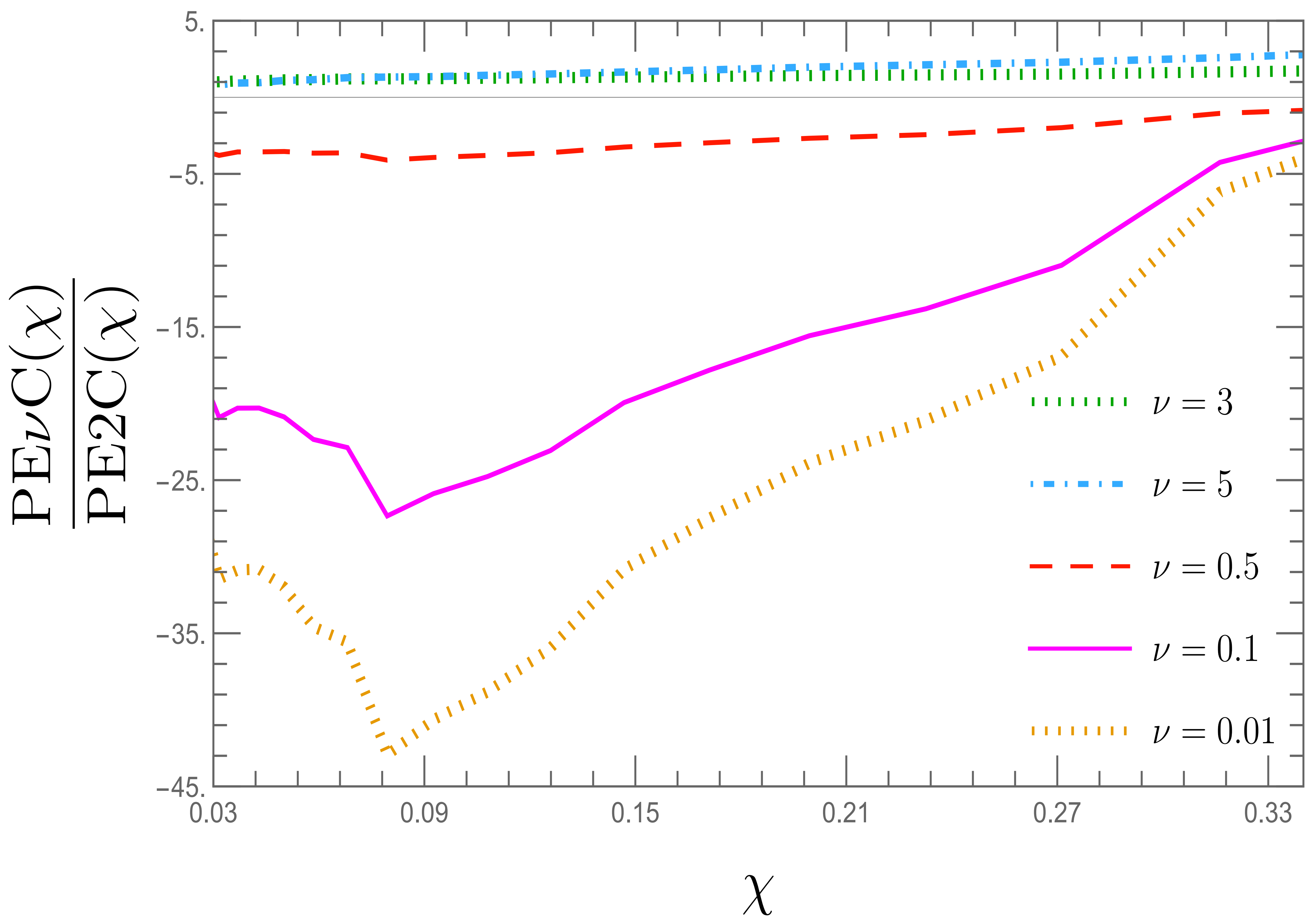
JEWEL Simulation

$\sqrt{s} = 5.02$ TeV $\quad L = 9$ fm $\quad T = 0.5$ GeV $\quad R = 0.4 \quad p_T \in [100 - 120]$ GeV $\quad |\eta| = 1.9$



Hadronization off

No initial state radiation



Hadronization on

Summary

- ν-correlators can be pivotal for separating the dynamics of large and small angle radiations. Similar to vacuum anomalous dimension may probe medium evolution

- Smaller ν values are more sensitive to large angle radiation compared to $\nu > 1$

- For $\tau_f \ll L$ smaller ν value correlators are enhanced

- Correlators for smaller ν value saturate at $\nu = 0.01$

- ν-correlators can be useful to quantify medium response dominated by soft dynamics

- Higher order calculations of jet function will provide more insight on the impact of resummation with a precise knowledge of scales for resummation

Thank you

for your attention

Measurement function

For two particle final state measurement function is defined as follows

$$\mathscr{M}^{[\nu]} = \sum_{a=1,2} \mathscr{W}_1^{[\nu]}(i_a)\delta(\chi) + \sum_{i_1<i_2} \mathscr{W}_2^{[\nu]}(i_1, i_2)\delta(\chi - \theta^2_{i_1 i_2})$$

single particle weight function

$$\mathscr{W}_1^{[\nu]}(i_a) = \frac{E^\nu_{i_a}}{\omega^\nu}$$

Two particle weight function

$$\mathscr{W}_2^{[\nu]}(i_1, i_2) = \frac{(E_{i_1} + E_{i_2})^\nu}{\omega^\nu} - \sum_{a=1,2} \mathscr{W}_1^{[\nu]}(i_a)$$

Environment operator

$$O^A_E(x) = \frac{1}{\mathbb{P}^2_\perp} \mathscr{O}^A_s(x)$$

Jet and medium functions

- Soft/Medium function explicitly factors out

$$\mathbf{B}_{AB}(x,y) = \mathrm{Tr}\Big[\mathbf{T}\Big\{e^{-i\int dt_l H_{s,I}(t_l)}\Big(\frac{1}{\mathbb{P}_\perp^2}\mathcal{O}_s^A(x)\Big)\Big\}\rho_M(0)\bar{\mathbf{T}}\Big\{e^{-i\int dt_r H_{s,I}(t_r)}\Big(\frac{1}{\mathbb{P}_\perp^2}\mathcal{O}_s^B(y)\Big)\Big\}\Big]$$

SCET operators

$$\mathcal{O}_n^{qA} = \bar{\chi}_n T^A \frac{\bar{n}}{2}\chi_n$$

$$\mathcal{O}_s^{qA} = \bar{\chi}_s T^A \frac{n}{2}\chi_s$$

- sinc function leads to LPM terms

$$J_{qR}(\chi, k_\perp; L) = \frac{e^{-i\frac{L}{2}(\mathbb{P}_+^A - \mathbb{P}_+^B)}}{2N_c}\mathrm{sinc}\Big[\frac{L}{2}(\mathbb{P}_+^A - \mathbb{P}_+^B)\Big]\sum_X \mathrm{Tr}\Big[\frac{\bar{n}}{2}\bar{\mathbf{T}}\Big\{e^{-i\int dt H_n(t)}\Big[O_n^{qB}(0)\Big]\chi_n(0)\Big\}\mathcal{M}\,|X\rangle\langle X|$$
$$\mathbf{T}\Big\{e^{-i\int dt H_n(t)}\Big[O_n^{qB}(0)\Big]\Big[\bar{\chi}_n(0)\Big]\Big\}\Big] + \mathcal{O}(H_G^4)$$

- Sinc function leads to LPM terms

$$J_{qV}(\omega, \chi, k_\perp; L) = \frac{1}{2N_c}\frac{1}{2}e^{-i\frac{L}{2}(\mathbb{P}_+^A + \mathbb{P}_+^B)}\mathrm{sinc}\Big[\frac{L}{2}(\mathbb{P}_+^A + \mathbb{P}_+^B)\Big]\sum_X \mathrm{Tr}\Big[\frac{\bar{n}}{2}\langle 0|\,\bar{\mathbf{T}}\Big\{e^{-i\int dt H_{n,I}(t)}\chi_n(0)\Big\}\mathcal{M}\,|X\rangle\langle X|\,\mathbf{T}\Big\{e^{-i\int dt H_n(t)}\Big[O_n^A(0)\Big]$$
$$\times\Big[O_n^B(0)\Big]\Big[\bar{\chi}_n(0)\Big]\Big\}|0\rangle\Big]\delta^{AB} + c.c + \mathcal{O}(H_G^4)$$

BFKL evolution equation

- From RG consistency the jet function obeys BFKL evolution equation

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

Scale for jet function

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

- Fixed order NLO jet function sets the boundary condition
- Running from jet scale to medium scale

Medium scale

$$\nu_f \sim Q_{\rm med}$$

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

- Resums $(a_p-1)\log(\nu_0/k_\perp)$
- Solution for $k_\perp \sim l_\perp$

$$\mathbf{S}_R^{[\nu]}(\chi,k_\perp) = \frac{1}{\pi k_\perp}\sqrt{\frac{\pi}{14\zeta(3)\bar{\alpha}Y}}e^{(a_p-1)Y}\int d^2l_\perp\frac{\mathbf{S}^{[\nu]}(\chi,l_\perp)}{l_\perp}e^{-\frac{\log^2(k_\perp/l_\perp)}{14\zeta(3)\bar{\alpha}Y}}$$

Medium function

- Medium function can be obtained from spectral function which can computed in perturbatively and can also be evaluated on lattice

$$\mathbf{B}(k_\perp) = D^g_>(k) + D^q_>(k) \qquad D_>(k) = (1 + f(k_0))\rho(k)$$

$D_>(k_\perp)$ is Weightman correlator in a thermal medium and depends on the properties of the medium

- In SCET framework spectral function is obtained from soft operators in the medium and also depends on the local properties of the plasma through soft operators

$$D^{AB}_E(K) = \int_0^\beta d\tau \int d^3x\, e^{iK\cdot X} \left\langle \frac{1}{\mathbb{P}^2_\perp} O^{g_n A}_s(X) \frac{1}{\mathbb{P}^2_\perp} O^{g_n B}_s(0) \right\rangle \propto \delta^{AB}\left[\ldots\right]$$

SCET operators

$$\mathcal{O}^{qA}_n = \bar{\chi}_n T^A \frac{\bar{n}}{2} \chi_n$$

$$\mathcal{O}^{qA}_s = \bar{\chi}_s T^A \frac{n}{2} \chi_s$$

$$\mathcal{O}^{gA}_s = \frac{i}{2} f^{ACD} \mathcal{B}^C_{S\perp\mu} \frac{n}{2} \cdot (\mathcal{P} + \mathcal{P}^\dagger) \mathcal{B}^{D\mu}_{S\perp}$$

- Leading order medium function

$$\mathbf{B}_{\mathrm{LO}}(k_\perp) = (8\pi\alpha_s)^2 \left(\frac{2\pi N_c^2}{16 k_\perp^4} \mathcal{J}^g(k_\perp) + \frac{2\pi N_f}{k_\perp^4} \mathcal{J}^q(k_\perp) \right)$$