INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS

EXCELENCIA MARÍA DE MAEZTU

Hamiltonian evolution of jets in the Glasma phase

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Based on
[2605.10413]
[2604.08520]

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Outline

1. Motivation and introduction
2. Quantum to classical correspondence
3. Kinetic vs. canonical momentum and the effect of gauge transformations
4. Light-front Hamiltonian formalism
5. Conclusions and outlook

1. MOTIVATION AND INTRODUCTION

Introduction and motivation

Jets are created in a hard process at the beginning of a heavy ion collision and **probe all the subsequent stages**

Propagation of jets in the QGP was largely studied but the relevance of the initial stages is still an open puzzle

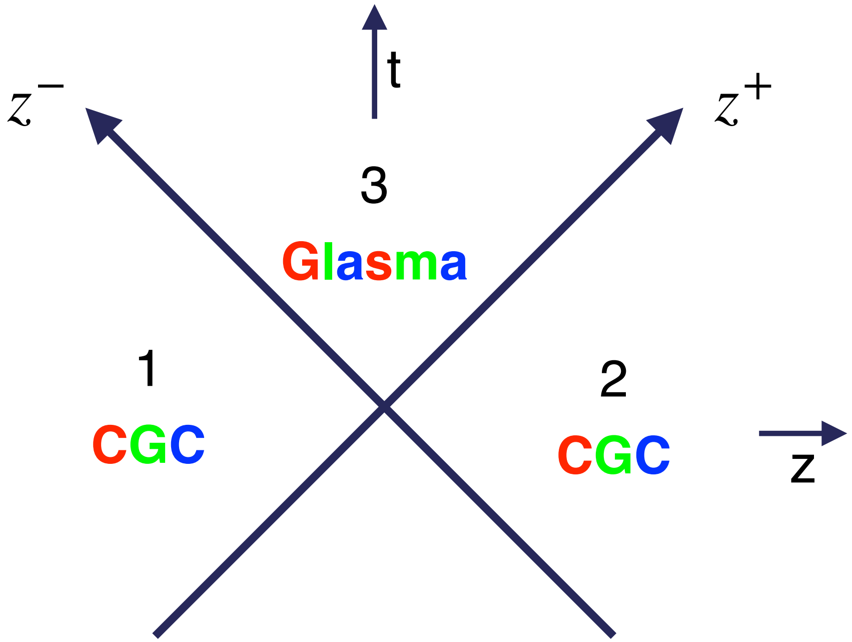
[Andres, Armesto, Niemi, Paatelainen, Salgado (1902.03231)] [Ipp, Müller, Schuh (2001.10001)]

Most of jets in Glasma studies rely on a **classical treatment** of the propagating particle, with recent attempts to include quantum effects

[Barata, Hauksson, Mayo, Sadofyev (2406.07615)]

We employ a Hamiltonian formalism to perform for the first time the real-time quantum evolution of a quark propagating through the Glasma phase!

The Glasma fields



We use **real-time lattice gauge theory** to solve CYM equation

[Krasnitz, Venugopalan (hep-ph/9809433)]

[Kovner, McLerran, Weigert (hep-ph/9505320)]

Initial condition derived from the CGC and the MV model in the Fock-Schwinger gauge

$$\mathscr{A}_\tau = 0$$

↓

Solve **sourceless Yang-Mills**

$$[D_\mu, F^{\mu\nu}] = 0$$

↓

Boost-invariant classical Glasma fields

The transverse Coulomb gauge

The Glasma fields are derived in the temporal gauge $\mathscr{A}_\tau = 0$, but there is a **residual gauge freedom**

We can additionally impose the **transverse Coulomb gauge condition**

$$\partial_{\underline{i}} \mathscr{A}_{\underline{i}} = 0 \qquad \underline{i} \in (x, y)$$

This choice **minimizes $\mathbf{Tr}[\mathbf{A}_{\underline{\mathbf{i}}}^2]$** reducing gauge artifacts

2. QUANTUM TO CLASSICAL CORRESPONDENCE

Classical particle dynamics

Dynamics of classical particles in a colored field are governed by **Wong's equations**

$$\frac{dx^\mu}{d\lambda} = \frac{1}{m} p^\mu_{kin}(\lambda)$$

$$\frac{dQ^a}{d\lambda} = -\frac{g}{m} f^{abc} Q^c(\lambda)\, \mathscr{A}^b_\mu(\lambda)\, p^\mu_{kin}(\lambda)$$

$$\frac{dp^\mu_{kin}}{d\lambda} = \frac{g}{m} Q^a(\lambda)\, \mathscr{F}^{\mu\nu,a}(\lambda)\, p^{kin}_\nu(\lambda)$$

Color rotation

$$Q(\lambda) = \mathscr{U}(\lambda;0) Q(0) \mathscr{U}^\dagger(\lambda;0)$$

with

$$\mathscr{U}(\lambda;0) = \mathscr{P} \exp\left[-ig\int_0^\lambda d\lambda' \frac{dx^\mu}{d\lambda'} \mathscr{A}_\mu(\lambda')\right]$$

Classical momentum broadening

$$\langle(\delta p_i^{kin}(\lambda))^2\rangle_Q = g^2 \int_0^\lambda d\lambda' \int_0^\lambda d\lambda'' \, \mathrm{Tr}[\tilde{f}_i(\lambda')\tilde{f}_i(\lambda'')]$$

where $\tilde{f}_i = \mathscr{U} f_i \mathscr{U}^\dagger$

Can be solved in limiting cases like **eikonal** or **static** quarks

Quantum evolution equations

We start from the quadratic form of the Dirac Hamiltonian

$$\hat{H} = \frac{1}{2m}\left(m^2 - (\hat{p}^\mu - g\hat{A}^\mu)^2\right) - \frac{g}{2m}\hat{S}^{\mu\nu}\hat{F}_{\mu\nu}$$

The time-evolution of any operator is then $\dfrac{d\hat{\mathcal{O}}_H}{d\lambda} = i[\hat{H}_H, \hat{\mathcal{O}}_H] + \dfrac{\partial\hat{\mathcal{O}}_H}{\partial\lambda}$

$$\frac{d\hat{x}^\mu}{d\lambda} = \frac{\hat{p}^\mu - g\hat{A}^\mu}{m} \qquad \frac{d\hat{S}^{\mu\nu}}{d\lambda} = \frac{2g}{m}\hat{S}^{\rho[\mu}\hat{F}^{\nu]}{}_\rho$$

$$\frac{d\hat{p}^\mu_{kin}}{d\lambda} = \frac{g}{2m}\left(\hat{p}^{kin}_\nu\hat{F}^{\mu\nu} + \hat{F}^{\mu\nu}\hat{p}^{kin}_\nu - \hat{S}^{\nu\rho}\hat{D}^\mu\hat{F}_{\nu\rho}\right)$$

$$\frac{d\hat{T}^a}{d\lambda} = \frac{g}{2m}f^{abc}\left(-\mathscr{A}^b_\mu(\hat{p}^\mu_{kin}\hat{T}^c + \hat{T}^c\hat{p}^\mu_{kin}) + \mathscr{F}^b_{\mu\nu}\hat{S}^{\mu\nu}\hat{T}^c\right)$$

Quantum to classical correspondence

Classical limit

$$\langle \hat{X}^{\mu} \rangle_{\psi} \to X^{\mu},\ \langle \hat{X}\,\hat{T}^{a} \rangle_{\psi} \to XQ^{a}$$

In the classical limit quantum evolution equations are reduced to classical Wong's equations

[Avramescu, CL, Lappi, Li, Salgado (2604.08520)]

Wong **Spin**

$$\frac{dx^{\mu}}{d\lambda} = \frac{p^{\mu}_{kin}}{m}$$

$$\frac{dp^{\mu}_{kin}}{d\lambda} = \frac{g}{m} Q^{a} \left(\mathscr{F}^{\mu\nu}_{a}\, p^{kin}_{\nu} - \frac{1}{2} S^{\nu\rho}\, \mathscr{D}^{\mu} \mathscr{F}^{a}_{\mu\nu} \right)$$

$$\frac{dQ^{a}}{d\lambda} = -\frac{g}{m} f^{abc} Q^{c} \left(\mathscr{A}^{b}_{\mu}\, p^{\mu}_{kin} - \frac{1}{2} S^{\mu\nu} \mathscr{F}^{b}_{\mu\nu} \right)$$

$$\frac{dS^{\mu\nu}}{d\lambda} = \frac{2g}{m} Q^{a} S^{\rho[\nu} F^{\mu],a}_{\ \ \rho}$$

3. KINETIC VS. CANONICAL MOMENTUM AND THE EFFECT OF GAUGE TRANSFORMATIONS

Kinetic and canonical momentum

For a particle propagating inside a color field **kinetic momentum is not the same as canonical momentum**

$$\hat{p}^{\mu}_{kin} = m\frac{d\hat{x}^{\mu}}{d\lambda} = \hat{p}^{\mu} - g\hat{A}^{\mu}$$

For an x- propagating eikonal quark in the Glasma the Lorentz force is given in terms of electric and magnetic fields

$$f^{y} = E_{y} - B_{z} \qquad f_{z} = E_{z} + B_{y}$$

We can isolate the components of the Lorentz force that contribute to the evolution equation of canonical momentum and define a **canonical momentum broadening**

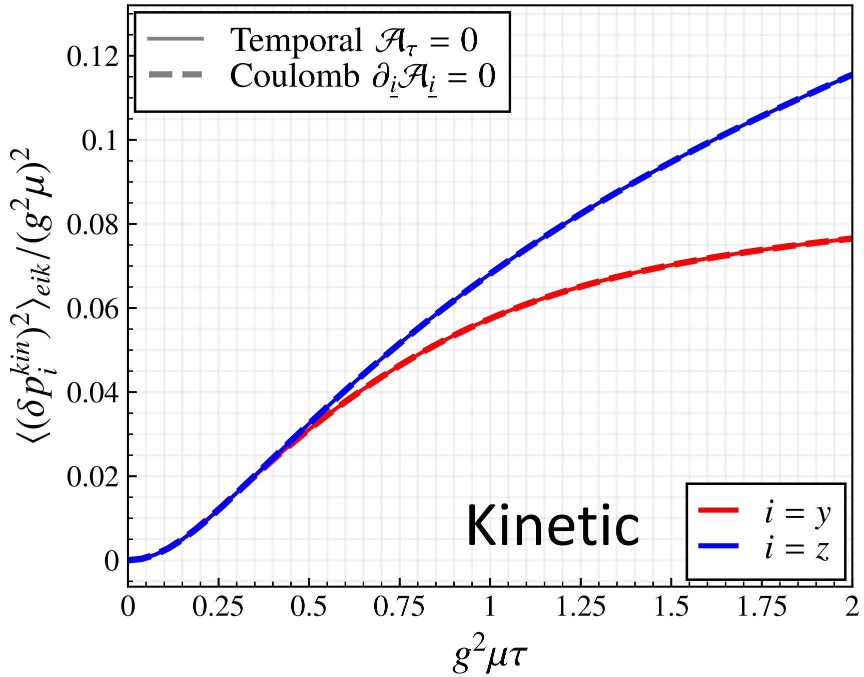
Kinetic and canonical momentum broadening

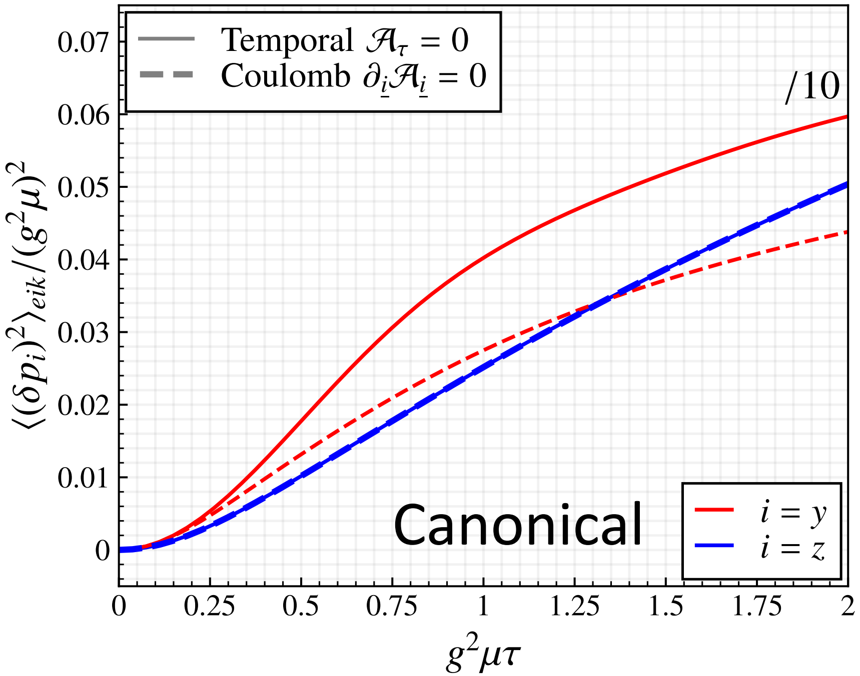
We extract classical momentum broadening for eikonal quarks in two different gauges

Kinetic momentum is the physical gauge invariant quantity

Canonical momentum depends on the gauge choice and therefore is not an observable

[Avramescu, CL, Lappi, Li, Salgado (2604.08520)]





Transverse Coulomb gauge fixing largely reduces canonical momentum broadening

Effect of the gauge choice on numerical errors

From the definition of the canonical momentum

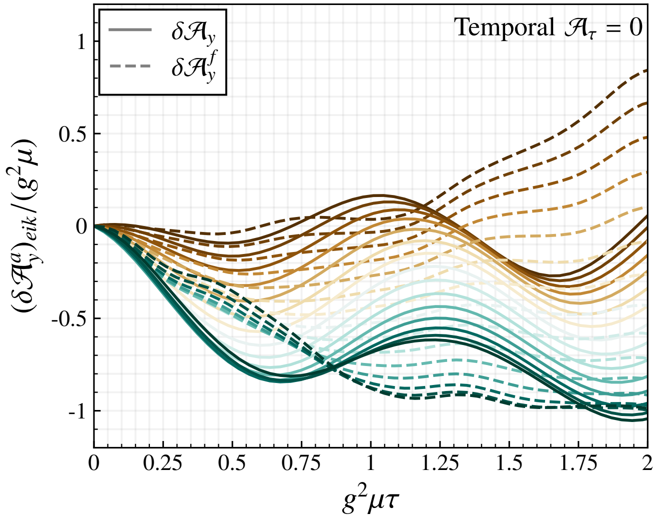
$$f_i^A = f_i^p - f_i \qquad \delta\mathscr{A}_i^f(\tau) \equiv \int_0^\tau d\lambda\, \tilde{f}_i^A(\lambda)$$

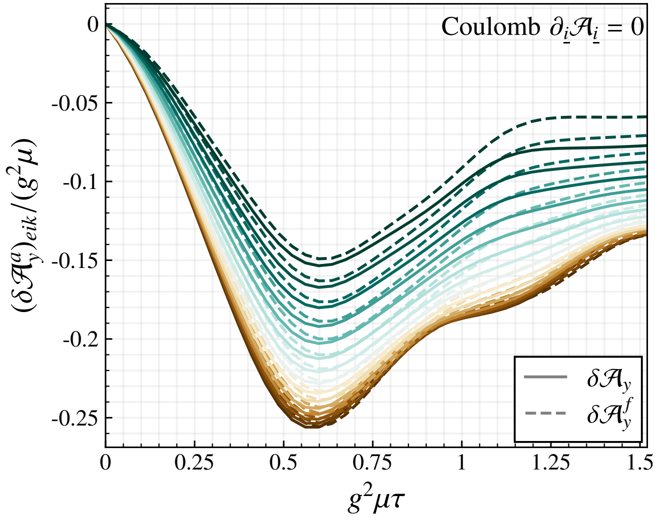
which should be equivalent to

$$\delta\mathscr{A}_i(\tau) \equiv \mathscr{U}(\tau;0)\mathscr{A}_i(\tau)\mathscr{U}^\dagger(\lambda;0) - \mathscr{A}_i(0)$$

Transverse Coulomb gauge fixing minimizes the accumulation of numerical errors in the calculation

[Avramescu, CL, Lappi, Li, Salgado (2604.08520)]





4. LIGHT FRONT HAMILTONIAN FORMALISM

Light-front Hamiltonian formalism

In the leading Fock sector of the quark jet $|q\rangle$

$$\mathscr{L} = \overline{\Psi}(x)(i\gamma^\mu D_\mu - m)\Psi(x)$$

$$\Big\downarrow$$

We work in the **light-front form**, where $x^+ = t + x$ is the temporal variable

Light-front Hamiltonian

$$P^- = \frac{m^2 + (\vec{p}_\perp - g\overrightarrow{\mathscr{A}}_\perp)^2}{p^+} + 2g\mathscr{A}_+ - 2g\frac{\mathscr{B}_x S^x}{p^+}$$

Kinetic energy

Interaction potential

Zeeman effect

Basis representation

We **expand the quark state in a basis** of eigenstates of the free theory

$$|\psi; x^+ > = \sum_\beta c_\beta(x^+)\,|\beta > \quad \text{where} \quad |\beta > = |p^+, \vec{p}_\perp, \lambda, c >$$

We solve the **Schrödinger equation** in terms of the basis coefficients and

$$\mathscr{M}_{\beta\beta'} = \langle \beta | P^- | \beta' \rangle$$

$$i\frac{\partial}{\partial x^+}|\psi, x^+\rangle = \frac{1}{2}P^-(x^+)|\psi; x^+\rangle \longrightarrow \mathrm{c}(x^+) = \mathscr{T}_+ \exp\left[-\frac{i}{2}\int_0^{x^+} ds \mathscr{M}(s)\right]\mathrm{c}(0)$$

Numerical framework known as **time-dependent Basis Light-Front Quantization** (tBLFQ)

[Li, Zhao, Maris, Chen, Li, Tuchin, Vary (2002.09757)] [Li, Lappi, Zhao (2107.02225)]
[Li, Lappi, Zhao, Salgado (2305.12490, 2504.07162)]

Momentum broadening

We obtain the evolution equations of the relevant operators in the **Heisenberg picture**

$$\frac{d\mathcal{O}_H}{dx^+} = \frac{i}{2}[P^-_H, \mathcal{O}_H] + \left(\frac{\partial \mathcal{O}}{\partial x^+}\right)_H \longrightarrow \frac{d\vec{x}_\perp}{dx^+} = \frac{\vec{p}_{\perp,H} - g\vec{\mathcal{A}}_{\perp,H}}{p^+}$$

In light-front dynamics, $\mathbf{p}^+$ **plays the role of the particle mass** in the non-relativistic theory

$$\boxed{\vec{p}^{\,kin}_\perp = p^+\frac{d\vec{x}_\perp}{dx^+} = \vec{p}_\perp - g\vec{\mathcal{A}}_\perp}$$

Kinetic momentum is not the same as the canonical momentum also in the quantum calculation

Quantum momentum broadening

We define the **momentum broadening quantum operator**

$$(\delta p^{kin}_{i,H}(x^+))^2 = (p^{kin}_{i,H}(x^+) - p^{kin}_{i,H}(0))^2$$

Direct calculation

$$\langle (\delta p_i^{kin}(x^+))^2 \rangle_\psi =_H \langle \psi | (\delta p_i^{kin}(x^+))^2_H | \psi \rangle_H$$
$$= \langle \psi; x^+ | (\delta p_i^{kin}(x^+))^2 | \psi; x^+ \rangle$$

More direct way, but requires to evolve the state back and forward in time

Lorentz force calculation

$$\frac{dp^{kin}_{i,H}}{dx^+} = \frac{g}{2} f_{i,H}(x^+)$$

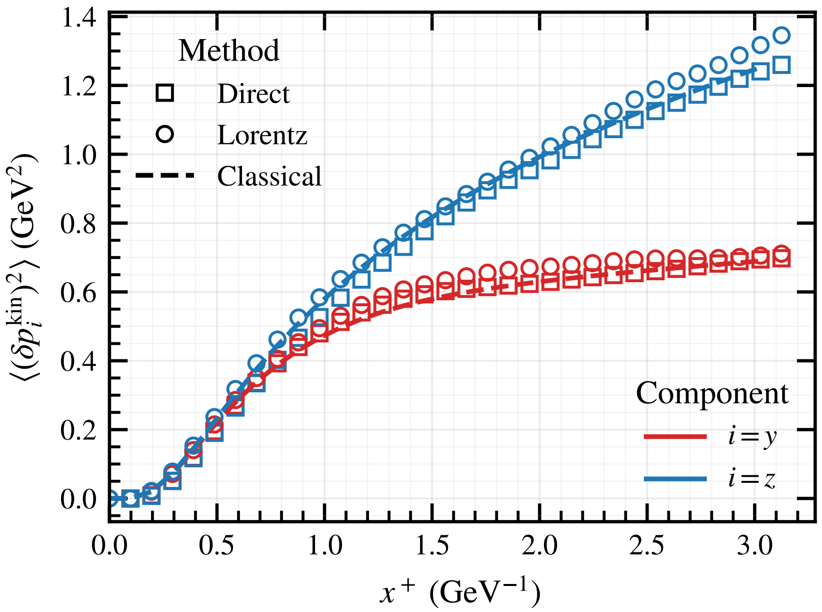
$$\langle (\delta p_i^{kin}(x^+))^2 \rangle_\psi = \frac{g^2}{4} \int_0^{x^+} ds^+ \int_0^{x^+} d\bar{s}^+ \langle \psi; 0 | f_{i,H}(s^+) f_{i,H}(\bar{s}^+) | \psi; 0 \rangle$$

where $f^y = \mathscr{E}_y - \mathscr{B}_z, \quad f^z = \mathscr{E}_z + \mathscr{B}_y$

Quantum momentum broadening results

We compare the momentum broadening obtained by both methods and with classical particle simulations using Wong's equations

[Ipp, Müller, Schuh (2001.10001)]



[Avramescu, CL, Lappi, Li, Salgado (2605.10413)]

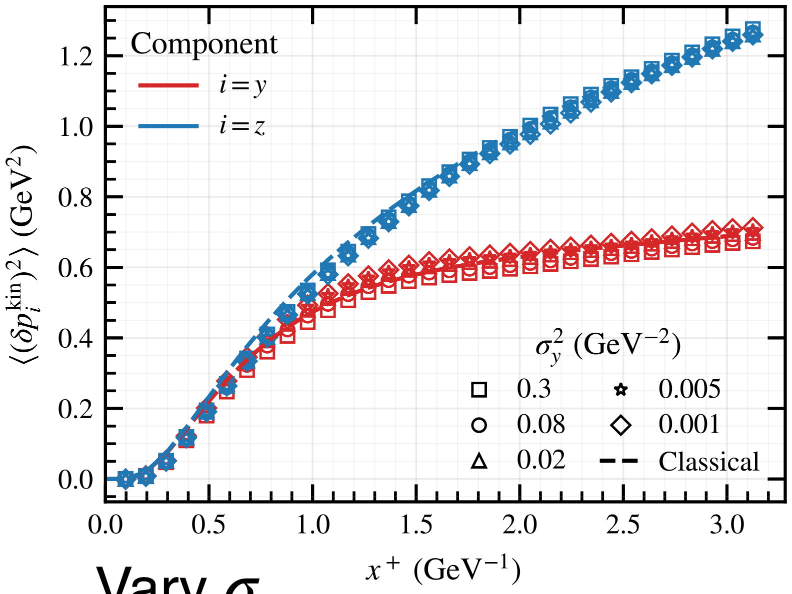
Both methods are equivalent and reproduce the classical particle results

Within our Fock-space truncation the more general quantum calculation reduces to the classical limit

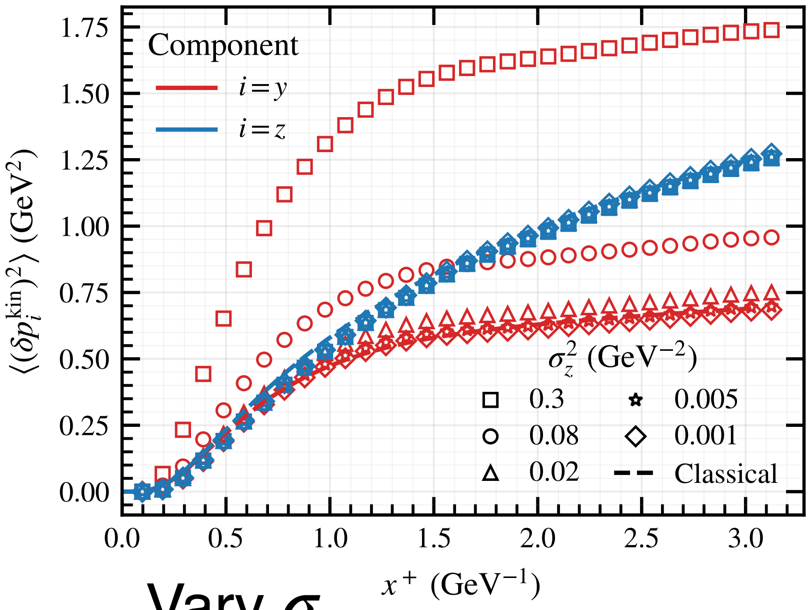
[Avramescu, CL, Lappi, Li, Salgado (2604.08520)]

Sensitivity to the width of the wavepackage

[Avramescu, CL, Lappi, Li, Salgado (2605.10413)]



Vary σ_y

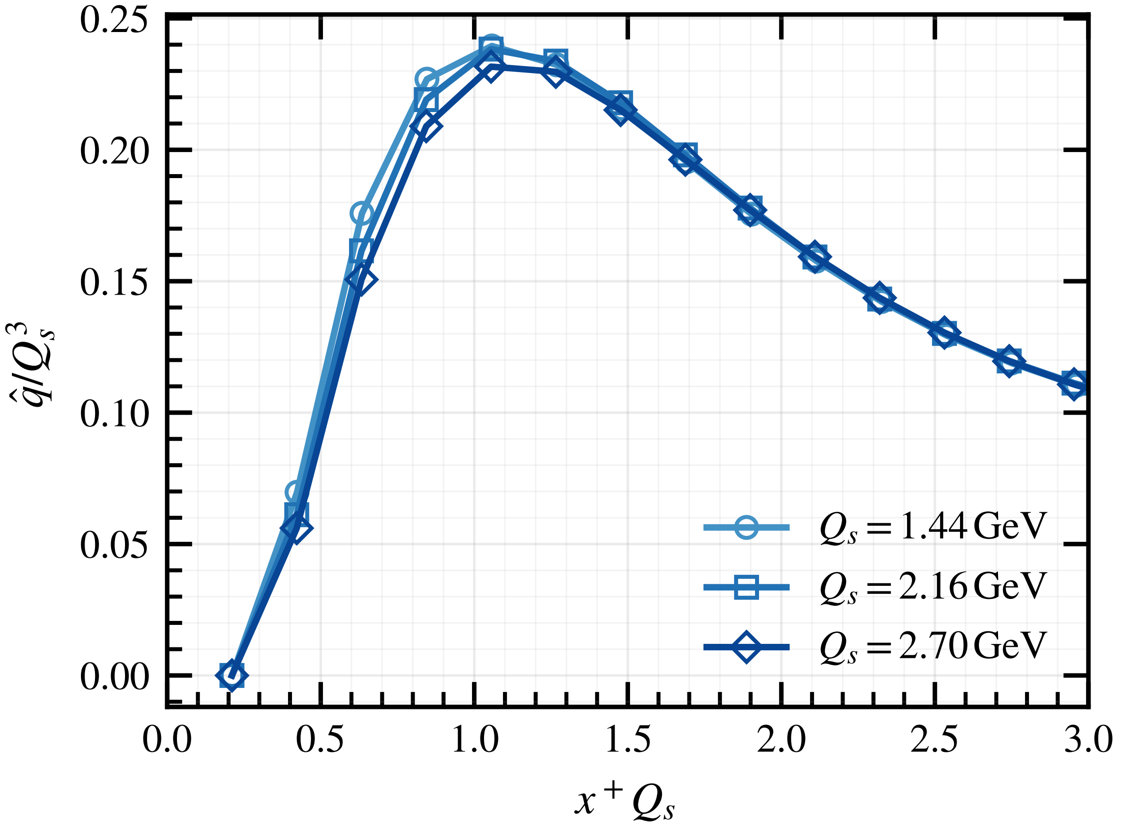


Vary σ_z

Our matching between Milne and Minkowski coordinates is only valid for small values of z

- Momentum broadening in the z direction insensitive to the width
- Momentum broadening in the y direction increases with σ_z
- Agreement with analytic predictions using an abelian toy model

Jet quenching parameter



[Avramescu, CL, Lappi, Li, Salgado (2605.10413)]

$$\boxed{\hat{q} = 2\frac{d\langle(\delta\vec{p}_\perp^{\,kin})^2\rangle}{dx^+}}$$

- The size and position of the peak show a **perfect scaling with $\mathbf{Q_s}$**
- Peaks at $x^+ \sim 1/Q_s$ (or $\tau \sim 1/(2Q_s)$), can be understood in terms of the **Glasma correlation domains**

Parametric estimates

[Apolinário, Lee, Winn (2203.16352)]

The jet quenching parameter in the Glasma is much larger than $\hat{q}_{QGP} \sim 3T^3$, but the lifetime is much shorter, $L_{\text{Glasma}} \sim 1/Q_s$, $L_{\text{QGP}} \sim R_A \sim 1.2\,\text{fm}\,A^{1/3}$.

We take as an starting point $Q_{s,Pb} \approx 2\,\text{GeV}$ and $T_{Pb} \approx 0.2\,\text{GeV}$ and consider that $Q_s^2 \propto A^{1/3}$ and $T \propto Q_s$

$$\boxed{\frac{\hat{q}_{\text{Glasma}}}{\hat{q}_{\text{QGP}}} \approx 50}$$

Valid across nuclear species

$$\boxed{\frac{\langle(\delta p_\perp^{kin})^2\rangle_{\text{Glasma}}}{\langle(\delta p_\perp^{kin})^2\rangle_{\text{QGP}}} = \frac{\hat{q}_{\text{Glasma}}}{\hat{q}_{\text{QGP}}}\frac{L_{\text{Glasma}}}{L_{\text{QGP}}} \approx 50\frac{(A_{Pb}/A)^{1/6}}{12A^{1/3}}}$$

$$\boxed{\left.\frac{\langle(\delta p_\perp^{kin})^2\rangle_{\text{Glasma}}}{\langle(\delta p_\perp^{kin})^2\rangle_{\text{QGP}}}\right|_{\text{Pb}} \approx 0.7}$$

$$\boxed{\left.\frac{\langle(\delta p_\perp^{kin})^2\rangle_{\text{Glasma}}}{\langle(\delta p_\perp^{kin})^2\rangle_{\text{QGP}}}\right|_{\text{O}} \approx 2.5}$$

Parametric estimates

BDMPS estimate $\Delta E \sim \alpha_s \hat{q}\, L^2$

[Baier, Dokshitzer, Mueller, Peigné, Schiff (hep-ph/9607355)]

$$\boxed{\frac{\langle(\delta p_\perp^{kin})^2\rangle_{\text{Glasma}}}{\langle(\delta p_\perp^{kin})^2\rangle_{\text{QGP}}} = \frac{\hat{q}_{\text{Glasma}}}{\hat{q}_{\text{QGP}}}\left(\frac{L_{\text{Glasma}}}{L_{\text{QGP}}}\right)^2 \approx 50\frac{(A_{Pb}/A)^{1/3}}{144A^{2/3}}}$$

$$\boxed{\left.\frac{\Delta E_{\text{Glasma}}}{\Delta E_{\text{QGP}}}\right|_{\text{Pb}} \approx 0.01}$$

$$\boxed{\left.\frac{\Delta E_{\text{Glasma}}}{\Delta E_{\text{QGP}}}\right|_{\text{O}} \approx 0.13}$$

The BDMPS estimate assumes independent scattering centers

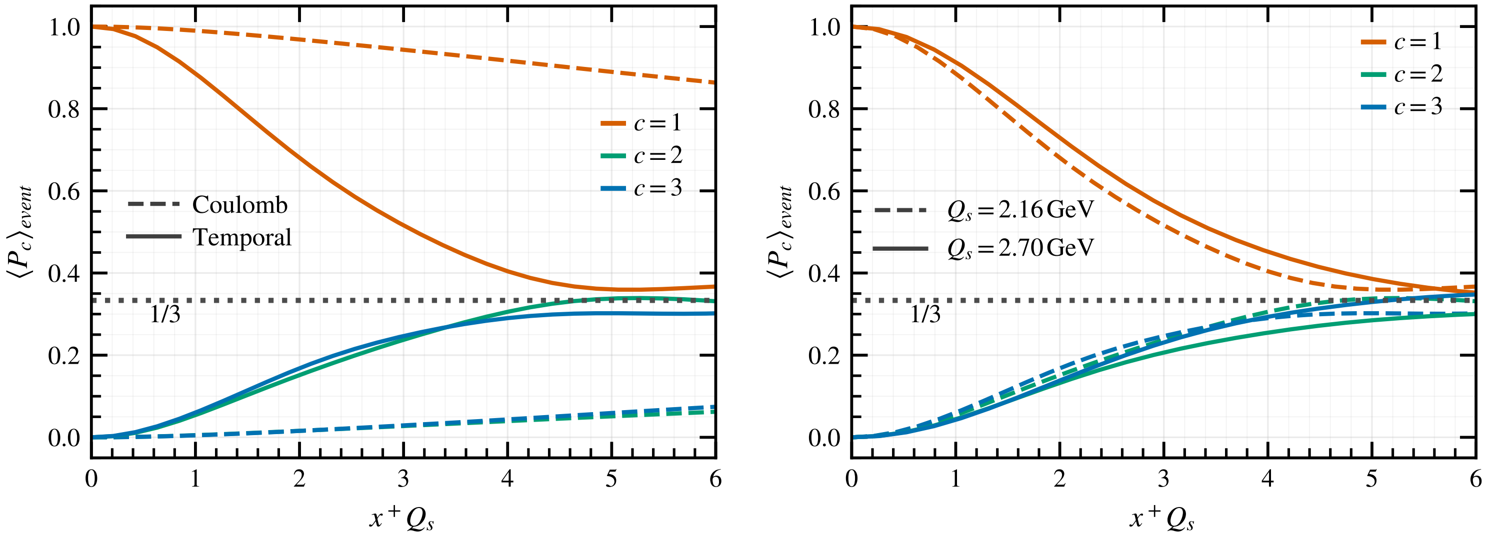
Rigorous calculation requires including the $|qg\rangle$ sector

The relative contribution of the initial stages to jet quenching gets largely enhanced in small systems

Color rotation

It is not an observable, but serves as a **probe of the magnitude of the background fields and the effect of gauge transformations**

[Avramescu, CL, Lappi, Li, Salgado (2605.10413)]



Very slow in the Coulomb gauge, much faster without Coulomb gauge fixing

For a given gauge the speed of the color rotation scales with Q_s

As expected Coulomb gauge fixing reduces the color rotation rate

Conclusions…

We can divide this work in two parts, in the first one:

- We showed how the **quantum evolution equations are reduced to Wong's equations** by taking the classical limit
- We explored the **differences between kinetic and canonical momentum** for a particle propagating in the Glasma and **signified the importance of the transverse Coulomb** gauge to minimize numerical errors

In the second

- We presented a formalism to study the **quantum real-time evolution** of particles in the Glasma phase of a heavy-ion collision, and shown that we can **reproduce the classical results**
- We studied the **effect of the jet localization** over momentum broadening and the **scaling of $\hat{q}$ with Q_s**
- We estimated the relative contribution of the Glasma phase to jet quenching and proposed that **light-ion collisions are the perfect playground to look for imprints of the initial stages**

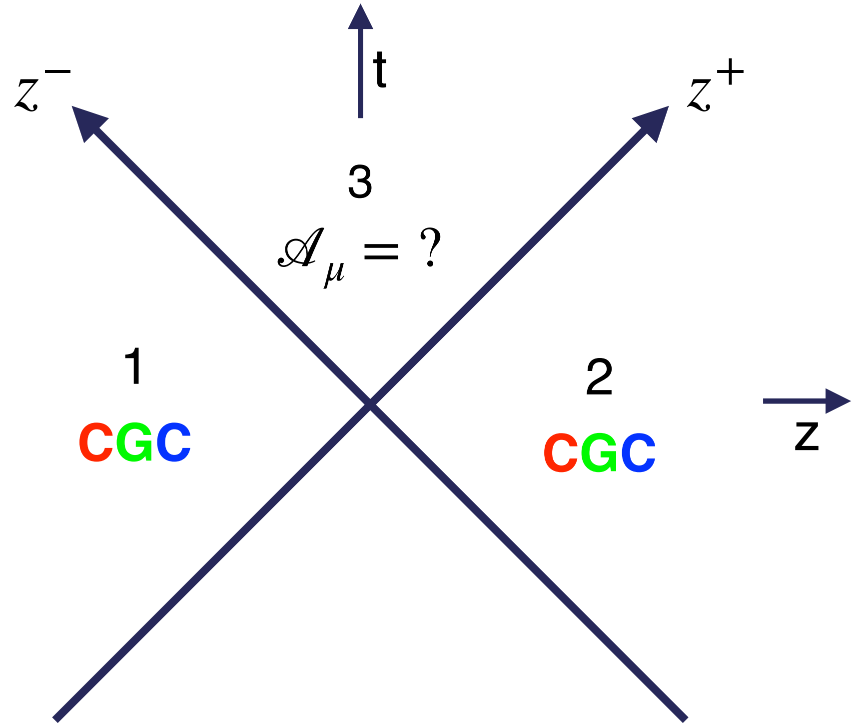
… and outlook

- **Include subeikonal corrections** to quark propagation in the medium
- **Include higher Fock sector contributions** like $|qg\rangle$ and compute **Glasma induced energy loss**

Thank you very much for your attention!

BACKUP SLIDES!

The Color Glass Condensate



High-energy nuclei before the collision can be **modeled using Color Glass Condensate** (**CGC**) in

Based on scale separation

Large x, static color charges

Small x, classical color fields

Must follow **classical Yang-Mills** equations

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

We work on the **MV model**, where the only relevant scale is the **saturation scale** Q_S

Matching between Milne and LC coordinates

$$\mathscr{A}_+(x^+, y, z) = \frac{1}{2}\left[\mathscr{A}_x\left(\tau(x^+, z), x(x^+), y\right) - \frac{z}{\tau^2}\mathscr{A}_\eta\left(\tau(x^+, z), x(x^+), y\right)\right]$$

$$\mathscr{A}_y(x^+, y, z) = \mathscr{A}_y\left(\tau(x^+, z), x(x^+), y\right) \qquad \mathscr{A}_z(x^+, y, z) = \frac{x^+}{2\tau^2}\mathscr{A}_\eta\left(\tau(x^+, z), x(x^+), y\right)$$

where $\tau = \sqrt{(x^+/2)^2 - z^2}$ and $x = x^+/2$

$\Big\downarrow$ Taylor

$$\mathscr{A}_+(x^+, y, z) \simeq \frac{1}{2}\left[\mathscr{A}_x\left(\tau(x^+), x(x^+), y\right) - \frac{4z}{(x^+)^2}\mathscr{A}_\eta\left(\tau(x^+), x(x^+), y\right)\right]$$

$$\mathscr{A}_y(x^+, y, z) \simeq \mathscr{A}_y\left(\tau(x^+), x(x^+), y\right) \qquad \mathscr{A}_z(x^+, y, z) \simeq \frac{2}{x^+}\mathscr{A}_\eta\left(\tau(x^+), x(x^+), y\right)$$

where $\tau = x = x^+/2$

Real-time lattice gauge theory

Transverse space with respect to beam direction (x, y) discretized in a lattice and transverse variables encoded in gauge links

$$U_{\underline{i}}(\tau, \vec{x}_\perp) = \exp\left[i g a_\perp \mathscr{A}_{\underline{i}} \left(\tau, \vec{x}_\perp + \frac{a_\perp}{2} \vec{e}_{\underline{i}} \right) \right]$$

and transverse gauge fields are obtain via logarithm

$$\mathscr{A}_{\underline{i}}(\tau, \vec{x}_\perp) = -\frac{i}{g a_\perp} \ln \left[U_{\underline{i}}(\tau, \vec{x}_\perp) \right]$$

Due to boost invariance $\mathscr{A}_\eta$ is not discretized in such a variables.

Classical color charge averages

Average of two classical color charges is defined as

$$\int dQ\, Q^a Q^b = T_R \delta^{ab}$$

and for any n-point function of the charges

$$\langle X \rangle_Q \equiv \int dQ\, X$$

This allows us to eliminate the classical color charges from the calculation of momentum broadening by tracing over the Lorentz force

Casimir rescaling needed to obtain the right color factor from classical charges

Light-front Hamiltonian and quantum many-body rep

$$P^-(x^+) = \int dx^- d^2\vec{x}_\perp \left[\frac{1}{2}\bar{\Psi}\gamma^+ \frac{m^2 - \nabla_\perp^2}{p^+}\Psi + g\bar{\Psi}(\gamma^+\mathscr{A}_+ + \gamma^i\mathscr{A}_i)\Psi + \frac{g^2}{2}\bar{\Psi}\gamma^i\mathscr{A}_i\frac{\gamma^+}{p^+}\gamma^j\mathscr{A}_j\Psi \right]$$

within our Fock space truncation

$$\Psi_c(x) = \sum_\lambda \int \frac{dp^+ d^2\vec{p}_\perp}{\sqrt{2p^+(2\pi)^3}}[u_\lambda(p)e^{-ip\cdot x}b_{\lambda,c}(p) + v_\lambda(p)e^{ip\cdot x}d^\dagger_{\lambda,c}(p)]$$

and the Hamiltonian reduces to

$$P^- = T_q + V_{\mathscr{A}^+} + V_{\vec{\mathscr{A}}_\perp} + W_q = \sum_{\lambda,\lambda'}\sum_{c,c'}\int dp^+ d\vec{x}_\perp B^\dagger_{\lambda',c'}(p^+,\vec{x}_\perp)\left[\frac{m^2\delta_{c,c'} + (\vec{p}_\perp\delta_{c,c'} - g\vec{\mathscr{A}}_{\perp,c'c})^2}{p^+}\delta_{\lambda,\lambda'} + 2g\mathscr{A}_{+,c'c}\delta_{\lambda,\lambda'} - g\frac{\mathscr{B}_{x,c'c}\sigma^3_{\lambda',\lambda}}{p^+}\right]B_{\lambda,c}(p^+,\vec{x}_\perp)$$

which can be written is a more compact form as in slide (16) in the quantum many-body representation

Direct evaluation of momentum broadening

$$\boxed{\langle (\delta p_i^{kin}(x^+))^2 \rangle_\psi = \langle (p_i^{kin}(x^+))^2 \rangle_\psi + \langle (p_i^{kin}(0))^2_\psi \rangle - 2\Re \langle p_i^{kin}(x^+) p_i^{kin}(0) \rangle_\psi}$$

$$\langle (p_i^{kin}(x^+))^2 \rangle_\psi = \langle \psi; x^+ | \left(p_i - g\mathscr{A}_i(x^+)\right)^2 | \psi; x^+ \rangle \qquad \langle (p_i^{kin}(0))^2 \rangle_\psi = \langle \psi; 0 | \left(p_i - g\mathscr{A}_i(0)\right)^2 | \psi; 0 \rangle$$

$$\begin{aligned}\langle p_i^{kin}(x^+) p_i^{kin}(0) \rangle_\psi &= \langle \psi; 0 | U^\dagger(x^+; 0) p_i^{kin}(x^+) U(x^+; 0) p_i^{kin}(0) | \psi; 0 \rangle \\ &= \langle \psi; x^+ | p_i - g\mathscr{A}_i(x^+) | \tilde{\psi}_i; x^+ \rangle\end{aligned}$$

where we have defined the auxiliary state

$$|\tilde{\psi}_i; 0 \rangle \equiv p_i^{kin}(0) | \psi; 0 \rangle \,, \quad |\tilde{\psi}_i; x^+ \rangle = U(x^+; 0) | \tilde{\psi}_i; 0 \rangle$$

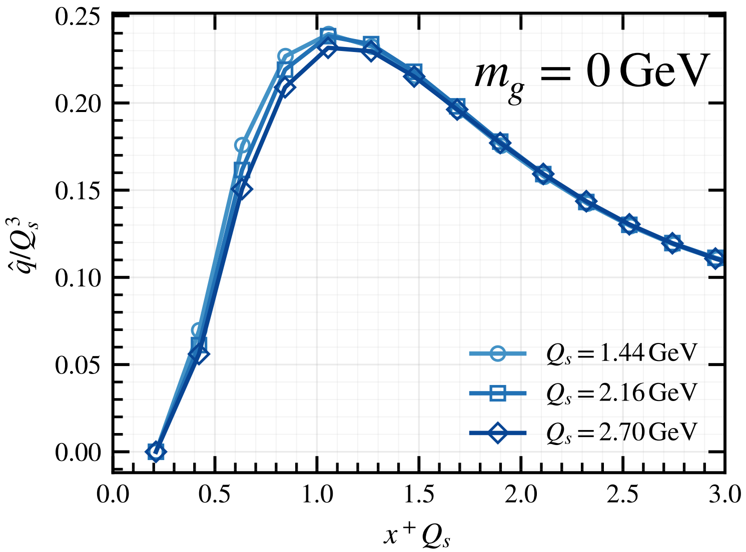
Abelian toy model for width sensitivity

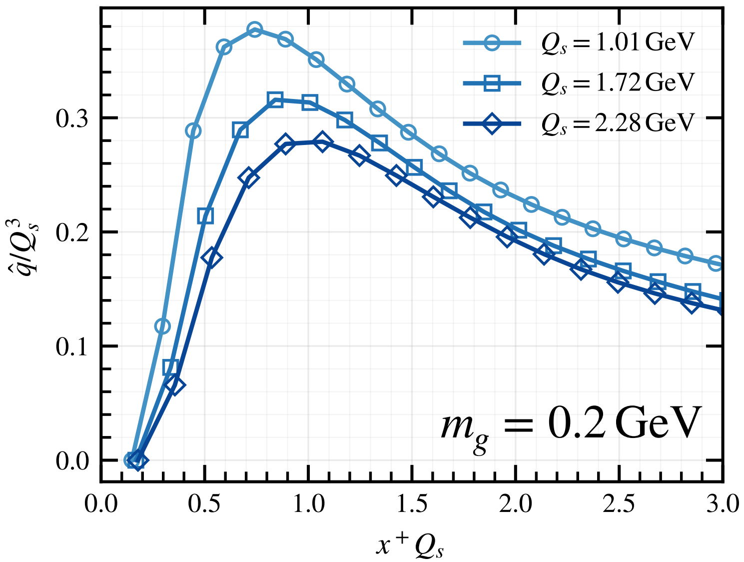
$$\langle(\delta p_y^{kin})^2\rangle = \frac{g^2}{4}\int_0^{x^+} ds^+ \int_0^{x^+} d\bar{s}^+ \left\langle \left[f_y(s^+)f_y(\bar{s}^+)\right]_{y=z=0} + \sigma_z^2 \left[\frac{4}{(s^+)^2}\partial_y \mathscr{A}_\eta\left(s^+\right)\frac{4}{(\bar{s}^+)^2}\partial_y \mathscr{A}_\eta\left(\bar{s}^+\right)\right]_{y=0}\right\rangle_{event}$$

$$\langle(\delta p_z^{kin})^2\rangle = \frac{g^2}{4}\int_0^{x^+} ds^+ \int_0^{x^+} d\bar{s}^+ \left\langle \left[f_z(s^+)f_z(\bar{s}^+)\right]_{y=z=0}\right\rangle_{event}$$

Momentum broadening in the z direction is insensitive to the wavepacket width, while momentum broadening in the y direction is sensitive to σ_z

Jet quenching parameter dependence on m_g





Q_s can be extracted from $g^2\mu$ and m_g through the Wilson line correlator **[Lappi (0711.3039)]**

- For $m_g = 0\,\mathrm{GeV}$ the size and position of the peak shows a **perfect scaling with $\mathbf{Q_s}$**
- For $m_g = 0.2\,\mathrm{GeV}$ the **exact scaling breaks** but **the approximate behavior holds**

[Avramescu, CL, Lappi, Li, Salgado (2605.10413)]