

华中科技大学

HUAZHONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Quantum simulation of dijet production in a QCD medium

Meijian Li 李枚键

Based on arXiv:2604.11616, JHEP 07 (2026) 063

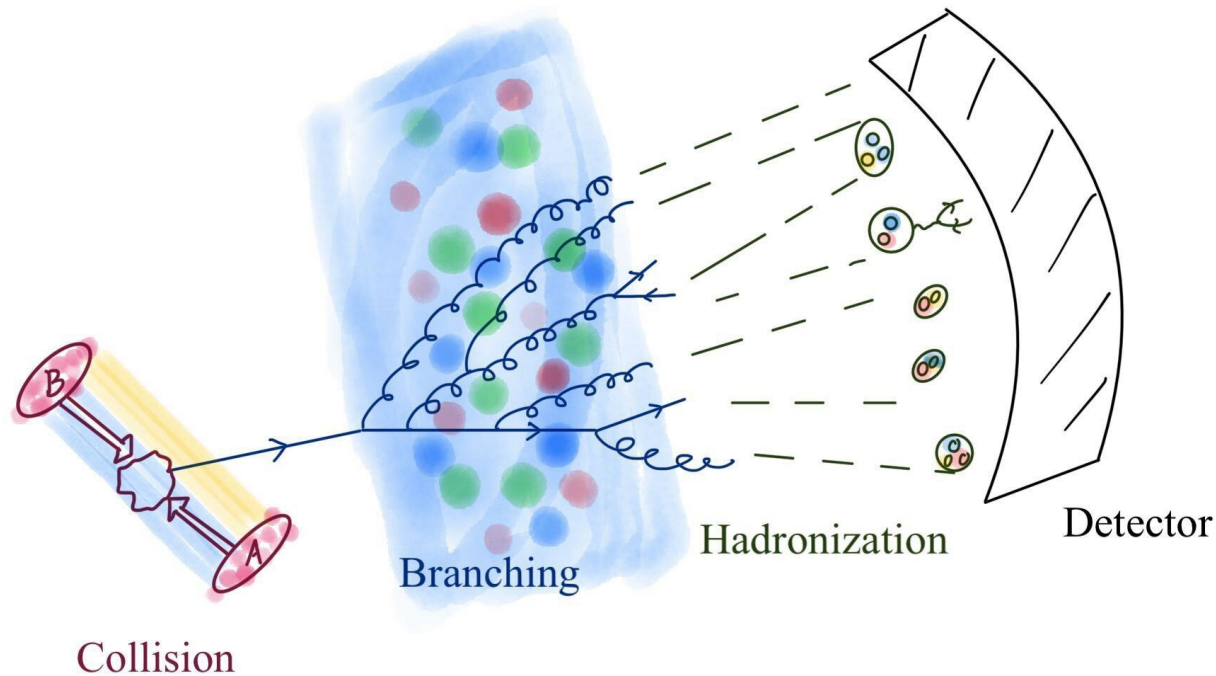
In collaboration with J. Barata(BNL), W. Qian(CCNU), C. A. Salgado(IGFAE) and J. M. Silva(UCLA)

第十二届中国 LHC 物理会议 (CLHCP2026)

October 28-November 1, 2026, Wuhan, China

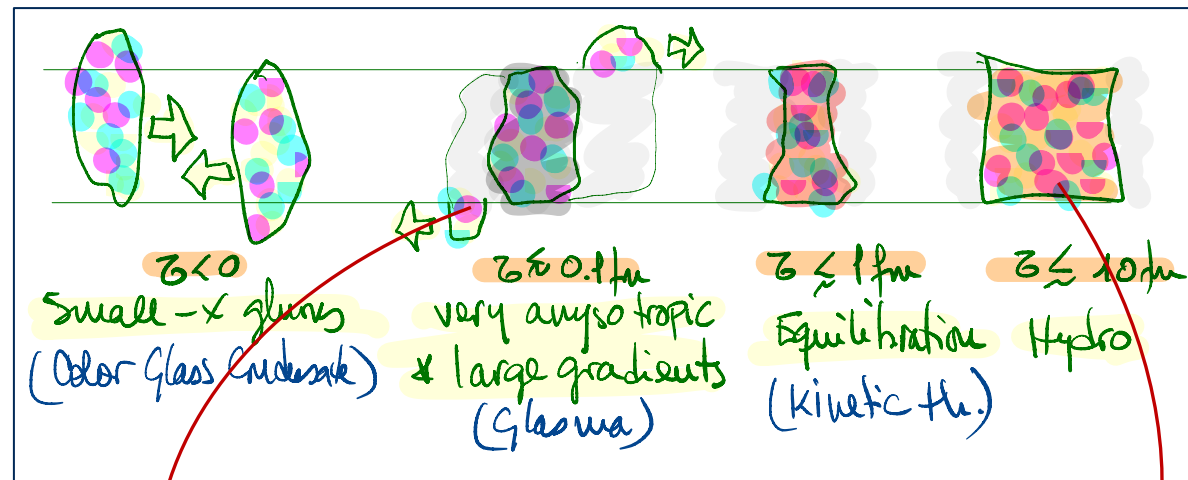
Jets in High-Energy Physics

- In high-energy collisions, **jets** are collimated beams of particles produced by the splitting of a common ancestor (quark or gluon).
 - Jets are **energetic QCD states** that evolve, radiate, and interact with the surrounding medium (e.g., quark-gluon plasma).
- The **perfect probes** to study QCD matter and space-time evolution!



Time evolution of HIC

➤ The (most) Standard Model of HIC

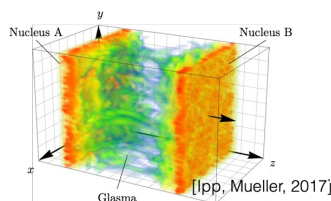


[Figure adapted from C. A. Salgado]

Color Glass Condensate

strong field, weak coupling,
large occupation numbers

classical fields by Yang-Mills eq.



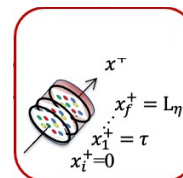
$$\partial_\tau \mathcal{P}^i = \tau \left[\mathcal{D}_i, \mathcal{F}_{ji} \right] - \frac{ig}{\tau} \left[\mathcal{A}_\eta, \left[\mathcal{D}_i, \mathcal{A}_\eta \right] \right],$$

$$\partial_\tau \mathcal{P}^\eta = \frac{1}{\tau} \left[\mathcal{D}_i, \left[\mathcal{D}_i, \mathcal{A}_\eta \right] \right],$$

Gaussian medium model

weakly coupled thermal plasma,
multiple soft scatterings,
many independent scattering centers

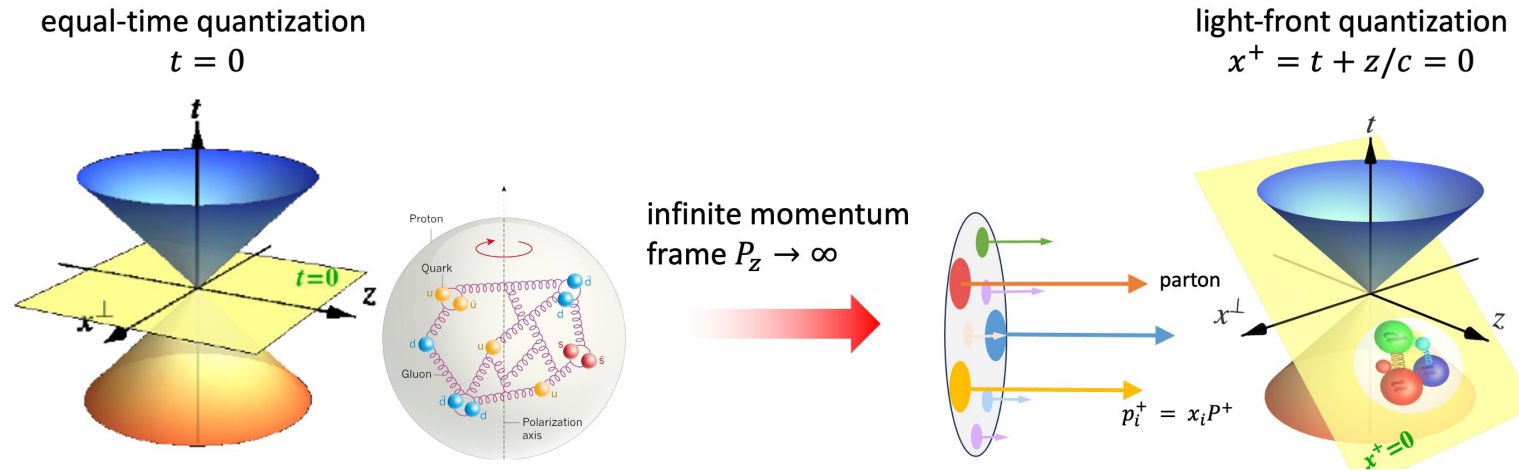
classical fields by Yang-Mills eq.



$$\langle \rho_a(x) \rho_b(y) \rangle = g^2 \tilde{\mu}^2 \delta_{ab} \delta^3(\vec{x} - \vec{y}),$$

$$(m_g^2 - \nabla_\perp^2) \mathcal{A}_a^-(x^+, \vec{x}_\perp) = \rho_a(x^+, \vec{x}_\perp)$$

Light Front Quantization



[Figure adapted from Yang Li]

- Bound states are solved from eigenvalue equations

$$P_{QCD}^- |\phi\rangle = P_\phi^- |\phi\rangle \Leftrightarrow \underbrace{(P_{QCD}^- P^+ - \vec{P}_\perp^2)}_{H_{LC} \text{ boost invariant}} |\psi_h(P, j, m_j)\rangle = M_h^2 |\psi_h(P, j, m_j)\rangle$$

- Evolution of a quantum state follows the Schrödinger equation

$$\frac{1}{2} P^- |\psi(x^+)\rangle = i \frac{\partial}{\partial x^+} |\psi(x^+)\rangle \quad \text{➤ Jet evolves through the medium in real time}$$

Discretization

- Fock sector expansion of quantum states: $|q\rangle_{\text{jet}} = \psi_q|q\rangle + \psi_{qg}|qg\rangle + \psi_{qgg}|qgg\rangle + \dots$

$$|g\rangle_{\text{jet}} = \psi_g|g\rangle + \psi_{gg}|gg\rangle + \psi_{ggg}|ggg\rangle + \dots$$

$$|\gamma^*\rangle_{\text{phys}} = \psi_\gamma|\gamma^*\rangle + \psi_{q\bar{q}}|q\bar{q}\rangle + \psi_{qqg}|qq\bar{q}\rangle + \dots$$

$$|q(\beta)\rangle = b_\beta^\dagger|0\rangle,$$

$$|\bar{q}(\beta)\rangle = d_\beta^\dagger|0\rangle,$$

$$|g(\beta)\rangle = a_\beta^\dagger|0\rangle.$$

$$|\psi(x^+)\rangle = \sum_{\beta} c_{\beta}(x^+)|\beta\rangle$$

Each single-particle basis state is labeled by five quantum numbers:

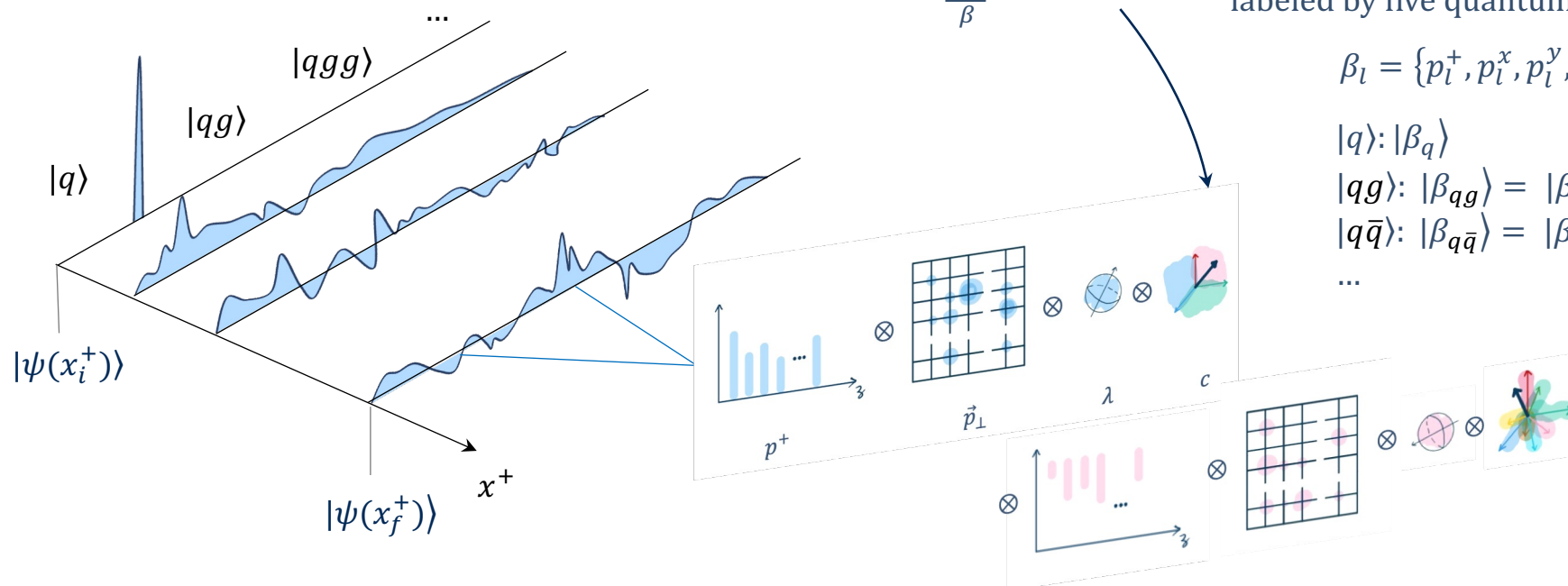
$$\beta_l = \{p_l^+, p_l^x, p_l^y, \lambda_l, c_l\}, (l = q, \bar{q})$$

$$|q\rangle: |\beta_q\rangle$$

$$|qg\rangle: |\beta_{qg}\rangle = |\beta_q\rangle \otimes |\beta_g\rangle$$

$$|q\bar{q}\rangle: |\beta_{q\bar{q}}\rangle = |\beta_q\rangle \otimes |\beta_{\bar{q}}\rangle$$

...



Discretization → Digitization

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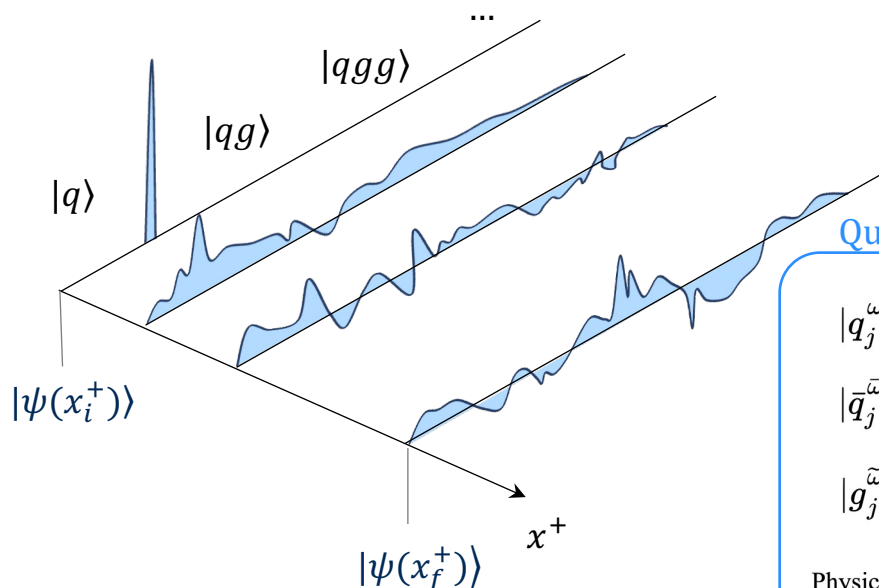
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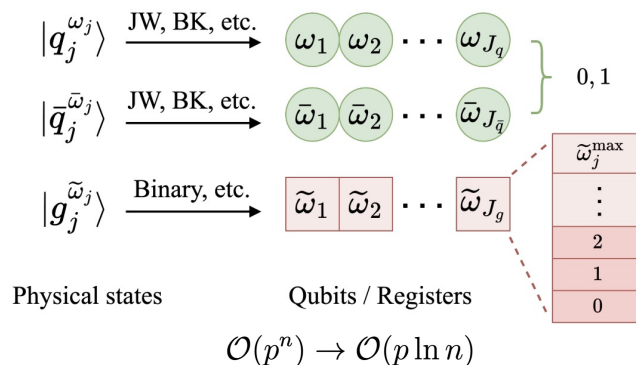
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...



Quantum implementation: Encoding



Evolution

- **Non-perturbative:** time evolution operator into a product of many sequential timesteps

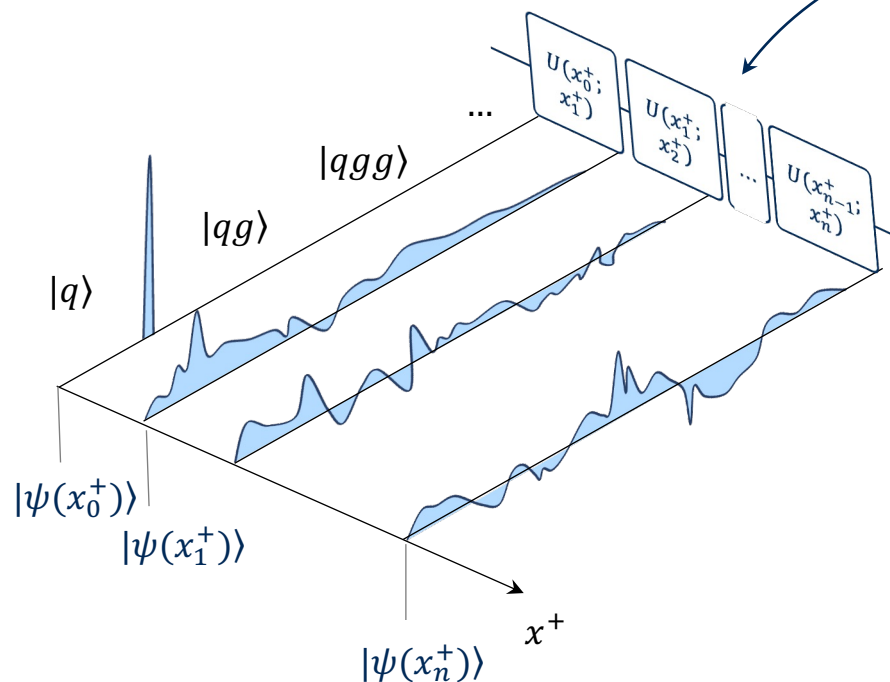
$$|\psi(x^+)\rangle = \mathcal{T}_+ e^{-\frac{i}{2} \int_0^{x^+} dz^+ P^-(z^+)} |\psi(0)\rangle$$

$\equiv U(x^+; 0)$

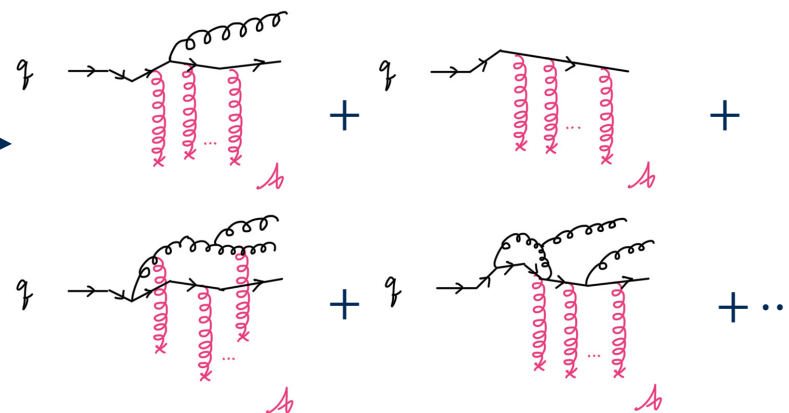
Trotterization

$$\prod_{k=1}^n \mathcal{T}_+ \exp \left[-\frac{i}{2} \int_{x_{k-1}^+}^{x_k^+} dz^+ P^-(z^+) \right] |\psi(0)\rangle$$

in which $\delta x^+ = x^+/n$, $x_k^+ = k\delta x^+$ ($k = 0, 1, 2, \dots, n$).



automatically **going beyond eikonal**
and include **quantum interference**
at every timestep:



Evolution → Trotterization

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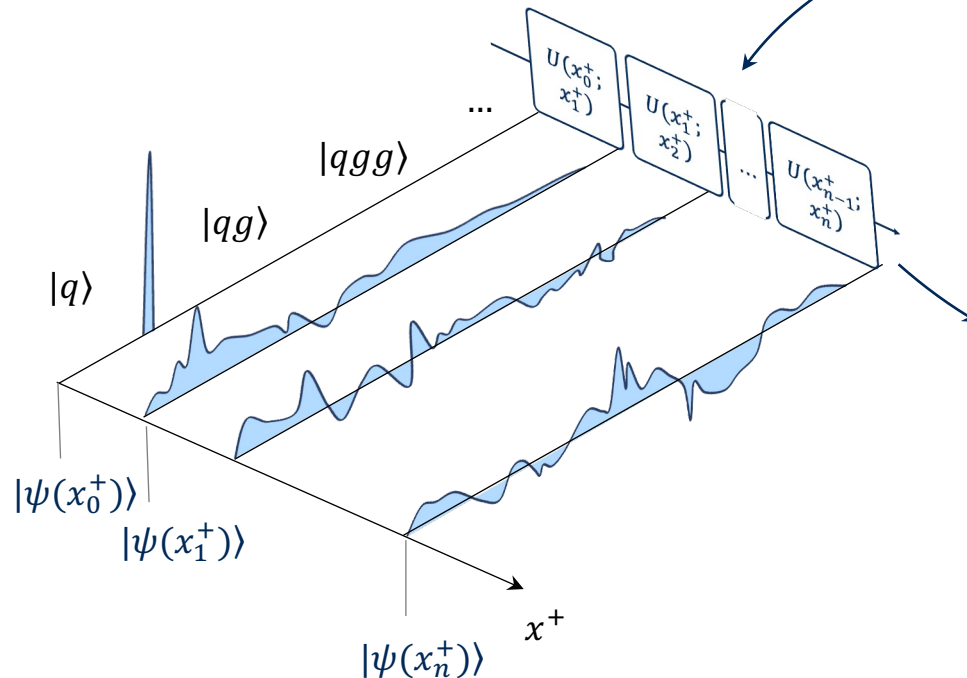
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Trotterization

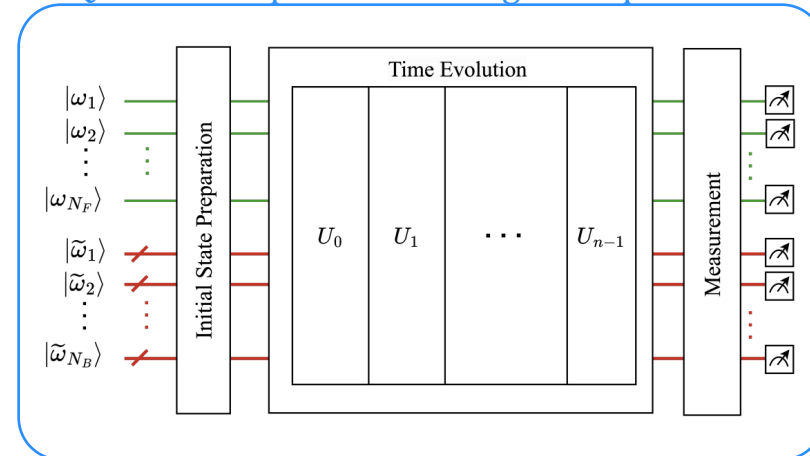
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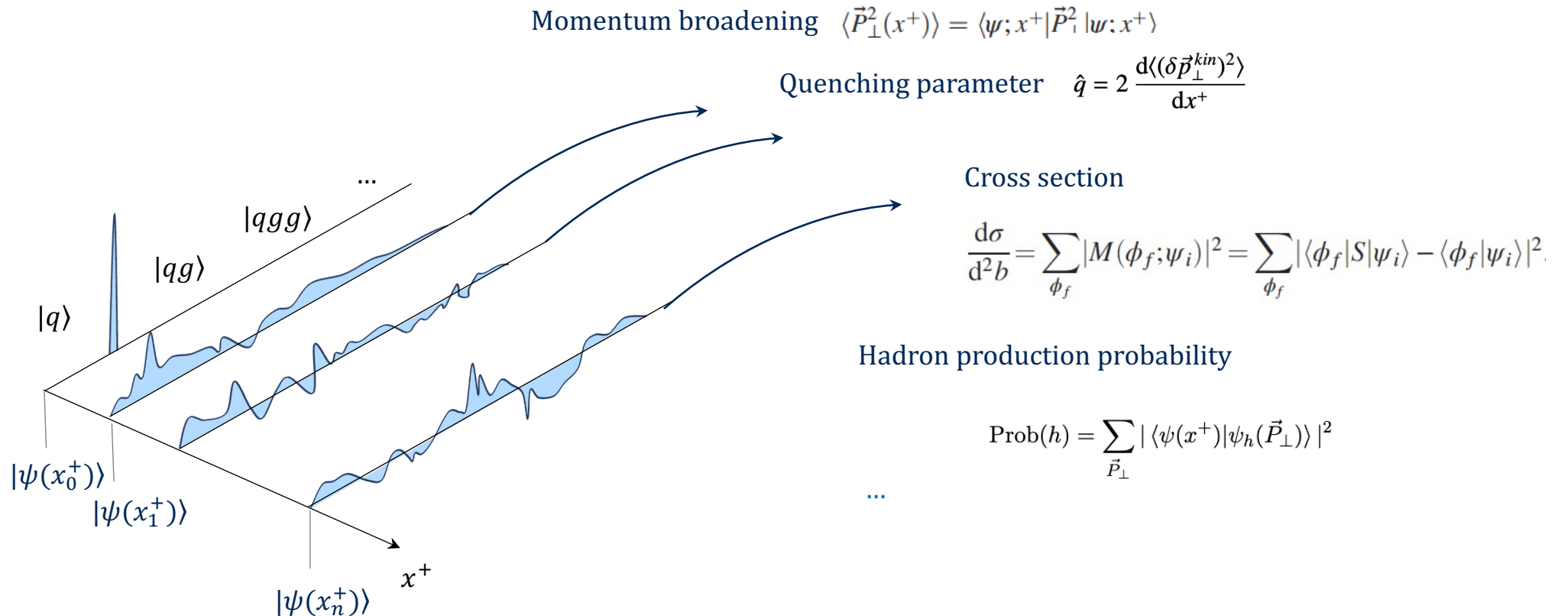


Quantum implementation: gate sequence



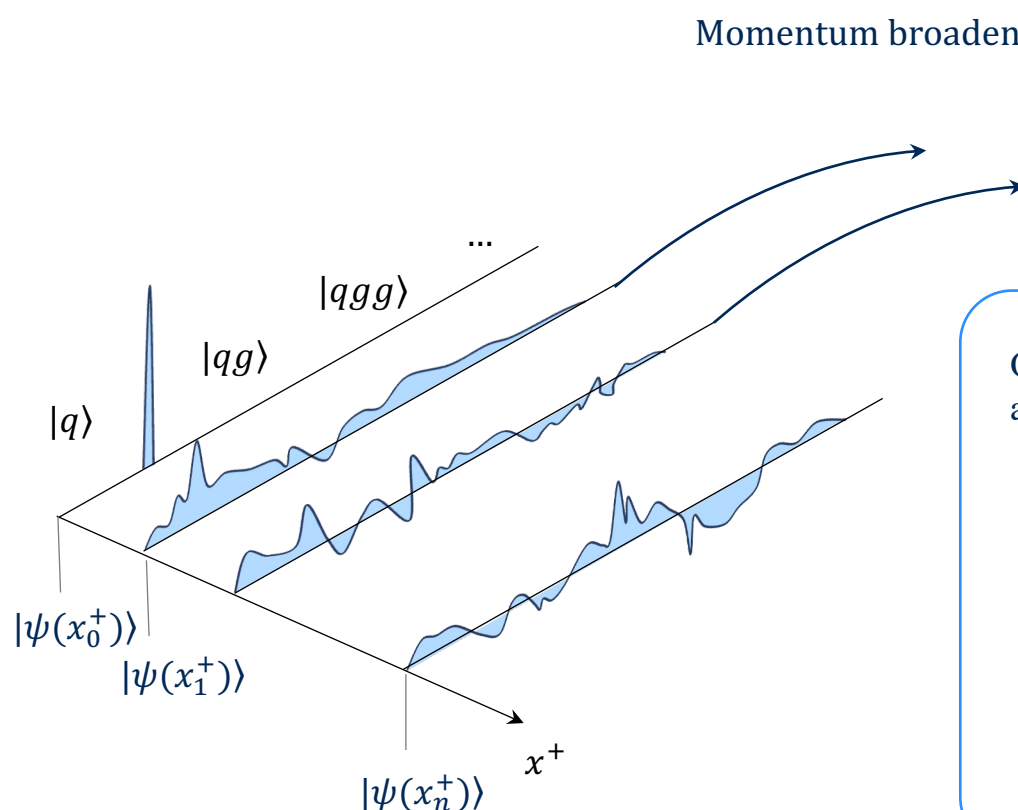
Observables

- Evaluation of physical quantities is **directly** from the quantum state : $O(x^+) = \langle \psi(x^+) | \hat{O} | \psi(x^+) \rangle$



Observables → Measurement

- Evaluation of physical quantities is **directly** from the quantum state : $O(x^+) = \langle \psi(x^+) | \hat{O} | \psi(x^+) \rangle$



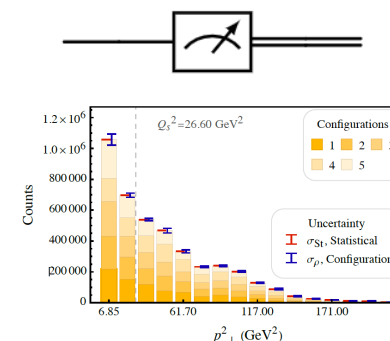
Quantum implementation: measurement

Quantum state
amplitude

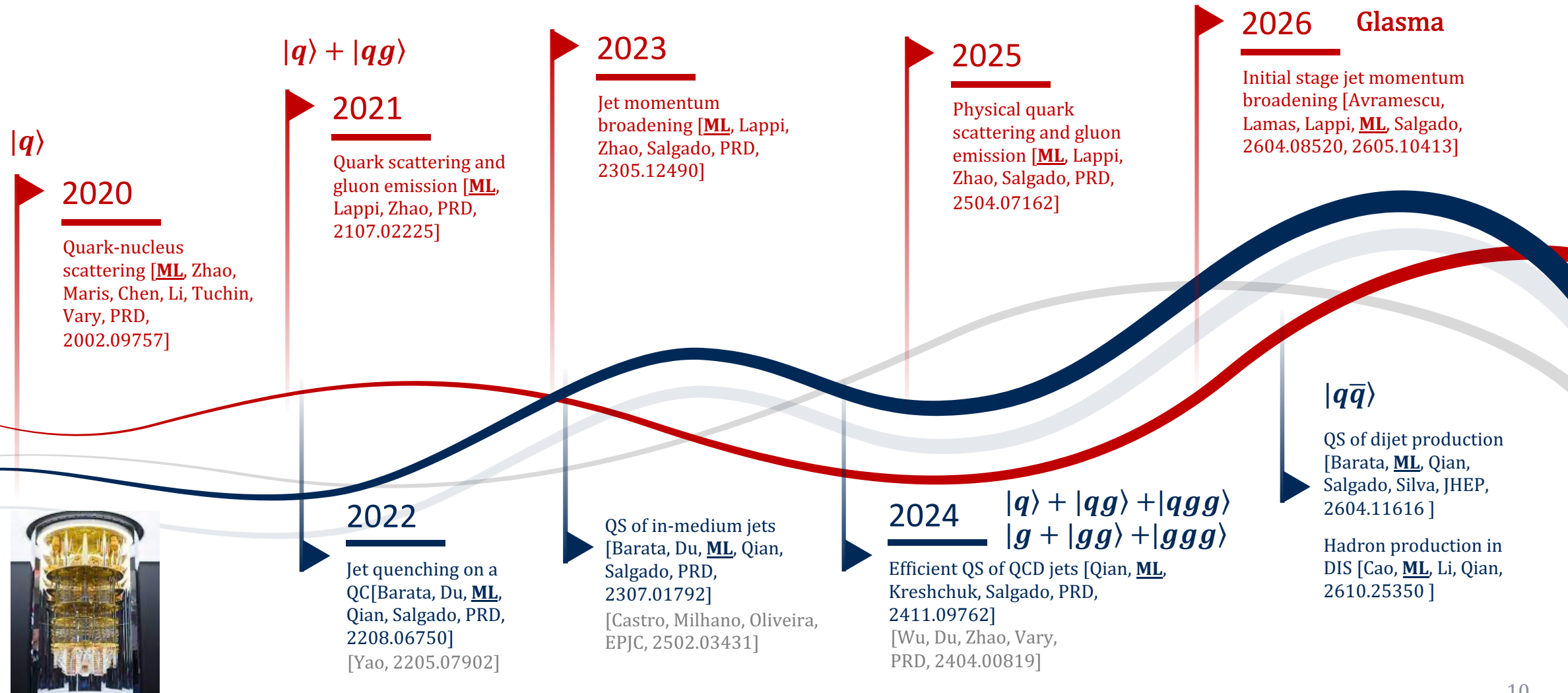
$$\begin{pmatrix} c_1 \\ \vdots \\ c_i \\ \vdots \\ c_n \end{pmatrix}$$

Classical state
 $P_i = |c_i|^2$

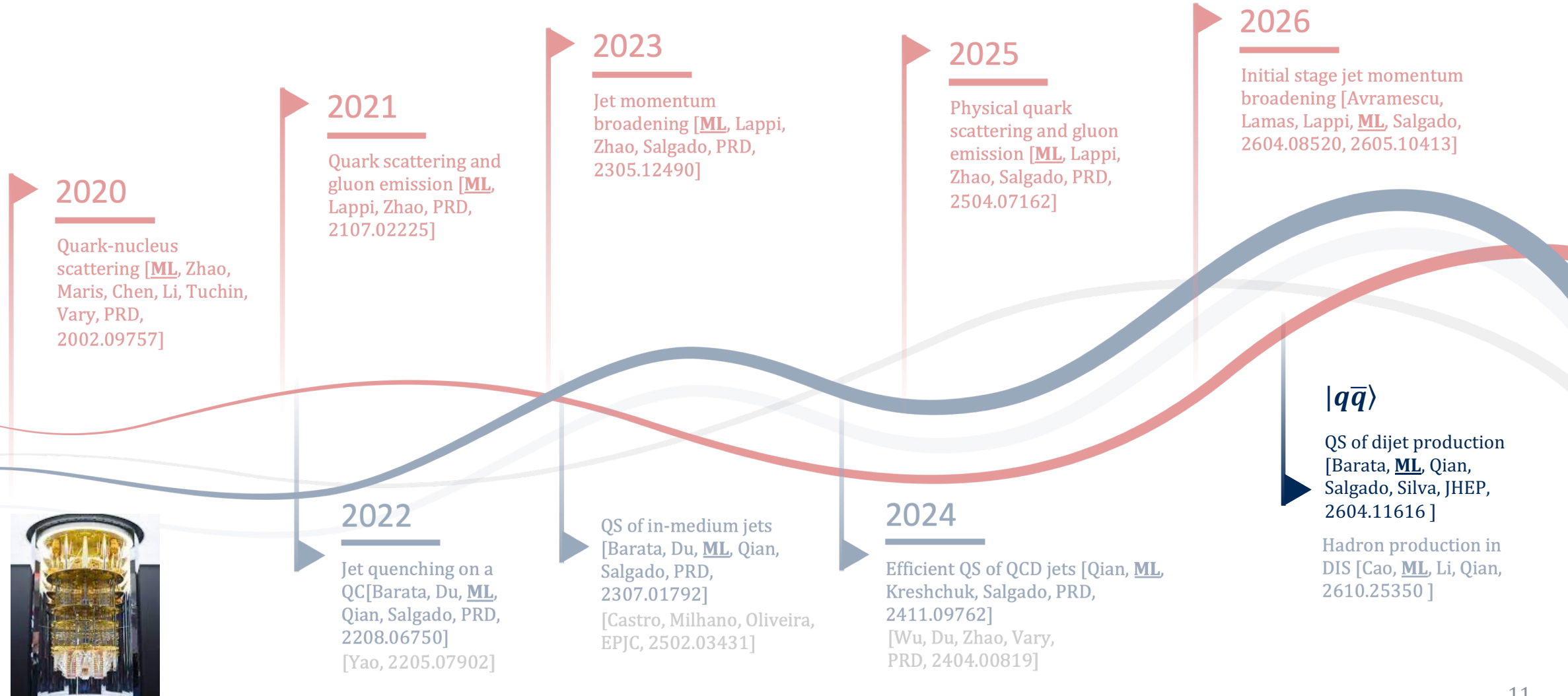
$$\begin{pmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{pmatrix}$$



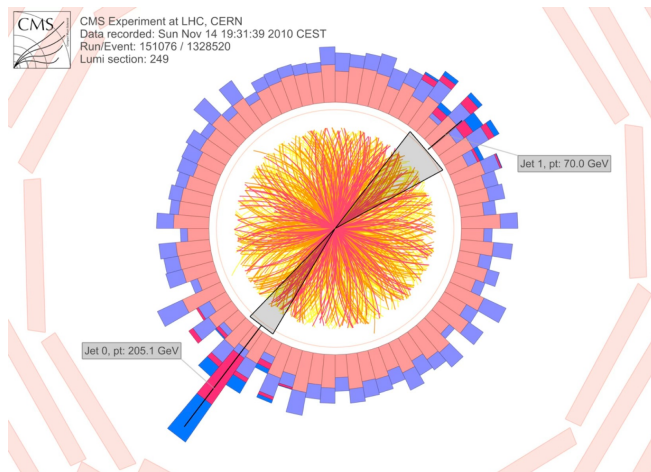
Progress: Real-time Jet classical quantum Simulations



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Dijet production in medium



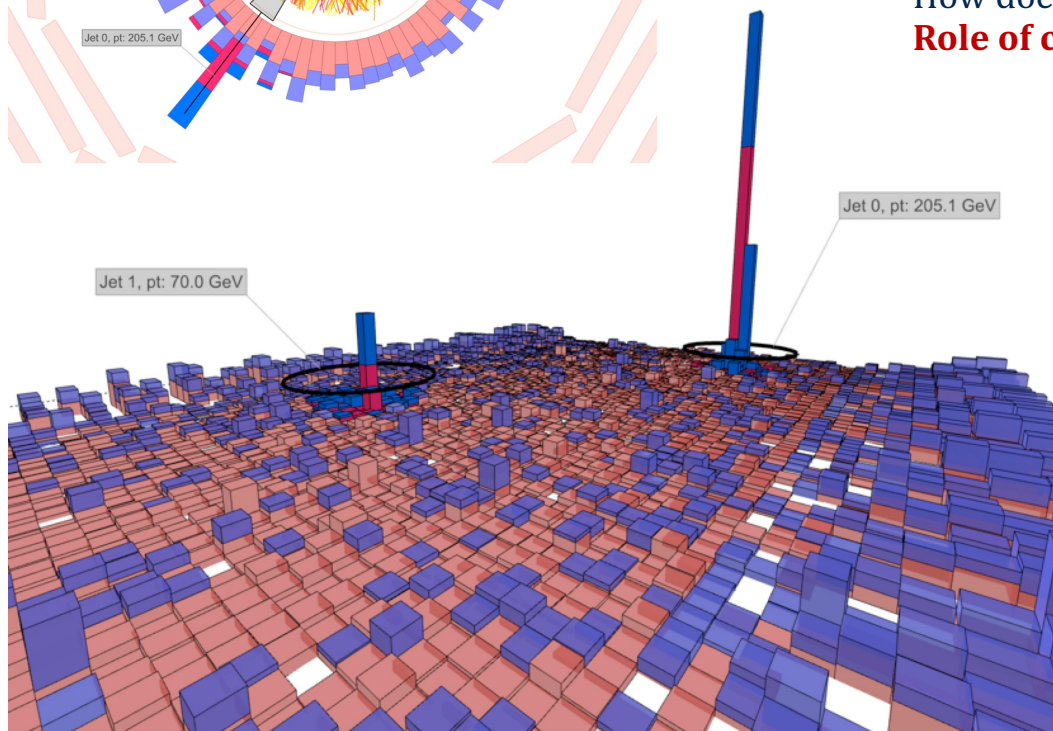
- **Key Observables at RHIC & LHC**

Dijet asymmetry and azimuthal decorrelation were among the **earliest signatures of jet quenching** in heavy-ion collisions.

- **Theoretical description**

How does the medium modify the antenna radiation pattern?

Role of color coherence



QCD antenna in vacuum - radiation within the two cones (quark and antiquark)

$$\left| \bar{u}^* \langle \text{quark} \rangle + \bar{u}^* \langle \text{antiquark} \rangle \right|^2$$

$$\omega \frac{dN}{d\omega d\theta} \sim \alpha_s G_F \left[R_q - J + R_{\bar{q}} - J \right]$$

The QCD medium can break color coherence - independent color rotation of q and qbar

$$\left| \bar{u}^* \langle \text{quark} \rangle + \bar{u}^* \langle \text{antiquark} \rangle \right|^2$$

$$\omega \frac{dN}{d\omega d\theta} \sim \alpha_s G_F \left[R_q - S_{q\bar{q}} J + R_{\bar{q}} - S_{\bar{q}q} J \right]$$

[Figure adapted from C. A. Salgado]

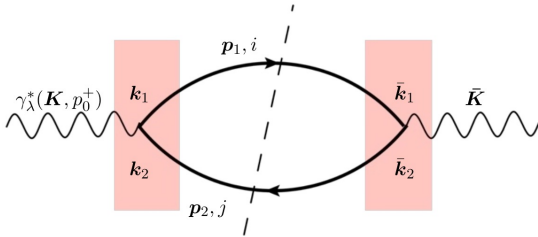
Dijet production in medium

- How to quantify medium effect on dijet production?

➤ Medium modification factor F_{med}

$$(2\pi) \frac{d\sigma}{dz d^2p} = (2\pi) \frac{d\sigma^{\text{vac}}}{dz d^2p} (1 + F_{\text{med}}(p^2, z))$$

- The usual perturbative calculation:



Start by writing down the amplitude

$$i\mathcal{M}^{ij,h,h'}(p_1, p_2, z, p_0^+) = \frac{e^{i(\frac{p_1^2}{2p_0^+} + \frac{p_2^2}{2p_0^+})x^+}}{2p_0^+} \sum_{\lambda=\pm 1} \int_{x^+, k_1, k_2} e^{-ix^+} i e V^{\lambda,h,h'}(\kappa, z) \times \mathcal{M}_0^\lambda(K, p_0^+) e^{-i\frac{\kappa^2}{2p_0^+}x^+} G^{ik}(x_\infty^+, p_1^+; x^+, k_1^+; p_1^+) \bar{G}^{kj}(x_\infty^+, p_2^+; x^+, k_2^+; p_2^+)$$

Obtain the cross sections

$$\begin{aligned} \frac{(2\pi)^3 d\sigma}{d^3\Omega_0 dz d^2p} &= \frac{1}{2z(1-z)} \sum_{i,j} \sum_{h,h'} |\mathcal{M}^{ij,h,h'}(p_1, p_2, z, p_0^+)|^2 \\ &= N_c e^2 P_{T1}(z) \sum_{\lambda=\pm 1} \left(\frac{1}{2\omega^2} \text{Re} \int_0^L dx^+ \int_t^L d\bar{x}^+ \int_{k_1, k_2, \bar{k}_1, \bar{k}_2} \right. \\ &\quad \mathcal{M}_0^\lambda(K) \mathcal{M}_0^{\lambda\dagger}(\bar{K}) (\kappa \cdot \bar{\kappa}) e^{-i\frac{\kappa^2}{2p_0^+}x^+} e^{i\frac{\bar{\kappa}^2}{2p_0^+}\bar{x}^+} C_4 - \frac{1}{p^2 \omega} \text{Re} i \int_0^L dx^+ \int_{k_1, k_2} \\ &\quad \left. \mathcal{M}_0^\lambda(K) \mathcal{M}_0^{\lambda\dagger}(P) (\kappa \cdot p) e^{-i\frac{\kappa^2}{2p_0^+}x^+} e^{i\frac{p^2}{2p_0^+}L} C_2 + \frac{|\mathcal{M}_0^\lambda(P)|^2}{p^2} \right). \end{aligned}$$

Extract F_{med}

$$\begin{aligned} F_{\text{med}}(p^2, z) &= \frac{p^2}{2\omega^2} \text{Re} \int_0^L dx^+ \int_{x^+}^L d\bar{x}^+ \int_{k_1, k_2, \bar{k}_1, \bar{k}_2} (\kappa \cdot \bar{\kappa}) e^{iK^2/2p_0^+ (\bar{x}^+ - x^+)} C_4|_{P=0} \\ &\quad - \frac{1}{\omega} \text{Re} i \int_0^L dx^+ \int_{k_1, k_2} (\kappa \cdot p) C_2|_{P=0} . \\ \int_{K, \bar{K}} e^{iK^2/2p_0^+ (\bar{x}^+ - x^+)} C_4|_{P=0} &= \int_q Q(p, q, \bar{\kappa}; L, \bar{x}^+) \mathcal{K}(q, \kappa; \bar{x}^+, x^+), \\ \int_K C_2|_{P=0} &= \mathcal{K}(p, \kappa; L, x^+), \end{aligned}$$

$$\begin{aligned} (F_{\text{med}})^{\text{HO, fctr.}}(p^2, z) &= -\frac{p^2}{2\omega} 2\text{Re} i \int_0^L dx^+ \left(\frac{C_2}{C_3} \right) e^{\frac{ip^2}{2\omega t}} - 2\text{Re} \left(1 - e^{-\frac{ip^2 \tan \Omega L}{2\omega t}} \right) \\ c_1(x^+) &= \frac{\Omega}{2i \sin \Omega x^+}, \quad c_2(x^+) = \frac{\Omega}{\tan \Omega x^+}, \\ c_3(x^+, \bar{x}^+) &= x^+ \left(-i \frac{\hat{q}(z^2 + (1-z)^2)}{2\omega} \right) - c_2(\bar{x}^+), \end{aligned}$$

Analytical derivations become too complicated,

approximations (large N_c , harmonic oscillator, factorizable assumption,...) are introduced!

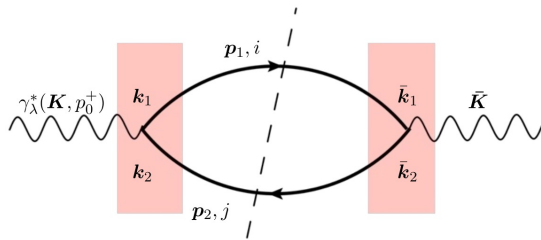
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How well do they work?

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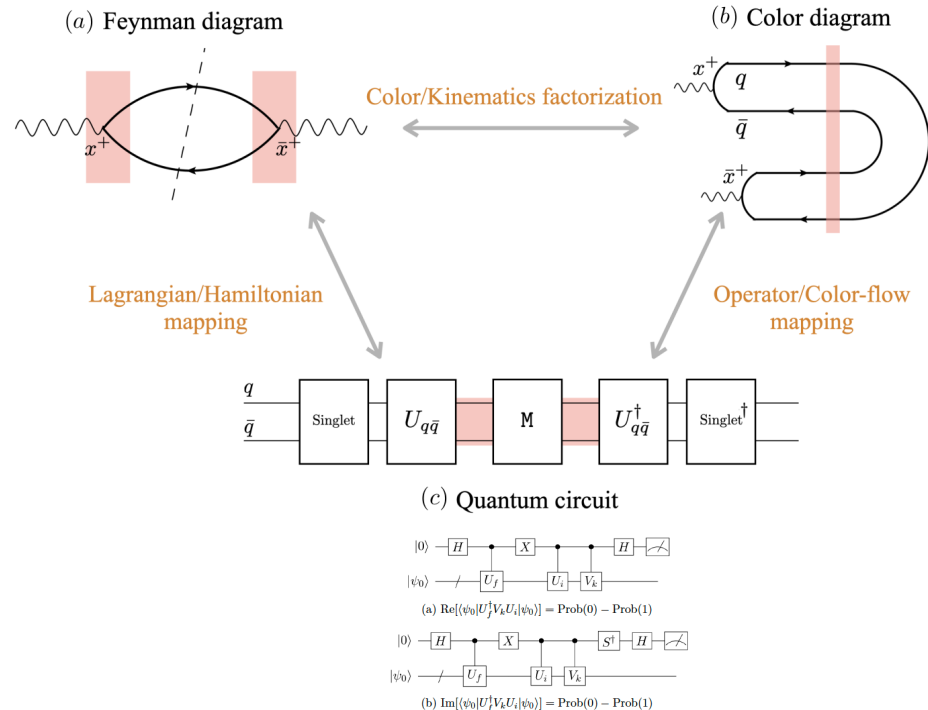
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- Light-front Hamiltonian + Quantum Simulation (QS) implementation



Real-time evolution of the dipole state

$$i \frac{\partial}{\partial x^+} |\psi; x^+\rangle = \frac{1}{2} P^-(x^+) |\psi; x^+\rangle \quad P^-(x^+) = P_{\text{KE}}^- + V_{\mathcal{A}}(x^+) = (P_{\text{KE},q}^- + V_{\mathcal{A},q}(x^+)) + (P_{\text{KE},\bar{q}}^- + V_{\mathcal{A},\bar{q}}(x^+))$$

Forward evolution

$$|\psi_R\rangle = U_{q\bar{q}}(L, x^+) |\psi_s(\mathbf{k}_1, \mathbf{k}_2)\rangle$$

Projector operation

$$I \otimes \mathbb{M} \otimes I = \sum_{i,j} |q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, j)\rangle \langle q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, j)|, \\ t^a \otimes \mathbb{M} \otimes t^a = \sum_{i,j,k,m} t_{km}^a t_{ij}^a |q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, m)\rangle \langle q(\mathbf{p}_1, j), \bar{q}(\mathbf{p}_2, k)|$$

Backward evolution

$$|\psi_L\rangle = U_{q\bar{q}}(L, \bar{x}^+) |\psi_s(\bar{\mathbf{k}}_1, \bar{\mathbf{k}}_2)\rangle$$

Approximations **NOT** needed!

Ensemble into F_{med}

$$\mathcal{C}_2 = \langle \langle \psi_s(\mathbf{p}_1, \mathbf{p}_2) | \psi_R \rangle \rangle,$$

$$\mathcal{C}_4 = \langle \langle \psi_L | (I \otimes \mathbb{M} \otimes I) | \psi_R \rangle \rangle,$$

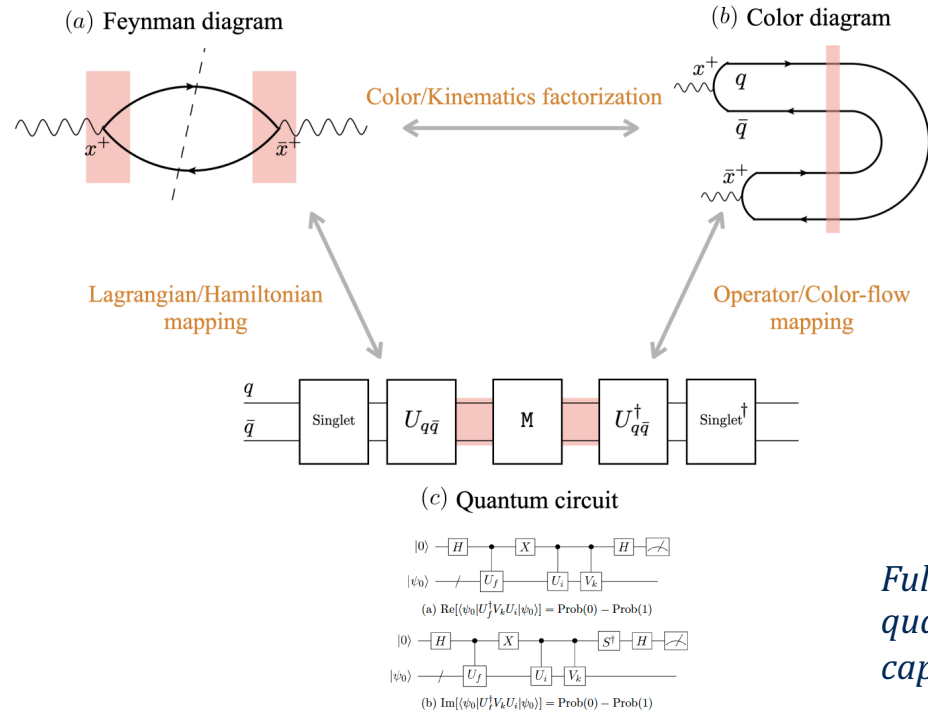
$$F_{\text{med}}(\mathbf{p}^2, z) = \frac{p^2}{2\omega^2} \text{Re} \int_0^L dx^+ \int_{x^+}^L d\bar{x}^+ \int_{\mathbf{k}_1, \mathbf{k}_2, \bar{\mathbf{k}}_1, \bar{\mathbf{k}}_2} (\kappa \cdot \bar{\kappa}) e^{i\mathbf{K}^2/2p_0^+ (\bar{x}^+ - x^+)} \mathcal{C}_4|_{\mathbf{p}=0} \\ - \frac{1}{\omega} \text{Re} i \int_0^L dx^+ \int_{\mathbf{k}_1, \mathbf{k}_2} (\kappa \cdot \mathbf{p}) \mathcal{C}_2|_{\mathbf{p}=0}.$$

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$$|\psi_R\rangle = U_{q\bar{q}}(L, x^+) |\psi_s(\mathbf{k}_1, \mathbf{k}_2)\rangle$$

Projector operation

$$I \otimes \mathbb{M} \otimes I = \sum_{i,j} |q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, j)\rangle \langle q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, j)|, \\ t^a \otimes \mathbb{M} \otimes t^a = \sum_{i,j,k,m} t_{km}^a t_{ij}^a |q(\mathbf{p}_1, i), \bar{q}(\mathbf{p}_2, m)\rangle \langle q(\mathbf{p}_1, j), \bar{q}(\mathbf{p}_2, k)|$$

Backward evolution

$$|\psi_L\rangle = U_{q\bar{q}}(L, \bar{x}^+) |\psi_s(\bar{\mathbf{k}}_1, \bar{\mathbf{k}}_2)\rangle$$

Approximations **NOT** needed!

Ensemble into F_{med}

$$\mathcal{C}_2 = \langle \langle \psi_s(\mathbf{p}_1, \mathbf{p}_2) | \psi_R \rangle \rangle,$$

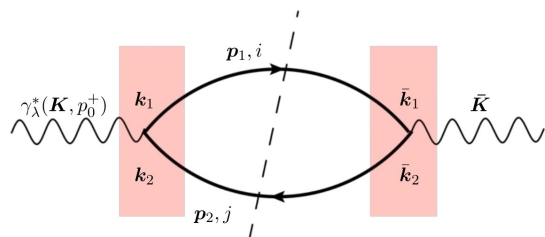
$$\mathcal{C}_4 = \langle \langle \psi_L | (I \otimes \mathbb{M} \otimes I) | \psi_R \rangle \rangle,$$

$$F_{\text{med}}(\mathbf{p}^2, z) = \frac{p^2}{2\omega^2} \text{Re} \int_0^L dx^+ \int_{x^+}^L d\bar{x}^+ \int_{\mathbf{k}_1, \mathbf{k}_2, \bar{\mathbf{k}}_1, \bar{\mathbf{k}}_2} (\kappa \cdot \bar{\kappa}) e^{i\mathbf{K}^2/2p_0^+ (\bar{x}^+ - x^+)} \mathcal{C}_4|_{\mathbf{p}=0} \\ - \frac{1}{\omega} \text{Re} i \int_0^L dx^+ \int_{\mathbf{k}_1, \mathbf{k}_2} (\kappa \cdot \mathbf{p}) \mathcal{C}_2|_{\mathbf{p}=0}.$$

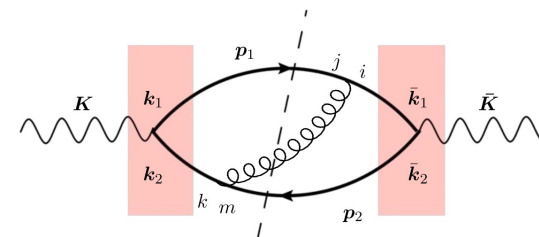
Full color structure,
quantum interference
captured!

Medium modification

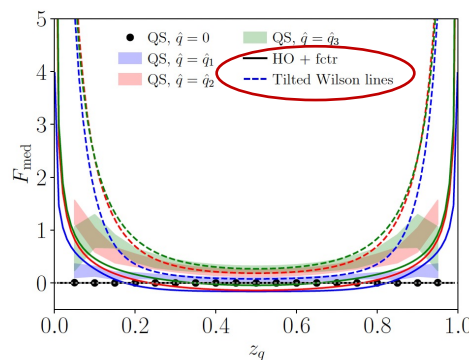
- Dipole formation in medium



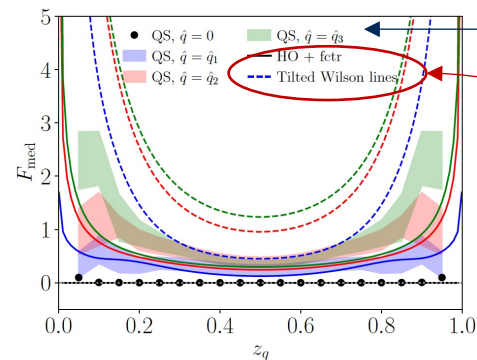
- Medium induced radiation



$$(2\pi) \frac{d\sigma}{dz d^2\mathbf{p}} = (2\pi) \frac{d\sigma^{\text{vac}}}{dz d^2\mathbf{p}} (1 + F_{\text{med}}(\mathbf{p}^2, z))$$



(a) $p^2 = 0.62 \text{ GeV}^2$

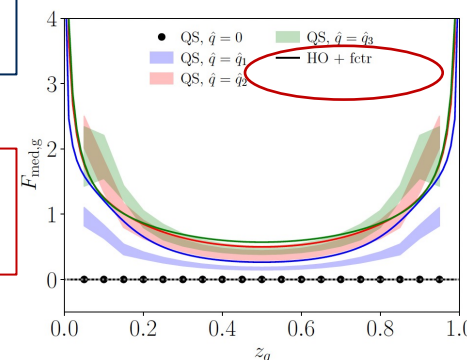


(b) $p^2 = 1.23 \text{ GeV}^2$

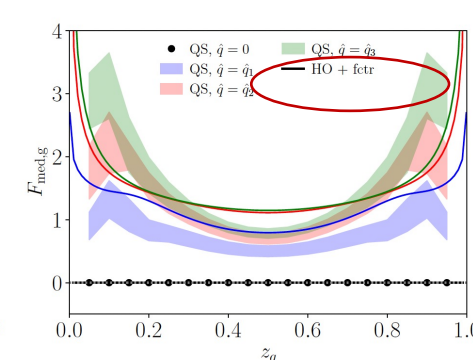
relative momentum $\mathbf{p} = (1 - z)\mathbf{p}_1 - z\mathbf{p}_2$

Quantum Simulation (QS)

analytical estimates with approximations



(a) $p^2 = 0.62 \text{ GeV}^2$



(b) $p^2 = 1.23 \text{ GeV}^2$

- QS results agree very well with analytical estimates in the *vacuum* case
- QS results show notable deviations in the *medium* cases, reflecting limitations of analytical approximations

Summary and Outlook

- ✓ We developed and applied a **non-perturbative** LF Hamiltonian approach to simulate the **real-time** evolution of dijet production in medium
 1. analyzed dipole formation and QCD antenna radiation pattern
 2. NOT relying on various approximations (large N_c , harmonic oscillator, factorizable,...)
 3. built Quantum Simulation framework including circuit implementation

Next:

- Inclusion of higher Fock sector contribution, $|\gamma^*\rangle_{phys} = |\gamma^*\rangle + |q\bar{q}\rangle + |q\bar{q}g\rangle + \dots$
- Direct photon state preparation on quantum circuit

Thank you!