INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS IGFAE

Light-Front Hamiltonian Approach to QCD Jets in the Quantum Era

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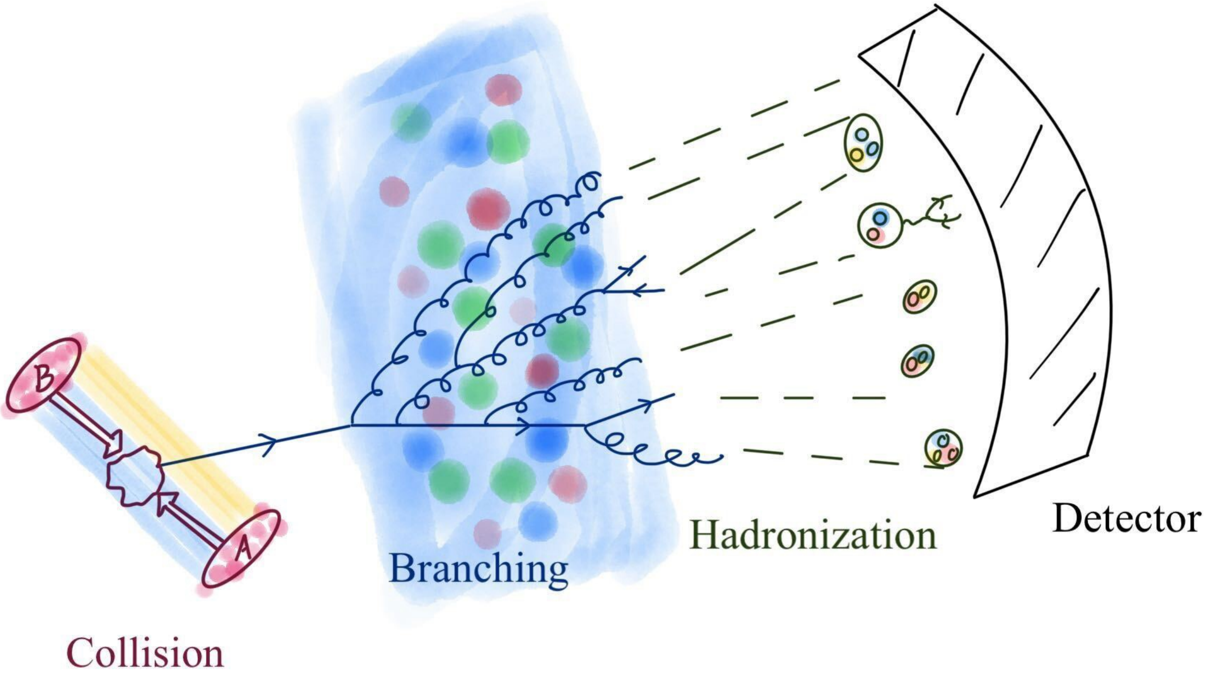
Outline

1. **Jets in High-Energy Physics**
2. LF Hamiltonian Approach for QCD jets in 3+1 D
3. From Classical to Quantum Simulations
4. Towards the Full Jet Process

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!



Jets in High-Energy Physics

Challenges and open questions:

- **Non-perturbative effects,** beyond eikonal and classical-path approximations
- **Quantum interference**
- **Hadronization process** from first-principles
    - ➢ Understanding the **real-time dynamics** of jet in QCD matter!

- ❑ *Hamiltonian lattice QCD*
- ❑ *Equal-time Hamiltonian*
- ❑ *Light-Front Hamiltonian*

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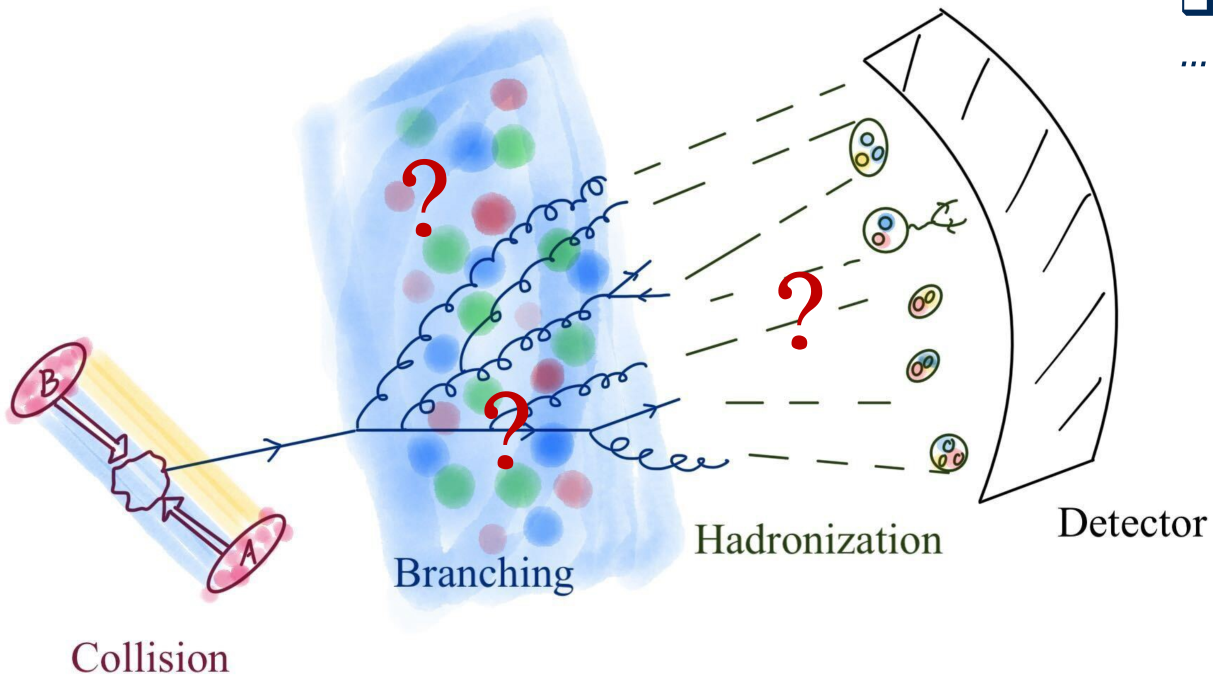

Outline

1. Jets in High-Energy Physics
2. **LF Hamiltonian Approach for QCD jets in 3+1 D**
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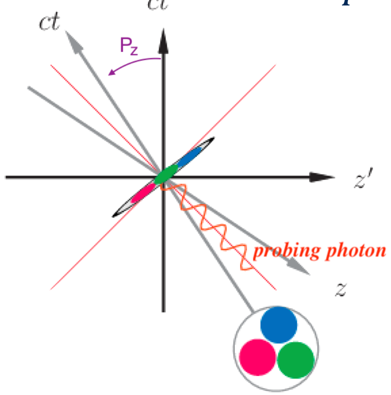
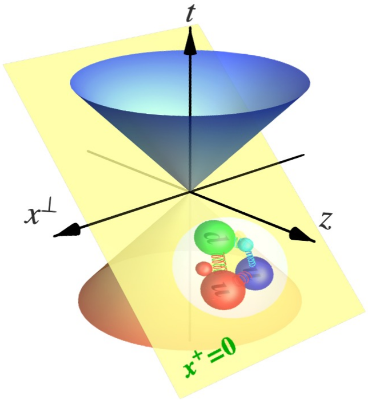
Light Front Quantization

- Infinite Momentum Frame $\xrightarrow{\neq}$
- Light Front Quantization

$P^z \to \infty$



the constituents become approximately collinear, hadron admits a simple partonic interpretation



time: $x^+ = x^0 + x^3$

Hamiltonian: $P^- = P^0 - P^3$

[Figures adapted from Yang Li]

- Bound states are solved from eigenvalue equations

$$P^-_{QCD}|\phi\rangle = P^-_\phi|\phi\rangle \Longleftrightarrow \underbrace{(P^-_{QCD}P^+ - \vec{P}^2_\perp)}_{H_{\rm LC}}|\psi_h(P,j,m_j)\rangle = M_h^2|\psi_h(P,j,m_j)\rangle$$

$H_{\rm LC}$ *boost invariant*

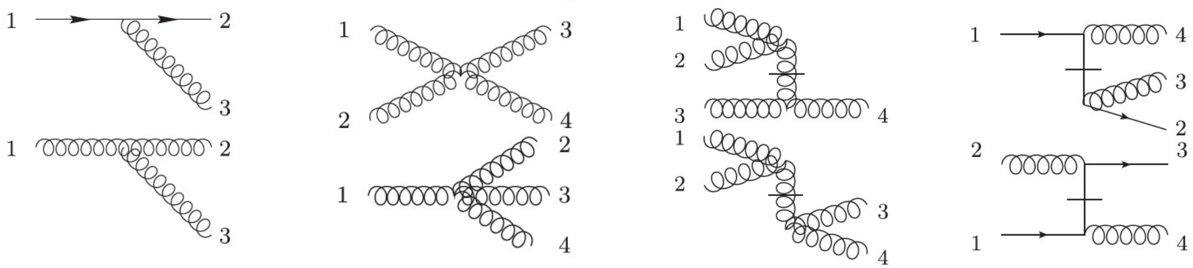
- Evolution of a quantum state follows the Schrödinger equation

$$\frac{1}{2}P^-|\psi(x^+)\rangle = i\frac{\partial}{\partial x^+}|\psi(x^+)\rangle$$

LF QCD Hamiltonian

- **first-principles**: QCD Lagrangian via Legendre transformation,

$$\mathcal{L} = -\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \qquad \rightarrow \qquad P^-(x^+) = P^-_{KE} + V_{qg} + V_{ggg} + V_{gggg} + W_f + W_g$$



- Canonical quantization on the LF, $\{\Psi_{+,c}(x),\Psi^\dagger_{+,c'}(y)\}_{x^+=y^+} = \Lambda_+\delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{c,c'}$, $[A_{i,a}(x),A^\dagger_{j,b}(y)]_{x^+=y^+} = -\frac{i}{4}\epsilon(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{i,j}\delta_{a,b}$,

$$\Psi_{\mu,c}(x) = \sum_{\bar{\alpha}} \frac{1}{\sqrt{p^+ 2L(2L_\perp)^2}}[b_\beta u_\mu(p,\lambda)e^{-ip\cdot x} + d^\dagger_\beta v_\mu(p,\lambda)e^{ip\cdot x}],$$

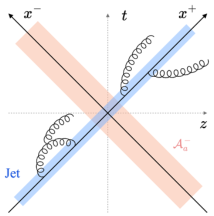
$$A_{\mu,a}(x) = \sum_{\bar{\alpha}} \frac{1}{\sqrt{p^+ 2L(2L_\perp)^2}}[a_\beta \epsilon_\mu(p,\lambda)e^{-ip\cdot x} + a^\dagger_\beta \epsilon^*_\mu(p,\lambda)e^{ip\cdot x}],$$

Hamiltonian takes second-quantized form, e.g.,

$$V_{qg} = \sum_{\beta_1,\beta_2}\sum_{\beta_3} \underbrace{\frac{g}{\sqrt{p_1^+ p_2^+ p_3^+ \Omega}} T^{a_3}_{c_2,c_1}\delta^{(3)}_{p_2-p_1+p_3}\,\Delta_1^{2,3}}_{\text{coefficient}}\;\underbrace{a^\dagger_{\beta_3} b^\dagger_{\beta_2} b_{\beta_1}}_{\text{operator}} + \text{H.c.},$$

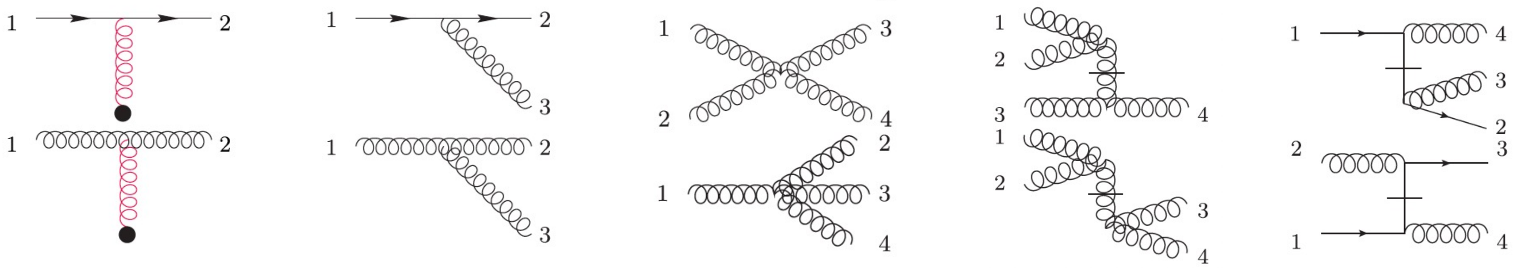
quantum numbers: $\{p^+, p^x, p^y, \lambda\ \ , c\ \ \}$

LF QCD Hamiltonian with medium



- **first-principles**: QCD Lagrangian via Legendre transformation, *background field*

$$\mathcal{L} = -\frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi, D_\mu = \partial_\mu + ig(A_\mu + \mathcal{A}_\mu) \rightarrow \quad P^-(x^+) = P^-_{KE} + V_{qg} + V_{ggg} + V_{gggg} + W_f + W_g + V_{\mathcal{A}}(x^+)$$



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- Canonical quantization on the LF, $\{\Psi_{+,c}(x), \Psi^\dagger_{+,c'}(y)\}_{x^+=y^+} = \Lambda_+\delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{c,c'}$, $[A_{i,a}(x), A^\dagger_{j,b}(y)]_{x^+=y^+} = -\frac{i}{4}\epsilon(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{i,j}\delta_{a,b}$,

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quantum numbers: $\{p^+, p^x, p^y, \lambda \;\;, c \;\;\}$

Hamiltonian takes second-quantized form, e.g.,

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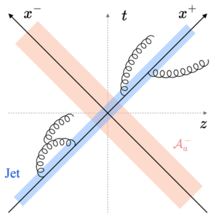
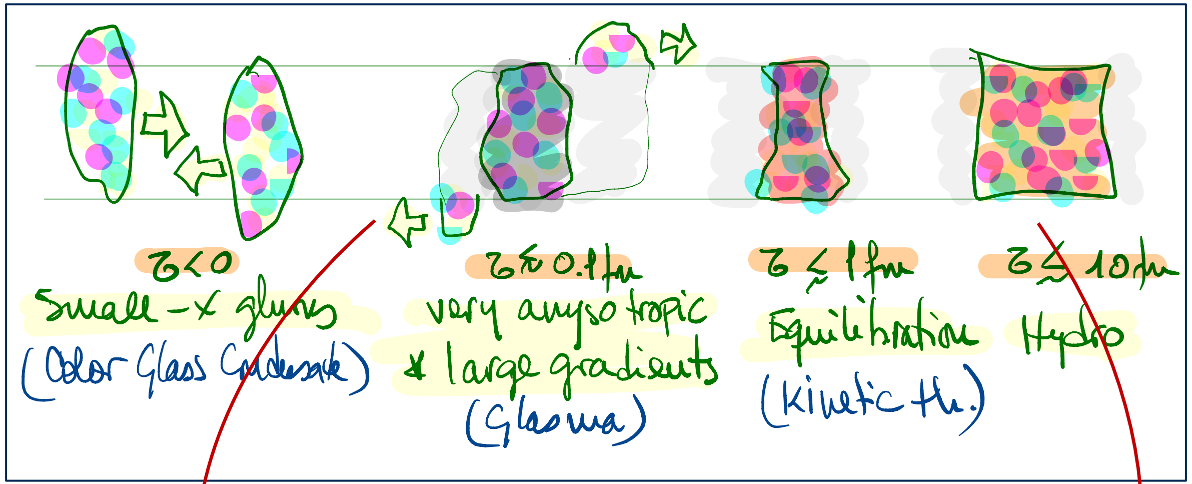
$$V_{q\mathcal{A}}(x^+) = \frac{2g}{\Omega_\perp}\sum_{\beta_1,\beta_2} \delta_{k_2^+,k_1^+}\delta_{\lambda_1,\lambda_2}T^a_{c_2,c_1}\mathcal{A}^a_+(\vec{p}_{2,\perp} - \vec{p}_{1,\perp}, x^+)\, b^\dagger_{\beta_2} b_{\beta_1}$$

LF QCD Hamiltonian with medium



- The (most) Standard Model of HIC

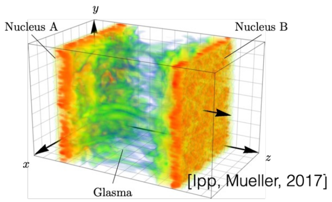


[Figure adapted from C. A. Salgado]

on the $\mathcal{A}_\mu$ amplitude level:

Color Glass Condensate
strong field, weak coupling,
large occupation numbers

classical fields by Yang-Mills eq.

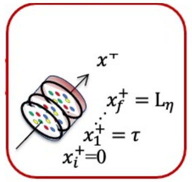


$$\partial_\tau \mathcal{P}^i = \tau \left[\mathcal{D}_j, \mathcal{F}_{ji}\right] - \frac{ig}{\tau}\left[\mathcal{A}_\eta, \left[\mathcal{D}_i, \mathcal{A}_\eta\right]\right],$$

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

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

classical fields by Yang-Mills eq.



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

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

Jet as a QCD state

- Fock sector expansion of quark/gluon jets: $|q\rangle_{\text{jet}} = \psi_q|q\rangle + \psi_{qg}|qg\rangle + \psi_{qgg}|qgg\rangle + \cdots$

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

$$|q(\beta)\rangle = b^{\dagger}_{\beta}|0\rangle,$$
$$|\bar{q}(\beta)\rangle = d^{\dagger}_{\beta}|0\rangle,$$
$$|g(\beta)\rangle = a^{\dagger}_{\beta}|0\rangle.$$

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

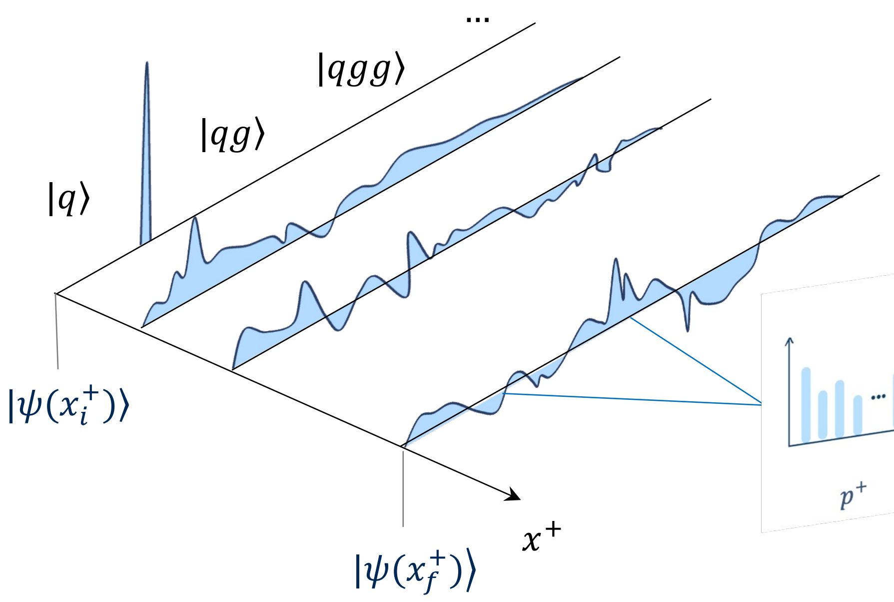
Each single-particle basis state is labeld by five quantum numbers:

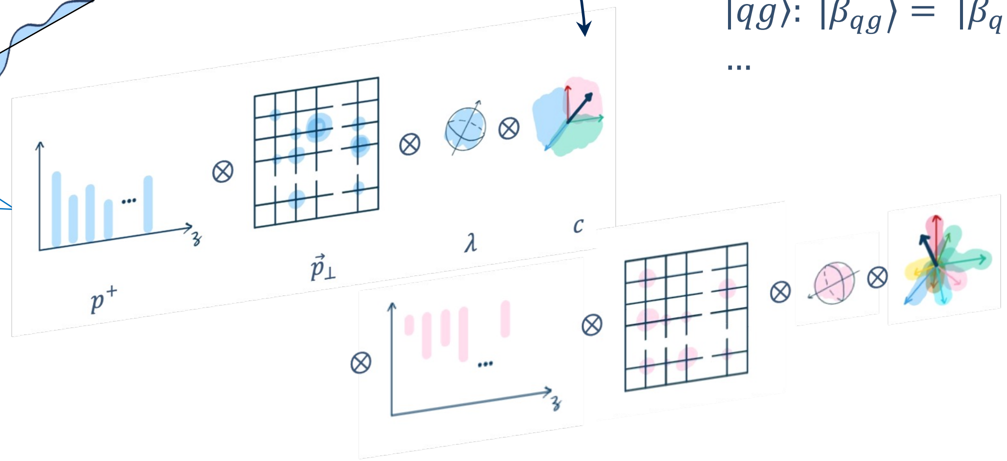
$$\beta_l = \{p_l^+, p_l^x, p_l^y, \lambda_l, c_l\}, (l = q, g)$$

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

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

…





Time evolution of QCD jets

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

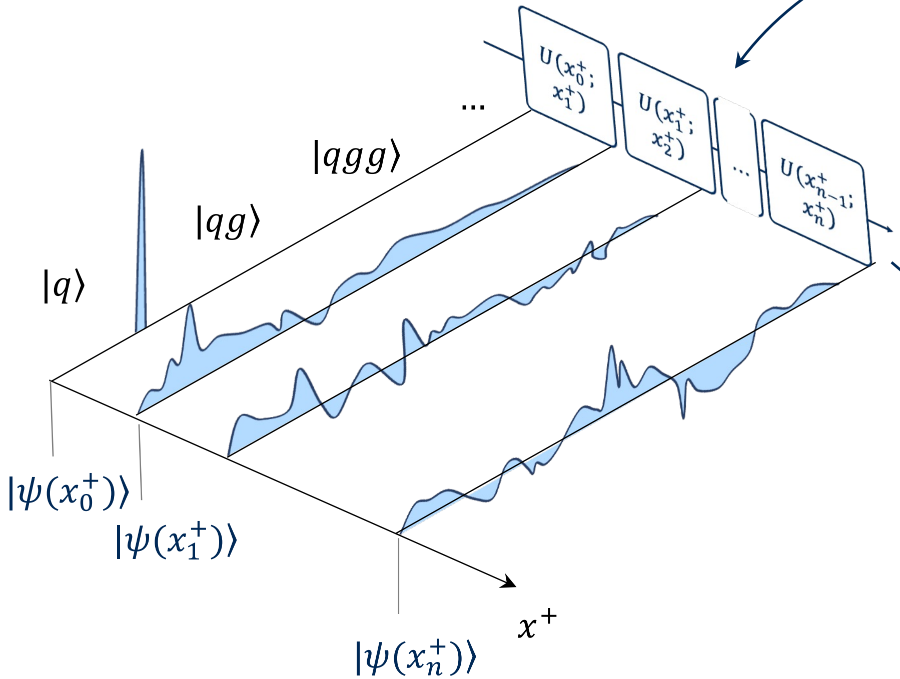
$$|\psi(x^+)\rangle = \mathcal{T}_+ e^{-\frac{i}{2}\int_0^{x^+} dz^+ P^-(z^+)} |\psi(0)\rangle$$

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

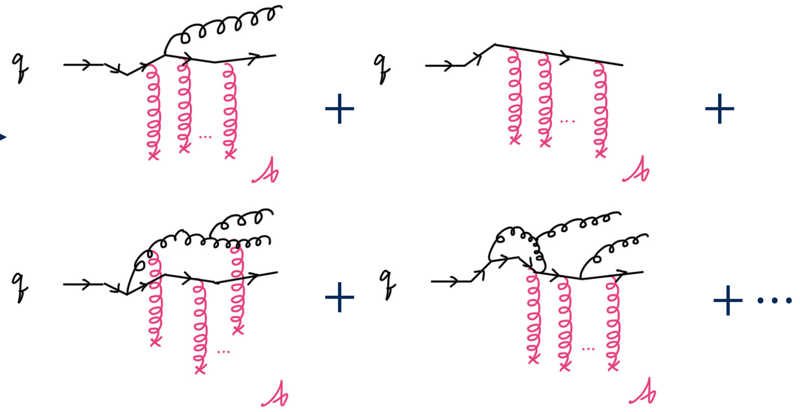
Trotterization

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

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 each timestep:

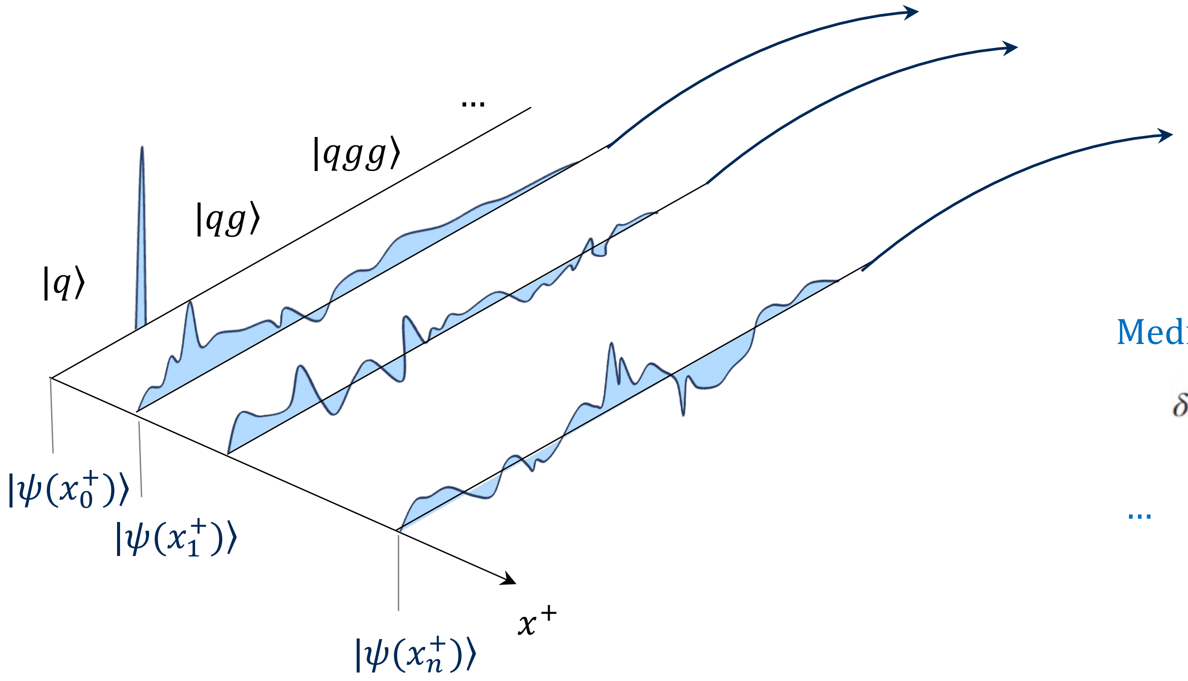


Extraction of physical quantities

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

Momentum broadening $\langle \vec{P}_\perp^2(x^+)\rangle = \langle\psi; x^+|\vec{P}_\perp^2|\psi; x^+\rangle$

Quenching parameter $\hat{q} = 2\,\frac{\mathrm{d}\langle(\delta\vec{p}_\perp^{\,kin})^2\rangle}{\mathrm{d}x^+}$



Cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 b} = \sum_{\phi_f}|M(\phi_f;\psi_i)|^2 = \sum_{\phi_f}|\langle\phi_f|S|\psi_i\rangle - \langle\phi_f|\psi_i\rangle|^2.$$

Medium-induced gluon radiation

$$\delta P_{|qg\rangle}(Q_s, x^+) \equiv P_{|qg\rangle}(Q_s, x^+) - P_{|qg\rangle}(Q_s = 0, x^+)$$

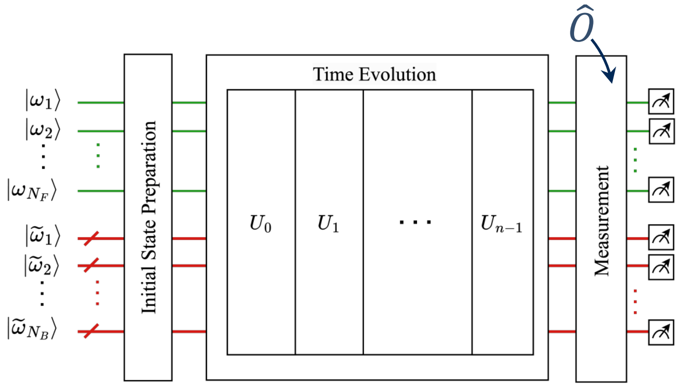
...

Well-applicable for both classical and quantum devices

- **Classical simulation:** sequential matrix multiplications of the Trotterized evolution operators acting on the jet wavefunction

$$\begin{pmatrix} c_1(x^+) \\ c_2(x^+) \\ \vdots \\ c_n(x^+) \end{pmatrix} = \Big[\quad U_n \quad\Big] \cdots \Big[\quad U_2 \quad\Big]\Big[\quad U_1 \quad\Big] \begin{pmatrix} c_1(0) \\ c_2(0) \\ \vdots \\ c_n(0) \end{pmatrix} \longrightarrow \quad O(x^+) = \langle \psi; x^+ | \hat{O} | \psi; x^+ \rangle$$

- **Quantum simulation:** sequential quantum gate operations on the jet state encoded in qubits



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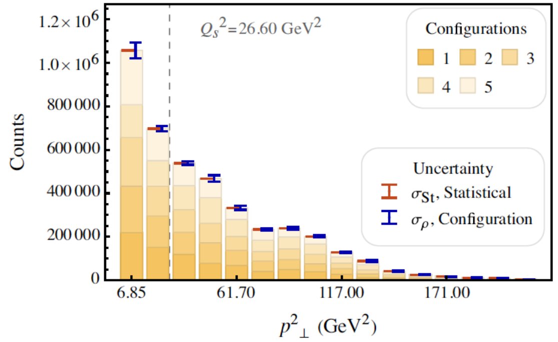

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1. Jets in High-Energy Physics
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3. **From Classical to Quantum Simulations**
4. Towards the Full Jet Process

Timeline: Real-time Jet (classical / quantum) Simulations

- **2020** — Quark-nucleus scattering [**ML**, Zhao, Maris, Chen, Li, Tuchin, Vary, PRD, 2002.09757] **1st CS** (classical)
- A quantum strategy to compute jet quenching parameter [Barata, Salgado, EPJC, 2104.04661] (quantum)
- **2021** — Quark scattering and gluon emission [**ML**, Lappi, Zhao, PRD, 2107.02225] (classical)
- **2022** — Jet quenching on a QC[Barata, Du, **ML**, Qian, Salgado, PRD, 2208.06750] **1st QS** (quantum)
- QS of jet [Yao, 2205.07902] (quantum)
- **2023** — Jet momentum broadening [**ML**, Lappi, Zhao, Salgado, PRD, 2305.12490] (classical)
- QS of in-medium jets [Barata, Du, **ML**, Qian, Salgado, PRD, 2307.01792] (quantum)
- **2024** — Quark-nucleus scattering using truncated Taylor series [Wu, Du, Zhao, Vary, PRD, 2404.00819] (quantum)
- Efficient QS of QCD jets [Qian, **ML**, Kreshchuk, Salgado, PRD, 2411.09762] **1st scalable QS** (quantum)
- **2025** — Jet evolution in a QC [Castro, Milhano, Oliveira, EPJC, 2502.03431] (quantum)
- Physical quark scattering and gluon emission [**ML**, Lappi, Zhao, Salgado, PRD, 2504.07162] (classical)
- **2026** — Initial stage jet momentum broadening [Avramescu, Lamas, Lappi, **ML**, Salgado, 2604.08520, 2605.10413] (classical)
- QS of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616] (quantum)

Timeline: Real-time Jet Simulations

(● classical; ◆ quantum)

- 2020 ● Quark-nucleus scattering [**ML**, Zhao, Maris, Chen, Li, Tuchin, Vary, PRD, 2002.09757] **1st CS** -------- $|q\rangle$
- ◆ A quantum strategy to compute jet quenching parameter [Barata, Salgado, EPJC, 2104.04661]
- 2021 ● Quark scattering and gluon emission [**ML**, Lappi, Zhao, PRD, 2107.02225]-------------------------------------- $|q\rangle + |qg\rangle$
- 2022 ◆ Jet quenching on a QC[Barata, Du, **ML**, Qian, Salgado, PRD, 2208.06750]
- ◆ QS of jet [Yao, 2205.07902]
- 2023 ● Jet momentum broadening [**ML**, Lappi, Zhao, Salgado, PRD, 2305.12490]------------------------------------ $|q\rangle + |qg\rangle, \hat{q}$
- ◆ QS of in-medium jets [Barata, Du, **ML**, Qian, Salgado, PRD, 2307.01792]
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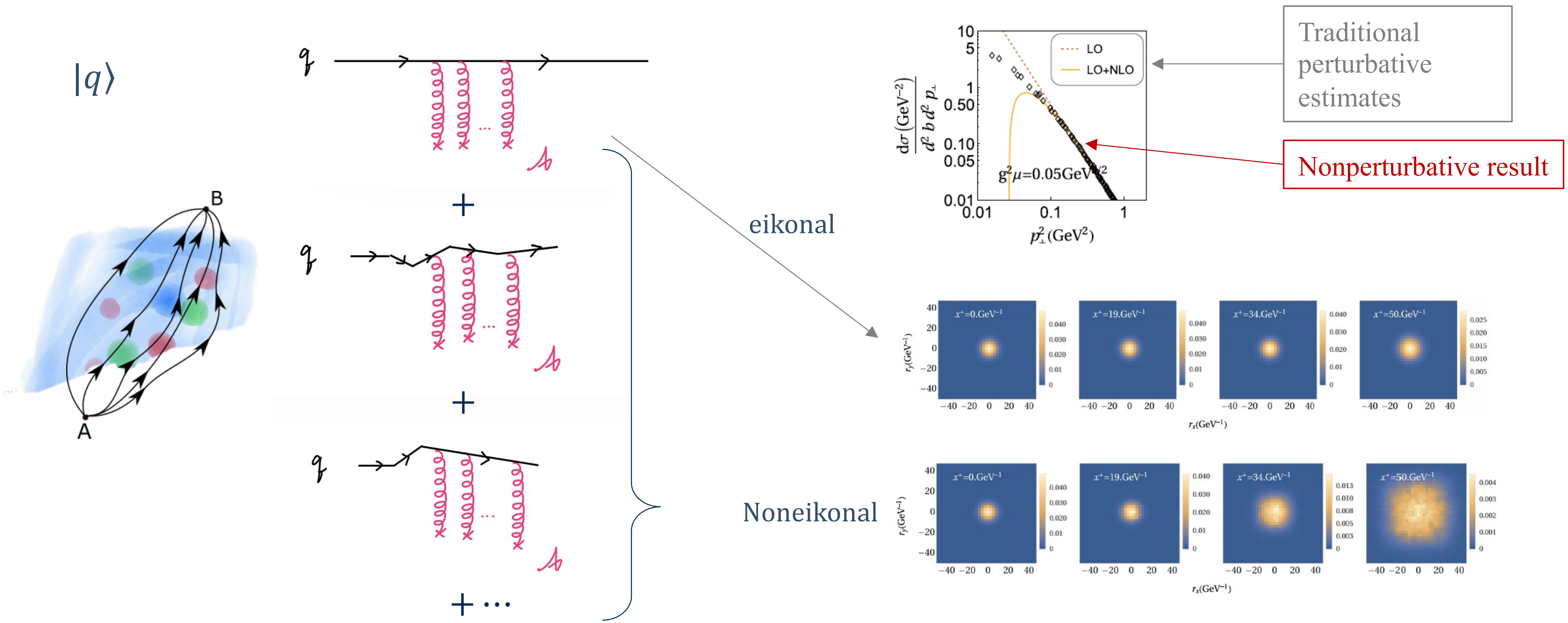
- 2025 ◆ Jet evolution in a QC [Castro, Milhano, Oliveira, EPJC, 2502.03431]
- ● Physical quark scattering and gluon emission [**ML**, Lappi, Zhao, Salgado, PRD, 2504.07162]--------------- $|q\rangle + |qg\rangle$, **dressed quark**
- 2026 ● Initial stage jet momentum broadening [Avramescu, Lamas, Lappi, **ML**, Salgado, 2604.08520, 2605.10413] $|q\rangle$, **Glasma**
- ◆ QS of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616]

Real-time Jet Simulations

2020 — Quark-nucleus scattering [**ML**, Zhao, Maris, Chen, Li, Tuchin, Vary, PRD, 2002.09757]

- ***Non-perturbative contributions:*** *more accurate pT distribution*
- ***Non-eikonal effects:*** the transverse coordinate distribution of the quark changes over time at a finite energy scale

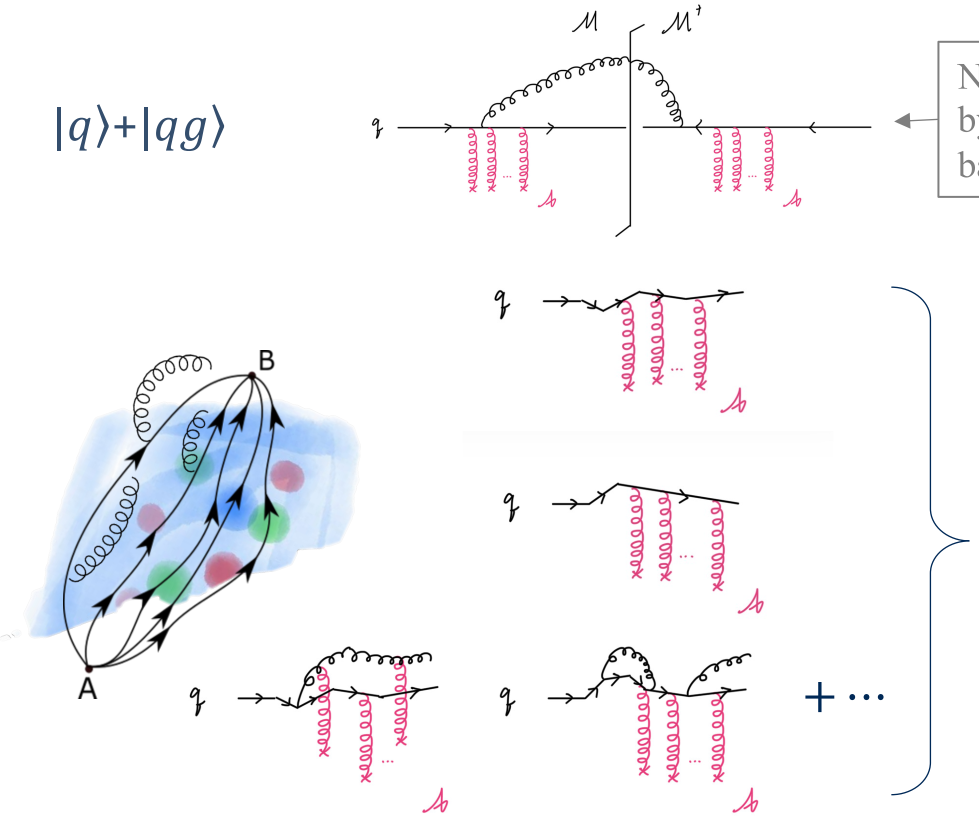


Real-time Jet Simulations

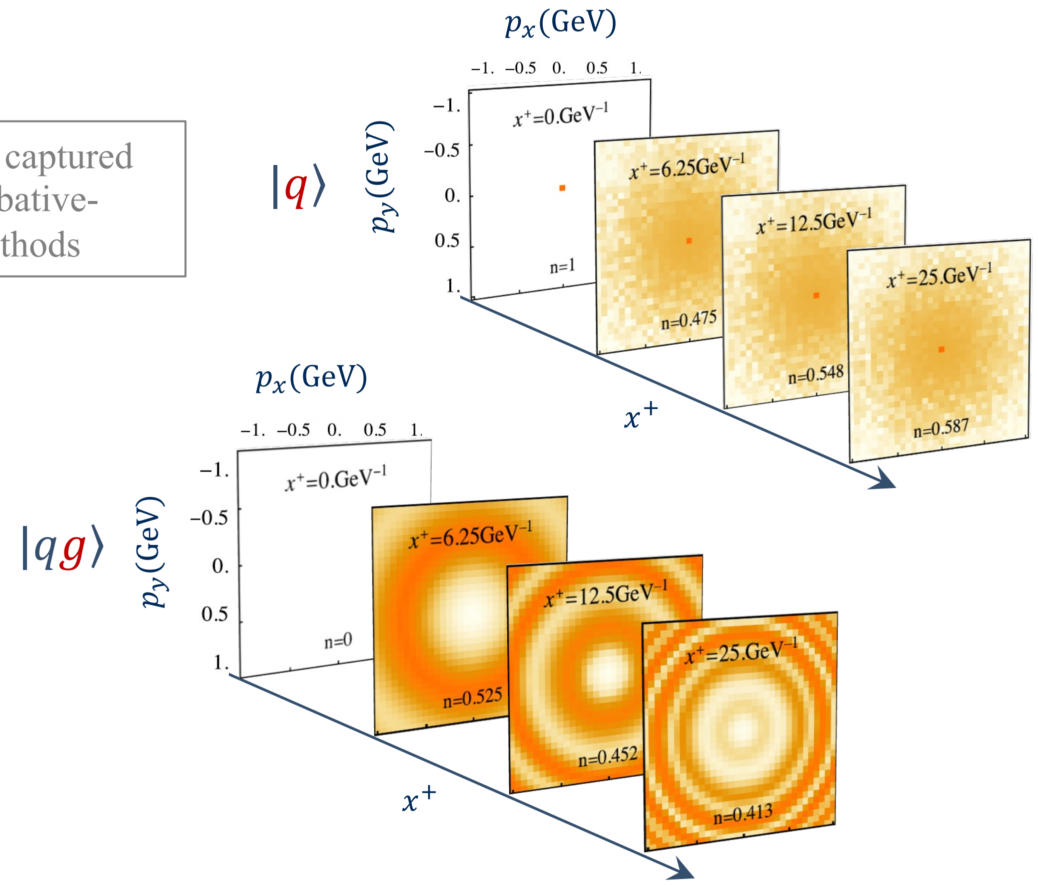
2021 Quark scattering and gluon emission [**ML**, Lappi, Zhao, PRD, 2107.02225]

- ***Quantum Interference:*** among kinetic energy, medium interaction, and gluon emission

$|q\rangle + |qg\rangle$



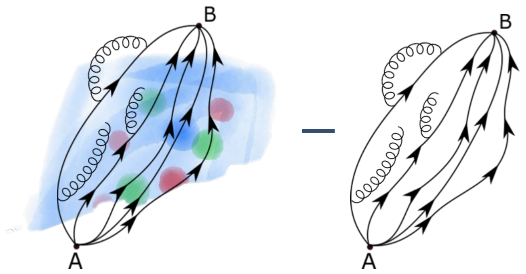
Not fully captured by perturbative-based methods

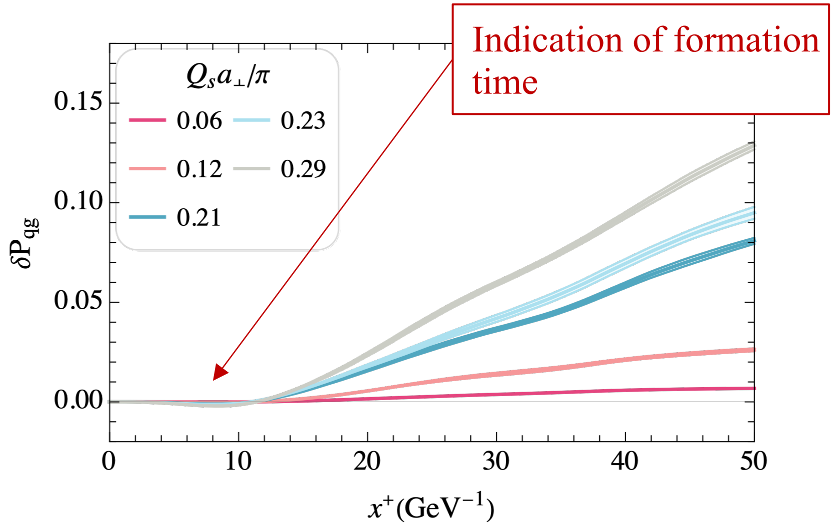


Real-time Jet Simulations

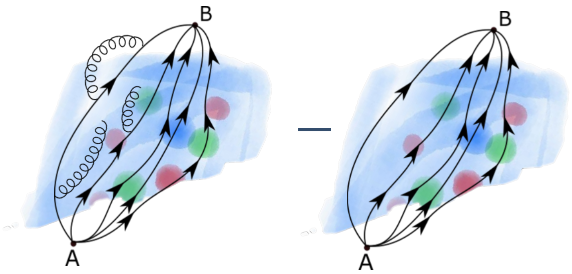
2023 —● Jet momentum broadening [**ML**, Lappi, Zhao, Salgado, PRD, 2305.12490]

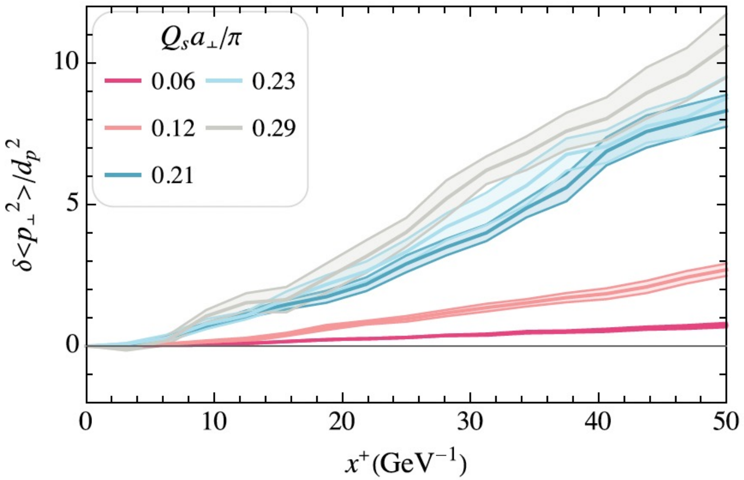
✓ ***Medium modification*** to gluon emission





✓ ***Radiative correction*** to momentum broadening



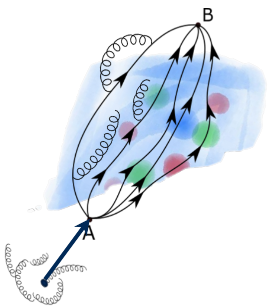


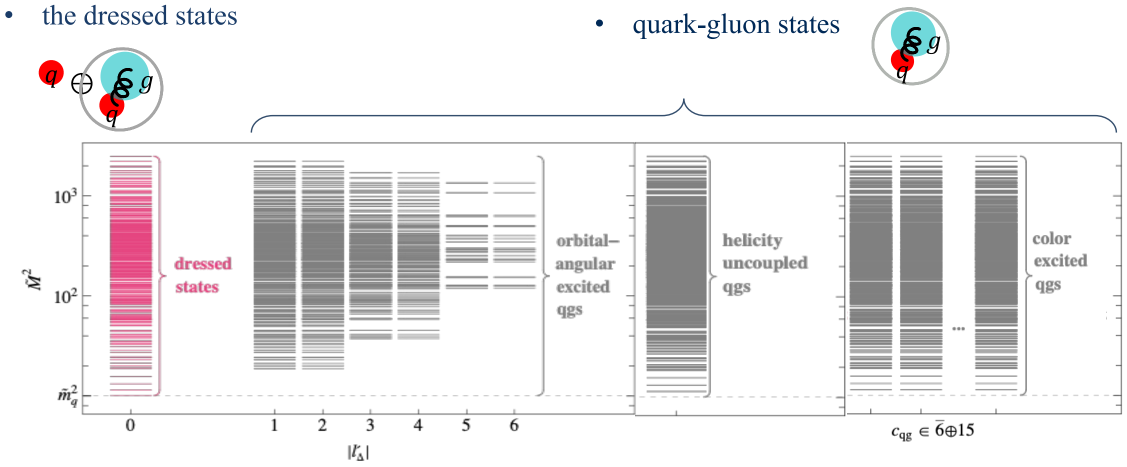
Real-time Jet Simulations

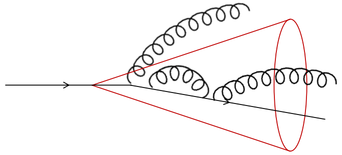
2025 Physical quark scattering and gluon emission [**ML**, Lappi, Zhao, Salgado, 2504.07162]

- ✓ ***Gluon dressing:*** when the quark originates far outside the medium, it gets dressed by gluon clouds
- ✓ ***C.M. and "Jet" momentum broadening:*** distinguish intrinsic and external gluons, more accurate interpretation of jet pT

$|q\rangle + |qg\rangle$

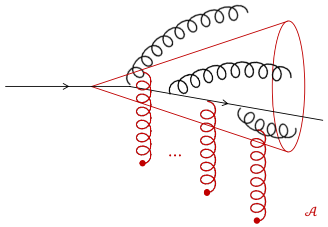


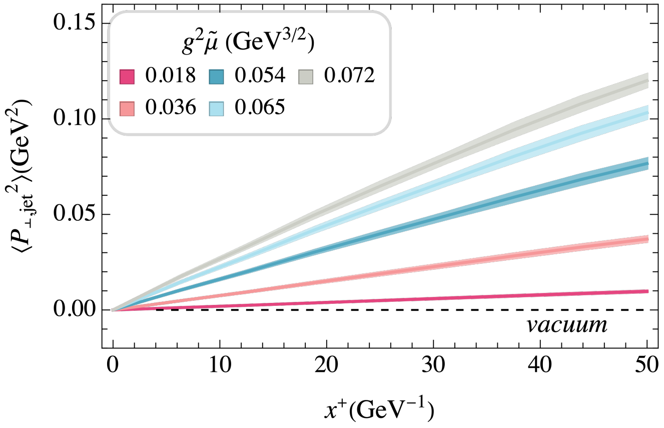




external gluons

intrinsic gluon cloud



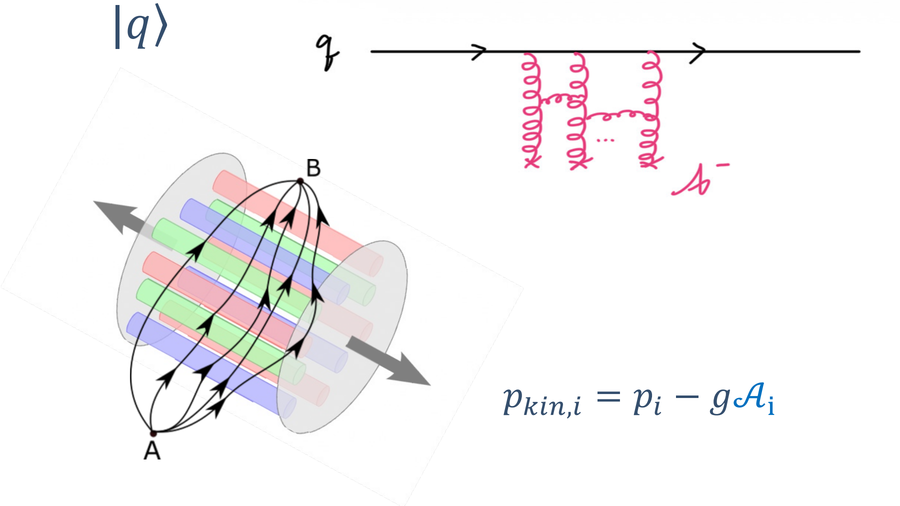


Real-time Jet Simulations

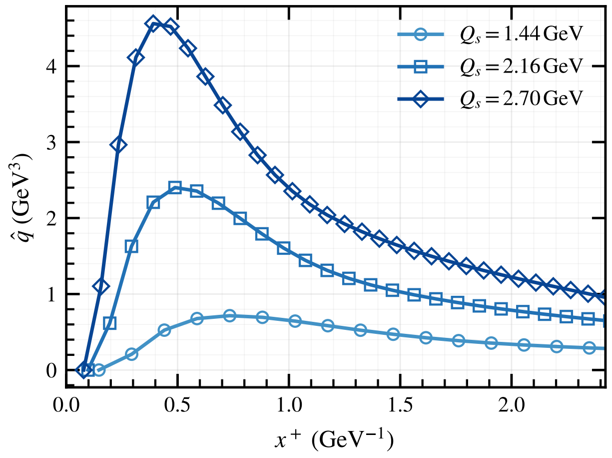
2026 —● Initial stage jet momentum broadening [Avramescu, Lamas, Lappi, **ML**, Salgado, 2604.08520, 2605.10413]

- ✓ **benchmark**: quenching parameter and momentum anisotropies in agreement with classical description
- ✓ **Quntum effects:** delocalization, first quantum treatment of jets inside the Glasma phase

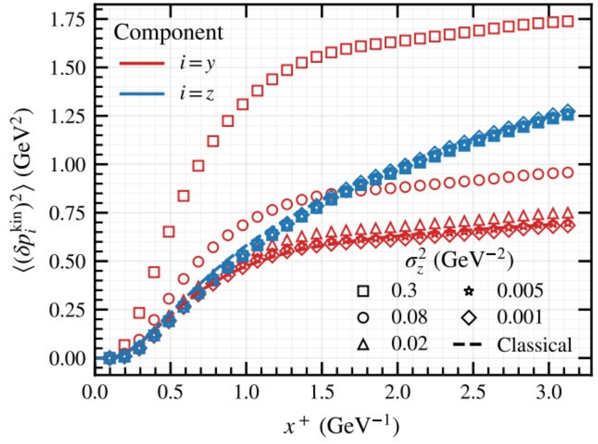
$|q\rangle$



$$p_{kin,i} = p_i - g\mathcal{A}_i$$

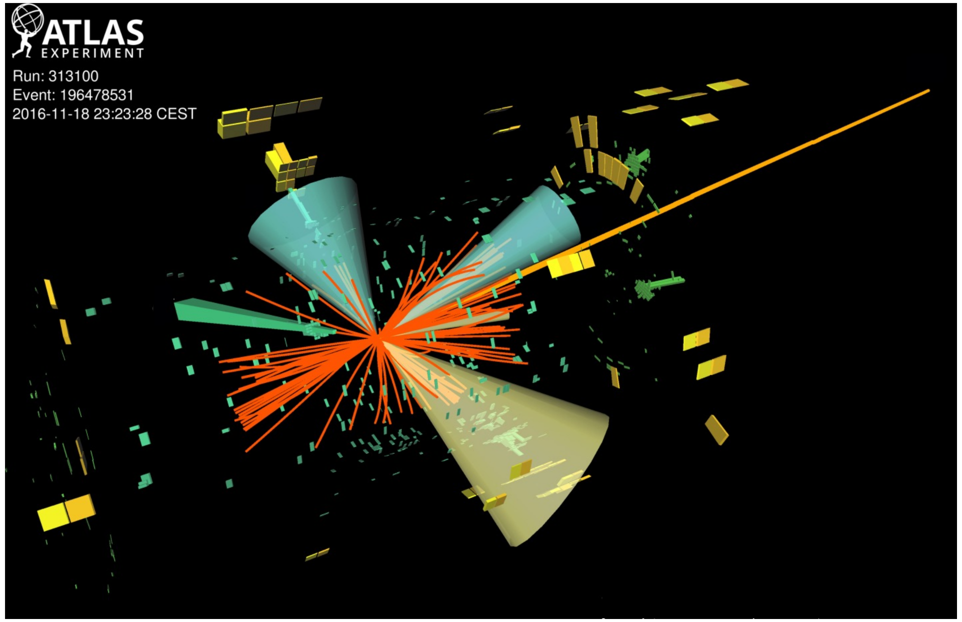


(a) Physical units

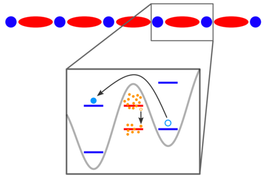


Quantum Simulations

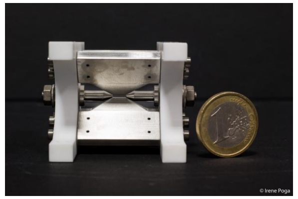
- Quantum simulation involves using one quantum system to study the behavior of another, often more complex, quantum system



- Analogue quantum computer: using a controllable quantum system



[Zache et al, 1802.06704]



[Figure: Paul linear trap at U. Granada]

✓ Digital quantum computer: using qubits and quantum gates

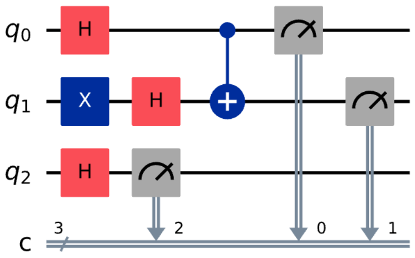
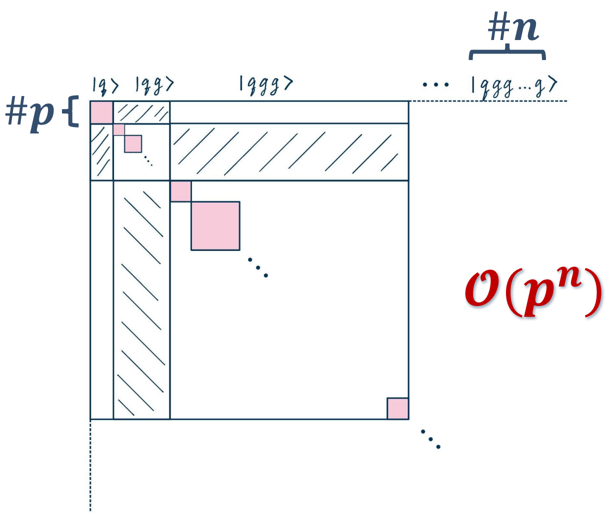


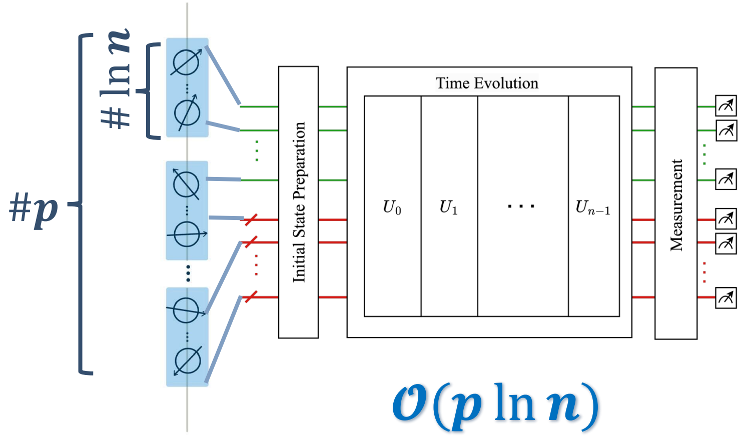
Figure: IBM Quantum Doc

Why Quantum Simulation?

- ***Challenge of the exponential wall:*** *Jet is intrinsically a quantum many-body system, particle number increases as it evolves*
- ***Quantum advantage:*** when a quantum computer can solve a problem significantly faster or more efficiently than any classical computer

	Classical simulations	**Quantum simulations**
Fock space	$\lvert q\rangle + \lvert qg\rangle + \lvert qg \ldots g\rangle$, #particle = n	
Physical modes	$\#\{p_\perp, p^+, \text{color}, \text{helicity}\} = p$	
Basis size/Qubits	#total = $\mathcal{O}(\mathrm{p^n})$	#qubits ≈ $\mathcal{O}(p \ln n)$
Interaction terms	Dim[H matrix] = $\mathcal{O}(\mathrm{p^n \times p^n})$	#operations = $\mathcal{O}(p^3)$

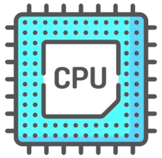


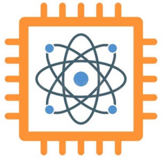


Why Quantum Simulation?

- ***Challenge of the exponential wall:*** *Jet is intrinsically a quantum many-body system, particle number increases as it evolves*
- ***Quantum advantage:*** when a quantum computer can solve a problem significantly faster or more efficiently than any classical computer

	Classical simulations	**Quantum simulations**
Fock space	$\|q\rangle + \|qg\rangle$	$\|q\rangle + \|qg\rangle + \|qgg\rangle, \|g\rangle + \|gg\rangle + \|ggg\rangle$
Physical modes	$\#p_\perp = 32^2, \#p^+ = 8$, $\#\text{color} = \text{SU}(3), \#\text{helicity} = 2$	$\#p_\perp = 2^2, \#p^+ = 2$, $\#\text{color} = \text{SU}(2), \#\text{helicity} = 1$
Basis size	$\#\text{total} \approx 2^{30}$	$\#\text{equivalent total} \approx 2^{11}$
Computational cost	$\#\text{memory} \approx 250$ GB, $\#\text{time/trotter} \approx 0.07h$ (CESGA FinisTerrae)	$\#\text{qubits} = 48$, $\#\text{time/(16 trotters)} \approx 10h$ (desktop)





➢ **We need to develop both formalisms at the Noisy intermediate-scale quantum (NISQ) Era!**

Real-time Jet Simulations on QC

Two paths taken:

- **Binary encoding**: map basis indices to binary strings

2022 — Jet quenching on a quantum computer [Barata, Du, **ML**, Qian, Salgado, PRD, 2208.06750]

2023 — Quantum simulation of in-medium jets [Barata, Du, **ML**, Qian, Salgado, PRD, 2307.01792]

- **Direct encoding**: map each particle state to an individual qubit/register

2024 — Efficient QS of QCD jets [Qian, **ML**, Kreshchuk, Salgado, PRD, 2411.09762]

2026 — Quantum simulation of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616]

Real-time Jet Simulations on QC

Two paths taken:

- **Binary encoding**: map basis indices to binary strings, “log” the whole thing

$$|q_0 q_1 \dots q_{N-1}\rangle$$

$$|\beta_i\rangle \rightarrow |01001 \dots 0\rangle$$

basis index — i_{bin}, binary representation

$\mathcal{O}(p^n) \rightarrow \mathcal{O}(n \ln p)$

- *Non-scalable: H matrix → Pauli strings*
- *Operations are basis-specific: H matrix*
- ✓ *Feasible for small-scale problems*

✓ **Direct encoding**: map each particle state to an individual qubit/register

$$|q_0 q_1 \dots q_i \dots q_{N-1}\rangle$$

$$|\psi_i\rangle \rightarrow |\ 0\ \ 0\ \ \dots\ \ 1\ \ \dots\ \ 0\ \rangle$$

physical modes — i-th register

$\mathcal{O}(p^n) \rightarrow \mathcal{O}(p \ln n)$

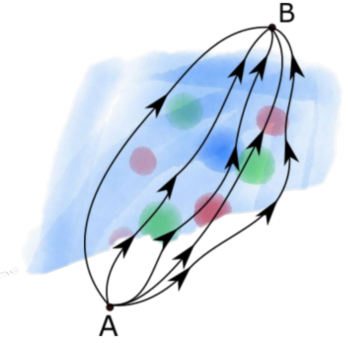
✓ *Scalable: H operators → Pauli strings*
✓ *Operations are universal: H operators*

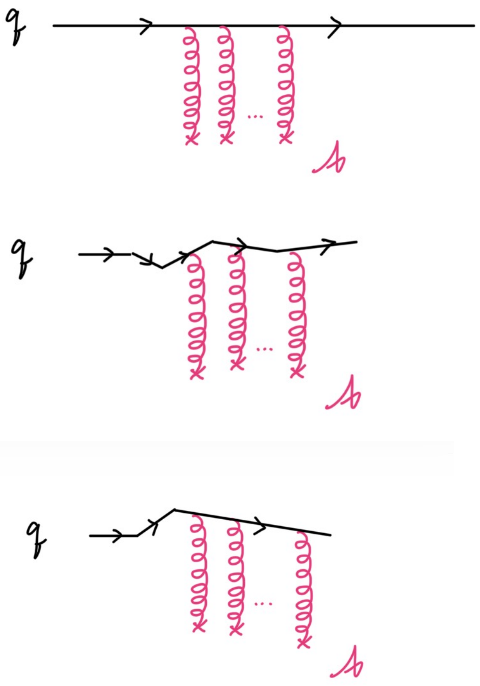
Real-time Jet Simulations on QC

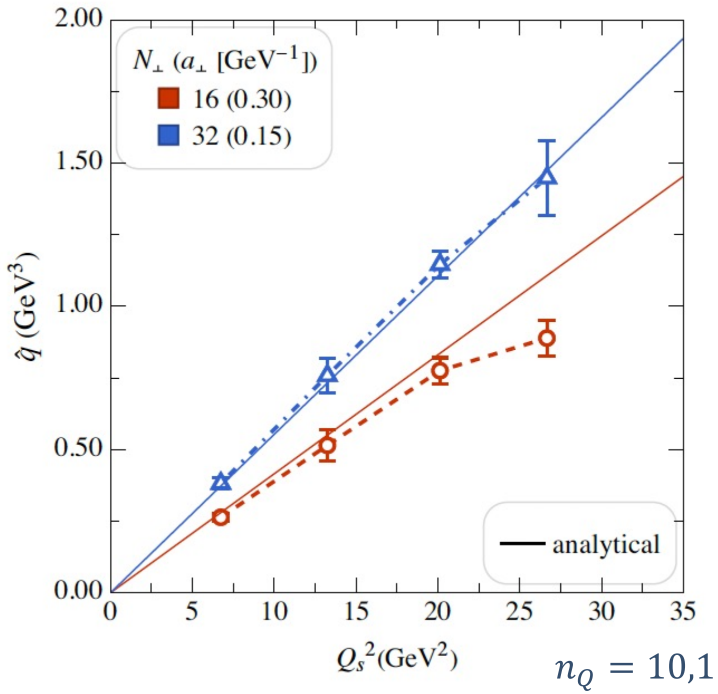
2022 ◆—— Jet quenching on a quantum computer [Barata, Du, **ML**, Qian, Salgado, PRD, 2208.06750]

✓ ***Extract the jet quenching parameter*** *(representing the rate of transverse momentum broadening per unit length in the medium) and demonstrate consistency with analytical predictions*

$|q\rangle$







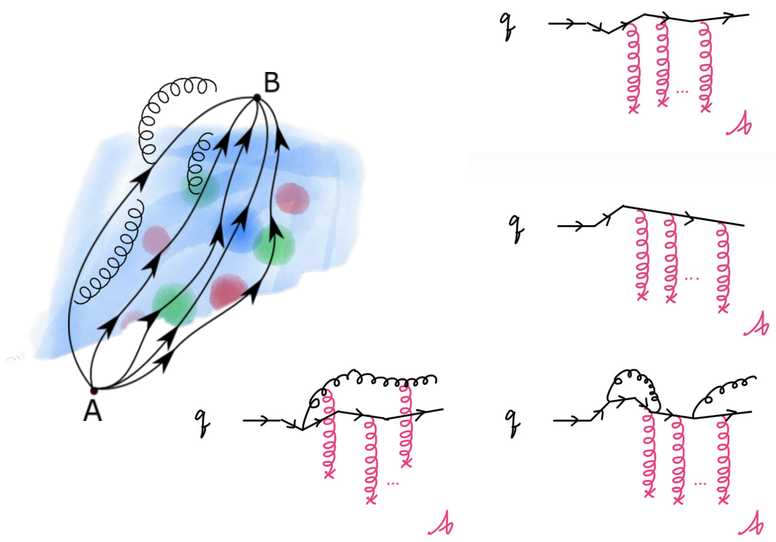
$n_Q = 10{,}12$

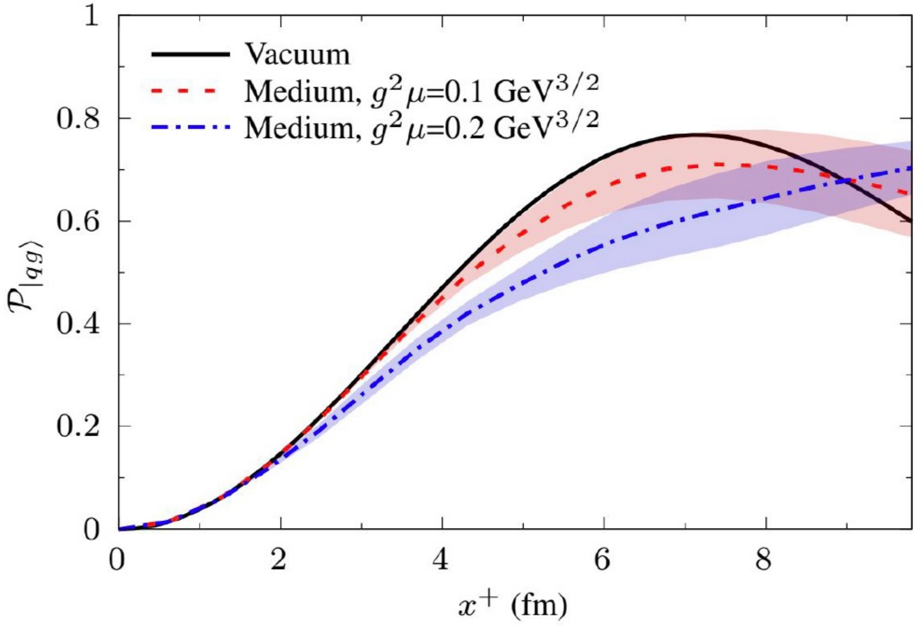
Real-time Jet Simulations on QC

2023 ◆—— Quantum simulation of in-medium jets [Barata, Du, **ML**, Qian, Salgado, PRD, 2307.01792]

✓ ***Interference effects:*** gluon emission of the jet is modified by the medium over time

$|q\rangle + |qg\rangle$





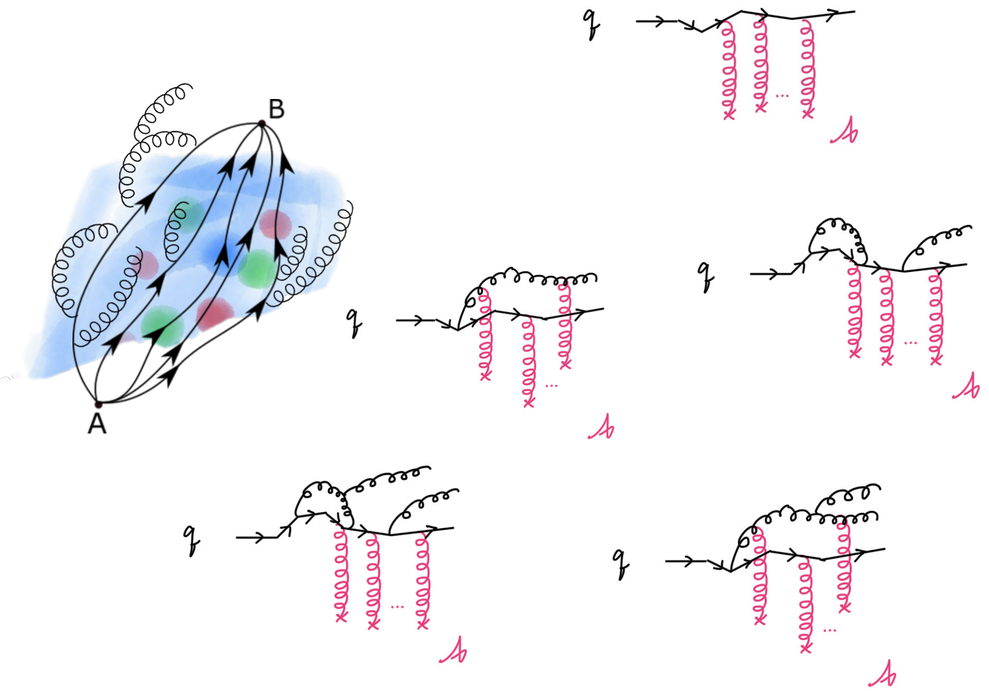
$n_Q = 9$

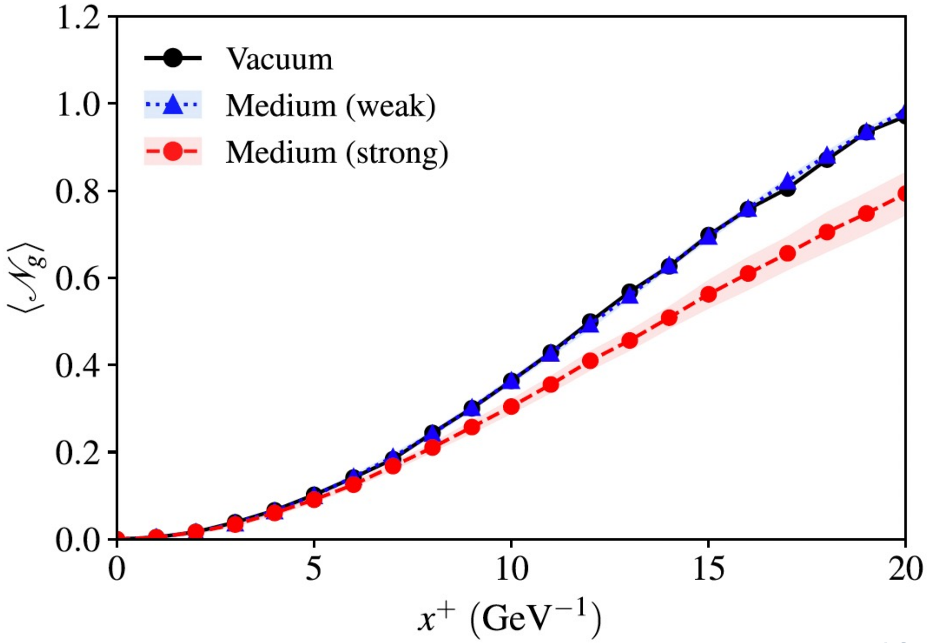
Real-time Jet Simulations on QC

2024 ◆—— Efficient QS of QCD jets [Qian, **ML**, Kreshchuk, Salgado, PRD, 2411.09762]

✓ ***Interference effects:*** gluon number of the jet is modified by the medium over time

$|q\rangle + |qg\rangle + |qgg\rangle$





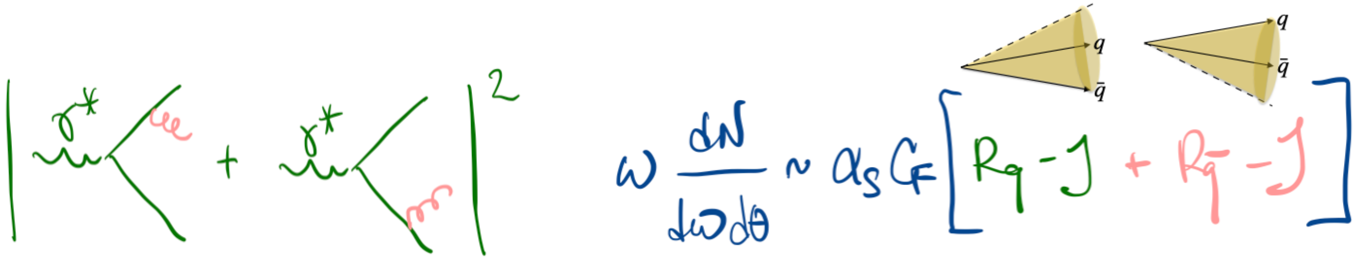
$n_Q = 48$

Real-time Jet Simulations on QC

2026 ◆—— Quantum simulation of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616]

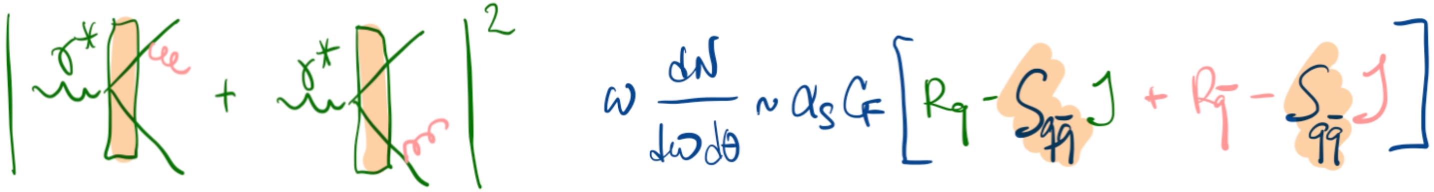
When partonic showers evolve in a medium, as in DIS or HICs, the resulting multi-particle distributions encode information about the surrounding matter

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



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

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

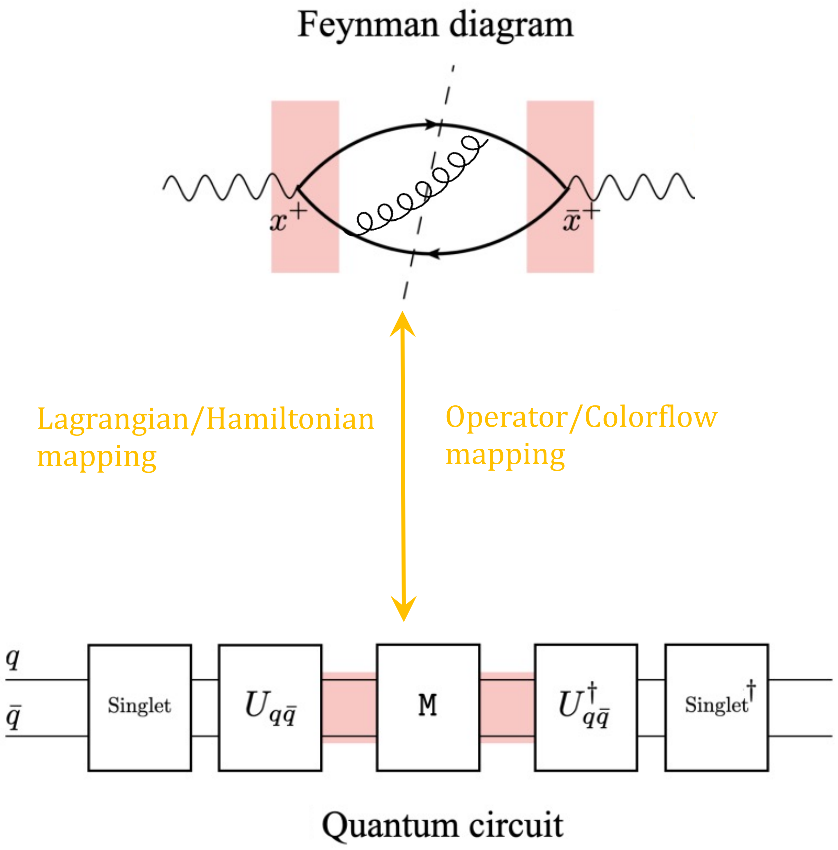


$$\omega \frac{dN}{d\omega\, d\theta} \sim \alpha_s C_F \left[R_q - S_{q\bar{q}} J + R_{\bar{q}} - S_{q\bar{q}} J \right]$$

[Figure adapted from C. A. Salgado]

Real-time Jet Simulations on QC

2026 ◆—— Quantum simulation of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616]



Feynman diagram: Propagators

$$\mathcal{G}^{ij}(x_2^+, \boldsymbol{x}_2; x_1^+, \boldsymbol{x}_1|p^+) = \int_{\boldsymbol{r}(x_1^+)=\boldsymbol{x}_1}^{\boldsymbol{r}(x_2^+)=\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r}\, \exp\left\{i\frac{p^+}{2}\int_{x_1^+}^{x_2^+} \mathrm{d}s^+\, \dot{\boldsymbol{r}}^2\right\} \mathcal{P}\exp\left\{ig\int_{x_1^+}^{x_2^+} \mathrm{d}s^+\, \mathcal{A}_a^-(s^+, \boldsymbol{r}(s^+))t^a_{ij}\right\}$$

$$U_{q\bar{q}}(x_2^+, x_1^+) = G(x_2^+, x_1^+; p_1^+)\bar{G}(x_2^+, x_1^+; p_2^+)$$

⇕ **equivalent**

LF Hamiltonian: time evolution operator

$$P^-(x^+) = P^-_{\mathrm{KE}} + V_{\mathcal{A}}(x^+)$$

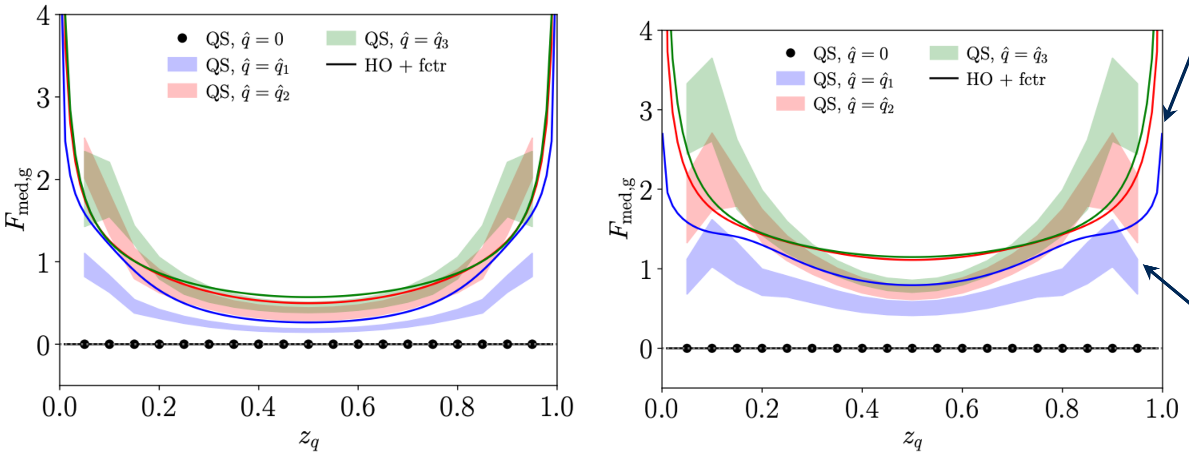
$$U_{q\bar{q}}(x_f^+, x_i^+) \equiv \mathcal{P}\exp\left[-\frac{i}{2}\int_{x_i^+}^{x_f^+} \mathrm{d}z^+ P^-(z^+)\right]$$

Real-time Jet Simulations on QC

2026 ◆—— Quantum simulation of dijet production [Barata, **ML**, Qian, Salgado, Silva, 2604.11616]

Medium **modification factor** of dipole cross section

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



(a) $\boldsymbol{p}^2 = 0.62\ \mathrm{GeV}^2$ (b) $\boldsymbol{p}^2 = 1.23\ \mathrm{GeV}^2$

Traditional analytical estimates

Approximations:

- Harmonic Oscillator → valid for limited range of $q\bar{q}$ separation
- factorization → valid for soft collinear $q\bar{q}$

LF Hamiltonian with QS

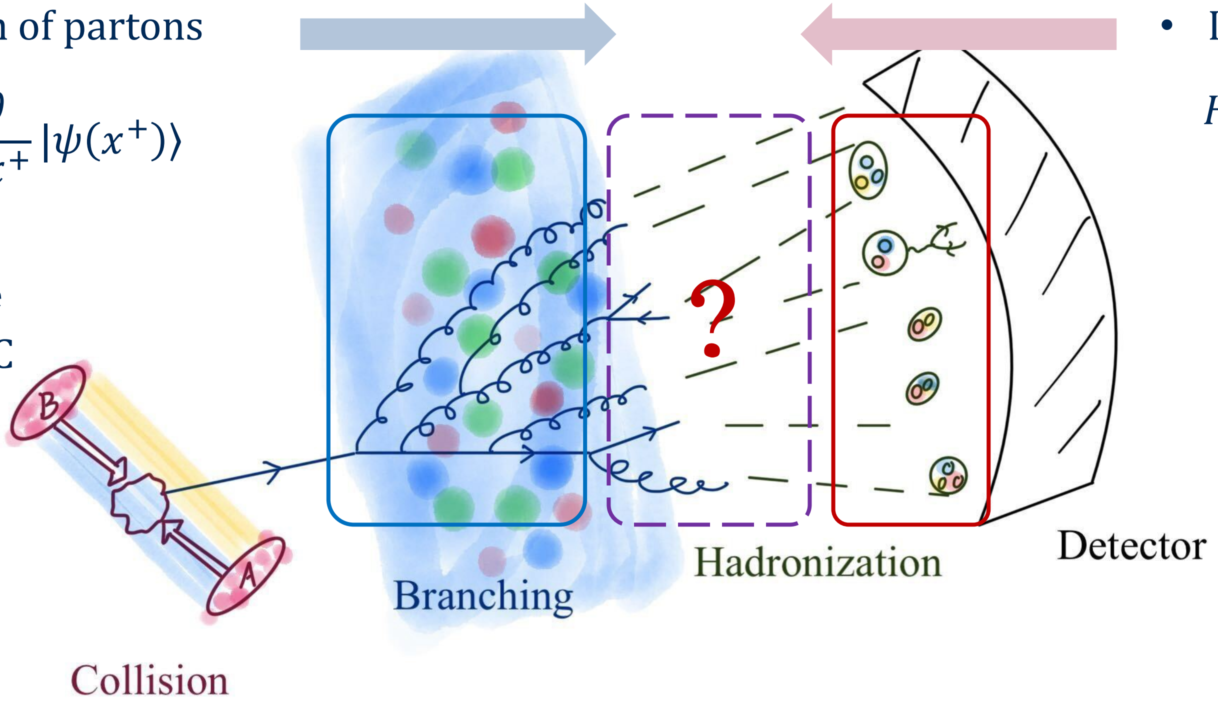
Exact! (within available phase space)

Outline

1. Jets in High-Energy Physics
2. LF Hamiltonian Approach for QCD jets in 3+1 D
3. From Classical to Quantum Simulations
4. **Towards the Full Jet Process**

Towards the Full Jet Process via LFH

- Real-time evolution of partons
- $\frac{1}{2}P^{-}|\psi(x^{+})\rangle = i\frac{\partial}{\partial x^{+}}|\psi(x^{+})\rangle$
  - Trotter evolve
  - Mapping to QC



- Internal structure of hadrons

$$H_{\mathrm{LC}}|\psi_h(P,j,m_j)\rangle = M_h^2|\psi_h(P,j,m_j)\rangle$$

  - Diagonalization: BLFQ, LF Holography,...
  - VQE, SSVQE,...

Hadronization: projection of partonic amplitude to hadron wavefunctions

[J. Gálvez-Viruet, F. J. Llanes-Estrada, N. Arenaza, M. Gómez-Rocha, T. J. Hobbs, 2510.18869]

Light-Front Hamiltonian Approach to QCD Jets

⇩

Real-time Dynamics of Nonperturbative QCD

Light-Front Hamiltonian Approach to QCD Jets in the Quantum Era

⇩

Real-time Dynamics of Nonperturbative QCD in a Scalable Way