INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS IGFAE

Real-Time Evolution of Dressed Quarks and Jet Energy Correlators

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Jets in High-Energy Physics

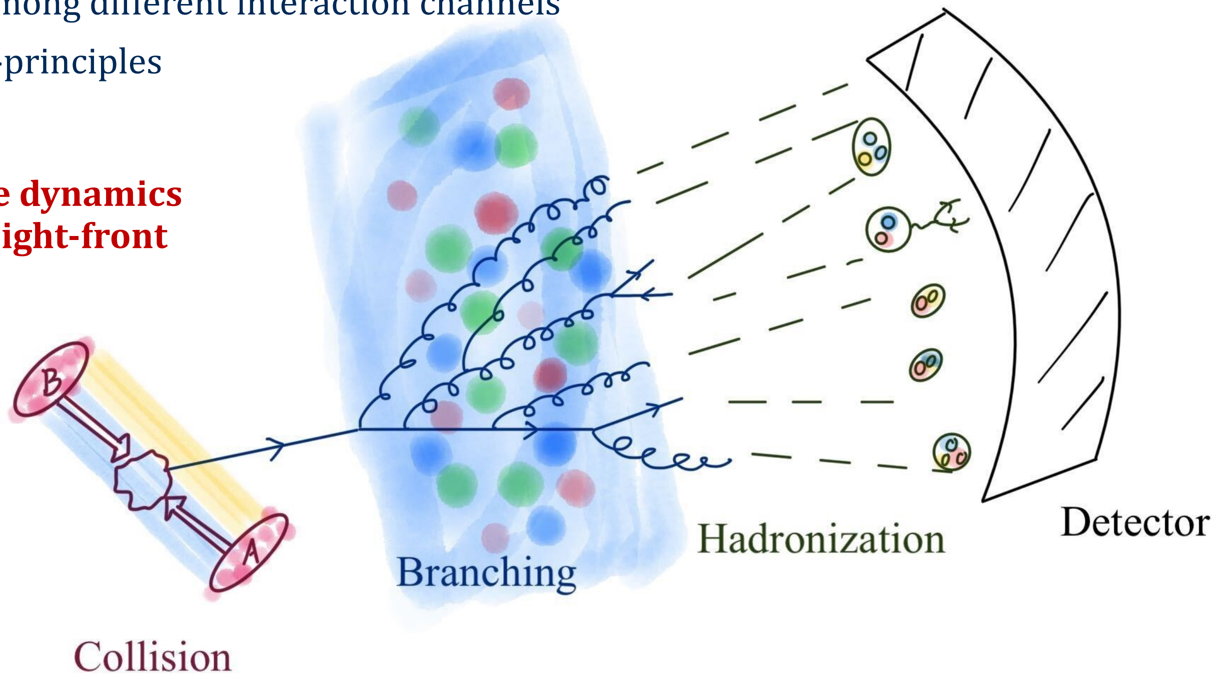
What are jets?

- Collimated beams of particles produced by the splitting of an energetic quark or gluon— the perfect probes to study QCD matter in heavy-ion collisions.

Open questions for jet physics in QCD matter:

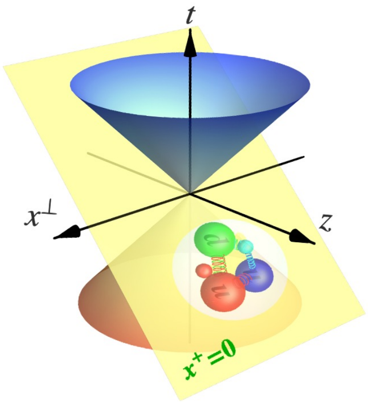
- **Non-perturbative effects** beyond eikonal and classical-path approximations
- **Quantum interference** among different interaction channels
- **Hadronization** from first-principles

➢ Understand the **real-time dynamics** of jets in QCD matter via **light-front Hamiltonian** approach



Light Front Quantization

Dynamics on the Light Front



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

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

Canonical quantization

$$\{\Psi_{+,c}(x), \Psi^\dagger_{+,c'}(y)\}_{x^+=y^+} = \Lambda_+ \delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{c,c'},$$

$$[A_{i,a}(x), A^\dagger_{j,b}(y)]_{x^+=y^+} = -\frac{i}{4}\epsilon(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)\delta_{i,j}\delta_{a,b},$$

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

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

- Bound states are solved from eigenvalue equations

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

boost invariant

- Evolution of a quantum state follows the Schrödinger equation

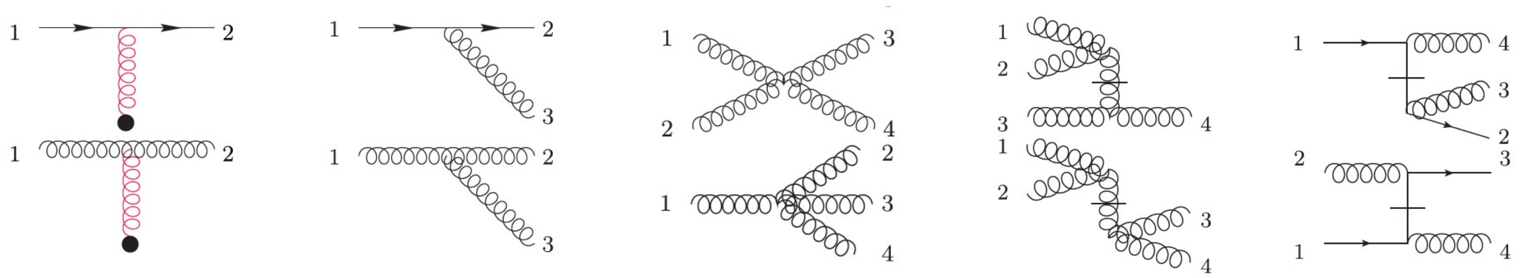
$$\frac{1}{2}P^-|\psi(x^+)\rangle = i\frac{\partial}{\partial x^+}|\psi(x^+)\rangle$$

LF QCD Hamiltonian with medium

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

background field

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



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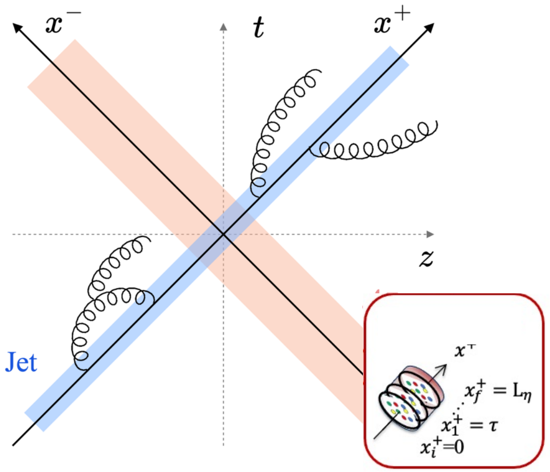


Background field $\mathcal{A}_\mu$
weakly coupled thermal plasma, multiple soft scatterings, many independent scattering centers

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:

$$|q\rangle_{\text{jet}} = \psi_q|q\rangle + \psi_{qg}|qg\rangle + \psi_{qgg}|qgg\rangle + \cdots$$

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

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

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

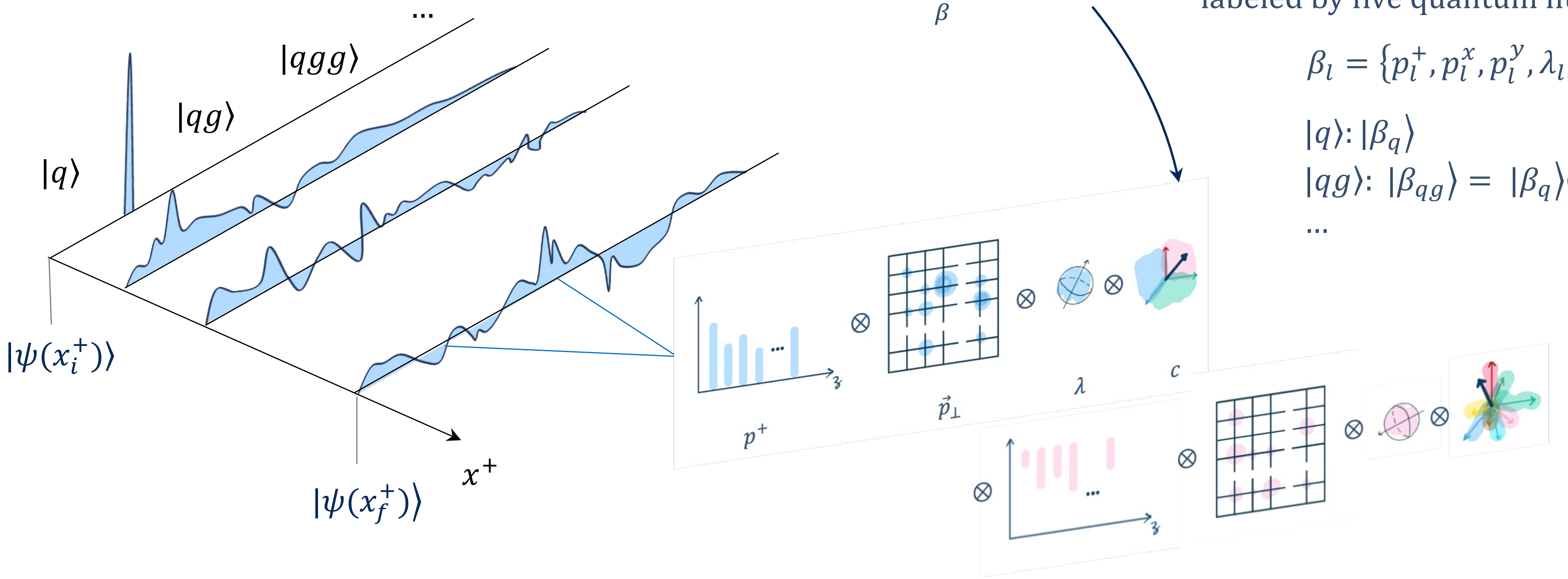
Each single-particle basis state is labeled by five quantum numbers:

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

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

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

...

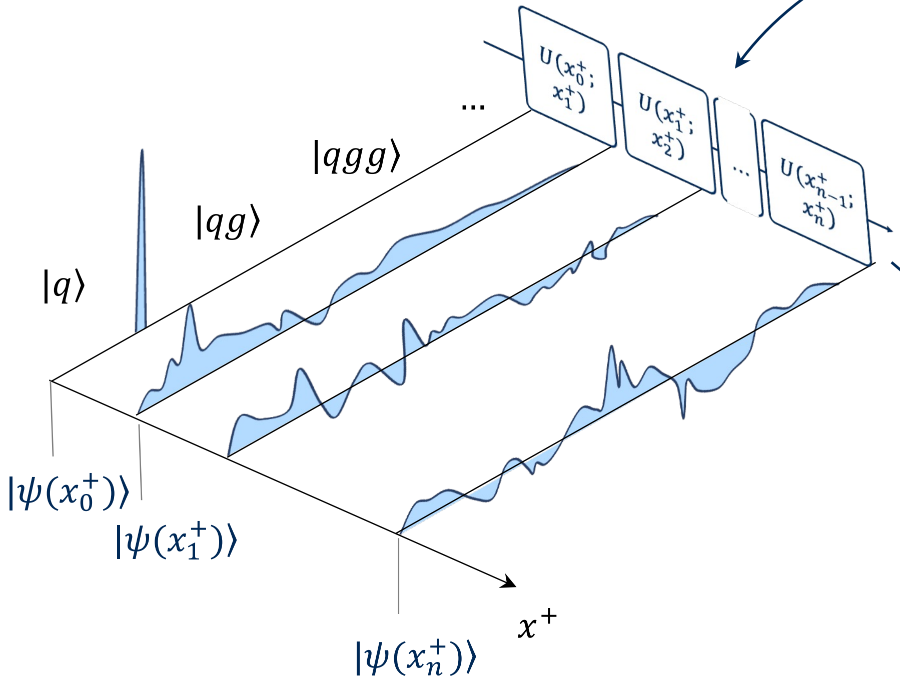


Time evolution of QCD jets

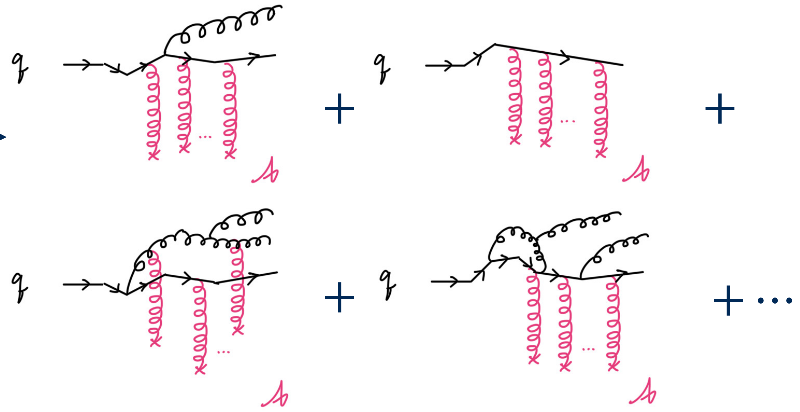
- **Non-perturbative**: time evolution operator into a product of many sequential timesteps

$$|\psi(x^+)\rangle = \underbrace{\boxed{\mathcal{T}_+ e^{-\frac{i}{2}\int_0^{x^+} dz^+ P^-(z^+)}}}_{\equiv\, U(x^+;\,0)} |\psi(0)\rangle \xrightarrow{\text{Trotterization}} \prod_{k=1}^{n} \mathcal{T}_+ \exp\left[-\frac{\mathrm{i}}{2}\int_{x_{k-1}^+}^{x_k^+} dz^+ P^-(z^+)\right] |\psi(0\,)\rangle$$

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

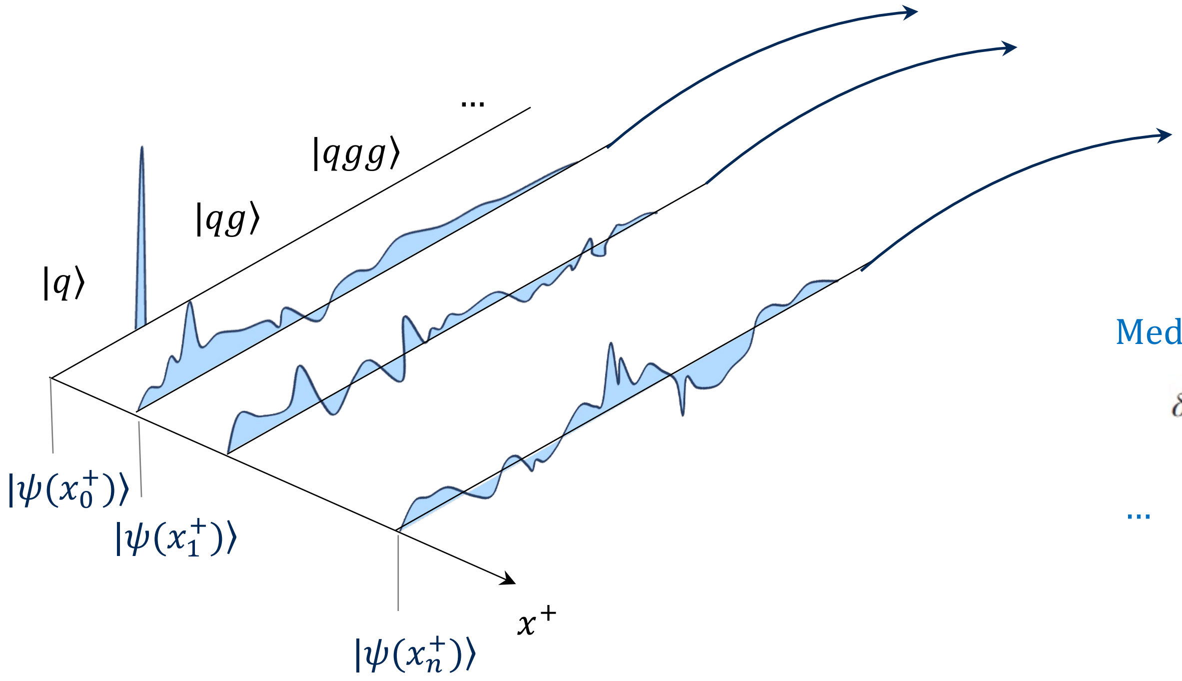


automatically **going beyond eikonal** and include **quantum interference** at each timestep:



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

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

...

Timeline: Real-time Jet classical quantum Simulations

$|q\rangle$

2020

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

$|q\rangle + |qg\rangle$

2021

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

2022

Jet quenching on a QC[Barata, Du, **ML**, Qian, Salgado, PRD, 2208.06750]

[Yao, 2205.07902]

2023

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

QS of in-medium jets [Barata, Du, **ML**, Qian, Salgado, PRD, 2307.01792]

[Castro, Milhano, Oliveira, EPJC, 2502.03431]

2024

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

$|g\rangle + |gg\rangle + |ggg\rangle$

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

[Wu, Du, Zhao, Vary, PRD, 2404.00819]

W. Qian's talk on Thursday

2025

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

2026 Glasma

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

QS of dijet production [Barata, **ML**, Qian, Salgado, Silva, JHEP, 2604.11616]

$|q\bar{q}\rangle$

Timeline: Real-time Jet classical / quantum Simulations

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

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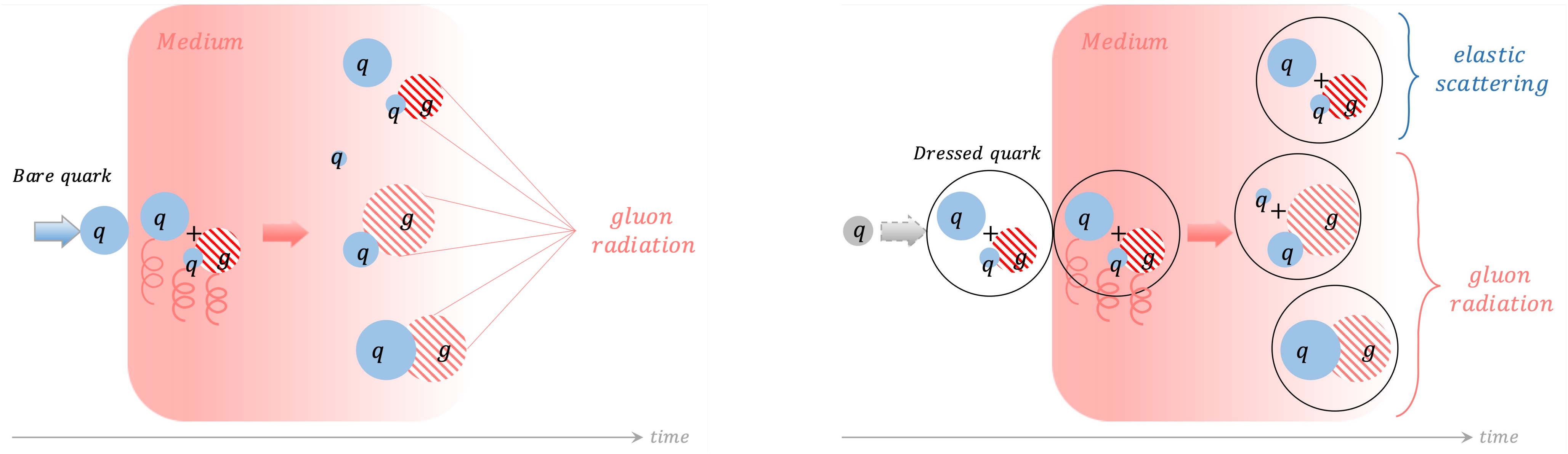
Real-time Jet Simulations: Dressed Quarks

Two-folded Motivations:

- How to describe quark that originates from far outside the medium?
- How to distinguish jet intrinsic and external gluons?



Schematic illustration of in-medium quark evolution in $|q\rangle + |qg\rangle$ Fock space

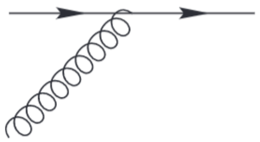
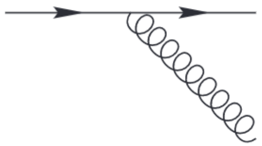
(a) initial state is a bare quark (b) initial state is a dressed quark

Solving for the Dressed Quarks

The dressed quark state is described as the eigenstate of the light-front QCD Hamiltonian with the quark quantum numbers. In $|q\rangle + |qg\rangle$,

$$\boxed{\mathcal{L}_{QCD} = -\frac{1}{4}\mathrm{F}_{\mathrm{a}}^{\mu\nu}F_{\mu\nu}^{a} + \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi \quad\rightarrow\quad \mathrm{P}_{QCD}^{-} = \mathrm{P}_{KE}^{-} + V_{qg}}$$

$$P_{QCD}^{-}|\phi\rangle = P_{\phi}^{-}|\phi\rangle \quad\Longleftrightarrow\quad \underbrace{(P_{QCD}^{-}P^{+} - \vec{P}_{\perp}^{2})}_{H_{\mathrm{LC}}}|\phi\rangle = M^{2}|\phi\rangle$$

Fock sector	$\|q\rangle$	$\|qg\rangle$
$\langle q\|$	$\mathrm{P}_{KE}^{-}(m_Q = m_q + \delta m)$	
$\langle qg\|$		$\mathrm{P}_{KE}^{-}(m_q)$

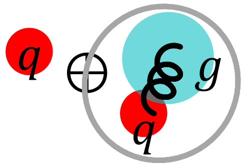
$\Downarrow$ Sector-dependent mass renormalization

$$H_{\mathrm{LC}}(\delta m)|\phi\rangle = m_q^2|\phi\rangle$$

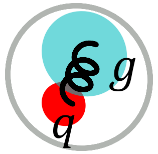
Solving for the Dressed Quarks

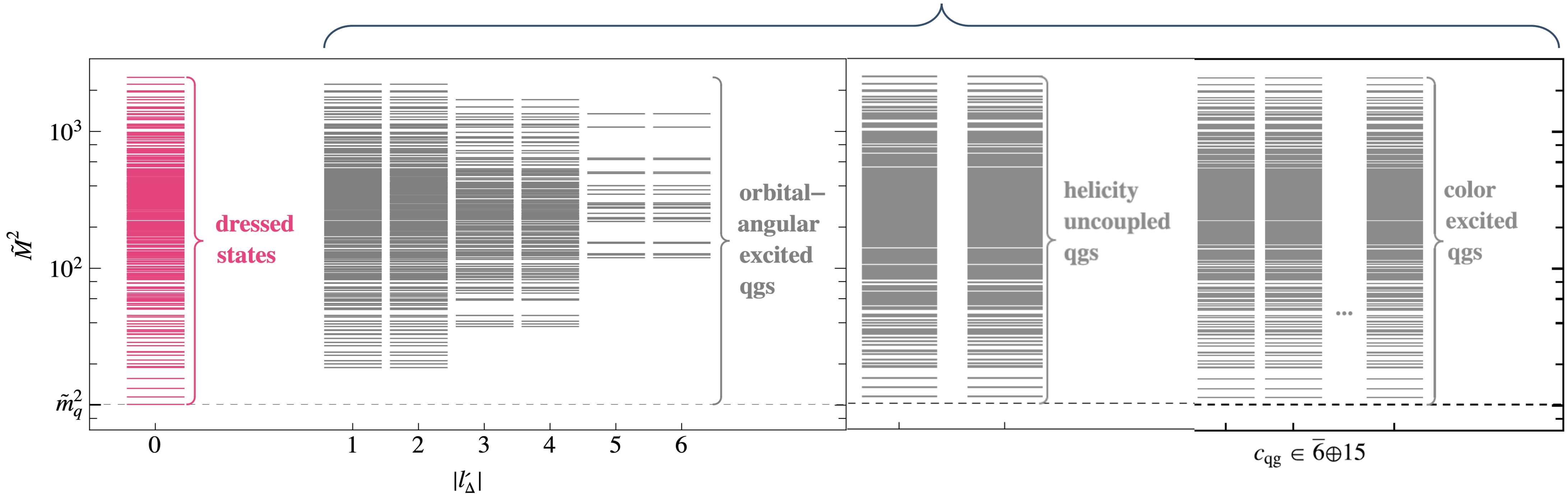
The eigenstates of the light-front QCD Hamiltonian in $|q\rangle + |qg\rangle$ are obtained by matrix diagonalization, and classified by quantum numbers:

- the dressed states



- quark-gluon states

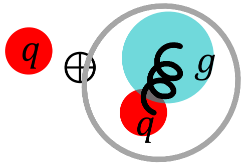


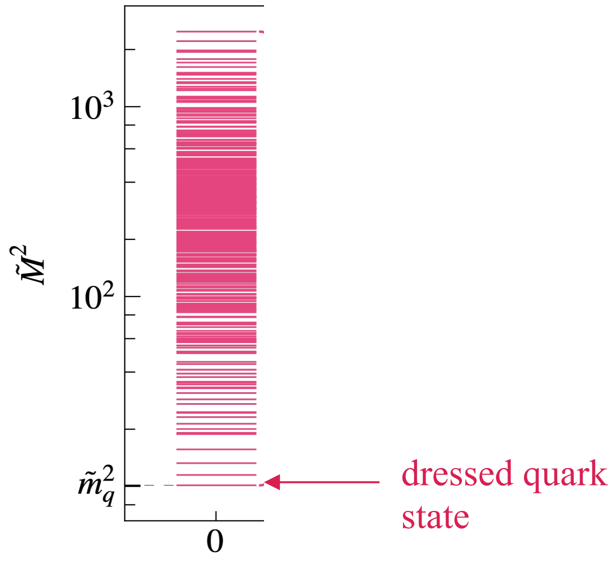


Dressed quark

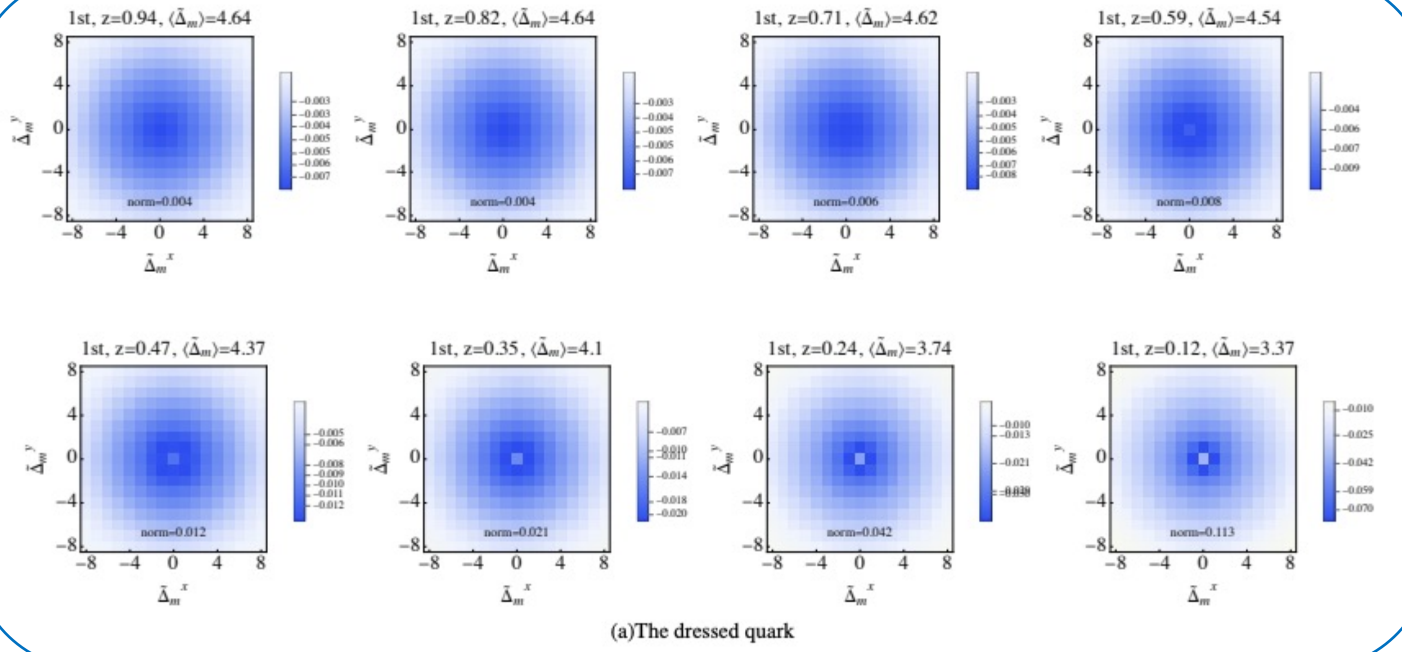
The eigenstates of the light-front QCD Hamiltonian in $|q\rangle + |qg\rangle$ are obtained by matrix diagonalization, and classified by quantum numbers:

- the dressed states





e.g., 79% $|q\rangle$ + 21% $|qg\rangle$

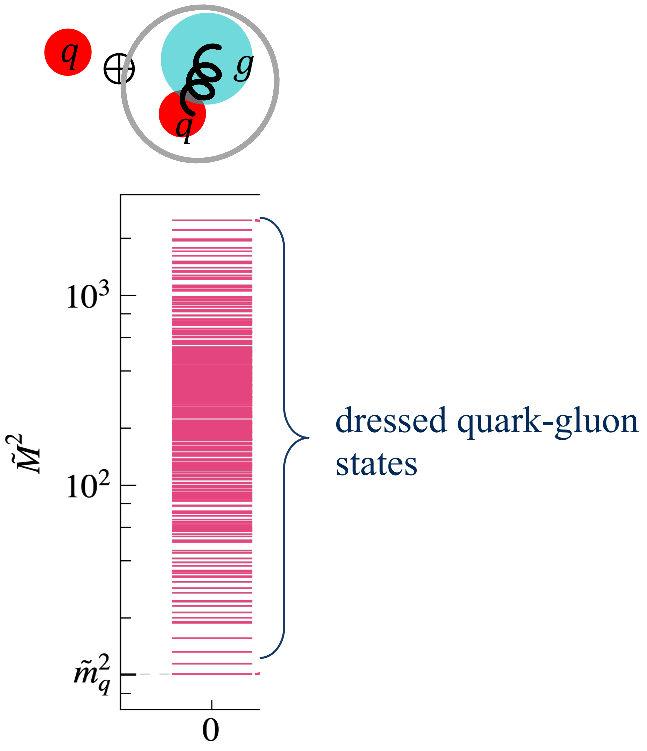


(a)The dressed quark

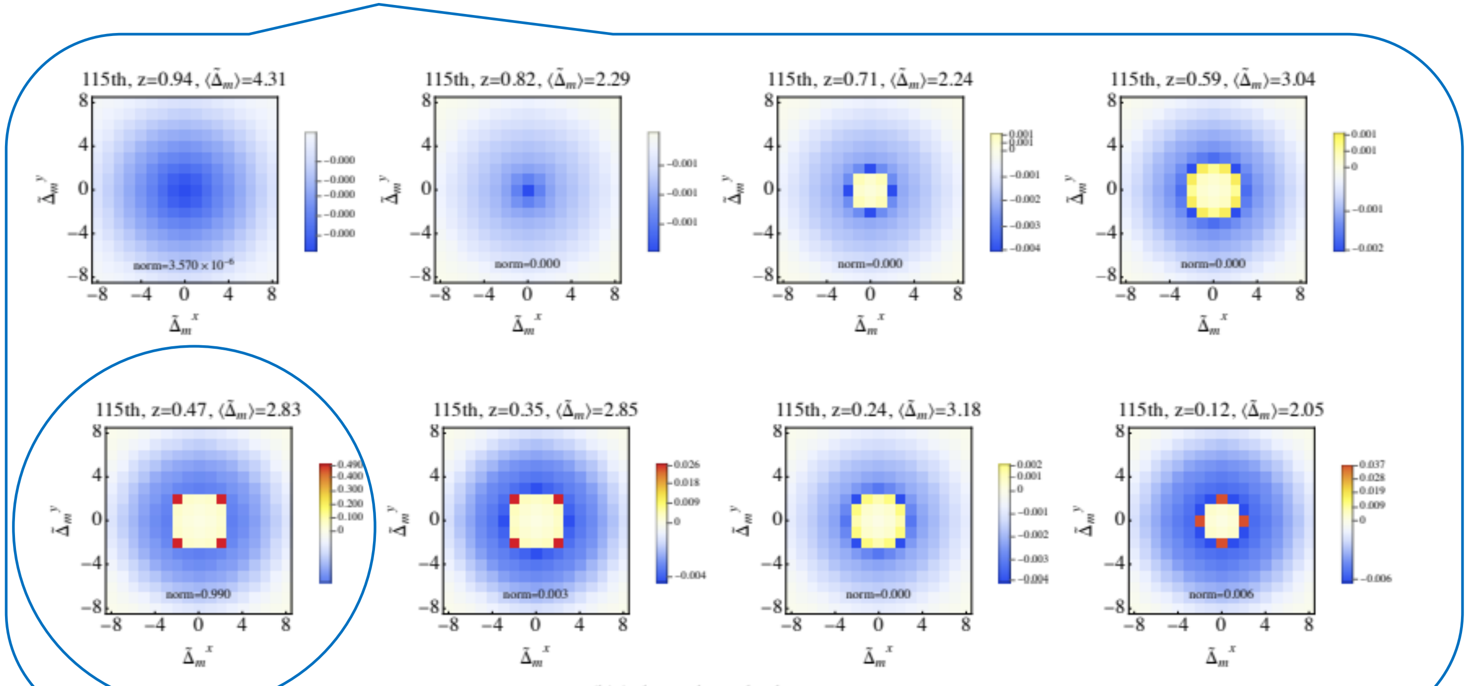
Dressed quark

The eigenstates of the light-front QCD Hamiltonian in $|q\rangle + |qg\rangle$ are obtained by matrix diagonalization, and classified by quantum numbers:

- the dressed states



e.g., 0.1% $|q\rangle$ + 99.9% $|qg\rangle$

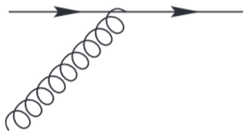
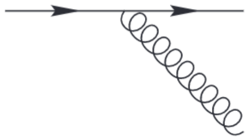


(b)A dressed quark-gluon state

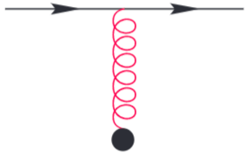
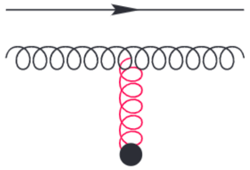
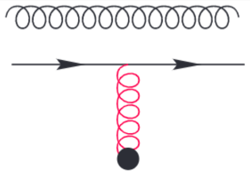
Jet evolution in medium

The evolution Hamiltonian has an additional background field, describing the medium

$$\mathcal{L}_{QCD} = -\frac{1}{4}\mathrm{F}_{\mathrm{a}}^{\mu\nu}F_{\mu\nu}^{a} + \bar{\psi}(i\gamma^{\mu}\overbrace{D_{\mu}}^{\partial_\mu + ig(A_\mu + \mathcal{A}_\mu)} - m)\psi \quad \rightarrow \mathrm{P}^{-}(x^{+}) = \mathrm{P}_{QCD}^{-} + V_{\mathcal{A}}(x^{+})$$

Fock sector	$\|q\rangle$	$\|qg\rangle$
$\langle q\|$	$\mathrm{P}_{KE}^{-}(m_Q = m_q + \delta m)$	
$\langle qg\|$		$\mathrm{P}_{KE}^{-}(m_q)$

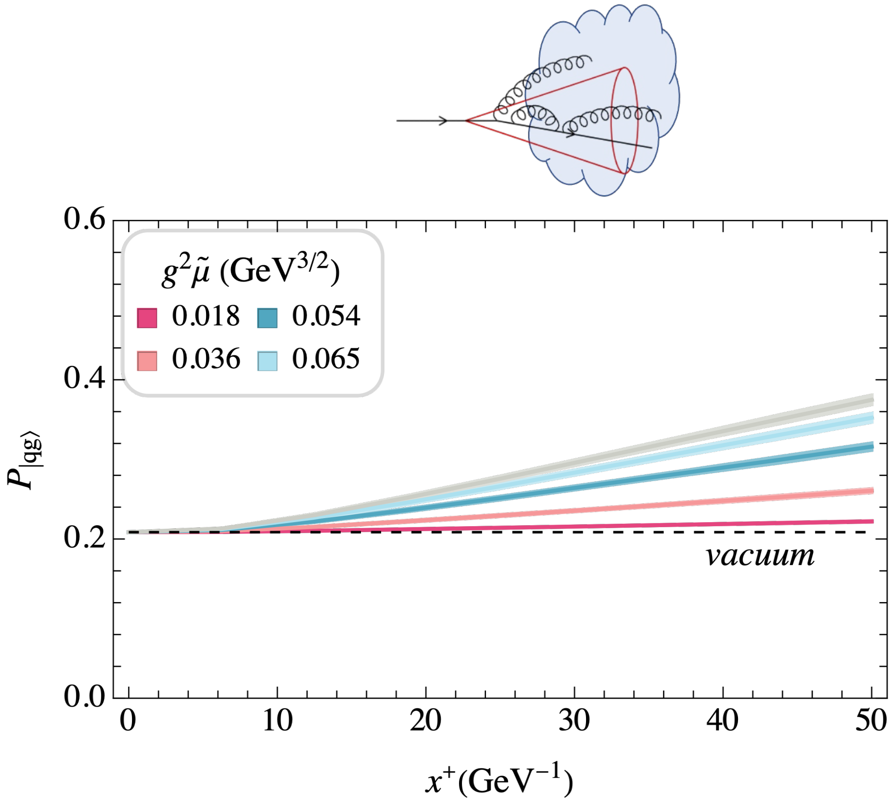
$+$

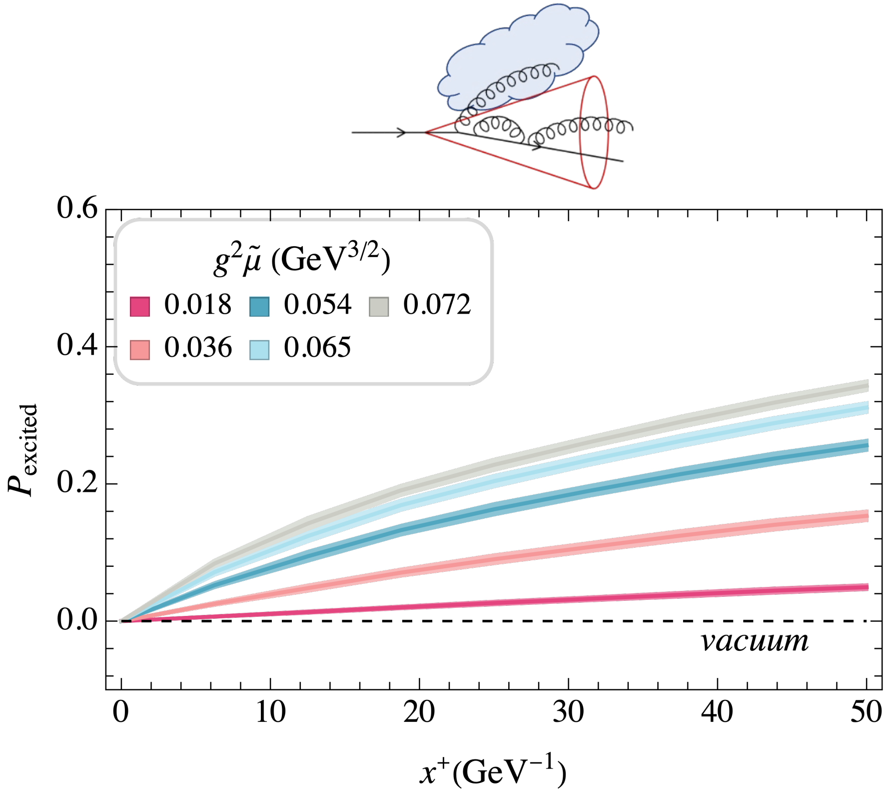
Fock sector	$\|q\rangle$	$\|qg\rangle$
$\langle q\|$		
$\langle qg\|$		 

Simulation results: gluon emission

Gluon emission is enhanced by the medium interaction

- $P_{|qg\rangle}$ counts the total gluons
- P_{excited} counts only the external gluons

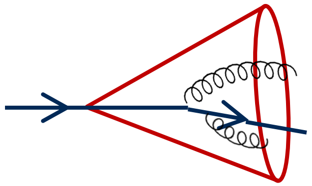


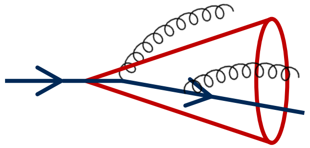


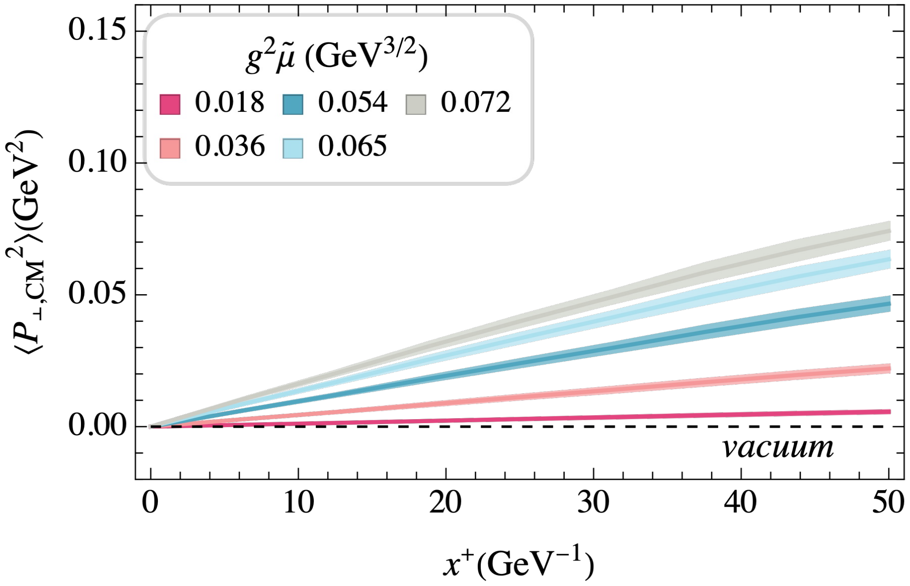
Simulation results: p_t broadening

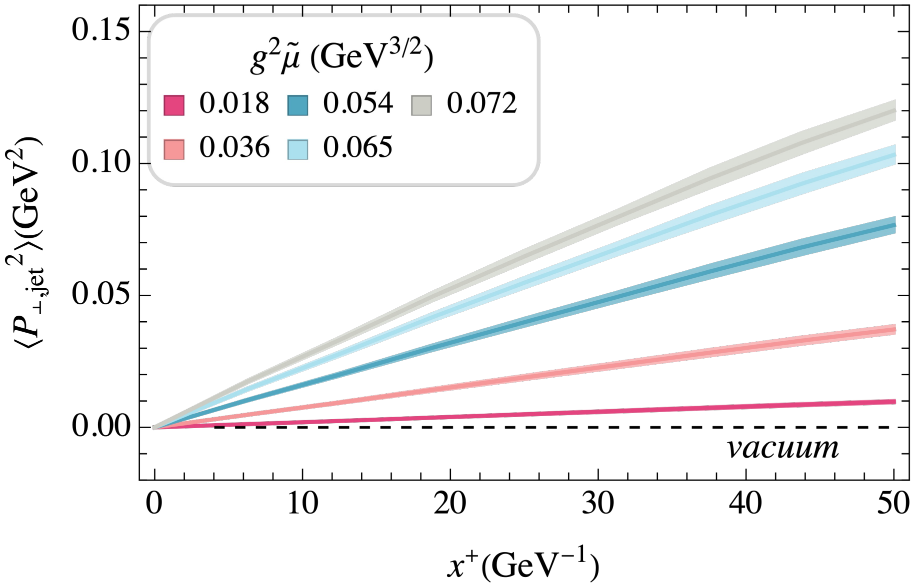
Momentum broadening is more profound at a stronger medium

- C.M. momentum consider the full state
- Jet momentum exclude the external gluons







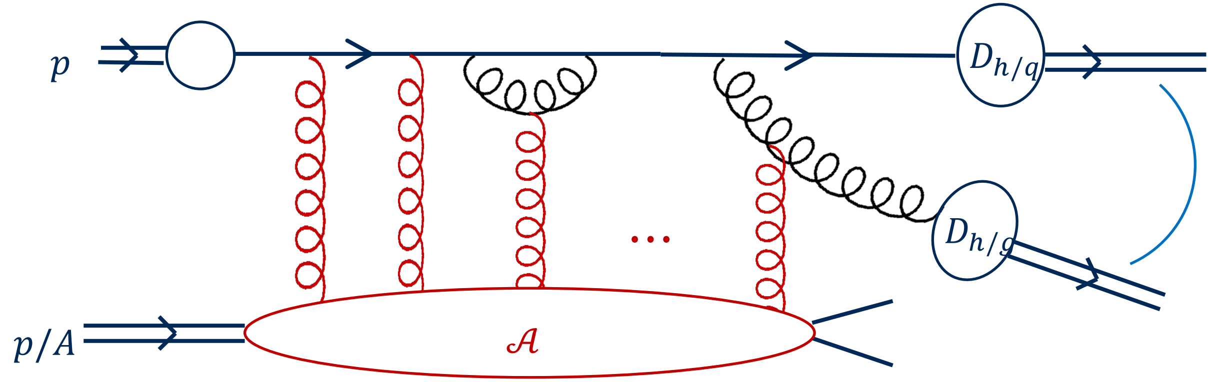


TEEC of quark-gluon dijet in pA collisions

Motivation: study small-x effects from observables in high energy experiments

- **Gluon saturation**: the gluon density of nucleons has been observed to grow rapidly with increasing energy, and will eventually be tamed down by nonlinear gluon recombination effects.
- **Transverse Energy-Energy Correlator (TEEC)** was developed as a suitable observable for colliders involving hadrons as transverse momenta are typically measured

$$\frac{\mathrm{d}\Sigma^{h_q+h_g}}{\mathrm{d}\tau}=\sum_{h_q}\sum_{h_g}\int \mathrm{d}y_{h_q}\int \mathrm{d}^2p_{\perp,h_q}\int \mathrm{d}y_{h_g}\int \mathrm{d}^2p_{\perp,h_g}\frac{\mathrm{d}\sigma^{p\mathcal{A}\to h_q h_g X}}{\mathrm{d}y_{h_q}\,\mathrm{d}y_{h_g}\,\mathrm{d}^2p_{\perp,h_q}\,\mathrm{d}^2p_{\perp,h_g}}\boxed{\frac{E_{h_qT}E_{h_gT}}{(\sum_{h'_q}E_{h'_qT})(\sum_{h'_g}E_{h'_gT})}}\delta\left(\tau-\frac{1+\cos\phi}{2}\right)$$



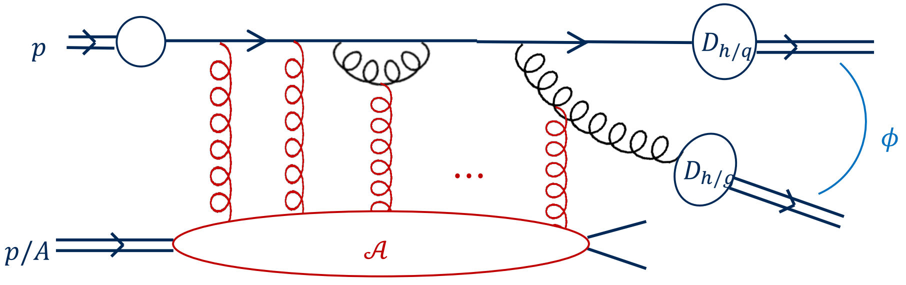
TEEC of quark-gluon dijet in pA collisions

- **Transverse Energy-Energy Correlator (TEEC)**

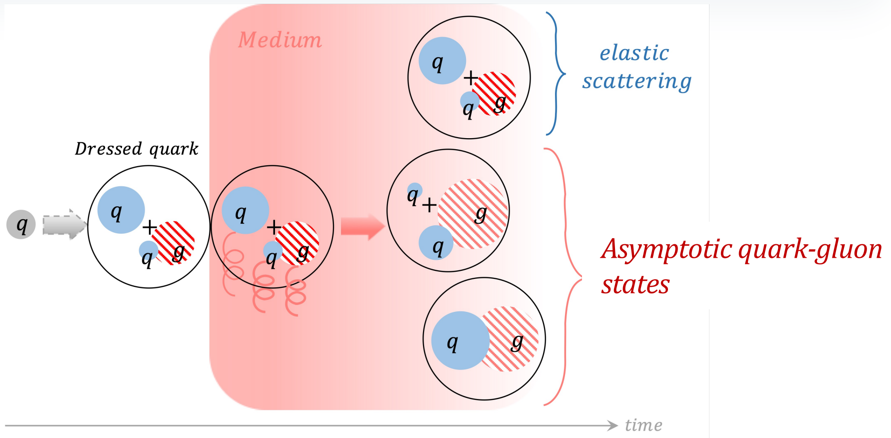
$$\frac{\mathrm{d}\Sigma^{h_q+h_g}}{\mathrm{d}\tau} = \sum_{h_q}\sum_{h_g}\int \mathrm{d}y_{h_q}\int \mathrm{d}^2p_{\perp,h_q}\int \mathrm{d}y_{h_g}\int \mathrm{d}^2p_{\perp,h_g}\frac{\mathrm{d}\sigma^{p\mathcal{A}\to h_q h_g X}}{\mathrm{d}y_{h_q}\,\mathrm{d}y_{h_g}\,\mathrm{d}^2p_{\perp,h_q}\,\mathrm{d}^2p_{\perp,h_g}}\boxed{\frac{E_{h_qT}E_{h_gT}}{(\sum_{h'_q}E_{h'_qT})(\sum_{h'_g}E_{h'_gT})}}\delta\left(\tau-\frac{1+\cos\phi}{2}\right)$$

Momentum sum rule $\Downarrow$ $\quad \sum_h \int_0^1 \mathrm{d}z_l D_{l\to h_l}(z_l,\mu) z_l = 1$

$$\int \mathrm{d}y_q\int \mathrm{d}^2p_{\perp,q}\int \mathrm{d}y_g\int \mathrm{d}^2p_{\perp,g}\frac{\mathrm{d}\sigma^{p\mathcal{A}\to qgX}}{\mathrm{d}y_q\,\mathrm{d}y_g\,\mathrm{d}^2p_{\perp,q}\,\mathrm{d}^2p_{\perp,g}}\delta\left(\tau-\frac{1+\cos\phi}{2}\right)$$



$p+\mathcal{A}\to h_q+h_g+X$



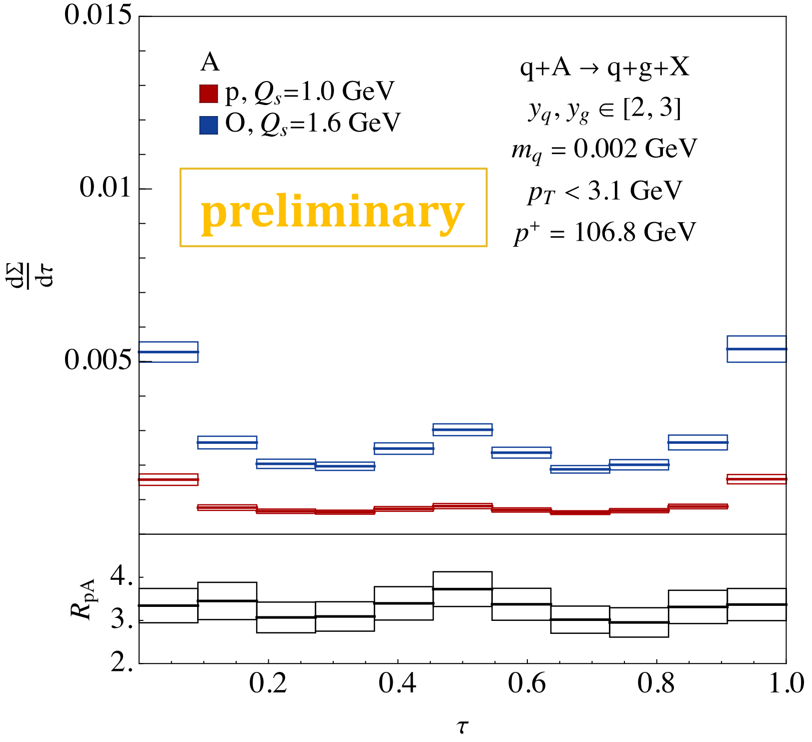
$q+\mathcal{A}\to q+g+X$

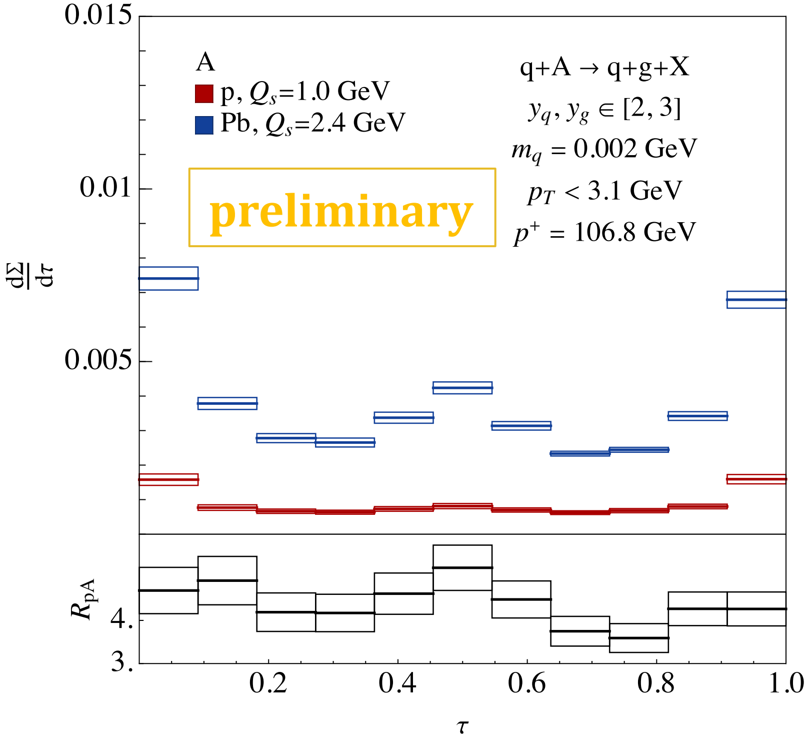
TEEC of quark-gluon dijet in pA collisions

TEEC is enhanced by nuclear effect

- TEEC is increasing as τ approach 0 and 1, and peaked around 0.5
- Enhancement in nuclear modification

$$Q_s^2 = C_F(g^2\tilde{\mu})^2 L_\eta/(2\pi^2) \qquad L_{\eta,A} = A^{1/3} L_{\eta,p}$$





Summary and outlook

✓ We developed and applied a **non-perturbative** computational approach to simulate the **real-time** evolution of in-medium jet

1. *obtained the* ***dressed quark states*** *and the excited* ***quark-gluon states***
2. *analyzed* ***gluon emission*** *from non-perturbative perspectives*
3. *extracted non-eikonal effect of* ***momentum broadening***
4. *calculating* ***transverse energy--energy correlator*** *of quark-gluon dijet*

- Expanding jet Fock space
- Hadronization from first principles
- Further development with quantum simulation

Thank you!