Entanglement dynamics in Deep Inelastic Scattering

from real-time quantum simulation

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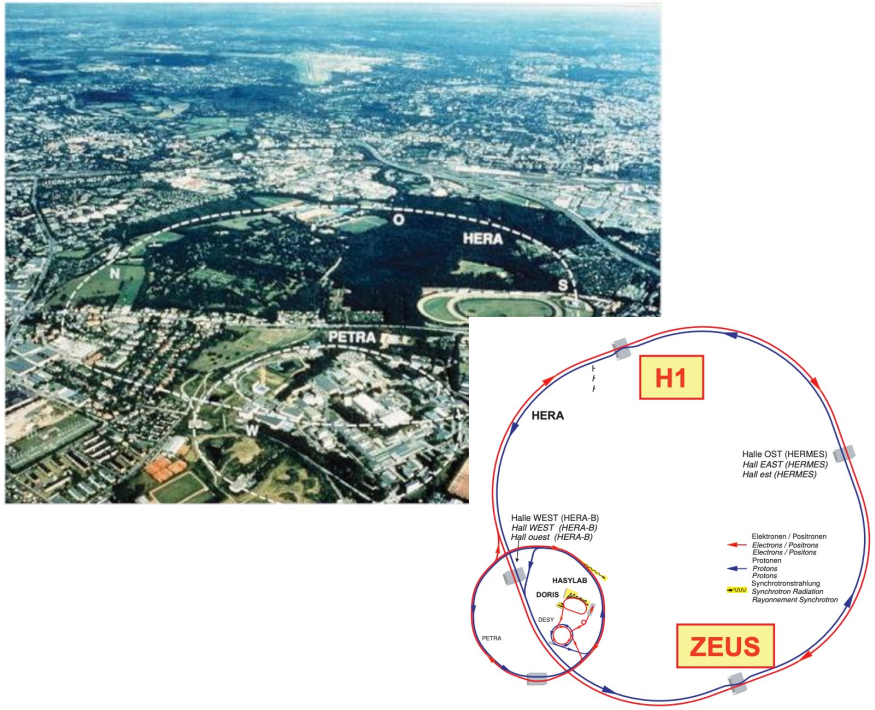
Based on arXiv:2610.25350, in collaboration with X. Cao (USTC), Y. Li (USTC), W. Qian (CCNU).

Quantum Entanglement Studies in Nuclear and Particle Physics

October 24-26, 2026, Fudan University, Shanghai, China

Deep Inelastic Scattering

Renewed and growing interests



HERA - H1, Zeus (1992-2007)
Hamburg, Germany

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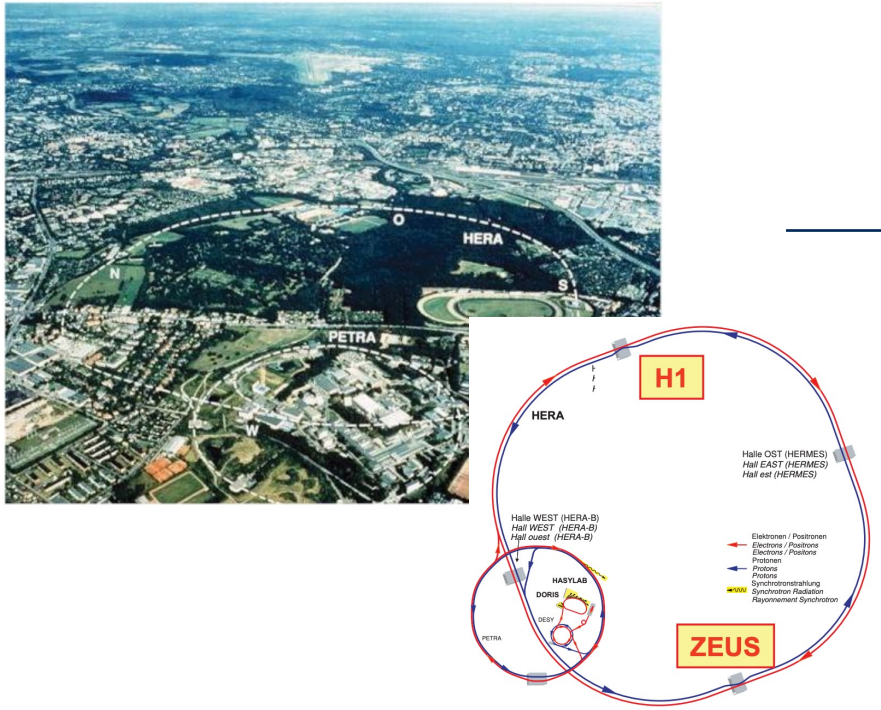

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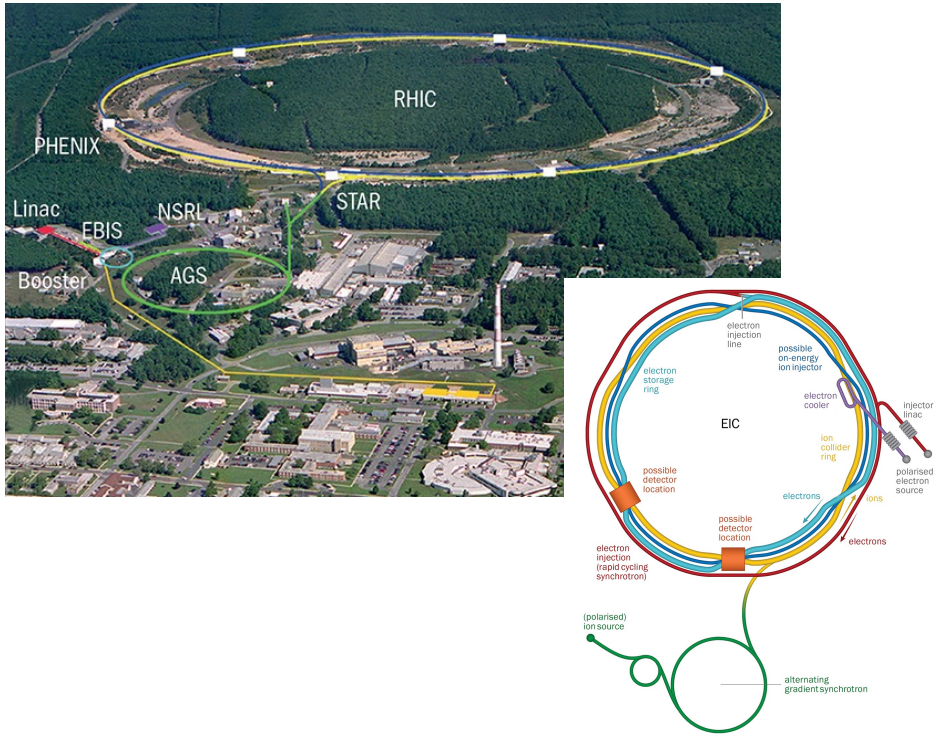
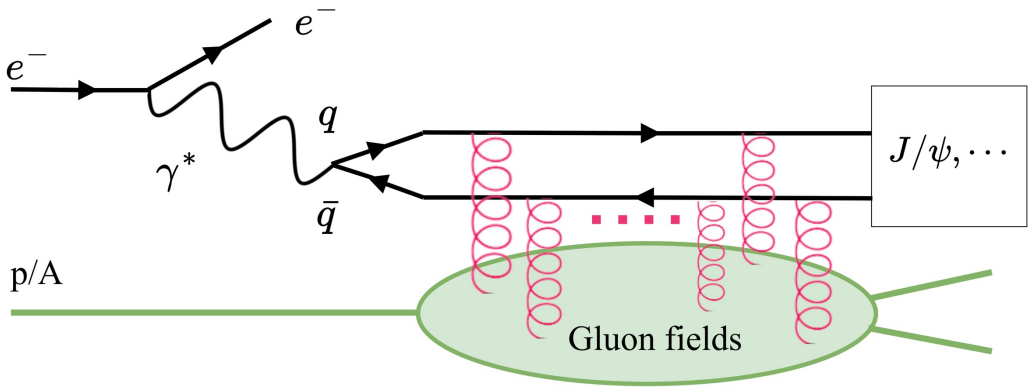


EIC (2030+)
New York, USA

+ LHeC, EicC, …

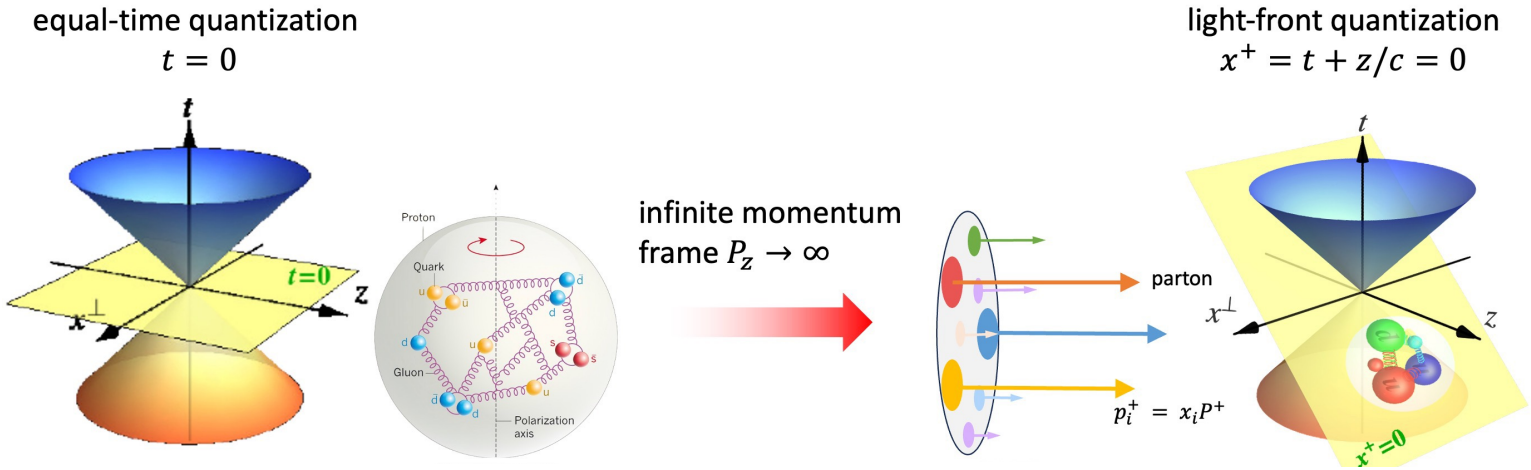
Hadron Production in DIS

- DIS at small x: $\gamma^* \rightarrow q\bar{q}$ dipole → nuclear color field → hadron
- Multiple scales in one process:
  - Initial splitting: perturbative
  - Hadron formation: nonperturbative
  - Quantum coherence preserved throughout
- Conventional approaches (factorization, MC generators) break quantum coherence
- Goal: first-principles, amplitude-level simulation preserving the full quantum state



$$\gamma^* + p/A \rightarrow J/\psi + X$$

Light Front Quantization



[Figure adapted from Yang Li]

- Bound states are solved from eigenvalue equations

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

boost invariant

- Evolution of a quantum state follows the Schrödinger equation

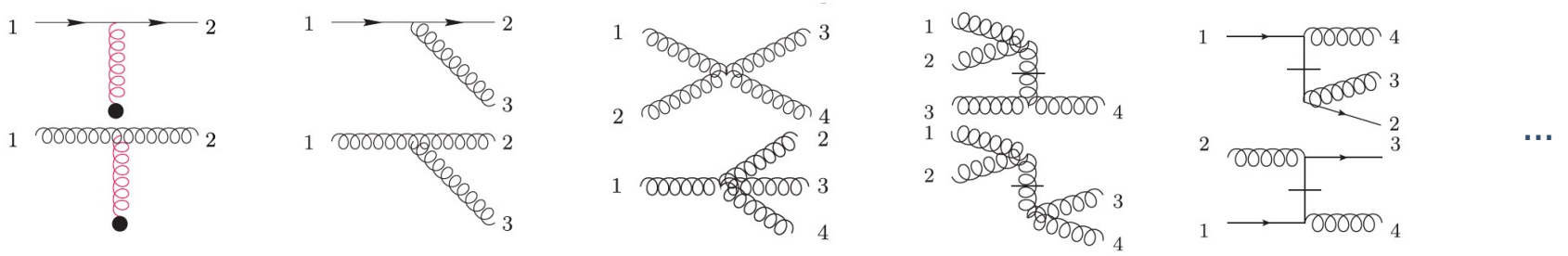
$$\frac{1}{2}P^-|\psi(x^+)\rangle = i\frac{\partial}{\partial x^+}|\psi(x^+)\rangle$$

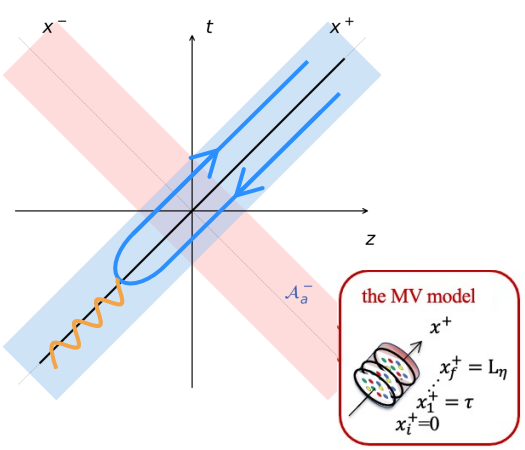
LF QCD Hamiltonian with *background*

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

background field

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





Color Glass Condensate in DIS: $\mathcal{A}_\mu$
strong field, weak coupling,
large occupation numbers

classical fields by Yang-Mills eq.

$$< \rho_a(x)\rho_b(y) > = \mathrm{g}^2\tilde{\mu}^2\delta_{ab}\delta^3(\vec{x}-\vec{y}), \qquad (m_g^2 - \nabla_\perp^2)\mathcal{A}_a^-(x^+,\vec{x}_\perp) = \rho_a\,(x^+,\vec{x}_\perp)$$

Saturation scale: $Q_s^2 = C_F(g^2\tilde{\mu})^2 L_\eta/(2\pi^2)$

Fock space expansion

- Fock sector expansion of quantum states:

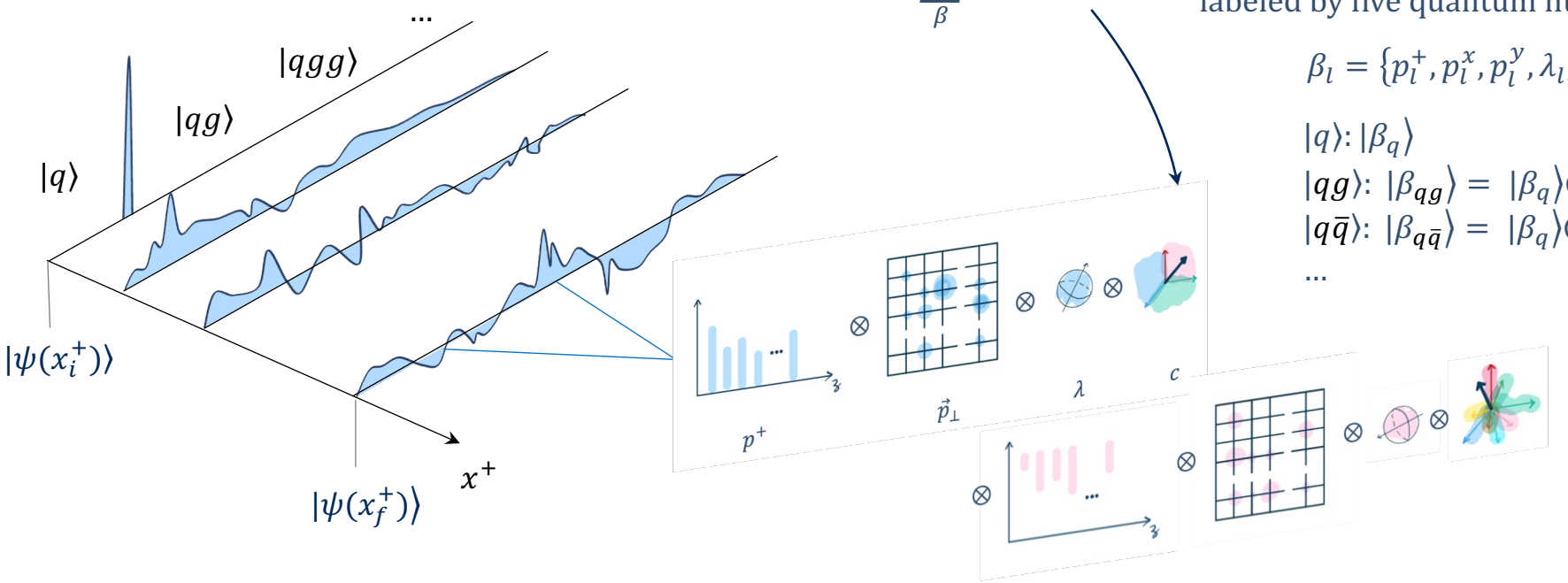
$$|q\rangle_{\text{jet}} = \psi_q|q\rangle + \psi_{qg}|qg\rangle + \psi_{qgg}|qgg\rangle + \cdots$$

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

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

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

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



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

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

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

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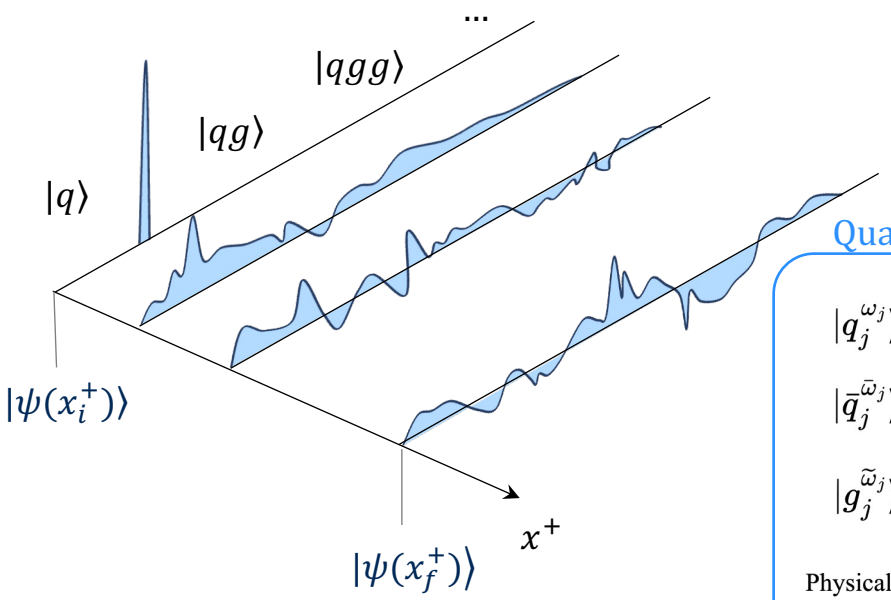

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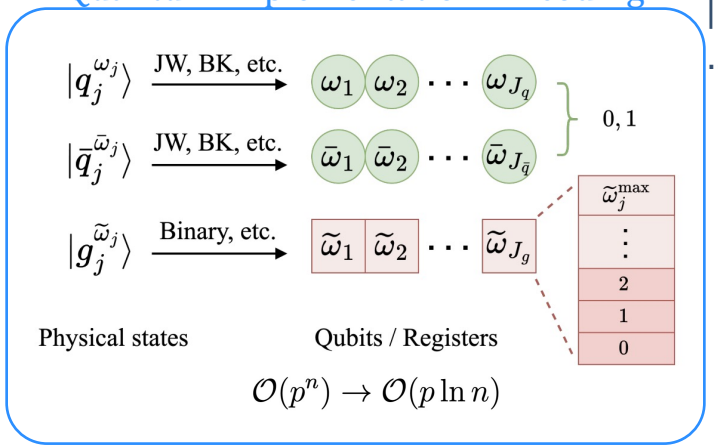
...

Quantum implementation: Encoding



Time evolution of quantum states

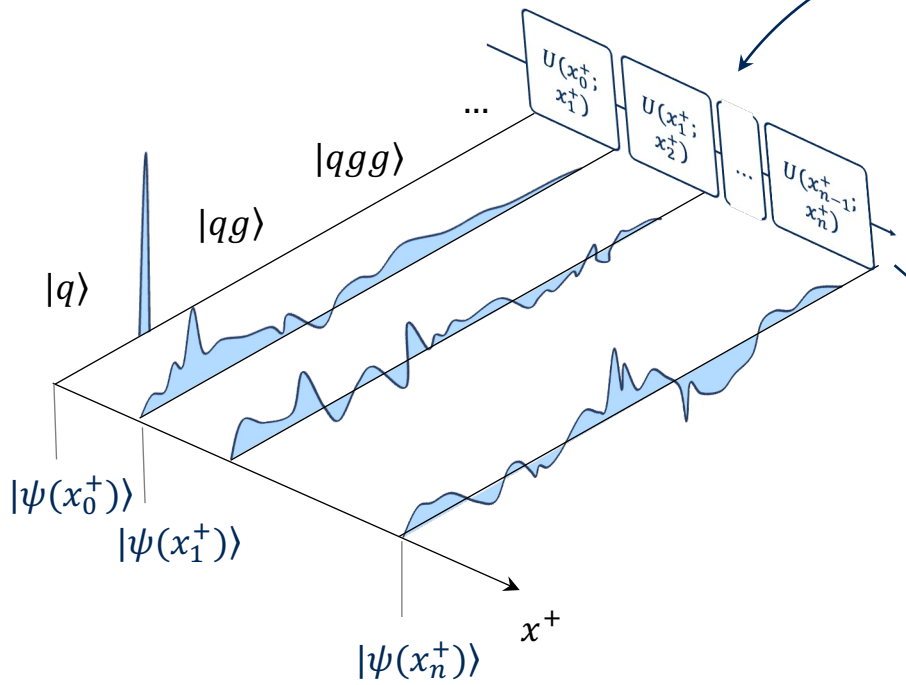
- **Non-perturbative**: time evolution operator into a product of many sequential timesteps

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

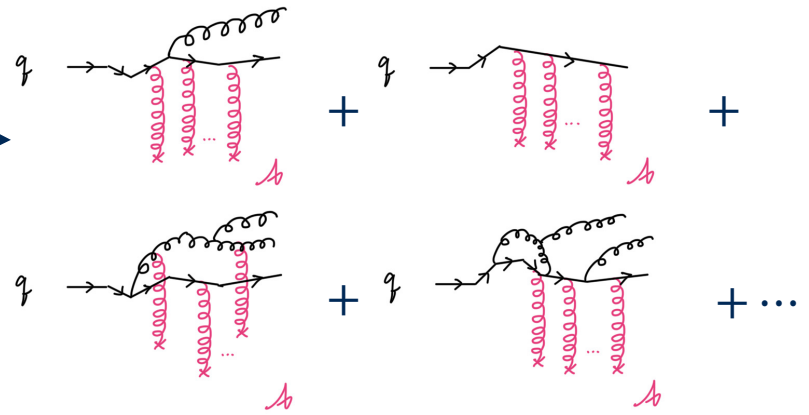
Trotterization

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

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:



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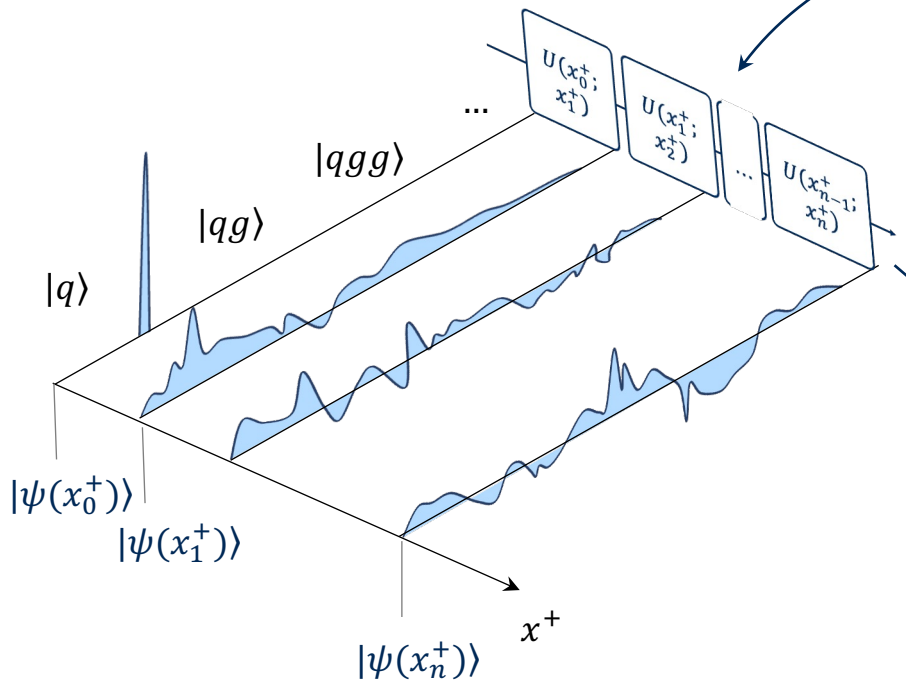
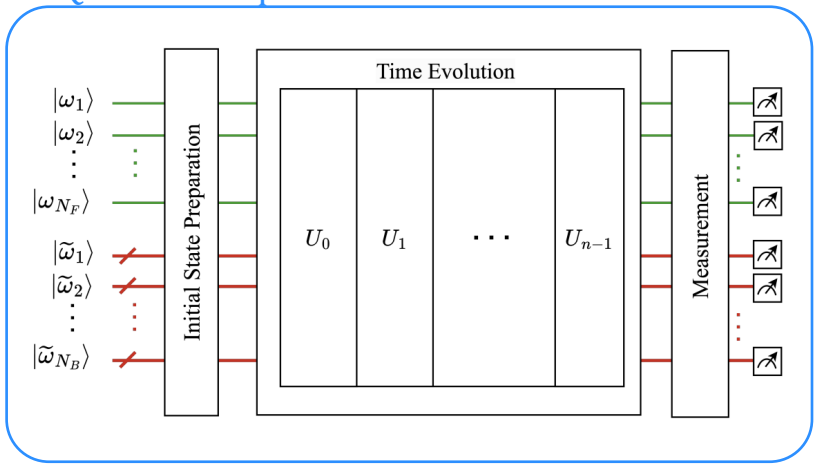
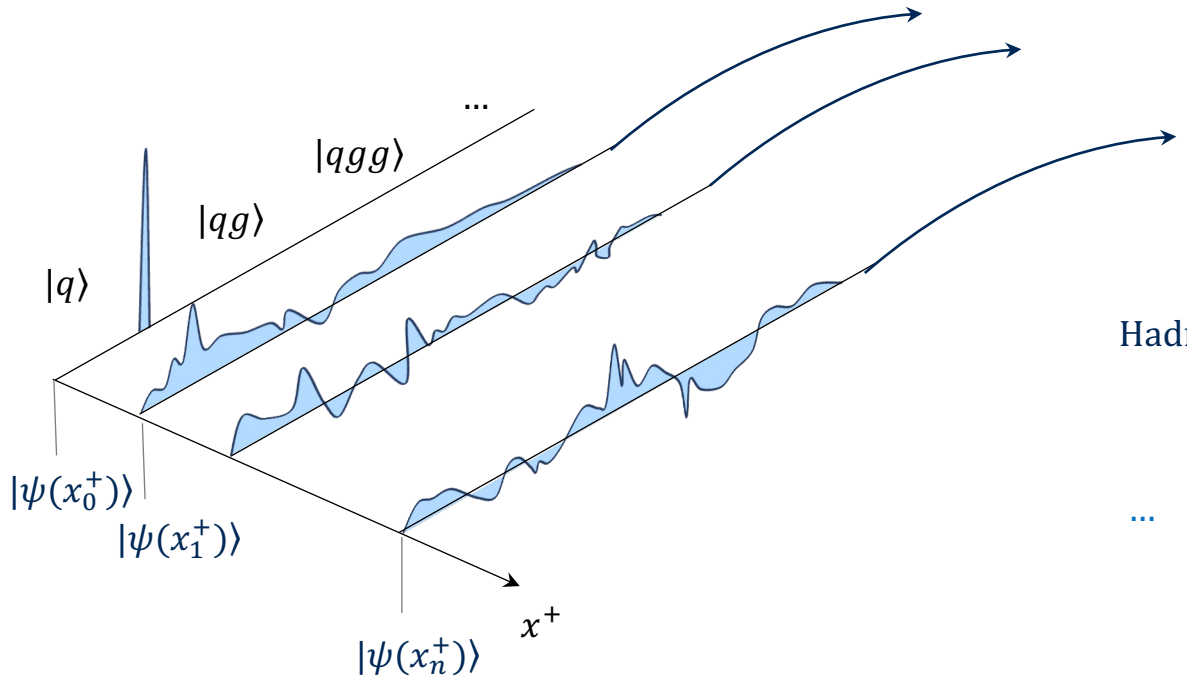


Quantum implementation: trotterization



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

Cross section

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

Hadron production probability

$$\mathrm{Prob}(h) = \sum_{\vec{P}_\perp}|\,\langle\psi(x^+)|\psi_h(\vec{P}_\perp)\rangle\,|^2$$

...

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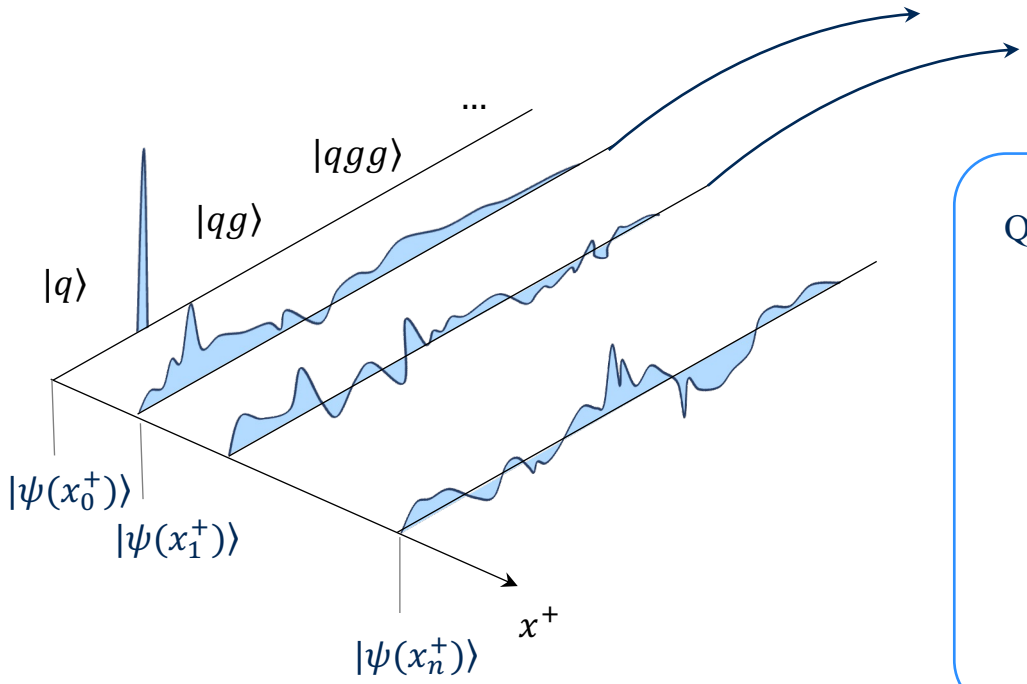


Quantum implementation: measurement

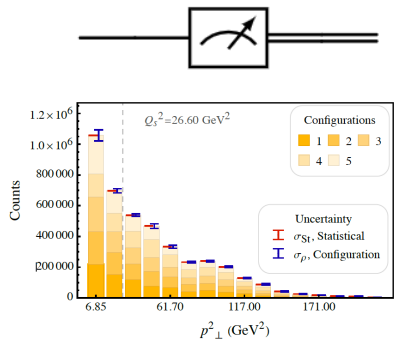
Quantum state Amplitude

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

Classical state

$P_i = |c_i|^2$

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



Progress: Real-time Jet classical / quantum Simulations

$|q\rangle$

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]

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

[Castro, Milhano, Oliveira, EPJC, 2502.03431]

2024

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

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

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

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2026 **Glasma**

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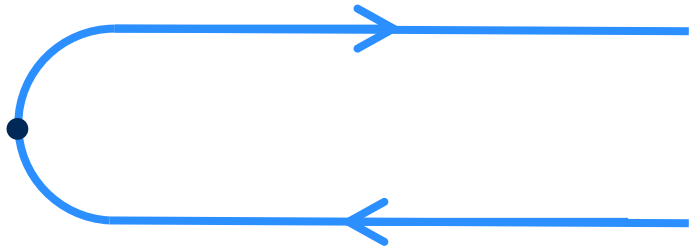
Initial States

Single-momentum dipole

- $\vec{p}_{q,\perp} = \vec{p}_{\bar{q},\perp} = \vec{0}_\perp$, color singlet
- Benchmark against analytical expectation

$$|\psi_{q\bar{q}}\rangle = \sum_{\beta}\sum_{\beta'} c_{\beta\beta'}\,|q(\beta)\bar{q}(\beta')\rangle$$

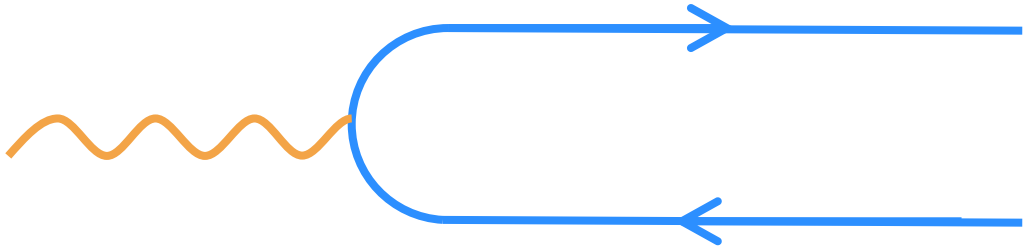
$$c_{\beta\beta'} = \begin{cases} \dfrac{1}{\sqrt{N_c}}, & \text{for } k^i = \bar{k}^i = 0, z = 1/2, k^+ = \bar{k}^+ = K/2, c = \bar{c} \\ 0, & \text{otherwise} \end{cases}$$



Virtual photon

- $q\bar{q}$ component of a photon state
- Physical DIS probe

$$|\gamma^*\rangle_{phys} = |\gamma^*\rangle + |q\bar{q}\rangle + |q\bar{q}g\rangle + \cdots$$



$$\psi^{(m_j=0)}_{s\bar{s}/\gamma}(\vec{k}_\perp, x, Q) = \mathcal{Q}_f e\sqrt{N_c}\sqrt{x(1-x)}\frac{2Qx(1-x)}{\epsilon^2 + k_\perp^2}\delta_{s,\bar{s}},$$

Initial States and nuclear target

Single-momentum dipole

- $\vec{p}_{q,\perp} = \vec{p}_{\bar{q},\perp} = \vec{0}_\perp$, color singlet
- Benchmark against analytical expectation

Virtual photon

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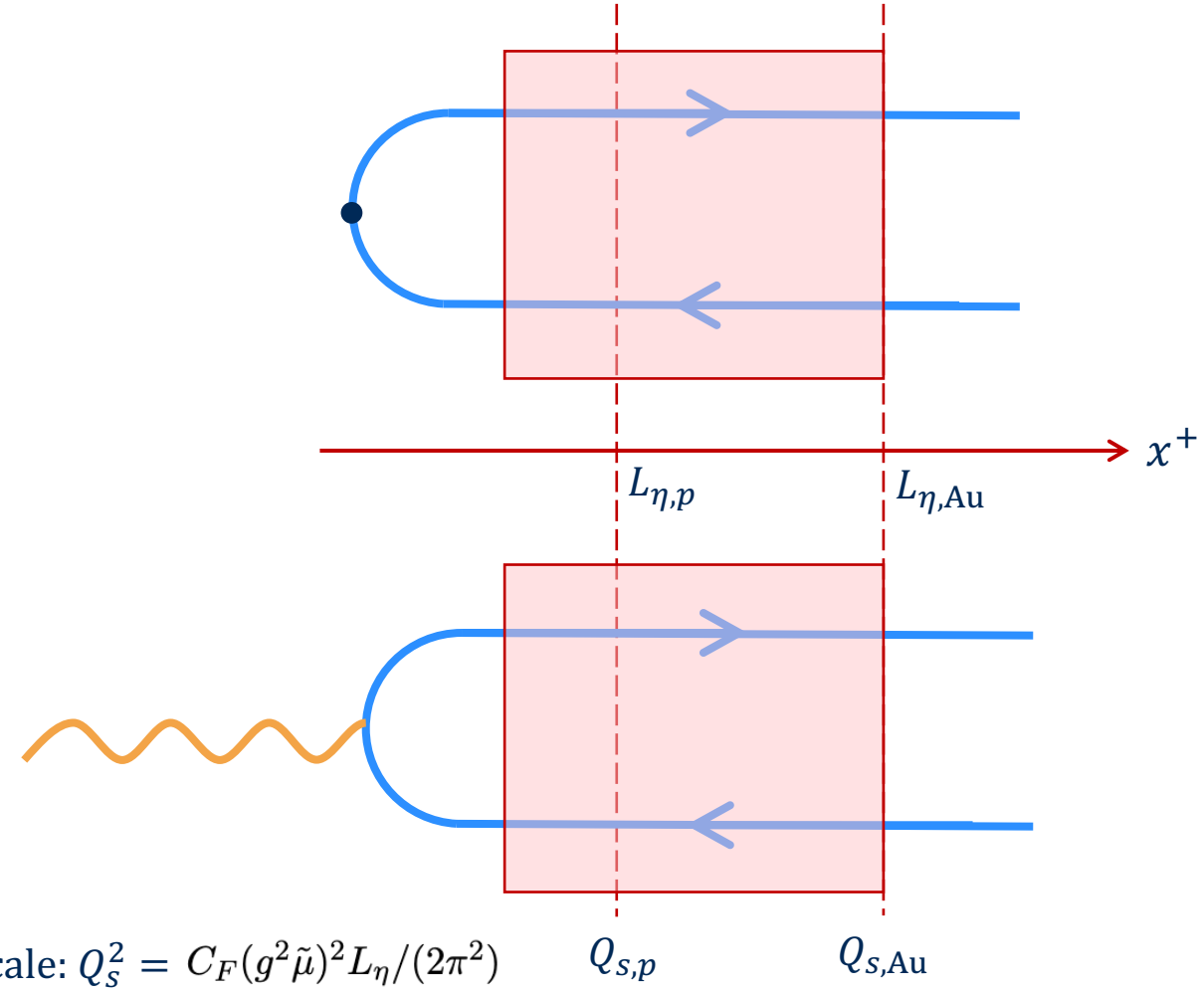
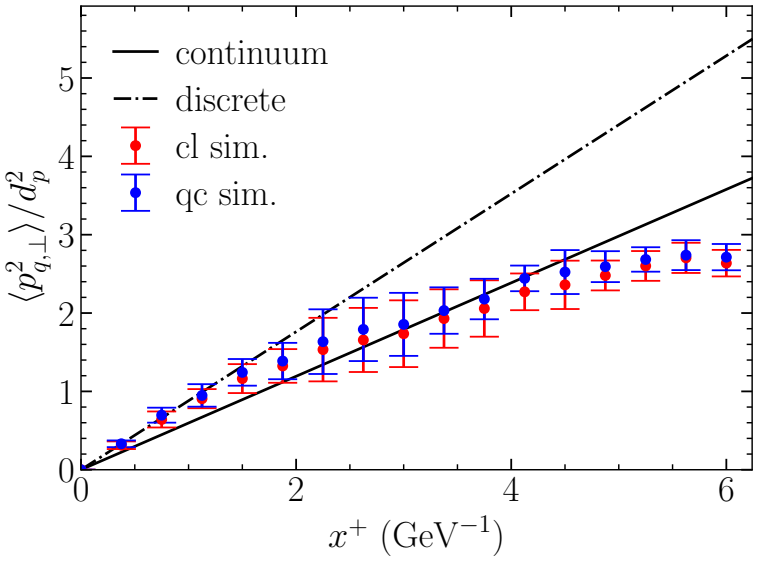


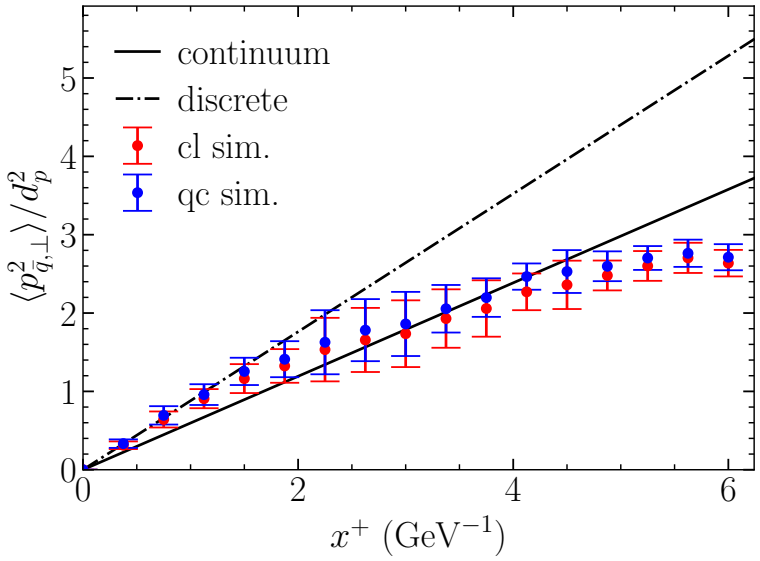
Saturation scale: $Q_s^2 = C_F(g^2\tilde{\mu})^2 L_\eta/(2\pi^2)$

$$L_{\eta,A} = A^{1/3} L_{\eta,p}$$

Momentum Broadening

Single-momentum dipole: q **$\bar{q}$**

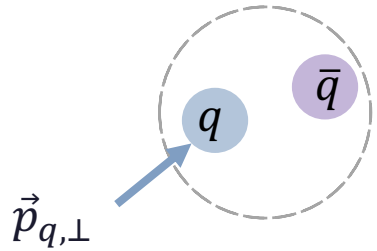


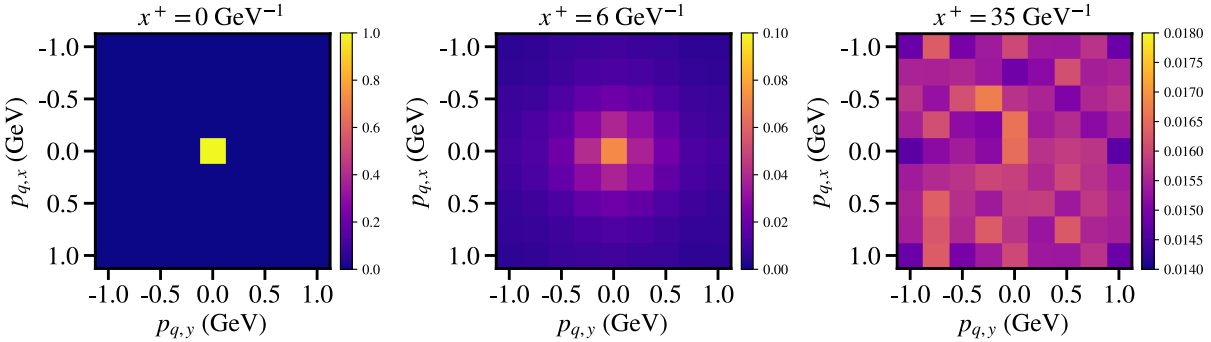


- Classical & quantum-circuit simulations agree
- Early times: linear growth, follows discrete analytical prediction
- Late times: saturates at $\langle p_\perp^2 \rangle / d_p^2 \approx 2N_\perp^2/3$
  - Finite-basis effect: wraps around periodic boundary

Evolution of momentum distribution

Single-momentum dipole

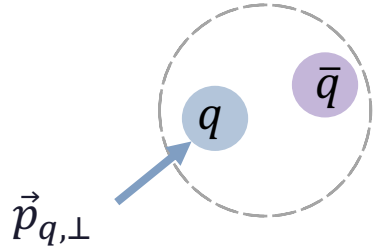




- Quark momentum broadens over time

Evolution of momentum distribution

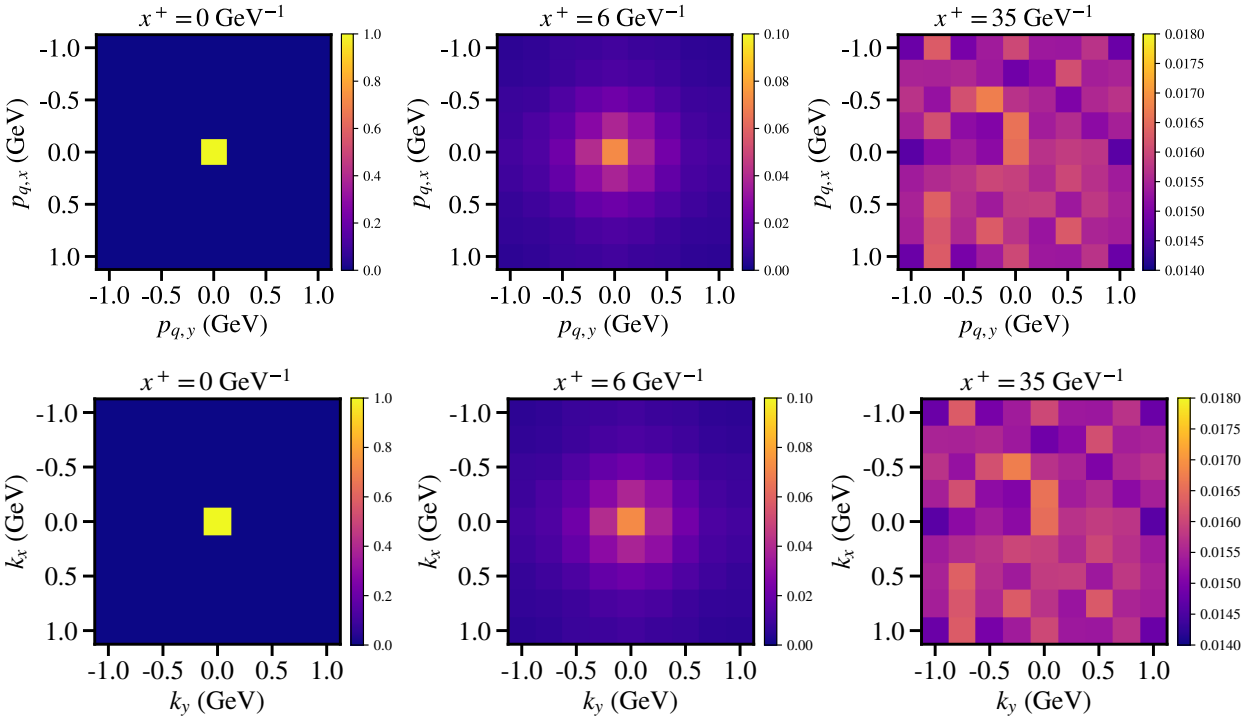
Single-momentum dipole



- quark momentum broadens over time

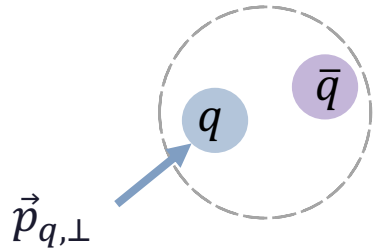
$$\vec{k}_\perp = (\vec{p}_{q,\perp} - \vec{p}_{\vec{q},\perp})/2$$

- relative momentum broadens



Evolution of momentum distribution

Single-momentum dipole



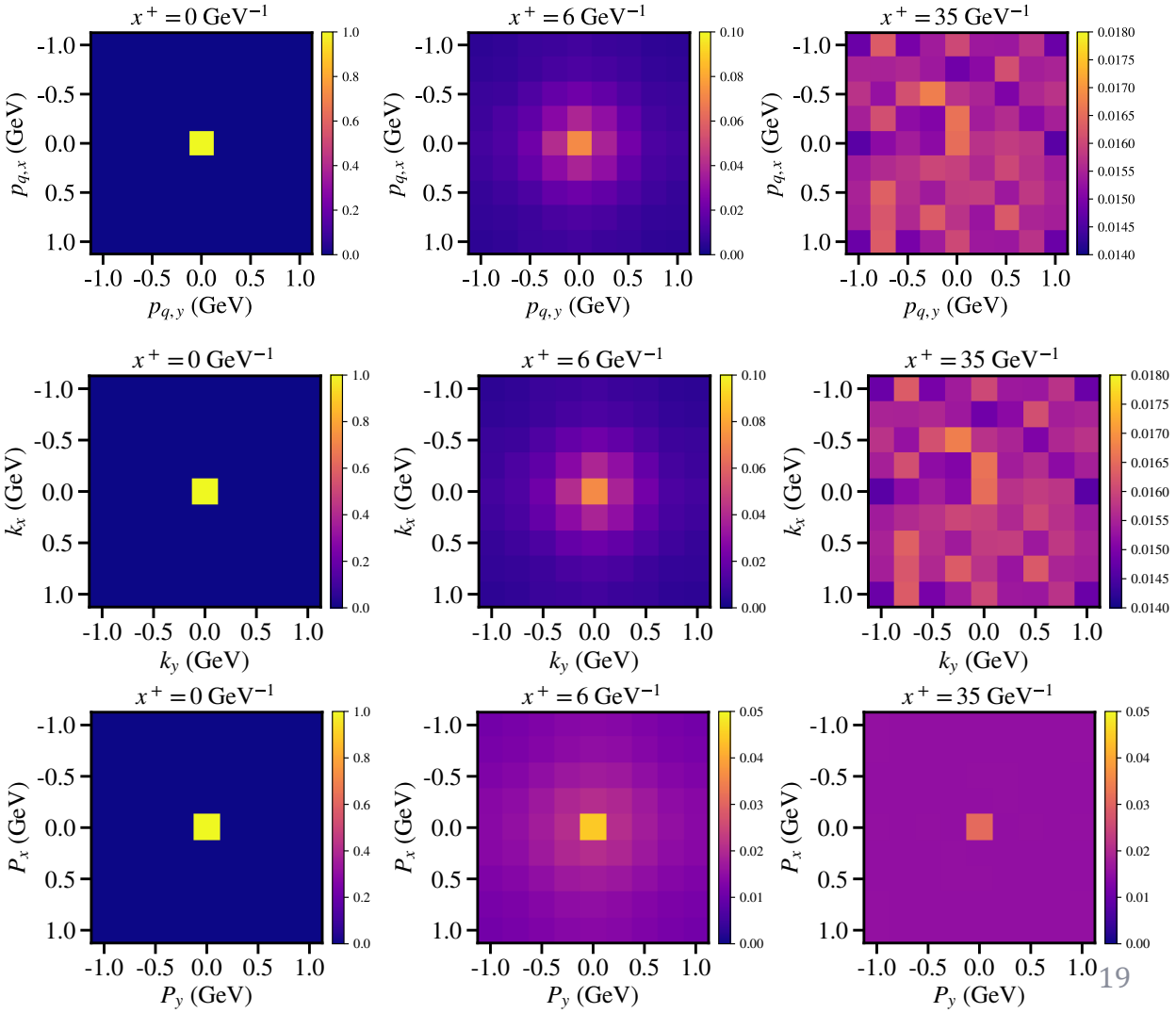
- quark momentum broadens over time

$$\vec{k}_\perp = (\vec{p}_{q,\perp} - \vec{p}_{\vec{q},\perp})/2$$

- relative momentum broadens

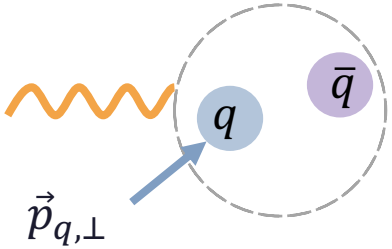
$$\vec{P}_\perp = \vec{p}_{q,\perp} + \vec{p}_{\vec{q},\perp}$$

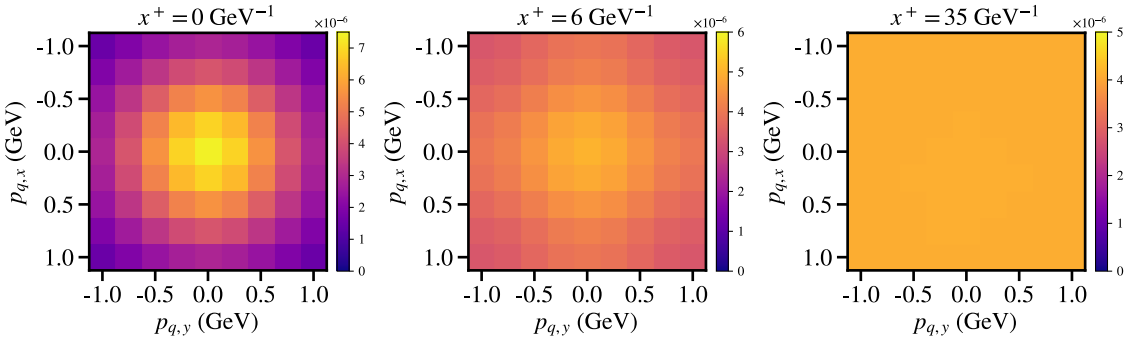
- C.M. momentum broadens faster
  - Peak at $\vec{P}_\perp = \vec{0}_\perp$: coincident component, color transparent



Evolution of momentum distribution

Virtual photon state





- quark momentum broadens over time

Evolution of momentum distribution

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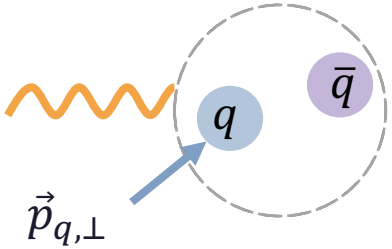
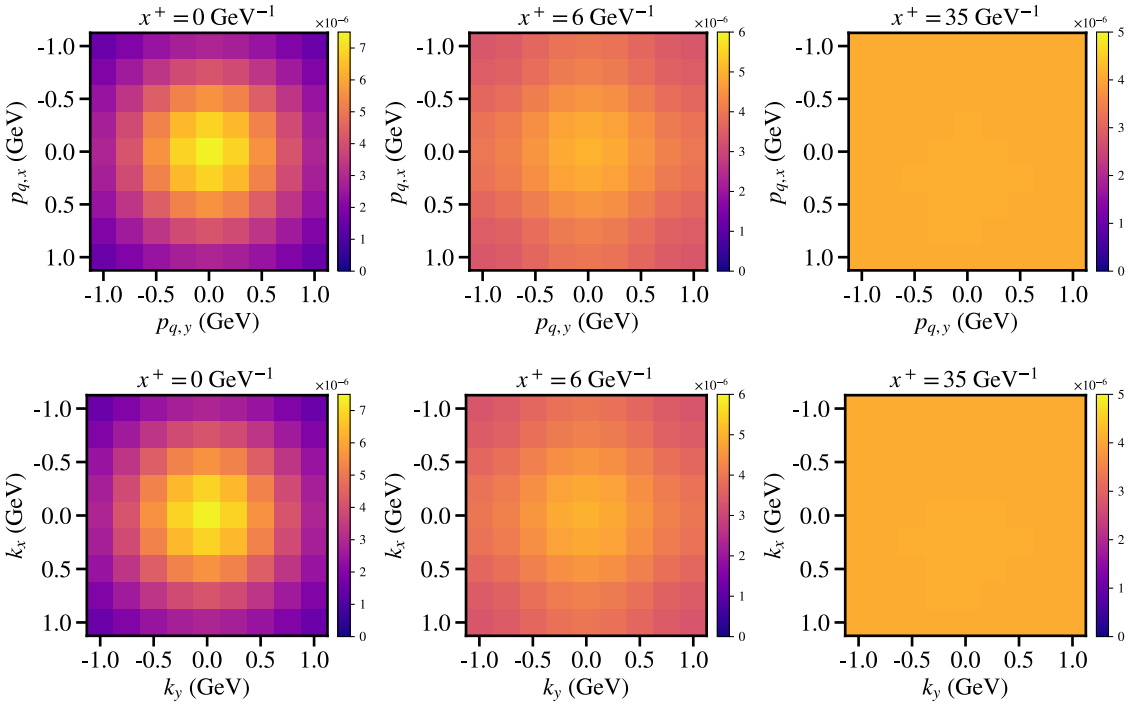


- quark momentum broadens over time

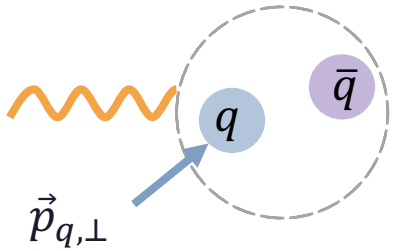
$$\vec{k}_\perp = (1-x)\vec{p}_{q,\perp} - x\vec{p}_{\vec{q},\perp}, x = p_q^+/P^+$$

- relative momentum broadens



Evolution of momentum distribution

Virtual photon state



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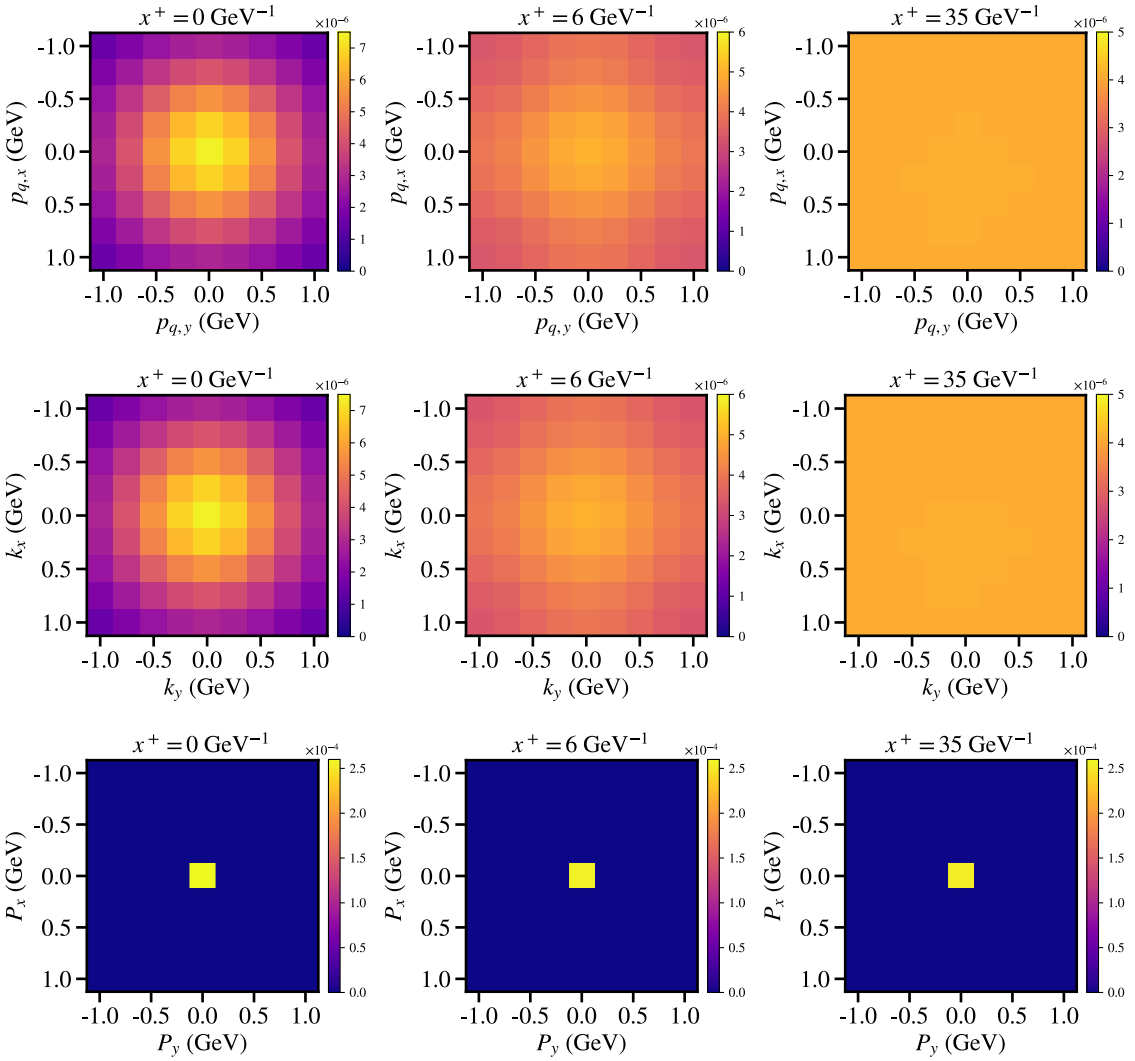
- relative momentum broadens

$$\vec{P}_\perp = \vec{p}_{q,\perp} + \vec{p}_{\vec{q},\perp}$$

- C.M. momentum barely broadens
  - $r_\perp \approx 0.73\ \mathrm{GeV}^{-1} \ll a_\perp \approx 3\ \mathrm{GeV}^{-1}$, strong correlation between q and $\bar{q}$



Cross Section

Cross section is defined as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 b} = \sum_{\phi_f} |M(\phi_f; \psi_{in})|^2$$

finite-time S-matrix

$$\begin{aligned} M(\phi_f; \psi_{in}) &= \langle \phi_f | S | \psi_{in} \rangle - \langle \phi_f | \psi_{in} \rangle \\ &= \langle \phi_f | \psi_{out} \rangle - \langle \phi_f | \psi_{in} \rangle \end{aligned}$$

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- **total cross section**

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}^2 b} = \Big\langle \sum_{\phi_f} |M(\phi_f;\psi_{in})|^2 \Big\rangle_{\mathrm{event}}$$

- **elastic cross section**

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2 b} = \sum_{\phi_f} \big|\langle M(\phi_f;\psi_{in})\rangle_{\mathrm{event}}\big|^2$$

event average = medium fluctuations from nuclear target

Cross Section

- **total cross section**

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}^2b} = \langle \sum_{\phi_f} |M(\phi_f;\psi_{in})|^2 \rangle_{\mathrm{event}}$$

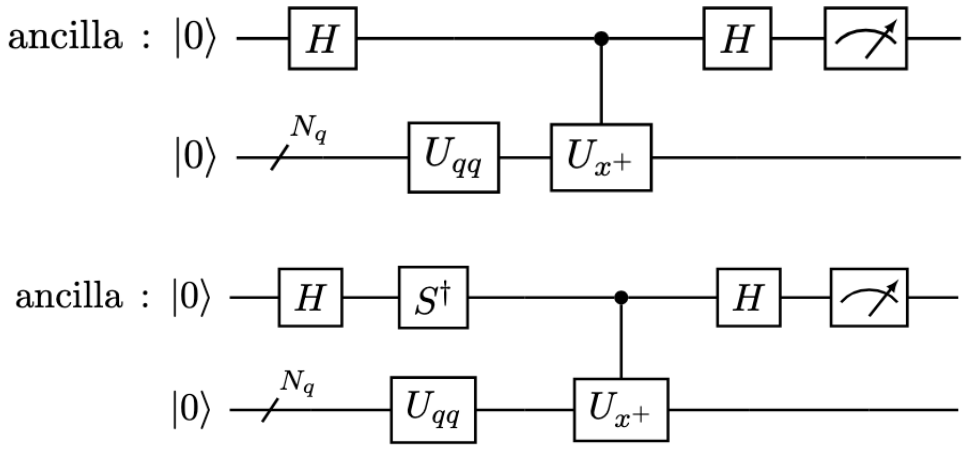
$$\frac{\mathrm{d}\sigma_{tot}}{\mathrm{d}^2b} = 2\left(1 - \langle \mathrm{Re}\,\langle\psi_{in}|\psi_{out}\rangle \rangle_{event}\right)$$

- **elastic cross section**

$$\frac{\mathrm{d}\sigma_{\mathrm{el}}}{\mathrm{d}^2b} = \sum_{\phi_f} |\langle M(\phi_f;\psi_{in})\rangle_{\mathrm{event}}|^2$$

$$\frac{\mathrm{d}\sigma_{el}}{\mathrm{d}^2b} = |\langle \mathrm{Re}\,\langle\psi_{in}|\psi_{out}\rangle - 1\rangle_{\mathrm{event}}|^2 + |\langle \mathrm{Im}\,\langle\psi_{in}|\psi_{out}\rangle\rangle_{\mathrm{event}}|^2$$

- Quantum implementation via Hadamard Tests

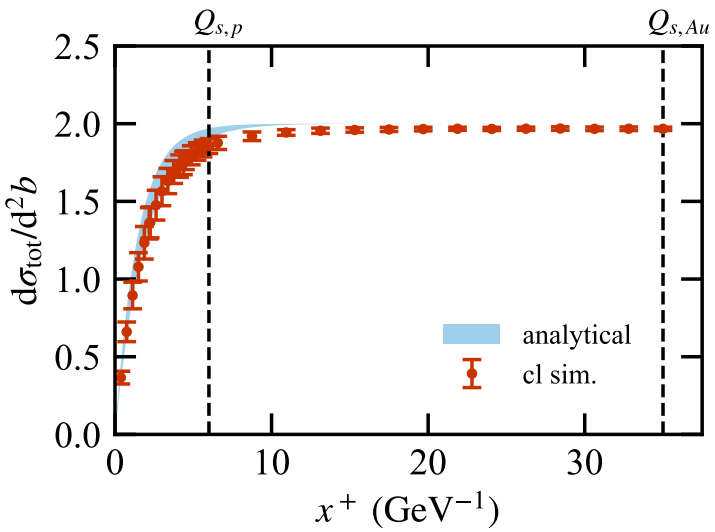


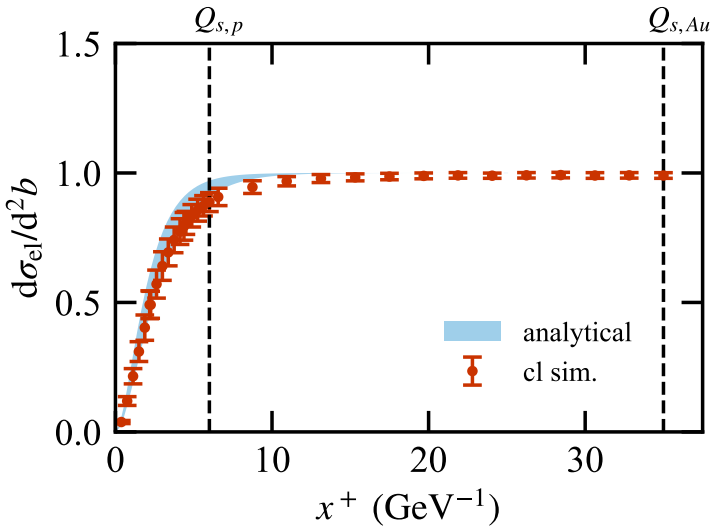
$$\mathrm{Re}\,\langle\psi_{in}|\psi_{out}\rangle = P(0) - P(1)$$

$$\mathrm{Im}\,\langle\psi_{in}|\psi_{out}\rangle = P(0) - P(1)$$

Cross Section

Single-momentum dipole





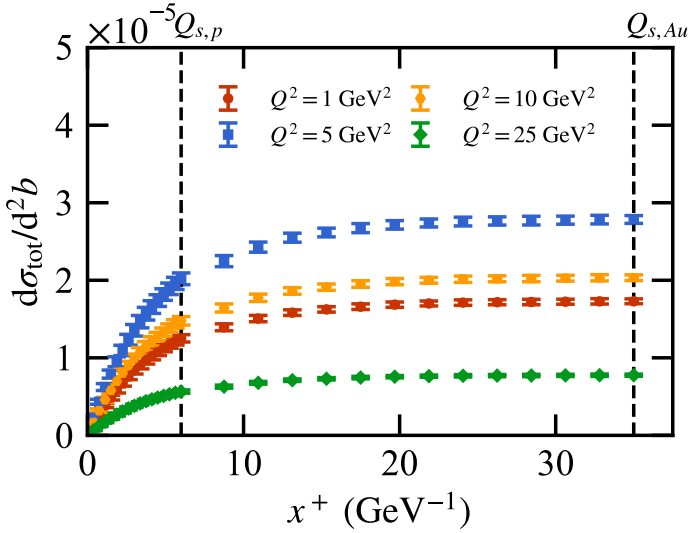
- Simulation results agree with analytical expectation
- Approaches black-disk limit ($d\sigma_{tot}/d^2b \to 2, d\sigma_{el}/d^2b \to 1$) at later time

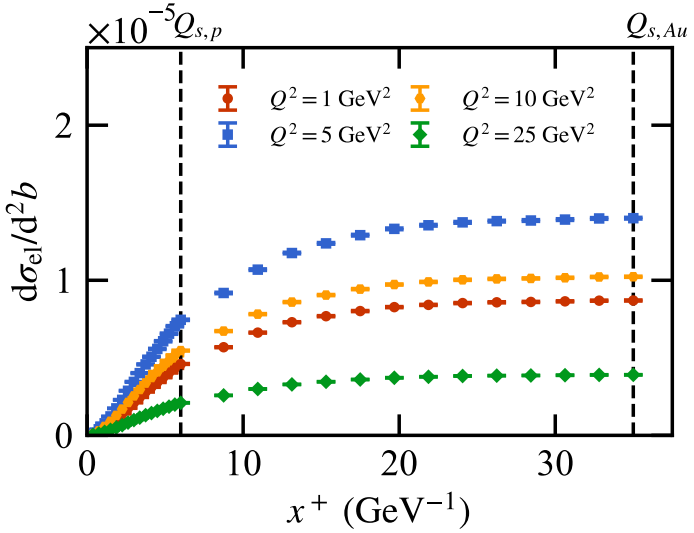
$$\left.\frac{\mathrm{d}\sigma_{q\bar{q},\mathrm{tot}}}{\mathrm{d}^2b}\right|_{p^+=\infty} = 2\left\{1-\exp\left[-C_F\frac{g^4\tilde{\mu}^2L_\eta}{4\pi m_q^2}\left[1-m_g|\vec{x}_\perp-\vec{y}_\perp|K_1(m_g|\vec{x}_\perp-\vec{y}_\perp|)\right]\right]\right\}$$

$$\left.\frac{\mathrm{d}\sigma_{q\bar{q},\mathrm{el}}}{\mathrm{d}^2b}\right|_{p^+=\infty} = \left\{1-\exp\left[-C_F\frac{g^4\tilde{\mu}^2L_\eta}{4\pi m_g^2}\left[1-m_g|\vec{x}_\perp-\vec{y}_\perp|K_1(m_g|\vec{x}_\perp-\vec{y}_\perp|)\right]\right]\right\}^2$$

Cross Section

Virtual photon state



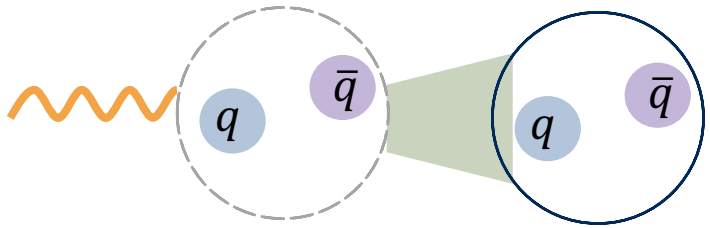


- Simulation results agree with analytical expectation
- Approaches black-disk limit ($d\sigma_{tot}/d^2b \to 2\, d\sigma_{el}/d^2b$) at later time for all Q^2
- Slower saturation compared to single-momentum dipole
- Non-monotonic Q^2 dependence: amplitude growth v.s. smaller dipole size

Hadron Production

The probability to produce a hadron via projection

$$\mathrm{Prob}(h) = \sum_{\vec{P}_\perp} |\, \langle \psi(x^+) | \psi_h(\vec{P}_\perp) \rangle \,|^2$$



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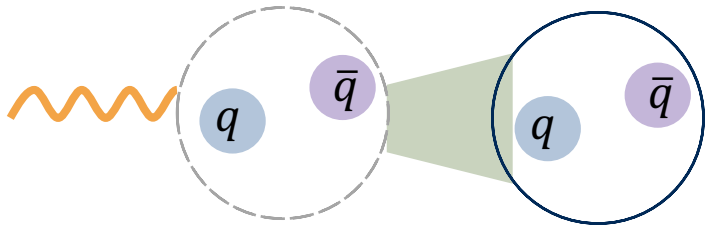

The associated nuclear modification factor: $R_A = \dfrac{\mathrm{Prob}_A(J/\psi)}{\mathrm{Prob}_p(J/\psi)}$

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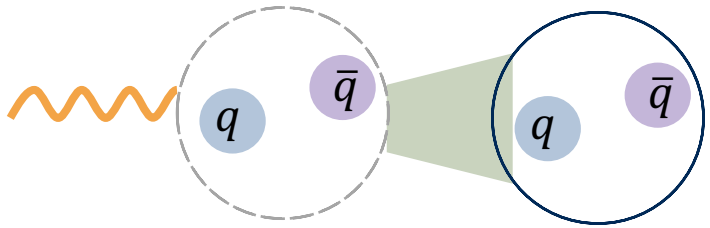

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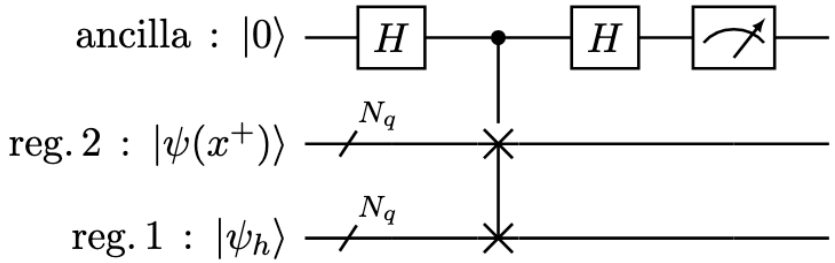
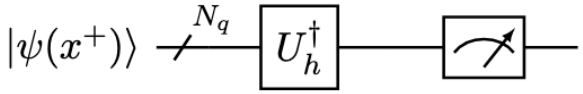
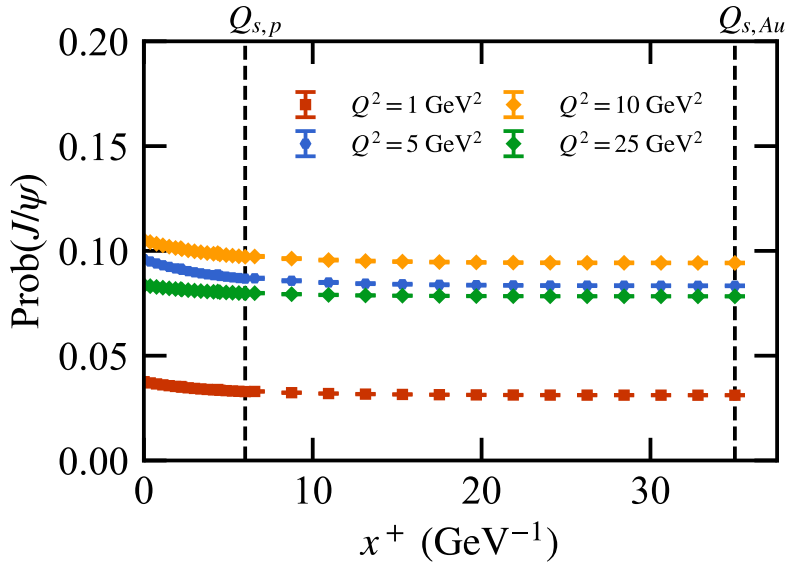
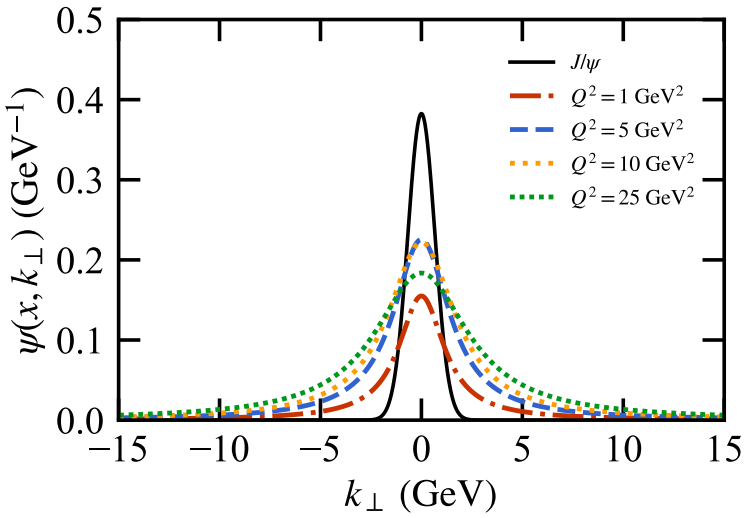
- Quantum implementation via SWAP test or inversion test





J/ψ Production

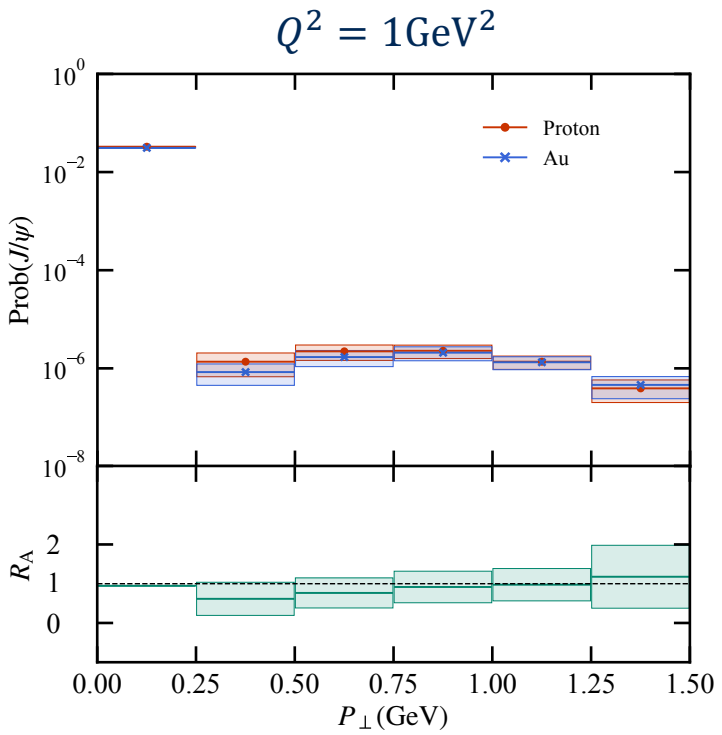


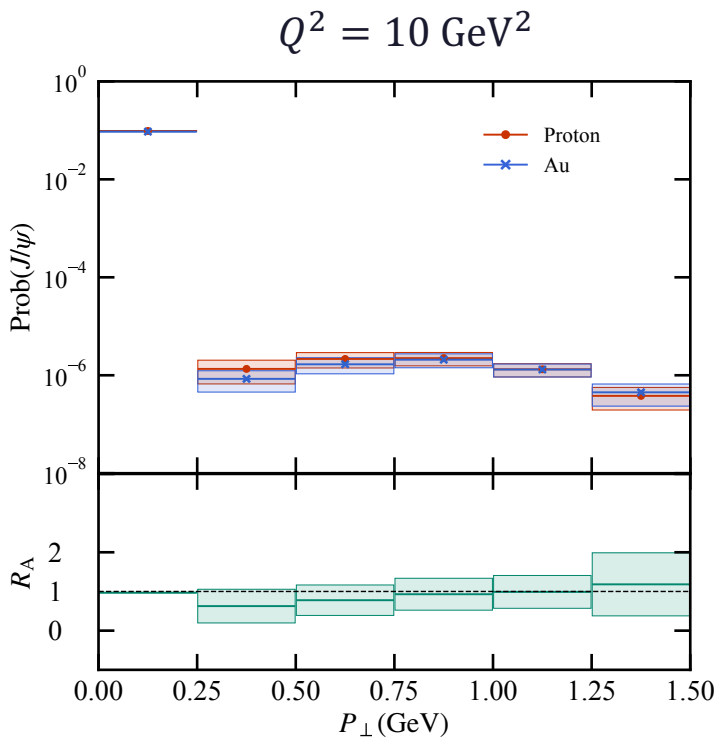


photon LFWF

- Prob(J/ψ) maximal at early x^+, decreases as medium scrambles the state
- Non-monotonic in Q^2 :
  - small Q^2 : photon amplitude grows
  - large Q^2 : wavefunction broadens

J/ψ Production





- Production dominated by $P_\perp \approx 0$ at both Q^2
  - color transparency, compact singlet barely kicked
- $R_A \approx 1$ at lowest and larger $P_\perp$
- Suppression at $P_\perp \sim 0.25$–0.5 GeV

Entanglement Entropy

- The von Neumann (vN) entropy of the reduced density matrix obtained by tracing out the antiquark degrees of freedom

$$S_{\mathrm{vN}}(x^+) = -\mathrm{Tr}[\rho(x^+)\log_2\rho(x^+)]$$

  - Normalize $q\bar{q}$ state to unity before tracing
  - Trace out antiquark degrees of freedom

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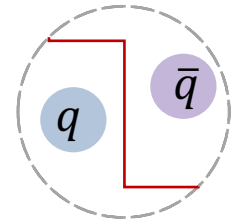
  - Event average $\langle\rho(x^+)\rangle_{event}$



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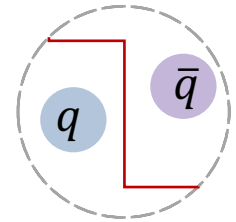
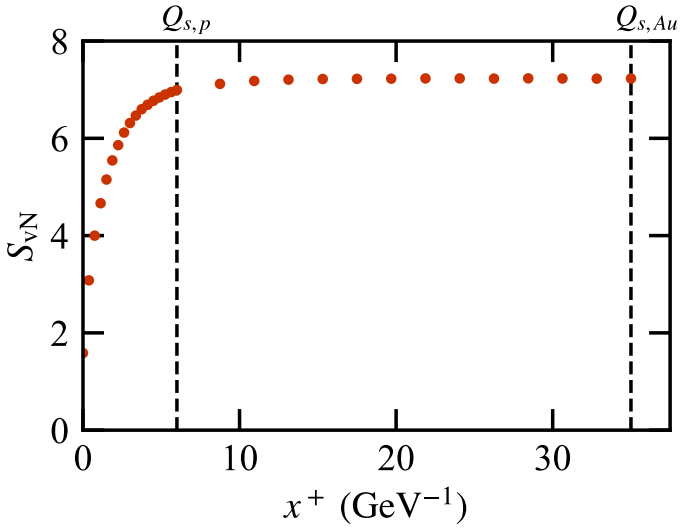


- On the discrete momentum basis representation
  - q Hilbert space: $K\times N_c(2N_\perp)^2$modes
  - p_q^+ conserved → longitudinal resolution K does not enter
  - Bounds: $0 \le S_{\mathrm{vN}} \le \log_2[N_c(2N_\perp)^2]$

S_{vN} measures entanglement between quark and antiquark in color × momentum space, induced by color rotations and momentum kicks by medium.

Entanglement Entropy

Single-momentum dipole



- $S_{\mathrm{vN}}(0) = \log_2 N_c \approx 1.6$
  - pure color entanglement of the singlet dipole
- Rapid growth due to medium interaction
- Asymptotic value: $\log_2[N_c(2N_\perp)^2] \approx 7.6$, quark fully randomized

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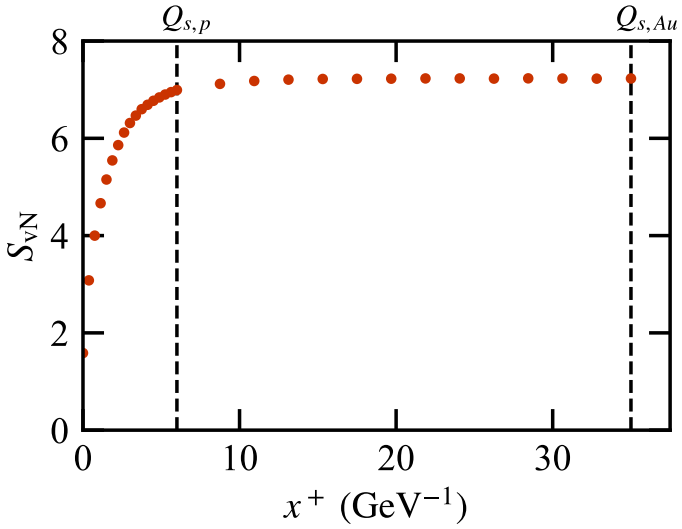

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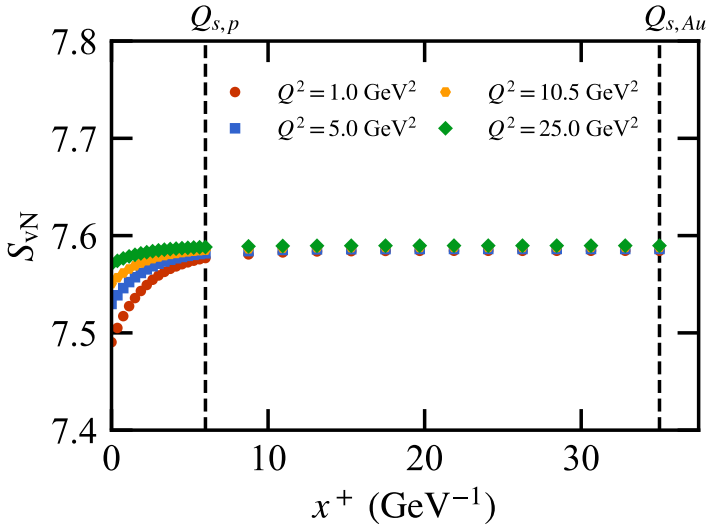
Virtual photon state



- Initial entropy already large, $S_{vN}(0) \approx 7.5$
  - Photon WF superposes many color × momentum modes
- Growth is modest but reaches same asymptotic value

Entanglement Entropy

Connection to observables

S_{vN} saturation ↔ Cross section saturation (black disk limit) ↔ Uniform momentum distribution

Entanglement entropy provides an observable-independent diagnostic of how strongly the medium scrambles the dipole system

Summary and Outlook

✓ We developed and applied a **non-perturbative** computational approach to simulate the **real-time** evolution of dipole-to-hadron production in DIS

1. Quantum simulation framework developed for in-medium dipole evolution
2. Cross sections agree with analytical expectations
3. J/ψ production and R_A
4. Entanglement entropy as an observable-independent diagnostic of medium effect

Next:

- Non-eikonal, $P^+ < \infty$
- Inclusion of higher Fock sector contribution, $|\gamma^*\rangle_{phys} = |\gamma^*\rangle + |q\bar{q}\rangle + |q\bar{q}g\rangle + \cdots$
- Photon state preparation on quantum circuit

Thank you!