Heavy Quarkonium Production in Nuclear Deep Inelastic Scattering

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Intro

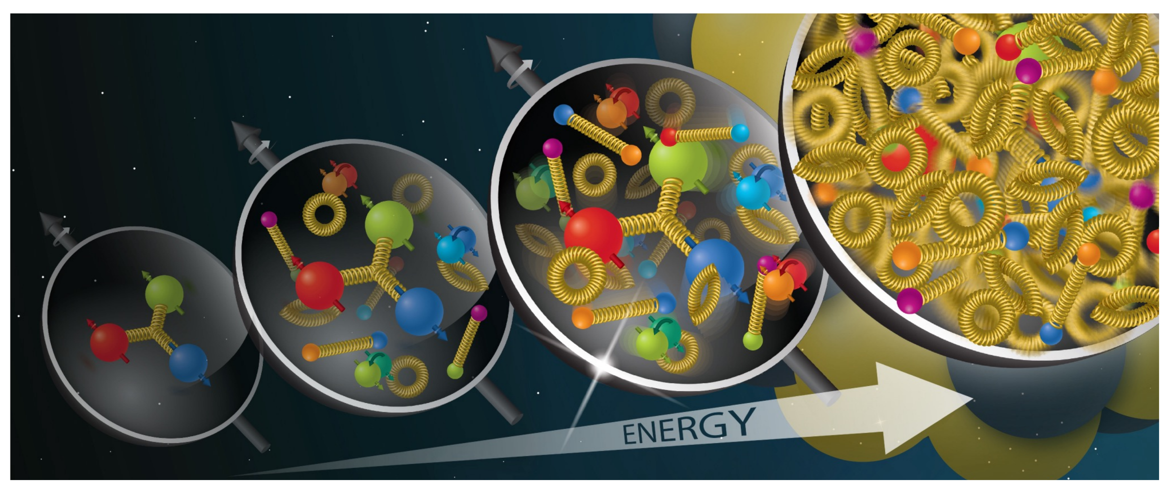
Our understanding of atoms has driven technology for the past century, but we still know shockingly little about the internal structure of protons and atomic nuclei.

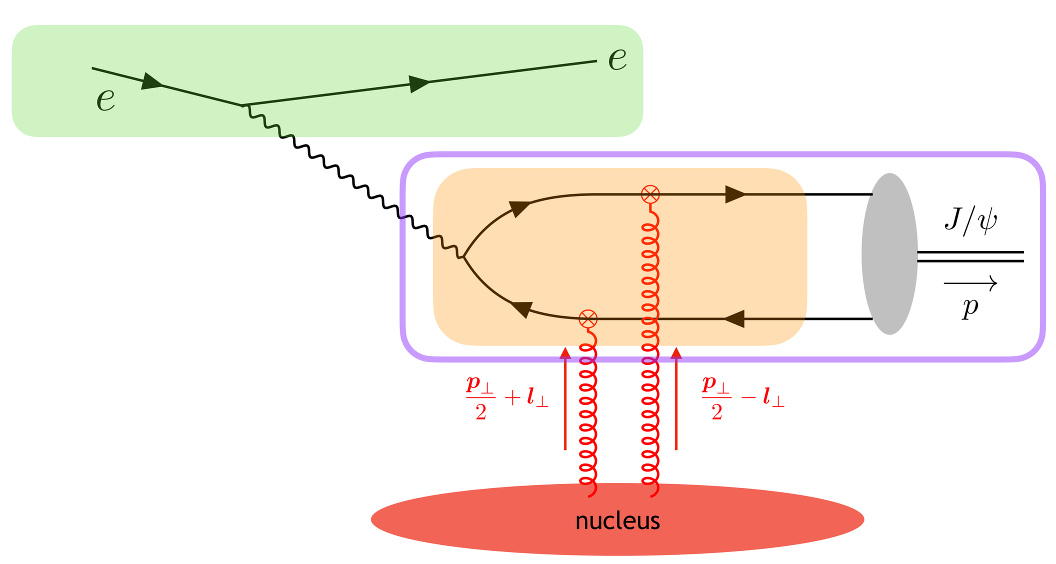
In this project we computed predictions on heavy quarkonium production in nuclear deep inelastic scattering (DIS) experiments at BNL's future Electron-Ion Collider as a potential gateway into probing the partonic structure of atomic nuclei, which is mediated by quantum chromodynamics (QCD).

Probing Nuclei

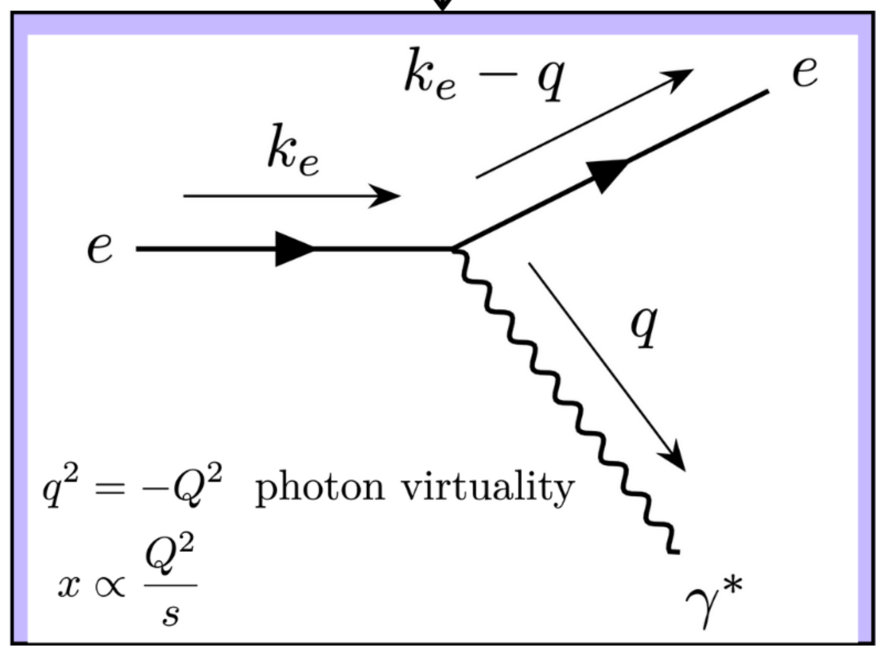
Our model of the proton is nearly 94 times lighter than an actual proton. The difference is generated by QCD.

Protons were believed to be 2 up quarks and 1 down quark, which we would expect to weigh $\sim 1.78\times 10^{-26} g$. But an actual proton is closer to $168\times 10^{-26} g$. At higher energy experiments, a sea of gluons and quark-antiquark pairs emerges, which increases in density until it becomes statistically favorable for the gluons to recombine, and a saturation is reached.





1 A fired electron emits a photon and scatters



DIS is like a microscope probing a nucleus. **Photon virtuality** is the **resolution**, and **x** measures the **shutter/exposure time**.

Small x = higher energy and finer resolution.

- Measured through electron's initial and final momentum.

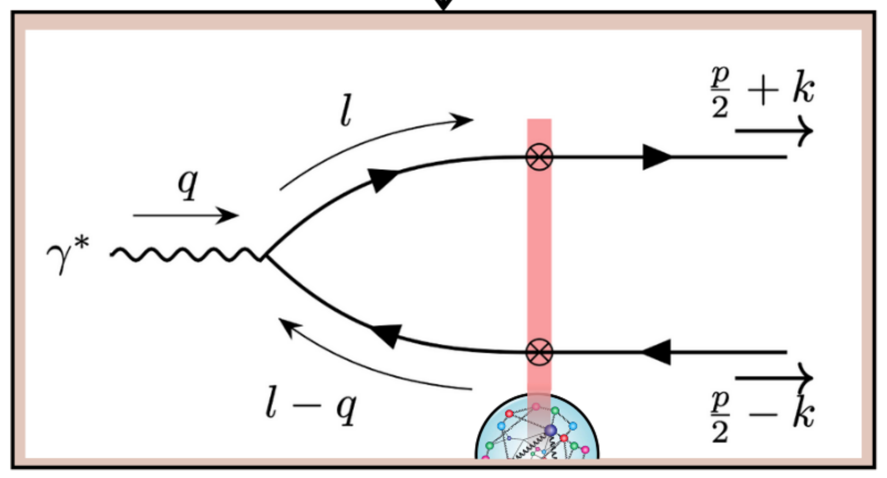
Computed using **Quantum Electrodynamics.**

- External lines represent incoming/outgoing particles; vertices mark interactions.
- Diagrams encode terms in a perturbative expansion of the scattering amplitude.

We convert from 16-component spatiotemporal basis to 9-component polarization basis of the emitted photon.

- 2 transverse modes + 1 longitudinal mode due to spacelike nature of internal photon.

2 The photon interacts with the nucleus



Photon splits into quark pair that interacts with the nucleus through the Strong interaction.

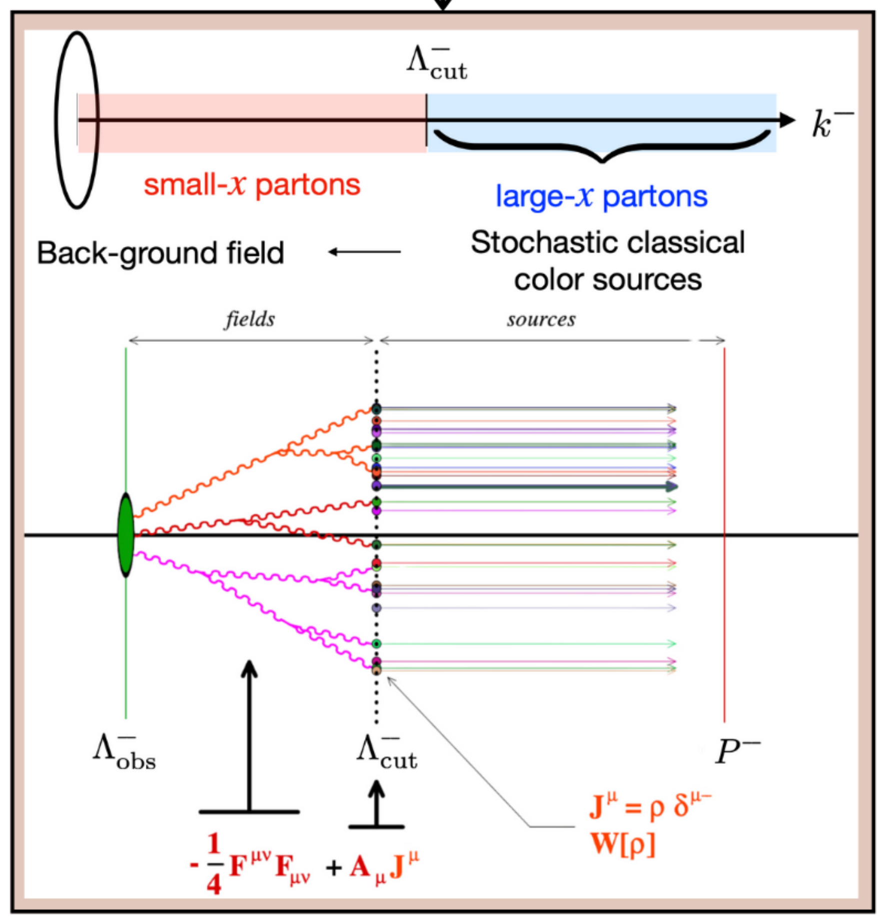
- Computation is **non-perturbative** in regular QCD due to gluon saturation.

Computed using **Color Glass Condensate** effective field theory.

- Quark-shockwave interaction accounts for multiple scattering to all orders.

Color Glass Condensate (CGC):

- Large-x partons generate color current: $J^\mu = g\delta^{\mu-}\rho(x)$
- Color current generates background color field: A^μ_{cl}
- Compute observables by averaging out modes with momentum fractions larger than x_0.



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

Light-cone Gauge $A^+ = 0$

YM Solution $A^\mu = \delta^{\mu-}\alpha(x^+, \boldsymbol{x}^\perp)$

$$\nabla^2_\perp \alpha(x^+, \boldsymbol{x}^\perp) = -g\rho(x^+, \boldsymbol{x}^\perp)$$

$$\langle \mathcal{O}(A)\rangle = \frac{\int \mathcal{D}A\, e^{i\mathcal{S}(A)}\mathcal{O}(A)}{\int \mathcal{D}A\, e^{i\mathcal{S}(A)}} \quad \text{where } \mathcal{S}(A) = \int d^4x\, \mathcal{L}$$

$$\mathcal{L} = \mathcal{L}_{\rm QCD} + A^\mu J_\mu$$

$$\langle \mathcal{O}(A)\rangle = \left(\int_{x_0}^1 \mathcal{D}\rho\, w_{x_0}(\rho)\right) \frac{\int_0^{x_0} \mathcal{D}A\, e^{i\mathcal{S}(A)}\mathcal{O}(A)}{\int_0^{x_0} \mathcal{D}A\, e^{i\mathcal{S}(A)}}$$

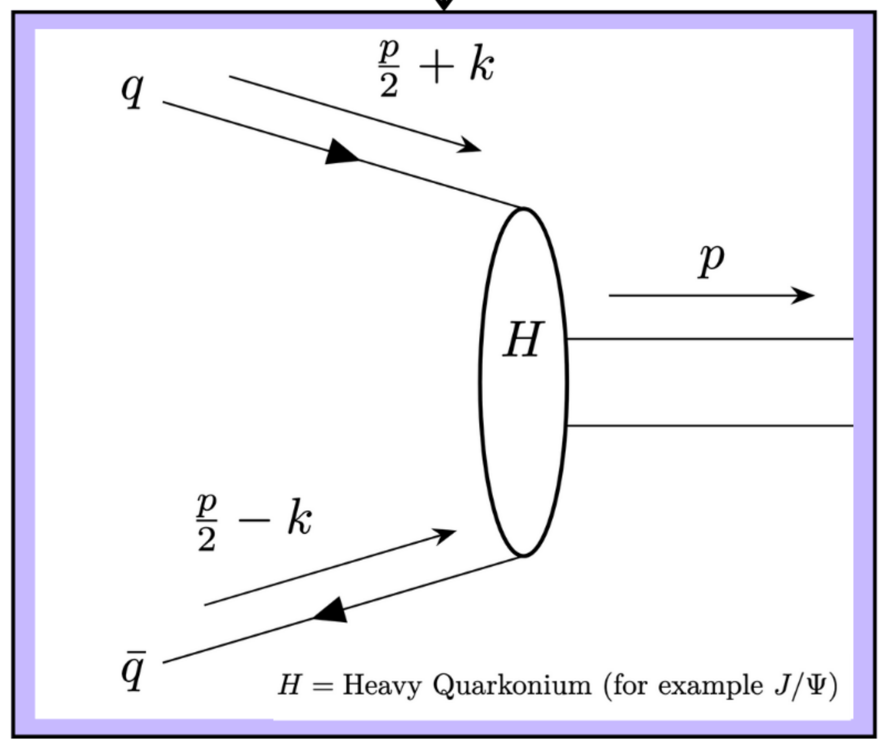
Non-perturbative average of color density function ρ

Perturbative path integral for A; $A = A_{\rm cl} + \delta A_{\rm quantum}$

Wilson Line Shockwave:

$$V(\boldsymbol{z}^\perp) = \mathcal{P}\exp\left(ig\int {\rm d}z^+ A^-(z^+, \boldsymbol{z}^\perp)\right)$$

3 Products recombine into quarkonium



The quark-antiquark pair recombine into a **bound state** called **quarkonium**, analogous to positronium.

Quarkonium formation depends on the quark pair's initial state.

- We **project** the initial state onto nonrelativistic quantum numbers and take a **weighted sum**.

This is a good approximation in **Nonrelativistic QCD** when the quarks are assumed to be very massive and not traveling at relativistic speeds.

Nonrelativistic QCD (NRQCD):

- Expansion of $\mathcal{L}$ in terms of v/c
- Quark pair factorization weighted average
- Short distance (high energy) effects calculable in full QCD.
- Long distance nonperturbative effects already determined experimentally.

$$d\sigma^H = \sum_\kappa d\hat{\sigma}^\kappa \langle \mathcal{O}^H_\kappa\rangle$$

Project $q\bar{q}$ amplitude to quantum states κ — Long distance matrix elements

The Full Process

$$\frac{{\rm d}\sigma^{J/\psi}}{{\rm d}x_{\rm Bj}{\rm d}y{\rm d}\boldsymbol{p}_\perp^2{\rm d}\phi_{eJ/\psi}} = \frac{\alpha_{\rm em}}{2\pi^2 y x_{\rm Bj}}\left\{ f_{\rm L}(y)\frac{{\rm d}\sigma_{\rm L}^{J/\psi}}{{\rm d}\boldsymbol{p}_\perp^2} + f_{\rm T}(y)\frac{{\rm d}\sigma_{\rm T}^{J/\psi}}{{\rm d}\boldsymbol{p}_\perp^2} + f_{\rm TL}(y)\frac{{\rm d}\sigma_{\rm TL}^{J/\psi}}{{\rm d}\boldsymbol{p}_\perp^2}\cos\phi_{eJ/\psi} + f_{\rm Tflip}(y)\frac{{\rm d}\sigma_{\rm Tflip}^{J/\psi}}{{\rm d}\boldsymbol{p}_\perp^2}\cos 2\phi_{eJ/\psi}\right\}$$

CGC computation

$$\frac{{\rm d}\hat{\sigma}^\kappa_\lambda}{{\rm d}\boldsymbol{p}_\perp^2} = \int \frac{{\rm d}^2\boldsymbol{l}_\perp}{2\pi}\int \frac{{\rm d}^2\boldsymbol{l}'_\perp}{2\pi}\widetilde{\Gamma}^\kappa_\lambda(\boldsymbol{p}_\perp, Q; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)\widetilde{\mathcal{G}}^\kappa(x_A, \boldsymbol{p}_\perp; \boldsymbol{l}_\perp, \boldsymbol{l}'_\perp)$$

Spin and polarization-dependent perturbative factor — Nuclear-dependent CGC distribution

Deriving Nuclei Structure

Our results will be used to experimentally test the gluon saturation phenomenon at the future Electron-Ion Collider.

This allows us to constrain the w function on color densities, informing us on how color-charged partons are distributed within protons and other nuclei at high energies.

These computations are highly complex, so we developed a Mathematica package to automatize them, providing a path forward to more complex calculations needed for higher accuracy, such as relativistic corrections.

Acknowledgements

Cheung, V., Kang, Z.-B., Salazar, F., & Vogt, R. (2024). Direct quarkonium production in DIS from a joint CGC and NRQCD framework. *Physical Review D*, *110*(9), 094039.

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