Taking X-Rays of the Proton

Accessing proton GPDs through heavy meson production

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7/25/2021

Abstract

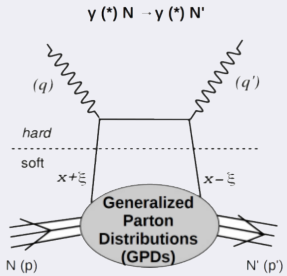
Heavy meson production is a key tool for accessing the **proton's inner dynamics.** These production reactions involve the proton's Generalized Parton Distributions **(GPDs)**, which correlate the longitudinal momenta and their transverse distribution of the proton’s composite partons.

We used ROOT to create a **new flexible generator** for the photoproduction, quasi-photoproduction, and electroproduction of vector mesons off a proton. The output phase space is weighted by the reaction cross-section, creating a **realistic graph of event count as a function of energy.** These graphs can be used to assist in **testing multiple theoretical models** of the proton, as well as **designing detectors** at the upcoming Electron-Ion Collider (EIC).

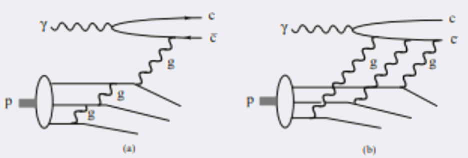
Background

Protons are composite particles, made up of three valence quarks and a surrounding gluon sea. It is impossible using current methods to solve for the behavior of these quarks and gluons analytically, so they are described using experimentally-fit models called Generalized Parton Distributions.

These GPDs are measured through the production amplitude of scattering reactions. Specifically, at high energies, the production amplitude can be factorized into a theoretically-calculable "hard" part and an experimental "soft" part that depends on the GPDs. These two parts can be separated on the Feynman diagram of a scattering process:

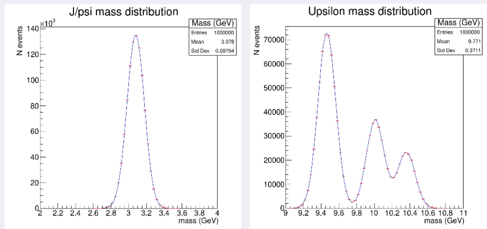


Different scattering reactions can access the proton's quark and gluon QPDs in different ways. Of particular interest are the photo- and electroproduction of heavy mesons, including the J/Ψ (cc) and ϒ (bb) mesons. Since the proton does not contain charm or bottom quarks, the amplitudes for these reactions depend strongly on the gluon GPDs. The two dominant reactions which produce these mesons are the two- and three-gluon exchange reactions:



Methods

We used C++ and ROOT to add simulations of J/Ψ and ϒ production to Marie Boer's DEEPSim generator. For J/Ψ, a Gaussian mass distribution centered at 3.069 GeV was used, representing a smeared Breit-Wigner distribution. Similar Gaussian mass distributions were used for the 1S, 2S, and 3S resonances of ϒ; these distributions were normalized using data from ϒ-production experiments at the LHC.



Events were generated from these distributions and observed through their lepton decay modes. The event count was then weighted by the differential cross section for the reaction.

For J/Ψ photoproduction, the following two and three-gluon cross sections were used:

$$\frac{d\sigma}{dtdx}_{2g} = v\frac{(1-x)^2}{(R_P M_{J/\psi})^2}F_{2g}^2(t) \quad \frac{d\sigma}{dt}_{3g} = v\frac{1}{(R_P M_{J/\psi})^4}F_{3g}^2(t)$$

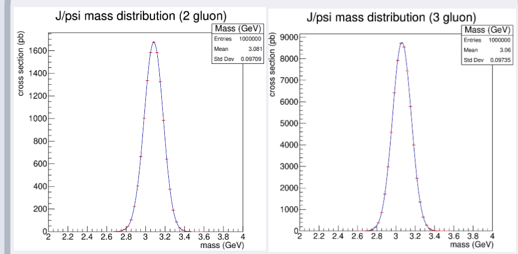
For ϒ photoproduction, we used

$$\frac{d\sigma}{dtdx} = \frac{\pi}{4t^4}\left(\frac{4N_c^4}{(N_c^2-1)^2}G(x,t) + \sum_f |q_f(x,t) + \overline{q}_f(x,t)|\right)|F_{Born}|^2$$

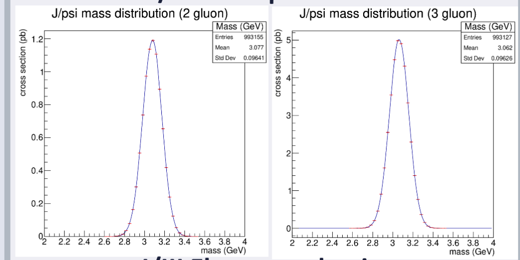
For both, the electroproduction cross-sections are simply the photoproduction cross-sections times a flux factor:

$$\frac{d\sigma}{dydQd\tilde{A}}_{ep} = \frac{\alpha_s}{2\pi Q^2(1+Q^2/M_P^2)^2}\left(\frac{1+(1-y)^2}{y} - \frac{2(1-y)}{y}\left(\frac{Q_{min}^2}{Q^2} - \frac{Q^2}{M_P^2}\right)\right)\frac{d\sigma}{d\tilde{A}}_{pp}$$

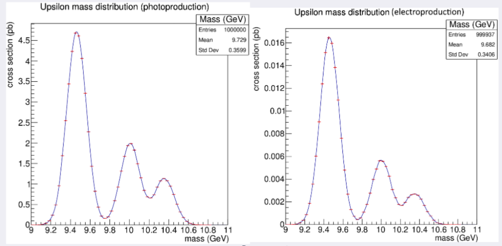
Results



J/Ψ Photoproduction



J/Ψ Electroproduction



ϒ Production

Discussion

Notable results include the three-gluon cross section dominating the two-gluon (at low energies), which was expected, and the very low cross section for ϒ even at high energies (~150 GeV). Further research might refine the cross-sections and GPDs used in the generator, in pursuit of making even more accurate simulations to guide the construction of the EIC.