Exclusive photoproduction of charmonium-photon pairs in the small-x kinematics

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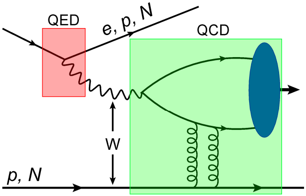
Exclusive photoproduction at high energies

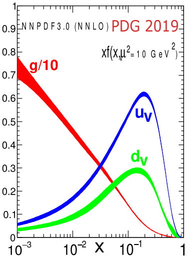
Exclusive photoproduction at high energies provides direct access to the gluon content of the hadron

High energy = small-x kinematics: $x^*_{Bj} \sim M_V^2/W^2 \leq 10^{-3}$

*(for quasireal photon)



- Relative signal purity (compared to inclusive channels)
- A large rapidity gap between final particles
- Gluon exchanges give a large contribution due to the high gluon density at small-x



$$\frac{d\sigma_{\gamma p \to J/\psi p}}{dt} \propto [xg_p(x)]^2$$

[Z. Phys. C 57 (1993) 89]

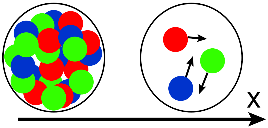
pp, pN, NN collisions

LHC: $5 * 10^{-6} \leq x_{Bj} \leq 10^{-2}$ [arXiv 1301.7084 hep-ex]

ep, eN collisions

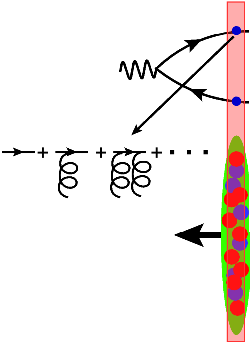
EIC: $5 * 10^{-4} \leq x_{Bj} \leq 10^{-1}$ [arXiv 1610.08922 hep-ex]

Color Glass Condensate (CGC) model



In the region $x \leq 10^{-3}$, the partonic picture is not applicable anymore $\Longrightarrow$ The relevant object is the dipole amplitude in the CGC framework.

Main ingredients of CGC



- A large number of gluons allows to treat them as static color sources, which generate an effective classical gauge field $A^{\mu}_{a}(x)$.
- Eikonal approximation: The parton (q or $\bar{q}$ in our case) moves along a straight line and interacts with the proton shock wave
  - All the interaction is encoded in the Wilson line

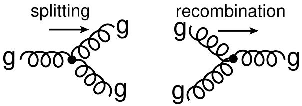
$$U(\mathbf{x}_{\perp}) = P \exp\left(ig \int dz^{-} A^{+a}(z^{-}, \mathbf{x}_{\perp}) t_a \right)$$

$U(\mathbf{x}_{\perp})$ resums the effect of multiple gluon exchanges for a parton crossing the shock wave at the point $\mathbf{x}_{\perp}$

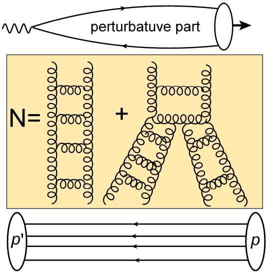
Dipole amplitude

Dipole amplitude = probability for a $q\bar{q}$ dipole to interact with a hadron

$$N(x, r, b) = 1 - \frac{1}{N_c}\mathrm{Tr}\left[U^\dagger(\mathbf{x}_1)U(\mathbf{x}_2)\right]$$



- Evolution in x: the nonlinear Balitsky–Kovchegov (BK) equation
  $\partial_Y N = \alpha_s \mathcal{K} \otimes \left(N - N^2\right) \quad [Y = \ln(1/x)]$
  growth − saturation



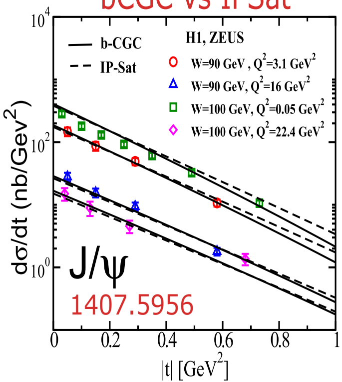
- The BK equation resums much more than a simple two-gluon exchange: it includes BFKL 'ladder' diagrams and 'fan' diagrams
- The BK equation has no known complete analytic solution. In practice, one uses phenomenological models (bCGC, IPsat, bSat,...)
- $N(x, r, b)$ can be defined for protons/neutrons or nuclei

There is a large amount of experimental data on the photoproduction of mesons (J/ψ, Υ, ρ, ...)

But this is not enough:

- many models (IPSat, bCGC, etc.) describe photoproduction equally well $\Longrightarrow$ we need to additionally constrain $N(x, r, b)$
- It is important to probe quarkonia with different quantum numbers in order to test the mechanisms of their formation and the universality of $N(x, r, b)$

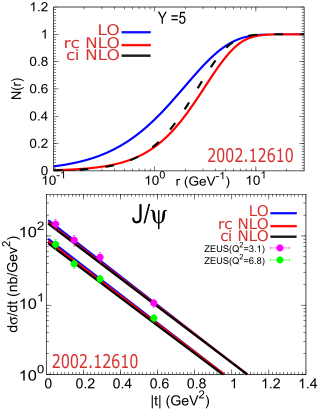
bCGC vs IPSat



Higher multipoles

LO observables are controlled by the dipole amplitude $N(x, r, b)$.
NLO: The emergence of higher multipoles

$$N_{2n} = 1 - \frac{1}{N_c}\mathrm{Tr}\left[U^\dagger(\mathbf{x}_1)U(\mathbf{y}_1)...U^\dagger(\mathbf{x}_n)U(\mathbf{y}_n)\right]$$



- NLO corrections can lead to substantially different fit parameters

On the other side

- Most phenomenological fits are based on LO, dominant contribution of dipole amplitude
  - LO provides reasonable fits of existing data (DIS, J/ψ photoproduction)
  - At NLO the x and t-dependences remain qualitatively similar to the LO results

New channles would help us test the universality of $N(x, r, b)$

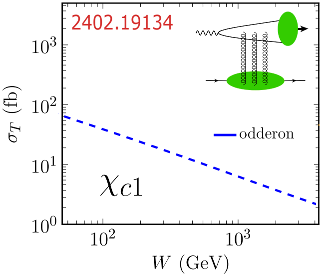
$$\gamma p \to \gamma \eta_c p \quad \text{and} \quad \gamma p \to \gamma \chi_{cJ} p$$

* $\gamma J/\psi$ can't proceed via pomeron exchanges, proceeds via suppressed odderon

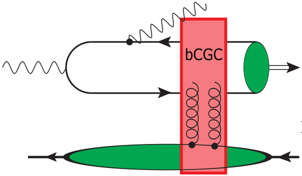
- The WFs of η_c, χ_{cJ} are known from literature
- χ_{cJ} has 3 different states $(J = 0, 1, 2)$ with similar masses
  - Since in the limit $m_c \gg \Lambda_{\mathrm{QCD}}$, spin–orbit interaction is suppressed, orbital wave functions of χ_{cJ} are almost identical which provides an ideal test for spin effects

- Charmonia η_c, χ_{cJ} are currently a very active topic in the context of future EIC
  - Study of the odderon (3-gluon echange in t-channel)
  - Control of background processes, e.g. Primakoff contribution (photon exchange in t-channel)
- The proposed channels have large feed-down contributions and must be removed with a simple cutoff ($M_{\gamma\eta_c} > M_{J/\psi}$ o $M_{\gamma\chi_c} > M_{\psi(2S)}$):

$\gamma p \to J/\psi p \to \gamma \eta_c p \qquad \gamma p \to \psi(2S) p \to \gamma \chi_c p$



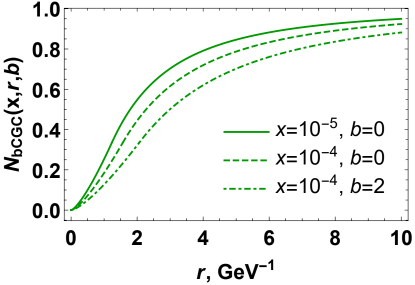
Example: photon emission before the shockwave



$$\mathcal{A}_1 = \int_0^{\alpha} dz_0 \prod_{k=1}^{3} (d^2\mathbf{r}_k) \Phi_{\mathcal{Q}}^{(h,\bar{h})\dagger} (\dots) \Psi_{\gamma\to\gamma\bar{Q}Q}^{(\lambda,\sigma,h,\bar{h})} (\dots) \times$$
$$\times \mathcal{N}\left(x, \mathbf{r}_{10}, \mathbf{b}_{10}\right) \exp\left[-i\mathbf{p}_\perp^{\mathcal{Q}} \left(\mathbf{b}_{10} - \frac{\bar{\alpha}}{\alpha}\mathbf{r}_\gamma\right) - i\mathbf{k}_\perp^{\gamma} \left(\mathbf{r}_\gamma + \mathbf{b}_{10}\right)\right]$$

- We will perform evaluations in the photon-proton collision frame
- The incoming and outgoing photons are supposed to be real

We use b-CGC model for the dipole amplitude

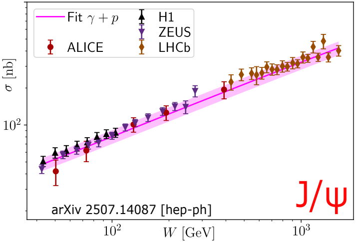


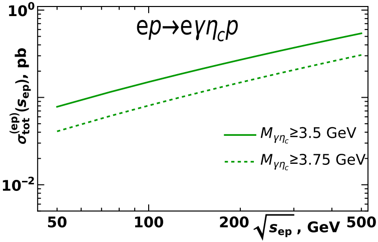
- Fitted simultaneously to inclusive DIS and exclusive processes (J/ψ, ρ ...)
- r-dependence interpolates between color transparency and black-disk limit
- Provides a realistic b-profile convenient for nuclear extensions $N^A(x, r, b)$
- At smaller x, gluon densities become larger, leading to a growth of $N(x, r, b)$

Expected rates with bCGC parametrization

$\sqrt{s_{ep}} = 141\ \text{GeV}, \quad \mathcal{L} = 10^{34}\ \text{cm}^{-2}\text{s}^{-1}, \quad \int dt\, \mathcal{L} = 100\ \text{fb}^{-1}$

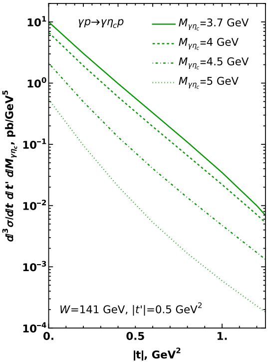
Meson	σ_{tot} [pb]	Decay channel	Branching	N_d	dN_d/dt [month^{-1}]
η_c	0.2	$\eta_c(1S) \to K_S^0 K^+ \pi^-$	2.6%	540	139
χ_{c0}	0.45	$\chi_c \to J/\psi\, \gamma$	0.08%	36	9.1
χ_{c1}	0.41	$J/\psi \to \mu^+ \mu^-$	2.0%	816	211
χ_{c2}	2.5		1.1%	2750	695

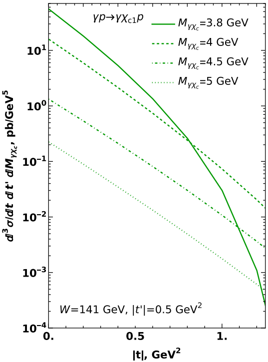


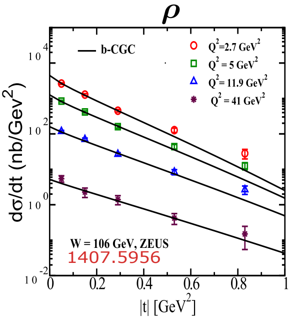


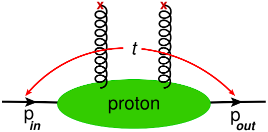
- We do not expect the onset of saturation for the proposed channels
    - Within current uncertainties there is no evidence for a saturation effects in the measured exclusive processes
- $\sigma \sim W^{\delta}$; $\delta = 0.6 - 0.7$ and almost does not depend on other variables and type of meson (encoded in the dipole amplitude)

Dependencies of the differential cross section



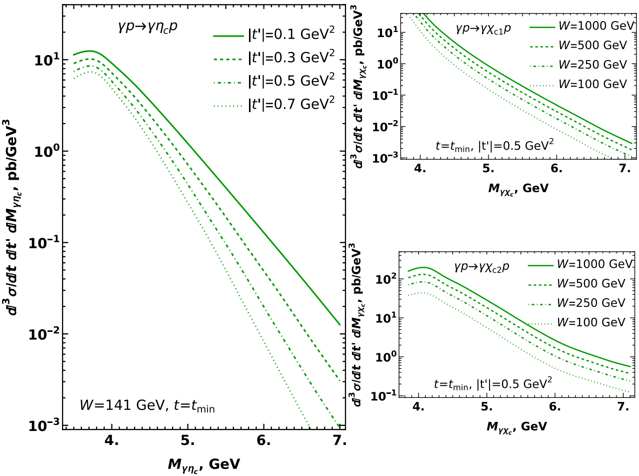




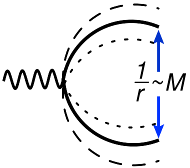


- $N(x, r, b)$ has a Gaussian profile in b, then $d\sigma/d\Omega \sim e^{-C*t}$
  - In log-scale: almost straight line
- There is additional suppression from constraints in the near-threshold kinematics when $M_{\gamma\mathcal{Q}} \to M_{\mathcal{Q}}$

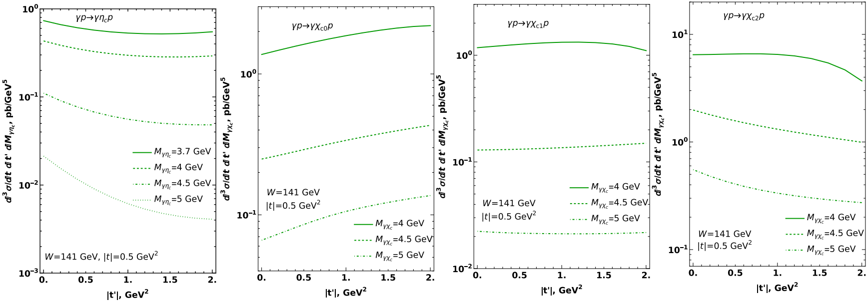
The observed t-dependence is the same for different mesons; It's also a general feature of $2 \to 2$ photoproduction of both light and heavy quarkonia



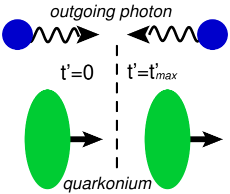
Photon-meson invariant mass: new independent kinematic variable



- encoded in the perturbative part
  - different dependence for different mesons
- responsible for the size of the dipole
- The differential cross section decreases rapidly as $M_{\gamma\mathcal{Q}}$ increases



The momentum transfer $t' = (k^{\gamma}_{out} - k^{\gamma}_{in})^2$ determines the angle between the meson and the final-state photon



- The photon and meson momenta are collinear at $t' = 0$ and become anti-collinear at $t'_{\max} = M^2_{\gamma\mathcal{Q}} - M^2_{\mathcal{Q}}$
- The t'-dependence is incorporated in the perturbative part
  - different dependence for different mesons
- The t' is rather mild for small $|t'| \ll |t'|_{\max}$

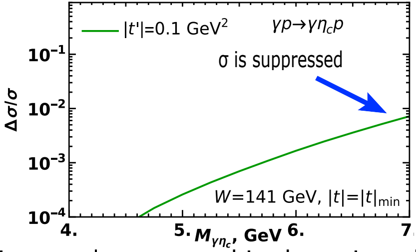
Polarizations of the particles

Helicity conservation is exact at $p_\perp^{\mathcal{Q}}=0$ where it coincides with the projection of the angular momentum on the collision axis

Helicity conservation law: $H_\gamma^{(in)}=H_{\mathcal{Q}}+H_\gamma^{(out)}$

For $p_\perp^{\mathcal{Q}}\neq 0$ the selection rule can be violated; however, the helicity-violating amplitudes are suppressed

Example for η_c $(H_{\eta_c}=0)$: We have the helicity–flip part $H_\gamma^{(in)}=-H_\gamma^{(out)}$ and the non-flip part $H_\gamma^{(\mathrm{in})}=H_\gamma^{(\mathrm{out})}$

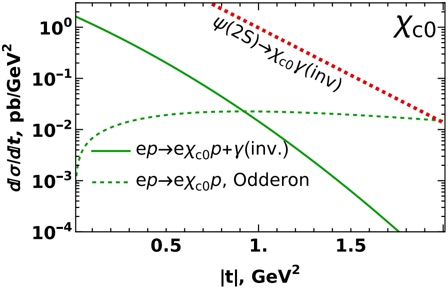


Helicity-flip part* is strongly suppressed in the region which gives the dominant contribution

* not suppressed only for χ_{c2}; for η_c, χ_{c0} and χ_{c1} it violates helicity conservation

Comparison with odderon-mediated channel

Odderon is taken from [PRD 110 (2024) 1, 014025]



The $\gamma\mathcal{Q}$ photoproduction can contaminate the aforementioned odderon-mediated $\mathcal{Q}$ production if the final photon is undetected!

- The dominant contribution for $\chi_c\gamma$ is radiative decay of $\psi(2S)$
  - The pictures for χ_{c1}, χ_{c2} and η_c are similar (with $J/\psi \to \eta_c\gamma$ feed-down contribution for η_c)
  - Feed-down contribution for the study of pomeron-mediated $\gamma\mathcal{Q}$ production can be easily eliminated by using cutoff on invariant mass
- The odderon-mediated process is the smallest one at $t \leq 1$ GeV^2

Conclusions

- ✔ The photoproduction of $\gamma\eta_c$ and $\gamma\chi_{cJ}$ is measurable at EIC and LHC energies
- ✔ The suggested channels when the emitted photon is not observed may contaminate the exclusive production of η_c and χ_{cJ} mesons via odderon
- ✔ We have found a large contribution from radiative decay may challenge the use of η_c, χ_c photoproduction for studies of odderons

Thank you for your attention!