The proton GPDs from quarkonia-photon pairs

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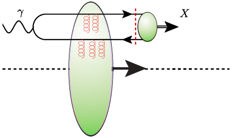
Factorization at high energies

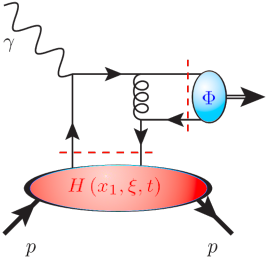
- All factorization approaches are based on set of assumptions, limited range of validity
  - Different schemes complement each other, don't duplicate
- **Previous talk**: very high energies ($x_B \leq 10^{-2}$)
  - Eikonal picture, Color Glass Condensate
    - ★ "frozen" partons fly through the gluonic field of the target



- **This talk:** moderate energies, partonic picture
  - Application: low- and middle-energy runs at EIC ($\sqrt{s_{ep}} \lesssim 100\,\mathrm{GeV}$)
  - Physical amplitudes:
    –Convolutions of factorized partonic distributions:

$$\mathcal{A} = \int dx_1\, dx_2 ... C\left(x_1,\, x_2,\, \xi\, ...\right) H\left(x_1, \xi, t\right) \Phi\left(x_2\right) ...$$

    –All hadronic properties encoded in $H\left(x_1, \xi, t\right)$, $\Phi\left(x_2\right)$...
    –Factorization theorems require that final-state hadrons are well-separated kinematically to suppress soft exchanges between them

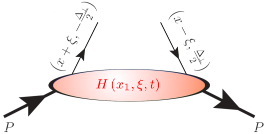


(Generalized) Partonic distributions

Cross-sections controlled by the **Generalized Parton Distributions**: [PDG 2024, Sec 18.6]

*Leading twist-2: 8 GPDs for each flavor, with different projectors $\Gamma, \mathcal{F}^{(\Gamma)}$

$$\int \frac{dz}{2\pi} e^{ix\bar{P}^+ z} \left\langle P' \left| \bar{\psi}\left(-\frac{z}{2}\right) \Gamma\, e^{i\int d\zeta n\cdot A} \psi\left(\frac{z}{2}\right) \right| P \right\rangle = \bar{U}(P')\, \mathcal{F}^{(\Gamma)} U(P)$$

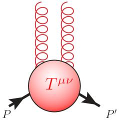


*For gluons use operators $G^{+\alpha} G^{+}_{\alpha}$, $G^{+\alpha}\tilde{G}^{+}_{\alpha}$, $\mathbb{S} G^{+i} G^{+j}$ in left-hand side

GPDs $\Rightarrow$ matrix elements of any physical observable represented by bilinear field operators

Example: Energy-momentum tensor

$$T^{\mu\nu} = -F^{\mu\alpha} F^{\nu}{}_{\alpha} + \frac{1}{4}\eta^{\mu\nu} F_{\alpha\beta} F^{\alpha\beta} + \frac{1}{2}\bar{\psi}\gamma^{\{\mu} iD^{\nu\}}\psi$$



$$\bar{P} = \frac{P + P'}{2}$$

$$\Delta = P' - P$$

$$\langle P' | T^{\mu\nu} | P \rangle =$$

$$\bar{U}(P') \left[A(t) \frac{\gamma^{\mu}\bar{P}^{\nu} + \gamma^{\nu}\bar{P}^{\mu}}{2} + B(t) \frac{\bar{P}^{\mu} i\sigma^{\nu\alpha}\Delta_{\alpha} + \bar{P}^{\nu} i\sigma^{\mu\alpha}\Delta_{\alpha}}{2M_N} + D(t) \frac{g^{\mu\nu}\Delta^2 - \Delta^{\mu}\Delta^{\nu}}{4M} \right] U(P)$$

Relation to GPDs:

$$\int_{-1}^{+1} dx\, x H(x,\xi,t) = A(t) + \xi^2 D(t), \quad \int_{-1}^{+1} dx\, x E(x,\xi,t) = B(t) - \xi^2 D(t),$$

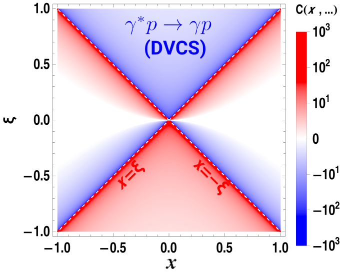
Rest frame of the hadron: Fourier images of A, B, D related to pressure, shear forces ...

Phenomenological constraints

$$\text{Physical observable}: \mathcal{A} = \int dx_1\, dx_2 \ldots C\,(x_1,\, x_2,\, \xi \ldots)\, H\,(x_1, \xi, t)\, \Phi\,(x_2) \ldots$$

– The model-independent extraction of GPDs from data ⇒ "deconvolution", classical inverse problem

– For all $2 \to 2$ processes coef. function $C\,(x, \xi)$ strongly peaked at line $x = \pm\xi$ ⇒
  *White-colored regions almost do not contribute to observable ...
  *Similar behavior for all $2 \to 2$ processes, and after we take into account NLO corrections, ...



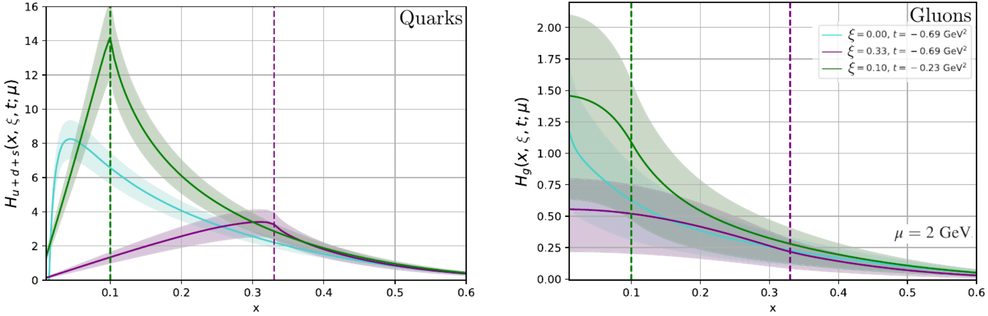
⇒*"Shadow GPD" problem: [PRD 108 (2023) 3, 036027]
– Poor sensitivity to behavior of GPDs in some regions
⇒Cross-sections constrain GPDs but usually don't allow to fix them uniquely

⇒We need various channels (preferably with different topology) to understand better the GPDs

What do we know about GPDs now ?

Typical GPD uncertainties:

[Phys. Rev. D 112 (2025), 074018]



– Unpolarized quark GPDs are reasonably well constrained
  * Phenomenological parametrizations: GUMP, GK, KM, JAM ...
  * More ambiguities for polarized/transversity GPDs, but there is a lot of developments in that direction

– Gluon GPDs are poorly constrained even for unpolarized case
  * Sizeable uncertainty in observables that get dominant contribution from gluons, more data are needed

Novel tools for femtography: $2 \to 3$ processes

Process: [Recent review: arXiv:2511.20402]

$$\gamma^{(*)} + p \to h_1 + h_2 + p$$

Various states h_1, h_2 considered in the literature:

$\ell\,\bar{\ell}$(DDVCS)	[PRD 107 (2023), 094035]
$\gamma\pi$, $\gamma\rho$	[JHEP 03 (2023) 241; PRD 107 (2023) 9, 094023 2]
$\gamma\gamma$	[JHEP 08 (2022) 103]
$\gamma\gamma^* \to \gamma\bar{\ell}\ell$	[Phys. Rev. D 103 (2021) 114002]
$\pi\rho$	[Phys.Lett.B 688 (2010) 154-167]
$\gamma\eta$, $\gamma\eta'$	[2511.19720]

Main advantage:

−Invariant mass $M_{h_1 h_2} \Rightarrow$ additional hard scale, can modify the coefficient function used to probe the GPDs
*Factorization is justified even in photoproduction regime

Our suggestion: $2 \to 3$ **processes with heavy mesons:**

−$h_1,\ h_2 = \gamma + \text{quarkonium}\ (\eta_c,\ \chi_c, J/\psi)$ **(this talk)**

−**Hard scales**: quark mass m_Q, invariant mass $M_{\gamma\mathcal{Q}}$ ($\approx$transverse momenta $\boldsymbol{p}_\gamma \approx -\boldsymbol{p}_\mathcal{Q}$).
*Dominant contribution from gluon GPDs in ERBL kinematics.

*

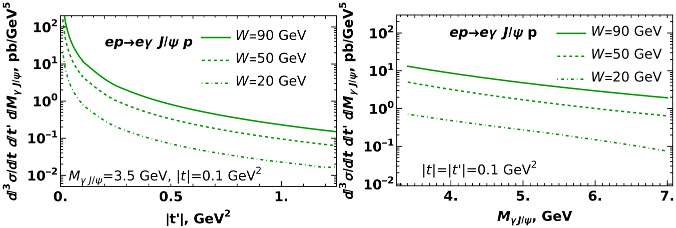
Photoproduction of $J/\psi\,\gamma$ pairs

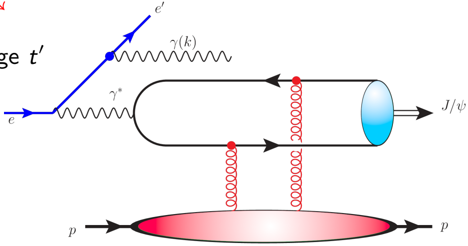
Most "popular" quarkonium: J/ψ (light, clean experimental signature)

—leading order contribution in α_s: "Bethe-Heitler"-style process ↘

*Photon emission from incoming or outgoing charged particles

**Photon γ^* is virtual, $p_{\gamma^*}^2 = t' = \mathcal{O}\left(M_{\gamma J/\psi}^2\right)$, suppressed at large t'





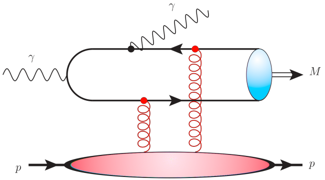
*This mechanism probes the same gluon GPD as simple J/ψ photoproduction ...

Photon emission from heavy lines: vanishes for $J/\psi\,\gamma$

—At chosen order in α_s, color structure is trivial, $g \sim \gamma$

—Similar result for any C-odd meson

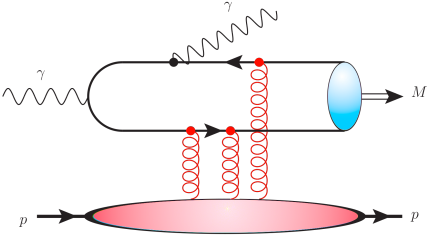
⇒ Relevant only for C-even quarkona $(\eta_c, \chi_c, ...)$



Photoproduction of $J/\psi\,\gamma$ pairs

Next-to-leading order: $J/\psi + \gamma$ may proceed:

Via 3-gluon exchange (3-point twist-3 GPDs)



—poorly known at present (dimensionality curse)

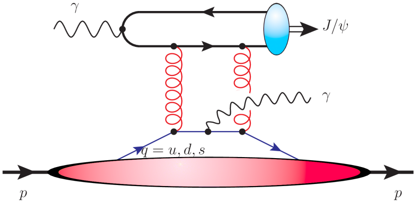
—most likely very small:

* Formally, $\alpha_s(m_c)g(x) < 1$
* recall negative "odderon" searches

$\Downarrow$

Will be disregarded in what follows

Via 2 gluon exchange (valence quark GPD)



—18 diagrams at (N)LO order

* The C-parity forbids emission of photon from charm, only from light quarks
* t-channel gluons are NOT collinear: large $\boldsymbol{p}_\perp$, $u' = \left(p_{J/\psi} - p_{\gamma_{\rm in}}\right)^2$
* Probe the GPD of valence (light) quarks

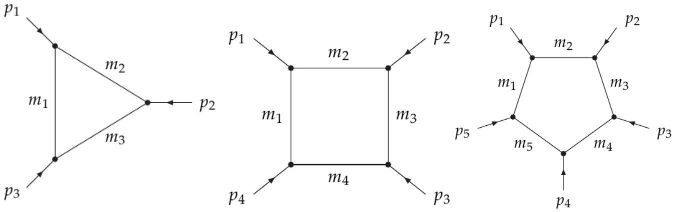
$$\frac{2}{3}H_u(x,\xi,t) - \frac{1}{3}H_d(x,\xi,t) - \frac{1}{3}H_s(x,\xi,t)$$

Photoproduction of $J/\psi\,\gamma$: technical details

Evaluation was done analytically in FeynCalc

−result expressed as a superposition of Passarino-Veltman functions $C_{\ldots}, D_{\ldots}, E_{\ldots}$

(also known as 3,4,5-point functions)



* Can be expressed via $\mathrm{Li}_2(\ldots)$, logarithms and rational expressions (very lengthy ...)

*Used PackageX to single out possible UV and IR parts (`PaXEvaluateUV[]`, `PaXEvaluateIR[]`)

** UV divergences don't appear at all, IR divergences vanish exactly in the final result

*For numerical evaluations used `LoopTools (Colliers)` libraries

−Cross-sections are smaller than for BH, suffers from numerical instabilities in PaVe-functions

$\Rightarrow$ $J/\psi\,\gamma$ might be challenging for GPD studies.

$\gamma p \to \gamma\, \eta_c\, p$ and $\gamma p \to \gamma\, \chi_c\, p$ photoproduction

We'll focus on the *C*-even charmonia now: η_c, χ_c

– The quarkonium η_c is the lightest, expect to have the largest cross-section

... Wave functions/LDMEs related to those of J/ψ in the heavy quark mass limit, smaller uncertainties

– The quarkonium χ_c is the lightest *P*-wave, 3 spin states ($J = 0, 1, 2$) with very close masses

... Very narrow states, decay primarily into $J/\psi\,\gamma$: experimentally very clean signal, easy for detection

... Can study various spins, helicity projections, independent tests

... The ratio $\sigma_{\gamma\chi_{c2}}/\sigma_{\gamma\chi_{c1}}$ can be used for tests of NRQCD LDME releation in the heavy quark mass limit:

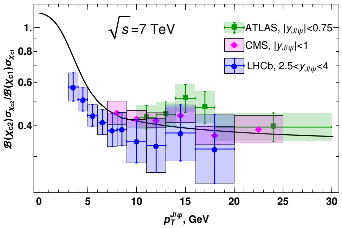
*Lesson from hadroproduction of χ_c@LHC

Description of $\sigma_{\chi_{c2}}/\sigma_{\chi_{c1}}$ requires at least one of the two assumptions:

1) Sizable Color Octets (CO) LDMEs

2) Heavily broken Heavy Quark Spin Symmetry (HQSS)

(Open question as of now)



How photoproduction of $\gamma\chi_c$ can help?

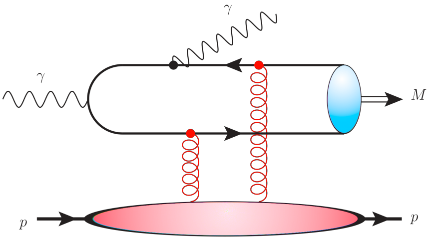
* There is no color octet contribution

* Other mechanisms are suppressed (provided $M_{\gamma\chi_c} > M_{\psi(2S)}$)

$\Rightarrow$Deviation of $\sigma_{\gamma\chi_{c2}}/\sigma_{\gamma\chi_{c1}}$ from theoretical prediction would be clear signal that HQSS is broken

LO: Exclusive photoproduction of $\gamma\eta_c$ and $\gamma\chi_c$ pairs

Hierarchy of scales: $M_{\gamma\eta_c} \sim M_{\gamma\chi_c} \sim 2m_c \gg m_p, \Lambda_{\rm QCD}$



Summation over all possible gluon and photon attachments is implied

– At leading order (LO): 24 diagrams
  * Many diagrams are related to each other due to C-parity, permutation of t-channel gluons ($x \leftrightarrow -x$ symmetry in coef. function)

– At NLO >500 diagrams;
  * Get also contributions from (sea) light quarks
  * Evaluation is highly repetitive, parallelizable, done in FeynCalc

– Full NLO expression is available for η_c; is very lengthy
  * Expressed in terms of Passarino-Veltman functions $B_{\dots}$, $C_{\dots}$, $D_{\dots}$, $E_{\dots}$, $F_{\dots}$

$\Downarrow$

Focus only on LO now

Coefficient functions for $\gamma\eta_c$ and $\gamma\chi_c$ photoproduction (LO)

$$C_{\gamma\eta_c}^{(++)}\left(r=\frac{M_{\gamma\eta_c}}{M_{\eta_c}},\,\alpha=\frac{p_{\eta_c}^+}{p_{\gamma\,(\mathrm{in})}^+},\,\zeta=\frac{x}{\xi}\right)=\frac{4\bar\alpha\mathfrak{C}_{\eta_c}}{\xi^2\alpha^2\left(1+\bar\alpha\right)^2\left(r^2-1\right)\left(\bar\alpha+1/r^2\right)}\times$$

$$\times\frac{1}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)\left(\zeta+\kappa-i0\right)\left(\zeta-\kappa+i0\right)}\left[\alpha^2\left(1+\bar\alpha\right)\left(\zeta^2+1\right)+\right.$$

$$+\frac{\left(\alpha^2-4\right)\zeta^4-2\left(\alpha^3-4\alpha+2\right)\zeta^2-\alpha\left(2\alpha^2+\alpha-4\right)}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^2}+$$

$$\frac{\left(1+\bar\alpha\right)^2\zeta^4+\alpha(\alpha^2+3\alpha-12)\zeta^2+\alpha(3\alpha^2+8\alpha-4)}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^4}-\frac{4\left(\zeta^2-3\alpha\right)}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^8}$$

$$\left.+\frac{-\alpha\left((\alpha-4)\zeta^2+11\alpha+8\right)+8\zeta^2+4}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^6}-\frac{4}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^{10}}\right]$$

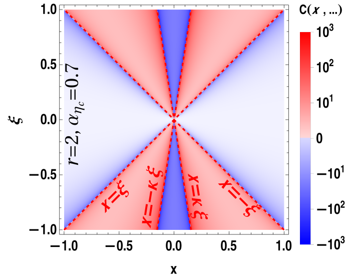
–Similar (relatively simple) expressions for other helicity components $C_{\gamma\eta_c}^{(\lambda,\sigma)}$, $C_{\gamma\chi_c}^{(\lambda,\sigma,H)}$, ...

...For χ_c the poles are at the same position, but of higher (2nd) order:

for P-wave take derivative over small relative momentum

...Helicities affect numerators, but not denominators (position of poles)

Coefficient function for $\gamma\eta_c$ and $\gamma\chi_c$ photoproduction (LO)



Location of poles in coef. function:

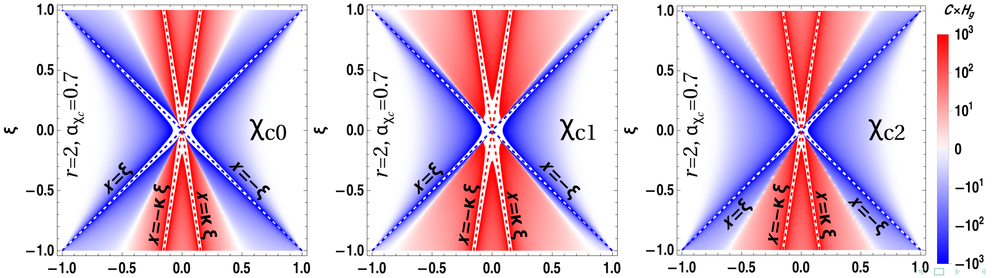
–Classical $x = \pm\xi \mp i0$ ($\zeta = \pm 1 \mp i0$)

–New poles at $x = \pm\kappa\,\xi \mp i0$ ($\zeta = \pm\kappa \mp i0$), where

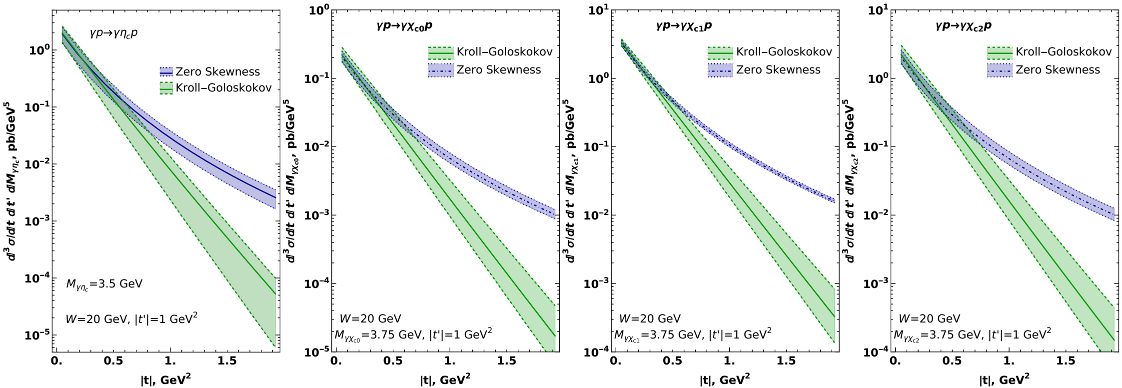
$$\kappa = \frac{1}{r^2}\frac{2 - \alpha r^2}{2 - \alpha}, \qquad |\kappa| \le 1 \qquad \text{(ERBL kinematics)}$$

...Values of $r = M_{\gamma\eta_c}/M_{\eta_c} \ge 1$ and $\alpha = p^+_{\eta_c}/q^+ \in \left(1/r^2, 1\right)$ in the physically allowed range

–For $\chi_c\gamma$ poles are of second order, much more pronounced (coef. function vanishes rapidly)



t-dependence of the cross-section



– Dependence on t is from GPD, not coef. functions. Almost the same for all ...
– Compare Kroll-Goloskokov and Zero Skewedness parametrizations for definiteness
– Width of the band=uncertainty due to NLO corrections, found varying fact. scale $\mu \in (0.5-2) M_{\gamma\chi_c}$
  * Reasonable at low energies W, grows rapidly due to BFKL logs $\sim \ln(1/x)$ in GPD parametrization
– Differential cross-sections $\sim 1-10$ pb for $\eta_c\gamma$, $\chi_c\gamma$

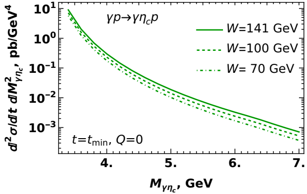
Dependence on invariant mass $M^2_{\gamma\mathcal{Q}}$ and variable t'

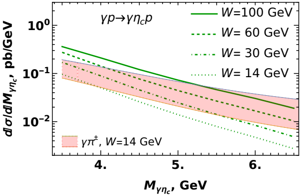
Invariant mass $M^2_{\gamma\mathcal{Q}} = (k_\gamma + p_\mathcal{Q})^2$:

– Determines $x \sim \xi \sim M^2_{\gamma\mathcal{Q}}/W^2$, so at large $M_{\gamma\mathcal{Q}}$ strong decrease of the cross-section due to decrease of gluon GPDs/PDFs

... $M^2_{\gamma\mathcal{Q}}$ also appears in the coef. functions, but this has only minor overall effect

... Similar dependence for all quarkonia, and even for $\gamma\pi^\pm$ (!) if compared at the same invariant mass $M_{\gamma M}$

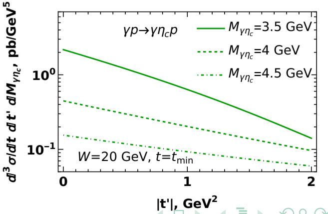




Momentum transfer to the photon $t' = (k_\gamma - q_\gamma)^2$:

– t' determine angles between γ, quarkonium in final state and collision axis

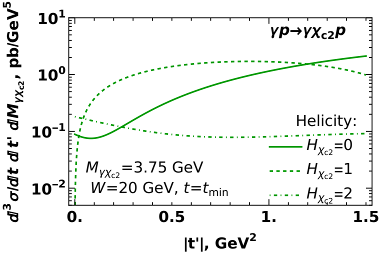
... dependence is encoded in coef. function, depends a lot on spin J of quarkonium, helicity (for $J \neq 0$).

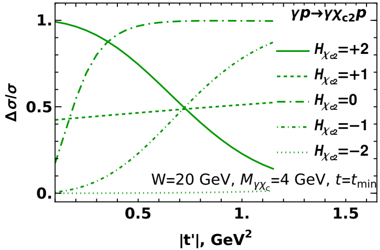


Understanding polarizations in $\gamma\eta_c$, $\gamma\chi_c$

– Helicity flip of the target suppressed, controlled by small GPDs $\tilde{H}, \ldots$ (negligible)

.... Can study contributions with or without helicity flip of the final state photon





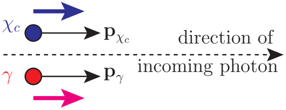
– Assume incoming photon has helicity "+"

– $\Delta\sigma/\sigma$ is a fraction of helicity flip contribution

Suppression at extremes for some components is due to angular momentum conservation:

$t' = 0$:

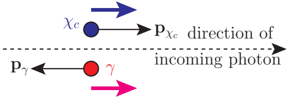
– final-state χ_c, γ move in the same direction



$$H_{\chi_c} + H_\gamma = H_{\rm in}$$

$|t'| = |t'|_{\rm max} = M^2_{\gamma\chi_c} - M^2_{\chi_c}$:

– final-state χ_c, γ move in opposite directions,



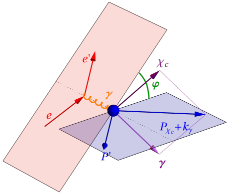
$$H_{\chi_c} - H_\gamma = H_{\rm in}$$

Angular asymmetries in electroproduction ($ep \to ep\gamma\mathcal{Q}$)

Strong polarization dependence$\Rightarrow$ observable even if detectors do not measure polarization:
Leptonic tensor $L_{\lambda,\bar{\lambda}}$ is **not** diagonal in helicity basis,

$$d\sigma\left(ep \to ep\gamma\eta_c\right) = L_{\lambda,\bar{\lambda}} A^{(\bar{\lambda})*} A^{(\lambda)} d\Omega \neq \underbrace{\mathrm{Flux}\left(e \to e\gamma^*\right) \times d\sigma\left(\gamma^* p \to p'\,\eta_c\gamma\right)}_{\text{equivalent photons approx.}}$$

$-$leads to dependence on angle φ between leptonic and hadronic planes:



$$\frac{d\sigma_{ep\to ep\gamma\eta_c}}{d\Omega} = \frac{d\sigma^{(T)}}{d\Omega} + \epsilon\frac{d\sigma^{(L)}}{d\Omega} + \sqrt{\epsilon(1+\epsilon)}\left(\cos\varphi\frac{d\sigma^{(LT)}}{d\Omega} + \sin\varphi\frac{d\sigma^{(L'T)}}{d\Omega}\right)$$

$$+\epsilon\cos 2\varphi\frac{d\sigma^{(TT)}}{d\Omega} + \epsilon\sin 2\varphi\frac{d\sigma^{(T'T)}}{d\Omega} \approx \frac{d\sigma^{(T)}}{d\Omega}\left(1 + c_2\cos 2\varphi + s_2\sin 2\varphi\right)$$

$-$Longitudinal (L) is suppressed at small-Q; $\epsilon \approx (1-y)/(1-y+y^2/2)$.
T, T' is interference of γ^* with opposite helicities in $A^{(\bar{\lambda})*}$, $A^{(\lambda)}$

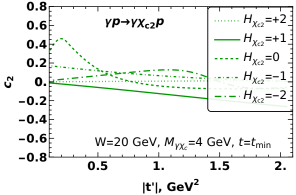
Definition of φ in collider kinematics:
$-$Assume $\hat{z}$ points in direction of collision axis, and φ_p, φ_e are azimuthal angles of recoil electron and proton
$-$ The angle φ is given by $\varphi = \varphi_e - \varphi_p$

Results for angular asymmetry in $\gamma\chi_c$, $\gamma\eta_c$

T, T' interference terms allow to probe the real and imaginary parts:

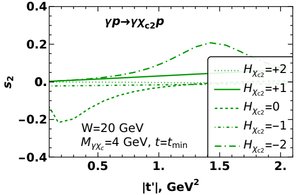
$$\frac{d\sigma^{(TT)}}{d\Omega} \sim \mathrm{Re}\left(\mathcal{A}^{(-,+)*}_{\gamma p\to\chi_c\gamma p}\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right), \quad \frac{d\sigma^{(T'T)}}{d\Omega} \sim \mathrm{Im}\left(\mathcal{A}^{(-,+)*}_{\gamma p\to\chi_c\gamma p}\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right)$$

–Easy to study: just extract φ -dependence of the recoil proton w.r.t. leptonic plane



$$\frac{d\sigma_{ep\to ep\gamma\chi_c}}{d\Omega} \approx \frac{d\sigma^{(T)}}{d\Omega}\left(1 + c_2\cos 2\varphi + s_2 \sin 2\varphi\right)$$

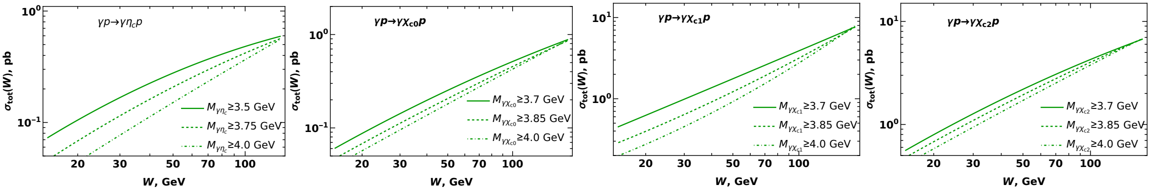
$$c_2 \approx \frac{2\epsilon\ \mathrm{Re}\left(\mathcal{A}^{(-,+)*}_{\gamma p\to\chi_c\gamma p}\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right)}{\left|\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right|^2 + \left|\mathcal{A}^{(-,+)}_{\gamma p\to\chi_c\gamma p}\right|^2}, \quad s_2 \approx \frac{2\epsilon\ \mathrm{Im}\left(\mathcal{A}^{(-,+)*}_{\gamma p\to\chi_c\gamma p}\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right)}{\left|\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}\right|^2 + \left|\mathcal{A}^{(-,+)}_{\gamma p\to\chi_c\gamma p}\right|^2}$$



–A sizable asymmetry is possible if both components $\mathcal{A}^{(+,+)}_{\gamma p\to\chi_c\gamma p}$ and $\mathcal{A}^{(-,+)}_{\gamma p\to\chi_c\gamma p}$ (w/ and w/o photon helicity flip) have comparable magnitudes.
…Is satisfied for η_c, χ_{c0} and for helicity component $H_{\chi_c} = 0$ helicity of χ_{c1}, χ_{c2}

–Asymmetries decrease as a function of W (smaller angles)

Yields and counting rates for $\gamma\eta_c$ and $\gamma\chi_c$ photoproduction



—Power law dependence on invariant energy $\sim W^\alpha$ $(W \equiv \sqrt{s_{\gamma p}})$

… Reflects x-dependence $\sim x^{-\nu}$ implemented in the GPD model $(\alpha \approx 4\nu)$

—Cutoff on minimal invariant mass $M_{\gamma\eta_c}$ to exclude feed-down contributions

Expected production and counting rates:

	$\sigma_{\rm tot}$	Production rates		Decay channel	Combined branching	Counting rates	
		N	dN/dt			N_d	dN_d/dt
η_c	49 fb	4.9×10^3	42/day	$\eta_c(1S)\to K^0_S K^+\pi^-$	2.6%	127	32/month
χ_{c0}	31 fb	3.1×10^3	27/day	$\chi_c \to J/\psi\,\gamma$	0.08 %	2.5	0.65/month
χ_{c1}	230 fb	2.3×10^4	199/day	$J/\psi \to \mu^+\mu^-$	2 %	460	120/month
χ_{c2}	250 fb	2.5×10^4	216/day		1.1 %	280	73/month
$\sqrt{s_{ep}} = 141\,\mathrm{GeV}$, $\int dt\,\mathcal{L} = 100\,\mathrm{fb}^{-1}$, $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$							

Summary

Photoproduction of quarkonia-photons may be interesting for GPD studies

— The $\chi_c\gamma$ and $\eta_c\gamma$ photoproduction are sensitive to GPD $H_g(x,\xi,t)$

— The $J/\psi\ \gamma$ is sensitive to:

* At LO: gluon GPD, convoluted with usual coefficient function of DV$J/\psi$P (dominant at small t')
* At NLO: valence quark GPD combination

$$\frac{2}{3}H_u(x,\xi,t)-\frac{1}{3}H_d(x,\xi,t)-\frac{1}{3}H_s(x,\xi,t)$$

*Dominant at large t', cross-sections and counting rates comparable to those of $\eta_c\gamma$, $\chi_c\gamma$

Thank You for your attention!