Photoproduction of heavy meson and photon pairs

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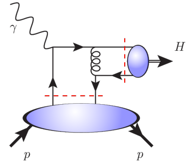
This talk is partially based on materials published in

PRD 107 , 034037; PRD 108 , 096031, PRD 109, 094001, arXiv:2408.01822.

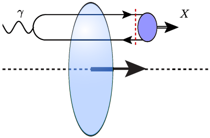
Proton structure

Complementary pictures of interactions, depend on kinematics (x_B, A):

- ▶ **Bjorken kinematics, moderate energies (** $x_B \gtrsim 10^{-2}$):
  - —Interaction of individual partons
  - —Target is characterized by its partonic distributions
  - —Multiparton distributions are suppressed by twist, $\mathcal{O}(\alpha_s)$



- ▶ **High energy (small-x_B) kinematics**:
  - —Partonic densities large, so partonic picture is not adequate
  - —**CGC picture**: [Ann. Rev. Nucl. Part. Sci. **60**, 463-489; PRD **49**, 2233; **49**, 3352; **50**, 2225]
  - —Eikonal picture, interaction with shockwave (gluonic field)
  - —Target ⇒ forward scattering amplitudes (dipole, quadrupole ...)
  - —Frequently formulated in terms of (unknown) weighting functional $W_Y[\rho]$ of color sources

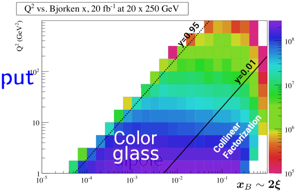


In both pictures the target is described by nonperturbative input

... should be extracted from experiments

... can be studied UPC@LHC, EIC

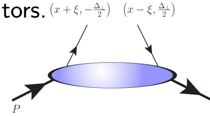
... (see kinematic coverage in (x_B, Q^2) ⇒)



Photoproduction at moderate energies ($x_B \gtrsim 0.01$)

Access to **Generalized Parton Distributions**:

—Nonperturbative objects, encode information about 2-parton correlators.



—Can be reinterpreted as hadron-parton helicity amplitudes

*Depend on parton flavour, 4 kinematic variables: x, ξ, t, μ^2

**Theoretical constraints: DGLAP, positivity, polynomiality

—Classification standardized since ∼2010 [PDG 2022, Sec 18.6]

— Dominant leading twist-2: 8 GPDs for each flavour, with different projectors $\mathbf{\Gamma}$, $\mathcal{F}^{(\Gamma)}$

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

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

Why GPDs are important ???

Many **physical observables** are constructed from **bilinear partonic operators**:
−Energy-momentum tensor (≈gravitational FFs, energy density, pressure & forces):

$$T^{\mu\nu} = -F^{\mu\alpha}F^{\nu}{}_{\alpha} + \frac{1}{4}\eta^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta} + \frac{1}{2}\bar{\psi}\gamma^{\{\mu}iD^{\nu\}}\psi + \eta^{\mu\nu}\bar{\psi}\left(i\hat{D} - m\right)\psi$$

−Angular momentum density:

$$M^{\mu\nu\rho} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_{\sigma}\gamma_5\psi + \frac{1}{2}\bar{\psi}\gamma^{\mu}x^{[\nu}iD^{\nu]}\psi - 2\mathrm{Tr}\left[F^{\mu\alpha}x^{[\nu}F^{\rho]}_{\alpha}\right] - x^{[\nu}g^{\rho]\mu}\mathcal{L}_{\mathrm{QCD}}$$

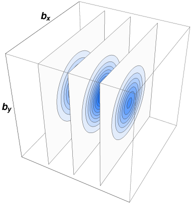
−Baryonic/electromagentic currents:

$$J^{\mu}_{\mathrm{baryonic}} = \bar{\psi}\gamma^{\mu}\psi, \qquad J^{\mu}_{\mathrm{em}} = \bar{\psi}\gamma^{\mu}\hat{Q}\psi$$

⇒(Moments of) GPDs contain information about contribution of each parton flavour to all these observables

⇓

Study of GPDs ≈ "3D tomography" of the hadron.



How can we study GPDs experimentally ?

Experimental constraints on GPDs:

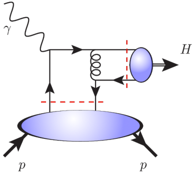
$$q(x) = \lim_{\xi, t \to 0} H(x, \xi, t)$$

1) Special limits (PDF, form factors)

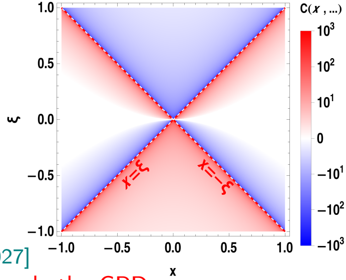
$$F(t) = \int dx\, H(x, \xi, t)$$

2) **2 → 2 processes** (DVCS, DVMP, TCS, WACS, ...)

- Rely on factorization (separation) of amplitude onto:
  - *soft hadron-dependent correlators (blobs), and
  - *perturbative process-dependent parts



- Amplitude is a convolution of GPD with process-dependent coef. function:
  $\mathcal{A} = \int dx\, C(x, \xi)\, H(x, \xi, \ldots)$
- Predominantly sensitive to GPDs at $x = \pm\xi$ boundary
  - *Similar behavior for all 2 → 2 processes, and after we take into account NLO corrections, ...



Recent discoveries: [PRD 108 (2023) 3, 036027]

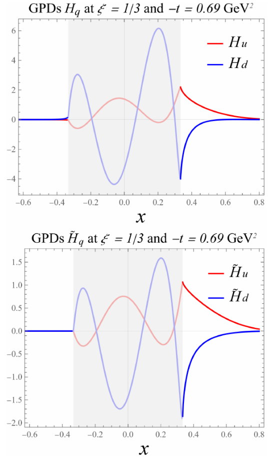
Deconvolution is impossible, Compton FFs don't fix uniquely the GPDs

What do we know about GPDs now ?

Quark sector:

[JHEP 05 (2023) 150]

GPDs species and flavors	Fully parameterized
H_{u_V} and $\widetilde{H}_{u_V}$	✔
E_{u_V} and $\widetilde{E}_{u_V}$	✔
H_{d_V} and $\widetilde{H}_{d_V}$	✔
E_{d_V} and $\widetilde{E}_{d_V}$	✘
$H_{\bar{u}}$ and $\widetilde{H}_{\bar{u}}$	✔
$E_{\bar{u}}$ and $\widetilde{E}_{\bar{u}}$	✘
$H_{\bar{d}}$ and $\widetilde{H}_{\bar{d}}$	✔
$E_{\bar{d}}$ and $\widetilde{E}_{\bar{d}}$	✘



–Qualitative understanding, phenomenological parametrizations (GK, KM, GUMP, ...)

*The behavior is especially poorly understood **in ERBL region** (grey-colored), for transversity GPDs and in gluonic sector. More experimental data are needed

New tool for proton tomography: $2 \to 3$ processes

Process:

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

States h_1, h_2 are light hadrons or photons, many possibilities studied in the literature:

$\gamma\pi$, $\gamma\rho$	[2212.00655, 2212.01034, JHEP 11 (2018) 179; 02 (2017) 054]
$\gamma\gamma$	[JHEP 08 (2022) 103; PRD **101**, 114027; **96**, 074008]
$\gamma\gamma^* \to \gamma\bar{\ell}\ell$	[Phys. Rev. D 103 (2021) 114002]
$\pi\rho$	[Phys.Lett.B 688 (2010) 154-167]

Main advantage:

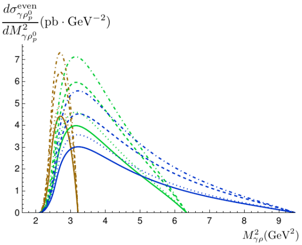
−Can vary independently kinematics of h_1, h_2 to probe GPDs at $x \neq \xi$

Challenge:

Cross-section significantly smaller than for $2 \to 2$ processes, especially for the states with additional γ in final state. Need high luminosity collider (EIC) photoproduction of $\gamma\pi$, $\gamma\rho$

► For typical (integrated) luminosity $\mathcal{L} \sim 100\,\mathrm{fb}^{-1}$ yields $N = \mathcal{L} \times \mathrm{pb} \gtrsim 10^5$ events

[JHEP 03 (23) 241, PRD 107, 094023]



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

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

$-h_1,\ h_2 = \gamma\,\eta_c$ (with large invariant mass $M_{\gamma\eta_c}$, to avoid feed-down contributions)

$-h_1,\ h_2 = J/\psi\ \eta_c$ (or other quarkonia pairs with opposite C-parity)

$-h_1,\ h_2 = DD^*$ meson pairs (largest cross-section, access to quarks)

Advantages:

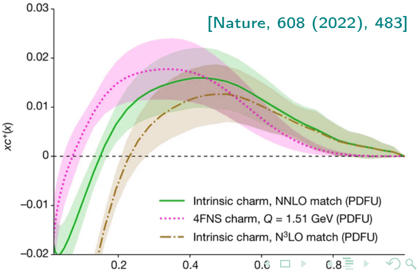
$-$Heavy quark mass plays the role of natural hard scale, $\alpha_s(m_Q) \ll 1$. No need to impose constraints on virtuality Q^2, ... (Bjorken regime)

*Can use NRQCD for quarkonia, heavy spin-favor symmetry for D-mesons, theoretically well understood

There is essentially no heavy quarks inside protons. The "intrinsic" charm does not exceed a few per cent.

$\Downarrow$

All final state heavy quarks stem from photon/gluon fragmentation



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

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

... Process $\gamma p \to \gamma\, J/\psi\, p$ requires C-odd exchanges in t-channel, suppressed

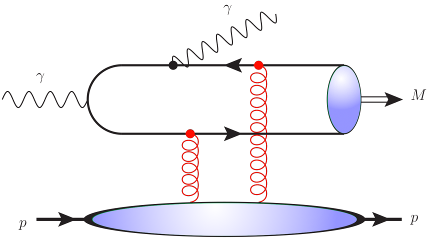
– Focus on kinematics of $M_{\gamma\eta_c} \gtrsim M_{J/\psi}$ to avoid feed-down contributions from $\gamma p \to J/\psi\, p$ (other feed-downs are negligible!)

– Interesting as **tool for study of GPDs**:
*Dominant contribution from GPDs H_g, E_g in ERBL kinematics

– Interesting as possible **background for odderon-mediated** $\gamma p \to \eta_c p$ channel.

Exclusive photoproduction of $\gamma\eta_c$ pairs

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



Summation over all possible gluon and photon attachments is implied

Leading order:

– 24 different diagrams overall (with account of permutations)

– Evaluation simplifies significantly in helicity basis

– Dominant contribution from GPDs H_g, E_g in ERBL kinematics

– Resembles $\gamma\pi^0$ productions, but has important differences due to heavy mass:

... In gluonic coefficient function for $\gamma\pi^0$ there are pinch singularities, when one of the final-state quarks and t-channel gluons is soft [2311.09146]

... Requires $\lim_{z\to 0,1}\Phi_\pi(z) = 0$, otherwise breaks collinear factorization

... In $\gamma\eta_c$ there is no such pinch singularities, heavy quark mass shifts the poles away.

Coefficient function for $\gamma\eta_c$ photoproduction

Relatively simple expressions, e.g.

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

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

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

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

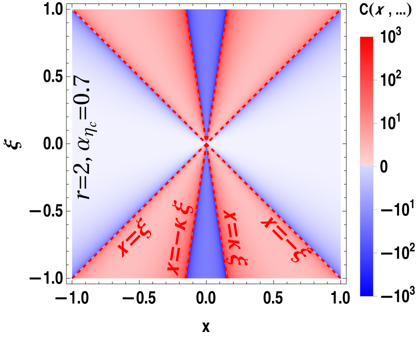
$$+\frac{-\alpha\left((\alpha-4)\zeta^2+11\alpha+8\right)+8\zeta^2+4}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^6}$$

$$\left.-\frac{4\left(\zeta^2-3\alpha\right)}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^8}-\frac{4}{\left(\zeta+1-i0\right)\left(\zeta-1+i0\right)r^{10}}\right]$$

– Similar expressions for other helicity components $C_{\gamma\eta_c}^{(+,-)}$, $C_{\gamma\eta_c}^{(-,+)}$, ...

– The contributions with photon helicity flip $C_{\gamma\eta_c}^{(+,-)}$, $C_{\gamma\eta_c}^{(-,+)}$ are suppressed as $1/r^2$ compared to $C_{\gamma\eta_c}^{(+,+)}$, $C_{\gamma\eta_c}^{(-,-)}$.

Coefficient function for $\gamma\eta_c$ photoproduction



Summation over all possible gluon and photon attachments is implied

Location of poles in coef. function:

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

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

$$\kappa = \frac{1}{r^2}\frac{2-\alpha r^2}{2-\alpha}.$$

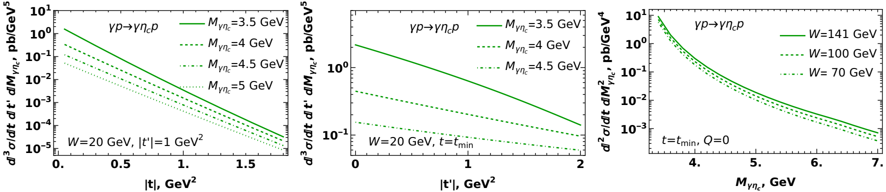
...In physical kinematics $r \geq 1$, $r^{-2} \leq \alpha \leq 1$, so parameter κ is bound by

$$|\kappa| \leq 1 \qquad \text{(ERBL kinematics)}$$

– Varying parameter $r = M_{\gamma\eta_c}/M_{\eta_c}$ and $\alpha = \left(M^2_{\eta_c} - t'\right)/M^2_{\gamma\eta_c}$ can study the GPDs in the whole ERBL region.

3-fold differential cross-section for $\gamma\eta_c$ photoproduction

[Kroll-Goloskokov parametrization]



Dependence on kinematic variables:

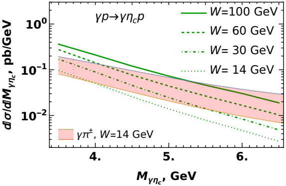
−Momentum transfer to the proton $t = (p' - p)^2$

... Controlled by t-dependence implemented in GPD

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

... gateway to probe the dependence on

$\alpha = \left(M_{\eta_c}^2 - t'\right)/M_{\gamma\eta_c}^2$



−Invariant mass $M_{\gamma\eta_c}^2 = (k_\gamma + p_{\eta_c})^2$

... Reflects $1/r^2$ suppression of the coef. functions

... Similar for the single- and 3-fold differential cross-section

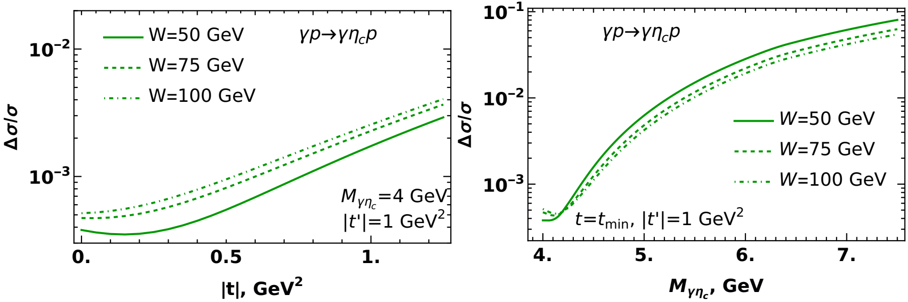
... Comparable to $\gamma\pi^\pm$ if compared at the same invariant mass $M_{\gamma M}$

−Dependence on invariant energy $\sim W^{0.7-0.8}$

... Reflects x-dependence $\sim x^{-\nu}$ implemented in the GPD model

Results for photon polarization in $\gamma\eta_c$

Ratio of the (photon) helicity flip to non-flip components:



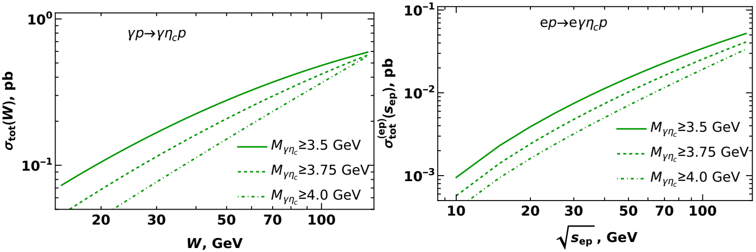
—As expected, at high energy helicity flip contribution is small

—At larger t, $M_{\gamma\eta_c}$ have larger contribution of helicity flip $\tilde{H}$, $\tilde{E}$

*Yields are still very small for experimental measurements in that kinematics

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

[Kroll-Goloskokov parametrization]



—Dependence on invariant energy $\sim W^{0.7-0.8}$ $(W \equiv \sqrt{s_{\gamma p}})$

... Reflects x-dependence $\sim x^{-\nu}$ implemented in the GPD model

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

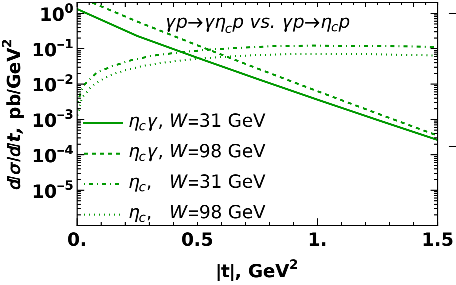
Production and counting rates:

	$\sigma_{\rm tot}$	Production rates		Counting rates	
		N	dN/dt	N_d	dN_d/dt
$\sqrt{s_{ep}} = 141\,{\rm GeV}$	49 fb	4.9×10^3	42/day	127	32/month

—For estimates used $\mathcal{L} = 10^{34}\,{\rm cm}^{-2}{\rm s}^{-1}$, $\int dt\,\mathcal{L} = 100\,{\rm pb}$

—Assumed detection via $\eta_c(1S) \to K_S^0 K^+ \pi^-$ with branching $\approx 2.6\,\%$

Comparison of η_c and $\gamma\eta_c$ photoproduction



Odderon-mediated η_c predictions from [PRD 108 (2023), 074005]

- The process $\gamma p \to \eta_c p$ is mediated by odderons (C-odd exchanges), considered in the literature as a clean channel for studies
- The process $\gamma p \to \gamma\eta_c p$ is mediated by C-even contributions (predominantly GPD H_g)

... If detector acceptance for photons $\ll 1$, the $\eta_c\gamma$ photoproduction can constitute significant background, especially at

$$|t| \leq 0.5\,\mathrm{GeV}^2$$

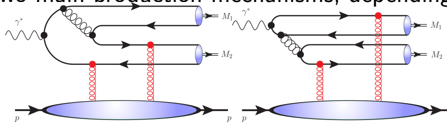
- In contrast to other backgrounds (*e.g.* Primakoff), $\eta_c + \gamma\,(\mathrm{invisible})$ will be the same for p and n, same by magnitude for $\gamma\eta_c$ and $\gamma\,\chi_c$ (no suppression due to Langau-Yang theorem)

Exclusive photoproduction of heavy mesons pairs

Quarkonia pairs ($J/\psi\,\eta_c$, $J/\psi\,\chi_c$, $B_c^+B_c^-$, $J/\psi\,\eta_b$, $\Upsilon(1S)\,\eta_c$)

—Only gluons contribute

—Two main production mechanisms, depending on heavy flavor content:

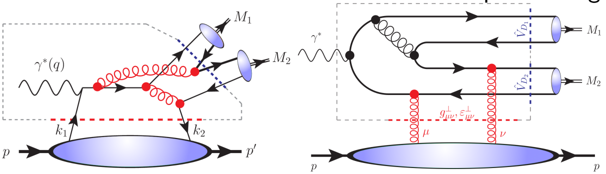


Can vary quantum numbers and kinematics of produced quarkonia in order to disentangle effects due to wave function and get detailed info about the target

Summation over all possible gluon attachments is implied

D-meson pairs (D^+D^{*-}, $D^0\bar{D}^{*0}$, $D_s^+D_s^{*-}$)

—Both light quarks and gluons contribute on equal footing at this order



Summation over all possible permutations of photon, gluon vertices is implied
In the right diagram, should sum contributions with photon attached to heavy or light quark lines

(!) For quark sector, only one light flavor contributes (d, u, s for meson pairs D^+D^{*-}, $D^0\bar{D}^{*0}$, $D_s^+D_s^{*-}$ respectively). Important for flavor separation

Hadronization into heavy mesons

Quarkonia: use NRQCD (justified in heavy quark mass limit)

- Use dominant color singlet projectors $\hat{V}_{J/\psi}$, $\hat{V}_{\eta_c}$ to project out contributions of $\bar{Q}Q$ pairs with proper quantum numbers:

  ... dominant contribution from color singlet LDME

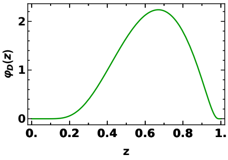
$$\mathcal{O}_{\eta_c}\left({}^1S_0^{[1]}\right) \approx \frac{1}{2}\mathcal{O}_{J/\psi}\left({}^3S_1^{[1]}\right)\left(1+\mathcal{O}\left(\Lambda/m_Q\right)\right)$$

  ... Color Octet mechanism not relevant at small p_T

D-**mesons**: use heavy spin-flavor symmetry.

– The DAs for all mesons are close to each other, though spin structure differs:

$$f_D\varphi_D\left(z,\mu^2\right)\left(\frac{1+\hat{v}}{2}\gamma_5\right),\quad f_D\varphi_D\left(z,\mu^2\right)\left(\frac{1+\hat{v}}{2}\right)\hat{\varepsilon}\left(p\right)$$



– Phenomenology: The DA $\varphi_D$is quite broad, not δ-function

Results for coefficient function

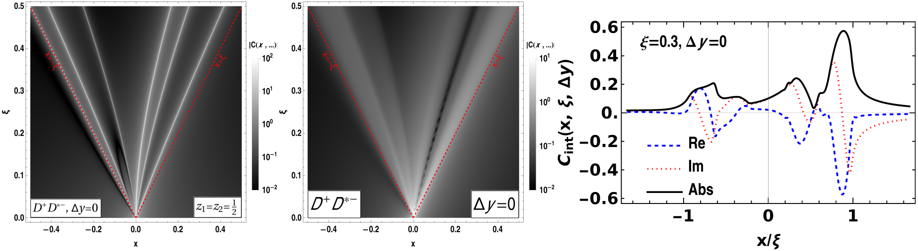
$$\{\mathcal{H}_{\mathfrak{a}},\,\mathcal{E}_{\mathfrak{a}}\}\sim\int dx\,\underbrace{\int dz_1 dz_2\, C_{\mathfrak{a}}\left(x,\,\xi,\Delta y,\,z_1,z_2\right)\varphi_D\left(z_1\right)\varphi_D\left(z_2\right)}_{C_{\mathfrak{a}}^{(\mathrm{int})}(x,\,\xi,\,\Delta y)}\{H_g,\,E_g\},$$

- Structure function $C_{\mathfrak{a}}(x,\,...)$ is meromorphic, with several simple poles in the integration region $|x|<1$.
  – Poles do NOT overlap for $m_Q\neq 0$, so integrals exist in Principal Value sense

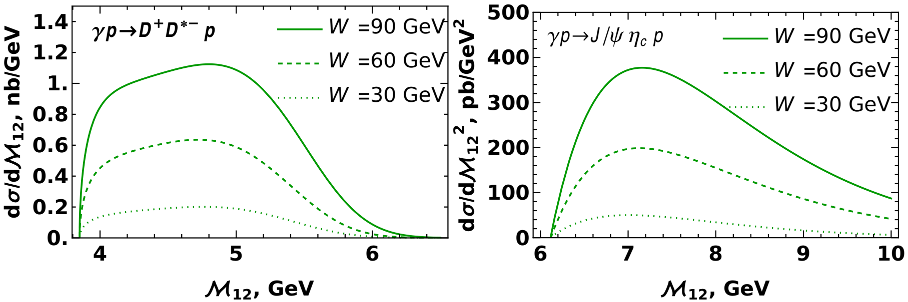
Density plot of coefficient function:

– Poles are seen as bright white lines in the left plot, all in ERBL region ($|x|\lesssim\xi$)

– *D*-**mesons**: convolution with DAs⇒poles are smoothed out (central and right plots)



Results for invariant mass dependence



– Pronounced peak at $M_{12} \approx 7\,\mathrm{GeV}$ for quarkonia pairs, and $M_{12} \approx 4.5$ GeV for D mesons

** Small relative momentum of mesons, $p_{\rm rel} \lesssim 2 - 3\,\mathrm{GeV}$

* See [PRD 107 , 034037; PRD 108 , 096031] for more detailed plots

Subtle point:

– Counting rates are suppressed by branchings ($e.g.$ $\mathrm{Br}(J/\psi \to \mu^+\mu^-)\mathrm{Br}(\eta_c \to K_S^0 K^+ \pi^-) \sim 1.5 \times 10^{-3}$)

* Nevertheless still on par with other $2 \to 3$ channels ($\gamma\pi$, $\gamma\rho$ photoproduction)

Summary

Exclusive photoproduction of quarkonia-photon and heavy quarkonia pairs can be used as a new probe of the gluonic GPDs of the target in ERBL kinematics

- $\gamma\eta_c$ **pairs**: Probe gluon GPDs only, possible background to odderon searches
  - Very simple coefficient function, just 2 poles in ERBL region
- **Quarkonia pairs**: Probe gluon GPDs only.
- *D*-**meson pairs**: probe gluon and quark GPDs of just 1 light quark flavor
  - Could be used to measure both quark and gluons in ERBL region.

- The cross-sections are large enough for experimental studies
  - Counting rates comparable to other $2 \to 3$ processes suggested in the literature

Thank You for your attention!