Exclusive photoproduction of open heavy flavor meson pairs

Novel tool for study of proton GPDs

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Foreword

Hadrons in QCD:

–Sophisticated strongly interacting dynamical systems

*Direct theoretical description challenging: requires modelling in nonperturbative regime, numerical lattice studies or purely phenomenological approaches

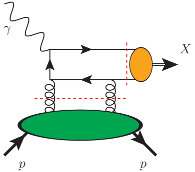
Phenomenological studies:

–Needed for verification of existing theoretical models or phenomenological paramertizations

–Rely on factorization (separation) of amplitude onto:

*soft hadron-dependent correlators (blobs), and

*perturbative process-dependent parts

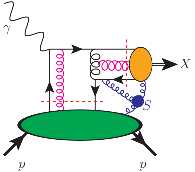


*Choosing different (known) states X, can change relative weight (contribution) of different Fock state components

–Require high energies, good kinematic separation of final-state hadrons:

*suppress soft final-state interactions between hadrons

*suppress higher twists, multiparton Fock states



–Light-cone description (quantization), effectively $P \to \infty$ frame

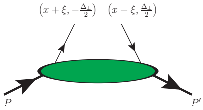
(Generalized) parton distributions: theoretical aspects

–Nonperturbative objects which encode information about 2-parton correlators

Might be reinterpreted in terms of hadron-parton amplitudes in helicity basis

*GPDs are different for each flavor, depend on 4 variables: x, ξ, t, μ^2

*Subject to nontrivial constraints (positivity, polynomiality, DGLAP evolution for μ^2-dependence)



⇒Challenge for modelling ("dimensionality curse")

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

– Leading twist-2 (dominant in many high-energy processes):

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

Γ	$\mathcal{F}^{(\Gamma)}$
γ^+	$H\gamma^+ + E\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}$
$\gamma^+\gamma_5$	$\tilde{H}\gamma^+\gamma_5 + \tilde{E}\frac{\gamma_5\Delta^+}{2m}$

Γ	$\mathcal{F}^{(\Gamma)}$
$i\sigma^{+i}$	$H_T i\sigma^{+i} + \tilde{H}_T\frac{\bar{P}^+\Delta^i - \bar{P}^i\Delta^+}{m^2} + E_T\frac{\gamma^+\Delta^i - \gamma^i\Delta^+}{2m} + \tilde{E}_T\frac{\gamma^+\bar{P}^i - \gamma^i\bar{P}^+}{m}$

$\bar{P} \equiv (P+P')/2$ $\Delta \equiv P' - P$

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

Experimental constraints on GPDs

Special limits:

−inelastic processes ⇒PDFs: $q\left(x,\mu^2\right) = H\left(x,0,0,\mu^2\right)$

−elastic scattering ⇒form factors: $F\left(t\right) = \int dx\, H\left(x,0,t,\mu^2\right)$

$2 \rightarrow 2$ **processes** (DVCS, DVMP, TCS, WACS, ...)

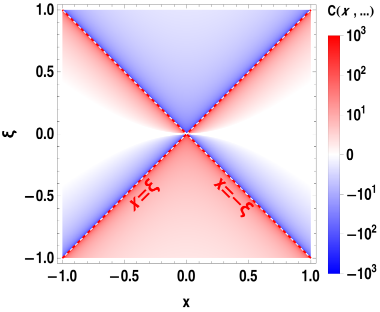
−Amplitude is a convolution of GPD with process-dependent coef. function:

$\mathcal{A} = \int dx \sum_a C_a\left(x,\xi\right) H_a\left(x,\xi,...\right),$

−Predominantly sensitive to GPDs near $x \approx \pm\xi$ boundary

$$C_{\mathrm{LO}}^{(\mathrm{DVCS})}(x,\xi) \sim \frac{1}{x-\xi+i0} + \frac{1}{x+\xi-i0}$$

*Deconvolution is impossible, Compton FFs don't fix uniquely the GPDs [PRD 103, 114019 (2021)]



−For DVMP have additional convolution with (broad) meson DAs, very nontrivial at NLO (smears the sharp peaks). However, still get dominant contribution from the region $x \approx \pm\xi$.

New tool for 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 benefit:

−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 states with additional γ in final state. Need high luminosity collider (EIC)

Our suggestion:

−Exclusive photoproduction of heavy meson pairs ($\gamma + p \to M_1 + M_2 + p$)
−Focus on D -mesons with opposite C-parity (e.g. $D^+ \; D^{*-}$), largest cross-section
 * Dominant contribution from unpolarized chiral even GPDs H_q, H_g
 * In $m_Q \to \infty$ limit, can use heavy spin-favor symmetry, so the DAs of D^+ and D^{*-} are related to each other
 * *Pairs with the same C-parity (e.g. $D^+ \; D^-$) are much more complicated:*
 (1) Contributions from chiral odd GPDs H_T, E_T, ...
 (2) C-odd exchanges in t-channel (γ or 3-gluon), not related to twist-2 GPDs.

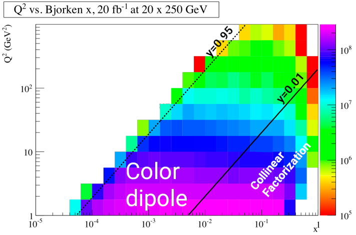
Kinematics choice: Electron Ion Collider

Typical values of variables ξ, x_B

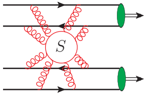
$$x_B \approx \frac{Q^2 + M_{12}^2}{Q^2 + W^2}, \qquad \xi = \frac{x_B}{2 - x_B}.$$

▷ Accessible kinematics (x_B, Q^2) depends on choice of electron-proton energy E_e, E_p

▷ Dominant: $Q^2 \approx 0$, $x_B, \xi \in \left(10^{-4}, 1\right)$

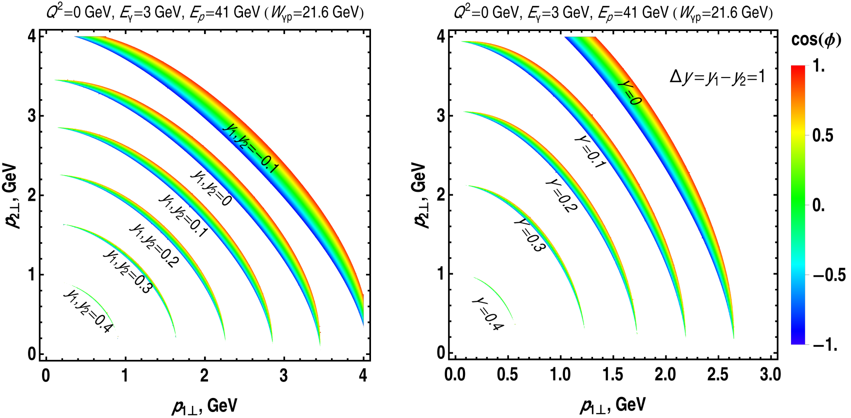


- Low-energy EIC runs to avoid $x_B, \xi \ll 1$ region (large NLO, saturation)
- We consider that $Q \sim M_D \sim W_{\gamma p}$ are large scales
  - Since $M_{12}^2 \gtrsim 4M_D^2 \sim 16\,\mathrm{GeV}^2$ and cross-section is suppressed at large Q as $\lesssim 1/Q^6$, "classical" Bjorken limit $Q \gg M_{12}$ is difficult to study experimentally
  - Production at central rapidities, rapidity gaps from γ^*, p
  - Constraint on relative velocity of mesons $v_{\mathrm{rel}} \gtrsim 2\alpha_s(m_Q)$, to exclude possible soft final state interactions ⇒ exclude near-threshold production.



Comment on kinematics of mesons

- Production at fixed Q^2, W of $\gamma^* p$ (fixed x_B) not very convenient:
  - Sophisticated kinematic constraints on rapidities y_1, y_2, transverse momenta $p_{\perp 1}$, $p_{\perp 2}$, and azimuthal angle ϕ between them: only certain domains (bands) are allowed:



- Alternative choice: work with $Q^2, y_1, \boldsymbol{p}_{1\perp}, y_2, \boldsymbol{p}_{2\perp}$
  - ▷ No kinematic constraints on $y_1, \boldsymbol{p}_{1\perp}, y_2, \boldsymbol{p}_{2\perp}$, explicit symmetry w.r.t. permutation of heavy mesons $1 \leftrightarrow 2$

Evaluations in collinear factorization framework

Evaluation is straightforward, amplitude (squared):

$$\sum_{\text{spins}} \left|\mathcal{A}^{(\mathfrak{a})}_{\gamma p\to M_1 M_2 p}\right|^2 = \frac{1}{(2-x_B)^2}\left[4\,(1-x_B)\left(\mathcal{H}_\mathfrak{a}\mathcal{H}^*_\mathfrak{a}+\tilde{\mathcal{H}}_\mathfrak{a}\tilde{\mathcal{H}}^*_\mathfrak{a}\right)-x_B^2\left(\mathcal{H}_\mathfrak{a}\mathcal{E}^*_\mathfrak{a}+\mathcal{E}_\mathfrak{a}\mathcal{H}^*_\mathfrak{a}+\right.\right.$$

$$\left.\left.+\,\tilde{\mathcal{H}}_\mathfrak{a}\tilde{\mathcal{E}}^*_\mathfrak{a}+\tilde{\mathcal{E}}_\mathfrak{a}\tilde{\mathcal{H}}^*_\mathfrak{a}\right)-\left(x_B^2+(2-x_B)^2\frac{t}{4m_N^2}\right)\mathcal{E}_\mathfrak{a}\mathcal{E}^*_\mathfrak{a}-x_B^2\frac{t}{4m_N^2}\tilde{\mathcal{E}}_\mathfrak{a}\tilde{\mathcal{E}}^*_\mathfrak{a}\right],$$

$$\{\mathcal{H}_\mathfrak{a},\,\mathcal{E}_\mathfrak{a}\} = \int dx\,dz_1\,dz_2\sum_{\kappa=q,g} C^{(\kappa)}_\mathfrak{a}(x,\,z_1,\,z_2,\,y_1,\,y_2)\,\{H_\kappa,\,E_\kappa\}\,\Phi_{D_1}(z_1)\,\Phi_{D_2}(z_2)\,,$$

$$\left\{\tilde{\mathcal{H}}_\mathfrak{a},\,\tilde{\mathcal{E}}_\mathfrak{a}\right\} = \int dx\,dz_1\,dz_2\sum_{\kappa=q,g} \tilde{C}^{(\kappa)}_\mathfrak{a}(x,\,z_1,\,z_2,\,y_1,\,y_2)\left\{\tilde{H}_\kappa,\,\tilde{E}_\kappa\right\}\Phi_{D_1}(z_1)\,\Phi_{D_2}(z_2)\,,$$

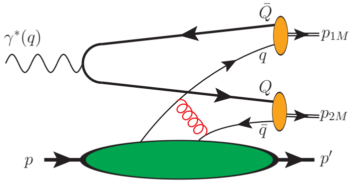
- ► Summation over quarks and gluons implied
- ► Disregard chiral-odd transversity GPDs (not known, should be negligible in small-t kinematics)
- ► Disregard intrinsic heavy flavors (not known, $\lesssim 2-3\%$)

►Due to choice of final state, only <u>one</u> of the light flavors contribute.
–Unique feature of this channel. Can use this for flavor separation of the light quark GPDs.

Coefficient function at order $\mathcal{O}(\alpha_s)$

– Focus on light flavors u, d, s

*Intrinsic heavy flavours (charm, bottom) in the target are negligible



OPE for matrix element $\left\langle M_1 M_2 p \left| J_\mu^{(\mathrm{em})}(0) e^{i d^4 x \mathcal{L}_{\mathrm{int}}} \right| p \right\rangle$:

*The first contribution shows up at $\sim \mathcal{O}(\alpha_s)$, formally dominates

*Just single diagram, requires gluon exchange between q, $\bar{q}$

– Is kinematically forbidden in collinear factorization: heavy quarks carry large momenta $z_1 p_{1M}$, $z_2 p_{2M}$, with $z_{1,2} \geq 0$

*Cannot be produced from a photon with $q^2 = -Q^2 \lesssim 0$, since for this diagram

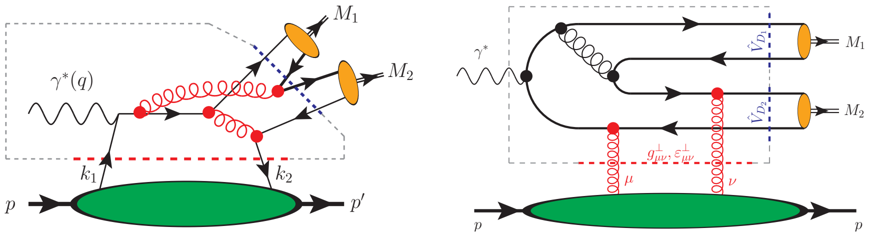
$$(z_1 p_{1M} + z_2 p_{2M})^2 = z_1^2 M_1^2 + z_2^2 M_2^2 + z_1 z_2 \left(M_{12}^2 - M_1^2 - M_2^2\right) \gtrsim 0$$

***Beyond collinear factorization, the diagram is not strictly forbidden, but is strongly suppressed (required p_T of quarks are $\sim M_1, M_2$)*

*For the same reason, drop all higher-order diagrams in which heavy quarks don't interact with gluons, or interaction reduces to a mere self-energy/vertex

Coefficient function at order $\mathcal{O}\left(\alpha_s^2\right)$

– 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

– Use light-cone gauge $n \cdot A = 0$

* Project $q, \bar{q}$ spinor indices onto γ^+, $\gamma^+\gamma_5$ to extract $C_{\mathfrak{a}}^{(q)}$, $\tilde{C}_{\mathfrak{a}}^{(q)}$
* Contract Lorentz indices of t-channel gluons with $g^\perp_{\mu\nu}$, $\varepsilon^\perp_{\mu\nu}$ to extract $C_{\mathfrak{a}}^{(g)}$, $\tilde{C}_{\mathfrak{a}}^{(g)}$

– Effective couplings of D-mesons to $\bar{Q}q$, $\bar{q}Q$ in $m_Q \to \infty$ limit:

$$\hat{V}_{D^\pm} \approx f_D \varphi_D\left(z, \mu^2\right) \frac{1 \pm \hat{v}}{2} \gamma_5, \; \hat{V}_{D^{*\pm}} \approx f_D \varphi_D\left(z, \mu^2\right) \frac{1 \pm \hat{v}}{2} \hat{\varepsilon}\left(p\right).$$

The same DAs φ_D for pseudoscalar and vector (heavy spin-flavor symmetry)

Results for coefficient function

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

- Structure function $C_{\mathfrak{a}}(x, \dots)$:

$$C_{\mathfrak{a}} \sim \sum_{\ell} \frac{\mathcal{P}_\ell(x, \dots)}{\mathcal{Q}_\ell(x, \dots)}$$

where $\mathcal{P}_\ell$, $\mathcal{Q}_\ell$ are polynomials of order $n_\ell \lesssim 3$ as a function of x.

– Each term might have up to 3 poles in the integration region $|x| < 1$

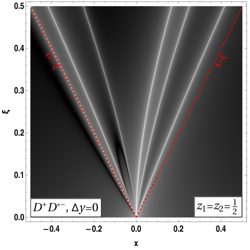
– Position of poles depends on kinematics $(\xi, \Delta y, z_1, z_2)$

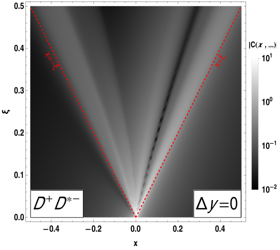
– Poles do NOT overlap for $m_Q \neq 0$, so integrals exist in Principal Value sense

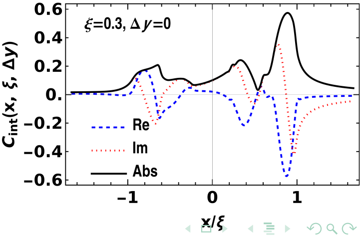
Density plot of coefficient function:

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

– After convolution with DAs, poles are smoothed out (central and right plots)

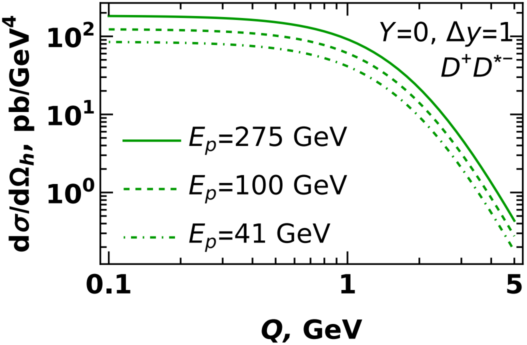






Results for Q^2-dependence

- Focus on D^+D^{*-} mesons for brevity (similar dependence for other D- and B-mesons)
  - Many good GPD parametrizations are known from the literature, use Kroll-Goloskokov for definiteness

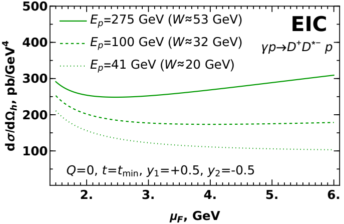


- The Q^2-dependence is controlled by $\mathcal{M}_{12} = \sqrt{(p_1 + p_2)^2} \gtrsim 2M_D \approx 4\,\mathrm{GeV}$
- very mild dependence for $Q^2 \lesssim \mathcal{M}_{12}^2$, yet $d\sigma \sim 1/Q^6$ for $Q^2 \gg \mathcal{M}_{12}^2$
- Transition scale largely independent on W

Dependence on factorization scale $\mu_F = \mu_r = \mu$

– Physical observables should not depend on μ, yet when we cut pert. series, such dependence appears due to omitted higher order terms

* At LO dependence on μ due to $\alpha_s(\mu)$, DGLAP evolution of GPDs



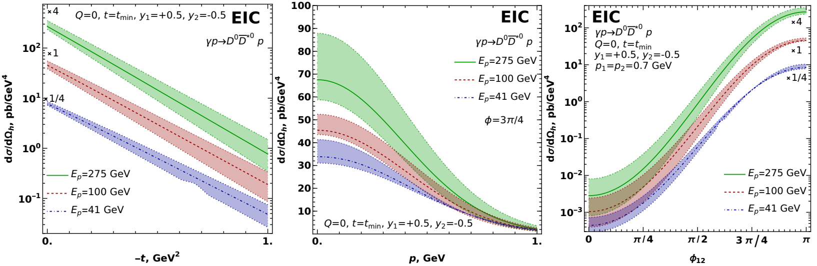
– At small W (large x_B) dependence is mild

– At large W (small x_B) dependence is more and more pronounced, since the omitted higher order loop corrections become more relevant, and the μ-dependence gets stronger

– We'll asume for definiteness that $\mu_F \approx m_D \approx 2\,\mathrm{GeV}$, yet consider uncertainty choice varying μ_F in the range $m_D/2 \lesssim \mu_F \lesssim 2m_D$

Results for t-dependence

– The t-dependence of $d\sigma/d\Omega_h$ largely reflects dependence implemented in GPDs

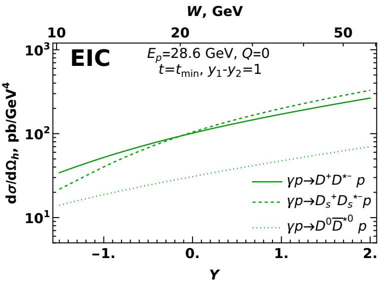


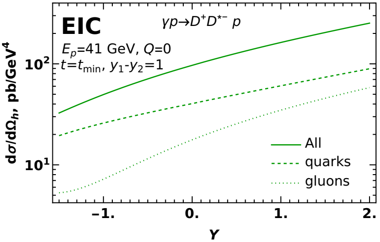
* Predominantly D-meson pairs are produced in back-to-back kinematics, with small p_T, as could be understood from

$$t = \Delta^2 = -\frac{4\xi^2 m_N^2 + \left(\boldsymbol{p}_1^\perp + \boldsymbol{p}_2^\perp\right)^2}{1-\xi^2}$$

* The colored band reflects uncertainty due to choice of the scale $m_D/2 \lesssim \mu_F \lesssim 2m_D$

Results for rapidity dependence





The increase of average rapidity

$$Y = \frac{y_1 + y_2}{2}$$

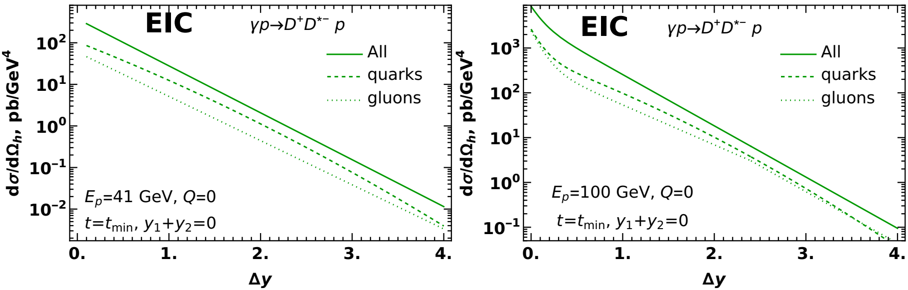
implies:

* Larger invariant energy W
* Smaller x_B, ξ
* Larger cross-section due to growth of $H(x, \xi, t)$ at small x

– The quark contributions dominate at larger x_B (negative $Y \lesssim -1$)

– The gluon contributions becomes more and more pronounced at smaller x_B (positive Y)

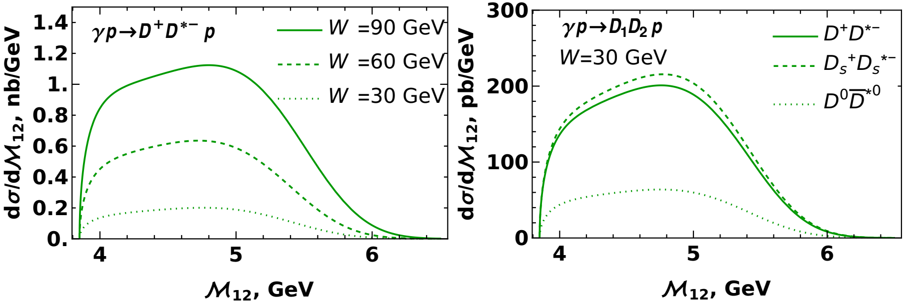
Dependence on rapidity difference



Left and right plots differ by values of proton energy E_p (and thus W)

– The cross-section drops rapidly as a function of Δy, since increase of Δy implies:
  * Larger longitudinal recoil to proton Δ_L
  * Larger values of $|t_{\min}|$, $|t| = |\Delta^2|$
  * Suppression of cross-section is due to t-dependence of $H_q(x, \xi, t)$, $H_g(x, \xi, t)$
  * The cross-section remains finite at $\Delta y \to 0$, yet should be careful with that region (collinear D-mesons, might get sizeable FSI). Keep $\Delta y \gtrsim 1$ for safety

Results for invariant mass dependence



–Pronounced peak at $M_{12} \approx 4 - 5\,\mathrm{GeV}$

*At small $\mathcal{M}_{12}$ growth due to phase space.

**At $\mathcal{M}_{12} \lesssim 4$ GeV the relative velocity $v_{\rm rel} \sim \alpha_s(m_Q)$, sizeable soft corrections, focus on $\mathcal{M}_{12} \gtrsim 4$ GeV.

*At larger $\mathcal{M}_{12}$ suppression due to form factors ($|t|$ increases due to kinematics)

Summary

Exclusive production of D-meson pairs might be used as a new probe of the GPD models:

- Probe gluon and quark GPDs of just one light quark flavor (u, d or s)
  * Sensitive to behaviour in the ERBL region $|x| \lesssim \xi$. Almost no contribution from outside

- The cross-section is large enough for experimental studies
  * On par with $\gamma^{(*)}p \to \gamma\pi^0\, p$, $\gamma^{(*)}p \to \gamma\rho^0\, p$ suggested by other authors

** For B-mesons all cross-sections have similar dependence on kinematic variables, but the cross-sections are too small (sub-picobarn level).*

Thank You for your attention!