Hard Exclusive Photoproduction of $\overline{D^0}$-Mesons within the Generalized Parton Picture

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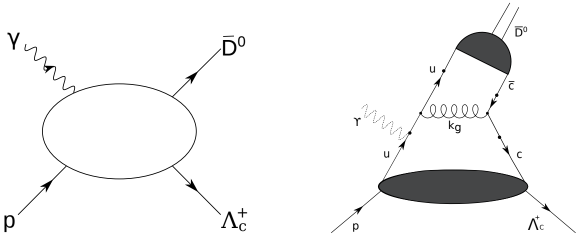
Outline

Motivation

- investigate the exclusive photoproduction $\gamma\, \mathbf{p} \to \mathbf{\Lambda_c^+}\, \overline{\mathbf{D^0}}$ using a *handbag mechanism*



- provides information of the intrinsic charm of the proton
- exclusive charm photoproduction is a nearly unexplored field, theoretically as well as experimentally
- a further application of $p \to \Lambda_c^+$ flavor changing GPDs, which were introduced by [Goritschnig A.T., Kroll P. and Schweiger W., Eur. Phys. J. A42 (2009)]

The General Setting

Our Framework

- pQCD:
  - describes (short distance) dynamics of quarks and gluons in a hadron (pQCD)
  - limited to the high energy regime $\to$ non-perturbative methods for the low energy regime are needed
- use hadronic matrix elements to describe the (long distance) binding effects (**G**eneralized **P**arton **D**istributions (GPDs) and **D**istribution **A**mplitudes (DAs))

$\to$ **Factorization**

A little bit of Kinematics. . . Symmetric CMS

incoming momenta

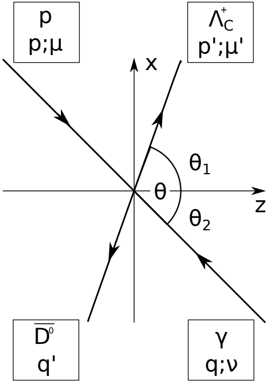
$$p = \left[(1+\xi)\bar{p}^+, p^-, -\frac{\boldsymbol{\Delta}_\perp}{2}\right] \quad \left(p^2 = m^2\right)$$

$$q = \left[q^+, q^-, +\frac{\boldsymbol{\Delta}_\perp}{2}\right] \quad \left(q^2 = 0\right)$$

outgoing momenta

$$p' = \left[(1-\xi)\bar{p}^+, p'^-, +\frac{\boldsymbol{\Delta}_\perp}{2}\right] \quad \left(p'^2 = M^2\right)$$

$$q' = \left[q'^+, q^-, -\frac{\boldsymbol{\Delta}_\perp}{2}\right] \quad \left(q'^2 = M_D^2\right)$$



- $\bar{p} := \frac{1}{2}(p + p')$
- $\xi := \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2\bar{p}^+}$
- $\Delta := p' - p = q - q'$

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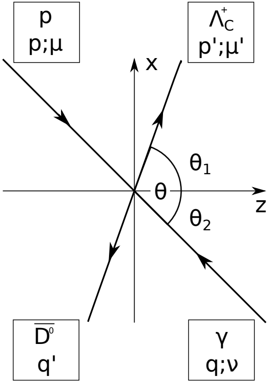

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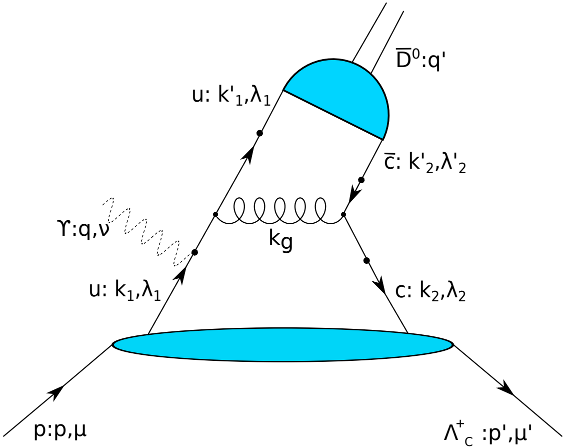
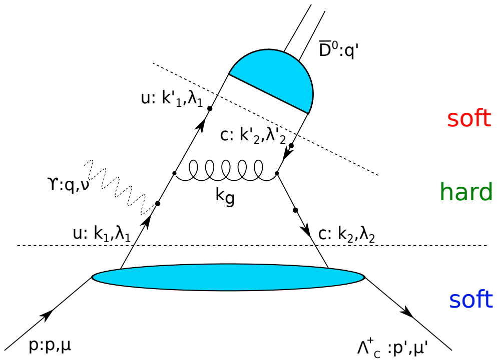
Handbag Picture of the Process

$s \geq (M + M_D)^2 \approx 17.23\ \text{GeV}^2$ $E^{\gamma}_{\text{lab}} \approx 8.7\ \text{GeV}$

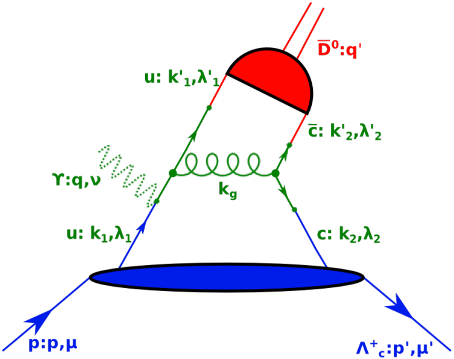


(possible) intrinsic charm content of the proton neglected



- hard-scattering process:
  described with 4 Feynman diagrams within pQCD
  (*natural hard scale*:heavy quark mass m_c)
- long distance effects of $p \to \Lambda_c^+$ transition:
  parameterized by flavor changing GPDs
- meson formation:
  parameterized by DA

Process Amplitude



$$
\begin{aligned}
\mathscr{M}_{\mu' 0,\mu\nu} \approx & \int \mathrm{d}^4\bar{k} \int \mathrm{d}^4 z_1 e^{i\bar{k}z_1} \int \mathrm{d}^4 k_1' \int \mathrm{d}^4 z_2\, e^{ik_1' z_2} \\
& \times \langle \Lambda_c^+ : p', \mu' | T\, \overline{\Psi}^c \left(-\frac{z_1}{2}\right) \Psi^u \left(+\frac{z_1}{2}\right) | p : p, \mu \rangle\, \widetilde{H}^\nu \left(\bar{k}, k_1', q\right) \\
& \times \langle \overline{D^0} : q' | T\, \overline{\Psi}^u (z_2)\, \Psi^c (0)\, | 0 \rangle
\end{aligned}
$$

$\left(\bar{k} := \frac{1}{2}\left(k_1 + k_2\right)\right)$

Factorization of Process Amplitude

Goal

separate soft hadronic matrix elements from hard parton scattering

Assumptions ("Soft Physics Approach"):

- parton virtualities are smaller than a typical hadronic scale $\Lambda \approx 1$ GeV:

$$k_u^{(\prime)2} \lesssim \Lambda^2 \quad \text{and} \quad |k_c^{(\prime)2} - m_c^2| \lesssim \Lambda^2$$

- intrinsic transverse momenta are restricted by:

$$\frac{\mathbf{k}_{i\perp}^{(\prime)2}}{x_i(z_i)} \lesssim \Lambda^2$$

- Λ_c^+- and $\overline{D^0}$-wave function peaked at $x_0 \approx \frac{m_c}{M}$ and $z_0 \approx \frac{m_c}{M_D}$
  ($x_0 \to 1$ and $z_0 \to 1$ for $m_c \to \infty$)

Factorization of Process Amplitude

Consequence:

- $\mathbf{k}_{\perp(1,2)}$ and $\mathbf{k}'_{\perp(1,2)}$ negligible as compared to $k^+_{(1,2)}$ and $k'^-_{(1,2)}$

$\Rightarrow$ partons are **on-mass-shell** and **collinear** to their parent hadron, i.e.

$$k_1 = x_1 p \quad \left(k_1^2 = 0\right) \qquad k'_1 = (1-z)q' \quad \left(k'^2_1 = m_c^2\right)$$

$$k_2 = x_2 p' \quad \left(k_2^2 = 0\right) \qquad k'_2 = z q' \quad \left(k'^2_2 = m_c^2\right)$$

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$$k_2 = x_2 p' \quad \left(k_2^2 = 0\right) \qquad k'_2 = zq' \quad \left(k_2'^2 = m_c^2\right)$$

Furthermore:

- $\widetilde{H}^\nu(\bar{k}, k'_1, q) \approx \widetilde{H}^\nu(\bar{k}^+, k_1'^-, q)$

  $\Rightarrow$ $\bar{k}^-$, $\bar{\mathbf{k}}_\perp$, $k_1'^+$ and $\mathbf{k}'_{1\perp}$ integrations can be done analytically:
  $\int \mathrm{d}^4\bar{k} \to \int \mathrm{d}\bar{k}^+$ and $\int \mathrm{d}^4 k'_1 \to \int \mathrm{d}k_1'^-$

  $\Rightarrow$ time ordering of field operators can be dropped
  [Diehl M. and Gousset T., Phys. Lett. B248 (1998)]

Simplified Process Amplitude

$$\mathscr{M}_{\mu'0,\mu\nu} \approx \int \mathrm{d}\bar{k}^+ \int \mathrm{d}k_1'^- \; \widetilde{H}^\nu(\bar{k}^+, k_1'^-, q)$$
$$\times \int \mathrm{d}z_1^- e^{i\bar{k}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' | \overline{\Psi}^c\left(-\frac{z_1^-}{2}\right) \Psi^u \left(\frac{z_1^-}{2}\right) | p : p, \mu \rangle$$
$$\times \int \mathrm{d}z_2^+ e^{ik_1'^- z_2^+} \langle \overline{D^0} : q' | \overline{\Psi}^u \left(z_2^+\right) \Psi^c (0) | 0 \rangle$$

Simplified Process Amplitude

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$\bar{x} = \frac{\bar{k}^+}{\bar{p}^+}$

Simplified Process Amplitude

$$\mathscr{M}_{\mu' 0, \mu\nu} \approx \int \mathrm{d}\bar{x}\, \bar{p}^+ \int \mathrm{d}k_1'^- \; \widetilde{H}^\nu \left(\bar{x}, k_1'^-, q\right)$$
$$\times \int \mathrm{d}z_1^- \; e^{i\bar{x}\bar{p}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' | \overline{\Psi}^c \left(-\frac{z_1^-}{2}\right) \Psi^u \left(\frac{z_1^-}{2}\right) | p : p, \mu \rangle$$
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Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

Generalized Parton Distributions (light-cone gauge $A^+ = 0$)

$\langle \boldsymbol{\Lambda_c^+} | \bar{\boldsymbol{\Psi}}^{\mathbf{c}} \boldsymbol{\Psi}^{\mathbf{u}} | \mathbf{p} \rangle$ written in terms of:
[Goritschnig A.T., Kroll P. and Schweiger W., Eur. Phys. J. A42 (2009)]
$\bar{p}^+ \int \frac{dz_1^-}{2\pi} e^{i\bar{x}\bar{p}^+ z_1^-} \times \ldots$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c \gamma^+ \Psi^u | p \rangle =$

  $$\overline{u}(p', \mu') \left[H^{cu}(\bar{x}, \xi, t) \gamma^+ + E^{cu}(\bar{x}, \xi, t) \frac{i\sigma^{+\nu}\Delta_\nu}{M+m} \right] u(p, \mu)$$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c \gamma^+ \gamma_5 \Psi^u | p \rangle =$

  $$\overline{u}(p', \mu') \left[\widetilde{H}^{cu}(\bar{x}, \xi, t) \gamma^+ \gamma_5 + \widetilde{E}^{cu}(\bar{x}, \xi, t) \frac{\Delta^+}{M+m} \gamma_5 \right] u(p, \mu)$$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c i\sigma^{+j} \Psi^u | p \rangle =$ $\qquad (\sigma^{\pm j} = i\gamma^\pm \gamma^j)$

  $$\overline{u}(p', \mu') \Big[H_T^{cu}(\bar{x}, \xi, t) i\sigma^{+j} + \widetilde{H}_T^{cu}(\bar{x}, \xi, t) \frac{\bar{p}^+ \Delta^j - \Delta^+ \bar{p}^j}{Mm} + E_T^{cu}(\bar{x}, \xi, t) \frac{\gamma^+ \Delta^j - \Delta^+ \gamma^j}{M+m} + \widetilde{E}_T^{cu}(\bar{x}, \xi, t) \frac{\gamma^+ \bar{p}^j - \bar{p}^+ \gamma^j}{(M+m)/2} \Big] u(p, \mu)$$

Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

Generalized Parton Distributions (light-cone gauge $A^+ = 0$)

valence Fock states of ground state hadrons are dominated by parton configurations with zero orbital angular momentum → 3 GPDs

$\bar{p}^+ \int \frac{dz_1^-}{2\pi} e^{i\bar{x}\bar{p}^+ z_1^-} \times \ldots$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c \gamma^+ \Psi^u | p \rangle =$

  $H^{cu}(\bar{x}, \xi, t)\, \overline{u}(p', \mu')\gamma^+ u(p, \mu)$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c \gamma^+ \gamma_5 \Psi^u | p \rangle =$

  $\widetilde{H}^{cu}(\bar{x}, \xi, t)\, \overline{u}(p', \mu')\gamma^+ \gamma_5 u(p, \mu)$

- $\ldots \langle \Lambda_c^+ | \bar{\Psi}^c i\sigma^{+j} \Psi^u | p \rangle =$

  $H_T^{cu}(\bar{x}, \xi, t)\, \overline{u}(p', \mu') i\sigma^{+j} u(p, \mu)$

Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

Transition Form Factors

- $u \to c$ transition GPDs have a **peak at** $\mathbf{\bar{x} = x_0 = \frac{m_c}{M}}$ $\Rightarrow$ in convolution integral they strongly weight $\bar{x}$ regions close to x_0
- *peaking approximation*: in hard scattering amplitude $\bar{x} \to x_0$
- applying p.a. the hard-scattering amplitudes can be taken out of the $\bar{x}$ integral

Transition FFs

$$\mathrm{FF}_i(\xi, t) = \int_\xi^1 \frac{\mathrm{d}\bar{x}}{\sqrt{\bar{x}^2 - \xi^2}} \mathrm{GPD}_i(\bar{x}, \xi, t)$$

Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

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Transition FFs

$$\mathrm{FF}_i(\xi, t) = \int_{\xi}^{1} \frac{\mathrm{d}\bar{x}}{\sqrt{\bar{x}^2 - \xi^2}} \mathrm{GPD}_i(\bar{x}, \xi, t) \qquad \bar{\mathbf{x}} \geq \xi$$

($\bar{x} \geq \xi$ . . . kinematical requirement to produce $c\bar{c}$-pair)

Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

Transition Form Factors

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GPD	$\xrightarrow{\int_\xi^1 \frac{\mathrm{d}\bar{x}}{\sqrt{\bar{x}^2-\xi^2}} + \text{p.a.}}$	**FF**
H^{cu}		R_V
$\widetilde{H}^{cu}$		R_A
H_T^{cu}		S_T

form factor decomposition of the integrated $p \to \Lambda_c^+$ transition matrix element

Hadronic Matrix Elements: Meson

$$\int \mathrm{d}k_1'^- \int \frac{\mathrm{d}z_2^+}{(2\pi)} e^{iz_2^+ k_1'^-} \langle \overline{D^0} : q' | \overline{\Psi}^u \left(z_2^+\right) \Psi^c (0) |0\rangle \approx \frac{1}{2\sqrt{6}}\, f_D \left(\frac{\not{q}' - M_D}{\sqrt{2}} \right) \gamma^5 \int_0^1 \mathrm{d}z\, \phi_D(z)$$

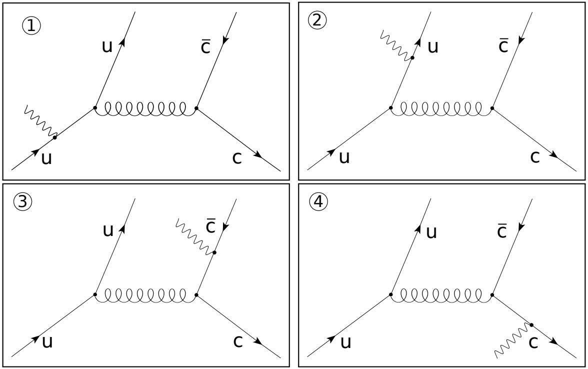
[Huang H. W. and Kroll P., Eur. Phys. C17 (2000)]

- f_D . . . decay constant
- massive pseudoscalar meson spin wave function
  [Beneke M. and Feldmann T., Nucl. Phys. B. 596 (2001)]
- ϕ_D . . . leading twist meson distribution amplitude

$$\phi_D(z) = \int \mathrm{d}^2\mathbf{k}_\perp \Psi_D(z, \mathbf{k}_\perp) \qquad \int \mathrm{d}z \phi_D(z) = 1$$

Hard Process

- hard-scattering amplitude = sum of 4 Feynman diagrams



- for fwd. scattering gluon propagators (and quark propagators) are still highly virtual (i.e. their virtuality is greater than 1 GeV^2)

Valence LCWF for Proton

- we choose
  [Bolz J. and Kroll P., Z. Phys. A 356 (1996)]

$$\Psi_P(x_1, x_2, x_3; \mathbf{k}_{\perp 1}, \mathbf{k}_{\perp 2}, \mathbf{k}_{\perp 3}) = N_p\,(1 + 3x_1)\exp\left[-{a_p}^2 \sum \frac{\mathbf{k}_{\perp i}^2}{x_i}\right]$$

N_p and a_p determined by means of fits to

- $F_1^N(Q)$
- $J/\Psi \to p\bar{p}$ decay width
- $u_v(x),\ d_v(x)$

$$\left.\begin{array}{lcl} N_p &=& 160.93\ \text{GeV}^{-2} \\ a_p &=& 0.75\ \ \text{GeV}^{-1} \end{array}\right\} \Rightarrow \begin{array}{lcl} P_p &=& 0.17 \\ \sqrt{\langle \mathbf{k}_\perp^2 \rangle} &=& 411\ \text{MeV} \end{array}$$

Valence LCWF for Λ_c^+

- use harmonic-oscillator type LCWF

$$\Psi_\Lambda(x_1, x_2, x_3; \mathbf{k}_{\perp 1}, \mathbf{k}_{\perp 2}, \mathbf{k}_{\perp 3}) = N_\Lambda \exp\left[-f(x_1)\right] \exp\left[-{a_\Lambda}^2 \sum \frac{\mathbf{k}_{\perp i}^2}{x_i}\right]$$

for the mass exponential $f(x_1)$ we use ideas of:

- *HQET* . . . $f_{KK}(x_1) = {a_\Lambda}^2 M^2 \frac{(x_1 - x_0)^2}{x_1(1-x_1)}$
  [Körner J.G. and Kroll P., Phys. Lett. B293 (1992)]
- *QCD sum rules* . . . $f_{BB}(x_1) = a_\Lambda M(1 - x_1)$
  [Ball P., Braun V. M. and Gardi E., Phys. Lett. B665 (2008)]

N_Λ and a_Λ chosen such that P_Λ and $\sqrt{\langle \mathbf{k}_\perp^2 \rangle_c}$ are

$$\left.\begin{aligned} N_\Lambda &= 2117\ \text{GeV}^{-2}(\text{BB})/3477\ \text{GeV}^{-2}(\text{KK}) \\ a_\Lambda &= 0.75\ \text{GeV}^{-1} \end{aligned}\right\} \Rightarrow \quad \begin{aligned} P_\Lambda &= 0.9 \\ \sqrt{\langle \mathbf{k}_\perp^2 \rangle_c} &\approx 450\ \text{MeV} \end{aligned}$$

FFs at $s = 20\ \mathrm{GeV}^2$ versus the CMS angle θ

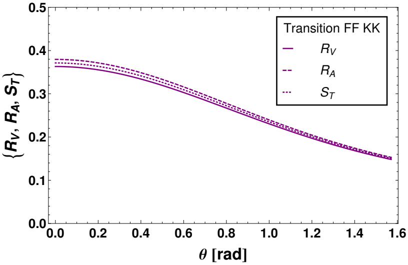
$\bar{x} \geq \xi$ DGLAP region $\Rightarrow$ allows for overlap representation
[Diehl M., Feldmann T., Jakob R. and Kroll P., Nucl.Phys. B596 (2001)]

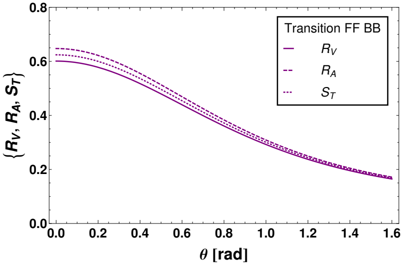
$$\text{GPDs} \xrightarrow{\int \mathrm{d}\bar{x}} \text{FF}$$

$$- R_V = S_T - \Delta R$$

$$- R_A = S_T + \Delta R$$

ΔR ... helicity of c-quark opposite to Λ_c^+ (controlled by ρ)





small overlap of the ρ term with proton LCWF $\Rightarrow R_V,\ R_A$ and S_T are almost identical

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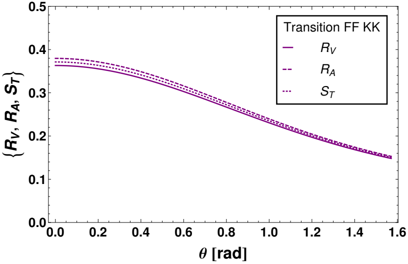
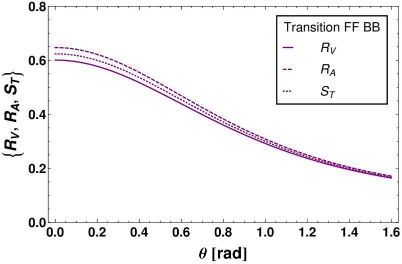




small overlap of the ρ term with proton LCWF $\Rightarrow$ R_V, R_A and S_T are almost identical

Meson DA (valence quark model)

LCWF for the $\overline{D^0}$:

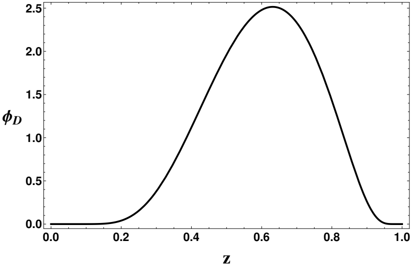
[Körner, J.G. and Kroll, P., Phys. Lett. B293 (1992)]

$$\Psi_D(z, \mathbf{k}_\perp) = N_D \exp\left[-{a_D}^2 M_D \frac{(z - z_0)^2}{z(1-z)}\right] \exp\left[-{a_D}^2 \frac{\mathbf{k}_\perp^2}{z(1-z)}\right]$$

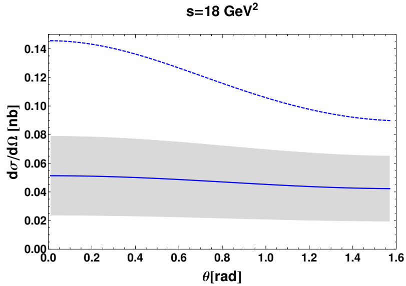
N_D and a_D chosen such that P_D and f_D are

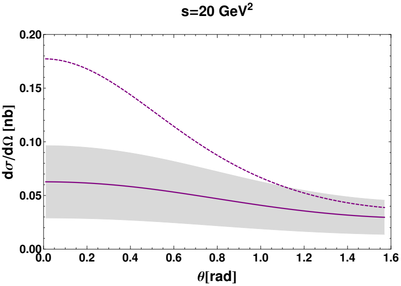
$$\left.\begin{aligned} N_D &= 55.18\mathrm{GeV}^{-2} \\ a_D &= 0.86\ \mathrm{GeV}^{-1} \end{aligned}\right\} \Rightarrow \qquad \begin{aligned} P_D &= 0.9 \\ f_D &= 206\ \ \mathrm{MeV} \end{aligned}$$

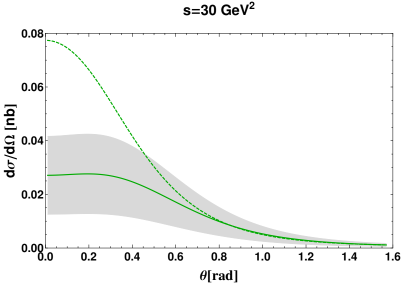
corresponding DA looks like



Estimation for Differential Cross Section

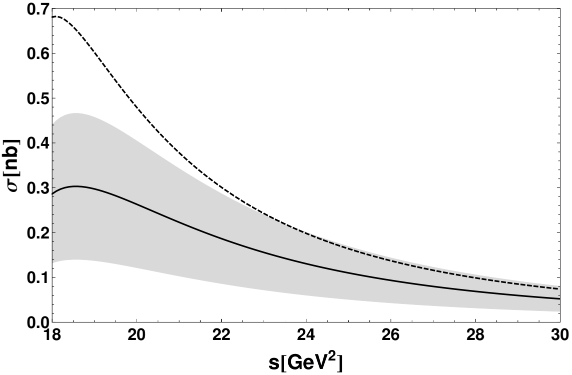






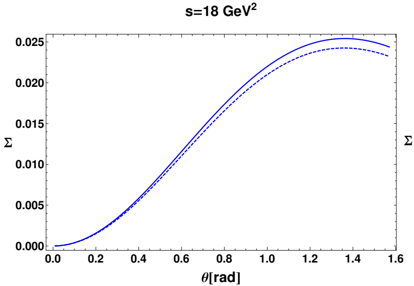
- solid: f_{KK} mass exponential
- dashed: f_{BB} mass exponential
- error assessment (grey bands)
  a_Λ: $\pm 10\%$
  P_Λ: varied in the range 0.7 to 1
  P_D: varied between 0.8 and 1
  $f_D = 206$ MeV $\pm\, 8.9$

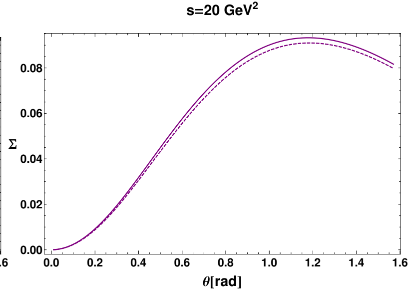
Estimation for Integrated Cross Section

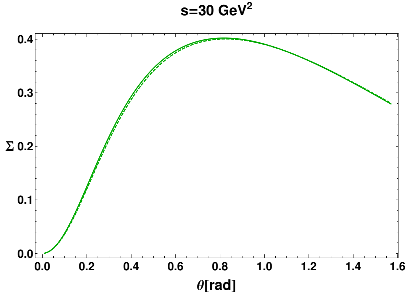


- solid: f_{KK} dashed: f_{BB}
- grey error band
- experimental finding of much larger cross sections could be an indication for a non-negligible charm-quark content of the proton

Estimation for Σ

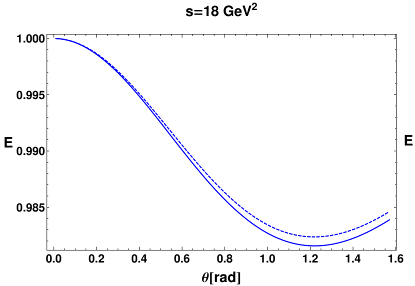


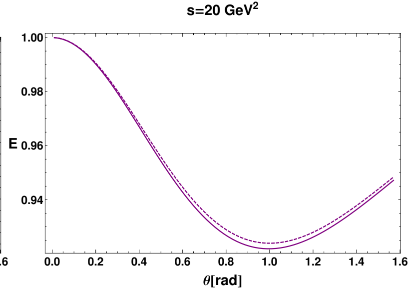


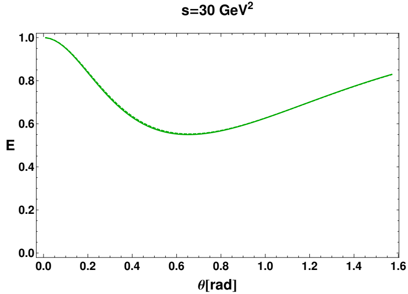


- $\Sigma \frac{d\sigma}{dt} = \frac{d\sigma_\perp}{dt} - \frac{d\sigma_\parallel}{dt}$
- solid: f_{KK} mass exponential
- dashed: f_{BB} mass exponential

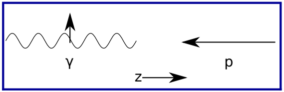
Estimation for E







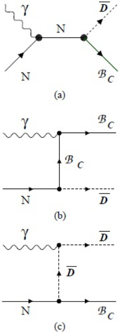
- solid: f_{KK} mass exponential
- dashed: f_{BB} mass exponential



Exclusive Charm Photoproduction in the Literature

only references found
[Rekalo, P.M. and Tomasi-Gustafsson, Phys. Lett. B 500 (2001)]
[Rekalo, P.M. and Tomasi-Gustafsson, Phys. Rev. D 69 (2004)]

- hadronic approach
- $\sigma_{\text{tot}} \approx 10 - 100$ nb at $E^{\gamma}_{\text{lab}} = 11$ GeV
  depends mainly on coupling $g_{ND\Lambda}$
  but: $g_{ND\Lambda}$ unknown
  $\to$ rely on SU(4)-symmetry
- different beam asymmetry behavior



Experimental data needed to decipher between different dynamical models!

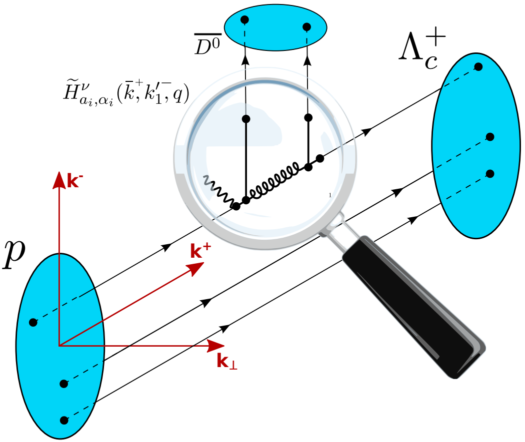
Summary

- presented a *"QCD inspired"* **model** for $\gamma\, \mathbf{p} \to \mathbf{\Lambda_c^+}\, \overline{\mathbf{D^0}}$
- under plausible physical restrictions on parton virtualities and intrinsic transverse momenta, one can factorize this process into a hard partonic subprocess and soft hadronic matrix elements
- partonic subprocess treated by means of pQCD
- hadronic matrix elements parameterized by 8 GPDs and a meson DA
  - overlap representation for the $p \to \Lambda_c^+$ transition GPDs: with s-wave LCWFs $\to$ 3 GPDs contribute
  - meson DA from a simple Gaussian model for the LCWF of the D-meson valence Fock state
- estimation for (unpolarized) differential and integrated cross sections
- estimation for non-vanishing spin observables Σ and E
- "...seems possible" @ JLAB12GeV (talk given by E. Chudakov) [http://hallaweb.jlab.org/12GeV/SuperBigBite/meetings/01/talk/chudakov-jpsi.pdf]

Thank you very much for your attention.

A Picture is worth a Thousand Words

$$\int \mathrm{d}k_1'^- \int \frac{\mathrm{d}z_2^+}{(2\pi)} e^{ik_1'^- z_2^+} \langle \overline{D^0} : q' | \overline{\Psi}^u_{a_3,\alpha_4}\left(\bar{z}_2^+\right) \Psi^c_{a_4,\alpha_4}(0) \, |0\rangle$$



$$\int \mathrm{d}\bar{x}\ \bar{p}^+ \int \frac{\mathrm{d}z_1^-}{(2\pi)} e^{i\bar{x}\bar{p}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' | \overline{\Psi}^c_{a_1,\alpha_1}\left(-\frac{\bar{z}_1^-}{2}\right) \Psi^u_{a_2,\alpha_2}\left(\frac{\bar{z}_1^-}{2}\right) |p : p, \mu\rangle$$

Hadronic Matrix Elements: $p \to \Lambda_c^+$ Transition

Outline of the Calculation

[Goritschnig A.T., Kroll P. and Schweiger W., Eur. Phys. J. A42 (2009)]

$$\bar{p}^+ \int \frac{\mathrm{d}z_1^-}{(2\pi)} e^{i\bar{x}\bar{p}^+ z^-} \langle \Lambda_c^+ : p', \mu' | \overline{\Psi}^c \left(-\frac{z_1^-}{2}\right) \Psi^u \left(\frac{z_1^-}{2}\right) | p : p, \mu \rangle$$

- algebraic manipulations of quark field operator product (projector techniques, inserting spinor products which are ~ 1 and using helicity projectors)
  $\Rightarrow$ different Dirac structures come into the game

$\bar{\Psi}^c \Psi^u$ in terms of ("leading twist" contributions)

$$\bar{\Psi}^c \gamma^+ \Psi^u, \quad \bar{\Psi}^c \gamma^+ \gamma_5 \Psi^u \quad \text{and} \quad \bar{\Psi}^c i\sigma^{+j} \Psi^u \qquad (\sigma^{\pm j} = i\gamma^\pm \gamma^j)$$

- decompose Dirac structures into Lorentz covariants:
  introduce Generalized Parton Distributions (GPDs)

Valence-Quark-Model for Proton and Λ_c^+

- valence Fock state of the proton
  [Sotiropoulos M. G. and Sterman G. F., Nucl. Phys. B425, 489 (1994)]

$$|p,+\rangle = \int [\mathrm{d}x]_3 [\mathrm{d}^2\mathbf{k}_\perp]_3$$
$$\left\{ \left(\Psi_{123}\mathscr{M}^{u}_{+-+} + \Psi_{213}\mathscr{M}^{u}_{-++}\right) - \left(\Psi_{132} + \Psi_{231}\right)\mathscr{M}^{u}_{++-} \right\}$$

- valence Fock state of the Λ_c^+
  [Goritschnig A.T., Kroll P. and Schweiger W., Eur. Phys. J. A42, 43 (2009)]

$$|\Lambda_c^+,+\rangle = \int [\mathrm{d}x]_3 [\mathrm{d}^2\mathbf{k}_\perp]_3$$
$$\left\{ \left(\mathscr{M}^{c}_{++-} - \mathscr{M}^{c}_{+-+}\right) + \rho\,(x_2 - x_3)\mathscr{M}^{c}_{-++} \right\} \Psi_\Lambda(x_i, \mathbf{k}_{\perp i})$$

- 3-quark states given by

$$\mathscr{M}^{q}_{\lambda_1\lambda_2\lambda_3} := \frac{1}{\sqrt{x_1 x_2 x_3}}\,|q : x_1, \mathbf{k}_{\perp 1}, \lambda_1\rangle\,|u : x_2, \mathbf{k}_{\perp 2}, \lambda_2\rangle\,|d : x_3, \mathbf{k}_{\perp 3}, \lambda_3\rangle$$

Final Expression for Process Amplitude

$$\mathcal{M}_{\frac{1}{2}0,\frac{1}{2}\nu} = \frac{1}{4\sqrt{6}}\, f_D \sqrt{1-\xi^2} \left[(R_V + R_A \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{\frac{1}{2},\frac{1}{1}} + (R_V - R_A) \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{-\frac{1}{2},-\frac{1}{2}} \right]$$

$$\mathcal{M}_{-\frac{1}{2}0,-\frac{1}{2}\nu} = \frac{1}{4\sqrt{6}}\, f_D \sqrt{1-\xi^2} \left[(R_V - R_A) \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{\frac{1}{2},\frac{1}{2}} + (R_V + R_A) \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{-\frac{1}{2},-\frac{1}{2}} \right]$$

$$\mathcal{M}_{\frac{1}{2}0,-\frac{1}{2}\nu} = \frac{1}{2\sqrt{6}}\, f_D \sqrt{1-\xi^2}\, S_T \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{\frac{1}{2},-\frac{1}{2}}$$

$$\mathcal{M}_{-\frac{1}{2}0,\frac{1}{2}\nu} = \frac{1}{2\sqrt{6}}\, f_D \sqrt{1-\xi^2}\, S_T \int \mathrm{d}z\ \phi_D(z) H^{\nu}_{-\frac{1}{2},\frac{1}{2}}$$

Spin Observables

- for spin observables we need *"usual" helicity amplitude* $\phi_{\mu' 0, \mu\nu}$: $\phi_{\mu' 0, \mu\nu}$ related to *LC-helicity amplitude* $\mathscr{M}_{\mu' 0, \mu\nu}$ by a unitary transformation

- non-vanishing single-polarization observable (photon asymmetry) :
$\Sigma \frac{d\sigma}{dt} = \frac{d\sigma_\perp}{dt} - \frac{d\sigma_\parallel}{dt} = \frac{1}{16\pi(s-m^2)^2} \mathrm{Re}\left(S_1^* S_2 - N D^*\right)$

- non-vanishing spin correlation:
$E \frac{d\sigma}{dt} = \frac{1}{32\pi(s-m^2)^2} \left(|N|^2 - |S_1|^2 + |S_2|^2 - |D|^2\right)$

$$N = \phi_{-\frac{1}{2}0, \frac{1}{2}1} \qquad S_1 = \phi_{-\frac{1}{2}0, -\frac{1}{2}1}$$
$$D = \phi_{\frac{1}{2}0, -\frac{1}{2}1} \qquad S_2 = \phi_{\frac{1}{2}0, \frac{1}{2}1}$$

[Barker I.S, Donnachie A. and Storrow, J.K., Nucl. Phys. B95 (1975)]

$p \to \Lambda_c^+$ transition: Quark Field Operators

write $\Psi^q = 1\Psi^q = \left(\mathscr{P}_+ + \mathscr{P}_-\right)\Psi^q$, $q = u, c$:

$$\Psi^q = \frac{1}{2}\left(\gamma^-\gamma^+ + \gamma^+\gamma^-\right)\Psi^q$$

Light-Quark Field Ψ^u

$$k_1 = \left[k_1^+, \frac{x_1^2 \boldsymbol{\Delta}_\perp^2/4}{2k_1^+}, -x_1\frac{\boldsymbol{\Delta}_\perp}{2}\right] \xrightarrow[transv.b.]{} \tilde{k}_1 = \left[k_1^+, 0, \mathbf{O}\right]$$

$(k_1^+ = x_1 p^+)$

eliminate γ^- using the energy projector

$$\sum_{\lambda_1} u\left(\tilde{k}_1, \lambda_1\right)\bar{u}\left(\tilde{k}_1, \lambda_1\right) = \tilde{k}_1^+\gamma^- + \tilde{k}_1^-\gamma^+ - \tilde{\mathbf{k}}_1\boldsymbol{\gamma}_\perp$$

$$= k_1^+\gamma^-$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Light-Quark Field Ψ^u

$$\Psi^u = \frac{1}{2k_1^+} \sum_{\lambda_1} \Big[u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \gamma^+ \Psi^u \right) + \gamma^+ u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \Psi^u \right) \Big]$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Light-Quark Field Ψ^u

$$\Psi^u = \frac{1}{2k_1^+} \sum_{\lambda_1} \Big[u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \gamma^+ \Psi^u\right) + \gamma^+ u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \Psi^u\right) \Big]$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Light-Quark Field Ψ^u

$$\Psi^u = \frac{1}{2k_1^+} \sum_{\lambda_1} \Big[u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \gamma^+ \Psi^u \right) + \gamma^+ u\left(\tilde{k}_1, \lambda_1\right) \left(\bar{u}\left(\tilde{k}_1, \lambda_1\right) \Psi^u \right) \Big]$$

go back to the CMS

$$\Psi^u(z_1/2) = \frac{1}{2k_1^+} \sum_{\lambda_1} u(k_1, \lambda_1) \left(\overline{u}(k_1, \lambda_1) \gamma^+ \Psi^u(z_1/2) \right)$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

write $\Psi^q = 1\Psi^q = \left(\mathscr{P}_+ + \mathscr{P}_-\right)\Psi^q,\ q = u, c$:

$$\Psi^q = \frac{1}{2}\left(\gamma^-\gamma^+ + \gamma^+\gamma^-\right)\Psi^q$$

Heavy-Quark Field Ψ^c

$$k_2 = \left[k_2^+, \frac{m_c^2 + x_2^2\boldsymbol{\Delta}_\perp^2/4}{2k_2^+}, x_2\frac{\boldsymbol{\Delta}_\perp}{2}\right] \xrightarrow[transv.b.]{} \hat{k}_2 = \left[k_2^+, \frac{m_c^2}{2k_2^+}, \mathbf{0}\right]$$

$(k_2^+ = x_2 p'^+)$

eliminate γ^- using the energy projector

$$\sum_{\lambda_2} u\left(\hat{k}_2, \lambda_2\right)\bar{u}\left(\hat{k}_2, \lambda_2\right) = \hat{k}_2^+\gamma^- + \hat{k}_1^-\gamma^+ - \hat{\mathbf{k}}_2\boldsymbol{\gamma}_\perp + m_c$$

$$= k_2^+\gamma^- + \frac{m_c^2}{2k_2}\gamma^+ + m_c$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Heavy-Quark Field Ψ^c

$$\Psi^c = \frac{1}{2k_2^+}\sum_{\lambda_2}\Big\{u\left(\hat{k}_2,\lambda_2\right)\left(\bar{u}\left(\hat{k}_2,\lambda_2\right)\gamma^+\Psi^c\right) + \gamma^+\Big[u\left(\hat{k}_2,\lambda_2\right)\left(\bar{u}\left(\hat{k}_2,\lambda_2\right)\Psi^c\right) - 2m_c\Psi^c\Big]\Big\}$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Heavy-Quark Field Ψ^c

$$\Psi^c = \frac{1}{2k_2^+} \sum_{\lambda_2} \left\{ u\left(\hat{k}_2, \lambda_2\right) \left(\bar{u}\left(\hat{k}_2, \lambda_2\right) \gamma^+ \Psi^c \right) + \gamma^+ \left[u\left(\hat{k}_2, \lambda_2\right) \left(\bar{u}\left(\hat{k}_2, \lambda_2\right) \Psi^c \right) - 2m_c \Psi^c \right] \right\}$$

$p \to \Lambda_c^+$ transition: Quark Field Operators

Heavy-Quark Field Ψ^c

$$\Psi^c = \frac{1}{2k_2^+}\sum_{\lambda_2}\left\{u\left(\hat{k}_2,\lambda_2\right)\left(\bar{u}\left(\hat{k}_2,\lambda_2\right)\gamma^+\Psi^c\right)\right.$$
$$\left. + \gamma^+\left[u\left(\hat{k}_2,\lambda_2\right)\left(\bar{u}\left(\hat{k}_2,\lambda_2\right)\Psi^c\right) - 2m_c\Psi^c\right]\right\}$$

go back to the CMS

$$\Psi^c(-z_1/2) = \frac{1}{2k_2^+}\sum_{\lambda_2} u(k_2,\lambda_2)\left(\overline{u}(k_2,\lambda_2)\gamma^+\Psi^c(-z_1/2)\right)$$

$p \to \Lambda_c^+$ transition: Quark Field Product

we have to deal with $\overline{\Psi}^c_{\alpha_1}(-z_1/2)\,\Psi^u_{\alpha_2}(+z_1/2) =$

$$= \frac{1}{4k_1^+ k_2^+} \sum_{\lambda_1} \Big[$$

$$\left(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,\lambda_1)\right)\ \left(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\right)\overline{u}_{\alpha_1}(k_2,\lambda_1)u_{\alpha_2}(k_1,\lambda_1)$$

$$+\left(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,-\lambda_1)\right)\ \left(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\right)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1)\Big]$$

$(\lambda_2 = \pm\lambda_1)$

$p \to \Lambda_c^+$ transition: Quark Field Product

we have to deal with $\overline{\Psi}^c_{\alpha_1}(-z_1/2)\,\Psi^u_{\alpha_2}(+z_1/2) =$

$$= \frac{1}{4k_1^+ k_2^+}\sum_{\lambda_1}\Big[$$

$$\left(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,\lambda_1)\right)\ \left(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\right)\overline{u}_{\alpha_1}(k_2,\lambda_1)u_{\alpha_2}(k_1,\lambda_1)$$

$$+\left(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,-\lambda_1)\right)\ \left(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\right)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1)\Big]$$

$p \to \Lambda_c^+$ transition: Quark Field Product

we have to deal with $\overline{\Psi}^c_{\alpha_1}(-z_1/2)\,\Psi^u_{\alpha_2}(+z_1/2) =$

$$= \frac{1}{4k_1^+k_2^+}\sum_{\lambda_1}\Big[$$
$$\Big(\overline{\Psi}^c(-z_1/2)\gamma^+u(k_2,\lambda_1)\Big)\,1\,\Big(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\Big)\overline{u}_{\alpha_1}(k_2,\lambda_1)u_{\alpha_2}(k_1,\lambda_1)$$
$$+\Big(\overline{\Psi}^c(-z_1/2)\gamma^+u(k_2,-\lambda_1)\Big)\,1\,\Big(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\Big)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1)\Big]$$

$$\frac{\overline{u}(k_2,\lambda_1)\gamma^+u(k_1,\lambda_1)}{2\sqrt{k_1^+k_2^+}} = 1 \qquad \frac{1}{i(2\lambda_1 i)^j}\,\frac{\overline{u}(k_2,-\lambda_1)i\sigma^{+j}u(k_1,\lambda_1)}{2\sqrt{k_1^+k_2^+}} = 1$$

$(\sigma^{\pm j} = i\gamma^{\pm}\gamma^j)$

$p \to \Lambda_c^+$ transition: Quark Field Product

we have to deal with $\overline{\Psi}^c_{\alpha_1}(-z_1/2)\,\Psi^u_{\alpha_2}(+z_1/2) =$

$$= \frac{1}{4k_1^+k_2^+}\sum_{\lambda_1}\Big[$$

$$\Big(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,\lambda_1)\Big)\,1\,\Big(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\Big)\overline{u}_{\alpha_1}(k_2,\lambda_1)u_{\alpha_2}(k_1,\lambda_1)$$

$$+\Big(\overline{\Psi}^c(-z_1/2)\gamma^+ u(k_2,-\lambda_1)\Big)\,1\,\Big(\overline{u}(k_1,\lambda_1)\gamma^+\Psi^u(z_1/2)\Big)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1)\Big]$$

$$\frac{\overline{u}(k_2,\lambda_1)\gamma^+ u(k_1,\lambda_1)}{2\sqrt{k_1^+k_2^+}} = 1 \qquad \frac{1}{i(2\lambda_1 i)^j}\,\frac{\overline{u}(k_2,-\lambda_1)i\sigma^{+j}u(k_1,\lambda_1)}{2\sqrt{k_1^+k_2^+}} = 1$$

$$u(k_1,\lambda_1)\overline{u}(k_1,\lambda_1) = k_1\cdot\gamma\,\frac{1-2\lambda_1\gamma_5}{2} \qquad u(k_2,\lambda_1)\overline{u}(k_2,\lambda_1) = \Big(k_2\cdot\gamma + m_c\Big)\frac{1+\gamma_5 S_1\cdot\gamma}{2}$$

$p \to \Lambda_c^+$ transition: Quark Field Product

$$\overline{\Psi}^c_{\alpha_1}(-z_1/2)\Psi^u_{\alpha_2}(z_1/2) = \frac{1}{2\sqrt{k_1^+ k_2^+}} \sum_{\lambda_1} \Big\{ \overline{\Psi}^c(-z_1/2)\gamma^+ \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,\lambda_1) u_{\alpha_2}(k_1,\lambda_1) - i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,-\lambda_1) u_{\alpha_2}(k_1,\lambda_1) \Big\} .$$

define vector, axial-vector and tensor currents

$$V^\mu(-z/2,z/2) := \overline{\Psi}^c(-z/2)\ \gamma^\mu\ \Psi^u(z/2) - \overline{\Psi}^u(z/2)\ \gamma^\mu\ \Psi^c(-z/2)$$

$$A^\mu(-z/2,z/2) := \overline{\Psi}^c(-z/2)\gamma^\mu\gamma_5\Psi^u(z/2) - \overline{\Psi}^u(z/2)\gamma^\mu\gamma_5\Psi^c(-z/2)$$

$$T^{\mu\nu}(-z/2,z/2) := \overline{\Psi}^c(-z/2) i\sigma^{\mu\nu}\Psi^u(z/2) - \overline{\Psi}^u(z/2) i\sigma^{\mu\nu}\Psi^c(-z/2)$$

$$T_5^{\mu\nu}(-z/2,z/2) := \overline{\Psi}^c(-z/2) i\sigma^{\mu\nu}\gamma_5\Psi^u(z/2) - \overline{\Psi}^u(z/2) i\sigma^{\mu\nu}\gamma_5\Psi^c(-z/2)$$

added antiparticle contribution to have manifest charge symmetry

$p \to \Lambda_c^+$ transition: Quark Field Product

$$\overline{\Psi}^c_{\alpha_1}(-z_1/2)\Psi^u_{\alpha_2}(z_1/2) =$$
$$\frac{1}{2\sqrt{k_1^+ k_2^+}} \sum_{\lambda_1} \Big\{ \overline{\Psi}^c(-z_1/2)\gamma^+ \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2)\overline{u}_{\alpha_1}(k_2,\lambda_1)u_{\alpha_2}(k_1,\lambda_1)$$
$$- \; i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1) \Big\} .$$

define vector, axial-vector and tensor currents

$$\begin{aligned}
V^+(-z/2,z/2) &:= \overline{\Psi}^c(-z/2)\;\gamma^+\;\Psi^u(z/2) && -\overline{\Psi}^u(z/2)\;\gamma^+ u\;\Psi^c(-z/2)\\
A^+(-z/2,z/2) &:= \overline{\Psi}^c(-z/2)\gamma^+\gamma_5\Psi^u(z/2) && -\overline{\Psi}^u(z/2)\gamma^+\gamma_5\Psi^c(-z/2)\\
T^{+j}(-z/2,z/2) &:= \overline{\Psi}^c(-z/2)i\sigma^{+j}\Psi^u(z/2) && -\overline{\Psi}^u(z/2)i\sigma^{+j}\Psi^c(-z/2)\\
T_5^{+j}(-z/2,z/2) &:= \overline{\Psi}^c(-z/2)i\sigma^{+j}\gamma_5\Psi^u(z/2) && -\overline{\Psi}^u(z/2)i\sigma^{+j}\gamma_5\Psi^c(-z/2)
\end{aligned}$$

$p \to \Lambda_c^+$ transition: Quark Field Product

$$\overline{\Psi}^c_{\alpha_1}(-z_1/2)\Psi^u_{\alpha_2}(z_1/2) =$$
$$\frac{1}{2\sqrt{k_1^+ k_2^+}} \sum_{\lambda_1} \Big\{ \overline{\Psi}^c(-z_1/2)\gamma^+ \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,\lambda_1) u_{\alpha_2}(k_1,\lambda_1)$$
$$- i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,-\lambda_1) u_{\alpha_2}(k_1,\lambda_1) \Big\}.$$

define vector, axial-vector and tensor currents

$$V^+(-z/2,z/2) := \overline{\Psi}^c(-z/2)\ \gamma^+\ \Psi^u(z/2) \quad - \overline{\Psi}^u(z/2)\ \gamma^+ u\ \Psi^c(-z/2)$$
$$A^+(-z/2,z/2) := \overline{\Psi}^c(-z/2)\gamma^+\gamma_5\Psi^u(z/2) \quad - \overline{\Psi}^u(z/2)\gamma^+\gamma_5\Psi^c(-z/2)$$
$$T^{+j}(-z/2,z/2) := \overline{\Psi}^c(-z/2) i\sigma^{+j}\Psi^u(z/2) \quad - \overline{\Psi}^u(z/2) i\sigma^{+j}\Psi^c(-z/2)$$
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$p \to \Lambda_c^+$ transition: Quark Field Product

$$\overline{\Psi}^c_{\alpha_1}(-z_1/2)\Psi^u_{\alpha_2}(z_1/2) =$$
$$\frac{1}{2\sqrt{k_1^+ k_2^+}} \sum_{\lambda_1} \Big\{ \overline{\Psi}^c(-z_1/2)\gamma^+ \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,\lambda_1) u_{\alpha_2}(k_1,\lambda_1)$$
$$- i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2) \overline{u}_{\alpha_1}(k_2,-\lambda_1) u_{\alpha_2}(k_1,\lambda_1) \Big\} .$$

define vector, axial-vector and tensor currents

$$V^+(-z/2,z/2) := \overline{\Psi}^c(-z/2)\ \gamma^+\ \Psi^u(z/2) \quad - \overline{\Psi}^u(z/2)\ \gamma^+ u\ \Psi^c(-z/2)$$
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\end{aligned}$$

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$$- i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1) \Bigg\} .$$

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$$- \; i(-2\lambda_1 i)^j \overline{\Psi}^c(-z_1/2) i\sigma^{+j} \frac{1+2\lambda_1\gamma_5}{2} \Psi^u(z_1/2)\overline{u}_{\alpha_1}(k_2,-\lambda_1)u_{\alpha_2}(k_1,\lambda_1) \Big\}\,.$$

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T_5^{+j} reproduces T^{+j} : $\quad T_5^j = (-1)^j T^{+k},\ k \neq j$ and $k, j = 1, 2$

$p \to \Lambda_c^+$ transition: Hadronic Matrix Element

finally we obtain with the following notation

$$\mathscr{H}^{cu}_{\mu'\mu} := \bar{p}^+ \int \frac{dz_1^-}{2\pi} e^{i\bar{x}\bar{p}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' |\, V^+(-z_1^-/2, z_1^-/2)\, | p : p, \mu \rangle$$

$$\widetilde{\mathscr{H}}^{cu}_{\mu'\mu} := \bar{p}^+ \int \frac{dz_1^-}{2\pi} e^{i\bar{x}\bar{p}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' |\, A^+(-z_1^-/2, z_1^-/2)\, | p : p, \mu \rangle$$

$$\mathscr{H}^{Tcu}_{j\mu'\mu} := \bar{p}^+ \int \frac{dz_1^-}{2\pi} e^{i\bar{x}\bar{p}^+ z_1^-} \langle \Lambda_c^+ : p', \mu' |\, T^{+j}(-z_1^-/2, z_1^-/2)\, | p : p, \mu \rangle$$

our final result for the $p \to \Lambda_c^+$ transition matrix element

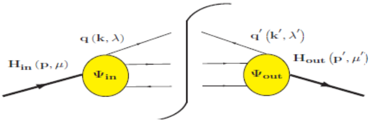
$$\bar{p}^+ \int \frac{\mathrm{d}z_1^-}{(2\pi)} e^{i\bar{x}\bar{p}^+ z^-} \langle \Lambda_c^+ : p', \mu' | \overline{\Psi}^c_{\alpha_1}\left(-\frac{z_1^-}{2}\right) \Psi^u_{\alpha_2}\left(\frac{z_1^-}{2}\right) | p : p, \mu \rangle =$$
$$\frac{1}{4\sqrt{k_1^+ k_2^+}} \sum_{\lambda_1} \Big\{ \Big[\mathscr{H}^{cu}_{\mu'\mu} + 2\lambda_1 \widetilde{\mathscr{H}}^{cu}_{\mu'\mu} \Big] \overline{u}_{\alpha_1}(k_2, \lambda_1) u_{\alpha_2}(k_1, \lambda_1)$$
$$-2\lambda_1 \Big[\mathscr{H}^{Tcu}_{1\mu'\mu} - 2\lambda_1 i \mathscr{H}^{Tcu}_{2\mu'\mu} \Big] \overline{u}_{\alpha_1}(k_2, -\lambda_1) u_{\alpha_2}(k_1, \lambda_1) \Big\} .$$

Modelling GPDs: Overlap Representation of GPDs

$\bar{x} \geq \xi$ DGLAP region $\Rightarrow$ allows for overlap representation

[Diehl M.,Feldmann T. Jakob. R. and Kroll P., Nucl.Phys. B596 (2001)]

$$\mathcal{H}^{cu}_{\mu'\mu} \sim \sum_{N,\beta} \int [d\bar{x}]_N \left[d^2\bar{\mathbf{k}}_\perp\right]_N \psi^{\mu'\,*}_{N,\beta',\mathrm{out}}\left(\{x', \mathbf{k}'_\perp\}\right) \psi^{\mu}_{N,\beta,\mathrm{in}}\left(\{x, \mathbf{k}_\perp\}\right)$$



$$|H : p, \mu\rangle = \sum_{N,\beta} \int [dx]_N \left[d^2\hat{\mathbf{k}}_\perp\right]_N \psi^{\mu}_{N,\beta}\left(x_i, \hat{\mathbf{k}}_{i\perp}\right) |N, \beta : x_1, .., x_N; \hat{\mathbf{k}}_1, .., \hat{\mathbf{k}}_N\rangle$$

Hard-Scattering Amplitude

transform $H^{hel,\nu}_{\lambda_2,\lambda_1}$ to the LC with the help of a unitary transformation

$$H^{\nu}_{\lambda_2,\lambda_1}(\bar{x}, zq', q) = \overline{u}(k_2, \lambda_2)\widetilde{H}^{\nu}_{D}(\bar{k}, k_1', q)u(k_1, \lambda_1)$$

$$\begin{pmatrix} u_H(\lambda = +1/2) \\ u_H(\lambda = -1/2) \end{pmatrix} = U \cdot \begin{pmatrix} u_{LC}(\lambda = +1/2) \\ u_{LC}(\lambda = -1/2) \end{pmatrix}$$

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$$\begin{aligned}
H^{1}_{\frac{1}{2},\frac{1}{2}} &= \frac{1}{\sqrt{1+\beta'^2}}\left[H^{hel,1}_{\frac{1}{2},\frac{1}{2}} - \beta' H^{hel,1}_{-\frac{1}{2},\frac{1}{2}}\right] \\
H^{1}_{\frac{1}{2},-\frac{1}{2}} &= \frac{1}{\sqrt{1+\beta'^2}}\left[H^{hel,1}_{\frac{1}{2},-\frac{1}{2}} - \beta' H^{hel,1}_{-\frac{1}{2},-\frac{1}{2}}\right] \\
H^{1}_{-\frac{1}{2},\frac{1}{2}} &= \frac{1}{\sqrt{1+\beta'^2}}\left[H^{hel,1}_{-\frac{1}{2},\frac{1}{2}} + \beta' H^{hel,1}_{\frac{1}{2},\frac{1}{2}}\right] \\
H^{1}_{-\frac{1}{2},-\frac{1}{2}} &= \frac{1}{\sqrt{1+\beta'^2}}\left[H^{hel,1}_{-\frac{1}{2},-\frac{1}{2}} + \beta' H^{hel,1}_{\frac{1}{2},-\frac{1}{2}}\right]
\end{aligned}$$

$\beta' := \frac{M}{p'^0 + |\mathbf{p}'|} \tan\frac{\theta_1}{2}$