\[ \pi^- p \rightarrow D^- \Lambda_c^+ \text{ within the Generalized Parton Picture} \]

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The Outline

1. Introduction

2. Reaction Mechanism

3. Results

4. Summary and Outlook

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\]
Introduction

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- hard scale $Q$ to resolve the hadron substructure
- specific final state $c + d + \ldots$

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$\pi^{-} p \rightarrow D^{-} \Lambda_c^{+}$ within the Generalized Parton Picture
Why should we study $\pi^- p \rightarrow D^- \Lambda_c^+$?

- charmed baryon spectroscopy at J-PARC
  - estimate cross section and spin observables
  - no theoretical study has been performed so far
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- further application/test of $p \rightarrow \Lambda_c^+$- transition generalized parton distributions (GPDs) introduced in
  - originally: $\bar{p} p \rightarrow \bar{\Lambda}_c^- \Lambda_c^+$
  - also: $\gamma p \rightarrow \bar{D}^0 \Lambda_c^+$
Why should we study $\pi^- p \rightarrow D^- \Lambda_c^+$?

• In general, production of charmed hadrons is interesting:
  Different models on the market which give different results.

  ⇒ What is the dominant production mechanism?
Double Handbag Mechanism

We use a *handbag* mechanism:

- expected to dominate in the intermediate energy region,
- minimal number of partons take part in the hard scattering,
- used to describe DIS, DVCS, wide-angle CS, TCS, $\bar{p}p$ annihilation into (heavy) baryons/mesons.
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$\pi^- p \rightarrow D^- \Lambda^+_c$ within the Generalized Parton Picture
Process Amplitude

\[ \mathcal{M} = FT \langle \Lambda_c^+ | \bar{\Psi}^c \Psi^u | p \rangle \times FT \langle D^- | \bar{\Psi}^u \Psi^c | \pi^- \rangle \times H \]
Process Amplitude

\[ M = FT \langle \Lambda_c^+ | \bar{\Psi}^c \Psi^u | p \rangle \times FT \langle D^- | \bar{\Psi}^u \Psi^c | \pi^- \rangle \times H \]

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factorization in the sense that

- hard part contains highly virtual partons: \( k_g^2 \geq 4m_c^2 \)
  \( H \) on tree level \( \rightarrow \) 1 Feynman diagram

- hadron matrix elements embody soft scales
  - restricted parton virtualities: \( |k|^2 \) and \( |k^2 - mc^2| \leq \Lambda^2 \)
  - restricted intrinsic parton transverse momenta: \( k_{\perp}/x \leq \Lambda^2 \)
  (\( \Lambda^2 \) of the order of 1 GeV^2)

\( \Rightarrow \) hadrons emit and re-absorb collinear, nearly on-shell partons
**Process Amplitude**

\[ \mathcal{M} = FT \left\langle \Lambda_c^+ \mid \bar{\Psi}^c \Psi^u \mid p \right\rangle \times FT \left\langle D^- \mid \bar{\Psi}^u \Psi^c \mid \pi^- \right\rangle \times H \]

- factorization in the sense that
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    - \( H \) on tree level \( \rightarrow 1 \) Feynman diagram
  - hadronic matrix elements embody *soft scales*
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Generalized Parton Distributions I

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\pi^- p \rightarrow D^- \Lambda_c^+ \text{ within the Generalized Parton Picture}
\]

\[
\text{FT } \langle \Lambda_c^+ : p', \mu' | \bar{\Psi}^c \Psi^u | p : p, \mu \rangle
\]
Generalized Parton Distributions I

- (quark) GPDs: FT of a product of bilocal quark field operators sandwiched between non-diagonal hadronic matrix elements

\[\langle \Lambda_+^+ : p', \mu' | \bar{\psi}^c \gamma^+ \psi^u | p : p, \mu \rangle\]

- \[\bar{\psi}^c \gamma^+ \psi^u : 2 \text{ GPDs}\]
- \[\bar{\psi}^c \gamma^+ \gamma_5 \gamma^+ \psi^u : 2 \text{ GPDs}\]
- \[\bar{\psi}^c i\sigma^{+j} \gamma^+ \psi^u : 4 \text{ GPDs}\]
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- parton interpretation in light-cone (LC) quantization (LC-gauge)

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Generalized Parton Distributions I

- (quark) GPDs: FT of a product of bilocal quark field operators sandwiched between non-diagonal hadronic matrix elements
- parton interpretation in light-cone (LC) quantization (LC-gauge)
- spin structure of the hadrons can be taken into account easily with GPDs

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Generalized Parton Distributions II

- $\bar{\Psi}^u \gamma^+ \Psi^c$ : 1 GPD
- $\bar{\Psi}^u i\sigma^+ j \Psi^c$ : 1 GPD

- Pseudoscalar meson to pseudoscalar meson transition simple: 2 GPDs

$\pi^- p \rightarrow D^- \Lambda^+_c$ within the Generalized Parton Picture
Overlap Representation of GPDs in terms of LCWFs


\[ \left| H \right\rangle = \sum_{N,\beta} \Psi_{N,\beta} \left| N, \beta \right\rangle \]
Overlap Representation of GPDs in terms of LCWFs


\[ |H\rangle = \sum_{N,\beta} \Psi_{N,\beta} |N, \beta\rangle \]

- properties of heavy hadrons are dominated by heavy valence quark: restriction on valence Fock states a good approximation
- LCWFs are the model input
- simple parton interpretation

\[ \pi^- p \rightarrow D^- \Lambda_c^+ \text{ within the Generalized Parton Picture} \]
Light Cone Wave Functions

\[ \pi^- \rightarrow D^- \Lambda_c^+ \] within the Generalized Parton Picture
Light Cone Wave Functions

\[
N_\pi \exp \left[ -a^2 \frac{k_{1\perp}^2}{x_a(1-x_a)} \right] \\
N_D \exp \left[ -f(x_a) \right] \exp \left[ -a^2_D \frac{k_{1\perp}^2}{x_a(1-x_a)} \right]
\]

\[
\Psi_\pi \rightarrow d \Psi_D \\
p \sim |u u d\rangle \\
\Lambda_c^+ \sim |c u d\rangle
\]


\[
N_p \left( 1 + 3x_a \right) \exp \left[ -a_p^2 \sum \frac{k_{1\perp i}^2}{x_i} \right] \\
N_\Lambda \exp \left[ -f(x_a) \right] \exp \left[ -a_\Lambda^2 \sum \frac{k_{1\perp i}^2}{x_i} \right]
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Light Cone Wave Functions

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\[ \begin{aligned} & N_p \left( 1 + 3x_a \right) \exp \left[ - a_p^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \quad \text{Feldmann T. and Kroll P., Euro. Phys. J. C12 (2000)} \\
& N_\Lambda \exp \left[ - f(x_a) \right] \exp \left[ - a_\Lambda^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \quad \text{Bolz J. and Kroll P., Z. Phys. A 356 (1996)} \end{aligned} \]

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- soft LCWF

- Gaussian exponential for intrinsic transverse mom.

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- \( L = 0 \) -> reduces # of GPDs

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\[ N_p \left(1 + 3x_a\right) \exp \left[ -a_p^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \]

- QCD sum rules for \( \Lambda_b \) \( (BB \ mass \ exp.) \)

- harmonic oscillator on the LC \( (KK \ mass \ exp.) \)

\[ N_\Lambda \exp \left[ -f(x_a) \right] \exp \left[ -a_\Lambda^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \]


Light Cone Wave Functions

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\[ \psi_\pi \rightarrow |u \ d\rangle \]
\[ u \rightarrow g \rightarrow c \]
\[ p \sim |u \ u \rangle \]
\[ \psi_D \rightarrow |\bar{c} \ d\rangle \]
\[ \Lambda_c^+ \sim |c \ u \ d\rangle \]

\[ N_p \left( 1 + 3 x_a \right) \exp \left[ -a_p^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \]

\[ N_{\Lambda} \exp \left[ -f(x_a) \right] \exp \left[ -a_{\Lambda}^2 \sum \frac{k_{\perp i}^2}{x_i} \right] \]

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**Light Cone Wave Functions**

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Every LCWF depend on 2 parameters:
- normalization constant \( N \)
- oscillator parameter \( a \)

- proton and pion LCWF: good constraints at hand
- Lambda and D LCWF: parameters fixed by physical conditions, e.g. valence Fock state prob., decay constant,...

\[ \pi^- p \rightarrow D^- \Lambda_c^+ \text{ within the Generalized Parton Picture} \]
We have all pieces of our process amplitudes determined:

- hard partonic subprocess. . . Feynman diagram
- non-perturbative effects. . . contained in GPDs, which are modeled by an overlap of LCWFs

Let‘s have a look at our results.
Estimate of Differential Cross Section

• diff. cross section (nb) vs. $\cos \theta$ for different values of Mandelstam $s$

• in the order of 1 nb
  - BB mass exp. produces a larger cross section

• shaded band: varied parameters of $\Lambda/D$ LCWF

$\pi^- p \rightarrow D^- \Lambda_c^+$ within the Generalized Parton Picture
Estimate of Integrated Cross Section

- integrated cross section (nb) vs. Mandelstam $s$
Estimate of Integrated Cross Section

- integrated cross section (nb) vs. Mandelstam $s$
- in the order of 1 nb
  ($D^*$ in the final state)

$\pi^- p \rightarrow D^- \Lambda_c^+$ within the Generalized Parton Picture
Estimate of Integrated Cross Section

- integrated cross section (nb) vs. Mandelstam $s$
- in the order of 1 nb
- AGS-experiment: upper bound of 15 nb for integrated cross section
Spin Correlations

- 2 depolarisation observables for different Mandelstam $s$ values vs. $\cos(\theta)$
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- Polarisation transfer from the proton to the $\Lambda_c^+$:
  - $L$ ... longitudinal
  - $S$ ... sideways
Spin Correlations

- 2 depolarisation observables for different Mandelstam $s$ values vs. $\cos(\theta)$
- Polarisation transfer from the proton to the $\Lambda_c^+$:
  - $L$ … longitudinal
  - $S$ … sideways
- Mild energy dependence
- Approximately independent of GPDs
  ⇒ characteristic for handbag mechanism

$\pi^- p \rightarrow D^- \Lambda_c^+$ within the Generalized Parton Picture
Exclusive Production of Charmed Hadrons

Within the **collinear fac. approach**, other reactions producing charmed hadrons have been investigated:

- integrated cross section in the order of 1 nb
  
  \[ \bar{p} \ p \rightarrow \bar{\Lambda}_c^- \ \Lambda_c^+ \]
  

  \[ \bar{p} \ p \rightarrow D^0 \bar{D}^0 \]
  


- integrated cross section in the order of < 1 nb
  
  \[ \gamma \ p \rightarrow \bar{D}^0 \ \Lambda_c^+ \]
  

\[ \pi^- \ p \rightarrow D^- \ \Lambda_c^+ \] within the Generalized Parton Picture
Exclusive Production of Charmed Hadrons

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  \[ \bar{p} p \rightarrow \bar{\Lambda}_c^- \Lambda_c^+ \]
  

- integrated cross section in the order of \(< 1 \text{ nb}\)
  
  \[ \bar{p} p \rightarrow D^0\bar{D}^0 \]
  

Other approaches would be

- Regge models,

- hadronic exchange models.
Exclusive Production of $\Lambda_c$ pairs

Different theoretical descriptions of $\bar{p}p \rightarrow \bar{\Lambda}_c^– \Lambda_c^+$ are controversial!
Exclusive Production of $\Lambda_c$ pairs

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- handbag mechanism
- charm produced perturbatively
- transition GPDs unknown -> modeling

$pQCD$


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- hadronic models
  - charm produced non-perturbatively via $H$ exchange (Reggeon or non Reggeon)
  - strong coupling at vertex unknown:
    - SU(4)$_f$ symmetry
    - QCD sum rules

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-手提袋机制
-标量二夸克模型

pQCD


hadronic models


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Exclusive Production of D meson pairs

Different theoretical descriptions of $\bar{p}p \rightarrow D^0 D^0$ are also controversial!

- pQCD

- hadronic models

- handbag mechanism
- scalar diquark model

Also a difference of 2-3 orders of magnitude!

$\pi^- p \rightarrow D^- \Lambda_c^+$ within the Generalized Parton Picture
Can we understand these differences?

Our model:

- $SU(4)_f$ symmetry breaking on the level of the wave function
  e.g. $p \rightarrow \Lambda_c$ overlaps considerably diminished compared to $p \rightarrow \Lambda$
  $\Rightarrow \sigma$ differs in 3 orders of magnitude $\rightarrow O(nb)$

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Unreggeized model:

\[
\sum_{M=D,D^*} g^2_{N,\Lambda_c,M} \frac{F^2_{N,\Lambda_c,M}}{t-m^2_M} \ 	ext{SU}(4)_f \text{ symmetry}
\]

vertex form factor

cutoff mass: $m_M + 1 \text{ GeV}$

$\sigma(\bar{p}p \to \bar{\Lambda}\Lambda) \approx \frac{m^2_{M_s}}{m^2_{M_c}} \approx \frac{1}{4}$

$\frac{\sigma(\bar{p}p \to \bar{\Lambda}_c\Lambda_c)}{\sigma(\bar{p}p \to \bar{\Lambda}\Lambda)} \approx 16$

$\pi^- p \to D^- \Lambda_c^+$ within the Generalized Parton Picture
Can we understand these differences?

Reggeized model:


\[
\sim \left( \frac{s}{s_0} \right)^{\alpha_{D^*}(t)-1}
\]

- $SU(4)_f$ breaking in the scale parameter (and Regge residues)
- different Regge parameters lead to different results in charm/strange suppression

for $\bar{p}p \rightarrow \bar{\Lambda}_c \Lambda$: difference of 2 order of magnitude as compared to pQCD
for $\pi^- p \rightarrow D^- \Lambda_c^+$: same order of magnitude as compared to pQCD
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Summary:

- Different models lead to different predictions.
- Differences in predictions up to 3 orders of magnitude.

Only the experiment can decide.
Interesting and excited times are ahead of us.
Summary and Outlook

- presented you a benchmark calculation for 
  \[ \pi^- p \rightarrow D^- \Lambda_c^+ \]

Outlook:
- \( D^*^- \Lambda_c^+ \) meson in the final state
- NLO calculation of hard part
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  - integrated cross section of the order of 1 nb
  - spin observables characteristic for handbag mechanism

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