Open charm production in exclusive reactions at PANDA-FAIR and J-PARC energy region

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The aim of our discussion is qualitative/quantitative estimation of open charm production in $\bar{p}p$ reactions with one flavor exchange

\[
\bar{p}p \rightarrow \bar{\Lambda}\Lambda(\Sigma) \quad \text{and} \quad \bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c(\Sigma_c)...
\]

\[
\bar{p}p \rightarrow \bar{K}K \quad \text{and} \quad \bar{p}p \rightarrow D\bar{D}...
\]

\[
\bar{p}p \rightarrow \bar{K}K^* \quad \text{and} \quad \bar{p}p \rightarrow D\bar{D}^*...
\]

and reactions with two flavor exchange

\[
\bar{p}p \rightarrow \bar{\Xi}\Xi \quad \text{and} \quad \bar{p}p \rightarrow \bar{\Xi}_c\Xi_c
\]

open charm production in $\pi p$ reactions

\[
\pi^- p \rightarrow D^{*-}\Lambda_c
\]

(J-PARC)

also in $pp$ reactions, like

\[
pp \rightarrow \Lambda_c\bar{D}^0 p \quad \text{and} \quad pp \rightarrow \Lambda_c\bar{D}^0 X
\]

mainly in forward production (large $x$)
Charmed and strange hadrons

\[ c\bar{u} \ (D^0) \ (1864) \text{ or } (D^{*0}) \ (2007) \]
\[ c\bar{d} \ (D^+) \ (1869) \text{ or } (D^{*+}) \ (2010) \]
\[ c\bar{c} \ (J/\psi) \ (3096) \]
\[ \bar{c}u \ (\bar{D}^0) \ (1864) \text{ or } (\bar{D}^{*0}) \]
\[ \bar{c}d \ (D^-) \ (1869) \text{ or } (D^{*-}) \]
\[ \rightarrow s\bar{u} \ (K^-) \ (494) \text{ or } (K^{*-}) \]
\[ \rightarrow s\bar{d} \ (\bar{K}^0) \ (498) \text{ or } (\bar{K}^{*0}) \]
\[ \rightarrow s\bar{s} \ (\phi) \ (1020) \]
\[ \rightarrow \bar{s}u \ (K^+) \ (494) \text{ or } (\bar{K}^{*+}) \]
\[ \rightarrow \bar{s}d \ (K^0) \ (498) \text{ or } (K^{*0}) \]
\[ cuu \ (\Sigma_c^{++}) \ (2452) \]
\[ cud \ (\Lambda_c^+) \ (2286) \text{ or } (\Sigma_c^+) \ (2451) \]
\[ cdd \ (\Sigma_c^0) \ (2452) \]
\[ \rightarrow suu \ (\Sigma^+) \]
\[ \rightarrow sud \ (\Lambda) \text{ or } (\Sigma^0) \]
\[ \rightarrow sdd \ (\Sigma^-) \]
\[ csu \ (\Xi_c^+) \ (2467) \]
\[ csd \ (\Xi_c^0) \ (2470) \]
\[ \rightarrow ssu \ (\Xi^0) \ (1315) \]
\[ \rightarrow ssd \ (\Xi^-) \ (1322) \]
Challenges of some utilized models
Open charm at high energy and pQCD models

\[ d\sigma_{H_c} \sim xG(x) \]

\[ xG(x)|_{x \to 1} \sim (1 - x)^5 \]

with \( x \approx 1 \)


\[ p + p \to \Lambda_c + X, \quad \sqrt{s} = 62 \text{GeV} \]

"Intrinsic charm model"
Brodsky et al, PLB93 (1980)

\[ \sim 1\% [c\bar{c}] \text{ in proton} \]
### Effective Lagrangian Models

**Example:** \( \bar{p}p \rightarrow K^- K^+ \)

![Graph showing data points for \( \bar{p}p \rightarrow KK^+ \)]

- Heidenbauer, Krein et al., (1993-2015) \( \bar{p}p \rightarrow Y Y \)
- Shyam & Lenske, (2015) \( \bar{p}p \rightarrow \bar{M} M \)


---

**Definite enhancement at forward production angles encourage for t-exchange channels**

\[
\mathcal{L}_{NYK} = -i \bar{N} \gamma_5 Y K + \text{h.c.} ,
\]

\[
\mathcal{L}_{NYD} = -i \bar{N} \bar{D} \gamma_5 Y_c + \text{h.c.} ,
\]

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“J-PARC hadron physics in 2016”
Amplitude and cross sections

\[ \bar{p} \quad \bar{K} \quad \wedge \quad \bar{p} \quad K \]

\[ \mathcal{L}_{NYK} = -i g_{KNY} \bar{N} \gamma_5 Y K + \text{h.c.}, \]

\[ A_{m_i n_i}^{\bar{p}p \rightarrow \bar{K}K}(s, t) = \frac{\bar{v}_{n_i} \left( p_Y \cdot \gamma - M_Y \right) u_{m_i}}{t - M^2} g_{KNY}^2 f^2(t) \]

\[ f(t) - \text{form factor} \]

\[ \frac{d\sigma}{dt} = \frac{1}{16\pi s (s - 4M_N^2)} \text{Tr}[AA^\dagger]; \quad \sigma_{\text{tot}} = \frac{1}{32\pi s p_i} \int_{-1}^{1} d\cos \theta \text{Tr}[AA^\dagger] \]

\[ \text{Tr}[AA^\dagger] = \frac{g_{KNY}^4 f^4(t)}{(t - M_Y^2)^2} F^2(s, t) \]

\[ F^2(s, t) = \frac{1}{2} \left( (s - 2M_N^2)(M_Y^2 - t) + 4M_N M_Y (M_N^2 + M_K^2 + t) \right. \]
\[ - \left. (M_N^2 - M_K^2 + t)^2 - M_N^2 (M_Y^2 + t) \right) \]
Kinematics: momentum transfers

\[ t = 2M_p^2 - 2E_pE_K + 2p_p\bar{p}_K \cos \theta \]

\[-t_{\text{max}} \equiv | -t |_{\text{max}} = -2M_p^2 + 2E_pE_K - 2p_p\bar{p}_K\]
\[ \sigma_{\text{tot}} \propto \text{Tr}[AA^\dagger] = \frac{1}{s} \frac{\gamma^4 K N Y}{(t - M_Y^2)^2} F^2(s, t) \]

\[ F^2(s, t) = \frac{1}{2} \left( (s - 2M_N^2)(M_Y^2 - t) + 4M_N M_Y (M_N^2 + M_K^2 + t) \right. \]
\[ \left. - (M_N^2 - M_K^2 + t)^2 - M_N^2 (M_Y^2 + t) \right) , \]

\[ \sigma_{\text{tot}} \approx \text{Constant} \quad \text{at} \quad s \ll M_i^2, |t| \]

\[ \sigma_{\text{tot}} \approx C \left( \frac{s}{s_0} \right)^{-\gamma} \quad \text{with} \quad \gamma \gg 1 \]

\[ \frac{\sigma_{\bar{D}D}}{\sigma_{\bar{K}K}} \leq 10^{-5} \]

**Limited region of application**

**Wrong energy dependence**

“J-PARC hadron physics in 2016”
Contrary to the hadron-exchange models, Regge approaches are work satisfactorily for strangeness production. Similarity of $\bar{p} p \rightarrow K K$ and $\bar{p} p \rightarrow D \bar{D}$ motivates for utilizing the Regge models for charm production.

\[
\begin{align*}
\bar{p} & \quad \bar{K} \\
\bar{K} & \quad \Lambda \\
\Lambda & \quad p \\
\end{align*}
\begin{align*}
\bar{p} & \quad D \\
D & \quad \Lambda_c \\
\Lambda_c & \quad p \\
\end{align*}
\]

Internal lines are associated with Regge trajectories.

\[
T_{\text{Regge}} \sim \left( -\frac{s}{s_R} \right)^{\alpha_R(t) - \frac{1}{2}}
\]

\[
\alpha_R(t) \simeq \alpha_R(0) + \alpha'_R t \rightarrow \text{linear trajectories}
\]

\[
R = \Lambda_c, \Sigma_c, D^* \ldots
\]

Therefore, there are doubts:

(1) Trajectories $\alpha(t)$ non-linear?

(2) What is a value of scale parameters $s_R$?

"J-PARC hadron physics in 2016"
V. Barger, R. Phillips, PRD 12 (1975)

\[
\frac{\text{charm}}{\text{strangeness}} < 10^{-6} \ldots 10^{-7}
\]
Possible solution is an approach based on non-perturbative quark-gluon string model discussed for the first time by S. Nussinov, (PRL 34 (1975) and F. Low, PRD 12 (1975)).

Essentially, they discussed formation and decay of a $q\bar{q}$ color tube with complicated intermediate (multi-particle) states.

The method of evaluation of observables based on utilizing the planar diagram for two body amplitude and it's cutting in s-channel


"J-PARC hadron physics in 2016"
\[ \text{Im} T_{ab \to cd} \sim \sum_{X} T_{ab \to X} \cdot T_{cd \to X}^{\dagger} \]

the use of optical theorem \[ \Rightarrow \] factorization:

\[ w_{ab \to cd}^2 \sim w_{ab \to ab} \times w_{cd \to cd} \]

probabilities of elastic scattering
The main advantage of Kaidalov’s approach based on

(i) factorization:

\[
\begin{align*}
\begin{array}{ccc}
  & b & d \\
  a & i & c \\
  j & & \end{array}
\end{align*}
\begin{align*}
\begin{array}{ccc}
  & b & b \\
  a & i & a \\
  j & & \otimes \\
  j & & c \\
  j & & c
\end{array}
\end{align*}
\]

\[w_{ab\rightarrow cd}^2 \sim w_{ab\rightarrow ab} \times w_{cd\rightarrow cd}\]

(ii) Regge type of the individual and the “required amplitude”:

\[
A_{ij} \sim \Gamma(1 - \alpha_{ij}(t)) \left(\frac{s}{s_{ij}}\right)^{\alpha_{ij}(t)-1}
\]

is a derivation of the consistent equations for \(\alpha_{ij}(t)\) and \(s_{ij}\):

\begin{enumerate}
  \item \[2\alpha_{ij}^0(0) = \alpha_{ii}^0(0) + \alpha_{jj}^0(0),\]
  \item \[2/\alpha_{ij}^\prime = 1/\alpha_{ii}^\prime + 1/\alpha_{jj}^\prime,\]
  \item \[(s_{ab;cd})^2(\alpha_{ij}-1) = (s_{ab})^{\alpha_{ii}(0)-1} \times (s_{cd})^{\alpha_{jj}(0)-1}.\]
\end{enumerate}

\[
s_{ab} = \left(\sum_i M_{i,\perp}\right) \left(\sum_j M_{j,\perp}\right)
\]

with \(M_{u,d\perp} \simeq 0.5 \text{ GeV}, \ M_{s\perp} \simeq 0.6 \text{ GeV}, \ M_{c\perp} \simeq 1.6 \text{ GeV}\)
Example: \( \pi^- p \rightarrow D^- \Lambda_c \)

\[
\omega^2_{\pi p \rightarrow D^- \Lambda_c} \sim \omega_{\pi^- p \rightarrow \pi^- p} \times \omega_{D^- \Lambda_c \rightarrow D^- \Lambda_c}
\]

[\( \rho \) (\( q\bar{q} \)) trajectory, \( J/\psi \) (\( c\bar{c} \)) trajectory]
Non-linear trajectory reflects behavior of QCD motivated $\bar{q}q$ potential $V(\rho)$

\[ \sigma(\rho) = \frac{dV(\rho)}{d\rho} \]

\[ E = 2 \int_0^R \frac{d\rho \sigma(\rho)}{\sqrt{1-(\rho \omega)^2}} \]

\[ J = 2 \int_0^R \frac{d\rho \sigma(\rho) \rho^2 \omega}{\sqrt{1-(\rho \omega)^2}} \]

\[ V(\rho) = \frac{a}{\pi \mu} \arctan(\pi \mu \rho) \quad \rightarrow \quad J = \frac{1}{\pi \mu} (a/\sigma) - \sqrt{(a/\sigma) - E^2} \]

"J-PARC hadron physics in 2016"
Non-linear Regge trajectories for diagonal channels in a square root form


\[ \alpha(t) = \alpha(0) + \gamma (\sqrt{T} - \sqrt{T - t}) \]

with \( T \gg 1 \text{GeV}^2 \)

In the diffractive region with \(-t \ll T\),

\[ \alpha(t) \simeq \alpha(0) + \frac{\gamma t}{2\sqrt{T}} \simeq \alpha(0) + \alpha' t \]

\[ \alpha' = \gamma / 2\sqrt{T} \]

where \( \gamma = 3.65 \text{ GeV}^{-1} \)

\( \alpha_\rho (t) \)

universal value

\[ \alpha_\rho, M_{K^*}, M_{K_3^*}, M_{J/\psi}, M_{D^*} \]

are taken as input
\[ \alpha_\rho(0) = 0.55, \quad \sqrt{T_\rho} = 2.46 \text{ GeV}, \quad \alpha'_\rho \simeq 0.742 \text{ GeV}^{-2}, \]
\[ \alpha_{K^*}(0) = 0.414, \quad \sqrt{T_{K^*}} = 2.58 \text{ GeV}, \quad \alpha'_{K^*} \simeq 0.71 \text{ GeV}^{-2}, \]
\[ \alpha_\phi(0) = 0.28, \quad \sqrt{T_\phi} \simeq 2.70 \text{ GeV}, \quad \alpha'_\phi \simeq 0.676 \text{ GeV}^{-2}, \]
\[ \alpha_{D^*}(0) = -1.02, \quad \sqrt{T_{D^*}} = 3.91 \text{ GeV}, \quad \alpha'_{D^*} \simeq 0.467 \text{ GeV}^{-2}, \]
\[ \alpha_{J/\psi}(0) = -2.60, \quad \sqrt{T_{J/\psi}} \simeq 5.36 \text{ GeV}, \quad \alpha'_{J/\psi} \simeq 0.34 \text{ GeV}^{-2}, \]
\[ s_{\bar{p}p: \bar{\Lambda}_c \Lambda_c} \simeq 5.98 \text{ GeV}^2. \]
\[ \alpha'_{dc}(0) \simeq -2.09, \quad \alpha'_{dc} \simeq 0.557 \text{ GeV}^{-2}, \]
\[ s_{\bar{p}p: D\bar{D}} \simeq 3.59 \text{ GeV}^2. \]
Reaction $\bar{p}p \rightarrow \bar{Y}Y$, $Y = \Lambda, \Sigma, \Lambda_c, \Sigma_c$...

\[
\begin{align*}
\bar{p} & \quad \bar{\Lambda} \\
\mathcal{R}_{K^*} & \\
p & \quad \Lambda \\
\end{align*}
\]

\[
\begin{align*}
\Gamma^{(p)}_\mu &= \bar{u}_\Lambda \left( (1 + \kappa_{K^*N\Lambda}) \gamma_\mu - \kappa_{K^*N\Lambda} \frac{(p_p + p_\Lambda)_\mu}{M_N + M_\Lambda} \right) u_p , \\
\Gamma^{(\bar{p})}_\mu &= \bar{v}_{\bar{p}} \left( (1 + \kappa_{K^*N\Lambda}) \gamma_\mu + \kappa_{K^*N\Lambda} \frac{(p_{\bar{p}} + p_{\bar{\Lambda}})_\mu}{M_N + M_\Lambda} \right) v_{\bar{\Lambda}} .
\end{align*}
\]

\[
T_{m_f n_f; m_i, n_i}^{\bar{p}p \rightarrow \bar{\Lambda}\Lambda} = C(t) \frac{s g_{K^*N\Lambda}^2}{s_0} \Gamma \left( 1 - \alpha_{s\bar{q}}(t) \right) \left( -\frac{s}{s_{\bar{p}p: \bar{\Lambda}\Lambda}} \right) \alpha_{s\bar{q}}(t) - 1
\]

\[
M_{m_f n_f; m_i, n_i}^{\bar{p}p \rightarrow \bar{\Lambda}\Lambda} (s, t) \quad \text{unknown residual function}
\]

\[
\begin{align*}
N^2(s, t) &= \frac{1}{F^2(s, t)}, \\
F^2(s, t) &= \text{Tr} \left( \Gamma^{(p)}_\mu \Gamma^{(p)}_\mu \right) \text{Tr} \left( \Gamma^{(\bar{p})}_\nu \Gamma^{(\bar{p})}_\nu \right) \left( g_{\mu\nu} - \frac{q_{\mu} q_{\nu}}{q^2} \right) \left( g_{\mu'\nu'} - \frac{q_{\mu'} q_{\nu'}}{q^2} \right)
\end{align*}
\]

$g_{KN\Lambda}, g_{K^*N\Lambda}, \kappa_{K^*N\Lambda} - \text{from hyper-nucleon physics (Nijmegen potential)}$

$\text{SU}(4) \longrightarrow g_{DN\Lambda c}(g_{D^*N\Lambda c}) = g_{KN\Lambda}(g_{K^*N\Lambda})$

\[
\sum_{\text{spins}} M M^\dagger = 1
\]

"J-PARC hadron physics in 2016"
$C(t) = \frac{0.54}{(1 - t/1.15)^2}$
Reactions \( \bar{p}p \rightarrow \bar{Y}Y, \ Y = \Lambda, \Sigma^0 \ (\Lambda_c, \Sigma_c^0) \)

\( t \)-dependence

“J-PARC hadron physics in 2016”
Reactions $\bar{p}p \rightarrow \bar{Y}Y$, $Y = \Lambda, \Sigma^0 (\Lambda_c, \Sigma_c^0)$

energy dependence

\[ \frac{d\sigma}{dt} (\mu b/GeV^2) \]

\[ \Delta s^{1/2} (GeV) \]
Comparison of two realization of QGSM for $\bar{p}p \rightarrow \bar{\Lambda}_c \Lambda_c$

A.T., B. Kämpfer

A.Khodjamirian, C. Klein, T. Mannel and Y.-M. Wang

The uncertainties caused by the residual function $C(t)$

The uncertainties caused by LCSR of strong couplings

$p_L = 15 \text{ GeV/c}$

$d\sigma/dt (\mu b/\text{GeV}^2)$

$-t (\text{GeV}^2)$

"J-PARC hadron physics in 2016"
Comparison of two realization of QGSM (average values)

A. T., B. Kämpfer

A. Khodjamirian, C. Klein, T. Mannael and Y.-M. Wang

The uncertainties caused by LCSR of strong couplings

The uncertainties caused by the residual function C(t)

For the average values both predictions are consistent with each other within a factor of 2

“J-PARC hadron physics in 2016”
Reaction $\bar{p}p \rightarrow KK (D \bar{D})$

\[
T_{m_i, n_i}^{\bar{p}p \rightarrow KK} = C'(t) \frac{g_{KNN}^2 M_Y \sqrt{s}}{s_0} \Gamma \left( \frac{1}{2} - \alpha_{\bar{s}q}(t) \right) \left( -\frac{s}{s_{\bar{p}p: \Lambda \Lambda}} \right)^{\alpha_{\bar{s}q}(t) - \frac{1}{2}} \otimes \mathcal{M}_{m_i, n_i}^{\bar{p}p \rightarrow KK}(s, t)
\]

\[\mathcal{M}_{m_i, n_i}^{\bar{p}p \rightarrow KK}(s, t) = \mathcal{N}(s, t) \left[ \bar{u}_{n_i} (\phi_Y - M_Y) u_{m_i} \right],\]

\[\mathcal{N}^2(s, t) = \frac{1}{F^2(s, t)},\]

\[F^2(s, t) = \frac{1}{2} \left( (s - 2M_N^2)(M_Y^2 - t) + 4M_N M_Y (M_N^2 + M_K^2 + t) \right) - (M_N^2 - M_K^2 + t)^2 - 2M_N (M_Y^2 + t)\]
Reaction $\bar{p}p \rightarrow \bar{K}K (D\bar{D})$

\[ a \]

\[ b \]

\[ c \]

d-diquark

$\mathcal{R}_{\bar{d}d}$  
$\mathcal{R}_{\phi(J/\psi)}$

"J-PARC hadron physics in 2016"
How to evaluate the di-quark trajectory?

\[
2 \alpha_{sd}(0) = \alpha_{ss}(0) + \alpha_{dd}(0),
\]
\[
2/\alpha'_{sd} = 1/\alpha'_{ss} + 1/\alpha'_{dd}
\]

\[
\alpha_{sd}(t) \equiv \alpha_{\Lambda}(t) = -0.65 + 0.94 t
\]

then

\[
\alpha_{dd}(t) = -1.58 + 1.542 t
\]

and allows to identify trajectory of \( \Lambda_c \)

\[
2 \alpha_{dc}(0) = \alpha_{dd}(0) + \alpha_{cc}(0),
\]
\[
2/\alpha'_{dc} = 1/\alpha'_{dd} + 1/\alpha'_{cc}
\]

\[
\alpha_{dc}(t) \equiv \alpha_{\Lambda_c}(t) = -2.09 + 0.557 t
\]
\[ C'(t) = \frac{0.38}{(1-t/1.15)^2} \]
Reactions \( \bar{p}p \rightarrow \bar{K}K (D\bar{D}) \)

\( t \)-dependence

\[
\begin{align*}
\text{\( \bar{p}p\rightarrow\bar{K}K \quad p_L=10 \text{ GeV/c} \)} & \quad (\Lambda, \Sigma^0) \\
\text{\( \bar{p}p\rightarrow\bar{K}K^\prime \)} & \quad \bar{K}^0K^\prime \\
\text{\( \bar{p}p\rightarrow\bar{D}\bar{D} \quad p_L=15 \text{ GeV/c} \)} & \quad (\Lambda_c^+, \Sigma_c^+) \\
\text{\( \bar{p}p\rightarrow\bar{D}\bar{D}^\circ \)} & \quad \bar{D}^\circ\bar{D}^\circ \\
\text{\( \bar{p}p\rightarrow\bar{D}\bar{D}^+ \)} & \quad \bar{D}^+\bar{D}^+ \\
\end{align*}
\]
Reactions $\bar{p}p \rightarrow \bar{K}K (D\bar{D})$  

$s$-dependence

---

$\bar{p}p \rightarrow \bar{K}K$ \hspace{1cm} $t_{\text{max}} = t = 0.2 \text{ GeV}^2$

$\bar{K}^0 K^0$

$K^- K^+$

$\bar{p}p \rightarrow D\bar{D}$ \hspace{1cm} $t_{\text{max}} = t = 0.2 \text{ GeV}^2$

$D^+ D^-$

$D^0 \bar{D}^0$
Comparison of two realization of QGSM for $\bar{p}p \rightarrow D\bar{D}$

A.T., B. Kämpfer


Reaction $\bar{p}p \rightarrow \bar{K}K^*$

$$d\sigma^{KK^*} \sim (2 \div 3) \ d\sigma^{KK}$$

$$\frac{\text{charm}}{\text{strangeness}} \sim 10^{-3} \ldots 10^{-4}$$
Double flavor exchange: and $\Xi_c \Xi_c$ in $\bar{p}p$ collisions

$a$

$Y = \Lambda, \Sigma^{0,+}$

$b$

$Y_c = \Lambda_c^{+}, \Sigma_c^{+,++}$

Cut (pole) diagrams

Cutkosky cutting rule

$$T_{\bar{p}p \rightarrow \Xi \Xi} \simeq T_{\text{cut}}$$

$$= -\frac{i}{16\pi} \sqrt{1 - \frac{4M_Y^2}{s}} \int \frac{d\Omega_Y}{4\pi} \sum_{\text{spins } \bar{Y}'Y} T_{\bar{p}p \rightarrow \bar{Y}'Y} T_{\bar{Y}'Y \rightarrow \Xi \Xi}$$
The vertex amplitudes: “effective region exchange”
The amplitude of $\bar{p}p \rightarrow \bar{Y}' Y \rightarrow \Xi^0 \Xi^0$ transition is a coherent sum with intermediate states

$\bar{Y}' Y = \bar{\Lambda} \Lambda, \Sigma^0 \Sigma^0, \Sigma^+ \Sigma^+, \Sigma^0 \Lambda, \bar{\Lambda} \Sigma^0$

SU(3) predicts

$g_{K^* \Lambda \Xi^0} * g_{K^* \Sigma^0 \Xi^0} < 0$

$$T_{\bar{p}p \rightarrow \Xi^0 \Xi^0} = g_A^4 \left( 1 + \frac{1}{9} + \frac{4}{9} - \frac{2}{3} \right) T_0 = \frac{8}{9} g_A^4 T_0$$

The ratio of cross sections looks as

$$\frac{\sigma_{\bar{p}p \rightarrow \Xi^- \Xi^-}}{\sigma_{\bar{p}p \rightarrow \Xi^0 \Xi^0}} \simeq \frac{\sigma_{\bar{p}p \rightarrow \Xi_c^0 \Xi^0_c}}{\sigma_{\bar{p}p \rightarrow \Xi_c^+ \Xi^+_c}} \simeq 4.$$

"J-PARC hadron physics in 2016"
Cross sections

differential

total

"J-PARC hadron physics in 2016"
Exclusive \( \pi p \to M^* \Lambda; \ M^* = K^{0,*}, \ D^{-*} \) reactions

\[
T_{\pi p \to \Lambda M^*} \simeq g_0^2 \frac{s}{\bar{s}} \Gamma (1 - \alpha_{R_{p\Lambda\Lambda_c}}(t)) \left( \frac{s}{s_0^R} \right)^{2(\alpha_{R_{p\Lambda\Lambda_c}}(t)-1)}
\]

\[
\alpha_{R_{p\Lambda\Lambda_c}}(t) = 0.414 + 0.71t
\]

\[
s_{R_{p\Lambda}} \simeq 1.59 \text{ GeV}^2
\]

\[
\frac{g_0^2}{4\pi} \simeq 0.8, \ \bar{s} \simeq 1 \text{ GeV}^2
\]
Differential cross sections

\[ \frac{d\sigma}{dt} (\mu b/GeV^2) \]

\[ t_{max} - t (GeV^2) \]

Total cross sections

\[ \sigma_{tot} (\mu b) \]

\[ p (GeV/c) \]


\[ \frac{C}{s} \approx 10^{-2} \ldots 3 \quad \text{VS.} \quad \frac{C}{s} \approx 10^{-6} \]

[cf. V. Barger, R. Phillips, PRD 12 (1975)]
Reactions \( pp \rightarrow \Lambda_c \bar{D} p \) and \( pp \rightarrow \Lambda_c \bar{D} X \)

\[
\frac{d\sigma^{pp\rightarrow \Lambda_c \bar{D} p}}{d\Omega} \sim \frac{d\sigma^{\pi p\rightarrow \Lambda_c \bar{D}}}{dt} \otimes \sigma^{\pi N}_{\text{tot}} \ d[PS]
\]


For J-PARC energies our work is in a progress

“J-PARC hadron physics in 2016”
Summary

- We have evaluated the cross sections for reactions, \( \bar{p}p \rightarrow Y_c Y_c, \ D \bar{D}, \ D^* \bar{D}, \ldots \) including double flavor exchange,

- and for \( \pi p \rightarrow D^* \Lambda_c \) reactions at \( E_{\text{lab}} \leq 20 \) GeV

- This result may be used for design of PANDA detector and “charm” program at JPARC

- And for further development of the theoretical approaches in “charmed physics”
Thank you very much for attention!
BACKUP
Longitudinal asymmetries

\[ A(s, t) = \frac{d\sigma^A - d\sigma^P}{d\sigma^A + d\sigma^P}, \]

where

\[ d\sigma^A \equiv d\sigma^\rightarrow \quad d\sigma^P \equiv d\sigma^\leftarrow \]

Polarized Antiproton EXperiment (PAX)

http://www.fz-juelich.de/ikp/pax/
Longitudinal asymmetry

\[ A = \frac{d\sigma^A - d\sigma^P}{d\sigma^A + d\sigma^P}, \quad d\sigma^A \equiv d\sigma^{\leftrightarrow}, \quad d\sigma^P \equiv d\sigma^{\Rightarrow} \]

\[ \theta = 0 \]

spin-conserving

spin-flip

\[ T_{m_f n_f; m_i, n_i} \sim A(s) \delta_{m_i m_f} \delta_{n_i n_f} \]
\[ + \frac{1}{\sqrt{2}} B(s) (1 - 4m_i m_f) \delta_{-m_i m_f} \delta_{-n_i n_f} \]

\[ A = \frac{B^2(s)}{A^2(s) + B^2(s)} \]
Structure of spin-flip amplitude

\[ B(s) = -\sqrt{2} \left( (1 + \kappa) \left( \frac{p_p}{E + M_N} - \frac{p_Y}{E + M_Y} \right) \right)^2 \]
\[ \mathcal{A} = \frac{B^2(s)}{A^2(s) + B^2(s)} \]
Asymmetry $s$-dependence

Reaction $\bar{p}p \rightarrow \bar{Y}Y$, $Y = \Lambda, \Lambda_c^+, \Sigma^0, \Sigma_c^+$
Longitudinal asymmetry

\[ \bar{p}p \rightarrow \bar{K}K (D\bar{D}) \]

\[ \theta = 0 \]

\[ J_{\text{final}} = 0 \]

\[ A \approx 1 \]

\[ d\sigma^P \equiv d\sigma^\Rightarrow \sim 0 \]
Asymmetry $t$-dependence

Reactions $\bar{p}p \rightarrow \bar{K}K$, $D\bar{D}$

\[ A \]

$\bar{p}p \rightarrow \bar{K}K$ $p_L=10$ GeV/c

$\bar{K}^0K^0$ $K^-K^+$

$\bar{p}p \rightarrow D\bar{D}$ $p_L=15$ GeV/c

$D^+D^-$ $D^0\bar{D}^0$

"J-PARC hadron physics in 2016"
Asymmetry \textbf{s-dependence}

Reactions $\bar{p}p \rightarrow \bar{K}K, \quad D\bar{D}$

$A$ versus $s^{1/2}$ (GeV)

$A$ versus $\Delta s^{1/2}$ (GeV)

"J-PARC hadron physics in 2016"
Longitudinal asymmetry

\[ \bar{p}p \rightarrow \bar{K}K^* \]

pure vector coupling!!!

\[ \theta = 0 \quad s_f = 1, \lambda_V = 1, 0 \]

\[ T_{\lambda_i; m_i, n_i} \sim \left( A \delta_{m_i n_i} + B \delta_{-m_i n_i} \right) \delta_{\lambda_i \lambda_V} \]

\[ \lambda_i = m_i + n_i \]

\[ A \approx \sqrt{2}, \quad B \approx \frac{M_N}{M_V} \]

\[ A = \frac{M_N^2 - 2M_V^2}{M_N^2 + 2M_V^2} \]

\[ \sim -0.3 (\bar{K}K^*) \]

\[ \sim -0.8 (D\bar{D}^*) \]
Reaction $\bar{p}p \rightarrow \bar{K}K^*$
Reaction $\bar{p}p \rightarrow D\bar{D}^*$

"J-PARC hadron physics in 2016"
OBE model

\[ \frac{\text{charm}}{\text{strangeness}} \approx 3 \cdot 10^{-2} \]

Fig. 2. Total reaction cross sections for \( \bar{p}p \rightarrow \Lambda \Lambda \) and \( \bar{p}p \rightarrow \Lambda_c^- \Lambda_c^+ \) as a function of the excess energy \( \epsilon \). The results for \( \bar{p}p \rightarrow \Lambda \Lambda \) (upper curves) are taken from our work [7]. The solid curves are results for the meson-exchange transition potential while the dashed curves correspond to quark-gluon dynamics. The \( \bar{p}p \rightarrow \Lambda_c^- \Lambda_c^+ \) results are obtained with the \( \bar{p}p \) interaction \( C \).
\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} C(s, M_\Lambda) |T(s, M_\Lambda)|^2 ,
\sim |1/(t - M_V^2)|^2
\]

\[-t_s = 0.22 \ldots 0.50\]

\[-t_c = 3.54 \ldots 5.33\]

\[
\frac{d\sigma^s}{d\sigma^c} \simeq 9.8 \times 54.4 \simeq 530
\]

\[
\frac{\text{charm}}{\text{strangeness}} \sim 2 \cdot 10^{-4}
\]
TABLE I. Parameters of the vector meson trajectories of the form (8). The intercept of the $\rho$ trajectory was taken as an input.

<table>
<thead>
<tr>
<th></th>
<th>$\rho$</th>
<th>$K^*$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha(0)$</td>
<td>0.55</td>
<td>0.414±0.006</td>
<td>0.27±0.01</td>
</tr>
<tr>
<td>$\sqrt{T}$, GeV</td>
<td>2.46±0.03</td>
<td>2.58±0.03</td>
<td>2.70±0.07</td>
</tr>
<tr>
<td>$\alpha(0)$</td>
<td>-1.02±0.05</td>
<td>-1.16±0.05</td>
<td>-2.60±0.10</td>
</tr>
<tr>
<td>$\sqrt{T}$, GeV</td>
<td>3.91±0.02</td>
<td>4.03±0.04</td>
<td>5.36±0.05</td>
</tr>
<tr>
<td>$\alpha(0)$</td>
<td>-7.13±0.17</td>
<td>-7.27±0.17</td>
<td>-8.70±0.18</td>
</tr>
<tr>
<td>$\sqrt{T}$, GeV</td>
<td>7.48±0.02</td>
<td>7.60±0.04</td>
<td>8.93±0.03</td>
</tr>
</tbody>
</table>

TABLE V. Parameters of the pseudoscalar meson trajectories of the form (8). (The parameters for the $K$ trajectory were found using the mass of $K_2$ from [29]. If we instead use a mass of the corresponding pure $ns$ state as found in Ref. [46], i.e., $M_{K_2}=1762±18$ GeV, the parameters change slightly: the intercept $-0.153±0.003$, and the threshold 2.93±0.07 GeV.)

<table>
<thead>
<tr>
<th></th>
<th>$\pi$</th>
<th>$K$</th>
<th>$\eta_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha(0)$</td>
<td>-0.0118±0.0001</td>
<td>-0.151±0.001</td>
<td>-0.291±0.003</td>
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<tr>
<td>$\sqrt{T}$, GeV</td>
<td>2.82±0.05</td>
<td>2.96±0.05</td>
<td>3.10±0.11</td>
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<tr>
<td>$\alpha(0)$</td>
<td>-1.61105±0.00005</td>
<td>-1.751±0.001</td>
<td>-3.2103±0.0001</td>
</tr>
<tr>
<td>$\sqrt{T}$, GeV</td>
<td>4.16±0.03</td>
<td>4.29±0.06</td>
<td>5.49±0.02</td>
</tr>
<tr>
<td>$\alpha(0)$</td>
<td>-7.41±0.17</td>
<td>-7.54±0.17</td>
<td>9.00±0.17</td>
</tr>
<tr>
<td>$\sqrt{T}$, GeV</td>
<td>7.89±0.16</td>
<td>8.01±0.16</td>
<td>9.24±0.12</td>
</tr>
</tbody>
</table>
TABLE II. Comparison of the masses of the spin-1, spin-3 and spin-5 states given by ten vector meson trajectories of the form (8) with data. All masses are in MeV.

<table>
<thead>
<tr>
<th></th>
<th>$J=1$</th>
<th></th>
<th>$J=3$</th>
<th></th>
<th>$J=5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This work</td>
<td>Ref. [29]</td>
<td>This work</td>
<td>Ref. [29]</td>
<td>This work</td>
</tr>
<tr>
<td>$\alpha_p(t)$</td>
<td>769.0±0.9</td>
<td>769.0±0.9</td>
<td>1688.8±2.1</td>
<td>1688.8±2.1</td>
<td>2124±19</td>
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<tr>
<td>$\alpha_K^+(t)$</td>
<td>896.1±0.3</td>
<td>896.1±0.3</td>
<td>1776±7</td>
<td>1776±7</td>
<td>2215±21</td>
</tr>
<tr>
<td>$\alpha_\phi(t)$</td>
<td>1015±17</td>
<td>1019.4</td>
<td>1863±31</td>
<td>1854±7</td>
<td>2305±42</td>
</tr>
<tr>
<td>$\alpha_{D^*}(t)$</td>
<td>2006.7±0.5</td>
<td>2006.7±0.5</td>
<td>2721±23</td>
<td></td>
<td>3191±22</td>
</tr>
<tr>
<td>$\alpha_{D^0}(t)$</td>
<td>2102±29</td>
<td>2106.6±2.1±2.7</td>
<td>2808±28</td>
<td></td>
<td>3279±30</td>
</tr>
<tr>
<td>$\alpha_{J^0}(t)$</td>
<td>3096.9</td>
<td>3096.9</td>
<td>3753±41</td>
<td></td>
<td>4240±39</td>
</tr>
<tr>
<td>$\alpha_{B^0}(t)$</td>
<td>5324.9±1.8</td>
<td>5324.9±1.8</td>
<td>5814±51</td>
<td></td>
<td>6217±46</td>
</tr>
<tr>
<td>$\alpha_{B^+}(t)$</td>
<td>5411±58</td>
<td>5416.3±3.3</td>
<td>5901±53</td>
<td></td>
<td>6306±49</td>
</tr>
<tr>
<td>$\alpha_{B^-}(t)$</td>
<td>6356±80</td>
<td></td>
<td>6853±72</td>
<td></td>
<td>7276±65</td>
</tr>
<tr>
<td>$\alpha_Y(t)$</td>
<td>9460.4±0.2</td>
<td>9460.4±0.2</td>
<td>9906±91</td>
<td></td>
<td>10304±84</td>
</tr>
</tbody>
</table>

TABLE VI. Comparison of the masses of the spin-0, spin-2 and spin-4 states given by ten pseudoscalar meson trajectories of the form (8) with data. (We take the error estimate on the $\eta_b$ mass as 10% of the calculated splitting, in agreement with Fig. 2 of the second paper of Ref. [45].) All masses are in MeV.

<table>
<thead>
<tr>
<th></th>
<th>$J=0$</th>
<th></th>
<th>$J=2$</th>
<th></th>
<th>$J=4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This work</td>
<td>Ref. [29]</td>
<td>This work</td>
<td>Ref. [29]</td>
<td>This work</td>
</tr>
<tr>
<td>$\alpha_\pi(t)$</td>
<td>135</td>
<td></td>
<td>1677±8</td>
<td></td>
<td>2237±26</td>
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<tr>
<td>$\alpha_K(t)$</td>
<td>493.7</td>
<td></td>
<td>1773±8</td>
<td></td>
<td>2333±27</td>
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<tr>
<td>$\alpha_\eta(t)$</td>
<td>698±14</td>
<td></td>
<td>1869±38</td>
<td></td>
<td>2429±54</td>
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<tr>
<td>$\alpha_{D^*}(t)$</td>
<td>1864.1±1.0</td>
<td></td>
<td>2692±19</td>
<td></td>
<td>3228±22</td>
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<tr>
<td>$\alpha_{D^0}(t)$</td>
<td>1971±19</td>
<td></td>
<td>2786±26</td>
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<td>3323±32</td>
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<tr>
<td>$\alpha_{D^*}(t)$</td>
<td>2979.8±2.1</td>
<td></td>
<td>3692±23</td>
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<td>4217±25</td>
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<td>$\alpha_{B^0}(t)$</td>
<td>5279.8±1.6</td>
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<td>5830±89</td>
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<td>6286±93</td>
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<tr>
<td>$\alpha_{B^+}(t)$</td>
<td>5369.6±2.4</td>
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<td>5920±89</td>
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<td>6376±93</td>
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<tr>
<td>$\alpha_{B^-}(t)$</td>
<td>6283±79</td>
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<td>6826±79</td>
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<td>7287±80</td>
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<tr>
<td>$\alpha_Y(t)$</td>
<td>9424±3.6</td>
<td></td>
<td>9914±148</td>
<td></td>
<td>10353±150</td>
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</tbody>
</table>