Mini Workshop on “Structure and productions of charmed baryons II”, 8.07∼09, 2014, J-PARC

Production of Charm and Strange Baryons

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Outline

$\pi^- p \to K^{*0}\Lambda$ $\pi^- p \to D^{*-}\Lambda_c^+$

1. Introduction & Motivation
2. Formalism
   (Feynman & Regge model)
3. Results : total cross section (σ)
   differential cross section
   ⇒ (dσ/dΩ, dσ/dt)
4. Summary

$\pi^- p \to D^{*-}\Lambda_c^+$ $\pi^- p \to D^{*-}\Sigma_c^+$

Limits on Charm Production in Hadronic Interactions near Threshold

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(Received 28 January 1985)

We present the results of an experiment to search for associated charm production near threshold in 13-GeV/c $\pi^- p$ interactions. A large-aperture proportional wire chamber spectrometer was sensitive to the decay fragments of the forward-produced D^{*-}'s expected from the two-body reactions $\pi^- + p \to D^{*-} + \Lambda_c^+, \Sigma_c^+, \ldots$. The missing baryon mass was determined from the vector momenta of the incident pion and the candidate D^{*-}. No evidence for these reactions was found, which resulted in a 7-nb upper limit (95% confidence level) for each of the cross sections $\sigma(\pi^- p \to D^{*-}\Lambda_c^+)$ and $\sigma(\pi^- p \to D^{*-}\Sigma_c^+)$.

Proposal P50 is submitted :

"Charmed Baryon Spectroscopy via the (π^-, D^{*-}) reaction"

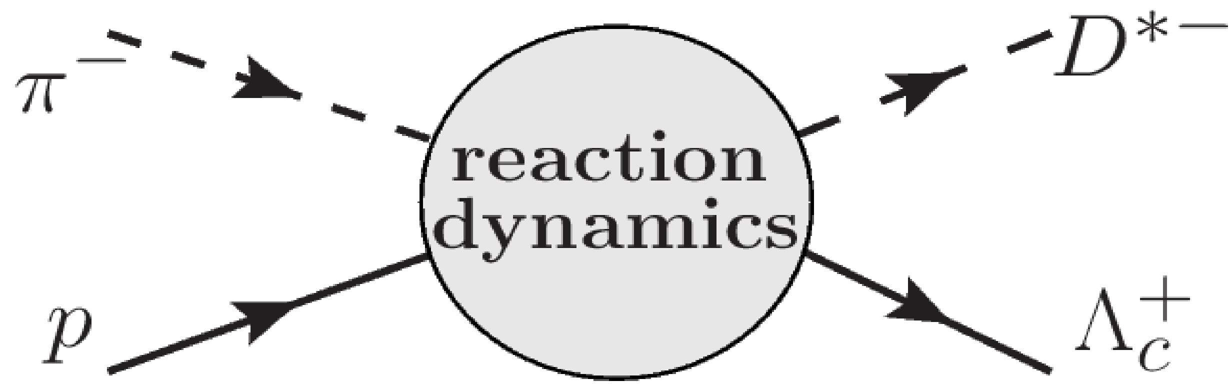
December 10, 2012

Executive Summary

We propose the spectroscopic study of charmed baryons via the (π, D^{*-}) reactions at the high-momentum (high-p) beam line of J-PARC to investigate the diquark degree of freedom in a hadron. The good diquark correlation is due to the color-spin interaction whose strength is proportional to the inverse of a quark mass. Therefore, there would be only one good diquark pair in a charmed baryon, which makes the study of excited charmed baryons unique and interesting.

We will supplement the high-p beam line with the dispersive ion optical elements so that a high-intensity pion beam with a resolution of $\Delta p/p$=0.1 % can be delivered. A new large acceptance spectrometer for the D^{*-} detection is designed to achieve a missing mass resolution of ~5 MeV. Charmed baryons from the ground state to highly excited states of $E_x \sim 1$ GeV will be identified in a missing mass spectrum of the $p(\pi, D^{*-})$ reaction. In addition to the masses and widths of charmed baryons, the spectrometer enables us to measure some of the decay branching ratios of an excited baryon by detecting decay products.

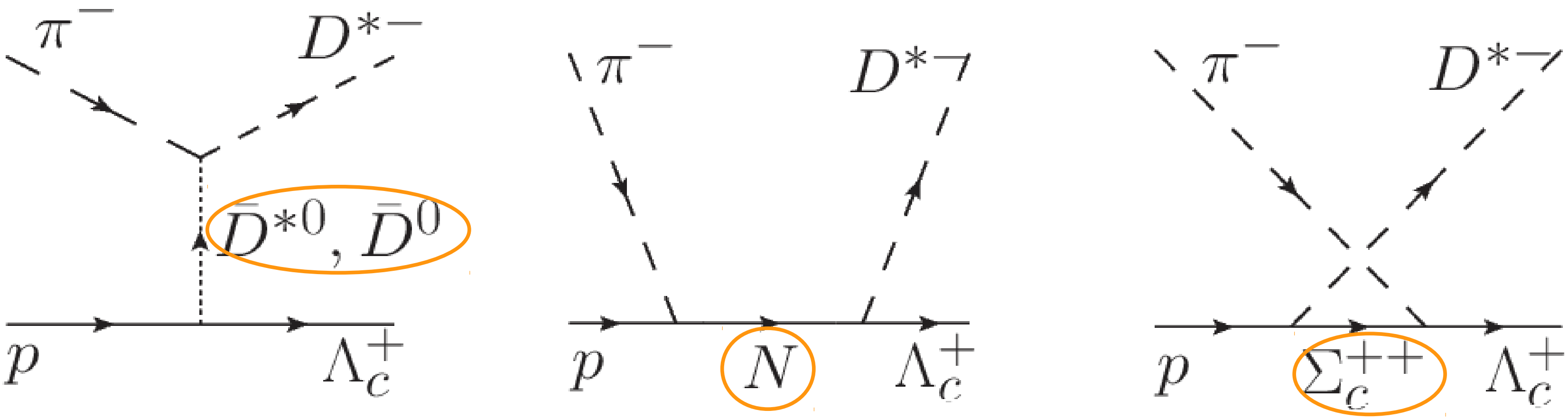
Here, we propose new charmed baryon spectroscopy by means of the missing mass method to shed lights on the diquark.



1.Feynman model	2. Regge model
The contribution of the particle of the ground state	The contribution of the particles of both the ground and excited states which lie on the same trajectory
Good at describing Low energy(threshold) behavior	Good at describing High energy behavior
Parameters : coupling constants, cut off masses in form factors	Parameters : coupling constants, Regge trajectories, scale parameters

1.Feynman Model

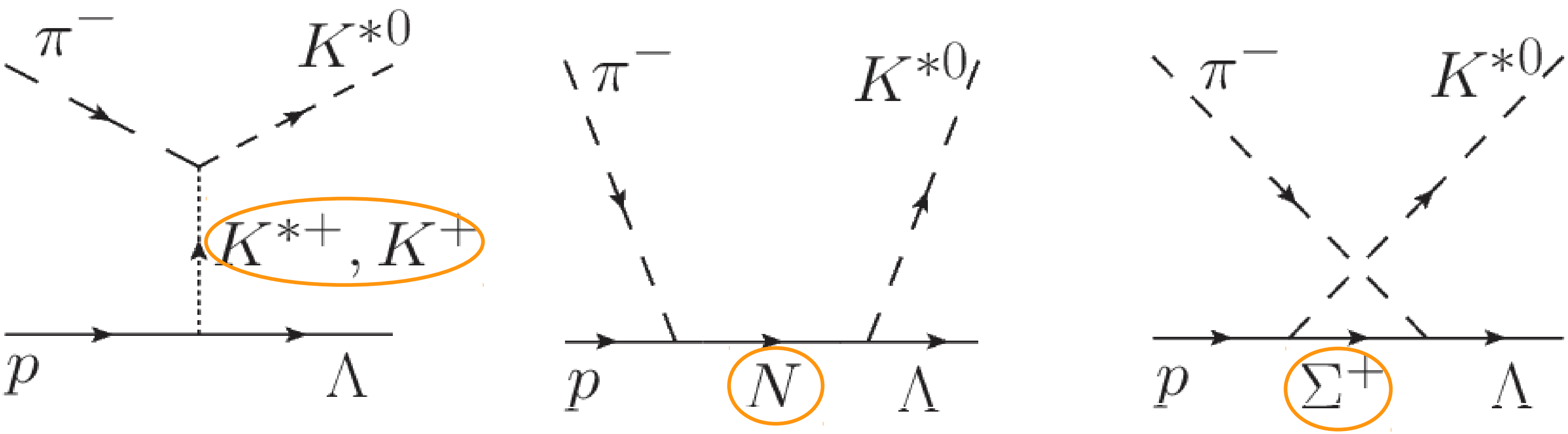
$$\pi^- p \to D^{*-}(1870)\Lambda_c^+(2286)$$



c quark

s quark

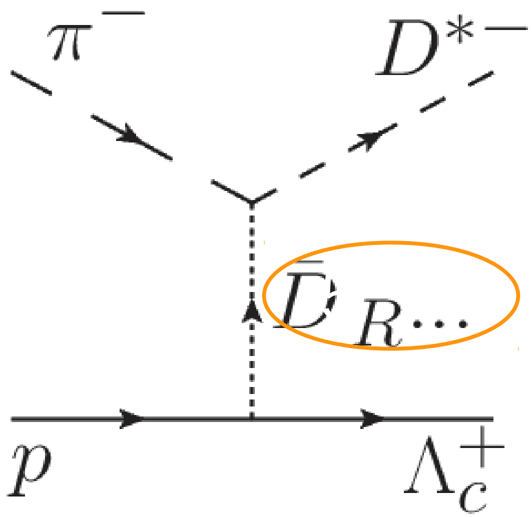
$$\pi^- p \to K^{*0}(892)\Lambda(1116)$$

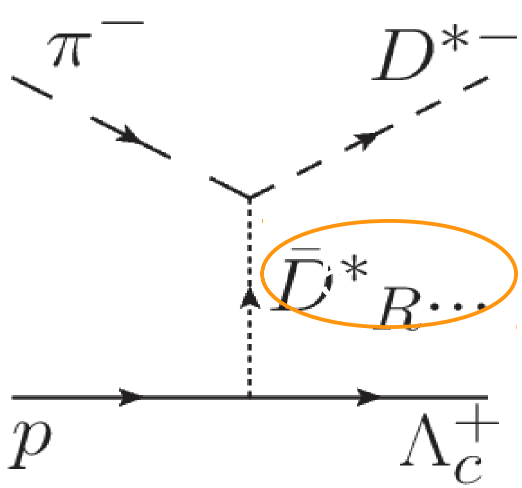


We will use the same coupling constants for both reactions.

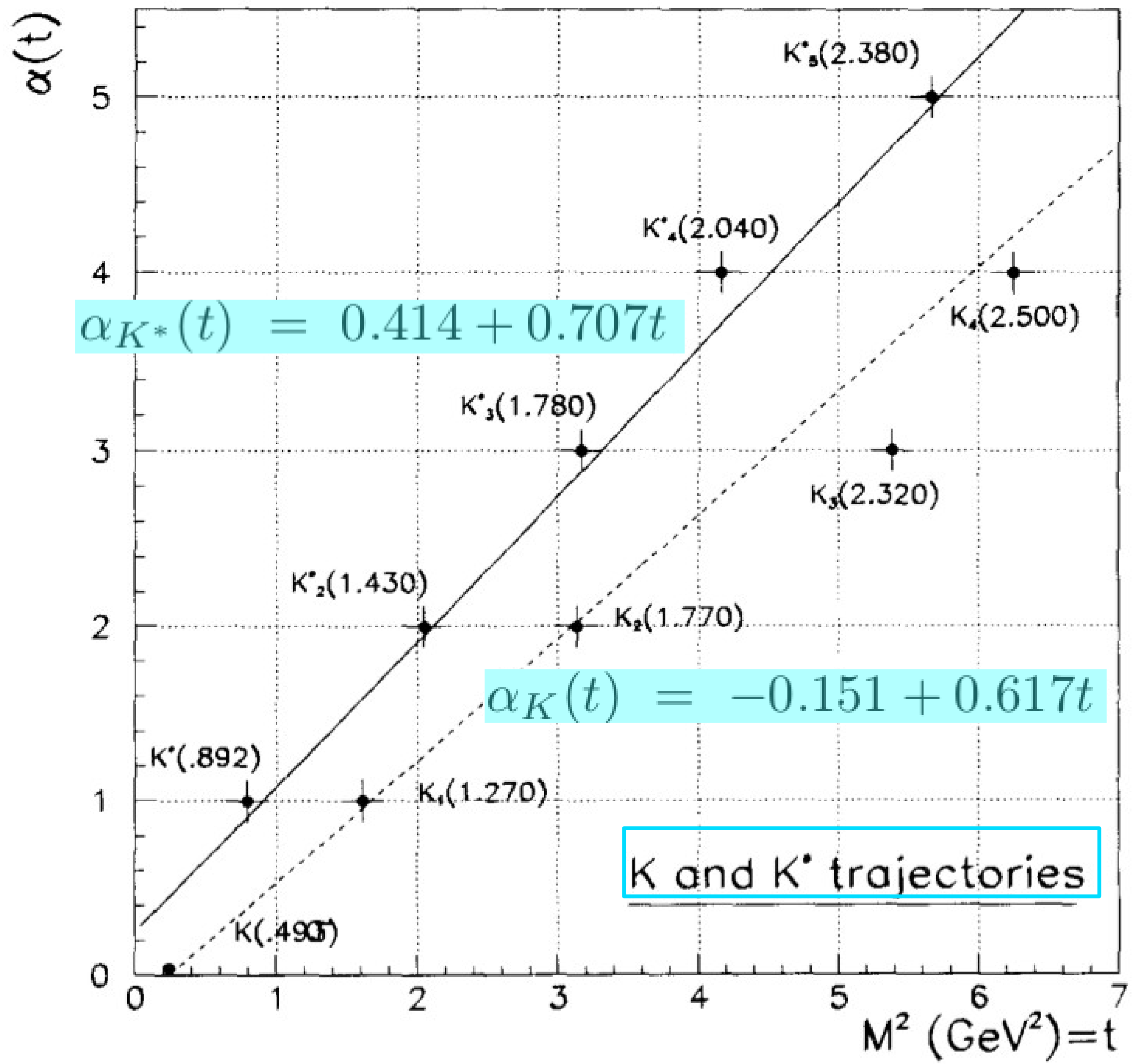
2.Regge Model

$$\pi^- p \rightarrow D^{*-}(1870)\Lambda_c^+(2286)$$

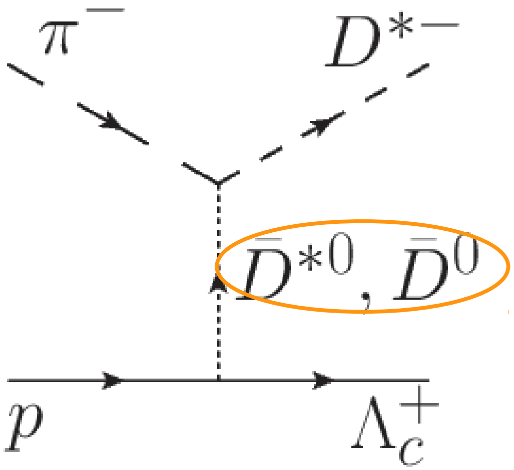




$$\alpha(t) = \alpha(0) + \alpha' t$$



Effective Lagrangians



t-channel

D -

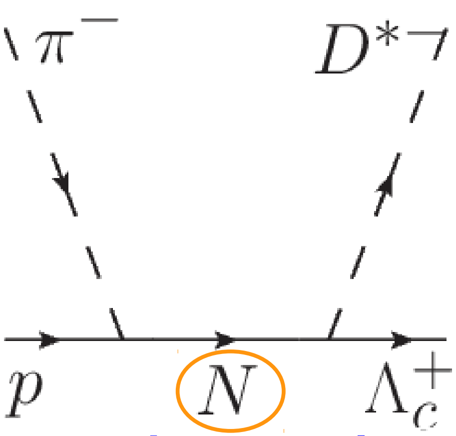
$$\mathcal{L}_{\pi D D^*} = -i g_{\pi D D^*} (\bar{D} \partial^\mu \boldsymbol{\tau} \cdot \boldsymbol{\pi} D^*_\mu - \bar{D}^*_\mu \partial^\mu \boldsymbol{\tau} \cdot \boldsymbol{\pi} D)$$

$$\mathcal{L}_{D N \Lambda_c} = -i g_{D N \Lambda_c} \bar{N} \gamma_5 \Lambda_c D + \text{h.c.}$$
$$\text{or} \quad \frac{g_{D N \Lambda_c}}{M_N + M_{\Lambda_c}} \bar{N} \gamma_\mu \gamma_5 \Lambda_c \partial^\mu D + \text{h.c.}$$

D* -

$$\mathcal{L}_{\pi D^* D^*} = -g_{\pi D^* D^*} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu D^*_\nu \boldsymbol{\tau} \cdot \boldsymbol{\pi} \partial_\alpha \bar{D}^*_\beta$$
$$(\text{or} \;\; g_{\pi D^* D^*} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu D^*_\nu \partial_\alpha \boldsymbol{\tau} \cdot \boldsymbol{\pi} \bar{D}^*_\beta)$$

$$\mathcal{L}_{D^* N \Lambda_c} = -g_{D^* N \Lambda_c} \bar{N} \left[\gamma_\mu \Lambda_c - \frac{\kappa_{D^* N \Lambda_c}}{2 M_N} \sigma_{\mu\nu} \Lambda_c \partial^\nu \right] D^{*\mu} + \text{h.c.}$$



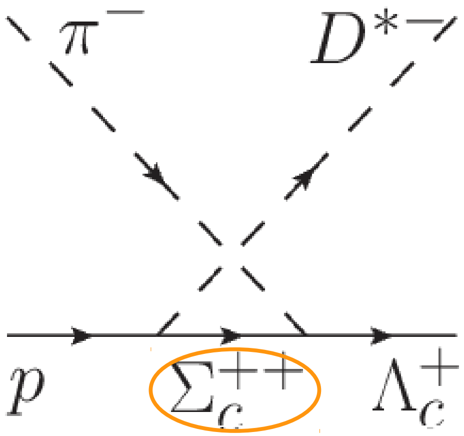
s-channel

N -

$$\mathcal{L}_{\pi N N} = -i g_{\pi N N} \bar{N} \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} N$$
$$\text{or} \quad \frac{g_{\pi N N}}{2 M_N} \bar{N} \gamma_\mu \gamma_5 \partial^\mu \boldsymbol{\tau} \cdot \boldsymbol{\pi} N$$

In our numerical calculation,
we will use the pseudovector form.

Effective Lagrangians



u-channel

Σ_c -

$$\mathcal{L}_{\pi\Sigma_c\Lambda_c} = \frac{g_{\pi\Sigma_c\Lambda_c}}{M_{\Lambda_c}+M_{\Sigma_c}}\bar{\Lambda}_c\gamma_\mu\gamma_5\partial^\mu\boldsymbol{\tau}\cdot\boldsymbol{\pi}\Sigma_c + \text{h.c.}$$

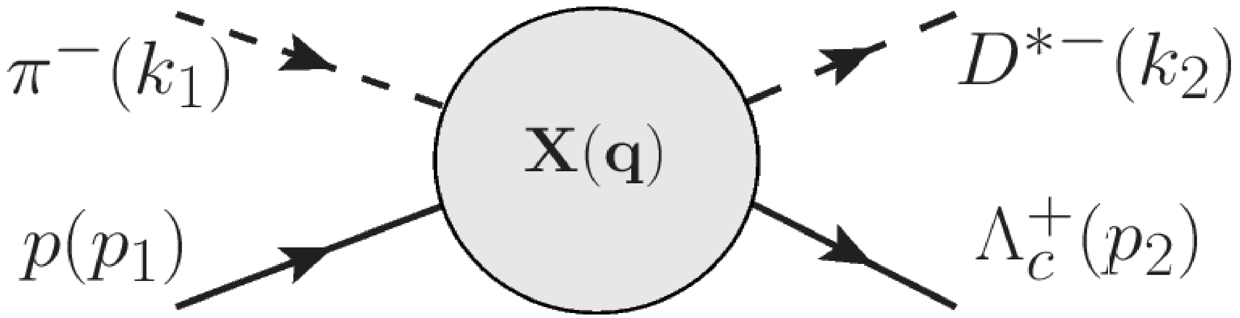
$$\mathcal{L}_{D^*N\Sigma_c} = -g_{D^*N\Sigma_c}\bar{N}\left[\gamma_\mu\Sigma_c - \frac{\kappa_{D^*N\Sigma_c}}{2M_N}\sigma_{\mu\nu}\Sigma_c\partial^\nu\right]D^{*\mu} + \text{h.c.}$$

Coupling Constants

$g_{\pi KK^*}$	$g_{\pi K^*K^*}$	$g_{KN\Lambda}$	$g_{K^*N\Lambda}$	$\kappa_{K^*N\Lambda}$	$g_{K^*N\Sigma}$	$\kappa_{K^*N\Sigma}$	$g_{\pi NN}$	$g_{\pi\Sigma\Lambda}$
6.56	7.45	13.24	-4.26	2.91	-2.46	-0.534	13.4	12.0

Exp. (first column) — SU(3) relation (second and third columns) — Nijmegen potential (NSC97a) (remaining columns)

1.1 Feynman Amplitude



$$\mathcal{M} = \bar{u}_{\Lambda_c}\, \mathcal{M}_X\, u_N$$

$$\begin{aligned}
\mathcal{M}_D &= \frac{-i}{t-M_D^2} g_{\pi D D^*} g_{D N \Lambda_c} \gamma_5 (\varepsilon^*_\mu k_1^\mu) \\
\mathcal{M}_{D^*} &= \frac{1}{t-M_{D^*}^2} g_{\pi D^* D^*} g_{D^* N \Lambda_c} \epsilon_{\mu\nu\alpha\beta} \left[\gamma^\mu - \frac{i\kappa_{D^* N \Lambda_c}}{M_N + M_{\Lambda_c}} \sigma^{\mu\lambda} q_\lambda\right] k_1^\nu k_2^\alpha \varepsilon^{*\beta} \\
\mathcal{M}_N &= \frac{i}{s-M_N^2} \frac{g_{\pi NN}}{2M_N} g_{D^* N \Lambda_c} \varepsilon^*_\mu \left[\gamma^\mu - \frac{i\kappa_{D^* N \Lambda_c}}{M_N + M_{\Lambda_c}} \sigma^{\mu\nu} k_{2\nu}\right] (\not{q} + M_N)(\gamma^\alpha k_{1\alpha})\gamma_5 \\
\mathcal{M}_{\Sigma_c} &= \frac{i}{u-M_{\Sigma_c}^2} \frac{g_{\pi \Sigma_c \Lambda_c}}{M_N + M_{\Lambda_c}} g_{D^* N \Sigma_c} (\gamma^\alpha k_{1\alpha})\gamma_5 (\not{q} + M_{\Sigma_c}) \varepsilon^*_\mu \left[\gamma^\mu - \frac{i\kappa_{D^* N \Lambda_c}}{M_{\Lambda_c} + M_{\Sigma_c}} \sigma^{\mu\nu} k_{2\nu}\right]
\end{aligned}$$

1.2 Feynman Amplitude & Cutoff Masses

$$\pi^- p \to K^{*0}\Lambda$$

$$\mathcal{M} = \mathcal{M}_K \cdot F_K + \mathcal{M}_{K^*} \cdot F_{K^*} + \mathcal{M}_N \cdot F_N + \mathcal{M}_\Sigma \cdot F_\Sigma$$

$$\pi^- p \to D^{*-}\Lambda_c^+$$

$$\mathcal{M} = \mathcal{M}_D \cdot F_D + \mathcal{M}_{D^*} \cdot F_{D^*} + \mathcal{M}_N \cdot F_N + \mathcal{M}_{\Sigma_c} \cdot F_{\Sigma_c}$$

$$F = \frac{\Lambda^4}{\Lambda^4 + (p^2 - M_{ex}^2)^2}$$

How to determine the cutoff masses, Λ ?

They are determined phenomenologically by fitting the experimental data for the total and differential cross section. → The same values are used.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm CM} = \frac{1}{64\pi^2 s}\frac{\mathbf{p}_{out}}{\mathbf{k}_{in}}\frac{1}{2}\sum_{s,s'}|\mathcal{M}|^2$$

2.1 Regge Propagator

D-exchange : $\frac{1}{t-M_D^2} \rightarrow P_{Regge}^{D} = \left(-\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{\alpha_D(t)} \Gamma(-\alpha_D(t))\frac{1}{s_0}$

D*-exchange : $\frac{1}{t-M_{D^*}^2} \rightarrow P_{Regge}^{D^*} = \left(-\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{\alpha_{D^*}(t)-1} \Gamma(1-\alpha_{D^*}(t))\frac{1}{s_0}$

D-exchange : $T_D(s,t) = M_D(s,t)\left(-\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{\alpha_D(t)} \Gamma(-\alpha_D(t))\frac{1}{s_0}$

D*-exchange : $T_{D^*}(s,t) = M_{D^*}(s,t)\left(-\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{\alpha_{D^*}(t)-1} \Gamma(1-\alpha_{D^*}(t))\frac{1}{s_0}$

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2}\frac{1}{2}\sum_{s,s',\lambda}|\mathrm{T}(s,t)|^2$$

In the Regge model, the energy dependence of the forward differential cross section follows the form :

$$\frac{d\sigma}{dt} \propto s^{2\alpha(0)-2}.$$

2.2 Regge Amplitude

$$\sum_{s,s',\lambda} |\mathcal{M}_D|^2(s,t) = (g_{DN\Lambda_c}\cdot g_{\pi DD^*})^2 \times$$
$$-t\Big[(M_{\Lambda_c}-M_N)^2\big(1+\frac{M_\pi^2}{M_{D^*}^2}\big) + \frac{1}{2M_{D^*}^2}(M_{D^*}^2-M_\pi^2)\Big]$$
$$+t^2\Big[1+\frac{M_\pi^2}{M_{D^*}^2}+\frac{1}{2M_{D^*}^2}(M_{\Lambda_c}-M_N)^2\Big] - t^3\frac{1}{2M_{D^*}^2}$$
$$\frac{1}{2M_{D^*}^2}(M_{\Lambda_c}-M_N)^2(M_{D^*}^2-M_\pi^2)$$

= At + Bt^2 + Ct^3 + D

A~ J : constant values

$$\sum_{s,s',\lambda} |\mathcal{M}_{D^*}|^2(s,t) = \frac{1}{2}(g_{D^*N\Lambda_c}\cdot g_{\pi D^*D^*})^2 \times$$
$$-s^2t + s^2t^2\frac{\kappa_{D^*N\Lambda_c}}{(M_N+M_{\Lambda_c})^2} - s(M_{D^*}^2-M_\pi^2)(M_{\Lambda_c}^2-M_N^2)$$
$$+st\Big[(M_\pi^2+M_N^2+M_{D^*}^3+M_{\Lambda_c}^2)+\kappa_{D^*N\Lambda_c}\frac{M_{\Lambda_c}-M_N}{M_{\Lambda_c}+M_N}(M_{D^*}^2-M_\pi^2)\Big]$$
$$-st^2\Big[1+\frac{\kappa_{D^*N\Lambda_c}^2}{(M_N+M_{\Lambda_c})^2}(+M_\pi^2++M_N^2+M_{D^*}^2M_{\Lambda_c}^2)\Big]+st^3\frac{\kappa_{D^*N\Lambda_c}^2}{(M_N+M_{\Lambda_c})^2}$$
$$-t\Big[(M_{\Lambda_c}^2-M_{D^*}^2)(M_N^2-M_\pi^2)+(1+\kappa_{D^*N\Lambda_c})^2\Big((M_N-M_{\Lambda_c})^2$$
$$(M_{D^*}^2+M_\pi^2)+\frac{1}{2}(M_{D^*}^2-M_\pi^2)^2\Big)+\frac{\kappa_{D^*N\Lambda_c}^2}{(M_N+M_{\Lambda_c})^2}\Big(-M_{D^*}^2M_N^2$$
$$(M_N^2-M_{\Lambda_c}^2+M_{D^*}^2)+M_\pi^2(M_{D^*}^2(M_N^2+M_{\Lambda_c}^2)+M_{\Lambda_c}^2(M_{\Lambda_c}^2-M_\pi^2-M_N^2))\Big)\Big]$$
$$+t^2\frac{1}{2}\Big[(1+\kappa_{D^*N\Lambda_c})^2((M_N-M_{\Lambda_c})^2+2(M_{D^*}^2+M_\pi^2))$$
$$+\frac{2\kappa_{D^*N\Lambda_c}^2}{(M_N+M_{\Lambda_c})^2}(M_{\Lambda_c}^2-M_{D^*}^2)(M_N^2-M_\pi^2)\Big]$$
$$-t^3\frac{1}{2}(1+\kappa_{D^*N\Lambda_c})^2$$
$$+\frac{1}{2}\Big[(1+\kappa_{D^*N\Lambda_c})^2(M_{D^*}^2-M_\pi^2)^2(M_N-M_{\Lambda_c})^2$$
$$-2(M_{D^*}^2M_N^2-M_\pi^2M_{\Lambda_c}^2)(M_{D^*}^2+M_N^2-M_{\Lambda_c}^2-M_\pi^2)\Big]$$

= As^2t + Bs^2t^2 : positive, dominant
+ Cs + Dst + Est^2 + Fst^3 : negative, dominant
+ Gt + Ht^2 + It^3 : positive
+ J : negative

$$\sum_{s,s',\lambda} |\mathcal{M}_D|^2(s,t=0) \propto \text{const.}$$
$$\sum_{s,s',\lambda} |\mathcal{M}_{D^*}|^2(s,t=0) \propto s$$

2.2 Regge Amplitude

$$\left(\frac{d\sigma}{dt}\right)_D(s,t) = \frac{1}{16\pi s^2}\frac{1}{2}\sum_{s,s',\lambda}|\mathcal{M}_D(s,t)|^2\left(\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{2\alpha_D(t)}\Gamma(-\alpha_D(t))^2\frac{1}{s_0^2}$$

$$\left(\frac{d\sigma}{dt}\right)_{D^*}(s,t) = \frac{1}{16\pi s^2}\frac{1}{2}\sum_{s,s',\lambda}|\mathcal{M}_{D^*}(s,t)|^2\left(\frac{s}{s_{\pi p;D^*\Lambda_c}}\right)^{2\alpha^*_D(t)-2}\Gamma(1-\alpha_{D^*}(t))^2\frac{1}{s_0^2}$$

$$\sum_{s,s',\lambda}|\mathcal{M}_D|^2(s,t=0)\propto \text{const.}$$

$$\frac{d\sigma}{dt}(s,t=0)\rightarrow s^{2\alpha(0)-2}$$

$$\sum_{s,s',\lambda}|\mathcal{M}_{D^*}|^2(s,t=0)\propto s$$

$$\frac{d\sigma}{dt}(s,t=0)\rightarrow s^{2\alpha(0)-3}$$

To cure this problem, we introduce new normalization Factor such that the amplitude has a correct large s behavior :
[Titov, Kampfer PRC.78.025201(2008)]

◇ $\mathcal{N}_{D^*} = (s/s_{\text{th}})^n$

$$\mathcal{M}_{D^*}\rightarrow\mathcal{N}_{D^*}\cdot\mathcal{M}_{D^*} = (s/s_{\text{th}})^{\frac{1}{2}}\cdot\mathcal{M}_{D^*}$$

◇ $\mathcal{N}_{D^*} = (t/t_{\text{th}})^n$

$$\mathcal{M}_{D^*}\rightarrow\mathcal{N}_{D^*}\cdot\mathcal{M}_{D^*} = (t/t_{\text{th}})^{-\frac{1}{2}}\cdot\mathcal{M}_{D^*}$$

2.3 Regge Parameters

(a) Regge trajectories : $\alpha(t) = \alpha(0) + \alpha' t$

(b) Energy scale parameter : $s_0^{\pi N \to D^* \Lambda_c}$

=> determined by using Quark-Gluon-String Model(QGSM).

Kaidalov, ZphysC.12.63(1982), Brisudova et al, PRD 61.054013(2000)

(c) Universal scale parameter : s_0

=> determined phenomenologically between 3 and 7 GeV.

2.3 Regge Parameters

(a) The intercept and the slope of the trajectory for the nondiagonal transition are related to the corresponding parameters for the diagonal transitions :

$$\alpha(t) = \alpha(0) + \alpha' t \;?$$

$$2\alpha_{ij} = \alpha_{\bar{i}i}(0) + \alpha_{\bar{j}j}(0) \qquad 2/\alpha'_{ij} = 1/\alpha'_{\bar{i}i} + 1/\alpha'_{\bar{j}j}$$

$$\pi^- p \to D^{*-}\Lambda_c^+$$

$$\begin{aligned}
\alpha_{\bar{u}u}(t) = \alpha_\pi(t) &= -0.0118 + 0.647t \\
\alpha_{\bar{c}c}(t) = \alpha_{\eta_c}(t) &= -3.2103 + 0.332t \\
\alpha_{uc}(t) = \alpha_D(t) &= -1.6115 + 0.439t
\end{aligned}$$

$$\begin{aligned}
\alpha_{\bar{u}u}(t) = \alpha_\rho(t) &= 0.55 + 0.742t \\
\alpha_{\bar{c}c}(t) = \alpha_{J/\Phi}(t) &= -2.60 + 0.340t \\
\alpha_{uc}(t) = \alpha_{D^*}(t) &= -1.02 + 0.467t
\end{aligned}$$

$$\pi^- p \to K^{*0}\Lambda$$

$$\begin{aligned}
\alpha_{\bar{u}u}(t) = \alpha_\pi(t) &= -0.0118 + 0.647t \\
\alpha_{\bar{s}s}(t) = \alpha_{\eta_s}(t) &= -0.291 + 0.606t \\
\alpha_{us}(t) = \alpha_K(t) &= -0.151 + 0.617t
\end{aligned}$$

$$\begin{aligned}
\alpha_{\bar{u}u}(t) = \alpha_\rho(t) &= 0.55 + 0.742t \\
\alpha_{\bar{s}s}(t) = \alpha_\phi(t) &= 0.27 + 0.675t \\
\alpha_{us}(t) = \alpha_{K^*}(t) &= 0.414 + 0.707t
\end{aligned}$$

Brisudova et al, PRD 61.054013(2000)

2.3 Regge Parameters

(b) The energy scale parameter is related to the corresponding parameters for the diagonal transitions :

$$\pi^- p \to D^{*-}\Lambda_c^+$$

$$s_0^{\pi N \to D^* \Lambda_c} = \left(s_0^{\pi N}\right)^{\frac{\alpha_\rho(0)-1}{2(\alpha_{D^*}(0)-1)}} \left(s_0^{D^* \Lambda_c}\right)^{\frac{\alpha_{J/\Psi}(0)-1}{2(\alpha_{D^*}(0)-1)}}$$

$$\alpha(t) = \alpha(0) + \alpha' t$$

$$m_u \approx 0.5, m_s \approx 0.6 \,[\mathrm{GeV}]$$

$$s_0^{\pi N} \approx 1.5, s_0^{D\Lambda_c} \approx 5.46 \,[\mathrm{GeV}^2]$$

$$s_0(D) = 4.25, s_0(D^*) = 4.75$$

$$\pi^- p \to K^{*0}\Lambda$$

$$s_0^{\pi N \to K^* \Lambda} = \left(s_0^{\pi N}\right)^{\frac{\alpha_\rho(0)-1}{2(\alpha_{K^*}(0)-1)}} \left(s_0^{K^* \Lambda}\right)^{\frac{\alpha_\phi(0)-1}{2(\alpha_{K^*}(0)-1)}}$$

$$\alpha(t) = \alpha(0) + \alpha' t$$

$$m_u \approx 0.5, m_c \approx 1.6 \,[\mathrm{GeV}]$$

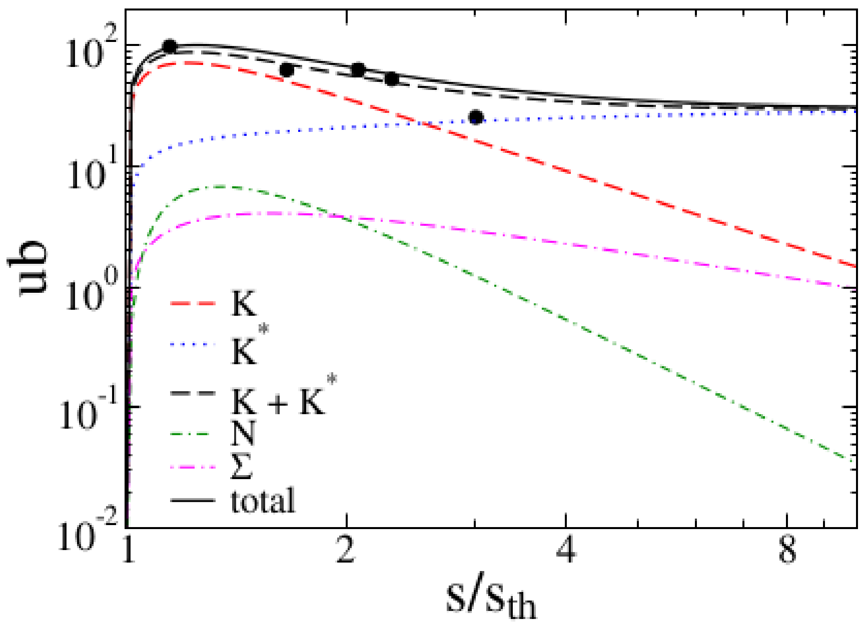
$$s_0^{\pi N} \approx 1.5, s_0^{K\Lambda} \approx 1.76 \,[\mathrm{GeV}^2]$$

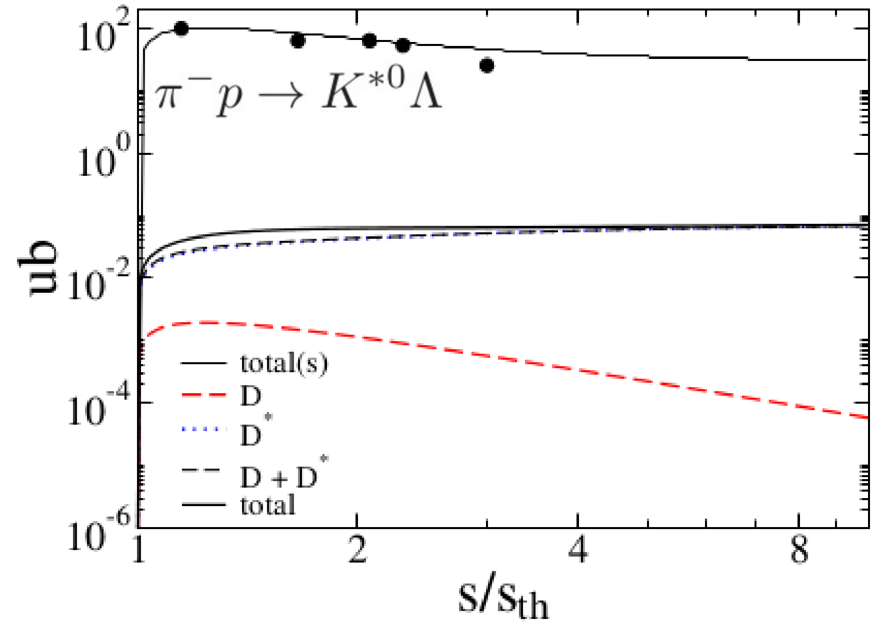
$$s_0(K) = 1.64, s_0(K^*) = 1.66$$

Brisudova et al, PRD 61.054013(2000)

<Total Cross Section> 1. Feynman model

$\pi^- p \to K^{*0}\Lambda$ $\pi^- p \to D^{*-}\Lambda_c^+$





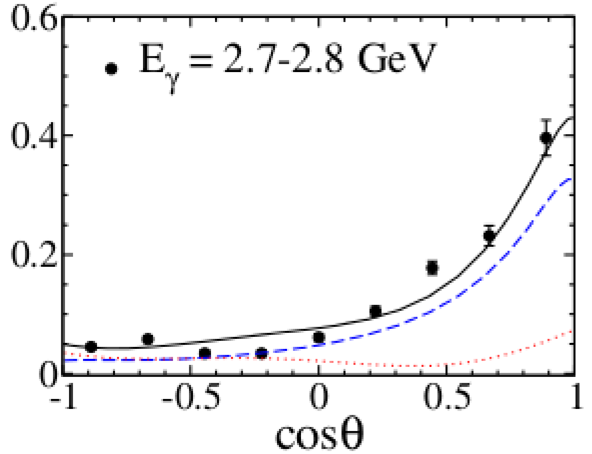
cutoff mass ⇨ K,K*(D,D*) : 0.55
(Λ)[GeV] N,Σ(N,Σc) : 0.70

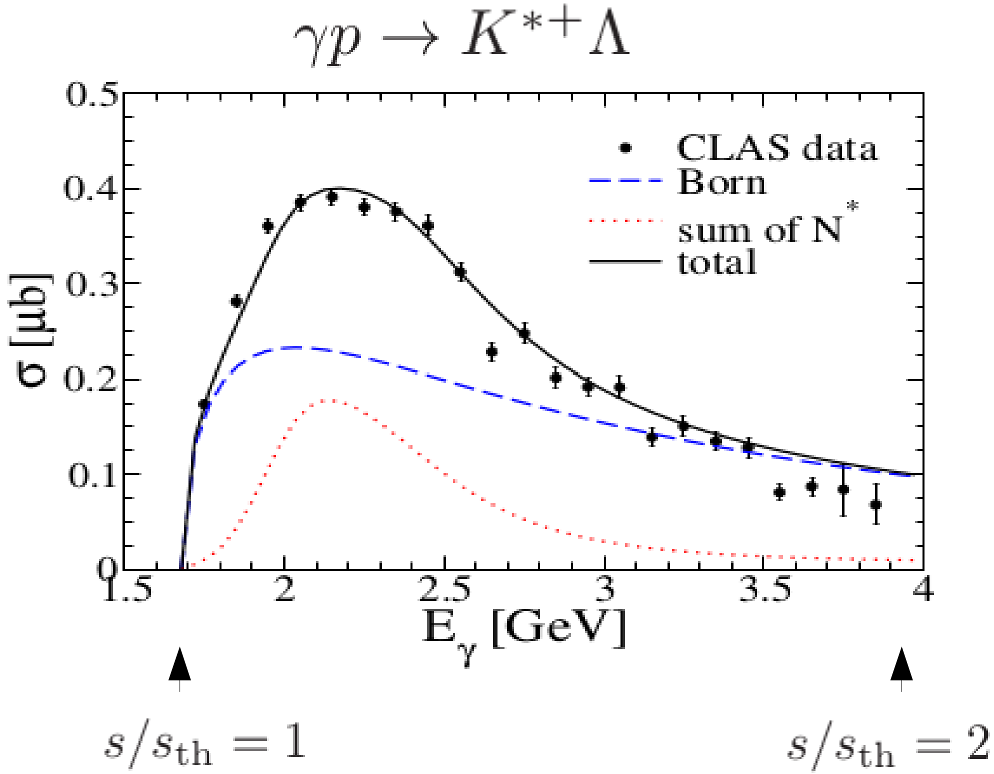
It comes from the relation $\sigma \sim s^{J-1}$ in the t-channel exchange model.

Exp. Data : Dahl et al, PR 163.1377(1967) Crennell et al, PRD 6.1220(1972)

1. Feynman model

ex)
Results for $\gamma p \to K^{*+}\Lambda$ reaction using Feynman model
(S.H.Kim et al, PRD 90. 014021(2014))



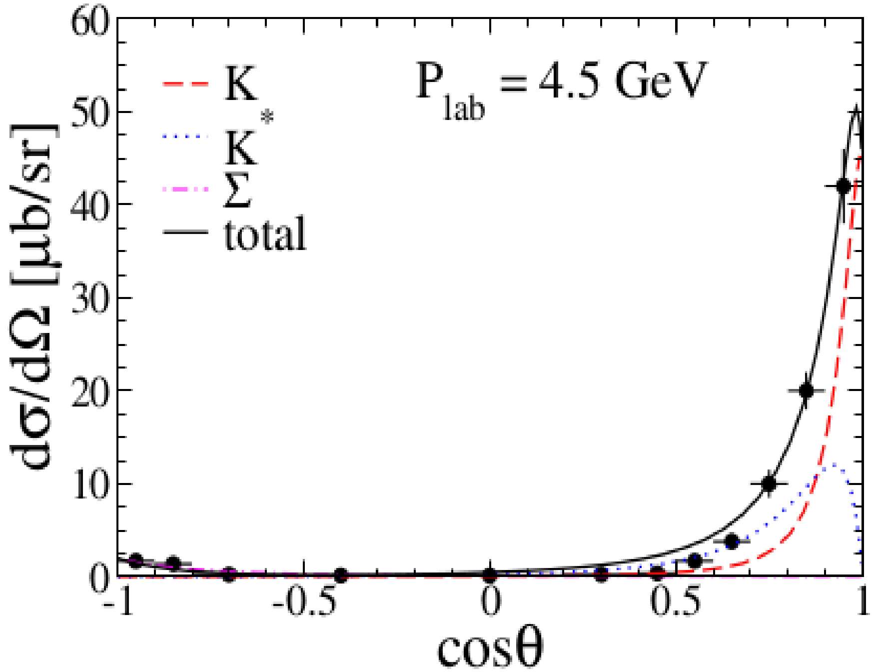


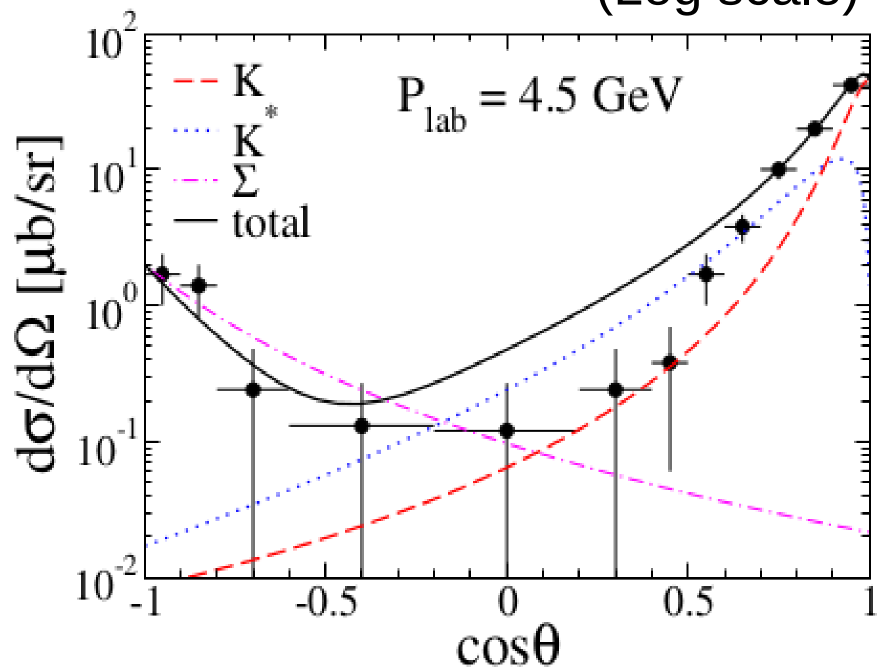
We have to employ another suitable theoretical method to explain reaction mechanisms at higher energies.
==> Regge Model

<Differential Cross Section> 1. Feynman model

$$\pi^- p \to K^{*0} \Lambda$$

(Log scale)



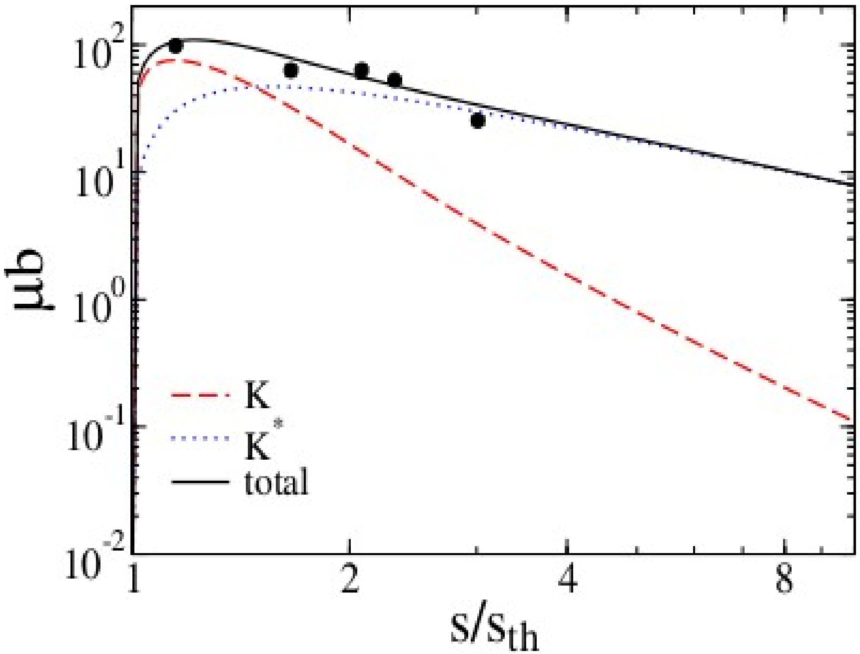


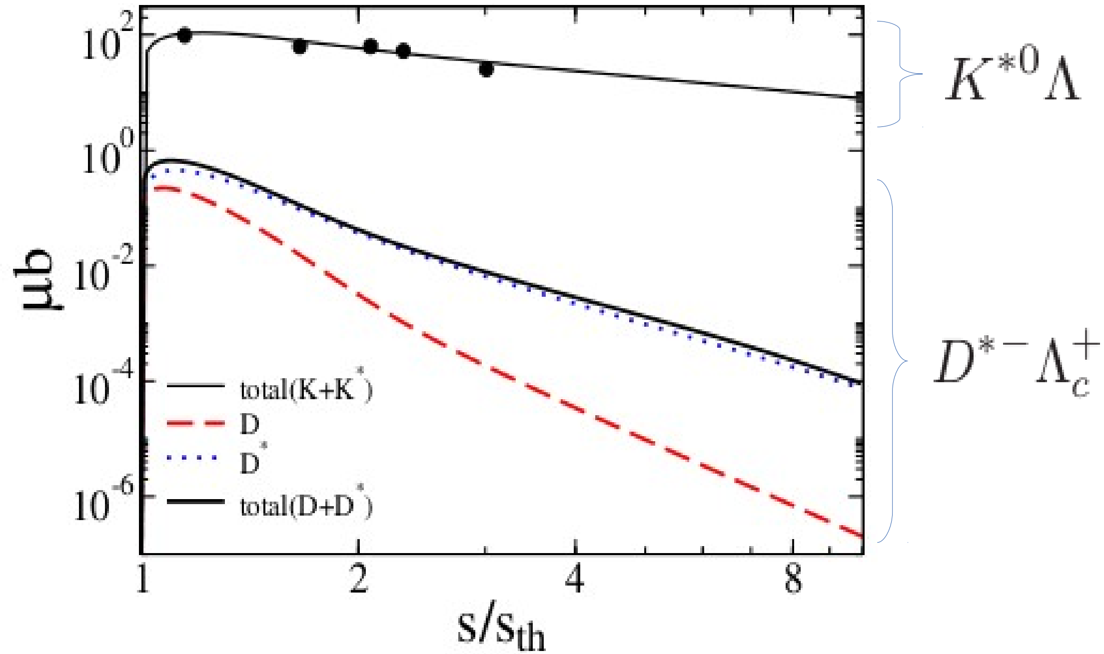
t-channel exchange(K and K*) is dominant showing
a very forward peak and some backward peak.
s- and u-channel's contributions are almost negligible.

Exp. Data : Crennell et al, PRD 6.1220(1972)

<Total Cross Section> 2. Regge model

$\pi^- p \to K^{*0}\Lambda$ $\pi^- p \to D^{*-}\Lambda_c^+$





The total cross section for the charm production (Πp → D*Λc)

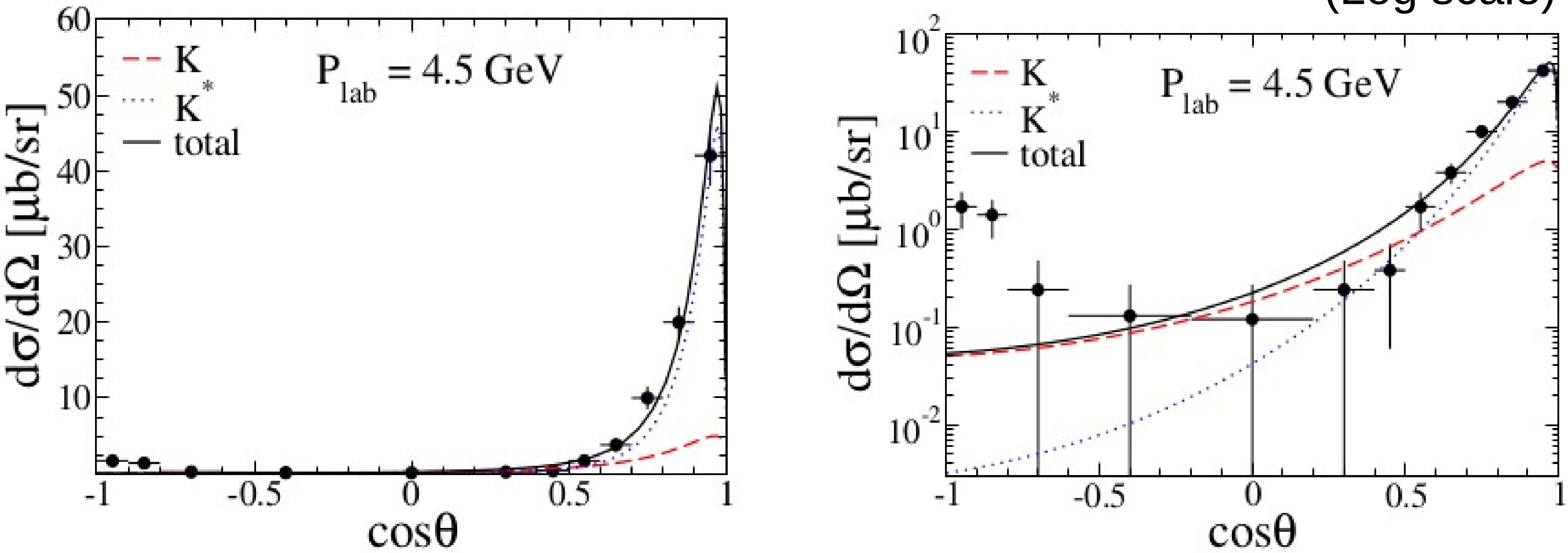
is 10^2 ~ 10^5 times smaller than that for the strange one(Πp → K*Λ).

Exp. Data : Dahl et al, PR 163.1377(1967) Crennell et al, PRD 6.1220(1972)

<Differential Cross Section> 2. Regge model

$$\pi^- p \rightarrow K^{*0}\Lambda$$

(Log scale)



The result for the K* exchange shows steeper behavior at forward direction than that for the K one.

Exp. Data : Crennell et al, PRD 6.1220(1972)

◇ We investigated pion induced production off the proton target, ($\pi p \to K^*\Lambda$, $\pi p \to D^*\Lambda_c$), within the Feynman and Regge model.

◇ In Feynman model, we take into account the contributions of $K(D)$, $K^*(D^*)$, N, and $\Sigma(\Sigma_c)$ particles.

In Regge approach, the $K(D)$ and $K^*(D^*)$ trajectories are considered.

The parameters are fixed by using the Quark-Gluon-String Model(QGSM).

◇ It turned out that the total cross section for the charm production ($\pi p \to D^*\Lambda_c$) is $10^2 \sim 10^5$ times smaller than that for the strange one($\pi p \to K^*\Lambda$).

◇ Further works : Baryon Regge model, Spin density matrices

Thank you very much for your attention