Inclusive pentaquark and strange baryons production in pp and Σp collisions at high energy

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Abstract

We calculate the cross sections for the inclusive production in the fragmentation region of $\Theta^+(1540)$ and $\Lambda(1520)$ in pp collisions and $\Lambda(1520)$ in Σp collisions at high energy using the K- and π-meson exchange diagrams, respectively. The contributions of these diagrams survive at asymptotically large energies and are energy independent in this region up to logarithmic and power corrections. We find that inclusive $\Theta^+(1540)$ production should be at the level of 1 μb $\times\, \Gamma_{\Theta KN}/\,1$ MeV. The ratio of the $\Theta^+(1540)$ over the $\Lambda(1520)$ yields is found to be $\sim 1\%$. The fraction of $\Lambda(1520)$ yields in Σp and pp collisions is ~ 2.7 that quantitatively agrees with the preliminary result of the Fermilab fixed target experiment E781.

1 Introduction

The possible existence of the Θ^+ pentaquark remains one of the puzzling mysteries of recent years. To date there are more than 20 experiments with evidence for this state, but criticism for the Θ^+ claim arises because similar number of high energy experiments did not find any evidence for the Θ^+, even though the other "conventional" three-quark hyperons such as $\Lambda(1520)$ hyperon resonance are seen clearly.

The situation is getting more intriguing, as recently CLAS collaboration reported negative results on Θ^+ photoproduction off proton and deuteron with high statistics. Meanwhile LEPS collaboration reported the new evidence of the Θ^+ in $\gamma d \to \Theta^+\Lambda(1520)$ [1]. Also, DIANA collaboration using increased statistics confirms its earlier result, and offers a new evidence for formation of a pentaquark baryon in the charge-exchange reaction $K^+n \to K^0p$ on a bound neutron [2]. New experiments are needed to confirm or refute the pentaquark existence.

Most of negative high energy experiments are high statistic hadron beam experiments. *E.g.* HERA-B, a fixed target experiment at the 920 GeV proton storage ring of DESY [3] finds no evidence for narrow signals in the $\bar{K}^0_S p$ channel and only sets modest upper limits for Θ^+ production of less than 16 μb/N and less than about 12% relative to $\Lambda(1520)$ in mid-rapidity region. This negative result would present serious rebuttal evidence to worry about. However, without obvious production mechanism of the Θ^+ (if it exists) or even $\Lambda(1520)$ the rebuttal is not very convincing.

In this paper we estimate the high-energy behavior of the Θ^+ and $\Lambda(1520)$ production cross sections in inclusive pp collisions using the K exchange diagram, which is known to survive at high energies in the beam/target fragmentation region. We show that the cross section of the Θ^+-production is suppressed compared to the production of $\Lambda(1520)$. This suppression is mainly due to the smallness of the coupling constant $G^2_{\Theta KN}$ compared to $G^2_{\Lambda KN}$ that in turn is

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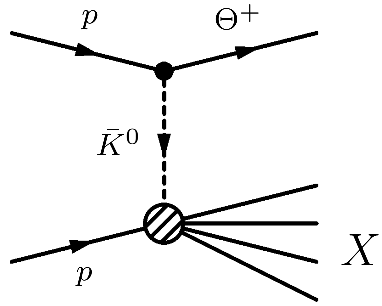

Figure 1: The $\bar{K}_0$ exchange diagram for the $\Theta^+(1540)$ production in inclusive pp scattering

related to the small width of the Θ^+. As a byproduct we also estimate the contribution of the π exchange diagram for the inclusive $\Lambda(1520)$ production in Σp collisions.

2 Inclusive cross sections

We assume that the Θ^+ exists. Consider the Θ^+ production in the reaction

$$p + p \to \Theta^+ + X \tag{1}$$

where X is unspecified inclusive final state carrying the strangeness -1. The $\bar{K}^0$ exchange diagram for $pp \to \Theta^+ X$ is shown in Fig. 1.

The standard expression for the single inclusive Θ^+ hadroproduction cross section in $p-p$ collisions in terms of the 4-momentum transfer squared $t = q^2$ and the invariant mass $W = \sqrt{s_1}$ of the $\bar{K}^0 p$ system is well known (see *e.g.* [6]). At high energy, it is more convenient to convert this expression to an integral over the Feynman variable x_F, the fraction of the incident proton momentum carried by the Θ^+ in the initial direction of the proton (in the center-of-mass system), and $k_\perp$, the transverse momentum of Θ^+ relative to the initial proton direction. Then the contribution of the K meson exchange to the double differential cross section for the Θ^+ inclusive production reads

$$\frac{d\sigma}{dx_F dk_\perp^2} = \frac{1}{4\pi} \frac{G^2_{\Theta K N}}{4\pi} J \frac{p}{E_\Theta} \Phi_{p\Theta}(t) F^4(t) \sigma_{\rm tot}^{\bar{K}^0 p}(s_1), \tag{2}$$

where

$$E_\Theta = \sqrt{x_F^2 p^2 + k_\perp^2 + m_\Theta^2}, \tag{3}$$

$$s_1 = s(p) + m_\Theta^2 - 2E_\Theta \sqrt{s(p)}, \tag{4}$$

$s(p) = 4(p^2 + m_p^2)$ being the center-of-mass energy squared, and

$$t = m_p^2 + m_\Theta^2 - 2E_\Theta \sqrt{p^2 + m_p^2} + 2x_F p^2. \tag{5}$$

The factor

$$J = \sqrt{\frac{\lambda(s_1, q^2, m_p^2)}{\lambda(s, m_p^2, m_p^2)}}, \tag{6}$$

where

$$\lambda(s, m_1^2, m_2^2) = s^2 - 2s(m_1^2 + m_2^2) + (m_1^2 - m_2^2)^2, \tag{7}$$

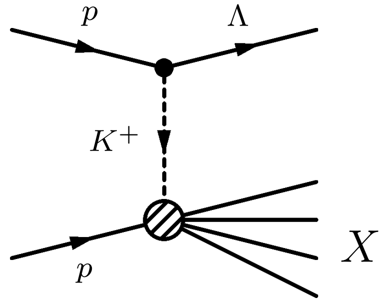

Figure 2: The K^+ exchange diagram for the $\Lambda(1520)$ production in inclusive pp scattering

is the ratio of flux factors in the pp and $\bar{K}^0 p$ reactions. The function $\Phi_{p\,\Theta}(t)$ is the squared product of the vertex function for $p \to \Theta^+ \bar{K}^0$ and the kaon propagator:

$$\Phi_{p\,\Theta}(t) = \frac{(m_p - m_\Theta)^2 - t}{(t - m_K^2)^2}. \tag{8}$$

To evaluate the cross sections away from the pole position $t = M_K^2$ we include the phenomenological form factor $F_K(t)$.

In the high energy limit with accuracy $\mathcal{O}(1/p^2)$

$$\begin{aligned} J \cdot \frac{p}{E_\Theta} &\approx \frac{1 - x_F}{x_F}, \quad s_1 \approx (1 - x_F)s, \\ t &\approx m_\Theta^2 + m_p^2(1 - x_F) - \frac{m_\Theta^2 + k_\perp^2}{x_F}, \end{aligned} \tag{9}$$

and Eq. (2) written in terms x_F and $k_\perp^2$ reads

$$\frac{d\sigma}{dx_F dk_\perp^2} = \frac{1}{4\pi} \frac{G_{\Theta KN}^2}{4\pi} \cdot \frac{1 - x_F}{x_F} \Phi_{p\,\Theta}(t) F^4(t) \sigma_{\rm tot}^{\bar{K}^0 p}(s_1). \tag{10}$$

Eq. (10) can be generalized for the fragmentation of a baryon a into a baryon b due to the exchange by the meson m (in particular, for the $\Lambda(1520)$ production in the reaction $p + p \to \Lambda(1520) + X$, see Fig. 2):

$$\frac{d\sigma_{ab}}{dx_F dk_\perp^2} = \frac{1}{4\pi} \frac{G_{bma}^2}{4\pi} \frac{1 - x_F}{x_F} \Phi_{ab}(t)\, F^4(t)\, \sigma_{\rm tot}^{mp}(s_1). \tag{11}$$

Explicit values of the coupling constants $G_{bma}^2/4\pi$ and expressions for Φ_{ab} used in our calculations are given below.

2.1 The $\Theta^+ KN$ vertex

The $\Theta^+ KN$ vertex for $J^P(\Theta^+) = \frac{1}{2}^+$ is

$$L_{\Theta KN} = iG_{\Theta KN}(K^\dagger \bar{\Theta} \gamma_5 N + \bar{N} \gamma_5 \Theta K), \tag{12}$$

with the operator γ_5 corresponding to positive Θ^+ parity. The Lagrangian (12) corresponds with the Θ^+ being a p-wave resonance in the $K^0 p$ system. The partial decay width $\Gamma_{\Theta \to K^0 p}$ is

$$\Gamma_{\Theta \to K^0 p} = \frac{G_{\Theta KN}^2}{4\pi} \cdot \frac{2p_K^3}{(m_\Theta + m_p)^2 - m_K^2}, \tag{13}$$

where $p_K = 260$ MeV/c is the kaon momentum in the rest frame of Θ^+. To extract the value for $G_{\Theta KN}$, we need the experimental information of the width $\Gamma_{\Theta KN}$, which is not known precisely but whose measurement is the subject of several planned dedicated experiments, see *e.g.* [7]. To provide numerical estimates, we will use the value $\Gamma_{\Theta\to K^0 p} = 1$ MeV. This corresponds to the full width $\Gamma_{\Theta KN} = \Gamma_{\Theta\to K^0 p} + \Gamma_{\Theta\to K^+ n} = 2$ MeV, which is consistent with the upper limit for the width derived from elastic KN scattering [8]. In the string model, a pentaquark containing three string junctions dissociates "fall apart" into two minimal color singlets containing only one string junction. Therefore the pentaquark decay is accompanied by the annihilation of the two string junctions. This may be an additional reason for the smallness of the pentaquark width.

Evaluating Eq. (13) with $\Gamma_{\Theta\to K^0 p} = 1$ MeV, we extract the value $G_{\Theta KN}$

$$\frac{G^2_{\Theta KN}}{4\pi} = 0.167 \cdot \frac{\Gamma_{\Theta\to K^0 p}}{1\ \text{MeV}}, \tag{14}$$

which will be used in the subsequent estimates for the inclusive cross section.

2.2 $\Lambda(1520)\, KN$ vertex

The $\Lambda(1520)\, KN$ vertex is

$$L_{\Lambda KN} = \frac{G_{\Lambda KN}}{m_K}\left(\bar{\Lambda}^\mu \gamma_5 N \partial_\mu K + \bar{N}\gamma_5 \Lambda^\mu \partial_\mu K^\dagger\right), \tag{15}$$

where Λ^μ is the vector spinor for the spin 3/2 particle. The Lagrangian (15) corresponds with the $\Lambda(1520)$ being a D-wave resonance in the $K^- p$ system.

We treat $\Lambda(1520)$ relativistically using the Rarita-Schwinger vector-spinor formalism [9] with the density matrix

$$L^{\mu\nu} = \frac{1}{4}(\hat{p}_\Lambda + m_\Lambda) \times \left[-g^{\mu\nu} + \frac{1}{3}\gamma^\mu\gamma^\nu + \frac{1}{3m_\Lambda}(\gamma^\mu p^\nu_\Lambda - \gamma^\nu p^\mu_\Lambda) + \frac{2}{3m^2_\Lambda} p^\mu_\Lambda p^\nu_\Lambda\right]. \tag{16}$$

The $\Lambda(1520) \to pK^-$ width is

$$\Gamma_{\Lambda\to K^- p} = \frac{G^2_{\Lambda KN}}{4\pi} \cdot \frac{2p_K^5}{3m_K^2} \cdot \frac{1}{(m_\Lambda + m_p)^2 - m_K^2}, \tag{17}$$

where $p_K = 246$ MeV/c is the kaon momentum in the rest frame of $\Lambda(1520)$. Using the PDG values of $\Gamma_{\text{tot}}(\Lambda(1520)) = 15.6$ MeV and $\text{Br}(\Lambda(1520) \to N\bar{K}) = 45\%$ we obtain

$$\Gamma_{\Lambda\to K^- p} = \frac{1}{2} \cdot \text{Br}(\Lambda \to N\bar{K}) \cdot \Gamma_{\text{tot}} = \frac{1}{2} \cdot 0.45 \cdot 15.6\ \text{MeV} = 3.51\ \text{MeV} \tag{18}$$

and

$$\frac{G^2_{\Lambda KN}}{4\pi} \approx 8.14. \tag{19}$$

The function $\Phi_{p\Lambda}(t)$ in Eq. (11) is

$$\Phi_{p\Lambda}(t) = \frac{(m_p + m_\Lambda)^2 - t}{6m^2_\Lambda m^2_K} \cdot \frac{((m_p - m_\Lambda)^2 - t)^2}{(t - m^2_K)^2}. \tag{20}$$

The expression (20) includes the factor $1/m_K$ in (15).

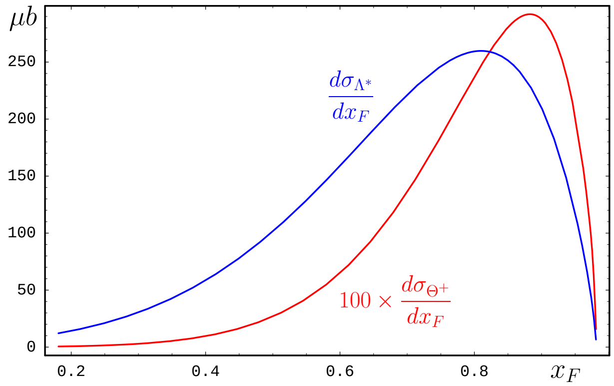

Figure 3: x_F dependence of the inclusive $pp \to \Theta^+(1540)$ and $\Lambda(1520)$ cross sections

2.3 $\Lambda(1520)\,\pi\Sigma$ vertex

The $\Lambda(1520)\,\pi\Sigma$ vertex is written in analogy with (15):

$$L_{\Lambda\pi\Sigma} = \frac{G_{\Lambda\pi\Sigma}}{m_\pi}\left(\bar{\Lambda}^\mu\gamma_5\Sigma\partial_\mu\pi + \bar{\Sigma}\gamma_5\Lambda^\mu\partial_\mu\pi^\dagger\right), \tag{21}$$

The $\Lambda(1520) \to \Sigma^+\pi^-$ width is

$$\Gamma_{\Lambda\to\pi^-\Sigma^+} = \frac{G^2_{\Lambda\pi\Sigma}}{4\pi}\cdot\frac{2p_\pi^5}{3m_\pi^2}\cdot\frac{1}{(m_\Lambda+m_\Sigma)^2-m_\pi^2}, \tag{22}$$

where $p_\pi = 266$ MeV/c is the pion momentum in the rest frame of $\Lambda(1520)$. Using the PDG values of $\mathrm{Br}(\Lambda(1520)\to\Sigma\pi) = 42\%$ we obtain

$$\Gamma_{\Lambda\to\pi^-\Sigma^+} = \frac{1}{3}\cdot\mathrm{Br}(\Lambda\to\pi\Sigma)\cdot\Gamma_{\text{tot}} = \frac{1}{3}\cdot 0.42\cdot 15.6\text{ MeV} = 2.18\text{ MeV} \tag{23}$$

and

$$\frac{G^2_{\Lambda\pi\Sigma}}{4\pi} \approx 0.353 \tag{24}$$

The function $\Phi_{\Sigma\Lambda}(t)$ is obtained from that given in Eq. (20) by substitution $m_p \to m_\Sigma$, $m_K \to m_\pi$.

3 Results

The total cross sections can be obtained by integrating (10) over $k_\perp^2$ and x_F

$$\sigma_{ab} = \frac{G^2_{bma}}{4\pi}\int dx_F\int dk_\perp^2\,K_{ab}(x_F,k_\perp^2)\,\sigma^{mp}_{\text{tot}}(s_1), \tag{25}$$

where s_1 is given in (9) and

$$K_{ab}(x_F,k_\perp^2) = \frac{1-x_F}{x_F}\,\Phi_{ab}(t)\,F^4(t). \tag{26}$$

The kinematical limits of integration in (10) are given by equation

$$x_F^2 + \frac{k_\perp^2}{p^2} \le \frac{(s(p)+m_b^2-s_0)^2-4s(p)m_b^2}{4p^2s(p)}, \tag{27}$$

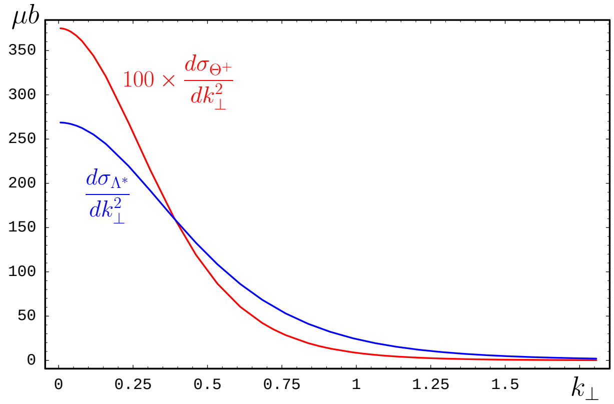

Figure 4: $k_\perp$ dependence of the inclusive $pp \to \Theta^+(1540)$ and $\Lambda(1520)$ cross sections

where $s_0 = (m_p + m_K)^2$ for the K-exchange and $s_0 = (m_p + m_\pi)^2$ for the π-exchange. We employ two representative examples for the form factor $F(t)$ in (10):

$$\mathrm{A}: \ F(t) = \frac{\Lambda^2 - m_K^2}{\Lambda^2 - t}, \quad \text{and} \quad \mathrm{B}: \ F(t) = \frac{\Lambda^4}{\Lambda^4 + (t - m_K^2)^2}, \tag{28}$$

the cut-off parameter Λ being a typical hadronic scale $\Lambda = 1$ GeV.

Because of (9) all the energy dependence of the right hand side of Eq. (10) is due to the factor $\sigma_{\bar{K}^0 p}(s_1)$. Since $\sigma(s_1)$ is slow varying function of $s_1 = (1 - x_F)s$, we can take it out of the integral at the point $\hat{s}_1 = (1 - \hat{x}_F)s$, where $\hat{x}_F$ is the point at which $d\sigma^{ab}/dx_F$ reaches the maximum[1]. Then we obtain

$$\sigma_{ab} \approx \frac{G_{bma}^2}{4\pi} \sigma_{\rm tot}^{mp}(\hat{s}_1) \hat{K}_{ab}, \tag{29}$$

where the quantities

$$\hat{K}_{ab} = \int dx_F \int dk_\perp^2 \, K_{ab}(x_F, k_\perp^2) \tag{30}$$

do not depend on energy, and $\sigma_{\rm tot}^{mp}(\hat{s}_1)$ is a constant up to logarithmic and power corrections.

For estimation we take the total cross sections $\sigma_{\rm tot}^{\bar{K}^0 p}$ and $\sigma_{\rm tot}^{K^+ p}$ to be a constant ($\sigma_{\rm tot}^{\bar{K}^0 p} \sim \sigma_{\rm tot}^{K^+ p} \sim 20$ mb at $\sqrt{s_1} \gtrsim 10$ GeV.) Then we obtain for the production cross sections[2]

$$\begin{gathered} \sigma(pp \to \Theta^+(1540)X) = 0.8\,(1.6) \times \frac{\Gamma_{\Theta \to K^0 p}}{1\ \mathrm{MeV}}\ \mu\mathrm{b}, \\ \sigma(pp \to \Lambda^+(1520)X) = 106\,(126)\ \mu\mathrm{b}, \end{gathered} \tag{31}$$

where the first values refer to the form factor (A) and the second ones to the form factor (B). The result for $\sigma(pp \to \Theta^+ X)$ matches well that of Ref. [10] for the inclusive $pp \to \Theta^+ X$ production[3] at $\sqrt{s} \lesssim 10$ GeV. If $\Gamma_{\Theta KN} = 0.36 \pm 0.11$ MeV as is claimed in [2], our result for the Θ^+ production cross section should be correspondingly smaller.

In scattering hadronic probes at high energy from nuclear target the only positive signal for the Θ^+ decaying to $K_S^0 p$ was reported by the SVD Collaboration, using 70 GeV proton in a fixed target arrangement $pA \to \Theta^+ X$ at a center-of-mass energy of about 11.5 GeV. Their

[1]The typical values of $\hat{x}_F$ are $\sim 0.8 - 0.9$, depending on the reaction considered; they tabulated in Table 1. Therefore, in the fragmentation region, the effective energy $\sqrt{\hat{s}_1}$ is *always much smaller* than $\sqrt{s}$.

[2]The values in (31) correspond to the region $x_F \gtrsim 0$. For pp scattering the total cross sections are two times larger.

[3]The authors of Ref. [10] used the standard expression for the inclusive cross section and $\sigma_{\rm tot}$ [6] taken from the parametrization of experimental data at low energies.

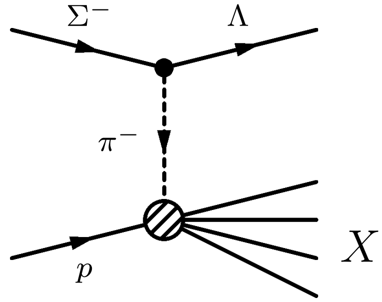

Figure 5: The π-meson exchange diagram in $\Lambda(1520)$ production in inclusive Σp scattering

initial report [4] recently was supported by a more detailed analysis [5] which increased their pentaquark signal by a factor of about 8. Our prediction for $\sigma(pp \to \Lambda(1520)^+ X)$ agrees with the preliminary result of the SVD-2 collaboration [5], but $\sigma(pp \to \Theta^+ X)$ is lower than the preliminary cross section estimation (for $x_F > 0$) of Ref. [5]: $\sigma \cdot \mathrm{Br}(\Theta^+ \to pK^0) \sim 6\ \mu$b.

The illustrative examples of x_F and $k_\perp$ distributions for the Θ^+ and $\Lambda(1520)$ are shown in Figs. 3, 4 for the form factor A. For the average transfer momenta squared of the Θ^+ we get

$$\langle k_\perp^2 \rangle = 0.29\,(0.17)\ \mathrm{GeV}^2, \tag{32}$$

while for the $\Lambda(1520)$

$$\langle k_\perp^2 \rangle = 0.73\,(0.22)\ \mathrm{GeV}^2, \tag{33}$$

respectively, where as above the first values refer to the form factor (A) and the second ones to the form factor (B).

The ratio of Θ^+ to $\Lambda(1520)$ production cross-sections is $\sim 1\%$. Our estimation is a bit larger than that obtained in the fragmentation-recombination model [11] but still is rather small and probably can be useful to explain why the Θ^+ production is suppressed in some high energy experiments.

In the same way it is possible to make quantitative predictions for other type of colliding particles. As an example, we estimate the cross section for the inclusive $\Lambda(1520)$ production in $\Sigma^- p \to \Lambda(1520)$ collisions at 600 GeV/c studied in the fixed target Fermilab experiment E771 (SELEX). In the fragmentation region of the Σ-hyperon this reaction can proceed via the π-meson exchange, see Fig. 5. Using $\frac{G^2_{\Lambda\pi\Sigma}}{4\pi}$ from (24) and $\sigma(\pi N) = 25\ \mu$b we get

$$\sigma(\Sigma p \to \Lambda(1520) X) = 314\,(340)\ \mu\mathrm{b}, \tag{34}$$

where, as before, the first value refer to the form factor (A) and the second ones to the form factor (B). Taking $\hat{x} = 0.83$ from Table 1 for the ratio of inclusive Σp and pp cross sections we get

$$\frac{\sigma(\Sigma p \to \Lambda(1520) X)}{\sigma(pp \to \Lambda(1520) X)} \approx 2.9\,(2.7), \tag{35}$$

that agrees with the preliminary experimental result

$$\frac{\sigma(\Sigma p \to \Lambda(1520) X)}{\sigma(pp \to \Lambda(1520) X)} \approx 2.6, \tag{36}$$

of the SELEX collaboration [12].

Table 1: The production cross sections (in units of μb) and $\langle k_\perp^2 \rangle$ (in units of GeV^2). Also are shown the values of $\hat{x}$ explained in the text

		$\Theta^+(1540)$			$\Lambda(1520)$		
		σ	$\langle k_\perp^2 \rangle$	$\hat{x}$	σ	$\langle k_\perp^2 \rangle$	$\hat{x}$
pp	A	0.8	0.29	0.90	107	0.73	0.83
	B	1.56	0.17	0.91	126	0.22	0.88
Σp	A				314	0.60	0.83
	B				340	0.21	0.85

4 Conclusions

Let us recall that our estimations may somehow depend on specific assumptions regarding for instance the K-meson exchange dominance at forward direction, and on the choice of the form factor. As an outlook, it would be interesting to go beyond the present calculation and to perform a systematic study of K, K^* and π Regge exchanges into inclusive production of (anti)strange baryons in pp collisions. We plan to come back to these issues in a next publication.

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