Inclusive $\Theta^+(1540)$ and $\Lambda(1520)$ production in pp and Σp collisions at high energy

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Many experiments from around the world have presented evidence for (and against) a possible exotic pentaquark spectrum. To date there are more than 20 experiments with evidence for the Θ^+, but similar number of high energy experiments did not find any evidence for the Θ^+, even though the other "conventional" three-quark hyperons such as $\Lambda(1520)$ are seen clearly.

Knowledge of the existence, or non-existence, of pentaquark states is of vital importance in the search for the mechanism of quark confinement.

OUTLINE

- Experimental background
- Inclusive production of the Θ^+ and $\Lambda(1520)$
- Coupling constants
- Theoretical expectations of the cross sections
- Conclusions

Table 1: **The Θ^+, $\Xi^{--}_{\frac{3}{2}}$, and Θ_c positive observations before 2005**

Collaboration	Reaction	Mass (MeV)
LEPS	$\gamma n \to K^+K^-n$ (^{12}C)	1540±10
DIANA (ITEP)	$K^+Xe \to K^0pXe'$	1539±2
CLAS(d)	$\gamma d \to K^+K^-pn$	1542±4
CLAS(p)	$\gamma p \to K^+K^0_s n$	1555±10
SAPHIR	$\gamma p \to K^+K^0_s n$	1540±2
HERMES	γd, $\Theta^+ \to pK_S \to p\pi\pi$	1528±3
νBC	$\nu d, Ne \to (pK^0_S)X$	1533±5
SVD-2	$pA \to (pK^0_S)X$	1526±3
COSY, Juelich	$pp \to (pK^0_S)\Sigma^+X$	1530±5
Dubna	$pC_3H_8 \to pK^0_SX$	1545.1±12.0
ZEUS	$ep \to (pK^0_S)X$	1522±3
NA49	$pp \to \Xi^-\pi^-(\pi^+) + X$	1862±2
H1	$ep \to D^{*-}p + X$	3099 ± 6

Experimental background 2005-06

CLAS-g11 (2005): negative results on the Θ^+ photoproduction in γp and γd. More than 10 times the statistics of previous measurements.

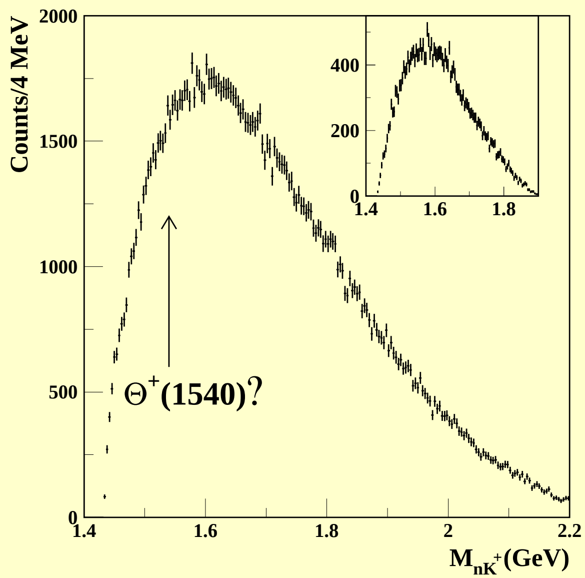

Figure 1: Experiment g11 at JLab. The nK^+ invariant mass distribution after all cuts. It is smooth and no narrow structures are evident. The arrow shows the position where evidence for the Θ^+ was found by previous experiments.

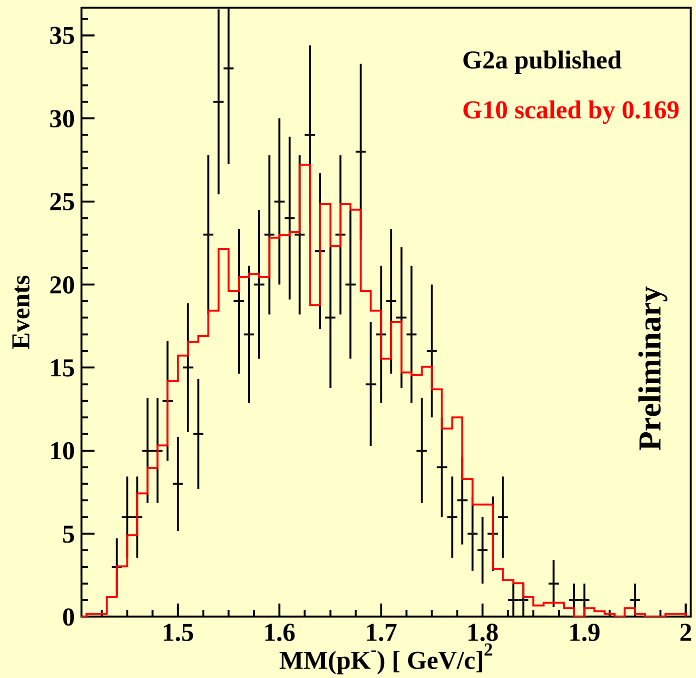

Figure 2: Missing mass of the pK^- system for the reaction $\gamma d \rightarrow pK^-K^+n$ measured at CLAS. The points with error bars are the previous CLAS results showing evidence for the Θ^+, the solid histogram shows new high-statistics results, scaled down by the factor 0.169, showing no evidence for the Θ^+

LEPS (2005): a new evidence of the Θ^+ in $\gamma d \to \Theta^+ \Lambda(1520)$.

CLAS (2006): negative results on Θ^+ photoproduction in $\gamma d \to \Lambda n K^+$

Still a convincing experiment is needed. Perhaps KN...

The quote about pentaquark:

From the presentation and discussions at the workshop, the unanimous view is that the gold-plated experiment which we need is the K^+ beam on nucleus. This makes DIANA (ITEP) data extremely valuable. The consensus is that the statistics of DIANA is a goal of primary importance...Marek Karliner, Pentaquark Workshop, JLab, October 2005

DIANA (2006): a new evidence for the Θ^+ formation in $K^+ n \to K^0 p$ on a bound neutron.

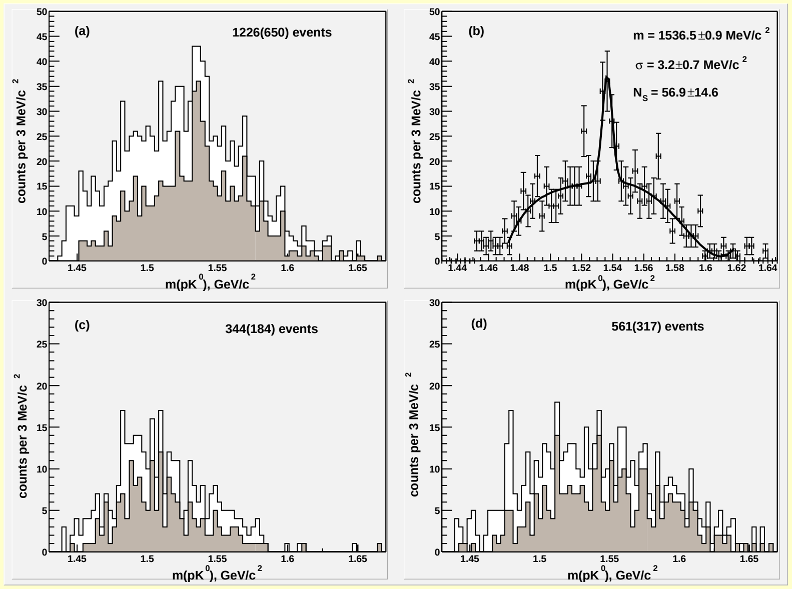

Figure 3: (b) Effective mass of the pK^0 system formed in the reaction $K^+ n \to K^0 p$ after all cuts. (c) $p_{\rm beam} < 445$ MeV/c, (d) $p_{\rm beam} > 525$ MeV/c. Two times the statistics of the previous measurements. After the DIANA collaboration, hep-ex/0603017

New experiments are needed to confirm or refute the Θ^+ existence.

Most of negative high energy experiments are high statistic hadron beam experiments.

Table 2: Upper limits on relative yields of Θ^+ and $\Lambda(1520)$ at 95% level

Experiment	Reaction	Upper limits	Comments
HERA-B	$pA \to K^0 pX$	$< 0.02 \times \Lambda^*$	mid-rapidity
CDF	$\bar{p}p \to K^0 pX$	$< 0.03 \times \Lambda^*$	mid-rapidity
E690	$pp \to K^0 pX$	$< 0.005 \times \Lambda^*$	800 GeV/c mid-rapidity
PHENIX	$Au + Au$	not given	
SVD-2	$pA \to K^0_S pX$	$4 - 6$ %	$x_F > 0$

HERA-B is a fixed target experiment at the 920 GeV proton storage ring of DESY
CDF stands for the Collider Detector at Fermilab
PHENIX high energy collision of heavy ions and protons at RHIC
SVD is a fixed target experiment at the 70 GeV proton beam in Protvino.

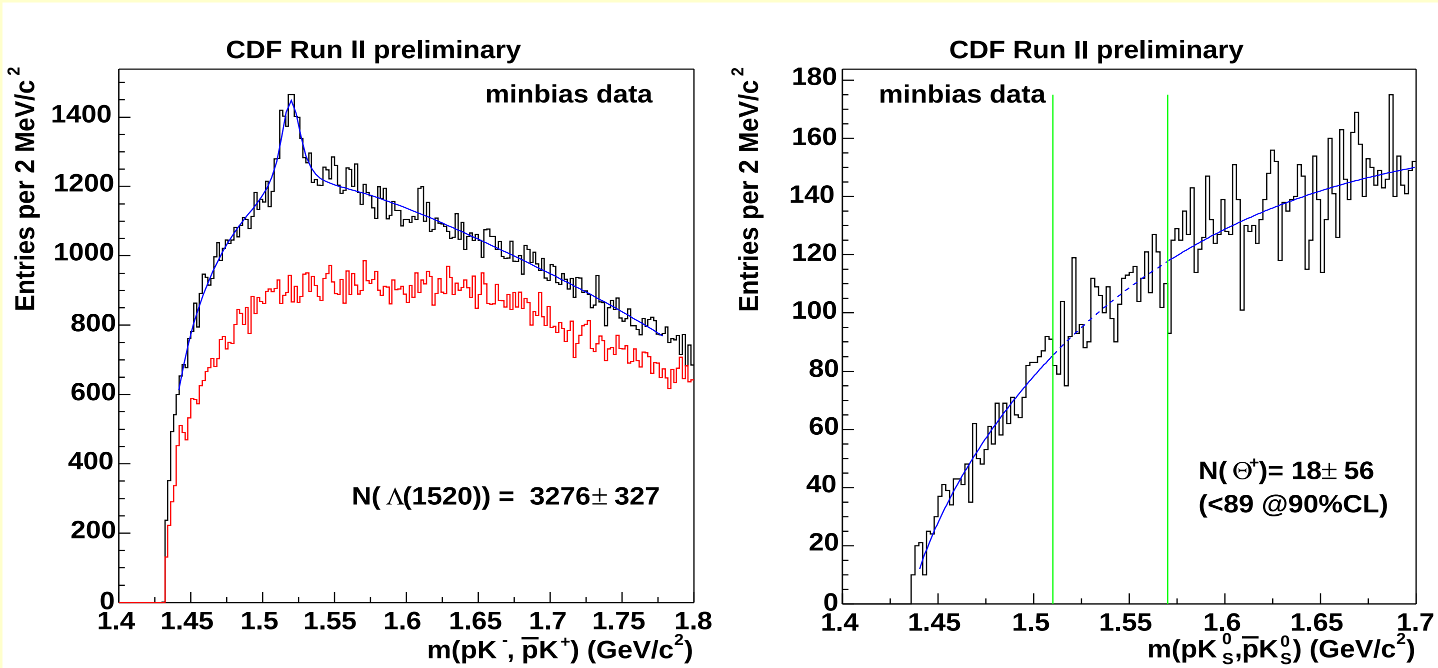

Figure 4: CDF II experiment. Left: an invariant mass spectrum of the pK^- (and pK^+) combinations showing well established resonance $\Lambda(1520)$. Right: an invariant mass spectrum of pK_S^0 combinations, two vertical lines indicate the Θ^+ search window.

IHEP result (SVD-2 detector) on $pA \to pK_S^0 X$ reaction with 70 GeV protons hep-ex/0509033:

- $M_\Theta = 1523 \pm 2(stat) \pm 3(syst)$ MeV, $\Gamma < 14$ MeV
- $\sigma \cdot \mathcal{B}R(\Theta^+ \to p\bar{K}^0) \sim 6$ μb
- $\Lambda(1520)$ cross section for $x_F > 0$ is estimated to be 100-150 μb

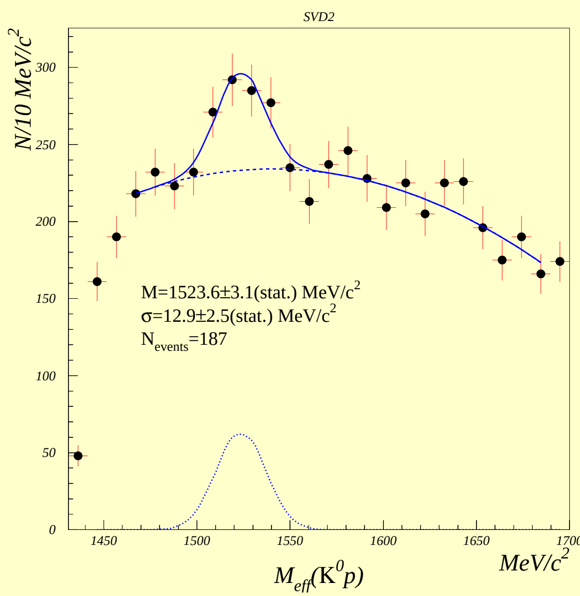

Figure 5: The pK_s^0 invariant mass spectrum after appropriate cuts.

The purpose of this talk is to estimate the Θ^+ and $\Lambda(1520)$ production cross sections in inclusive pp collisions using the K exchange diagram, which we believe is at work for the inclusive production in the beam/target fragmentation region.

The contributions of these diagrams survive at high energies and are energy independent in this region up to logarithmic and power corrections.

We find that inclusive Θ^+ production should be at the level of

$$1\ \mu\text{b} \times \Gamma_{\Theta K N}/1\ \text{MeV}.$$

The ratio of the Θ^+ over the $\Lambda(1520)$ yields is $\sim 1\%$ or less.

The Θ^+-production is suppressed compared to the production of $\Lambda(1520)$ due to the smallness of the coupling constant $G^2_{\Theta K N}$ compared to $G^2_{\Lambda K N}$ that in turn is 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 studied in the fixed target Fermilab experiment E771 at 600 GeV/c

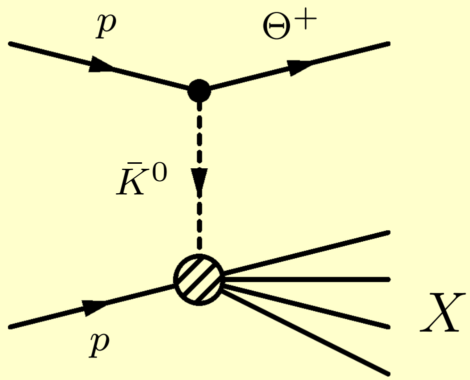

Figure 6: The $\bar{K}_0$ exchange diagram for the Θ^+ production

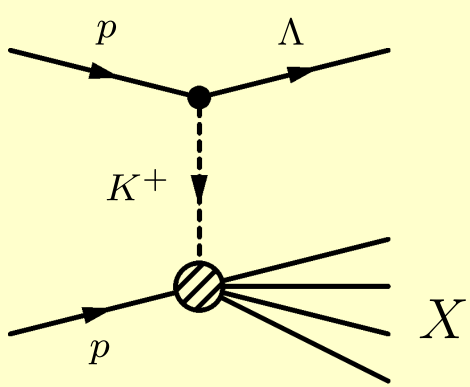

Figure 7: The K^+ exchange diagram for the $\Lambda(1520)$ production

The double differential cross section for $pp \to \Theta^+ X$ is

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

x_F is 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 $\mathbf{k}_\perp$ is the transverse momentum of Θ^+ relative to the initial proton direction.

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

$$s_1 \approx (1-x_F)s, \quad t \approx m_\Theta^2 + m_p^2(1-x_F) - \frac{m_\Theta^2 + k_\perp^2}{x_F}$$

General case: fragmentation $a \to b$, exchange by a meson m

$$\frac{d\sigma_{ab}}{dx_F dk_\perp^2} = \frac{1}{4\pi} \frac{G^2_{bma}}{4\pi} \frac{1-x_F}{x_F} \Phi_{ab}(t) F^4(t) \sigma_{\mathsf{tot}}^{mp}(s_1)$$

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

$$\Phi_{p\Lambda} = \frac{(m_p + m_\Lambda)^2 - t}{6m_\Lambda^2 m_K^2} \cdot \frac{((m_p - m_\Lambda)^2 - t)^2}{(t - m_K^2)^2}$$

$$\Phi_{\Sigma\Lambda} = \frac{(m_\Sigma + m_\Lambda)^2 - t}{6m_\Lambda^2 m_\pi^2} \cdot \frac{((m_\Sigma - m_\Lambda)^2 - t)^2}{(t - m_\pi^2)^2}$$

The only unknown are $G^2_{bma}/4\pi$ and $F(t)$.

The $\Theta^+(1540)KN$ vertex

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

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

with the operator γ_5 corresponding to positive Θ^+ parity. The partial decay width $\Gamma_{\Theta\to K^0 p}$

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

where $p_K = 260$ MeV/c. To provide numerical estimates, we use $\Gamma_{\Theta\to K^0 p} = 1\,\mathrm{MeV}$, which is consistent with the upper limit for the width derived from elastic KN scattering. Then

$$\frac{G^2_{\Theta KN}}{4\pi} = 0.167 \cdot \frac{\Gamma_{\Theta\to K^0 p}}{1\ \mathrm{MeV}}.$$

$\Lambda(1520)\, KN$ vertex

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

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

where Λ^μ is the vector spinor for the spin 3/2 particle. The $\Lambda(1520) \to pK^-$ width is

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

$$\Gamma_{\text{tot}}(\Lambda(1520)) = 15.6 \text{ MeV and } \mathcal{B}R(\Lambda(1520) \to N\bar{K}) = 45\%, \quad \text{(PDG)}$$

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

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

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

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

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

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

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

where $p_\pi = 266\ \mathrm{MeV/c}$ 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

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

and

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

The total cross sections

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

where

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

All the energy dependence is due $\sigma_{\text{tot}}^{mp}(s_1)$ which is slow varying function of $s_1 = (1-x_F)s$. One 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. The typical values of $\hat{x}_F$ are $\sim 0.8 - 0.9$, depending on the reaction considered. Therefore, in the fragmentation region,

the energy $\sqrt{\hat{s}_1} \approx (0.3-0.4)\sqrt{s}$ is always much smaller than $\sqrt{s}$

The result is

$$\sigma_{ab} = \frac{G_{bma}^2}{4\pi}\sigma_{\text{tot}}^{mp}(\hat{s}_1)\hat{K}_{ab},$$

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

Two representative examples for the form factors $F(t)$

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

the cut-off parameter $\Lambda = 1$ GeV. We take

$$\sigma_{\text{tot}}^{\bar{K}^0 p} \sim \sigma_{\text{tot}}^{K^+ p} \sim 20 \text{ mb}$$

Then

$$\sigma(pp \to \Theta^+ X) = 0.8\ (1.6) \times \frac{\Gamma_{\Theta \to K^0 p}}{1 \text{ MeV}}\ \mu\text{b},$$

$$\sigma(pp \to \Lambda(1520)^+ X) = 106\ (126)\ \mu\text{b}, \quad \text{agrees with SVD2}$$

The first values refer to the form factor (A) and the second ones to the form factor (B).

If $\Gamma_{\Theta KN} = 0.36 \pm 0.11$ MeV (new Diana value), our result for the Θ^+ production cross section should be correspondingly smaller. One can expect that the K^* exchange yields the cross sections of the similar order of magnitude.

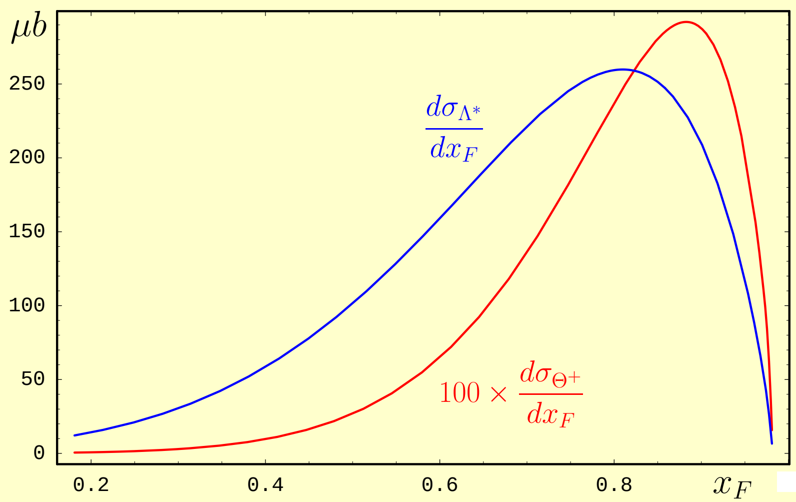

Figure 8: x_F dependence of the inclusive $pp \to \Theta^+$ and $\Lambda(1520)$ cross sections

The typical $k_\perp$ dependence of the inclusive $pp \to \Theta^+$ and $\Lambda(1520)$ cross sections

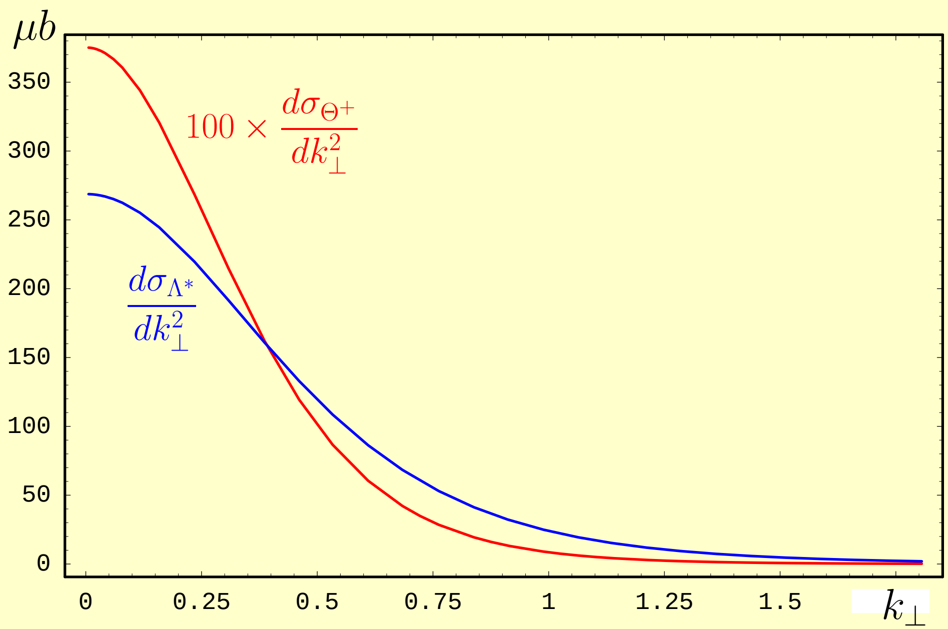

Table 3: The production cross sections (in units of μb) and $\langle k_\perp^2 \rangle$ (in units of GeV^2).

Reaction	FF	Θ^+			$\Lambda(1520)$		
		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

The last two entries refer to the fixed target Fermilab experiment E771 (SELEX) at 600 GeV/c

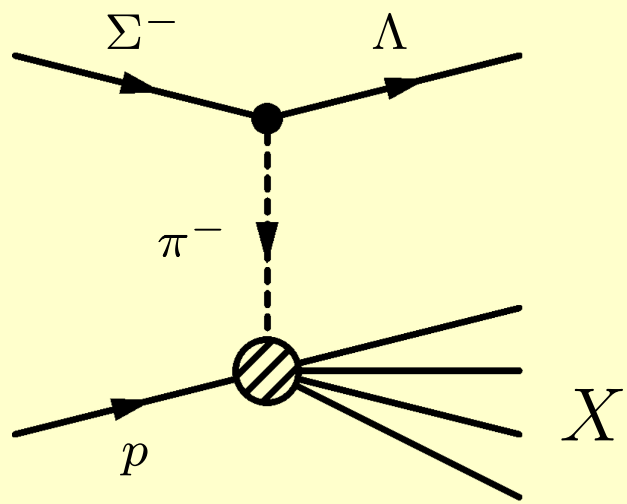

Figure 9: The π exchange diagram for $\Lambda(1520)$ inclusive production in Σp

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

$$\frac{\sigma(\Sigma p \to \Lambda(1520) X)}{\sigma(pp \to \Lambda(1520) X)} \approx 2.9\,(2.7)\ \ (\mathrm{exp}\ \approx 2.6\ \mathrm{from\,the\,SELEX})$$

It seems that one-meson exchange diagram works !

Conclusions

- Still a convincing experiment is needed
- Fragmentation cross sections in inclusive pp are of order

  1 μb for the Θ^+ and 100 μb for the $\Lambda(1520)$

- Our estimations are no more than a guess, as it may somehow depend on our specific assumptions regarding for instance the meson exchange dominance at forward direction, not to say the intrinsic uncertainty coming from the choice of the form factor.
- Further theoretical investigations of production mechanisms are welcome