DOES PENTAQUARK θ^+ EXIST?

(Viewing from HEPD)

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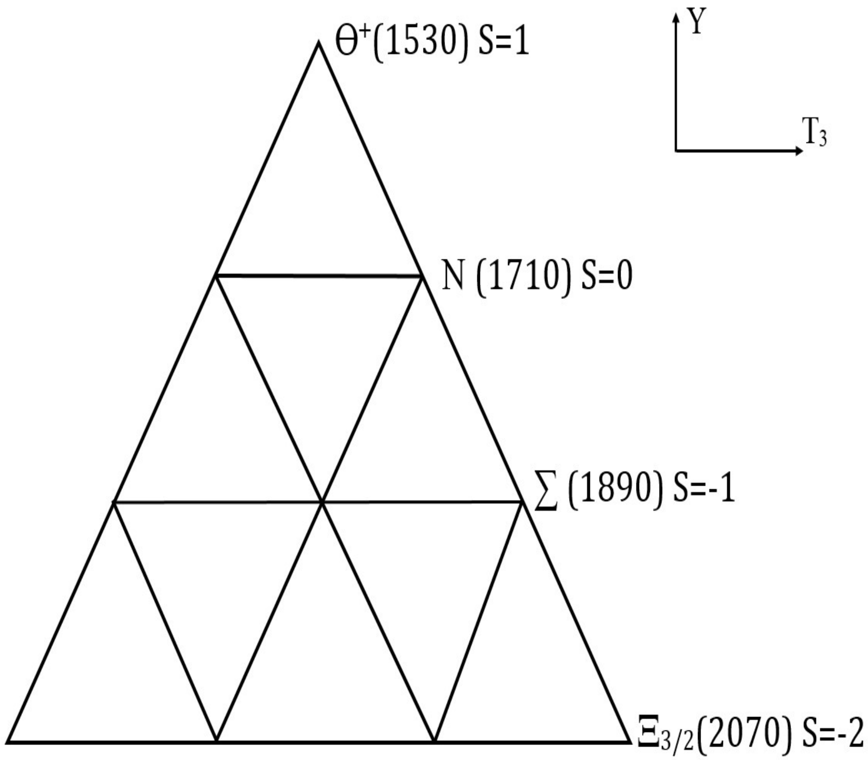
Contents

Model by Diakonov, Petrov, and Polyakov

- Anti-decuplet of pentaquarks
  $M = (1.89 - 0.18 \cdot Y)$ GeV$/c^2$, $Y = B + S$, $Q = T_3 + Y/2$.
  Mass of N dublet is put equal to 1710 GeV$/c^2$.
  Quark content: $\theta^+ = uudd\bar{s}$. Quantum numbers: $B = 1$, $S = 1$, $Y = 2$, $T = 0$, $J^P = \frac{1}{2}^+$
  Model parameters are fixed by parameters of meson octet, baryon octet and decuplet, and the mass of $N(1710)$.
  Then $M_{\theta^+} = 1.53$ GeV$/c^2$, $\Gamma_{tot} < 15$ MeV$/c^2$.
  θ^+ is stable particle when $M_{\theta^+} < M_N + M_K$, since $\theta^+ \to n + K^+$ and $\theta^+ \to p + K^0$.



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First Evidences that θ^+ Exists

- First data in 2003 year
- LEPS Collaboration, Phys. Rev. Lett. 91 (2003) 012002.

  Reaction $\gamma + n \to \theta^+ + K^- \to K^+ + K^- + X$ on ^{12}C,

  Assumed $X = n$, $0.9 < M_X < 0.98$ GeV$/c^2$.

  $M_{\theta^+} = (1.54 \pm 0.01)$ GeV$/c^2$, $\Gamma_{tot} < 25$ MeV$/c^2$,

  significance $S/\sqrt{B} = 19.0/\sqrt{17.0} = 4.6\sigma$,

  but $S/\sqrt{S+B} = 3.2\sigma$.
- DIANA Collaboration, Phys. At. Nucl. 66 (2003) 1715.

  Reaction $K^+ + Xe \to p + \pi^+ + \pi^- + X$,

  Subprocess $K^+ + n \to \theta^+ \to p + K^0$, $K^0_S \to \pi^+ + \pi^-$.

  $M_{\theta^+} = (1.539 \pm 0.002)$ GeV$/c^2$, $\Gamma_{tot} < 9$ MeV$/c^2$,

  significance $S/\sqrt{B} = 29/\sqrt{44} = 4.4\sigma$.

First Evidences that θ^+ Exists

- CLAS Collaboration, Phys. Rev. Lett. 91 (2003) 252001.

  Reaction $\gamma + d \rightarrow K^+ + K^- + p + n$.

  $M_{\theta^+} = (1.542 \pm 0.005)$ GeV$/c^2$, $\Gamma_{tot} < 21$ MeV$/c^2$,

  significance $S/\sqrt{B} = 43/\sqrt{54} = (5.2 \pm 0.6)\sigma$.

- SAPHIR Collaboration, Phys. Lett. B572 (2003) 127.

  Reaction $\gamma + p \rightarrow \bar{K}^0 + \theta^+ \rightarrow \bar{K}^0 + K^+ + n$,

  oscillation $\bar{K}^0 \rightarrow K^0_S + K^0_L$, decay $K^0_S \rightarrow \pi^+ + \pi^-$.

  $M_{\theta^+} = (1.540 \pm 0.004 \pm 0.002)$ GeV$/c^2$, $\Gamma_{tot} < 25$ MeV$/c^2$,

  significance 4.8σ, $N_{\theta^+} = 63 \pm 13$, $\sigma_{\theta^+} = 300$ nb.

First Evidences that θ^+ Exists

- Bandwagon effects (after 2003 year)
- Neutrino experiments WA21, WA25, WA59, E180, E632, (CERN and Fermilab data were reanalyzed)
  Phys. At. Nucl. 67 (2004) 682.
  Reaction $\nu_\mu(\bar{\nu})_\mu + T \to K^0_S + p + X$, $K^0_S \to \pi^+ + \pi^-$,
  $T = p,\ d,\ Ne - H_2$ mix.
  $M_{\theta^+} = (1.533 \pm 0.005)$ GeV$/c^2$, $\Gamma_{tot} < 20$ MeV$/c^2$,
  significance 6.7σ.
- HERMES Collaboration, Phys. Lett. B585 (2004) 213.
  Reaction $\gamma + d \to K^0_S + p + X$, $X = n$, $K^0_S \to \pi^+ + \pi^-$.
  $M_{\theta^+} = (1.528 \pm 0.0026 \pm 0.0021)$ GeV$/c^2$,
  $\Gamma_{tot} < 4.3$ MeV$/c^2$,
  significance $(3.4 \div 6.3)\sigma$.

Vanishing Pentaquarks

- Null and Negative Results
- CLAS negative result (no θ^+ signal)
  CLAS against SAPHIR data for the same reaction
  $\gamma + p \to \bar{K}^0 + K^+ + n$
  $\sigma_{\theta^+} = \sigma(\gamma + p \to \theta^+ + \bar{K}^0) < 0.8$ nb, $L = 70 pb^{-1}$,
  $N_{\theta^+} = L\sigma_{\theta^+} = 56000$. SAPHIR: $\sigma_{\theta^+} = 300$ nb.
- Belle null result
  Reaction $K^+ + n \to \theta^+ \to p + K^0$, $K^0_S \to \pi^+ + \pi^-$,
  $\sigma(\theta^+)/\sigma(\Lambda(1520)) < 0.02$, $N_{obs}(\Lambda(1520)) = 15519 \pm 412$.
  For $M_{\theta^+} = 1540$ MeV, $N(\theta^+) = 29 \pm 65$,
  $N(\theta^+) < 94$ at 90% CL.

Vanishing Pentaquarks

- Bandwagon effects of not to observe the θ^+ pentaquark
- HERMES Collaboration, Phys. Lett. B585 (2004) 213.
  Phys. Rev. D91 (2015) 057101

  The same reaction $\gamma + d \to K^0_S + p + X$, $K^0_S \to \pi^+ + \pi^-$.

  Previous: $M_{\theta+} = 1.528$ GeV$/c^2$, $\Gamma_{tot} < 4.3$ MeV$/c^2$,

  significance $(3.4 \div 6.3)\sigma$.

  New: $M_{\theta+} = 1.522$ GeV$/c^2$, $N_{\theta+} = 68^{+98}_{-31}(stat) \pm 13(sys)$.
  significance 2σ.
- But LEPS and DIANA insist on the θ^+ observation
  LEPS 2019: $\gamma + d \to K^+ + K^- + p + n$ significance 3 σ.
  DIANA 2018 study angular distribution: significance 7.1σ.
- None discovery can be made by majority voting

Coherent Background

- Ignorance of coherence in data processing

Example: reaction $\gamma + d \to K^+ + K^- + p + n$.

Signal: $\gamma + n \to \theta^+ + K^- \to (K^+ + n) + K^-$.
Amplitude $F_{\theta+}$. Proton spectator.
First background process:
$\gamma + d \to \phi + p + n \to (K^+ + K^-) + p + n$. Amplitude F_ϕ.

Second background process: $\gamma + p \to \Lambda(1520) + K^+ \to$
$\to (p + K^-) + K^+$. Amplitude F_{Λ^*}. Neutron spectator.

The sum of amplitudes describes the reaction cross section
$\sigma \propto |F_{\theta+} + F_\phi + F_{\Lambda^*} + F_{NR}|^2$, ($NR$ - Non-Resonance)
instead of the sum of subprocess cross sections

$$\sigma_{\theta+} + \sigma_\phi + \sigma_{\Lambda^*} + \sigma_{NR} \propto |F_{\theta+}|^2 + |F_\phi|^2 + |F_{\Lambda^*}|^2 + |F_{NR}|^2.$$

Usually the cross sections of background processes σ_ϕ and σ_{Λ^*} are subtracted from the cross section of the process under study (σ). This may provide false peaks.

Search for θ^+ in Hadronic Channels

- What does the CLAS negative result mean?

  The cross section of θ^+ production by virtual photon is lower than the CLAS threshold of observation.

- This does not mean that θ^+ with small width does not exist, but it was not observed only in photoproduction.

- The most perspective process for searching θ^+ is hadron scattering of elementary particles.

  since the largest branchings of θ^+ decay are hadronic: $Br(\theta^+ \to p + K^0)$ and $Br(\theta^+ \to n + K^+)$.

- Nuclear targets should be excluded to avoid Fermi motion and rescattering (smearing) effects.

Search for θ^+ in Hadronic Channels

- Examples of perspective hadronic reactions

$\pi^- + p \rightarrow \theta^+ + K^-$, $E_\pi \geq 1.67$ GeV, for $M_{\theta^+} = 1.53$ GeV.

$\bar{p} + p \rightarrow \theta^+ + \bar{\theta}^-$, $E_{\bar{p}} \geq 4.05$ GeV (PANDA).

- Cross section of $\theta^+ + \bar{\theta}^-$ production in $\bar{p} + p$ collision

In the simplest model of K^0 exchange

the cross section maximum is given by

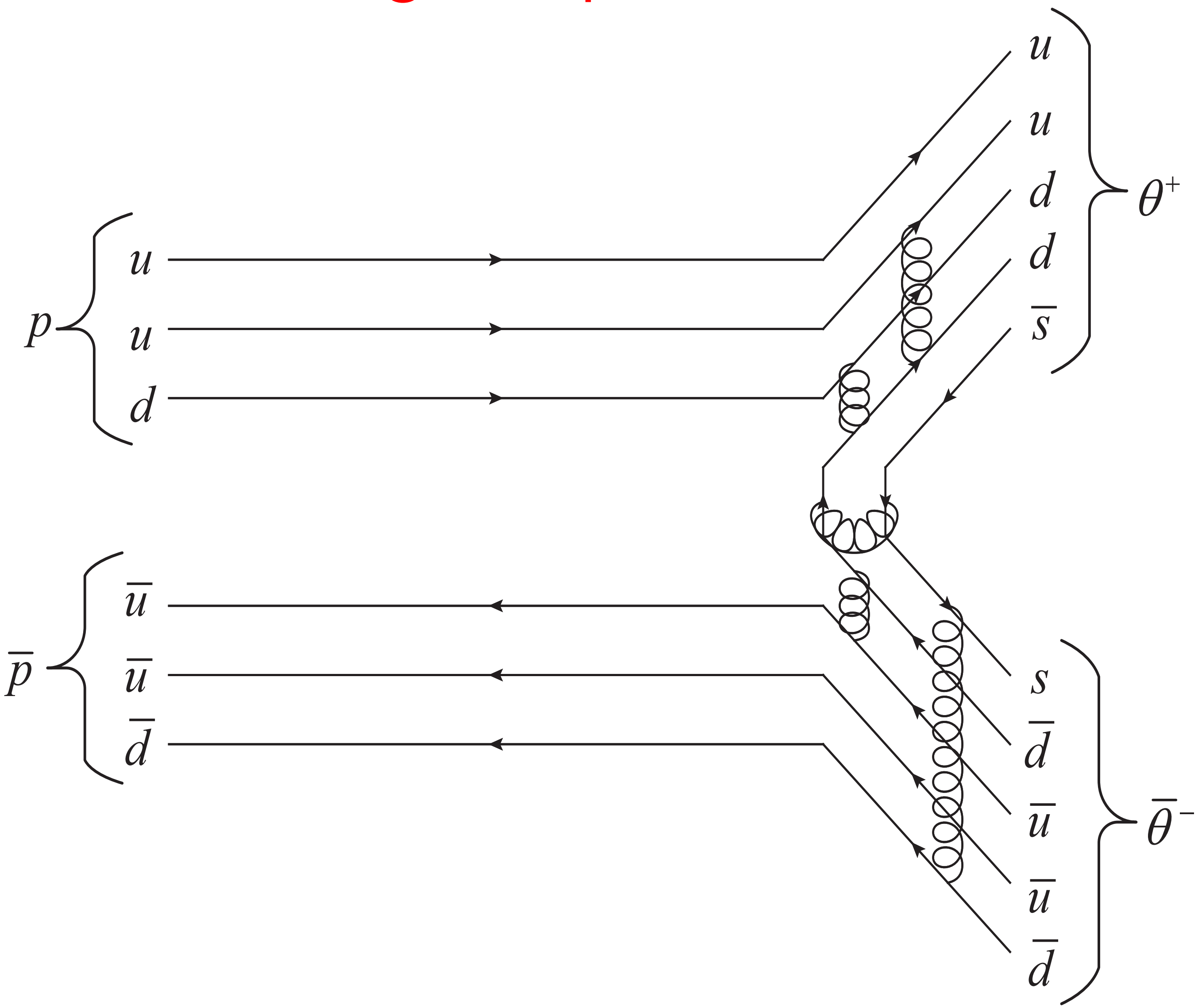
$\sigma_s(\bar{p} + p \rightarrow \theta^+ + \bar{\theta}^-) = 0.5 \cdot (\Gamma_{tot})^2\ \mu b$,

where the total width of θ^+ is measured in MeV and the beam energy is 5 GeV.

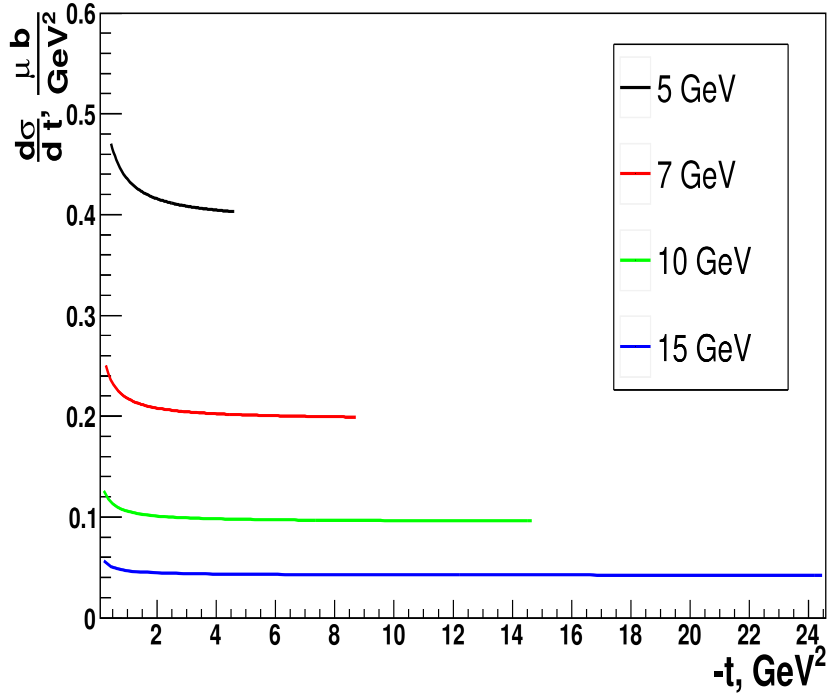
$\mathcal{L}_{PANDA} = 2 \cdot 10^{32}$ cm$^2 s^{-1}$, $\dot{N} = L \cdot \sigma = 100 \cdot (\Gamma_{tot})^2\ s^{-1}$.

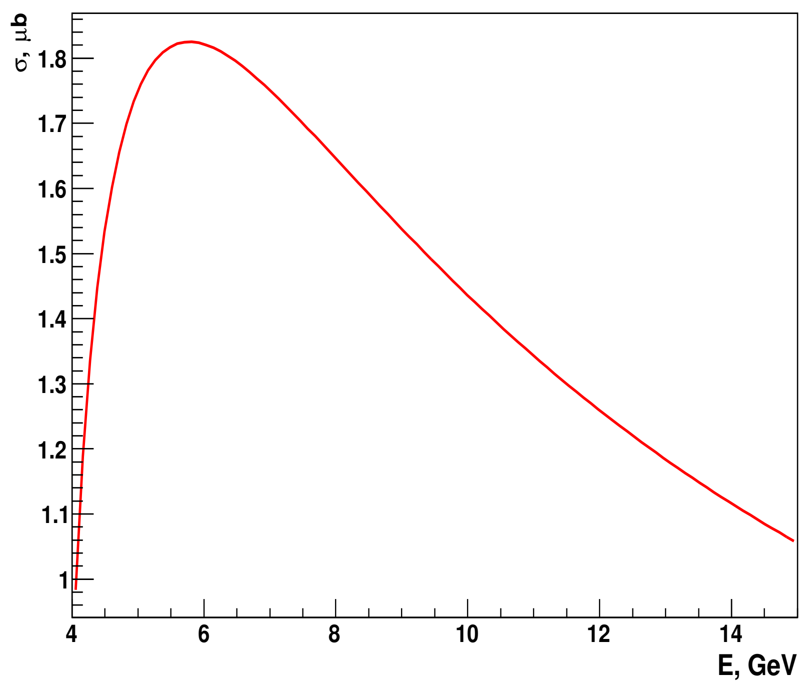
Pentaquark Production through Kaon Exchange

- Kaon Exchange Graph



- Differential and total cross sections





$$M_{\theta+} = 1.53\ \text{GeV}/c^2,\ \Gamma_{\theta+} = 2\ \text{MeV}/c^2$$

Requirements to Suppress Background

- Ratio R^s_{bg} of signal to background
  If we put for rough estimate $\Gamma_{tot} = 1$ MeV and the total cross section of $\bar{p}p$ scattering $\sigma^{tot}_{\bar{p}p} = 50$ mb
  we get $R^s_{bg} = \sigma_s / \sigma^{tot}_{\bar{p}p} = 10^{-5}$.
- The main problem for PANDA experiment is to suppress the background by a factor of about $10^5 \div 10^6$.
- Reaction $\bar{p} + p \to (\bar{p} + \pi^+ + \pi^-) + (p + \pi^+ + \pi^-)$
  Br$(\theta^+ \to p + K^0) \approx 0.5$, probability of transition $K^0 \to K^0_S$ is 0.5, and Br$(K^0_S \to \pi^+ + \pi^-) \approx 0.69$.
  This gives addition small factor $\approx 1/32$ for R^S_{bg}.
- Demand that the final state should contain only
  $\bar{p} + p + 2\pi^+ + 2\pi^-$ reduces the cross section of background processes significantly $(\sigma_{bg} \ll \sigma^{tot}_{\bar{p}p})$

Requirements to Suppress Background

- Choice of $\pi^+\pi^-$ pairs and cuts for K_S^0 mass

  The $\pi^+\pi^-$ pairs are to be chosen in such a way that the sum of two squares $(M_{\pi^+\pi^-} - M_{K_S^0})^2$ is minimal, where $M_{K_S^0}$ is the PDG value. Restriction on maximal values of $(M_{\pi^+\pi^-} - M_{K_S^0})^2$ reduces background.
- Cuts for decay length

  There are two long living particles K_S^0 in reaction:
  $\bar{p} + p \to \theta^+ + \bar{\theta}^- \to (\bar{p} + \bar{K}^0) + (p + K^0)$, $K^0 \to K_S^0$.
  Applying cuts for the minimal distances between the K_S^0 decay vertex position and the $\bar{p}p$ interaction point we can suppress background significantly.
- Collinearity cuts

  Trajectories of K^0 and $\bar{K}^0$ are to correspond to their three-momenta. These cuts suppress background also.

Advantages of Searching θ^+ at PANDA

- Search in θ^+ Mass Region from 1217 MeV to 1834 MeV

  $2.22 \geq E_{\bar{p}} \geq 6.23$ GeV (PANDA: $1.5 \geq E_{\bar{p}} \geq 15.0$ GeV)

  Molecular model: $|P_c^+ >= |\Sigma_c + \bar{D}^* >$,

  $|\theta^+ >= \alpha|p + K^0 > +\beta|n + K^+ >$,

  $|\theta^+ >= \alpha|p + K^{*0} > +\beta|n + K^{*+} >$,

  $\theta^+ \to p + \pi^+ + \pi^-$, $M_{\theta^+} \geq m_p + 2m_{\pi^+} = 1217$ MeV

  $\theta^+ \to n + K^+$, $M_{\theta^+} \geq m_n + M_{K^+} = 1433$ MeV.

  $\theta^+ \to p + K^{*0}$, $M_{\theta^+} \geq m_p + M_{K^{*0}} = 1834$ MeV.

- High statistics experiment:

  $\dot{N}_D = \epsilon_D L \cdot \sigma_s = \epsilon_D \cdot 100 \cdot (\Gamma_{tot})^2 \ s^{-1}$, $\epsilon_D \sim 1\%$.

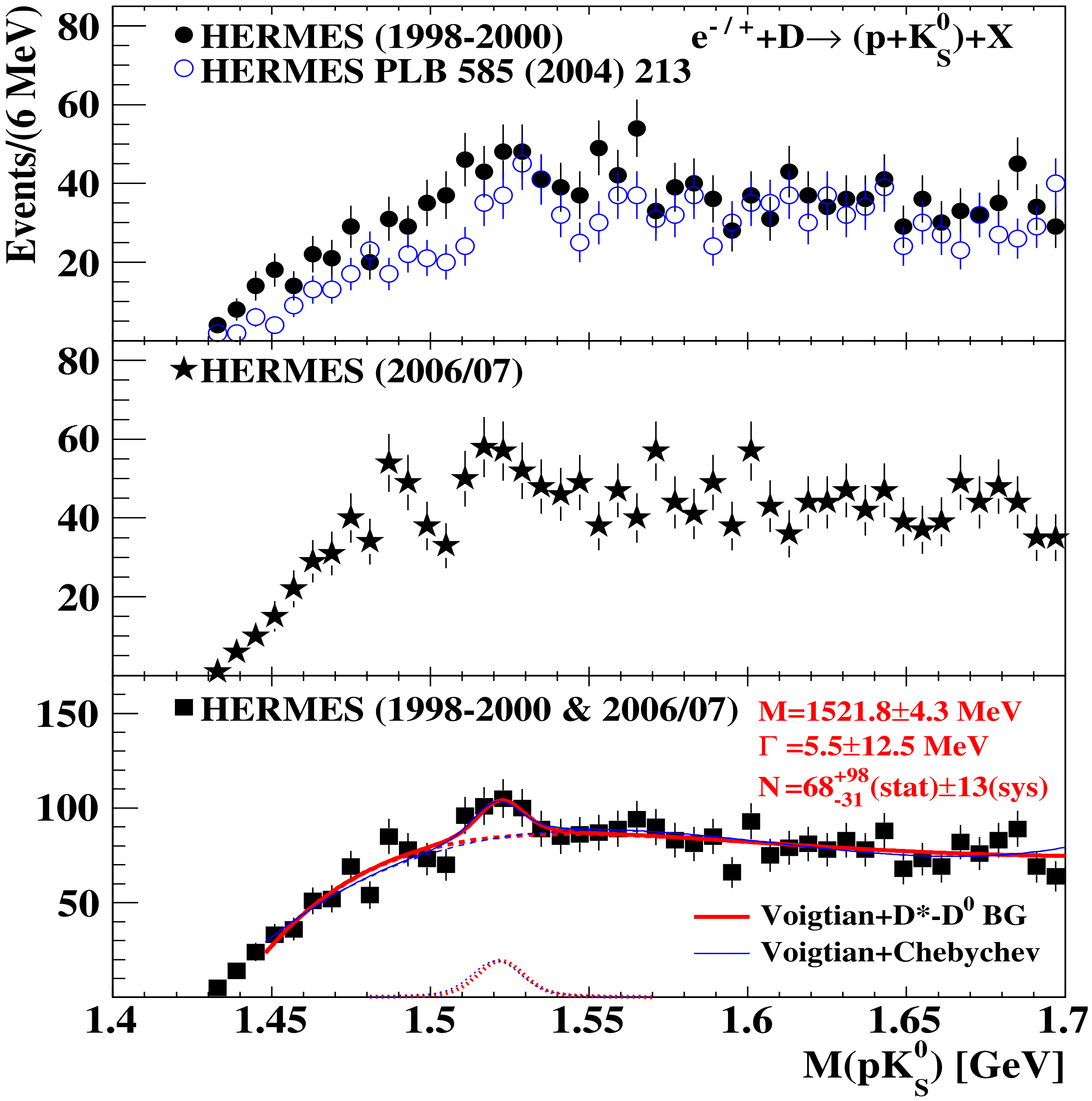
- Possibility to establish strangeness

  $\bar{p} + p \to \theta^+ + \bar{\theta}^-$, $\theta^+ \to n + K^+$, $\bar{\theta}^- \to \bar{p} + \bar{K}^0$.

Conclusions

- Neither existence nor non-existence of the θ^+ pentaquark is not established now
- Search in wide region of θ^+ mass should be performed
- It is desirable not to use nuclear targets to avoid the Fermi motion and rescattering effect contributions
- It is highly likely that the most perspective reactions for θ^+ production are hadronic ones
- Production rate for the θ^+ pentaquark in the PANDA experiment can be about a few events per second
- Search for the θ^+ pentaquark at PANDA can be realized in wide mass region even below kaon production threshold
- The most serious problem of the PANDA experiment is to find effective requirements to suppress background process contributions

Backup Slides



Backup Slides

- Differential Cross Section for $\theta^+\bar{\theta}^-$ Production

$$\frac{d\sigma}{dt} = \frac{g^4[(M_\theta - m_N)^2 - t]^2}{16\pi s(s-4m_N^2)(M_K^2 - t)^2}$$

- Total Cross Section for $\theta^+\bar{\theta}^-$ Production $\sigma_{tot} =$

$$\frac{g^4}{16\pi s(s-4m_N^2)}\Big\{[(M_\theta - m_N)^2 - M_K^2]^2\Big[\frac{1}{M_K^2 - t_{min}} - \frac{1}{M_K^2 - t_{max}}\Big]$$

$$+2[(\mathrm{M}_\theta - m_N)^2 - M_K^2]\ln\Big[\frac{M_K^2 - t_{max}}{M_K^2 - t_{min}}\Big] + t_{min} - t_{max}\Big\}.$$

Here $(-t_{max})/(-t_{min})$ is maximal/minimal value of $(-t)$.

- Total Width of the Pentaquark Decay $\theta^+ \to N + K$

$$\Gamma_{tot} = \frac{g^2[(M_\theta - m_N)^2 - M_K^2]}{4\pi M_\theta^2}P_0 \equiv \frac{g^2 P_0^3}{\pi[(M_\theta + m_N)^2 - M_K^2]},$$

where $P_0 = \frac{\sqrt{[(M_\theta - m_N)^2 - M_K^2][(M_\theta + m_N)^2 - M_K^2]}}{2M_\theta}.$