Production of Pentaquark States in pp Collisions within the Microcanonical Ensemble

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Abstract

The microcanonical statistical approach is applied to study the production of pentaquark states in pp collisions. We predict the average multiplicity and average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ and their antiparticles at different energies.

Recently an exotic baryon $\Theta^+(1540)$ with the quantum numbers of K^+n has been reported in several experiments[1, 2, 3, 4, 5]. The $\Theta^+(1540)$ can not be a three quark state. Its minimal quark content is $(uudd\bar{s})$, a $q^4\bar{q}$ pentaquark state.

Pentaquark states have theoretically investigated since a long time in the context of the constituent quark model[6, 7]. Some of these are expected to have charge and strangeness quantum number combinations that can not be explained by three quark-quark states. A variety of models has been employed to construct $q^4\bar{q}$ pentaquark states differently and predict differently masses and quantum numbers. For example, the chiral soliton (Skyrme) model[8] predicts that the lightest member of the SU(3)-flavour $(\overline{10}_f, \frac{1}{2}^+)$-let has $m_\Theta = 1540\,\mathrm{MeV}$. The reported $\Theta^+(1540)$ agrees with the prediction remarkably well. The other members of the $(\overline{10}_f, \frac{1}{2}^+)$ antidecuplet are isospin-multiplets of N, Σ and Ξ. In an uncorrelated quark model[7], in which all quarks are in the ground state of a mean field, the ground state of $q^4\bar{q}$ has negative parity. This is in striking difference to the chiral soliton model. In Jaffe's model[9], $\Theta^+(1540)$ is recognized as a bound state of an antiquark with two highly correlated spin-zero ud diquarks. Hence the lightest $q^4\bar{q}$ state

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can not be $\Theta^+(1540)$ but belongs to the N isospin-multiplets with minimal quark content, i.e. $uudd\bar{u}$. Other models regard $\Theta^+(1540)$ as a member of the SU(3) flavour (27_f)-let. Missing members of the multiplet are assigned to reported particles[10].

The common members of above mentioned models are $\Theta^+(1540)$ and the multiplets of Ξ, which can be $\Xi^{--}(ddss\bar{u})$, $\Xi^-(dssq\bar{q})$, $\Xi^0(ussq\bar{q})$ or $\Xi^+(uuss\bar{d})$, where $q\bar{q}$ is a hidden quark-antiquark pair $u\bar{u}$ or $d\bar{d}$. Recently the NA49 collaboration [11] also presented the results of a search of $\Xi^{--}(1860)$ and $\Xi^0(1860)$.

The estimation of $\Theta^+(1540)$ and $\Xi(1860)$ yields at different collisions energies independent of abovementioned models will be helpful for the search for pentaquark states from proton-proton collisions in the ongoing experiments in SPS and RHIC. Some work has been done using the statistical hadronization approach within grandcanonical and canonical ensembles. However the system is small in proton-proton collisions, and a microcanonical ensemble should be justified.

The dynamical model NEXUS has also been used to estimate the yields of $\Theta^+(1540)$ and $\Xi(1860)$, via employing the microcanonical ensemble to hadronize the remnants (formed by spectator quarks from the collisions)[12]. Here we use the microcanonical ensemble to study the production of pentaquark states in pp collisions. The microcanonical parameters are well studied already in previous work via fitting the 4π yields of charged pions, proton and antiproton. We organise the paper as followed: first we explain the model, how pentaquark states are produced in pp collisions, then we check how reliable the microcanonical parameters are, then we present our results, the yields and average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ and their antiparticles, and finally we compare our results to some other theoretical work and discuss our predictions on SPS and RHIC experiments.

Here we use the microcanonical ensemble to study the production of pentaquark states in pp collisions. In the microcanonical ensemble, we consider the final state of a proton-proton collision as a "cluster" characterized by its volume V (the sum of individual proper volumes), its energy E (the sum of all the cluster masses) and the net flavour content $Q = (N_u - N_{\bar{u}}, N_d - N_{\bar{d}}, N_s - N_{\bar{s}})$, decaying "statistically" according to phase space. More precisely, the probability of a cluster to hadronize into a configuration $K = \{h_1, p_1; \ldots; h_n, p_n\}$ of hadrons h_i with four momenta p_i is given by the micro-canonical partition function $\Omega(K)$,

$$\Omega(K) = \frac{V^n}{(2\pi\hbar)^{3n}} \prod_{i=1}^{n} g_i \prod_{\alpha\in\mathcal{S}} \frac{1}{n_\alpha!} \prod_{i=1}^{n} d^3p_i\, \delta(E - \Sigma\varepsilon_i)\, \delta(\Sigma\vec{p}_i)\, \delta_{Q,\Sigma q_i}, \tag{1}$$

with $\varepsilon_i = \sqrt{m_i^2 + p_i^2}$ being the energy, and $\vec{p}_i$ the 3-momentum of particle i. n_α is the number of hadrons of species α, and g_i is the degeneracy of particle i. The term $\delta_{Q,\Sigma q_i}$ ensures flavour conservation and the net flavour content $Q = (4, 2, 0)$; q_i is the flavour vector of hadron i. The symbol $\mathcal{S}$ represents the set of hadron species considered: The ordinary $\mathcal{S}$

contains the pseudoscalar and vector mesons $(\pi, K, \eta, \eta', \rho, K^*, \omega, \phi)$ and the lowest spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ baryons $(N, \Lambda, \Sigma, \Xi, \Delta, \Sigma^*, \Xi^*, \Omega)$ and the corresponding antibaryons. We generate randomly configurations K according to the probability distribution $\Omega(K)$. For the details see ref. [13].

We add the pentaquark states $\Theta^+(1540)$, $\Xi(1860)$ and their antiparticles into $\mathcal{S}$. The Θ^+ has quark contents $(uudd\bar{s})$. The $\Xi(1860)$ can be $\Xi^{--}(ddss\bar{u})$, $\Xi^-(dssq\bar{q})$, $\Xi^0(ussq\bar{q})$ or $\Xi^+(uuss\bar{d})$. The spin of pentaquark states can not be determined by experiments yet, and it is generally accepted they are spin-$\frac{1}{2}$ particles, and their degeneracy factor $g = 2$.

In our approach, because of the heavy masses of the pentaquark states, the hadron configurations containing them appear very rarely. Therefore, if the pentaquark states $\Theta^+(1540)$, $\Xi(1860)$ are spin-$\frac{3}{2}$ particles, then their yields will be twice as that of spin-$\frac{1}{2}$ according to Eq. (1), and their average transverse momenta will not be effected by their spins. Our simulation has proven this point. In the following we report the results assuming they are spin-$\frac{1}{2}$ particles.

For $\Xi^-(dssq\bar{q})$ and $\Xi^0(ussq\bar{q})$, the $q\bar{q}$ can be $u\bar{u}$ or $d\bar{d}$. Some consider the two multiplets of Ξ as three-quark q^3 states, $\Xi^-(dss)$ and $\Xi^0(uss)$. In the microcanonical calculation, we do not need to distinguish between q^3 and $q^4\bar{q}$, the two cases yields the same results when the masses and degeneracy factors are the same, because the $q\bar{q}$ of the same flavour does not play any role in conserving flavours or charge in the microcanonical statistical hadronization approach.

The microcanonical parameters $(E,\ V)$ for pp collisions at a given energy $\sqrt{s}$/GeV are obtained by fitting the 4π multiplicities of the most copiously produced particles $(p,\ \bar{p},\ \pi^+,\ \pi^-)$ [14, 15]:

$$\begin{aligned} E/\mathrm{GeV} &= -3.8 + 3.76\ln\sqrt{s} + 6.4/\sqrt{s} \\ V/\mathrm{fm}^3 &= -30.0376 + 14.93\ln\sqrt{s} - 0.013\sqrt{s}. \end{aligned}$$

After add pentaquarks states into the hadron set, we still check the 4π multiplicities of p, $\bar{p}$, π^+, π^-, see fig. 1. Adding pentaquarks states into the hadron set does not change the yields of light particles, except for antiproton. About 10% more antiprotons are produced to compensate the net baryon numbers carried by the pentaquark states.

Because the microcanonical calculation has no strangeness suppression factor, so strange hadrons are overproduced[15]. However, with a global factor 1/3 to scale strange hadrons such as K, Λ and $\bar{\Lambda}$, microcanonical calculations (solid lines) are compared with the data[16, 17] (empty squares), c.f. Fig. 2. Since Ξ has two strange constituent quarks, we should scale the yields with a factor 1/9. In Fig. 2, Ξ^- from microcanonical calculation scaled by factor 1/9 agrees with the UA5 data[18].

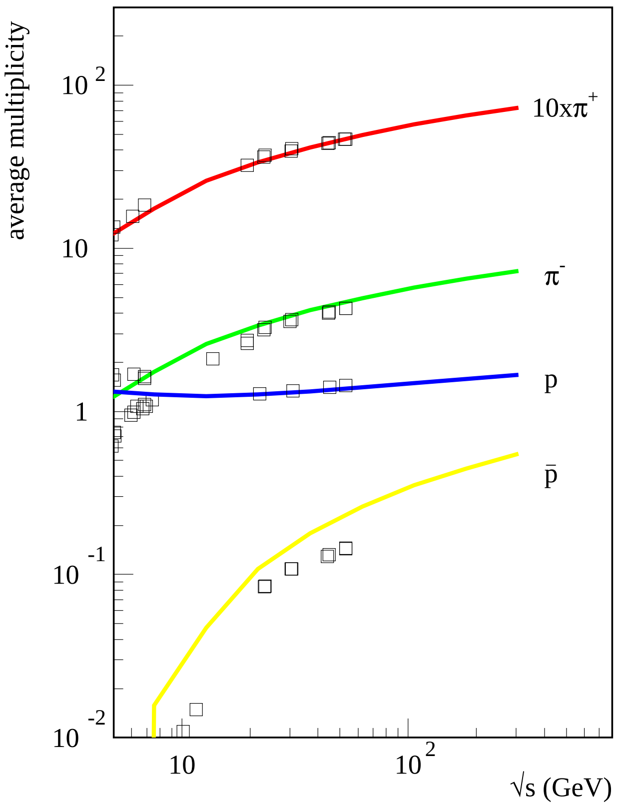

Figure 1: p, $\bar{p}$, π^+, π^- excitation functions. The empty square points are experimental data[16], solid lines are microcanonical calculation after adding the pentaquark states into the hadron set.

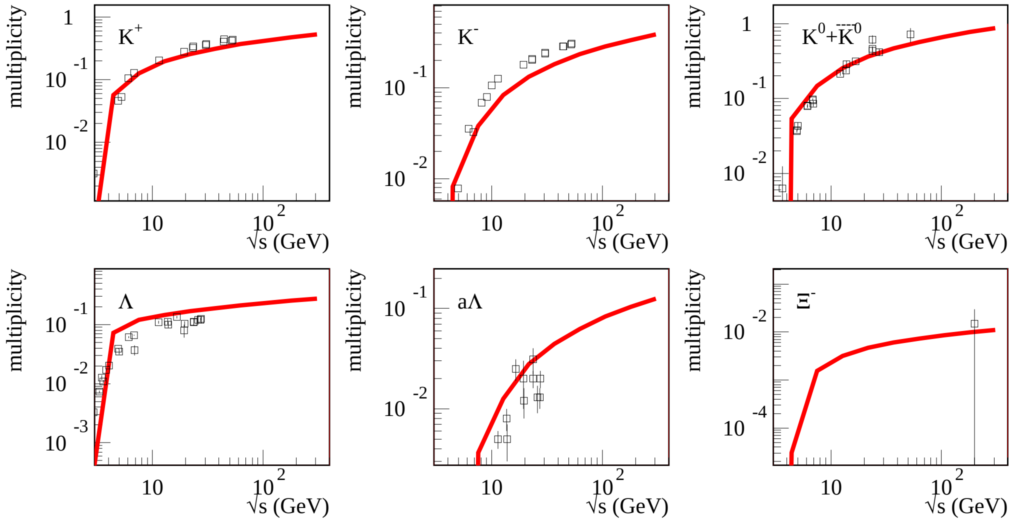

Figure 2: With a global factor 1/3 to scale strange hadrons such as K, Λ and $\bar{\Lambda}$, the microcanonical calculation(solid lines) can reproduce the data[16, 17](empty squares). In the last plot, Ξ^- from microcanonical calculation scaled by factor 1/9(solid line) agrees with data(empty square) [18].

The particle yields of Θ^+(solid line) and its antiparticle (dashed line) from pp collisions at different collision energies are shown in Fig. 3. A factor 1/3 for Θ^+ and its antiparticle has been taken to account for the strangeness suppression. The yields of the $\Xi(1860)$ (solid lines) and the antiparticles(dashed lines) are showed in Fig. 4. A factor 1/9 has been taken. With the increase of collision energy, more and more pentaquarks states are produces, except Θ^+. We can see in Fig. 3, $\Theta^+$is favoured at low energies because of the channel $p + p \to \Theta^+ + \Sigma^+$ [19].

With the 4π yields of charged pions, protons and antiprotons as input, the microcanonical calculation can predict reliably the average transverse momentum of both non-strange

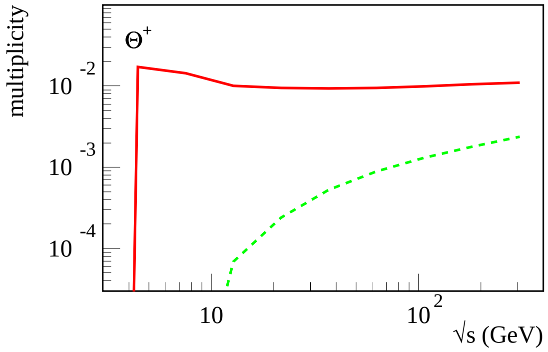

Figure 3: The particle yields of Θ^+(solid line) and its antiparticle (dashed line).

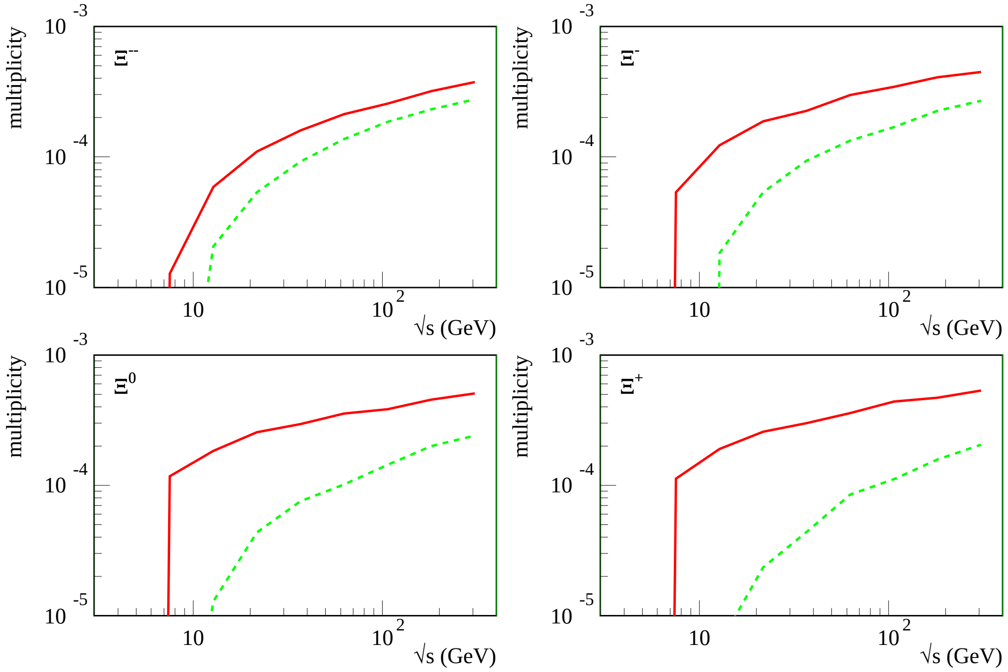

Figure 4: The particle yields of Ξ(1860) (solid lines) and their antiparticles(dashed lines).

and strange hadrons[15]. In Fig. 5 we also show the average transverse momentum of Θ^+(1540) and Ξ(1860)(solid lines) and their antiparticles(dashed lines). The difference between the average transverse momentum of $\Xi^{--}(ddss\bar{u})$, $\Xi^{-}(dss)$, $\Xi^{0}(uss)$ and $\Xi^{+}(uuss\bar{d})$ from microcanonical calculation is ignorable. So do their antipartciles. Now we compare our results to the previous research results at SPS and RHIC energies. It is expected that the yields of pentaquark states should be more than NEXUS[12]. And we find indeed Θ^+ and Ξ(1860) are $2 \sim 3$ times more. The particle ratio Θ/p is about 0.7%, which agrees suprisingly well with the prediction from a quark molecular dynamics model prediction 0.6%[20], while grandcanonical ensemble[21] estimation is about 6%. The particle ratio $\Xi^{--}(1860)/\Xi^{-}$ is 2% at SPS and 3% at RHIC, which is $3 \sim 4$ bigger than grandcanonical fitting [22].

The inclusive cross section $\sigma_{pp\rightarrow\Theta^+}$ near the production threshold estimated with empirical coupling constants and form factor is $20\,\mu b$[19], which is about ten times smaller than our results.

In conclusion, we presented a calculation of the yields of different pentaquark states in pp collisions using the microcanonical approach. We obtain roughly 10^{-2} (almost independent of energy) for the Θ^+, whereas the Ξ yields increase strongly with energy, reaching 4 x 10^{-4} at RHIC.

Acknowledgements

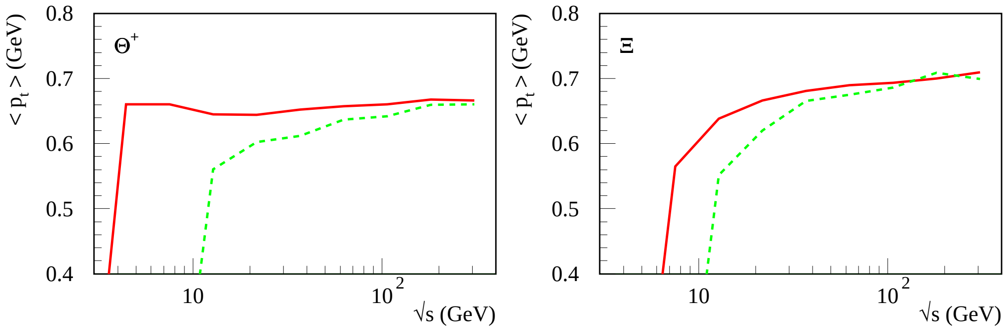

Figure 5: The average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$(solid lines) and their antiparticles(dashed lines).

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