η-MESON PRODUCTION
IN NUCLEON–NUCLEON COLLISIONS*

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New experimental data are presented on the energy dependence of the total cross-sections for the $np \to d\eta$ and quasi-two-body $pp \to pp\eta$ reactions, where the final diproton is detected at very low excitation energy. Differential cross-sections of $pp \to pp\eta$ away from threshold show the influence of higher partial waves and a partial wave decomposition is attempted.

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1. Introduction

If one looks in a dictionary one sees that the original definition of a symposium was "A drinking party at which there was intellectual conversation". Further research reveals that, in a game sometimes played at symposia, participants swirled the dregs in their wine glasses and flung them at a target — but not, apparently, in Kraków!

The possibility that the η meson might form some kind of quasi-bound state with a nucleus has excited physicists for many years. It was first suggested by Haider and Liu [1], on the basis of the η-nucleon information available in 1986, that the lightest nucleus where this was likely to happen was ^{12}C. However, no unambiguous signals for the production of such a state below the ηA threshold have ever been found, in part due to the enormous hadronic backgrounds associated with non-η events.

On the other hand, if the ηA pole is close to threshold it should influence the ηA production data a little above threshold, in much the same way that the deuteron bound state dominates S-wave neutron–proton spin-triplet scattering. It was therefore argued [2] that the available data on $pd \to$ $^3\text{He}\,\eta$ might signal the formation of $^3_\eta\text{He}$. The obvious drawback of such an

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approach is that low energy production data can never determine whether there is a bound state (*e.g.* the deuteron) or a virtual state (*e.g.* the spin-singlet NN system). One possible way of resolving this ambiguity is to study the A-dependence of low energy η production and use the fact that the binding should increase with atomic number [3]. I shall here show new results in the $A = 2$ systems and leave others to discuss $A > 2$.

2. The ηd interaction

The ηd interaction was studied at CELSIUS in two different kinematical regimes, *viz* quasi-free $pd \rightarrow p_{\mathrm{sp}}d\eta$ [4] and the same reaction at much lower energies, *i.e.* well below the threshold in nucleon–nucleon collisions [5]. A consistent FSI description of both data sets was achieved by dividing the ηd invariant mass distribution by the corresponding phase space.

The results obtained from the two CELSIUS experiments are shown in Fig. 1 in terms of the ηd excitation energy, where it is seen that the ratios drop by about a factor of four over 10 MeV. This is an indication of a strong final state interaction (FSI) which, in scattering length approximation, may be written as

$$\mathrm{FSI} \propto 1/\left|1 - ika_{\eta d}\right|^2 , \tag{1}$$

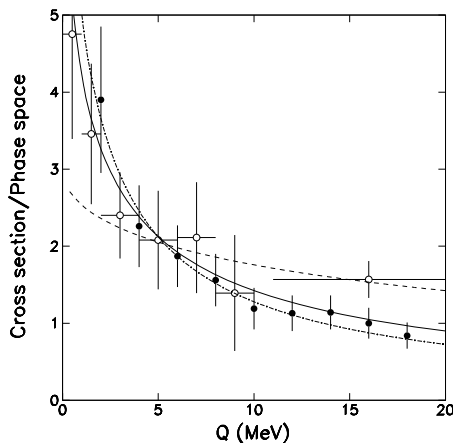where k is the ηd relative momentum.

Fig. 1. Ratio of the cross-section for the production of the $d\eta$ system to phase space, as a function of the excitation energy in the $d\eta$ rest frame, for the $pn \rightarrow d\eta$ total cross-section (open circles) [4] and the $pd \rightarrow pd\eta$ reaction at 1032 MeV (closed circles) [5]. The broken, solid and chain curves are the predictions of the scattering length formula of Eq. (1) using $a_{\eta d} = (0.73 + 0.56i)$ fm, $(1.64 + 2.99i)$ fm, and $(-4.69 + 1.59i)$ fm, respectively [6]. The overall normalisations are arbitrary.

Three-body estimations of the complex scattering length $a_{\eta d}$ depend critically on the η-nucleon input [6] and calculations made using modest, strong, and very strong $a_{\eta N}$ values are shown in Fig. 1. The very strong case leads to a quasi-bound ηd state whereas in the strong case it is merely a virtual state. Above-threshold data cannot distinguish between them.

New data are currently being analysed at COSY-ANKE [7]. When using a deuteron beam, a spectator proton $p_{\rm sp}$ will be fast and therefore measured in the ANKE forward detector along with other charged particles. Data were taken on $dp \to p_{\rm sp}dX$ at the maximum COSY deuteron beam energy of 2.27 GeV and the meson X identified using the missing-mass technique. Since the central neutron energy is below the $d\eta$ threshold, only the upper part of the Fermi momentum will contribute to η production. The below-threshold data provide a robust method for background subtraction and, when this is carried out, the η signal shown in Fig. 2 is very clean and the whole η angular domain is sampled.
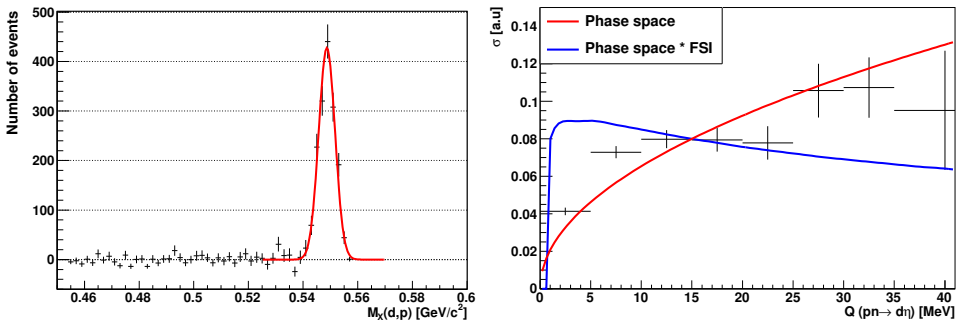

Fig. 2. Left: Missing-mass spectrum after background subtraction for the $dp \to dpX$ reaction at 2.27 GeV from preliminary ANKE data for $5 < Q < 10$ MeV [7]. Right: Preliminary unnormalised $np \to d\eta$ total cross-sections extracted from $dp \to dpX$ data at 2.27 GeV assuming quasi-free production [7]. The phase-space dependence and this modified by the FSI with $a_{\eta d} = (1.64 + 2.99i)$ fm are shown.

If the data are interpreted in terms of quasi-free production, the energy dependence of the total cross-section can be extracted and the results of this are presented in arbitrary units in Fig. 2. When normalised at 15 MeV, the curve representing the variation expected on the basis of phase space underestimates the near-threshold rise but the introduction of the FSI with $a_{\eta d} = (1.64 + 2.99i)$ fm overdoes things in this region. The analysis is very preliminary and it is too soon to draw firm conclusions. However, it is possible that the problem resides in the quasi-free assumption because, at only a slightly lower energy, it was claimed that quasi-free production might account for less than half of the observed cross-section [5].

3. The $pp \to pp\eta$ reaction away from threshold

In order to study the effects of S-wave rescattering of the η meson from a proton pair, and hence investigate the ηpp FSI, it is important to know at what point higher partial waves are needed for the description of the $pp \to pp\eta$ reaction. This means that one has to measure differential observables away from threshold. The production of the η in proton–proton collisions was investigated by the CELSIUS-WASA Collaboration at $Q = 40$ and 72 MeV by detecting the η through its $3\pi^0$ decay [8]. However, the data from the two-photon decay branch have been subjected to a much more refined analysis, which is now approaching completion [9].

The Dalitz plots for the $pp \to pp\eta$ reaction shown in Fig. 3 look similar when the meson is detected through its $3\pi^0$ [8] or 2γ decay [9]. The distributions are far from uniform and the data at both 40 and 72 MeV show a deep valley along the diagonal where $m(\eta p_1) \approx m(\eta p_2)$. This is probably due to the η being able to form the $N^*(1535)$ with only one nucleon at a time. The valley implies that there must be higher partial waves in both the pp and ηpp systems, at least $L_{pp}\ell_\eta = Pp$. It should also be noticed that the pp FSI is only significant at 40 MeV.
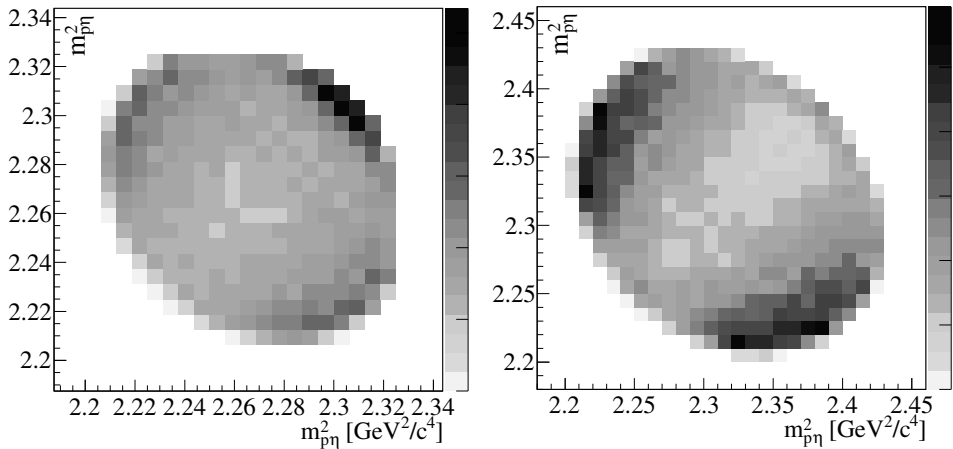

Fig. 3. Dalitz plots for the $pp \to pp\eta$ reaction at (left) $Q = 40$ MeV and (right) $Q = 72$ MeV [9].

Since only the start of the $N^*(1535)$ is sampled, even at 72 MeV, it is tempting to parametrise the data with partial wave amplitudes with constant coefficients. Although the $N^*(1535)$ will not be explicitly included, factors arising from the angular momentum barriers and the pp FSI will.

The square of the $pp \to pp\eta$ matrix element, averaged over polarisations, is [9]

$$
\begin{aligned}
\langle|\mathcal{M}|^2\rangle \;=\; & |A_{Ss}|^2 + \tfrac{1}{9}|A_{Sd}|^2 k^2 \left[3(\hat{p}\cdot\vec{k})^2 + k^2\right] + \tfrac{1}{9}|A_{Ds}|^2 q^2 \left[3(\hat{p}\cdot\vec{q})^2 + q^2\right] \\
& + \tfrac{2}{3}\mathrm{Re}\left\{A_{Ss}^* A_{Sd}\right\}\left[3(\hat{p}\cdot\vec{k})^2 - k^2\right] + \tfrac{2}{3}\mathrm{Re}\left\{A_{Ss}^* A_{Ds}\right\}\left[3(\hat{p}\cdot\vec{q})^2 - q^2\right] \\
& + \tfrac{2}{9}\mathrm{Re}\left\{A_{Sd}^* A_{Ds}\right\}\left[9(\hat{p}\cdot\vec{k})(\hat{p}\cdot\vec{q})(\vec{k}\cdot\vec{q}) - 3\left(q^2(\hat{p}\cdot\vec{k})^2 + k^2(\hat{p}\cdot\vec{q})\right)^2 + k^2 q^2\right] \\
& + |A_{Ps}|^2 q^2 + 2|A_{Pp}|^2 (\vec{k}\cdot\vec{q})^2 \,,
\end{aligned}
\tag{2}
$$

where terms up to fourth order in combinations of the η ($\vec{k}$) and pp relative momentum ($\vec{q}$) have been retained for partial waves up to D in the incident pp system, where the c.m. momentum is $\vec{p}$. The five partial wave amplitudes $A_{L_{pp}\ell_\eta}$ are in the standard notation, where L_{pp} is the angular momentum in the final pp system and ℓ_η that of the η with respect to the recoiling pp.

The momentum factors associated with particular partial wave combinations are, of course, necessary but the critical assumption in the analysis is that the $A_{L_{pp}\ell_\eta}$ themselves are constant, apart from the pp FSI in the final S-wave. This effect has been taken into account by multiplying the amplitudes by the ratio of the Paris pp wave function, including the Coulomb distortion, to the plane wave evaluated at a pp separation of 1 fm [10].

A large variety of one-dimensional data were fitted simultaneously at 40 and 72 MeV. Since the phases of A_{Ps} and A_{Pp} are irrelevant at this level, this involved the determination of seven real parameters. The distributions fitted include those in the invariant masses, the η c.m. angle, as well as the Gottfried–Jackson angle. The fits were made to the raw spectra, after the model had been passed through the full simulation of the CELSIUS-WASA set-up. However, the results shown here are in terms of cross-sections, where the acceptance has been evaluated using the model with the best-fit parameters.

The invariant mass distributions shown in Fig. 4 are well reproduced at 40 MeV but for the 72 MeV data, where the statistics are higher, the description in the FSI region is poor. This better description of the data at 40 MeV persists also for the η angular distributions shown in Fig. 5. These are clearly more bowed than the earlier COSY-TOF results at 41 MeV [11]. In the simple model of Eq. (2), deviations from isotropy must come from Ss–Sd interference and these must be too small in the model at 72 MeV.

If higher partial waves cause some problems at large excess energies, what happens at lower values of Q? In fact, with the parameters tuned to describe the 40 and 72 MeV data, the shapes of the COSY-11 data at 15.5 and 10 MeV are well described, as can be judged from the results shown in
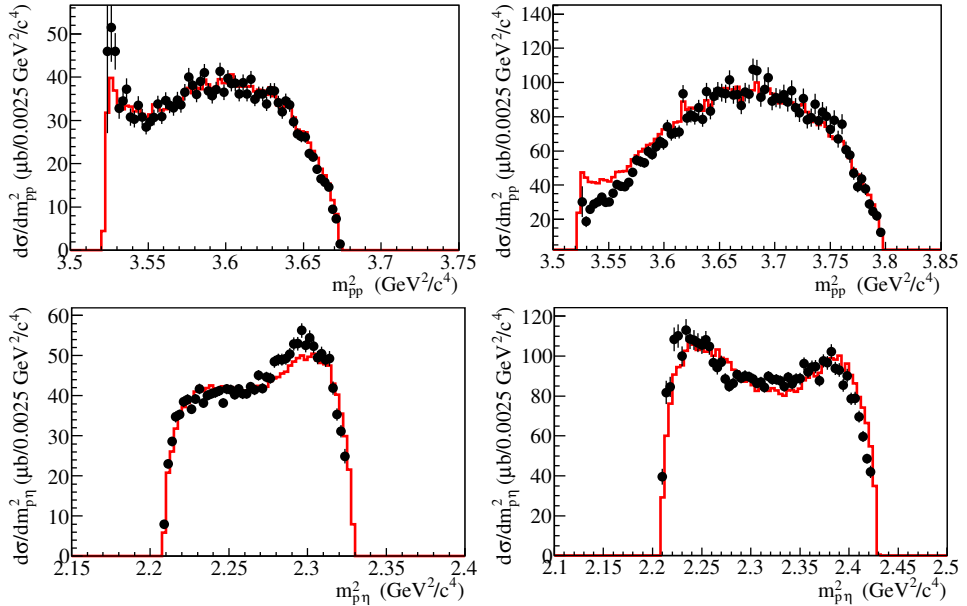
Fig. 4. Invariant mass distributions for the $pp \rightarrow pp\eta$ reaction at (left) $Q = 40$ MeV and (right) $Q = 72$ MeV [9] compared to the best fit on the basis of Eq. (2).
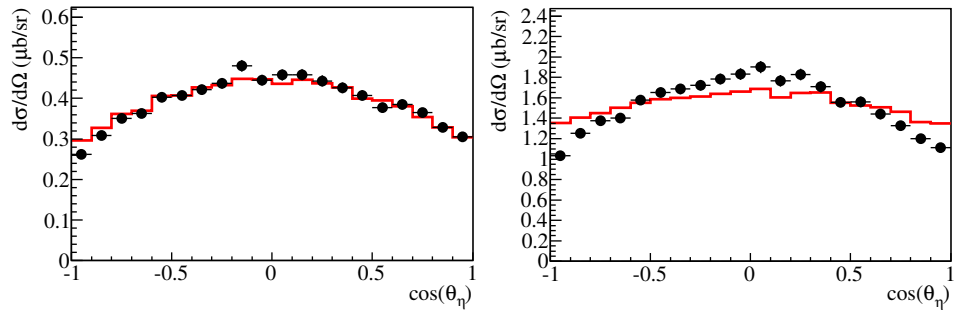

Fig. 5. Angular distributions of the η from the $pp \rightarrow pp\eta$ reaction at (left) $Q = 40$ MeV and (right) $Q = 72$ MeV [9] compared to the best fit on the basis of Eq. (2).

Fig. 6. In this analysis, higher partial waves in the pp system are vital for the description of the data at the largest s_{pp}; it is the significant contribution from the Ps wave that gives more events at high m_{pp} and hence low $m_{p\eta}$. Since there is no associated angular dependence, this is NOT a proof and an unambiguous separation of Ps from Ss would require a measurement of the initial spin–spin correlation parameter.
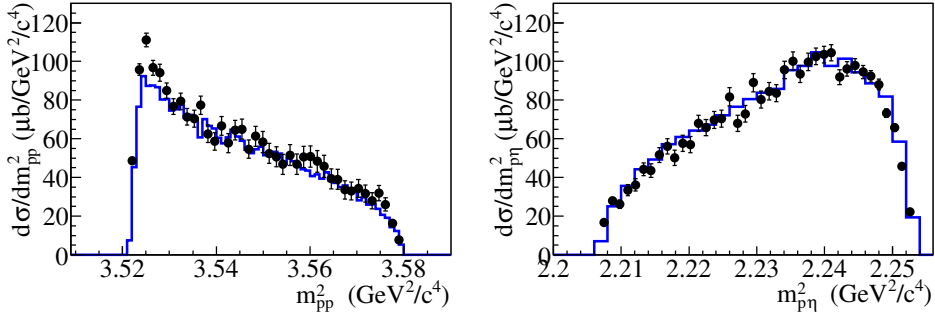
Fig. 6. Invariant mass distributions for the $pp \to pp\eta$ reaction at $Q = 15$ MeV [12] compared to the predictions of Eq. (2), using the standard parameters.

If the only energy dependence of the partial wave amplitudes were through the kinematic and FSI factors of Eq. (2), the energy dependence of the total cross-section could be predicted. This is shown in Fig. 7 along with the contributions from individual partial waves. Since the scaling is arbitrary, we do not know if disagreement is due to a FSI effect at small excess energy or the constancy ansatz at large Q. In the $pn \to d\eta$ case the FSI effect extends up to 10 MeV and this could reach even further for $pp \to pp\eta$ because the pp subsystem could then take up some of the energy.
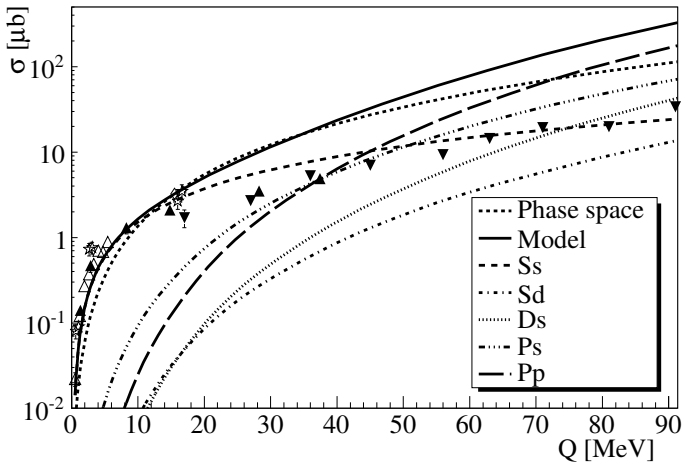

Fig. 7. Total cross-sections for the $pp \to pp\eta$ reaction compared to the predictions of Eq. (2), using the standard parameters. The contributions from individual partial waves within the model are indicated. The experimental data are taken from Refs. [4, 12–16].

4. The quasi-two-body $pp \to pp\eta(\eta')$ reactions

To study the ηpp FSI experimentally, we need to control to some extent the higher partial waves. The ηd case is simpler because it is a two-body system, which leads me to my final points.

The ANKE spectrometer has only limited acceptance, but it can measure well $pp \to \{pp\}_S X$, where the diproton $\{pp\}_S$ has an excitation energy below 3 MeV, so that it is dominantly in the $^1S_0$ state. Data have already been published for the η at $Q \approx 55$ MeV [18] and it is seen from the preliminary missing-mass data at 2.57 GeV shown in Fig. 8 that there is a clear η' signal, also at $Q \approx 55$ MeV. Approximately 500 events are expected to be extracted from the signal.
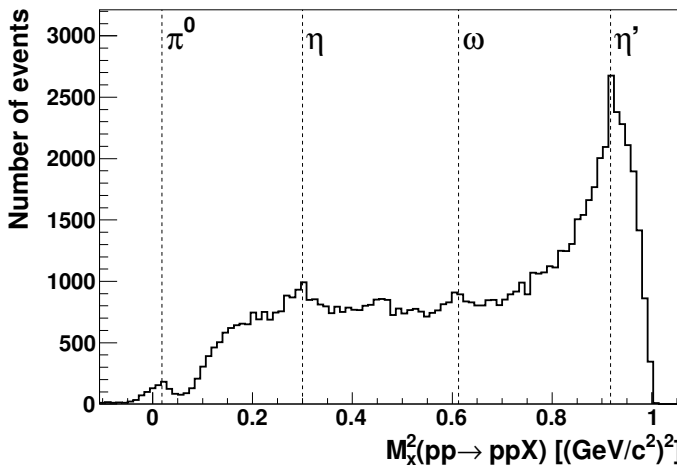

Fig. 8. Missing-mass spectrum in the $pp \to ppX$ reaction at 2.57 GeV from preliminary ANKE data, where a cut of 3 MeV has been placed on the excitation energy in the recoiling pp system.

There are, as yet, very few measurements in the domain of the ANKE kinematics, where $E_{pp} < 3$ MeV and $\cos\theta_\eta > 0.95$. However, points at $Q = 15.5$ [12] and 10 MeV [17] could also be extracted from COSY-11 data and these are shown in Fig. 9 along with a phase-space $\sqrt{Q}$ dependence. The deviations from $\sqrt{Q}$ at small Q are due, in part, to the $\{pp\}_S$ system not having a fixed mass, but there must be Physics in the behaviour between 15.5 and 55 MeV. More data of this kind in the low E_{pp} region are necessary to establish the extent of the $\eta\{pp\}_S$ FSI.
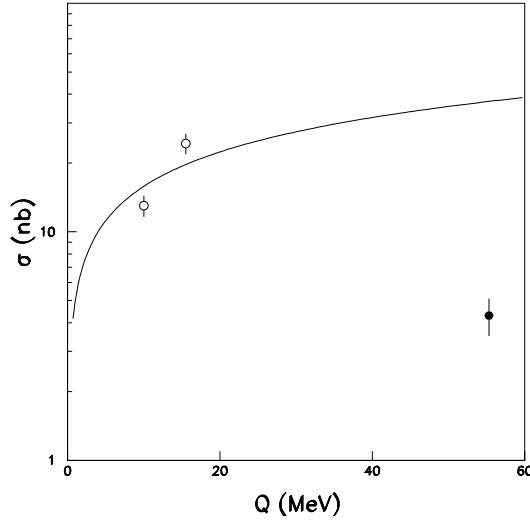
Fig. 9. Cross-section for $pp \to \{pp\}_S\eta$ in the ANKE conditions where $E_{pp} < 3$ MeV and $\cos\theta_\eta > 0.95$. The open circles are from COSY-11 data [12, 17] and the closed one from ANKE [18]. The curve represents a simple phase-space dependence $\propto \sqrt{Q}$.

5. Conclusions

Three new data sets have here been presented on η production in nucleon–nucleon collisions. Preliminary ANKE results seem to show some ηd FSI, though perhaps not as strong as CELSIUS and much weaker than that for η^3He. On the other hand, one must be cautious about the assumption that these sub-threshold data can be interpreted purely in terms of the single-scattering approximation.

The broad conclusions that might be drawn from the CELSIUS $pp \to pp\eta$ data are that the valleys in the Dalitz plots demonstrate that higher partial waves, at least Pp, are necessary at both 40 and 72 MeV. The model with constant amplitudes (apart from kinematic factors) fitted to the 40 MeV data describes very well the 10 and 15.5 MeV results. However, even here one needs more than just Ss-wave and by 72 MeV far higher partial waves may be required. On the other hand, the proposed parameterisation is far from unique and, for example, the Sd amplitude has been neglected for an incident pp F-wave. Constant amplitudes, apart from the FSI and kinematic factors, must overestimate the cross-section at large Q. The excess in the high mass part of the s_{pp} spectrum is "explained" as being due to higher partial waves in the pp system. It should though be noted that a similar shape is seen in the COSY-11 $pp \to pp\eta'$ data [17]. Does this mean that Ps waves enter at the same relative rate for η and η' production?

In this symposium we are, of course, mainly interested in the FSI of the η with nucleons and nuclei and this would undoubtedly be simpler to study in the pp case if one looked at the quasi-two-body $pp \to \{pp\}_S\eta$ reaction. The numbers of partial waves and kinematic variables are vastly reduced and one could then concentrate on the critical $\eta\{pp\}_S$ relative momentum. For this we need more data!

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