EPJ A special talk
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The legacy of the experimental hadron physics programme at COSY

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The hadronic physics programme at the COoler SYnchrotron and storage ring (COSY) of the Forschungszentrum Jülich ended 18 months ago

Although some experiments are still being analysed, I will attempts to review the major achievements in the field realised from over twenty years of intense research.

I have chosen ten sets of experiments that will hopefully convince you that COSY has changed the field for the future. This represents a personal choice, but a wider selection is to be found in the review article being prepared for the European Physical Journal A.

Today’s menu – Wilkin’s choice

1. Proton-proton elastic scattering
2. The WASA dibaryon
3. Neutron-proton elastic scattering
4. Large acceptance hyperon production
5. The hyperon cusp
6. η-mesic nuclei
7. Non-strange meson production in *NN* collisions
8. Kaon pair production
9. Determination of the mass of the η meson
10. Amplitude analysis of $NN \to \{pp\}_S\pi$ at 353 MeV

Proton-proton elastic scattering

In a meeting devoted to mesons, why waste time on elastic *NN* scattering? There are **many** reasons.

1) $NN \to N\Delta \to NN$ crucial above a few hundred MeV.
2) Distortion of the initial waves in say $pp \to pp\eta$ requires an understanding of the *pp* interaction.

There have been stupendous advances at COSY in the measurement of *pp* elastic scattering using the EDDA, ANKE, and KOALA detectors.

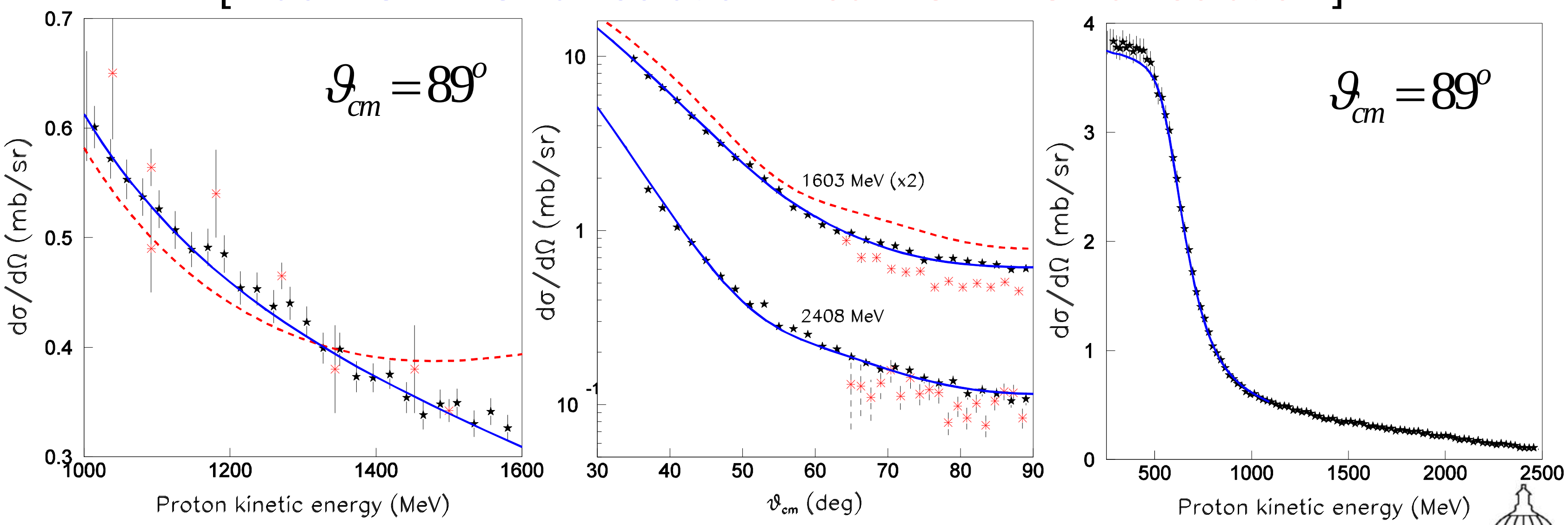
These all involved measurements with very thin targets inside the COSY ring, where double-scattering experiments were impractical. Hence only initial spin degrees of freedom could be studied.

EDDA detected both protons from *pp* elastic scattering and killed the background by demanding the correlation

$$\cot \vartheta_{\text{lab}}^{1} \cdot \cot \vartheta_{\text{lab}}^{2} = 1 + T_{\text{lab}} / 2m_{p}.$$

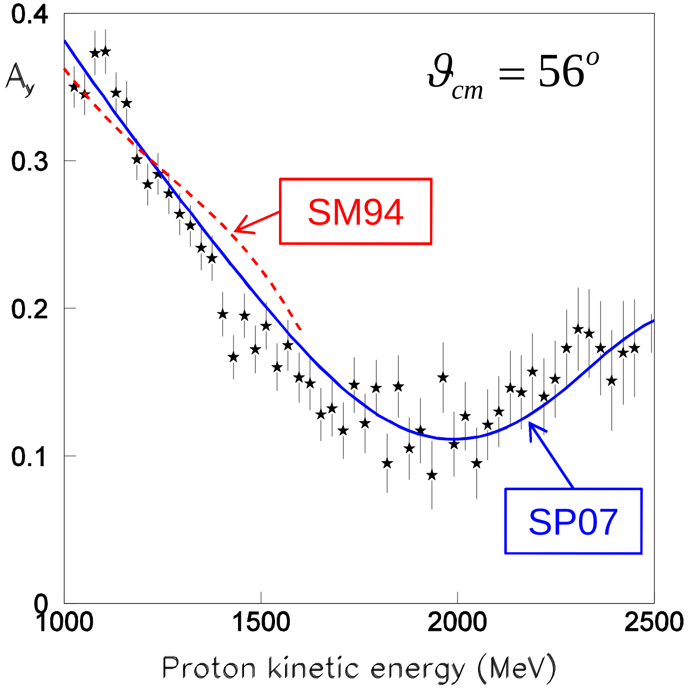
Having to detect both protons means that data were only available for $\vartheta_{cm} \geq 35^{o}$. The measurements could be carried out during acceleration (and deceleration) in COSY and hence over a continuum of energies from 230 to 2590 MeV. Data were obtained on the differential cross section, the proton analysing power, and spin-correlations which completely revolutionised the partial wave analysis.

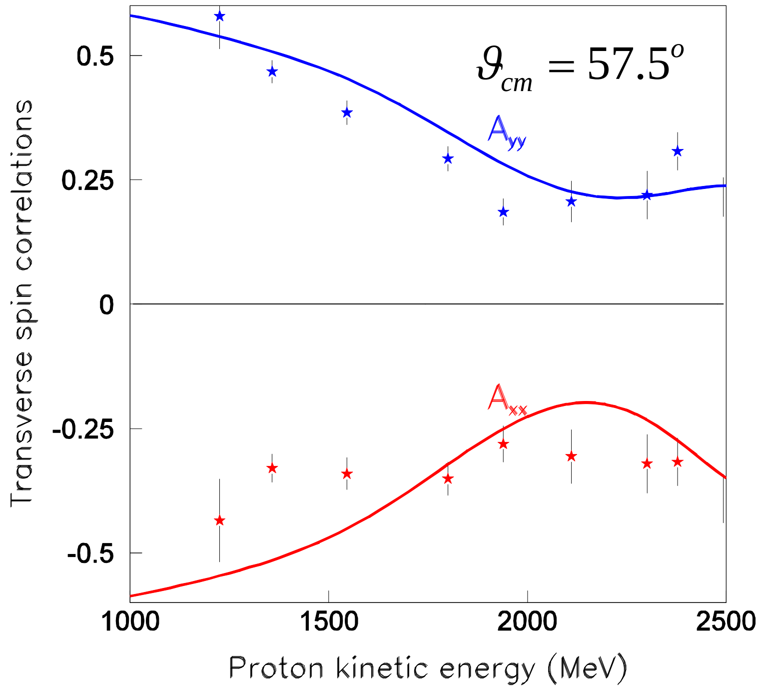
[Blue = SAID SP07 solution. Red = SAID SM94 solution.]



Normalisation fixed at one energy

Small subsample of EDDA results





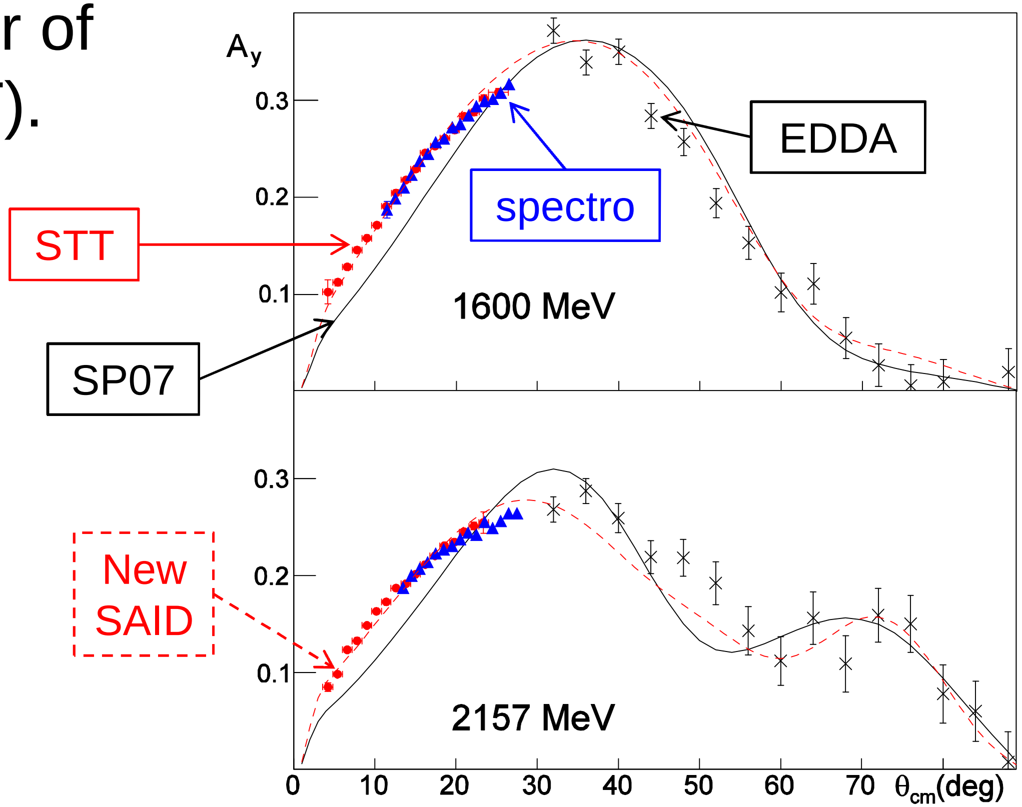
The EDDA analysing power measurements were carried out with a polarised target.

Spin correlations required the beam to be polarised as well and, due to the passage through the depolarising resonances, fixed energies were more robust.

ANKE measured *pp* elastic scattering analysing powers at smaller angles than EDDA by measuring one final proton and its energy/momentum. Results were obtained by detecting the fast proton in a magnetic spectrometer or the slow recoil in a pair of tracking telescopes (STT).

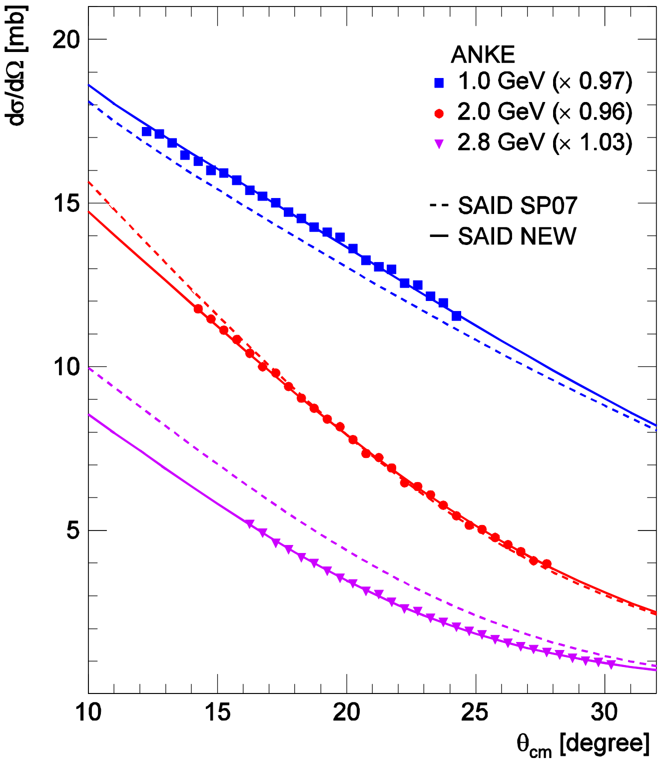
Note that the points refer to EDDA data at one energy – but they have many energies in these regions.

The SP07 solution has the wrong shape for A_y at small angles – an updated solution (New SAID) was produced.

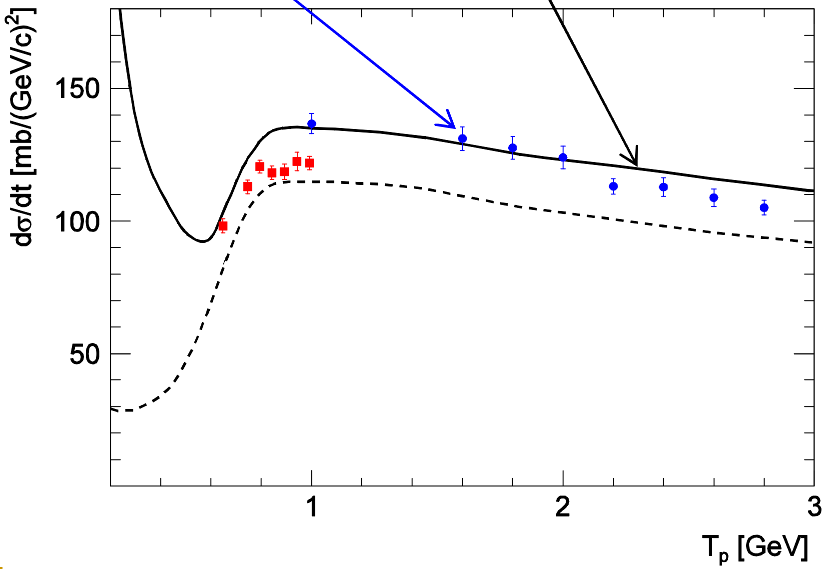


ANKE measured the normalisation (luminosity) by studying the energy loss through electromagnetic interactions in the target. Total precision claimed ±3%.

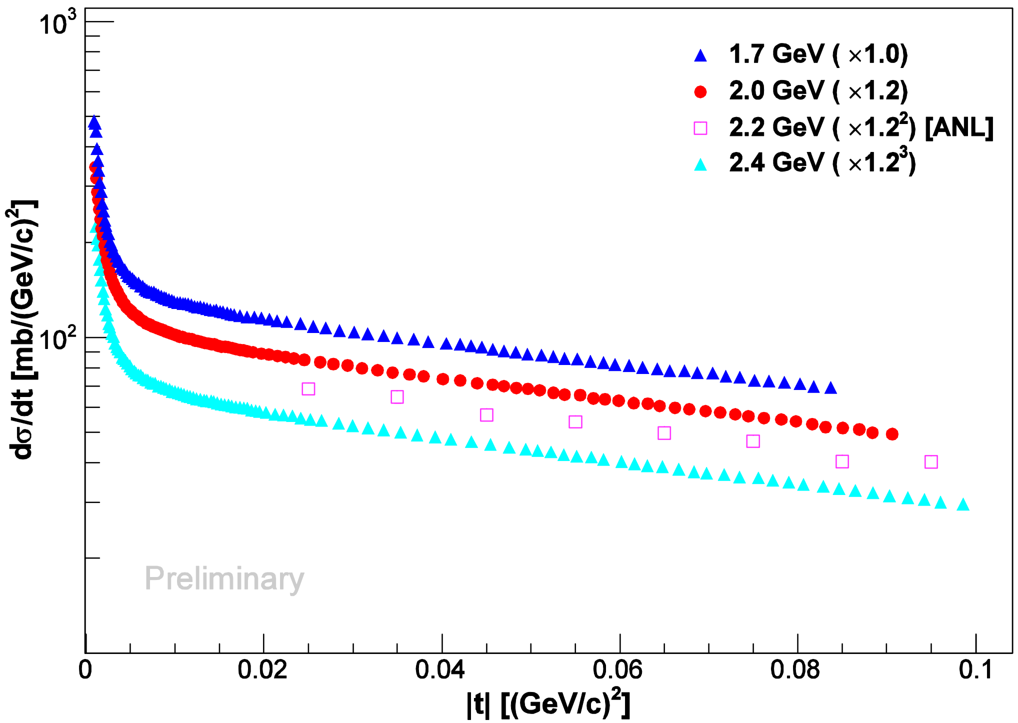
Results did not always agree with the SAID SP07 solution that was tuned to fit the larger angle EDDA data. Agreement with the new solution could be achieved if the data were allowed to float with the systematic errors.



Extrapolation of the Coulomb-corrected cross sections to the forward direction agree with forward dispersion relations:



Even <u>smaller</u> angles could be studied with the KOALA recoil detector of the PANDA collaboration, which was designed to measure the luminosity in $\bar{p}p \to \bar{p}p$.



Data are taken over a range of momentum transfers *t*, where Coulomb, Coulomb-Nuclear interference, and Nuclear are important.

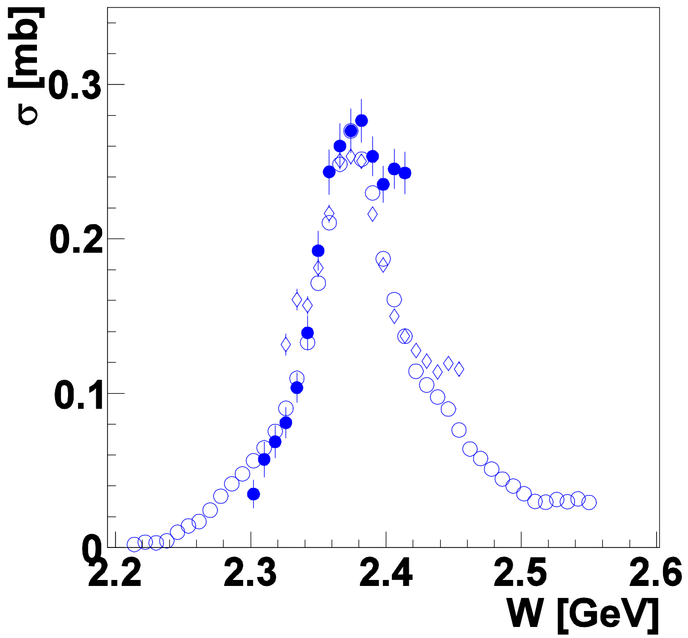
The normalisation is estimated by fitting the data and realising that pure Coulomb cross section is unambiguous.

The luminosity may be fixed by the height of the Coulomb peak – but with what error?

The apparent quality of the data is impressive and preliminary estimates give reasonable numbers but we must wait for the evaluation of systematic uncertainties. N.B. There is some overlap with the ANKE range.

The WASA dibaryon

The search for dibaryons has a long and generally frustrating history. The inspiration came from six-quark bag models that predict several states. But the only confirmed dibaryon was the deuteron, where the relevant degrees of freedom are (probably) pions and nucleons.



The WASA collaboration at CELSIUS and COSY measured the total cross section for quasi-free $np \rightarrow d\pi^0\pi^0$ by using a deuteron beam or a deuterium target. The c.m. energy W is spread by the Fermi momentum but, by reconstructing the whole event, W could be evaluated with some precision.

A very impressive peak was obtained at the same position in all three experiments at

W = 2.38 GeV with $\Gamma \approx 70$ MeV.

Suggested this was a dibaryon, d*(2380).

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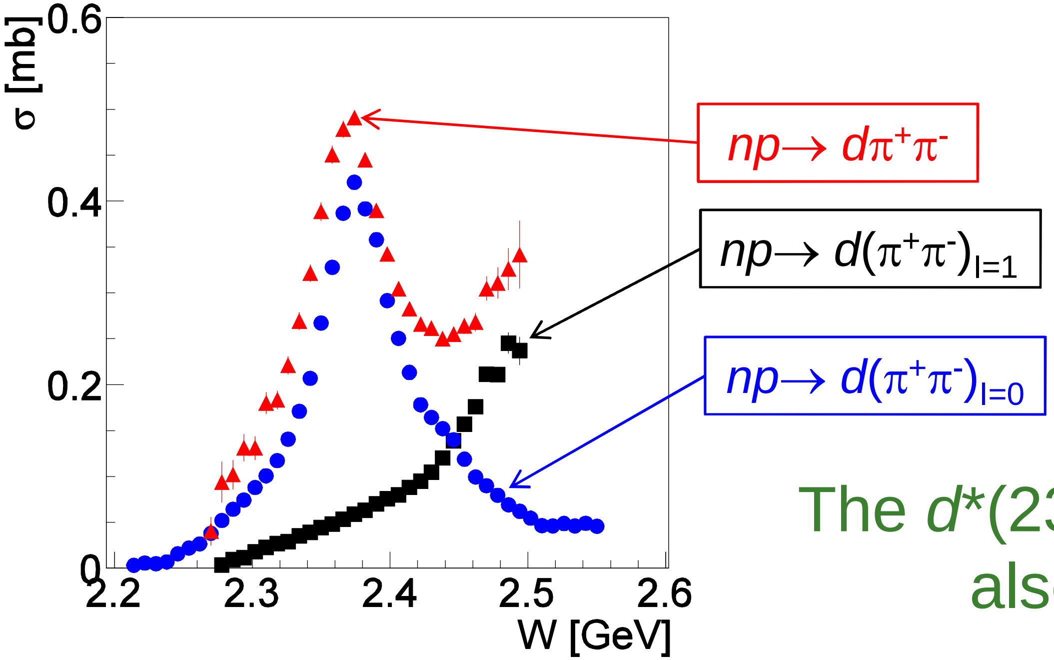
Seems to be associated with ABC enhancement at low $\pi^0\pi^0$ masses.

If d*(2380) is a dibaryon, it must have unique quantum numbers. Angular distribution seems to prefer $J^P = 3^+$ over 1^+.

3$^+$ assignment is supported by evidence from the partial wave decomposition of the inelastic cross section.



By measuring also the total cross section for $pp \rightarrow d\pi^+\pi^0$ the group could decompose the contributions from isoscalar and isovector $\pi\pi$ pairs.

The *d**(2380) structure is seen also in $np \rightarrow d\pi^+\pi^-$.

Though there is still some doubt if the *d**(2380) is really a dibaryon resonance, it is a good working hypothesis that must be tested further.

If it exists, is it a 6q state or is it a bound state of $\Delta(1232)\Delta(1232)$? If $\Delta\Delta$, why is the width so narrow?

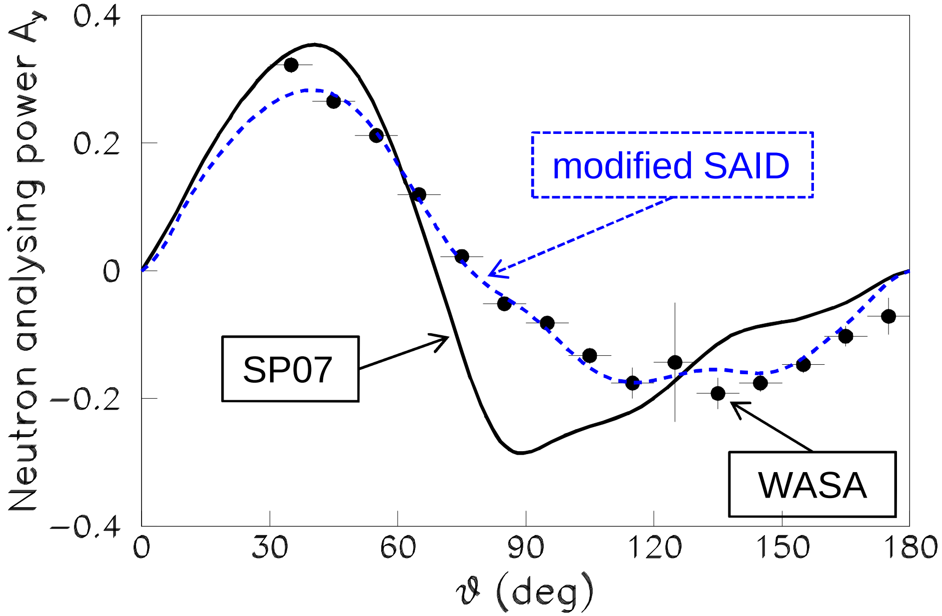
Even if it turns out not to be a dibaryon, it is still a very important observation in our field.

Extra evidence must be sought, and for this we turn to neutron-proton elastic scattering.

Neutron-proton elastic scattering

At the outset it must be stressed that the WASA dibaryon is close to the upper limit of validity of the SAID partial wave analysis of *np* elastic scattering – due to a lack of data.

COSY was not designed for secondary neutron beams but measurements could be made of quasi-free np scattering



using a deuteron beam,

$$\vec{d}p \to p_{\text{spectator}}\, pn$$

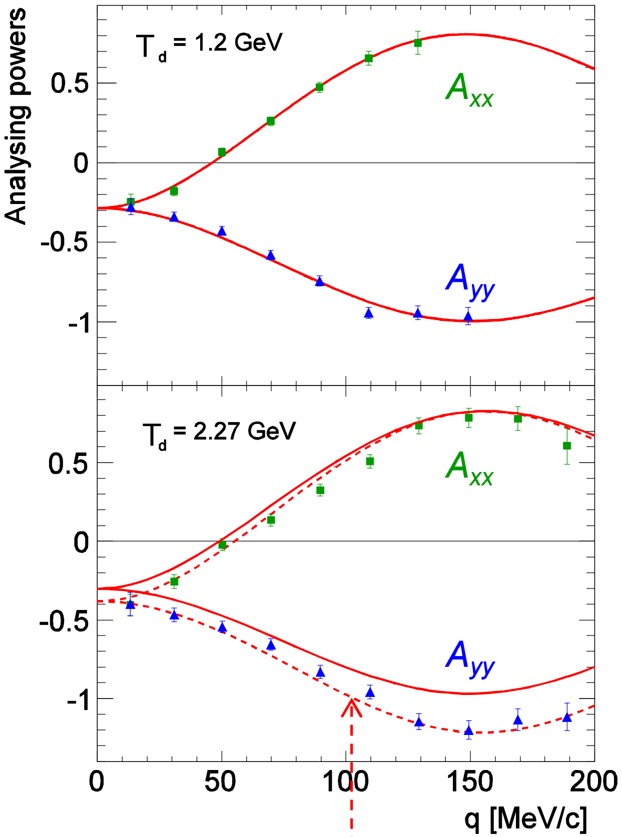
which is interpreted as

$$\vec{n}p \to pn.$$

Old (SP07) and new SAID solutions were smeared over the Fermi momentum. New solution consistent with 3^+ dibaryon but this is <u>not</u> a proof!

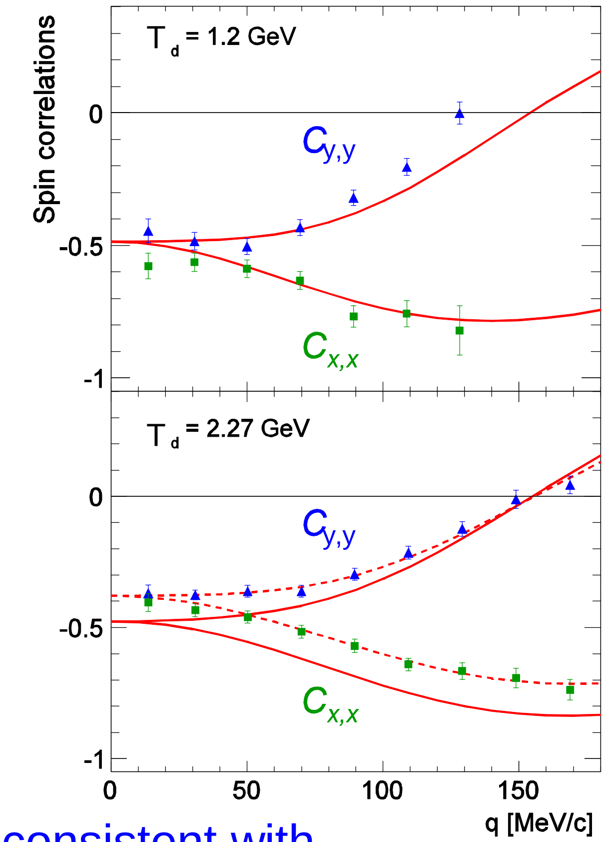
Earlier evidence from COSY on the SAID *np* solution

dp → $\{pp\}_s n$ at small angles between the deuteron and diproton is very sensitive to the *np* spin dependence <u>if E_{pp} is small</u>.



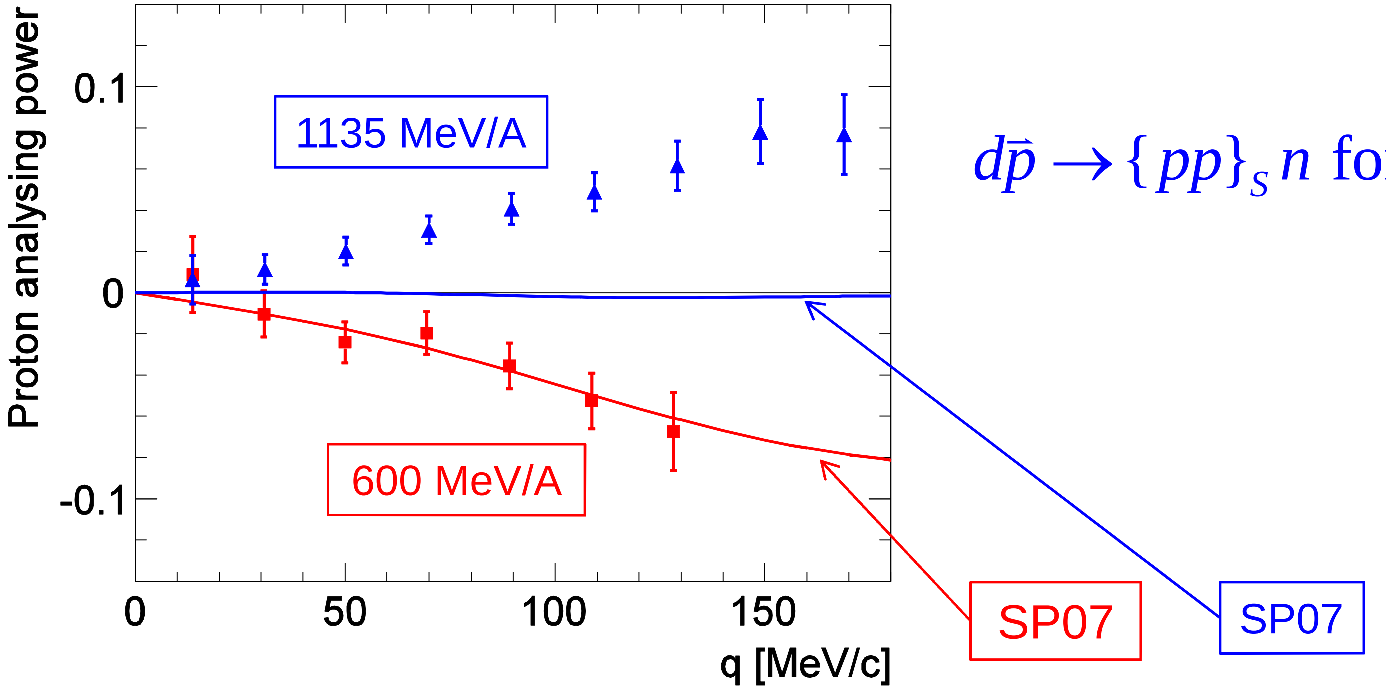
At 600 MeV per nucleon, impulse approximation describes well deuteron ← tensor analysing power & dp spin correlations →

At 1135 MeV per nucleon, impulse approximation requires reduction of the longitudinal spin-spin amplitude in order to describe the deuteron ← tensor analysing power & dp spin correlations →



Modified SAID PWA amplitudes.

Modifications not inconsistent with that required to describe WASA data

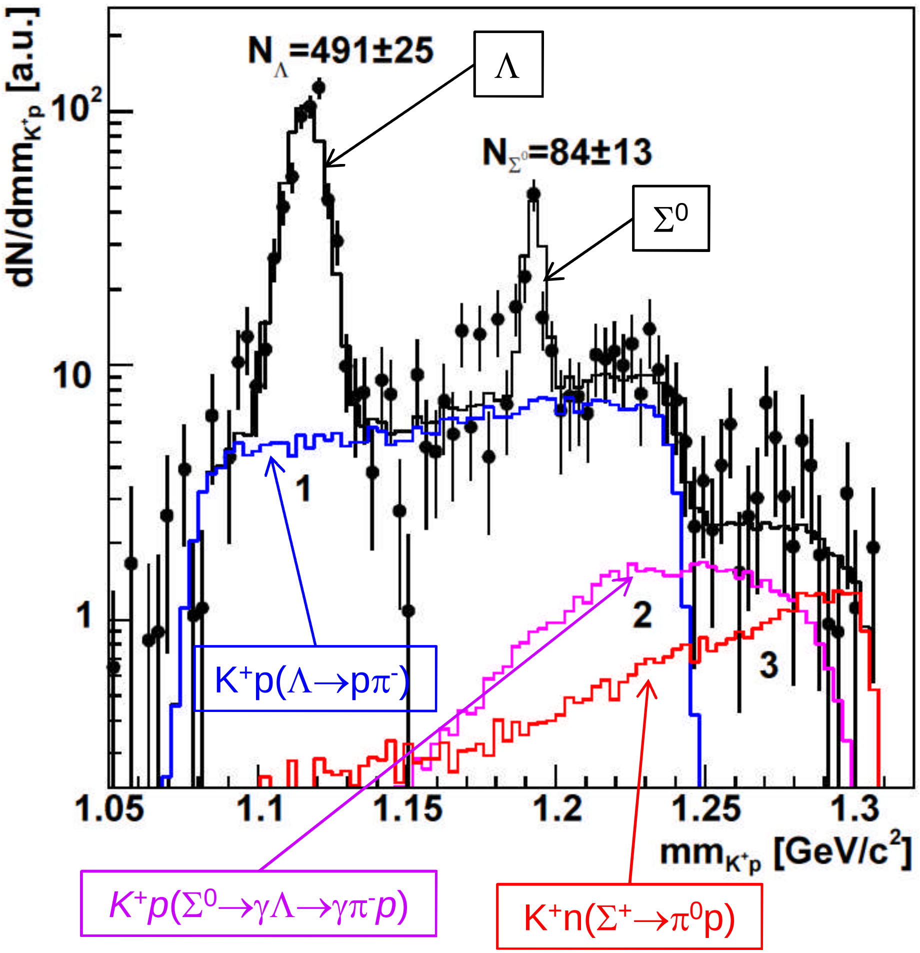


$d\vec{p} \rightarrow \{pp\}_S n$ for $E_{pp} < 3$ MeV

SAID SP07 solution seems to underestimate the spin-orbit amplitude needed to describe $p\vec{n} \rightarrow np$ in the region of 1135 MeV per nucleon.

There is a lack of good quality neutron-proton data in and above the *d**(2380) position.

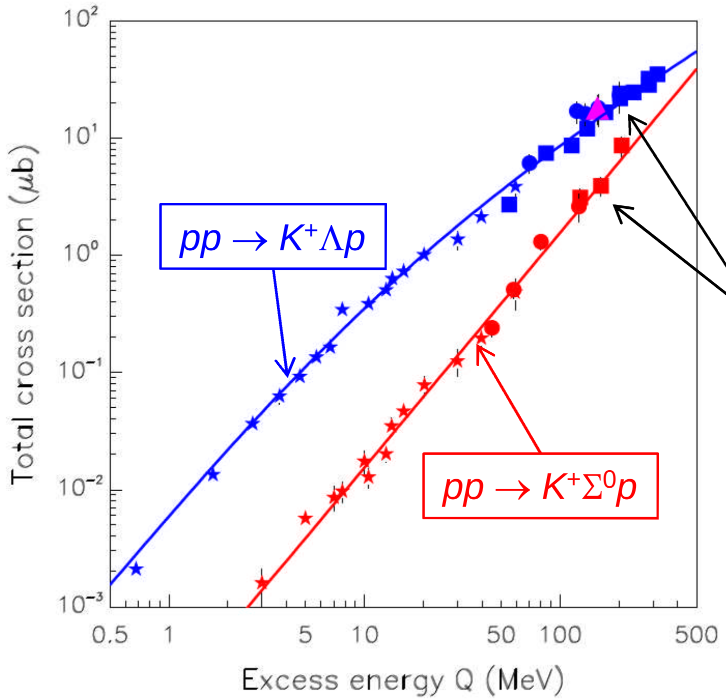
Large acceptance hyperon production



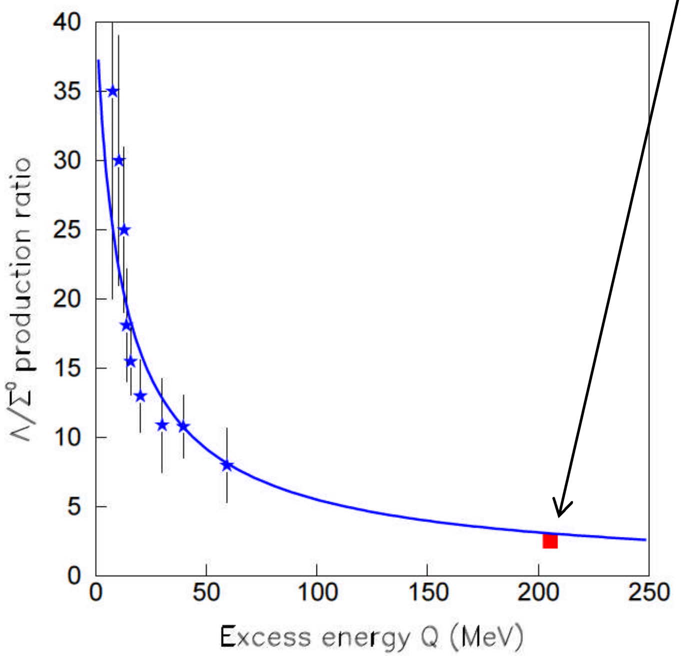
ANKE data @ 2.16 GeV

By detecting the K^+ and p from $pp \to K^+pX$ one can see peaks from Λ and Σ^0 production but there are large physics backgrounds due to the misidentification of the direct proton.

Near threshold the acceptance of COSY-11 or ANKE for K^+p pairs is sufficient to extract total cross sections as functions of the excess energy $Q = \sqrt{s} - \Sigma\, m_{final}$.



But at high Q the COSY-11 and ANKE acceptance is too small. (COSY-TOF provides the squares)



The Q dependence of the ratio of Λ to Σ^0 production seems to depend on the Λp final state interaction:

$$R = C / \left(1 + \sqrt{1 + Q / B_0}\right)^2,$$

where $B_0 \approx 5.2$ MeV.

COSY-TOF has sufficient acceptance and statistics (200,000 events at 2.95 GeV/*c*, $Q \approx 200$ MeV) to allow Dalitz plots to be constructed.

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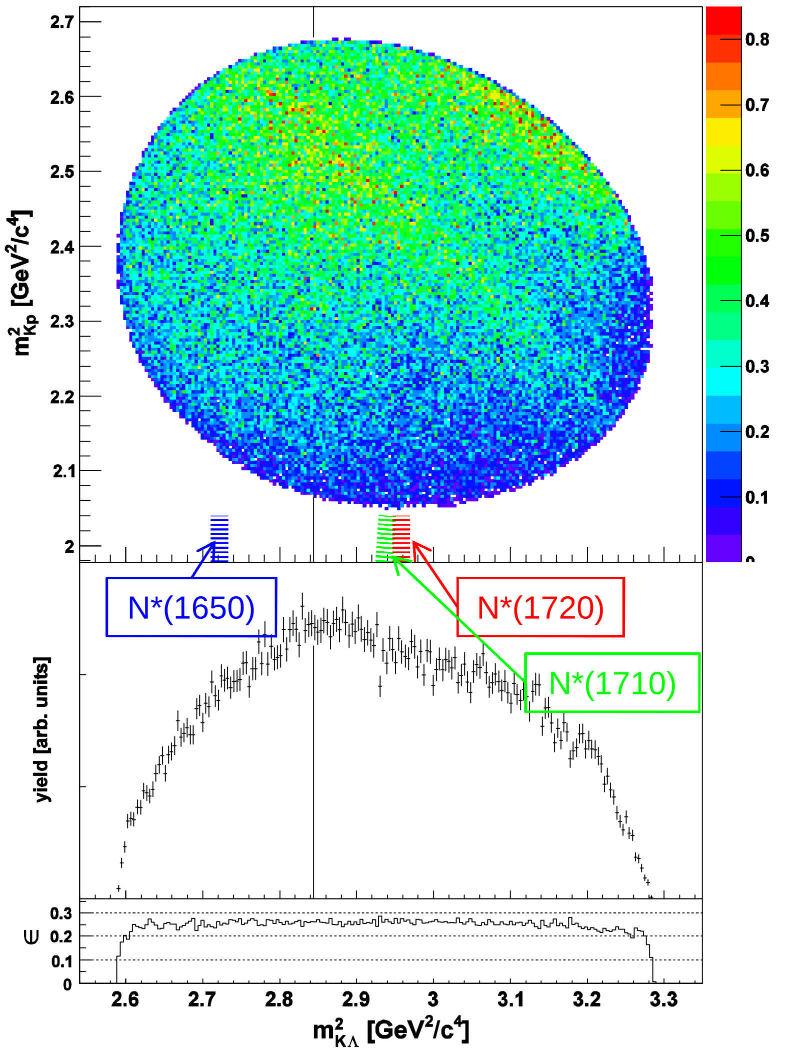
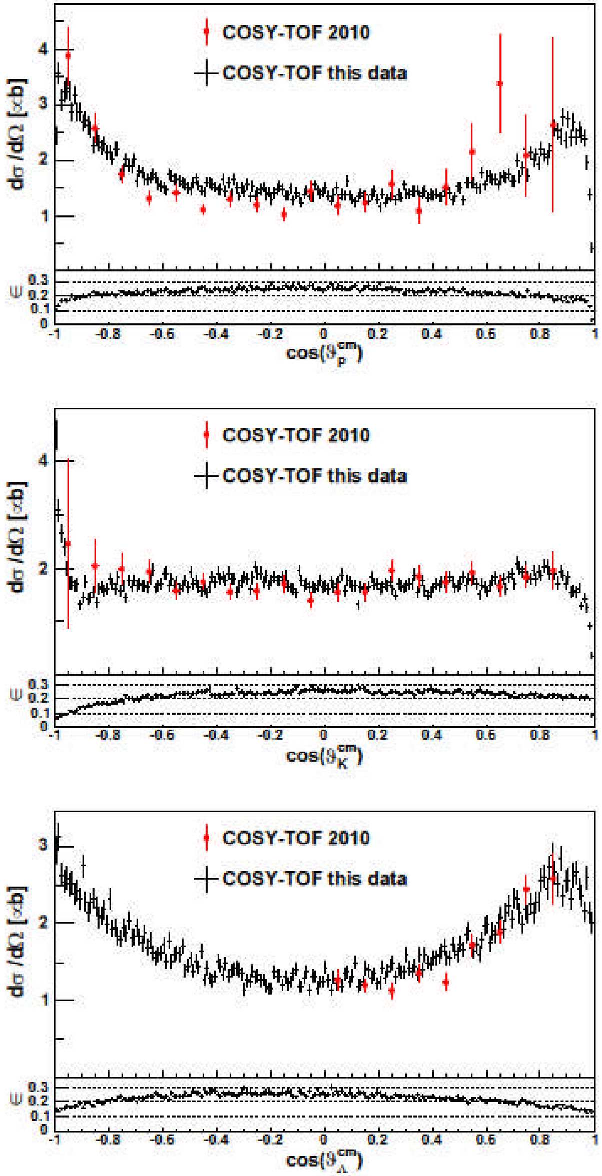


Lower energy data show the clear influence of the $N^*(1650)$ resonance [the second S_{11}] with minor effects coming from the $N^*(1710)$ and $N^*(1720)$ isobars.

Important because it shows that the underlying dynamics is $pp \rightarrow pN^*$, where the isobar decays into $K^+\Lambda$.

The excess of events along the antidiagonal is connected with the cusp at the Σ threshold (discussed in #5).

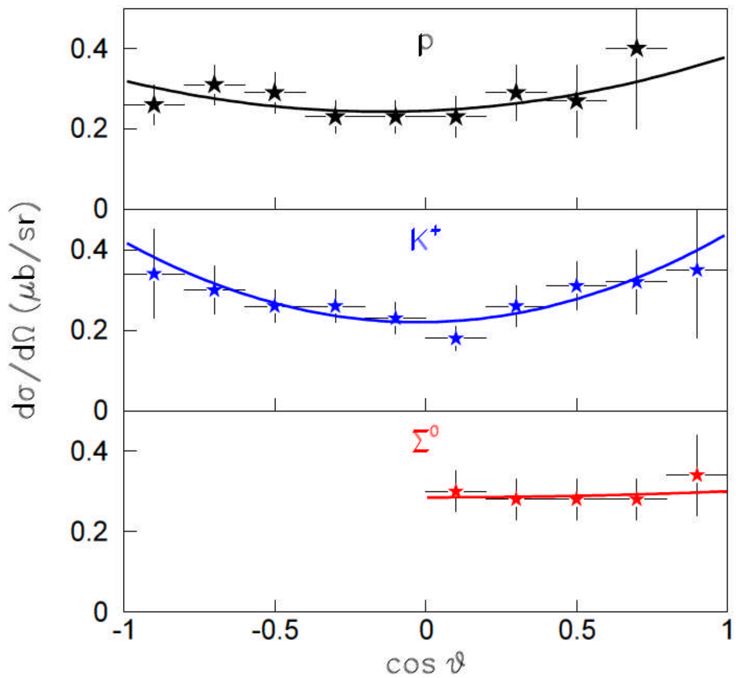
$pp \rightarrow K^{+}\Lambda p$ @ 2.95 GeV/c

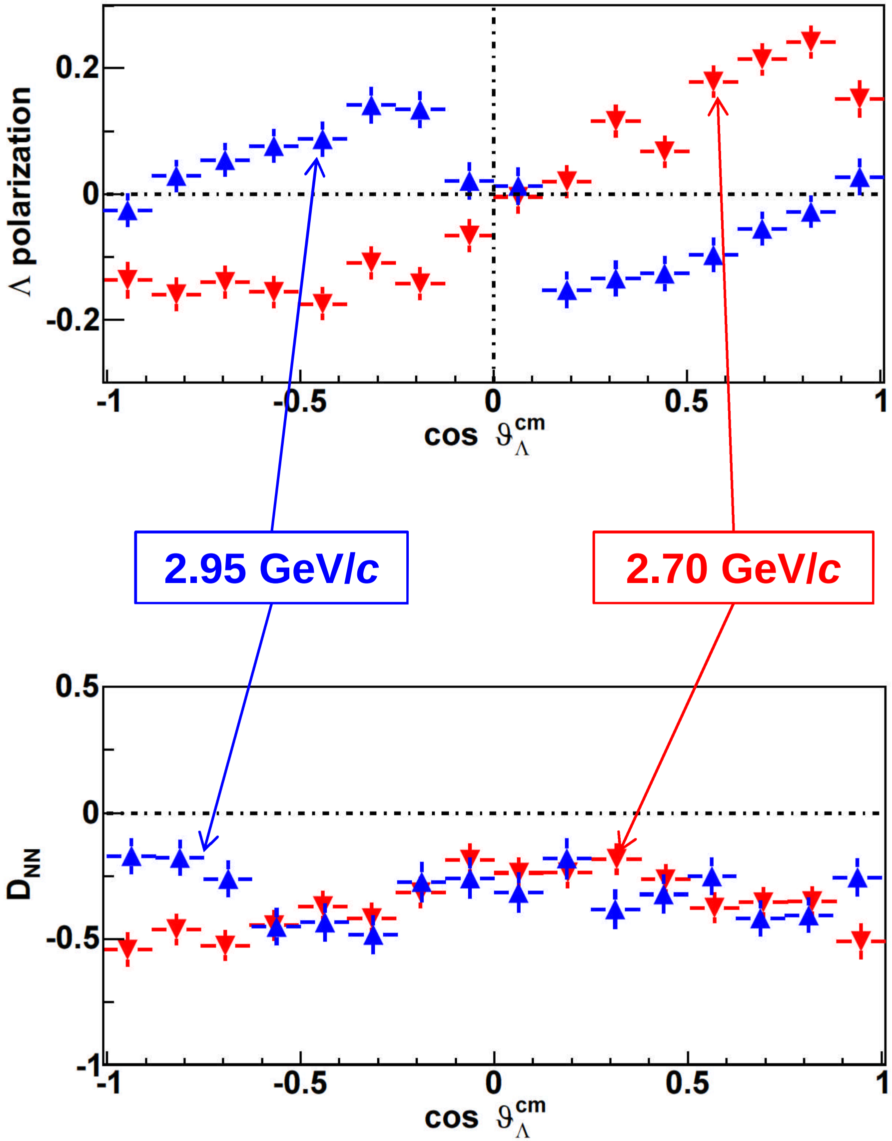


The high acceptance of the COSY-TOF detector also allowed angular distributions to be extracted in the c.m. (and helicity & Gottfried-Jackson) frame.

The distributions should be symmetric about 90º but there is some problem at extreme angles.

$pp \rightarrow K^{+}\Sigma^{0}p$ @ 3.06 GeV/c





4

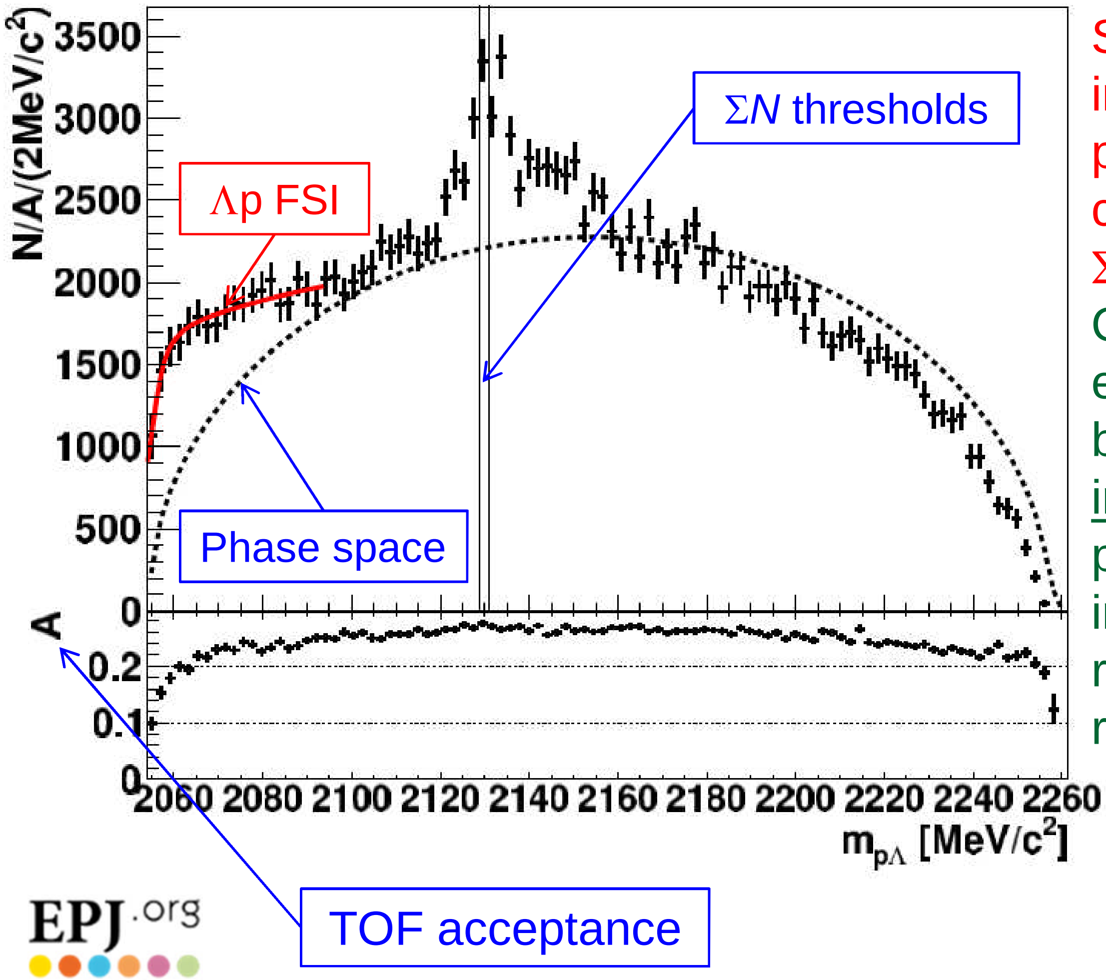
COSY-TOF has good angular coverage and can therefore measure well the proton analysing power, the Λ polarisation *P*(Λ), and the spin transfer D_{NN} between the proton and the Λ in the well identified pp → K^+Λp reaction.

P(Λ) changes sign between 2.70 and 2.95 GeV/*c* but D_{NN} (which is a tensor quantity) is much more stable.

Laget argues that K exchange gives negative D_{NN} and π gives positive. However, It is already known for η production that it is likely that ρ exchange is more important than π and this could be even more true here.

The hyperon cusp

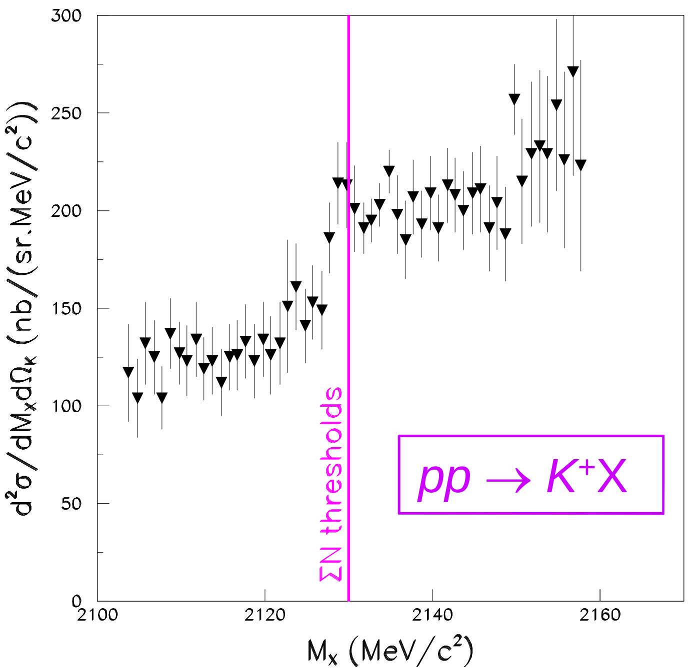
The COSY-TOF collaboration measured unambiguously the reaction $pp \to K^+\Lambda p$ at a beam momentum of 2.95 GeV/c. The data show a very pronounced peak in the vicinity of $m_p + m_{\Sigma^0}$ or $m_n + m_{\Sigma^+}$.



Since the acceptance is smooth in this region, this must be a physics effect, linked to the coupling between the Λp and ΣN channels.

One is therefore seeing the effects of $pp \to K^+\Sigma N$ followed by $\Sigma N \Leftrightarrow \Lambda p$. This contribution <u>interferes</u> with direct $pp \to K^+\Lambda p$ production and, since it is an interference effect, there is no reason for it to look like a simple resonance peak.

Cusps are very common in reactions involving strange particles but they are very hard to model. Peak depends relative amplitudes for direct $pp \to K^+\Sigma N$ and $pp \to K^+\Lambda p$ as well as the $\Sigma N \Leftrightarrow \Lambda p$ coupled-channel potential.



If only the K^+ is detected it is not possible to distinguish true Σ production from Λ production where there is a cusp at the ΣN thresholds.

HIRES collaboration measured $pp \to K^+X$ at $\theta_K = 0^o$ and found a big jump at $M_X \approx M_\Sigma + M_N$. Before the size of the cusp was firmly established, this was presented as evidence for Σ production.

η-mesic nuclei

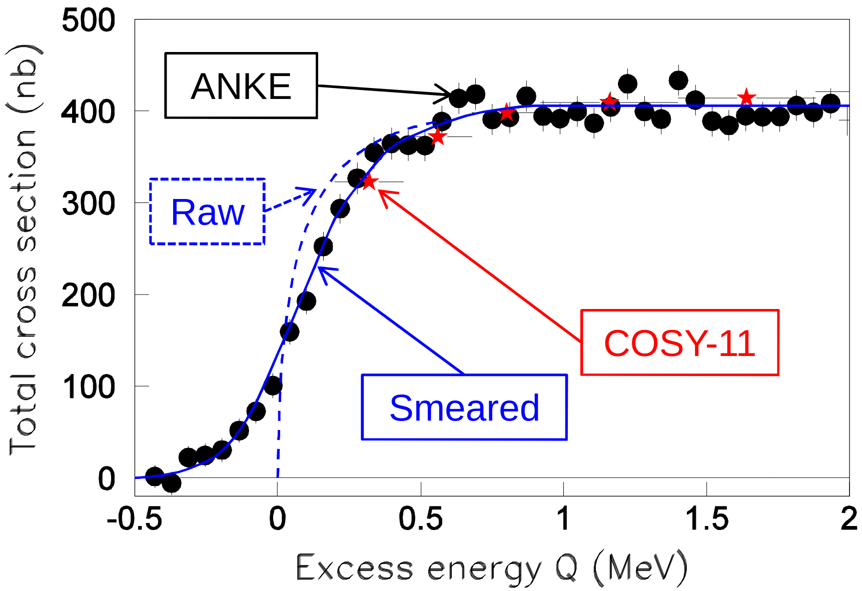
Over twenty years ago it was suggested that the attraction between the η meson and protons and nucleons might be strong enough for the η to bind to some nuclei. Estimates were uncertain because of ambiguities in η*N*. Since the state can decay by emitting pions, it is at best "quasi-bound".

Many searches were made in the bound-state region where η-mesic nuclei must decay through pion or nucleon emission. None of these results has been completely convincing – the non-η background is horrendous.

The alternative is to look at η production very close to threshold on very light nuclei and then try to extrapolate in energy to see if one can identify a pole. Though this method overcomes the background problem, it cannot tell if any identified state is quasi-bound or quasi-antibound.

$dp \rightarrow {}^3He\ \eta$

There were several measurements at Saclay that showed that the $dp \rightarrow {}^3He\ \eta$ reaction had a very strange energy dependence near threshold, probably due to a final state interaction (FSI) between the η and the ${}^3He$. By far the most detailed measurements were carried out at COSY.



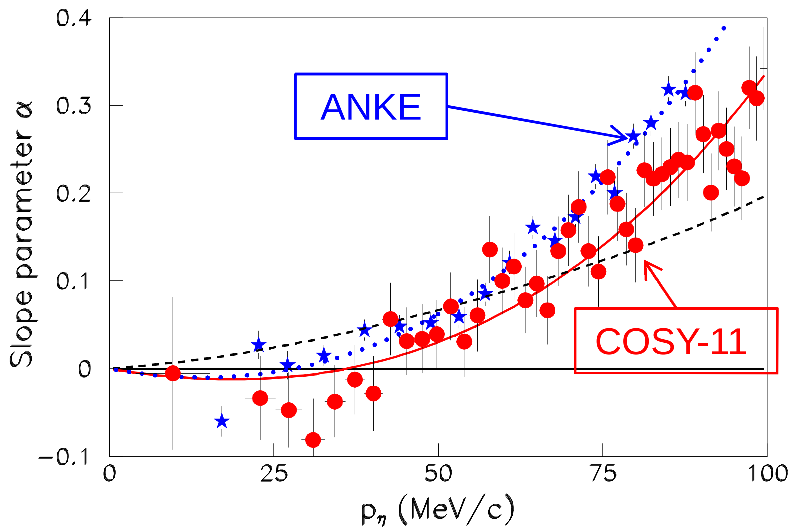
The COSY-11 and ANKE data were completely consistent – but it is crucial to take into account the momentum resolution of the beam! The value of the excess energy *Q* (the energy above threshold in the c.m. frame) was determined by the size of the ${}^3He$ ellipse.

Total cross section jumps to its plateau value within about 0.5 MeV.
Fit gives pole at Q_0 = [(-0.30±0.15±0.04) ± i(0.21±0.29±0.06)] MeV.
Sign of imaginary part cannot be fixed.

If it is a ^{3}He η FSI effect, it should be seen for other entrance channels – checked by measuring the tensor analysing power. Extra information comes from the angular dependence. Define

$$\alpha = \frac{d}{d(\cos\vartheta_\eta)} \ell n\left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{\cos\vartheta_\eta=0}$$

If α came from simple *s:p* interference, it should vary linearly with p_η. It doesn't!

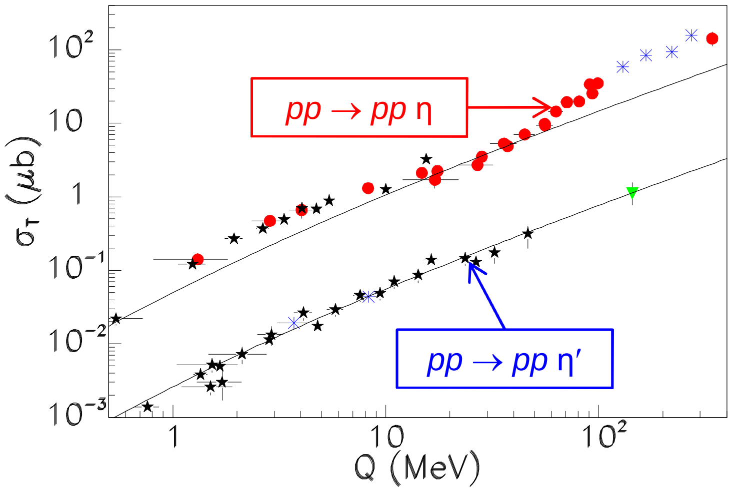


The non-linearity arises because the phase of the *s*-wave production amplitude is varying very fast due to the pole.

This is the best evidence for the existence of a pole associated with η production but it doesn't tell you whether the state is quasi-bound or quasi-antibound.

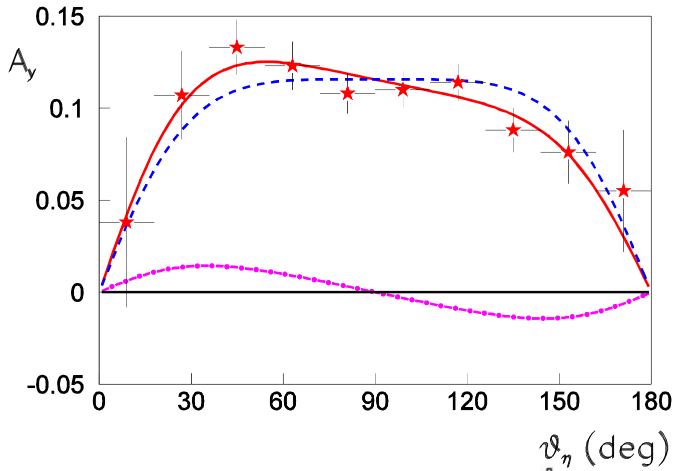
Similar indications from γ^3He → η^{3}He, but resolution is not good.

Non-strange meson production in *NN* collisions

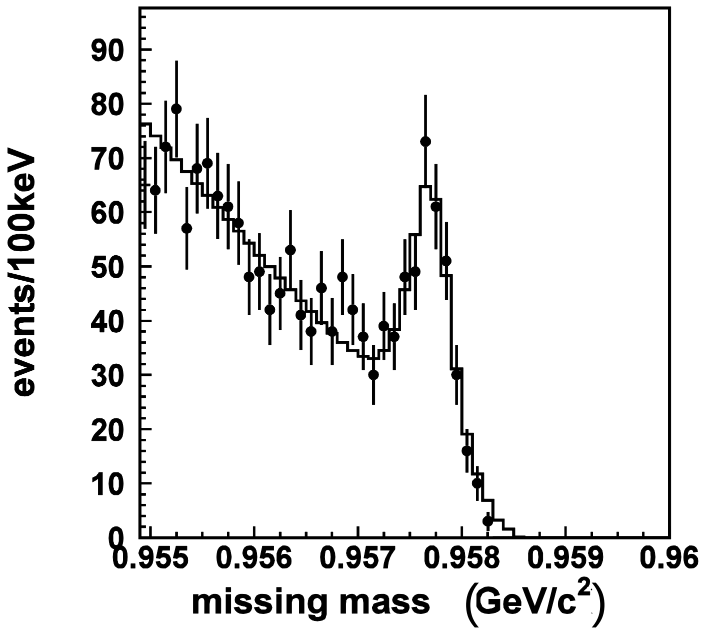


Before the COSY-11 work there were very few measurements of the production of mesons heavier than the π in *pp* collisions near threshold. Their results dominate the total cross sections for η and η′ production. Curves represent phase-space modified by *S*-wave *pp* FSI. Deviations for the η at large *Q* come from higher partial waves. At low *Q* there are effects from the η*p* attraction..

Many differential distributions for η production have also been determined, mainly by the COSY-11 group and these also show evidence for higher *pp* final waves. However, the first <u>significant</u> measurement of the analysing power in $\vec{p}p \to pp\eta$ was carried out at COSY-WASA at *Q* = 72 MeV. Data suggest that A_y arises mainly from *Pp*:*Ps* interference.



The $pp \to pp\,\eta'$ reaction



The COSY-11 collaboration determined two important features from their data on η′ production. Only the two final protons were measured and the meson identified from the missing-mass peak. Close to threshold the mass resolution is very good but the momentum spread of the COSY beam ≈ 2.5 MeV/*c*. However, COSY-11 was situated in a dispersive region so that it only "saw" ≈ 0.06 MeV/*c.*

First direct measurement of the η′ width:

$$\Gamma = (0.226 \pm 0.017_{stat} \pm 0.014_{syst})\ \mathrm{MeV}/c^2.$$

For the $pp \to pp\,\eta$ reaction, the variation of the total cross section with Q indicates strong η*p* attraction near threshold. It is this that gives rise to possible η-mesic nuclei.

There is no suggestion of an analogous effect for $pp \to pp\,\eta'$ and the COSY-11 data allowed limits to be put on the η′*p* scattering length.

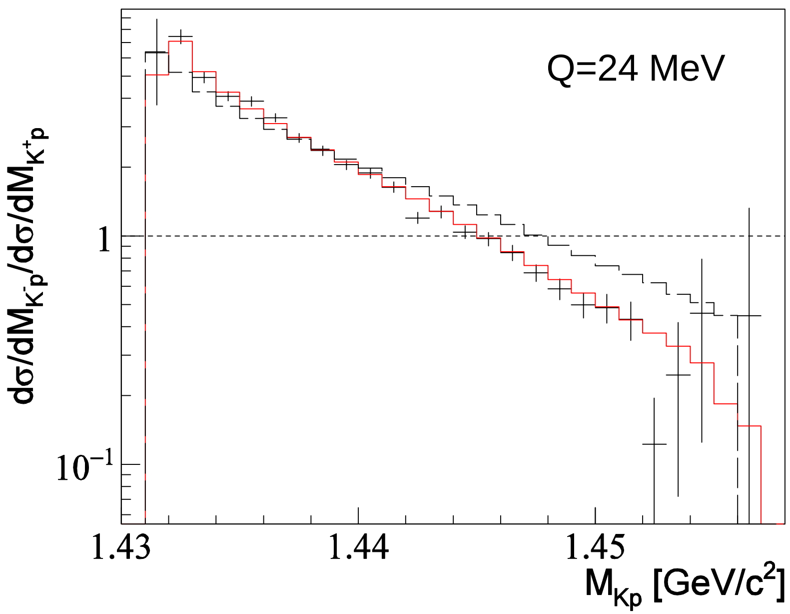
I would not put any money on bound η′ in nuclei!

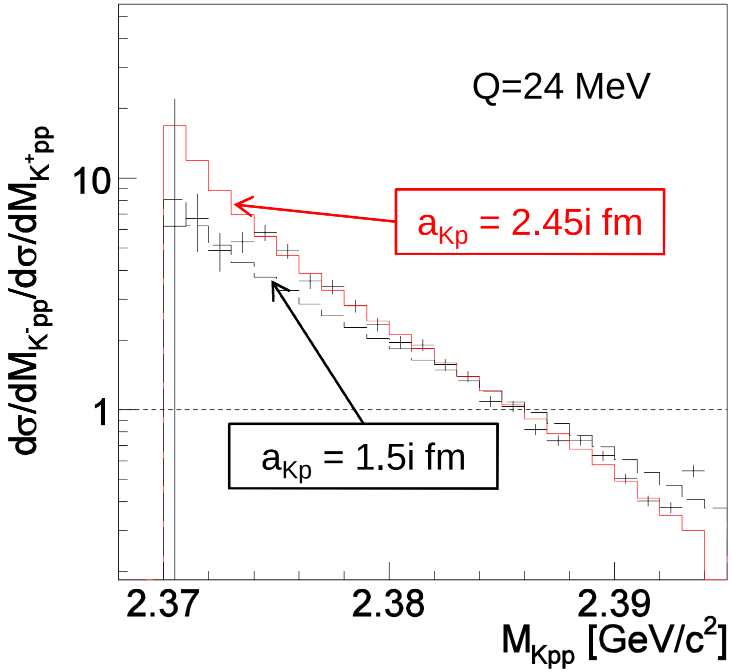
Kaon pair production

The first measurements of $pp \to ppK^+K^-$ by the COSY-11 collaboration suggested that the K^- was preferentially attracted to one (or both) of the final protons.

This was repeated with higher statistics at higher energies at ANKE, where the initial drive came from the study of ϕ production in $pp \to pp(\phi \to K^+K^-)$.

$$\text{Define } R_{Kp} = \frac{\mathrm{d}\sigma / dM_{K^-p}}{\mathrm{d}\sigma / dM_{K^+p}} \text{ and } R_{Kpp} = \frac{\mathrm{d}\sigma / dM_{K^-pp}}{\mathrm{d}\sigma / dM_{K^+pp}}$$

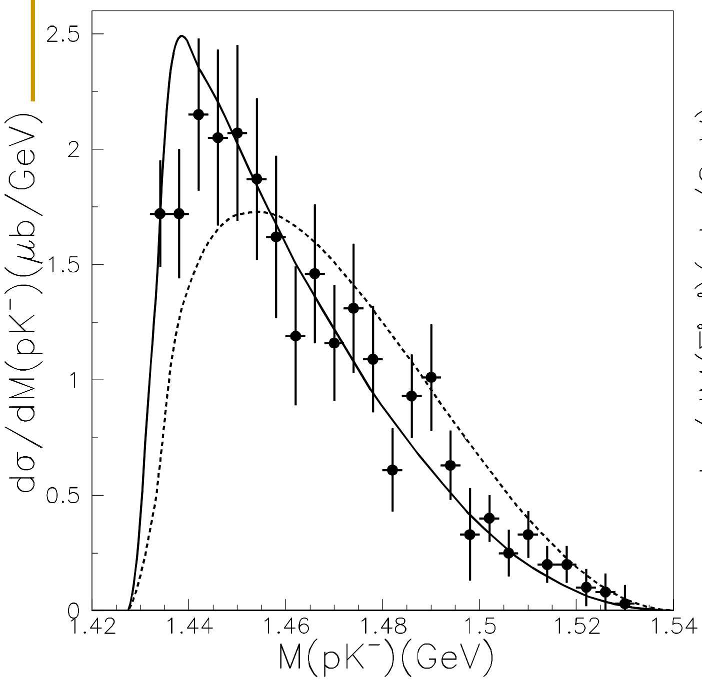


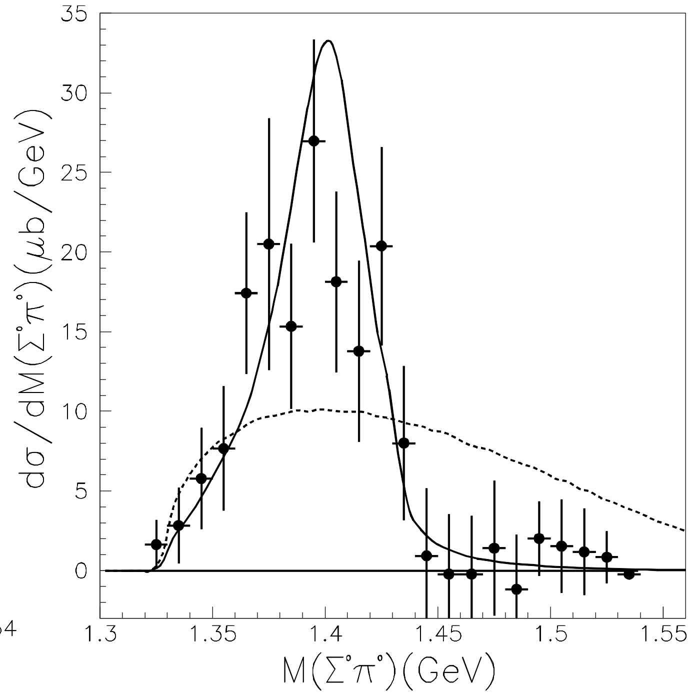


There is over an order of magnitude difference between low and high *Kp* masses (and similarly for *Kpp*) due to the K^-p attraction, probably driven by the $\Lambda(1405)$. Assume that the final state interactions factorise:

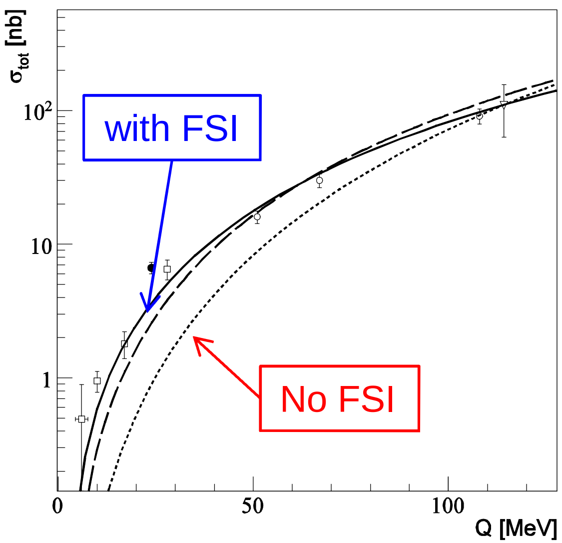
$$\boxed{F = F_{pp}(q_{pp}) \times F_{Kp}(q_{Kp1}) \times F_{Kp}(q_{Kp2}) \times F_{KK}(q_{KK}),}$$

where q_{pp}, q_{Kp1}, q_{Kp2}, and q_{KK} are the magnitudes of the relative momenta in the *pp*, two K^-p, and K^+K^- systems. Describes well both the *Kp* and *Kpp* ratios with K^-p effective scattering length (within this ansatz) of 2.5i fm.





Perhaps the $\Lambda(1405)$ is acting as doorway state for kaon pair production: $pp \to K^+p\,\Lambda(1405)$, with the tail of the hyperon decaying into K^-p. Joint fit gets the right shapes but normalisation out by factor of 0.4



Perhaps relevant for the deeply bound K^-pp controversy.

The energy dependence of the non-ϕ contribution to the $pp \to ppK^+K^-$ total cross section can be “understood” if FSI effects are included.

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Determination of the mass of the η meson

$$m_\eta = (547.873 \pm 0.005_{stat} \pm 0.023_{syst})\ \mathrm{MeV}/c^2.$$

This may be the most precise measurement of m_η in the PDG table – but who needs to know it to five significant figures?
It is the method that is important here!

Two measurements of *dp* (*pd*) $\to$ ^{3}He η got the "wrong" value. Since the masses of the other particles are known very accurately, need to measure precisely the energy Q above threshold and the corresponding beam momentum.

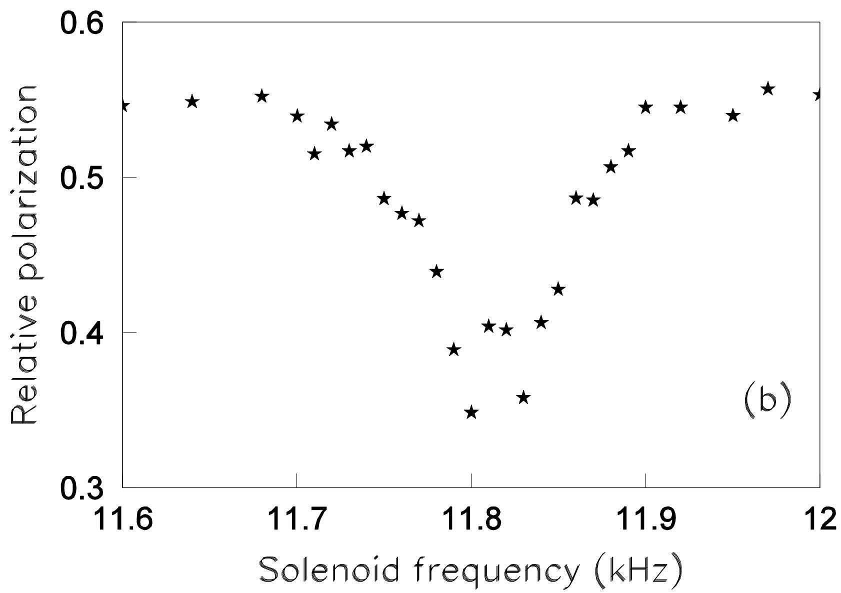
The determination of Q was discussed in connection with 6, the possible $^3_\eta\mathrm{He}$ mesic nucleus. Systematic effects are minimised by extrapolating to $Q = 0$.

The rotation frequency f_0 of COSY is known accurately but there is significant uncertainty in the exact orbit. Much greater accuracy is achieved by measuring the effects of a depolarising resonance induced by a solenoid on a polarised circulating deuteron beam.

The deuteron total energy E_d depends on the ratio of the depolarising frequency to the rotation frequency:

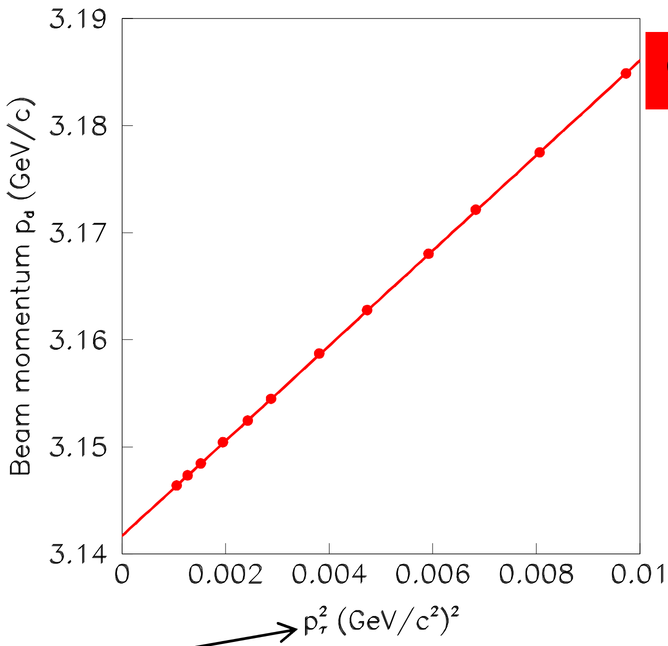
$$E_d = \frac{m_d c^2}{|G_d|}\left(1 - \frac{f_{\mathrm{Sol}}}{f_0}\right)$$

Gyromagnetic anomaly



f_{Sol} can be measured to $\approx 10^{-5}$.

determined from depolarising frequency



Experiment was carried out at twelve momenta close to threshold. Curve shows the expected miniscule deviations from linearity.

determined from $pd \to {}^3\text{He}\,\eta$

Threshold momentum determined as $3.141688 \pm 0.000021_{stat}$ GeV/*c*.

Most precise measurement ever carried out at COSY.

Such high precision was only possible because the full angular distribution of the $dp \to {}^3\text{He}\,\eta$ reaction fell within the acceptance of the ANKE spectrometer.

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Physics & Astronomy UCL

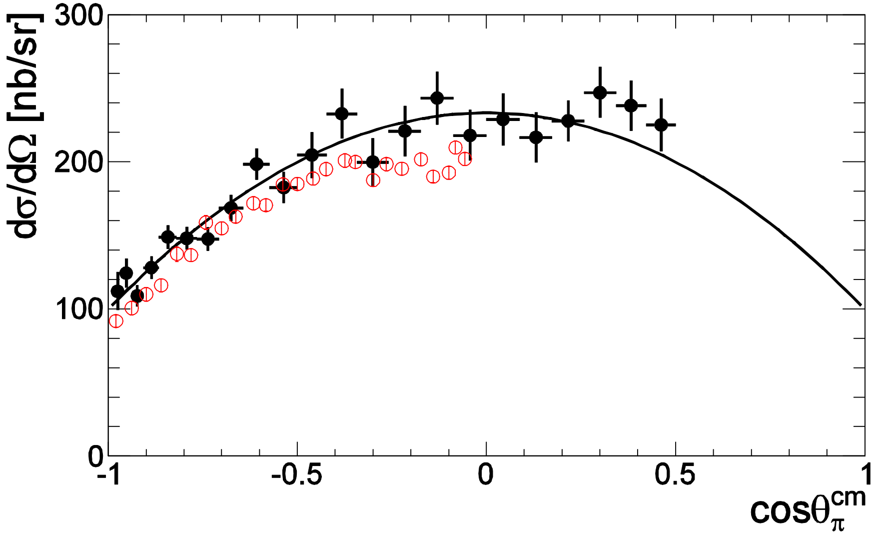
Amplitude analysis of $NN \to \{pp\}_s \pi$ at 353 MeV

The aim is to do a complete partial wave analysis of a subset of a single meson production reaction in *NN* collisions. By choosing the excitation energy $E_{pp} < 3$ MeV, it is hoped that the final *pp* system is in a relative *S*-wave, *i.e.*, $\{pp\}_s = {}^1S_0$.

Ideal experiment for COSY because no polarisations have to be measured in the final state. There should be less ambiguity than $pp \to d\pi^+$.

Results will provide strong tests for phenomenological models and more fundamental approaches, *e.g.*, chiral perturbation theory.

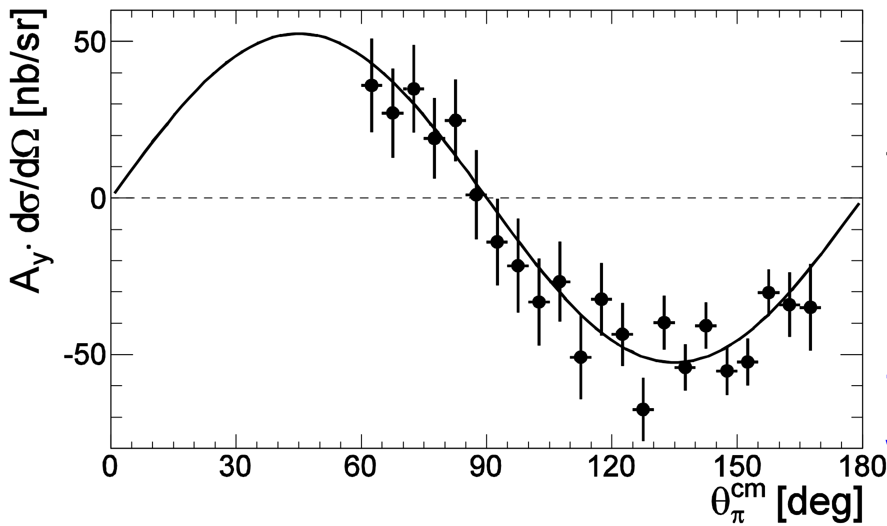
$pp \to \{pp\}_s \pi^0$



The cross section is symmetric about 90° and the analysing power antisymmetric. At low energies, three partial waves should dominate:

$$^3P_0 \to {}^1S_0 s\ ,\ {}^3P_2 \to {}^1S_0 d\ ,\ {}^3F_2 \to {}^1S_0 d$$

The data would support the determination of three real parameters – but not three complex amplitudes.

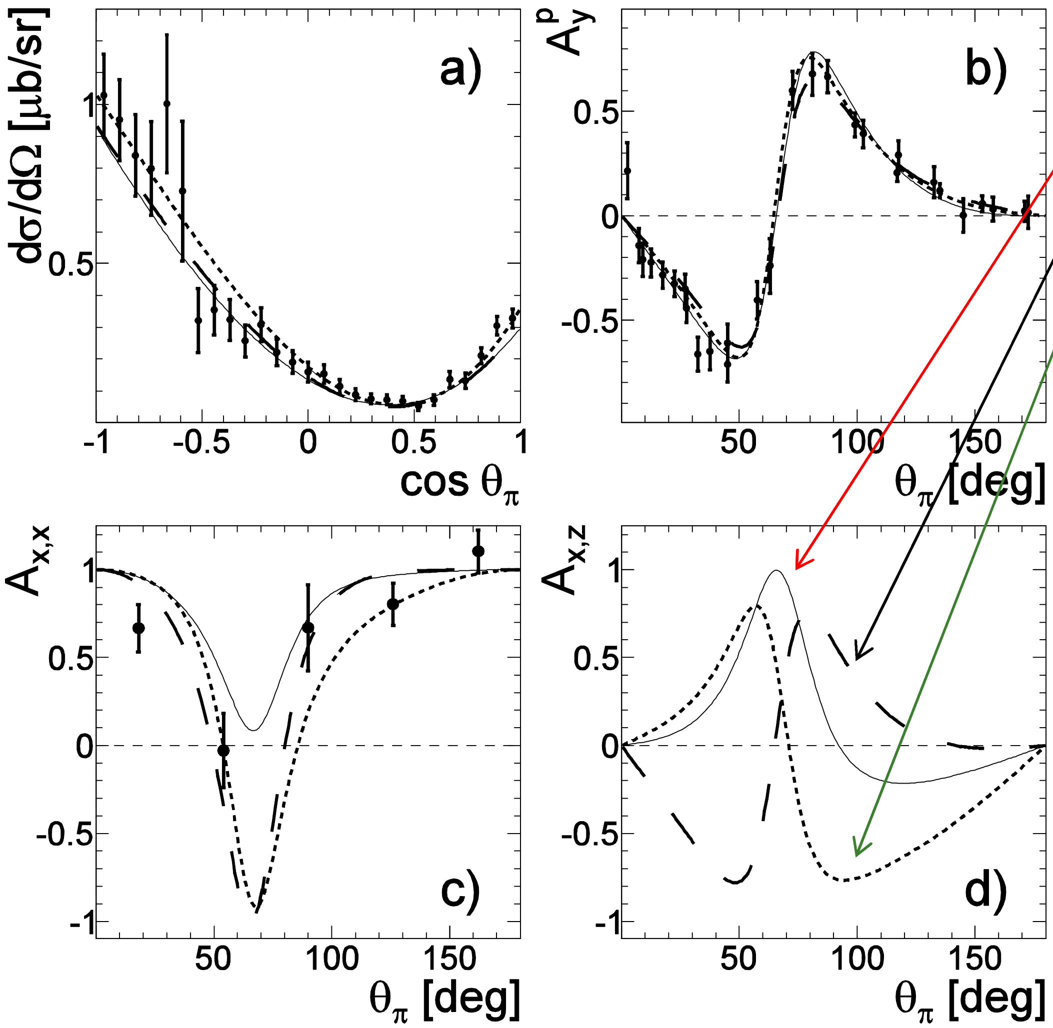


Since three initial waves are uncoupled or are weakly coupled, assume the Watson theorem and take the phases from the phase shift analysis of *pp* elastic scattering in the $^3P_0$, $^3P_2$, and $^3F_2$ states.

The $^3F_2 \to {}^1S_0 d$ amplitude was consistent with zero.

There are three discrete solutions for $pn \to \{pp\}_s \pi^-$

$$\left(\mathrm{Im}(^3S_1 \to {}^1S_0 p) / \mathrm{Re}(^3S_1 \to {}^1S_0 p),\ \mathrm{Im}(^3D_1 \to {}^1S_0 p) / \mathrm{Re}(^3D_1 \to {}^1S_0 p)\right)$$



=

1) (-0.44, -1.32)

2) (+0.02, -0.48)

3) (+0.29, -0.53)

to be compared to the free nucleon-nucleon values of $\left(\tan\delta(^3S_1), \tan\delta(^3D_1)\right) =$ (+0.03,-0.46)

A measurement of $A_{x,z}$ would identify clearly if solution-2 were the correct one. But why is the Watson theorem so good for strongly coupled channels?

No measurement could be made – Siberian snake not ready in time.

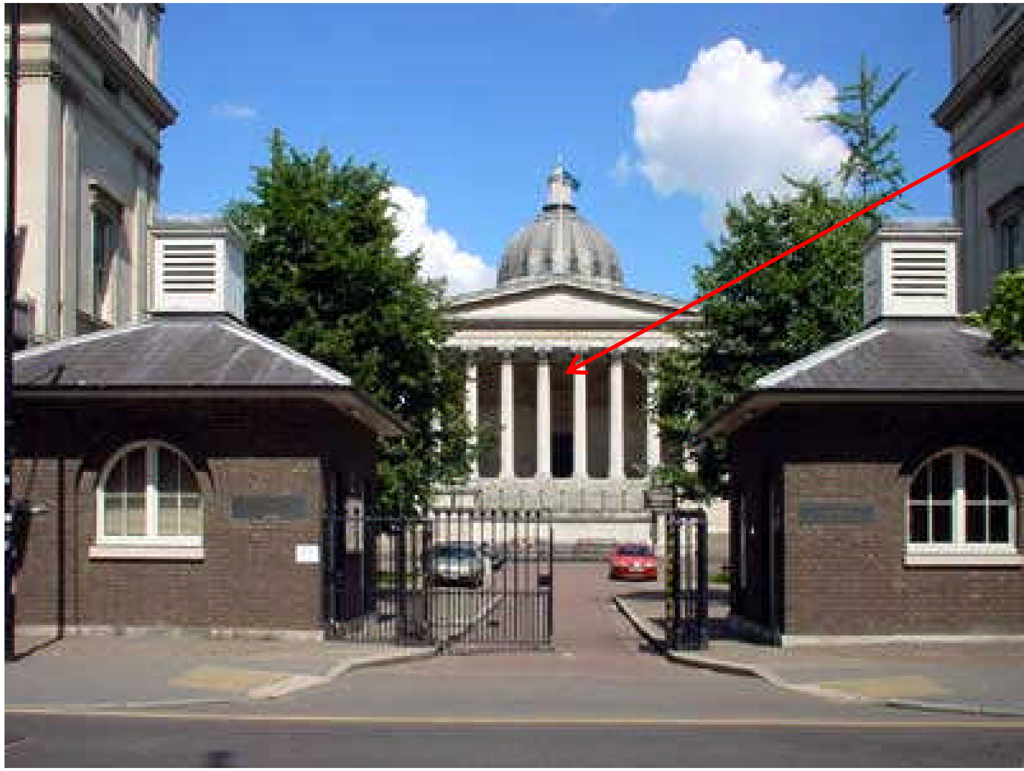
This was a personal selection from an 80 page review that contains 100+ figures that gave a flavour of the rich hadronic programme at COSY.

Though perhaps controversial. It might be even more controversial if I tried to draw up a list of what could have been achieved with say two more years of beam time!

Other people, especially the participants, would make a different choice. Hence

$$\Longrightarrow$$

Please read the EPJA review and make up your own minds!



The Wilkins building

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