Meson Production

at COSY-TOF and COSY-ANKE

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The COSY-TOF and COSY-ANKE spectrometers

These two COSY facilities are different in almost every respect.

The Time-of-Flight spectrometer sits on an external beam and its barrel has a tremendously large acceptance. It relies for it success on measuring the velocities of many particles, with the possibility of doing kinematic fits. It is especially suited for neutral strange particle production, because the time-delayed vertex, from say $\Lambda \to p\pi^-$, can be shown to come after the target.

ANKE is a magnetic spectrometer situated at an internal target station of the circulating COSY beam. It can measure the momenta of a variety of positive and negative ejectiles, in particular K^+ and "spectator" protons. However, the overall acceptance is very small and often only tiny bits of phase space are sampled. Unlike TOF, it can also do inclusive or semi-inclusive experiments.

In their different ways, both ANKE and TOF are eminently suitable for strange particle studies ⇒⇒⇒⇒⇒⇒⇒⇒

Bethe & de Hoffmann, "*Mesons and Fields*" (1955)

In 1955 these physicists called the Λ^o, Σ^-, Σ^o and Ω^- baryons, as well as the θ and τ mesons,

"CURIOUS" Particles

We could have been saying that the K^+ had curiosity value +1 and talk about "associated curiosity production" or up, down and "curious" quarks.

Bethe & de Hoffmann, "*Mesons and Fields*" (1955)

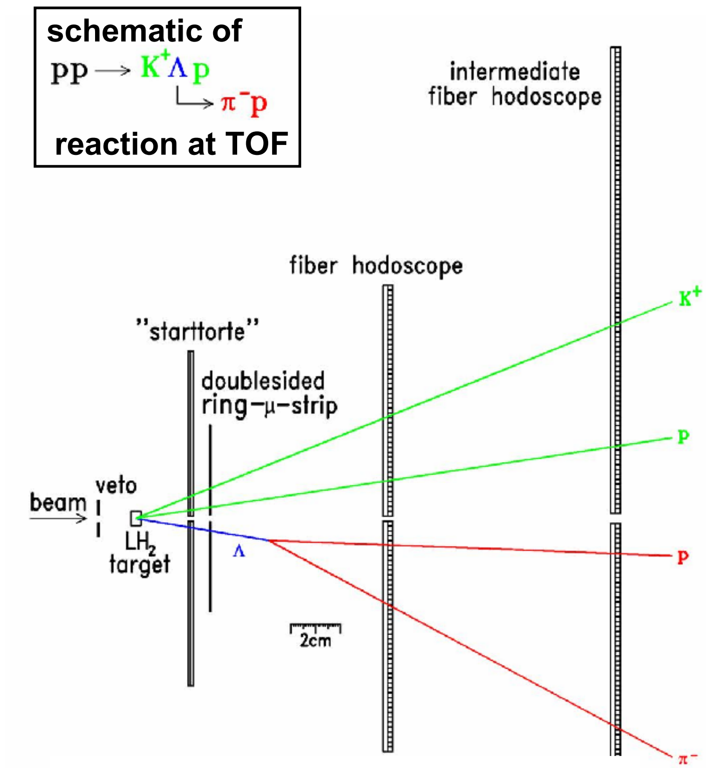
In 1955 these eminent physicists called the Λ^o, Σ^-, Σ^o and Ω^- baryons, as well as the θ and τ mesons,

Now called Ξ^-

"CURIOUS" Particles

We could have been saying that the K^+ had curiosity value +1 and talk about "associated curiosity production" or up, down and "curious" quarks.

The $pp \rightarrow K^{+}p\Lambda$ reaction at COSY-TOF



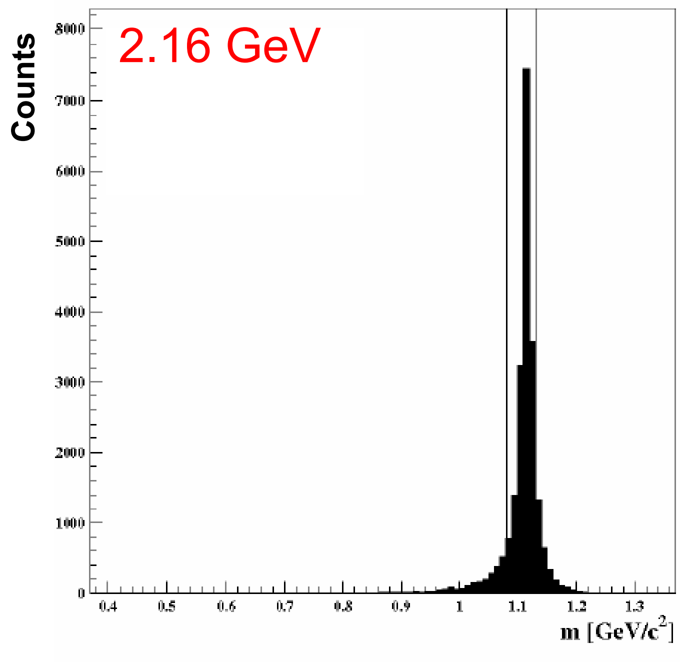
Start region of the COSY-TOF detector

No magnetic field – relies on topology, timing, and direction information.

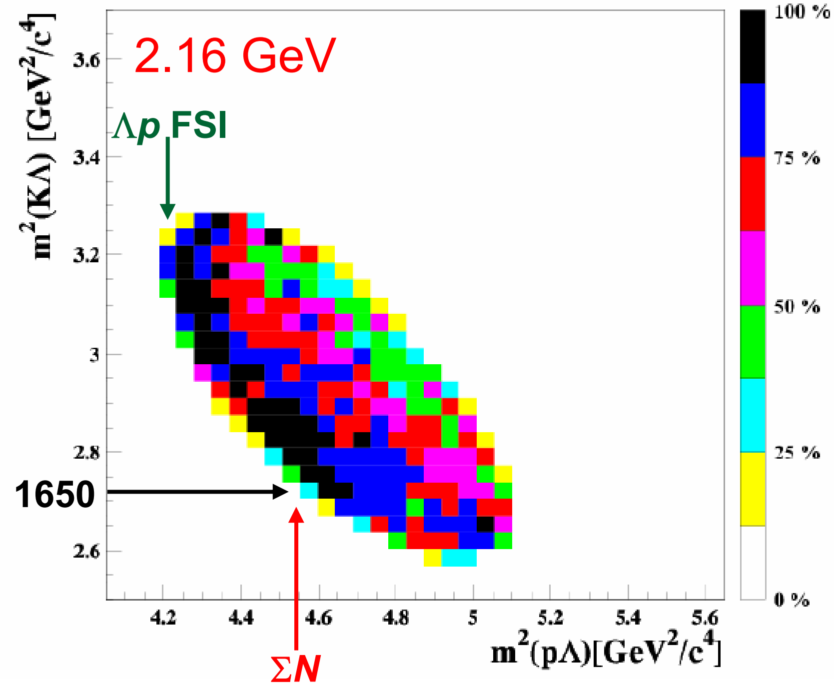
The "starttorte" counts the initial number of charged particles and provides the start signal. The silicon microstrip fixes the track positions and the fibre hodoscopes register the change in multiplicity from two to four arising from the $\Lambda \rightarrow \pi^{-}p$ decay. About 3.4m downstream a series of hodoscopes provides stop signals and further track information. All in vacuum.

The powerful trigger is the multiplicity change between the starttorte and fibre hodoscopes. After identification of the Λ, the momenta of all three primary particles are calculated, the background cleaned up, and right at the end a kinematic fit made.

Abd El-Samad, Phys.Lett.B 688 (2010) 142

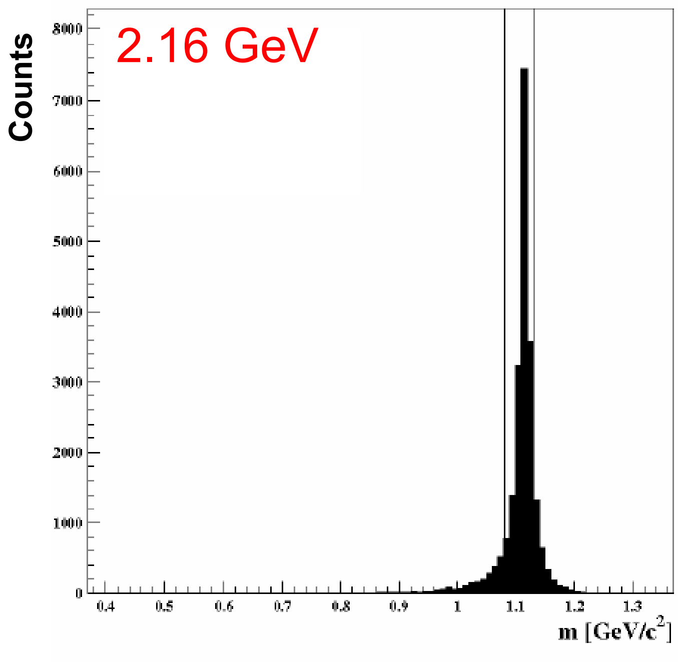


Background due to Σº production ≈ 4%.

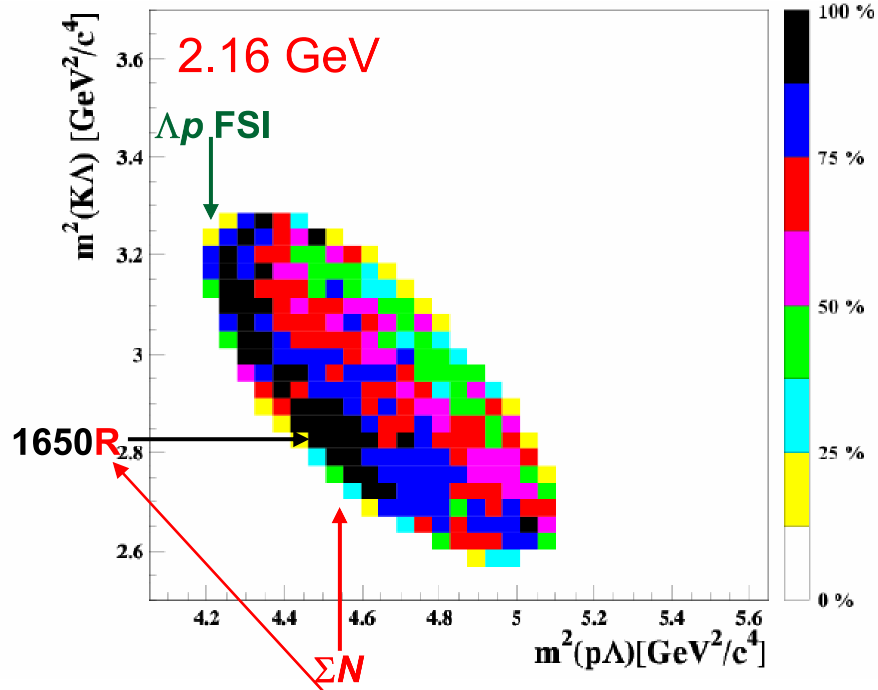


pp → K⁺Λp Dalitz plot

The position of the *N**(1650) is marked on the Dalitz plot but the peak in $\pi^- p \rightarrow K^o\Lambda$ will actually occur at a higher value due to the phase space for the $K^o\Lambda$ channel.



Background due to Σ^o production ≈ 4%.

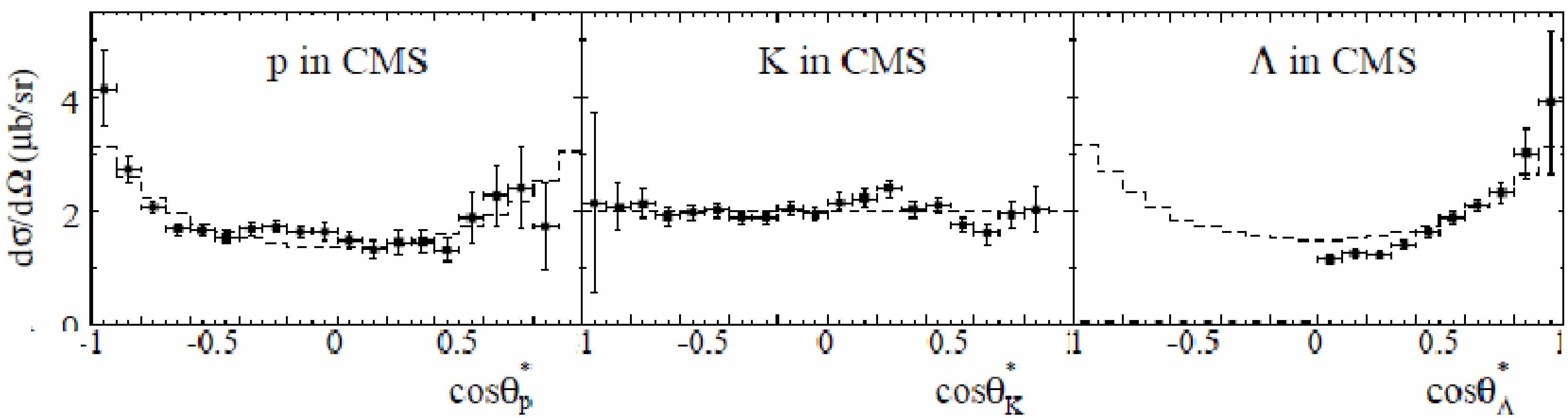


pp → $K^+\Lambda$p Dalitz plot

The position of the *N**(1650) is marked on the Dalitz plot but the peak in $\pi^- p \rightarrow K^o\Lambda$ will actually occur at a higher value due to the phase space for the $K^o\Lambda$ channel.

Plot maximum seems to be associated with the combined effects of the *N**(1650) and the ΣN threshold

Angular distributions*

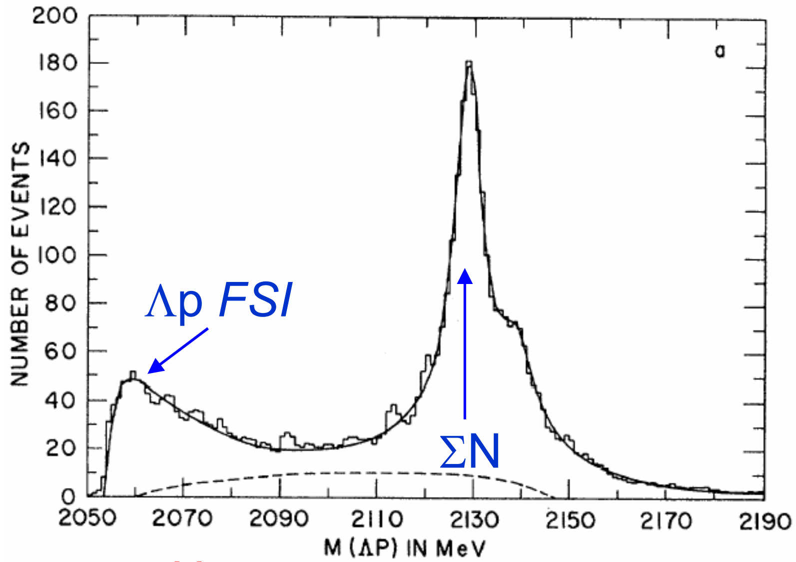


COSY-TOF data at 2.26 GeV (ε = 239 MeV)

The K^+ distribution is flat but there is non-isotropy for the proton and the Λ hyperon.

* COSY-TOF, submitted to EPJA (2010)

ΣN:Λp Coupled-channel (cusp) effects

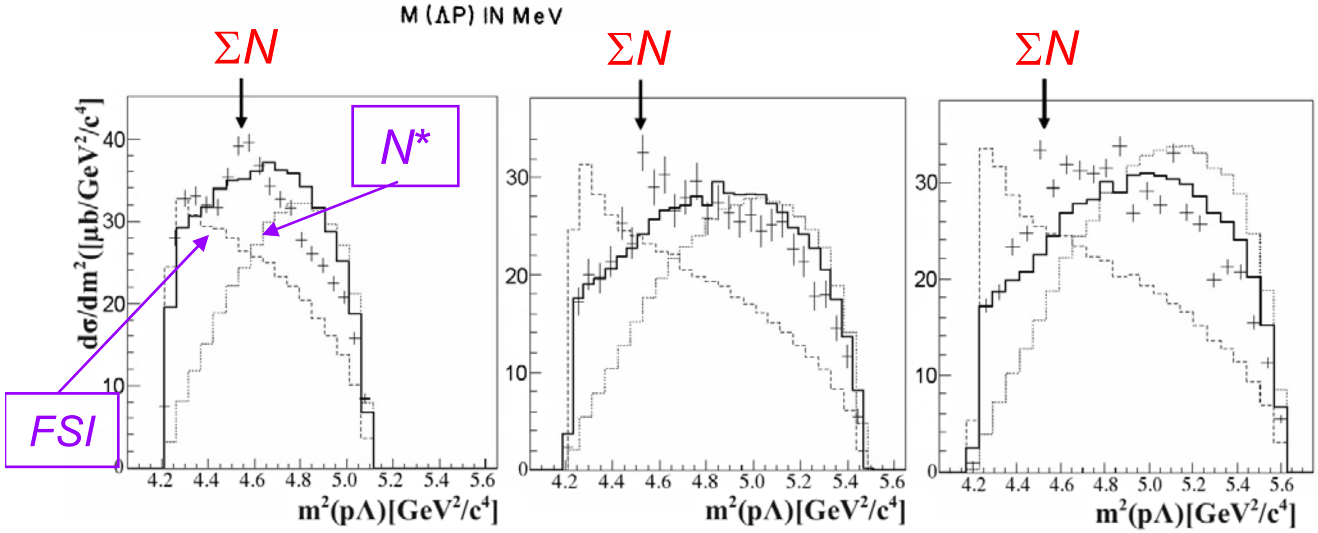


Kaon absorption at rest, $K^{-}d \rightarrow \Lambda p \pi^{-}$ *, shows strong coupled-channel effects due to $\Lambda p \Leftrightarrow \Sigma N$. One <u>sees</u> Λp final states but they must be produced by

$K^{-}d \rightarrow \pi^{-}\{\Sigma N\}^{+}$

$\searrow \{\Lambda p\}$.

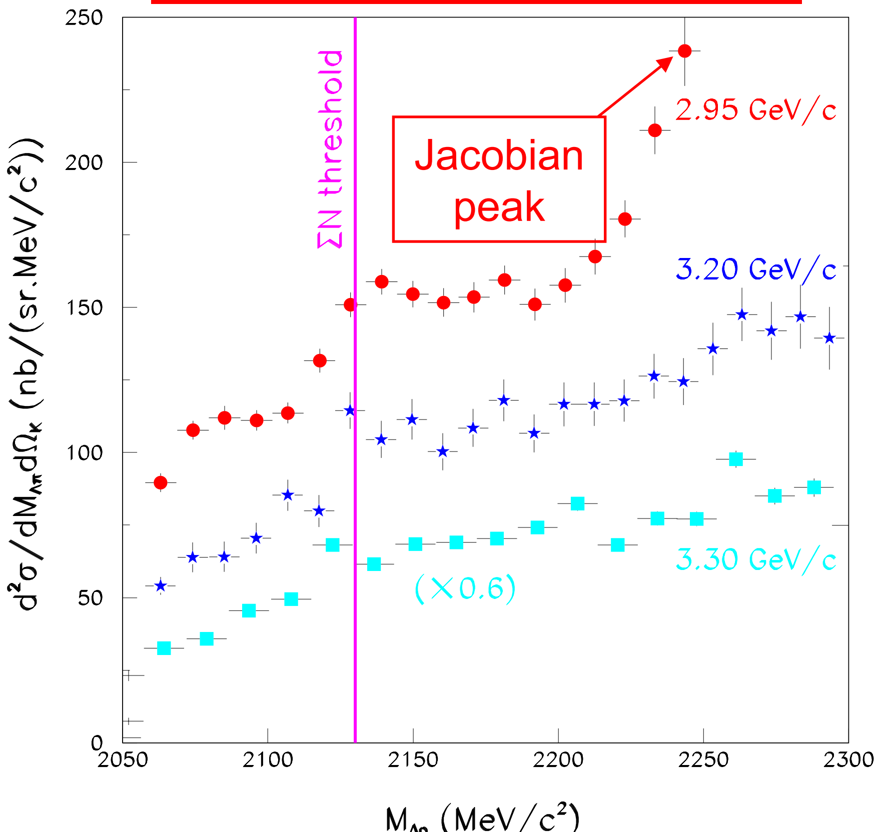
Are similar effects visible in the new high statistics COSY-TOF data?



The Λp mass spectra were interpreted by TOF in terms of *FSI* and *N** contributions. There is always an excess at the ΣN threshold, especially at the lowest energy.

* T.H.Tan, Phys.Rev.Lett. 23 (1969) 395

Forward $pp \to K^+p\Lambda$ data



COSY-TOF data [El-Samad, PLB 688 (2010) 142] on $pp \to K^+p\Lambda$ can be compared with forward inclusive K^+ data that Dr Siudak will present, if the K^+ angular distribution is isotropic in the c.m. frame, as indicated by TOF 2.26 GeV data.

The lowest energy data (2.16 GeV) show a strong rise just before the ΣN threshold, after which it remains pretty flat until it increases again towards the edge of phase space (Jacobian peak).

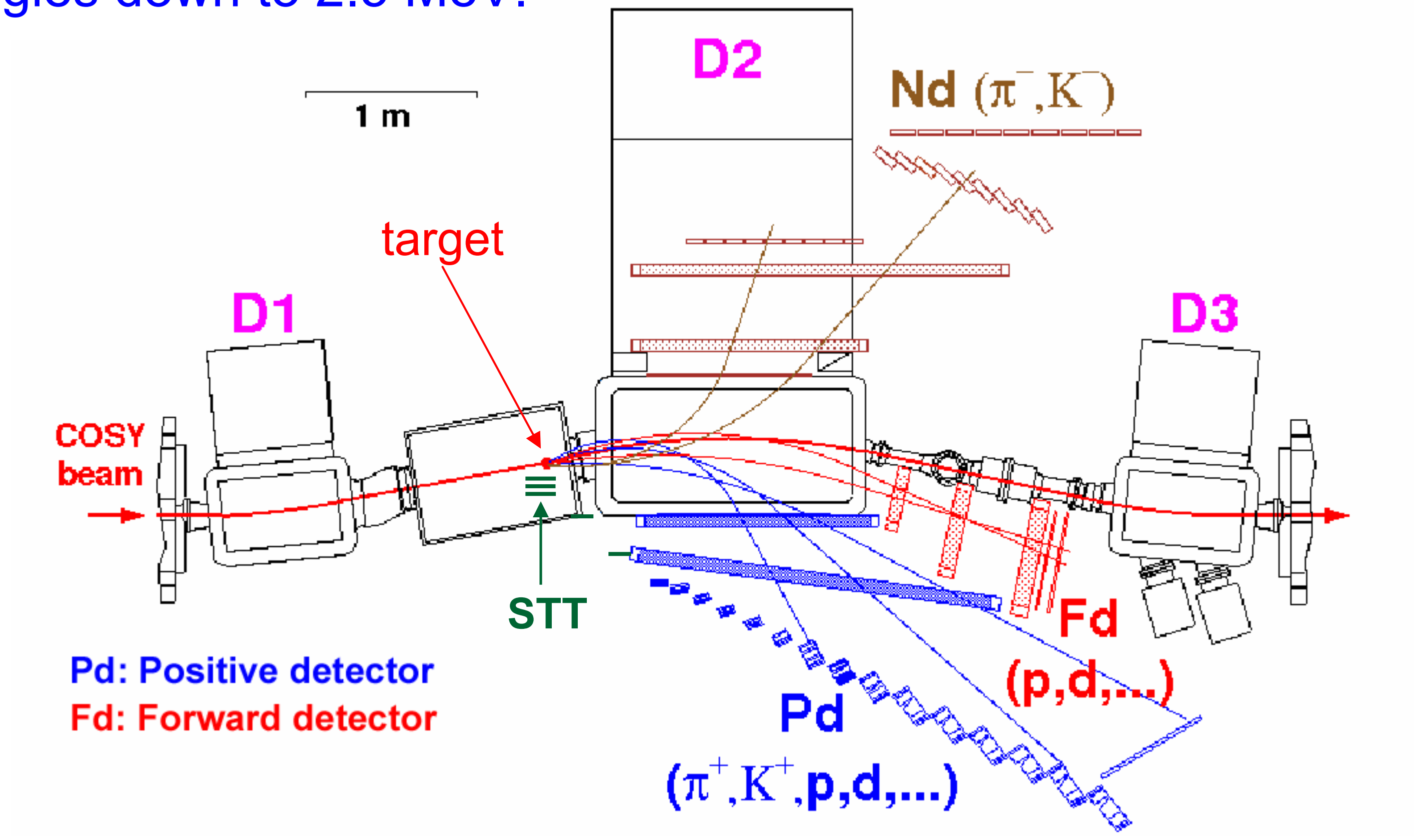
Evidence for any cusp effect is much weaker at the higher energies. Effects may decrease as the Λp *S*-wave is a smaller fraction of the available phase space – but statistics in the cusp region are much higher at 2.16 GeV.

The $pp \to K{+}p\Lambda$ cross section does not drop back to the pre-cusp level !

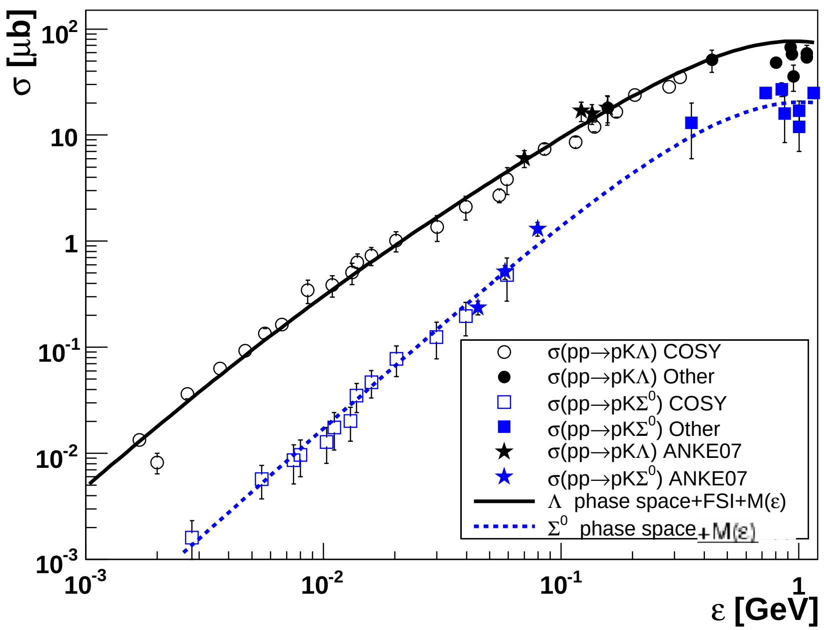
The threshold region is fascinating

The ANKE Facility

D1 & D3 deflect the beam; D2 is the analysing magnet. The individual counters in the positive detector can identify K^+ against a 10^5 background. The STTs in the target vacuum chamber measure "spectator" protons with energies down to 2.5 MeV.



$pp \to K^+p\Lambda$ and $pp \to K^+p\Sigma^o$ total cross sections



ANKE results are consistent with world data but there are large systematic uncertainties for Λ.

The energy dependence of the world data on the $pp \to K^+p\Lambda$ total cross section shows the influence of the strongly attractive $p\Lambda$ FSI.

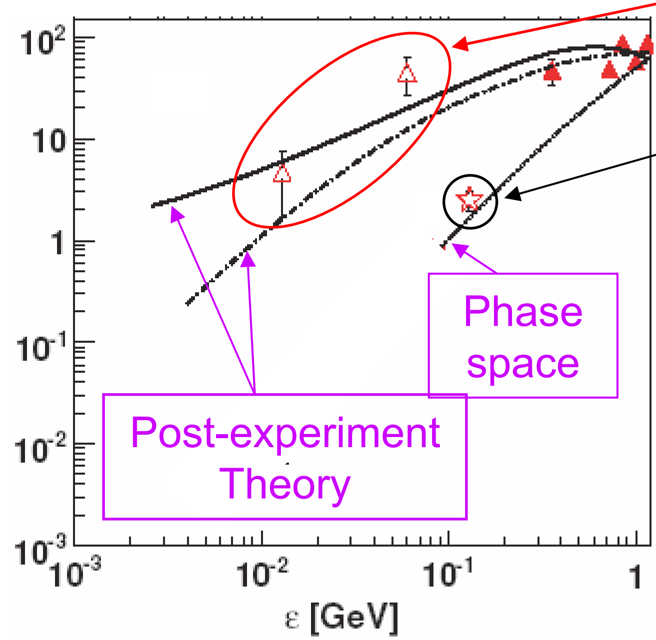
On the other hand, analogous results for $pp \to K^+p\Sigma^o$ are well described by phase space for excess energies up to about 100 MeV, *i.e.,* no obvious *FSI* effects.

In this region Λ production is about an order of magnitude stronger than Σ^o at the same excess energy.

The $pp \rightarrow K^{+}n\Sigma^{+}$ cross section

Although there were high energy bubble chamber data, the first modern experiment was carried out at COSY-11* by detecting the neutron in coincidence with the presumed K^{+}.

Found remarkably high cross sections at 13 and 60 MeV, about two orders of magnitude higher than for Σ^{o} production.



First measurement at ANKE ** at 126 MeV gave a much lower result.

Could there be an anomalous *FSI* behaviour near threshold to make these data consistent?

Unlikely, because $\Sigma^{o}p$ and $\Sigma^{+}n$ are both mixtures of I=1/2 and I=3/2 and there is no anomalous $\Sigma^{o}p$ *FSI*.

* T.Rożek, Phys.Lett.B 643 (2006) 251

** Yu.Valdau, Phys.Lett.B **652** (2007) 245

The ANKE measurements*

By stopping K^+ and looking for their decay, the mesons can be identified against a background of $\approx 10^5$ more protons and π^+.

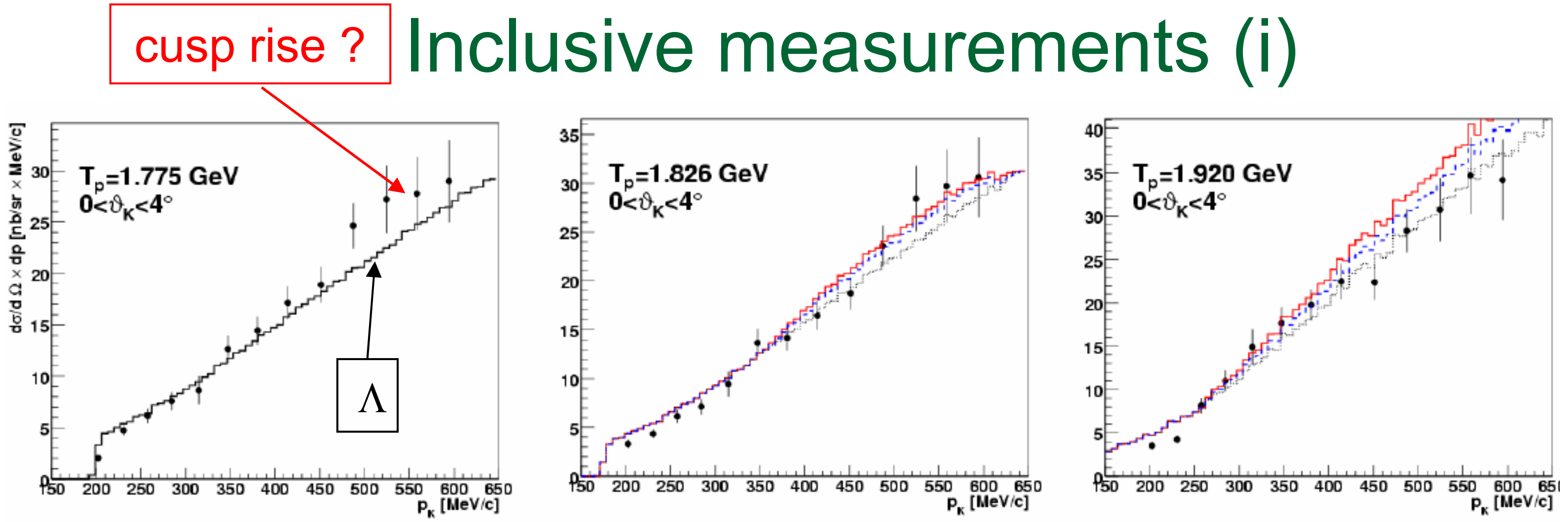
Data were taken at four excess energies (13, 47, 60, 82 MeV) and cross sections evaluated using three different techniques:

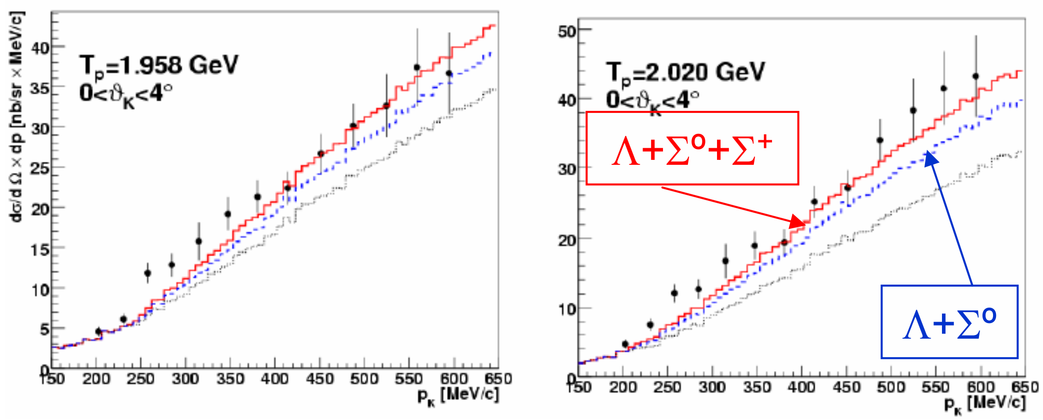
- Inclusive K^+ production,
- Study of K^+p coincidences,
- Study of $K^+\pi^+$ coincidences.

All three methods give consistent answers and show that the Σ^+ production cross section is rather similar to that for Σ^0.

* Yu.Valdau, Phys.Rev.C **81** (2010) 045208

Inclusive measurements (i)



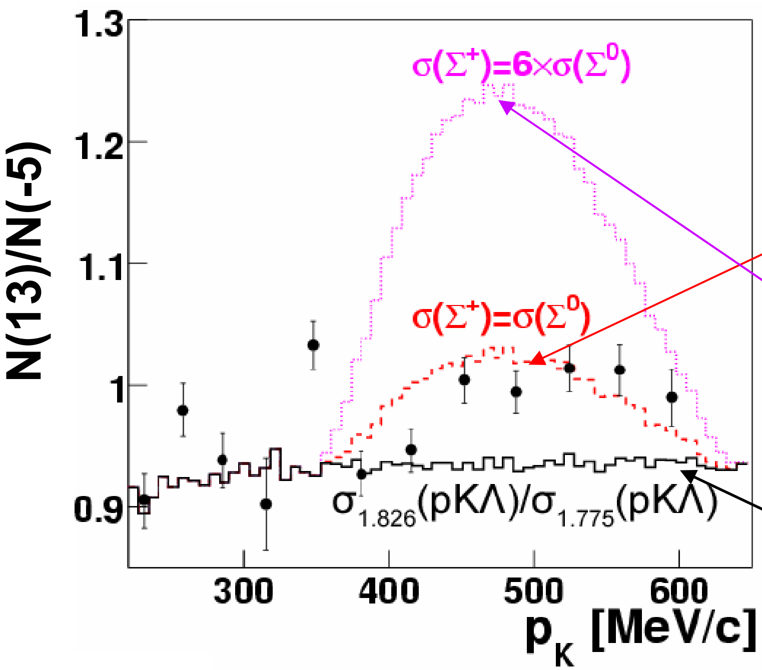


Points are measured at four energies above threshold and one below. Dominated by $pp \rightarrow K^{+}p\Lambda$, for which the modelling is quite ambiguous (far from threshold).

Simulations are carried out using world or self-consistent total hyperon production cross sections. Can only say from these spectra that Σ production cannot be VERY large.

Inclusive measurements (ii)

More meaningful numbers can be obtained by taking ratio of count rates just above (+13 MeV) and just below (-5 MeV) threshold, normalised to the same luminosity. Ratio does not depend upon telescope efficiency



and acceptance. All Σ events should come from $350 < p_K < 650$ MeV/c where the acceptance is high (≈25%);

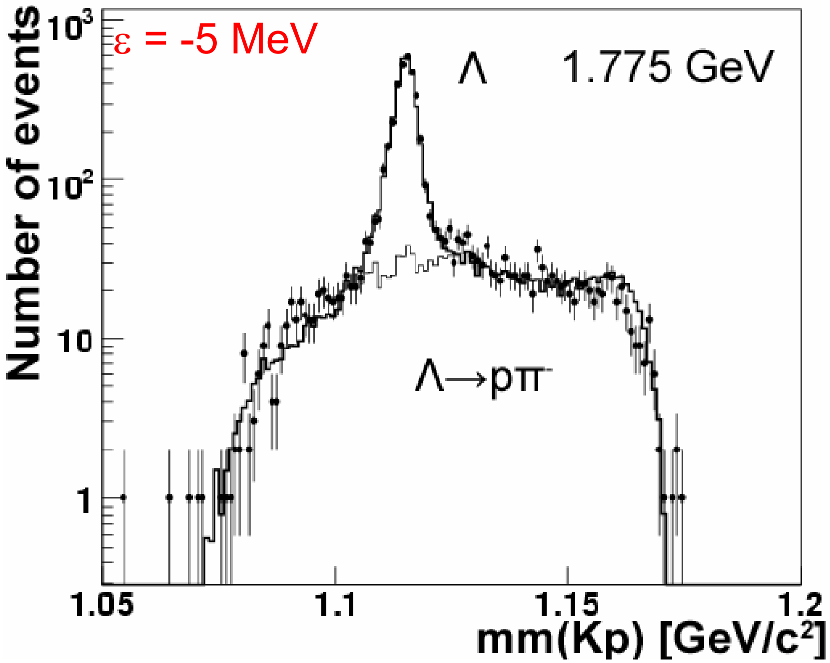
$\sigma(\Sigma^+) \approx \sigma(\Sigma^o)$ describes the data;

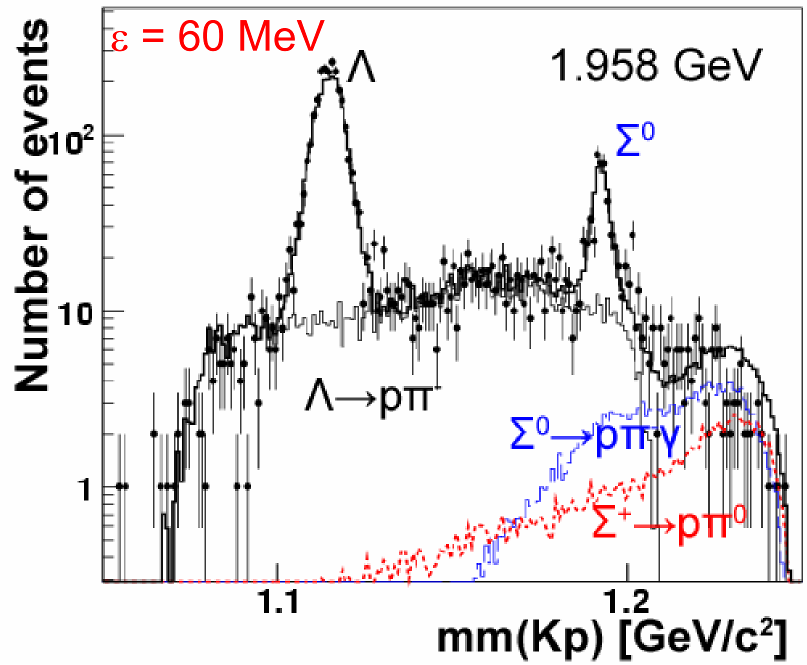
$\sigma(\Sigma^+) = 6\sigma(\Sigma^o)$ [limit obtained from isospin arguments] is far too high!

Simulation of Λ contribution quite flat – but includes no cusp effects!

Conservative upper limit; $\sigma(\Sigma^+) < 45$ nb at $\varepsilon = 13$ MeV.

Kaon-proton coincidences





The K^+p missing mass shows peaks from $pp \to K^+p\Lambda$ and $pp \to K^+p\Sigma^o$.

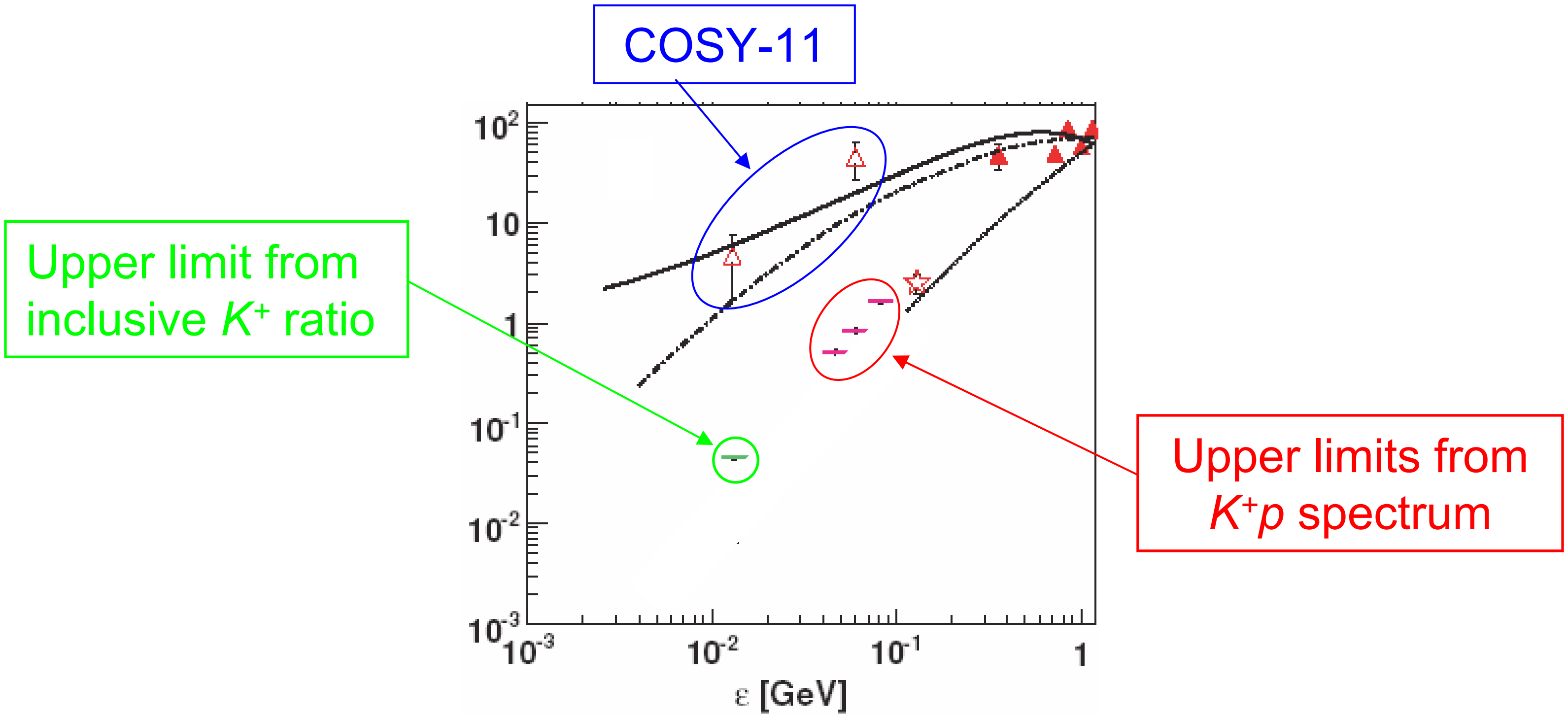
The observed proton could come from decays $\Lambda \to p\pi^-$, $\Sigma^o \to p\pi^-\gamma$, $\Sigma^+ \to p\pi^o$.

The Λ cannot contribute to the background at the largest missing masses.

Estimate of Σ^+ cross section depends on the value for Σ^o.

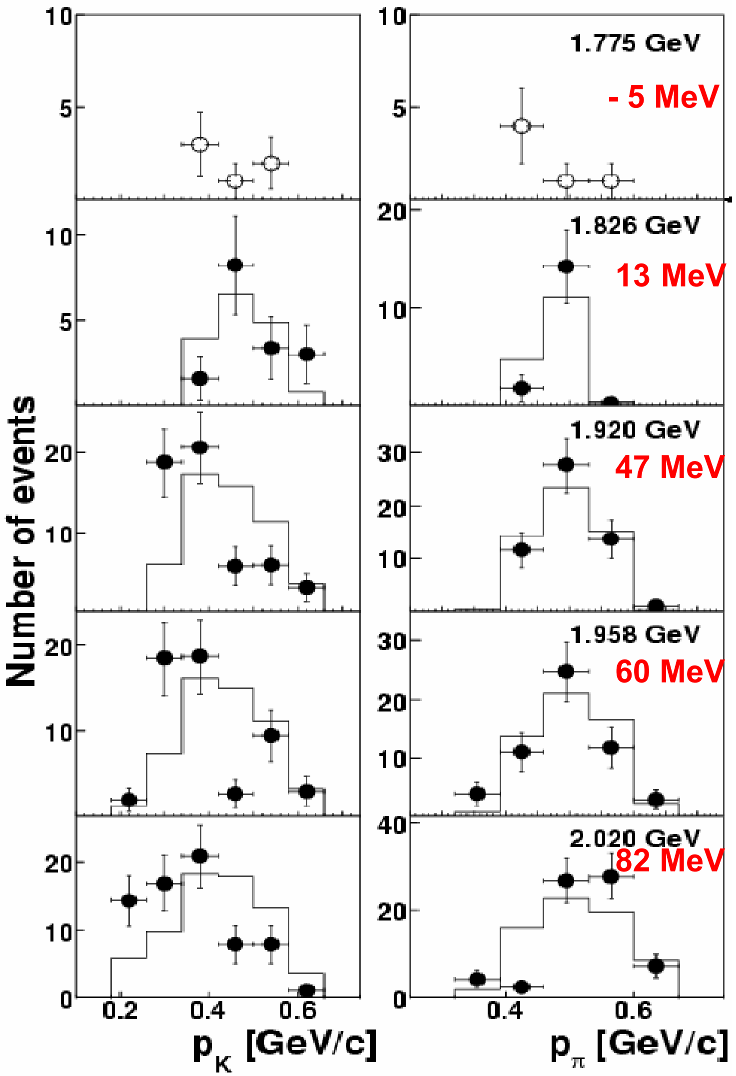
Upper limits can be derived by assuming that there is no Σ^o production!

Upper limits on the $pp \to K^+ n \Sigma^+$ cross section



But one can do much better from the study of the $K^+\pi^+$ coincidences ⇒⇒⇒⇒⇒⇒⇒

Kaon-pion coincidences

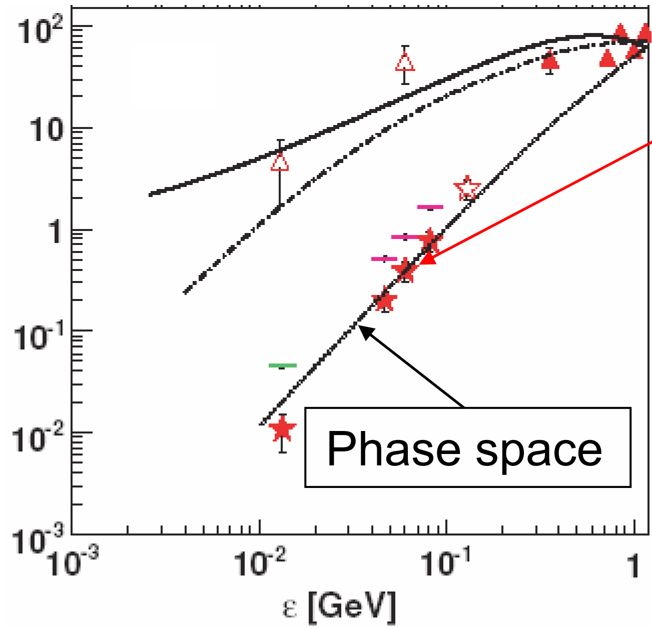


Below threshold for $pp \to K^+ n \Lambda \pi^+$ (1.975 GeV), the only source of $K^+\pi^+$ coincidences is $pp \to K^+ n \Sigma^+$.

Random coincidences can be estimated from below-threshold data and subtracted bin-by-bin (taking the luminosity into account).

Kaon and pion momentum spectra for these few "gold-plated" events are tolerably reproduced by the simulations. Cross sections have small systematic errors but larger statistical ones.

The pp → $K^+ n \Sigma^+$ total cross section



New ANKE points fall well below the upper bounds.

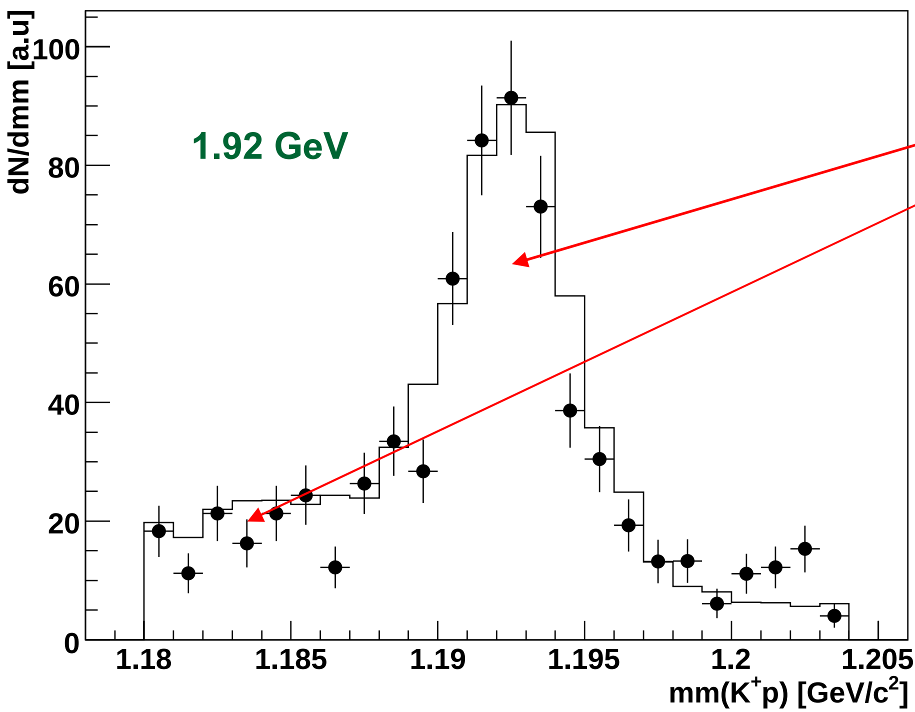
The ratio of Σ^+/Σ^o production is ≈ 0.7±0.1, which is about two orders of magnitude less than that found at COSY-11.

Energy dependence is close to phase space, though perhaps a little steeper. This could be statistical but, if real, could arise from a repulsive (or absorptive) Σ^+*n FSI.*

How might one investigate the low energy Σ*N* system?

$\Sigma^0 p$ Final State Interaction

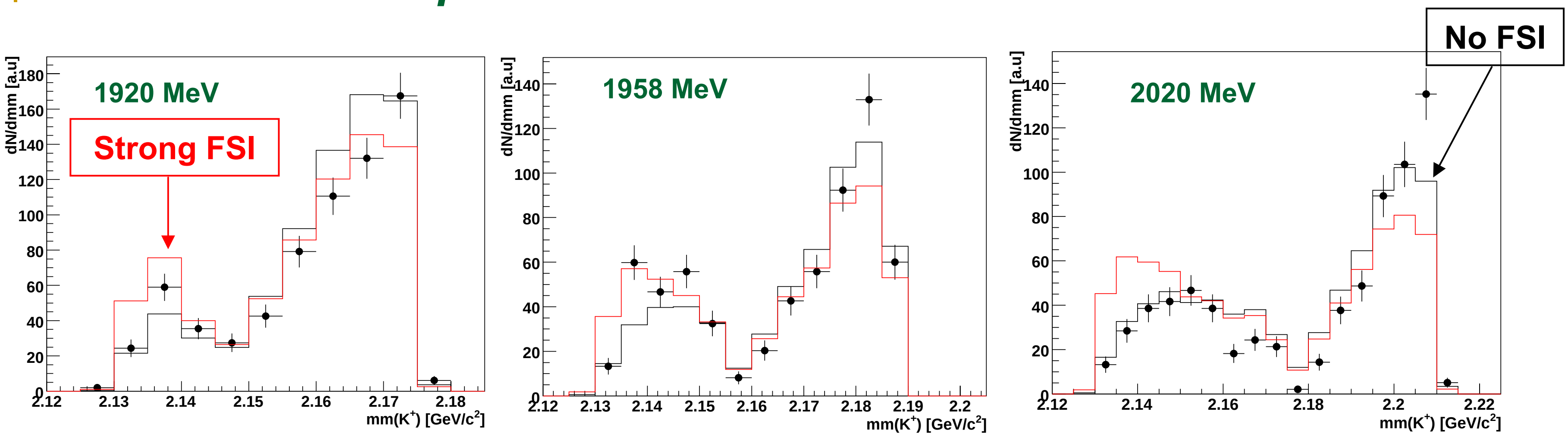
Although we know that the Λp *FSI* is very strong near threshold, much less is known about that between the Σ^0 hyperon and nucleons.



The study of K^+p missing-mass data shows a clean <u>Σ^0 peak</u> sitting on top of a background associated with decay protons.

For events in the peak, one can look at the $\Sigma^0 p$ invariant mass distribution (*i.e.* the K^+ missing-mass spectrum).

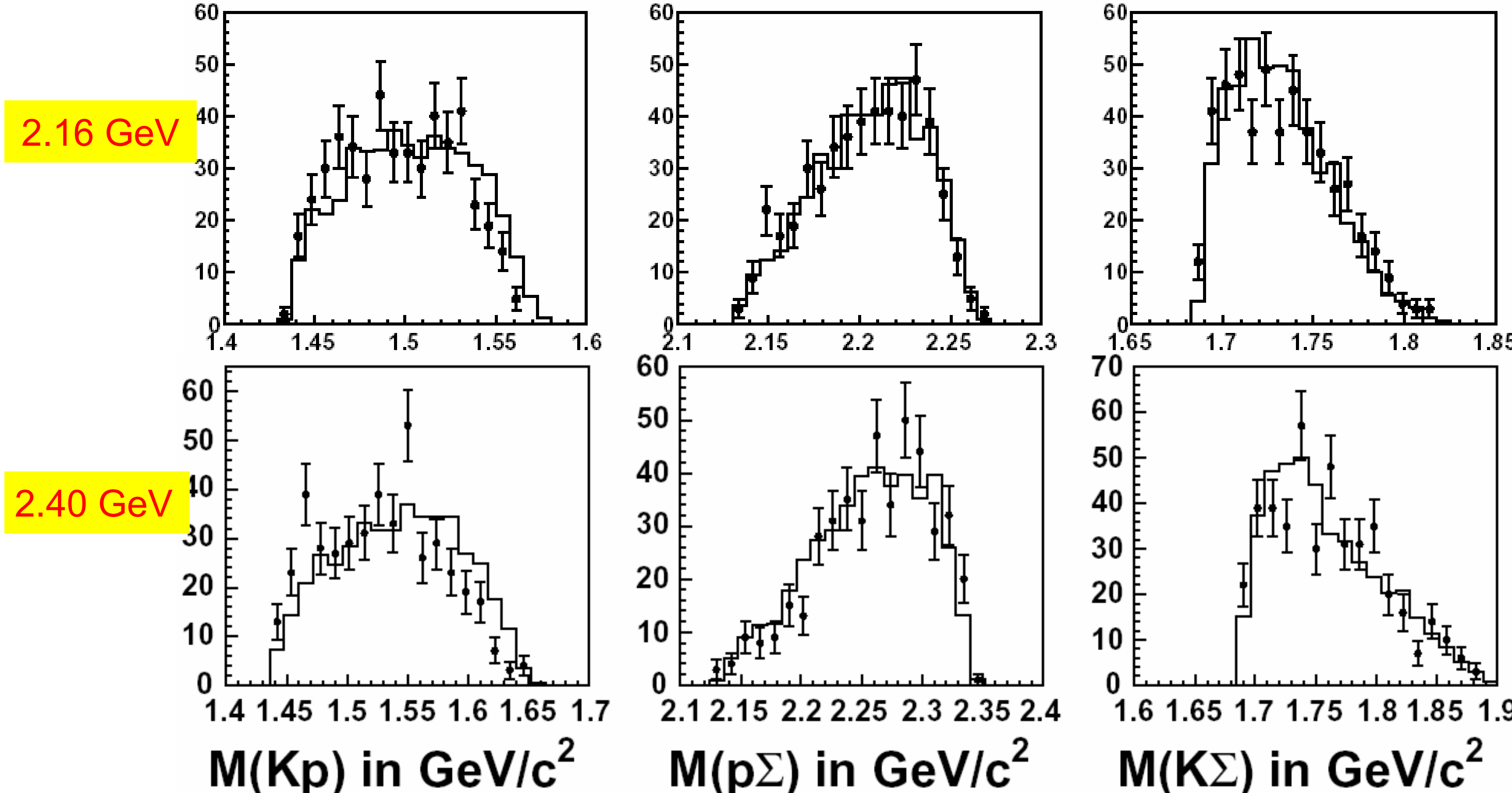
ANKE $\Sigma^o p$ Invariant Mass Distributions



The limited acceptance of ANKE leads to a hole in the mass spectrum, but this is seen in both the data (points) and the phase-space simulation (black histogram). The red histogram corresponds to taking an *FSI* with the same strength as Λp.

Although the results are far from conclusive, there is no indication here of a very strong $\Sigma^o p$ final state interaction.

Earlier experiment at COSY-TOF on *pp* $\rightarrow K^{o}p\Sigma^{+}$ * showed no sign also for a I=3/2 Σ^{+}*p FSI*, though the *FSI* region was small at these higher energies. [Simulation included N* effects but these did not alter the FSI conclusions.]



* L.Karsch, PhD thesis, 2005

The $pn \to K^o \Lambda p$ reaction*

The use of a deuterium target at **COSY-TOF** allows the study of the $pd \to p_{sp} K^o p \Lambda$ reaction. Unlike ANKE, the spectator proton is not detected. However, the reaction has the great feature of two delayed decays, *viz.* $K^o \to \pi^+ \pi^-$ and $\Lambda \to p \pi^-$, for which COSY-TOF is ideally suited. ≈1000 fully reconstructed events are expected from the pilot run, though the c.m. energy has also to be evaluated event-by-event and so the events are spread over a wide range.

* M.Krapp, IKP-Jülich Annual Report 2009

A complementary approach has been proposed at **ANKE**, where the spectator from $pd \to p_{sp} K^+ n \Lambda$ would be detected in the STT**.

** A.Dzyuba, COSY proposal 2010

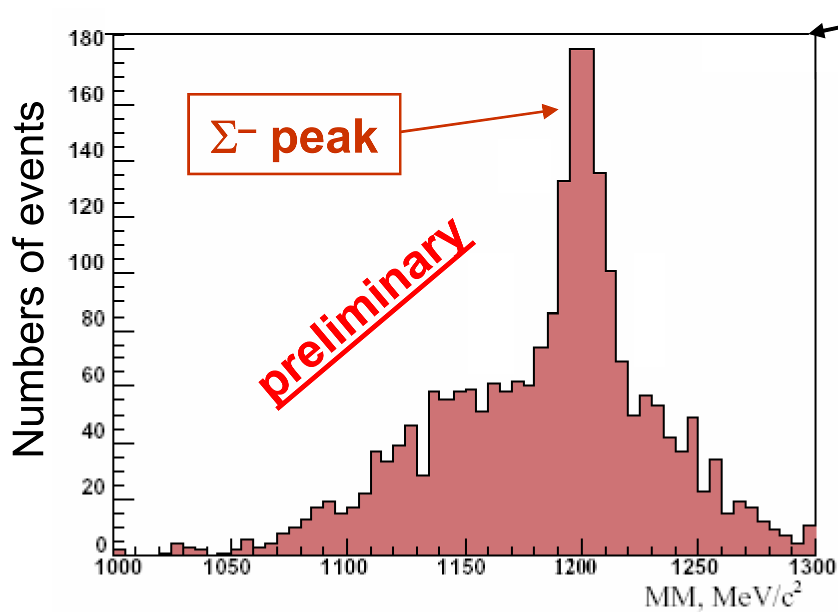
The total cross sections for $pp \to K^+ p \Lambda$, $pn \to K^o p \Lambda$, and $pn \to K^+ p \Lambda$ are linked by isospin, though there can be interferences between isospin 0 and 1 in differential observables.

The $pn \to K^+p\Sigma^-$ reaction*

Data have been taken at ANKE on $pd \to p_{sp}K^+pX^-$.

"Spectator" protons were detected in one of the silicon tracking telescopes placed next to the ANKE target. The STT can measure well the energies and angles of protons with energies down to about 2.5 MeV.

Triple coincidence leads to the missing-mass spectrum:



There are about 500 Σ^- events at each of two beam momenta (2915 MeV/c and 3015 MeV/c). These will allow the total cross section to be extracted up to an excess energy of ≈ 100 MeV.

Values end of 2010 ??

* E.Shikov, Diploma thesis 2009

Physics & Astronomy UCL

Comparison of $pp \to pK^+\Sigma^0\pi^0$ and $pp \to pK^+pK^-$

There have been measurements of both the $pp \to pK^+\Sigma^0\pi^0$ * and $pp \to pK^+pK^-$ ** reactions at 2.83 GeV at ANKE.

* I.Zychor, Phys.Lett. B **660** (2008) 167

** Y.Maeda, Phys. Rev. C **77** (2008) 015204

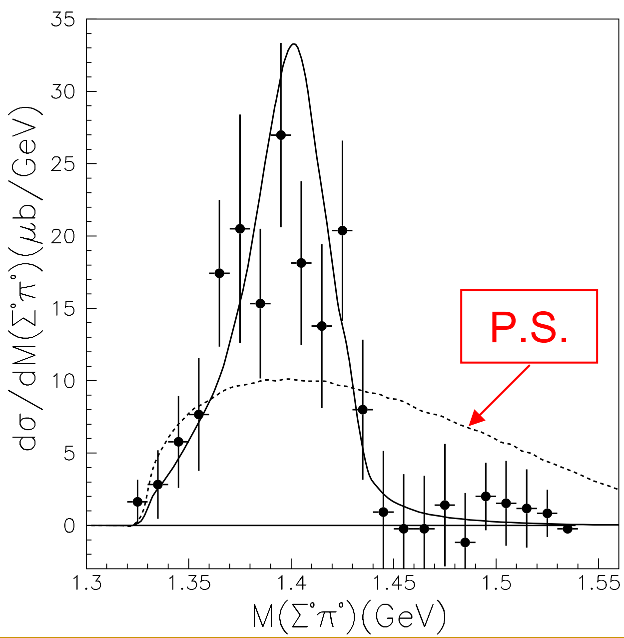
Could these two associated production reactions be connected in some way?

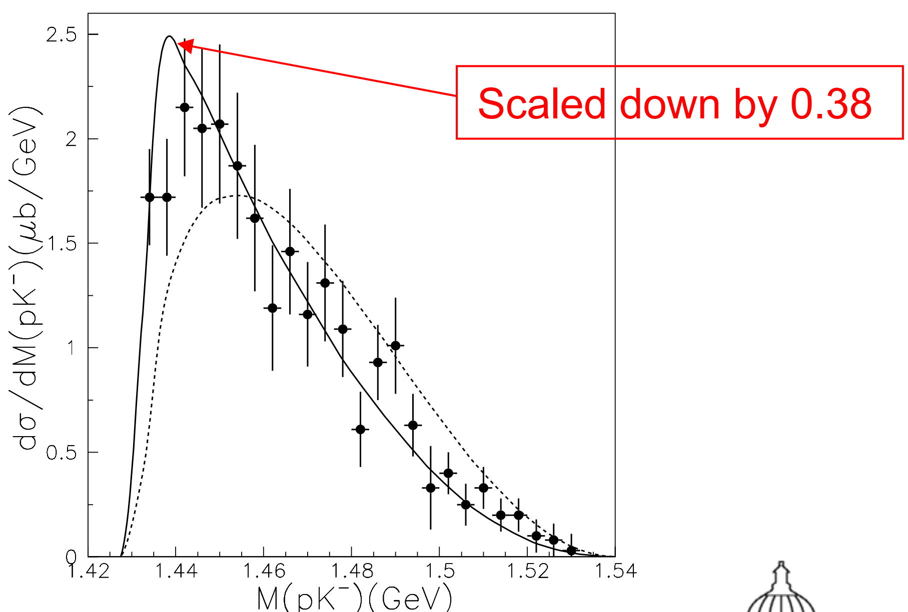
This might happen if the $\Sigma^0\pi^0$ and pK^- were both produced through the decay of the $\Lambda(1405)$ resonance. What we would then be seeing is different manifestations of the reaction $pp \to pK^+\Lambda(1405)$.

In a new phenomenological meson-exchange model ***, the reaction is assumed to proceed via the production and decay of the $N^*(1535) \to K^+\Lambda(1405)$, since it is believed that the $N^*(1535)$ isobar contains a lot of hidden strangeness. This assumption determines the strengths of the cross sections but not the shapes of the spectra.

*** Ju-Jun Xie & CW, arXiv:1005.2957

Shapes and relative strengths fixed mainly by low energy $K^-p \rightleftharpoons \pi^0\Sigma^0$ physics. Experimental data have been parameterised in terms of a separable potential*, which gives a single $\Lambda(1405)$ pole. The good shape descriptions are not evidence against the two-pole theories, since shapes are probably determined mainly by the low energy experimental data. K^-p prediction too high by 2.7; $\Sigma^o\pi^o$ is about right.





* N.V.Shevchenko, PRL **98** (2007) 082301

Physics & Astronomy UCL

Cross section ratio depends very little at all on the $N^*(1535)$ assumptions; the effects of the low-energy coupled-channel physics dominate:

$$R_{K\pi} \equiv \frac{\sigma(pp \to K^+ p K^- p)}{\sigma(pp \to K^+ p \pi^o \Sigma^o)} = \frac{0.065 \pm 0.024 \text{ (Experiment)}}{\approx 0.025 \text{ (Model)}},$$

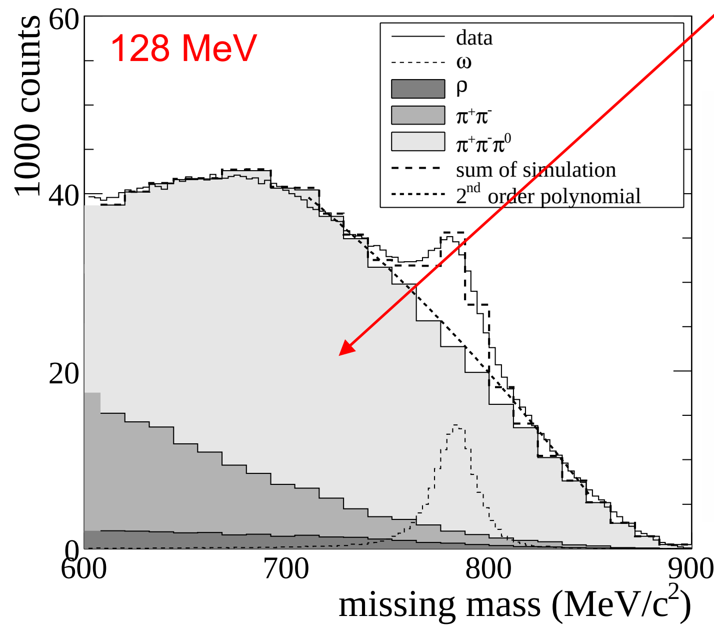
where the φ-meson contribution is excluded in the K^+K^- case.

The plausible agreement here suggests that K^+K^- production near threshold is also mainly driven by intermediate hyperon states and not, for example, by production of scalar mesons.

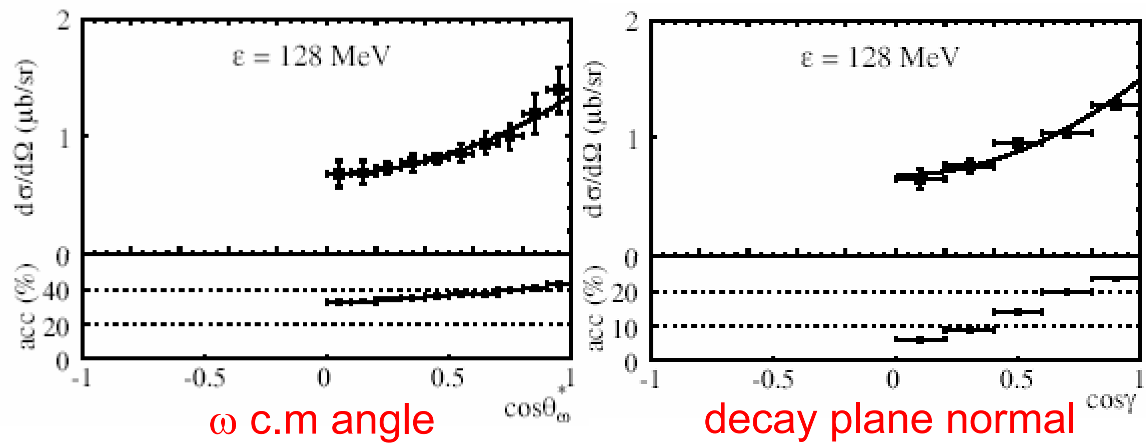
Although I have chosen to highlight here the COSY-TOF and COSY-ANKE contributions in “curiosity” production, they have also undertaken lots of non-strangeness studies.

pp → *pp*ω at COSY-TOF at ε = 92, 128, 173 MeV*

Trigger was four particles coming directly from the target which, at these energies, are dominantly from $pp(\omega\rightarrow\pi^+\pi^-\pi^o)$, $pp\pi^+\pi^-\pi^o$, and $pp\pi^+\pi^-$ final states. The latter can be reduced by looking at coplanarity of events. Pions and protons are reasonably well separated in TOF. Acceptance is very large ≈ 2/3 but the background from direct 3π production is big.



Plethora of differential observables deduced:



Angular distribution in c.m. shows influence of higher partial waves but even more interesting is that in the normal to the $\omega\rightarrow\pi^+\pi^-\pi^o$ decay plane, which defines the ω tensor polarisation.

* M.Abdel-Bary, EPJA **44** (2010) 7

Diproton production at ANKE

Another speciality of ANKE is the study of the missing-mass reaction $pp \to \{pp\}_s X^o$, where the two final protons have very low excitation energy (E_{pp}< 3 MeV) so they are in a spin-zero $^1S_0$ state. This is a quasi-two-body reaction.

Data have been published on the unpolarised cross sections when $X^o = \pi^o$ * and $(\pi\pi)^o$ **, η **.

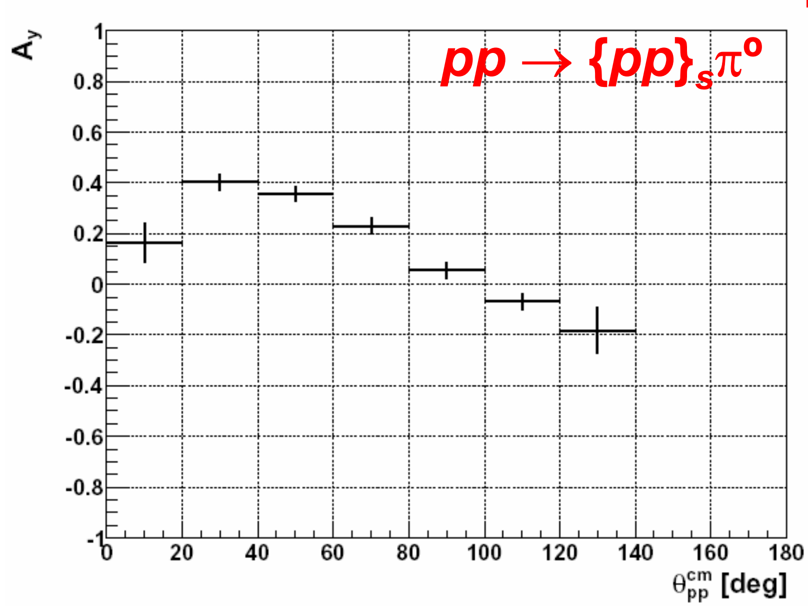
* V.Kurbatov, PLB **661** (2008) 22

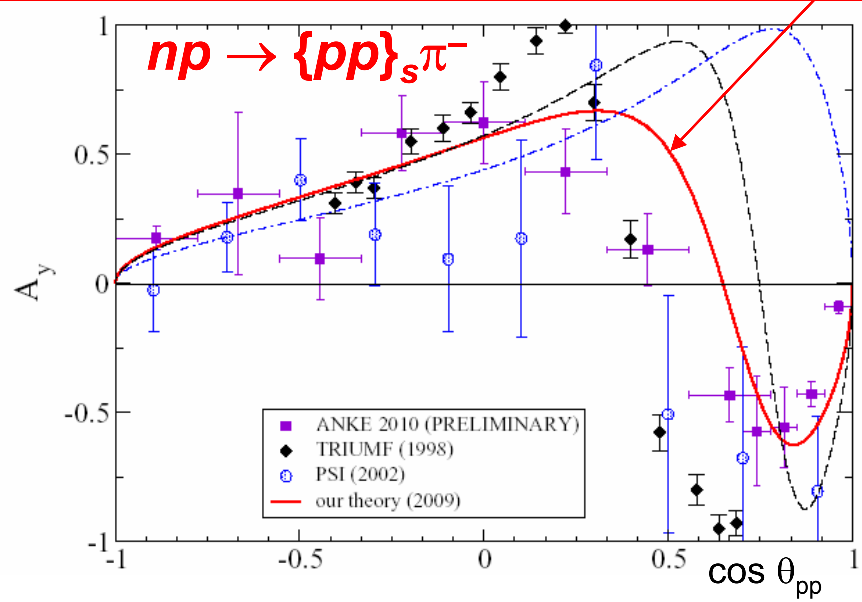
** S.Dymov, PRL **102** (2009) 192301

There is an extensive programme to measure all spin observables in $pp \to \{pp\}_s\pi^o$ and $np \to \{pp\}_s\pi^-$ at $T_p \approx$ 350 MeV in order to link up with chiral perturbation theory.

Preliminary values of analysing powers at $T_p \approx$ 350 MeV

V. Baru, Phys. Rev. C **80** (2009) 044003





Preliminary A_y measurements for $\vec{p}p \to \{pp\}_s \pi^o$ * and $\vec{n}p \to \{pp\}_s \pi^-$ * *.

* A.Kulikov, COSY #158 (2007)

** S.Dymov, COSY #192 (2008)

Data are sensitive to a ChPT *p*-wave contact term. Red curve shows preferred theoretical solution (Baru), but this ignores pion *d*-waves. However, A_y for π^o production would vanish if there were not at least *d*-waves.

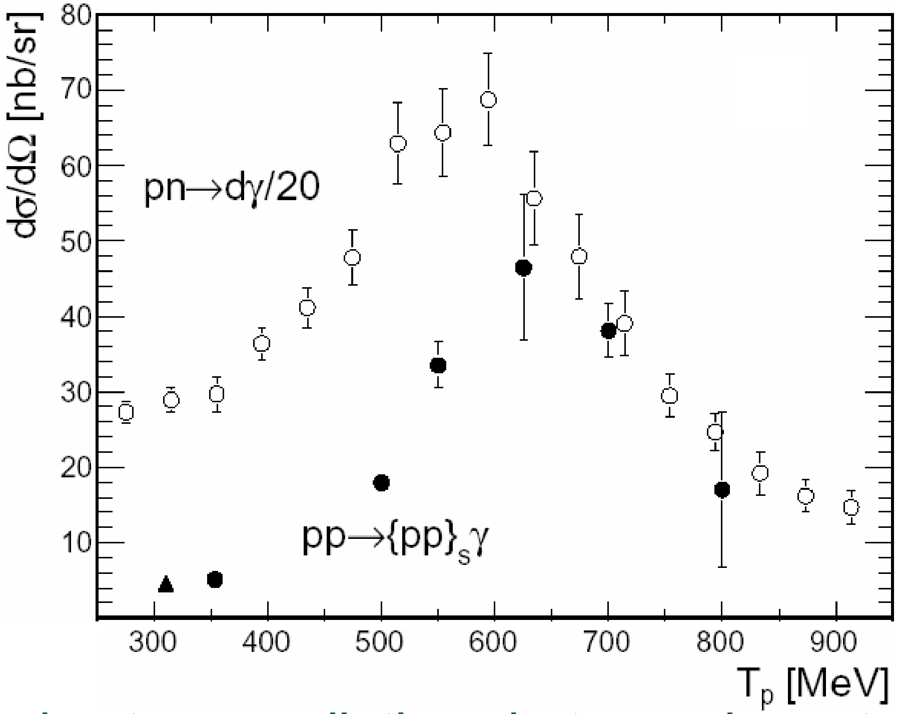
Spin correlation*** in $\vec{n}\vec{p} \to \{pp\}\pi^-$ will isolate *p*-wave effects.

*** S.Dymov, COSY Proposal June 2010

Proton-proton bremsstrahlung

ANKE also obtained interesting results on $pp \to \{pp\}_s\gamma$ *,**.

Average cross section for θ_γ<20º



Although not meson production, the Physics is so similar, with *S*-wave ΔN intermediate states dominating $pn \to d\gamma$ for $T_p > 400$ MeV. This M1 transition forbidden for $pp \to \{pp\}_s\gamma$.

Peak is shifted to higher energies, possible due to the ΔN system being in a *P*-wave.

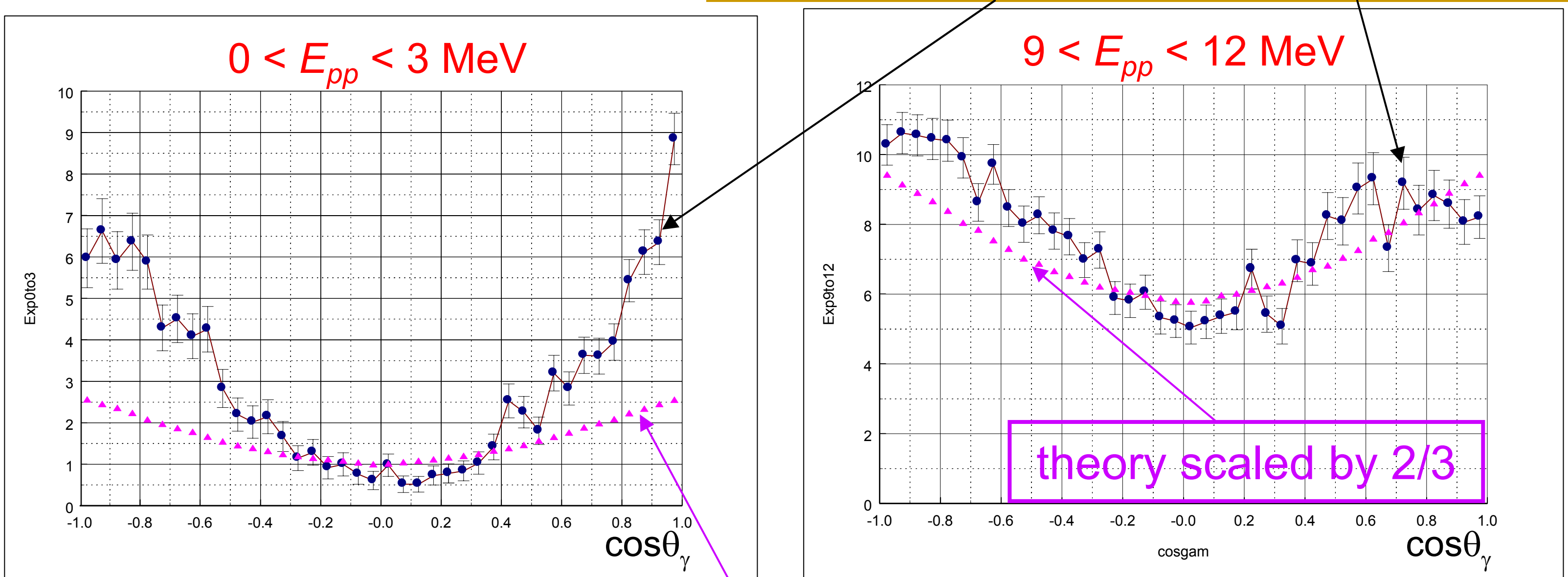
No reliable theoretical calculations published in the $^1S_0$ limit, possibly due to cancellations between large terms which eliminate the *M*1term.

* V.Komarov, PRL **101** (2008) 102501

** D.Tsirkov, arXiv1005.2014

CELSIUS-WASA data on $pp \to pp\gamma$ at 310 MeV

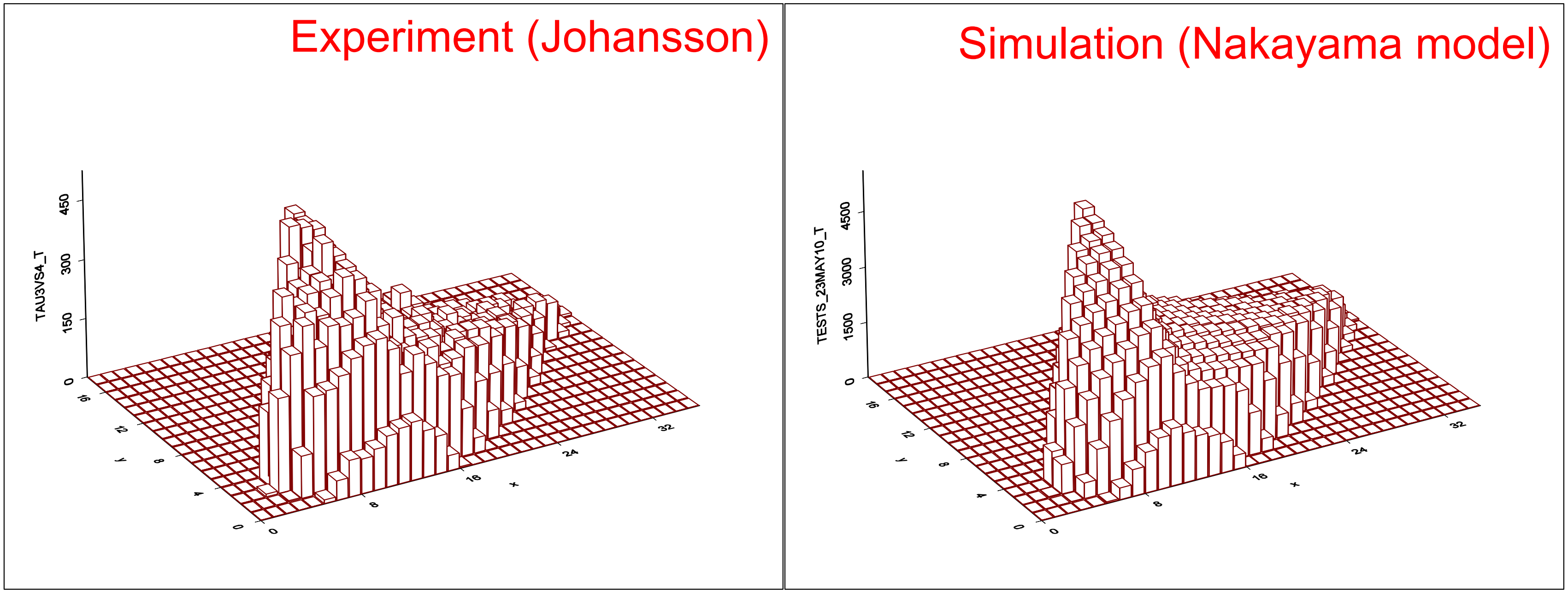
High statistics data available over a much wider kinematic domain than ANKE – but only at one energy. A.Johansson & CW, PLB **673** (2009) 5



K.Nakayama & H.Haberzettl, Phys.Rev.C**80** (2009) 051001

New theoretical calculation resolved previous discrepancies with existing data for T_p < 200 MeV. Extending these calculations to 310 MeV, including some ΔN effects, gives good description away from low E_{pp} region.

Dalitz plots of E_{p1} versus E_{p2} in c.m. system



The low E_{pp} region is a small fraction of the total but, apart from that and a scaling factor of 2/3, the new Nakayama model does extremely well. The challenge is to extend this into the full Δ region, where the ANKE data show significant peaking.

What is the most exciting of the goodies presented?

This is a question of taste, but the most intriguing for me is the ΣN threshold region.

The variety of measurements at COSY and elsewhere [including the inclusive K^+ production data from HIRES, to be shown by Dr Siudak] may allow us to understand better the coupling between the ΣN and ΛN systems.

One challenge for the future would be to try to separate cleanly the spin S=1 and S=0 effects and this would entail the use of polarised beams or target – but preferably both!

Thanks and Goodbye!

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Supplementary sheets