Strangeness production on the neutron

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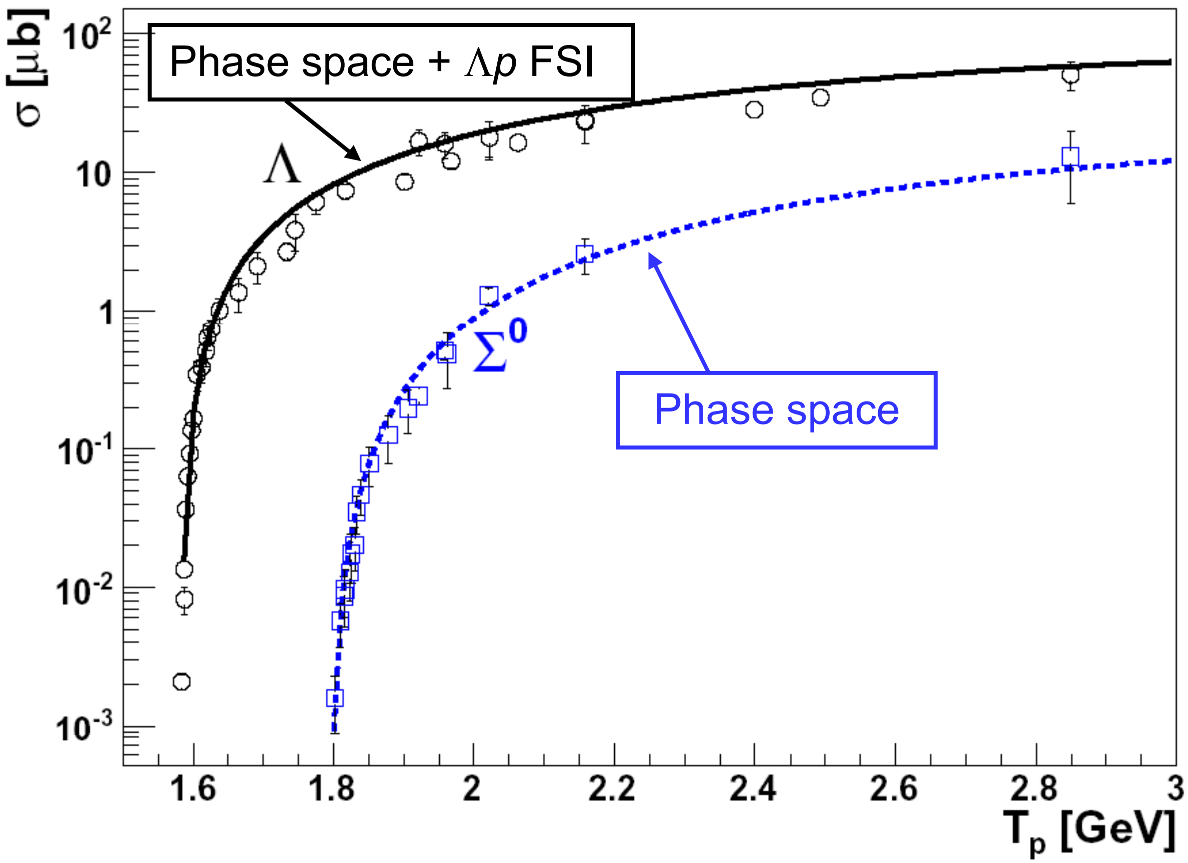
There are three strangeness-conserving *K*+ production channels open in *pp* collisions close to threshold. Most widely investigated is $pp \rightarrow K^+\Lambda p$; data on total cross sections, Dalitz plots, and angular spectra exist. Total cross sections and angular distributions are also available for $pp \rightarrow K^+p\Sigma^o$.



Recent data suggest that total cross section $\sigma(pp\rightarrow K^+n\Sigma^+) \approx 0.7\sigma(pp\rightarrow K^+p\Sigma^o)$.

But almost nothing is known about hyperon production in proton-neutron collisions.

Important to know $R = \sigma_{pn}^{K^+} / \sigma_{pp}^{K^+}$ for several reasons.

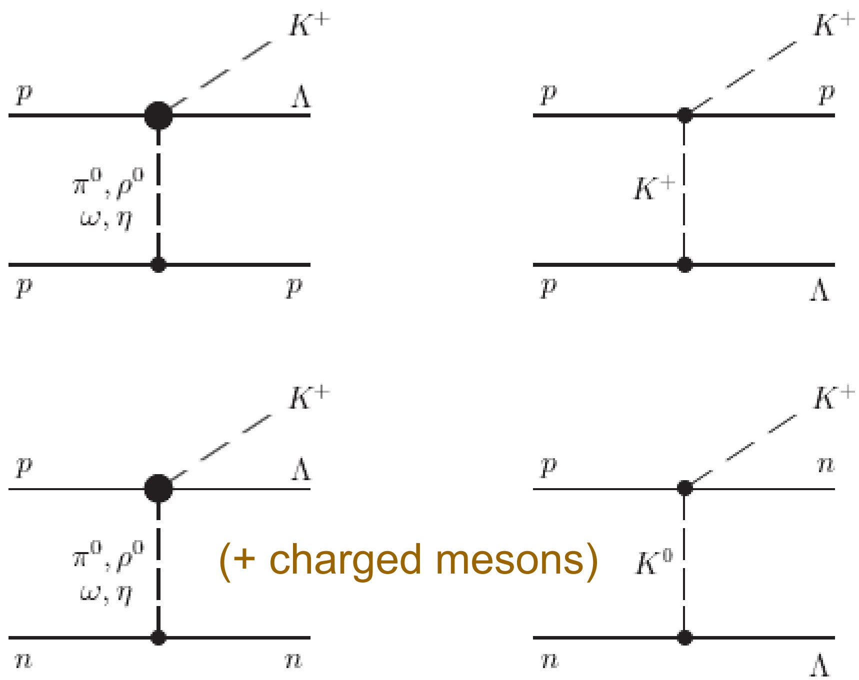
- Modelling of K^+ production in *p*A and AA collisions
- Modelling of K^+ production in nucleon-nucleon collisions.

Several indirect attempts have been made to estimate K^+ production in proton-neutron collisions

- 3 GeV *pA* collisions $\Rightarrow$ $R = 5 \pm 7.5$.
- 2.1 GeV/A *p* and *d* incident on NaF $\Rightarrow$ $R < 1$.
- 2.5 GeV *pp* and *p*C collisions $\Rightarrow$ $R \approx 1$.
- 2.02 GeV *pd* collisions $\Rightarrow$ $R \approx 3$ (very model-dependent).

There is nothing terribly convincing – Let's turn to theory.

One-boson-exchange models for $NN \to K^+\Lambda N$



Bare OBE diagrams

No consensus as to what mesons are important!

1) COSY-TOF data show strong influence of *N**(1650) decaying into $K^+\Lambda$, $\Rightarrow$ non-strange exchange.

2) Spin-transfer parameter from $\vec{p} \to \vec{\Lambda}$ (D_{NN}) interpreted as evidence for strangeness exchange.

The *N** evidence is much stronger but, even if one keeps only non-strange exchange, the results depend enormously on the relative π *versus* ρ contributions.

Near-threshold η production is driven by the $S_{11}(1535)$.
Near-threshold K^+ production is driven by the $S_{11}(1650)$.
Hence there is a lot of similarity between the two reactions.

Now η production in *pn* collisions is about 6.5 times stronger than in *pp*, *i.e.,* the isospin I=0 cross section is about TWELVE times stronger than the I=1.

Theoretical modelling suggests that, if one keeps only π and ρ exchange, there is destructive interference between them for $pp \to pp\eta$ but constructive for $pn \to pn\eta$.

A quantitative description of the available data can be achieved if one estimates the ρ coupling to the $S_{11}(1535)$ using Vector Meson Dominance and photoproduction data. This gives the ratio of the two production amplitudes $x = D_\pi/B_\rho = 0.7$.

Fäldt & CW, Physica Scripta **64** (2001) 427

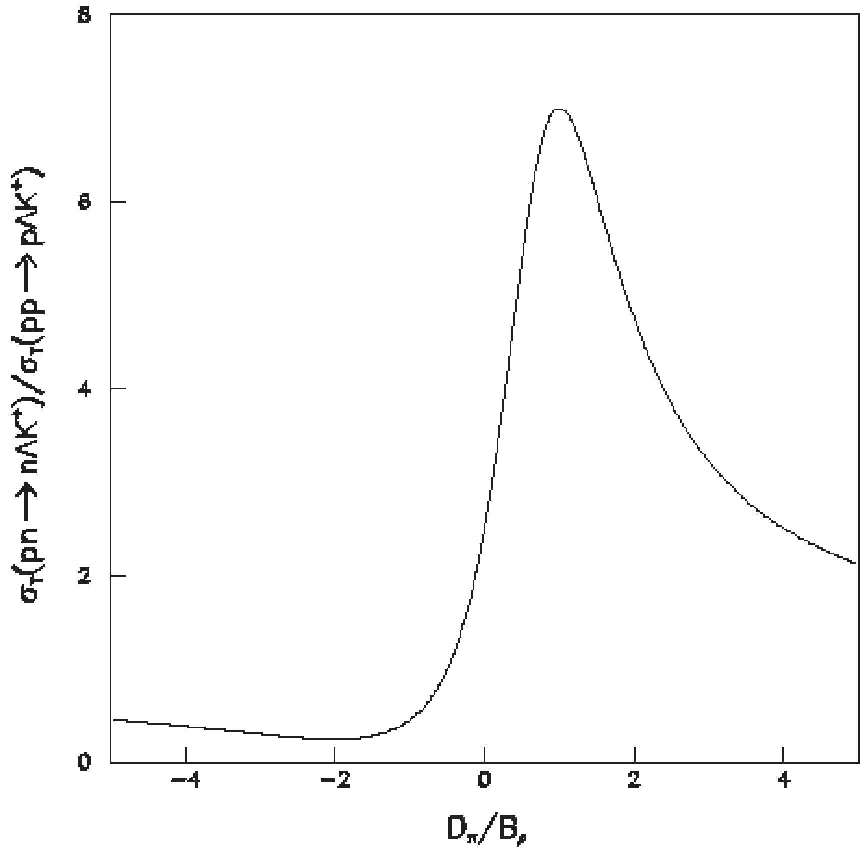
In order to reduce the theoretical uncertainty, let us compare η and K^+ production in *NN* collisions directly. The value of x changes because the π and ρ couplings to the two S_{11} isobars is different. Scaling with the appropriate elementary amplitudes gives

$$x = D_\pi / B_\rho = 0.7\left(\frac{f(\pi^- p \to K^0\Lambda) f(\gamma p \to \eta p)}{f(\pi^- p \to \eta n) f(\gamma p \to K^+\Lambda)}\right),$$

where ρ-dominance has been assumed for photoproduction.

The experimental data determine well the modulus of *x*; $|x| = 0.9\pm0.2$. If one keeps just the two S_{11} isobars, the phases between the amplitudes *f* should largely cancel and *x* should be almost real, with two possible values $x = \pm(0.9\pm0.2)$, depending whether one has constructive or destructive π-ρ interference.

Fäldt & CW, EPJA **24** (2005) 431



Near-threshold cross section ratio predicted as a function of the ratio of the π/ρ-exchange strength

Cross section ratio depends critically on $x = D_\pi/B_\rho$.

Simple model predicts $x = \pm(0.9\pm0.2)$.

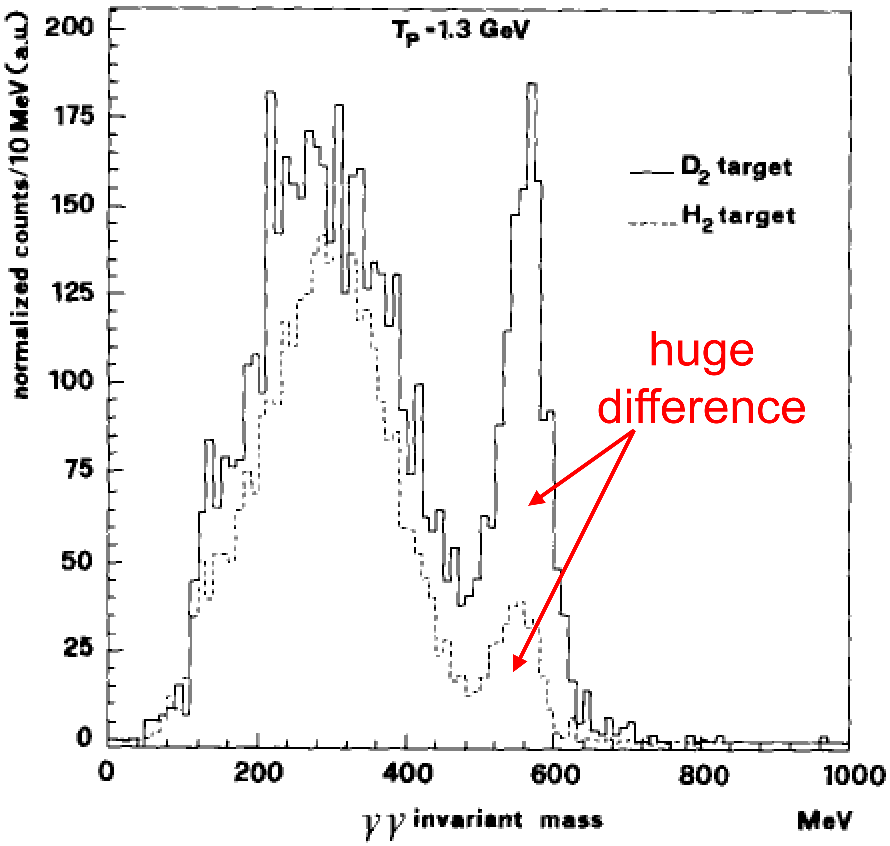
If x is positive, $R \approx 7$.

If x is negative, $R = 0.5\pm0.2$

Without fixing the signs of the coupling of the π and ρ to the two S_{11} isobars, one will always end up with two possible values of R.

Fäldt & CW, EPJA **24** (2005) 431

First proof that η production was MUCH stronger in *pn* than *pp* collisions was from the PINOT comparison of inclusive *pd* → η*X* and *pp* → η*X*′.



Only later semi-exclusive data from CELSIUS showed

$$\frac{\sigma(pn \to pn\eta)}{\sigma(pp \to pp\eta)} \approx 6.5.$$

[Constructive π/ρ interference for *pn* and destructive for *pp*.]

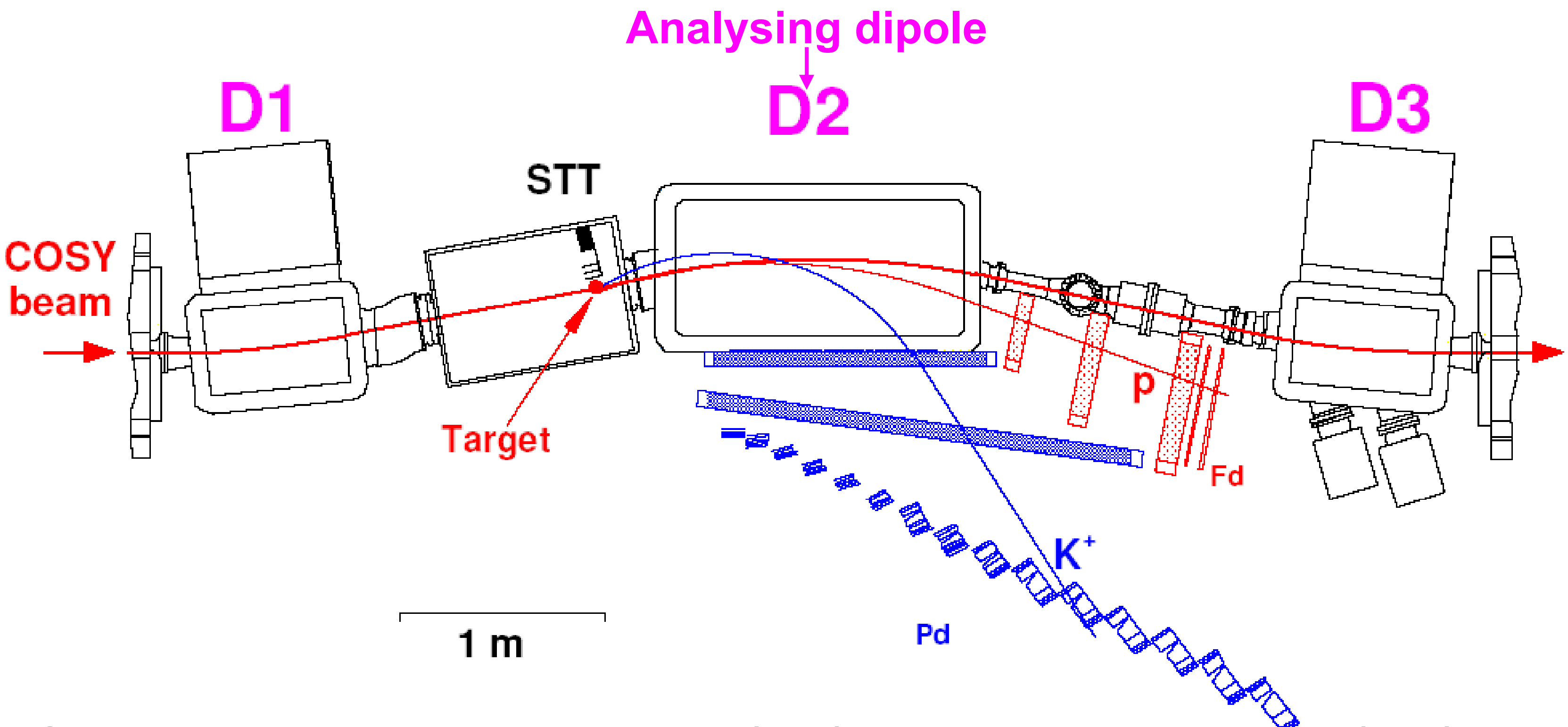
Method suggests that inclusive production of K^+ in *pd* and *pp* collisions could lead to useful *pn*/*pp* estimate.

Hence the COSY-ANKE *pp*/*pd* → K^+ experiment!

E.Chiavassa, PLB **337** (1994) 192

The COSY-ANKE Facility

is situated inside the COSY storage ring.



Only the Forward detector (Fd), Positive detector (Pd) and the silicon tracking telescope (STT) were used in experiments at 1.83, 1.92, 2.02, and 2.65 GeV.

Y.Valdau, arXiv:1109.0176 (nucl-ex)

Crucial element in the experiment is the positive detector of fifteen range telescopes placed in the focal plane of D2. These study the products of the K^+ delayed decay. The time measurements allow a clear K^+ identification even when the background from protons and π^+ is 10^6 higher.

Inclusive kaon production only requires the range telescopes. This would be completely equivalent to the Pinot η experiment.

The forward detector is needed to measure the fast proton from elastic *pp* scattering or *pd* scattering or breakup in order to determine the luminosity. In the *pd* case the luminosity could also be fixed by measuring the recoil deuteron from elastic *pd* scattering in the silicon tracking telescope.

The typical luminosity uncertainty was $\approx$ 10-15%.

Experimental Results

Number of K^+

integrated luminosity

$$d\sigma^{K^+} \equiv \frac{d^2\sigma_{K^+}}{d\Omega\, dp} \approx \frac{N_{K^+}}{\Delta\Omega\, \Delta p} \frac{1}{L^{\mathrm{tot}} \varepsilon_{K^+}},$$

overall detection efficiency

counter solid angle

momentum bite

where

$$\varepsilon_{K^+} = \varepsilon^{\mathrm{tel}} \times \varepsilon^{\mathrm{scint}} \times \varepsilon^{\mathrm{MWPC}} \times \varepsilon^{\mathrm{acc}}$$

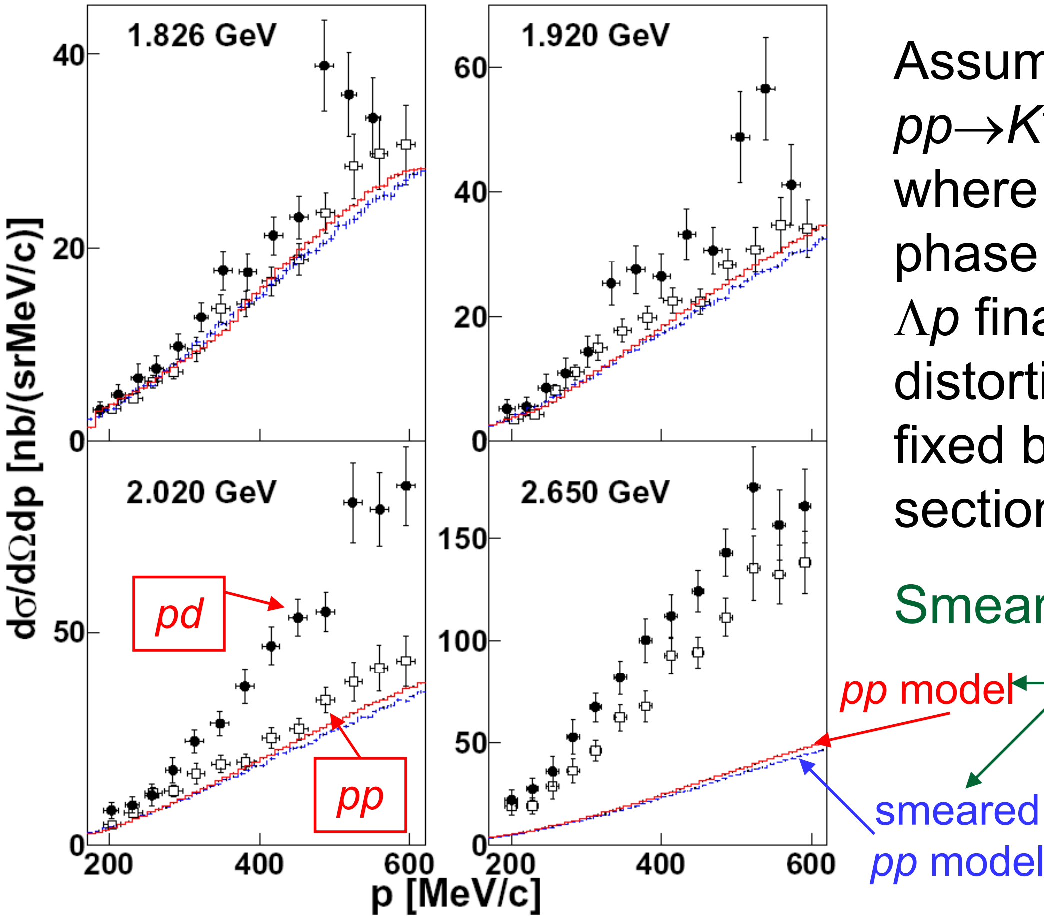
$\varepsilon^{\mathrm{tel}}$ is the main systematic uncertainty ($\approx 10-15\%$)

When data were taken under identical conditions (2.65 GeV), lots of corrections drop out and we are left with:

$$d\sigma^{K^+}_{pd} / d\sigma^{K^+}_{pp} = \left(N^{K^+}_{pd} / N^{K^+}_{pp} \right) \times \left(L^{\mathrm{tot}}_{pp} / L^{\mathrm{tot}}_{pd} \right),$$

which is identical to Pinot for the η.

Laboratory double-differential cross sections for K^+ production in proton-proton and proton-deuteron collisions averaged over production angles $\vartheta < 4^\circ$.



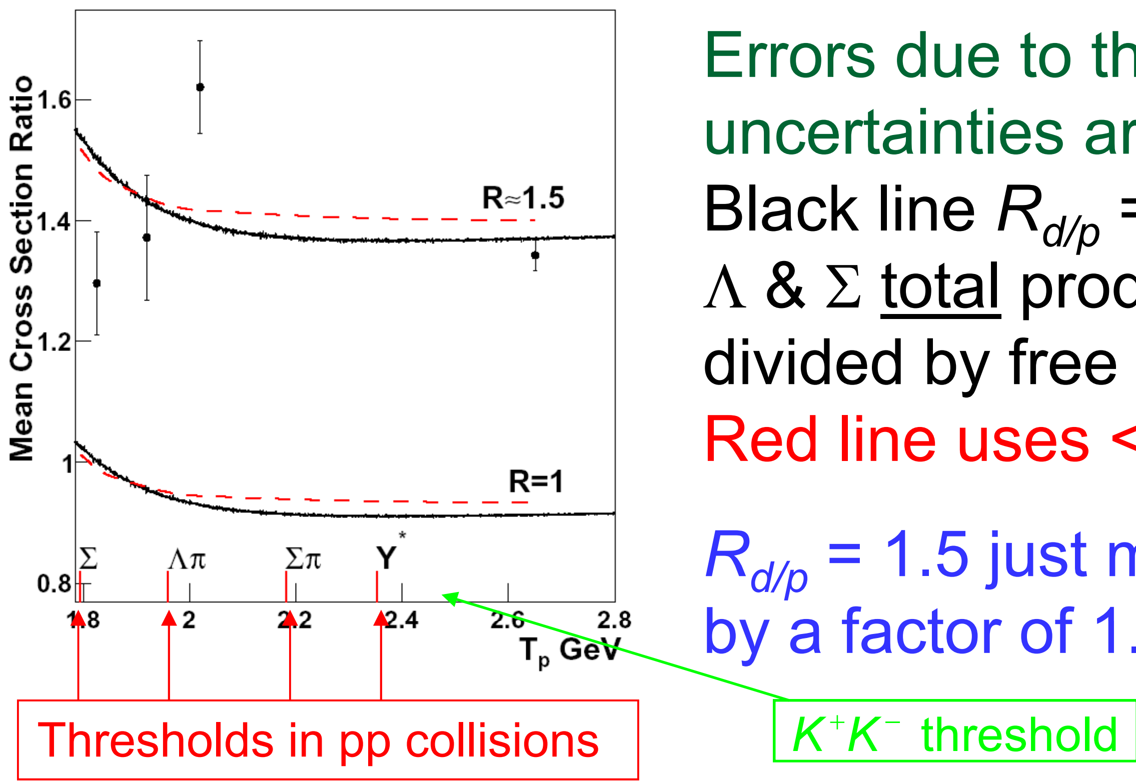
Three-channel *pp* model

Assume that the only reactions are $pp \to K^+ p\Lambda$, $pp \to K^+ p\Sigma^0$, $pp \to K^+ n\Sigma^+$, where Σ production is given by phase space but for Λ include also Λp final state interaction and N^* distortion of $K^+\Lambda$. Normalisations fixed by the measured total cross sections.

Smearing over the Fermi motion in the deuteron is unimportant.

Model fails completely at high energy when many more channels are open.

Ratio $d\sigma_{pd}^{K^+} / d\sigma_{pp}^{K^+}$ averaged over the K^+ momentum



Errors due to the normalisation uncertainties are not included here.

Black line $R_{d/p}$ = 1 Fermi-smeared Λ & Σ total production cross sections divided by free hydrogen data.

Red line uses < 4º differential data.

$R_{d/p}$ = 1.5 just multiplies these curves by a factor of 1.5.

Above the Y* = Σ(1385) & Λ(1405) thresholds, the simple three-channel model has no chance of working.

Agreement with $R_{d/p}$ = 1.5 curve is fortuitous!

Numerical values

T_p (GeV)	$d\sigma_{pd}^{K^+} / d\sigma_{pp}^{K^+}$
1.826	1.28±0.03±0.28
1.920	1.38±0.06±0.30
2.020	1.65±0.10±0.36
2.650	1.34±0.04±0.23

Weighted average of the first three results gives

$$R_{d/p} = \sigma_{pd}^{K^+} / \sigma_{pp}^{K^+} = 1.4 \pm 0.2.$$

Including a 5% correction from shadowing in the deuteron, get

$$R_{d/p} = \sigma_{pn}^{K^+} / \sigma_{pp}^{K^+} = 0.5 \pm 0.2$$

(same as one of the F&W solutions!).

At low energies, where only Λ production is possible, isospin gives a further constraint:

$$\sigma(pn \to K^+ n\Lambda) = \sigma(pn \to K^0 p\Lambda) > \sigma(pp \to K^+ p\Lambda)/4.$$

Now the *pn* system is half *I*=0 and half *I*=1. Furthermore, since the final state is equally likely to be K^+ or K^0 production, the ANKE result suggests

$$\tfrac{1}{4}[\sigma^{I=0} + \sigma^{I=1}] = (0.5 \pm 0.2)\sigma^{I=1},$$

which means that

$$\sigma^{I=0}(NN \to K^+ N\Lambda)/\sigma^{I=1}(NN \to K^+ N\Lambda) = 1.0 \pm 0.8,$$

so that K^+ production may be independent of isospin.

If the interference of π/ρ exchange is constructive for I=0 in $NN \rightarrow \eta$, then theory can reproduce well experiment:

$$\sigma_{pn}^{\eta} / \sigma_{pp}^{\eta} \approx 6.$$

If the interference of π/ρ exchange is constructive for I=0 in $NN \rightarrow K^{+}$, then theory can reproduce well experiment:

$$\sigma_{pn}^{K^+} / \sigma_{pp}^{K^+} = 0.5 \pm 0.2.$$

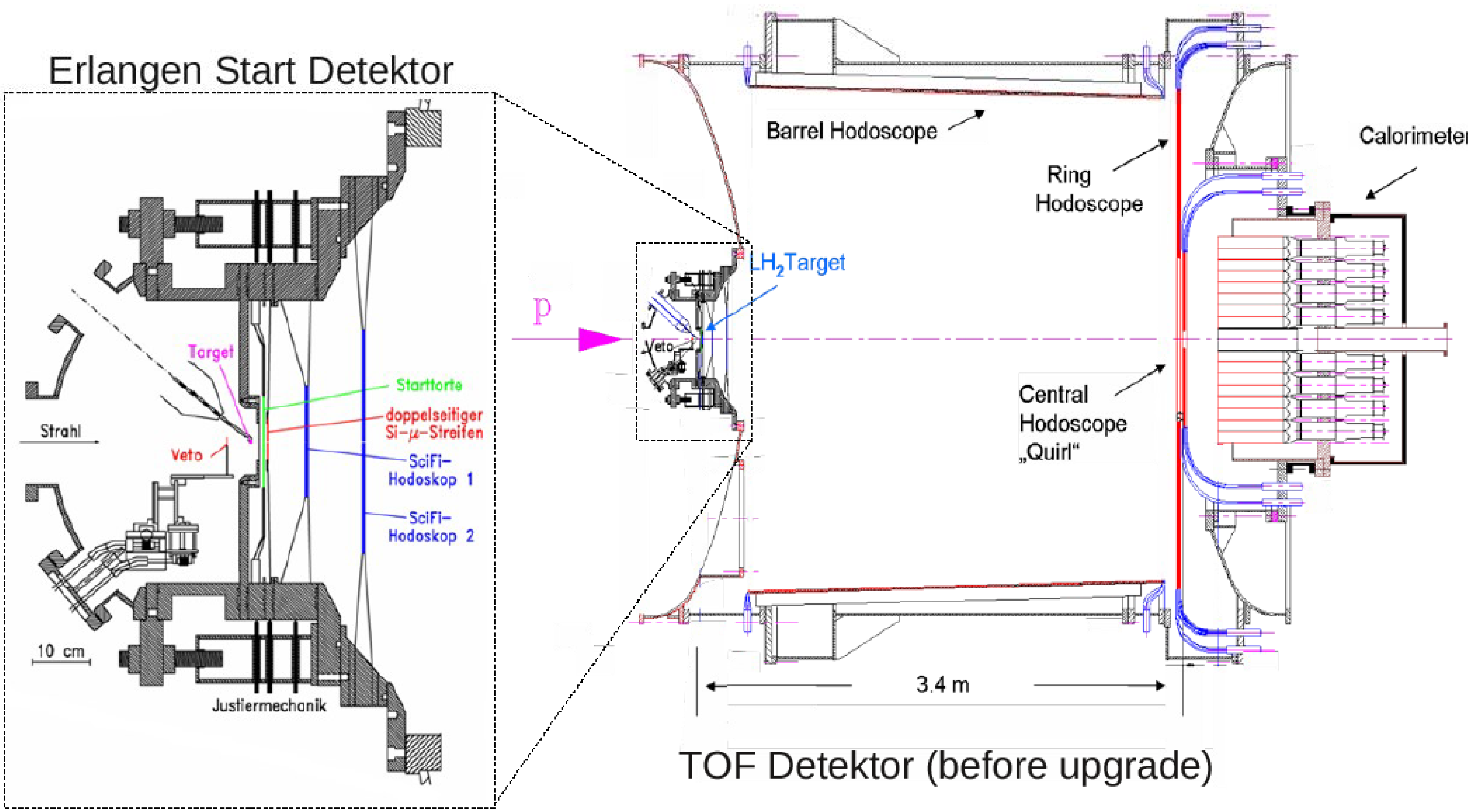
To go further one would need a true dynamical model of the two S_{11} isobars that can predict the phases of the couplings to the π and ρ.

Can one do better by measuring an exclusive reaction? Two complementary approaches tried.

1: COSY-TOF studied the $pd \rightarrow p_{sp}K^0\Lambda p$ reaction by measuring the fast proton in coincidence with the charged decay products of $K^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$. The spectator proton ($p_{sp}$) was reconstructed from kinematics.
Main difficulty: event identification.

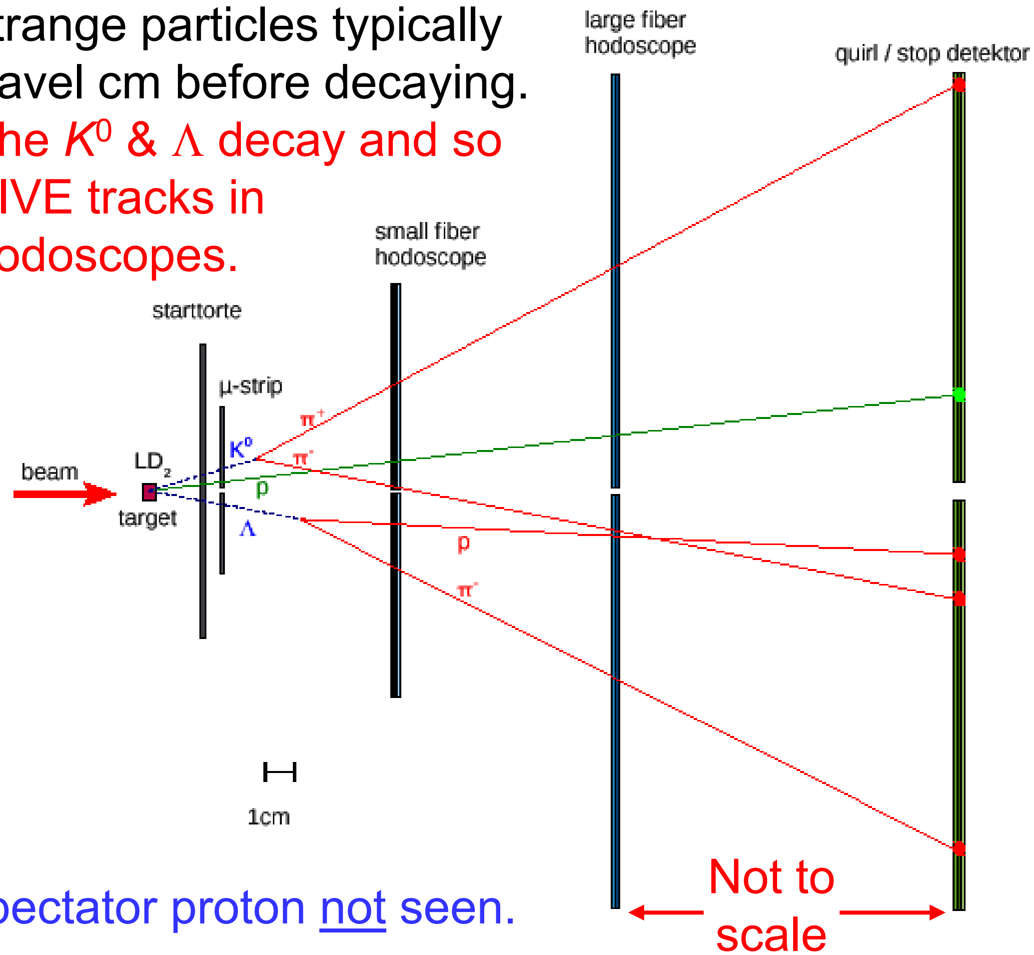
2: COSY-ANKE measured $pd \rightarrow p_{sp}K^+X$. Although only the spectator proton p_{sp} and the K^+ were detected, below the thresholds for Σ production the only possible final state was $p_{sp}K^+\Lambda p$.
Main difficulty: small acceptance of ANKE spectrometer.

The COSY-TOF facility used for $pd \to p_{sp}K^0\Lambda p$



Ideal topology $pd \rightarrow p_{sp}K^0\Lambda p$ reaction

Only fast proton seen in silicon microstrip. Fast strange particles typically travel cm before decaying. The K^0 & Λ decay and so FIVE tracks in hodoscopes.



Spectator proton not seen.

Timing information is obtained from the start counter and stop detector.

But there is no magnetic field and so event identification must be primarily on basis of kinematics & geometry.

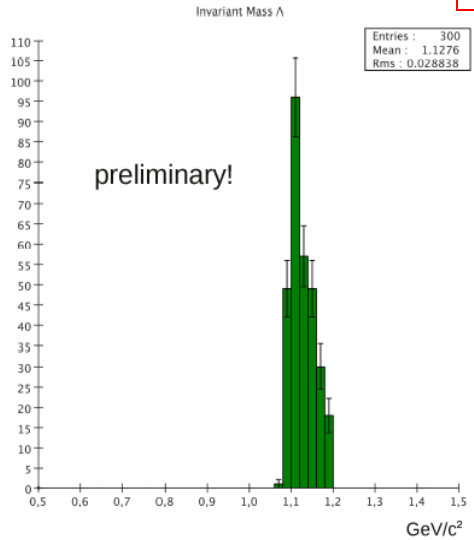
Main difficulty is identifying the two decay vertices from the four tracks with their measurement errors – the combinatorial background. First check that one pair is consistent with the Λ and then see if the other could fit the K^0_S.

Combinatorial background much more of a problem than the physical background.

Use now being made of the timing information from the start to the stop counters – though this might introduce a bias that has to be checked.

Monte Carlo with Fermi motion
40.000 simulated events

$\Lambda \rightarrow p\pi^-$



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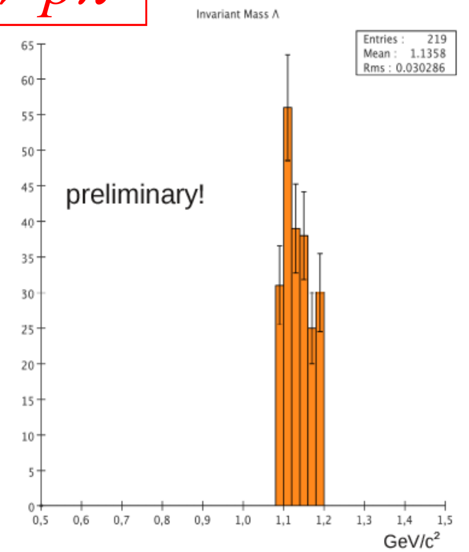
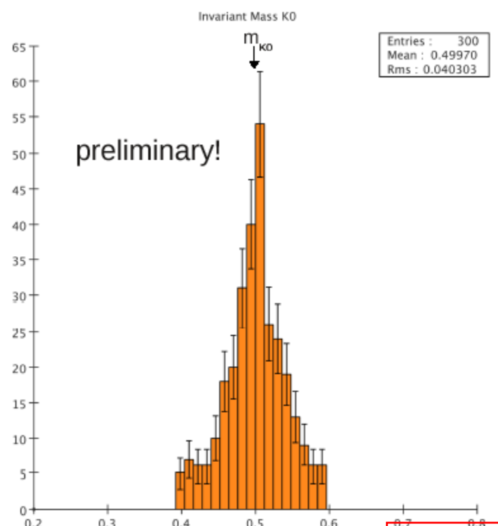


Monte Carlo with Fermi motion
40.000 simulated events



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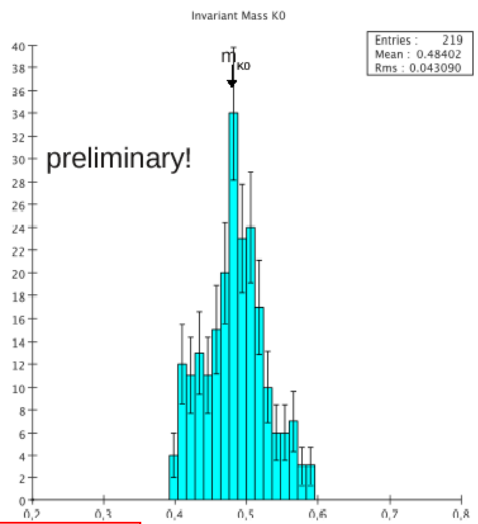


$K_S^0 \rightarrow \pi^+\pi^-$

The accepted events look very believable, but is it possible that some events were lost in the process?

The "uninteresting" events are ≈ 5×10^5 more frequent

Preliminary results at 3.059 GeV/*c*

- 85 million events recorded
- 32 hours of measurement time
- 60% analysed by March 2011
- In total, between 300 & 600 reconstructed $K^0\Lambda p$ final states expected, depending upon selection criteria.

Initial estimate (<u>very</u> preliminary)

$\sigma(pd \rightarrow p_{sp}K^0\Lambda p)$ = (5.0 ± 0.5 ± 1.0) μb

at p_p=3.059 GeV/c, T_p = 2.261 GeV.

COSY-TOF preliminary result suggests:

$$R = \frac{\sigma\left(pn \to K^0 \Lambda p\right)}{\sigma\left(pp \to K^+ \Lambda p\right)} = 0.20 \pm 0.02_{\mathrm{stat}} \pm 0.04_{\mathrm{sys}}$$

at T_p = 2.261 GeV ($Q \approx$ 238 MeV).

This falls below the isospin bound of R > ¼, though the error bars could push it over.

It also lies below the inclusive estimate of R = 0.5 ± 0.2, but this estimate may not be valid for these exclusive channels at such high energies.

On the other hand, bubble chamber measurements at 6 GeV/c give R = 0.46 ± 0.08 ± systematics (but this is much higher in energy!).

The $pd \to p_{sp}K^0\Lambda p$ reaction seems to be at the edge of what the original COSY-TOF facility could handle (though the apparatus has now been much improved).

There is only one directly visible prompt track (the fast proton) and only few track points of the decay particles. In addition, the separation of the decays of the Λ and the K^0_S needs “some tricks” and the use of the timing information.

The treatment of the timing will be checked in the analysis of a second data set taken at 2.95 GeV/c (2.157 GeV).

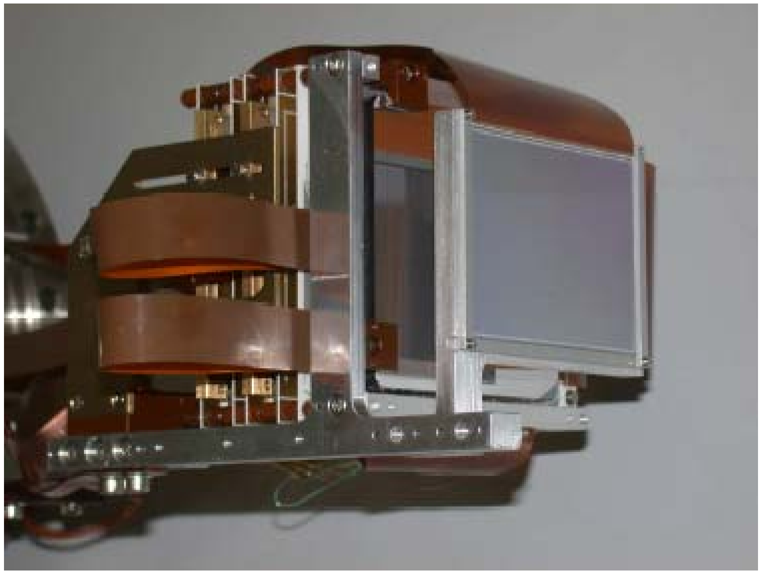
The ANKE $pd \to p_{sp}K^{+}\Lambda n$ experiment

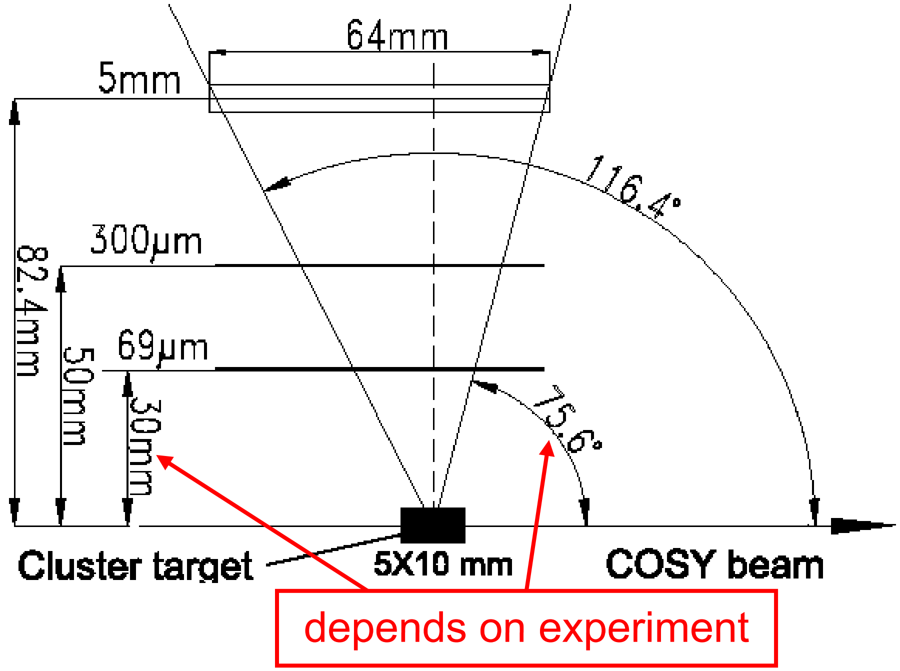
The K^{+} can be identified with high confidence in the range telescopes and the spectator proton measured in one of the silicon tracking telescopes (STT) placed inside the target chamber. Below the threshold for Σ production, the p_{sp} and K^{+} could only have come from $pd \to p_{sp}K^{+}\Lambda n$.

Experiment carried out in Spring 2011 and results will not be available before 2012.

Main constraint will come from the design of the STT, which we must now look at.

Silicon Tracking Telescope (STT)





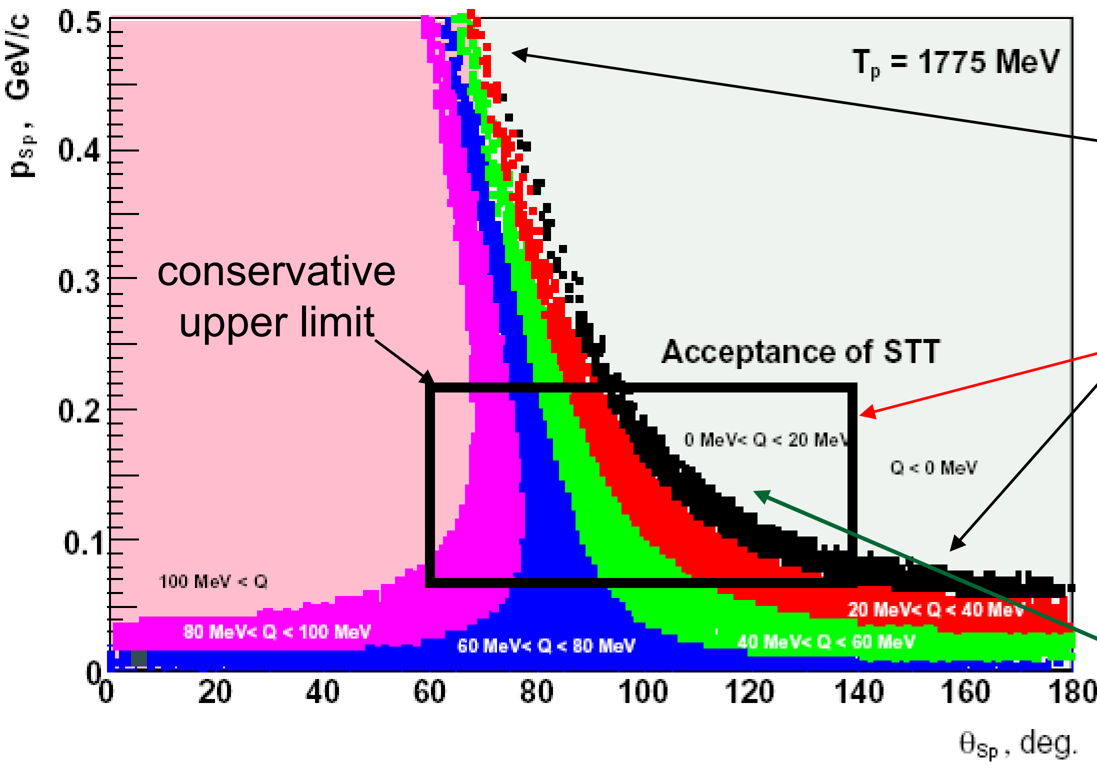
Telescope arrangement of three double–sided silicon strip detectors:
Layer-1: 65µm thick with 316 strips one side and 256 on the other,
Layer-2: 300µm thick with identical geometry to Layer-1, and
Layer-3: 5mm thick with 96 strips on each side, Area = 64 × 64mm^2.

In order to get the angle of a recoil proton through measurements with the strips, it has to pass through the first layer and be stopped in the second or third. (Particle identification via the ΔE-E method using different layers).

Protons with kinetic energies in the range $2.5 < T_p < 30$ MeV can be identified with resolution of ≈ 200 keV. Angular resolution of 1º to 6º depends upon angle.

Major problem is that $T_p = 2.5$ MeV corresponds to a proton momentum of 68 MeV/*c*, which is high for a Fermi momentum. About half the events are lost because of this cut!
Second layer stops protons up to 6 MeV and only about 30% of spectator protons have energies higher than this.

Spectator proton energy and angle fixes *Q* to a few MeV



Value of *Q* depends mainly on combinations p_{sp}^2 & $p_{sp}\cos\theta_{sp}$.

STT acceptance depends on angular coverage (distance from target).

Q < 0 data used for background studies.

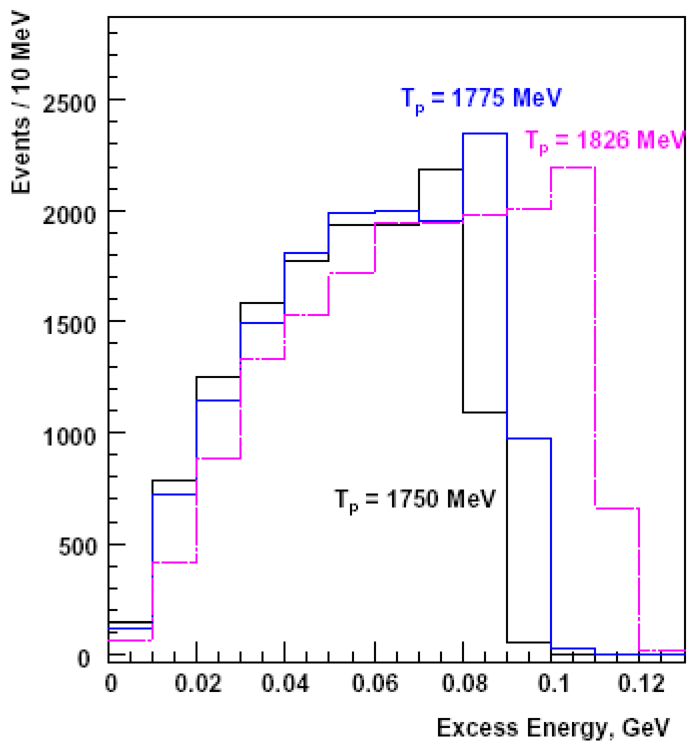
Simulation @ 1.826 GeV

Whole range of *Q* will be studied simultaneously and data will have to be binned because of statistics, not resolution.

Luminosity will be determined to ≈ 5% by measuring the frequency change in the machine due to the energy loss in the beam-target interactions. This uses the Schottky technique discussed by David Chiladze in measurement of the proton-proton elastic differential cross section. He is achieving there a precision of about 3%

The value of luminosity will be checked by measuring proton-deuteron elastic scattering, with the deuteron being detected in the STT.

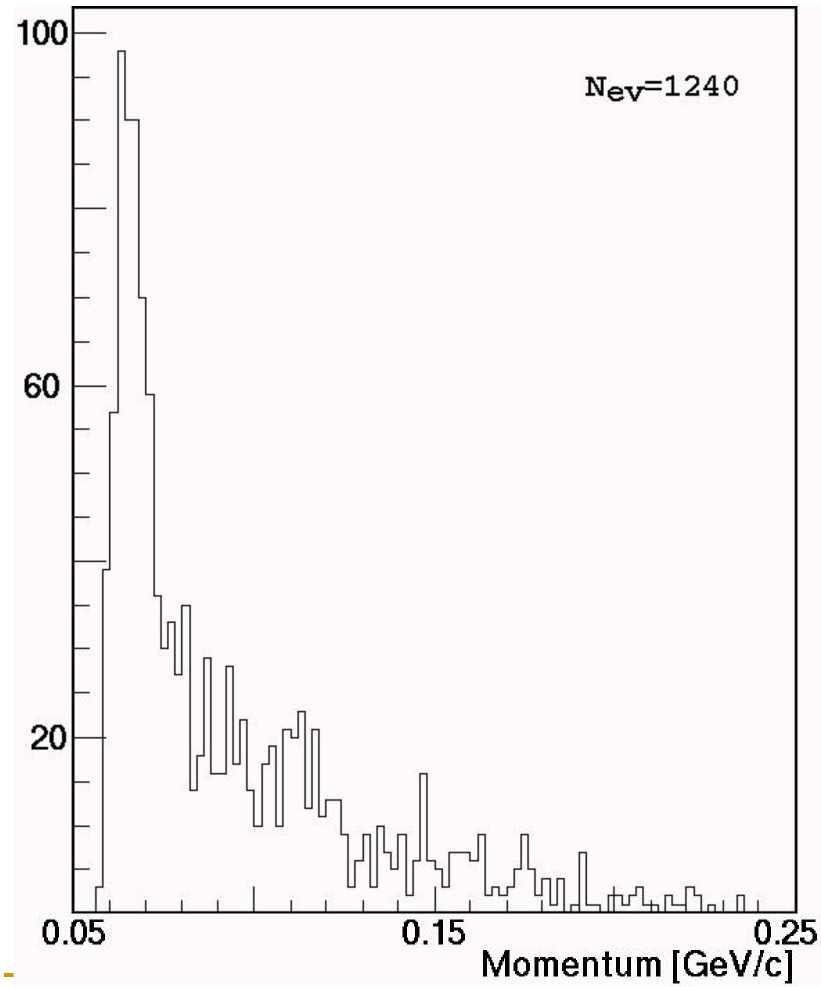
Simulation results



Counts expected after 3 weeks of beam time at 1.826 GeV. There would have been fewer counts if the energy were lowered to 1.775 GeV, though somewhat more in the low *Q* region.

This is a little optimistic because simulation assumed that K^+ production in *pn* was as strong as in *pp*. The placing of the STT was not quite optimal, but all this was compensated by a much enhanced luminosity so that in one week of beam time we expect ≈ 60-80% of these counts.

Initial analysis of ≈ 5% of the data. The momentum of a "spectator" proton in the STT in coincidence with an identified K+. Note the sharp cut-off at 60 MeV/c caused by the need for the proton to go through the first STT layer.



There is a sharp fall of the count rate with momentum. This is as expected on the basis of the deuteron wave function – but note that these are not yet acceptance corrected.

To ensure the validity of the spectator model, we will put a cut on the highest acceptable momentum – perhaps at 140 MeV/c.

Conclusions

Hyperon production in proton-neutron collisions is very challenging experimentally. If one carried out inclusive K^+ production experiments on hydrogen & deuterium under identical conditions, one could get precisions on the ratio of better than $\approx$10%. Present ANKE data could be improved.

COSY-TOF can measure exclusively with high acceptance. Hard to get reliable unambiguous trigger and not easy close to threshold due to small cross sections. Must wait for results.

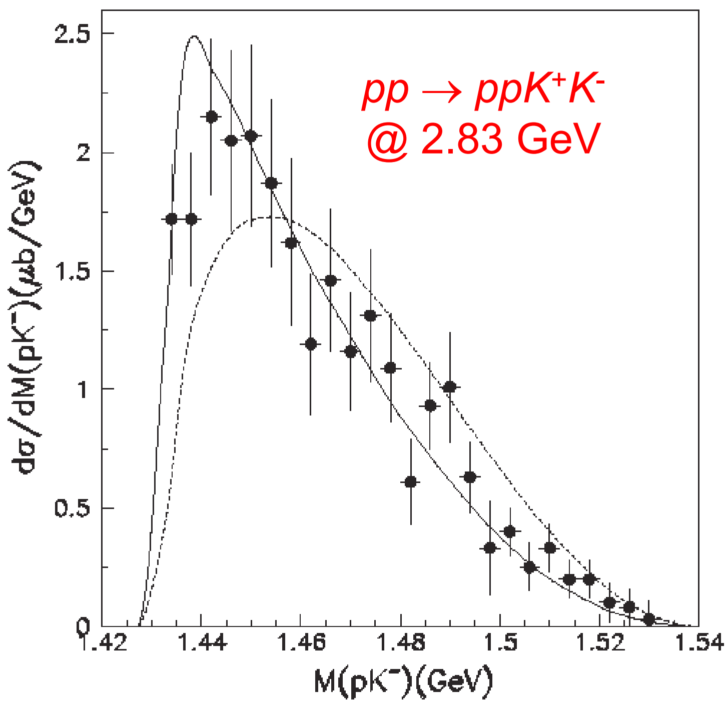
COSY-ANKE has very good K^+ trigger but small acceptance. Too few events to detect the decay products of $\Lambda \to p\pi^-$ in the $pd \to p_{sp}K^+\Lambda n$ reaction. Should still get reliable cross sections below Σ threshold. Must wait for results.

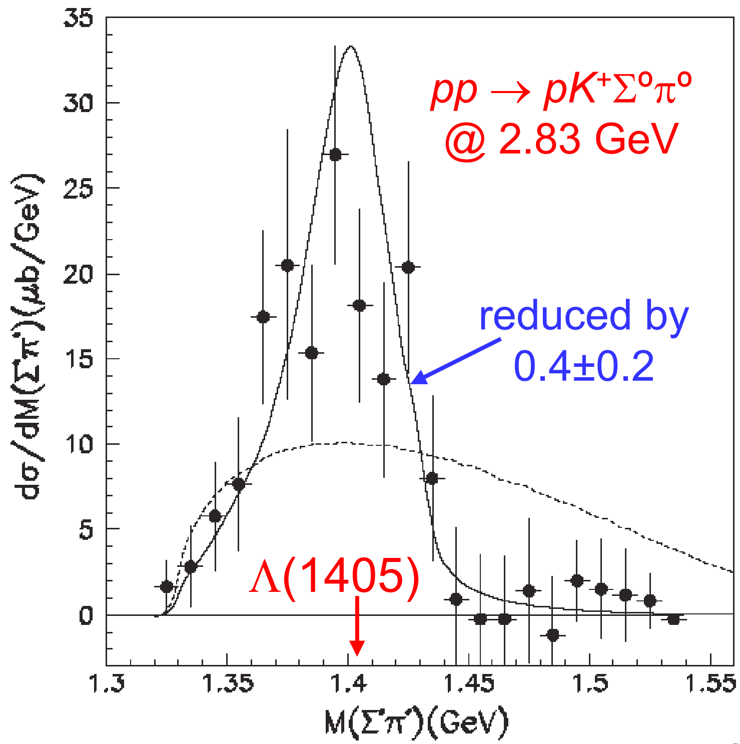
TOF & ANKE largely complementary!

Speculation on Heavier Hyperons: $\Lambda(1405)$

Inclusive data above $\Lambda(1405)$ threshold still gives production in *pn* about half that in *pp*. Is there other possible information?

Most $pp \to ppK^+K^-$ seems to proceed via $pp \to pK^+\Lambda(1405)$.





Xie & CW, PRC **82** (2010) 025210

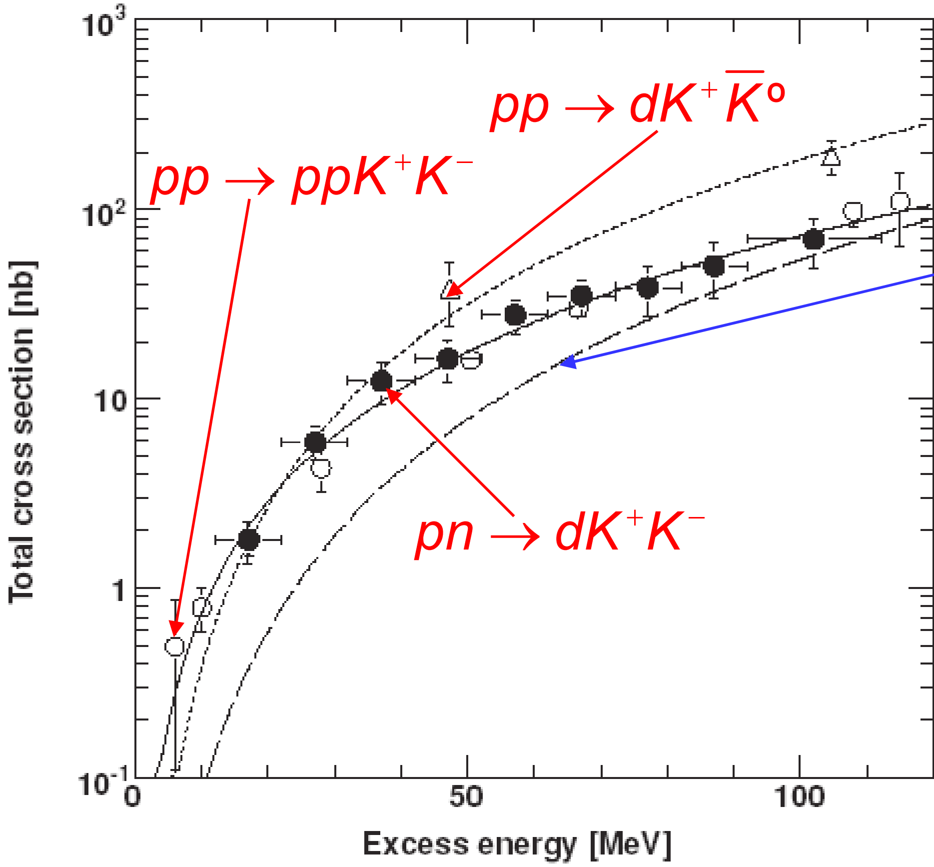
Physics & Astronomy UCL

If $\sigma[pp \rightarrow K^+p\Lambda(1405)] \approx 2\,\sigma[pn \rightarrow K^+n\Lambda(1405)]$,

we would expect K^+K^- pair production to be twice as strong in proton-proton collisions as in proton-neutron.

Is there any evidence for this?

ANKE measured



but not $pn \to pnK^+K^-$.

ROUGH estimate of $pn \to \{pn\}_{I=0}\ K^+K^-$ cross section from $pn \to dK^+K^-$ with final state interaction theory.

Lower than $pp \to ppK^+K^-$ by a factor of ≈1.5 to ≈ 4.

But, without knowing the $\{pn\}_{I=1}$, we cannot draw any real conclusions. Need <u>direct</u> $pn \to pnK^+K^-$ measurement.

Maeda, PRC **77** (2008) 015204
Dzyuba, EPJA **38** (2008) 1
Maeda, PRC **79** (2009) 018201

Thanks and Goodbye!

Typical London weather ?