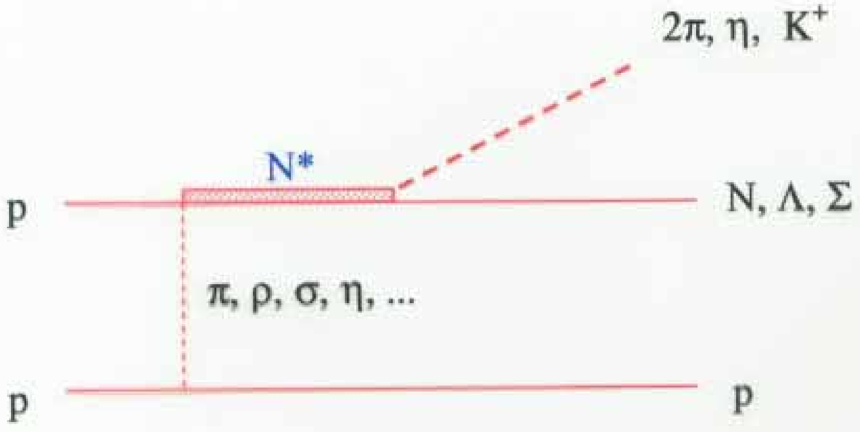
Resonances in Meson Production from Nucleon-Nucleon Interactions

Bo Höistad, Uppsala Sweden, talk at the NStar 2002 workshop, Pittsburgh, October 2002

- Introduction
- The $pp \to pN\pi\pi$ reaction
- The $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma^0$ reactions
- The $pp \to pp\eta$ reaction
- Conclusions

Resonance production in pp collisions near threshold



The excitation of the resonance can be caused by several different mesons.
Possible resonances being excited are:

$N^* = N(1440)P_{11}, N(1520)D_{13}, ...$ for 2π
$N^* = N(1535)S_{11}, ...$ for η
$N^* = N(1650)S_{11}, N(1710)P_{11}$ .... For K^+

Available data on the $pp \rightarrow pN\pi\pi$ reaction from experiments near the threshold at the CELSIUS-ring in Uppsala

Reaction	Threshold (MeV)	Beam Energy (MeV)
$pp \rightarrow pp\pi^+\pi^-$	600	650, 680, 725, 750
$pp \rightarrow pp\pi^0\pi^0$	579	650, 725, 750, 775
$pp \rightarrow pn\pi^+\pi^0$	592	725, 750, 775

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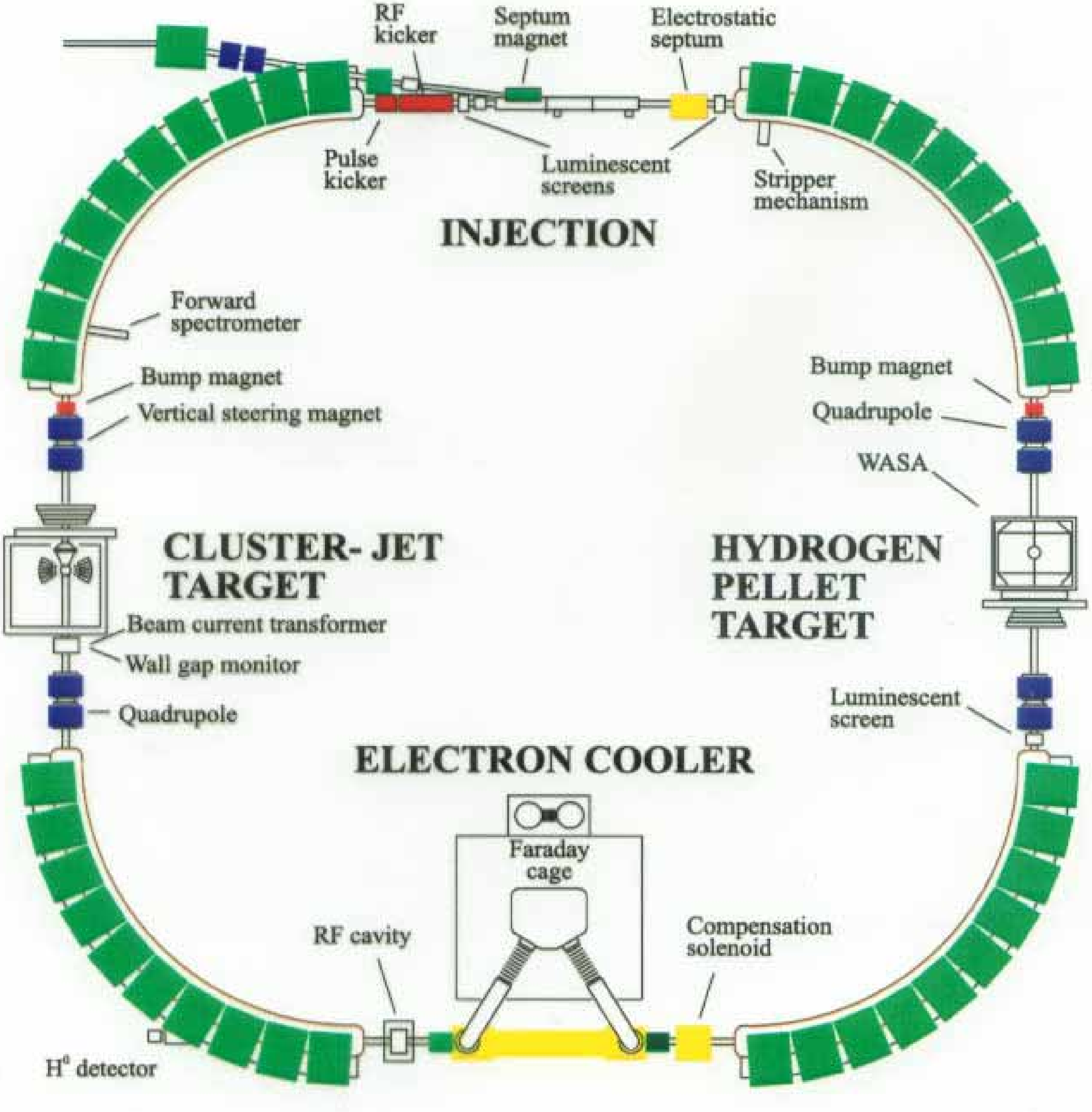
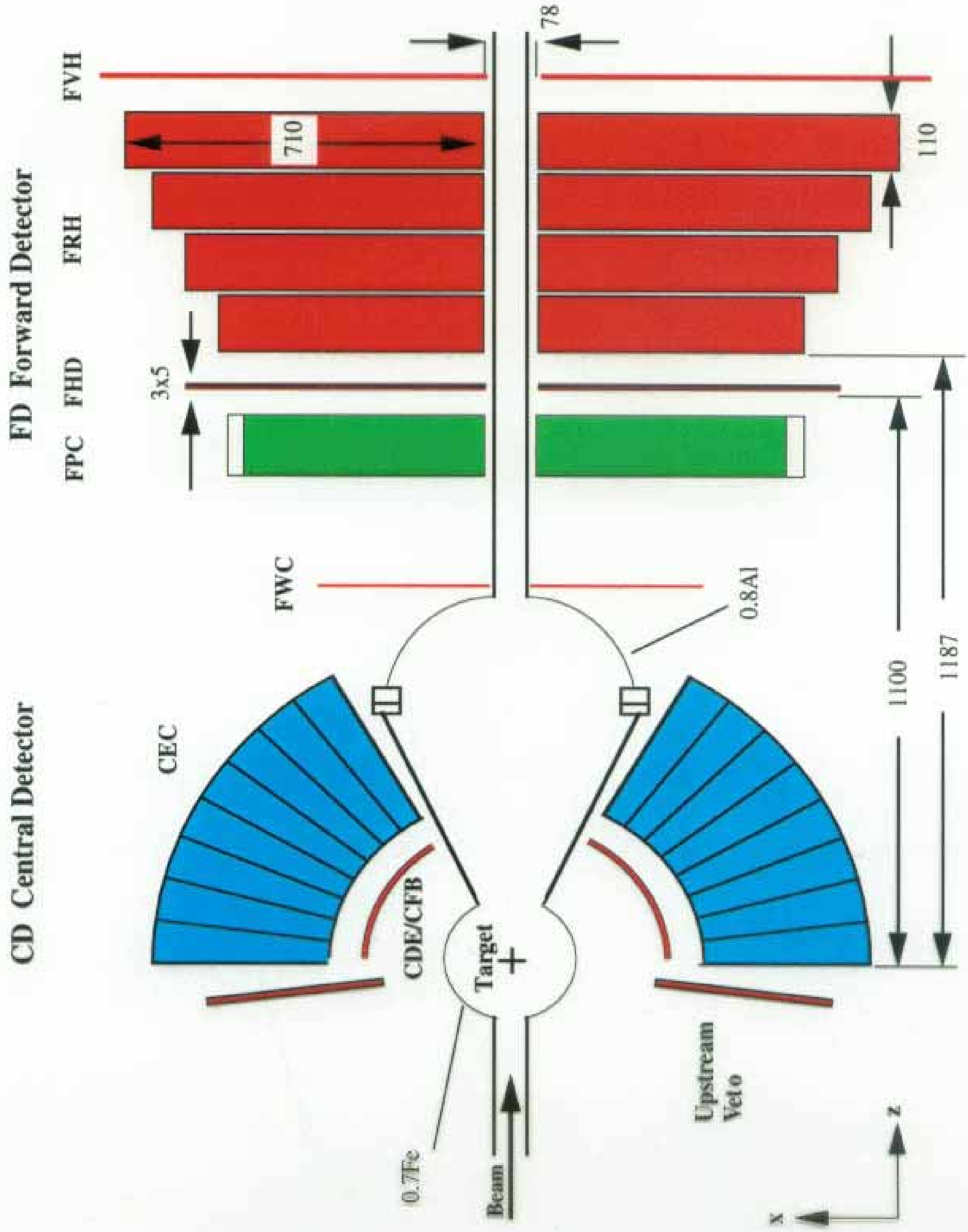
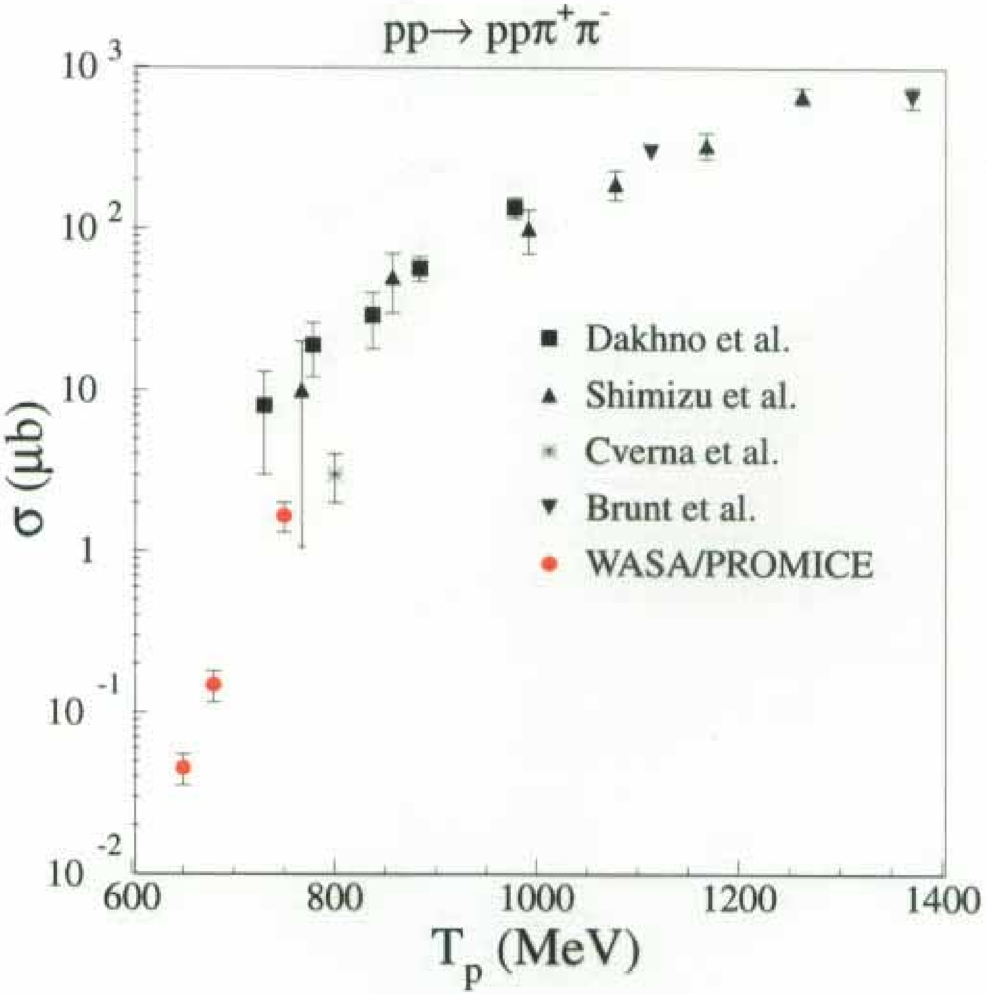
The CELSIUS storage ring

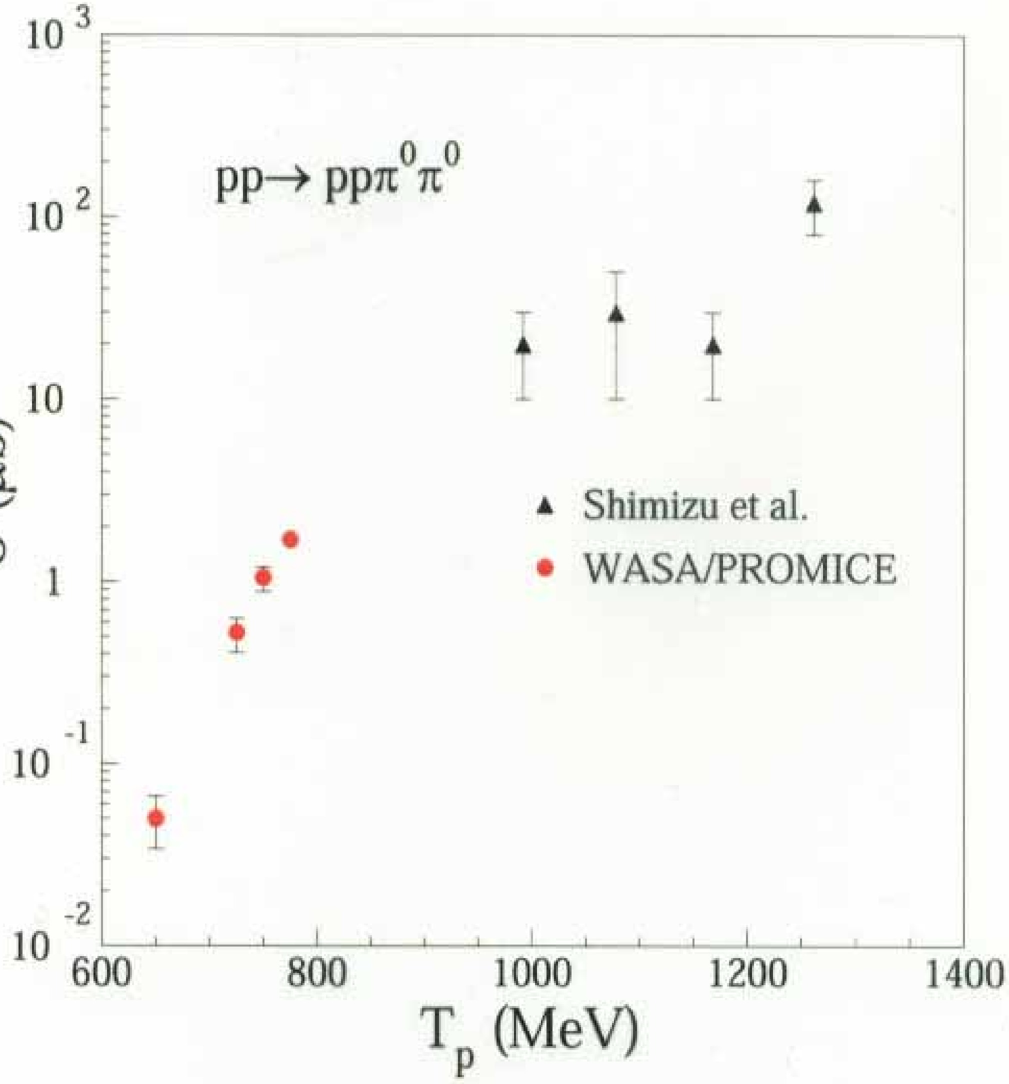


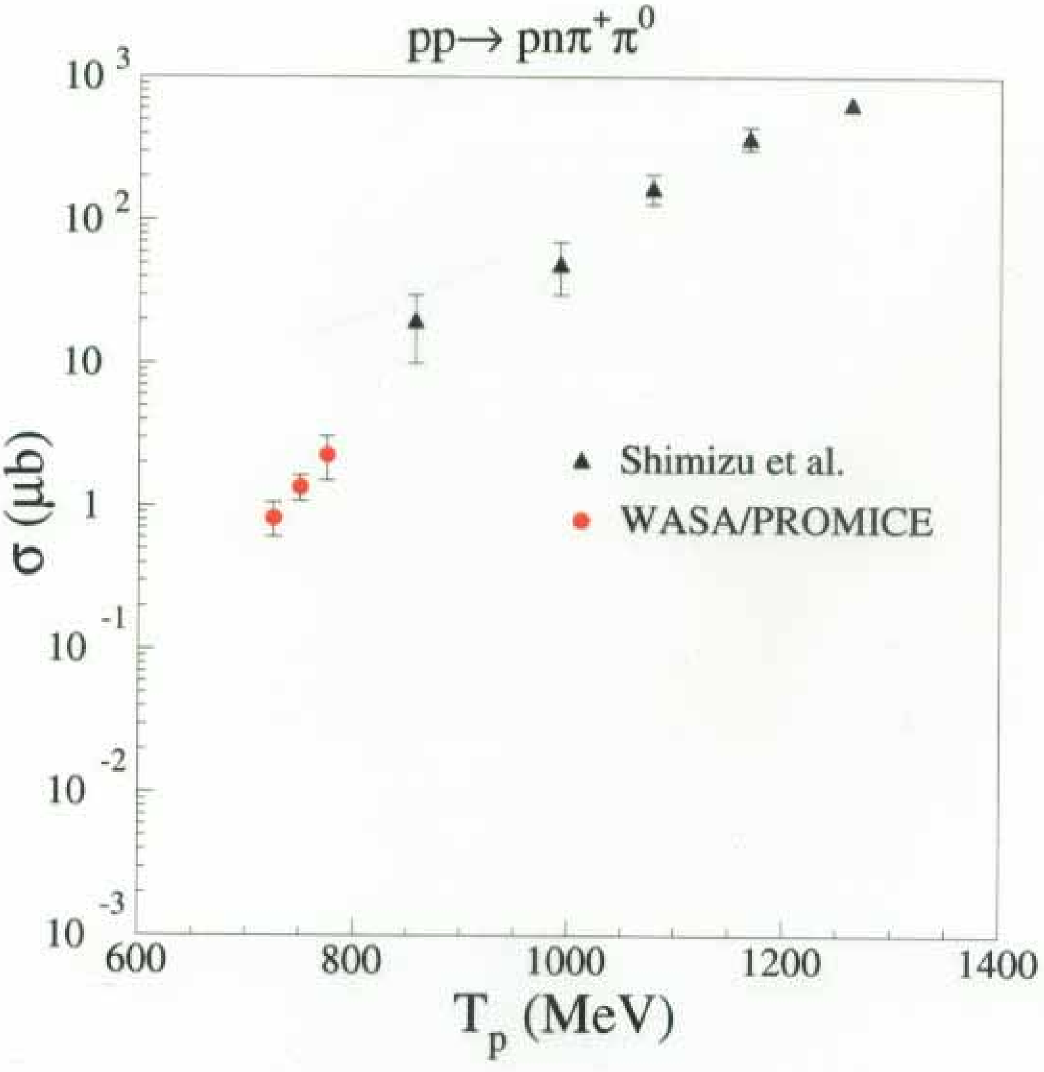
The PROMICE/WASA detector



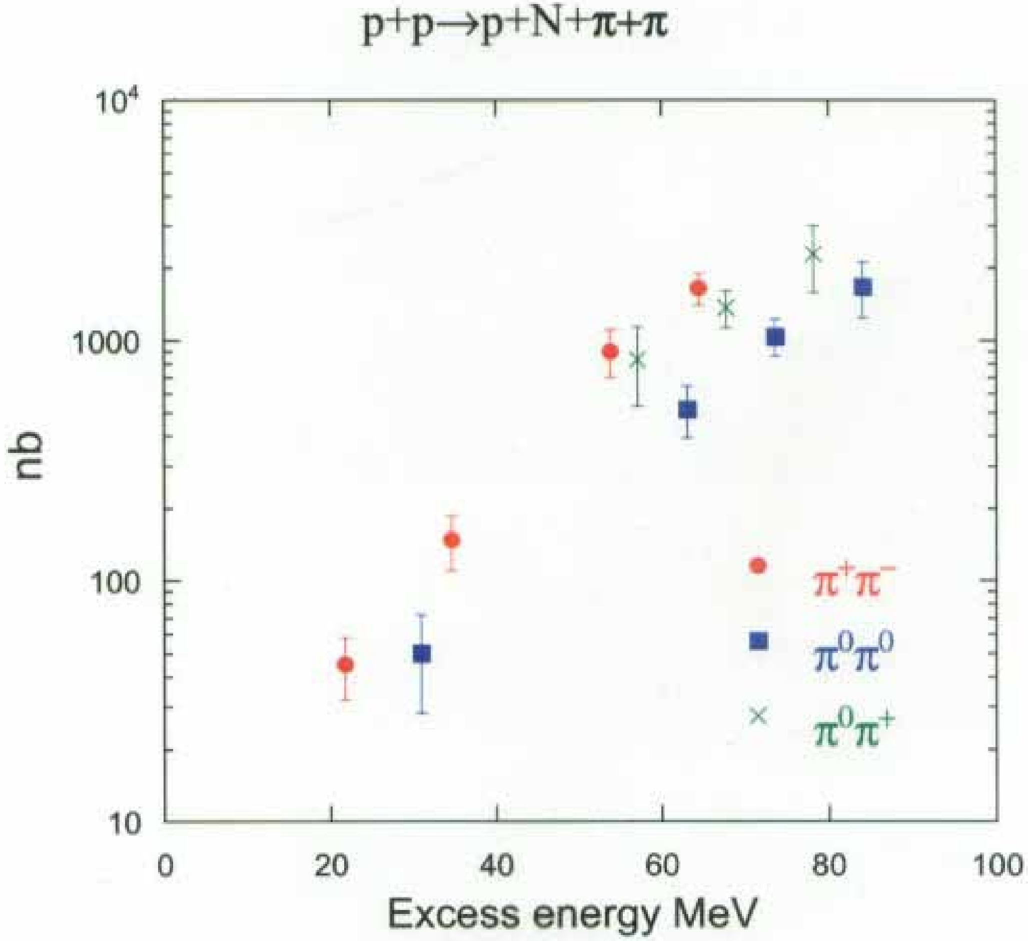


$pp \rightarrow pp\pi^+\pi^-$
10^3
10^2
10
1
10^{-1}
10^{-2}
600
800
1000
1200
1400
σ (μb)
T_p (MeV)
Dakhno et al.
Shimizu et al.
Cverna et al.
Brunt et al.
WASA/PROMICE


$pp \rightarrow pp\pi^0\pi^0$
▲ Shimizu et al.
● WASA/PROMICE
σ (μb)
T_p (MeV)
10^3
10^2
10
1
10^{-1}
10^{-2}
600
800
1000
1200
1400



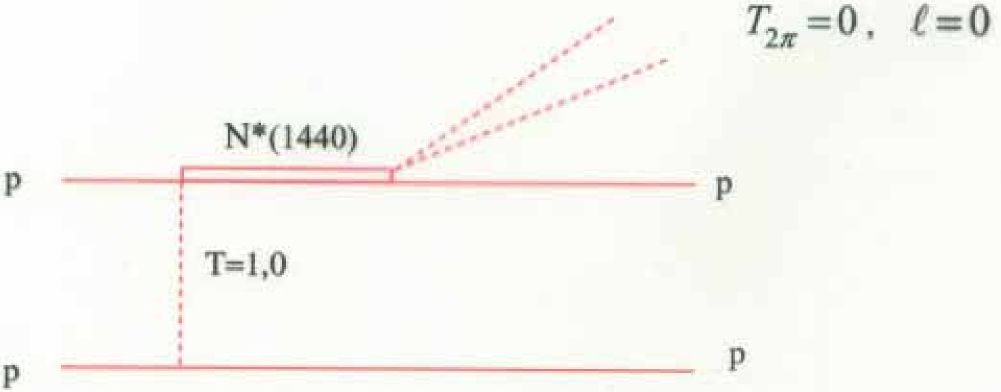
$pp \rightarrow pn\pi^+\pi^0$
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
σ (μb)
600
800
1000
1200
1400
T_p (MeV)
▲ Shimizu et al.
● WASA/PROMICE


p+p→p+N+π+π
10^4
1000
100
10
nb
0
20
40
60
80
100
Excess energy MeV
● π⁺π⁻
■ π⁰π⁰
× π⁰π⁺

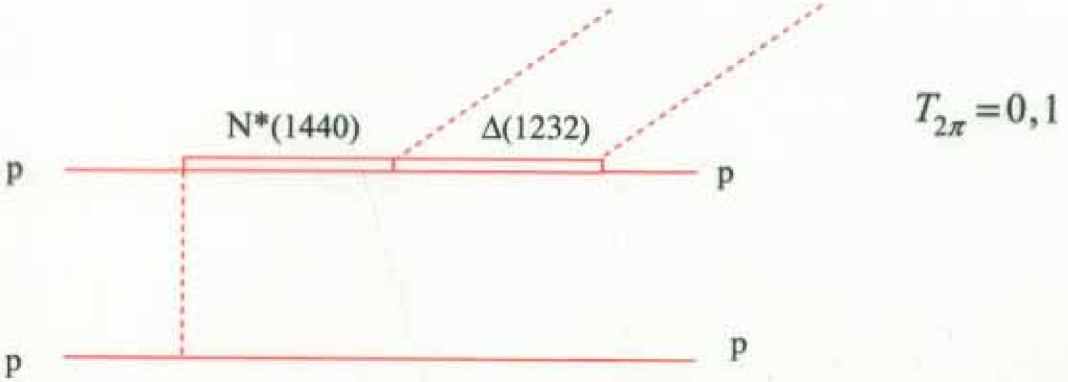
Resonance production

★ Production via N*(1440)P_{11}, $J^P = \frac{1}{2}^+$, $T = \frac{1}{2}$ Decays with 30-50 % to 2π
Threshold ≈ 1140 MeV pp collisions

The N*(1440) has a 5-10% probability to decay directly into 2π.

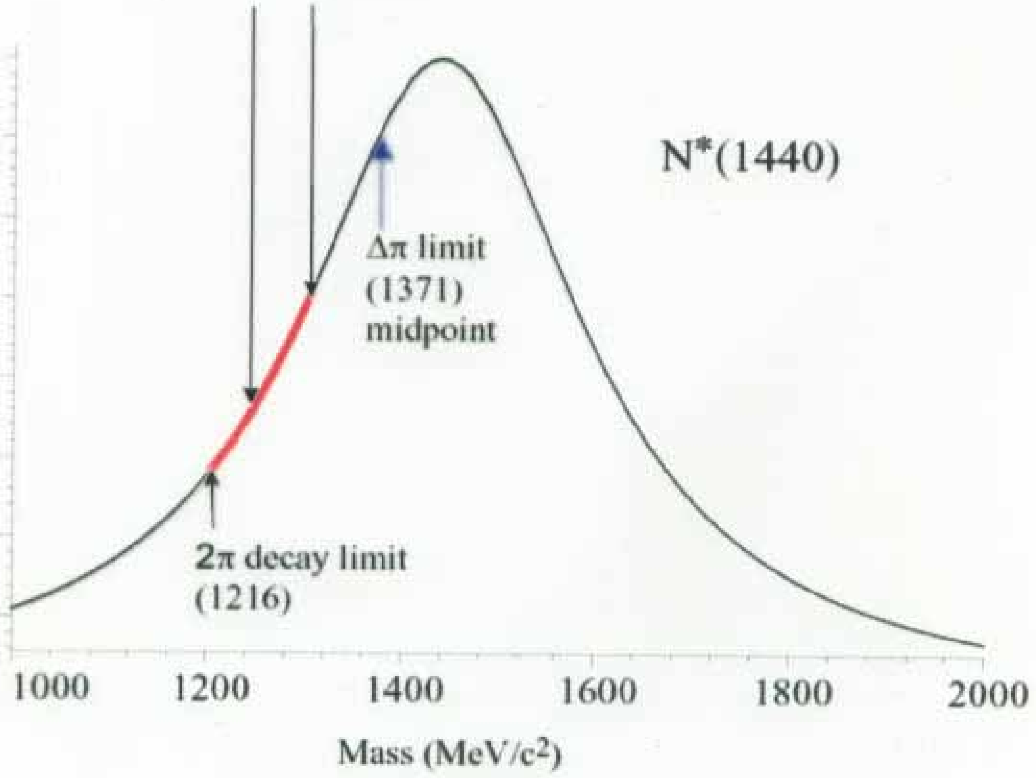


The N*(1440) has a 20-30% probability to decay into a Δ and a π. This gives the alternative decay route to get 2π in the final state.



Kinematical mass limits for $pp \rightarrow pN^* \rightarrow pp\pi\pi$ at

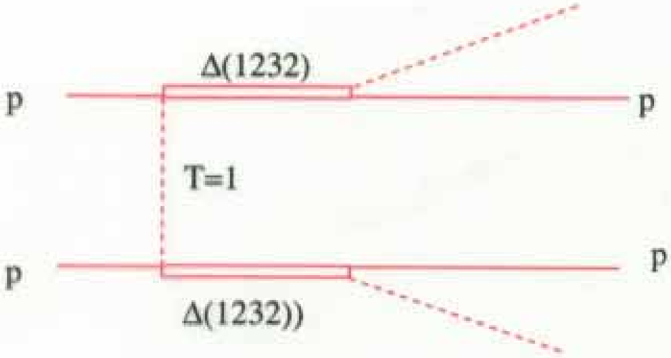
T_p= 650, 775 MeV



The ratio of the decay channels $\frac{N^* \rightarrow \Delta\pi}{N^* \rightarrow N(2\pi)_{\ell=0}} = \frac{20-30\%}{5-10\%}$ given by the PDG is ≈ 3

This ratio will be much smaller at energies corresponding to the red section.

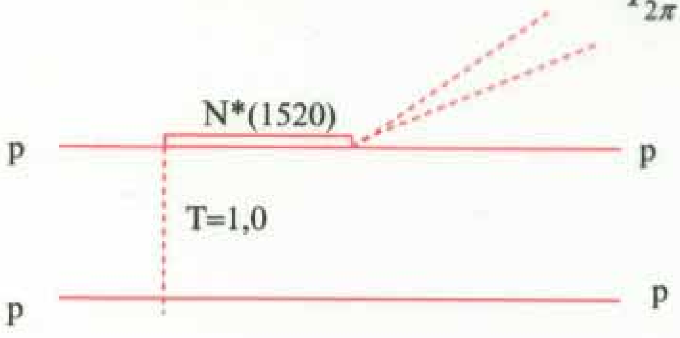
★ Production via double Δ.   Threshold ≈ 1360 MeV in pp collisions.



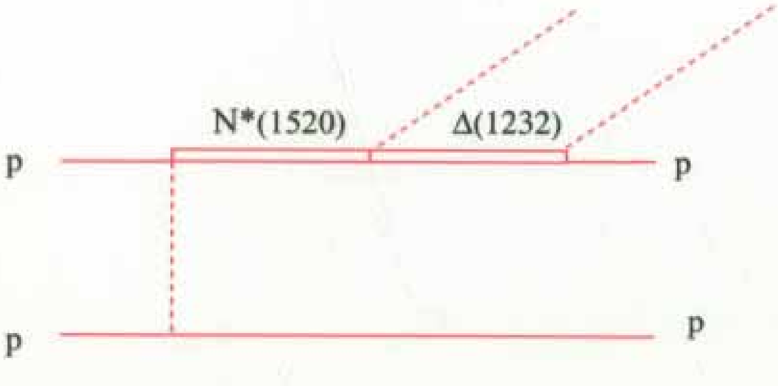
$T_{2\pi} = 0, 1, 2$

★ Production via N(1520)D_{13} $J^P = \frac{3}{2}^+$, $T = \frac{1}{2}$ Decays with 40-50% to 2π.
Threshold ≈ 1344 MeV in pp collisions.

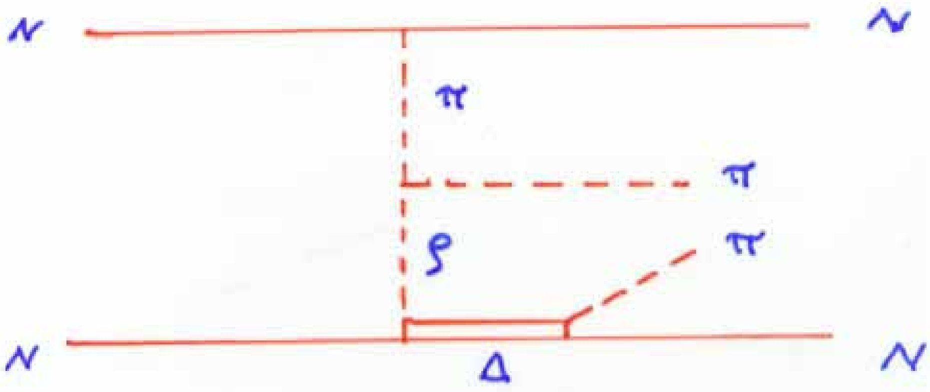
$T_{2\pi} = 0$, $\ell = 0$



< 8%



15-25%

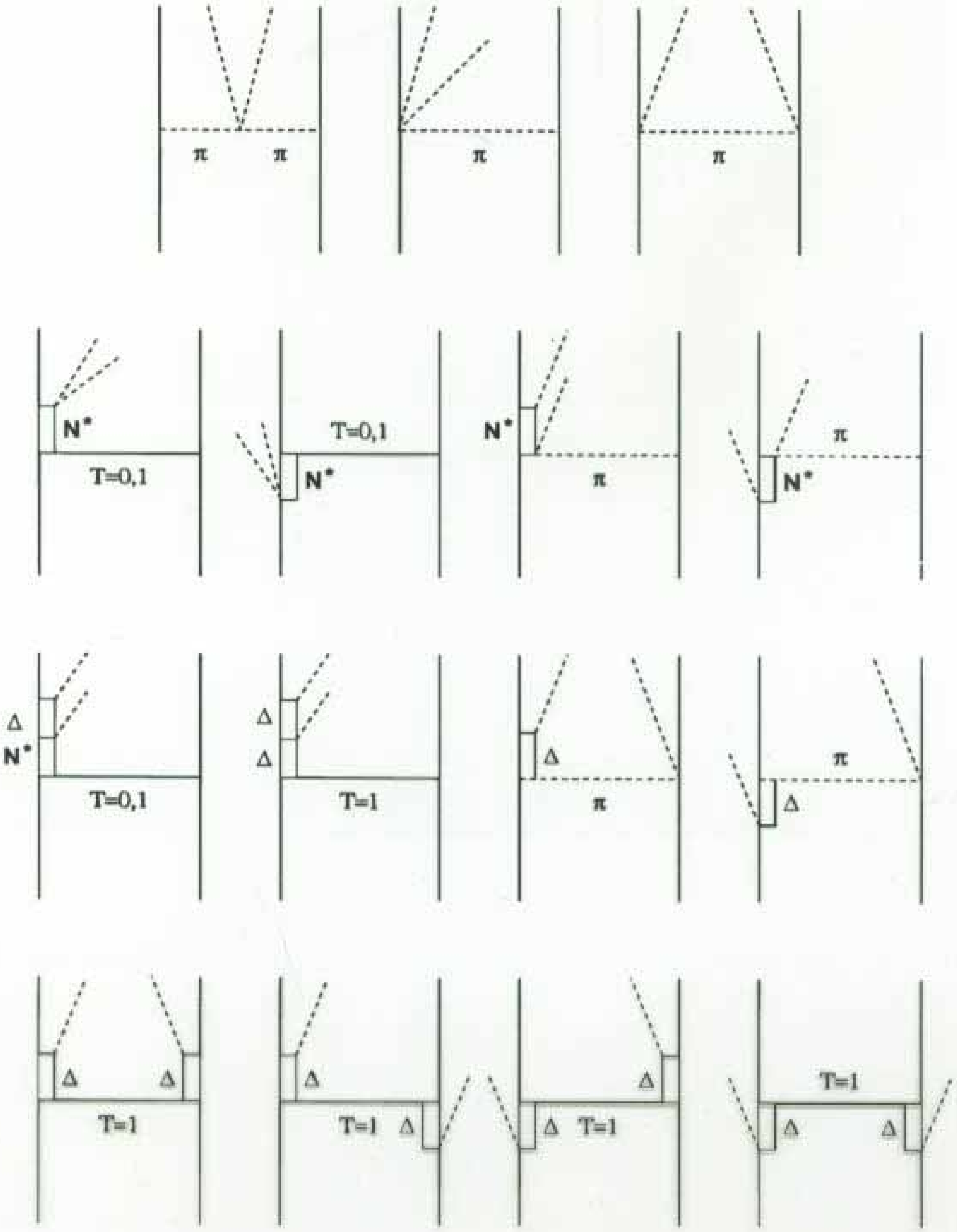


$\pi^- p \to n \pi^0 \pi^0$ dominated by $\underline{\pi^- p \to \pi \Delta}$

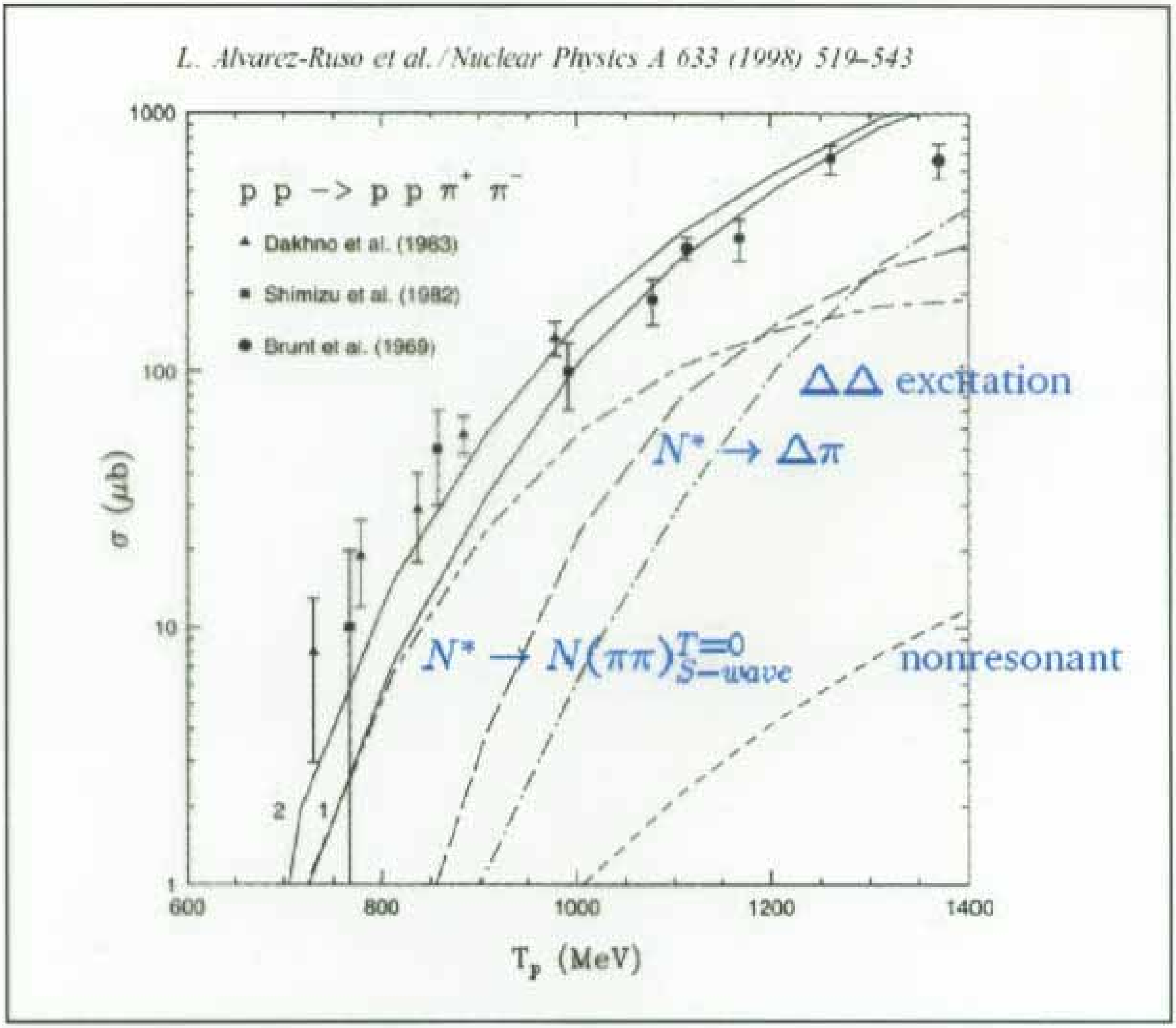
No Roper excitation !?

Set of Feynman diagrams for $NN \to NN\pi\pi$

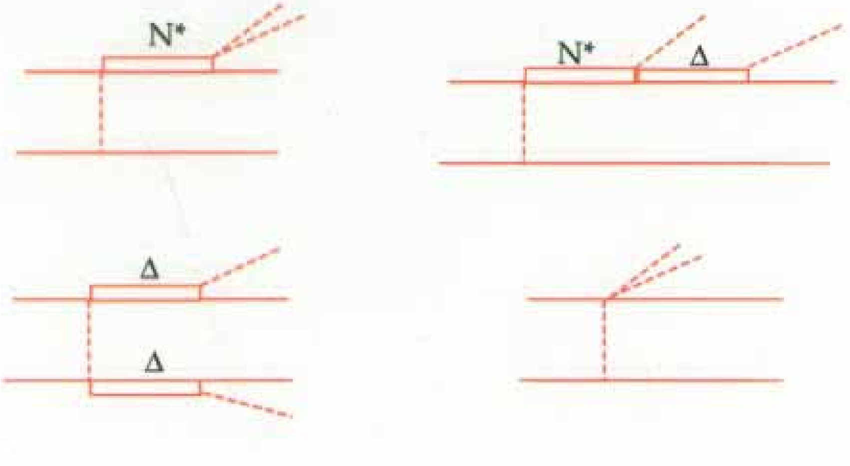
L. Alvarez-Ruso, E. Oset, E. Hernández, Nucl.Phys. A 633 (1998) 519



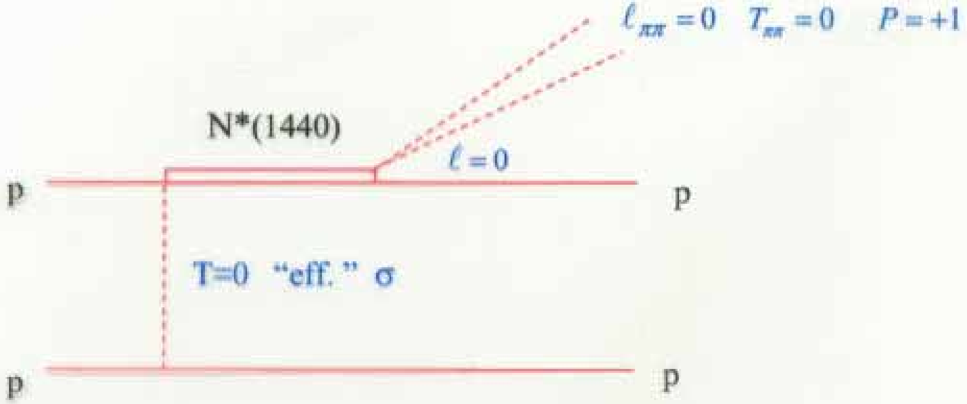
Predictions by L. Alvares-Ruso, thesis 1999.



L. Alvarez-Ruso et al. / Nuclear Physics A 633 (1998) 519–543



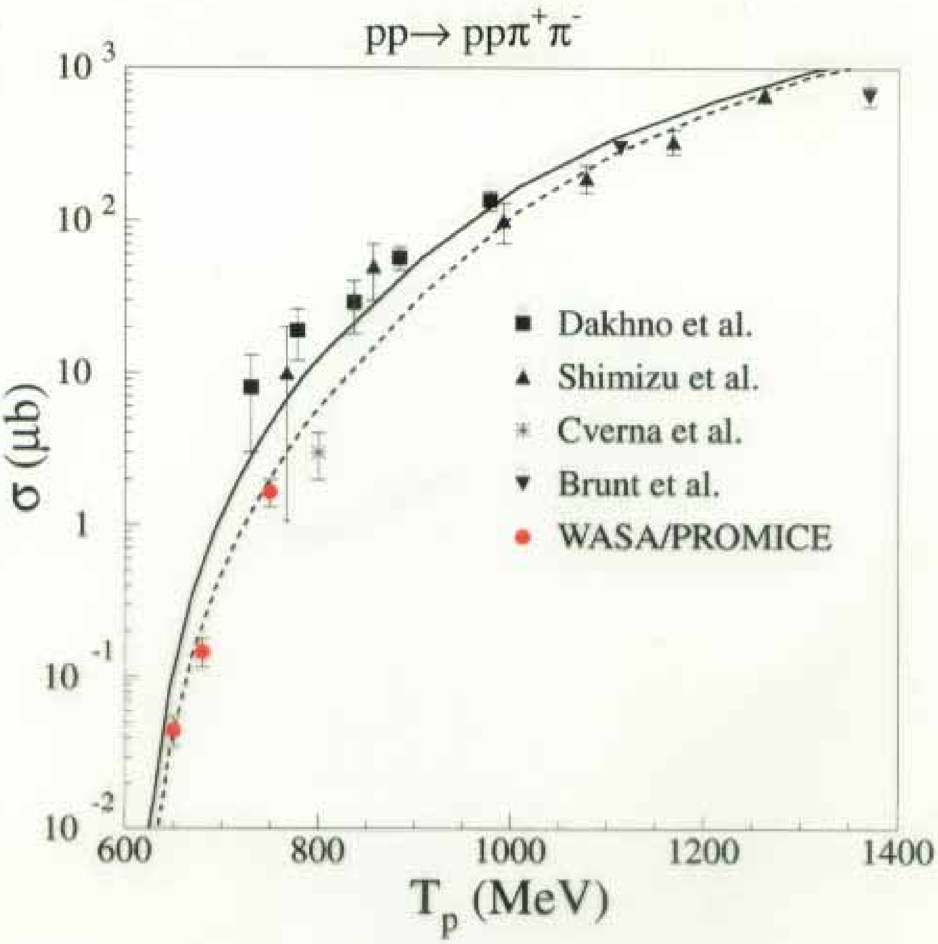
Dominating amplitude close to threshold for the reactions $pp \to pp\pi^+\pi^-$ and $pp \to pp\pi^0\pi^0$ according to Alvarez-Ruso

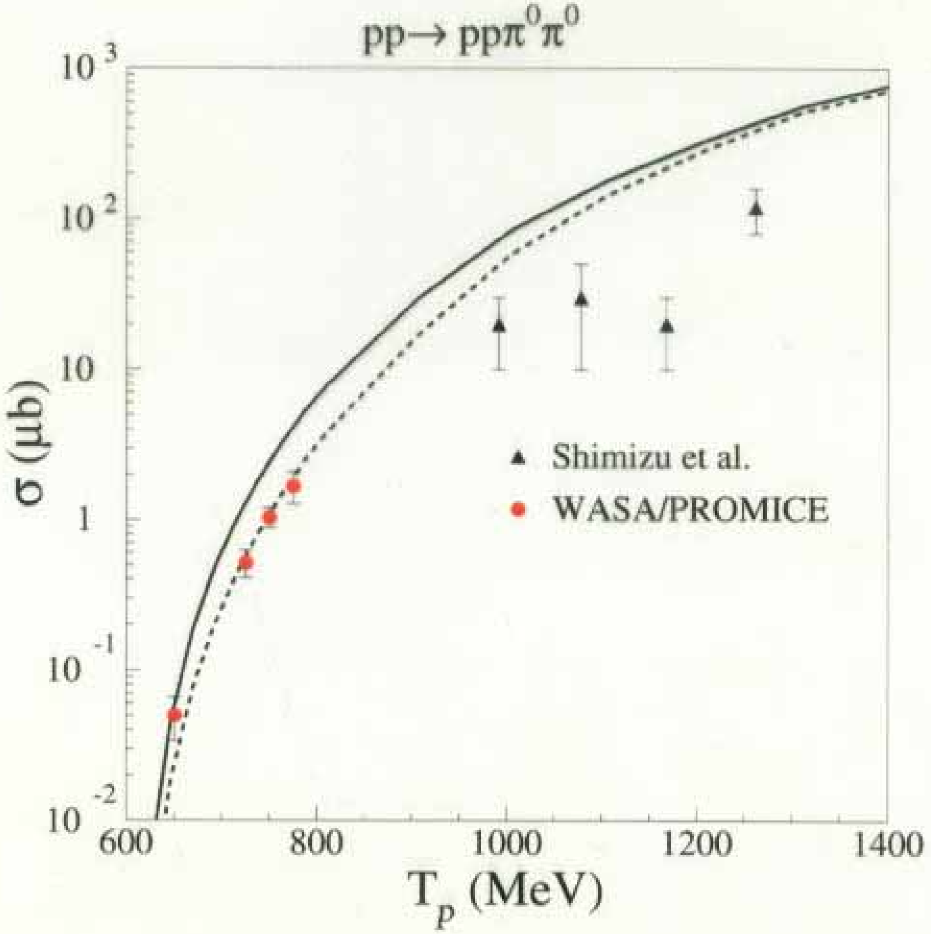


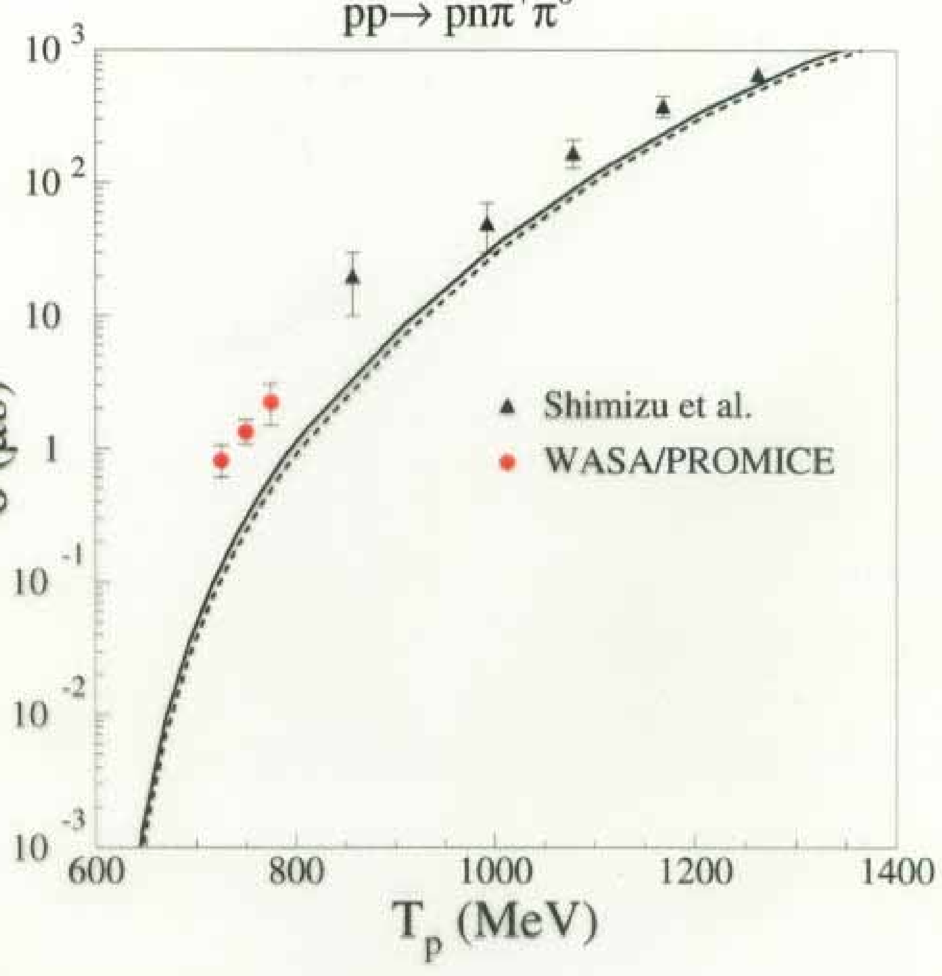
T=0 dominance is indicated from $\alpha p \to \alpha' p$ scattering. Effective σ exchange. The derived $NN^*\sigma$ coupling strength is 1.33! This is large compared to the value ≈ 0.5 derived (model dependent) from the partial decay width of the $N^*(1440) \to N + (2\pi)^{T=0}_{S-wave}$ channel (M. Soyeur)

$N^*(1440) \to N + (2\pi)^{T=0}_{S-wave}$ (5–10%). Preferred transition close to threshold.

Note! The $pp \to pn\pi^+\pi^0$ reaction is not allowed in this process, since $(\pi^+\pi^0)$ has no isospin zero component.


pp→ ppπ+π-
10 3
10 2
10
1
10 -1
10 -2
σ (μb)
600
800
1000
1200
1400
T p (MeV)
Dakhno et al.
Shimizu et al.
Cverna et al.
Brunt et al.
WASA/PROMICE


pp→ ppπ0π0
10 3
10 2
10
1
10 -1
10 -2
σ (μb)
600
800
1000
1200
1400
T p (MeV)
Shimizu et al.
WASA/PROMICE


pp→ pnπ⁺π⁰
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
σ (μb)
600
800
1000
1200
1400
Tp (MeV)
▲ Shimizu et al.
● WASA/PROMICE

Isospin Analysis

The total $NN \to NN\pi\pi$ cross section can be expressed in terms of isospin matrix elements $M_{T_i T_{2\pi} T_f}$, where T_i denotes the initial isospin of the nuclen pair T_f denotes the final isospin of the nucleon pair and $T_{2\pi}$ denotes the isospin of the produced pion pair. A relative phase ϕ appears only between the elements M_{101} and M_{121}, where $T_{\pi\pi} = 0$ and $T_{\pi\pi} = 2$.

$$\sigma(pp \to pp\pi^+\pi^-) = \tfrac{1}{120}|M_{121}|^2 + \tfrac{1}{8}|M_{111}|^2 + \tfrac{1}{6}|M_{101}|^2 + \tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp \to pp\pi^0\pi^0) = \tfrac{1}{60}|M_{121}|^2 + \tfrac{1}{12}|M_{101}|^2 - \tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp \to pn\pi^+\pi^0) = \tfrac{3}{40}|M_{121}|^2 + \tfrac{1}{8}|M_{111}|^2 + \tfrac{1}{4}|M_{110}|^2$$

$$\sigma(pp \to nn\pi^+\pi^+) = \tfrac{3}{20}|M_{121}|^2$$

Note that these cross sections depend very differently on the different amplitudes.

The proton-proton initial state leads to 5 unknowns and 4 isospin independent cross sections. In order to find all amplitudes one has to have data from proton-neutron collisions as well.

Let us write down one of those amplitudes, e.g.

$$\sigma(pn \to pp\pi^-\pi^0) = \sigma(pn \to nn\pi^+\pi^0) = \tfrac{3}{80}|M_{121}|^2 + \tfrac{1}{16}|M_{111}|^2 + \tfrac{1}{24}|M_{011}|^2$$

Note that here we get the additional amplitude M_{011} not occurring for the *pp* collisions. Including all *pn* channels one also get the M_{000} amplitude.

Assumptions about the dynamics of the reaction process restrict the number of matrix elements that can contribute.

Close to threshold one can assume that $\ell_{2\pi}=0$. Since the wave function $\psi(2\pi)$ must be symmetric it follows that $T_{2\pi}=0$ or 2. In the same way if $\ell_{2\pi}=1$ it follows that $T_{2\pi}=1$.

Assuming that the reactions goes via the $N^*(1440)$ where the pion pair has $\ell_{2\pi}=0$ and consequently $T_{2\pi}=0$. That means that only the amplitude M_{101} remains, and one gets

$$\sigma(pp\rightarrow pp\pi^+\pi^-)=\tfrac{1}{6}|M_{101}|^2$$

$$\sigma(pp\rightarrow pp\pi^0\pi^0)=\tfrac{1}{12}|M_{101}|^2$$

$$\sigma(pp\rightarrow pn\pi^+\pi^0)=0$$

Note that $\sigma(pp\rightarrow pp\pi^+\pi^-)=2\sigma(pp\rightarrow pp\pi^0\pi^0)$,
and also that
$\sigma(pn\rightarrow pp\pi^-\pi^0)=\sigma(pn\rightarrow nn\pi^+\pi^0)=\sigma(pp\rightarrow nn\pi^+\pi^+)=0$

Assume that the reaction goes via a double delta $\Delta\Delta$ then for $\ell_{2\pi}=0$ we can have $T_{2\pi}=0$ or 2. That means that the amplitudes M_{101} and M_{121} remain, and one gets

$$\sigma(pp\rightarrow pp\pi^+\pi^-)=\tfrac{1}{120}|M_{121}|^2+\tfrac{1}{6}|M_{101}|^2+\tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp\rightarrow pp\pi^0\pi^0)=\tfrac{1}{60}|M_{121}|^2+\tfrac{1}{12}|M_{101}|^2-\tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp\rightarrow pn\pi^+\pi^0)=\tfrac{3}{40}|M_{121}|^2$$

What can we learn from the present data?

Assume that $\ell_{2\pi}=0$ is the dominant pion configuration.
From the isospin analysis we find that for $\ell_{2\pi}=0$, then $T_{2\pi}=0$ or 2, and the contributing matrix elements becomes

$$\sigma(pp\to pp\pi^{+}\pi^{-})=\tfrac{1}{120}|M_{121}|^{2}+\tfrac{1}{6}|M_{101}|^{2}+\tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp\to pp\pi^{0}\pi^{0})=\tfrac{1}{60}|M_{121}|^{2}+\tfrac{1}{12}|M_{101}|^{2}-\tfrac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi$$

$$\sigma(pp\to pn\pi^{+}\pi^{0})=\tfrac{3}{40}|M_{121}|^{2}$$

From the experimental data we get the approximate result that

$\sigma(pp\to pp\pi^{+}\pi^{-})\approx\sigma+\Delta\sigma$ and $\sigma(pp\to pp\pi^{0}\pi^{0})\approx\sigma-\Delta\sigma$

$\sigma(pp\to pn\pi^{+}\pi^{0})\approx\sigma$ ($\sigma\approx 1.0\ \mu\text{b}$ and $\Delta\sigma\approx 0.45\ \mu\text{b}$ at Q=60 MeV)

This result can be used to determine the matrix elements and one gets from above that

$$\sigma(pp\to pp\pi^{+}\pi^{-})+\sigma(pp\to pp\pi^{0}\pi^{0})=\tfrac{1}{40}|M_{121}|^{2}+\tfrac{1}{4}|M_{101}|^{2}$$

Since $|M_{121}|^{2}=\frac{40}{3}\sigma$ we thus get that $|M_{101}|^{2}=\frac{20}{3}\sigma$

The amplitude $|M_{121}|^{2}$ is thus twice as large as $|M_{101}|^{2}$!

The channel $N^{*}(1440)\to p+(2\pi)^{T=0}_{S-wave}$ (directly or via the $N^{*}\to\Delta\pi$ branch) can only be involved in $|M_{101}|^{2}$, while double $\Delta\Delta$ can be involved in both $|M_{121}|^{2}$ and $|M_{101}|^{2}$.
This indicates that $\Delta\Delta$ is the dominating reaction amplitude at threshold!!

But what about the cross section? The different amplitudes come with drastically different coefficients!

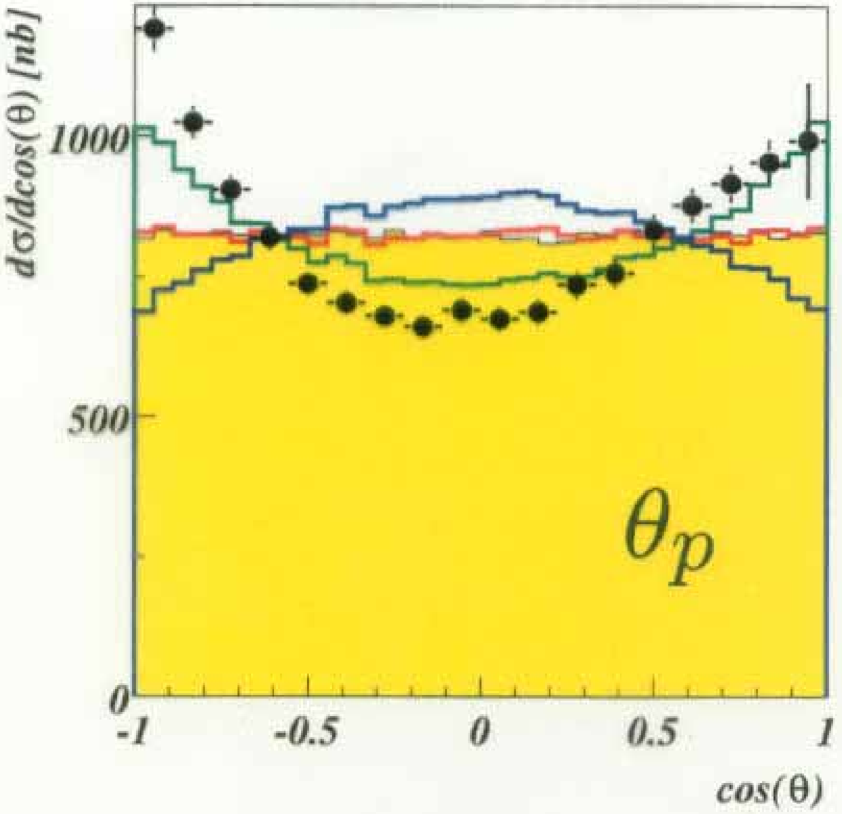
Look at the sum of the reactions to avoid the $\cos\phi$ term

$$\sigma(pp \to pp\pi^+\pi^-)+\sigma(pp \to pp\pi^0\pi^0)=\tfrac{1}{40}\left|M_{121}\right|^2+\tfrac{1}{4}\left|M_{101}\right|^2=\tfrac{1}{3}\sigma+\tfrac{5}{3}\sigma$$

The dominating part to the cross section comes from the $\left|M_{101}\right|^2$ term, which contains the Roper resonance (as well as the double $\Delta\Delta$)

Accordingly, the large $pp \to pn\pi^+\pi^0$ cross section, not allowing Roper excitation, does not contradict a large sensitivity to the Roper resonance in the $(pp \to pp\pi^+\pi^-)$ reaction.

Differential cross section of the $pp \to pp\pi^+\pi^-$ reaction at 750 MeV



Black points represent the data.

Close to threshold and for *s-wave* pion production, the shape of the proton angular distribution depends only on the type of meson being exchanged.

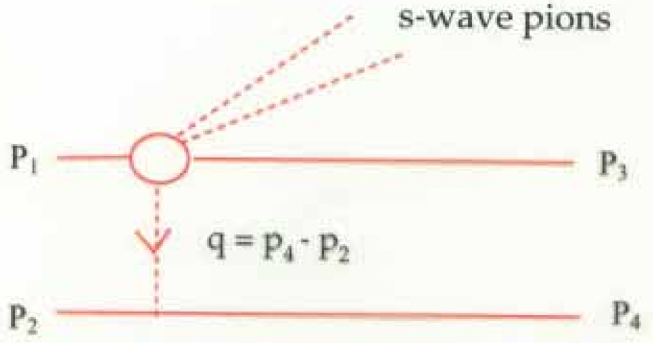
$$A_\sigma \sim (\bar{\psi}_4 \psi_2) \frac{1}{q^2 - m_\sigma^2} (\bar{\psi}_3 \psi_1)$$

Sigma exchange

$$A_\pi \sim (\bar{\psi}_4 \gamma_5 \psi_2) \frac{1}{q^2 - m_\pi^2} (\bar{\psi}_3 \gamma_5 \psi_1)$$

Pion exchange

Assuming a reaction process close to threshold



An approximate expression for the cross section variation can be derived as

$$\sigma(\theta_p) \sim 1 - a \cdot \cos^2(\theta_p)$$

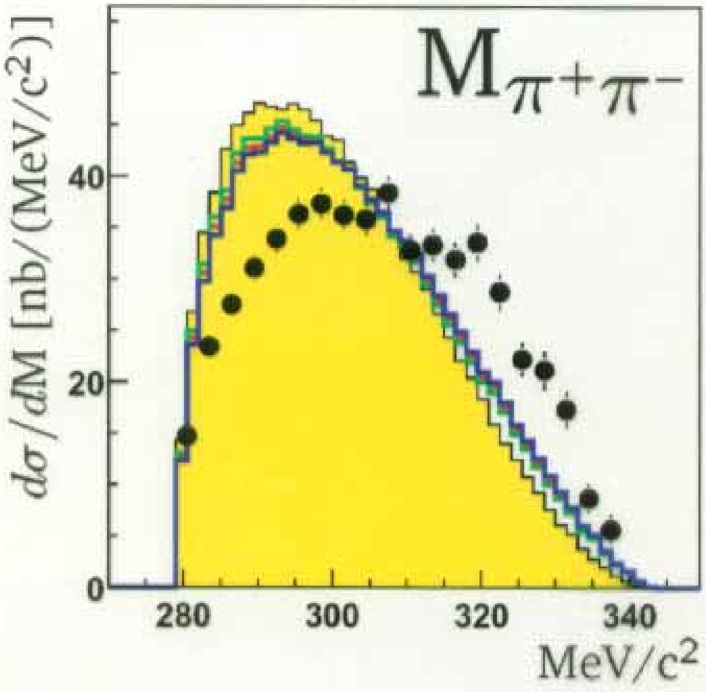
The constant a depends on the mass and the momentum of the exchanged particle

$a > 0$ for σ and ρ exchange

$a < 0$ for π exchange or

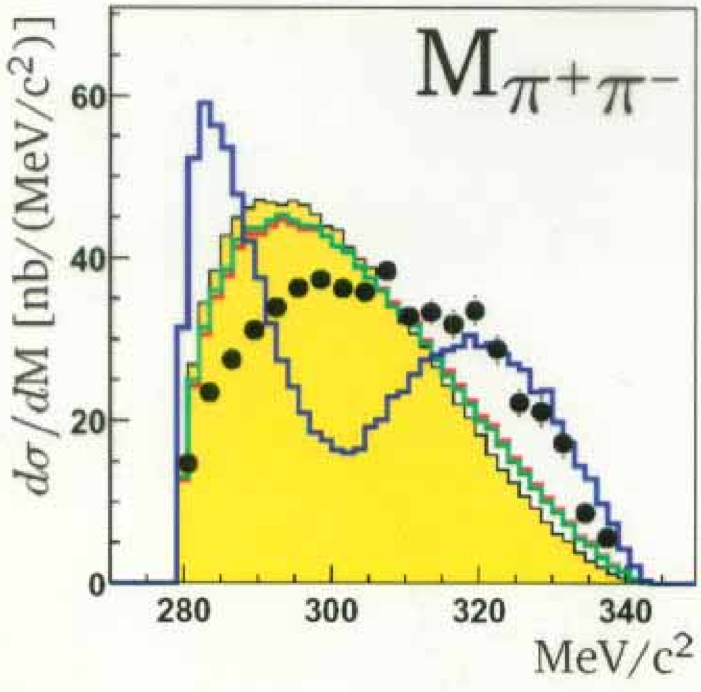
The experimental shape of $\sigma(\theta_p)$ suggests σ or ρ exchange !

Invariant mass distribution of the two pions in the $pp \rightarrow pp\pi^+\pi^-$ reaction at 750 MeV



$N^*(1440) \rightarrow N(\pi\pi)^{T=0}_{S-wave}$

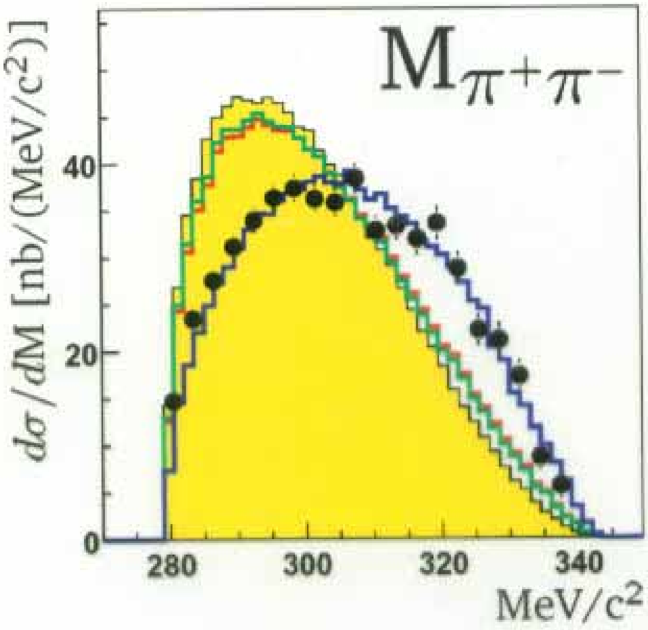
No pion momentum dependence



$N^*(1440) \rightarrow \Delta\pi$

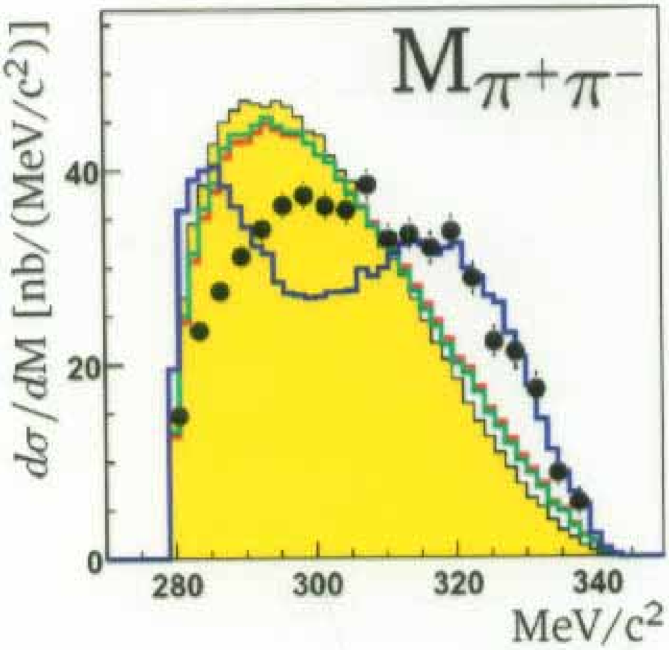
Pion momentum dependence

$2\bar{k}_1 \cdot \bar{k}_2 + i\bar{\sigma} \cdot (\bar{k}_1 \times \bar{k}_2)$



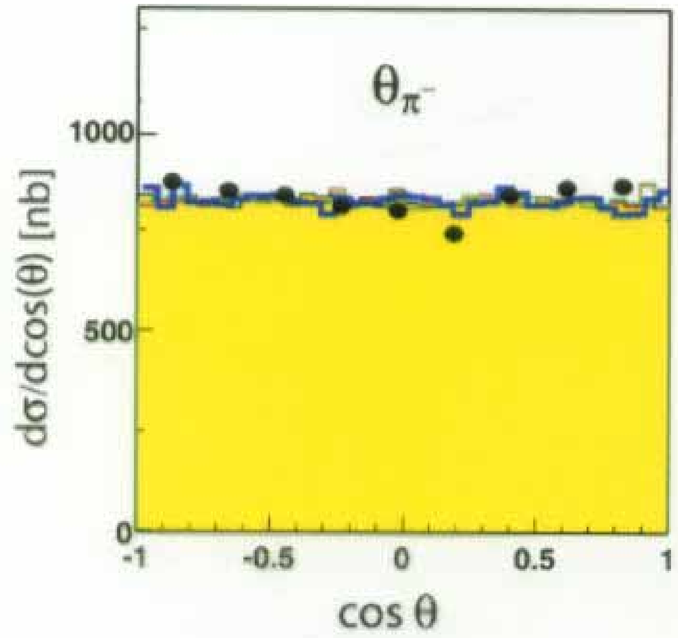
$$N^*(1440) \rightarrow \begin{cases} N(\pi\pi)_{s-wave} \\ \Delta\pi \quad (20\%) \end{cases}$$

in the amplitude

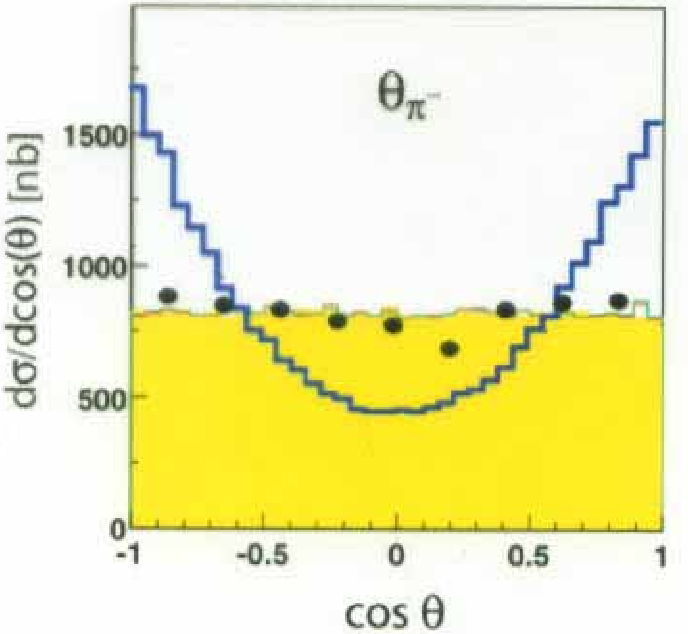


$pp \rightarrow \Delta\Delta$

Cross section distribution from $pp \to pp\pi^-\pi^+$ at 750 MeV, versus the pion angle, in the overall CM system



$$N^*(1440) \to \begin{cases} N(\pi\pi)_{S-wave} \\ \Delta\pi \;\; (20\%) \end{cases}$$



$pp \to \Delta\Delta$

$\sigma(\theta_{\pi^-}) \sim 1+3\cos^2(\theta_{\pi^-})$

A fit to data at 750 and 775 MeV using the amplitude

$A \sim 1 + c\bar{k}_1 \cdot \bar{k}_2 (3D_{\Delta^{++}} + D_{\Delta^0})$ for the decay into the N2π and $\Delta\pi$ branches, gives a value for the constant c. The D:s are the Δ propagators.

The ratio of the $\Delta\pi$ and N2π branches can then be calculated and at masses where the measurements are done, and one gets

R(1264)= 0.04 and R(1272) = 0.06

Using the same expression to calculate the ratio at the resonance pole gives

R(1440) = 3.9 which compares favorable with the PDG value, 3-4.

Summary and final remarks for the $pp \rightarrow pN\,2\pi$ reaction

- Data from the $pp \rightarrow pp\pi^+\pi^-$ reaction on total cross section, invariant mass distributions as well as angular distributions seem to support a reaction process dominated by Roper excitation. This reaction channel is thus a potential probe to study the Roper resonance. Excitation modes, decay modes, coupling constant, width.

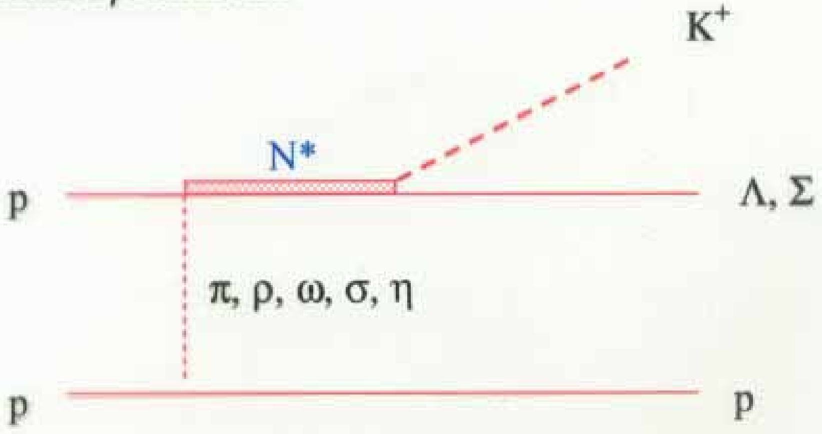
- However, the large cross section on the $pp \rightarrow pn\pi^+\pi^0$ reaction channel implies that other amplitudes must be large. Double delta? These other amplitudes are unfavored in the $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pp\pi^0\pi^0$ reaction channels due to isospin statistics.

- Theoretically, the full picture of the $pp \rightarrow NN\pi\pi$ reaction needs to be understood in better detail. The cross sections for reaction channels where Roper excitation is forbidden are presently underestimated. The $g^2_{N^*N\sigma}$ coupling constant! Uncertainties in the Lagrangians!

- Experimentally, more data are needed, in particular for the reaction channel $pp \rightarrow nn\pi^+\pi^+$ which contains only the T=2 isospin amplitude
  $\sigma(pp \rightarrow nn\pi^+\pi^+) = \frac{3}{20}\left|M_{121}\right|^2$.
  Strong efforts should be put on obtaining angular distributions.

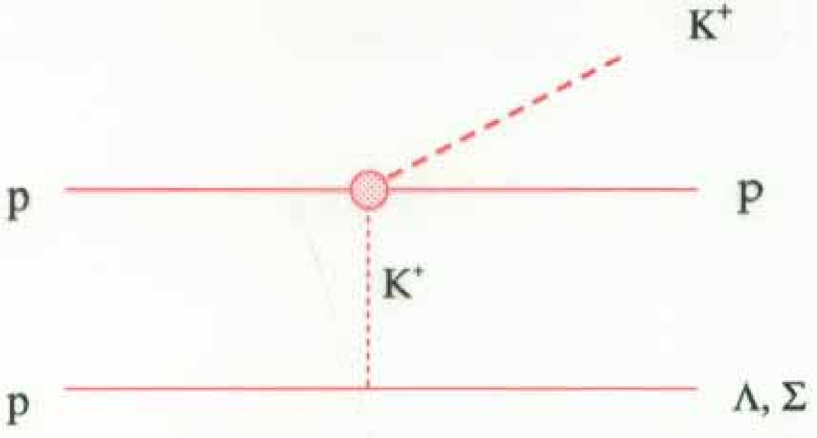
The $pp \to pK^+\Lambda$ and $pp \to pK^+\Sigma$ reactions

Resonant production



Possible resonance are: $N^* = N(1650)S_{11}, N(1710)P_{11}, N(1720)P_{13}$

Non resonant production



$$\frac{g^2_{\Lambda N K}}{g^2_{\Sigma N K}} = 27 \text{ in } SU(6)$$

COSY-11 Collaboration

September 2002

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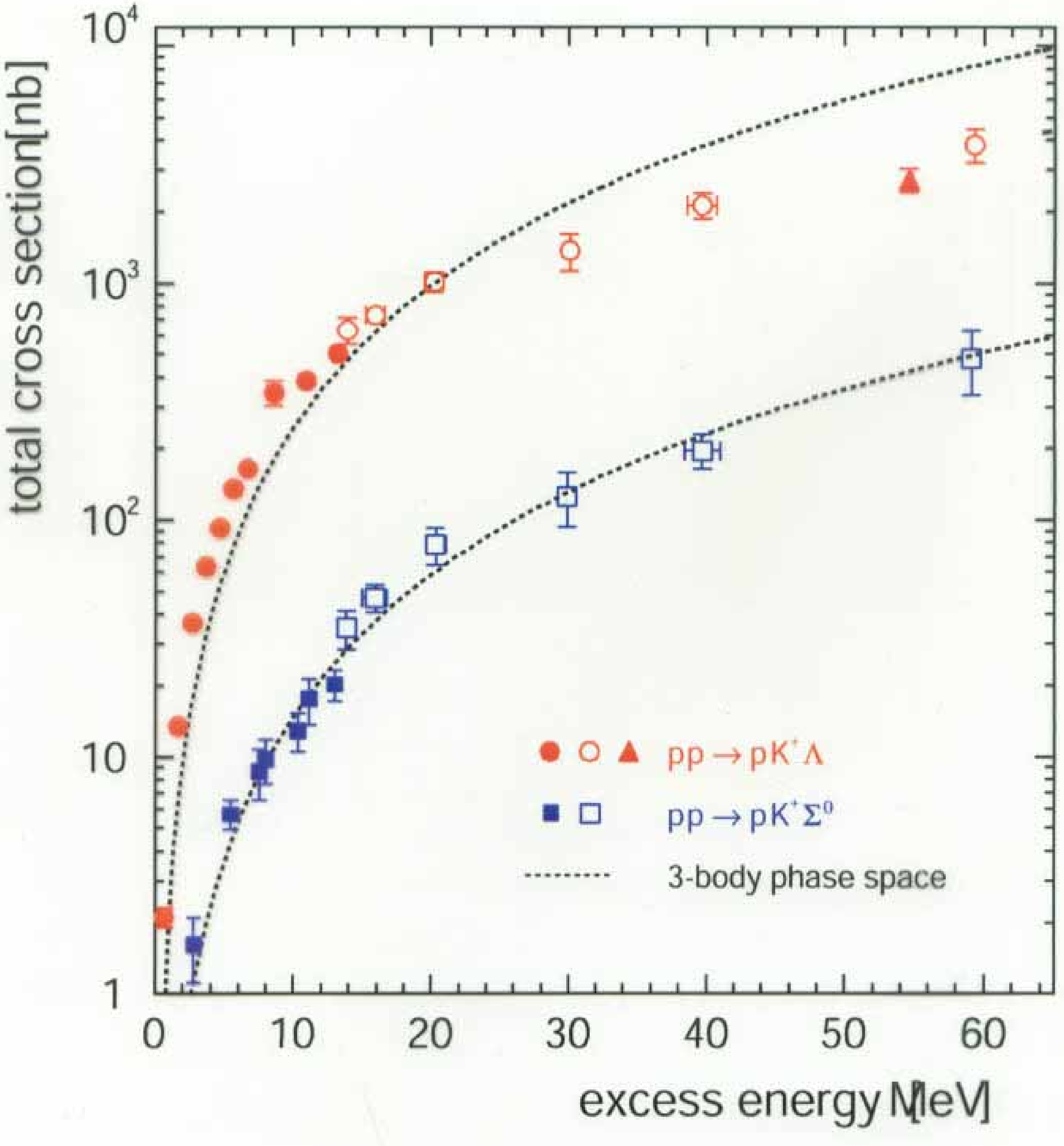
Hyperon Production at COSY-11

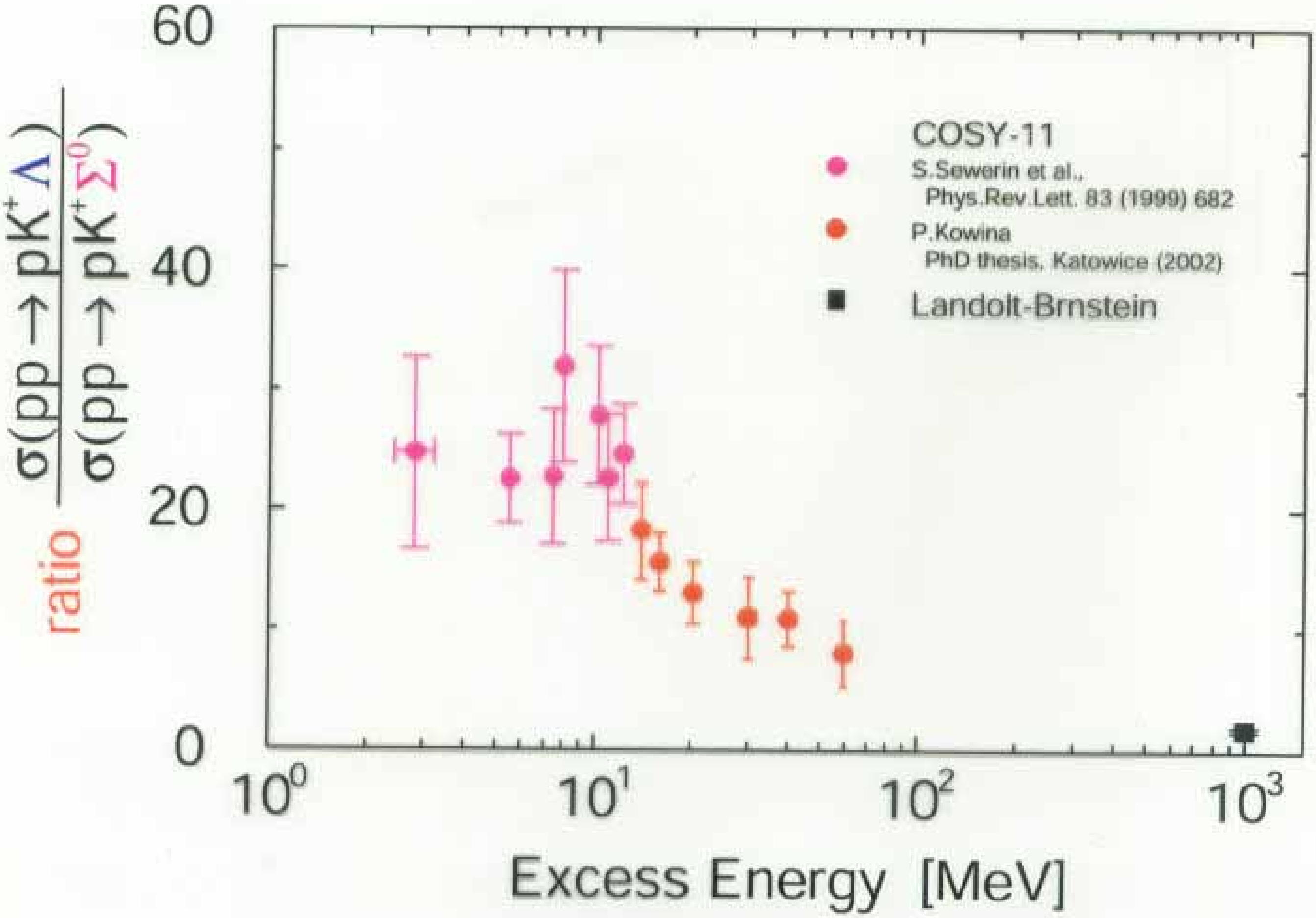


□ ○ P.Kowina (COSY-11), Ph.D. thesis, Katowice (2002)

■ ● S.Sewerin et al. (COSY-11), Phys. Rev. Lett. 83 (1999) 682

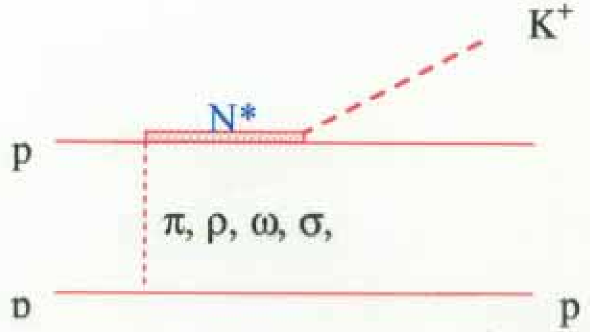
▲ R.Bilger et al. (COSY-TOF), Phys. Lett. B 420 (1998) 217

Energy dependence in the Λ/Σ^0 ratio from the $pp \rightarrow pK^+\Lambda$ and $pp \rightarrow pK^+\Sigma^0$ reactions

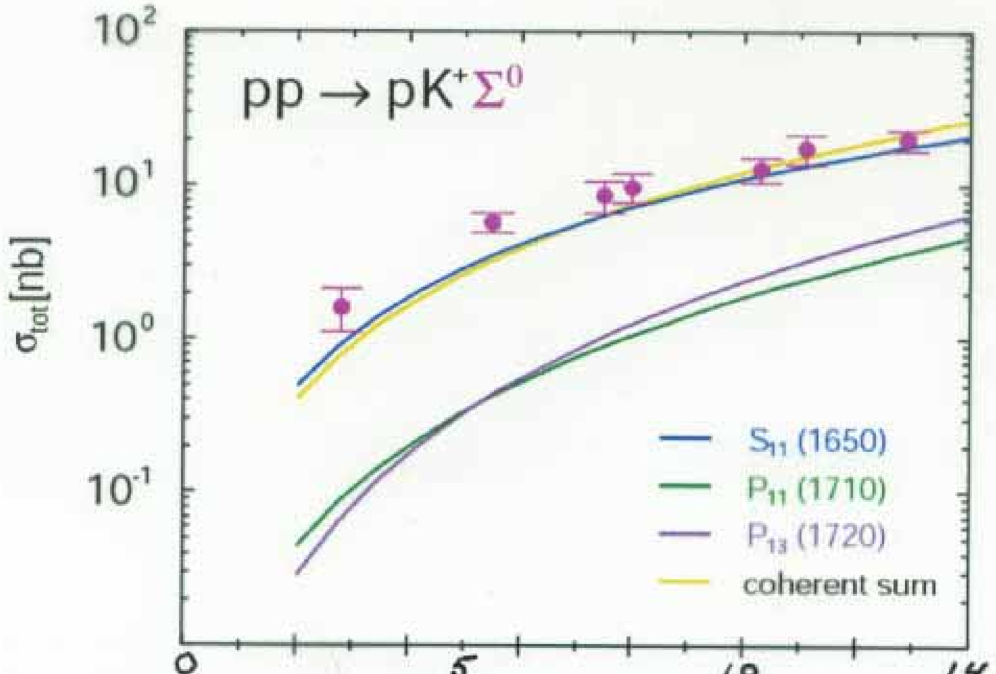


Resonance production in an effective Lagrangian approach

R.Shyam, G.Penner, U.Mosel Phys.Rev. C 63 (2001) 022202

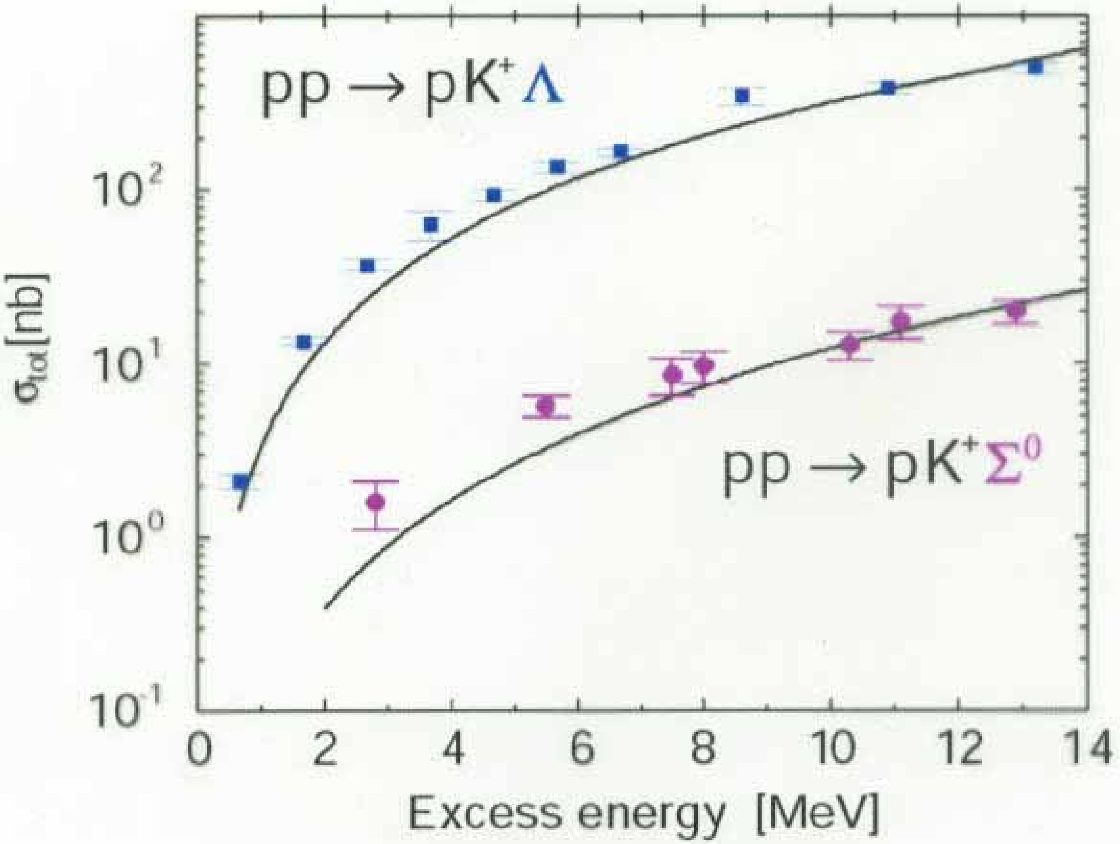


Contributions from different resonances.

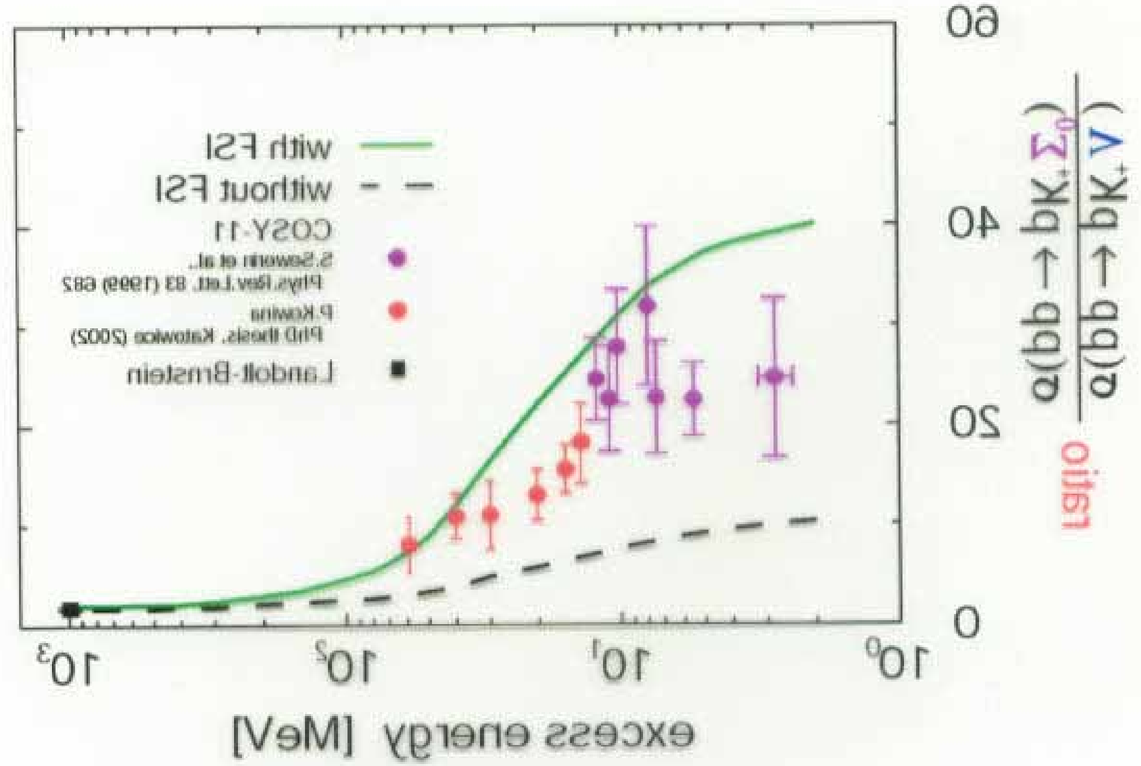


Note the dominant contribution from the $N^*(1650)S_{11}$ resonance.
The same feature is prevalent for the $pp \rightarrow pK^+\Lambda$ reaction.

Prediction of cross sections, *R.Shyam et al.*



The dominant contribution to the resonance excitations comes from one pion exchange



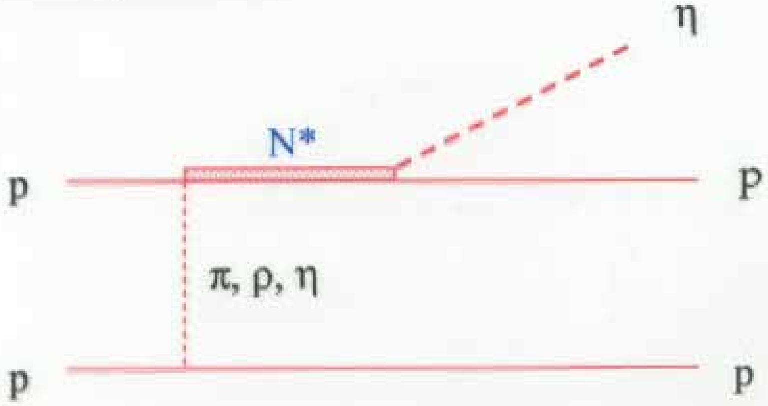
The final state interaction gives the largest effect on the ΛK/ΣK ratio at low energies (provided that it is correctly described by Watson-Migdal theory).

A small energy variation in the ratio comes from the relative importance of the N*(1650) and N*(1710) at different energies.

At large energies the ratio is given by the ratio of the partial decay modes of N*(1710) to ΛK and ΣK (≈ 2.5).

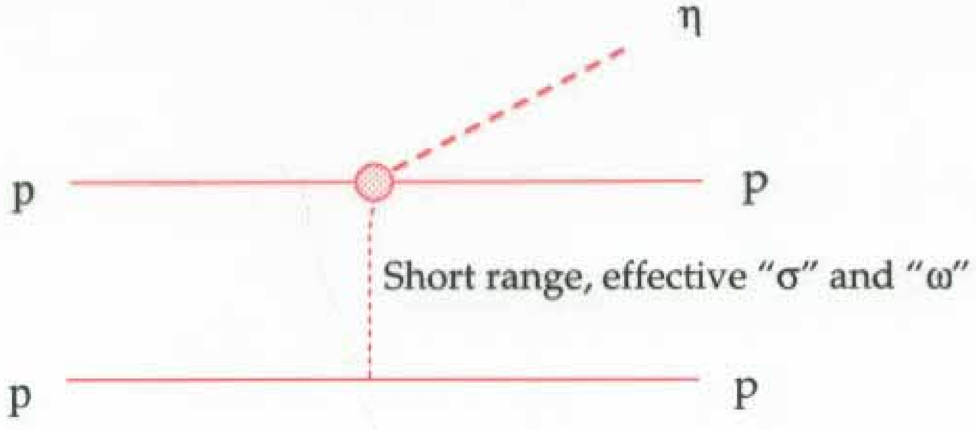
The $pp \to pp\eta$ reaction at threshold energies

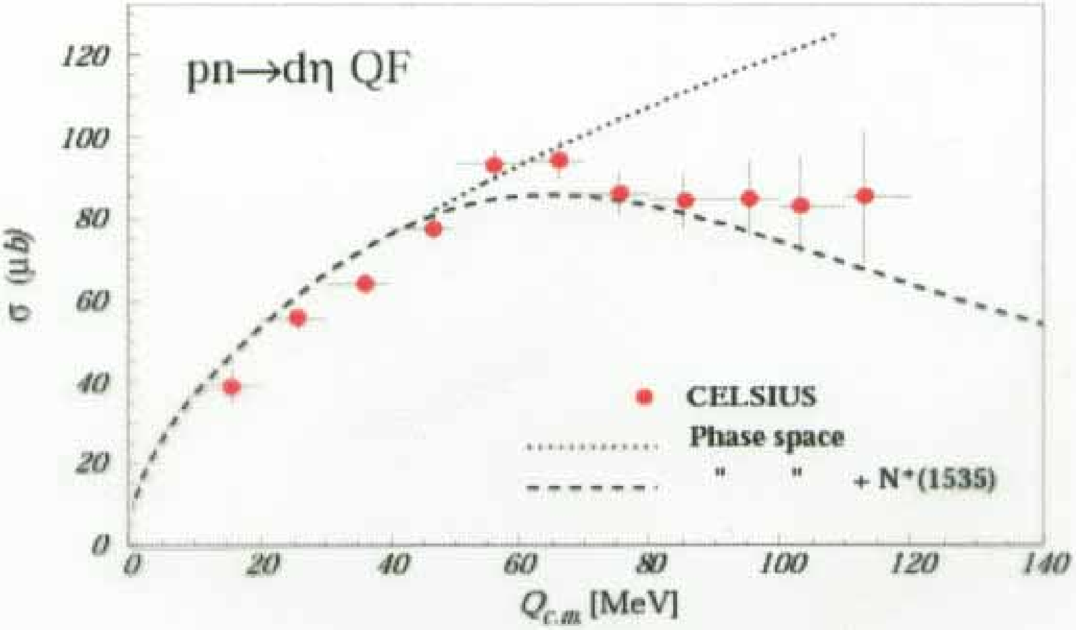
Resonant production



Possible resonance is $N^* = N^*(1535)S_{11}$, which decays to Nη with 30-55% and to Nπ with 35-55%.

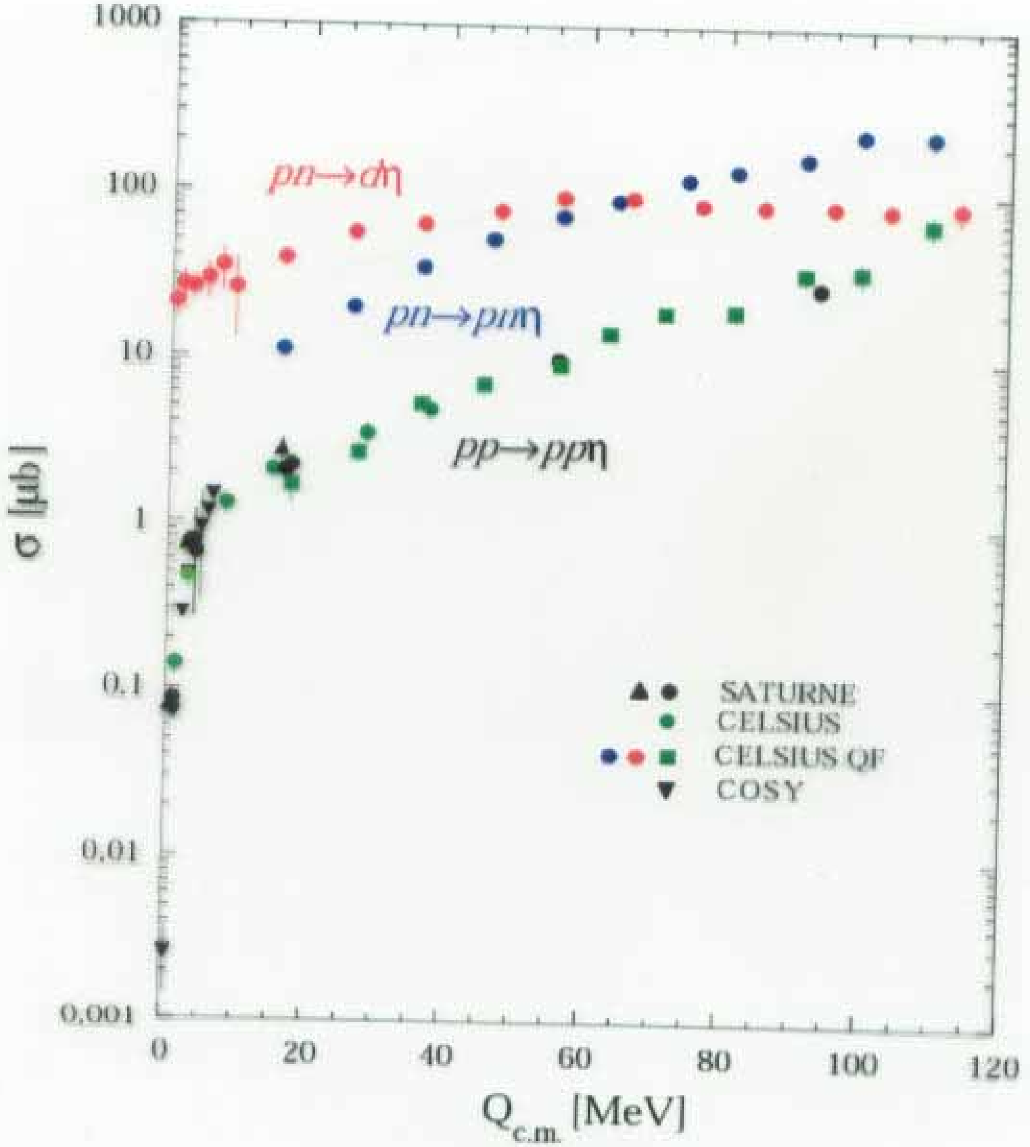
Non resonant production





H. Calen *et al.*, PRL 79(97)2462

A Breit-Wigner describing the N*(1535) combined with the two particle phase space, arbitrarily normalized to data.



Nota that the cross section ratio pn→pnη/ pp→ppη is around 6

Concluding remarks

Meson production in pN-collisions near the energy threshold seems to involve selective resonance production

$\pi^+\pi^-$ or $\pi^0\pi^0 \Rightarrow P_{11}(1440)$

$K^+\Lambda,\ K^+\Sigma^0 \Rightarrow S_{11}(1650)$

$\eta \Rightarrow S_{11}(1535)$

To extract information on excitation and decay modes, coupling constants, from these resonances, realistic model calculations are needed. In particular the influence from FSI must be mastered.