Striking structures in $pp \to (pp)_{S-\mathrm{wave}}\pi^0$

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- Peak structures in $pp \to (pp)_{S-\mathrm{wave}\pi^0}$

- Charge dependence in $NN \to d\pi$? (with H. Machner)

$NN \to (NN)_{S-\mathrm{wave}}\pi$

$pp \to (pp)_{S-\mathrm{wave}}\pi^0$ has presented some surprises:

- Close to threshold cross section unexpectedly high (H.O. Meyer et al., NPA 539, 633).
- Was not explained by $\Delta(1232)$ (Niskanen PLB 289, 227).
- **Still much suppressed as compared with** $pp \to (pp)_{\mathrm{triplet}}\pi^+$.
- For final $^1S_0\, l_\pi$ only "tensor coupled" initial states $^3P_0$, $^3P_2$, $^3F_2, \ldots$ (and l_π even) possible $\Rightarrow$ some mechanisms suppressed
- New mechanisms suggested (T.S.H. Lee and D.-O. Riska, PRL 70,2237 and E. Hernandez and E. Oset, PLB 350, 158).

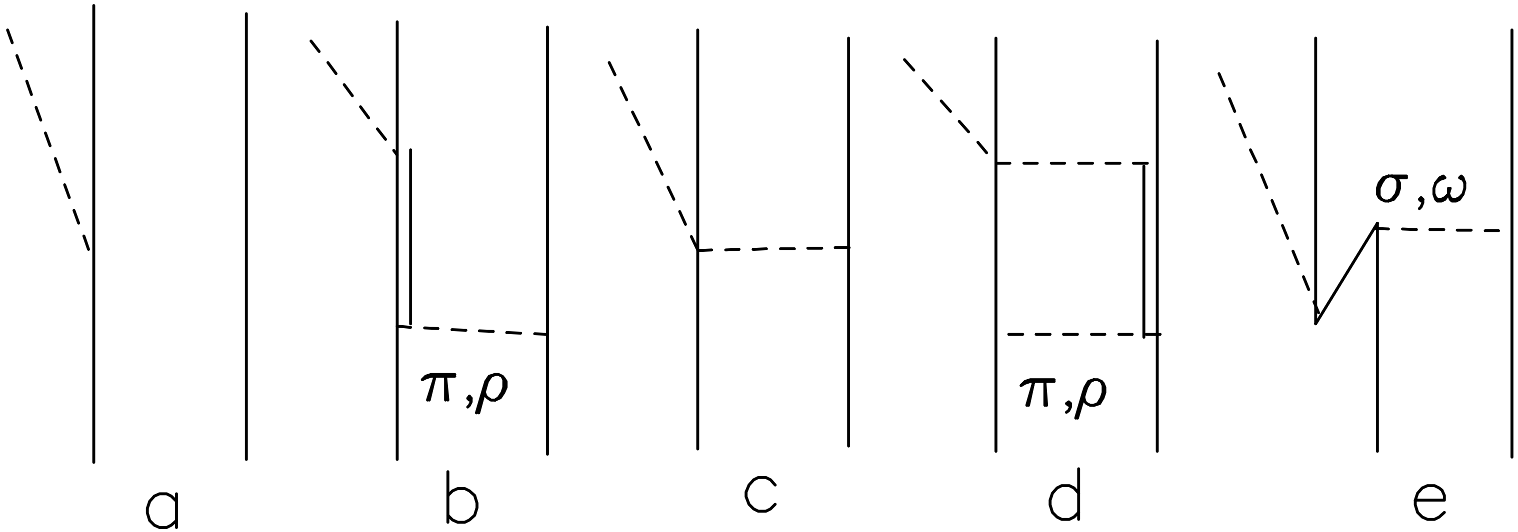
More recently even above threshold constraint of final state nucleons to relative S wave possible (with low-energy cut for nucleons):

R. Bilger et al., NPA 693, 633 threshold to 400 MeV, Celsius

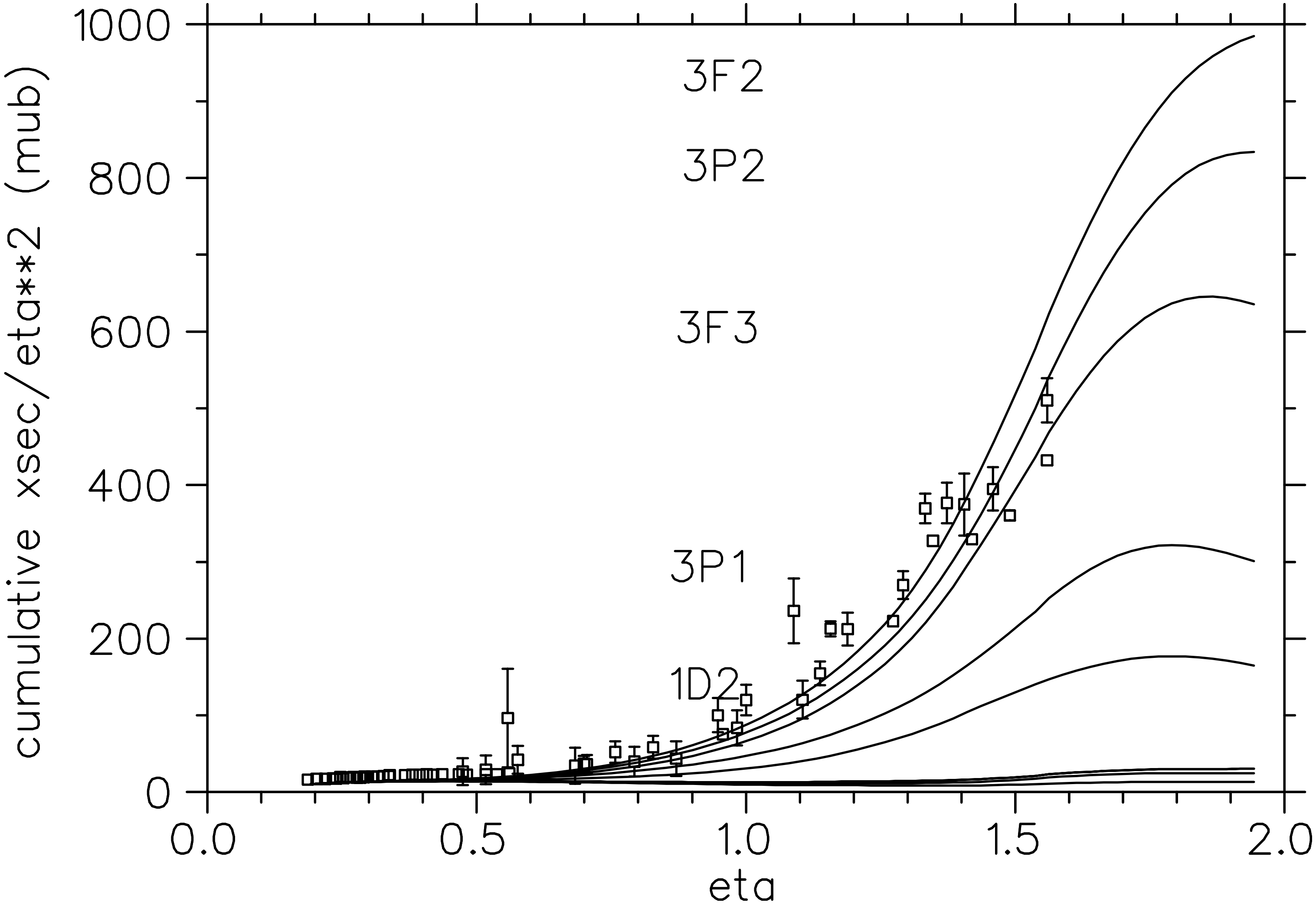
S. Dymov et al., PLB 635, 270 at 800 MeV, COSY

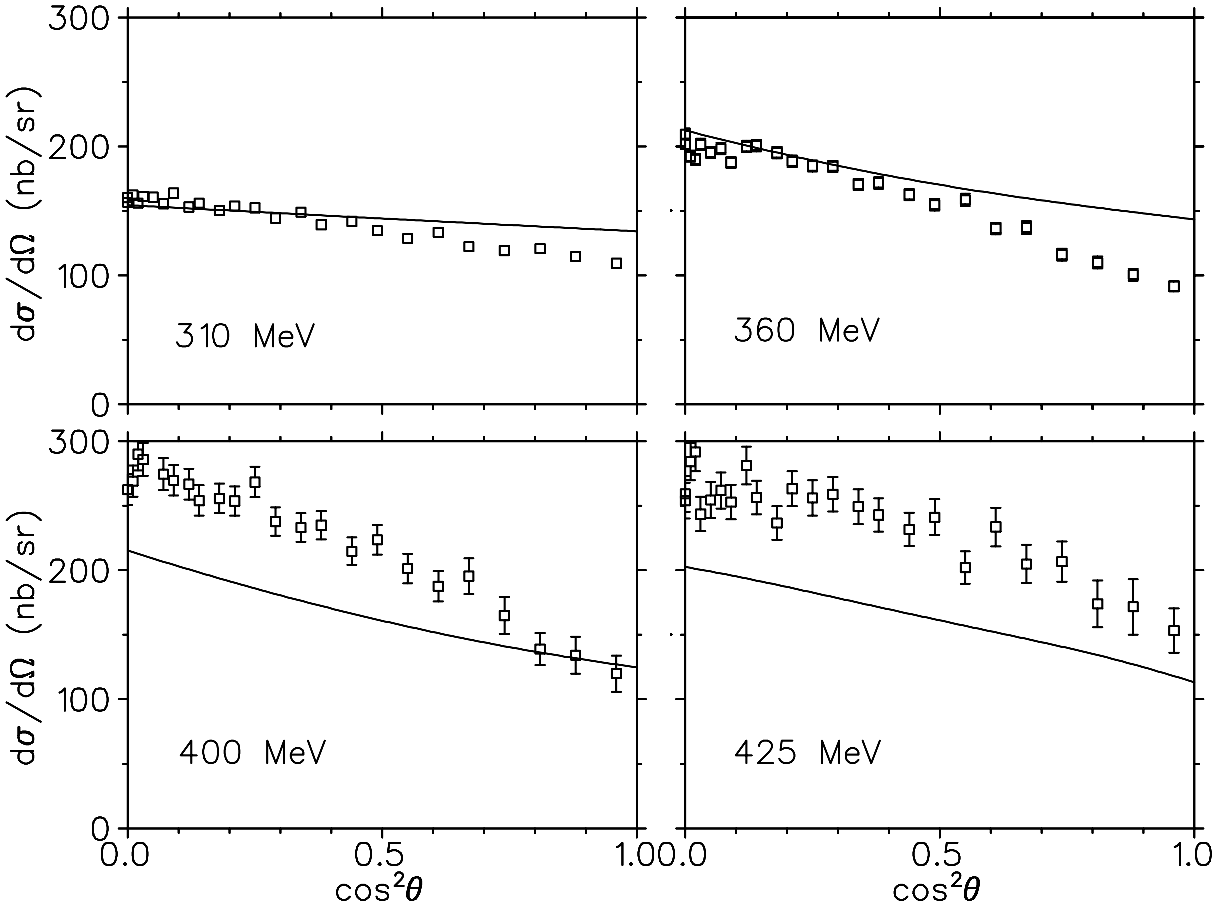
Model includes "direct" production from (distorted) nucleons, s-wave pion rescattering, p-wave pion rescattering through $\Delta(1232)$ by $N\Delta$ coupled channels and "heavy meson exchange".

Mechanisms for pion production

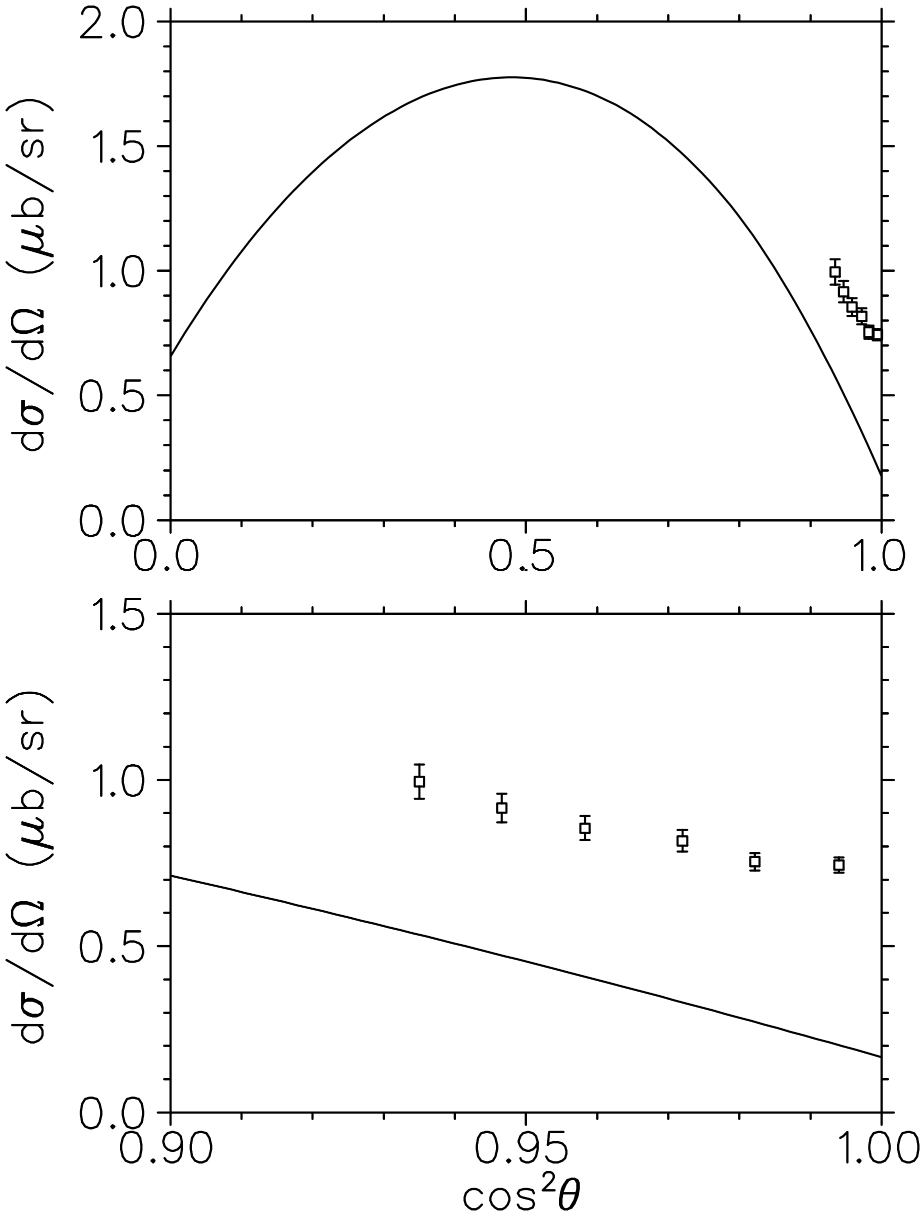


Predictions of total cross section of $pp \to (pp)_{S-\mathrm{wave}}\pi^0$ in partial waves





Model results vs. some Celsius data. Cut of 3 MeV on final pp energy.

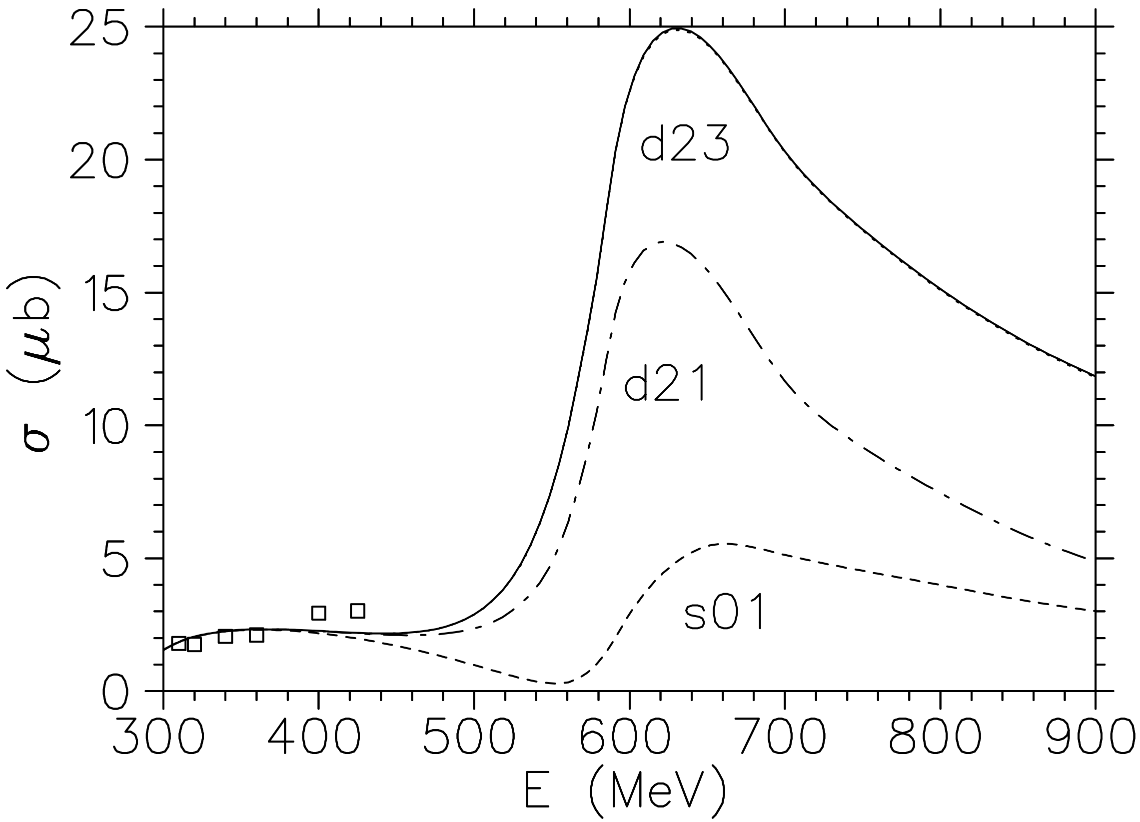


Model results vs. ANKE data at 800 MeV.

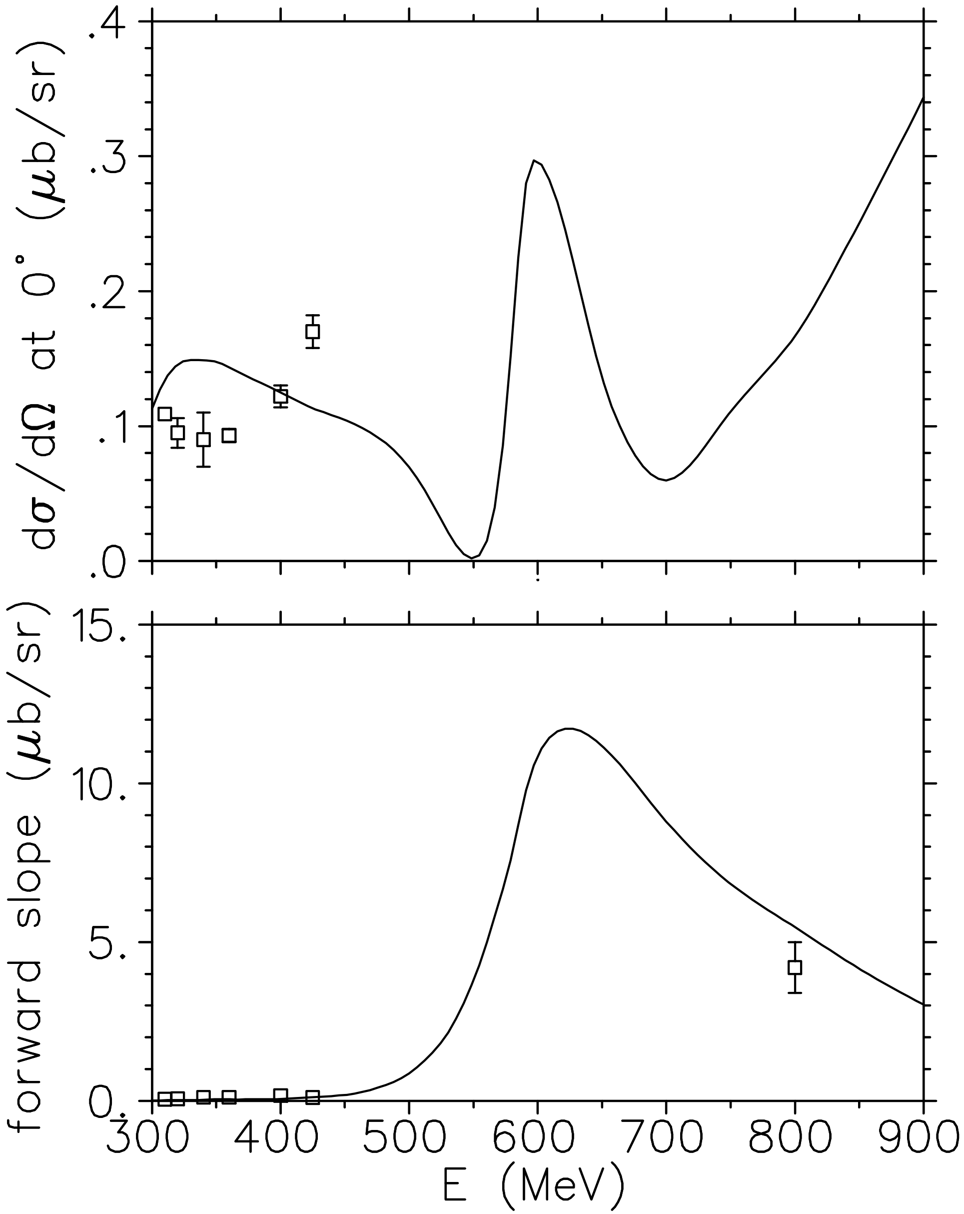
Strongly destructive interference in forward direction ⇒ extreme sensitivity to amplitudes.

Intermediate energy range totally uncharted.

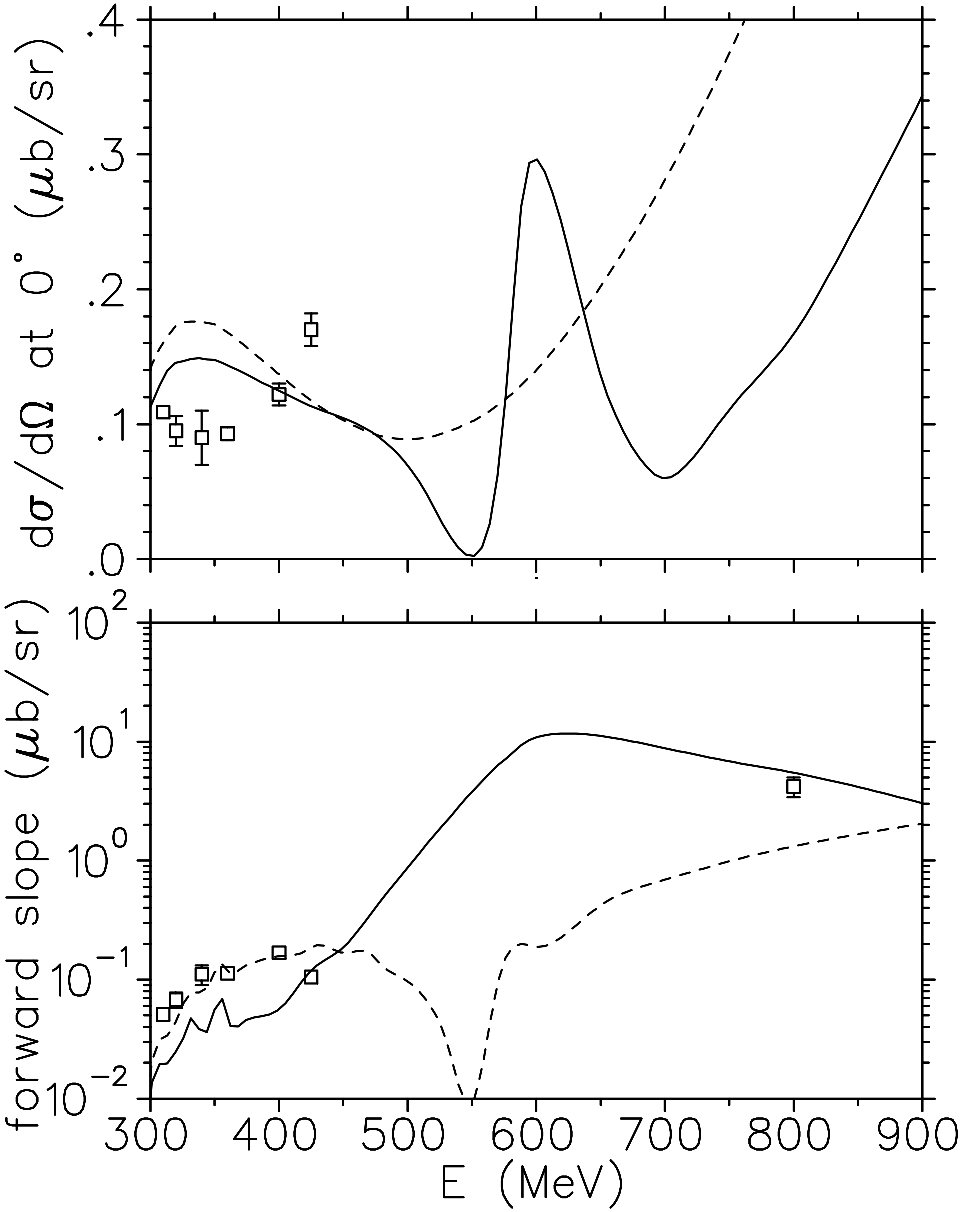
Partial wave contributions show significant structure as functions of energy - reflection of the Δ.



Three about equally important partial wave amplitudes.

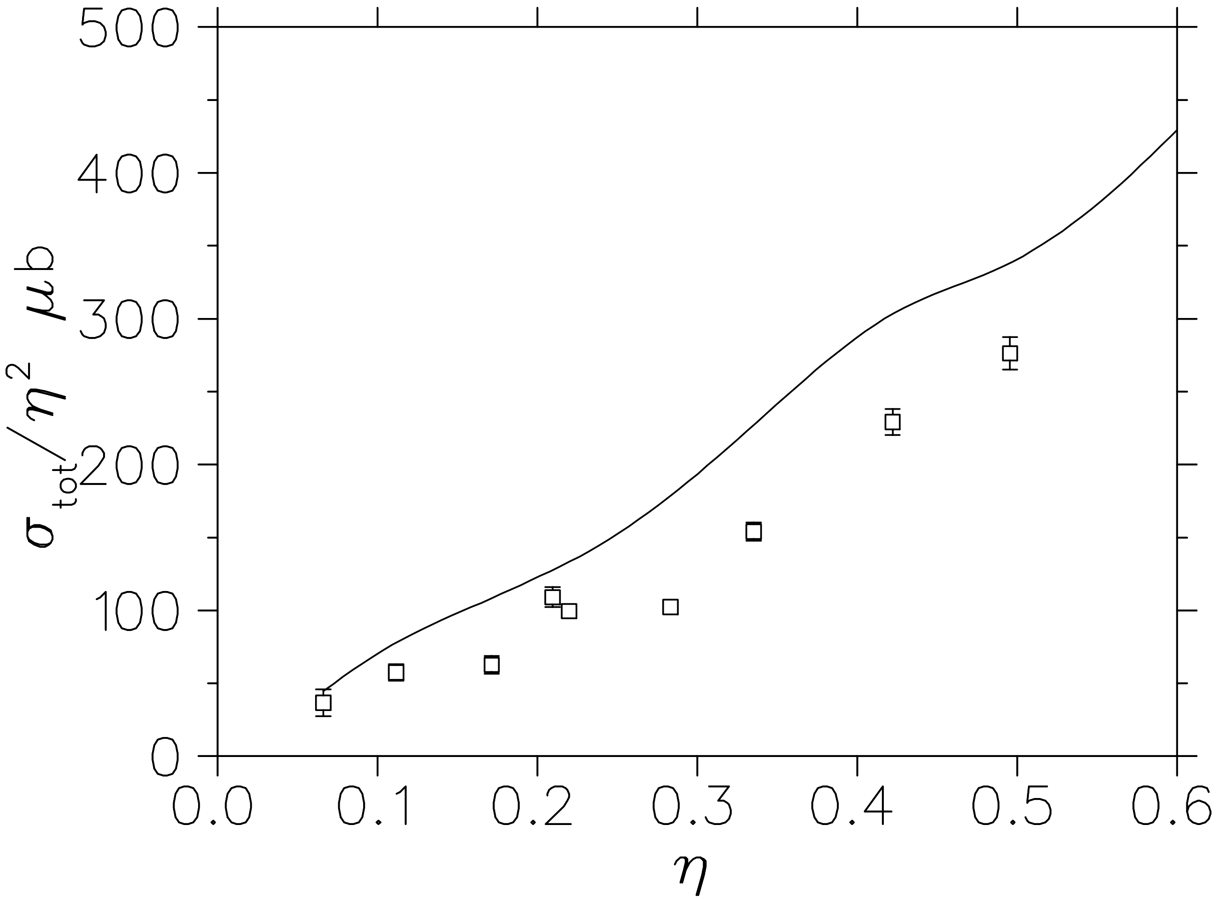


Structures appear even more strikingly in forward cross section and its slope. Sensitivity to interferences of the Δ and nucleon background.



Nucleon background "smooth" (dashed). Above 550 MeV purely nucleonic slope of wrong sign.

Total cross section of $pp \to (pn)_{^3S_1-^3D_1-\mathrm{wave}}\pi^+$



Overestimate by $\approx$ 25%. Scale uncertainty 12% in experiment.

Summary on $pp \longrightarrow (pp)_{S-\mathrm{wave}}$

With small cut on final NN energy can look at few matrix elements as functions of pion momentum, i.e. of momentum transfer, **essentially at single momentum.**

Very delicate interference effects seem to give unexpectedly strong sensitivity to the Δ component.

Without cut in momentum-integrated cross section sensitivity smeared off.

Striking energy and angular dependencies. Probably spin observables offer some excitement, too.

$pn\pi^+$ final state study just beginning.

Charge dependence in $NN \to d\pi$?

Charge independence (CI) of nuclear forces:

strong nuclear forces same for pp, nn, np and pn in same spin-spatial states
i.e. invariant in arbitrary rotations of the isospin space

Special case: **charge symmetry (CS)** $\boldsymbol{n} \leftrightarrow \boldsymbol{p}$
mirror isospin $\boldsymbol{T_z} \longrightarrow -\boldsymbol{T_z}$

Broken: changes in e.g. nuclei minor but for us differences have profound consequences.

If symmetry exact, then in terms of **isospin eigenstates**

$$\frac{d\sigma(pp \to \pi^+ d)}{d\sigma(np \to \pi^0 d)} = \frac{|\langle 1,1|S|1,1\rangle|^2}{|1/\sqrt{2}\,\langle 1,0|S|1,0\rangle + 1/\sqrt{2}\,\langle 1,0|S|0,0\rangle|^2}$$

with $\langle 1,0|S|0,0\rangle = 0$ (CS, isospin conservation)

and $\langle 1,1|S|1,1\rangle = \langle 1,0|S|1,0\rangle$ (CI).

Therefore

$$\frac{d\sigma(pp \to \pi^+ d)}{d\sigma(np \to \pi^0 d)} = 2\,,$$

much used proportionality to relate these reactions.

Symmetry in interactions broken at least by

- electromagnetic interactions (CIB and CSB)
- neutron-proton mass difference (CSB, CIB)
- meson mass differences (CIB)
- meson mixing ($\eta\pi^0$, $\rho^0\omega$) (CSB, CIB)
- basic origin up- and down-quark mass difference and EM interactions of quarks

Cause both **CIB and CSB nuclear interactions**

CIB nuclear interactions

In low energy NN scattering well known

$$|a_{np}(\text{singlet})| > |a_{nn}(\text{singlet})|\,, \qquad \approx 23 \text{ vs. } 17\,\text{fm}$$

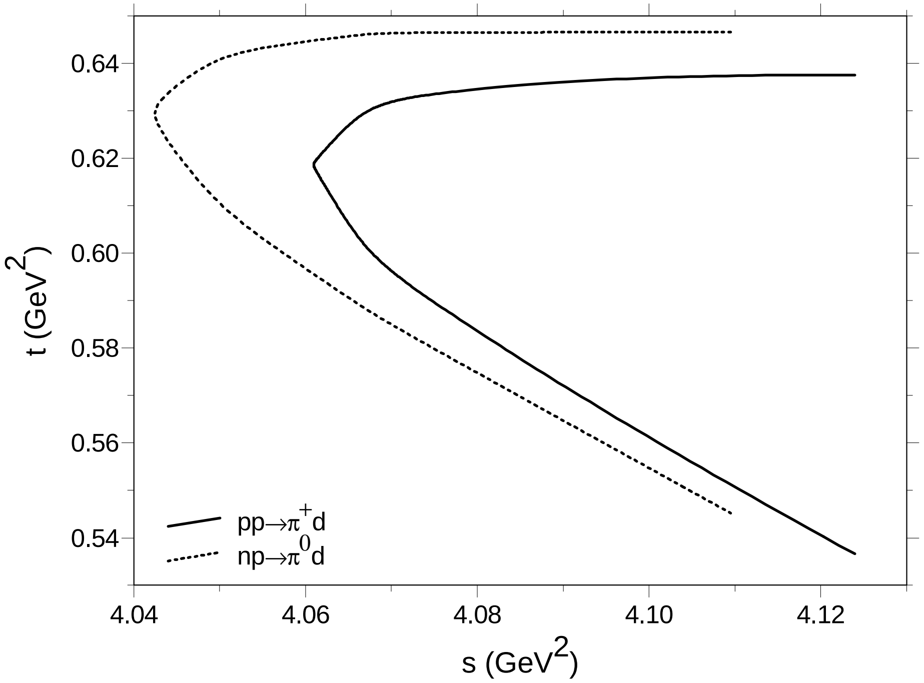
i.e. np interaction more attractive.
Origin mainly $\pi^\pm$ and π^0 mass difference $\Rightarrow$ isotensor force.
Class II $\propto 3\tau_{10}\tau_{20} - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$ in classification of Henley& Miller.
Nonzero only for $T = 1$.

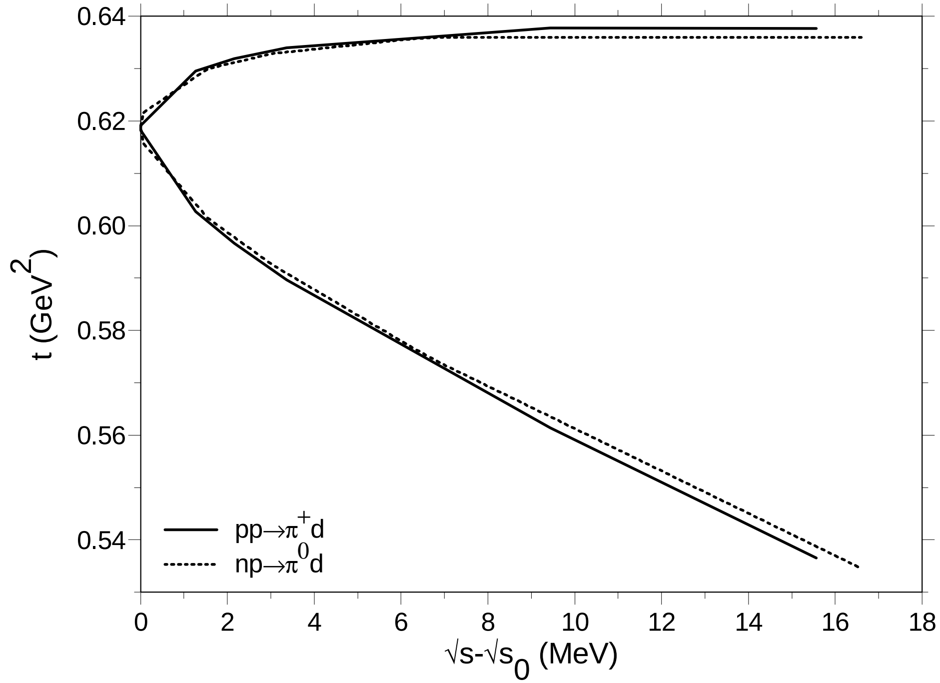
CSB seen also in meson production $np \to d\pi^0$ (Opper et al. PRL **91**, 212302) and in $dd \to \alpha\pi^0$ (Stephenson et al., PRL **91**, 142302)

CIB in meson production largely unexplored.

Kinematic considerations

Different masses $\Rightarrow$ different thresholds $\Rightarrow$ E vs. q_π different.





Ranges of s and t $\qquad t_0 = t_+ + 0.01065$ GeV^2

Theoretical study without CIB interactions

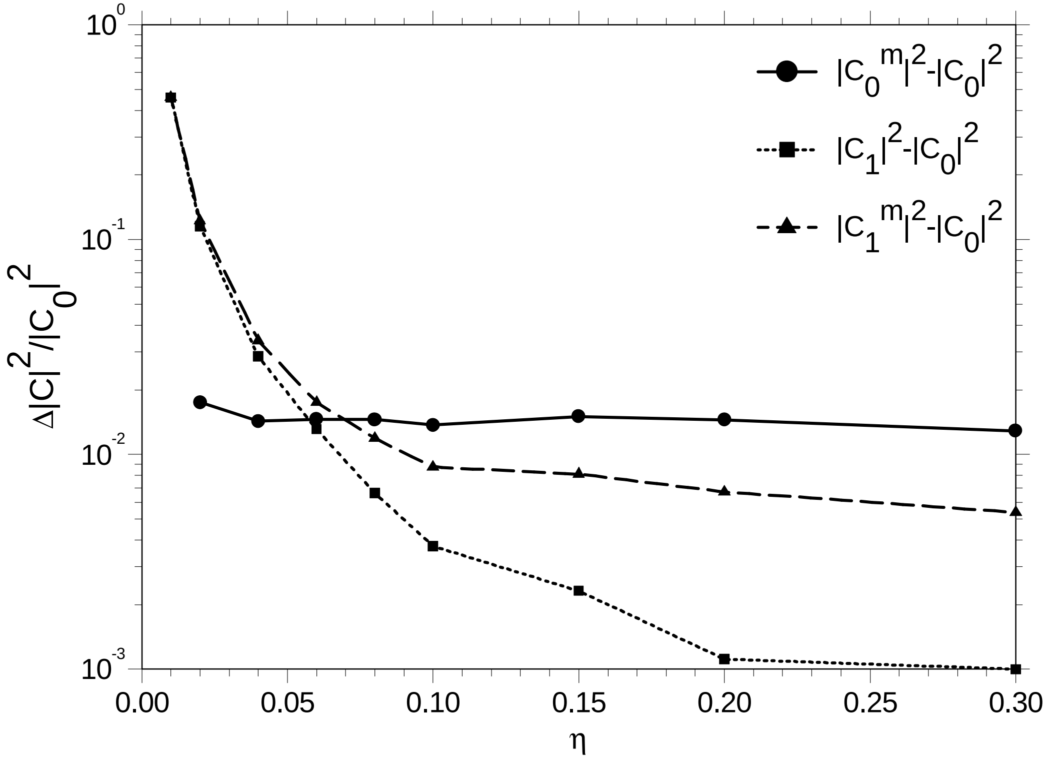
CIB in $pp \to d\pi^+$ vs. $np \to d\pi^0$ was studied including only effects of different thresholds (kinematics) and Coulomb (Niskanen and Vestama, PLB **394**, 253). Separation of phase space and dynamical matrix elements

$$\frac{d\sigma(\theta)}{d\Omega} = \underbrace{\frac{1}{4(2\pi)^2\hbar^4}\frac{p_\pi^*}{p_N^*}\frac{E_N E_p E_d E_\pi}{s}}_{} \underbrace{\sum_{\mu SM} |\langle \psi_d^\mu \mid H^\pi \mid \phi^{SM}\rangle|^2}_{}$$

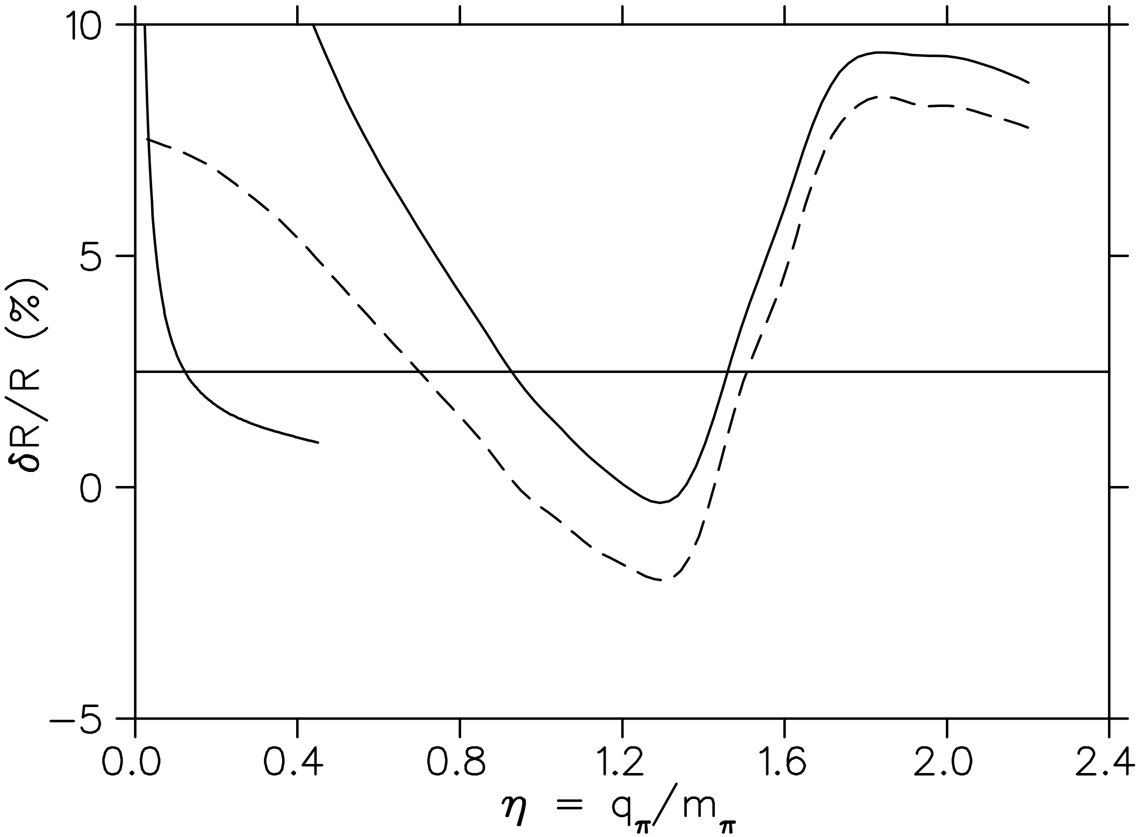
$$\equiv \qquad P_{Np} \qquad\qquad R_{Np}$$

$$\begin{aligned} \delta\sigma &\equiv 2\sigma(np) - \sigma(pp) \\ &= \frac{P_{np}+P_{pp}}{2}(R_{np}-R_{pp}) + (P_{np}-P_{pp})\frac{R_{np}+R_{pp}}{2}. \end{aligned}$$

Also Coulomb removed by extended source penetration factors.



Coulomb penetration factors for p wave and for extended source vs. point-like charge s-wave factor.



Relative differences of reduced np and pp reaction cross sections (phase space and Coulomb removed)

Differences between reduced (phase space and Coulomb corrected) cross sections seen at several % level (even close to 10%), albeit model dependent (weakly).

Can that be seen in existing data?

Problems:

- Neutron beams inferior to proton beams
- Normalization of neutron beams (viceous circle)
- No precise differential cross section data for np and pp at same energy (what is "same" energy?).

Solution(?):

- Globalism
- Relative observables (energy and angular dependence)

Global fits

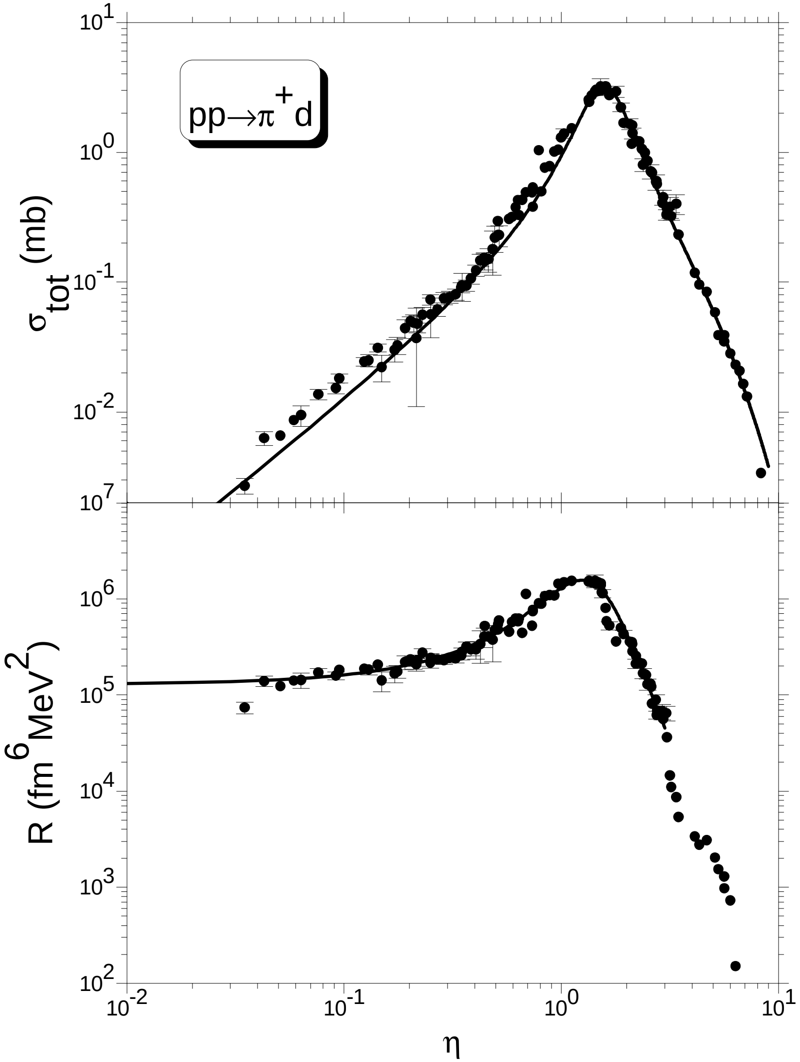
Total (reduced) cross section of $pp \to d\pi^+$ can be well fitted with function

$$\boldsymbol{R_{pp} = \left[\frac{b_1 b_3^2}{(b_2-\eta)^2+b_3^2}\right]^2}$$

with

$b_1\,(\mathrm{fm}^3\mathrm{MeV})$	b_2	b_3
1252.347 ± 11.232	1.2503 ± 0.0064	0.7922 ± 0.0108

Even though analytic structure not correct (not function of η^2 but η), may be useful as easy-to-use parameterization.



Fit to raw $pp \to d\pi^+$ total cross sections

Fit to reduced (phase space and Coulomb removed) cross sections

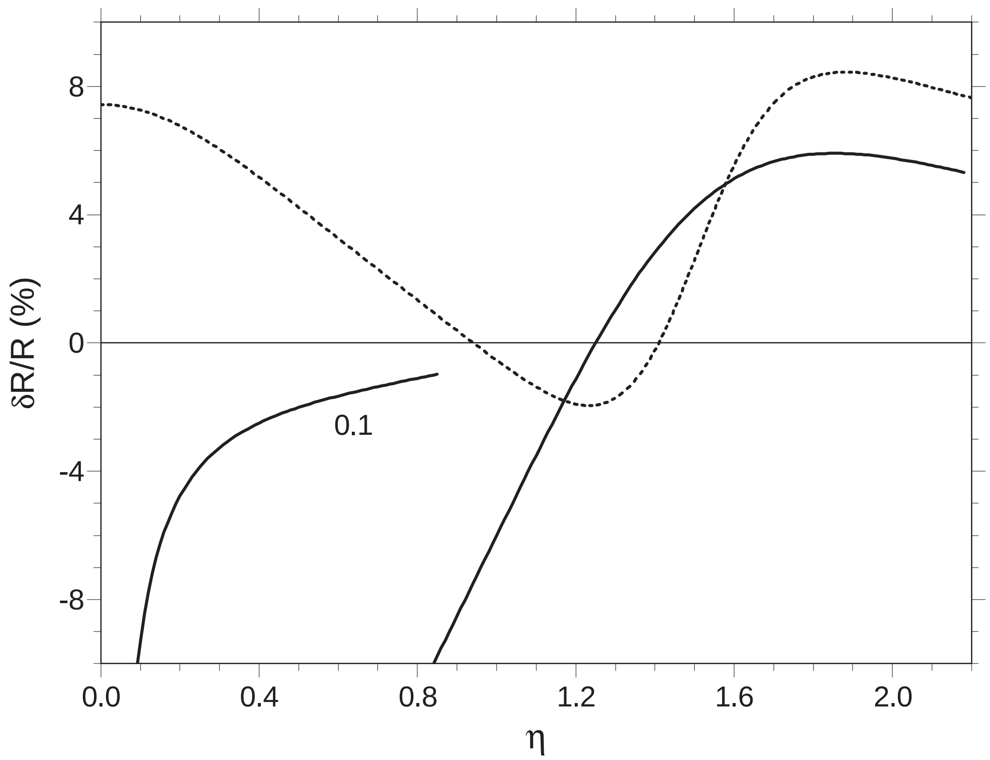
One motivation: aim to "model independent" prediction based on different thresholds by

$$\delta R \equiv R_{np} - R_{pp} = \frac{\mathrm{d}R_{pp}}{\mathrm{d}E_i} \left(E_i(np) - E_i(pp)\right).$$

Expect: Due to larger threshold for pp expect np to "lag behind" especially in climbing the Δ hill ($i.e.$ negative δR).

Is **not** enough except to some extent in Δ peak slope.

Physical meaning: *If* one could have varying initial nucleon energy with constant final momentum, then matrix elements **would decrease** with that energy close to threshold – model dependent behaviour.

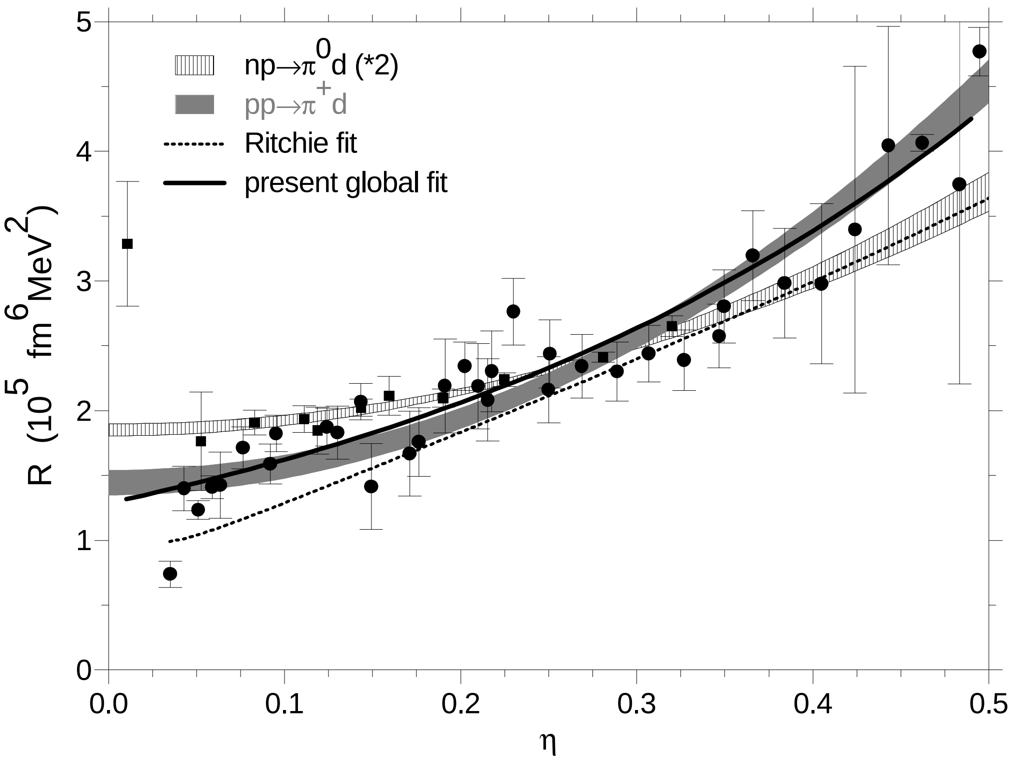


Model vs. "model independent" predictions. Probably cannot avoid model dependence.

Threshold energy dependence

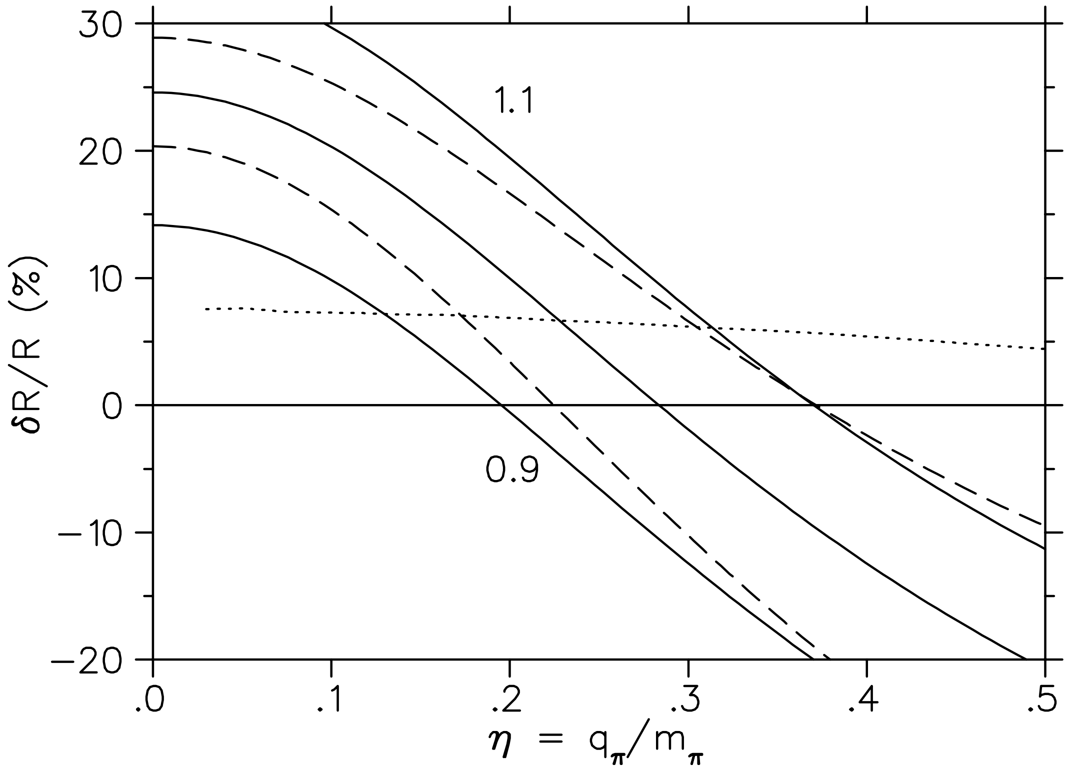
Rather high quality data on $np \to d\pi^0$ in threshold region exist from TRIUMF. Can be fitted by low energy expansion

$$\boldsymbol{R = \alpha_0(1 + \alpha_1\eta^2)} \qquad \text{economic choice.}$$



Comparison of threshold np and pp data
np data squares,
pp data dots

Fitted energy dependencies different: pp much steeper.



Relative difference from model (dots) and fits with also np cross section renormalized by factors 0.9 and 1.1.

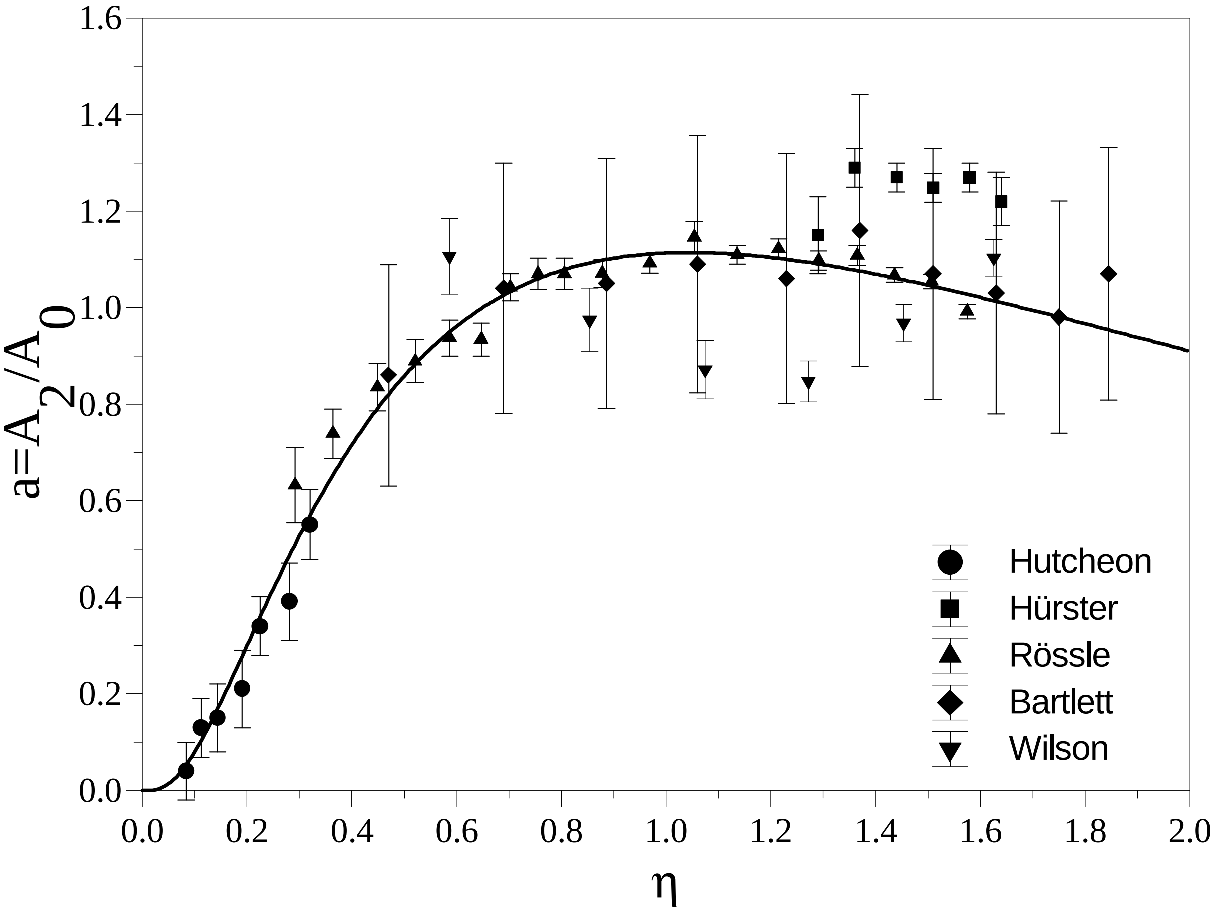
Cannot reconciliate fit and charge independent model.

Angular distributions

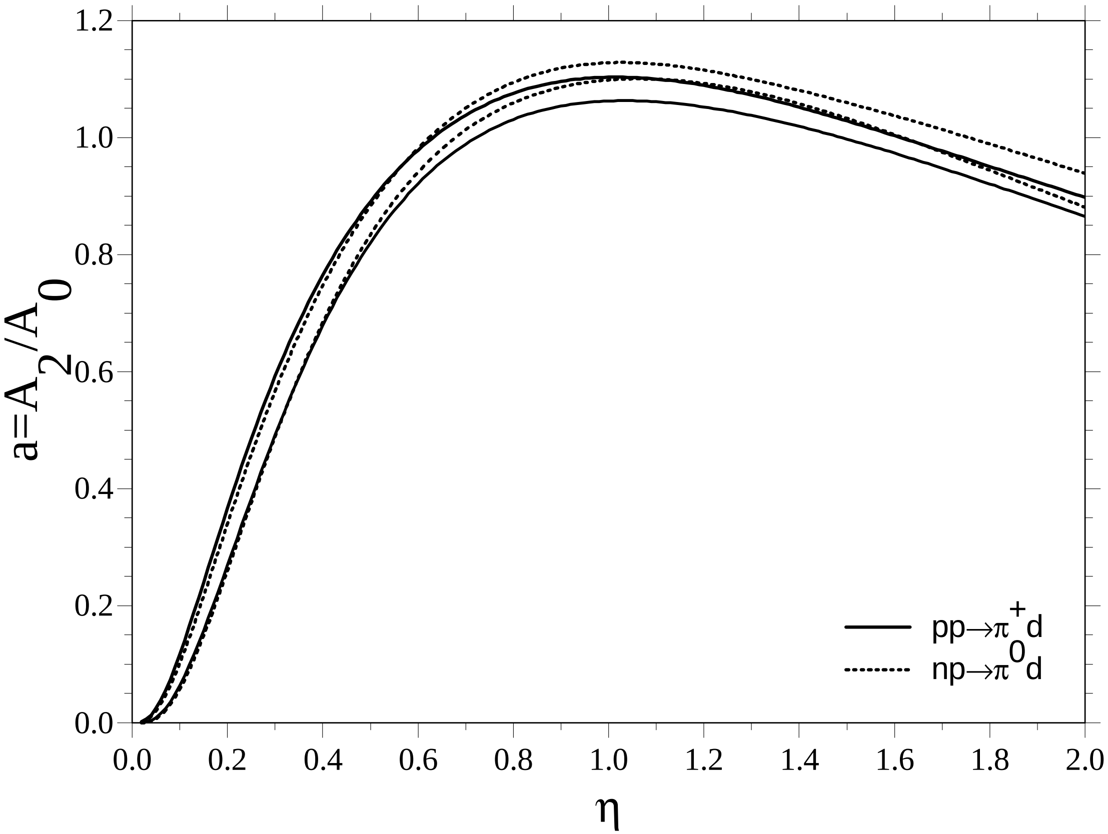
Can be fitted by

$$4\pi \frac{d\sigma(\eta, \cos\theta)}{d\Omega} = A_0(\eta) P_0(\cos\theta) + A_2(\eta) P_2(\cos\theta)$$
$$= \sigma(\eta) \left[1 + a(\eta) P_2(\cos\theta)\right]$$

(with higher polynomials at higher energies).
Measure of anisotropy $a(\eta) = A_2(\eta)/A_0(\eta)$ independent of normalization and fitted as function of η.



Quality of np anisotropy $a(\eta)$ and fit.



Confidence intervals (on 95% level) of the fitted np and pp anisotropies

Summary on Charge Dependence Study

CIB searched trying to compare $pp \to d\pi^+$ and $np \to d\pi^0$.

Neutron beam normalization problem $\Rightarrow$
relative quantities useful, fits like $\text{obs} \sim \sigma_{\text{tot}}(1 + a * rel.q)$.

Possible deviation from expectations without CIB forces in energy dependence of total cross section.

More (and better) experiments with neutrons needed.

Another avenue: more complicated $pd \to {}^3\text{He}\pi^0$ vs. $pd \to {}^3\text{H}\pi^+$ avoids initial state normalization.