OUTLINE

- A bit of history.
- The $\overline{p}$ annihlation at rest in Deuterium:
  - The spin of the φ.
  - The $\pi^+\pi^-\pi^-$ Dalitz plot.
  - The $\omega \rightarrow \pi^+\pi^-$ branching fraction.
  - Are captures at rest really in $\overline{p}n$ S-wave?
- The $\overline{p}$ interactions in flight:
  - Elatsic and inelastic scattering.
  - Charge exchange, $\overline{p}p \rightarrow \overline{n}n$
- Controversies: the "S(1929)" and the problems of low energy $\overline{p}p$.

ROME 1961-7?: ANTIPROTONS

- Romano starts collaboration with Trieste and CERN:
  low energy $\overline{p}$ interactions, in the Saclay Hydrogen bubble chamber.
- Giancarlo, while at Brookhaven, starts collaboration with Syracuse:
  $\overline{p}n$ annihilation at rest in the 30" Columbia-BNL Deuterium B.Ch.

Symbiosis between Roma-Trieste and Rome-Syracuse experiments.

Two-prong approach, complementarity of studies:

- $\overline{p}$ interactions in Hydrogen and in Deuterium.
- Interactions in flight and annihilations at rest.

Romano [5], early in the game, 1967, feels the need of clarifying all the parameters needed to correctly compare the results of $\overline{p}$'s stopping in H_2 and D_2.

1961-197?: Intense years of scanning, measuring and processing bubble chamber pictures:

- The “Laboratorio Analisi Fotogrammi”
- The “Mangiaspagos” and the installation of the IBM-1800.
- The team of programmers and scanners.
- Processing at the Bologna INFN “Centro di Calcolo”
- Installation of the IBM-1040 at the University of Rome.

First Results: $\overline{p}n$ annihilation at rest.

Why at rest? Well defined initial state:

Day, Snow and Sucher: Because of Stark effect, $\overline{p}$ nuclear capture from atomic high n but L=0 atomic state.

Argument supported by experiment by measurement of the moderation time of π^-, K^- and Σ^-.

Then in Hydrogen:

$P(\overline{p}p) = -1$, $C(\overline{p}p) = (-1)^S$, $G(\overline{p}p) = (-1)^S$

In Deuterium, naively (impulse approximation):

$P(\overline{p}n) = -1$, $C(\overline{p}n) = (-1)^S$, $G(\overline{p}n) = -(-1)^S$

In Deuterium: need to consider internal motion of the deuteron and suppress three-body interactions ($\overline{p}np$) accepting only events with $p(p) < 250$ MeV/c .

Matching the properties of the final state determines the initial spin.

CONFIRMATION OF THE SPIN OF THE φ. [2]

Collected:

13 $\overline{p}d \rightarrow \pi^- \varphi\ p_{sp} \rightarrow \pi^- K^0_S\ K^0_L\ p_{sp}$

33 $\overline{p}d \rightarrow \pi^- \varphi\ p_{sp} \rightarrow \pi^- K^- K^+\ p_{sp}$

Choice of φ spin, $\pi^-\varphi$ orbital L:

φ decay angular distribution determined.

Only one choice is acceptable:

$J(\varphi) = 1$, with $L = 1$: $P(\chi^2) = 0.92$

All others: $P(\chi^2) = 10^{-2}$ to 10^{-6}

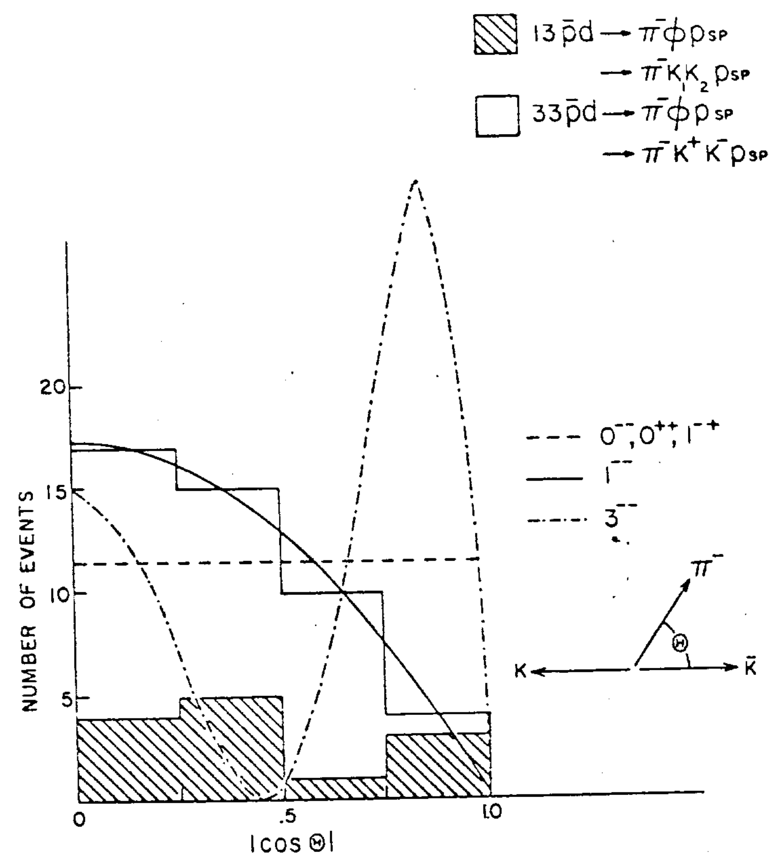


FIG. 2. The angular distribution of the π^- with respect to the $\overline{K}$ in the φ c.m. system. The theoretical curves are for various J^{PG} φ assignments and S-state $\overline{p}n$ absorption.

φ spin clearly confirmed.

THE PECULIAR DALITZ PLOT OF $\overline{p}n \to \pi^-\pi^-\pi^+$. [4]

Collected:

2785 events with $p(p_{sp}) < 150$ MeV/c.

$11 \times$ Padova-Pisa statistics.

Because of $G(3\pi) = -1$:

initial $\overline{p}n$ state must be singlet.

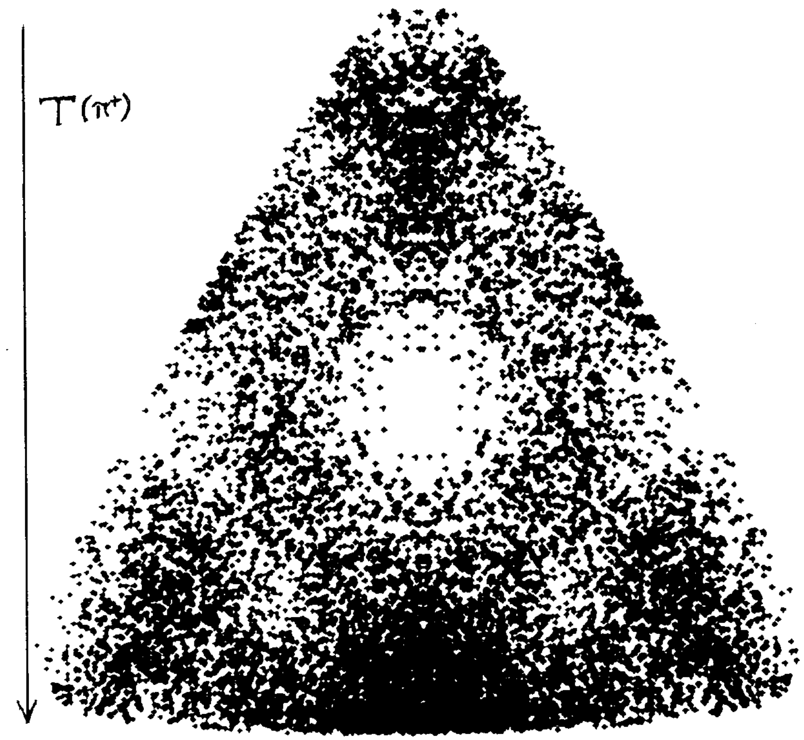
Naive interpretation:

superposition of $\pi\pi$ resonances.

Best (but not good, 190/65) fit:

σ^0, f^0, very little ρ^0, plus

ad hoc $\pi^-\pi^-$ threshold effect.



Big hole in the middle?

Flurry of theoretical papers based on the Veneziano Model.

Lovelace, Rubinstein and Altarelli, Berger, Boldrighini and Pugliese, ...

$\pi\pi$ MASS AND ANGULAR DISTRIBUTIONS

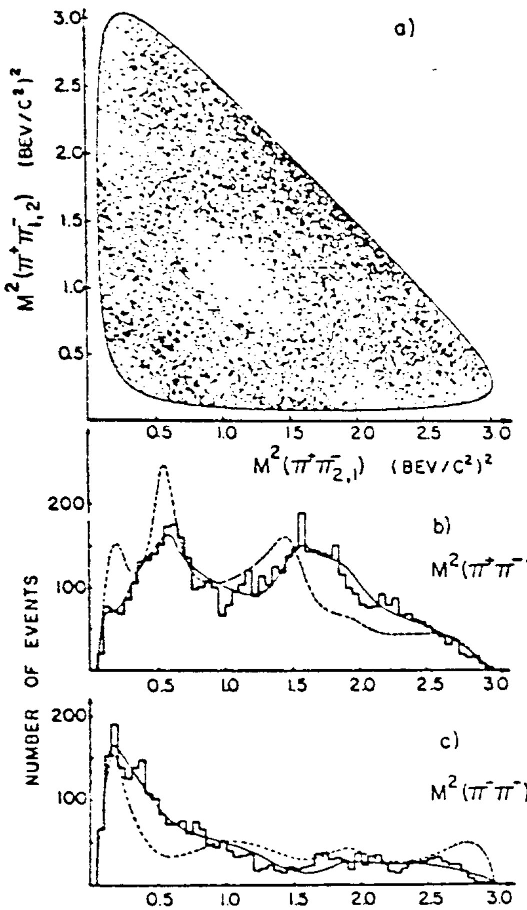


FIG. 1. (a) Symmetrized Dalitz plot of the $\pi^-\pi^-\pi^+$ final state, with its projections (b) on the $M^2(\pi^+,\pi^-)$ axis, and (c) on the $M^2(\pi^-,\pi^-)$ axis. The curves correspond to fit 1 (dashed line), fit 5 (solid line).

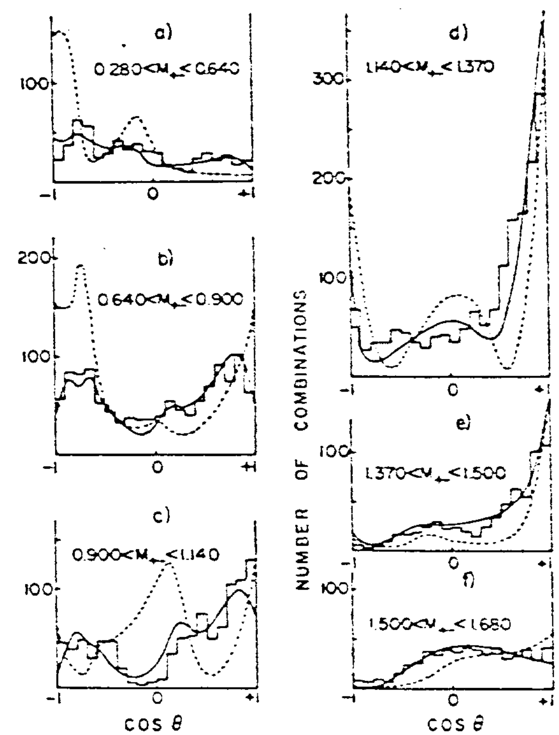


FIG. 2. Angular distributions of the π^+ relative to the (π^+,π^-) di-pion line of flight, in the di-pion c.m. system for various $M(\pi^+,\pi^-)$ regions. The curves are as in Figs. 1(b) and 1(c).

Upper Limit to the $\omega \rightarrow \pi^+\pi^-$ Decay Rate. [10]

Advantage of using $\overline{p}n$ annihilation:

$\overline{p}n \rightarrow \omega n \pi$ and $\overline{p}n \rightarrow \rho^0 n \pi$ proceed from different initial spin or parity states, hence incoherent.

Select following reactions:

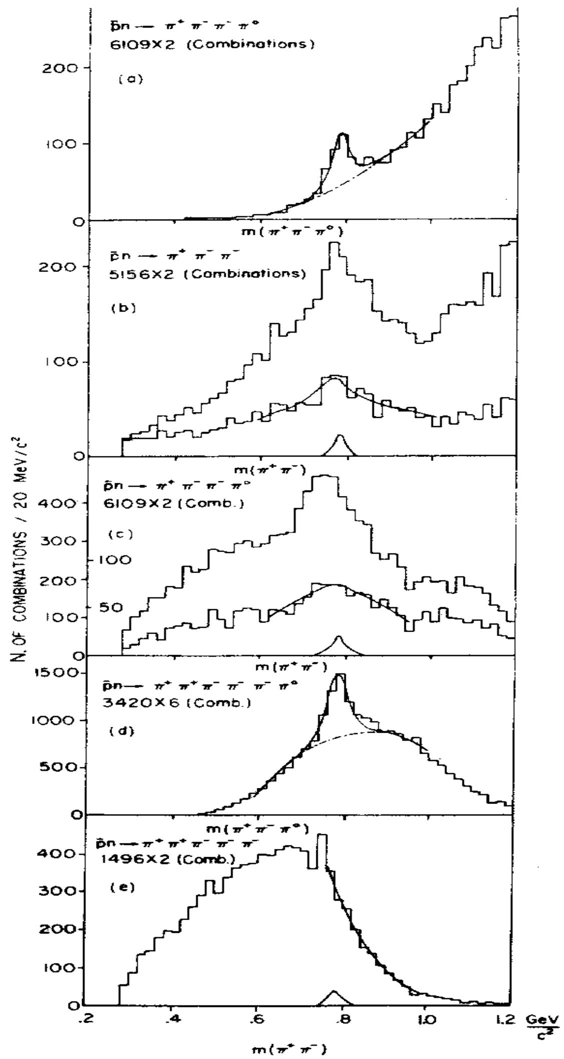
1. $\overline{p}d \rightarrow p_{sp} \omega \pi^-$ $[(\pi^+\pi^-\pi^0)\pi^-$ and $(\pi^+\pi^-)\pi^-]$
2. $\overline{p}d \rightarrow p_{sp} \omega \pi^- \pi^0$
3. $\overline{p}d \rightarrow p_{sp} \omega \pi^- \pi^- \pi^+$

Plot $m^2(\pi^+\pi^-\pi^0)$ for first and third reaction,

Plot $m^2(\pi^+\pi^-)$ for all three reactions.

Compare with mass resolution.

Write $m^2(\pi^+\pi^-)$ signal distribution as interference of the ω and $\epsilon\rho^0$.



Extract from fits:

$N(\omega\to\pi^+\pi^-)$ and $N(\omega\to\pi^+\pi^-\pi^0)$.

$$\text{Get} : R \equiv \frac{(\omega\to\pi^+\pi^-)}{(\omega\to\pi^+\pi^-\pi^0)}$$

as function of χ^2 of fit.

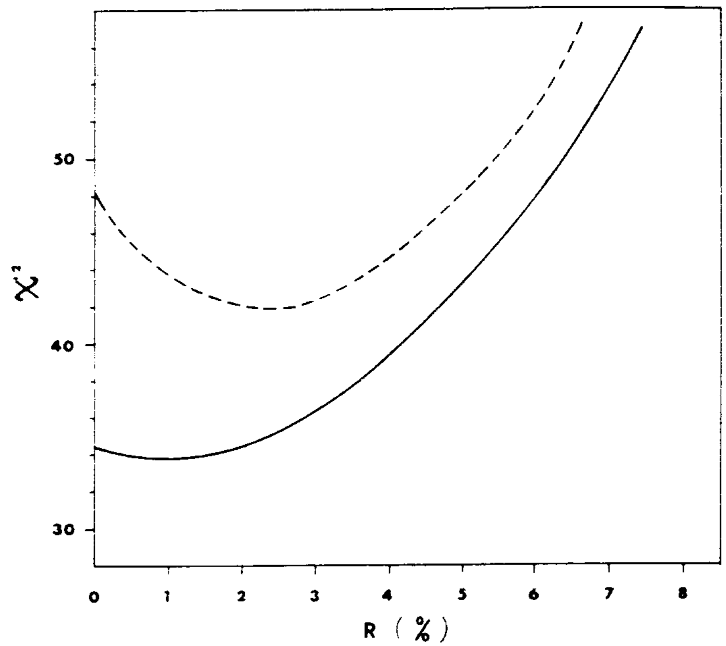


FIG. 2. Total χ^2 of the fits to our $m(\pi^+\pi^-)$ distributions as a function of R, with (solid-line curve) and without (dashed line) ρ contribution.

Conclusion: $R < 3.5\%$

PDG 2002:

$\mathcal{B}(\omega\to\pi^+\pi^-) = (1.70\pm0.28)\%$

$$R = \frac{(\omega\to\pi^+\pi^-)}{(\omega\to\pi^+\pi^-\pi^0)} = (1.90 \pm 0.19)\%$$

Really only S-wave annihilation at rest?

Esperimental evidence (1962 CERN, 1965 Columbia) from small ratio

$$\frac{\bar{p}p \to K_S^0 K_S^0 \text{ (odd L initial state)}}{\bar{p}p \to K_S^0 K_L^0 \text{ (even L initial state)}} \sim 1.5\%$$

Counter-evidence?

The $\bar{p}p \to \pi^0\pi^0$ results Columbia-Syracuse [11].

Spark chamber experiment at BNL (1970): $\bar{p}$ annihilation at rest in H_2.

$\bar{p}p \to \pi^0\pi^0$ can only come from $\bar{p}p$ in odd L state.

Result:

$$\frac{(\bar{p}p \to \pi^0\pi^0) \text{ at rest}}{(\bar{p}p \to \text{ all annihilations})} = 4.8 \times 10^{-4} (\pm 20\%),$$

implying

$$\frac{(\bar{p}p)\ (\text{L odd},\ \text{I} = 0)}{(\bar{p}p \to \pi\pi)} = 0.39\ (\pm 20\%)$$

Quite substantial annihilation at rest in P-wave.

Can this be generalized to all annihilation channels?

REACTIONS TO DEVONS *et al.* BY BIZZARRI *et al.*.

Combine results from Columbia-Syracuse in Deuterium and Syracuse-Demokritos in Hydrogen [15]

From Romano's detailed analysis [5], get probabilities of capture in P and S-wave, P_H and $S_H = 1 - P_H$ in Hydrogen as well as P_D and $S_H = 1 - P_D$ in Deuterium, independently of specific channel.

Determination of P_H and P_D needs estimate of a_p^t,
the fraction of $\overline{p}p$ capture from triplet S_1^3 state in Deuterium.
Educated estimate of a_p^t (≤ 0.45) leads to:

$$P_H \leq 0.024^{+0.024}_{-0.018} \qquad P_D \leq 0.19 \pm 0.12$$

or, with help of theoretical models of $\mathcal{N}\overline{\mathcal{N}}$ interactions:

$$P_H \simeq 0.04 \qquad i.e.\ S_H \simeq 0.96 \qquad P_D \simeq 0.28 \text{ (for } {}^3S_1\overline{p}p \rightarrow \pi\pi \text{ only)}$$

Analysis confirms of S-wave capture, but statistics are poor!

Comparison of annihilation to $\pi\pi$ and to $K\overline{K}$ in H_2 and D_2 (taking into account different limits in $p(p_{sp})$:

$$\mathrm{S-wave}: \ \frac{\overline{p}p\rightarrow K^0\overline{K}^0}{(\overline{p}p\rightarrow\pi^+\pi^-)_{I=1}} = (33\pm 5)\%$$

$$\mathrm{P-wave}: \ \frac{\overline{p}p\rightarrow K^0\overline{K}^0}{(\overline{p}p\rightarrow\pi^+\pi^-)_{I=0}} = (0.7^{+0.6}_{-0.3})\%$$

Enormous dependence (factor 40) on L-state!

Is the enhancement of $\overline{p}p\rightarrow\pi^0\pi^0$ of dynamical origin?

Much later, new results from LEAR: any additional information?

Note on effects of Fermi motion in deuteron [14]:

it induces P-wave $\overline{p}n$ annihilations also from S atomic orbitals.

Effect is reduced to $\sim 4\%$ if $p(p_{sp}) < 80$ MeV/c.

Conclusion: Observation of P-wave $\overline{p}\mathcal{N}$ in D_2 must be corroborated by study of $p(p_{sp})$ distribution.

$\overline{p}D \rightarrow \Lambda K \mathrm{n}\pi^{\pm}$ [9]

Incompatible with impulse model of $\overline{p}n$ interaction in Deuterium.

- Impulse model plus rescattering? $\overline{p}d \rightarrow K^+K^-n$ followed by $K^-n \rightarrow \Lambda\pi^-$.

Estimated frequency $(0.65 \pm 0.07) \times 10^{-5}$.

Observed frequency: $(3.2 \pm 1.7) \times 10^{-5}$.

- Test: K energy spectrum.

Kaon energy should be smeared $m(p)$, *i.e.* momentum = 798±25 MeV/c.

Instead it is spread between 0.3 and 1.0 GeV/c.

- Contrary to $K\overline{K}$ nπ final states, no trace of K^* production in Λ events.

- Recoil proton spectrum in other $\overline{p}D$ interactions [1]:

84% as expected from deuteron wave function.

16% smooth background up to kinematical limit.

- Relatively high observed frequency, spread out Kaon spectrum, and lack of K^* production, indicate inadequacy of impulse model plus rescattering.

Some kind of three-body interaction seems to be at work.

$\overline{p}p$ INTERACTIONS IN FLIGHT

In 81-cm Saclay Hydrogen Bubble chamber.

CERN-Roma-Trieste [3, 6, 7, 12, 13]

Elastic, Charge-exchange, Inelastic, $\overline{p}p \rightarrow \pi^+\pi^-$ and K^+K^- cross sections.

Detailed, discriminant comparison with phenomenological $\overline{p}p$ interaction models:

- Koba and Takeda: black sphere
- Ball and Chew: $\overline{\mathcal{N}}$-$\mathcal{N}$ potential + absorbtive core.
- Ceschia and Perlmutter: elaboration of Ball and Chew's.
- Spergel: as above, with more parameters.
- Nemirovskii and Strokov: use an imaginary potential to get annihilation.
- Brian and Phillips: real plus imaginary potential. Very good fit, clearly best of all.

From 50 to 180 MeV $\overline{p}$ kinetic energy, in 15 energy bins.

Accurate determination of the $\overline{p}$ energy, crucial to avoid contamination by annihilation at rest.

Elastic scattering

From angular distributions: at least L=2 for $T \leq 100$ MeV, at least L=3 above that.

Momentum transfer t distribution consistent with diffraction by black sphere of radius $R = a + \lambdabar$ with $a = 1.04\ fm$.

Sharp forward peak of π^-observed also in $\overline{p}p \to \pi^+\pi^-$ [8]

While K^- is backward peaked in $\overline{p}p \to K^-K^+$.

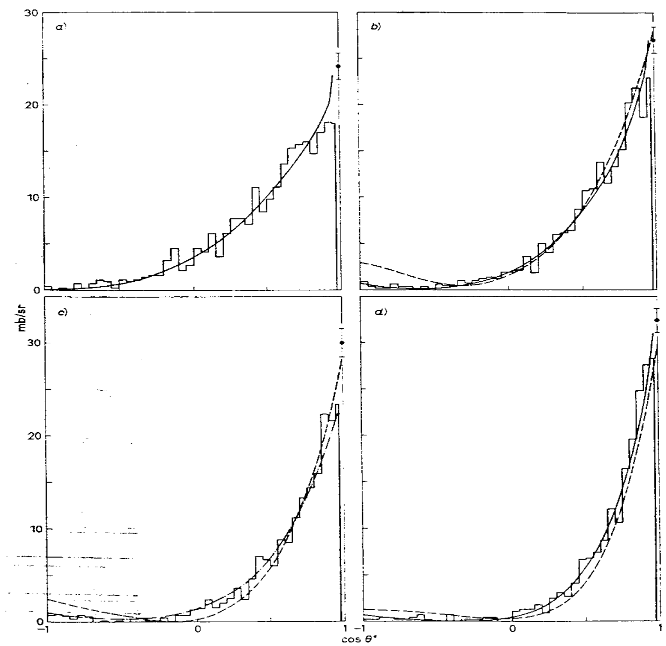


Fig. 4. – Comparison of experimental differential cross-sections $d\sigma/d\Omega$ with theoretical predictions. Data at *a)* 62.7 MeV, *b)* 99.8 MeV, *c)* 136.8 MeV, *d)* 163.3 MeV. Theory: —— Bryan and Phillips at *a)* 62.7 MeV, *b)* 99.8 MeV, *d)* 163.3 MeV; – – – Ceschia and Perlmutter at *b)* 96 MeV, *c)* 133 MeV, *d)* 170 MeV; —·—·— Spergel at *c)* 140 MeV.

Best model is potential model of Brian and Phillips:

Real part is sum of one-boson-exchange terms.

Imaginary part : $V(r) = V_0(1 + e^{r/c})$ $\quad V_0 = -60$ GeV $\quad c = 1/6$ fm.

Charge-exchange $\overline{p}p \rightarrow \overline{n}n$.

Process is part of the $\overline{p}p \rightarrow$0-prongs.

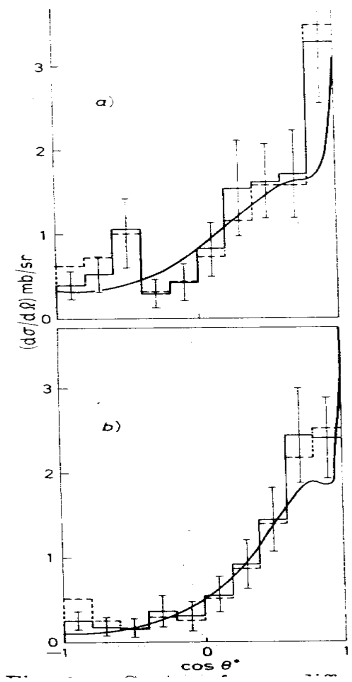
Use $\overline{n}$ annihilation "star":

425 "stars" found, events with two 0-prong interaction, 3 events with p recoil were excluded, leaving 215 events.

Several corrections and detection probability estimated.

Events are weighted by the detection probability.

Kinematics complicated by p-n mass difference.



Two $\overline{p}$ kinetic energy subsamples: 50-115 and 115-180 MeV.

Charge exchange amplitude sensitive to details of the interaction because:

difference of scattering amplitudes in I=0 and I=1 states:

Brian and Phillips model, with parameters from elastic scattering, is good description of data.

Other model easily discarded.

Controversies [12, 13]

Two papers devoted to dispute sloppy work of other groups.

Very low energy $\overline{p}p$ annihilation in flight.

Detailed discussion of limits of $p(\overline{p})$ to be free from annihilations at rest.

Suggestion of new technique to reduce stopping $\overline{p}$ contamination:

Measure incoming $p(\overline{p})$ by fitting large angle elastic scattering.

Estimate that claimed [17] rapid rise of $\overline{p}$ absorption absorption cross section for $p(\overline{p}) < 300$ MeV/c is due to contamination of stopping $\overline{p}$.

Discussion of $\overline{p}p$ diffraction scattering:

no need of anomalously large interaction radius.

Smallness of elastic cross section is due absorbing core of radius $a \simeq 1$ fm that causes absorption for $L < a/\lambdabar$.

THE "S(1929)" [18, 19, 20]

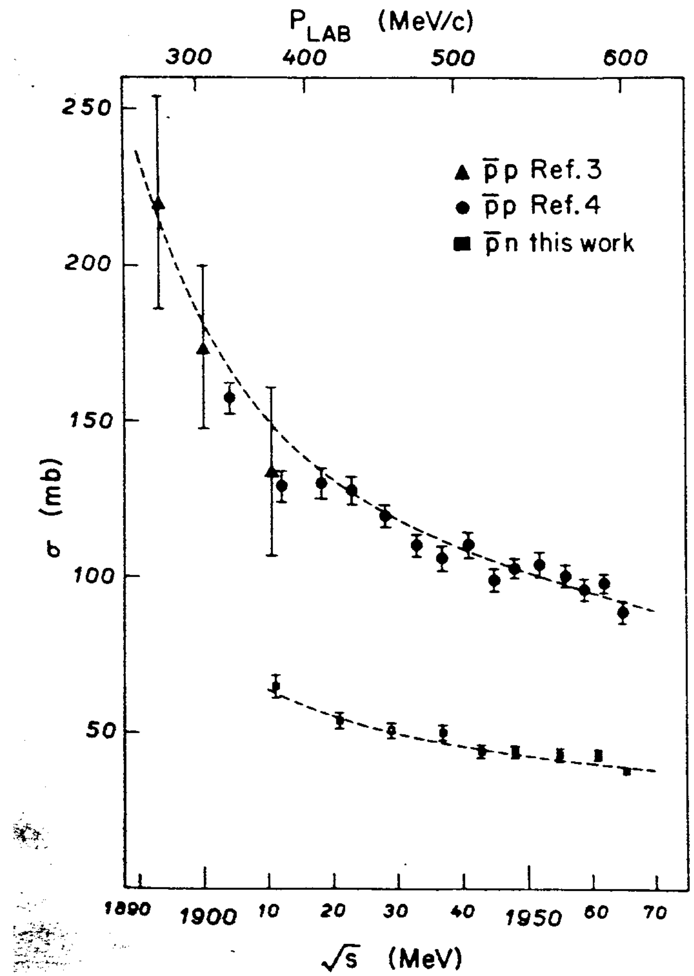
Search for proposed "S(1929)" resonance ($\Gamma \leq 35$ MeV) in $\overline{p}p$ and $\overline{p}n$ interactions.

Both total vs kinetic energy are very smooth:

$$\sigma(\overline{p}\mathcal{N}) = c + a\lambda\!\!\!/$$

Attempt to add BW results in limits to $(\Gamma(\overline{p}\mathcal{N})\Gamma)(2J_1) < 0.25$.

Reported observation of bump in $\overline{p}p$ backward scattering [20] is likely to be still a diffractive scattering effect predicted by theoretical models.



No sign of claimed resonances in $\overline{p}p \rightarrow \pi^+\pi^-$ or K^+K^- [8].

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