ESNT workshop
CEA/SPhN
March 4-5, 2013

Connections between chiral forces and the Nijmegen PWA*

Rob G.E. Timmermans
KVI, University of Groningen

* Title assigned by the organizers

university of groningen / KVI / theory

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Lessons from the Nijmegen *NN* PWA for serious people

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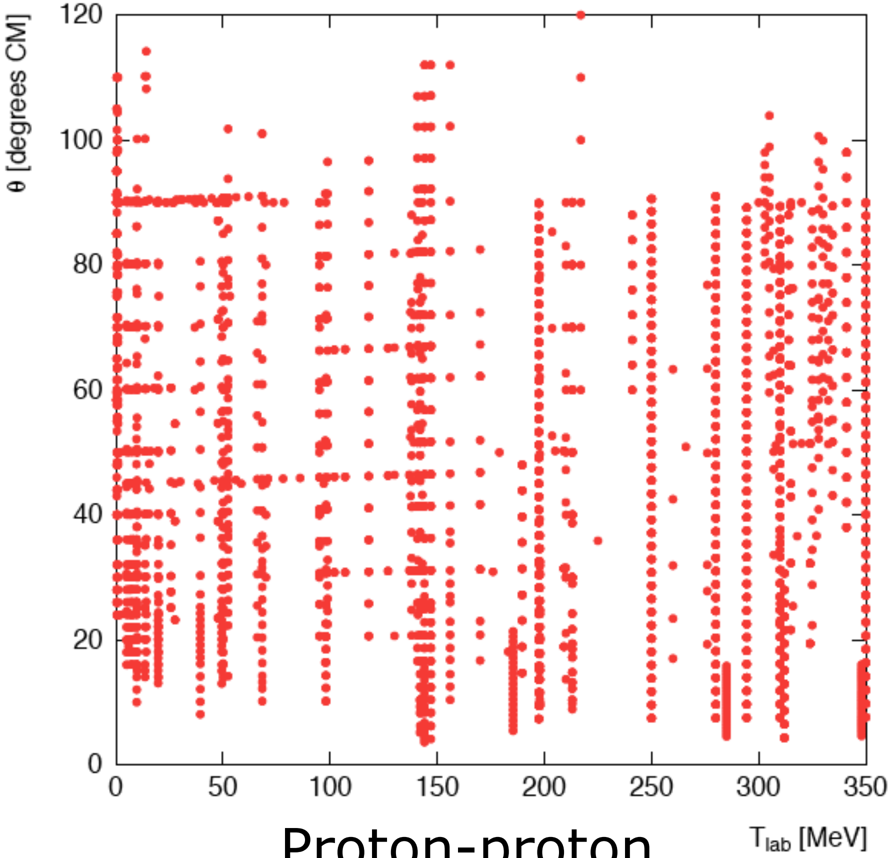
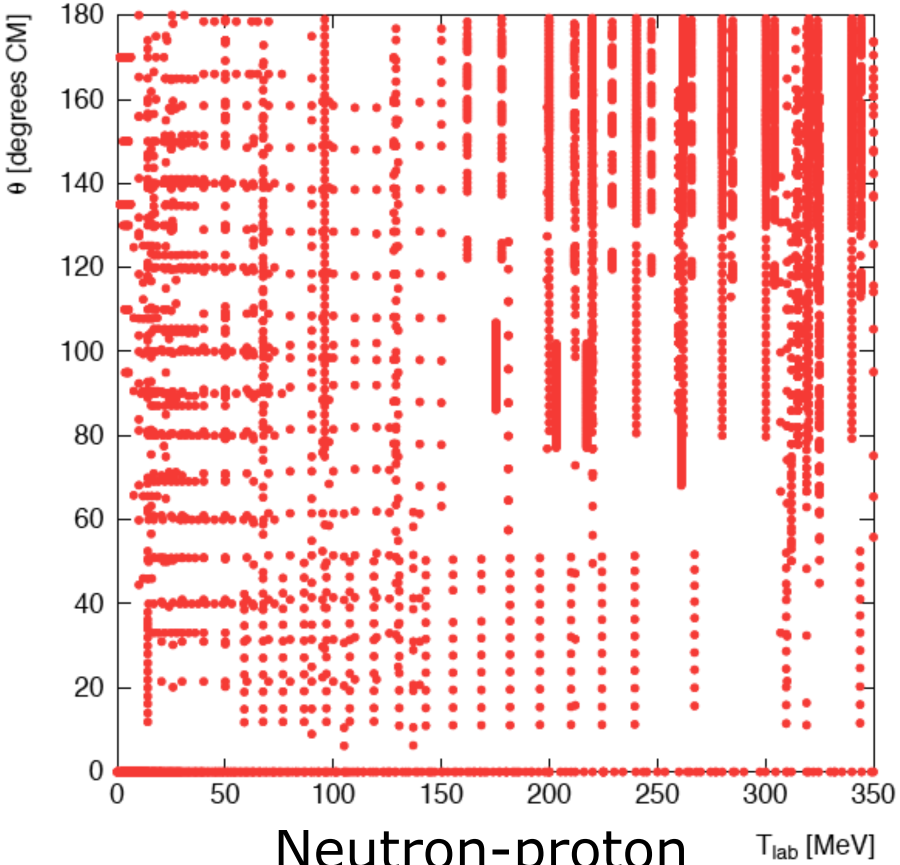
Abundance plots of the *NN* scattering data



Proton-proton



Neutron-proton

Q1: What information is in these data?

Q2: Is there a need for more experiments?

The database of the PWA (below 350 MeV)

Proton-proton

Type	# data
σ_{tot}, $\Delta\sigma_L$, $\Delta\sigma_T$	—
$d\sigma/d\Omega$	947
A_y	816
A_{ii}, C_{nn}	876
D, D_t	114
R, R′, A, A′	237
Rest	36
All	*3026*

High quality

Neutron-proton

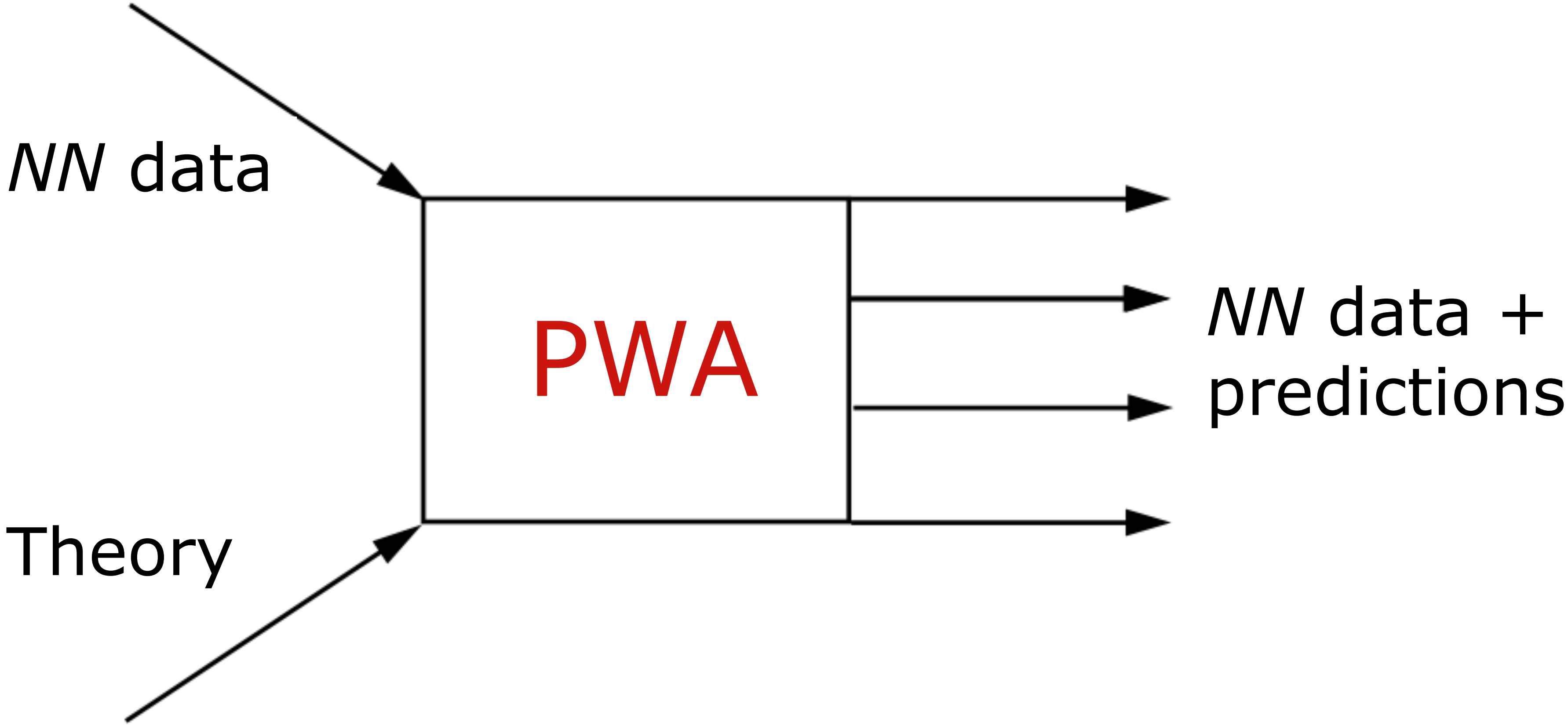
Type	# data
σ_{tot}, $\Delta\sigma_L$, $\Delta\sigma_T$	275
$d\sigma/d\Omega$	1475
A_y	1213
A_{yy}, A_{zz}	327
D_t	122
R_t, R_t', A_t, A_t'	162
Rest	78
All	*3652*

Good quality

No shortage of *NN* data…

This is the "true" database after some serious data doctoring!

Experiment ⇔ PWA ⇔ Theory



- *NN* data = *every* experimental data set (points + errors, statistical & systematic) published in a regular physics journal since 1955

- Theory input = as model independent as possible, Coulomb *etc.*

Outline of the talk:

I. The Nijmegen *NN* PWA

- History, strategy & implementation

II. "PWA93": the power & the glory

- Capita selecta

III. "χPWA": the long & the short

- Heuristic power counting

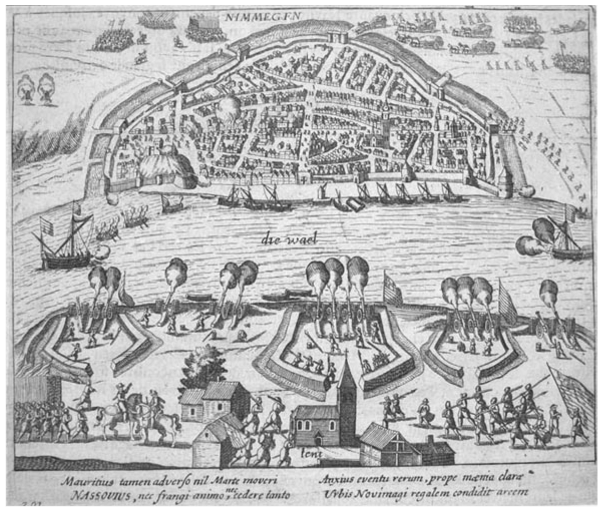
IV. Doctoring data: the sound & the fury

- The art of fielding

V. Outlook: What is left?

I. The Nijmegen *NN* PWAs

A.k.a. Those who do not know history…



Siege of Nijmegen, 1591

H.A. Bethe, "Nuclear physics," centenary review, Rev. Mod. Phys. **71**, S6 (1999).

Awakenings: 0.3-3 MeV *pp* PWA

Motivation:
- New *pp* data at very low energy ("Basel" & "Zürich" data)
- Better treatment of long-range interaction (EM & OPE)
- Consistent use of statistical methods in data analysis

"A more personal reason to do a PSA is the fact that for many years we have been a regular user of the PSAs of Arndt *et al*. We felt that in order to understand and appreciate this and related work better we needed to do this work ourselves."

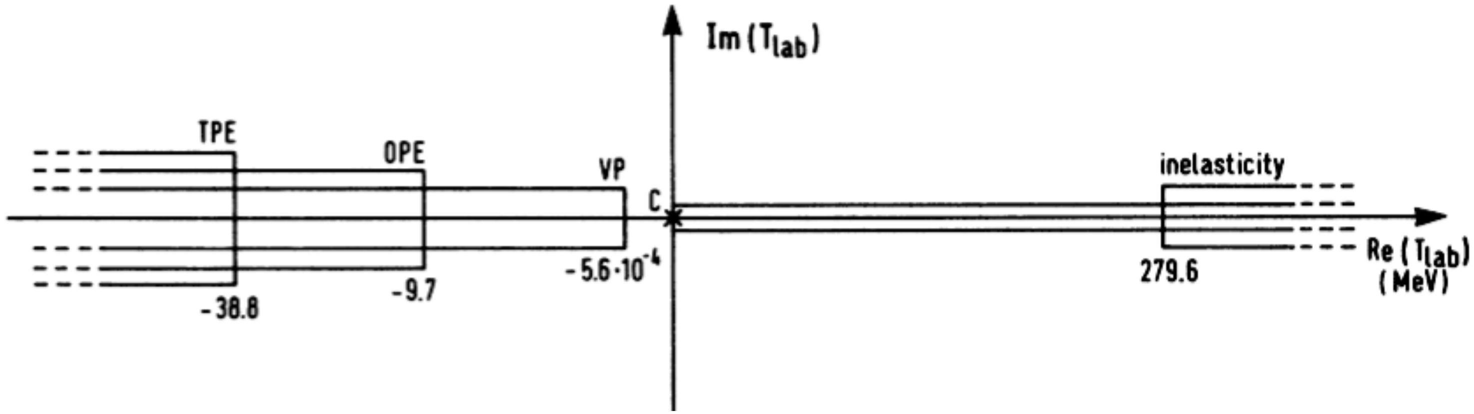
- PWA is impossible without *theory input*, cannot parametrize $\delta_L(E)$
- Need good theory for the *energy dependence* of the amplitudes

Strategy:
(i) Calculate long-range interaction V_L from field theory
(ii) Treat short-range interaction V_S completely general

W.A. van der Sanden, A.H. Emmen, and J.J. de Swart, THEF-NYM-83.11

Analyticity of the S matrix

NN forces = "left-hand cuts"



Cut structure of the S matrix in the complex T_{lab} plane

Rapid energy dependence ← nearby cuts ← *long-range* interaction

Slow energy dependence ← far-away cuts ← *short-range* interaction

Coulomb	$1/r$	Vac. pol.	$\exp(-2m_e r)/r^{3/2}$
Rel. corr. + 2γ	$1/r^2$	OPE	$\exp(-m_\pi r)/r$
Magn. mom.	$1/r^3$	TPE	$\exp(-2m_\pi r)/r^{5/2}$

Modified effective-range expansion

Separate $V = V_L + V_S \quad \delta_\ell = (\delta_L)_\ell + (\delta_S)_\ell$

Effective-range function: $(F_L)_0 = A_0^L k \cot(\delta_S)_0 + B_0^L$

Standard: $V_L = 0 \quad (\delta_L)_0 = 0, A_0^L = 1, B_0^L = 0$

$$F_0 = k \cot(\delta_0)$$

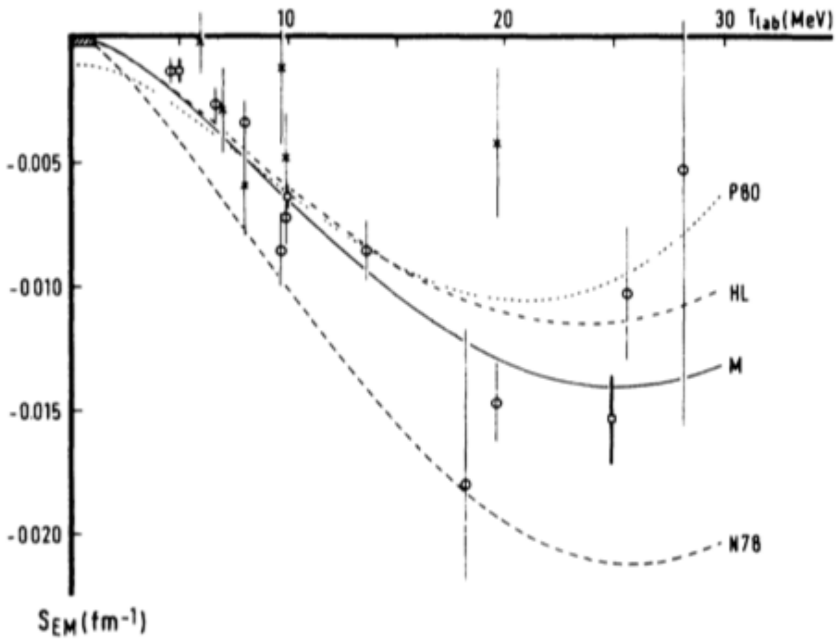
Coulomb: $V_L = V_C \quad (F_C)_0 = C_0^2(\eta) k \cot(\delta_0) + 2k\eta\, h(\eta)$

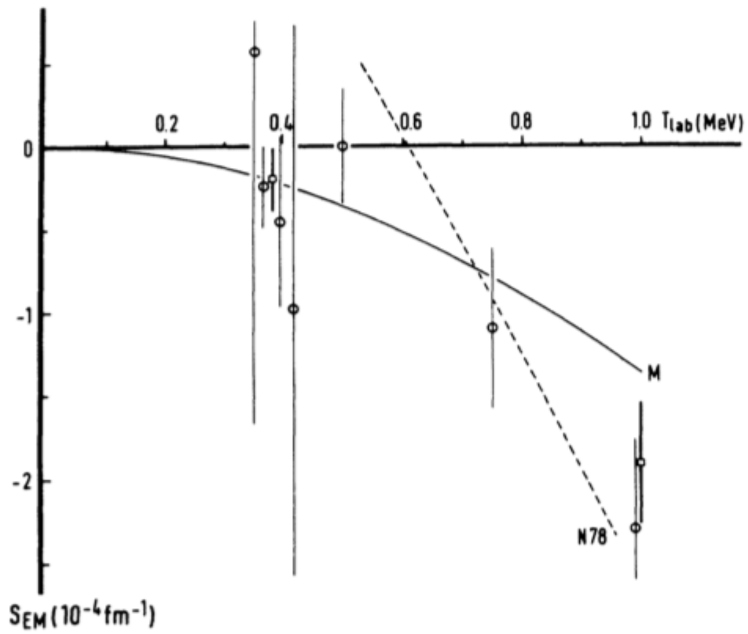
$$\begin{cases} C_0^2(\eta) = \dfrac{2\pi\eta}{e^{2\pi\eta} - 1} & \eta = \alpha / v_{\text{lab}} \\ h(\eta) = \text{Re}\left[\Psi(1 + i\eta)\right] - \ln(\eta) \end{cases}$$

G.J.M. Austen, PhD thesis, University of Nijmegen (1982).

"Shape": $(S_{\rm EM})_0 = (F_{\rm EM})_0 - \left[-\frac{1}{a_{\rm EM}} + \frac{1}{2}\, r_{\rm EM}\, k^2 \right]$

Effective-range approx. accurate below ~1 MeV, ~2% below 30 MeV



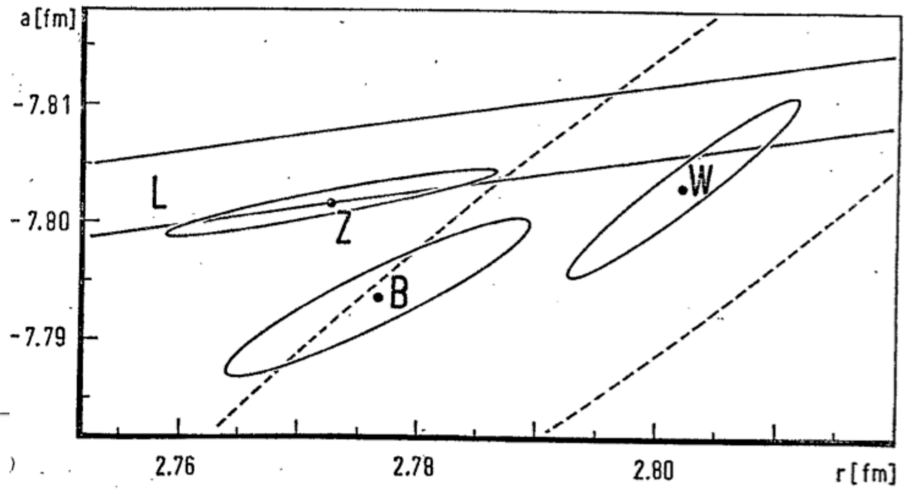


Remove OPE cut: $(F_\pi)_0 = -\frac{1}{a_\pi} + \frac{1}{2} r_\pi k^2 - \frac{P_\pi k^4}{1 + Q_\pi k^2}$

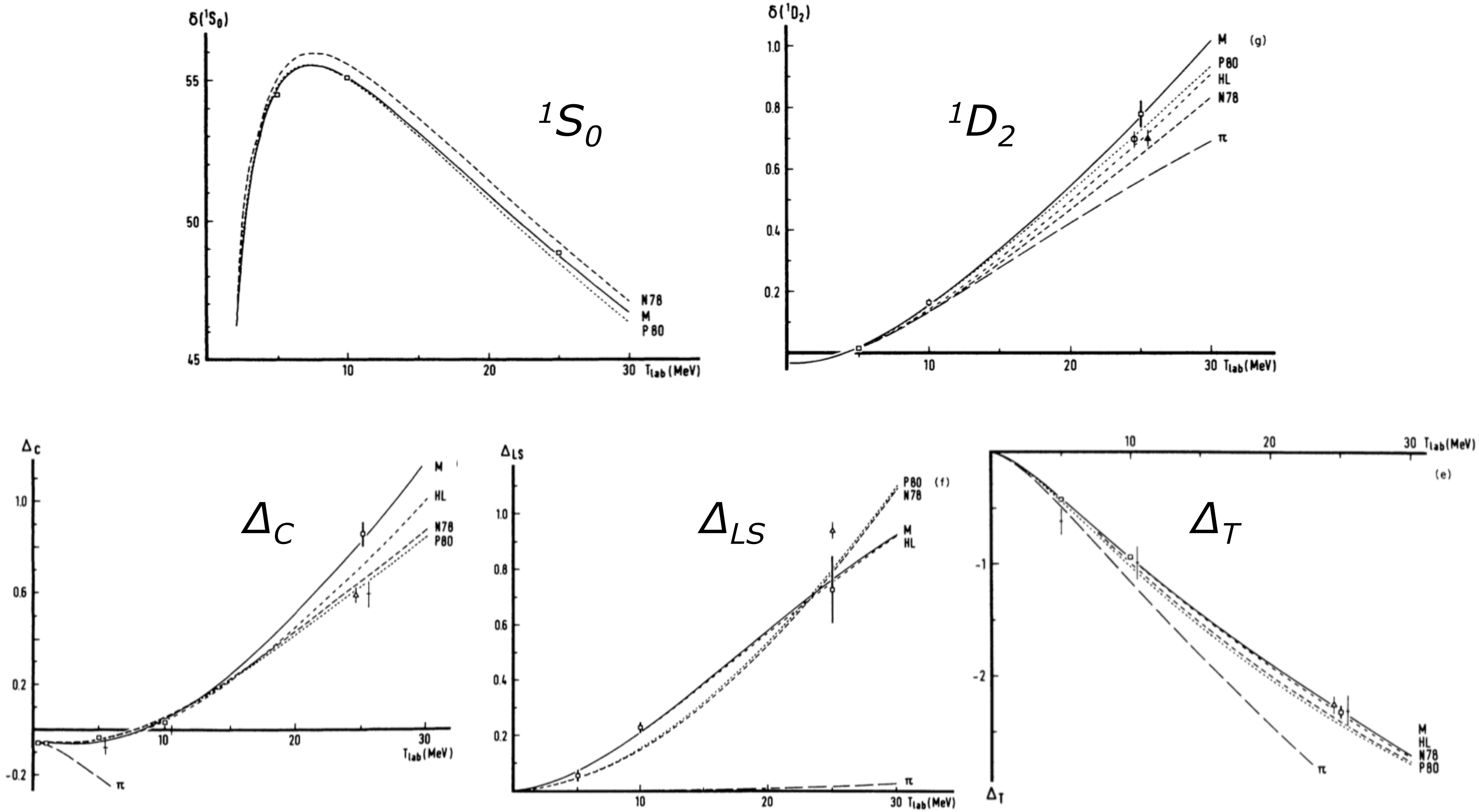
Hard to achieve numerical accuracy (artificial problem…)

TABLE III. Data reference table. me = multienergy, sg = single group. All phase shifts tabulated are with respect to Coulomb functions in degrees (from the bar decomposition of the total S matrix).

T_{lab} (MeV)	Institute, Reference	Number, Type of data[a]	% norm error	Deleted data	Predicted norm[b]	χ^2_{me}	χ^2_{sg}	sg phases	me phases	Comments
0.337 66, . . . , 0.405 17	Los Alamos64 70	5σ	∞	0.372 83 MeV	1.0162	3.79	3.52	$^1S_0 = 14.5127 \pm 0.0068$ at 0.382 54 MeV	14.5096	d
0.350 03, . . . , 0.420 03	Zürich78 3	36σ	∞		0.9976	38.79	38.76	$^1S_0 = 14.5100 \pm 0.0033$ at 0.382 54 MeV	14.5096	c
0.350 09	Zürich78 3	17σ	0.16		0.9993	25.18	25.06	$^1S_0 = 13.190 \pm 0.027$	13.199	c,e
0.400 04	Zürich78 3	3σ	0.21		1.0009	1.05	0.88	$^1S_0 = 15.26 \pm 0.14$	15.20	
0.420 06	Zürich78 3	22σ	0.16		0.9993	38.06	37.88	$^1S_0 = 15.987 \pm 0.025$	15.976	c,e
0.499 23	Zürich78 3	39σ	0.16		0.9990	31.78	28.18	$^1S_0 = 18.8916 \pm 0.0060$ $\Delta_C = -0.0600 \pm 0.0039$	18.8979 −0.0558	c
0.499 25	Basel73 4,5	3σ	0.03	all						f
0.749 96	Zürich78 3	26σ	0.16		0.9988	16.14	14.04	$^1S_0 = 26.691 \pm 0.011$ $\Delta_C = -0.0619 \pm 0.0042$	26.684 −0.0558	c
0.991 83	Zürich78 3	31σ	0.16		0.9989	25.45	22.12	$^1S_0 = 32.443 \pm 0.014$ $\Delta_C = -0.0580 \pm 0.0040$	32.418 −0.0561	c
0.991 9	Basel73 4,5	3σ	0.03	all						f
1.397, . . . , 3.037	Wisconsin66 69	51σ		all						
1.880 6	Basel73 4,5	3σ	0.03	all						
4.978	Kyoto75 75	17σ	0.4							
5.05	Wisconsin82 6,7	11P	1.0							
6.141	Erlangen79 9	6P	0.0	all						
6.141	Berkeley68 68	17σ	0.4	all						
6.968	Kyoto75 75	17σ	0.4							



First album: 0-30 MeV *pp* PWA



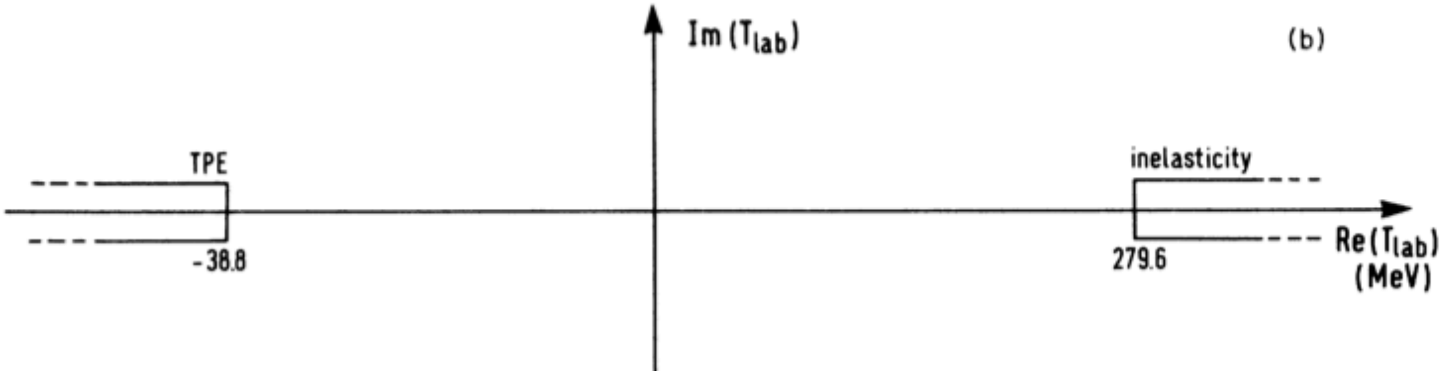
J.R. Bergervoet *et al.*, PRC **38**, 15 (1988).

The *P*-matrix method

Radial Schrödinger equation: $$\left(\frac{d^2}{dr^2} + k^2 - \frac{L^2}{r^2} - 2\mu V(r)\right)\chi(r) = 0$$

Boundary condition: $$P(b;\ k^2) = b\left(\frac{d\chi}{dr}\cdot\chi^{-1}\right)_{r=b}$$

Sum of poles: $$P(b;\ k^2) = c + k^2\sum_{n=1}^{\infty}\frac{r_n}{k^2 - k_n^2}$$



Cut structure of the *P* matrix in the complex T_{lab} plane

Wigner, Breit; H. Feshbach and E.L. Lomon, AP **29**, 19 (1964);
R.L. Jaffe and F.E. Low, PRD **19**, 2105 (1979).

$^1S_0$: $$P(k^2) = c_0 + \frac{r_0 k^2}{k^2 - k_0^2}$$

$^3P_0$, $^3P_1$: $$P(k^2) = c_{1J} + d_{1J} k^2$$

$^3P_2$-ε_2-$^3F_2$: $$P(k^2) = \begin{pmatrix} c_{12} + d_{12}k^2 & 0 \\ 0 & c_{32} \end{pmatrix} \quad c_{32} = 4$$

$^1D_2$: $$P(k^2) = c_2$$

10 parameters

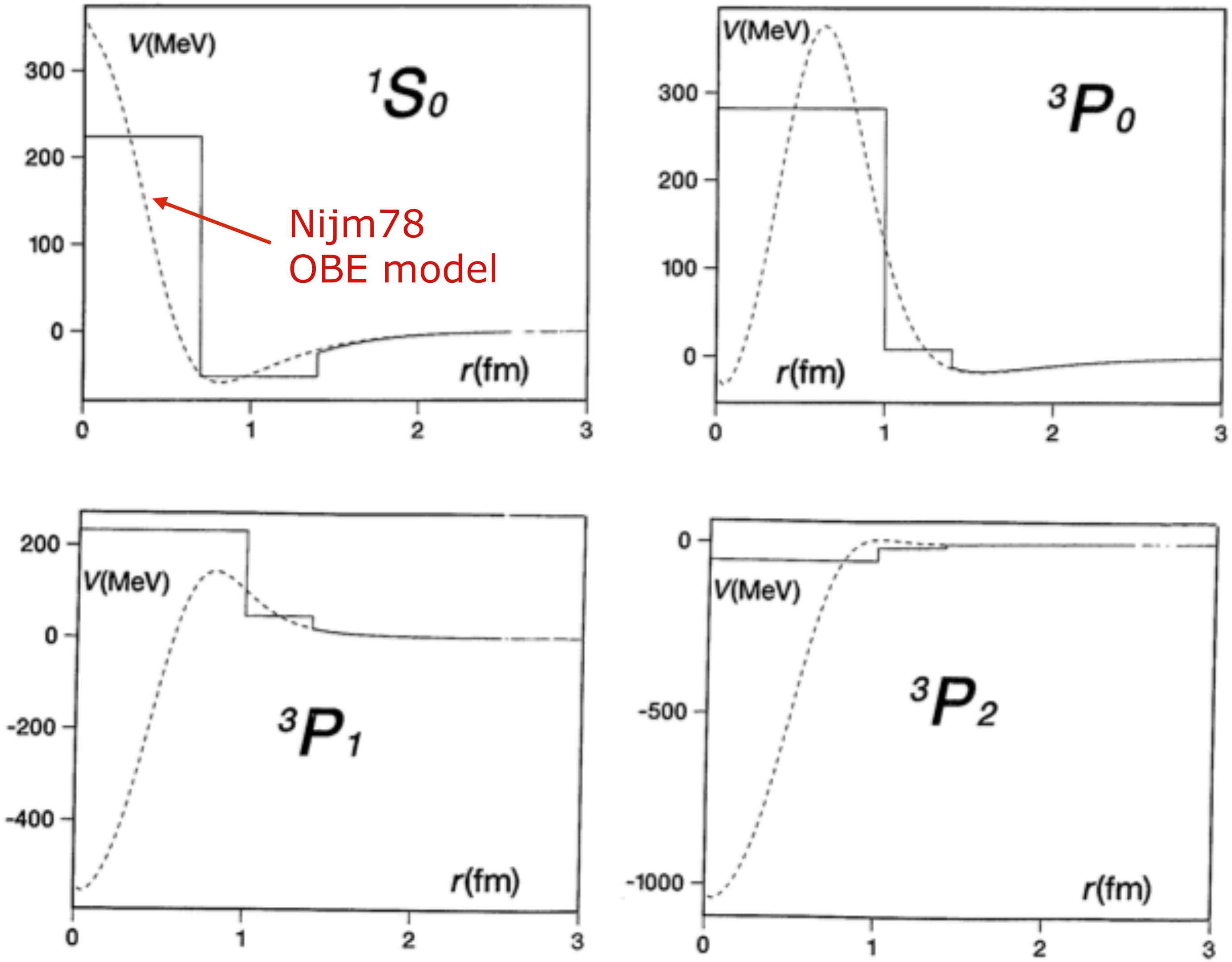
Partial wave	Parameter	Fitted value	Free value
	$g^2_{pp\pi^0}/4\pi$	14.5±1.2	
$^1S_0$	c_0	0.230±0.013	1
	r_0	1.58±0.86	2
	k_0^2	3.3±1.5	5.0
$^3P_0$	c_{10}	3.39±0.77	2
	d_{10}	−2.9±1.5	−0.4
$^3P_1$	c_{11}	1.70±0.48	2
	d_{11}	−0.25±0.86	−0.39
$^3P_2$-ϵ_2-$^3F_2$	c_{12}	1.355±0.030	2
	d_{12}	−0.20±0.16	−0.39
$^1D_2$	c_2	1.01±0.31	3

Free *P* matrix: $c = \ell + 1$, $r_n = 2$, $k_n = z_n/b$

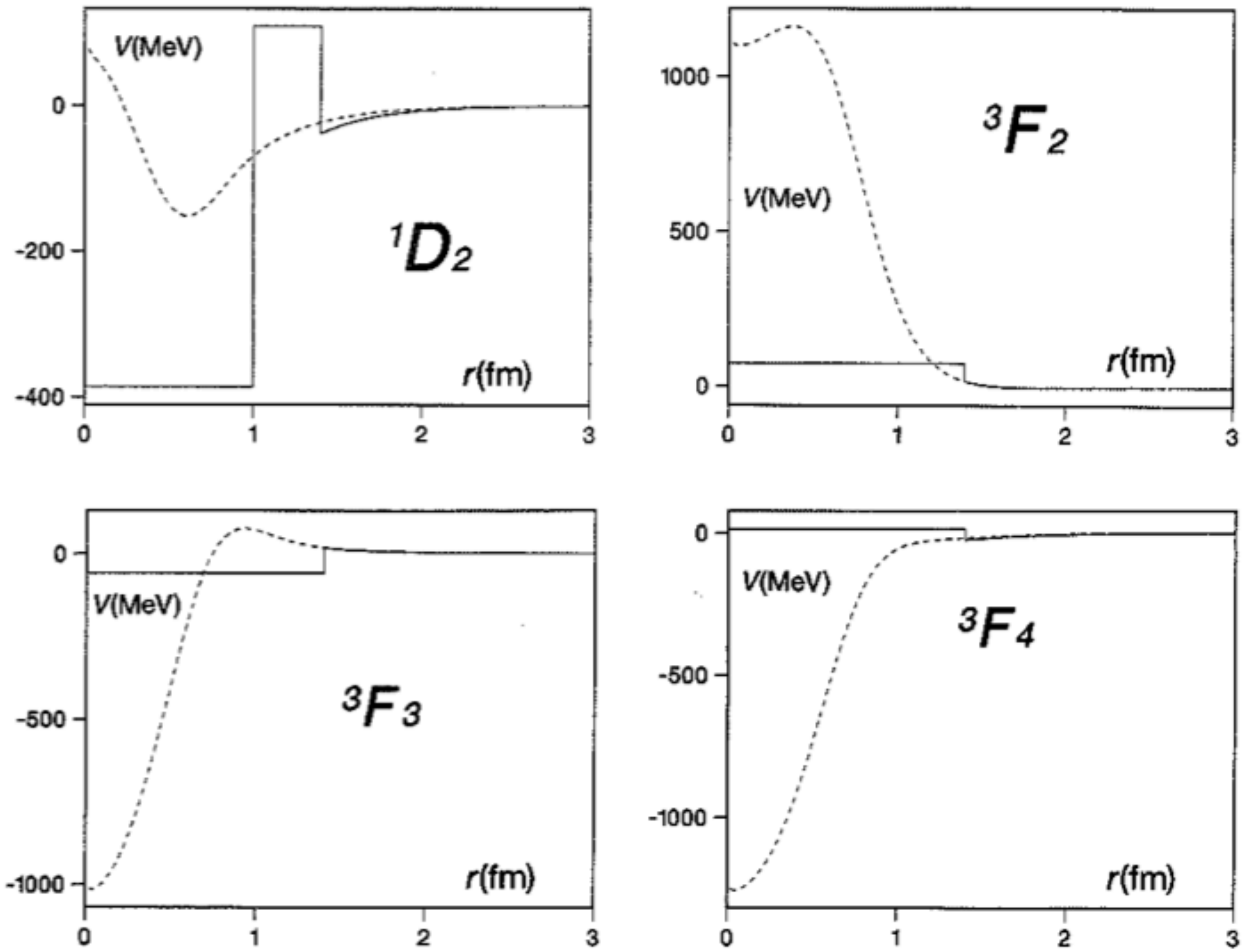
II. PWA93: the power & the glory

"All phase shifts and mixing parameters can be determined accurately"

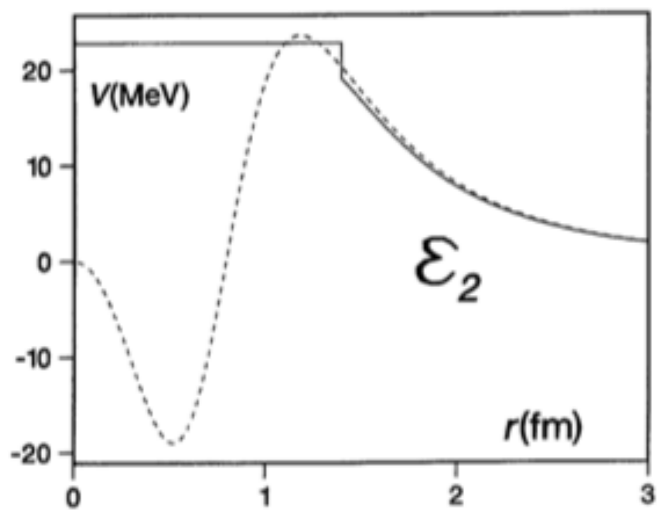
"A local *pp* potential model"

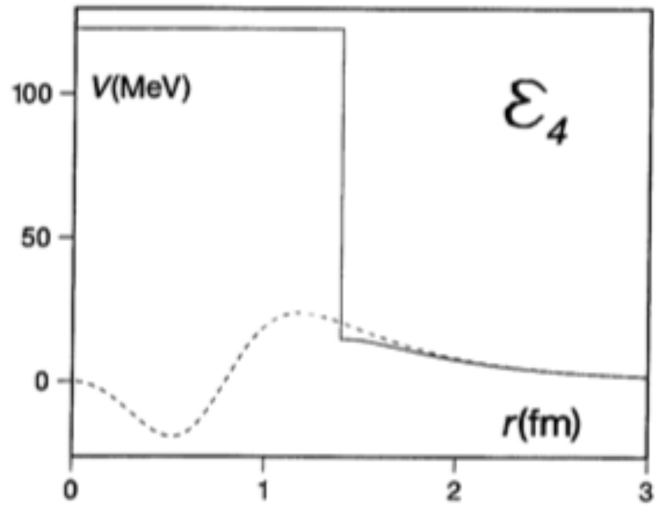


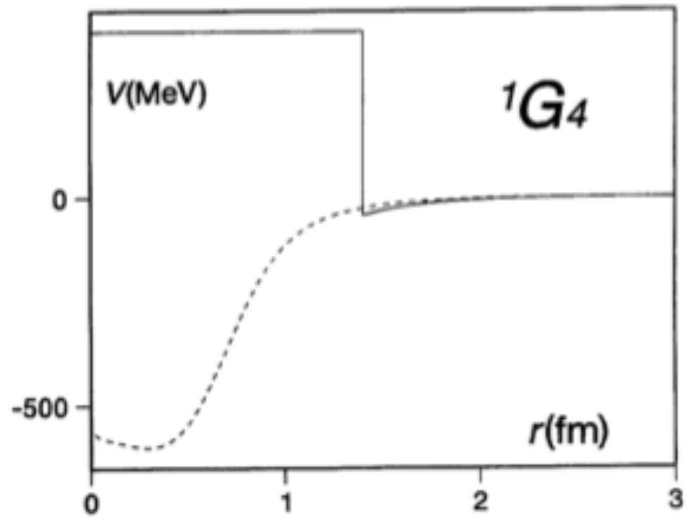
J.R. Bergervoet, PhD thesis, University of Nijmegen (1987).



The details of the short-range physics do not matter







partial wave	a(fm)	f_{med}	V_1(MeV)	V_2(MeV)
$^1S_0$	0.7	1.2	224 ± 5	−52.0 ± 0.4
$^3P_0$	1.0	1.0	282 ± 72	7 ± 12
$^3P_1$	1.0	1.0	232 ± 40	48 ± 7
$^3P_2$	1.0	1.0	−54 ± 2	−15.8 ± 0.8
$^1D_2$	1.0	1.8	−387 ± 8	107 ± 3
ε_2	-	1.0	23 ± 2	
$^3F_2$	-	1.0	75 ± 20	
$^3F_3$	-	0.5	−58 ± 14	
$^3F_4$	-	1.6	14 ± 21	
$^1G_4$	-	1.8	399 ± 97	
ε_4	-	1.6	123 ± 65	

O(20) parameters

"PWA93": 0-350 MeV *pp* & *np* PWA

- *P*-matrix parametrization
- energy-dependent, *r*-independent square wells

- database up to $T_{\rm lab}$ = 350 MeV
- first *pp* PWA 0-350 MeV
- *np* PWA, *I=0 and* $^1S_0$(*np*) waves searched
  other *I=1* waves corrected from *pp* for EM and pion mass

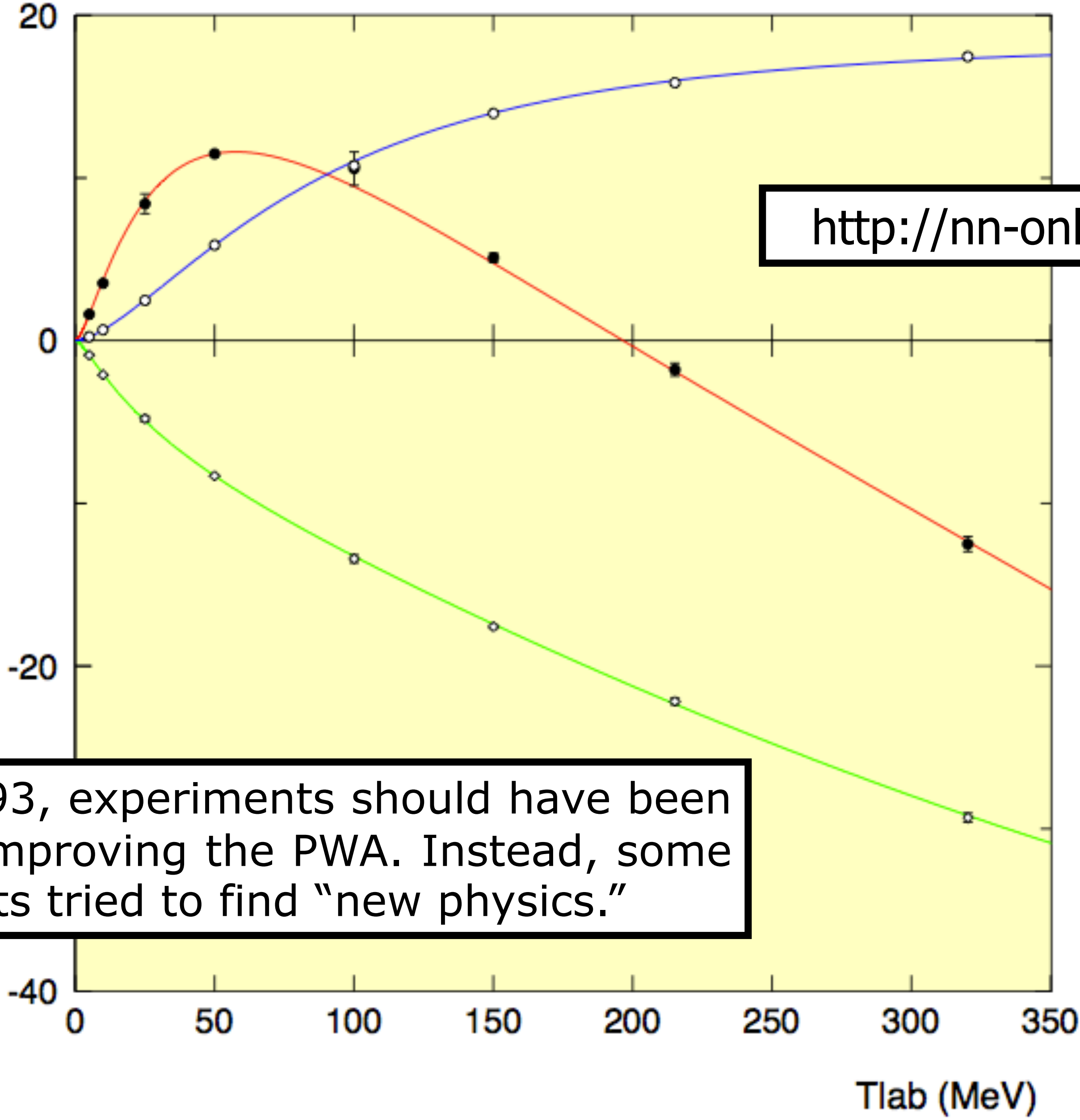
Intermediate-range physics required:
- Nijmegen "soft-core" OBE potential Nijm78
- check model dependence: Paris80 potential

"EFT is like the Antarctic, cold and barren:
freeze out everything, only nucleons and pions...
no ρ, ω, φ, η, η′, ε, no pomeron, no extended nucleon…"

"All phase shifts and mixing parameters can be determined accurately"

J.R. Bergervoet *et al.*, PRC **41**, 1435 (1990);
V.G.J. Stoks *et al.*, PRC **48**, 792 (1993).

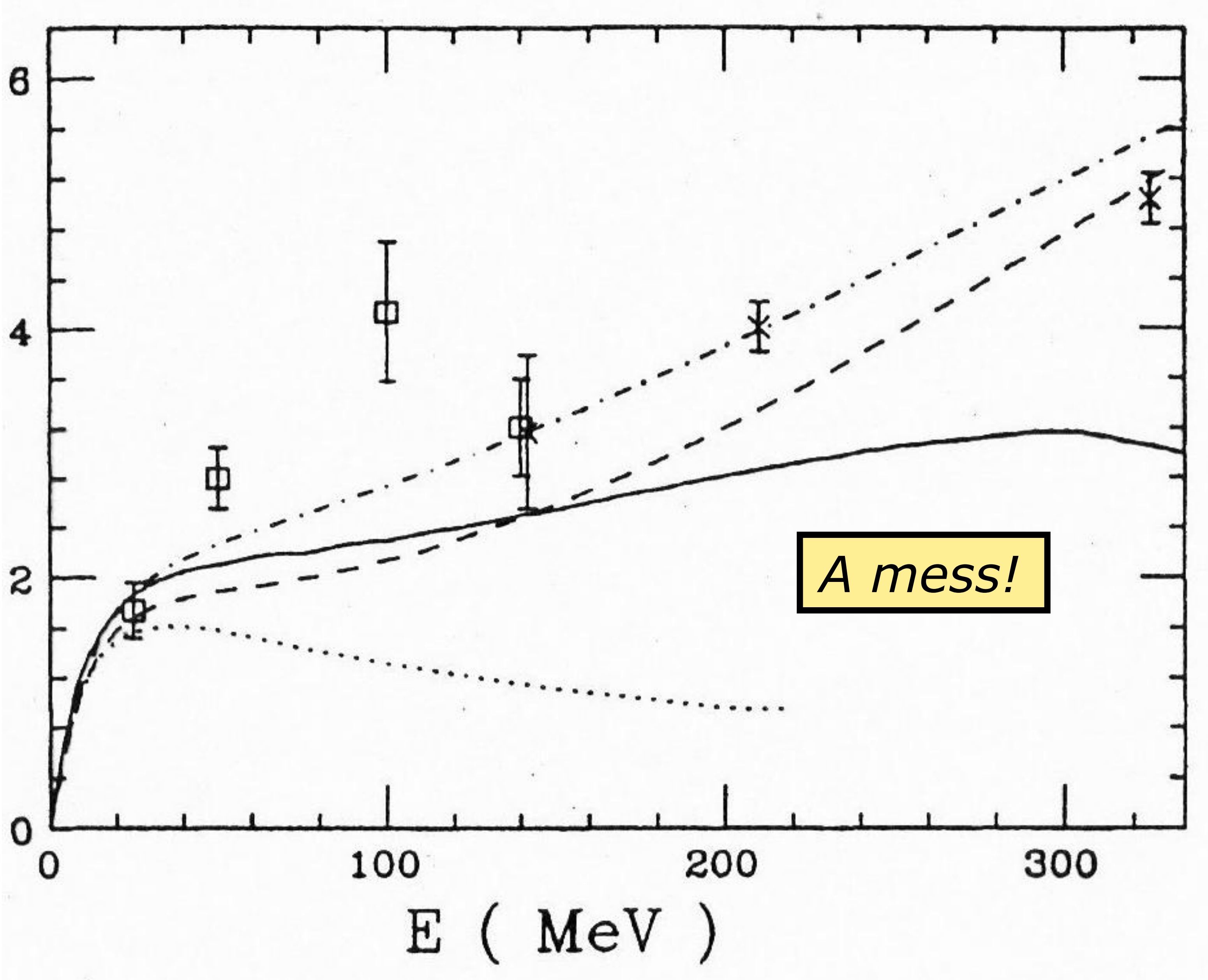
The $^3P_{0,1,2}$ phase shifts after the PWA



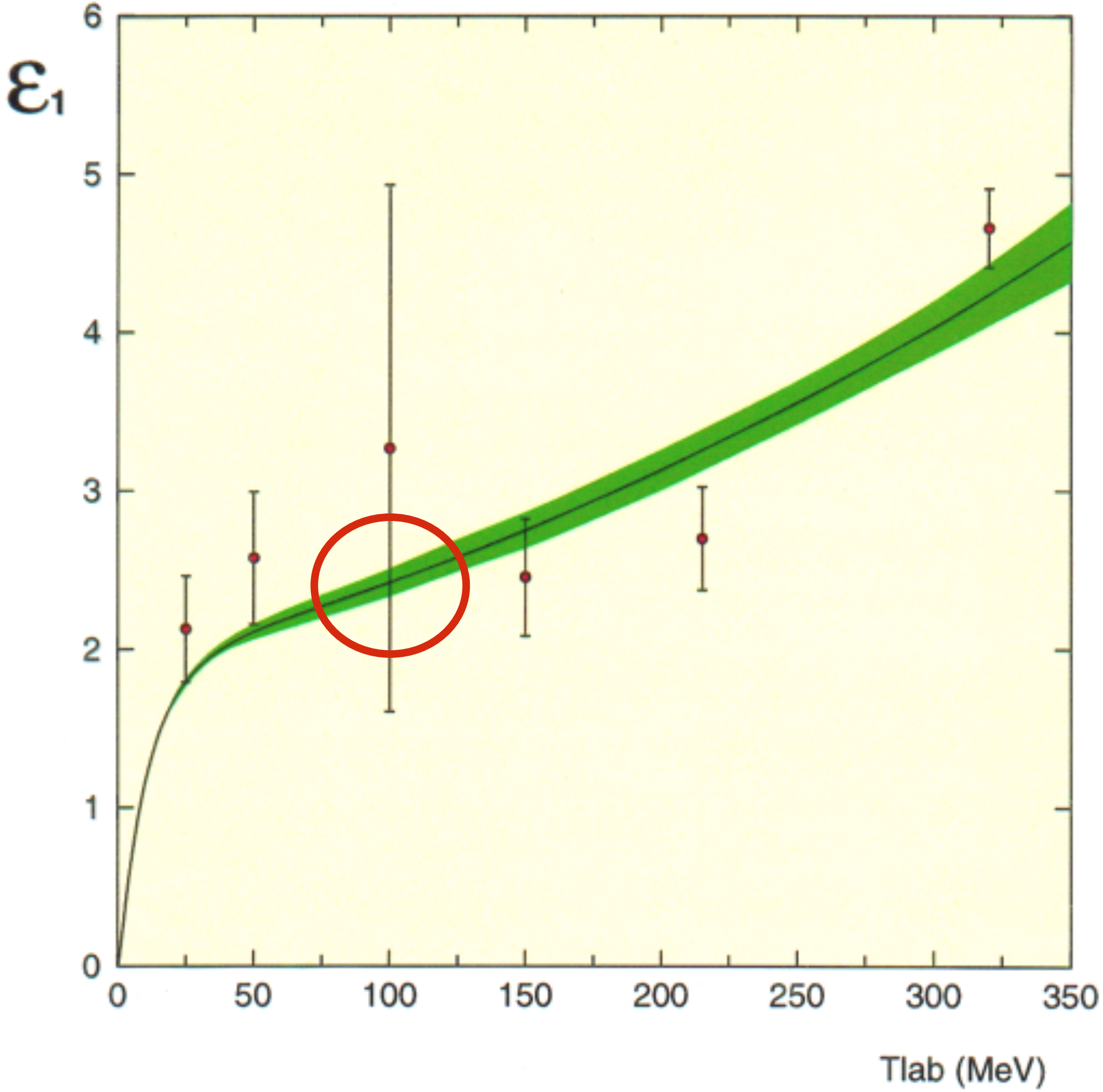
http://nn-online.org

After PWA93, experiments should have been aimed at improving the PWA. Instead, some experiments tried to find "new physics."

The $^3S_1$-$^3D_1$ mixing parameter ε_1 *before* the PWA



The $^3S_1$-$^3D_1$ mixing parameter ε_1 *after* the PWA



Note: multi-energy (with error!) vs. single-energy

Energy-dependent (multi-energy) versus single-energy PWA

Example 1:

50.04 MeV *pp* A_y data

Constrains the ^3P_J phases *i.e.* tensor & spin-orbit

		Δ_T	Δ_{LS}
m.e.	w/o	−3.745°(22)	2.601°(34)
	with	−3.733°(12)	2.606°(21)
s.e.	w/o	−3.759°(43)	2.509°(87)
	with	−3.741°(14)	2.592°(28)

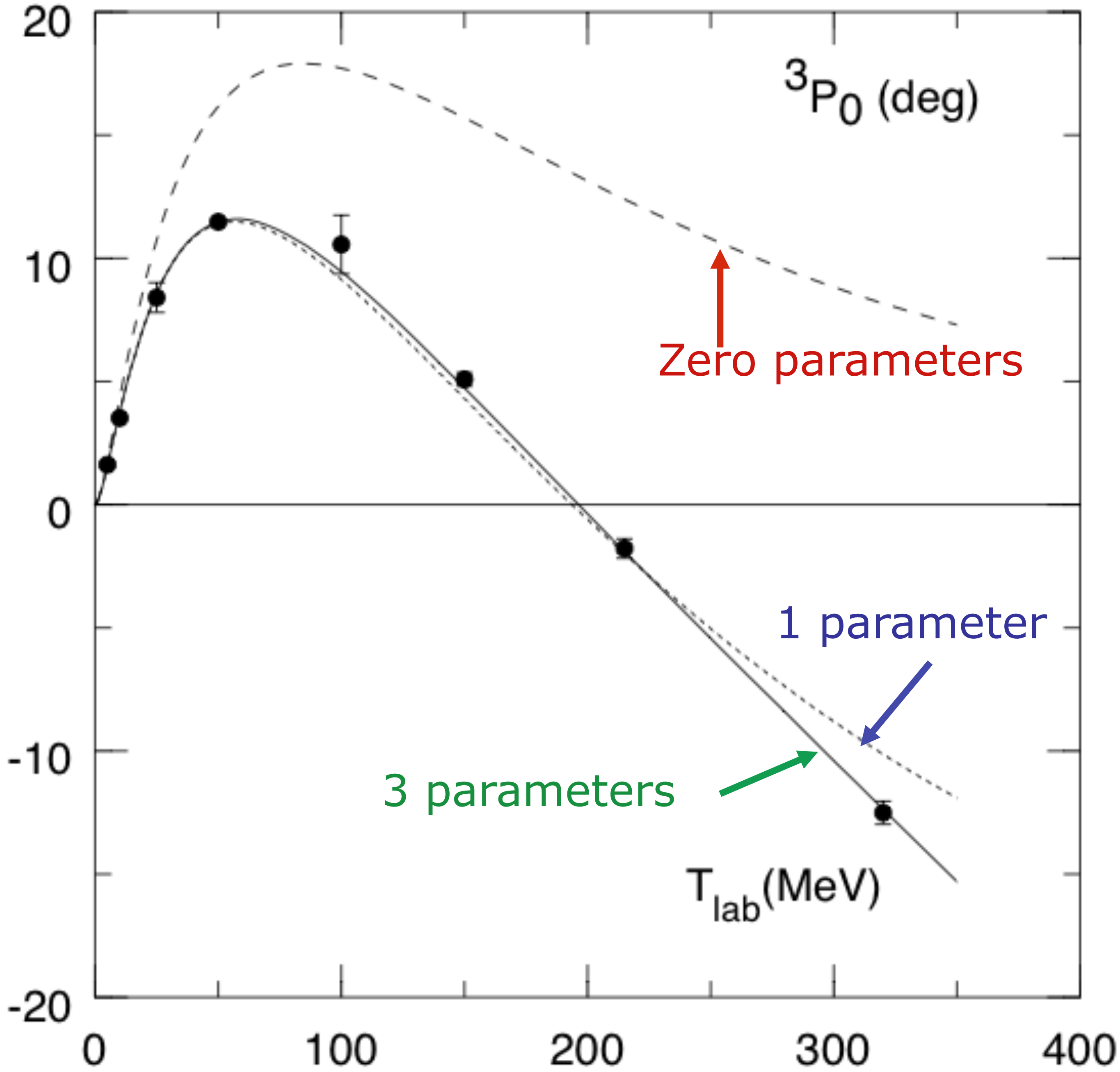
Example 2:

67.5 MeV *np* A_{zz} & $\Delta\sigma_L$ data

Constrains the $^1P_1$ phase & the mixing parameter ε_1

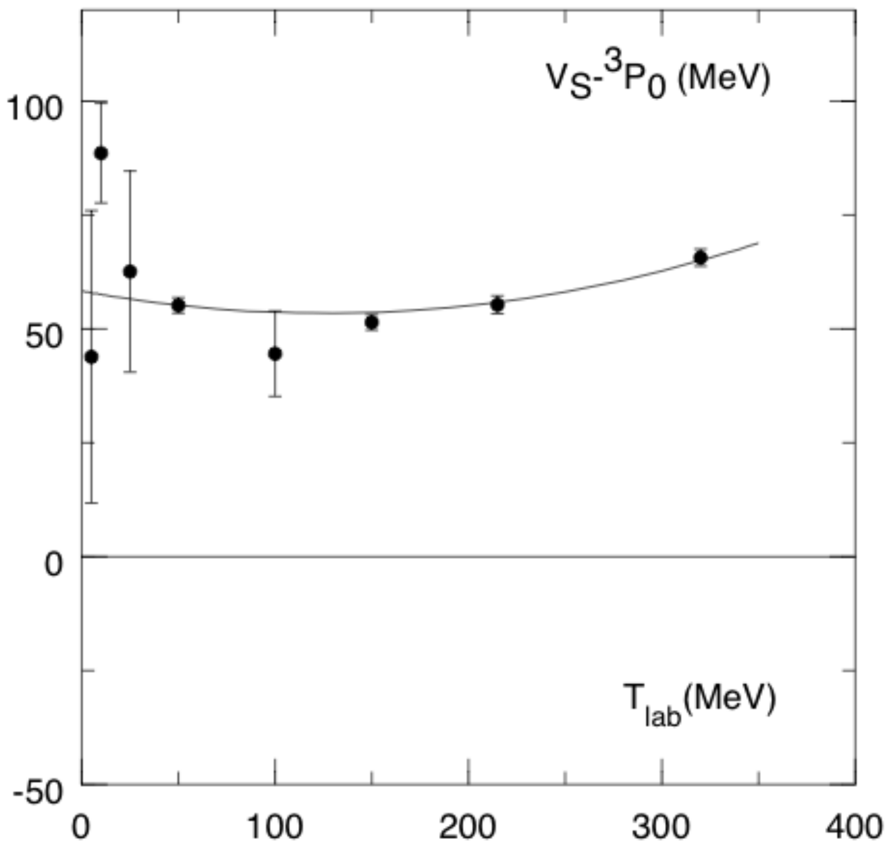
		$\delta(^1P_1)$	ε_1
m.e.	w/o	−9.78°(11)	2.15°(34)
	with	−9.67°(08)	2.11°(21)
s.e.	w/o		5.69°(64)
	with		2.57°(36)

More stable, accurate, and precise

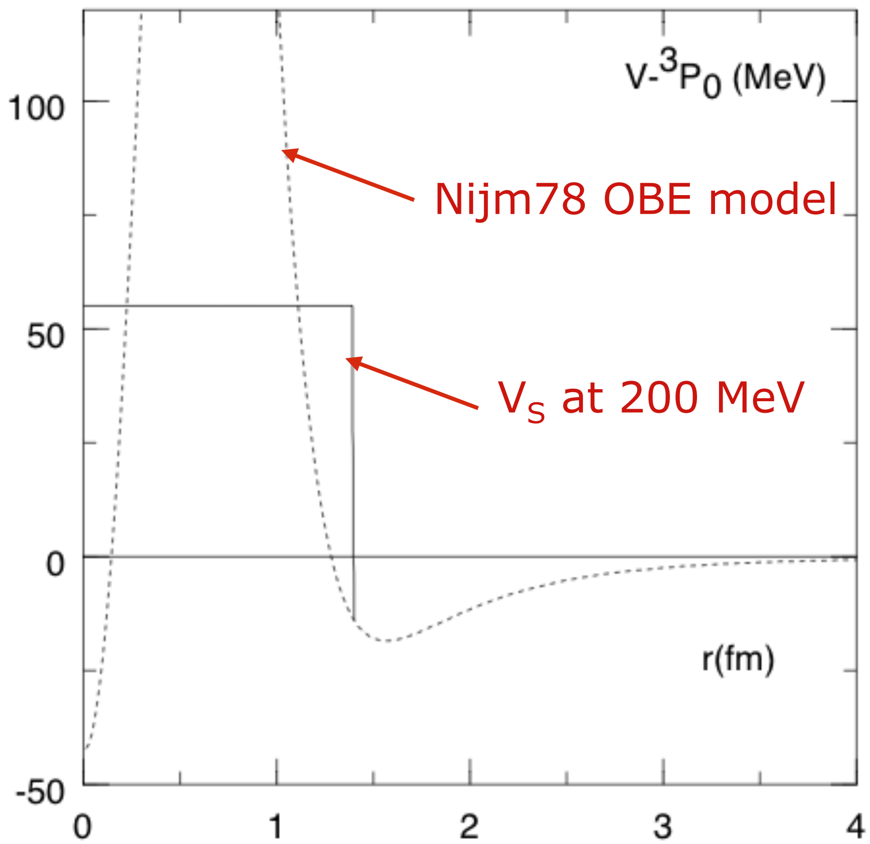


20
10
0
-10
-20
0
100
200
300
400
$^3P_0$ (deg)
Zero parameters
1 parameter
3 parameters
T_{lab}(MeV)

Energy dependence of the short-range interaction for $^3P_0$



Radial dependence of the potential for the $^3P_0$ wave



Generation II "HQ" (High-Quality) potential models
Nijm-I,II ('93), Reid93, AV18 ('95), CD-Bonn ('96)

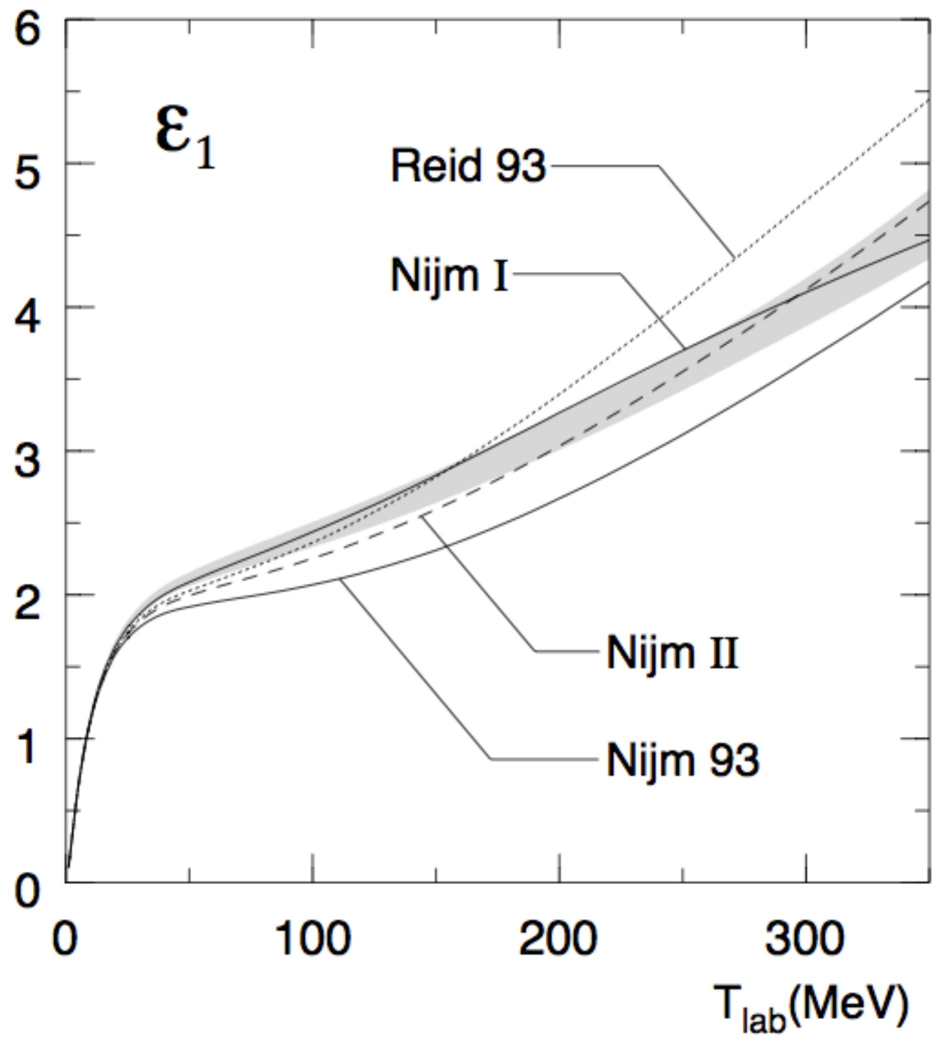
Outcome of PWA93

$\chi^2/N_{data} \approx 1$ below 350 MeV

parameters ≈ 40-50

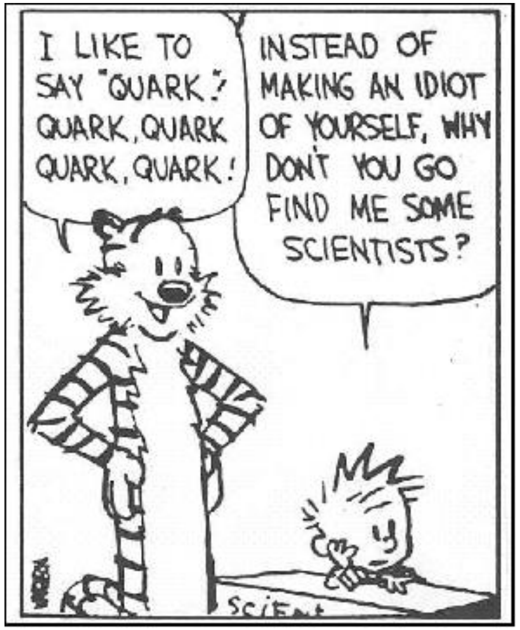
OPE & very different
short-range phenomenology

Alternative PWAs?



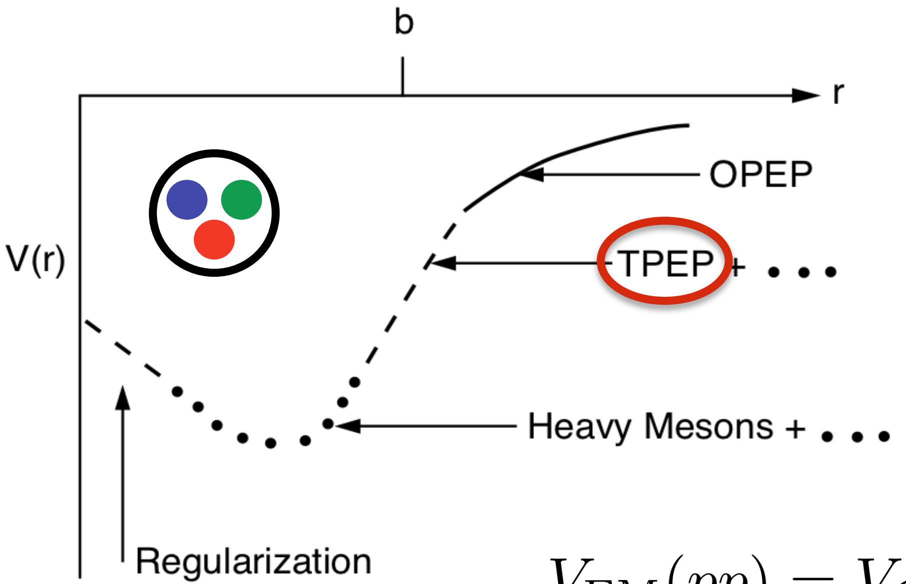
III. χPWA: the long & the short

A.k.a. what about QCD?



"You know, young man, symmetries are overrated in physics…"

0-350 MeV *pp* χPWA



$$(\Delta + k^2)\,\psi = 2M_r V_L\,\psi$$

χPWA as a "tool" to study
- the long-range interaction
- chiral EFT, heuristically

$$V_{\rm EM}(pp) = V_{C1} + V_{C2} + V_{\rm VP} + V_{\rm MM}(pp)$$
$$V_{\rm EM}(np) = V_{\rm MM}(np)$$

Coulomb + two-photon exchange:

$$V_{C1} = \frac{\alpha'}{r}$$

$$V_{C2} = -\frac{1}{2M_p^2}\left[(\Delta + k^2)\frac{\alpha}{r} + \frac{\alpha}{r}(\Delta + k^2)\right] \simeq -\frac{\alpha\alpha'}{M_p r^2}$$

Higher partial waves $J \geq 5$ treated in CDWBA

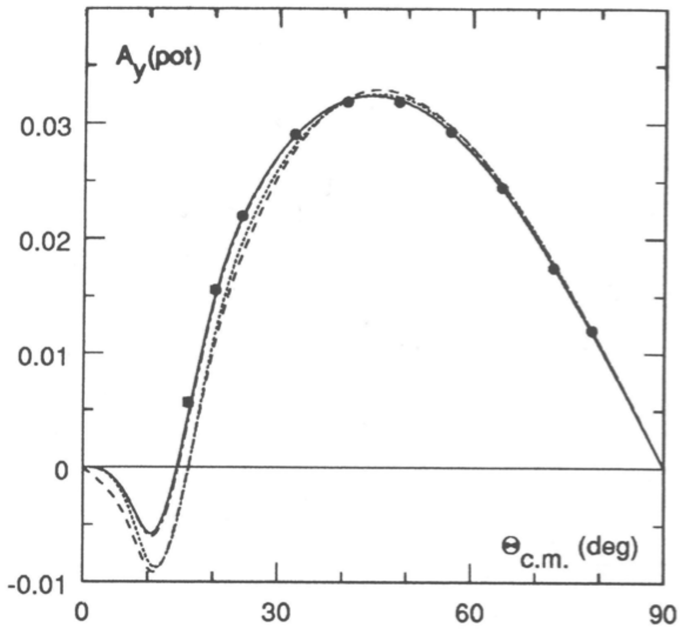
Long-range EM effects

Magnetic-moment interaction:
long-range spin-orbit and tensor force

$$V_{\rm MM}(pp) = -\frac{\alpha}{4M_p^2 r^3}\left[\mu_p^2 S_{12} + (6+8\kappa_p)\mathbf{L}\cdot\mathbf{S}\right]$$

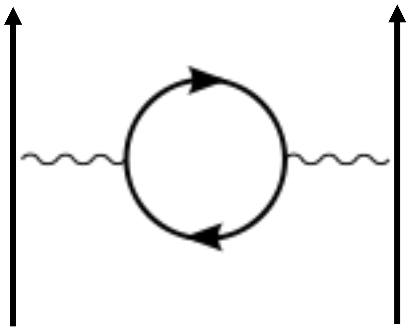
$$V_{\rm MM}(np) = -\frac{\alpha\kappa_n}{2M_n r^3}\left[\frac{\mu_p}{2M_p}S_{12} + \frac{1}{M_r}(\mathbf{L}\cdot\mathbf{S}+\mathbf{L}\cdot\mathbf{A})\right]$$

Effect in *pp* χPWA: $\Delta\chi^2_{\rm min} \approx -400$, so *20 s.d.*



Vacuum polarization (enhances V_C):
long-range: $1/2m_e \approx 200$ fm
relevant in proton-proton $^1S_0$ wave

$$V_{\rm VP} = \frac{2\alpha}{3\pi}\frac{\alpha'}{r}\int_1^\infty dx e^{-2m_e r x}\left(1+\frac{1}{2x^2}\right)\frac{\sqrt{x^2-1}}{x^2}$$



Effect in *pp* χPWA: $\Delta\chi^2_{\rm min} \approx -215$, so *15 s.d.*

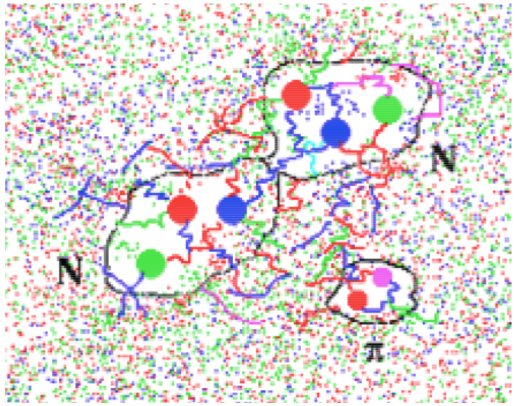
M.C.M. Rentmeester *et al.*, PRL **82**, 4992 (1999).

One-pion exchange: the "glue" of nuclei

$$V(m) = \frac{1}{3}\left(\frac{m}{m_{\pi^\pm}}\right)^2 \frac{e^{-mr}}{r}\left[\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + S_{12}\left(1+\frac{3}{(mr)}+\frac{3}{(mr)^2}\right)\right]$$

Charge-dependent OPE:

$$V_\pi(pp) = f_p^2 V(m_{\pi^0})$$
$$V_\pi(np) = -f_0^2 V(m_{\pi^0}) + (-)^{I+1} 2 f_c^2 V(m_{\pi^+})$$



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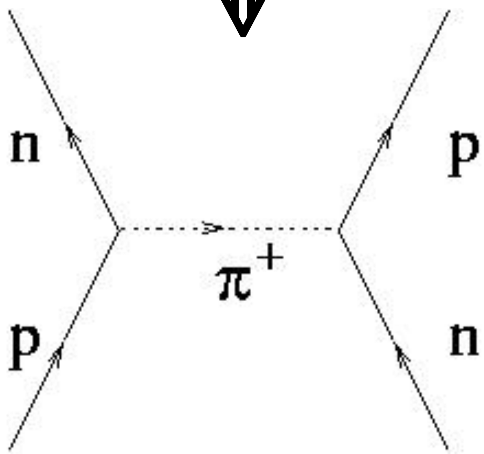


Recommended value:

$$f^2 = 0.0750(9)$$

Goldberger-Treiman relation:

$$\sqrt{4\pi} f = g_A m_{\pi^+} / F_\pi$$

i.e. the "discrepancy" ≈1.2% = $O(m_\pi^2/\Lambda^2)$

R.G.E. Timmermans *et al.*, PRL **67**, 1074 (1991);
U. van Kolck *et al.*, PLB **371**, 169 (1996).

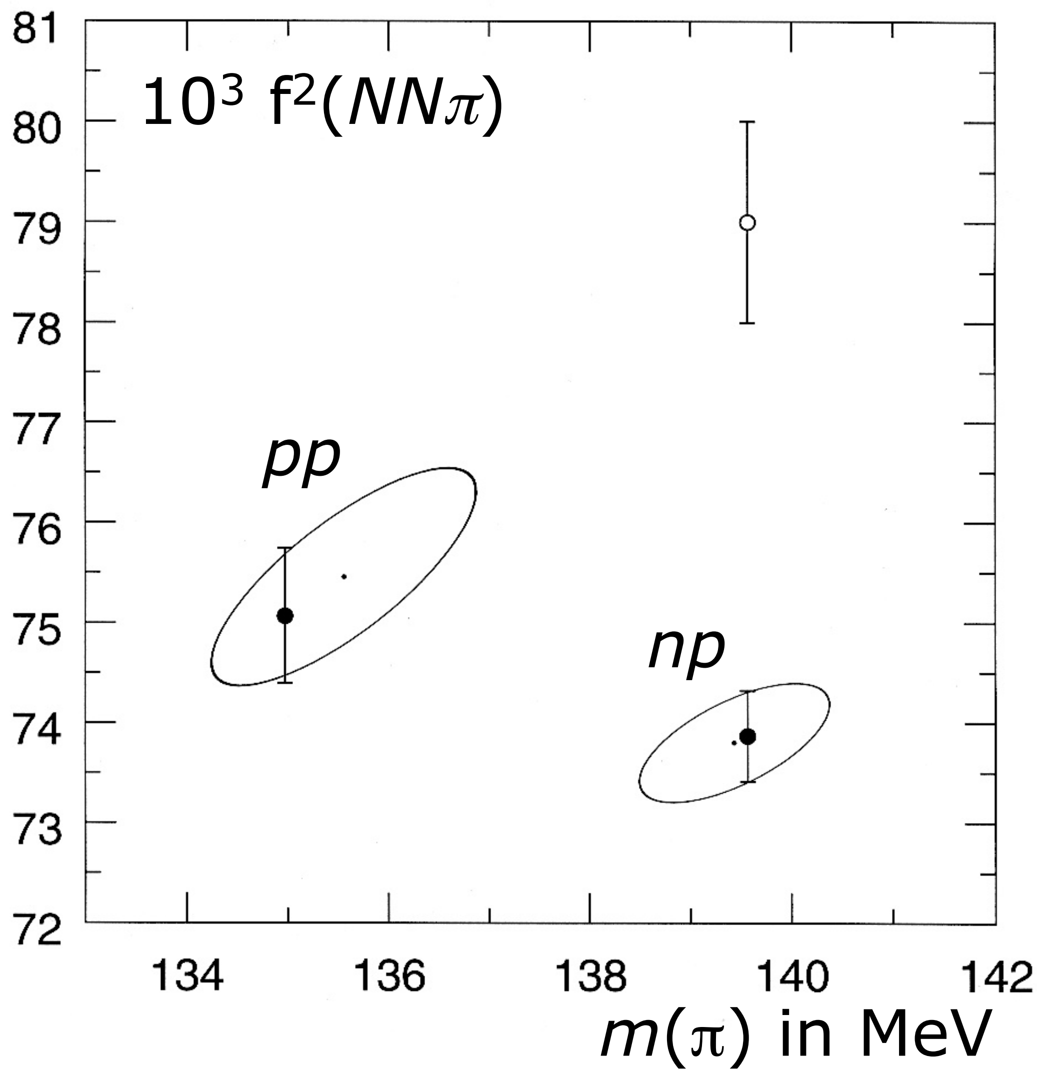
“Seeing” one-pion exchange

The coupling constant is determined *at the pion pole* from long-range OPE

Fit the pion masses from the *pp* and the *np* data:

$$m_{\pi^0} = 135.6(10)\ \mathrm{MeV}$$
$$m_{\pi^\pm} = 139.6(13)\ \mathrm{MeV}$$

No significant evidence, yet, for isospin violation: $f(pp\pi^0) \approx f(nn\pi^0) \approx f(np\pi^\pm)$



Λ_0 (MeV)	500.0	750.0	1000.0	1250.0	∞
$10^3\, f^2_{pp\pi^0}$	75.2(0.5)	75.0(0.5)	75.0(0.5)	75.0(0.5)	75.0(0.5)
$\chi^2_{\rm min}$	1786.3	1786.4	1786.4	1786.4	1786.4

No dependence on:
- cutoff in $NN\pi$ form factor
- energy range of the fit
- type of observable
- partial wave

Partial wave	$10^3\, f^2$(wave)	$10^3\, f^2$(rest)	$\chi^2_{\rm min}$
$^1S_0$	79.7(1.9)	74.5(0.6)	1779.8
$^1D_2$	74.6(0.8)	74.6(0.6)	1786.0
$^1G_4$	74.6(2.1)	74.6(0.6)	1786.0
$^3P_0$	72.7(1.7)	74.8(0.6)	1784.6
$^3P_1$	74.9(0.7)	74.3(0.8)	1785.6
$^3P_2$–$^3F_2$	74.7(0.8)	74.6(0.6)	1786.0
$^3F_3$	73.3(1.3)	74.8(0.6)	1784.8
$^3F_4$–$^3H_4$	75.1(0.9)	74.5(0.6)	1785.6

Type	$N_{\rm dat}$	χ^2(min)	$10^3\, f^2_{pp\pi^0}$(min)
$d\sigma/d\Omega$	821	822.7	76.5(0.9)
A_y	558	580.0	75.0(0.9)
A_{ii},C_{nn}	66	51.9	71.0(2.1)
D,D_t	97	104.9	72.0(1.9)
R,R',A,A'	209	193.1	74.9(1.6)
rest	36		
all	1787	1786.4	75.0(0.5)

Type	$N_{\rm dat}$	χ^2(min)	$10^3\, f^2_c$(min)
$\sigma_{\rm tot}$,$\Delta\sigma_{\rm L}$,$\Delta\sigma_{\rm T}$	252	229.5	75.1(1.1)
$d\sigma/d\Omega$	1350	1363.2	75.6(0.6)
A_y	738	717.8	74.8(0.4)
A_{yy},A_{zz}	86	71.2	74.4(0.6)
D_t	43	39.5	75.1(1.1)
R_t,R'_t,A_t,A'_t	43	54.7	73.1(1.0)
all	2512	2480.4	74.8(0.3)

V. Stoks, R. Timmermans, and J.J. de Swart, PRC **47**, 512 (1993).

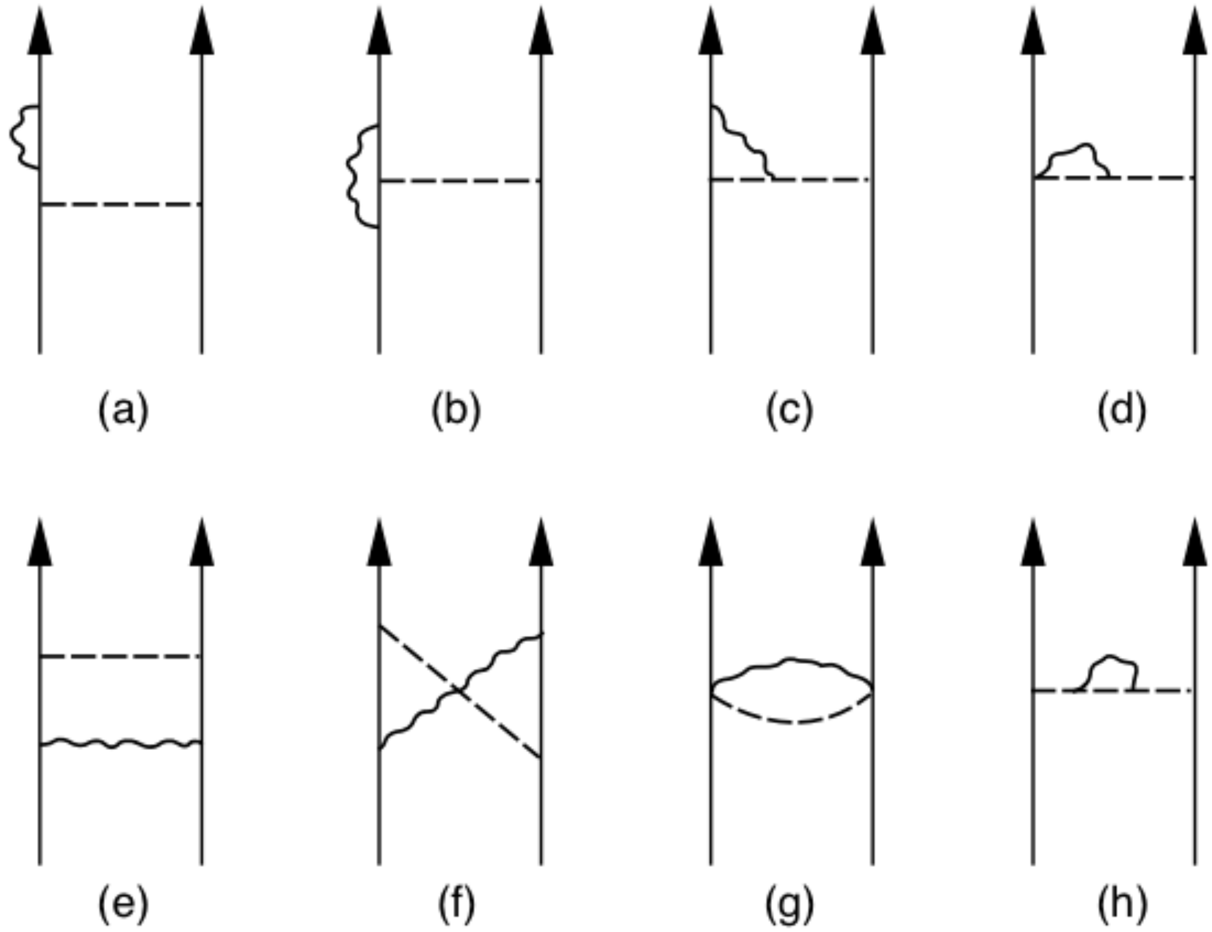
Pion-photon exchange

Radiative corrections to OPE calculated from χPT

np PWA to 500 MeV

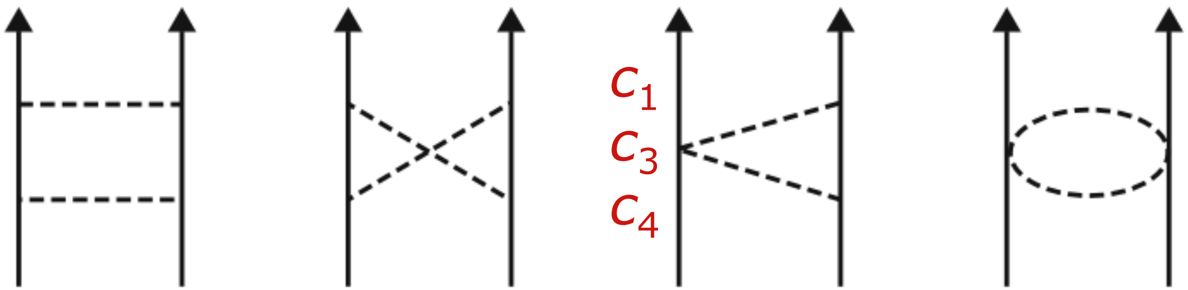
$N_{data} \approx 4100$
$\Delta\chi^2_{min} \approx -0.8$

no effect of $f(NN\pi)$



M.C.M. Rentmeester *et al.*, PRL **80**, 4386 (1998).

Chiral two-pion exchange



Leading-order χTPE: isoscalar spin-spin & tensor force
isovector central force
Next-to-leading order: strong isoscalar attaction $\sim c_3$
isovector tensor force $\sim c_4$

	b = 1.4 fm		b = 1.8 fm	
	N_{par}	χ^2_{min}	N_{par}	χ^2_{min}
Nijm78	19	1968.7	...	...
OPE	31	2026.2	29	1956.6
OPE + TPE(l.o.)	28	1984.7	26	1965.9
OPE + χTPE	23	1934.5	22	1937.8

N_{data}=1951

With long-range OPE+χTPE, a ~perfect χ^2/N_{data}~1 is possible

M.C.M. Rentmeester *et al.*, PRL **82**, 4992 (1999).

"Seeing" two-pion exchange

*NN*ππ coupling constants:
"integrated-out" Δ,*N**'s, heavy mesons:

c_3 : Δ(1232), ε(760), …
c_4 : Δ(1232), ρ(770), …

$c_1 = -0.76(7)/\mathrm{GeV}$ (input)

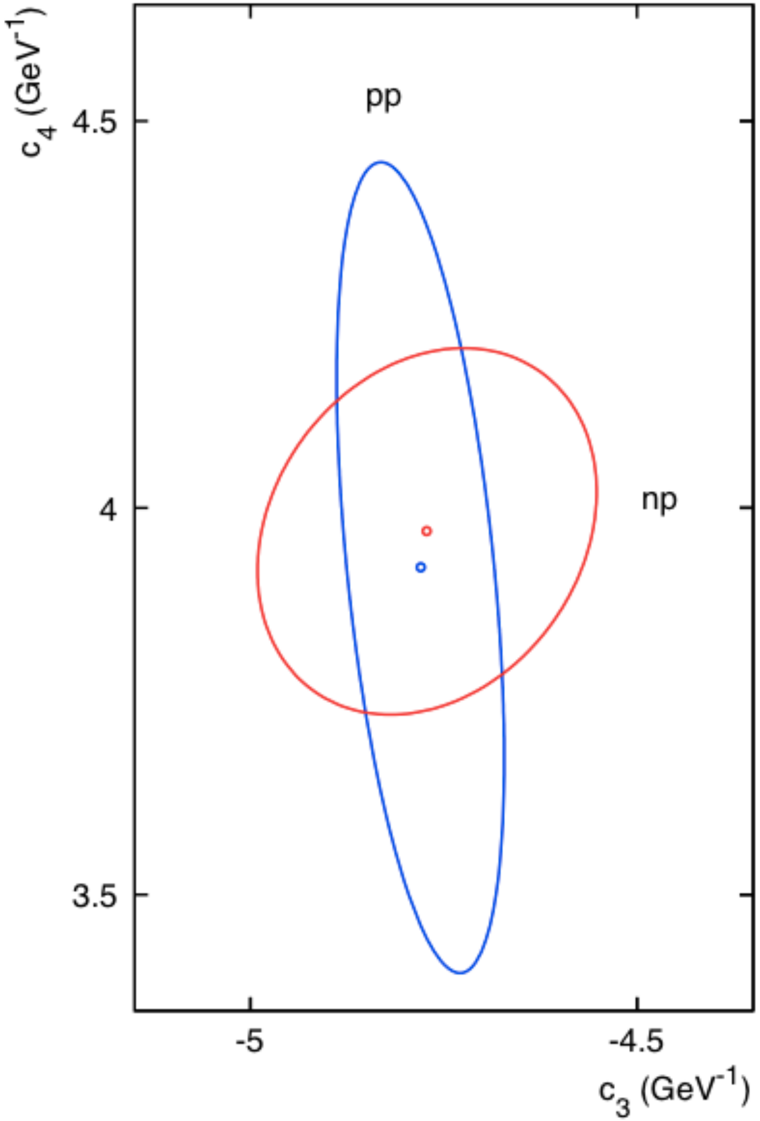
Fitted values:

$c_3 = -4.78(10)/\mathrm{GeV}$
$c_4 = +3.96(22)/\mathrm{GeV}$

consistent with (less reliable) π*N* values

Fit pion mass in long-range χTPE:

$$m_\pi = 128(9)\ \mathrm{MeV}$$



M.C.M. Rentmeester *et al.*, PRL **82**, 4992 (1999); PRC **67**, 044001 (2003).

Heuristic power counting $V_L \longleftrightarrow V_S$

P matrix: state- and energy-dependent, short-range square wells ($J \leq 4$):

$$P_\beta(b;k^2) = P_{\text{free},l}(b;k^2 - 2M_r V_{S,\beta}) \;\text{ with }\; V_{S,\beta}(k^2) = \frac{1}{2M_r}\sum_{n=0}^{N} a_{n,\beta}(k^2)^n$$

pp	# PWA	N²LO	N³LO	*np*	# PWA	N²LO	N³LO
$^1S_0$	4	2	4	$^1S_0$	(3)	-	(1)
$^3P_0$*	3	1	2	$^1P_1$	3	1	2
$^3P_1$	2	1	2	$^3S_1$-ε_1-$^3D_1$	3-2-2	2-1-0	4-2-1
$^1D_2$	2	0	1	$^3D_2$*	2	0	1
$^3P_2$-ε_2-$^3F_2$*	3-2-1	1-0-0	2-1-0	$^1F_3$	1	0	0
$^3F_3$	1	0	0	$^3D_3$-ε_3-$^3G_3$	1-1-0	0-0-0	1-0-0
$^1G_4$	1	0	0	$^3G_4$*	0	0	0
$^3F_4$-ε_4-$^3H_4$*	2-0-0	0-0-0	0-0-0				
Total	21	5	12	Total	15+(3)	4	11+(1)

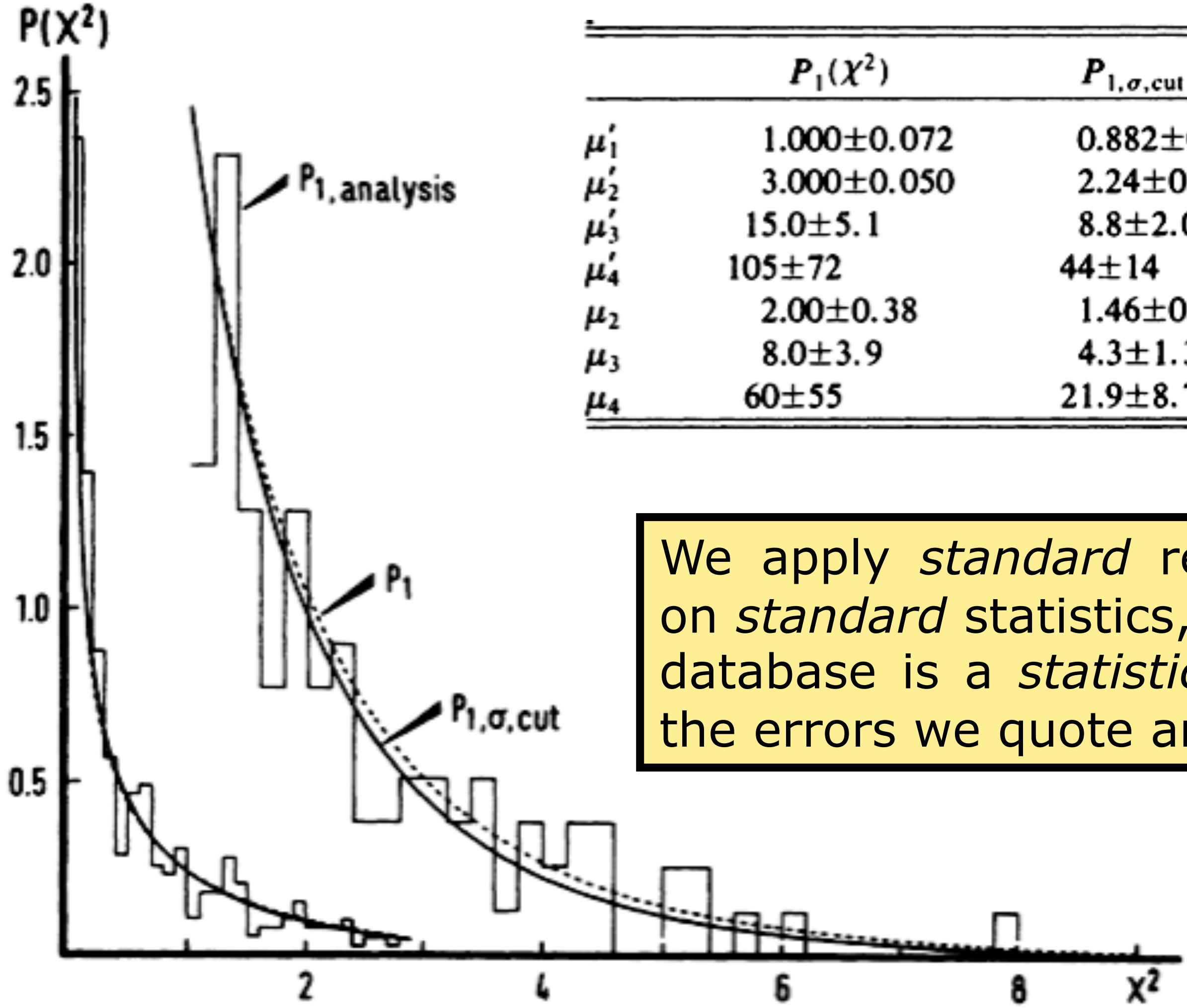
* Attractive $1/r^3$ tensor force

A. Nogga *et al.*, PRC **72**, 054006 (2005); M.C. Birse, PRC **74**, 014003 (2006).

IV. "Doctoring data": the sound & the fury…

A.k.a. χ^2-paranoia…

Lies, damned lies & statistics



	$P_1(\chi^2)$	$P_{1,\sigma,\mathrm{cut}}(\chi^2)$	$P_{1,\mathrm{analysis}}(\chi^2)$
μ_1'	1.000±0.072	0.882±0.061	0.883
μ_2'	3.000±0.050	2.24±0.32	2.24
μ_3'	15.0±5.1	8.8±2.0	8.5
μ_4'	105±72	44±14	40
μ_2	2.00±0.38	1.46±0.23	1.46
μ_3	8.0±3.9	4.3±1.3	3.9
μ_4	60±55	21.9±8.7	18.3

We apply *standard* rejection criteria based on *standard* statistics, to make sure that the database is a *statistical ensemble* and that the errors we quote are really statistical!

We do not determine if expt's are right or wrong, but we do decide whether they are statistically acceptable, yes or no.

PRL **94,** 082303 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Measurement of the Absolute *np* Scattering Differential Cross Section at 194 MeV

M. Sarsour,[1] T. Peterson,[1,*] M. Planinic,[1,†] S.E. Vigdor,[1] C. Allgower,[1] B. Bergenwall,[2] J. Blomgren,[2] T. Hossbach,[1] W. W. Jacobs,[1] C. Johansson,[2] J. Klug,[2] A. V. Klyachko,[1] P. Nadel-Turonski,[2] L. Nilsson,[2] N. Olsson,[2] S. Pomp,[2] J. Rapaport,[3] T. Rinckel,[1] E. J. Stephenson,[1] U. Tippawan,[2,4] S. W. Wissink,[1] and Y. Zhou[1]

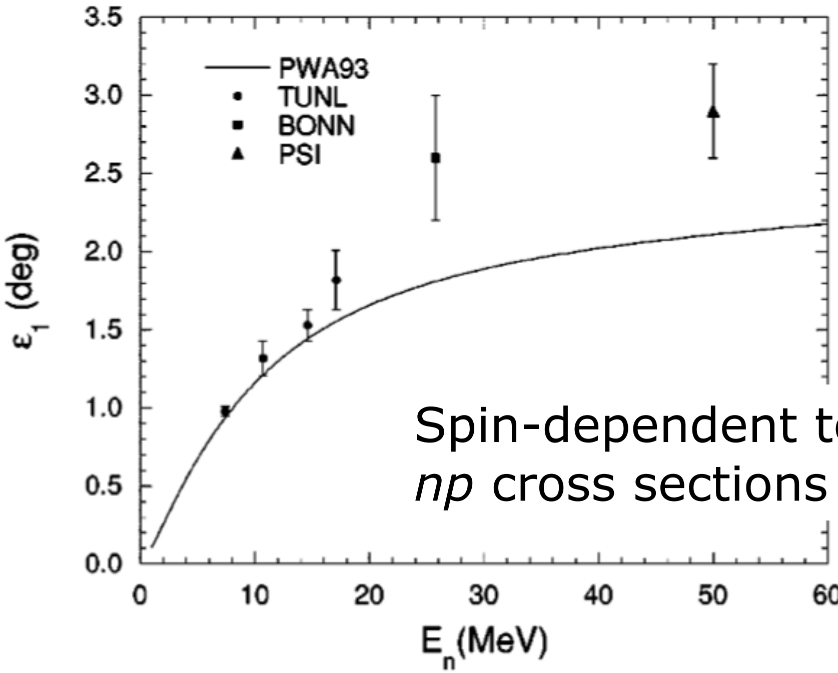
[1]*Indiana University Cyclotron Facility and Department of Physics, Bloomington, Indiana 47408, USA*

[2]*Uppsala University, Uppsala, Sweden*

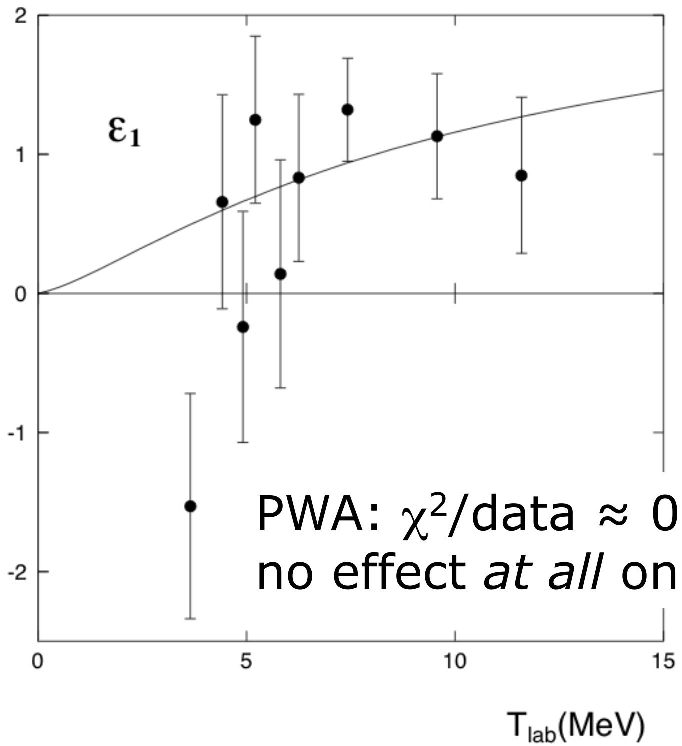
“The neutron-proton elastic scattering database at intermediate energies is plagued by experimental inconsistencies and cross section normalization difficulties. These problems have led the most sophisticated partial-wave analyses (PWA) of the data to *ignore* the majority (*including the most recent*) of measured cross sections, while the literature is filled with heated debates over experimental and theoretical methods, including *radical “doctoring”* (angle-dependent renormalization) *to “salvage” allegedly flawed data*.* Meanwhile, an empirical evaluation of a fundamental parameter of meson-exchange theories of the nuclear force - the charged-pion coupling constant - hangs in the balance.”

* J.J. de Swart & R.G.E. Timmermans, PRC **66**, 064002 (2002).

TUNL data & the tensor force



Spin-dependent total *np* cross sections



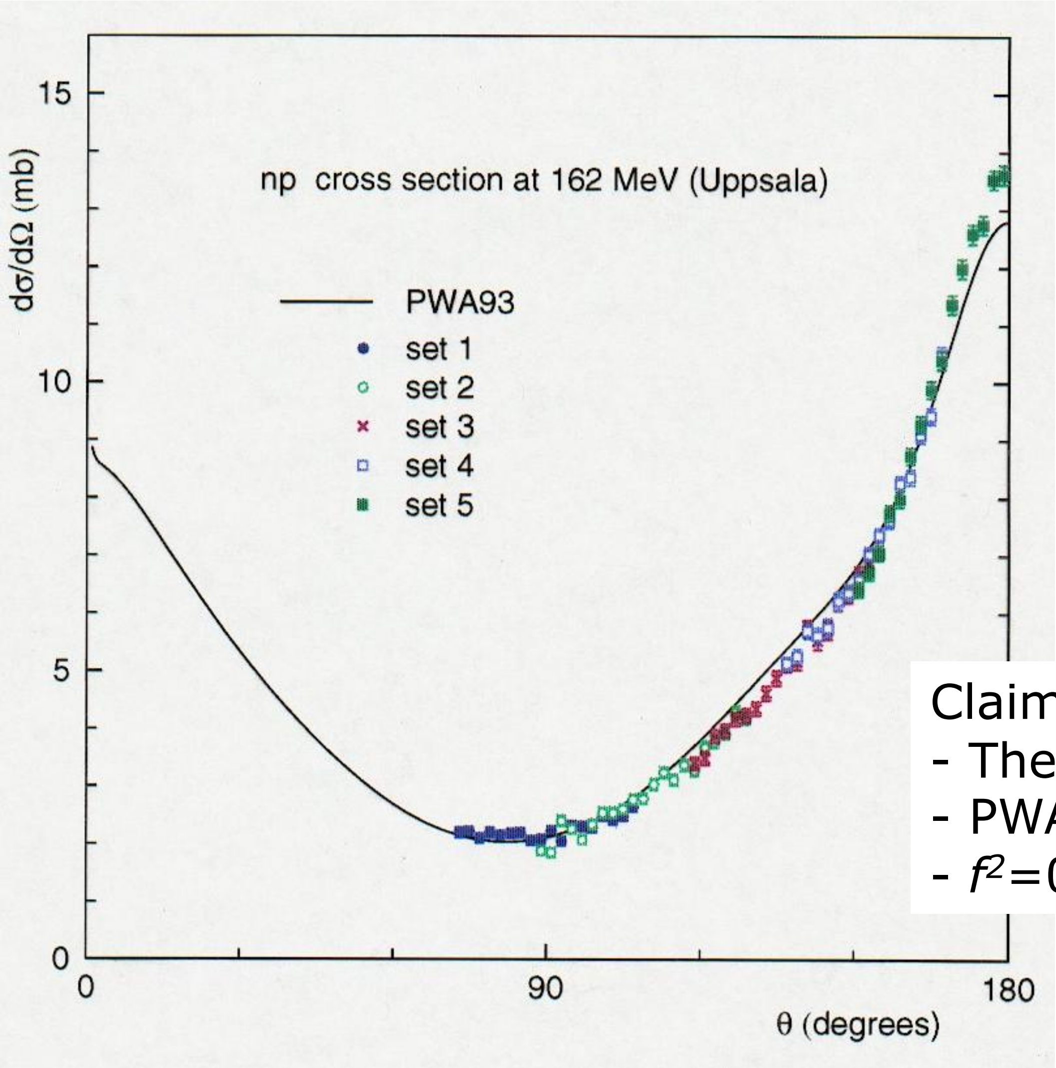
PWA: χ^2/data ≈ 0.6
no effect *at all* on ε_1

“Our values support an *NN* tensor force that is stronger than predicted by all modern *NN* potential models and PWAs … *new concepts* are needed…” *

These TUNL data were incorrectly normalized; they were *doctored!*

* Raichle *et al*., PRL **83**, 2711 (1999);
Walston *et al.*, PRC **63**, 014004 (2000); PRC **65**, 047002 (2002).

A very famous experiment @ Uppsala

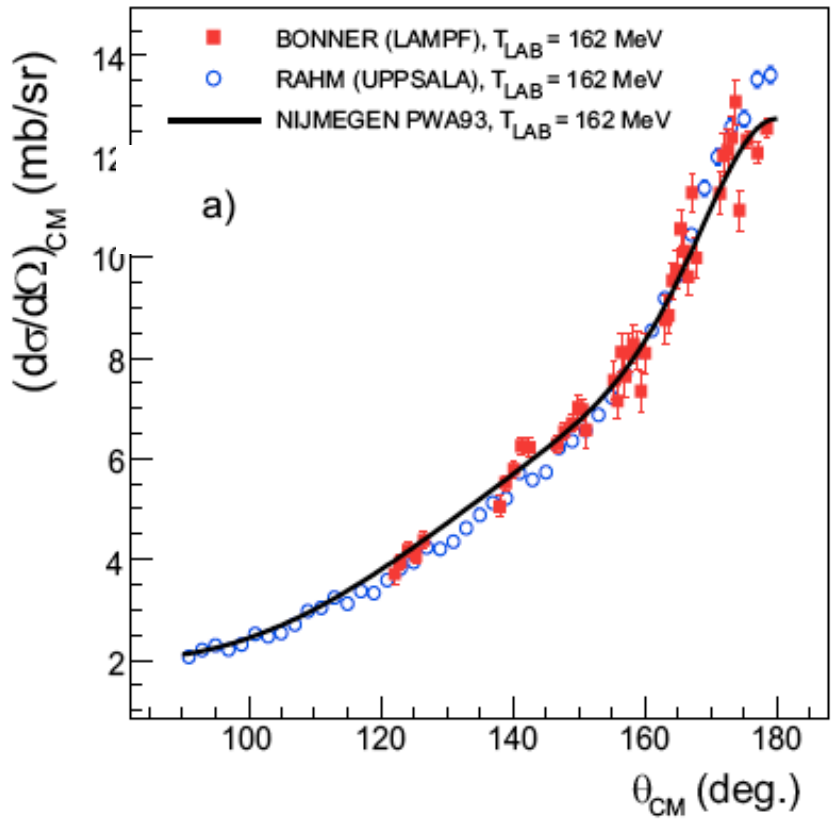


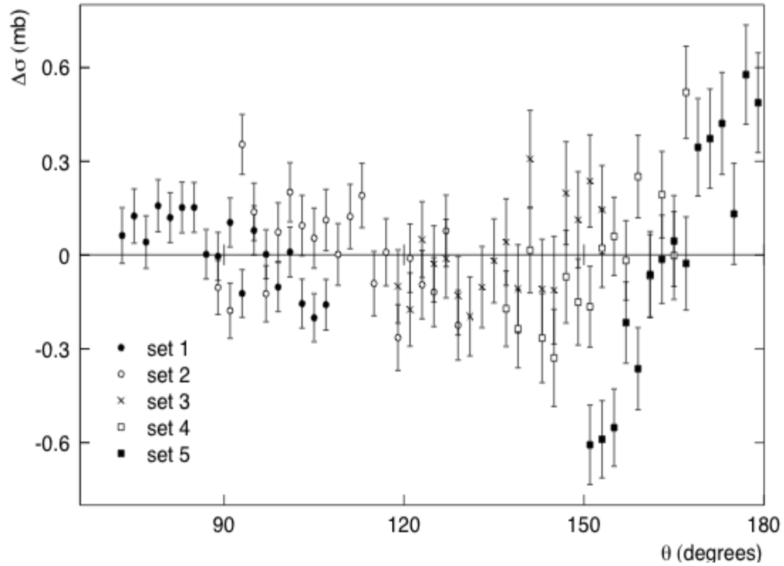
The backward peak is due to *interference* of $\pi^{\pm}$ exchange and the background

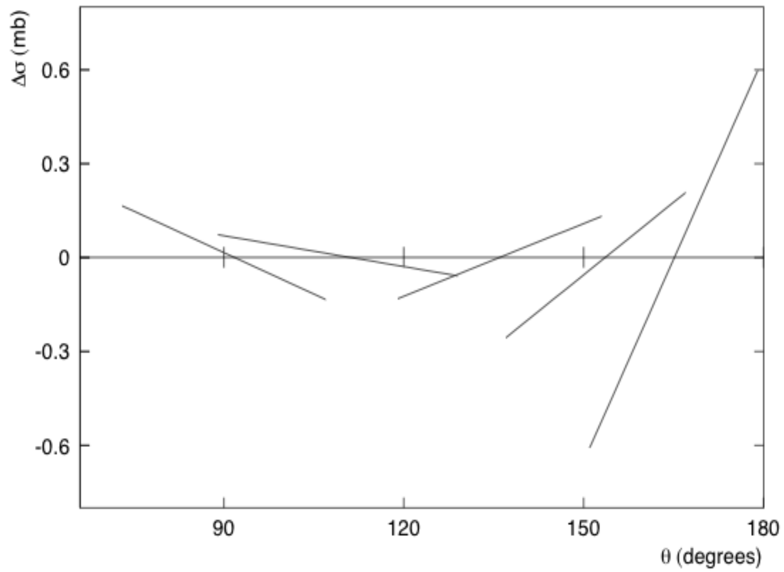
Claims:

- There are *two families* of *np* data
- PWAs are biased to one family
- f^2=0.0808(3) from 31 points

T.E.O. Ericson *et al.*, PRL **75**, 1046 (1995);
J. Rahm *et al.*, PRC **57**, 1077 (1998).



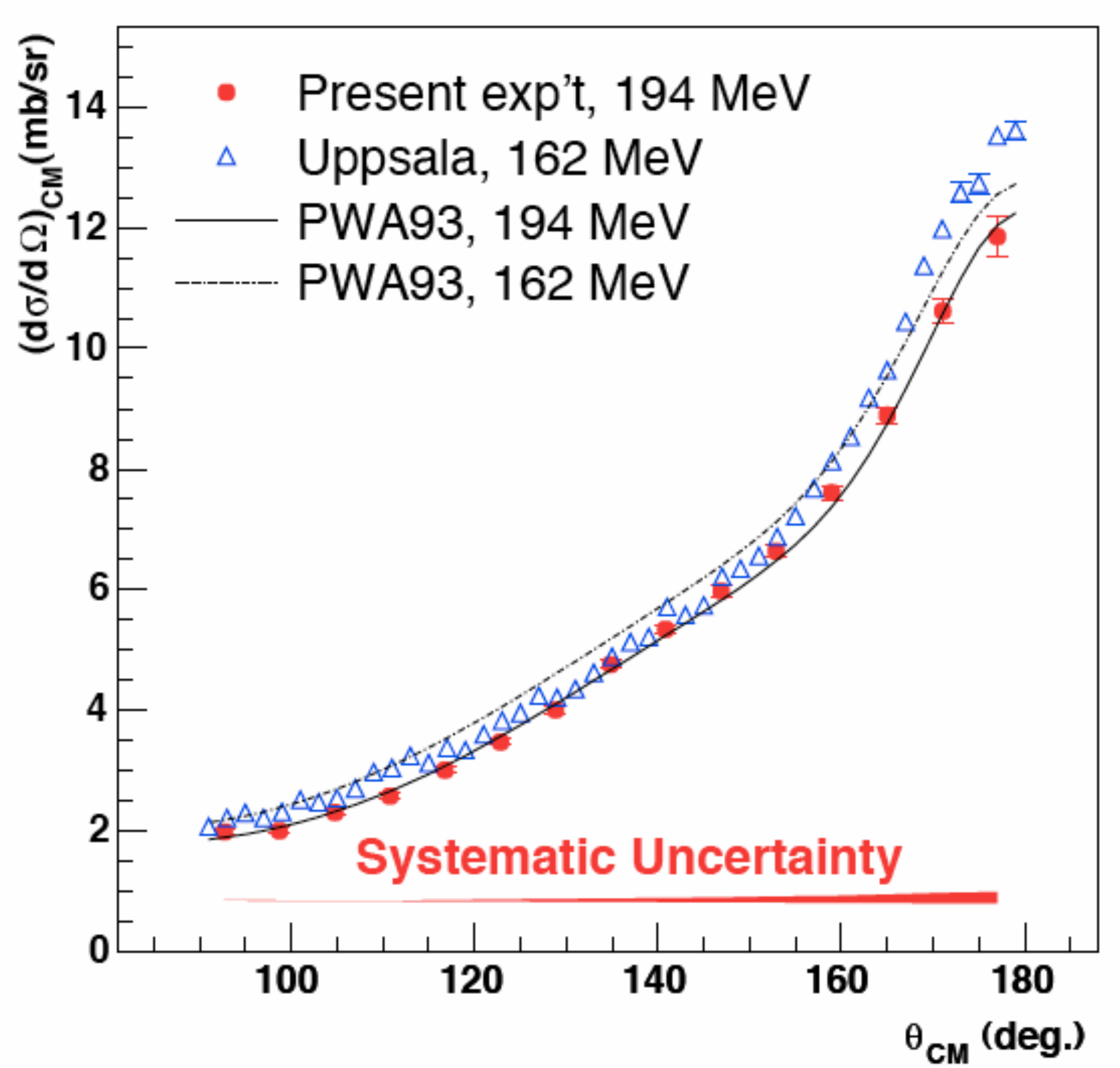




- the 31 data have χ^2 = 264 (30 *s.d.*!)
- the data were incorrectly normalized
- the data were internally inconsistent

The data were "doctored" by the experimentalists…

10 years down the road...



M. Sarsour et al. (IUCF), PRL **94**, 082303 (2005); PRC **74**, 044003 (2006).

The parable* of the three baseball umpires

First umpire:
"I calls 'em the way I sees 'em."

Second umpire:
"I calls 'em the way they *are* !"

Third umpire:
"They ain't *nothin'* until I calls 'em!"

Experimentalists may have no doubt that their data are right, but the PWA, and not any fact of the matter, decides whether a dataset is a "ball" or a "strike."

*A short fictitious story that illustrates a moral attitude [Merriam-Webster].

The fate of new experiments in the PWA

Q: Don't we have enough *NN* data ?!
A: That depends on the ambition:
to really study CIB, one certainly needs better *np* data.

New expt's should aim to improve the PWA.

Three possible outcomes:
(i) the expt has to be rejected on statistical grounds…
(ii) the expt is correct but irrelevant…
(iii) *the expt is correct and contains new information!*

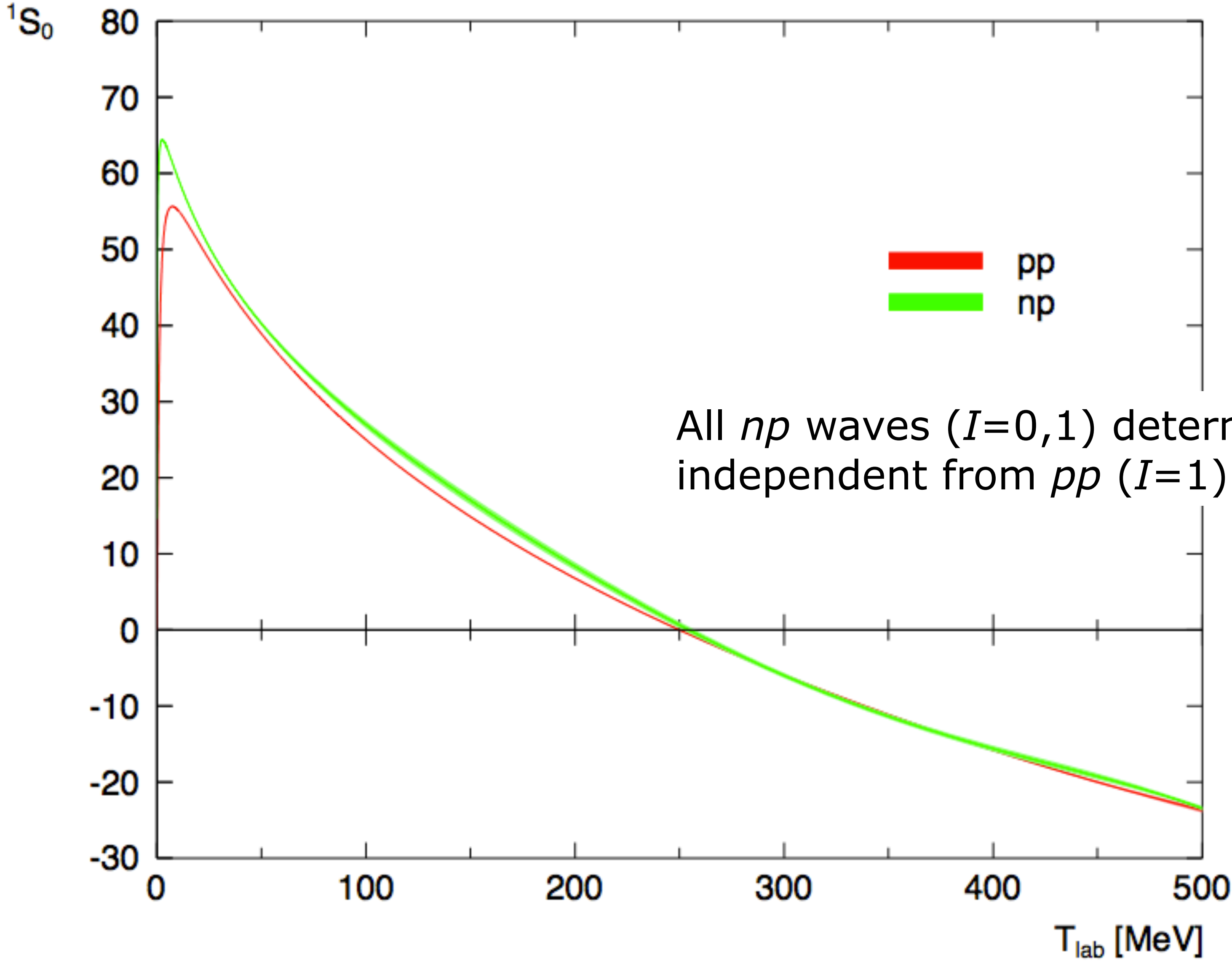
Unfortunately, cases (i) and (ii) occur often in recent years.

High counting rates → systematic errors start to dominate…
Bad for PWA! We need new methods* to handle syst. errors.

* R.L. Kelly and R.E. Cutkosky, PRD **20**, 2782 (1979);
J.J. de Swart and R.G.E. Timmermans, PRC **66**, 064002 (2002).

V. Outlook: What is left to keep us off the streets?

0-500 MeV *pp* & *np* χPWA



All *np* waves (I=0,1) determined independent from *pp* (I=1) waves

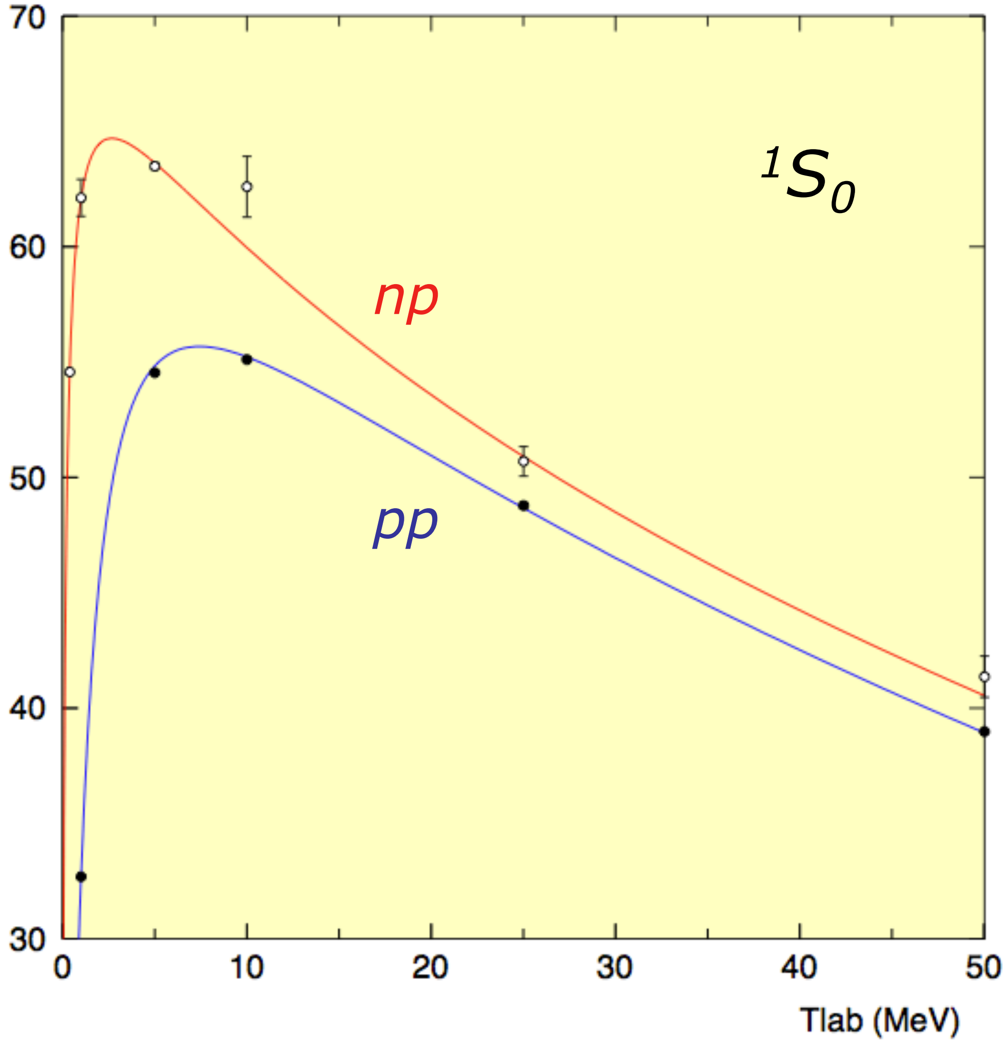
Old laptop of M.C.M. Rentmeester, unknown location…

Isospin violation, *pp* vs. *np*, in χPWA

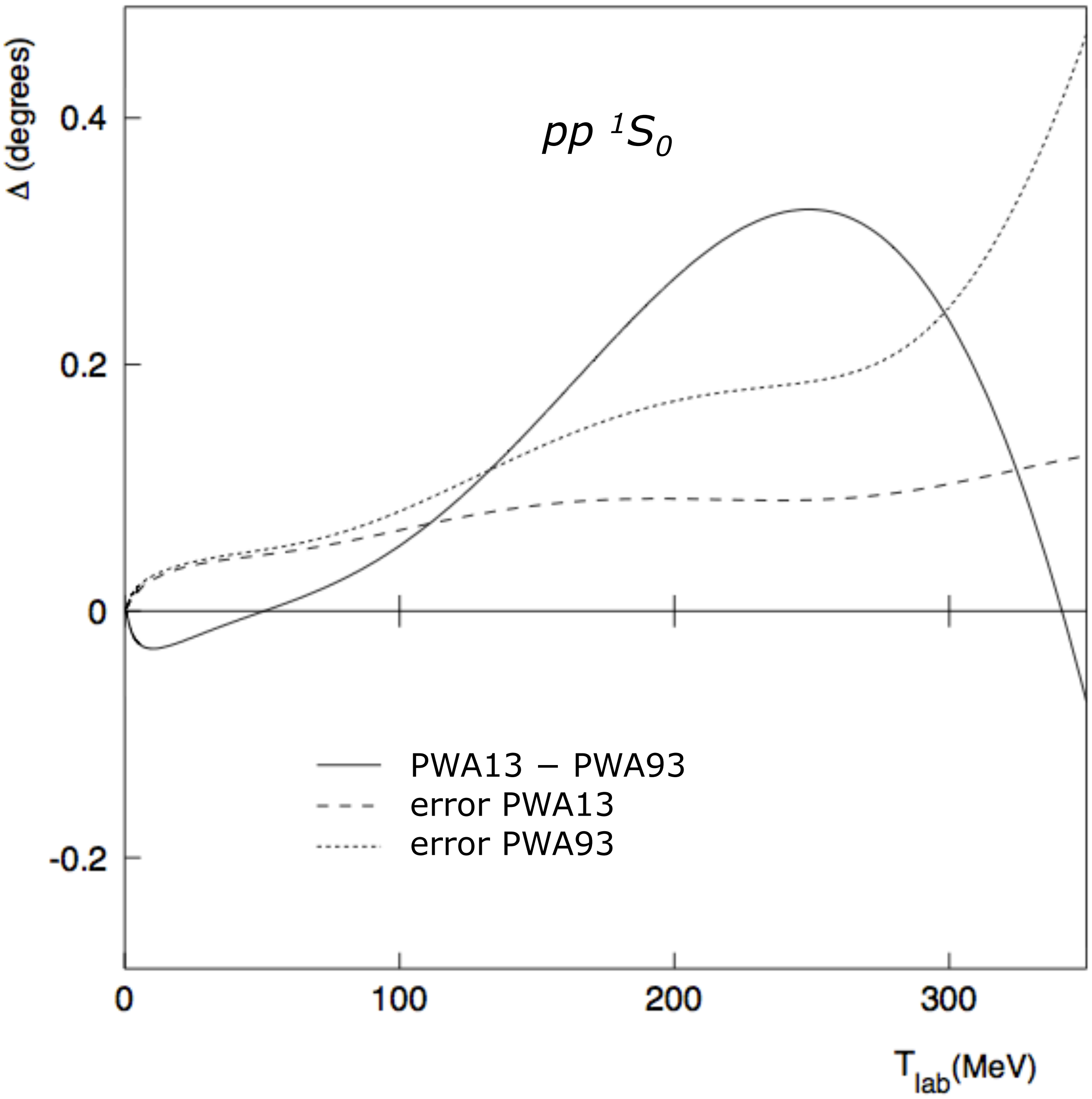
Isospin violation is due to EM and the up-down quark-mass difference in QCD.

In χPWA we can study CIB for all low partial waves not just for the $^1S_0$ wave, but also *e.g.* the ^3P waves.

The long-range interaction contains the most relevant isospin violation predicted by χPT, *i.e*. EM and in OPE, but not yet in TPE.

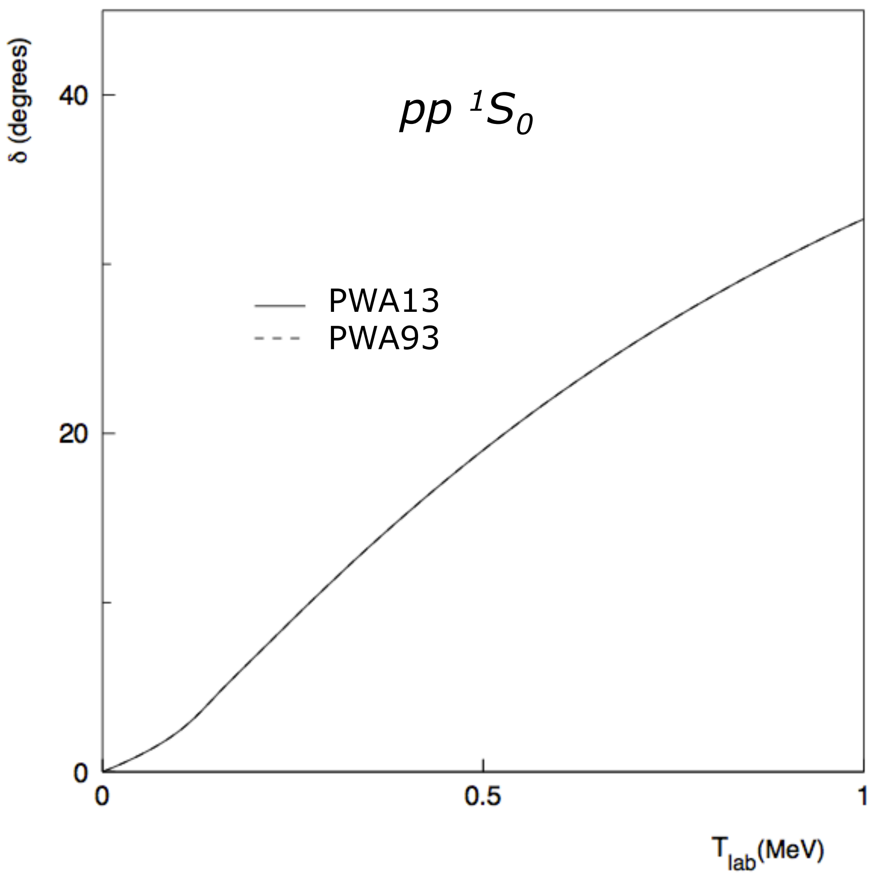


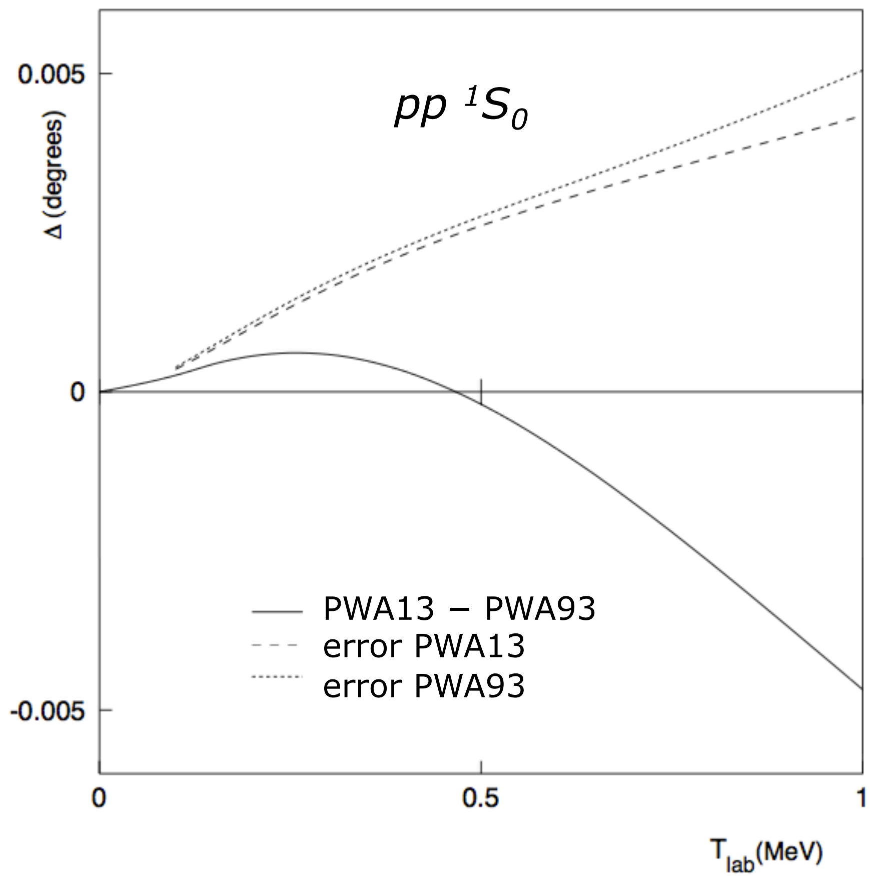
U. van Kolck *et al*., PLB **371**, 169 (1996);
J. Friar *et al*., PRC **60**, 034006 (1999), *ibid*. **68**, 024003 (2003).



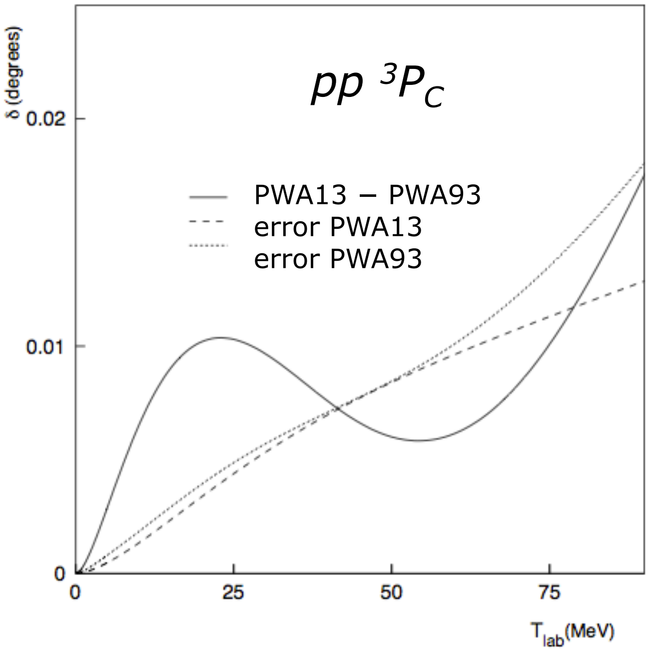
Δ (degrees)
0.4
0.2
0
-0.2
pp ¹S₀
PWA13 − PWA93
error PWA13
error PWA93
0
100
200
300
T lab (MeV)

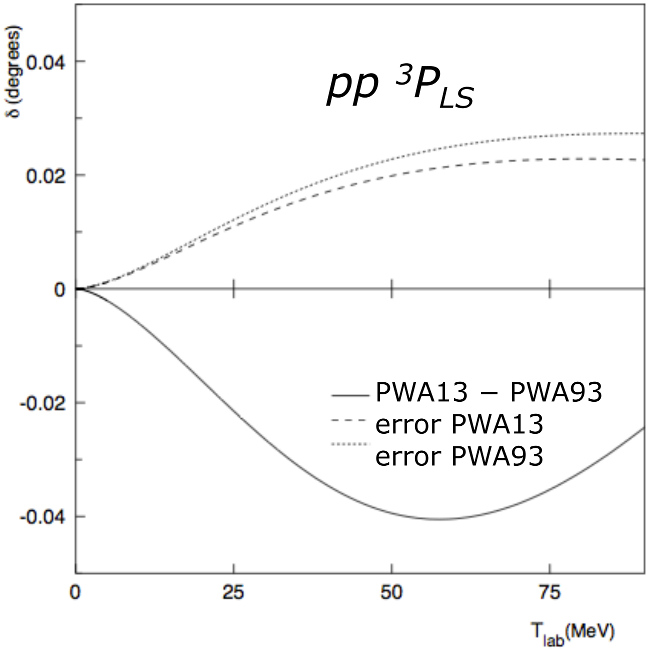
$pp\ ^1S_0$ wave below 1 MeV:

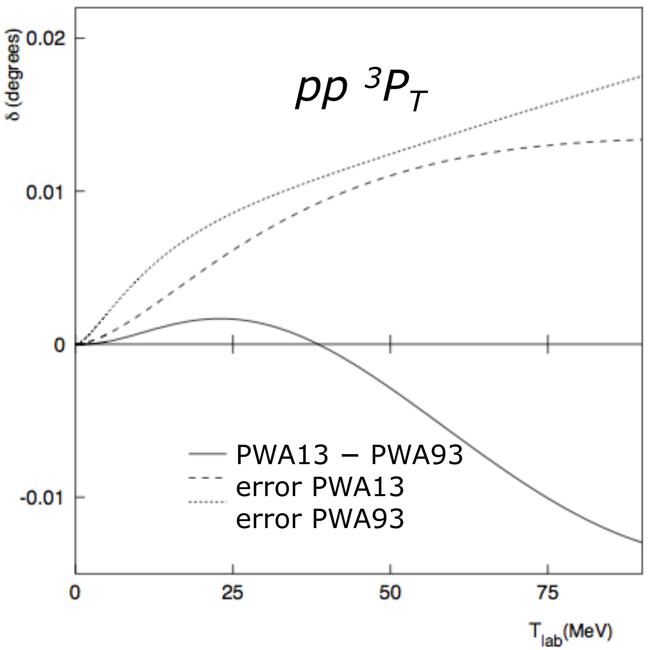




Different intermediate-range interaction: HBE versus TPE

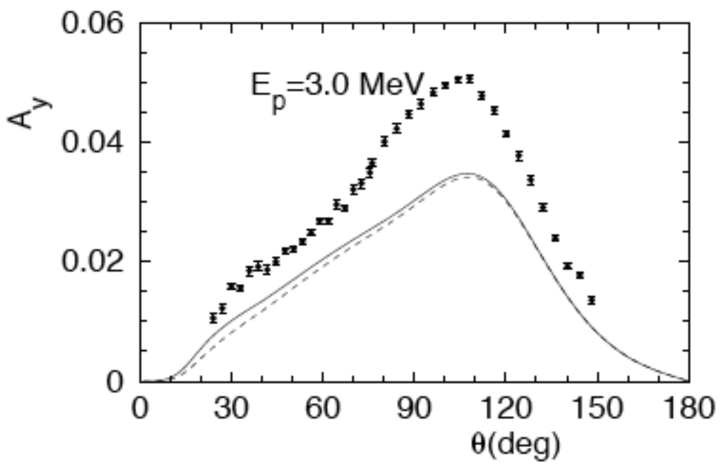




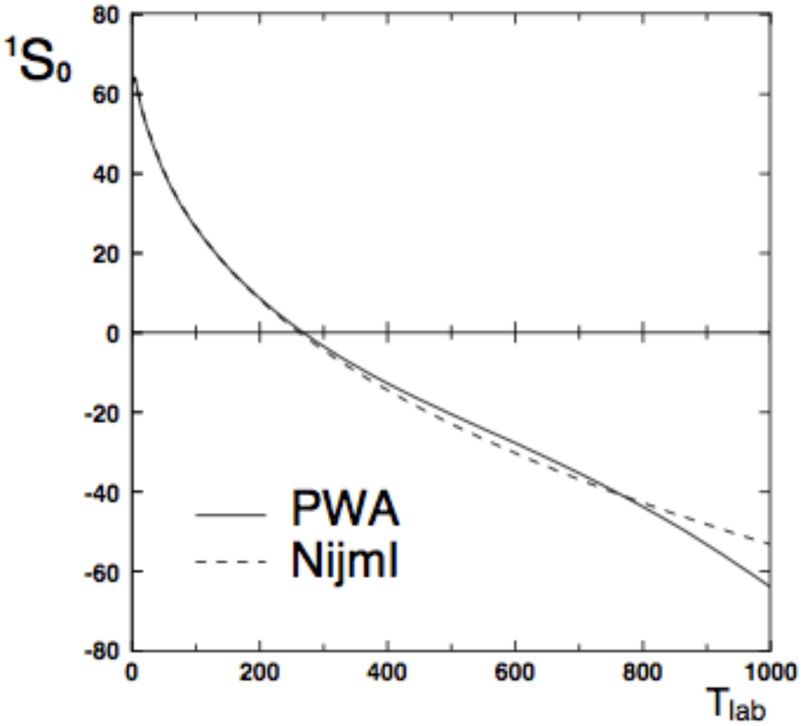


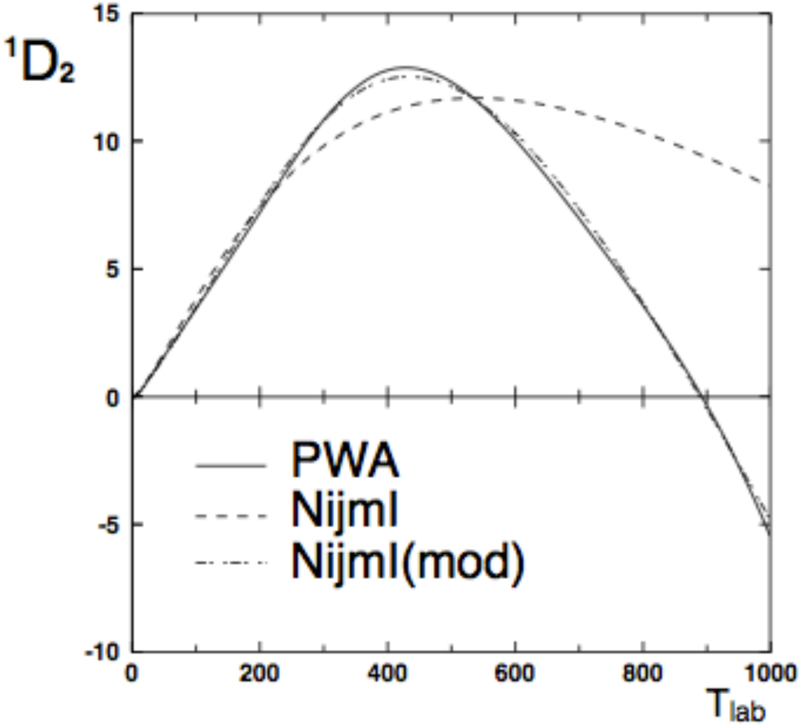
Low-energy *pp* $^3P_{0,1,2}$ waves:

- changes w.r.t. PWA93 within errors
- no "solution" for *pd*, *nd* "A_y-puzzle"…



Optical potentials up to 1000 MeV





Add imaginary part: $V = V_R - i\, V_I$

np PWA up to T_{lab} = 1 GeV
biggest effect in $^1D_2$ and $^1F_3$ waves

Interval	# data	χ^2	$\Delta\chi^2$
0-350	2549	2519	11
350-400	254	306	13
400-450	319	337	105
450-500	866	905	651
0-500	3988	4067	880

Old laptop of M.C.M. Rentmeester, unknown location…, possibly Mexico…

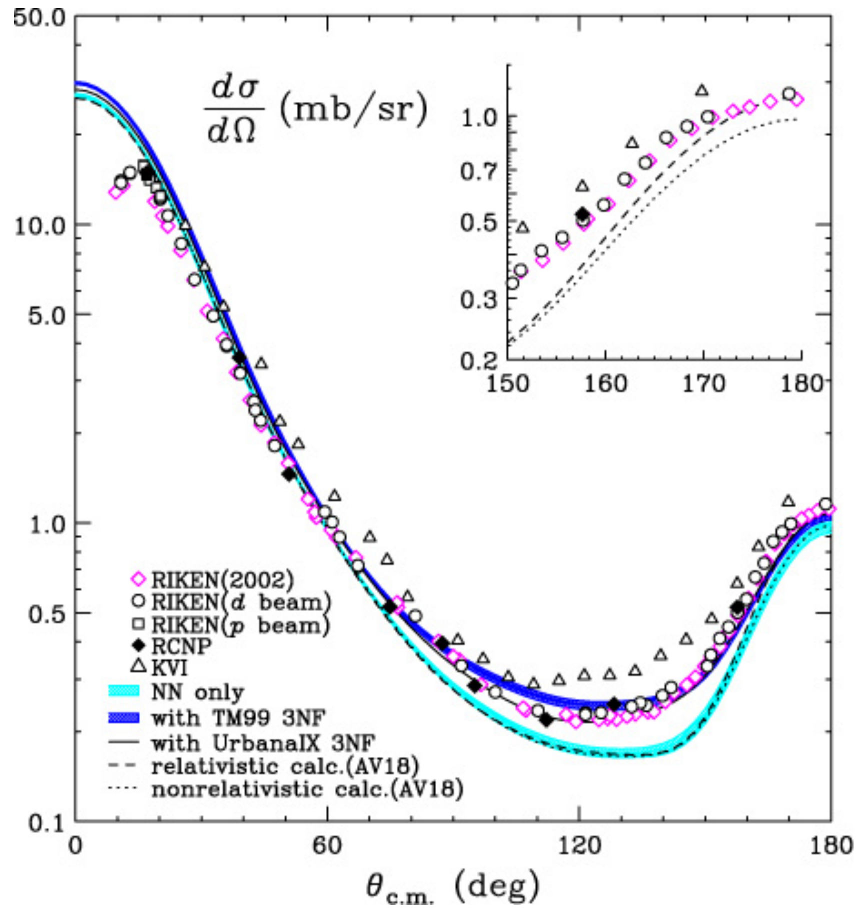
PWA as bridge between exp't and theory

Is a similar (major) effort worthwhile for other systems?
- the three-nucleon system
- antinucleon-nucleon scattering*

Needs a high-quality database
Apply the rules of statistics

Unfortunately, about 15-20% of the data have to be rejected.

Waste of time & effort & $, euro's, or Swedish crowns…

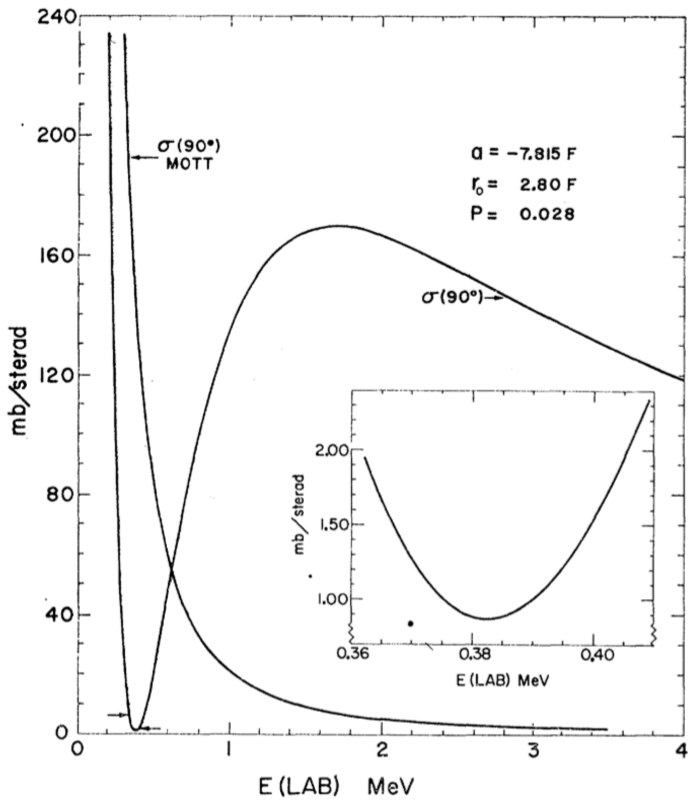


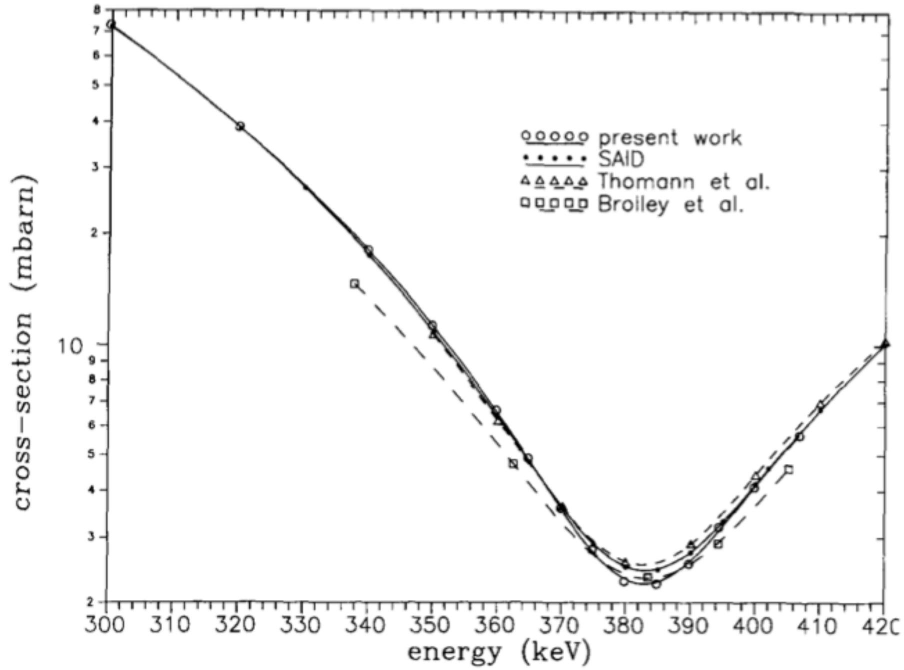
K. Sekiguchi *et al.*, PRL **95**, 162301 (2005).

* D. Zhou and R.G.E. Timmermans, PRC **86**, 044003 (2012).

Full circle: A new 0.3-3 MeV *pp* PWA?

Coulomb-nuclear interference minimum @ T_{lab} = 382.54 keV
- based on Los Alamos (1964) & Zürich (1978) *pp* data
- normalizes the Sun: *pp* fusion reaction $p+p \rightarrow d+e+\nu$





New *pp* data from Münster
- completely at odds…
- "pionless" EFT with Coulomb?

H. Dombrowski *et al.*, NPA **619**, 97 (1997).

PWA83 → PWA93 → PWA03 → PWA13 → PWA23

(Our) PWA is a high-precision tool to:
- improve models / test theories for the *NN* interaction
- study & improve the database, plan new expt's
- study the long-range interaction V_L

Input into the PWA:
- the "raw" database (over 5000 *pp* and 5000 *np* points)
- theory (model independent): EM interaction, OPE + χTPE

Output of the PWA:
- phase-shift parameters, inelasticities + errors: $\delta_L(E)$, $\eta_L(E)$
- correlations (χ^2-hypersurface)
- parameters in V_L, *e.g.* the pion coupling constant $f_{NN\pi}$
- "true" database + rejected data sets

Ultimately, one has to fit the data with χEFT, or QCD, of course!

Some open questions & final thoughts

o Q: Is anything relevant still missing in the long-range potential?

- Δ(1232), isospin violation, three-pion exchange, …

o Q: Is it worthwhile to reformulate χPWA as χEFT?

- consistency of the power counting, V_L versus V_S

o Q: Is the χPWA with its *r*-space regulator cutoff independent?

- "cutoff" *b* was varied within 1-2 fm
- highly singular potentials, $V \sim 1/r^{6,7}$

o Q: Should one apply Bayesian fitting strategies*?

- energy range (breakdown scale)? <350 MeV?

Thank you for your attention!

* M.R. Schindler & D.R. Phillips, AP **324**, 682 (2009).