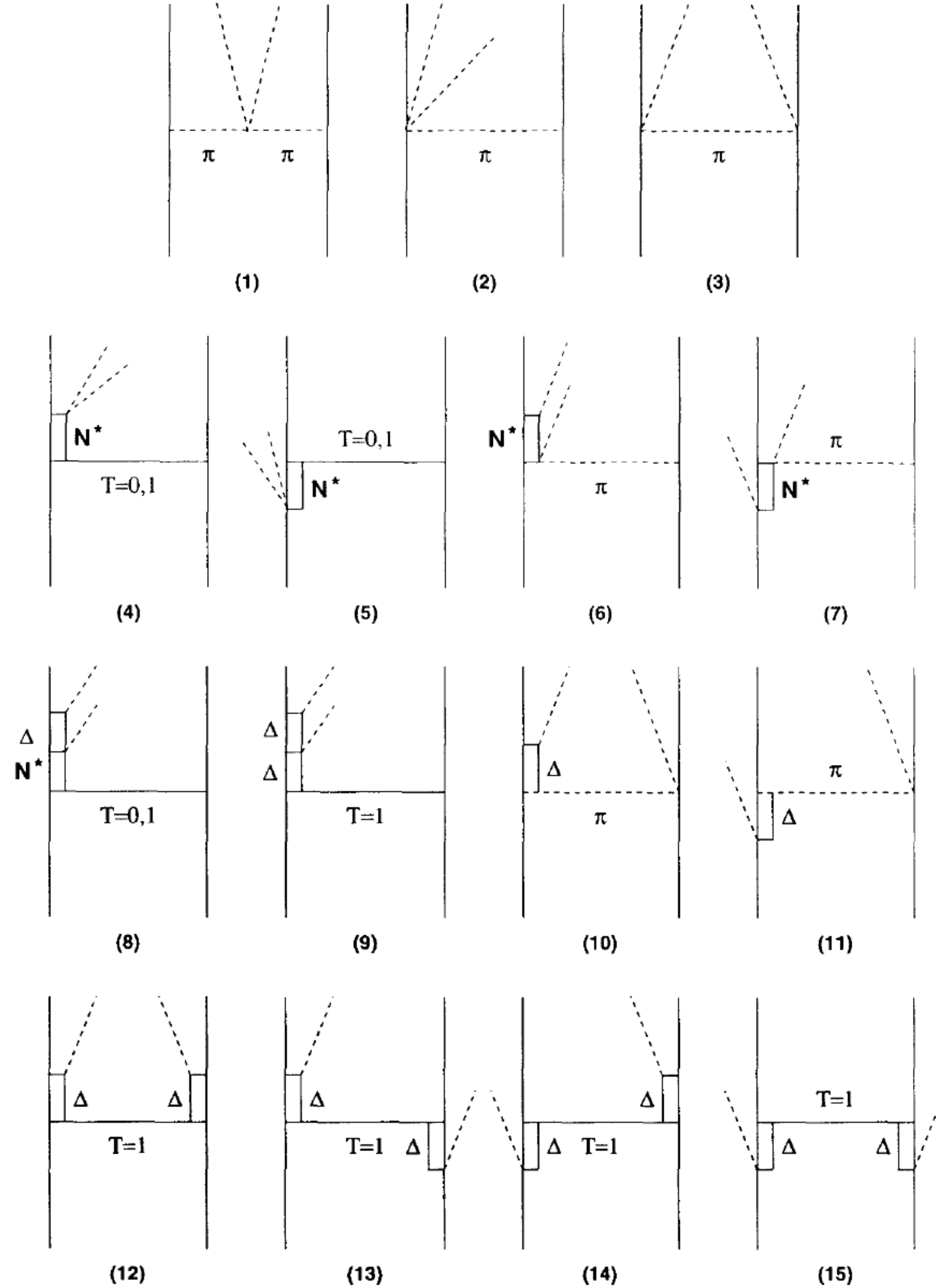
The NN $\rightarrow$ NN $\pi\pi$ revisited

E. Oset, IFIC Valencia

The Valencia model
The glorious days
Limits seen and improvements
The pn -> d $\pi^0\pi^0$ puzzle
Isospin channels
Relationship to pn -> p n $\pi^0\pi^0$ channel, Wilkin
The pp ->ppX reaction with small pp mass of ANKE
The pp -> pp $\pi^0\pi^0$ with small pp mass of COSY
Reflections and suggestions

The Valencia model , NPA (98),

Alvarez Ruso, E. O., Hernandez



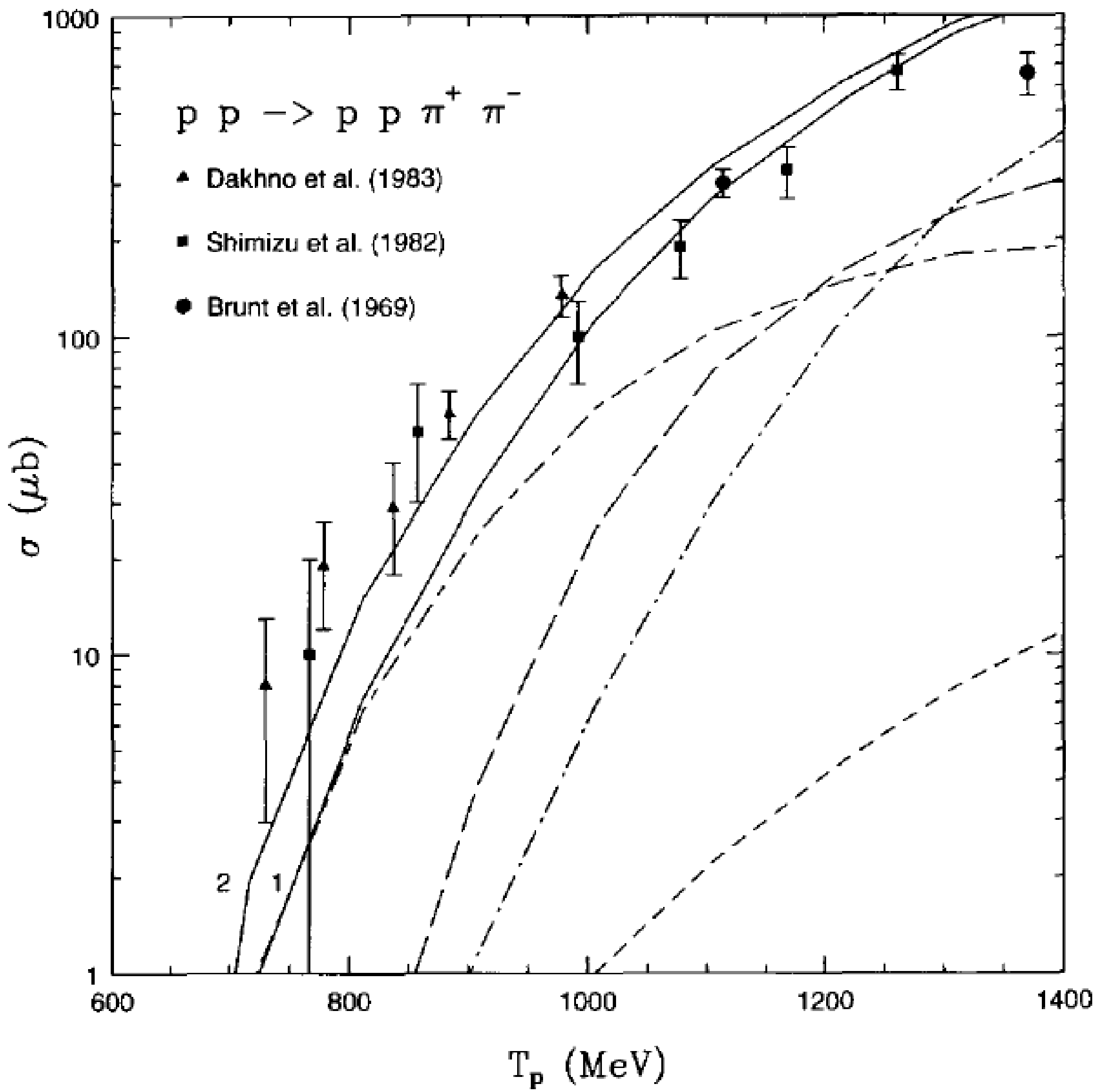
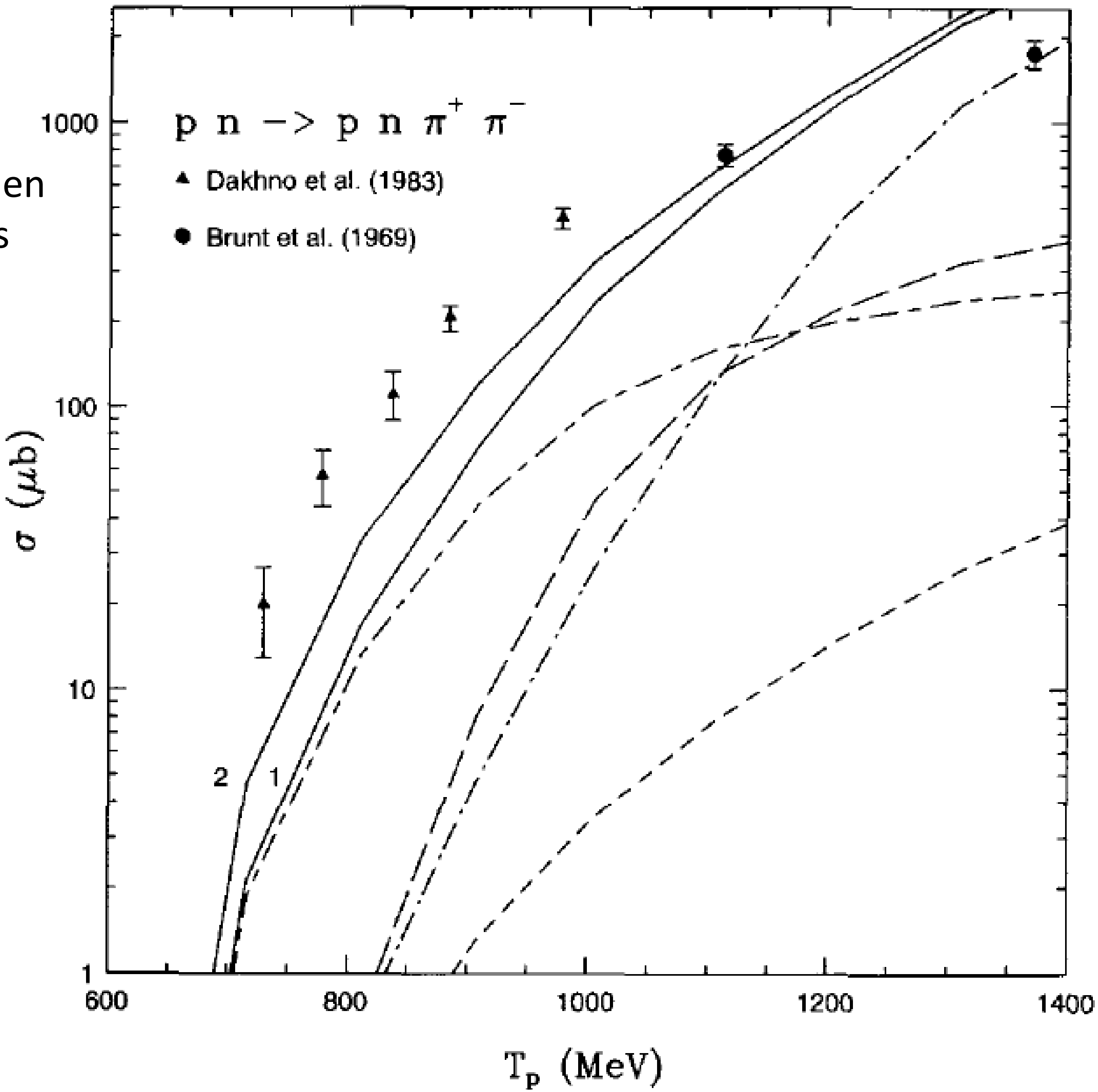
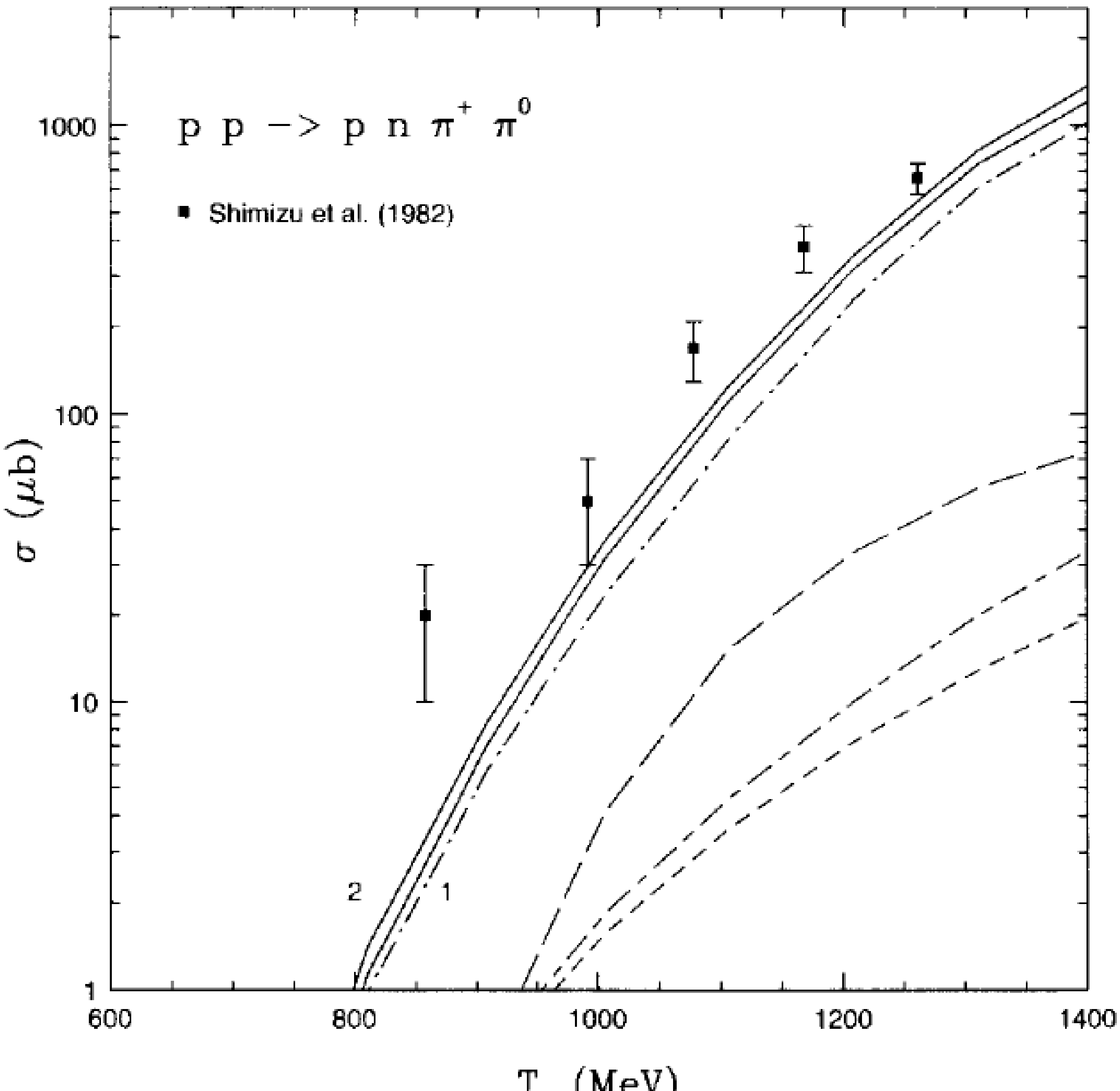


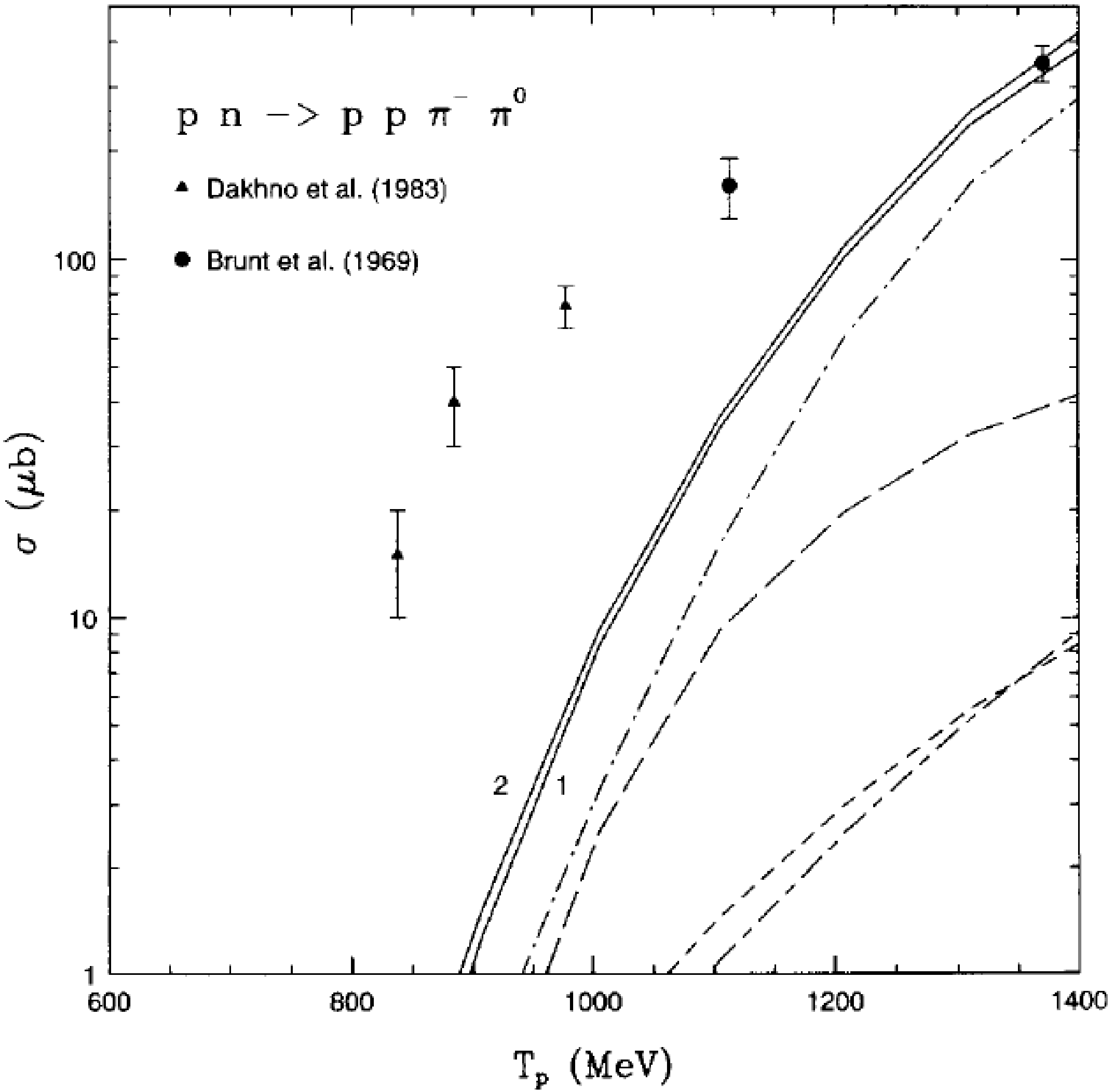
Fig. 3. Total cross section for the $pp \to pp\pi^+\pi^-$ channel as a function of the incoming proton kinetic energy in the laboratory frame. Solid line, total (line labelled 1 for set I and 2 for set II of c_1^*, c_2^* parameters); long-short dashed line, $N^* \to N(\pi\pi)^{T=0}_{\text{S-wave}}$; long-dashed line, $N^* \to \Delta\pi$; dash-dotted line, Δ excitation mechanisms; short-dashed line, non-resonant terms from diagrams (1)–(3). The partial contributions are calculated with set I. Experimental data are taken from Refs. [12–14].

Note COSY peak when pn is the d, appears at 1700 MeV





p p -> p n π⁺ π⁰
Shimizu et al. (1982)
σ (μb)
T_p (MeV)
1000
100
10
1
600
800
1000
1200
1400
2
1



p n -> p p π^- π^0
Dakhno et al. (1983)
Brunt et al. (1969)
σ (μb)
T_p (MeV)
1
10
100
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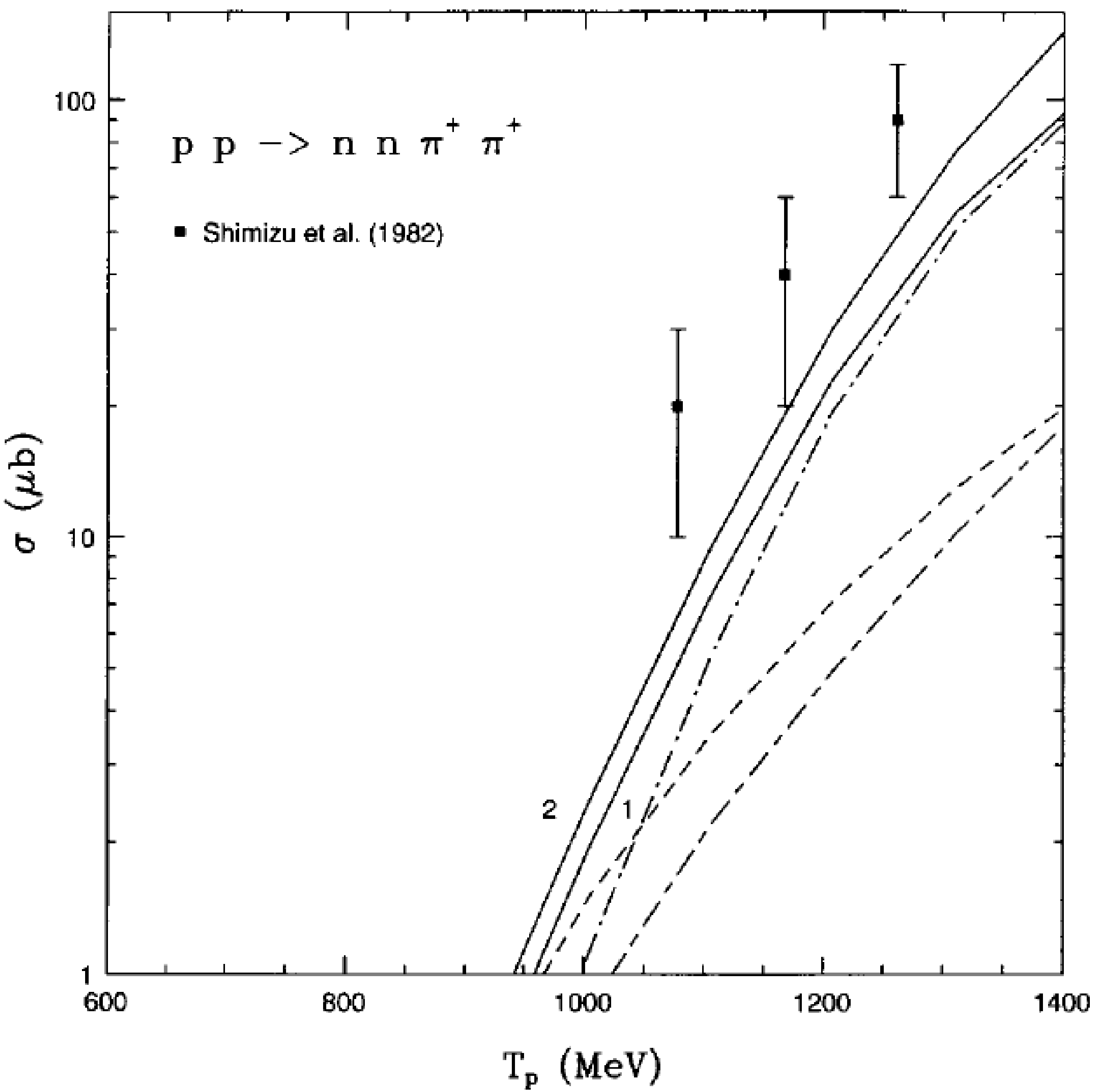
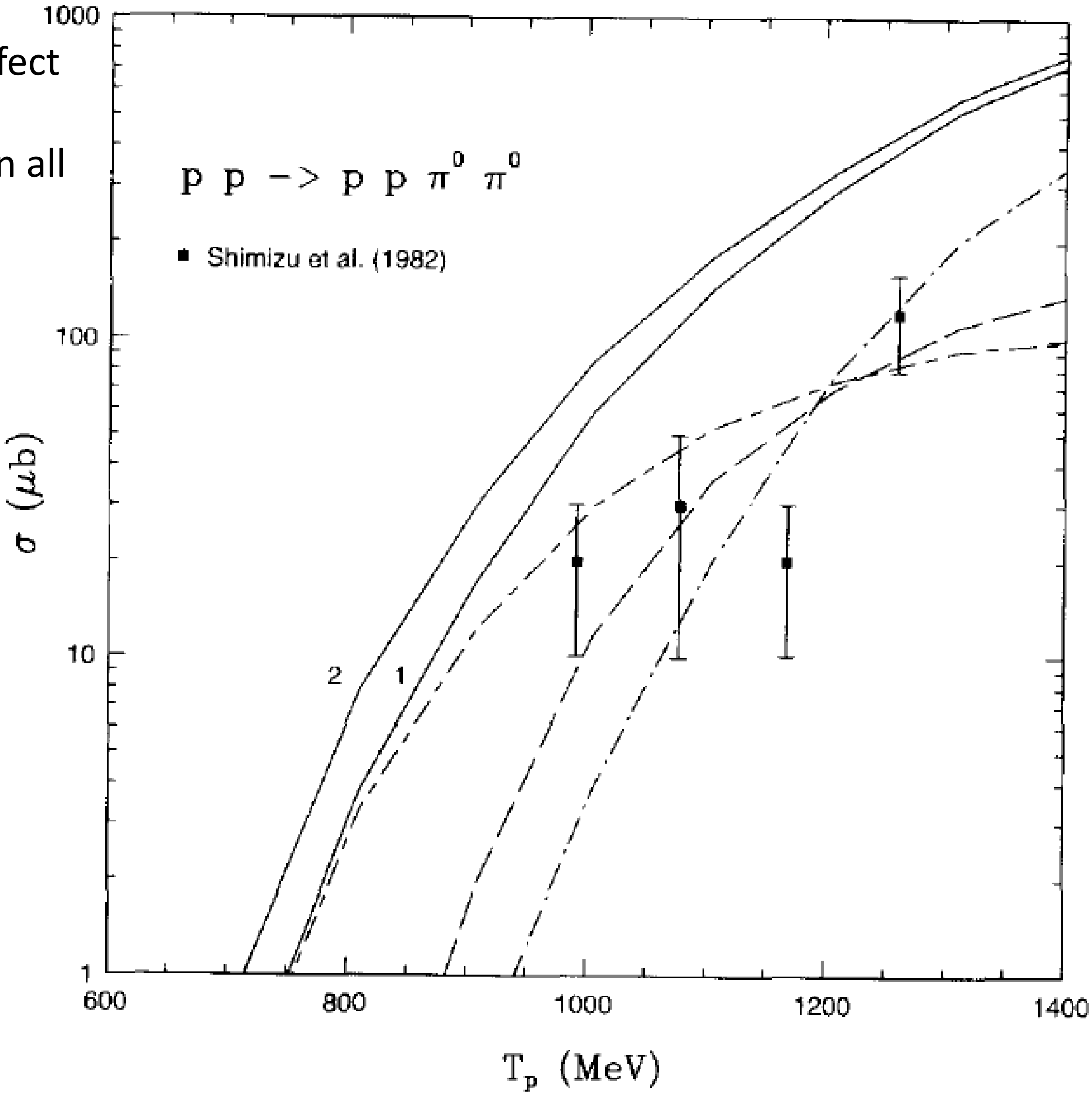
1000
1200
1400
2
1



p p -> n n π^+ π^+
Shimizu et al. (1982)
2
1
100
10
1
600
800
1000
1200
1400
σ (μb)
T_p (MeV)

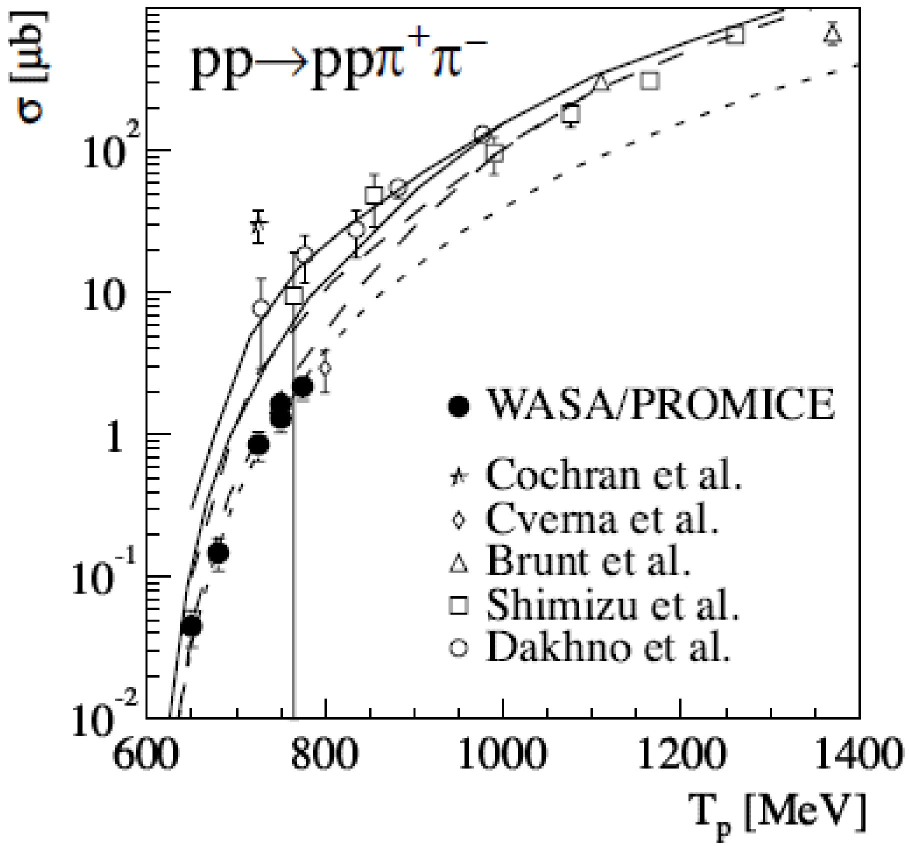
The model is not perfect but povides the right order of magnitude in all channels.
Also limited to small energies



Support for the model: PRC (03)

The $pp \to pp\pi^+\pi^-$ reaction studied in the low-energy tail of the Roper resonance

J. Pätzold,[1] M. Bashkanov,[1] R. Bilger,[1] W. Brodowski,[1] H. Calén,[2] H. Clement,[1] C. Ekström,[2] K. Fransson,[3] J. Greiff,[4]



Question:
Has the normalization changed?
Reading papers I find that the normalizations for related reactions were changed twice

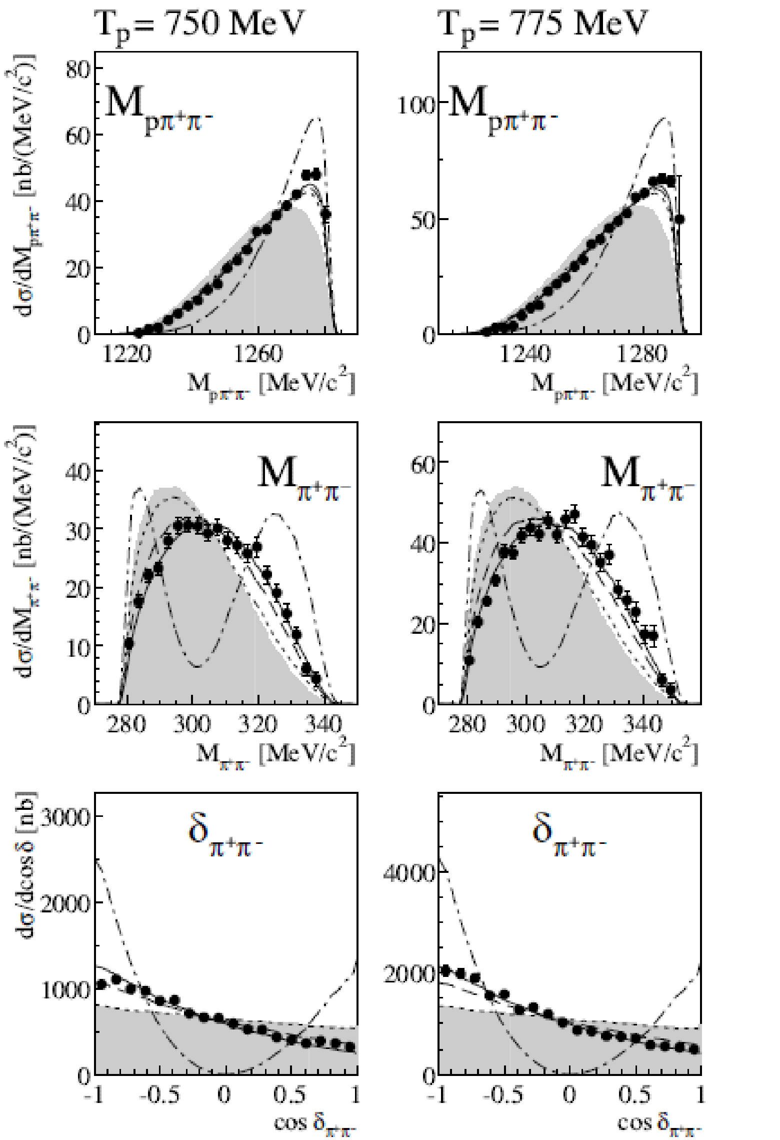


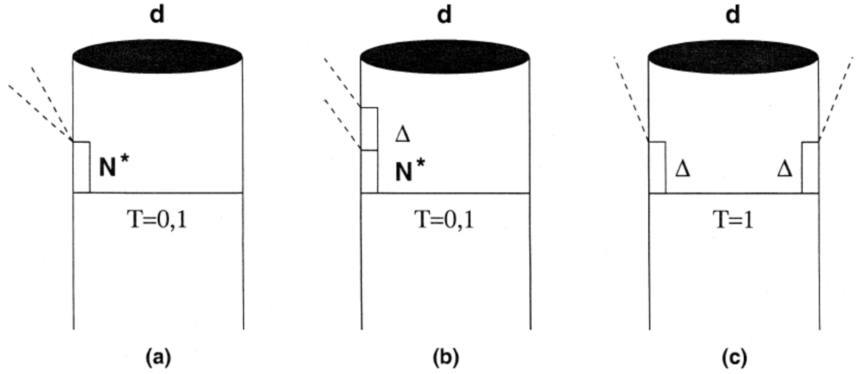
FIG. 4. Invariant masses $M_{p\pi^+\pi^-}$ and $M_{\pi^+\pi^-}$ as well as the opening angle $\delta_{\pi^+\pi^-}$ between the two pions for both 750 (left) and 775 MeV (right) beam energies. The data are shown in comparison to phase space (shaded area) and MC simulations for pure decays $N^* \to N\sigma$ (dotted), $N^* \to \Delta\pi$ (dashed dotted), and their interference with $c' = -37$ (dashed) and -61 (solid) $(\mathrm{GeV}/c)^{-2}$ using Eq. (2).

$$\mathcal{A} \sim 1 + c\,\mathbf{k}_1 \cdot \mathbf{k}_2 (3D_{\Delta^{++}} + D_{\Delta^0})$$

The data supports the dominance of the N* excitation with N* -> N ππ together with N* -> Δ π -> N ππ

The role of the Roper resonance in $np \to d(\pi\pi)^0$

L. Alvarez-Ruso PLB (99)



Restricted model,
Energy T_n=0.79 GeV

Note the huge effect of interference!!!

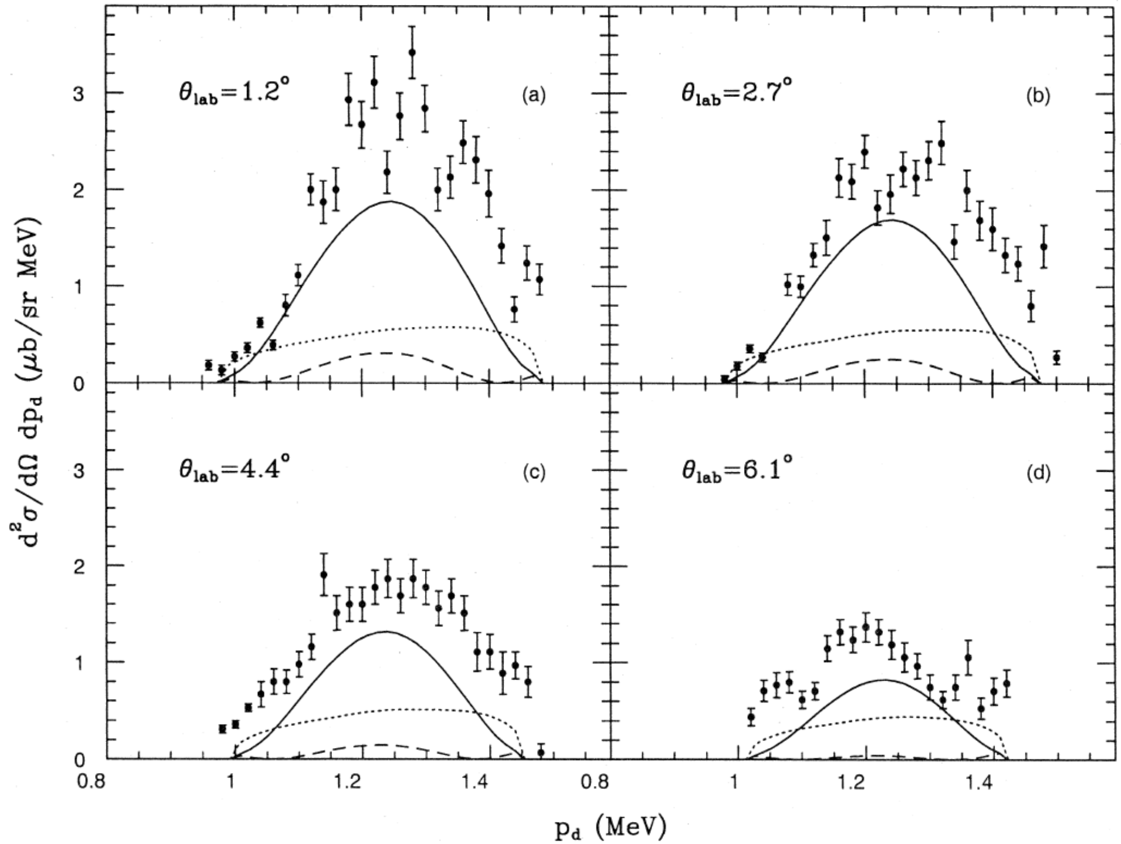


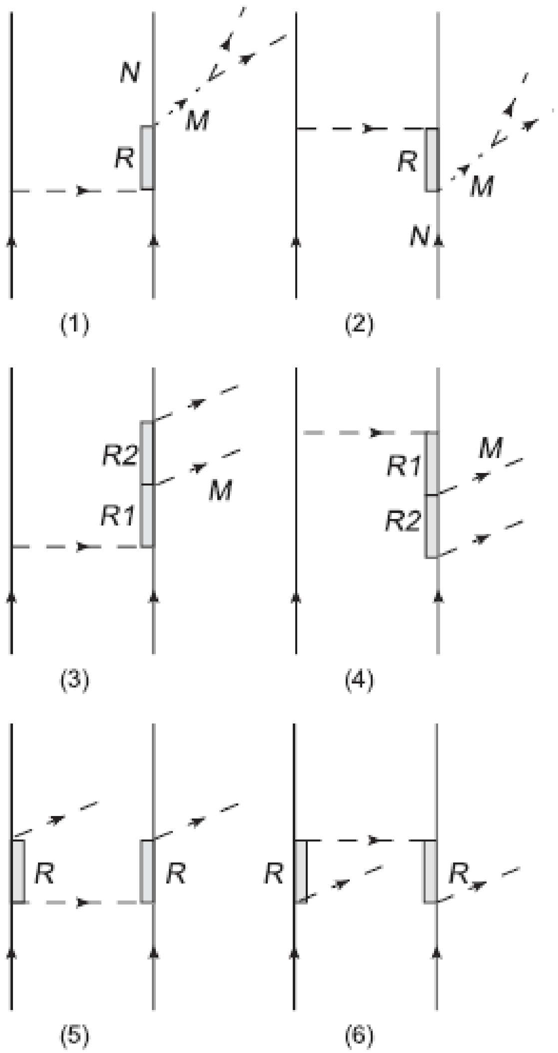
Fig. 2. Deuteron momentum spectra for $np \to d(\pi\pi)^0$ at $p_n = 1.46$ GeV/c and different laboratory angles (solid lines) compared to the measured data [15]. The dotted line corresponds to the $N^* \to N(\pi\pi)^{T=0}_{\text{S-wave}}$ mechanism (Fig. 1a); the short-dashed line stands for the $N^* \to \Delta\pi$ (Fig. 1b).

Limits to the model and improvements

Phenomenological analysis of the double-pion production in nucleon-nucleon collisions up to 2.2 GeV

PRC (10)

Xu Cao,[1,3,5,*] Bing-Song Zou,[2,3,4] and Hu-Shan Xu[1,3,4]



Same philosophy as Valencia model but Δ(1600) and Δ(1620) are added

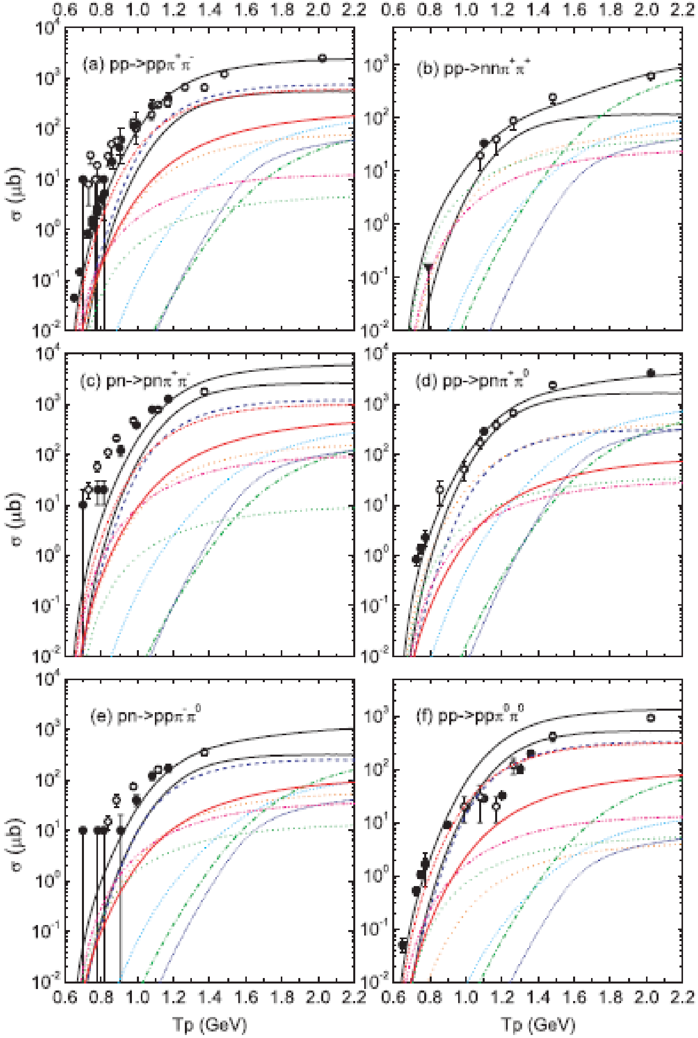


FIG. 2. (Color online) Total cross sections of $NN \to NN\pi\pi$. The black solid, red short-dash-dotted, blue dashed, orange dotted, green dotted, cyan short-dashed, green dash-dotted, royal short-dotted, magenta dash-dot-dotted, bold red, and bold solid curves correspond to contribution from double-Δ, $N^*(1440) \to N\sigma$, $N^*(1440) \to \Delta\pi$, $\Delta \to \Delta\pi$, $\Delta \to N\pi$, $\Delta^*(1600) \to \Delta\pi$, $\Delta^*(1600) \to N^*(1440)\pi$, $\Delta^*(1620) \to \Delta\pi$, nucleon pole, $N \to \Delta\pi$, and the full contributions, respectively. The solid circles and triangles represent the data from Ref. [6,9–11]. The open circles represent the old data [14].

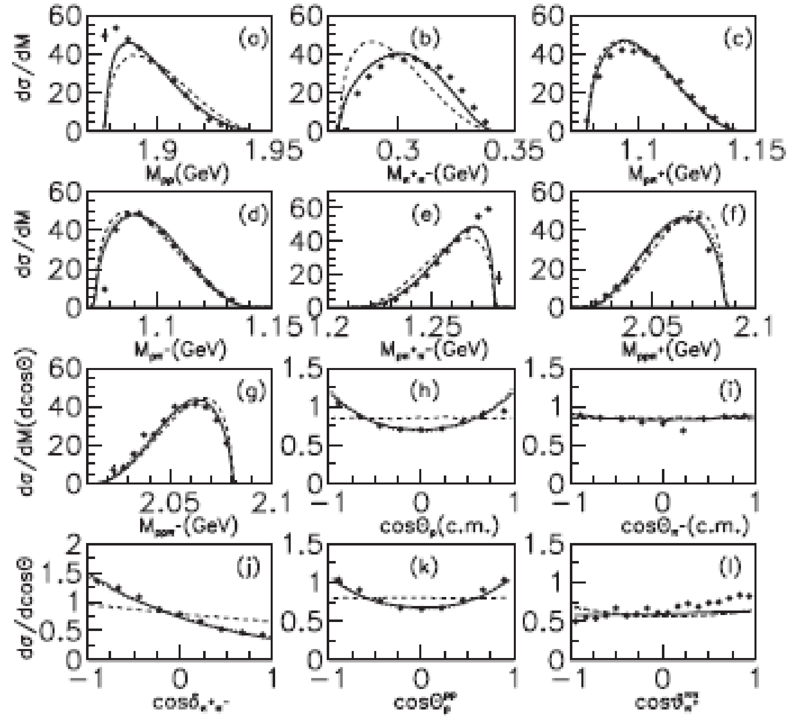


FIG. 5. Differential cross sections of $pp \to pp\pi^+\pi^-$ at beam energies 750 MeV. The dashed, dotted, and solid curves correspond to the phase space, $N^*(1440) \to N\sigma$, and full model distributions, respectively. The data are from Ref. [6].

Impressive agreement with experiment in spite of NO HAVING INTERFERENCE of the different terms.

Theoreticians unhappy.

Other improvements are done by the Tuebingen group

PLB (11)

$\Delta\Delta$ excitation in proton–proton induced $\pi^0\pi^0$ production

T. Skorodko[a], M. Bashkanov[a], D. Bogoslawsky[b], H. Calén[c], H. Clement[a,*], E. Doroshkevich[a],

They reduce the ρ-exchange strength, resulting in an improvement of the Valencia model.

The surprise

PRL(09)

Double-Pionic Fusion of Nuclear Systems and the "ABC" Effect: Approaching a Puzzle by Exclusive and Kinematically Complete Measurements

M. Bashkanov,[1] C. Bargholtz,[11] M. Berłowski,[6] D. Bogoslawsky,[2] H. Calén,[3] H. Clement,[1] L. Demiroers,[5]

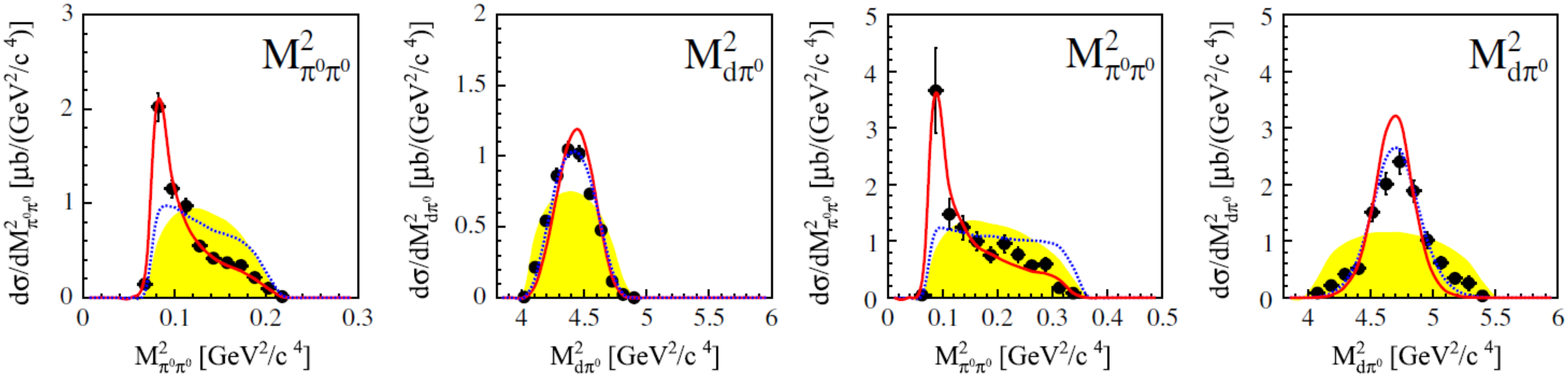
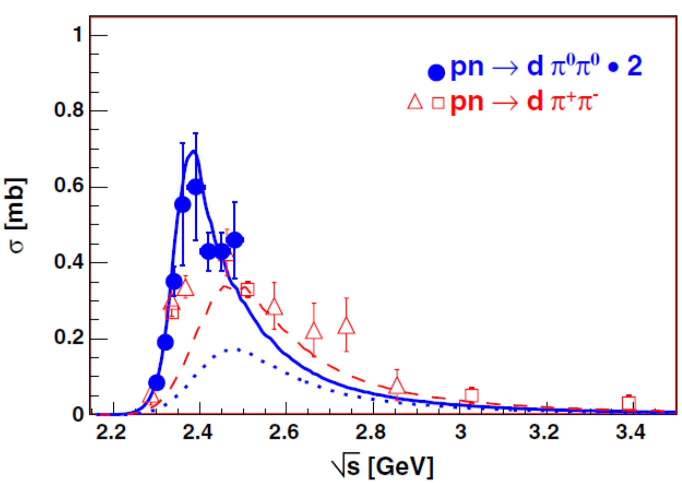
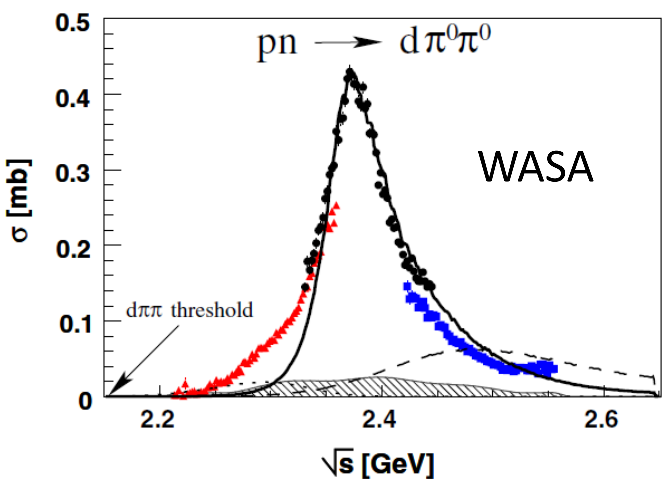
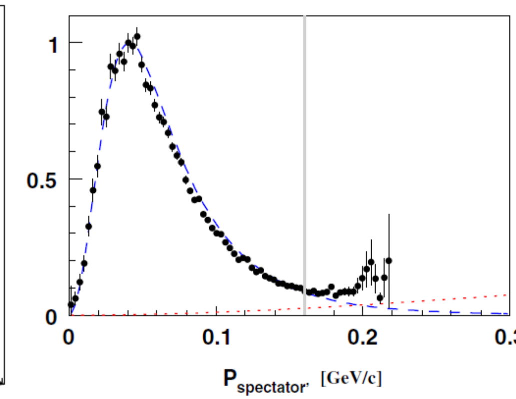


FIG. 2 (color online). Distributions of the invariant masses $M_{\pi^0\pi^0}$ and $M_{d\pi^0}$ from the exclusive measurements (full dots) of the $pn \rightarrow d\pi^0\pi^0$ reaction at effective collision energies of 1.00–1.03 (left) and 1.34–1.37 GeV (right). The shaded areas show the pure phase-space distributions. Solid and dotted curves give $\Delta\Delta$ calculations with and without the assumption of an s-channel resonance, respectively. All curves are normalized to the experimental integral cross section.







Is this peak a dibaryon resonance?

Is it related to the deuteron fusion form factors?

Why simultaneously peak in energy and dominance of low pi pi invariant mass.

Could it be that the two pions going together minimizes the transfer momentum to the deuteron? $\pi^0\pi^0$ in I=0 can be in S-wave together.

Then in pp -> d $\pi^+\pi^0$ (I=1) the peak should not appear. Confirmed by exp.

But then $\pi^+\pi^-$ also has a I=0 component, and the enhancement should also be seen. Does not look like in PRL (09)

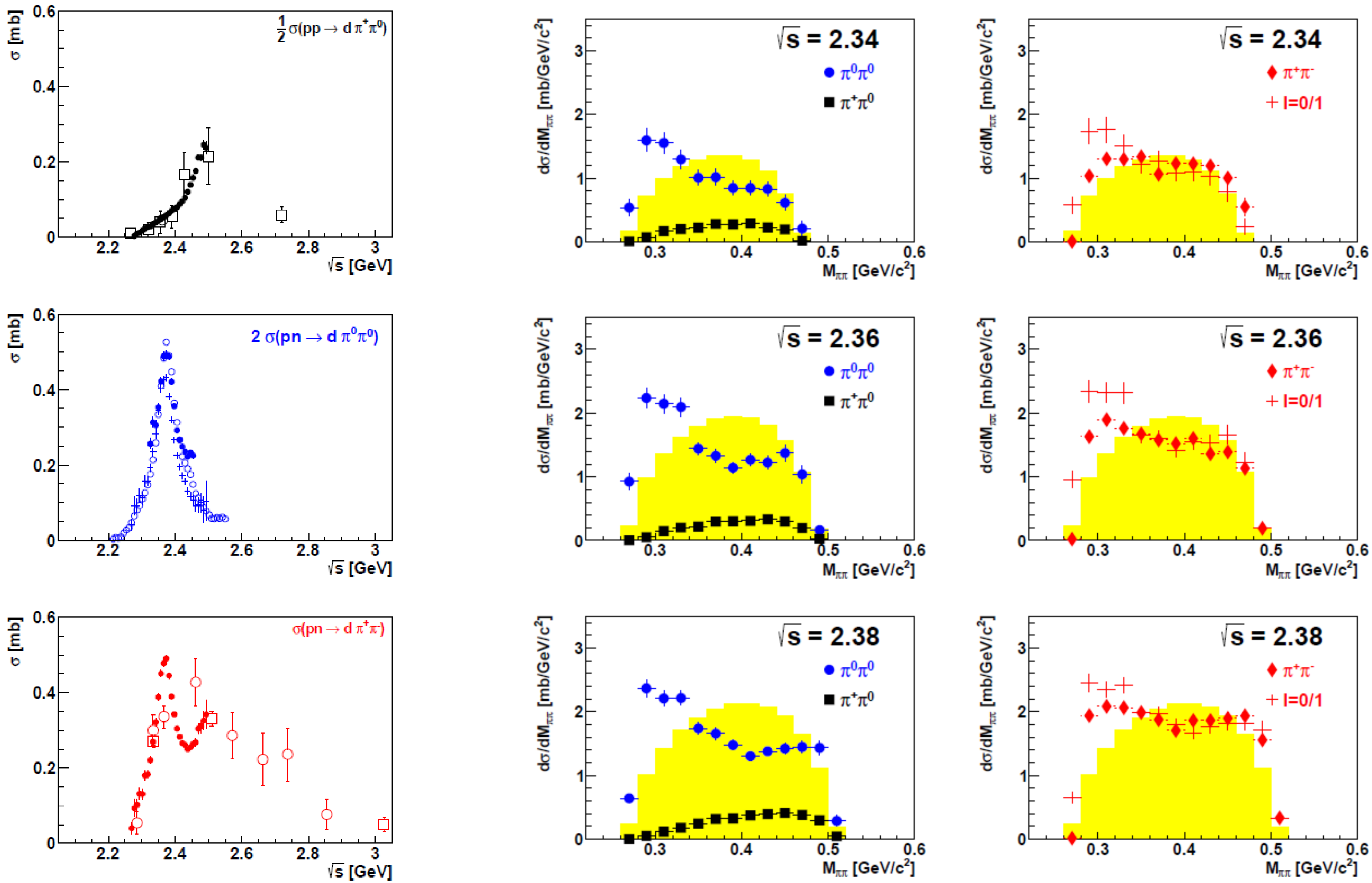
But WASA good…

Isospin Decomposition of the Basic Double-Pionic Fusion in the Region of the ABC Effect

(2012)

The WASA-at-COSY Collaboration

P. Adlarson[a], W. Augustyniak[b], W. Bardan[c], M. Bashkanov[d], T. Bednarski[c], F.S. Bergmann[e], M. Berłowski[f], H. Bhatt[g],



If the peak is a nuclear effect, added by Bose statistics, then one should look for the elementary reaction….COSY PACS suggestion

Faeldt and Wilkin come back to it: PLB (11)

Estimation of the ratio of the $pn \to pn\pi^0\pi^0 / pn \to d\pi^0\pi^0$ cross sections

G. Fäldt [a], C. Wilkin [b,*]

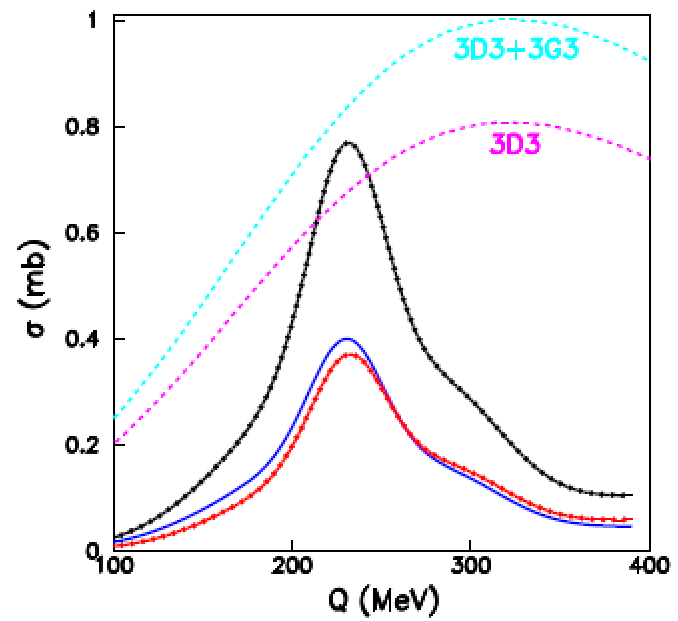


Fig. 1. Total cross section for the $pn \to d\pi^0\pi^0$ reaction as a function of the excess energy Q. The solid (blue) curve represents a parameterisation [3] of the COSY-WASA data [2]. The cross section predicted for $pn \to pn\pi^0\pi^0$ on the basis of an $L = 2$ decay using the ratio of Fig. 2 is shown by the dot-dashed (red) curve and the sum of the two components by the higher dot-dashed (black) curve. The inelastic cross sections in the $^3D_3$ (magenta) and the $^3D_3 + {}^3G_3$ (turquoise) waves taken from the SAID current solution [4] and scaled by an isospin factor of 1/6 are shown as dashed curves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

Wilkin reinterpreted : Quantum Mechanics and Final State Interaction for pedestrians

Lippman Schwinger equation

$$T = V + V \frac{1}{E - H_0} T$$

Take $\langle \vec{p}\,' | V | \vec{p} \rangle = v\, \theta(\Lambda - p)\, \theta(\Lambda - p')$

$\Rightarrow \quad \langle \vec{p}\,' | T | \vec{p} \rangle = t\, \theta(\Lambda - p)\, \theta(\Lambda - p')$

$$t = v + v G t = v(1 + G t) \quad ; \quad t = \frac{v}{1 - vG} = \frac{1}{v^{-1} - G}$$

and $G = \displaystyle\int_{p<\Lambda} d^3p \, \frac{1}{E - m_1 - m_2 - \vec{p}^{\,2}/2\mu}$

Pole at the deuteron mass : $v^{-1} - G(M_d) = 0$

Deuteron wave function :

$$H |\Psi\rangle = E |\Psi\rangle \quad ; \quad (H_0 + V) |\Psi\rangle = E |\Psi\rangle$$

$$|\Psi\rangle = \frac{1}{E - H_0} V |\Psi\rangle$$

$$\langle \vec{p} | \Psi \rangle = v \frac{\theta(\Lambda - p)}{E - m_1 - m_2 - \vec{p}^{\,2}/2\mu} \int_{k<\Lambda} d^3k \, \langle k | \Psi \rangle$$

Coupling and residues at the pole

$$t \simeq \frac{g^2}{E - M_d}$$

A few lines (Gamermann, Nieves, E.O. and Ruiz Arriola PRD 81 (10) 014029

$$g \equiv v \int_{k<\Lambda} d^3k \, \langle k | \Psi \rangle$$

$$\langle \vec{p} | \psi \rangle = \frac{g\, \theta(\Lambda - p)}{E - m_1 - m_2 - \vec{p}^2/2\mu}$$

But $g^2 = \lim (E - M_d)\, t = \lim \frac{E - M_d}{v^{-1} - G} \overset{\text{L'Hôpital}}{=} \frac{1}{-\frac{dG}{dE}}$

$$\Rightarrow \quad g^2 = \frac{\gamma}{8\pi\mu^2\left(\arctan\left(\frac{\Lambda}{\gamma}\right) - \frac{\gamma\Lambda}{\gamma^2+\Lambda^2}\right)} \quad ; \quad \gamma \equiv \sqrt{2\mu B}$$

B binding energy

When $\gamma \to 0$ (small binding)

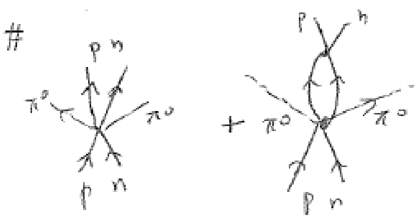
$$\lim_{\gamma \to 0} g^2 = \frac{\gamma}{4\pi^2\mu}$$

Weinberg PR (65)

#

$$t_p = V_p\, G\, g \equiv V_p\, G(M_d)\, g$$

#



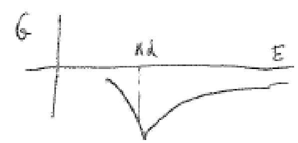
$$t'_p = V_p + V_p\, G\, t_{pn \to pn}$$
$$= V_p\,(1 + G\, t_{pn \to pn})$$
$$= V_p \frac{t_{pn \to pn}}{v} = V_p\, G(M_d)\, t_{pn \to pn}$$

But from pole of deuteron $v^{-1} - G(M_d) = 0$

Thus: $\frac{t'_p}{t_p} \equiv \frac{1}{g}\, t_{pn,pn} \approx \frac{1}{g} \frac{g^2}{E - M_d} \approx \frac{1}{g} \frac{1}{-\frac{1}{a} + \frac{1}{2} r_0 k^2 - ik}$

F+W result

Better use sth else for instance effective range.



CONCLUSION OF Faeldt and Wilkin

The peak should be seen also in the

$pn \to \underbrace{pn}\ \pi^0\pi^0$ reaction

⇓ with energy close to threshold

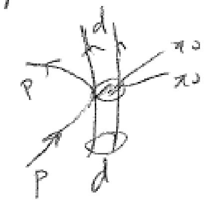
But this is true independent on the reason for the peak !!

So it does not tell us about the reason for it.

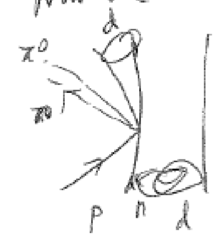
However, it could divert if

1) other mechanisms are at play

for instance: coherent production



Now one assumes dominance of



≡ deuteron disintegration + recombination with incoming proton.

2) If $(pn)_{final}$ are not at threshold the arguments in favour of $\pi^0\pi^0$ going together no longer hold.

Observation of an "ABC" Effect in Proton-Proton Collisions

ANKE PRL (09)

S. Dymov,[1,2,*] M. Hartmann,[3,4] A. Kacharava,[3,4] A. Khoukaz,[5] V. Komarov,[1] P. Kulessa,[6] A. Kulikov,[1] V. Kurbatov,[1]

pp ->pp X with $E_{pp} < 2m_p + 3$ MeV

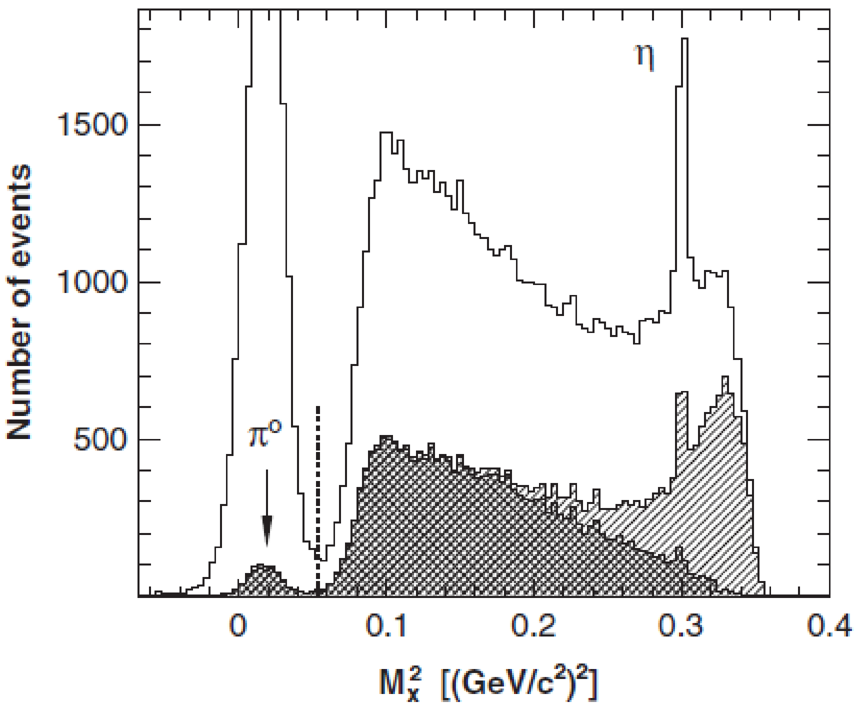


FIG. 1. Distribution in missing mass squared of the $pp \to ppX$ reaction at 1.4 GeV. Imposing a Δt cut to select the two protons gives the open histogram. The lightly shaded plot corresponds to the additional requirement that $E_{pp} < 3$ MeV, and the heavy shading reflects the further $\cos\vartheta_{pp} > 0.95$ cut to match the overall ANKE acceptance. The positions of the π^0 and η peak are indicated, as is the two-pion threshold (dotted line).

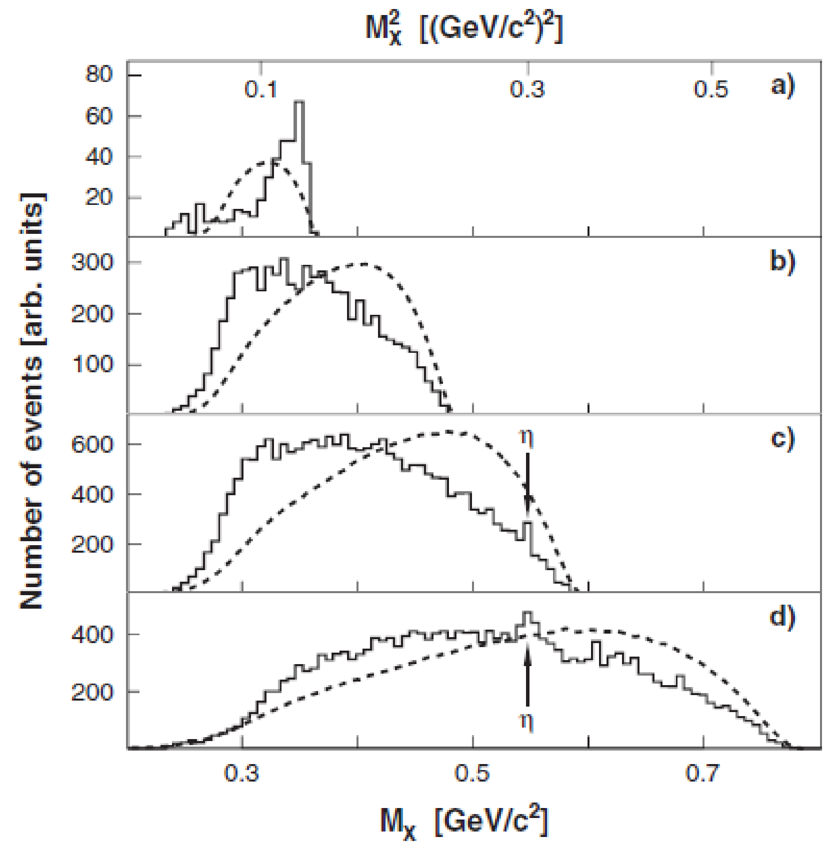


FIG. 2. Distribution in missing mass of the $pp \to \{pp\}_s X$ reaction for $E_{pp} < 3$ MeV and $\cos\vartheta_{pp} > 0.95$ at (a) 0.8, (b) 1.1, (c) 1.4, and (d) 2.0 GeV. The η signal is seen at the expected position for the two higher energies. The curves represent normalized simulations within a phase-space model.

T_p GeV	$(M_X^{\max})^2$ $(\text{GeV}/c^2)^2$	σ_X nb	ξ %	A_S/A_D	A_D
0.8	0.123	12 ± 2	34	-1.23 ± 0.10	1.09 ± 0.05
1.1	0.219	389 ± 6	2.3	-0.20 ± 0.03	1.00
1.4	0.326	563 ± 6	2.4	-0.10 ± 0.03	0.48 ± 0.01
2.0	0.549	456 ± 5	5.8	-0.23 ± 0.02	0.17 ± 0.01

Question: what happens to cross section between T_p=1.4 and 2.0 GeV? Would it have a peak at 1.7 GeV?

Related problem: PLB(11)

$\Delta\Delta$ excitation in proton–proton induced $\pi^0\pi^0$ production

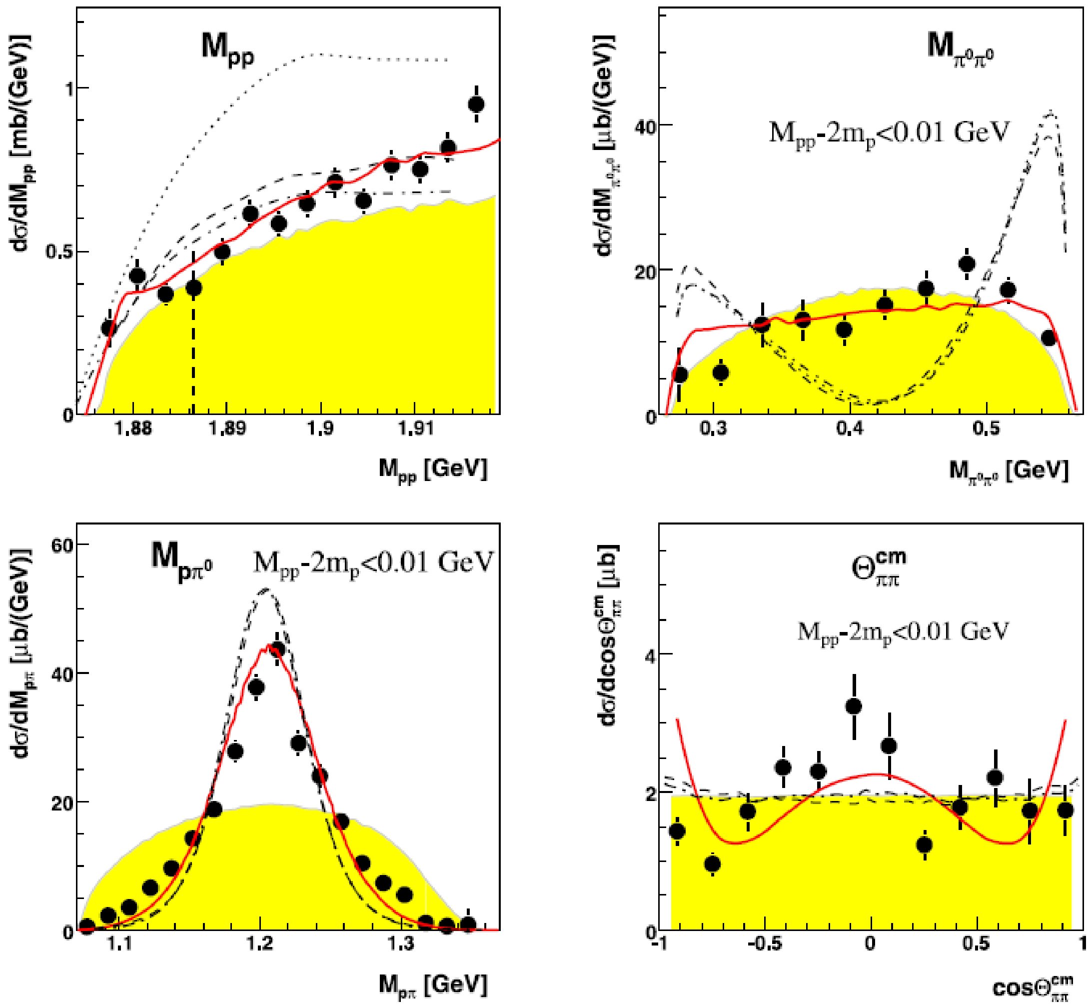
T. Skorodko [a], M. Bashkanov [a], D. Bogoslawsky [b], H. Calén [c], H. Clement [a,*], E. Doroshkevich [a],

pp->pp $\pi^0\pi^0$ with pp in quasi ^{2}He. In practice $E_{pp}<2m_p+10$ MeV

No accummulation of strength of $m_{\pi\pi}$ around threshold!!

This is at T_p=1.3 GeV, the highest energy studied in this work

It would be convenient to run energies around 1.7 GeV and with a smaller band of E_{pp}



ANKE experiment is incomplete but this is not an answer to ANKE

Reflexions and suggestions

The study of the pn -> pn$\pi^0\pi^0$ reaction must be done, both with a very narrow energy band of E_{pn} and for the whole range of E_{pn}.
This would tell us if having a deuteron in the final state in pn -> d$\pi^0\pi^0$ has to do with the peak observed or not.

If the peak disapears in the pn -> pn$\pi^0\pi^0$ with no restriction on E_{pn} or substantailly widens, we can say good bye to the "resonance".

Related pp -> pp $\pi^0\pi^0$ around T_p=1.7 GeV and narrow band of E_{pp} will help understand.

Theoretical studies are needed. Hopefully improving the present models: Valencia model not tested for so high energies.
Beijing model needs to consider interference: one must sum amplitudes, not cross sections of different mechanisms.
Even with less demanding models, the nuclear effects should be evaluated.