Compton scattering by nucleons

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Experiments carried out in the frame of the A2 collaboration at the accelator MAMI in Mainz.
Theory developed in cooperation with the P.N. Lebedev Physical Institute in Moscov.

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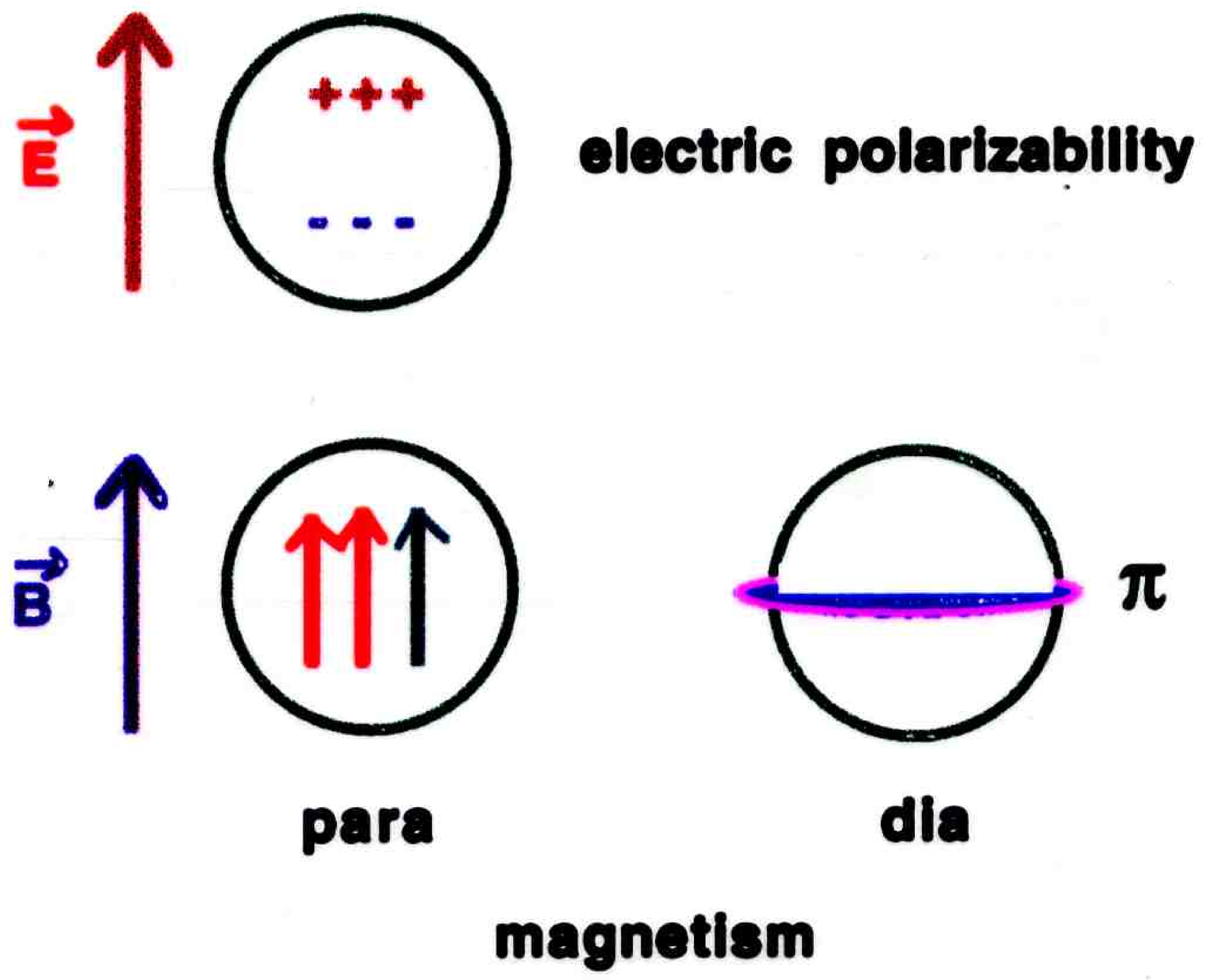
Electric and magnetic polarizabilities



$$\vec{D} = 4\pi\alpha\vec{E} \qquad \vec{M} = 4\pi\beta\vec{H}$$

$$f = f_B + \omega\omega'\alpha\epsilon\cdot\epsilon' + \omega\omega'\beta\mathbf{s}\cdot\mathbf{s}'$$

$$\alpha = 2\sum_{n\neq 0}\frac{|\langle n^{(i)}|D_z|0\rangle|^2}{E_n^{(i)} - E_0^{(i)}} + Z^2\frac{e^2\langle r_E^2\rangle}{3M} + \Delta\alpha(c.m.)$$

$$\beta_{para} = 2\sum_{n\neq 0}\frac{|\langle n^{(i)}|M_z|0\rangle|^2}{E_n^{(i)} - E_0^{(i)}}$$

$$\beta_{dia} = -e^2\sum_i \frac{q_i^2}{6m_i}\langle 0|\rho_i^2|0\rangle - \frac{\langle 0|\mathbf{D}^2|0\rangle}{2M}$$

R.N. Lee, A.I. Milstein, M. Schumacher; Phys. Rev. Lett. 87 (2001) 051601; Phys. Rev. A 64 (2001) 032507; Phys. Lett. B 541 (2002) 87

Definition of polarizabilities

$$T^{\mathrm{LAB}}(\theta = 0) = f_0(\omega)\epsilon' \cdot \epsilon + g_0(\omega)\, i\,\sigma \cdot (\epsilon' \times \epsilon)$$

$$T^{\mathrm{LAB}}(\theta = \pi) = f_\pi(\omega)\epsilon' \cdot \epsilon + g_\pi(\omega)\, i\,\sigma \cdot (\epsilon' \times \epsilon)$$

$$f_0(\omega) = -\frac{e^2}{4\pi m} q^2 + \omega^2\,(\alpha + \beta) + \mathcal{O}(\omega^4)$$

$$g_0(\omega) = \omega\left[-\frac{e^2}{8\pi m^2}\,\kappa^2 + \omega^2 \gamma_\circ + \mathcal{O}(\omega^4)\right]$$

$$f_\pi(\omega) \sim -\frac{e^2}{4\pi m} q^2 + \omega\omega'\,(\alpha - \beta) + \mathcal{O}(\omega^2 \omega'^2)$$

$$g_\pi(\omega) \sim \frac{e^2}{8\pi m^2}(\kappa^2 + 4q\kappa + 2q^2) + \omega\omega'\,\gamma_\pi + \mathcal{O}(\omega^2 \omega'^2)$$

Sum Rules

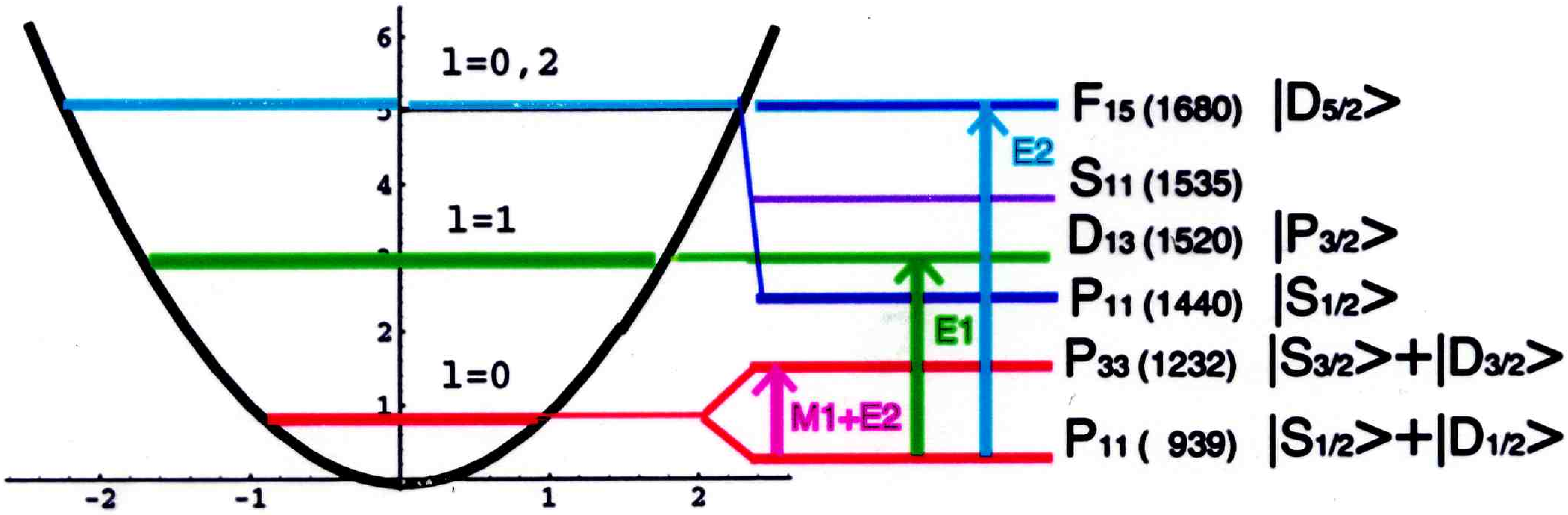
$\alpha + \beta$	Baldin 1960
κ^2	Gerasimov-Drell-Hearn 1966
$\alpha - \beta$	Bernabeu-Ericson-FerroFontan-Tarrach 1974/77
γ_π	L'vov-Nathan 1999

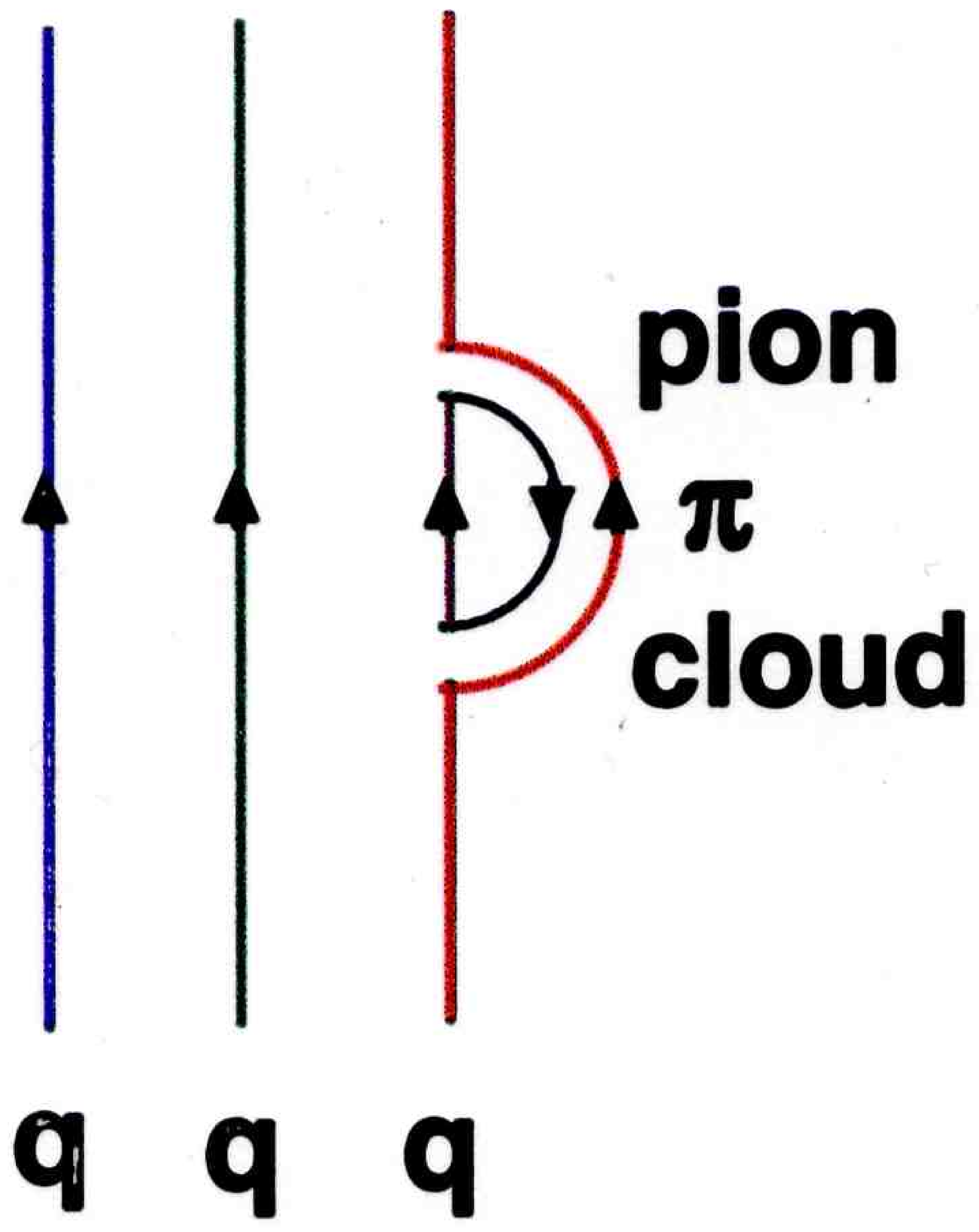
$$\alpha + \beta = \frac{1}{2\pi^2}\int_{\omega_0}^{\infty} \frac{\sigma(\omega)}{\omega^2} d\omega$$

$$\frac{2\pi^2 \alpha_e \kappa^2}{M^2} = \int_{\omega_0}^{\infty} \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega} d\omega$$

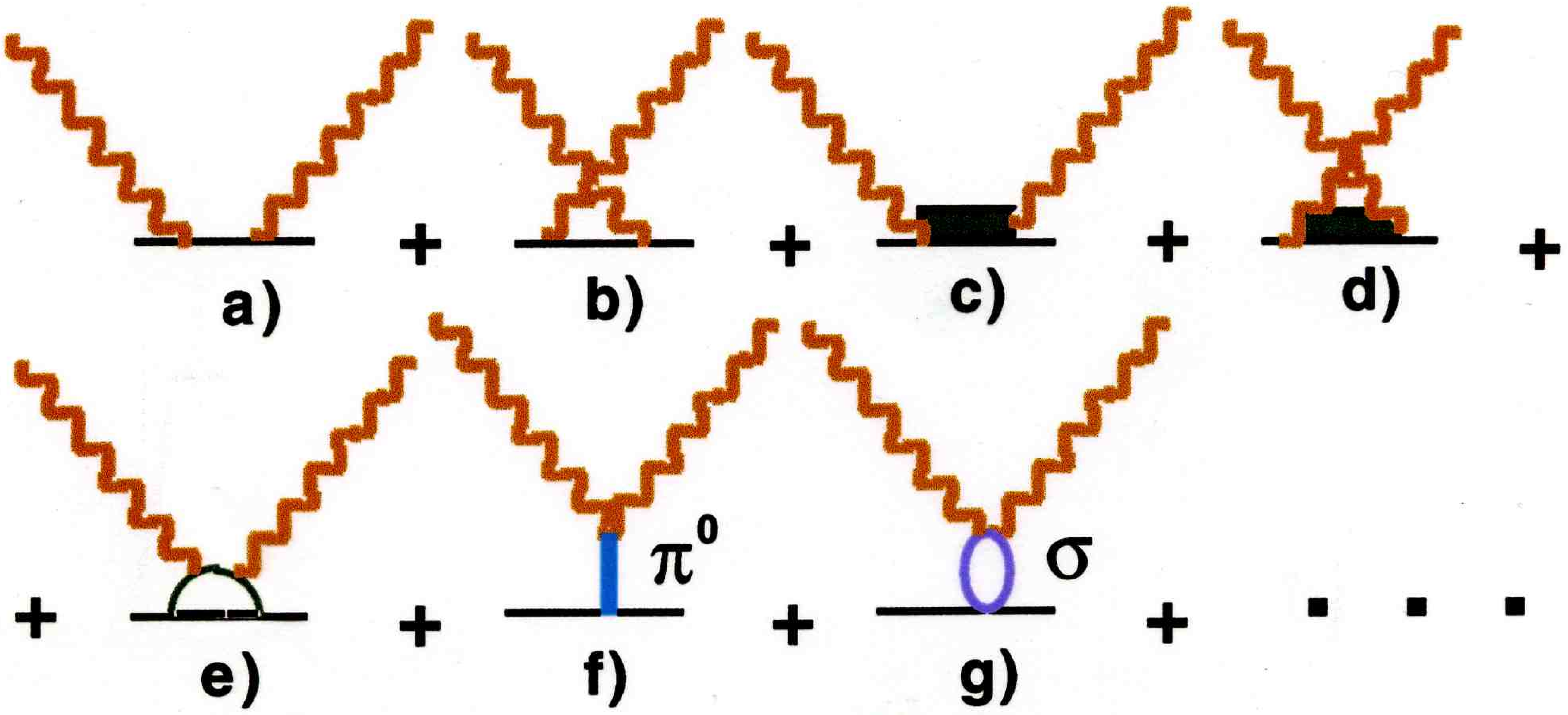
Constituent quark - pion structure of the nucleon

The main (giant) resonances of the nucleon in the harmonic oscillator model





Graphs contributing to Compton scattering



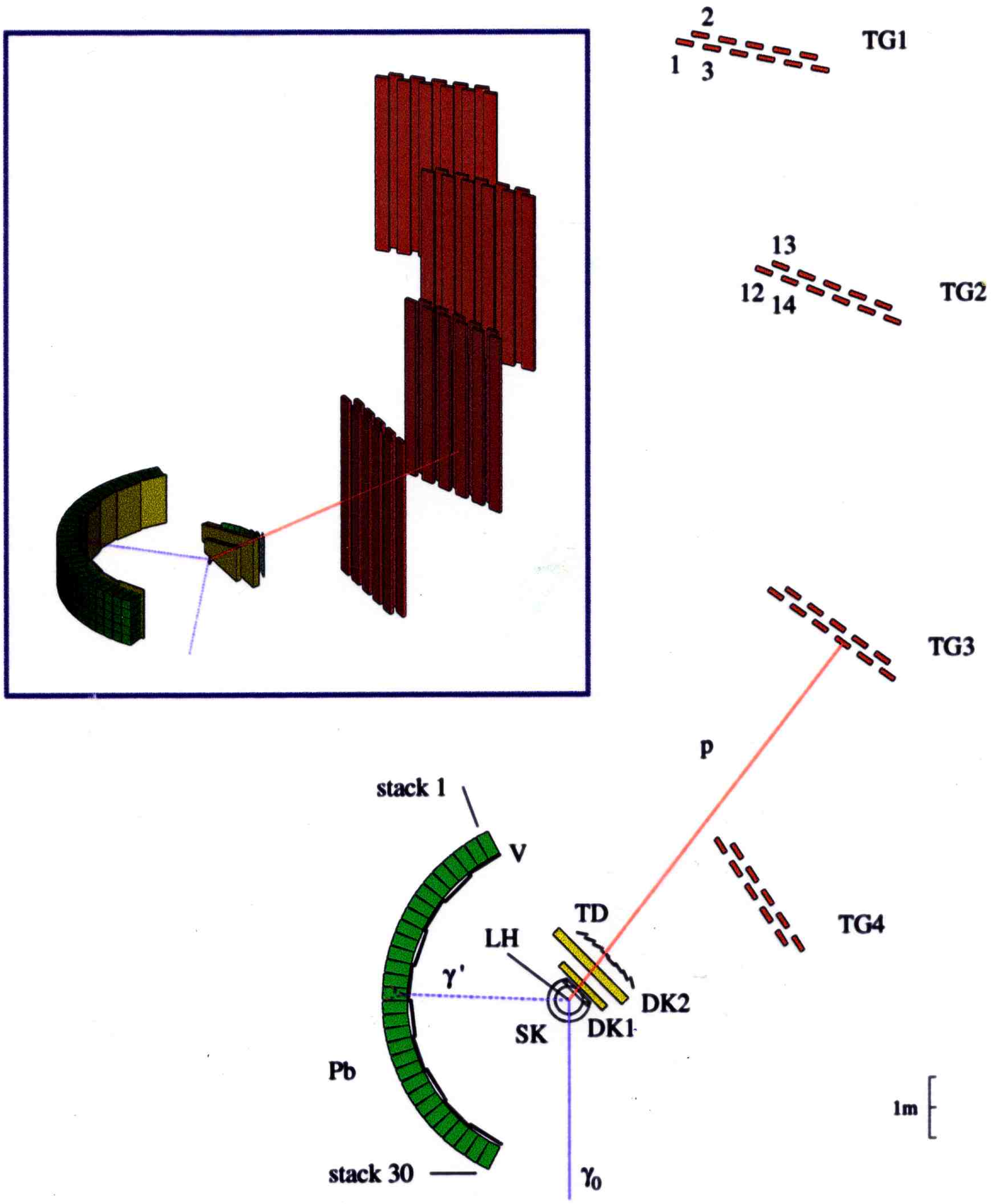
a) Born term
b) crossed Born term
c) resonant Compton scattering
d) crossed resonant Compton scattering
e) representative graph describing Compton scattering by pions
f) π^0 pole term
g) t-channel $\pi\pi$ (σ-meson) contribution

The t-channel $\pi\pi$ (σ-meson) contribution is the dominant part of the processes contributing to $\alpha - \beta$.

Has this graph the structure of a pole term?

How can this graph be incorporated into a nucleon model?

The LARge Acceptance arrangement



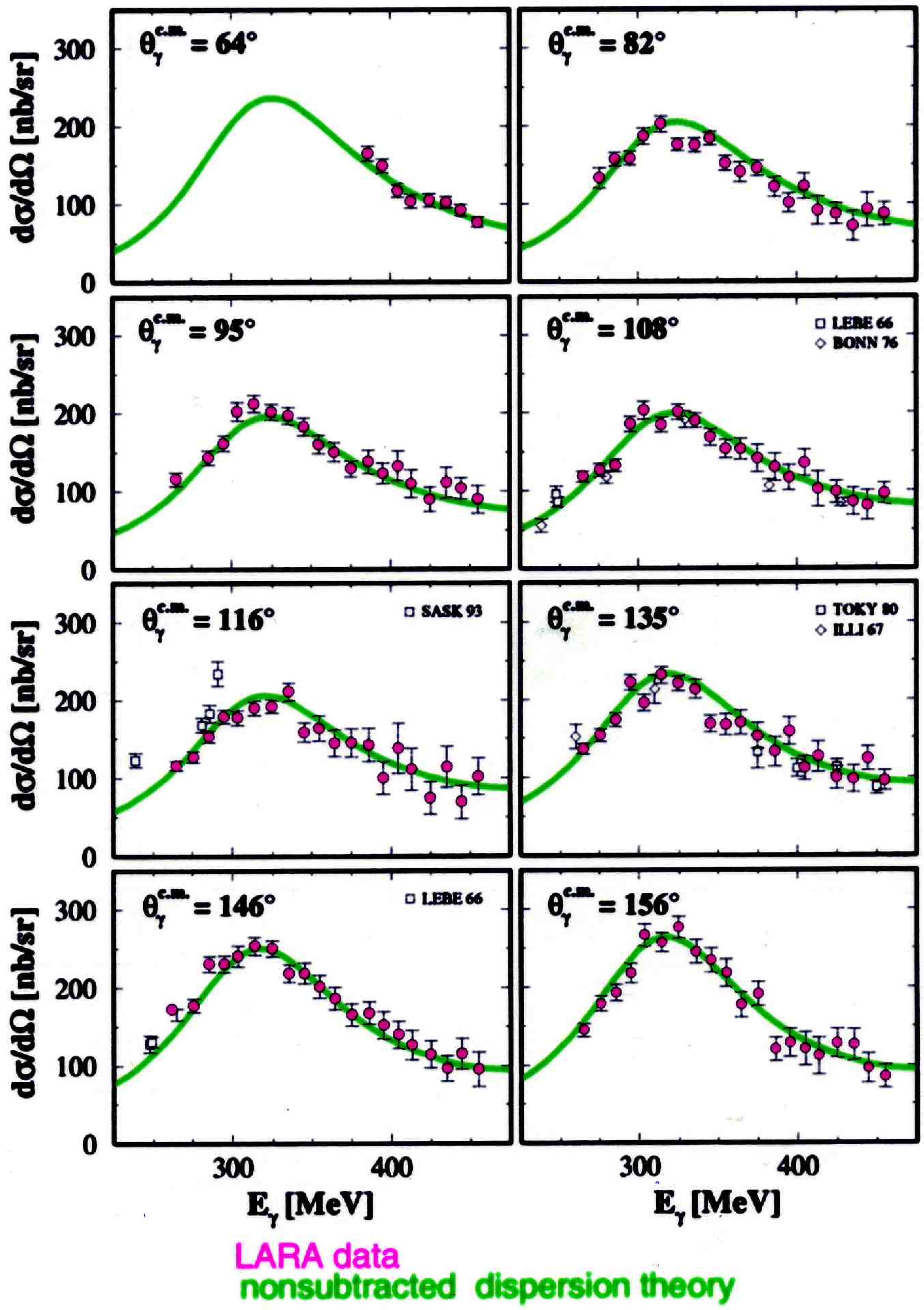
photon arm

proton arm

G. Galler et al., Phys. Lett. B 503 (2001) 245

S. Wolf et al., Eur. Phys. J. A 12 (2001) 231

Compton scattering in the Δ range

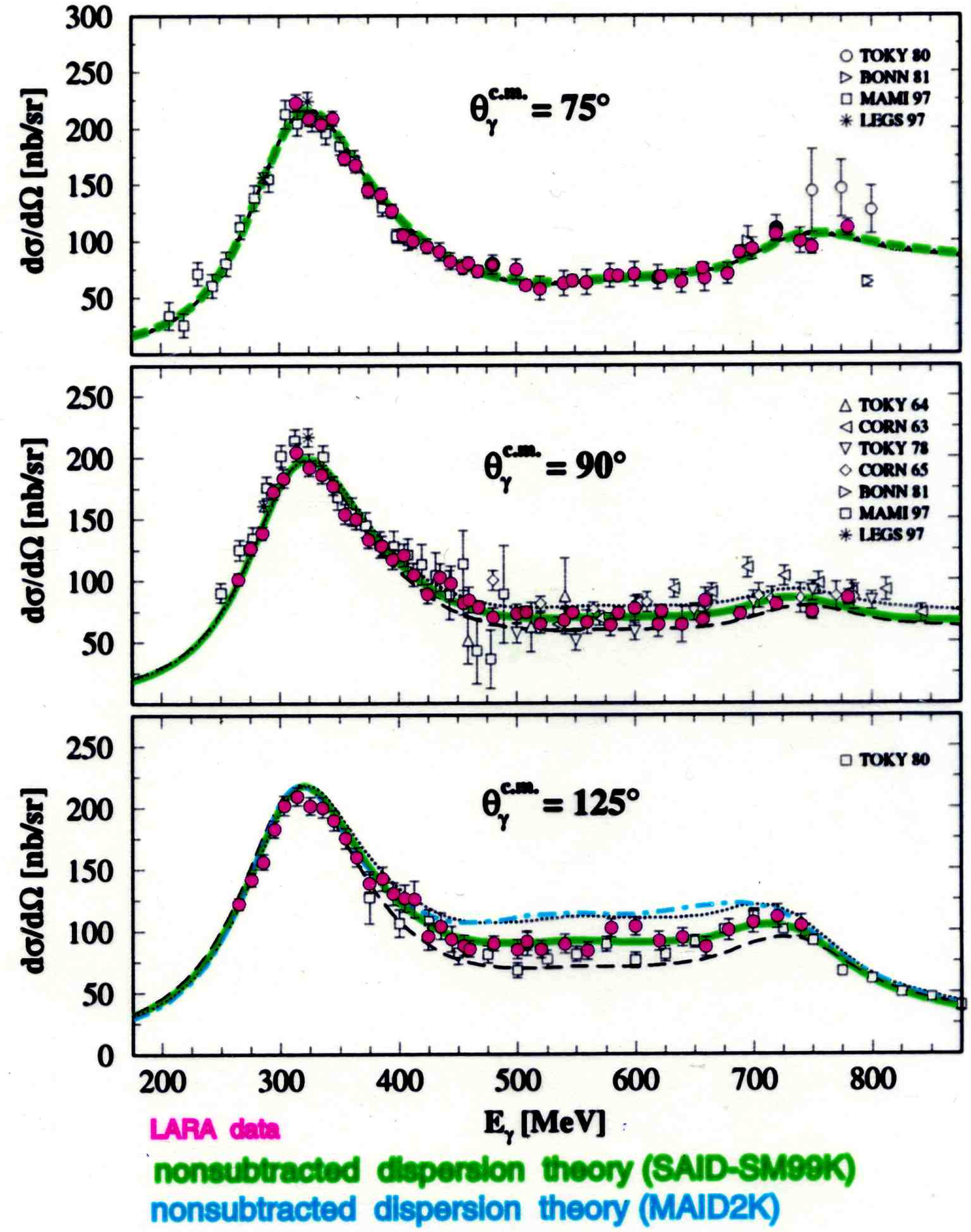


8 out of **24** energy distributions obtained for the Δ range using the **LAR**ge **A**cceptance arangement

G. Galler et al., Phys. Lett. B 503 (2001) 245

S. Wolf et al., Eur. Phys. J. A 12 (2001) 231

The mass parameter of the σ meson pole

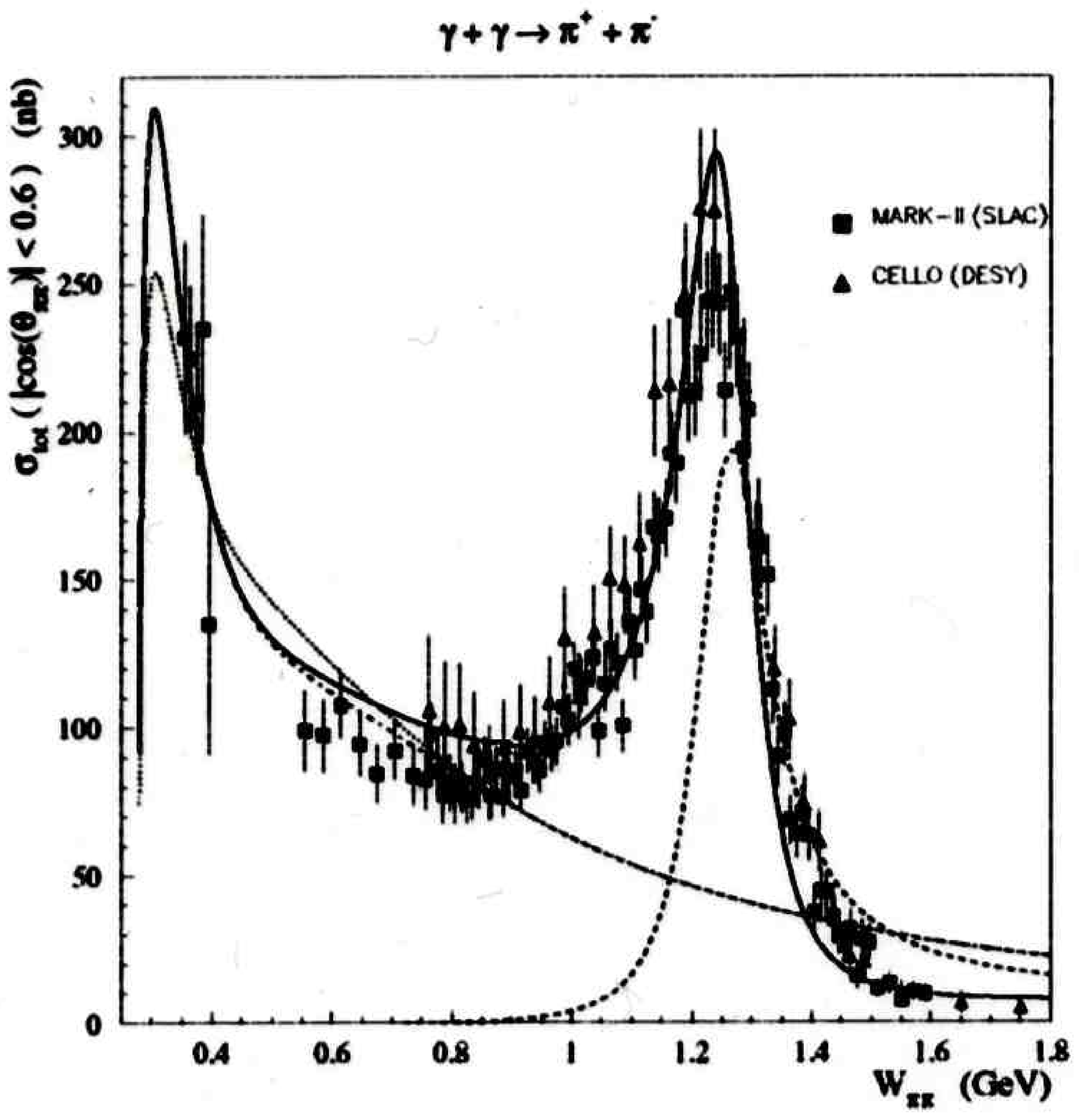


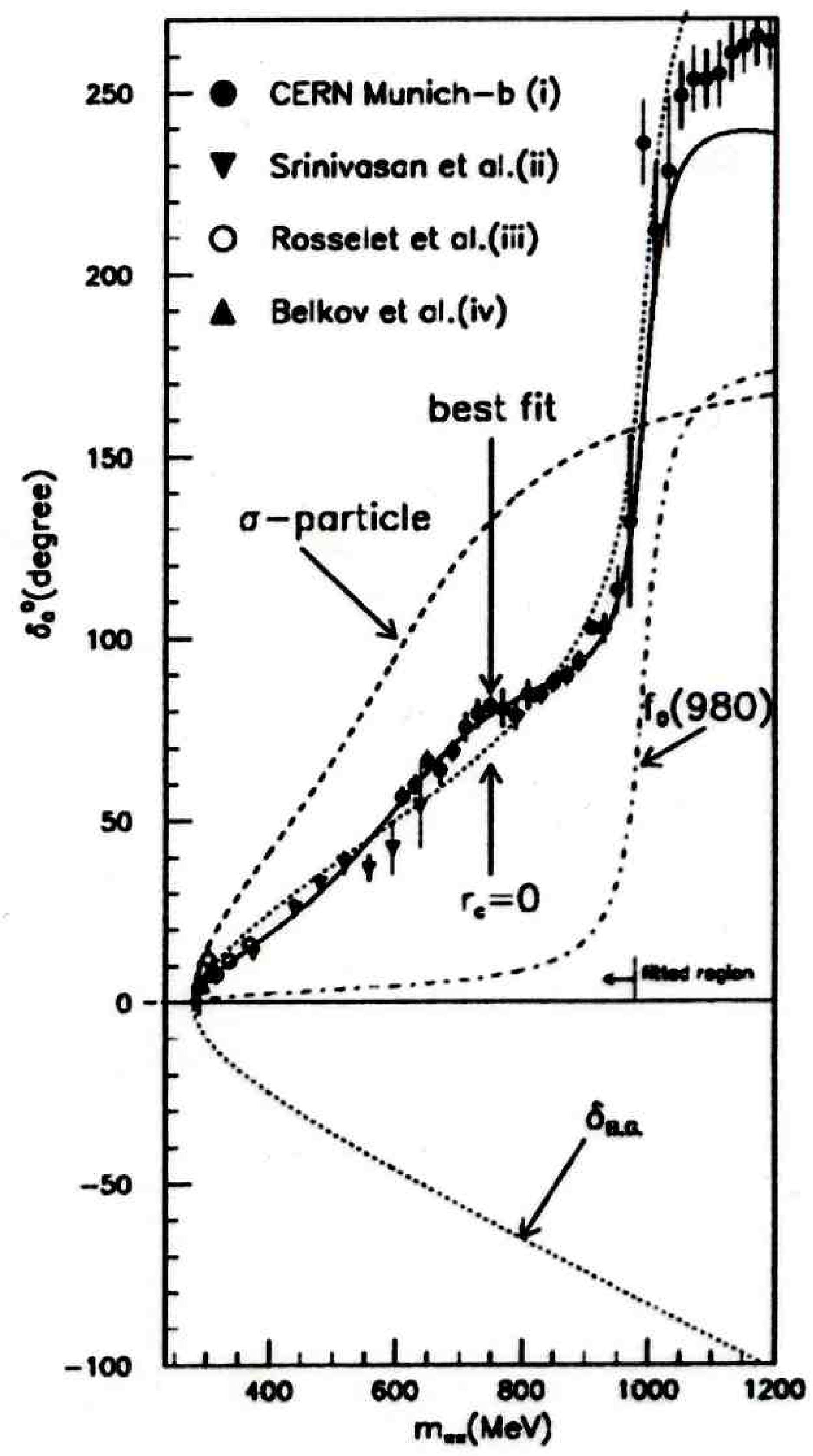
Variation of parameter m_σ	
green curve:	$m_\sigma = 600$ MeV (SAID-SM99k parameterization)
blue curve:	$m_\sigma = 600$ MeV (MAID2K parameterization)
upper black:	$m_\sigma = 800$ MeV (SAID-SM99k parameterization)
lower black:	$m_\sigma = 400$ MeV (SAID-SM99k parameterization)

G. Galler et al., Physics Letters B 503 (2001) 245
S. Wolf et al., Eur. Phys. J. A 12 (2001) 231

S.S. Kamalov et al. nucl.-th./020702 MAID&SAID

$\alpha - \beta$ from dispersion theory





The $f_0(600)$ or σ in the $\pi + N \to N\pi\pi$ reaction

$\sqrt{s}$(pole)	$\sqrt{s}(\delta_s = 90°)$	author
$(470 \pm 30) - i(295 \pm 20)$ MeV	844 ± 13 MeV	Leutwyler 2001
$(585 \pm 20) - i(193 \pm 35)$ MeV	~ 900 MeV	Ishida 2003

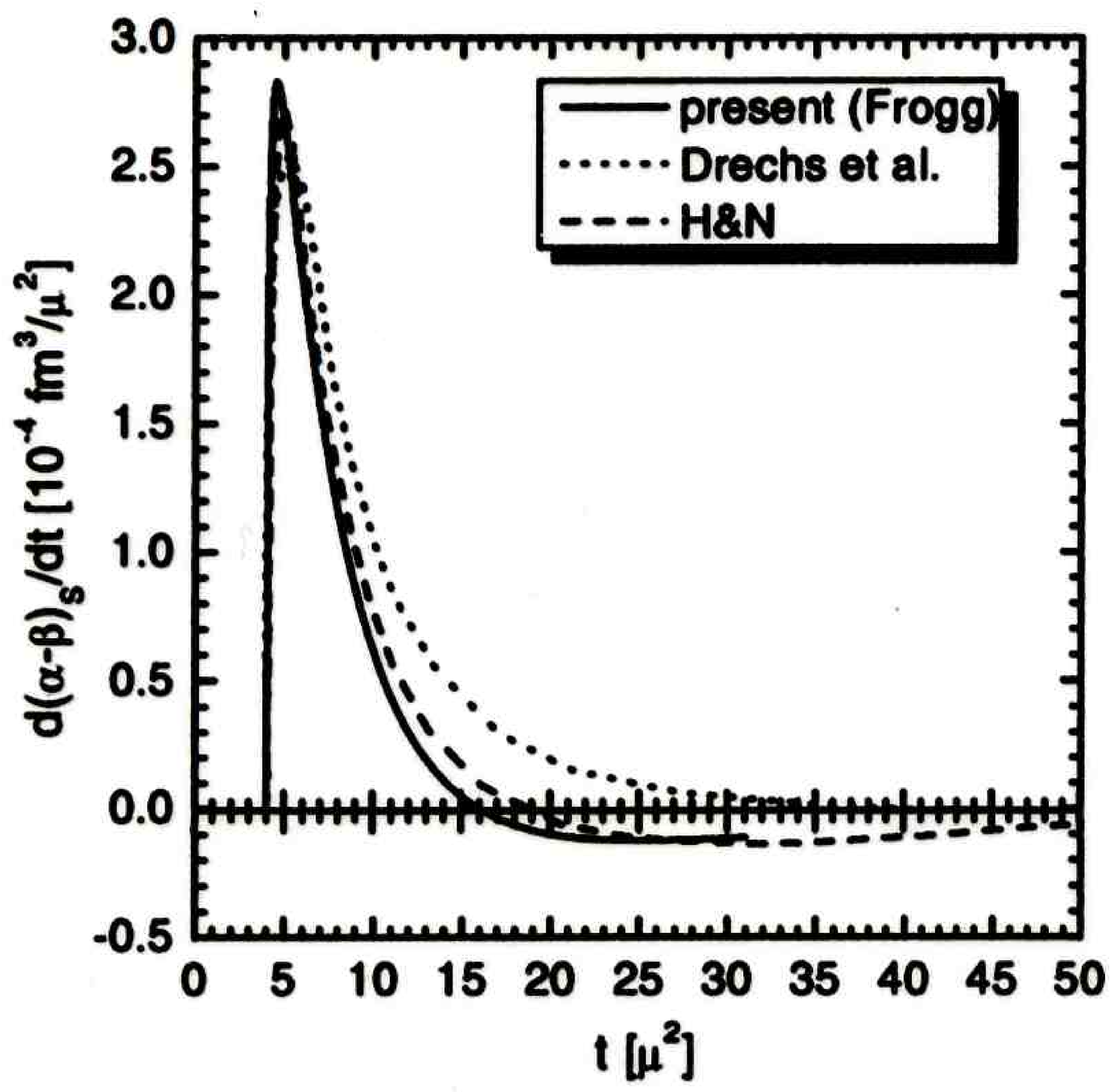
The $f_0(600)$ or σ in the $\gamma\gamma \to \pi^0\pi^0$ reaction

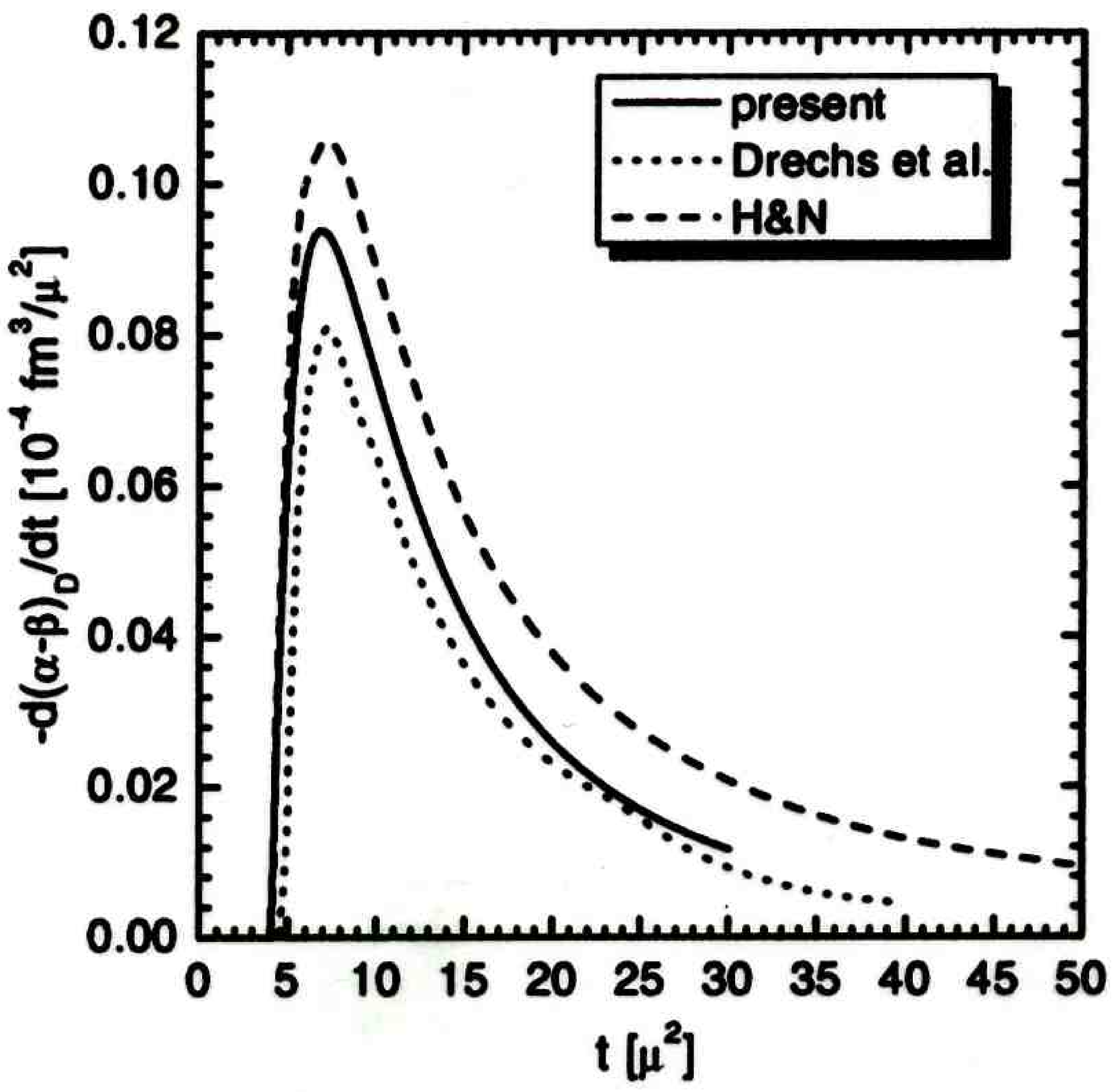
m_σ	Γ_σ (MeV)	$\Gamma_{\sigma\to\gamma\gamma}$ (keV)	author
547 ± 45 MeV	1204 ± 362 MeV	0.62 ± 0.19	Fil'kov 1999

Dispersion sum rule (BEFT) for $\alpha - \beta$

J. Bernabeu, T.E.O. Ericson, C. Ferro Fontan, Phys. Lett 49 B (1974) 381
J. Bernabeu,B. Tarrach, Phys. Lett 69 B (1977) 484

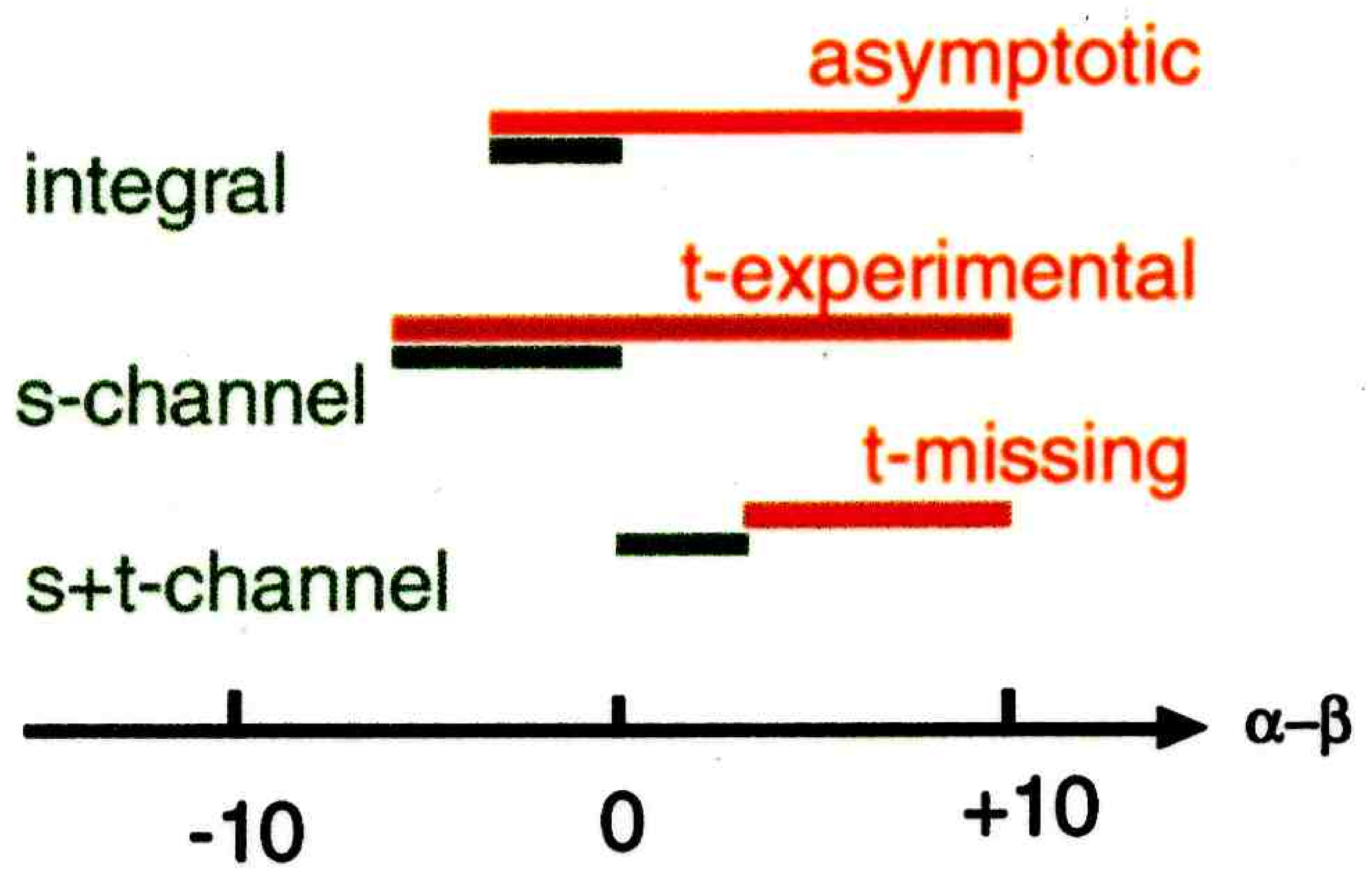
$\theta = 180°$ fixed-θ dispersion relation: $(\alpha-\beta)^{s+t} = (\alpha-\beta)^{s} + (\alpha-\beta)^{t}$



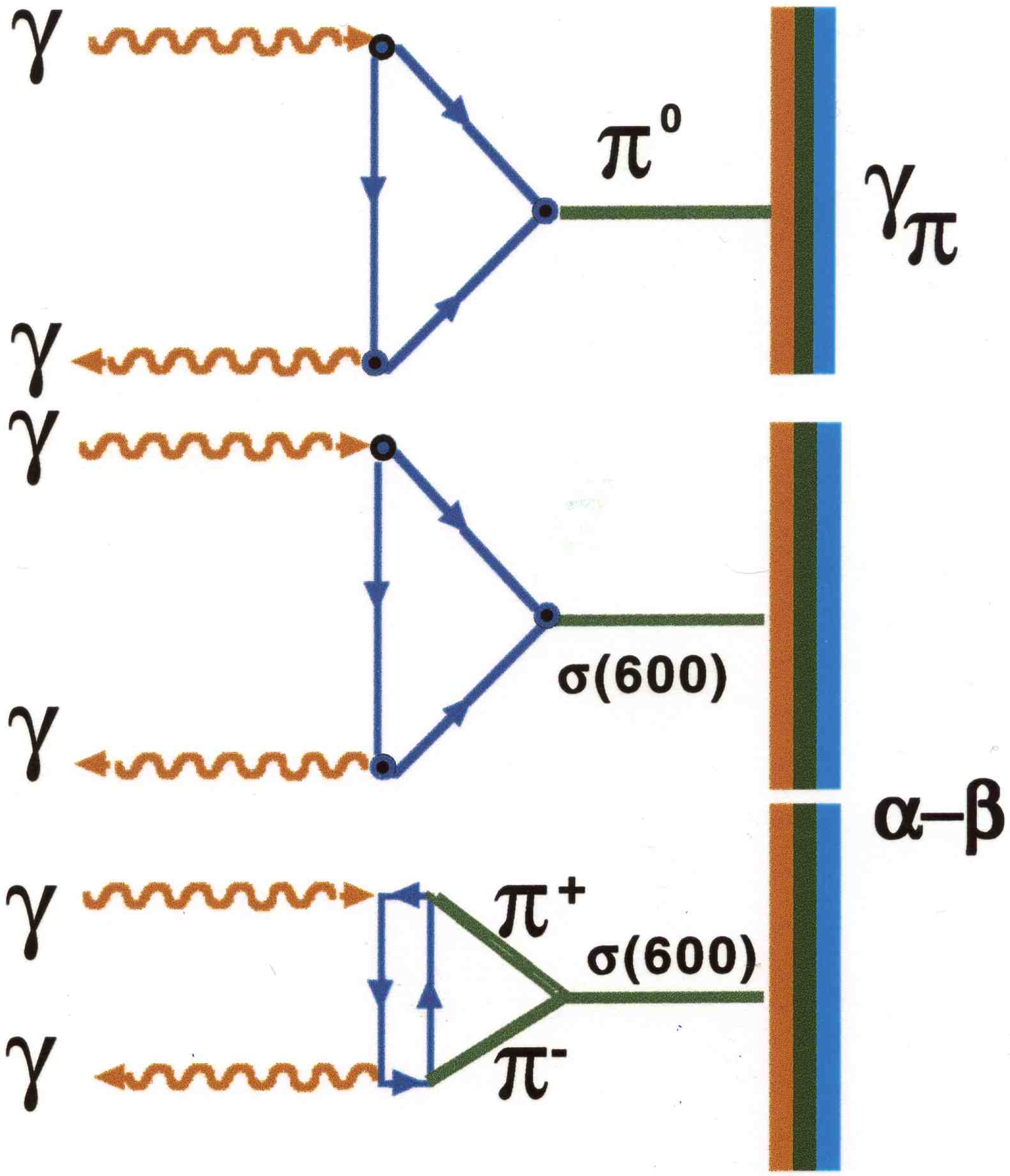


$(\alpha_p-\beta_p)^s$	$(\alpha_p-\beta_p)^t$	$(\alpha_p-\beta_p)^{s+t}$	authors
-5.4	+8.6	$+(3.2^{+2.4}_{3.6})$	Holstein,Nathan
-5.56	+16.46	+(10.9±0.2)	Drechsel,Pasquini,Vanderh.
-(6.0±1.0)	+(9.2±1.0)	+(3.2±1.4)	Levchuk, L'vov

Holstein, A.M. Nathan, Phys. Rev. D 49 (1994) 6101
Drechsel, Pasquini, Vanderhaeghen, hep-ph/0212124, Phys. Rept. 378 (2003) 99
M.I. Levchuk, A.I. L'vov, private communication 2004 (preliminary)



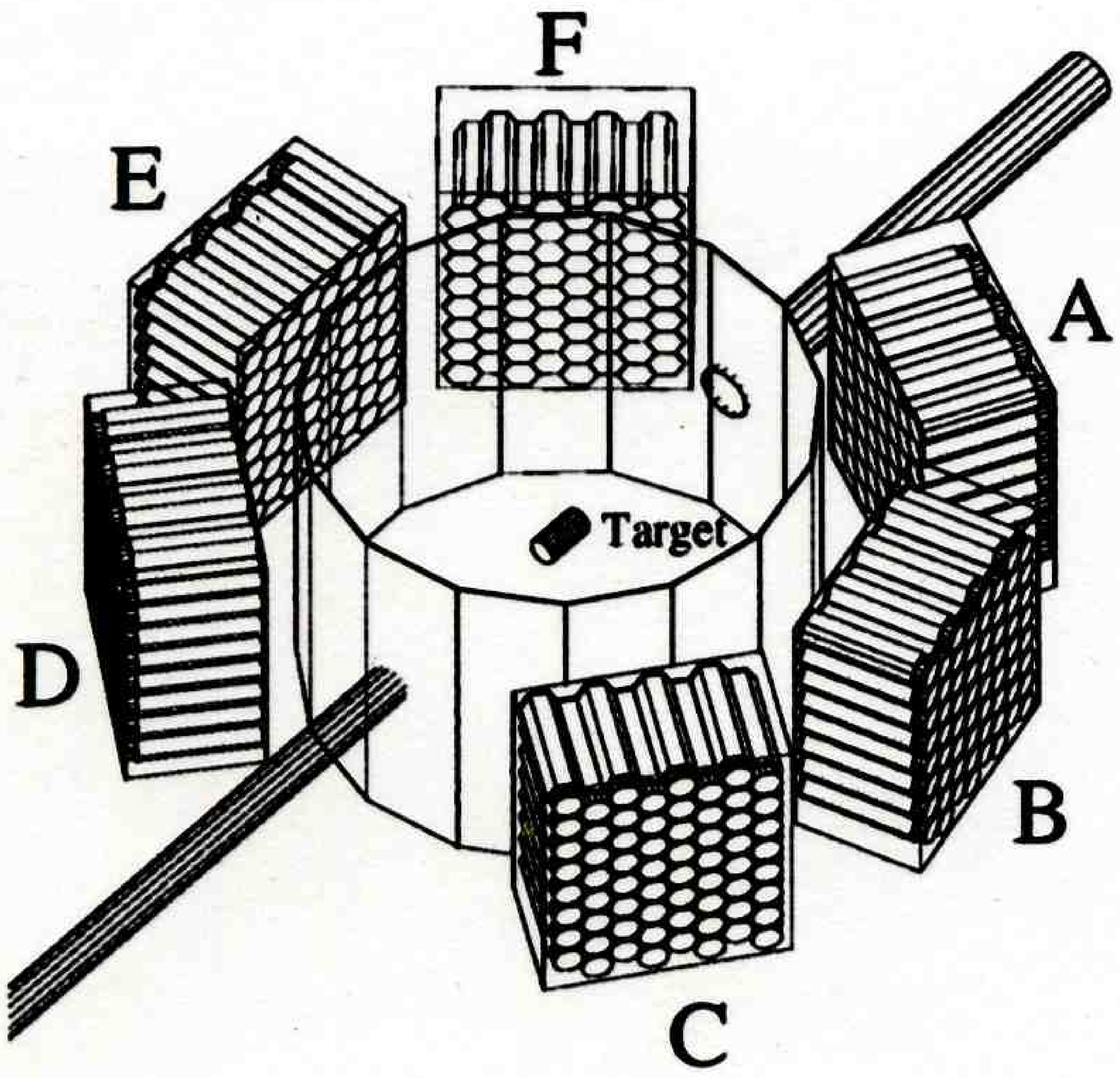
Backward scattering of photons

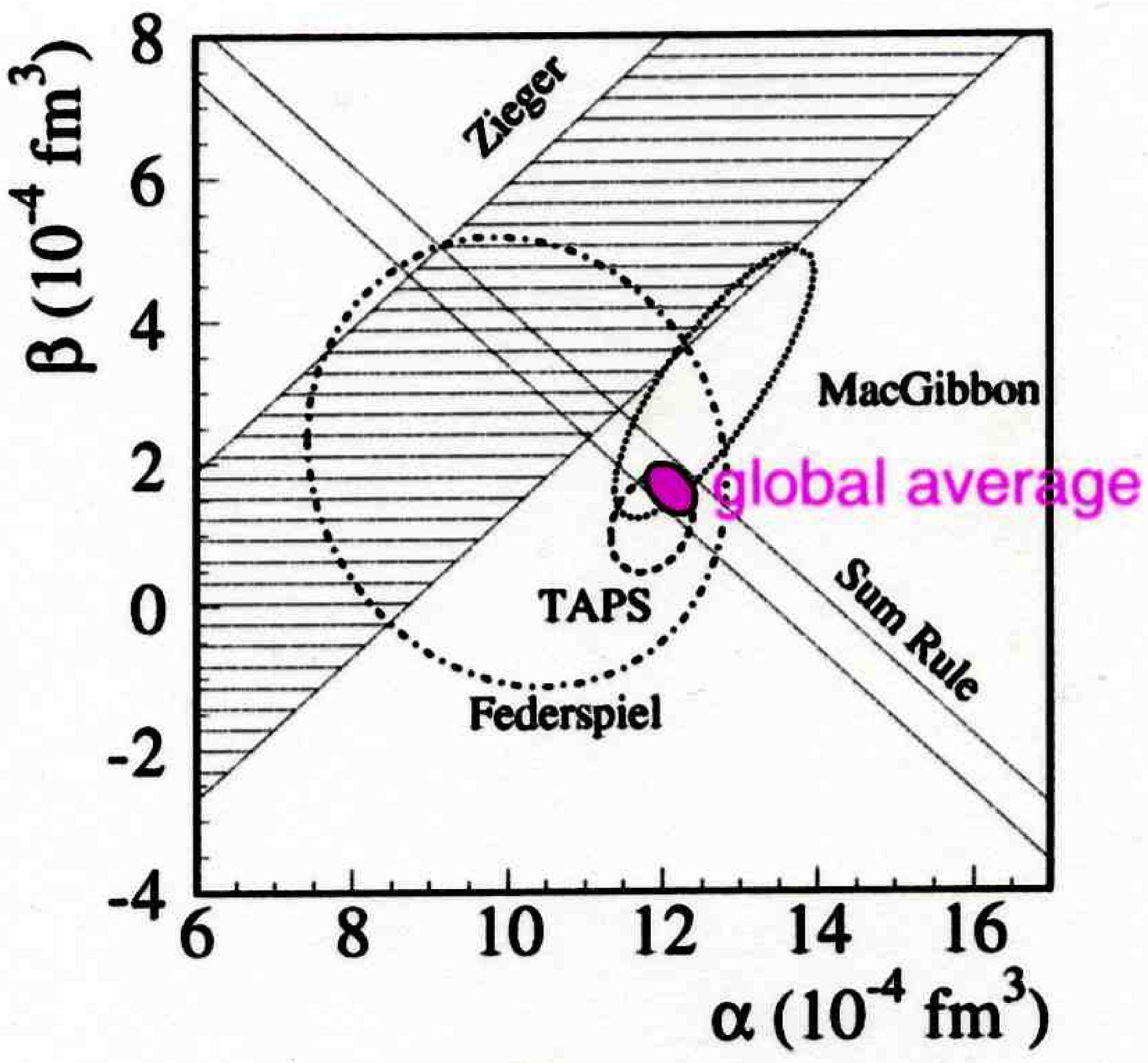


$$|\sigma\rangle = \cos\theta_\sigma|q\bar{q}\rangle + \sin\theta_\sigma|\pi\pi\rangle$$

θ_σ=mixing angle of the $q\bar{q}$ and $\pi\pi$ contents of the σ meson

Polarizabilities of the proton

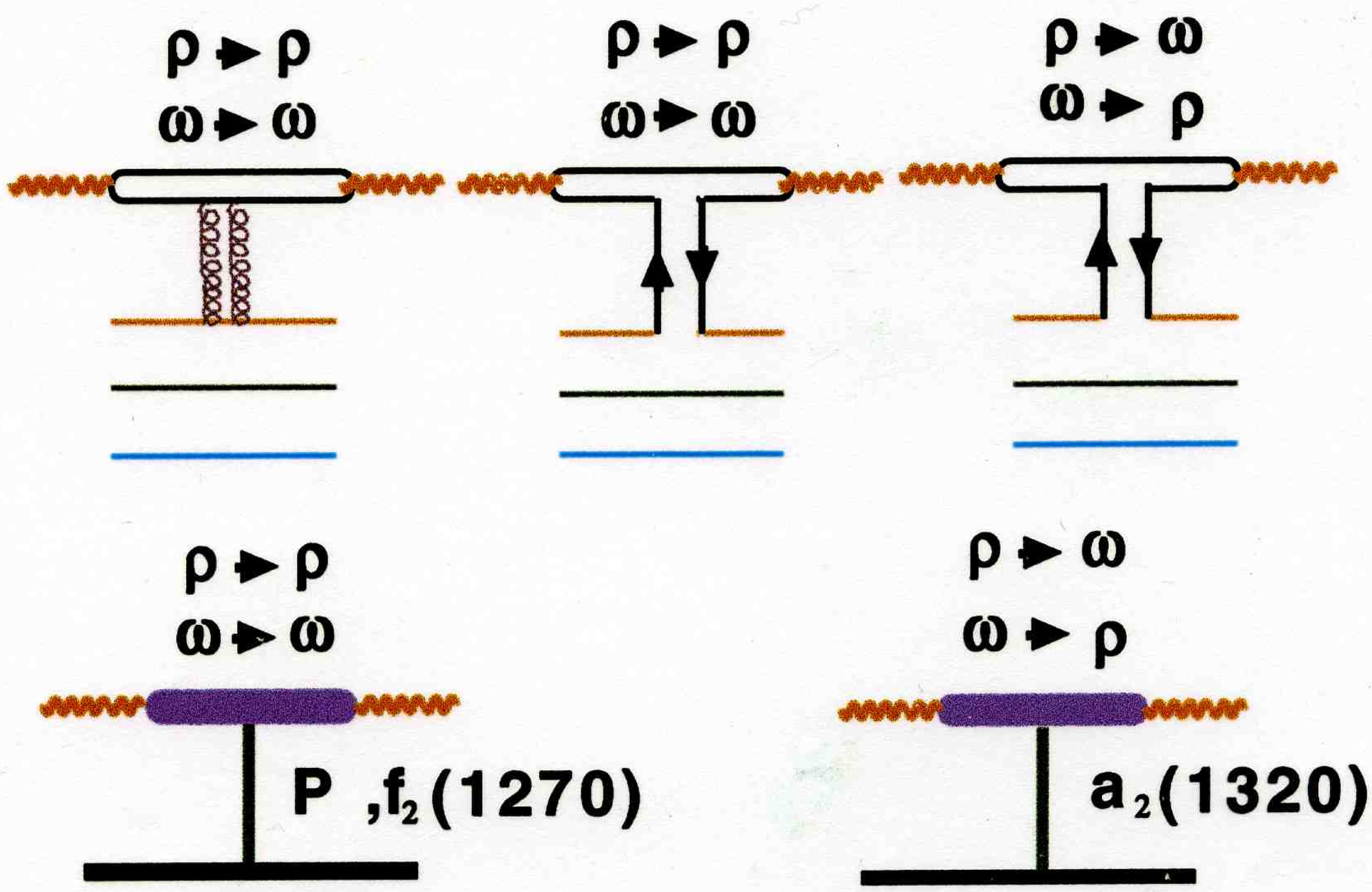




Experiments 1950–2000:	$\alpha_p = 11.7 \pm 1.1$
TAPS@MAMI 2001:	$\alpha_p = 11.9 \pm 1.4$
Experiments 1950–2000:	$\beta_p = 2.3 \pm 1.1$
TAPS@MAMI 2001:	$\beta_p = 1.2 \pm 0.8$
Without sum rule constraint	
Experiments 1950–2000:	$\alpha_p + \beta_p = 14.0 \pm 1.4$
TAPS@MAMI 2001:	$\alpha_P + \beta_p = 13.1 \pm 1.3$
Weighted avarage	$\alpha_P + \beta_p = 13.6 \pm 1.0$
Baldin's sum rule	$\alpha_P + \beta_p = 13.9 \pm 0.3$

V. Olmos de León (Mainz), et al., Eur. Phys. J. A 10 (2001) 207

The asymptotics of the $\alpha + \beta$ amplitude



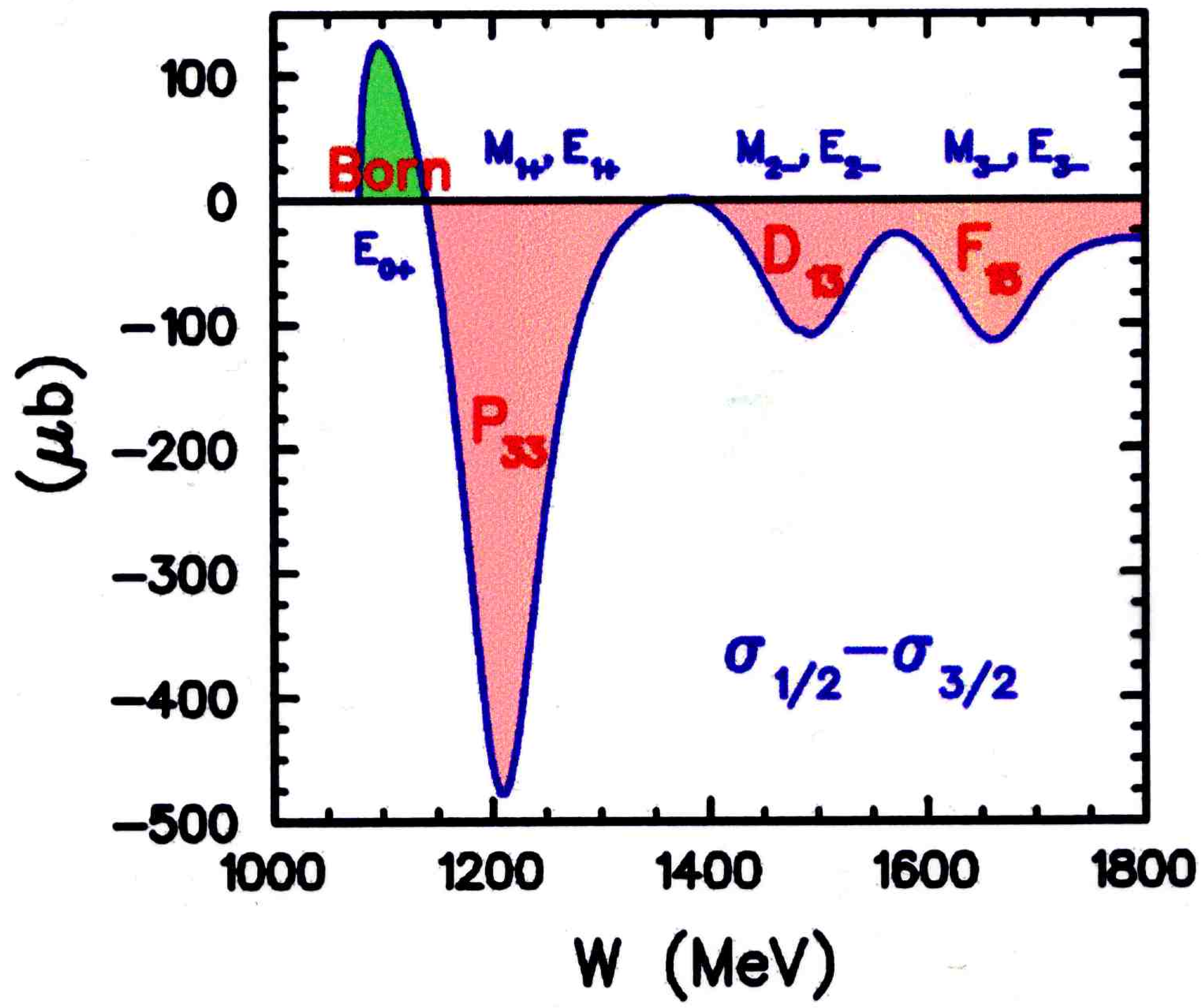
The graphs take into account that the allowed states in the t-channel are $2^{++}, 4^{++}, 6^{++}, 8^{++}, \cdots$. P denotes the Pomeron. There is no pole term which only makes a contribution to the real part of the asymptotic amplitude.

Asymtotics of the GDH amplitude

For the GDH amplitude the allowed states in the t-channel are $3^{++}, 5^{++}, 7^{++}, 9^{++}, \cdots$. These states my form the frequently discussed $a_1 - f_1$ Regge trajectory. It is improble that there is an additional pole term which only makes a contribution to the real part of the amplitude.

Gerasimov-Drell-Hearn

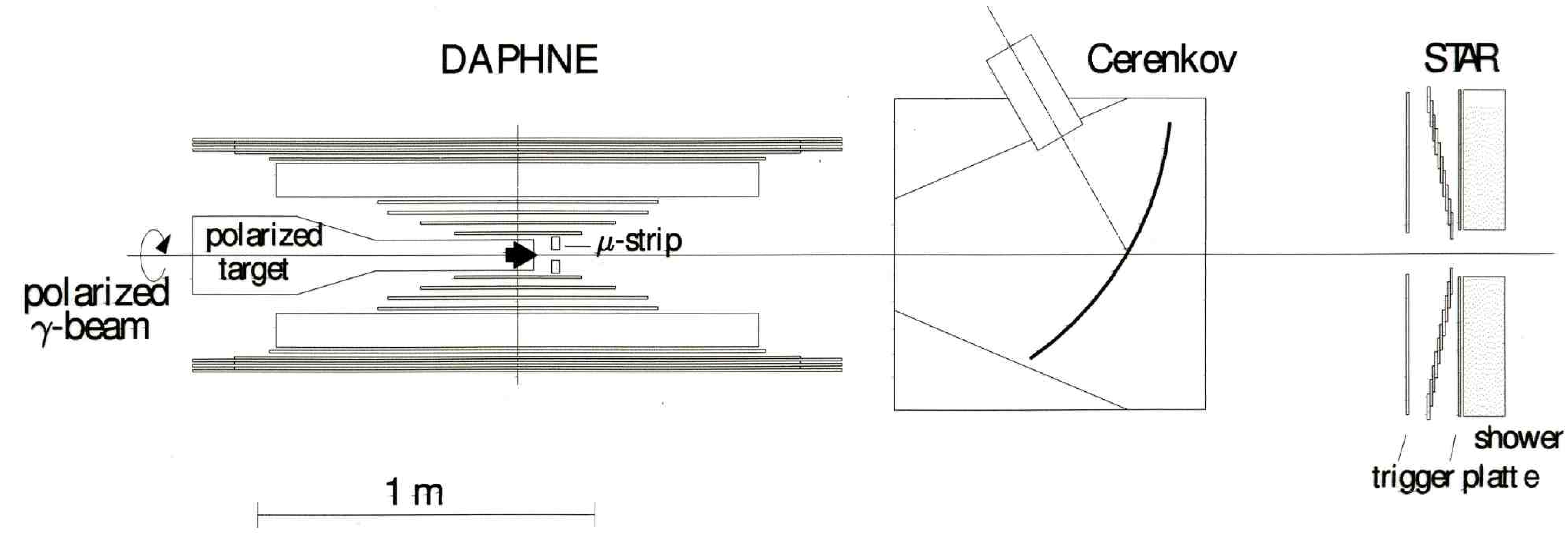
$$I_{\mathrm{GDH}} = \int_{\nu_{\mathrm{thr}}}^{\infty} \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu} d\nu = -\frac{2\pi^2\alpha_e}{M^2}\kappa^2 \qquad (1)$$

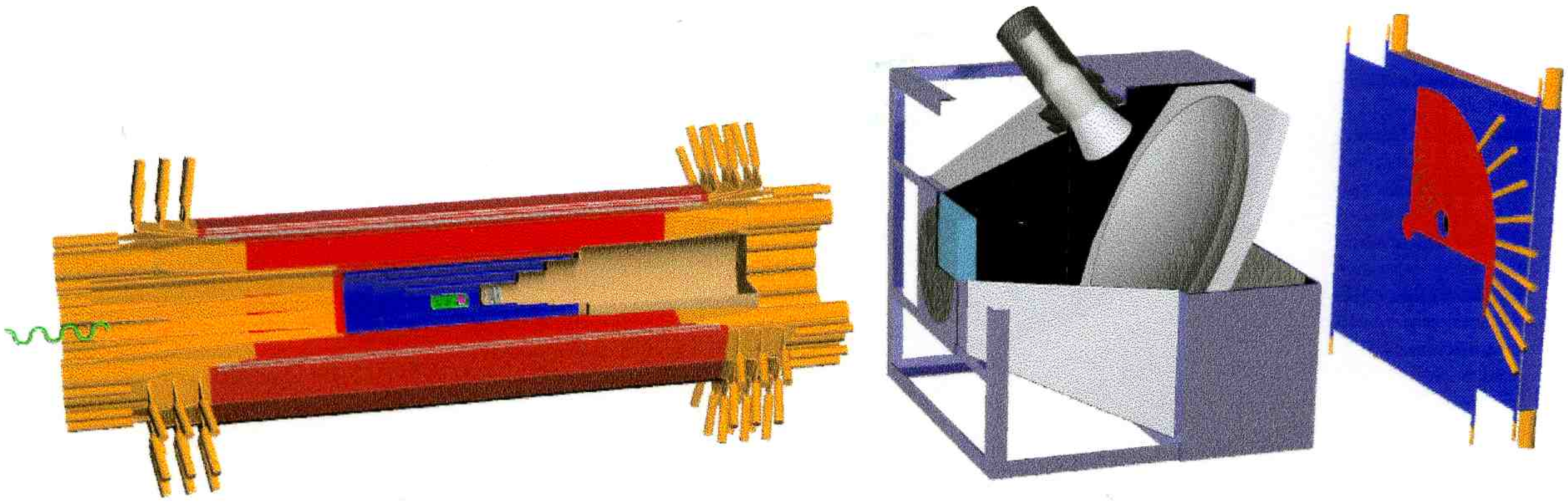


1π partial wave analysis with 2π estimate (unit = μb)

	proton	neutron	
GDH	-205	- 233	sum rule
1π 2π	-194 -65	-146 -35	partial wave analysis estimate
total	-259	-181	large discrepancies

The Gerasimov-Drell-Hearn Apparatus





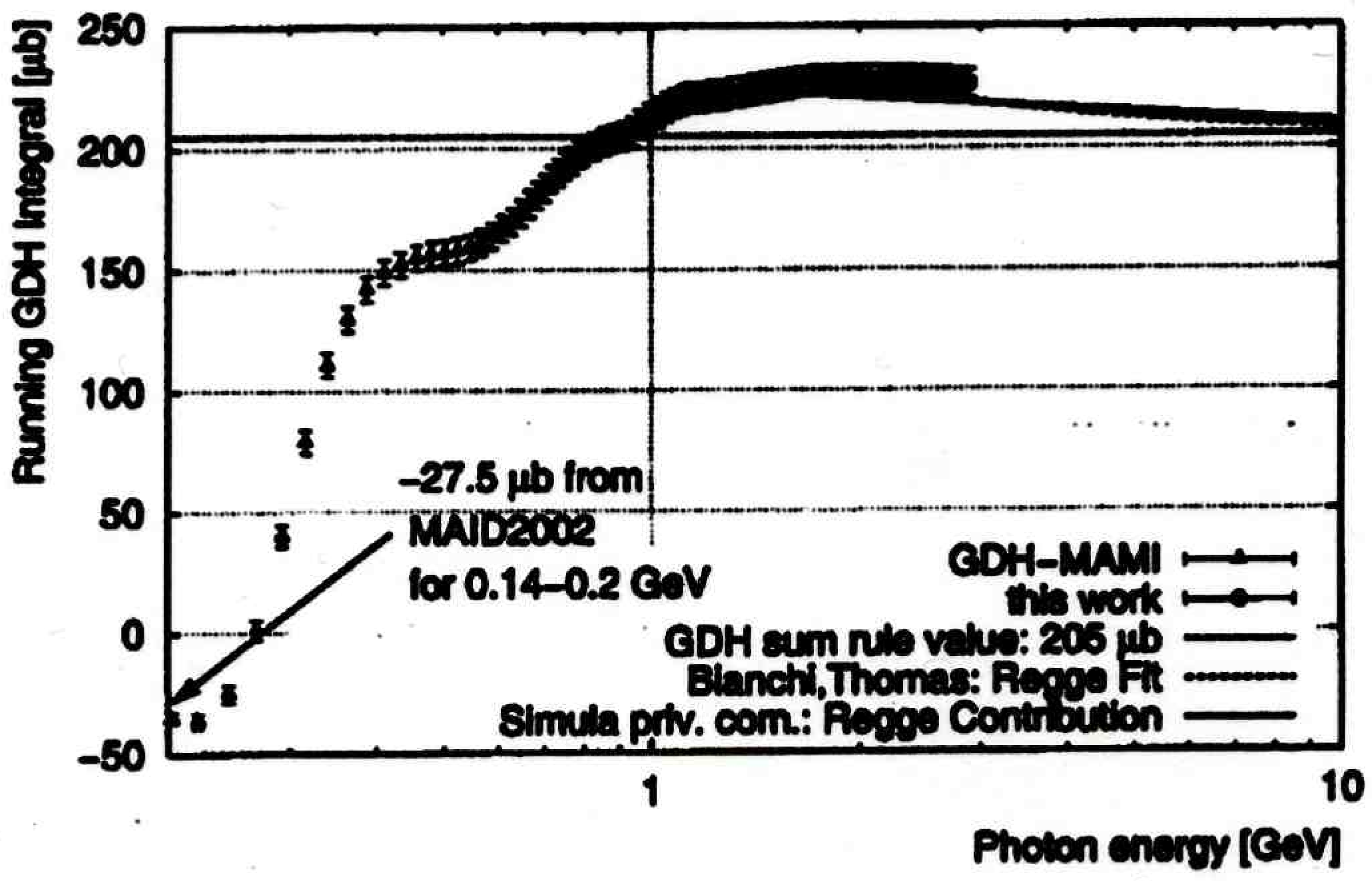
DAPHNE:Three wire chambers and sectorized annulus of plastic scintillators

MIDAS: Silicon strip array

CERENKOV veto-detector

STAR: Plastic scintillator arrangement

Gerasimov-Drell-Hearn



Running GDH integral, I_{GDH}, up to 2.9 Gev. Error bars indicate statistical errors only.

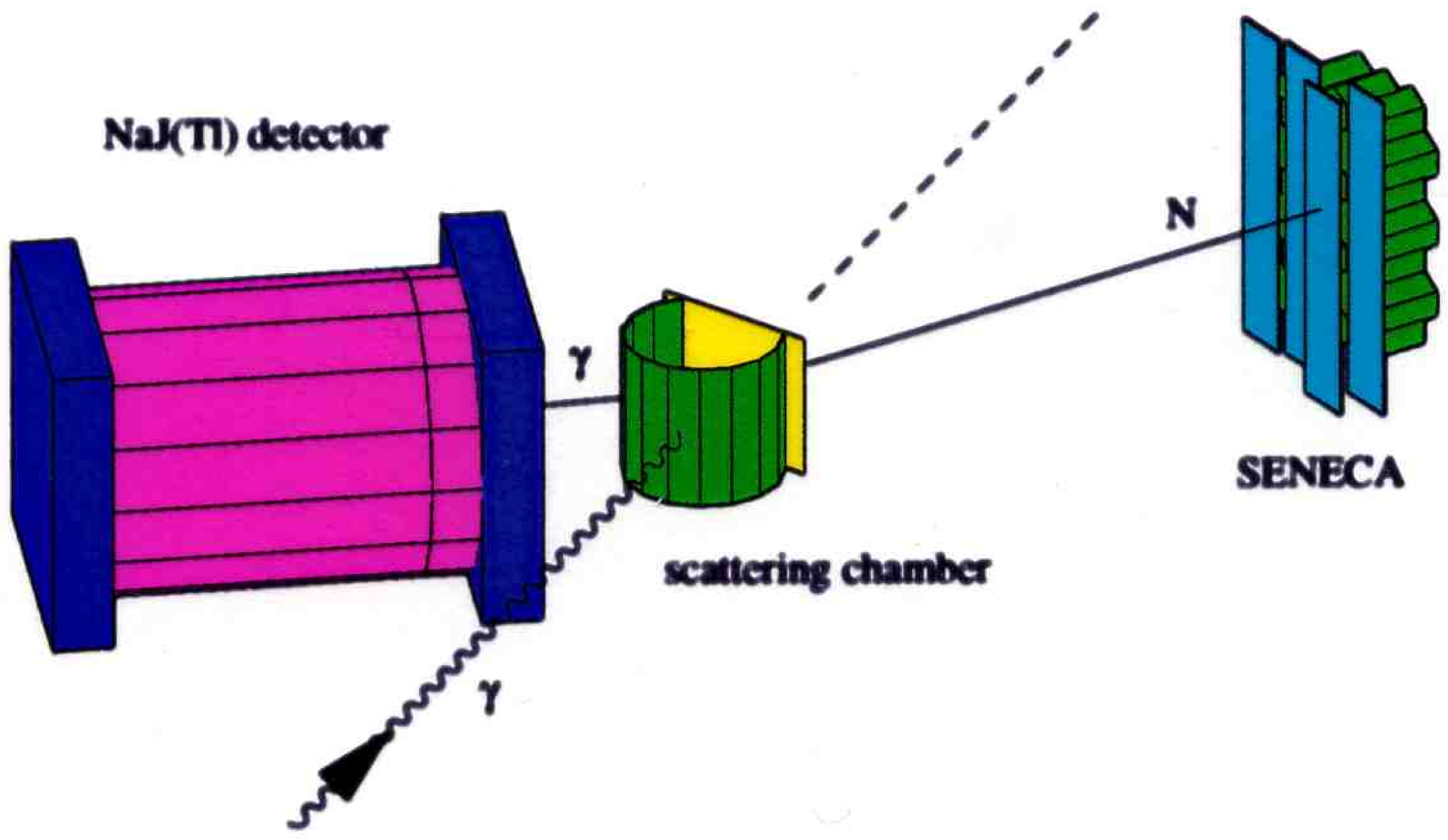
Measured values of the GDH integral I_{GDH} and model predictions for the unmeasured ranges

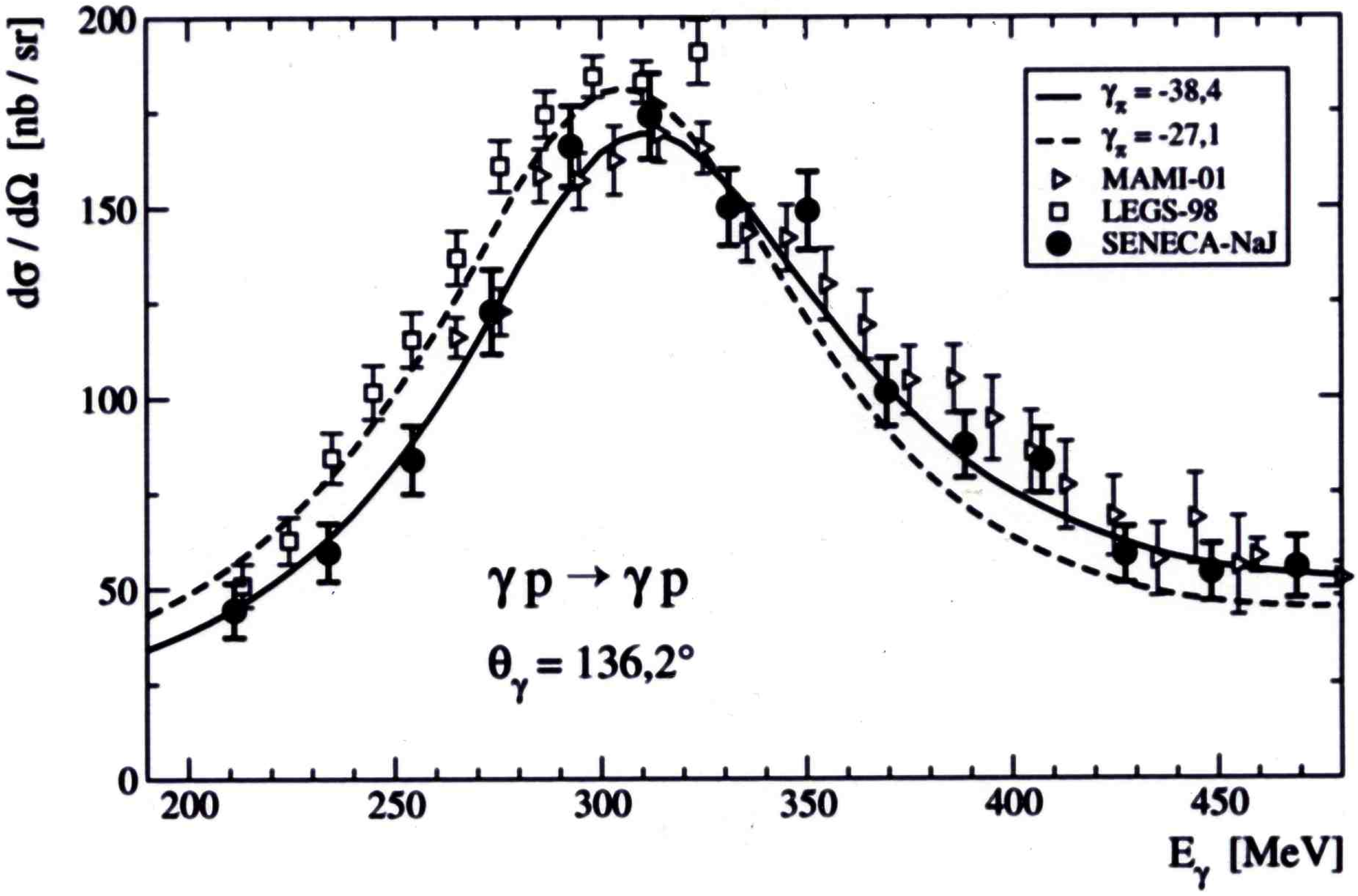
	E_γ [GeV]	I_{GDH} [μ b]
MAID2002	0.14-0.20	-27.5 $\pm$ 3
measured (GDH-Collaboration)	0.20-2.90	254 $\pm$ 5 $\pm$ 12
Bianchi and Thomas	> 2.9	-14
Simula et al.	> 2.9	-13
GDH integral	$0.14 - \infty$	$\approx 213\ \mu b$
GDH sum rule	$\nu_{\mathrm{thr}} - \infty$	$205\ \mu b$

Bianchi and Thomas: Phys. Lett. B 450 (1999) 439

Simula et al.: Phys. Rev. D 65 (2002) 034017

Test of the NaI(Tl)-SENECA apparatus and redetermination of the backward spin polarizability γ_π



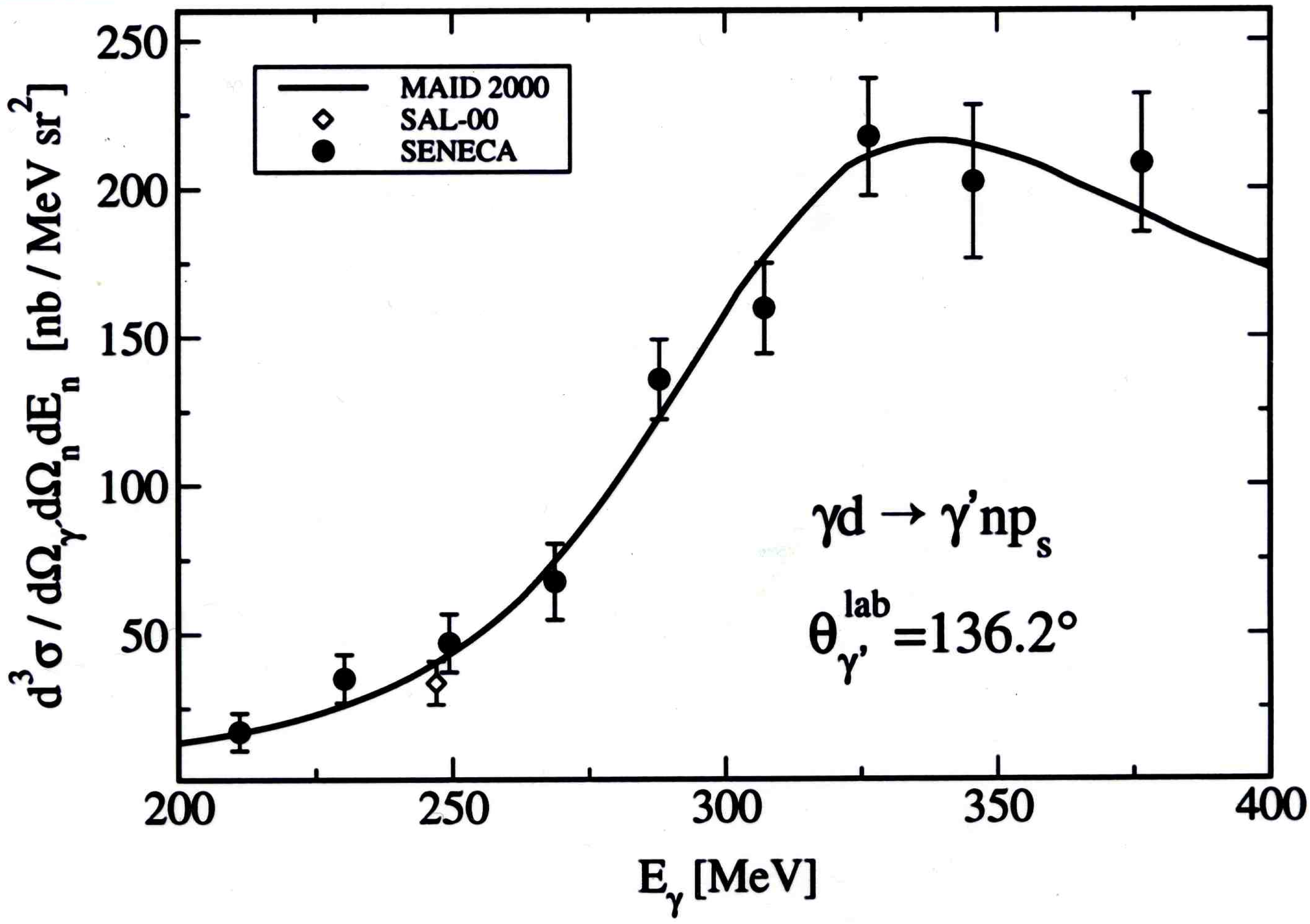


LEGS data: $\gamma_\pi = -27.2 \pm 3.1 \times 10^{-4}\mathrm{fm}^4$

M. Camen et al., Phys. Rev. C 65 (2002) 032202(R)

$\gamma_\pi = -38.7 \pm 1.8 \times 10^{-4}\mathrm{fm}^4$

Results of quasi-free Compton scattering by the neutron



Dissertation K. Kossert, Göttingen 2001

K. Kossert et al., Phys. Rev. Lett. 88 (2002) 162301

Data consistent with:

$\gamma_\pi(\text{neutron}) = 58.6 \times 10^{-4} \text{fm}^4$

$\alpha_n - \beta_n = 9.8 \pm 3.6(\text{stat})^{+2.1}_{-1.1}(\text{syst}) \pm 2.2(\text{model})$

Summary of polarizabilities of the nucleon

Experimental polarizabilities for proton and neutron

structure constant	proton	neutron	
α	12.2 ± 0.6	12.5 ± 2.3	present work
β	1.8 ∓ 0.6	2.7 ∓ 2.3	present work
γ_π	-38.7 ± 1.8	$+58.6 \pm 4.0$	present work
γ_π	-39.5 ± 2.4	$+52.5 \pm 2.4$	sum rule
$\gamma_\pi(\mathrm{t-channel})$	-46.6	$+43.4$	$\pi^0 + \eta + \eta'$
$\gamma_\pi(\mathrm{s-channel})$	$+7.9 \pm 1.8$	$+15.2 \pm 4.0$	present work
$\gamma_\pi(\mathrm{s-channel})$	$+7.1 \pm 1.8$	$+9.1 \pm 1.8$	sum rule

Units of electromagnetic polarizabilities: $10^{-4}\ \mathrm{fm}^3$
Unit of spin polarizabilty: $10^{-4}\ \mathrm{fm}^4$

$$\gamma_\pi(\mathrm{t-ch.}) = \frac{1}{2\pi m}\left[\frac{g_{\pi NN}F_{\pi^0\gamma\gamma}}{m^2_{\pi^0}}\tau_3 + \frac{g_{\eta NN}F_{\eta\gamma\gamma}}{m^2_\eta} + \frac{g_{\eta' NN}F_{\eta'\gamma\gamma}}{m^2_{\eta'}}\right]$$

$$\gamma_\pi(\mathrm{s-ch.}) = -\frac{1}{2\pi m}\left[A_2^{\mathrm{int}}(0,0) + A_5^{\mathrm{int}}(0,0)\right]$$

$$\gamma_\pi(\mathrm{s-ch.}) = \int_{\omega_0}^{\infty}\sqrt{1+\frac{2\omega}{m}}\left(1+\frac{\omega}{m}\right)\sum_n P_n[\sigma^n_{3/2} - \sigma^n_{1/2}]\frac{d\omega}{4\pi^2\omega^3}$$

Summary

- It has been shown that Compton scattering by the proton is well represented by the unsubtracted fixed-t dispersion theory in the whole angular range and up to 800 MeV. In the second resonance region and at large scattering angles there are strong indications for a scalar pole in the t-channel.
- Precize values for the electromagnetic polarizabilities of the proton confirm the validy of the Baldin sum rule. This agreement may be understood in terms of vector meson dominance which forces t-channel exchanges to make contributions to the photoabsorption cross section only.
- The GDH-integral overfulfils the GDH sum rule prediction between 1 GeV and 2.9 Gev. There are arguments that Regge asymptotics makes negative contributions to the GDH integral, thus probably making the GDH sum rule valid.
- The electromagnetic polarizabilities of the neutron have been measured with good precision. When compared with the proton data no major isovector component is observed.
- The backward spin polarizability γ_π for the proton and the neutron have been found in agreement with the LN sum rule prediction. This shows that in case of t-channel poles fixed-t dispersion theory and fixed-θ dispersion theory lead to the same result.
- The difference $(\alpha_p - \beta_p)$ deviates from the predictions of the BEFT sum rule by a large amount. This shows that a large $\langle q\bar{q}|$ component in the σ meson is very likely to exist. There is ongoing work to put this finding on a firm theoretical basis.