SFB 443

Hadron Physics at the Mainz Microtron MAMI

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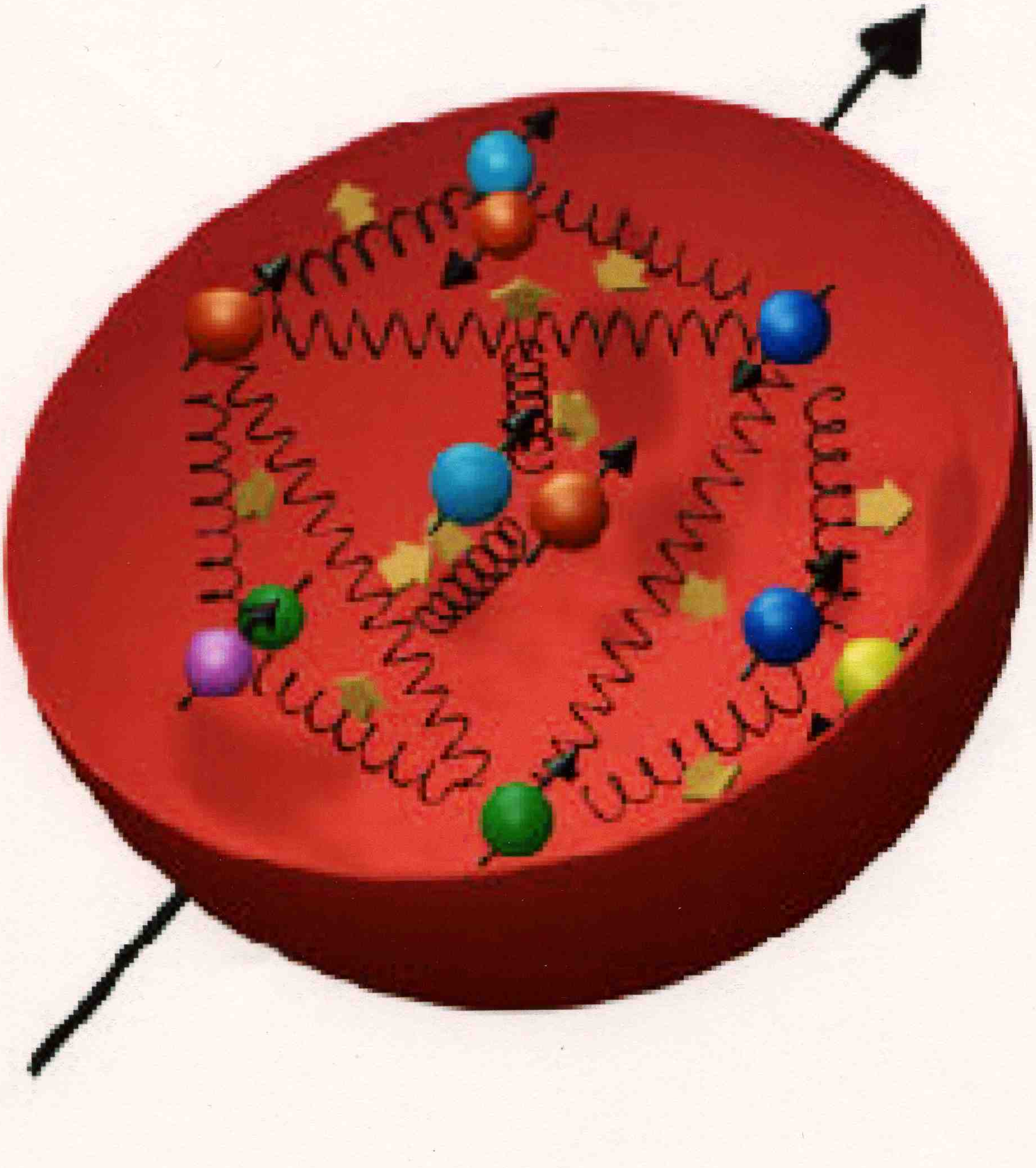
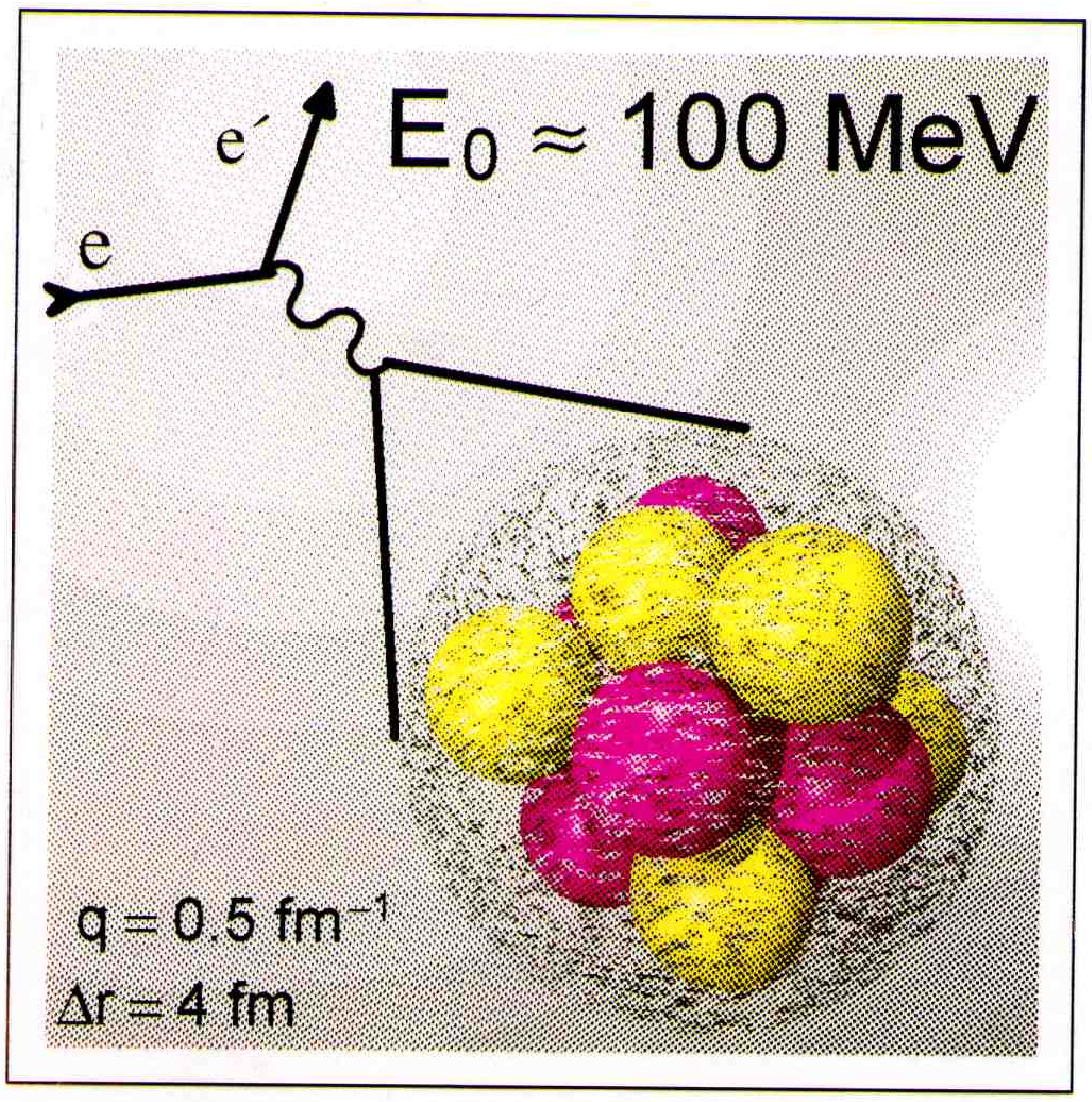
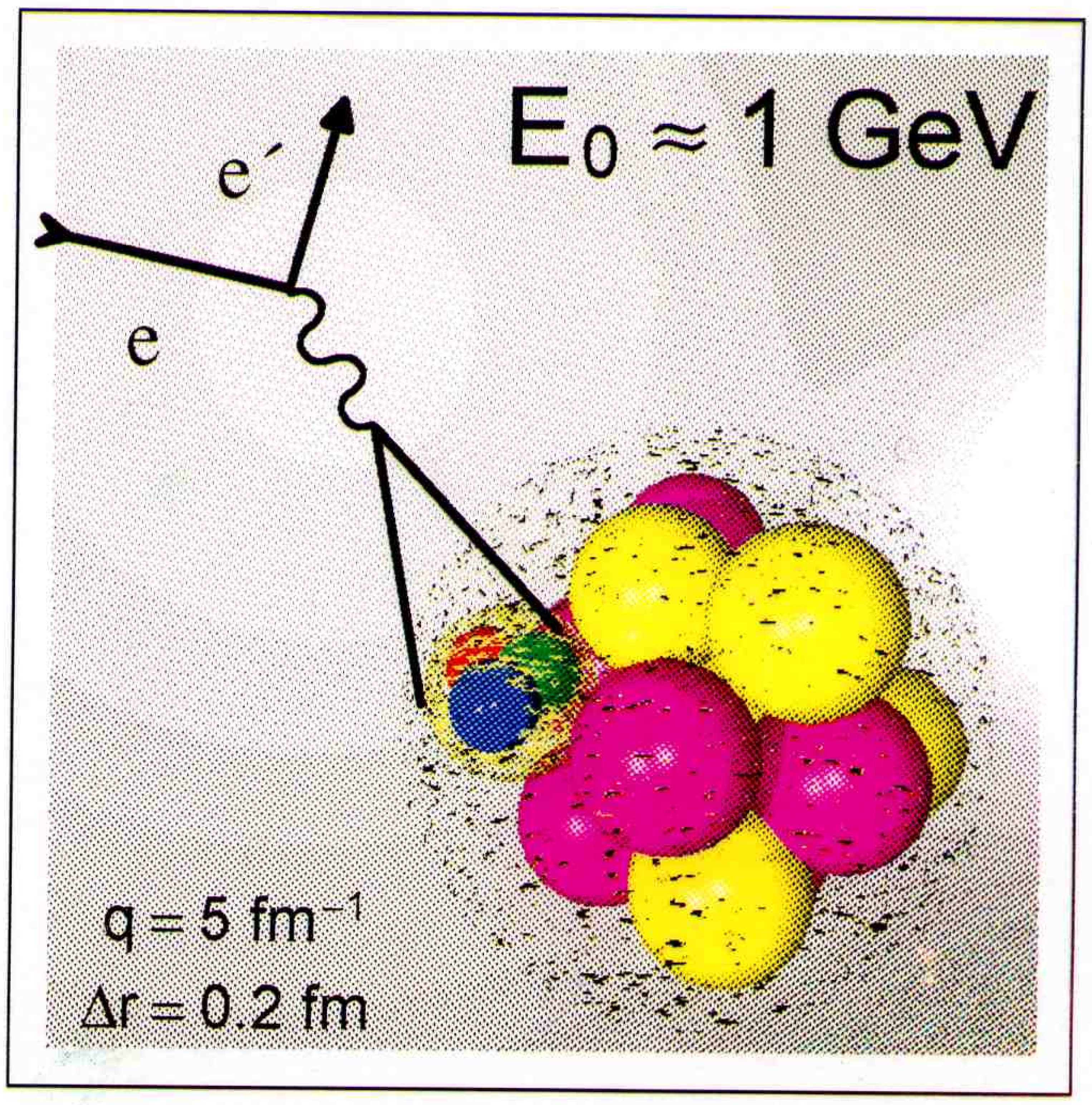
1. Introduction: Why and how hadron physics?
2. Recent highlights of MAMI
    - Form factors of the nucleon
    - Pion polarizability
3. MAMI C
    - Energy increase to 1500 MeV: MAMI C
    - CB@MAMI
    - KAOS@MAMI
4. Extended oportunities at MAMI C
    - overview
    - nucleon resonances in selective decay channels
5. Conclusions

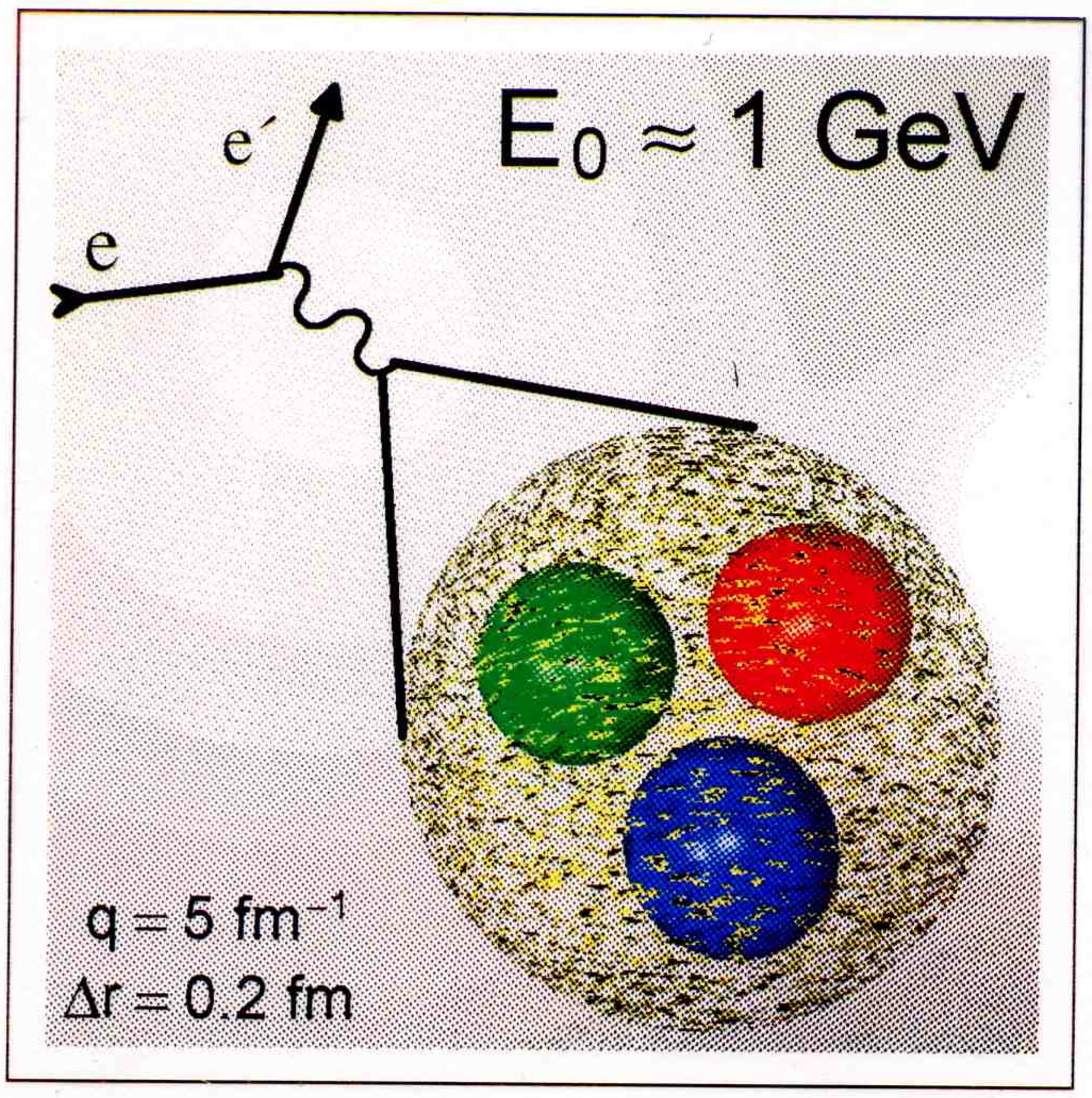


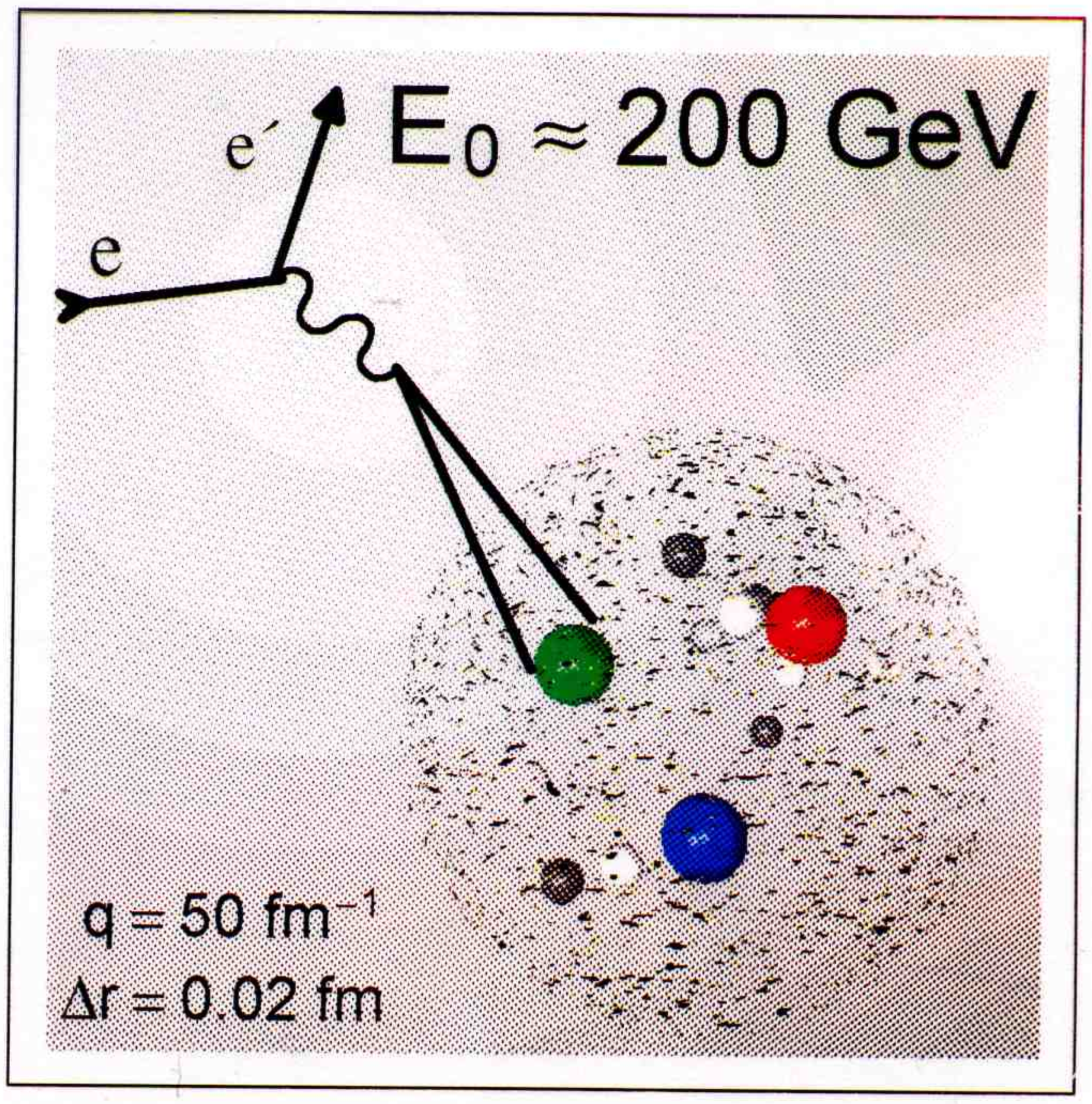
Nucleus



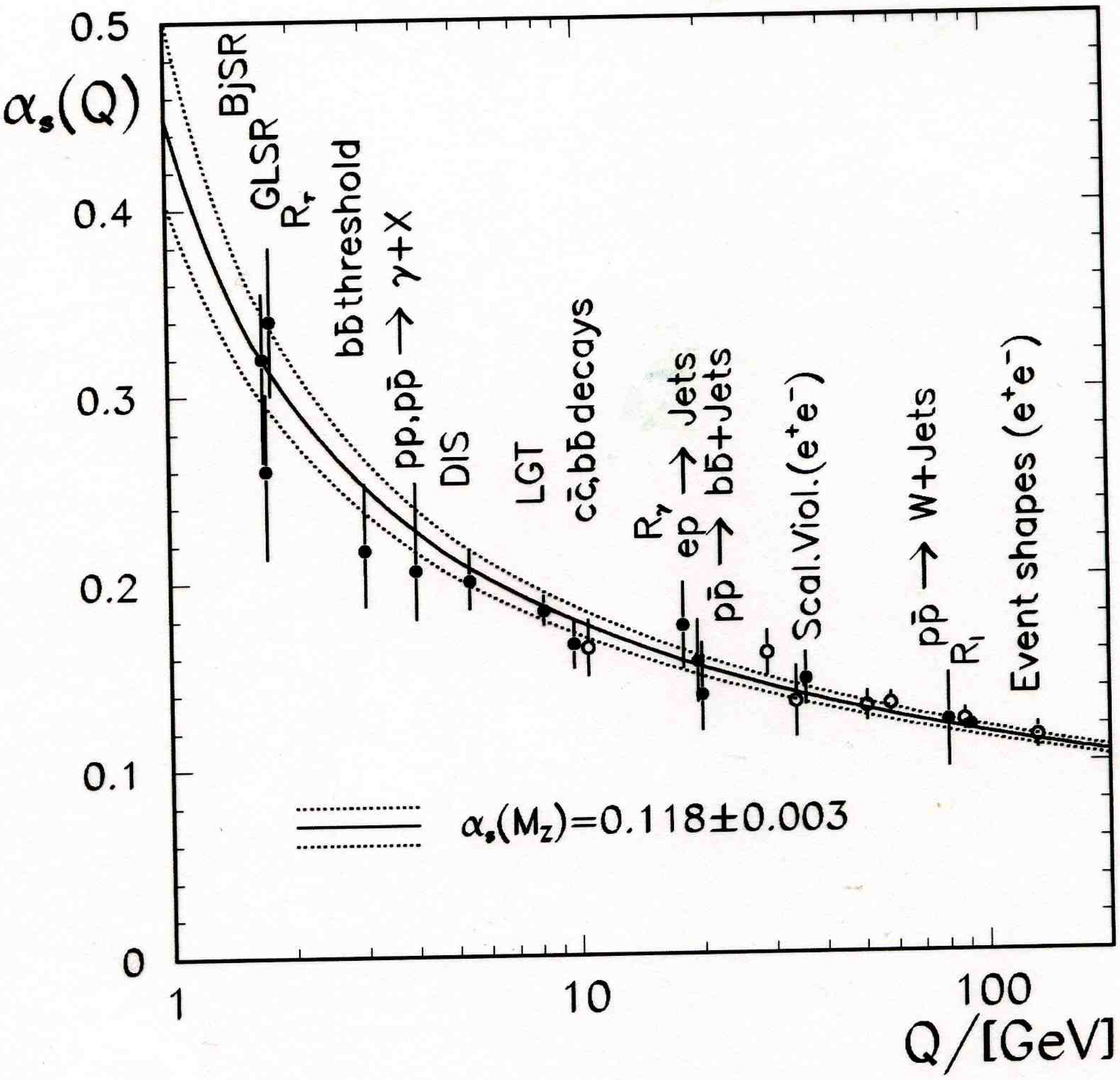


Nucleon





running coupling constant of the strong interaction



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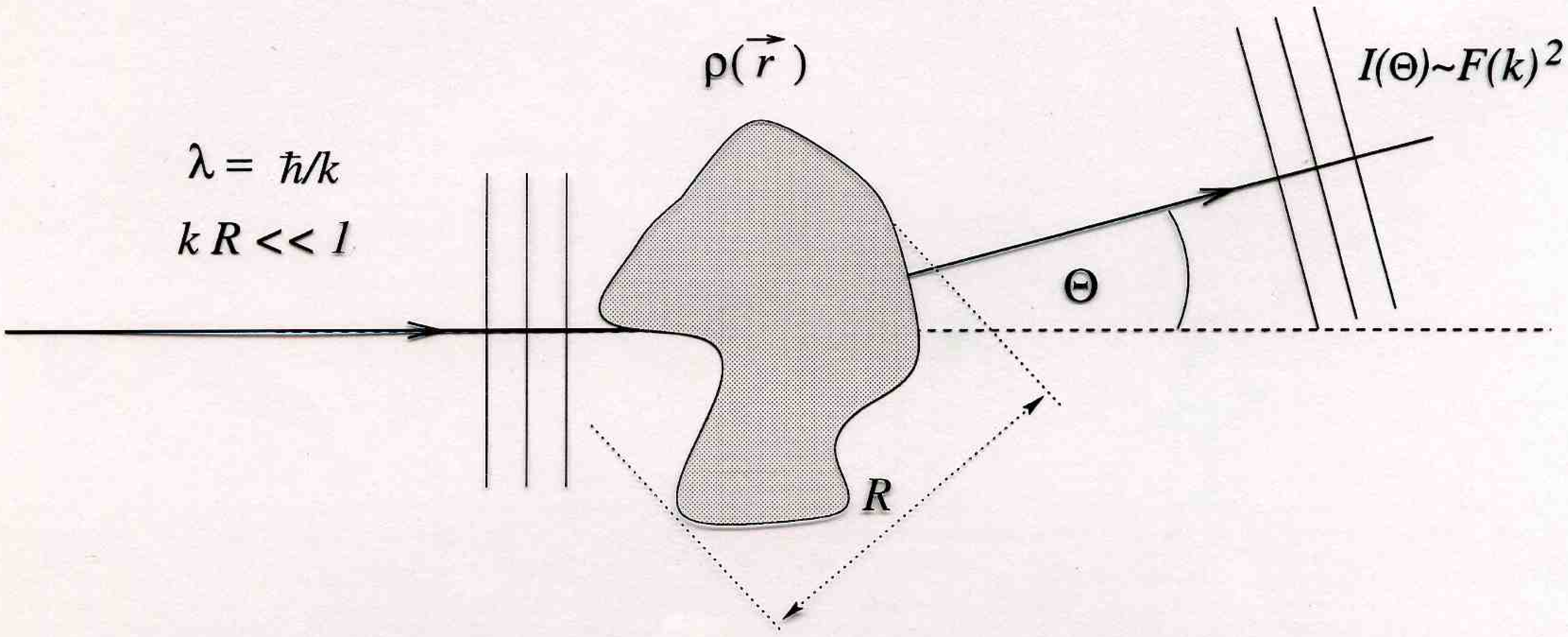
Form factors of the nucleon

Elastic Formfactors

scattering of light:



$$I(\Theta) \; = \; I_0 \cdot \left(\frac{d\sigma}{d\Omega}\right)_{Thompson} \cdot |F(\vec{k})|^2$$

$$F(\vec{k}) \; = \; \int \left(\rho(\vec{r}) \cdot e^{i\vec{k}\cdot\vec{r}}\right) \, d^3\vec{r}$$

elastic electron–nucleon–scattering:

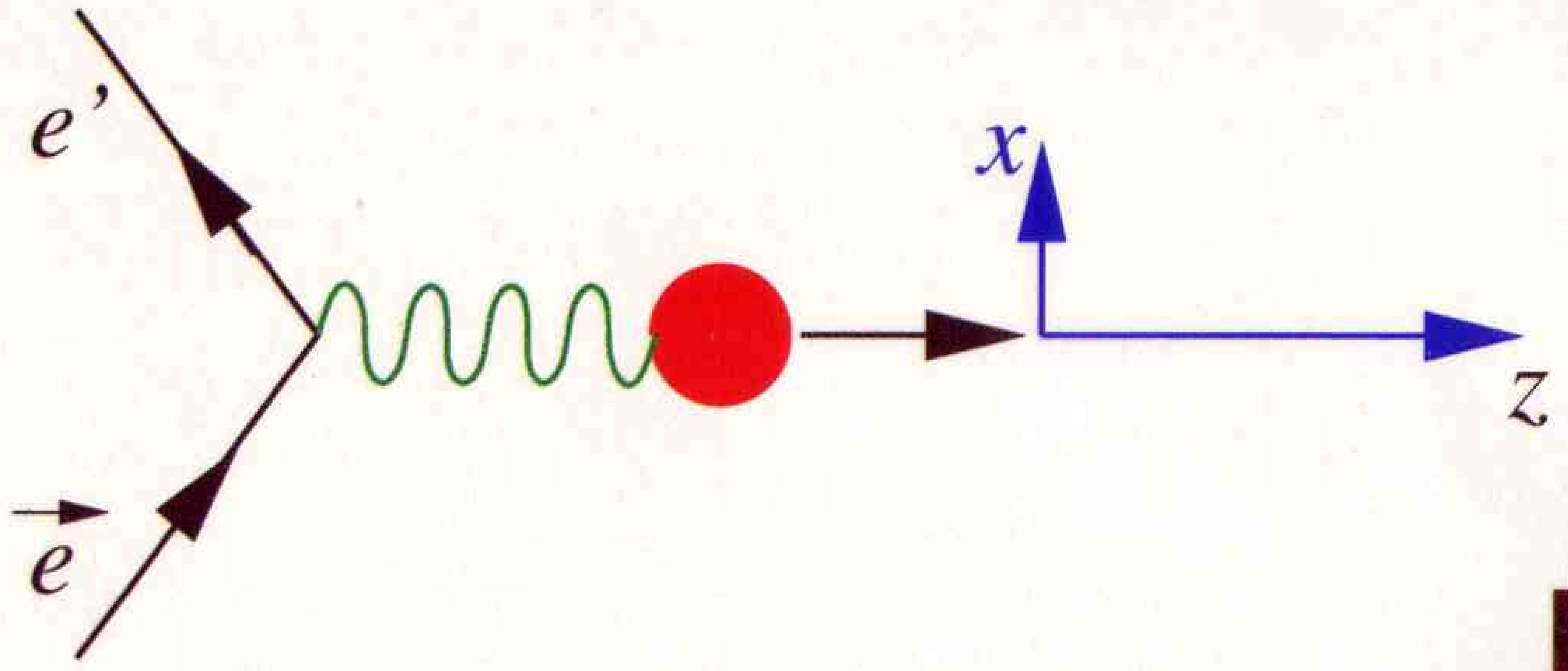
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \left(\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 \; + \; \tau} + 2\tau \, G_M^2(Q^2) \, \tan^2\frac{\Theta}{2} \right)$$

$$Q^2 \; = \; \vec{q}^{\,2} - \omega^2; \quad \tau \; = \; Q^2/4\,M^2$$

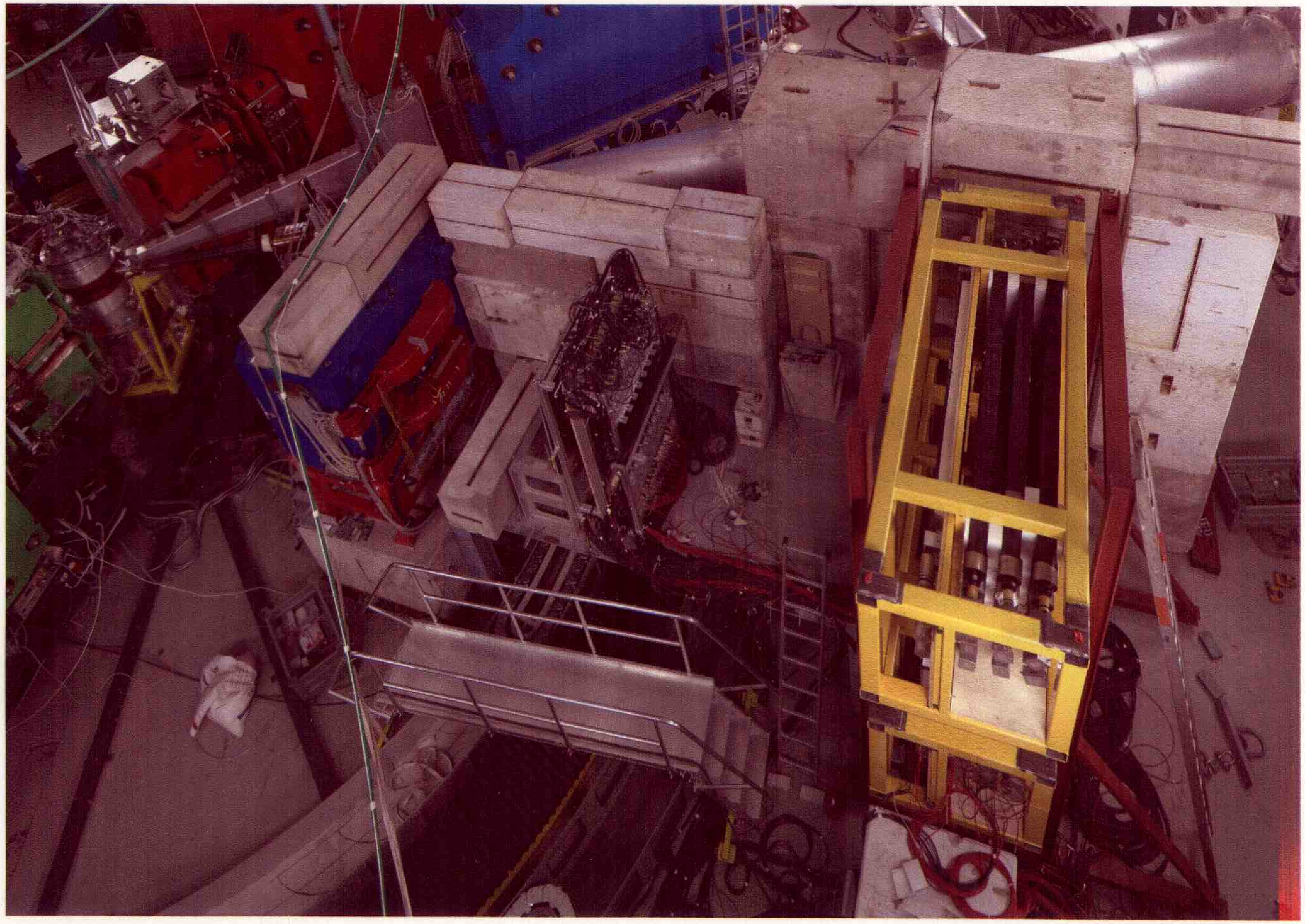
4 formfactors : $G_{E,p}(Q^2), \; G_{M,p}(Q^2)$

$G_{E,n}(Q^2), \; G_{M,n}(Q^2)$

Measurement of $G_{E,n}$ in $\mathrm{D}(\vec{e}, e'\vec{n})p$



$$\boxed{\text{Asymmetry } A = P_e \mathcal{A}_{\text{eff}} P_t \sin\Phi_n}$$

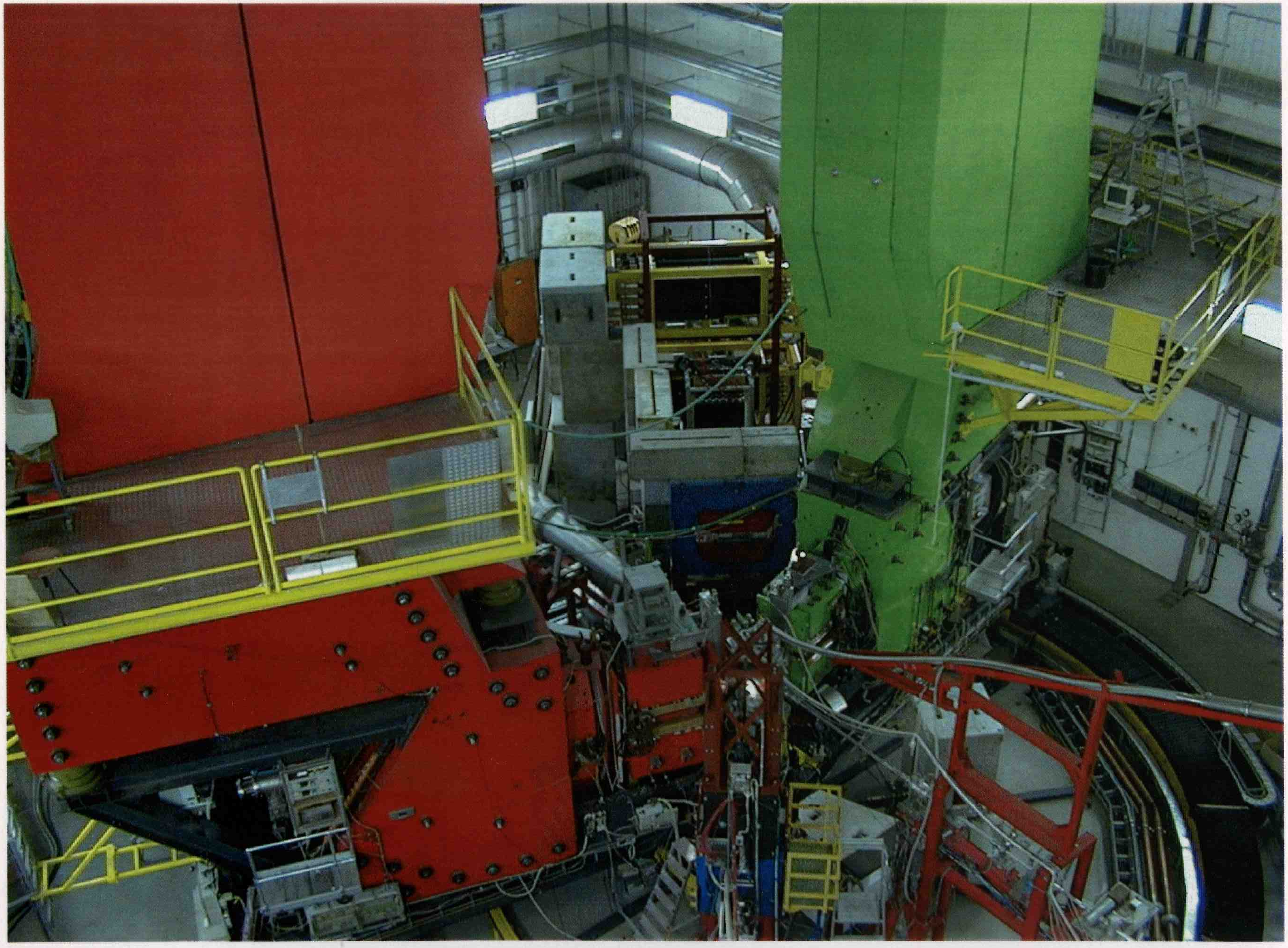


$$
\boxed{
\begin{aligned}
\mathcal{P}_x &= -hP_e \frac{aG_E G_M}{G_E^2 + bG_M^2} \\
\mathcal{P}_y &= 0 \\
\mathcal{P}_z &= hP_e \frac{cG_M^2}{G_E^2 + bG_M^2}
\end{aligned}
}
$$

Arnold, Carlson & Gross,
PR C **23** (1981), 363

Method:
T. N. Taddeucci et al.,
NIM **A241** (1985), 448

A1 Three Spectrometer Setup

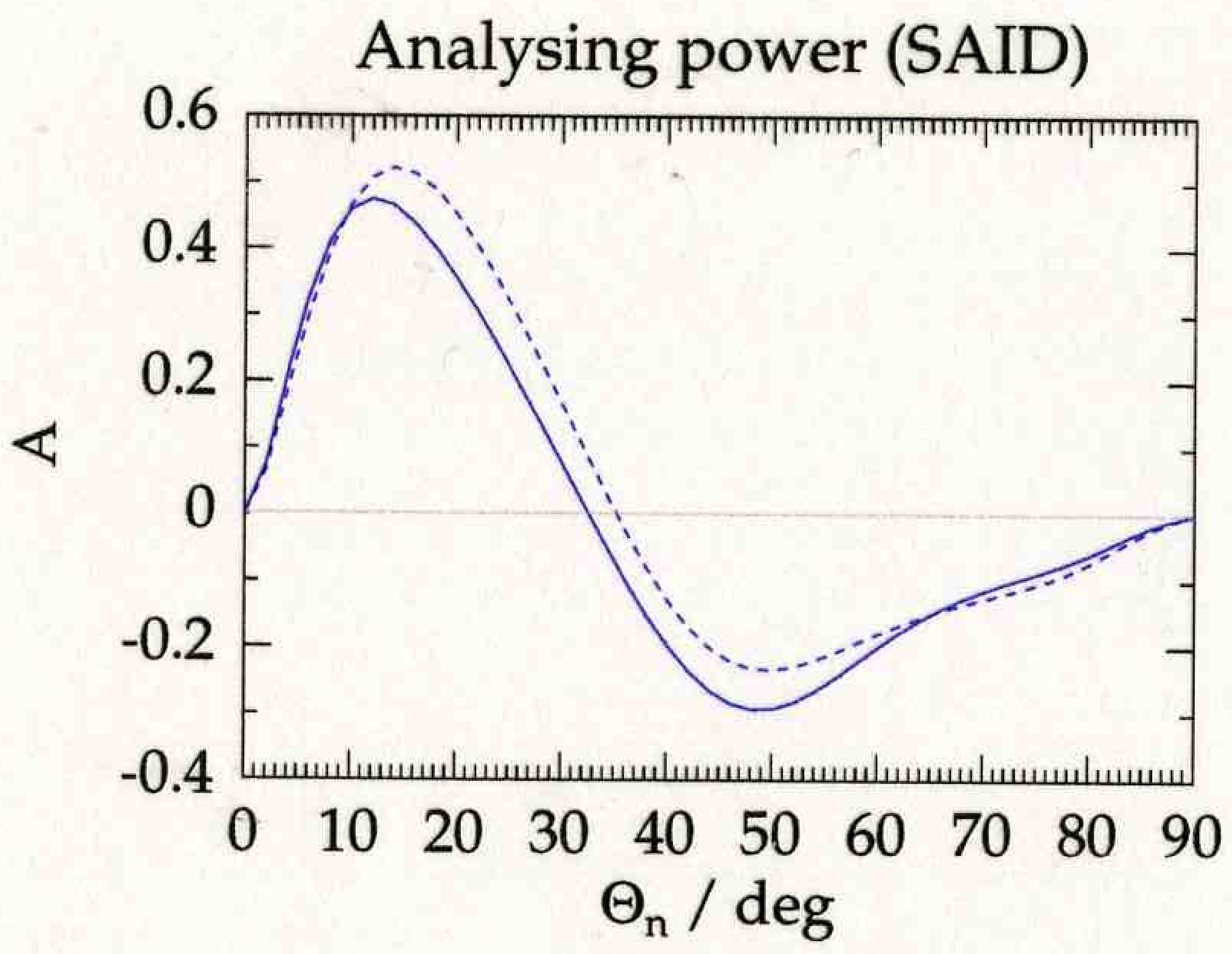


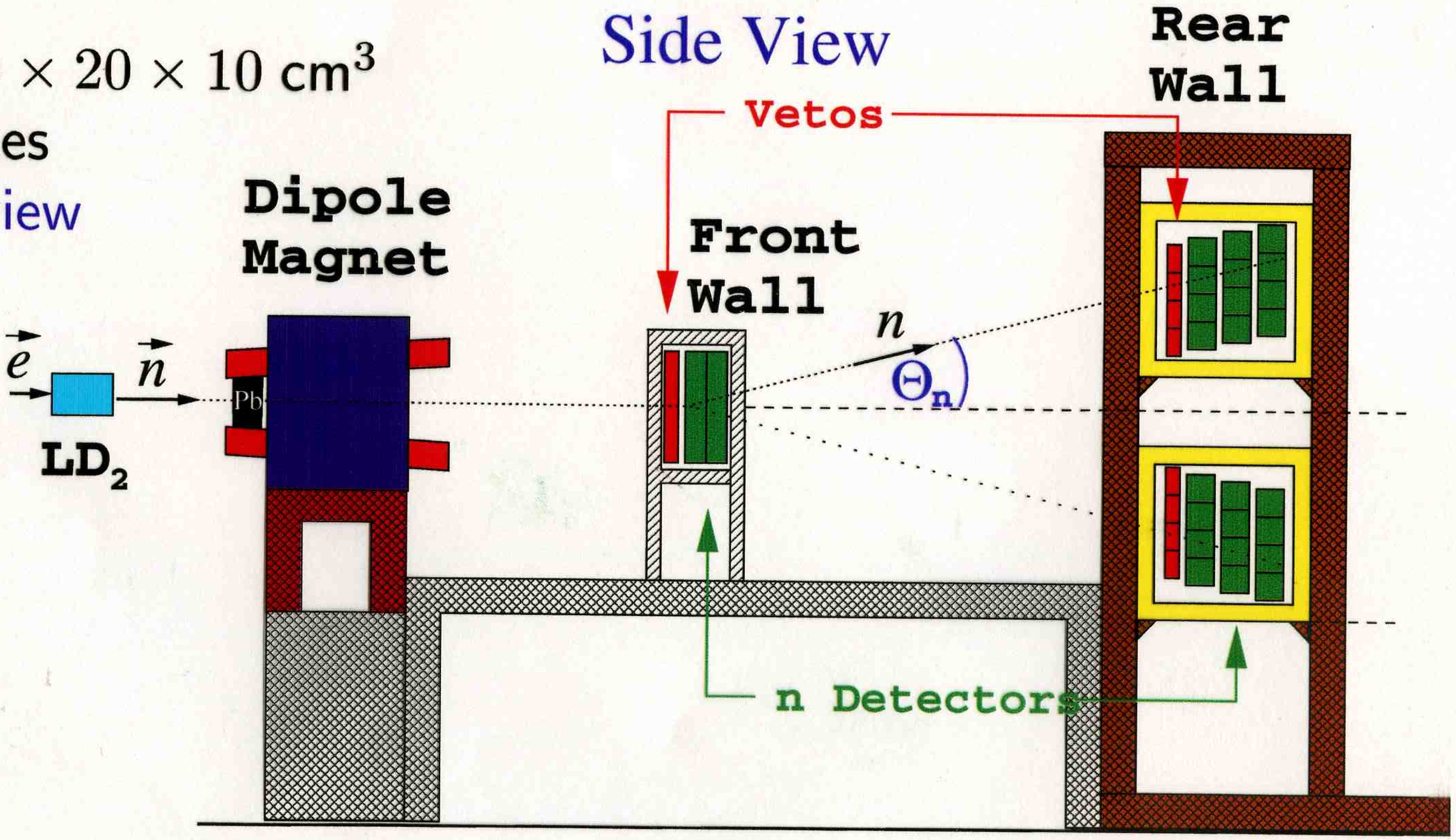
Neutron Polarimeter, Rear Wall

24 scintillator bars, $180 \times 20 \times 10$ cm^3

$\Rightarrow$ high background rates

$\Rightarrow$ avoid direct target view



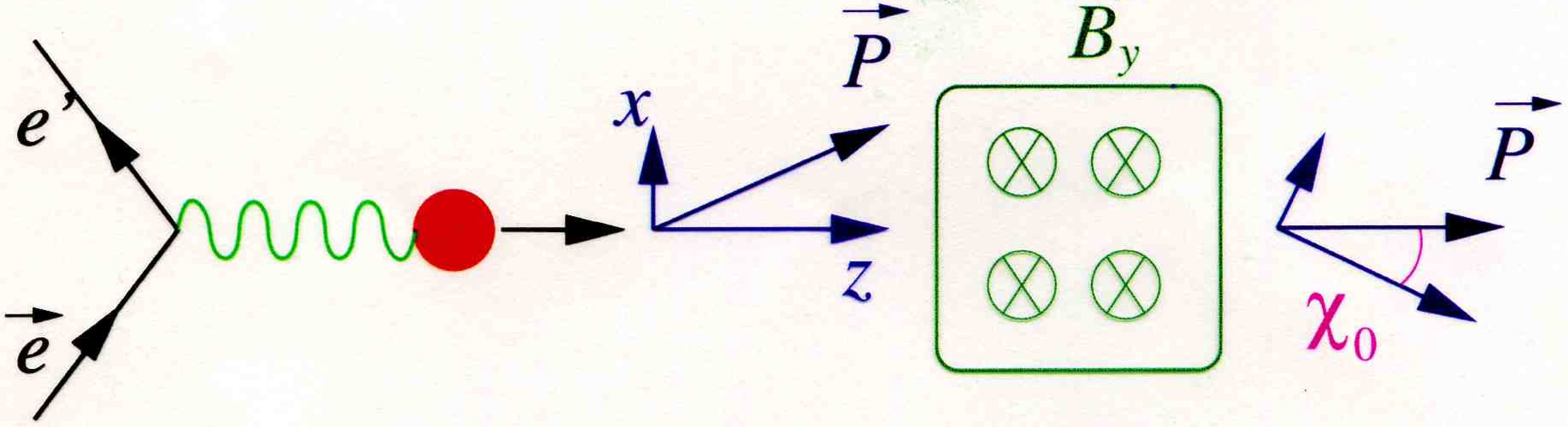


Spin Precession Method

Mixing of two spin components by precession of neutron spin in magnetic field,

$$\mathcal{P}_t(\chi) = \mathcal{P}_x \cos(\chi) + \mathcal{P}_z \sin(\chi) =: \mathcal{P}_0 \sin(\chi - \chi_0)$$

(M. Ostrick et al., PRL **83** (1999) 276)

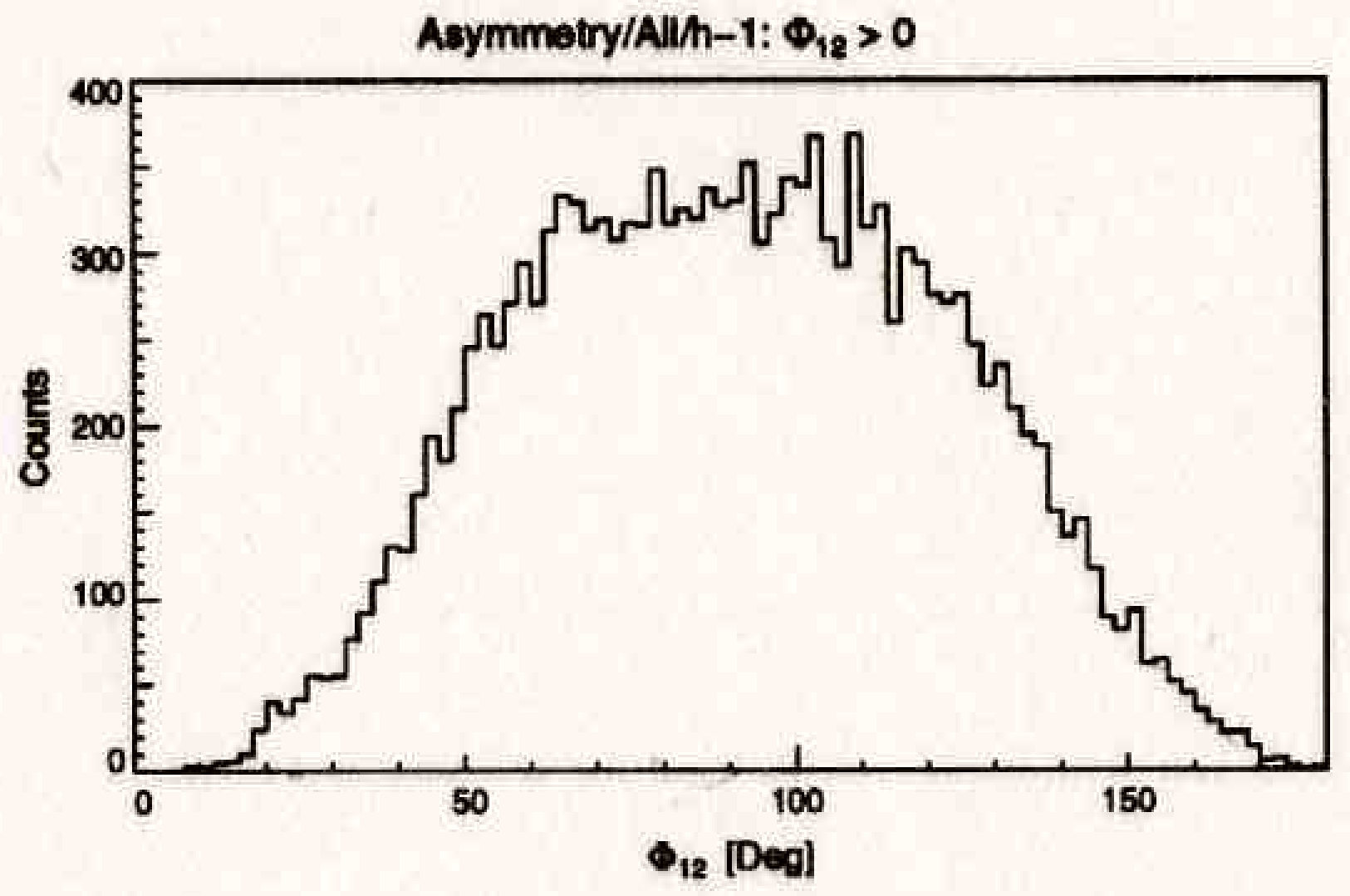


$$\tan \chi_0 = \frac{\mathcal{P}_x}{\mathcal{P}_z} = \frac{A_x}{A_z} = \frac{a\,\mathcal{A}_{\text{eff}} P_e}{c\,\mathcal{A}_{\text{eff}} P_e} \cdot \frac{G_{E,n}}{G_{M,n}} \quad .$$

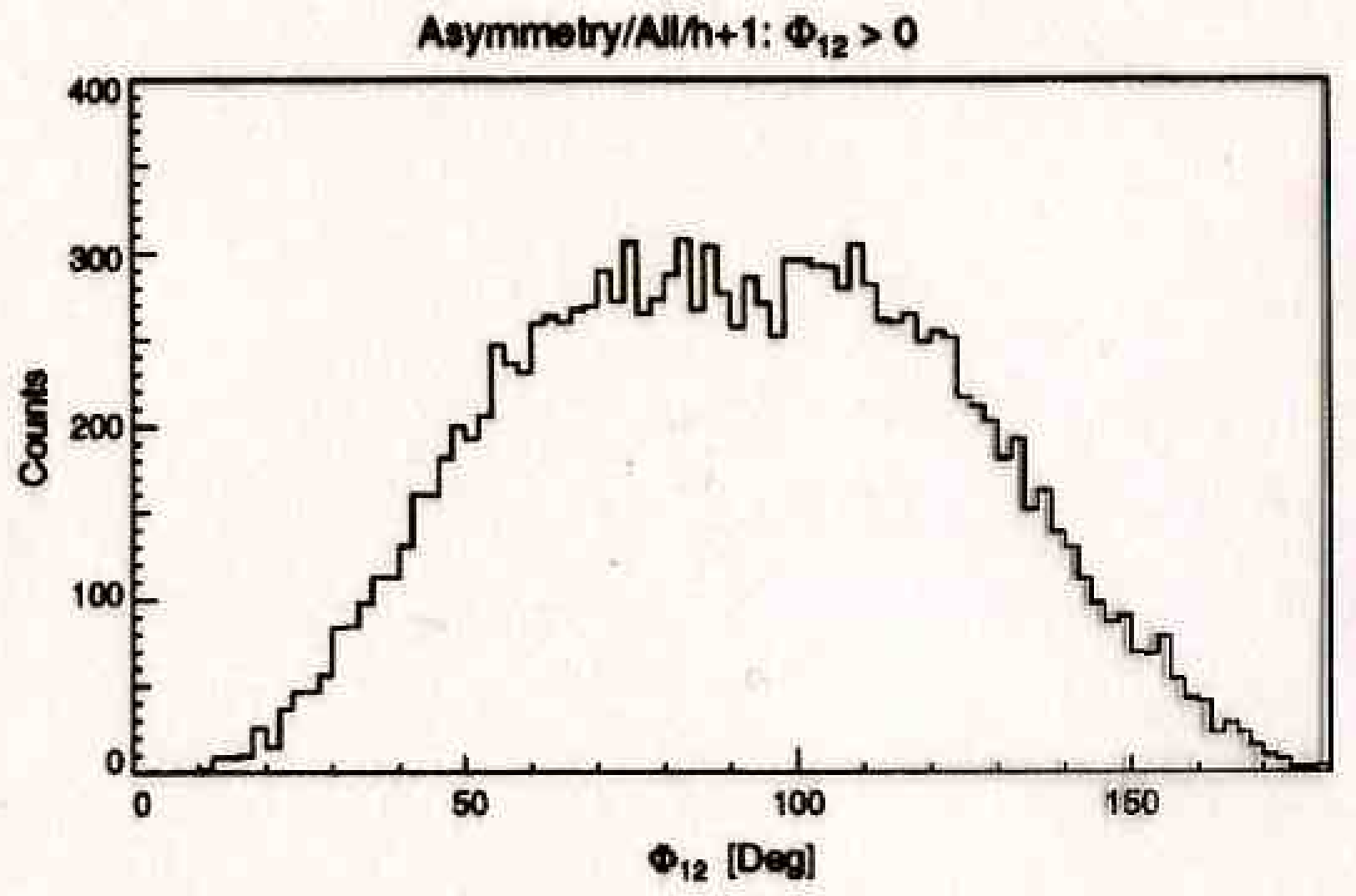
Asymmetries

Φ_n distributions:

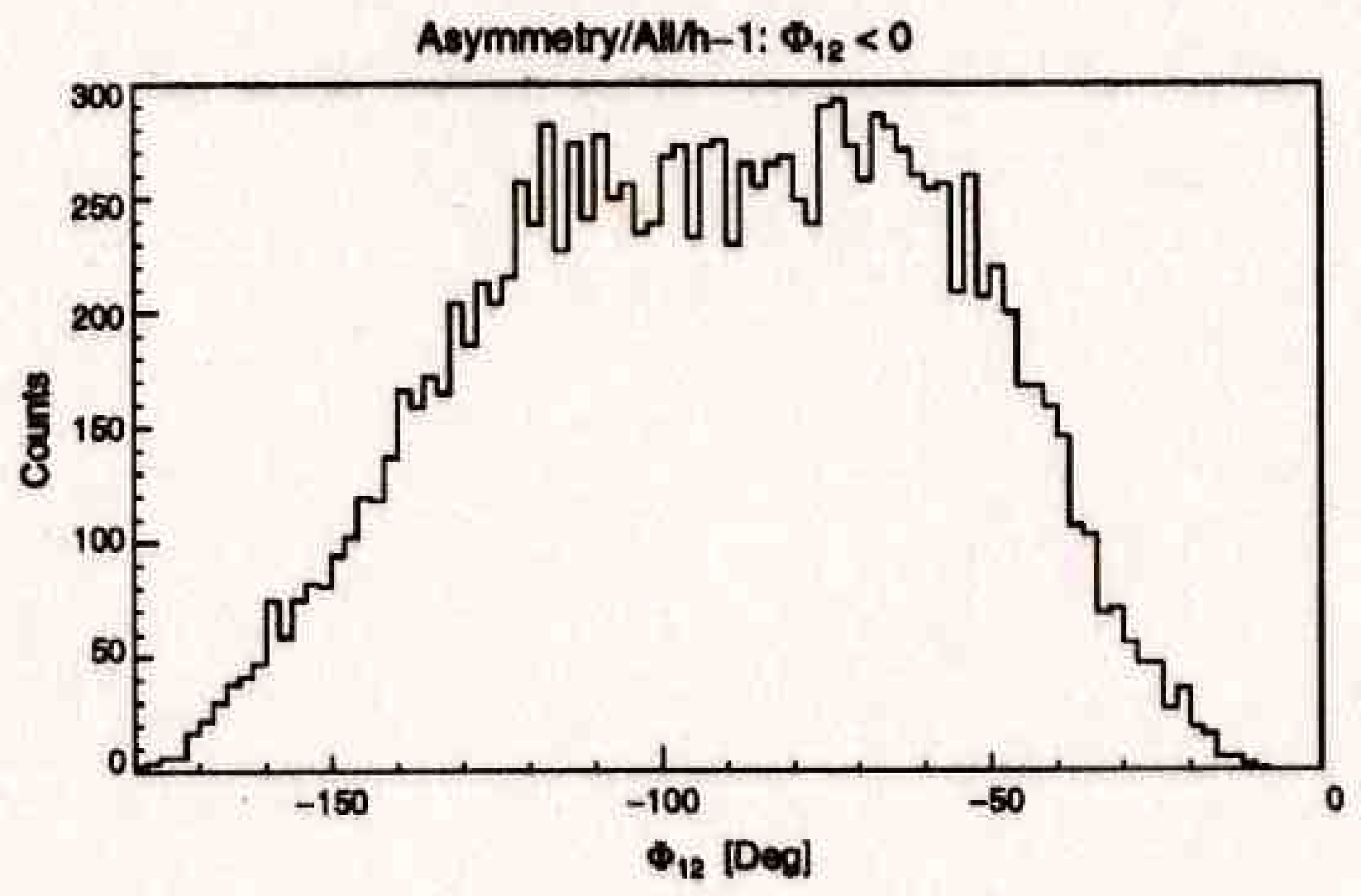
$h = -1,\ \Phi_n > 0$



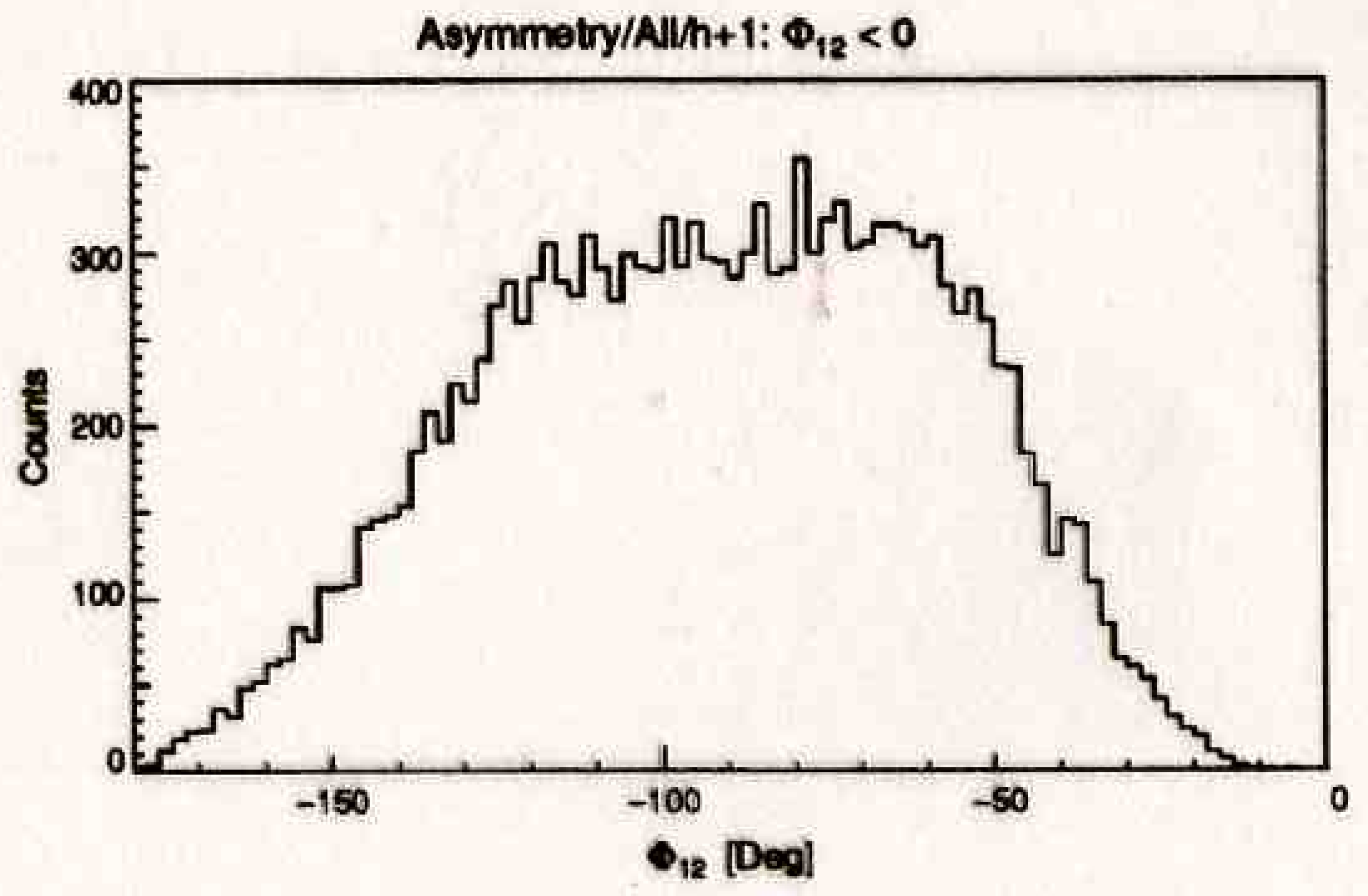
$h = +1,\ \Phi_n > 0$



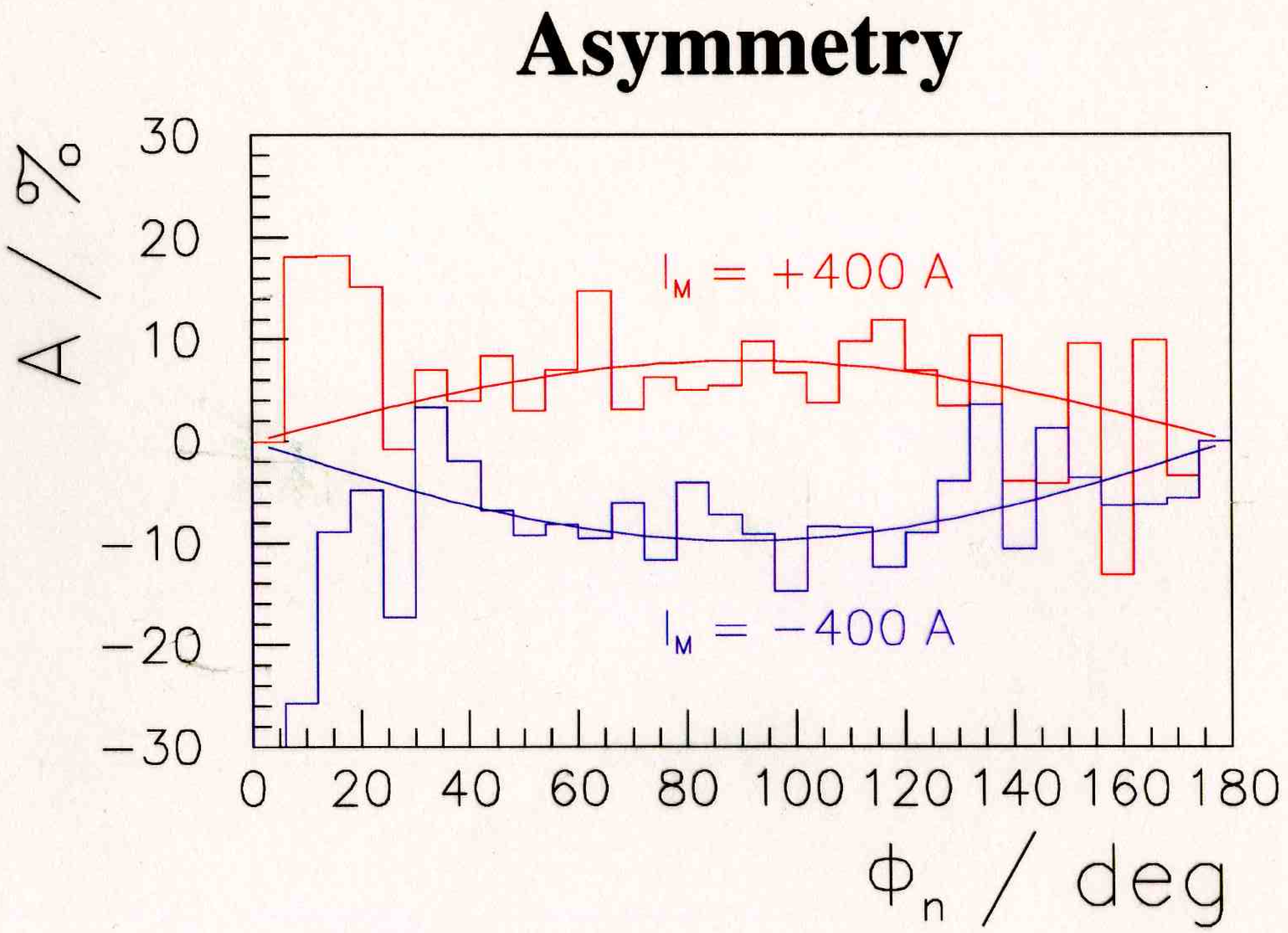
$h = -1,\ \Phi_n < 0$



$h = +1,\ \Phi_n < 0$

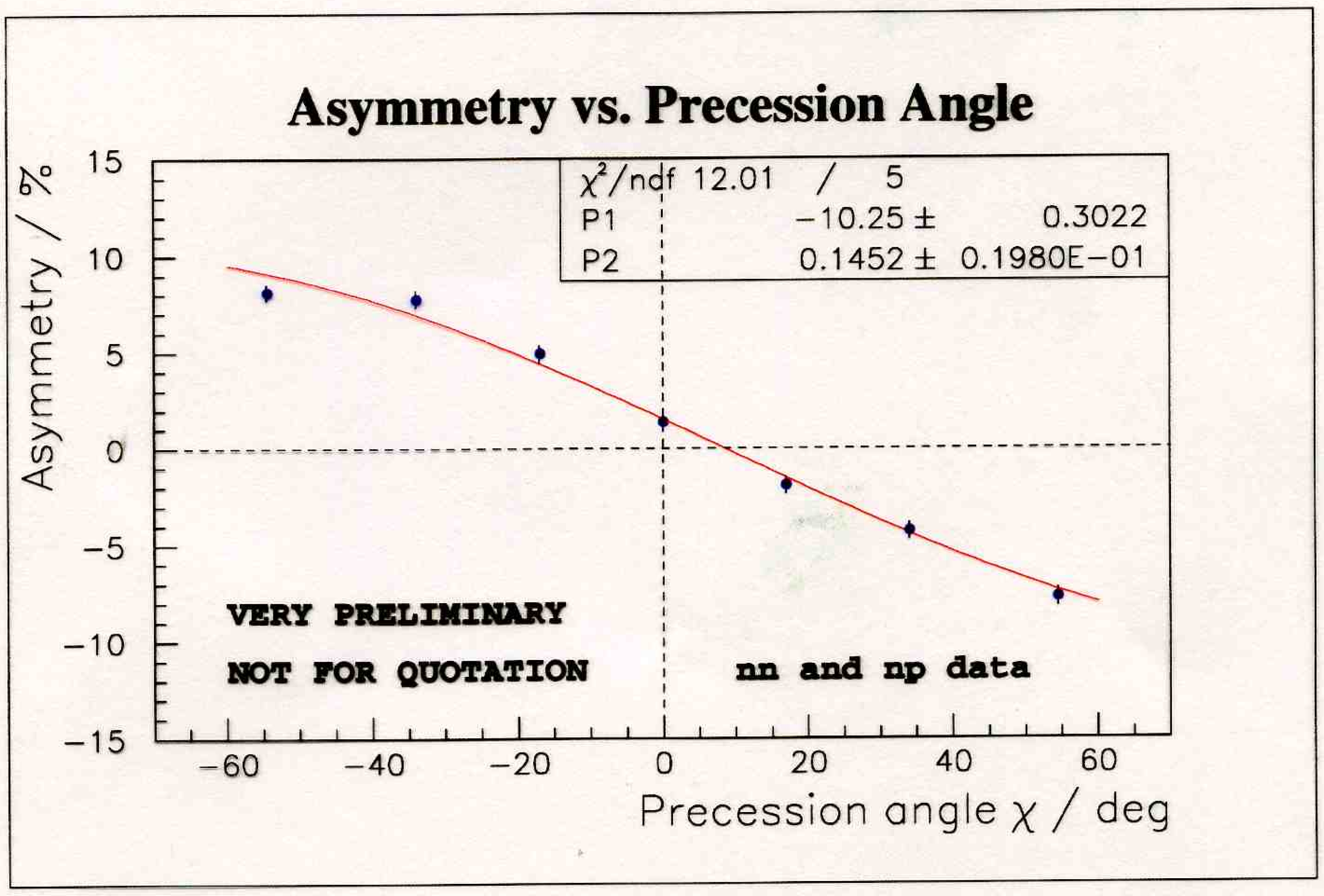


$$A(\Phi_n) = \frac{\sqrt{N^+(\Phi_n)N^-(\Phi_n+\pi)} - \sqrt{N^+(\Phi_n+\pi)N^-(\Phi_n)}}{\sqrt{N^+(\Phi_n)N^-(\Phi_n+\pi)} + \sqrt{N^+(\Phi_n+\pi)N^-(\Phi_n)}}$$



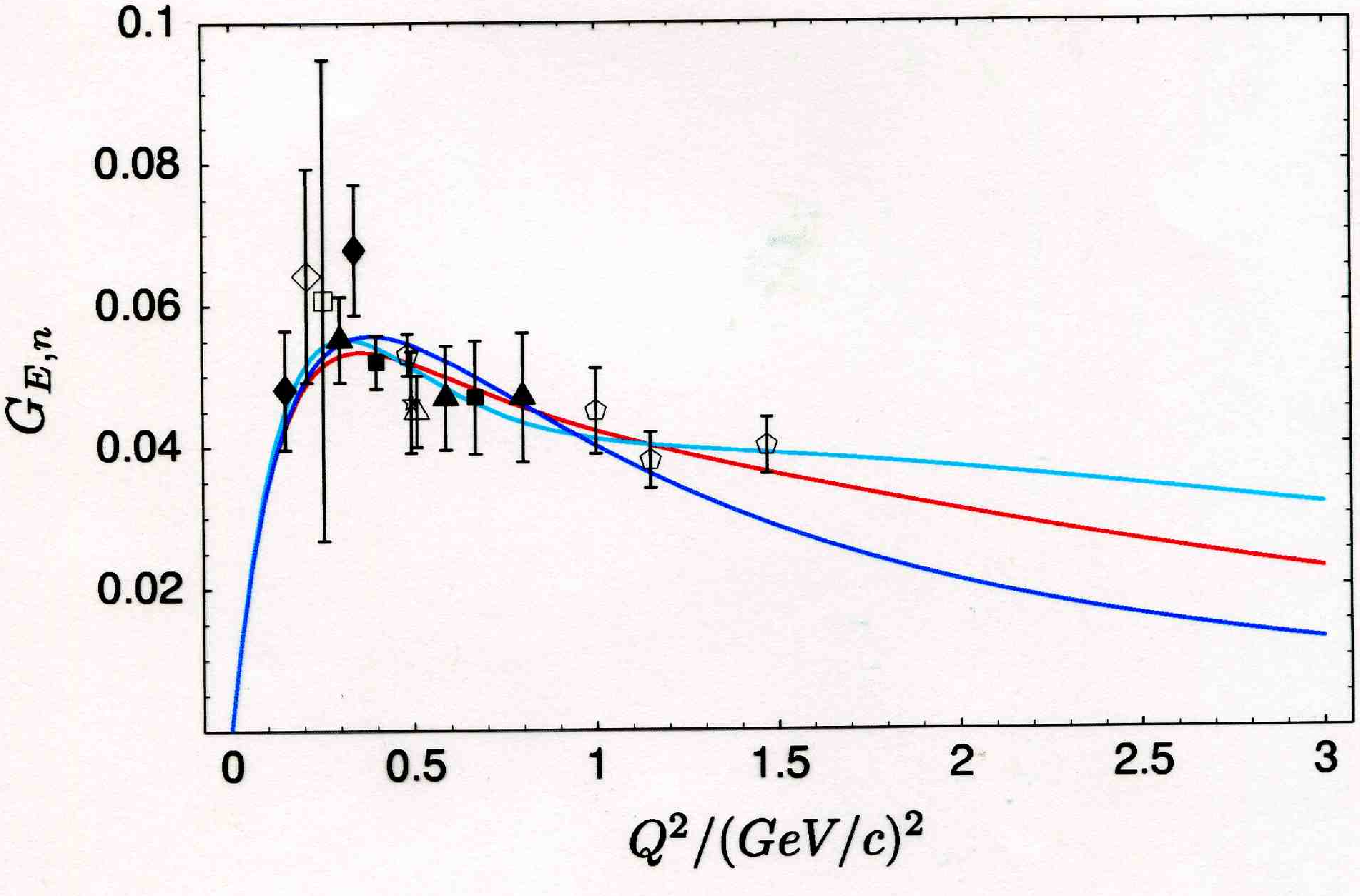
Asymmetries

Plot asymmetries as function of spin precession angle χ

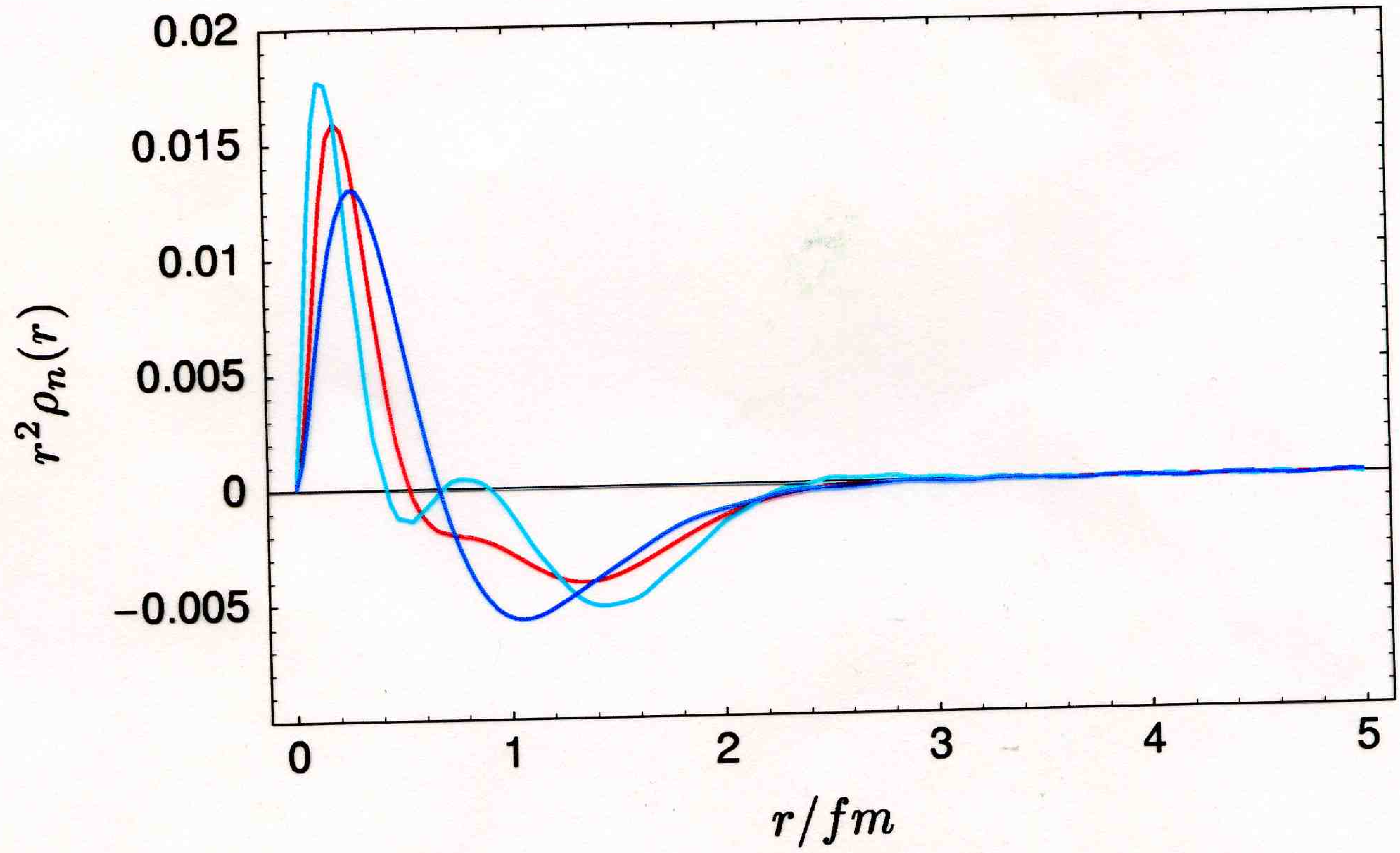


Michael Seimetz

electric form factor of the neutron



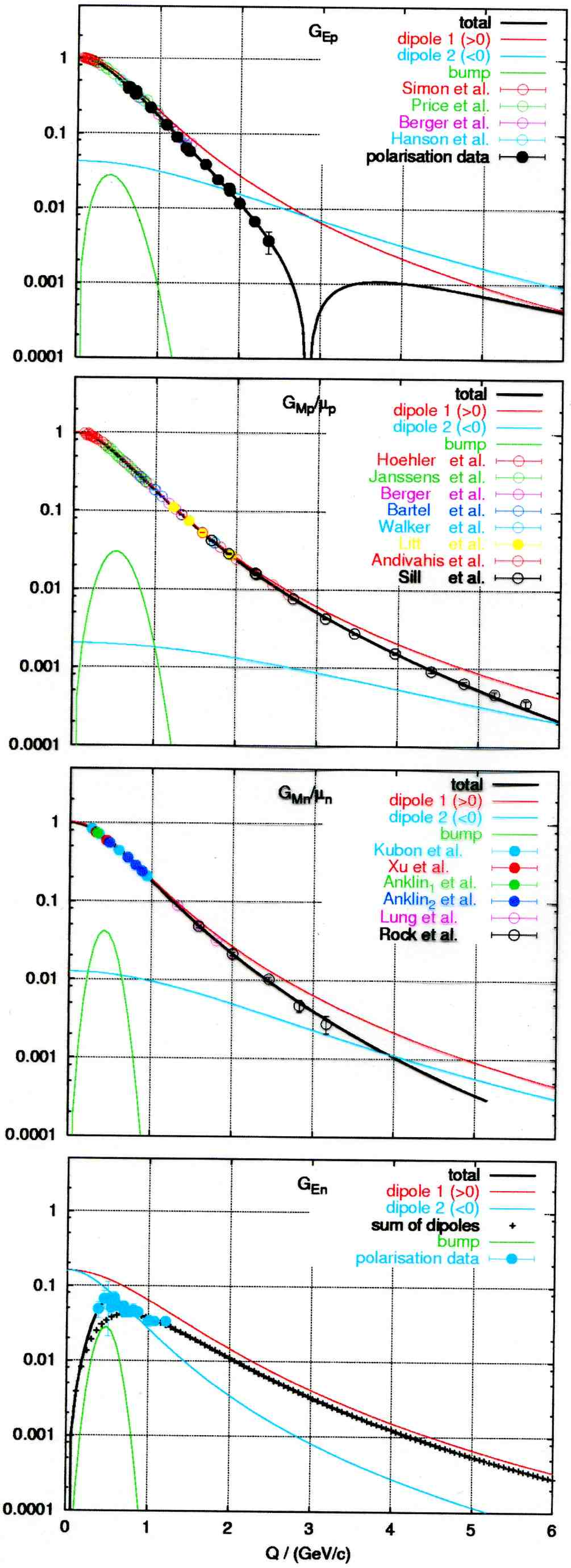
electric charge distribution of the neutron



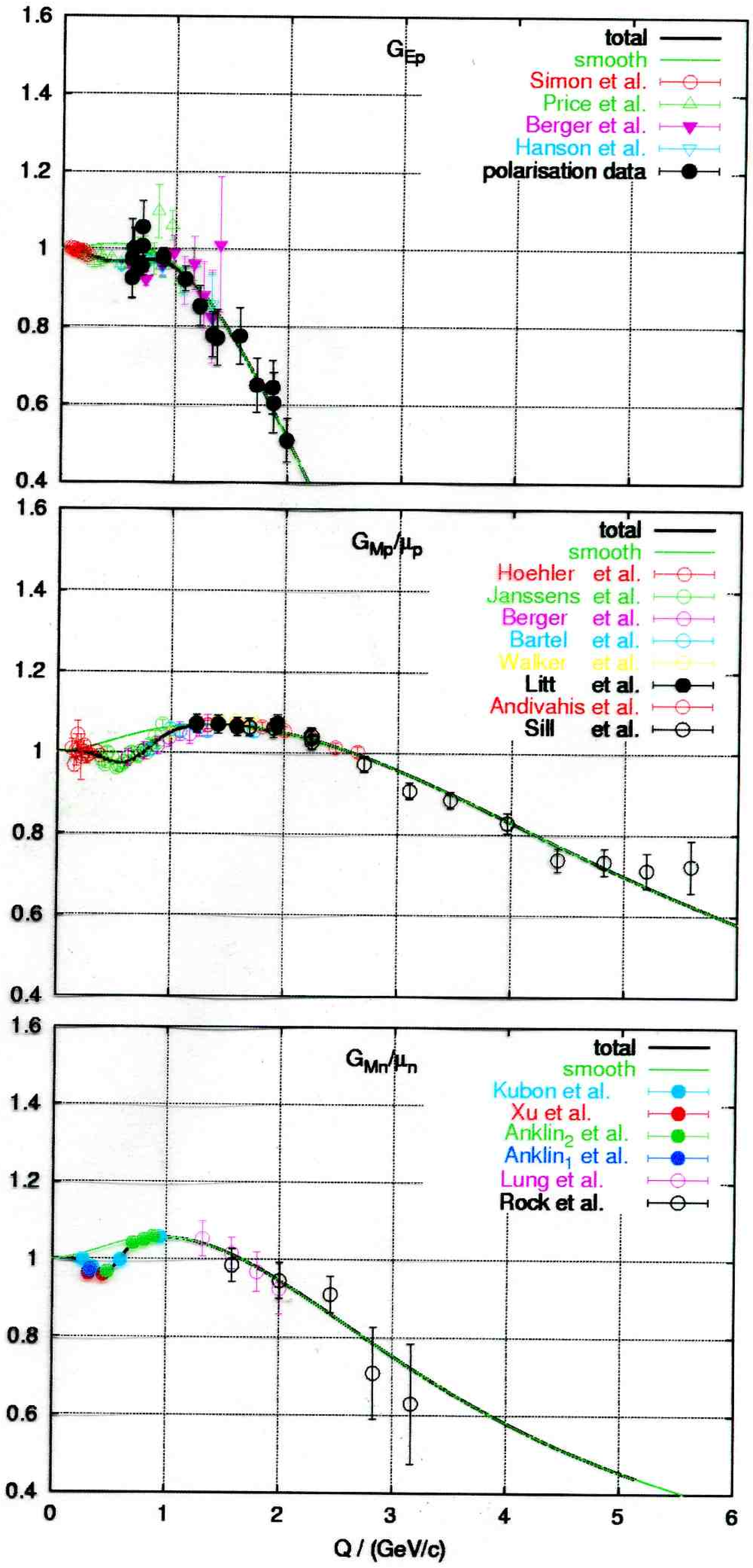
Form factors of the nucleon

fit with 2 dipole shapes and 1 “Gauss”

form factors

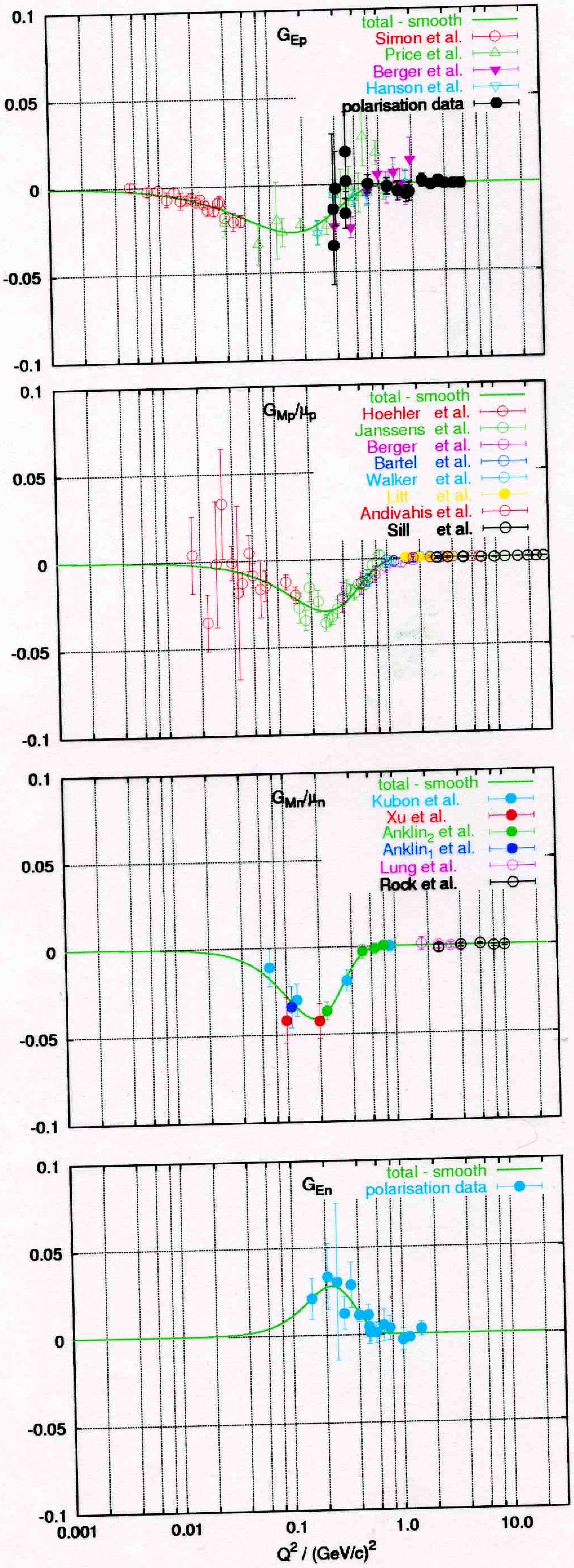


form factor / standard dipole



Form factors of the nucleon

measurement minus smooth fit ≡ 2 dipole shapes plus “Gauss”



mami
MAINZER MIKROTRON

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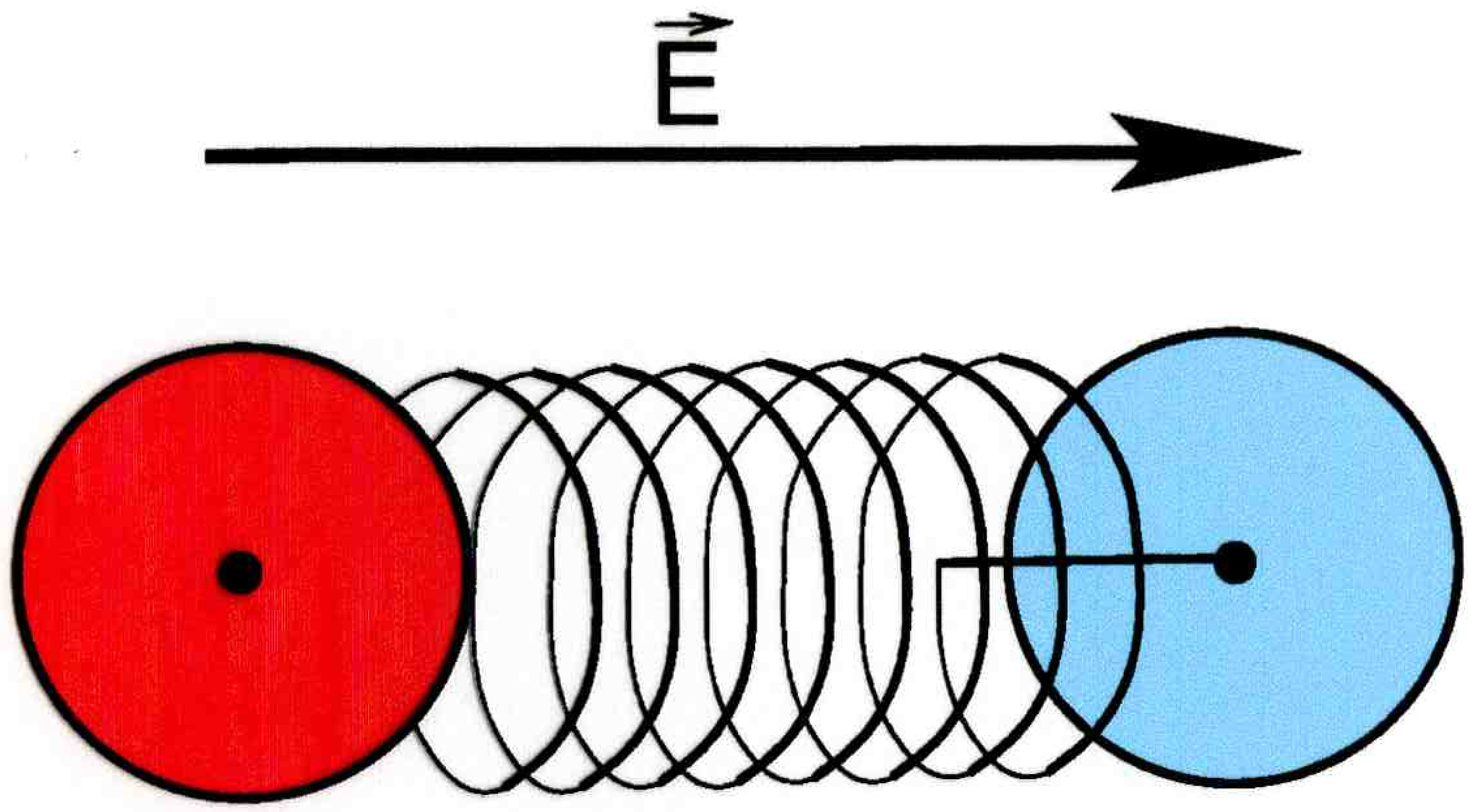
Measurement of the π^+ polarizability in the $\gamma p \rightarrow \gamma' \pi^+ n$ reaction.

Meaning of the polarizability of a composed system

electric polarizability α



spring

$$\vec{p}_{el} := q\delta = q\frac{q}{D}\vec{E} =: \varepsilon_0 \alpha \vec{E} \quad \curvearrowright \quad \alpha = \frac{1}{\varepsilon_0}\frac{q^2}{D} = 4\pi\hbar c\,\alpha_{QED}\frac{\zeta^2}{D}; \quad D = \frac{G}{4}\frac{r^4}{R^3}$$

$$\alpha_{spring} = \hbar c\frac{\alpha_{QED}}{G}16\pi\frac{R^3}{r^4}\zeta^2$$

$$\boxed{\alpha_{spring} \propto \frac{\alpha_{QED}}{\alpha_{spring}} length^3}$$

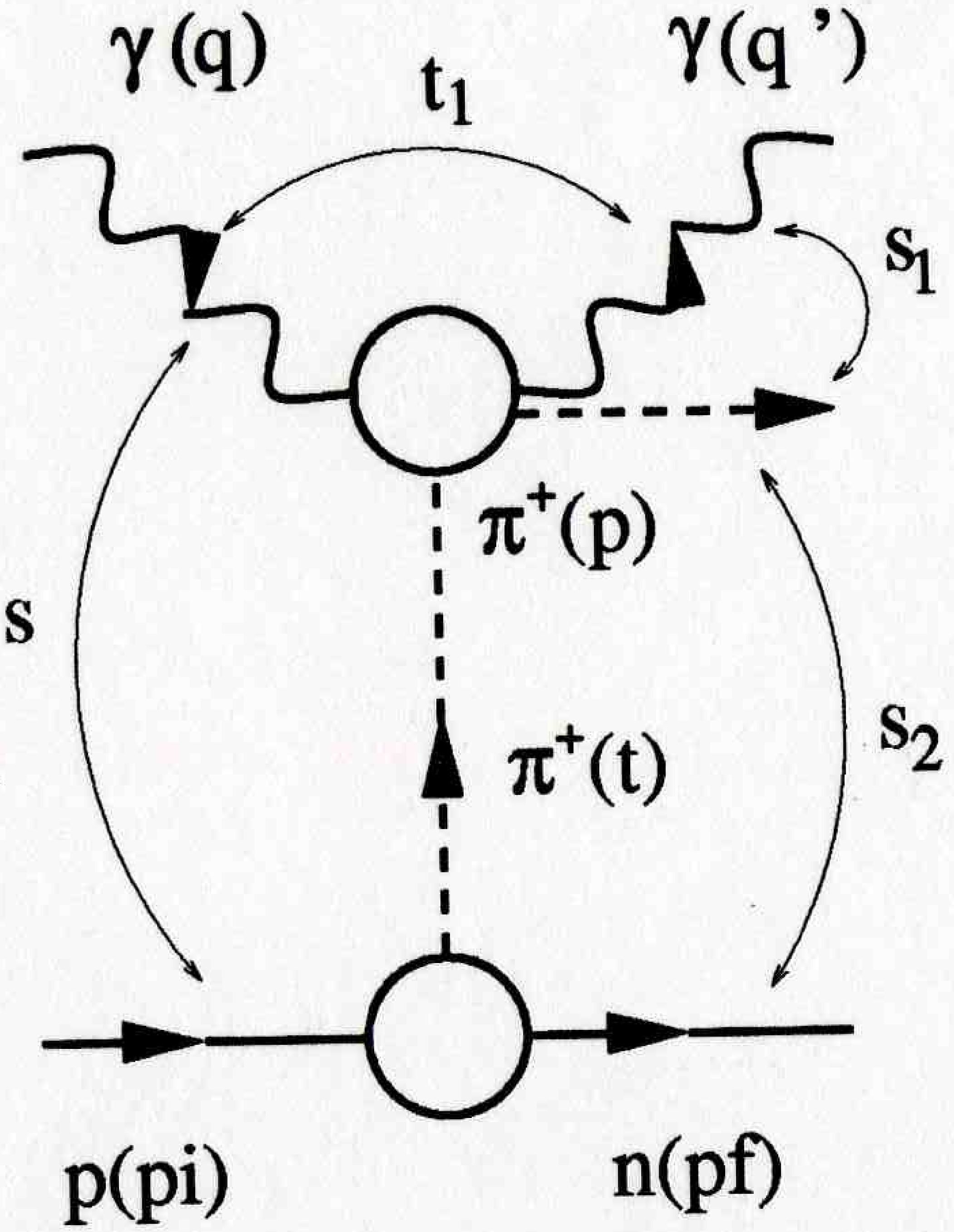
Experimental situation

Experiments	$\alpha_{\pi^\pm}/10^{-4}\mathrm{fm}^3$	$\alpha_{\pi^0}/10^{-4}\mathrm{fm}^3$
$\pi^- Z \to \gamma\pi^- Z$, Serpukhov (1983)	$6.8 \pm 1.4 \pm 1.2$	
$\gamma p \to \gamma\pi^+ n$, Lebedev Phys.Inst. (1984)	20 ± 12	
D. Babusci *et al.* (1992)		
$\gamma\gamma \to \pi^+\pi^-$: PLUTO (1984)	$19.1 \pm 4.8 \pm 5.7$	
DM 1 (1986)	17.2 ± 4.6	
DM 2 (1986)	26.3 ± 7.4	
MARK II (1990)	2.2 ± 1.6	
$\gamma\gamma \to \pi^0\pi^0$: Crystal Ball (1990)		$\pm 0.69 \pm 0.11$
F. Donoghue, B. Holstein (1993)		
$\gamma\gamma \to \pi^+\pi^-$: MARK II	$2.7 \pm ?$	
$\gamma\gamma \to \pi^0\pi^0$: Crystal Ball		$-0.5 \pm ?$
	$(\alpha+\beta)_{\pi^0}/10^{-4}\mathrm{fm}^3$	$(\alpha-\beta)_{\pi^0}/10^{-4}\mathrm{fm}^3$
A. Kaloshin, V. Serebryakov (1994)		
$\gamma\gamma \to \pi^0\pi^0$: Crystal Ball	1.00 ± 005	-0.6 ± 1.8
L. Fil'kov, V. Kashevarov (1999)		
$\gamma\gamma \to \pi^0\pi^0$: Crystal Ball	0.98 ± 003	-1.6 ± 2.2

Theoretical predictions

- chiral perturbation theory
  - $\star$ $(\alpha+\beta)_{\pi^+} = 0$ in leading order $O(p^4)$
    $(\alpha+\beta)_{\pi^+} = (0.3 \pm 0.1) \times 10^{-4}\mathrm{fm}^3$ in order $O(p^6)$
  - $\star$ $(\alpha-\beta)_{\pi^+} \approx 5.4 \times 10^{-4}\mathrm{fm}^3$ one loop (Bijens, Cornet, 1988; Danoghue, Holstein 1989; Belluci, Gasser, Sainio, 1994)
    $(\alpha-\beta)_{\pi^+} = (4.4 \pm 1.0) \times 10^{-4}\mathrm{fm}^3$ two loops (Bürgi, 1997)
- Nambu-Jona-Lasino model
  $\alpha = -\beta = (3.0 \pm 0.6) \times 10^{-4}\mathrm{fm}^3$; $(\alpha-\beta)_{\pi^+} = (6.0 \pm 0.8) \times 10^{-4}\mathrm{fm}^3$
- Dispersion relations
  $(\alpha-\beta)_{\pi^+} = (10.3 \pm 1.9) \times 10^{-4}\mathrm{fm}^3$ (Lev Fil'kov, Kashevarov, 1999)
- non linear σ model
  $(\alpha-\beta)_{\pi^+} = 20 \times 10^{-4}\mathrm{fm}^3$ (Bernard, Hiller, Weise, 1988)
- Dubna quark confinement model
  $(\alpha-\beta)_{\pi^+} = 7.05 \times 10^{-4}\mathrm{fm}^3$ (Ivanov, Mizutani, 1992)

Basic idea for measuring the π^+ polarizability.



$$\begin{aligned}
s &= (p_1+k_1)^2 = m_p^2 + 2m_pE_\gamma \\
t &= (p_2-p_1)^2 = (m_n-m_p)^2 - 2m_p(E_n-m_n) \\
t_1 &= (k_2-k_1)^2 = -2E_\gamma E_{\gamma'}(1-\cos\theta_{\gamma\gamma'}) \\
s_1 &= (k_2+q_2)^2 = m_\pi^2 + 2E_{\gamma'}(q_{20} - \mid \vec{q}_2 \mid \cos\theta_{\gamma'\pi^+}) \\
s_2 &= (p_2+q_2)^2 = s + t_1 - 2m_pE_{\gamma'} \\
z &= cos\theta_{\gamma\gamma'}^{cm}
\end{aligned}$$

$$\frac{d\sigma_{\gamma\pi}}{d\Omega} = \left(\frac{d\sigma_{\gamma\pi}}{d\Omega}\right)_B - \frac{e^2}{4\pi}\frac{m_\pi^3(s_1-m_\pi^2)^2}{4s_1^2[(s_1+m_\pi^2)+(s_1-m_\pi^2)z]}$$
$$\times\left\{(1-z)^2(\alpha_{\pi^\pm}-\beta_{\pi^\pm}) + \frac{s_1^2}{m_\pi^4}(1+z)^2(\alpha_{\pi^\pm}+\beta_{\pi^\pm})\right\}$$

background reaction

only backward direction of γ detection is interesting and covered (TAPS)

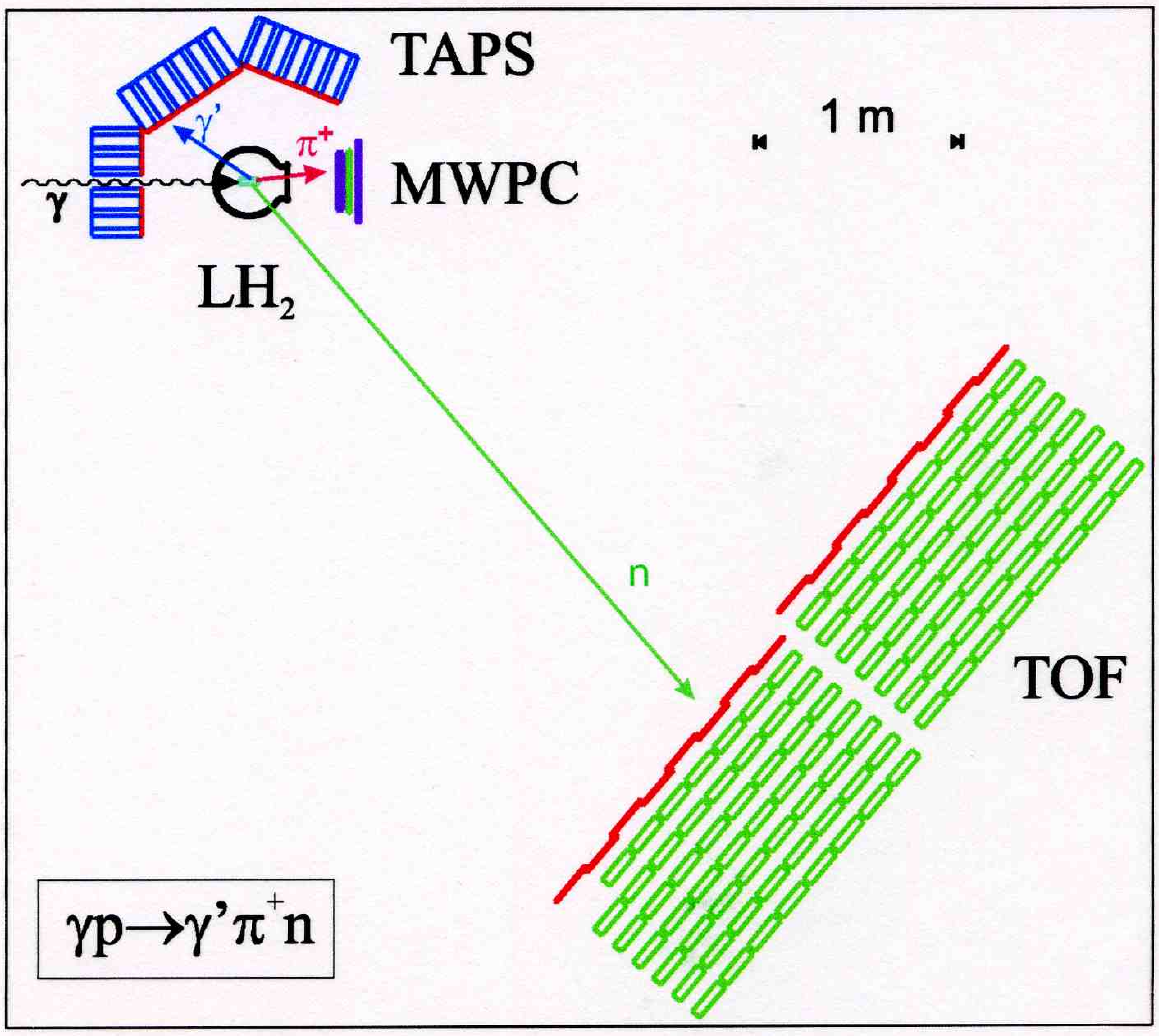
↷ background

$$\gamma p \to \pi^0 \pi^+ n \to \gamma' \underset{\substack{\downarrow \\ \text{lost}}}{\gamma} \pi^+ n \to \gamma' \pi^+ n$$

choice of detector setup supresses this abundant reaction,
Monte Carlo simulations show that with analysis methods:

- optimized cut ↷ background $\leqslant$ 3%
- constrained fits ↷ background $\leqslant$ 10%

Experimental Set-up



TAPS:

A: 192 BaF2, $\theta=68^\circ$

B: 192 BaF2, $\theta=124^\circ$

C: 144 BaF2, $\theta=180^\circ$

MWPC:

4 planes×128 wires, $\theta=0^\circ$

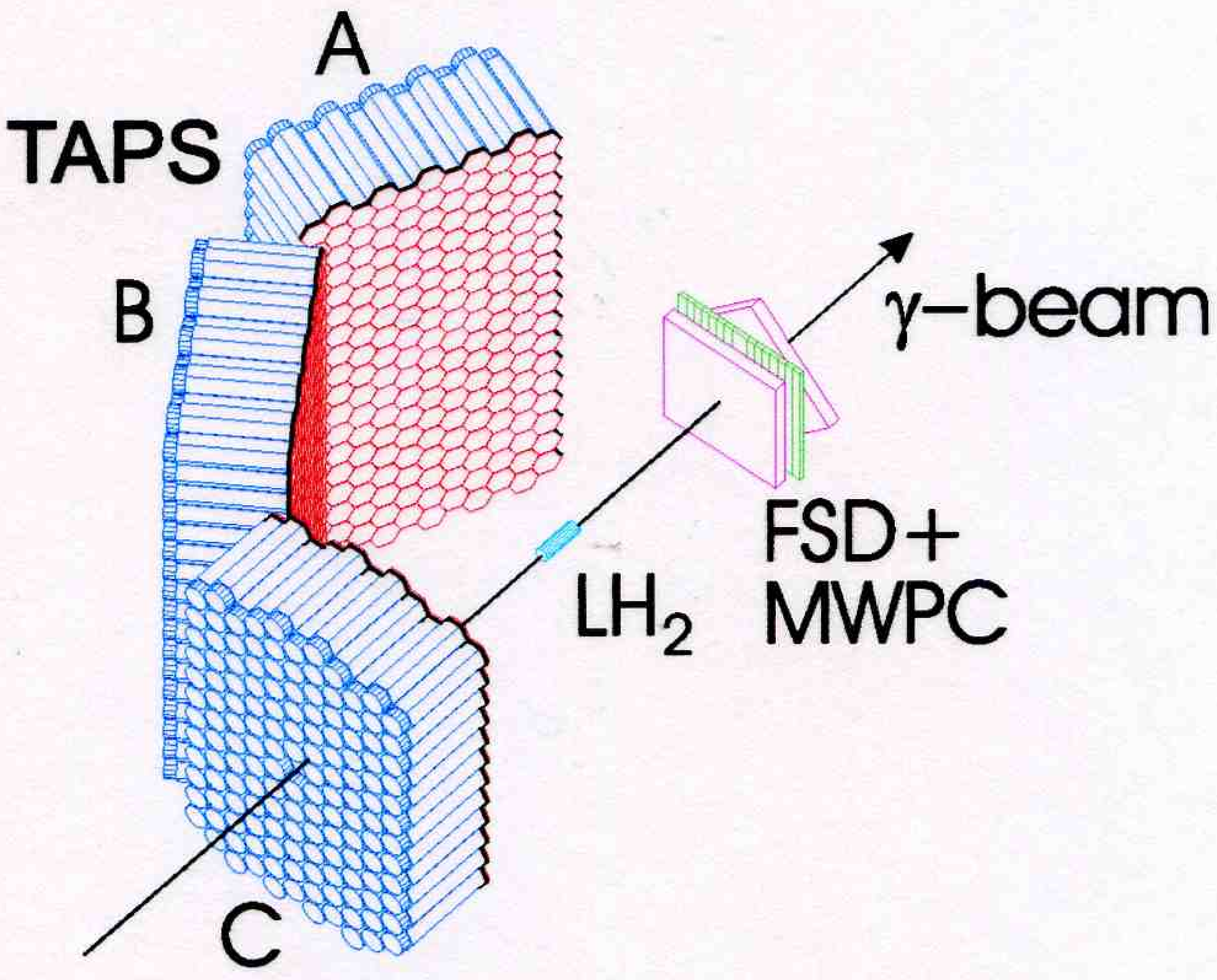
TOF:

111 bars, $300\times20\times5$ cm^3, $\theta=40^\circ$

16 veto bars $300\times22\times1$cm^3

Target:

LH$_2$ 11 cm long , 3 cm dia.



Differential cross section

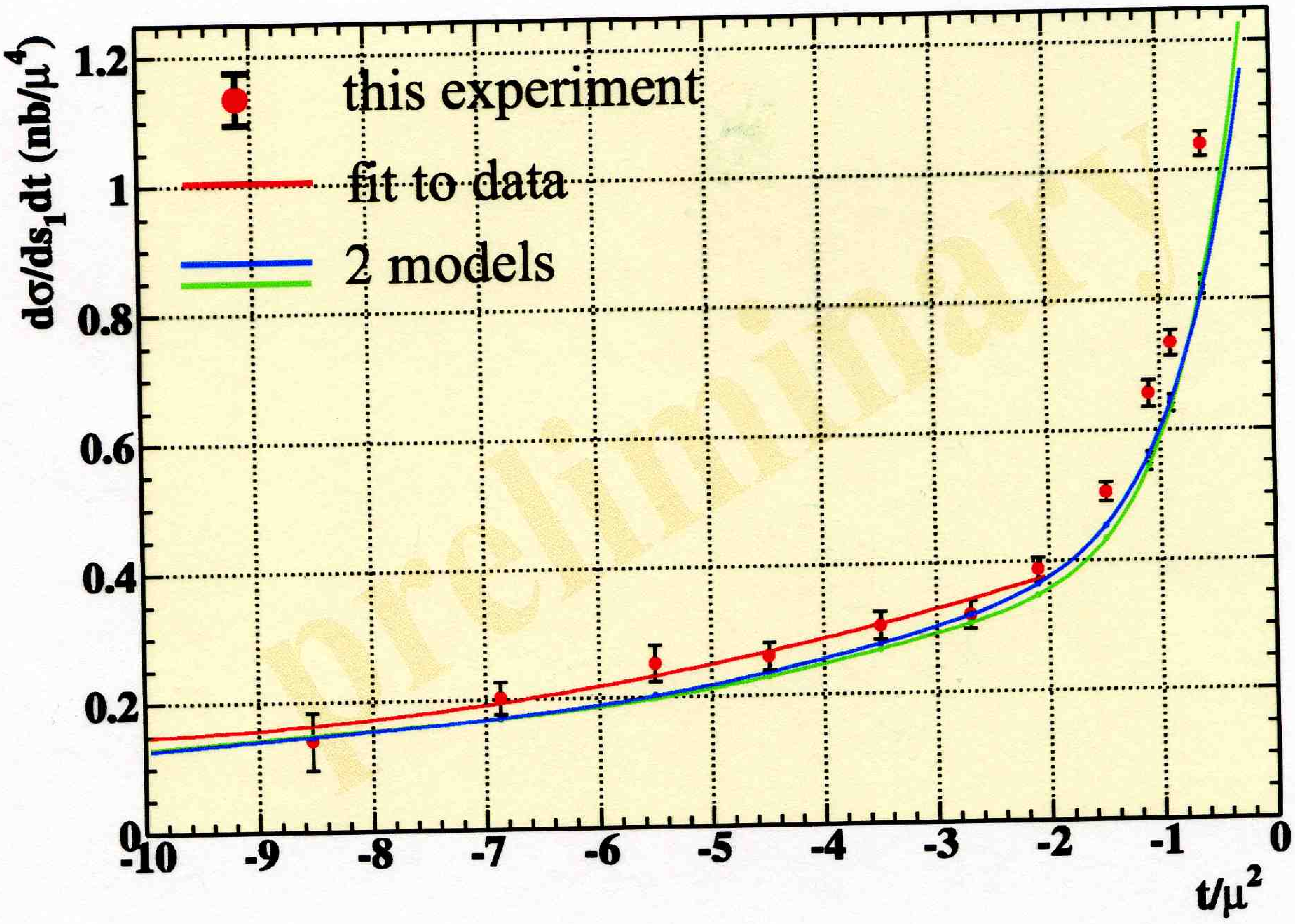
$\gamma\ p \longrightarrow \gamma'\ \pi^+\ n$

$537\ \mathrm{MeV} < E_\gamma < 817\ \mathrm{MeV}$

$140^\circ < \theta^{cm}_{\gamma\gamma'} < 180^\circ$

$1.5\ \mu^2 < s_1 < 5\ \mu^2$

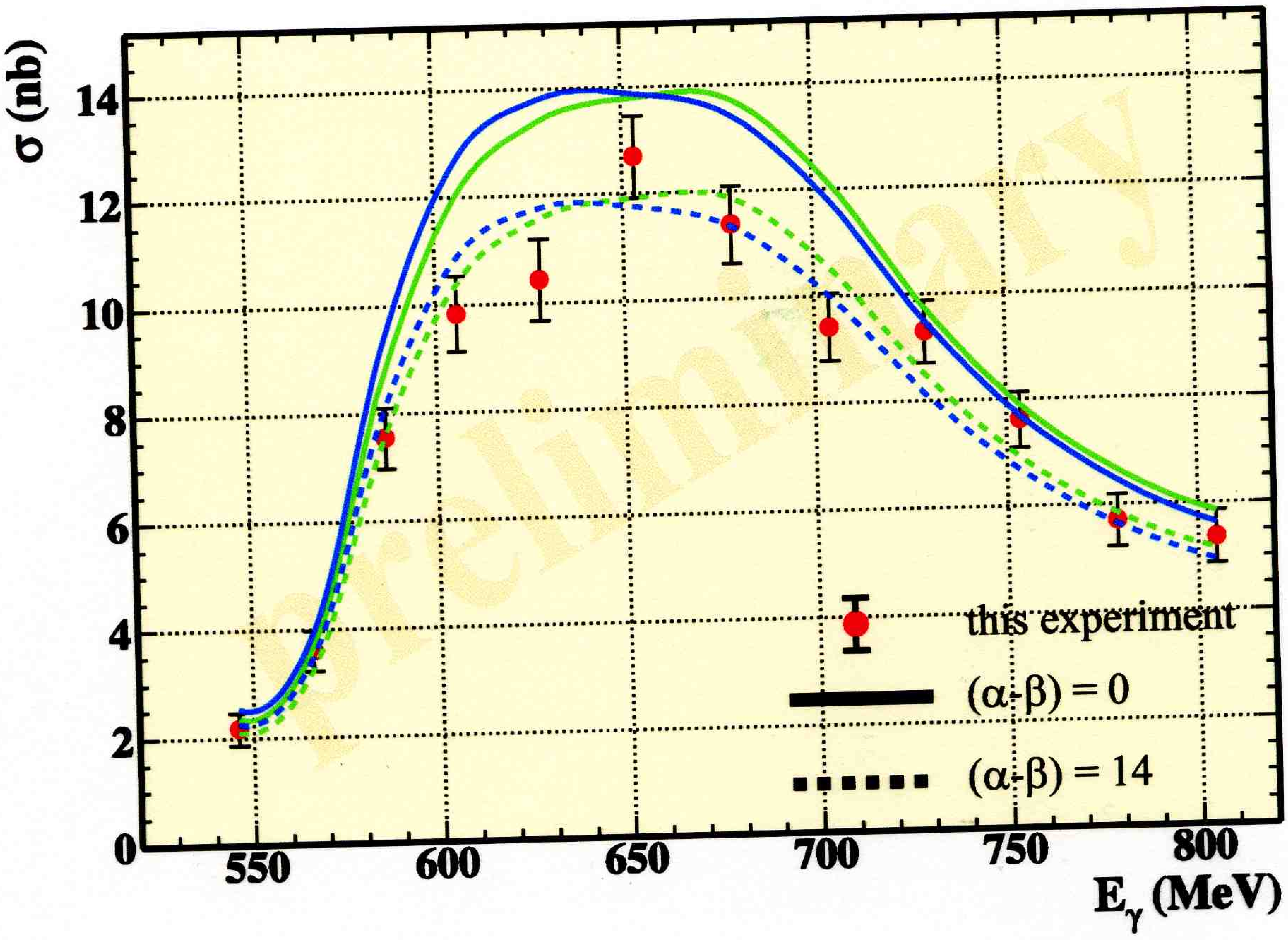
Insensitive to pion polarizability!



Pion Polarizability

$$\gamma \; p \longrightarrow \gamma' \; \pi^+ \; n$$

cross section for: $140^\circ < \theta^{cm}_{\gamma\gamma'} < 180^\circ$
$-12\,\mu^2 < t < -2\,\mu^2$
$5\,\mu^2 < s_1 < 15\,\mu^2$



Model 1: Unkmeir $(\alpha-\beta)=(12.2\pm1.6\pm3.3)\times10^{-4}\ \mathrm{fm}^3$

Model 2: Fil'kov $(\alpha-\beta)=(11.1\pm1.4\pm2.8)\times10^{-4}\ \mathrm{fm}^3$

Conclusions

Final result for pion polarizabilty $(\alpha-\beta)_{\pi^+}$:

$$(\alpha-\beta)_{\pi^+} = (11.6 \pm 1.5_{stat} \pm 3.0_{syst} \pm 0.5_{model}) \times 10^{-4}\mathrm{fm}^3$$

deviates by 2 standard deviations from the

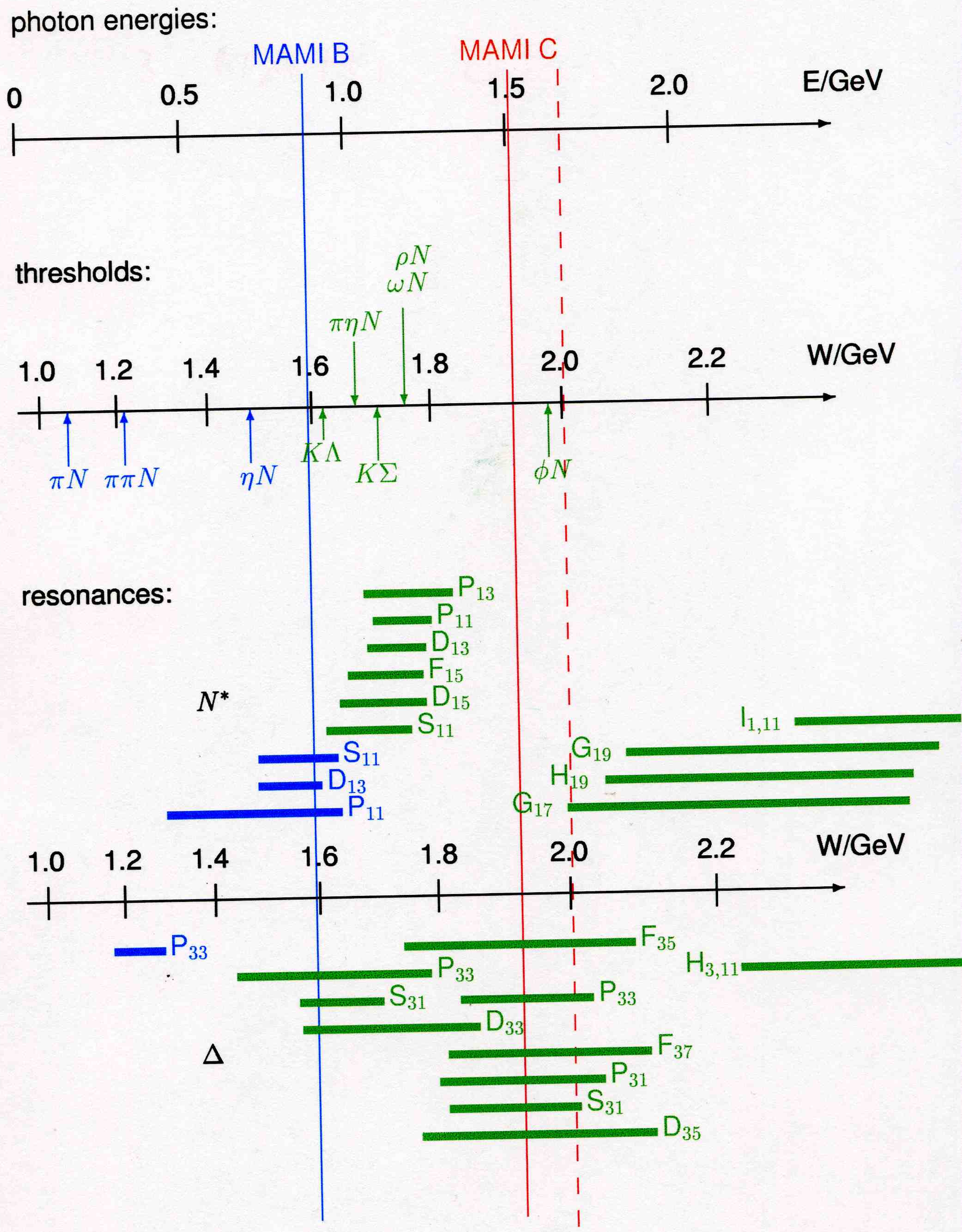
Chiral Perturbation Theory result;

significant deviation, but a real problem?

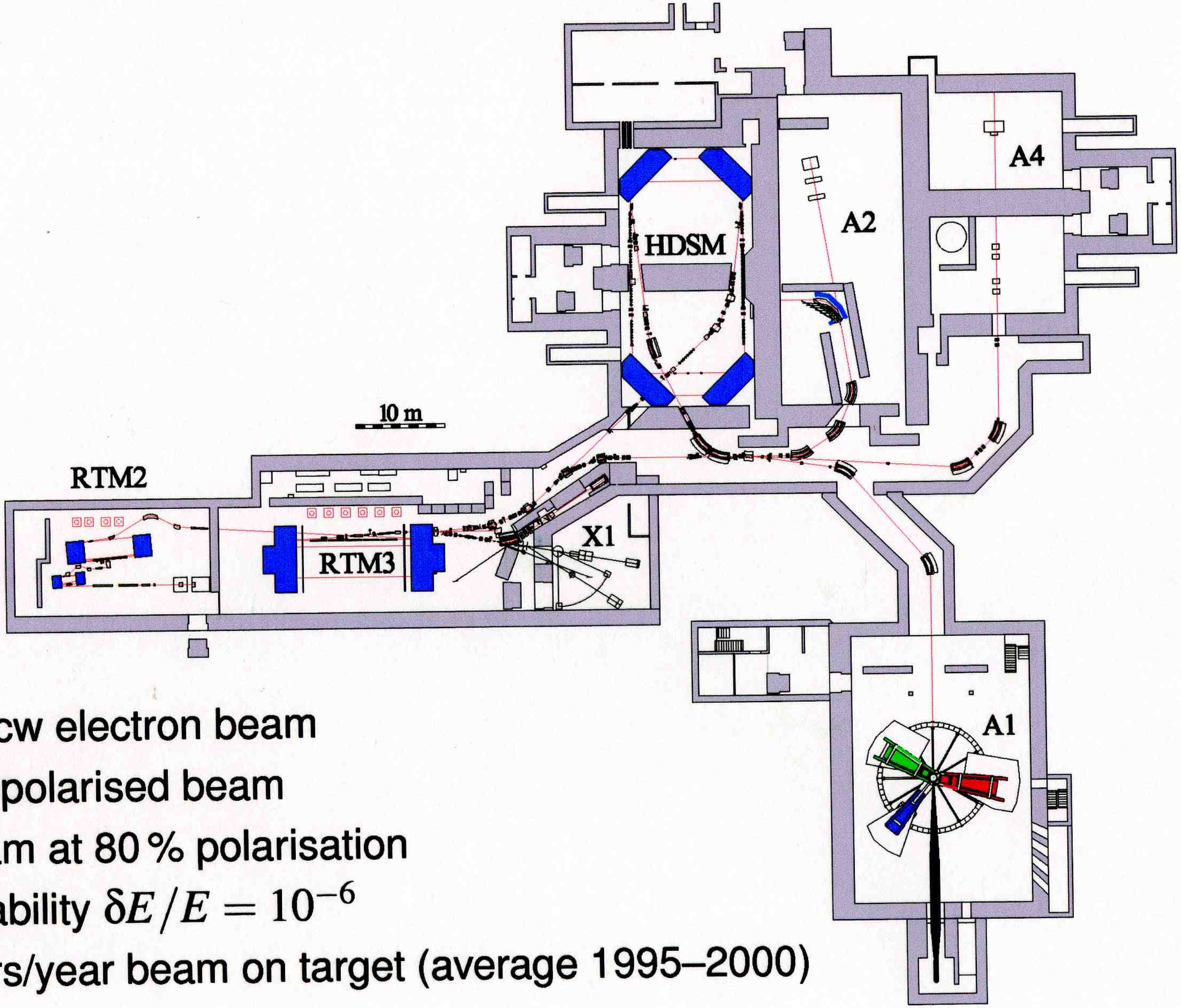
Explanations:

- “off-shell-pion”
  the initial pion is virtual, the final is the asymptotic pion
  replace point like initial pion by form factor ↷ discrepancy increases
- Chiral Perturbation Theory fails
  expansion for small external momenta, but how small?
  deviations manifest if $\lambda_\pi \gtrapprox \lambda_{\gamma^*}$, i.e. if spatial size of pion is resolved
- modification of pion cloud picture
  pion cloud $\equiv$ transitional layer between superconductor (QCD vacuum) and normal conductor (interior of hadron, confined quarks and gluons)?

ranges of physics

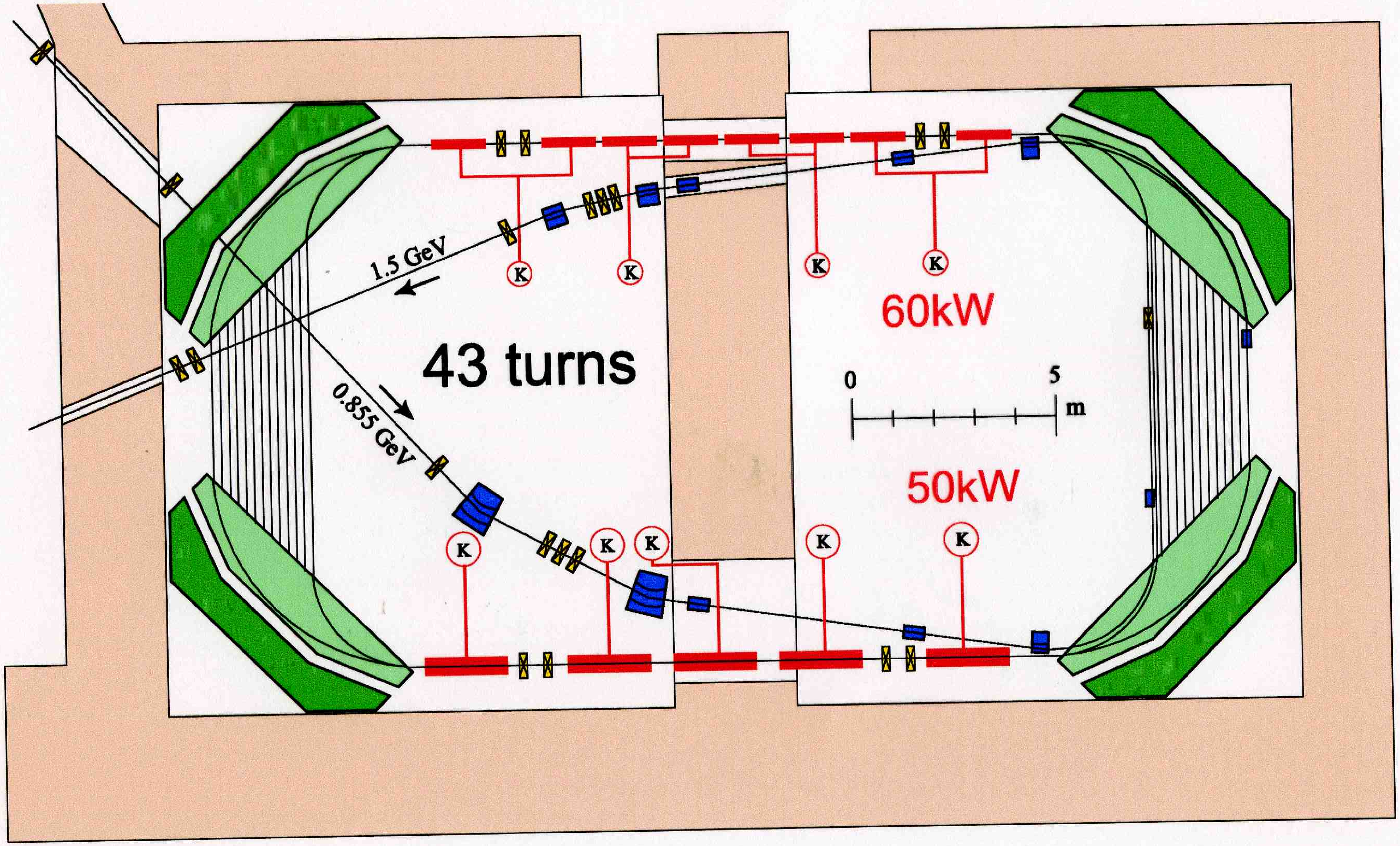


The MAMI accelerator



- 855 MeV cw electron beam
- 100 μA unpolarised beam
- 30 μA beam at 80 % polarisation
- energy stability $\delta E/E = 10^{-6}$
- 5500 hours/year beam on target (average 1995–2000)

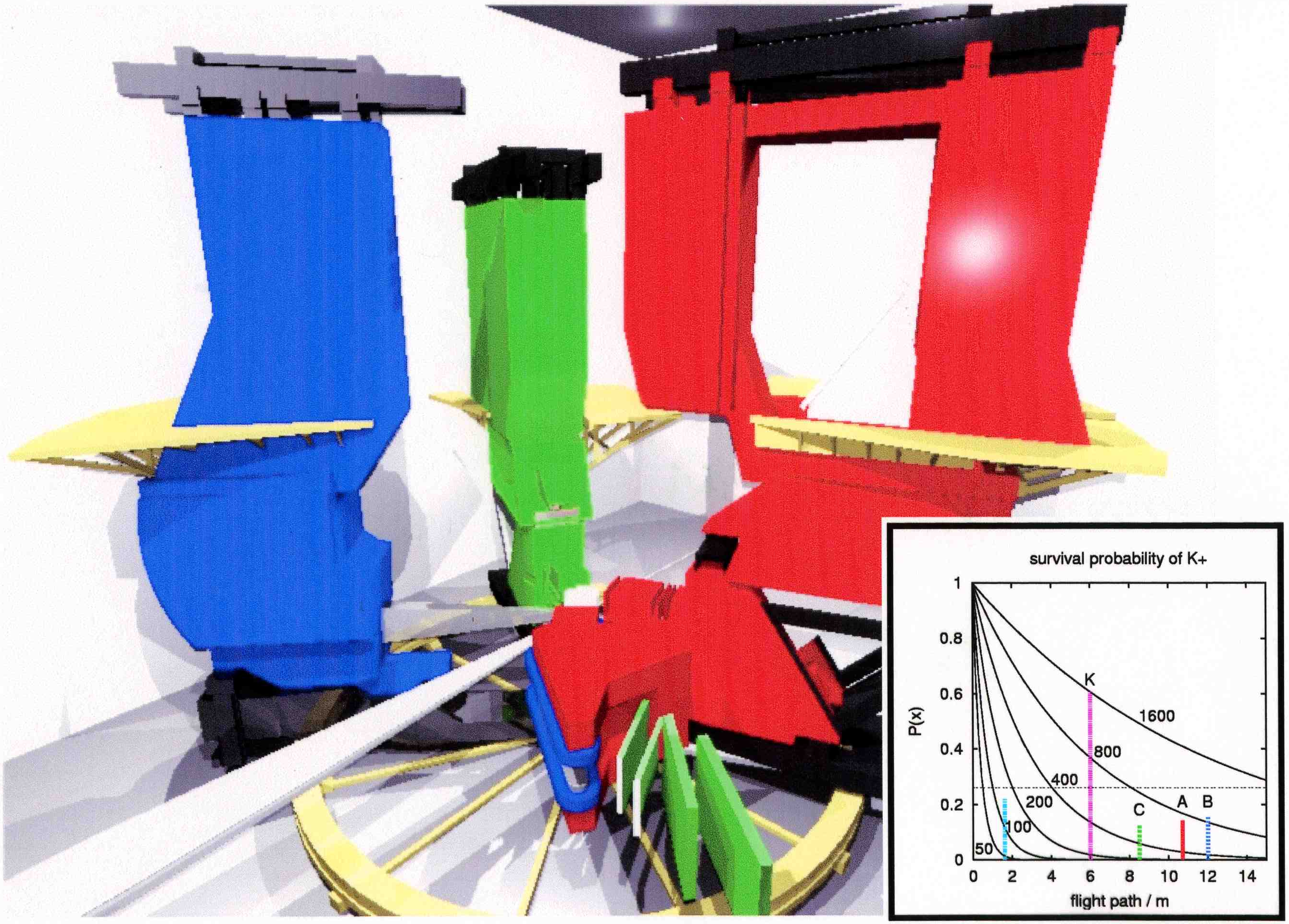
MAMI C



MAMI collaborations and their experimental equipment

- A1 collaboration
  - ⋆ 3-Spectrometer-Set-up
  - ⋆ π Short Orbit Spectrometer
  - ⋆ neutron polarimeter and detectors
  - ⋆ $^3\overrightarrow{He}$ target
  - ⋆ KAOS Kaon short orbit Spectrometer
- A2 collaboration
  - ⋆ Photon-Tagger
  - ⋆ DAPHNE, TAPS, etc.
  - ⋆ Crystal Ball
  - ⋆ $\vec{p}$ target
- A4 collaboration
  - ⋆ granulated Cherenkov detector
  - ⋆ high power LH_2 target

KAOS @ A1


survival probability of K+
P(x)
flight path / m
1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
50
100
200
400
800
1600
K
C
A
B

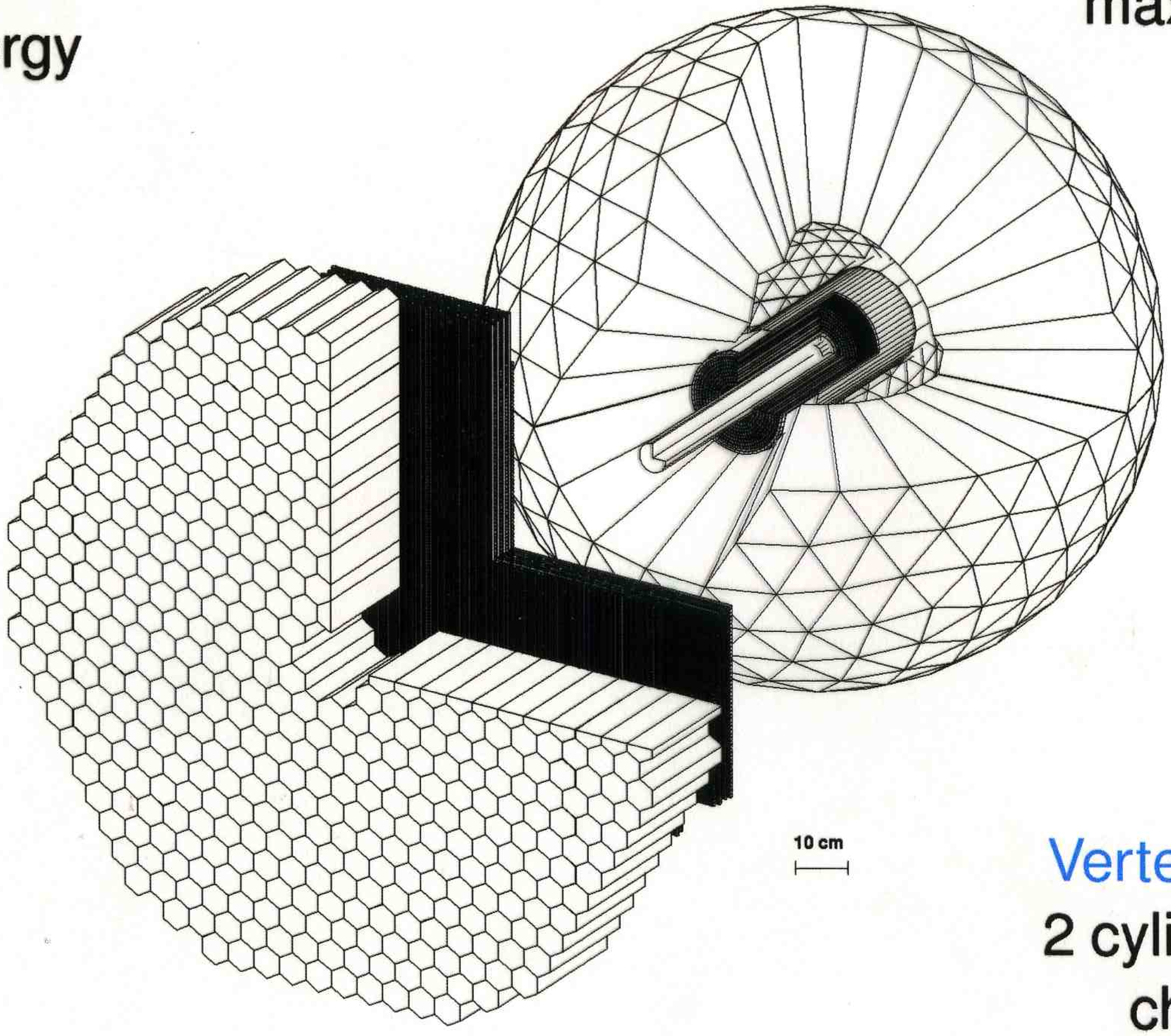
Crystal Ball and TAPS at MAMI

TAPS

510 BaF_2 detectors
max. kinetic energy
$\pi^{\pm}$: 180 MeV
$K^{\pm}$: 280 MeV
p : 360 MeV

Crystal Ball

672 NaJ detectors
max. kinetic energy
$\mu^{\pm}$: 233 MeV
$\pi^{\pm}$: 240 MeV
$K^{\pm}$: 341 MeV
p : 425 MeV



Vertex detectors

2 cylindrical wire chambers
480 wires, 320 strips

24 thin plastic counters
particle identifcation

Physics Program at MAMI

- MAMI B $(180\ MeV < E < 885\ MeV)$: from 1992 to 2005 and beyond
- MAMI C $(180\ MeV < E \lesssim 1500\ MeV)$: starting 2005

1. Structure of the Nucleon
   - form factors G_E^p, G_E^n, G_A
   - polarizabilities at $Q^2 = 0$ and $Q^2 > 0$
   - spin structure
   - nucleon resonances in selective decay channels
     - ⋆ $\gamma\, p \rightarrow \Delta\, \gamma_{internal\ decay} \rightarrow p\, \pi^0\, \gamma$ $\curvearrowright$ magnetic moment of $\Delta(1232)$
     - ⋆ Roper resonance
2. Mesonic Structure of the Nucleon
   - threshold production of mesons $\pi, 2\pi, \eta, \pi\eta, 2\eta, \rho, \omega, \ldots$
   - structure of mesons: formfactors, polarizabilities
   - mesonproduction in the region of the resonances

3. Strange Hadrons - Strangeness in Strongly Interacting Systems

- strange meson production at threshold: chiral dynamics
- K^0 formfactors
- hyperons: formfactors, polarization, resonances
- hypernuclei: momentum distribution of Λ in the nucleus,
  separated L/T structure functions

4. Parity Violation in Electron Scattering

- electric and magnetic flavour singlet form factors:
  strangeness in proton and neutron
- transverse polarization ↷ two photon exchange

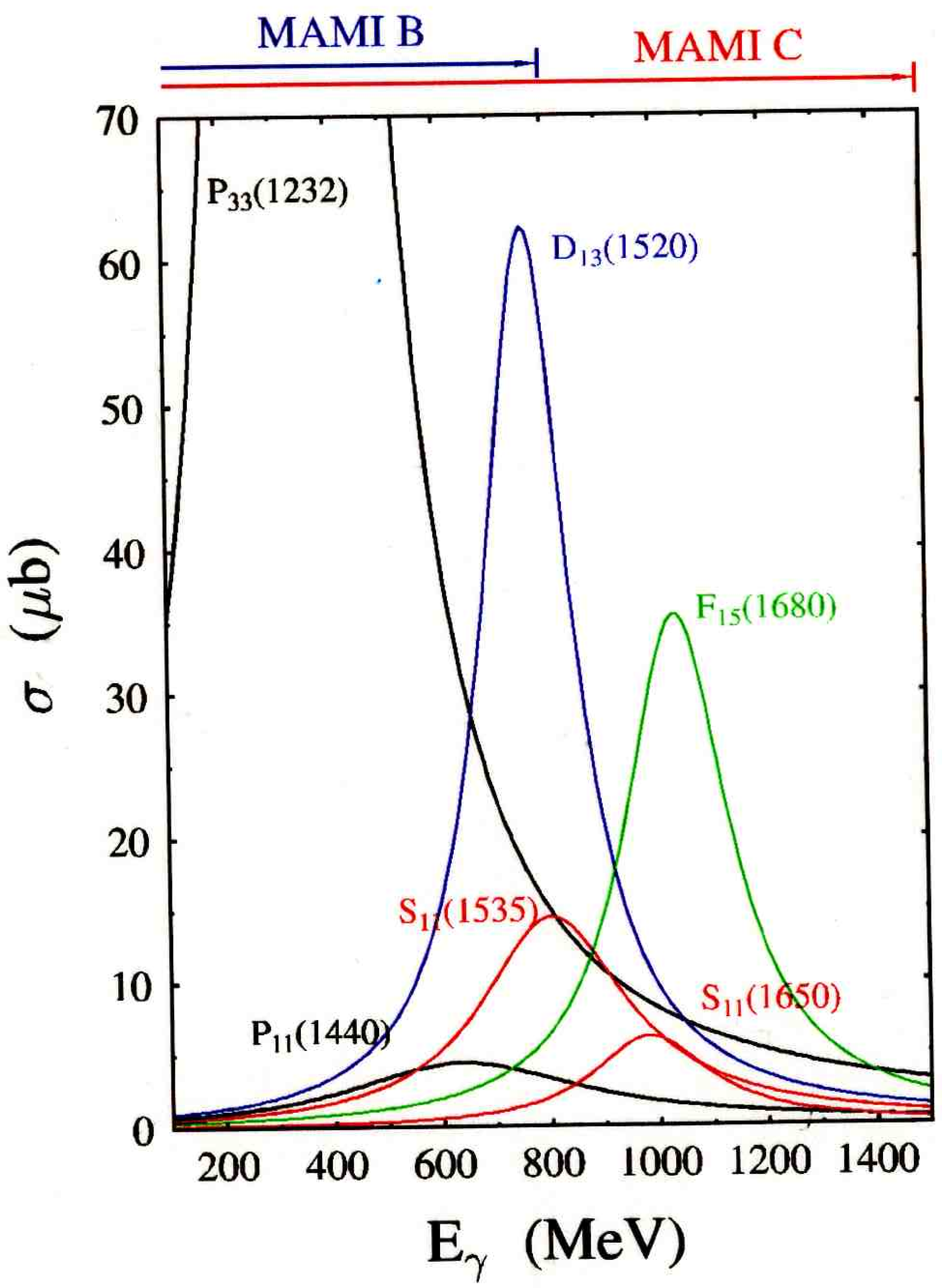
5. Few Nucleon Systems

- structure of few nucleon systems:
  wave functions, MEC, RC, BC, ...
- GDH sum rule in few nucleon systems
- $E2/M1$ ratio for bound nucleons
- mesons in the nuclear medium

Nucleon Resonances

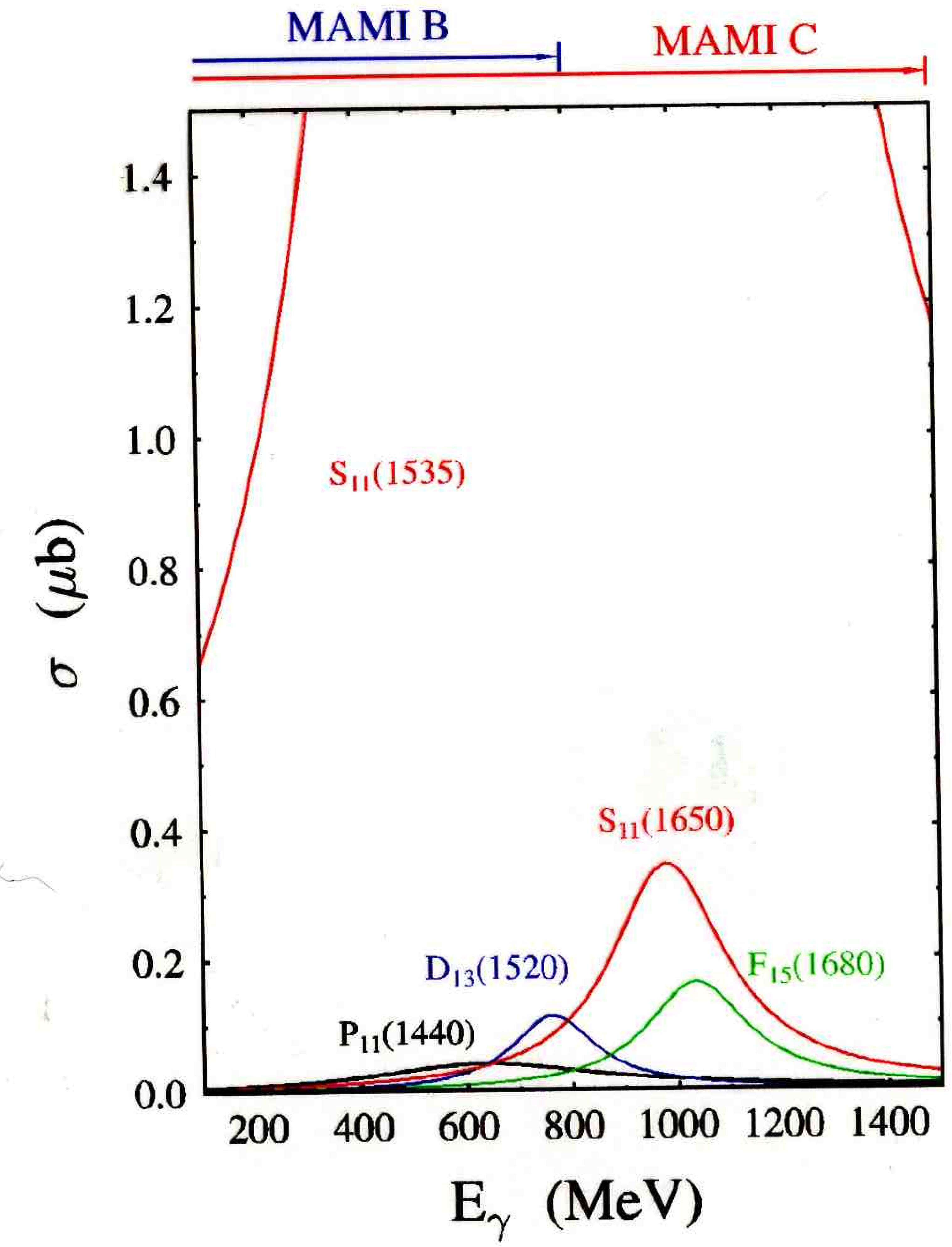
pion production

$\gamma + N \rightarrow N^* \rightarrow N + \pi$



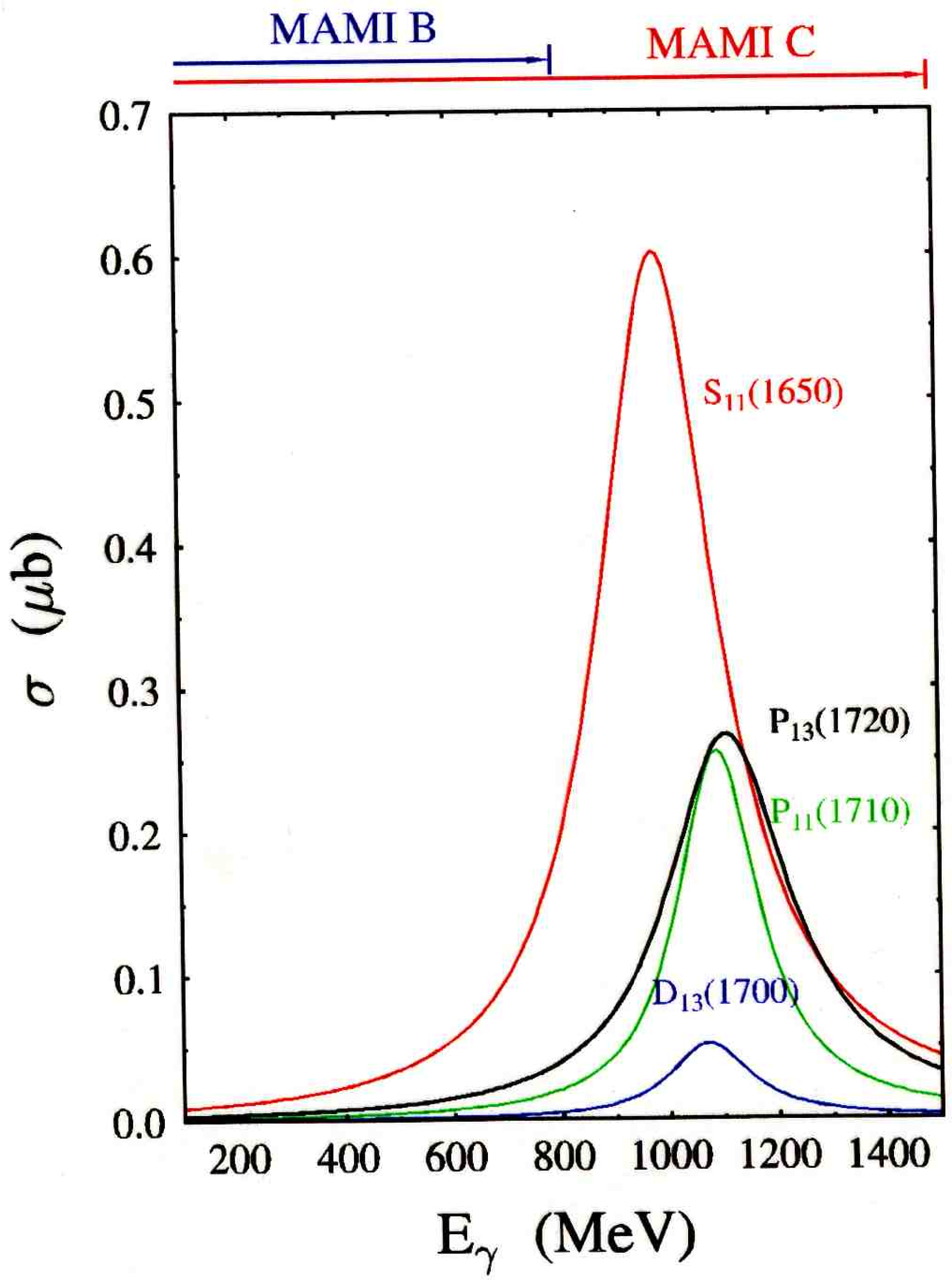
eta production

$\gamma + N \rightarrow N^* \rightarrow N + \eta$



kaon production

$\gamma + N \rightarrow N^* \rightarrow K^+ + \Lambda$



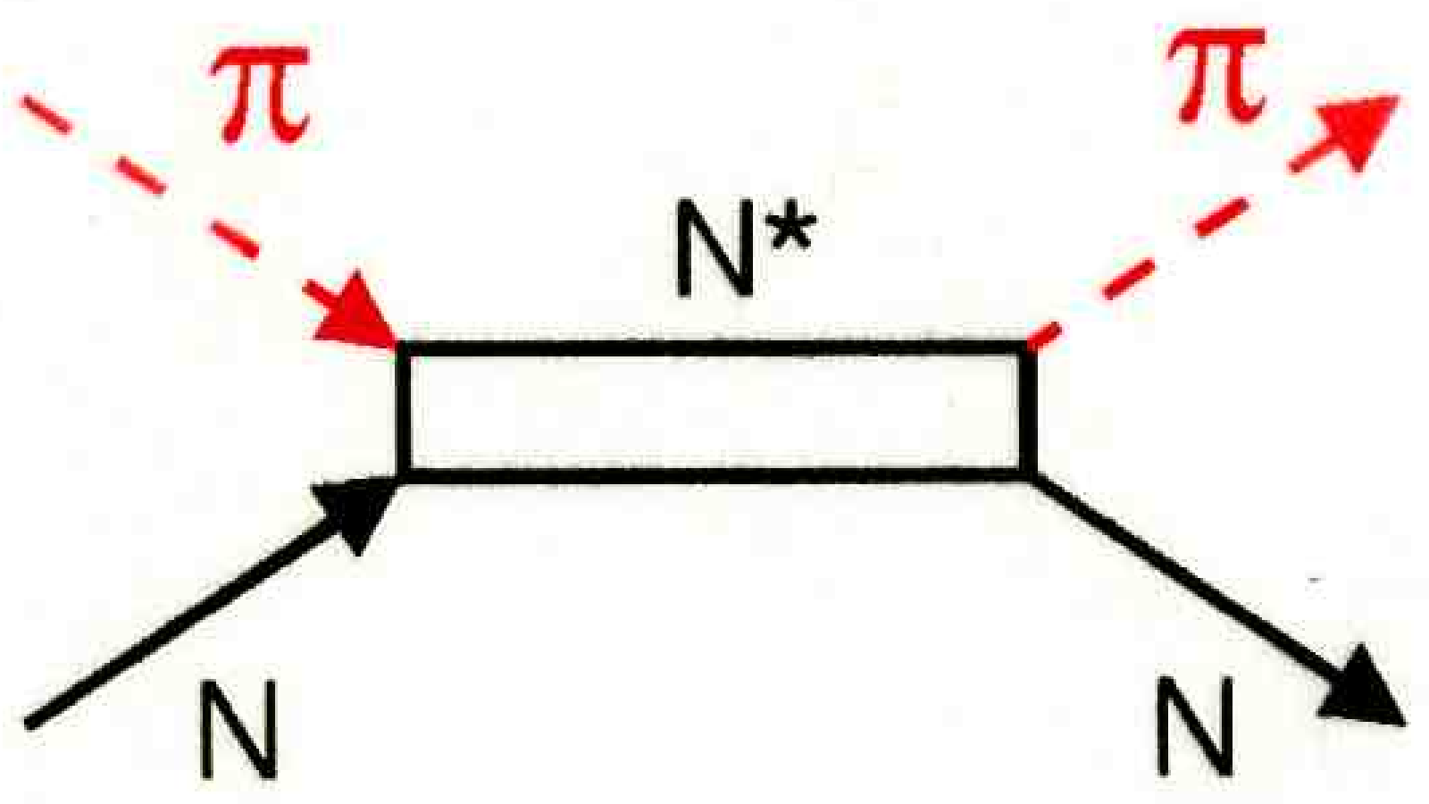
Problem : overlapping resonances

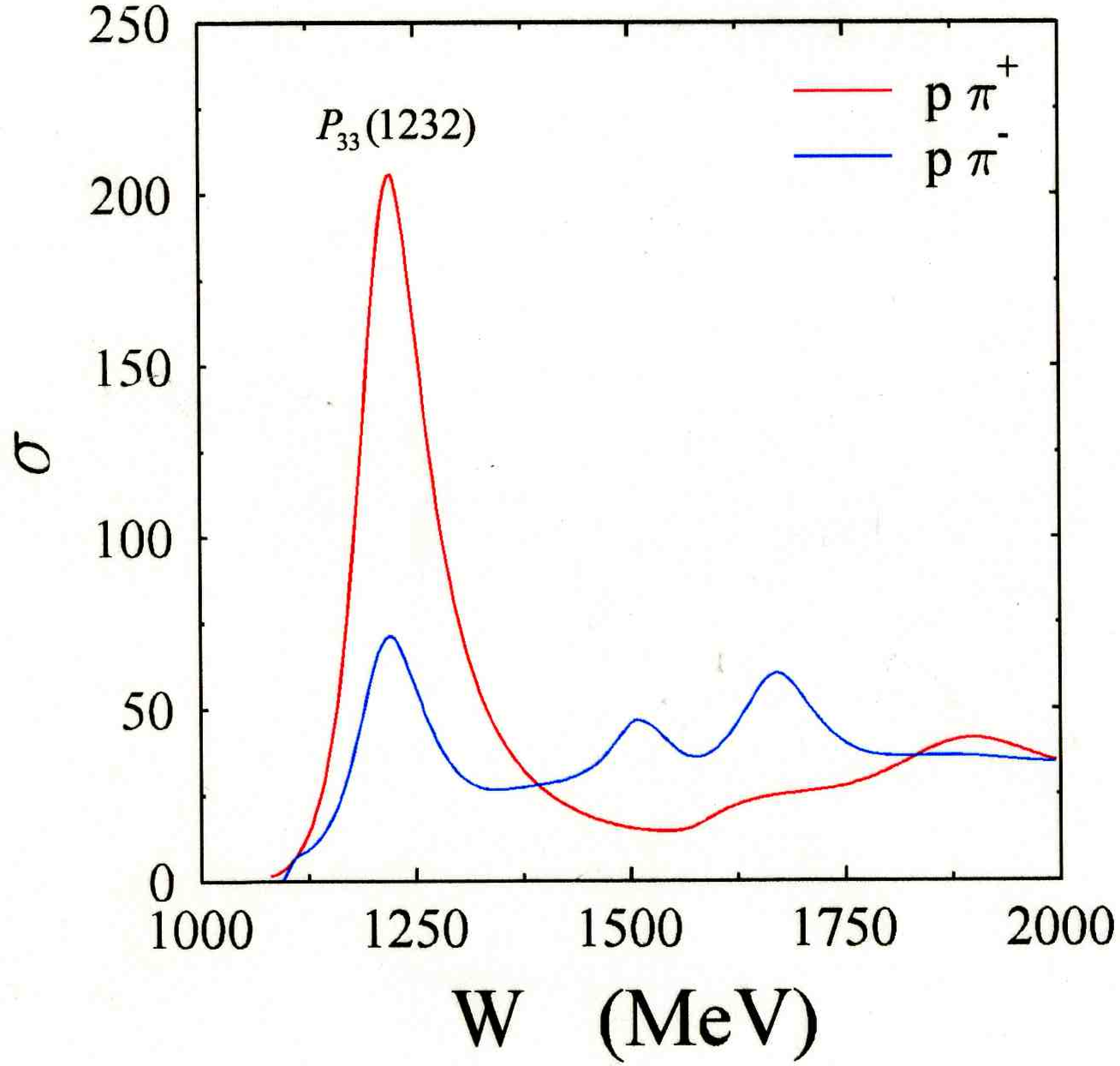
Solution : polarization observables

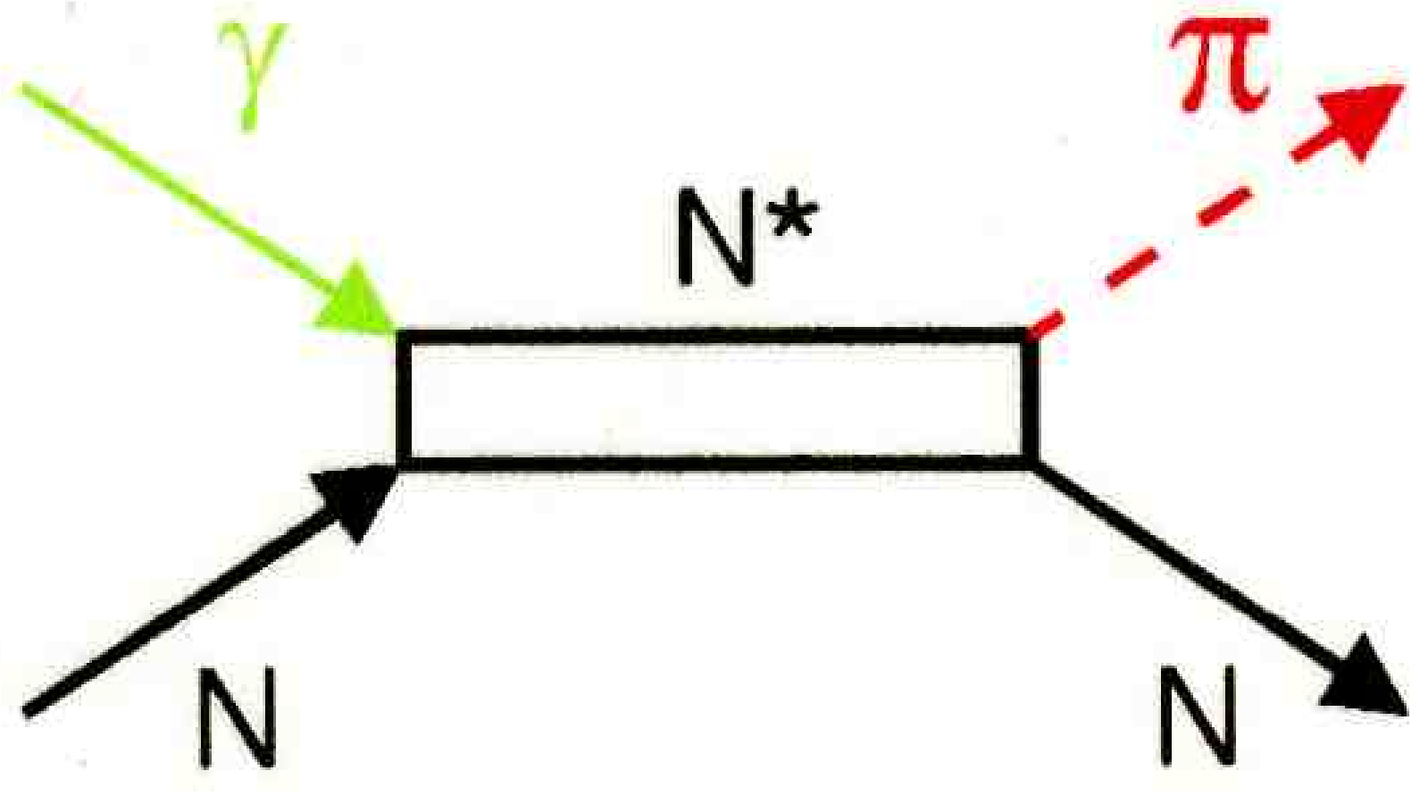
MAMI C : polarized photons, polarized targets
and recoil-proton polarimeter

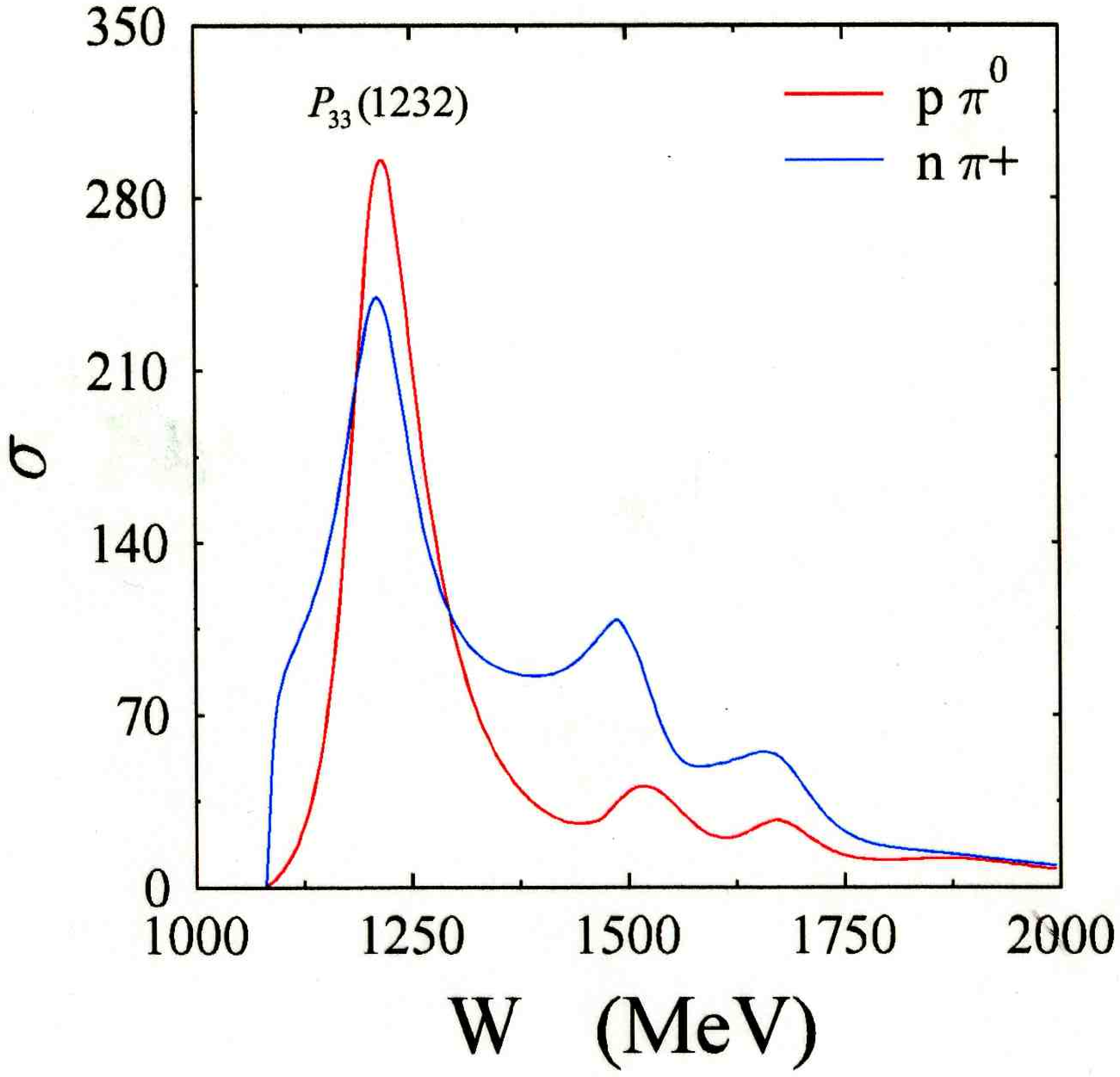
Nucleon Resonance

1951 E. Fermi : $\pi^+ + p \rightarrow p + \pi^+$ discovery of the first nucleon resonance $P_{33}(1232)$



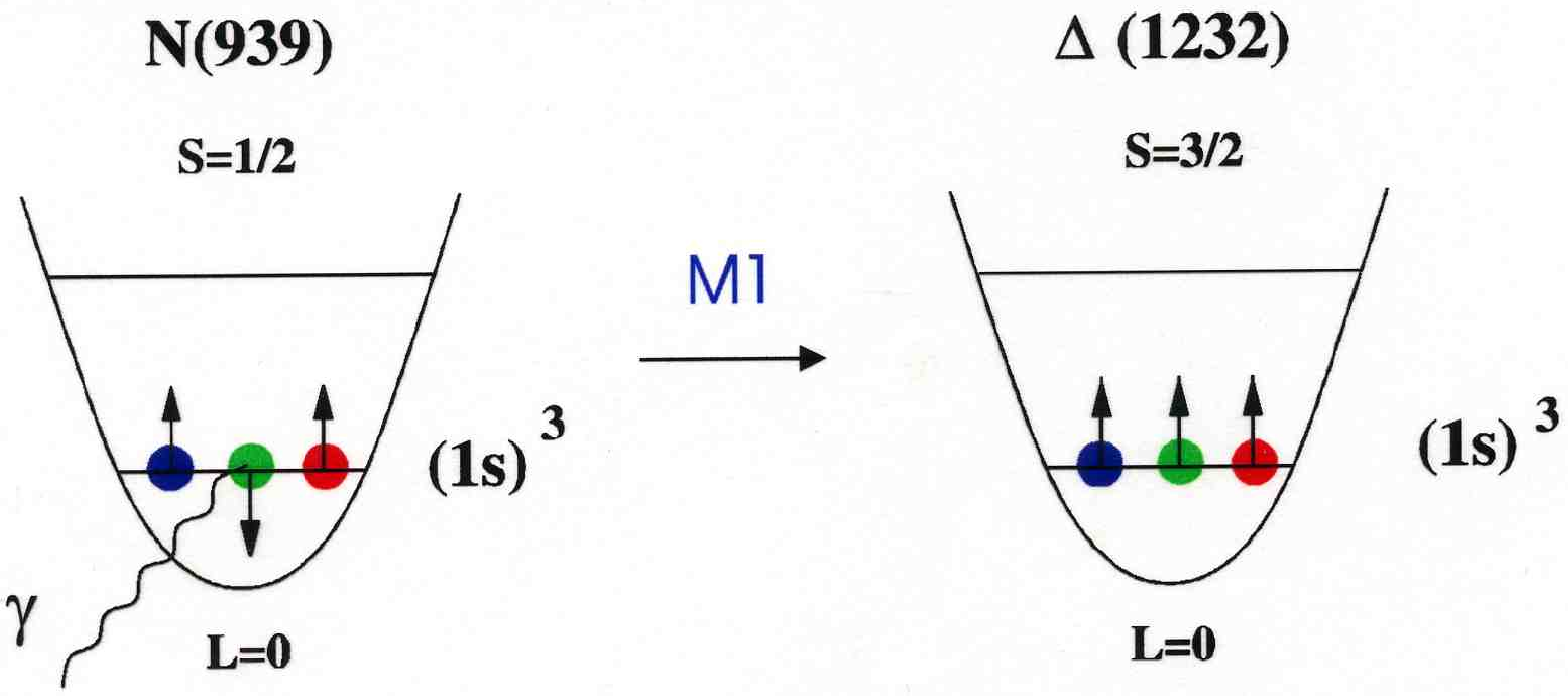






$\Delta^+(1232)$ Resonance

$\Delta^+(1232)$ resonance nucleon first excited state

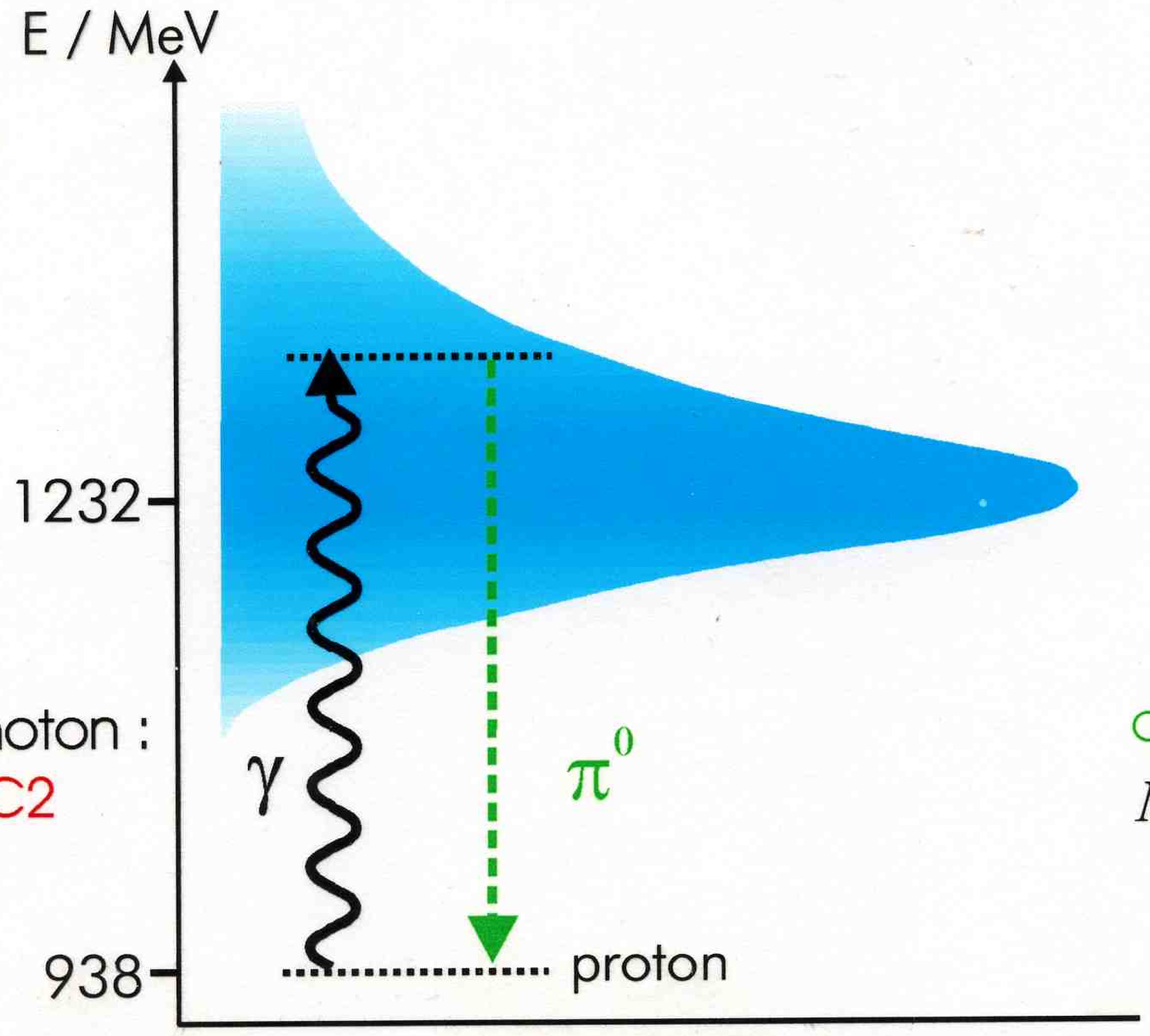


precise electro- and photoproduction data : $\gamma + p \rightarrow \Delta^+ \rightarrow \pi^0 + p$

magnetic dipole transition M1

electric quadrupole transition E2

Coulomb quadrupole transition C2

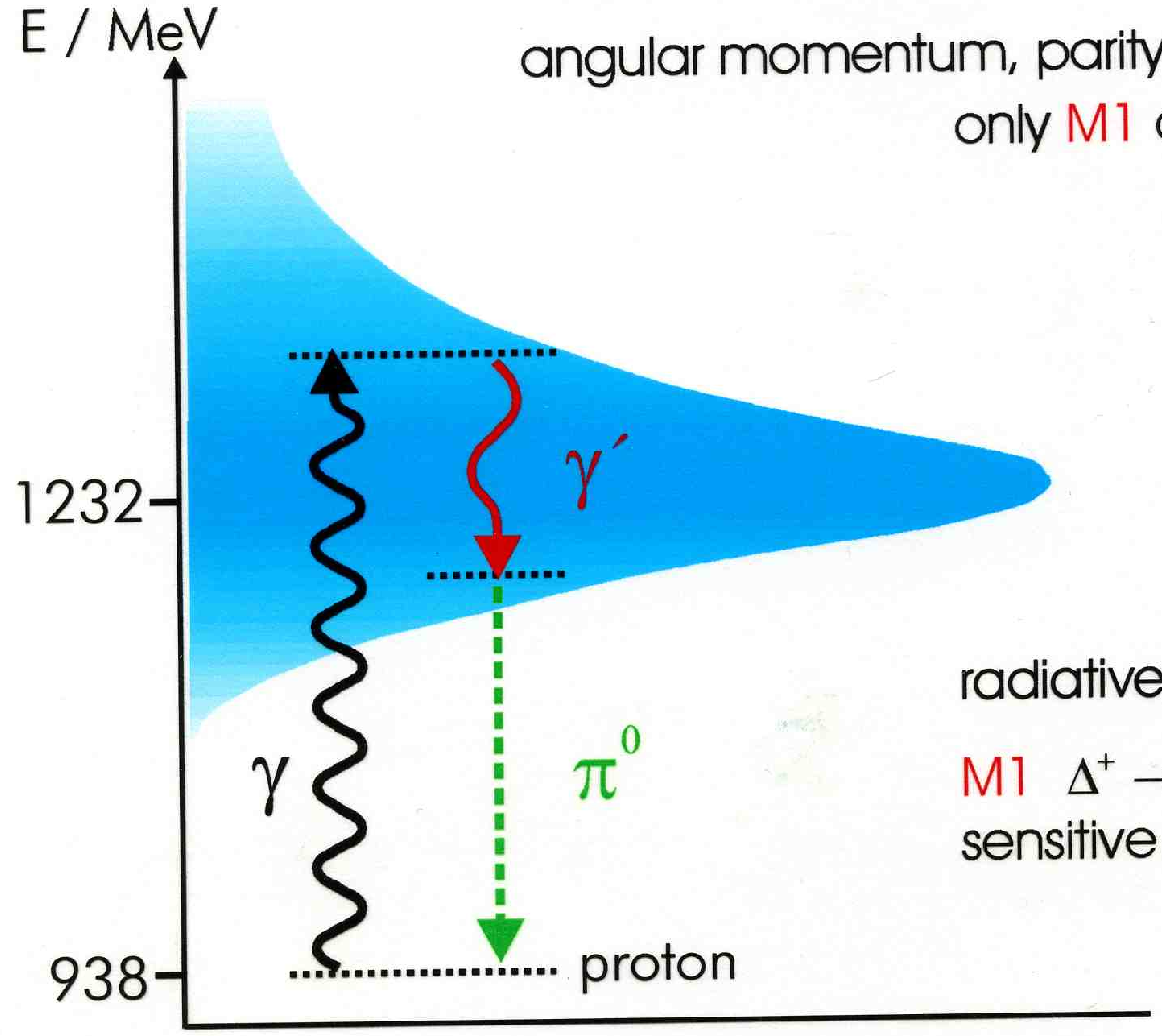


incoming photon :
M1, E2 und C2

outgoing pion :
$M_{1+}^{3/2}, E_{1+}^{3/2}, S_{1+}^{3/2}$

$\Delta^+(1232)$ Magnetic Moment

radiative pion photoproduction: $\gamma + p \rightarrow \Delta^+ + \gamma' \rightarrow \pi^0 + p + \gamma'$

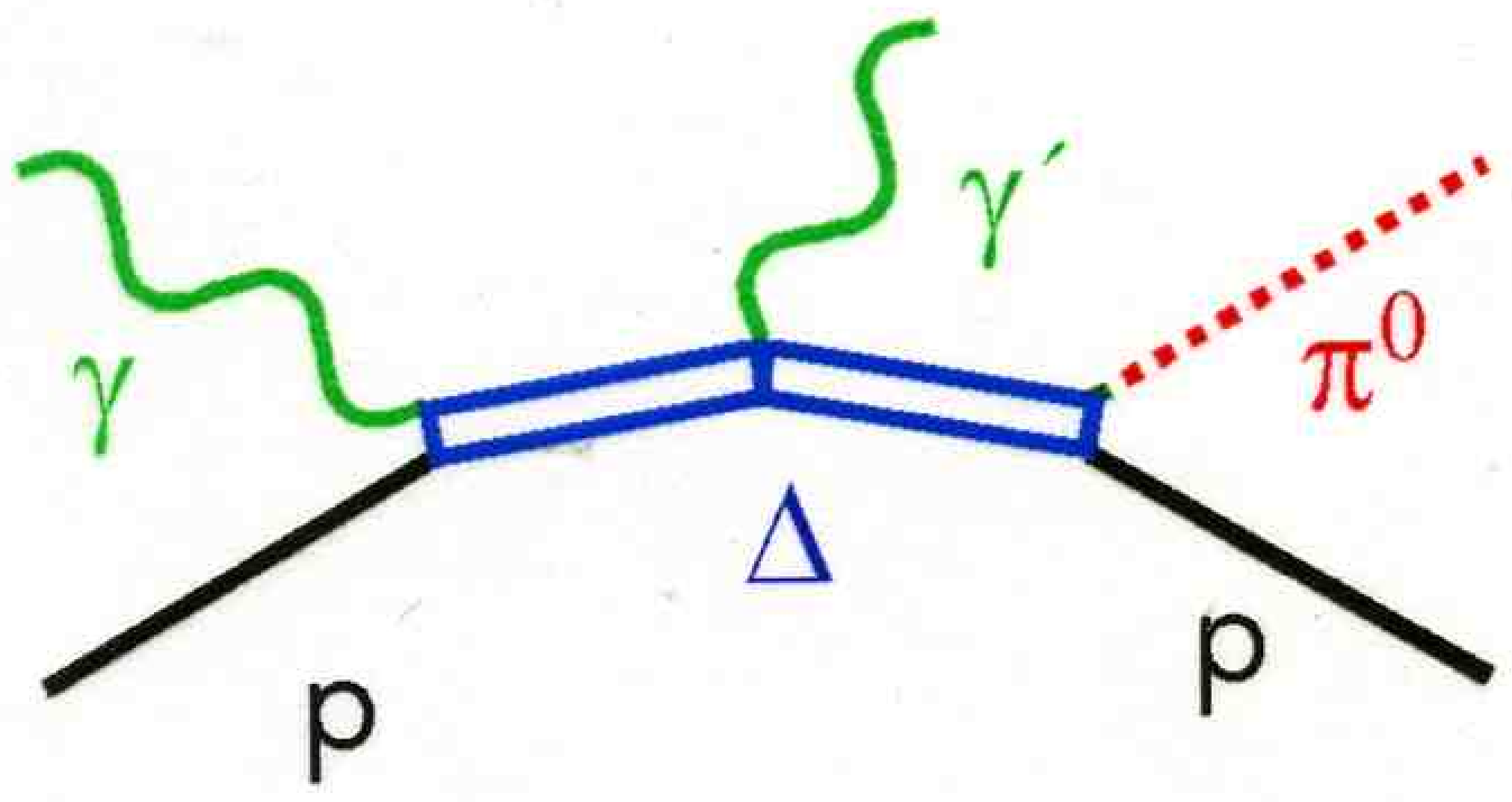


angular momentum, parity and time reversal
only M1 and M3 possible

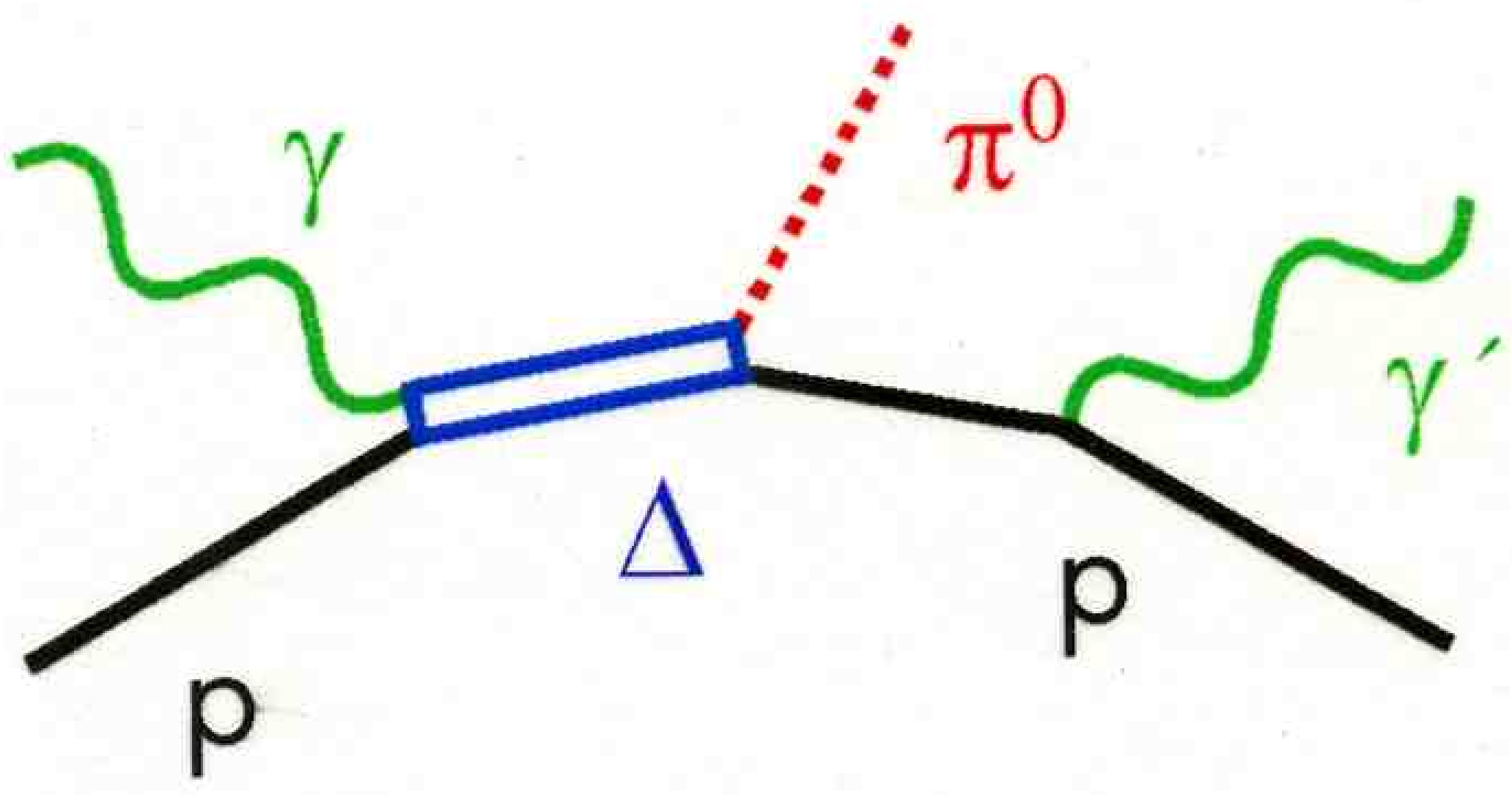
radiative photon γ'

M1 $\Delta^+ \rightarrow \Delta^+\gamma'$ transition
sensitive to $\mu(\Delta^+)$

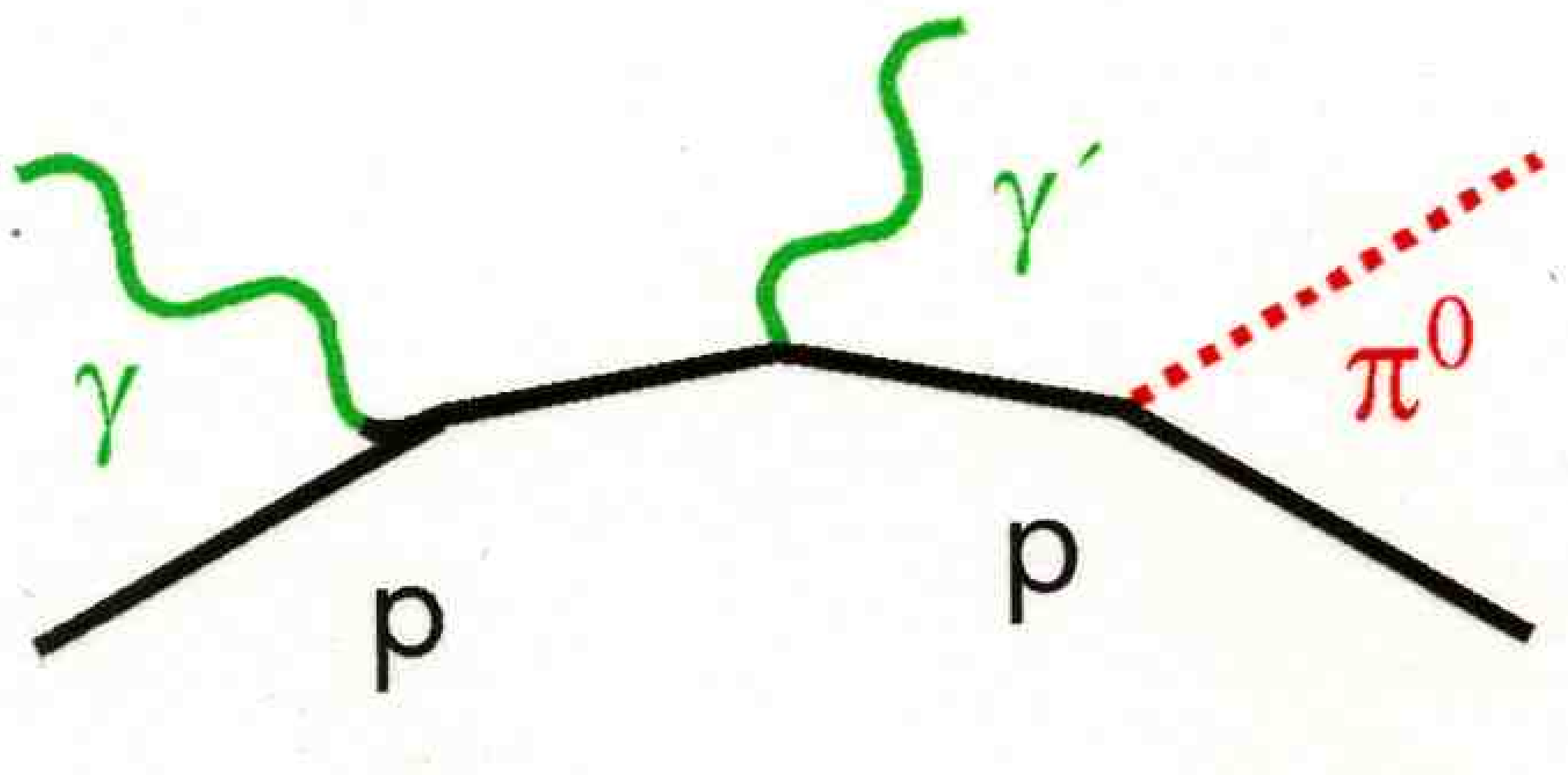
Δ excitation and identification
of the $p\pi^0\gamma'$ final state



Problem :
Proton bremsstrahlung



Nonresonant contributions
small in Δ-resonance region



16 Polarization Observables in Meson Photoproduction

Photon		Target			Recoil			Target-Recoil			
					x'	y'	z'	x'	x'	z'	z'
		x	y	z				x	z	x	z
unpolarized	σ	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linearly polarized	$-\Sigma$	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circularly polarized	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

good experimental results only for :

$\sigma\ ,\Sigma , T\ , E$

Observable G
sensitive to $P_{11}(1440)$

$\vec{\gamma}\ \vec{p} \rightarrow p\pi^0$

Kaon threshold production

$\vec{\gamma}\ p \rightarrow K^0 \vec{\Sigma}^+$ $\quad \vec{\Sigma}^+ \rightarrow p\pi^0$ self analyzing

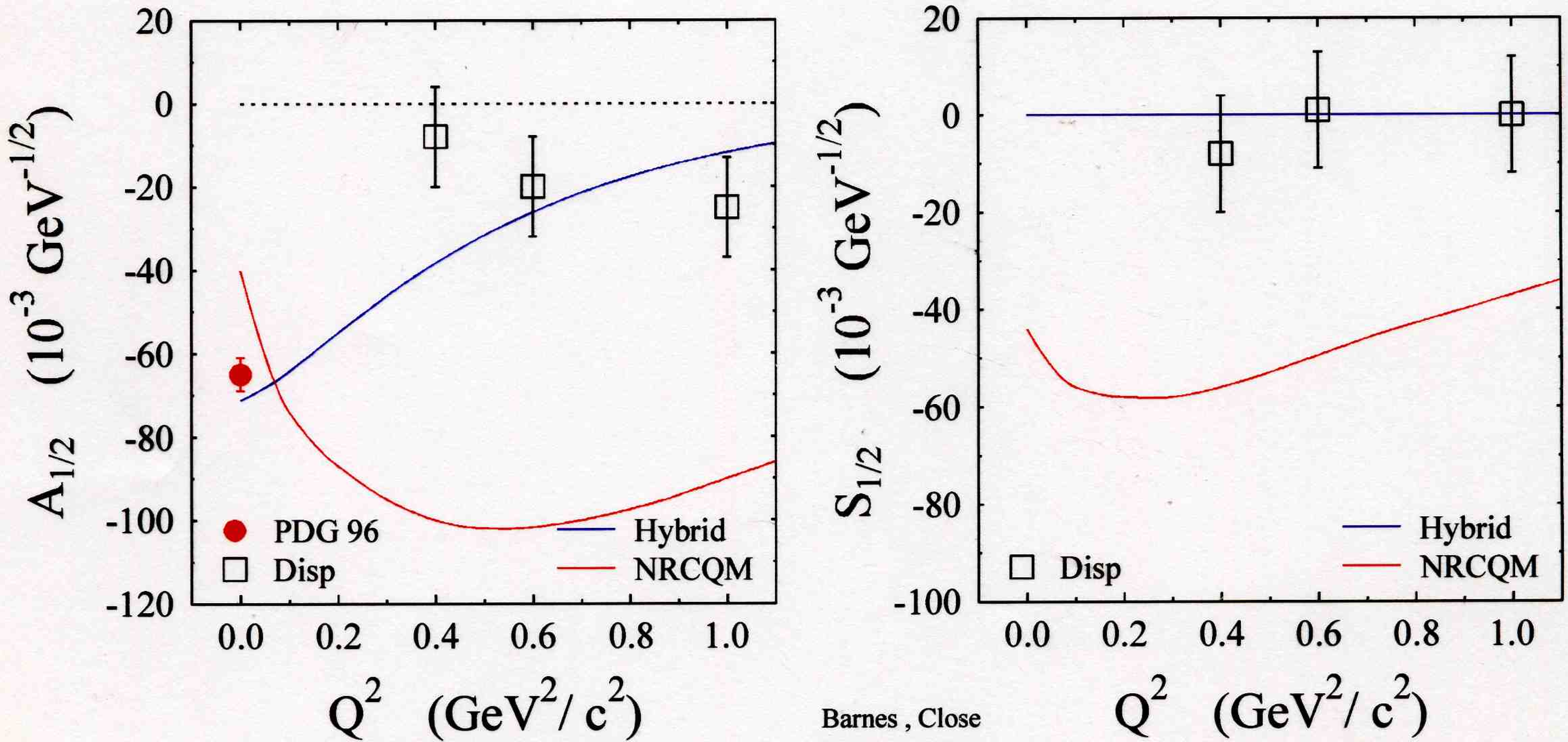
Observable E
sensitive to GDH sum rule

Roper Resonance

quark picture : $P_{11}(1440)$ radial excitation

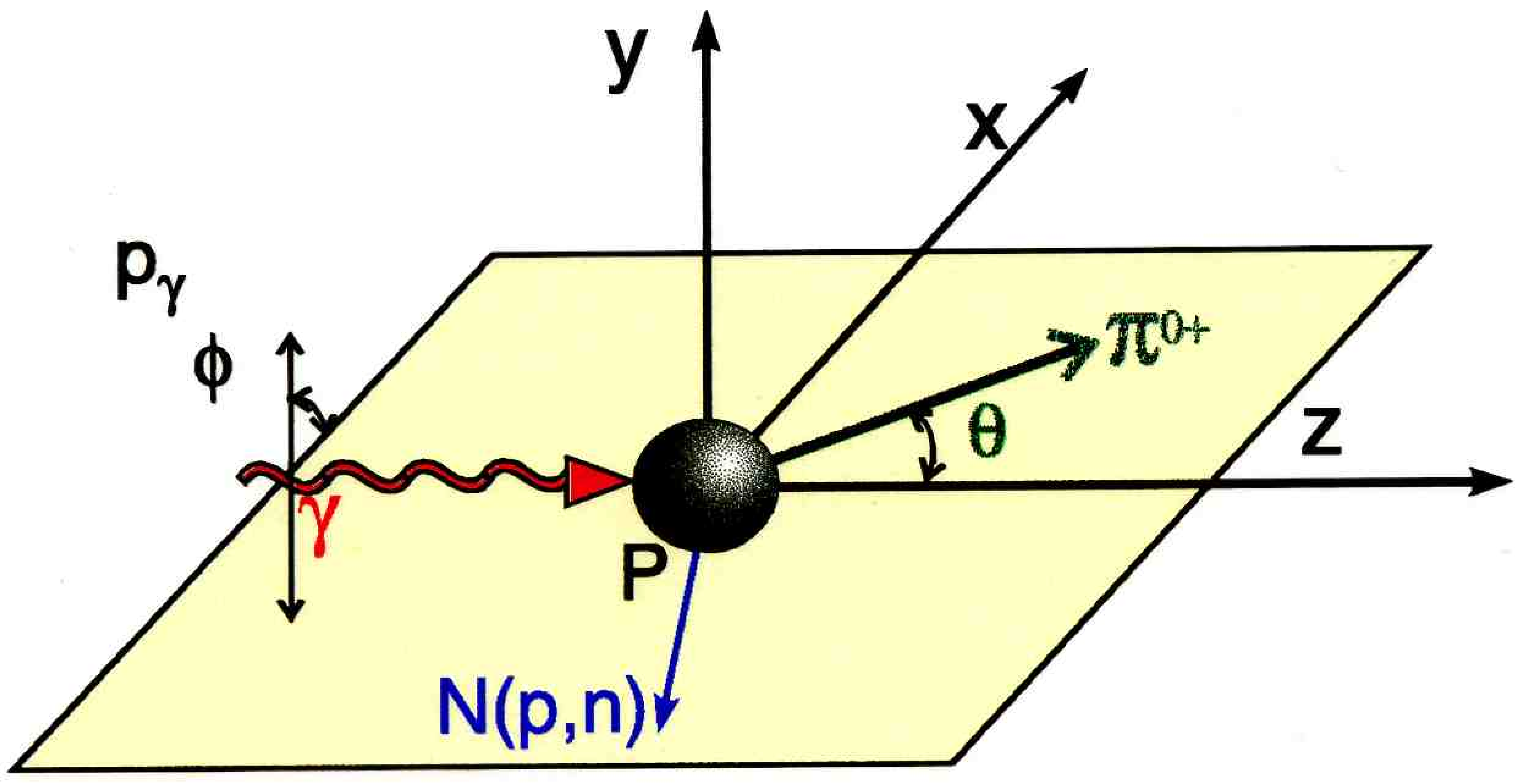
problems :
- $M \approx 1440\, MeV \quad \Gamma \approx 350\, MeV$
- helicity amplitudes $A_{1/2}$ and $S_{1/2}$ absolute value and sign
- Q^2 dependence of $A_{1/2}$ and $S_{1/2}$

proposed solutions :
- not a |3q> excitation
- hybrid|3q g>
- $N\sigma$ molecule
- two resonances



Barnes , Close
Li , Burkert

The Double Polarization Observable G



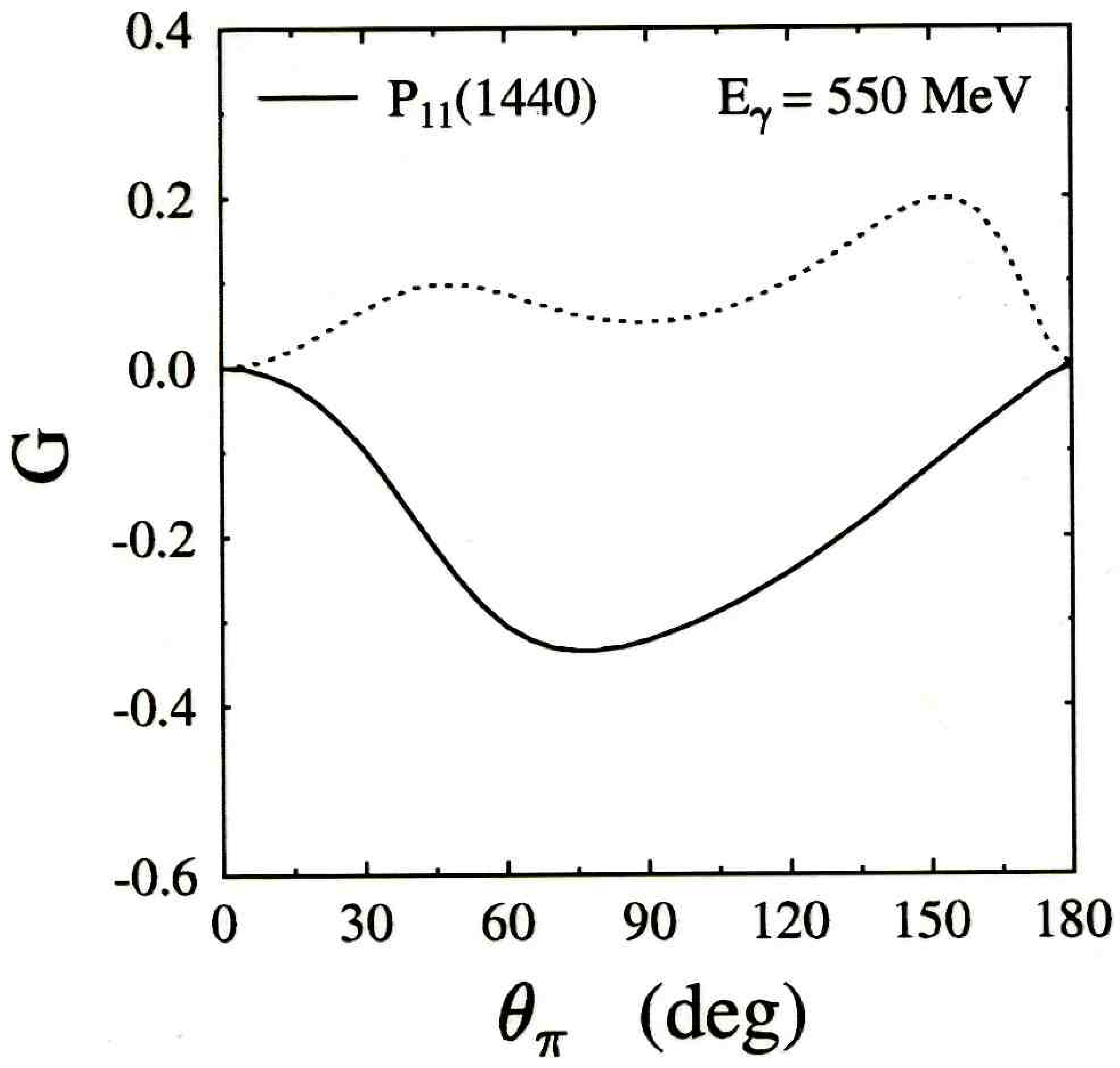
$$\vec{\gamma} + \vec{p} \rightarrow N + \pi = \begin{cases} n+\pi^+ \\ p+\pi^0 \end{cases}$$

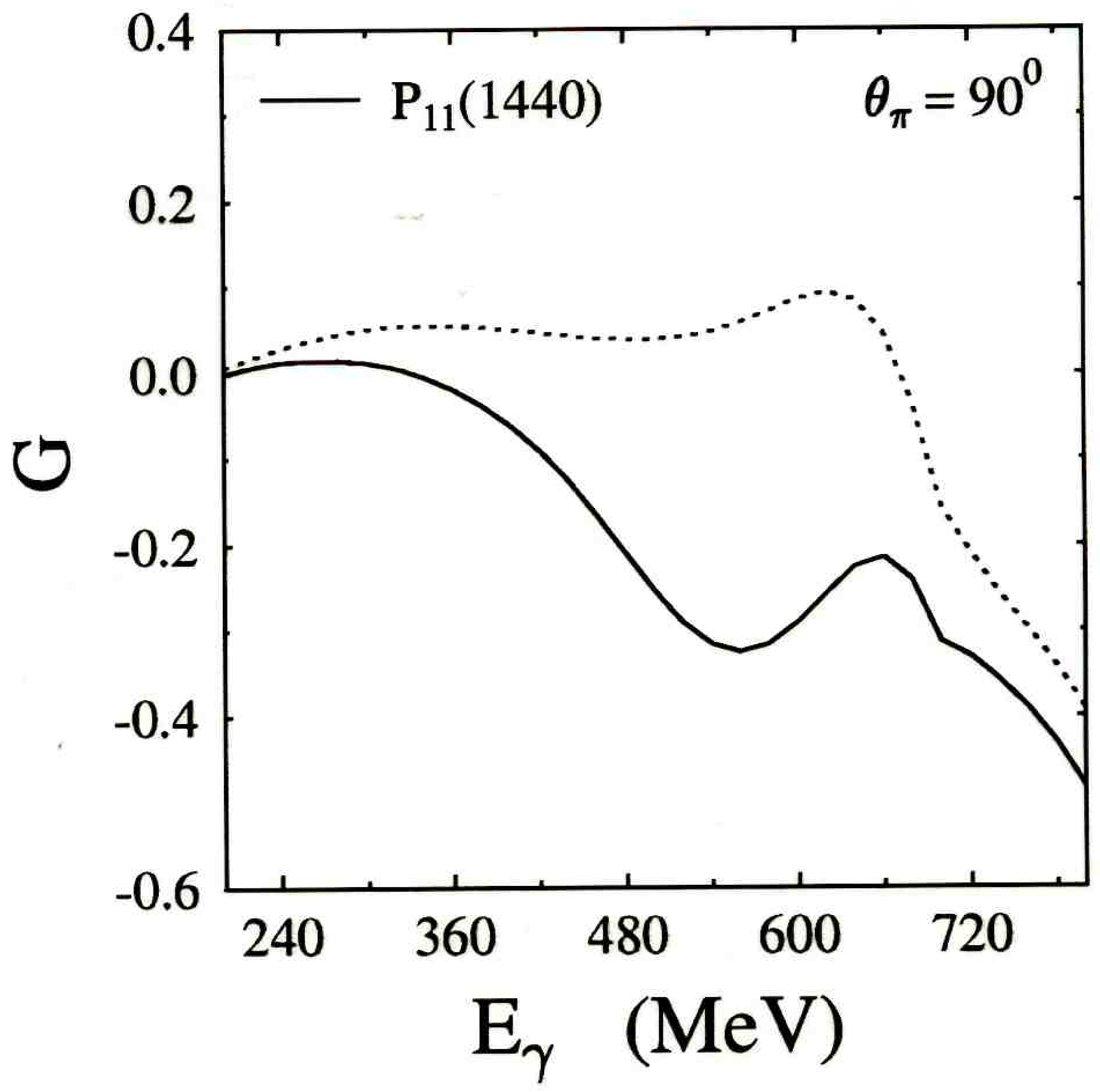
$\vec{\gamma}$: linearly polarized photons

$\vec{p}$: longitudinally polarized protons

$$\frac{d\sigma}{d\Omega}(\phi,\theta) = \frac{d\sigma}{d\Omega}(\theta)\left\{1 - p_\gamma \Sigma \cos(2\phi) + p_\gamma p_z G \sin(2\phi)\right\}$$

$$\boxed{G \sim \mathrm{Im}M_{1-}\,\mathrm{Re}M_{1+}}$$

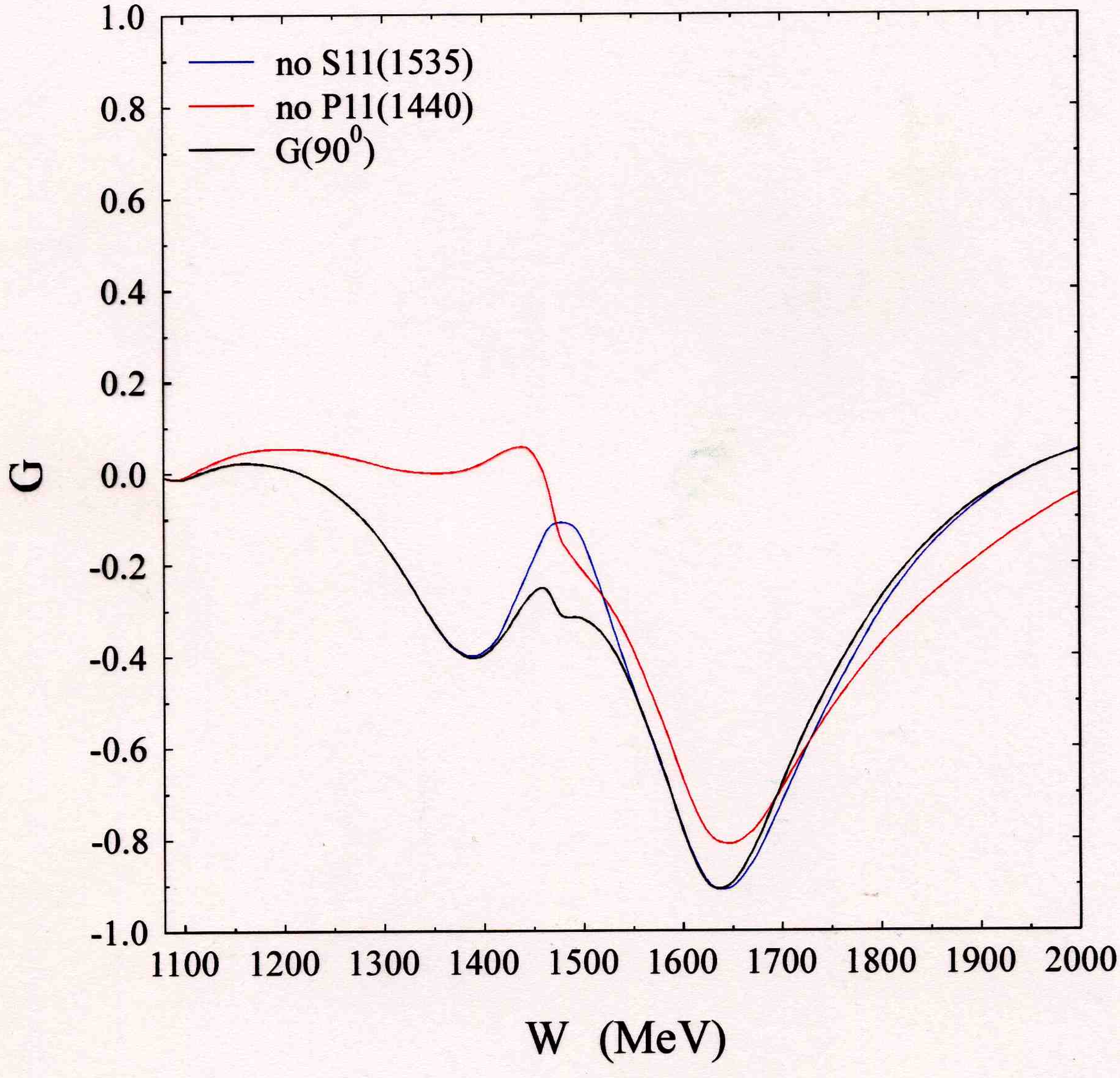




Roper Resonance

$\vec{\gamma}\,\vec{p} \rightarrow p\,\pi^0$

Asymmetry G



Crystal Ball @ MAMI C

Conclusions I

- Mainz Microtron MAMI
  produces significant information about hadrons
  - form factors of the nucleon
    2% effect at the π wavelength or larger in
    $G_{E,p}, G_{E,n}, G_{M,p}, G_{M,n}$
  - pion polarizability $(\alpha - \beta)_{\pi^+}$
    2 standard deviations from ChPTh ($\chi P\Theta$) calculations
    nature of π cloud?
  - pion photoproduction $p(\gamma, \pi^0)p$, $p(\vec{\gamma}, \pi^0)p$
    good agreement with ChPTh at $Q^2 = 0$
  - pion electroproduction $p(e, e'p)\pi^0$, $p(\vec{e}, e'p)\pi^0$
    less good agreement with ChPTh at $Q^2 > 0$
  - helicity dependent photo production $p(\overset{\curvearrowright}{\gamma}, \{\pi^+, \pi^0, 2\pi\})$
    reasonable agreement with effective models for π^+, π^0
  - weak form factors $p(\vec{e}, e)p$
    first results about strangeness content of nucleon published
    experiments in broader kinematical range in progress

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Conclusions II

- Significant hadron observables and methods promising connections to non perturbative QCD have emerged:
  - $\ast$ observable:
    - form factors and polarizabilities of baryons and mesons
    - selected resonance amplitudes below $W < 1.9\ GeV$
    - threshold reactions $(\gamma^*, \{n * \pi, K, \eta, \omega, \rho, \ldots\})$
  - $\ast$ experiment:
    - polarization of dense targets and high intensity beams
    - detectors with large acceptance or excellent resolution
  - $\ast$ theory:
    - chiral perturbation theory, QCD inspired models, lattice gauge theory
- MAMI B (885 MeV) 1992 - 2004
  MAMI C (1500 MeV) 2005 - 201X