Open questions in hadron physics
Spectroscopy with the Crystal–Barrel Detector

Volker Credé

- Introduction
- The Crystal–Barrel Detector at LEAR (CERN)
  - Meson spectroscopy in $\bar{\mathrm{p}}\mathrm{p}$ reactions at rest and the search for exotic states
- The Crystal–Barrel Experiment at ELSA: initial configuration (2000/2001)
  - Baryon spectroscopy (photoproduction of neutral mesons: $E_\gamma < 3$ GeV)
  - $\gamma\,\mathrm{p} \;\rightarrow\; \mathrm{p}\,\pi^0$ $(\mathrm{p}\,\eta)$ $\Rightarrow$ differential and total cross sections
  - $\gamma\,\mathrm{p} \;\rightarrow\; \mathrm{p}\,\pi^0\,\pi^0$ $(\mathrm{p}\,\pi^0\,\eta)$ $\Rightarrow$ total cross sections and PWA
- Summary and outlook: polarization measurements with CB/TAPS (2003)

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Access to QCD and fundamental questions

Breaking of chiral symmetry can be treated perturbatively

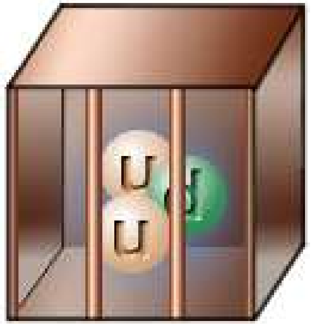
Application of perturbation theory allows access to QCD

very small energies

resonance region at intermediate energies

very large energies

Do we understand bound systems within the framework of QCD ?



⇒ Development of QCD-inspired models can help to find answers to ...

... the fundamental questions

- What are the relevant degrees of freedom and the corresponding effective interactions responsible for hadronic phenomena?
- What are the mechanisms for confinement and for chiral symmetry breaking?

Renaissance of Hadron Spectroscopy

Recently discovered new states ➜ Beginning of new spectroscopy ?

Mesons

- $D^{*+}_{sJ}(2317) \to D^+_s\,\pi^0$ at BaBar

  (B. Aubert et al., Phys. Rev. Lett. **90** (2003) 242001)

- $D^{+}_{sJ}(2457) \to D^{*+}_s\,\pi^0$ at CLEO

  (D. Besson et al., Phys. Rev. **D68** (2003) 032002)

⇒ Observation of missing 0^+ and 1^+ states in the D^+_s ($c\bar{s}$) system ?

⇒ ... or even DK molecules or tetraquarks ?

- $B^\pm \to K^\pm\,\pi^+\,\pi^-\,J/\psi$ at BELLE

  (S.K. Choi et al., hep–ex/0303032)

Baryons

- Observation of Θ^+ with $S = 1$

  (LEPS, CLAS, DIANA, SAPHIR, etc.)

- Observation of Ξ^{--} with $Q = -2$

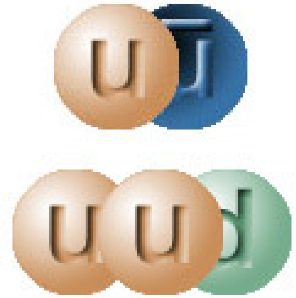
  (C. Alt et al. [NA49 Coll.], hep–ex/0310014)

⇒ Observation of pentaquark states as members of an antidecuplet ?

Observation of an enhancement at $p\bar{p}$ threshold in $J/\psi \to \gamma\,\eta_c \to \gamma\,p\bar{p}$

(BES Coll. at HADRON'03 conference)

The quark model of hadrons



- Mesons $(q\overline{q})$ $\quad q \otimes \overline{q} = 3 \otimes \overline{3} = 8 \oplus 1$
- Baryons (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter, however, QCD also predicts so–called exotic states

$\Rightarrow$ simplest possibility: $\underbrace{q \otimes \overline{q} \otimes q = 15 \oplus 6 \oplus 3 \oplus 3}$

$\Downarrow$

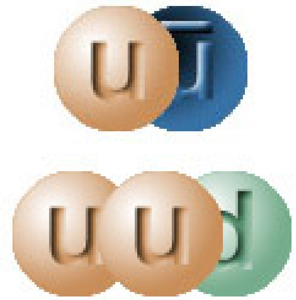
Does not work: color singlets needed !

$\Rightarrow$ multiple of (qqq) and $(q\overline{q})$ necessary

- Glueballs: $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$
- Hybrids: $q \otimes \overline{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus 1$ $\quad \Rightarrow \quad \boxed{(q\overline{q})^l((q)^3)^m(g)^n}$,

$l + m \geq 1 \quad$ for $\quad n = 1$

The quark model of hadrons



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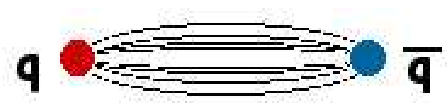

Exciting the flux tube

Hybrids

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$l + m \geq 1 \quad$ for $\quad n = 1$

The search for new forms of matter

All exotic states of hadrons can be subdivided into three groups:

1. States with explicitly exotic values of principal quantum numbers

Θ^+	with $S = 1$
Ξ^{--}	with $Q = -2$

The search for new forms of matter

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2. States with exotic combinations of J^{PC}
   $\Rightarrow$ forbidden for ordinary $\mathrm{q\bar{q}}$ states:
   0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, etc.

$$\left.\begin{array}{l} \pi_1(1400) \rightarrow \eta\pi^- \\ \pi_1(1600) \rightarrow \eta'\pi^- \end{array}\right\} J^{PC} = 1^{-+}$$

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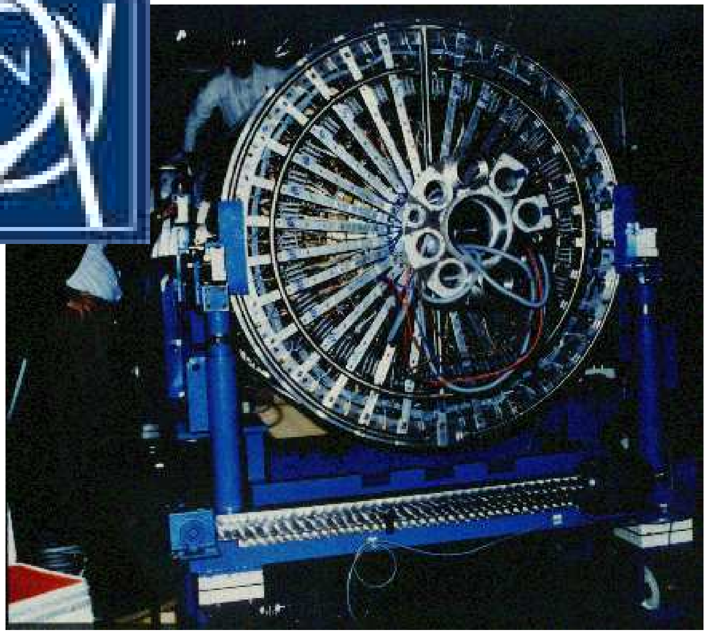
3. States with hidden exotic properties
   $\Rightarrow$ Problem: predicted glueballs can mix with ordinary $q\bar{q}$ states

$$\left.\mathrm{f}_0(1500)\right\} J^{PC} = 0^{++}$$

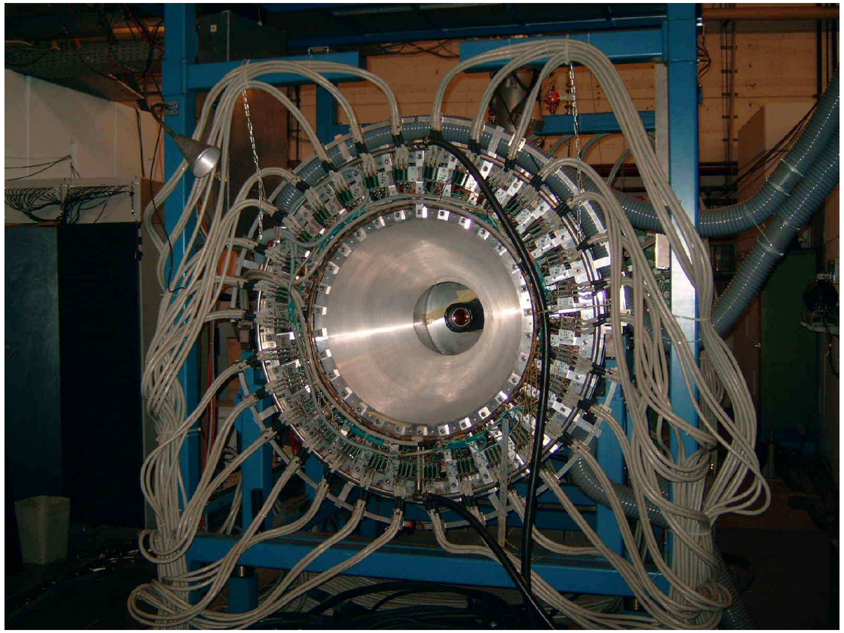
Evidence far from solid
$\Rightarrow$ Details needed for a full understanding are missing

Spectroscopy with the Crystal–Barrel Detector



2000 - present (University of Bonn)

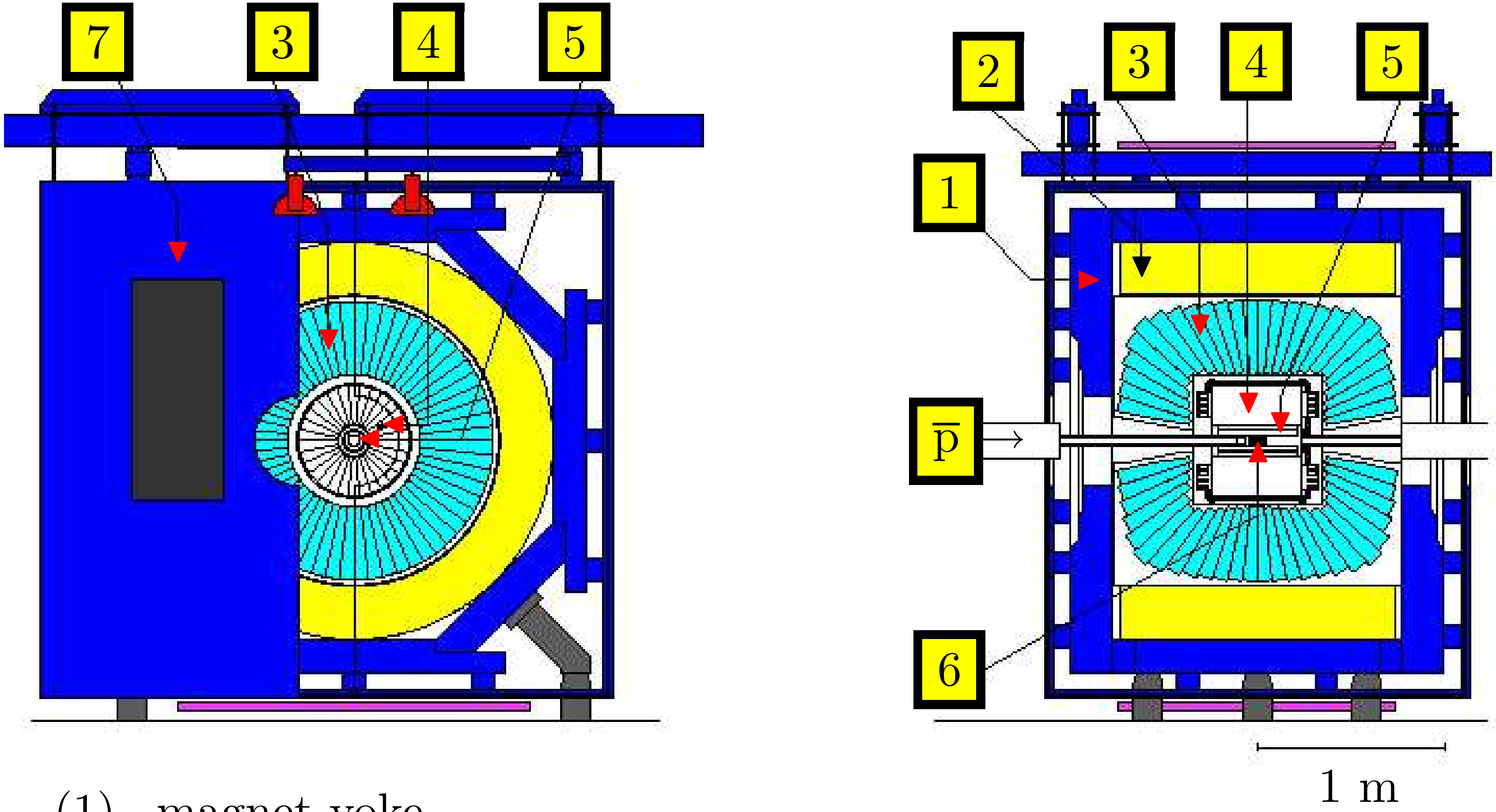
- Photoproduction experiments at ELSA
  - ⇒ Spectroscopy of light baryons (... and mesons)



1989 - 1996 (at LEAR/CERN)

- Investigation of $\bar{\mathrm{p}}\mathrm{p}$ and $\bar{\mathrm{p}}\mathrm{d}$ annihilations
  - ⇒ Annihilation dynamics in the non-perturbative regime of QCD
  - ⇒ Search for *baryonium* ($\bar{\mathrm{p}}\mathrm{p}$ bound states)
- Spectroscopy of light mesons

The Crystal–Barrel Detector at LEAR



(1) magnet yoke

(2) magnet coils

(3) CsI barrel calorimeter

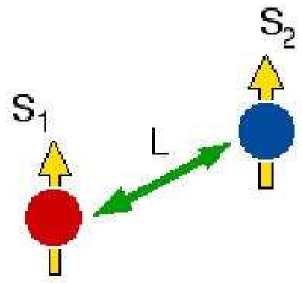
(4) jet drift chamber (JDC)

(5) proportional wire chamber

(6) target (liquid H_2, deuterium)

(7) one half of the endplate

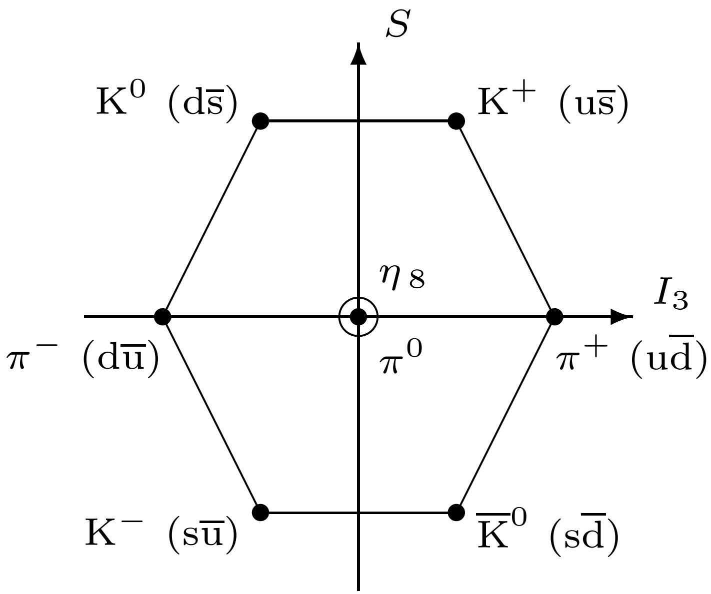
Ordinary mesons and assigned quantum numbers

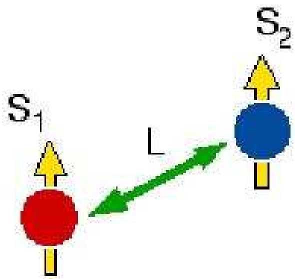


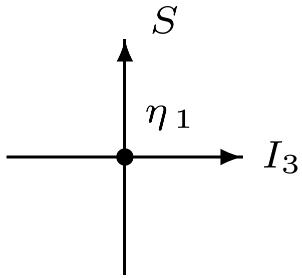
$J^{PC} \equiv {}^{2s+1}L_J$

- Parity $P = (-1)^{L+1}$
- Charge conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = (-1)^{L+1+I}$

Ordinary mesons and assigned quantum numbers







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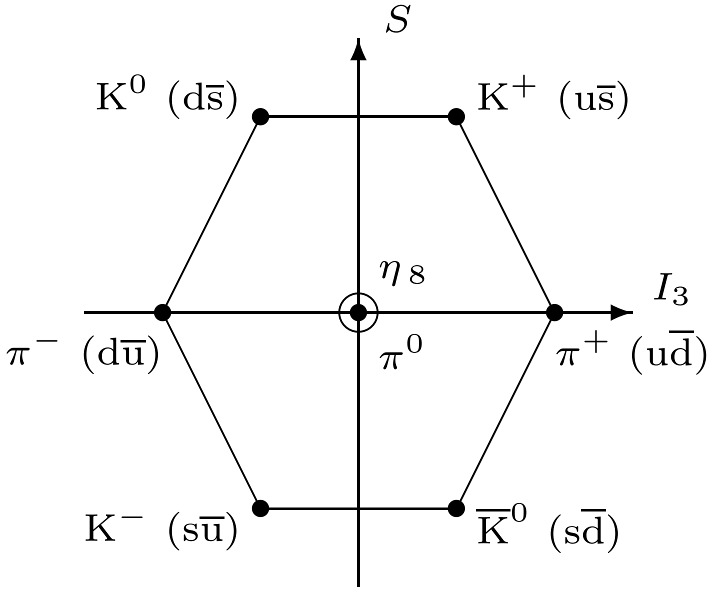
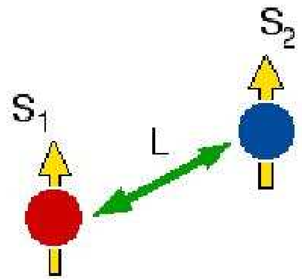
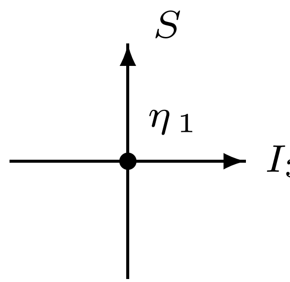
Nonet of pseudoscalar mesons
$J^{PC} = 0^{-+} \quad (L = 0,\ S = 0)$

Ordinary mesons and assigned quantum numbers







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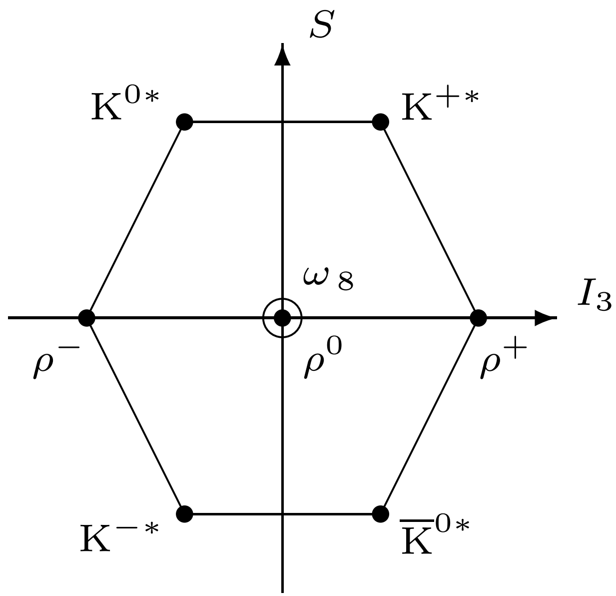
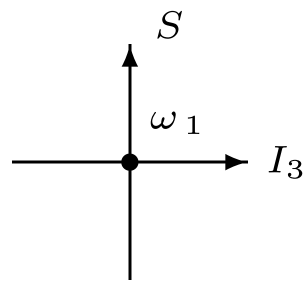
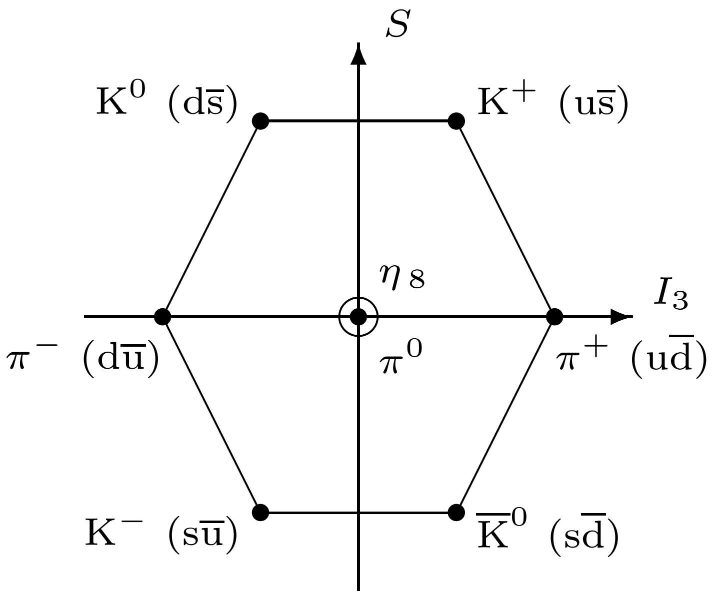
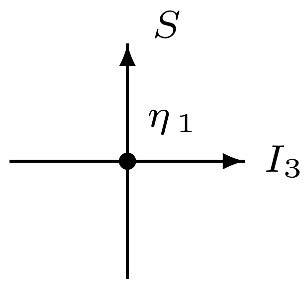
Nonet of vector mesons
$J^{PC} = 1^{--} \quad (L = 0,\ S = 1)$





Ordinary mesons and assigned quantum numbers





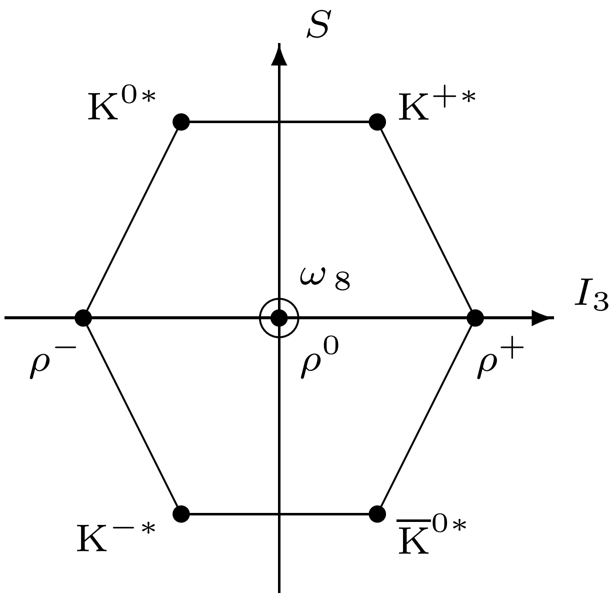
What about nonets of radial and orbital excitations ?

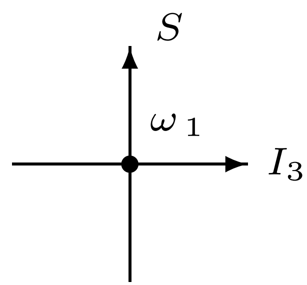
$\Rightarrow$ Meson spectroscopy

$\Rightarrow$ Hints for exotic mesons from overpopulation of nonets

Nonet of pseudoscalar mesons
$J^{PC} = 0^{-+}$ $(L = 0,\ S = 0)$

Nonet of vector mesons
$J^{PC} = 1^{--}$ $(L = 0,\ S = 1)$





The technique of Partial Wave Analysis

Measured intensity (incoherent sum over all possible $\overline{\mathrm{p}}\mathrm{N}$ initial states):

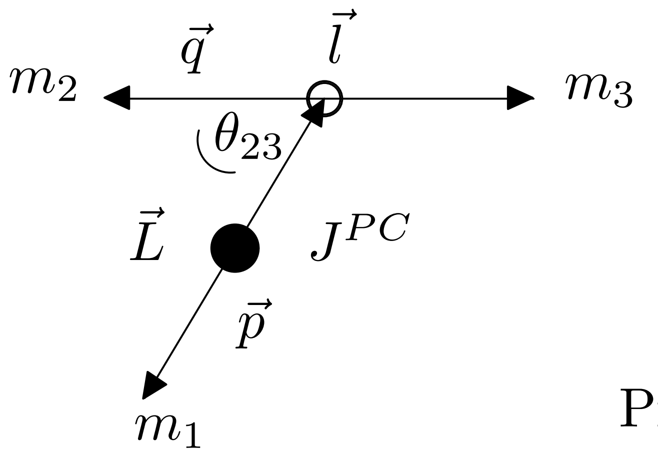
$$I = \sum_{J^{PC}(\overline{\mathrm{p}}\mathrm{N})} \underbrace{|A_{J^{PC}}|^2}$$

$B_L(p)$: centrifugal barrier of initial decay

$$A_{J^{PC}} = \sum_{a}^{\text{possible amplitude}} \left(\sum_{i}^{\text{combinations}} \mathrm{CG}_i \cdot H_{J^{PC},L,l}(\Theta) \cdot B_L(p) \cdot \hat{F}_l(q) \right)$$

Angular dependence in terms of helicity amplitudes

$$H_{\lambda_1\lambda_2,M}(\theta,\phi) = D^J_{\lambda M}(\theta,\phi) \sum_{ls} \alpha_{ls} \left\langle J\lambda | ls0\lambda \right\rangle \left\langle s\lambda | s_1 s_2 \lambda_1, -\lambda_2 \right\rangle$$

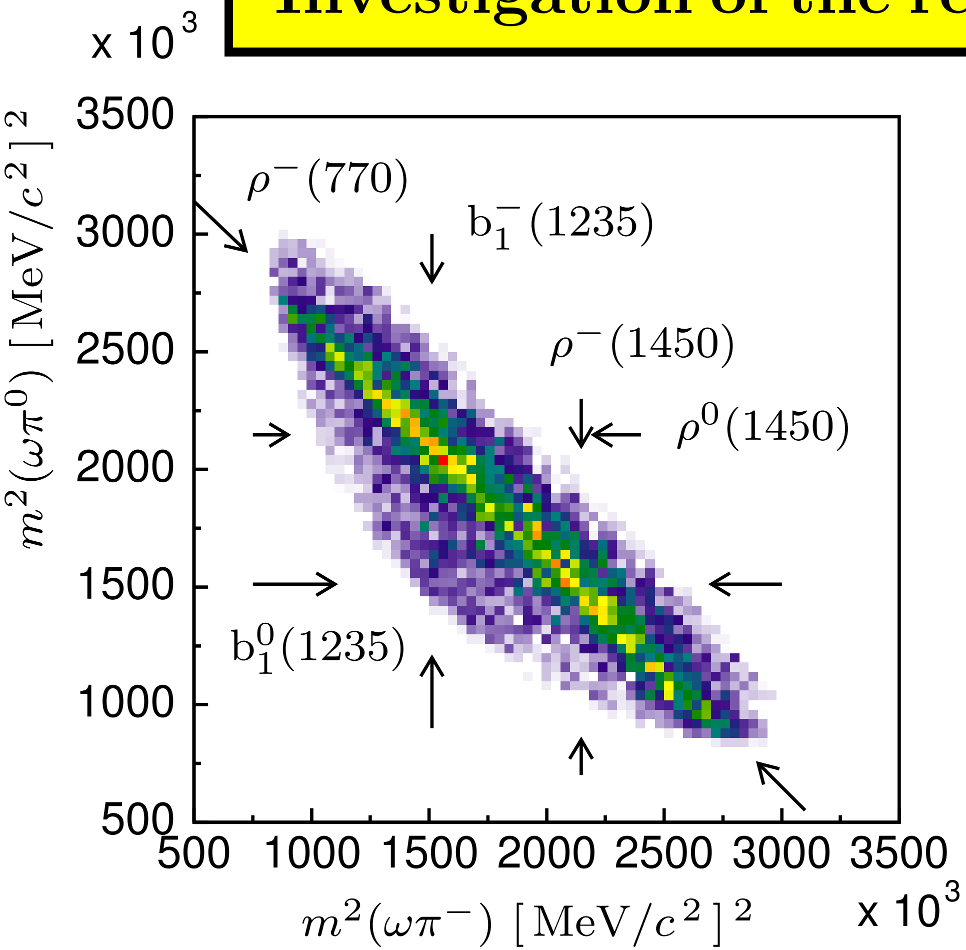


In simplest case, $\hat{F}$ given as Breit–Wigner function

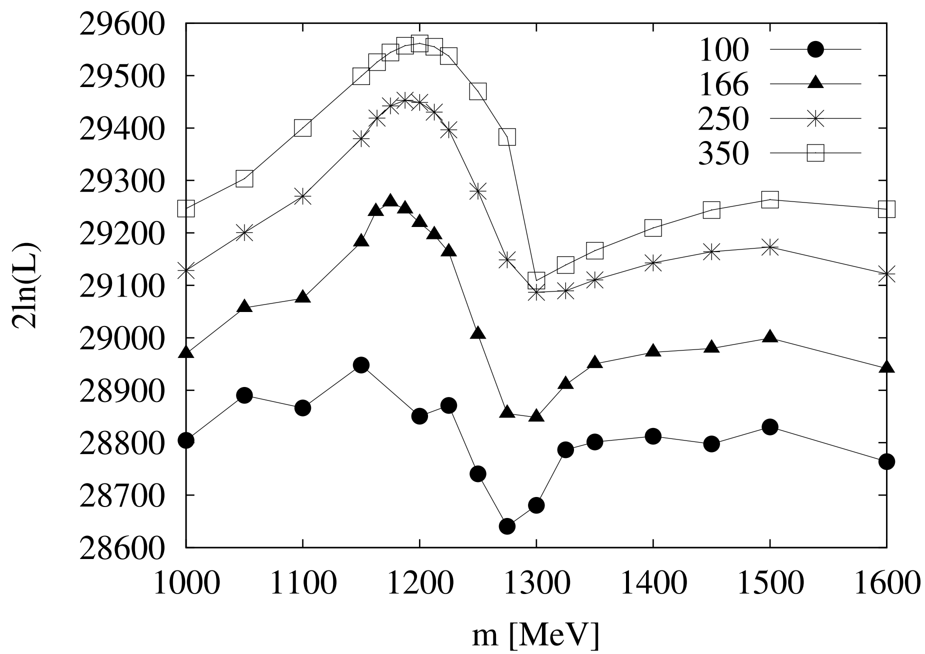
$\Rightarrow$ Parametrization of $\hat{F}$ in K–matrix formalism

$$\hat{F} = \underbrace{(I - i\hat{K}\rho)^{-1}}_{\text{Propagation and decay}} \quad \underbrace{\hat{P}}_{\text{Production}}$$

Hint for an exotic state with $J^{PC} = 1^{--}$
Investigation of the reaction $\bar{\mathrm{p}}\mathrm{d} \rightarrow \omega\pi^-\pi^0 + \mathrm{p}_{\text{spectator}}$



More than just $\rho(770)$ $\rho(1450)$ $\rho(1700)$
in the spectrum of ($I = 1$) vector mesons
$\Rightarrow$ good reasons for $\rho(1200)$



PhD thesis Burkhard Pick, Bonn 2000
(submitted to Nucl. Phys. **A**)

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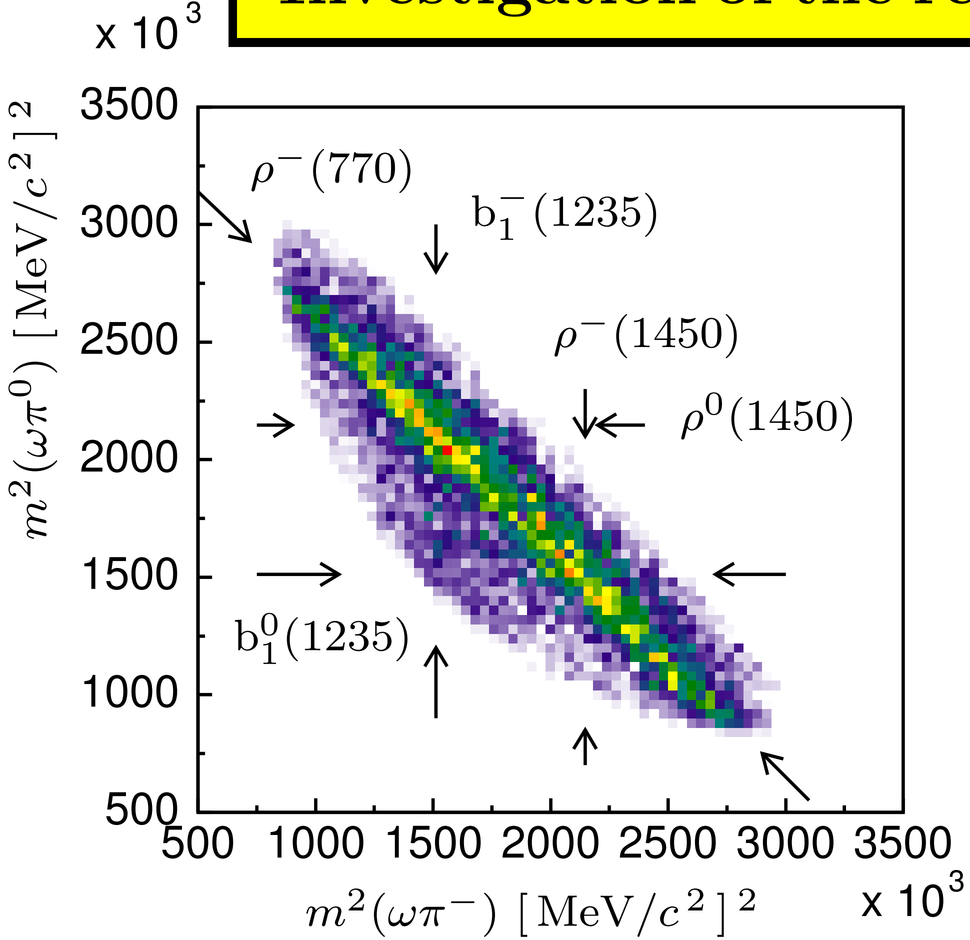

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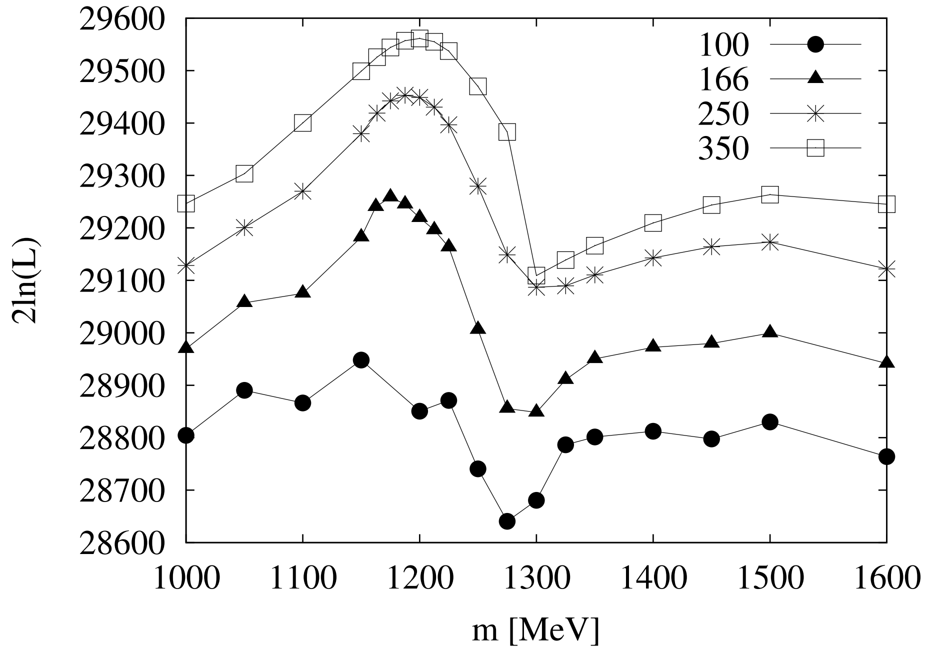

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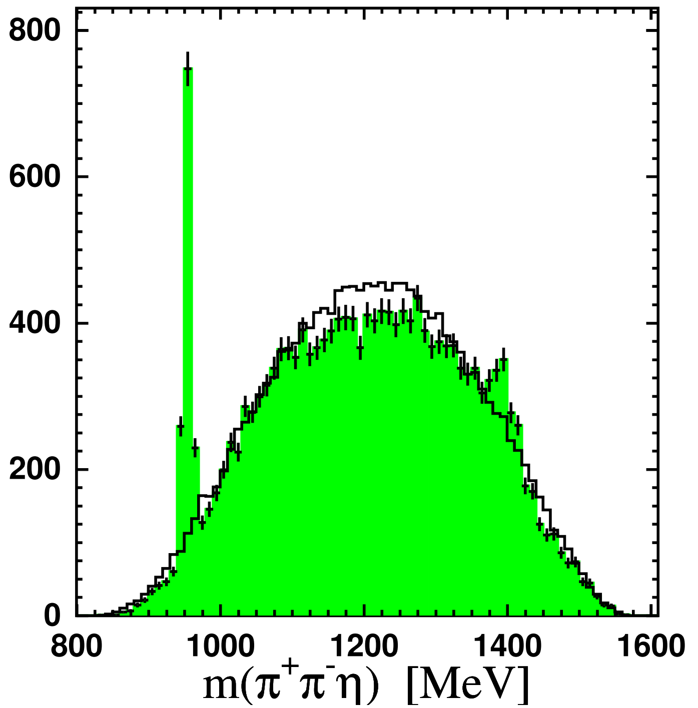
Possible scenario:
(mixing scheme
including a hybrid)

$$\begin{pmatrix} \rho(1200) \\ \rho(1450) \\ \rho(1700) \end{pmatrix} = \mathcal{M} \begin{pmatrix} |2\,^3S_1\rangle \\ |H_0\rangle \\ |1\,^3D_1\rangle \end{pmatrix}$$

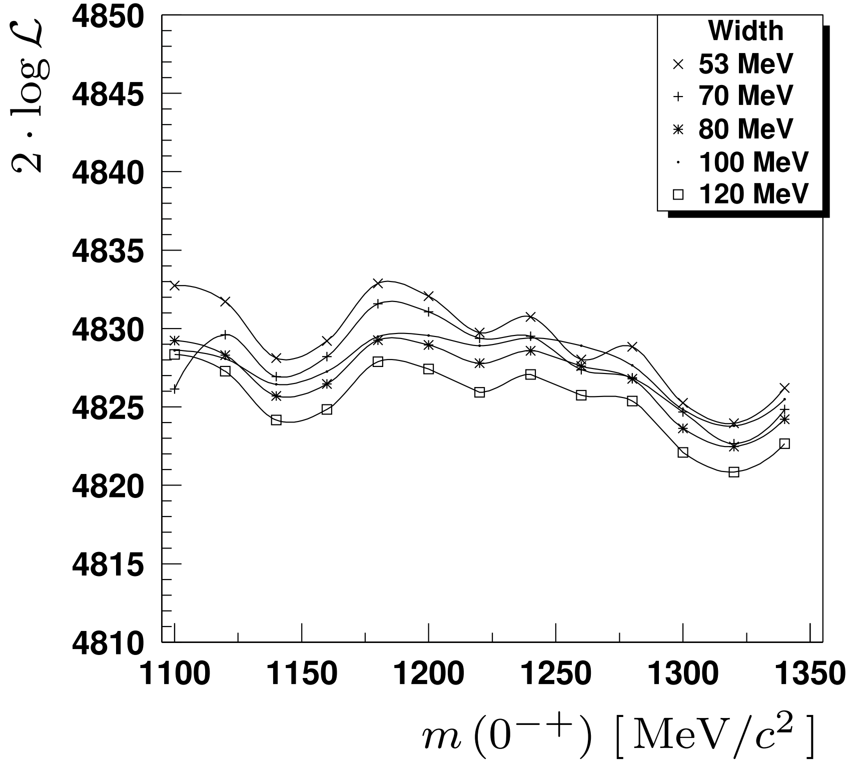
Hint for an exotic state with $J^{PC} = 0^{-+}$?
Investigation of the reaction $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^+\pi^-\pi^+\pi^-\eta$



Interpretation of PDG

$\eta(1295)$ first radial excitation of the η $(2\,^1\mathrm{S}_0)$

$$\eta(1440) \begin{cases} \eta(1400) & \text{exotic candidate} \\ \eta(1480) & \text{radial excitation of the } \eta' \ (2\,^1\mathrm{S}_0) \end{cases}$$



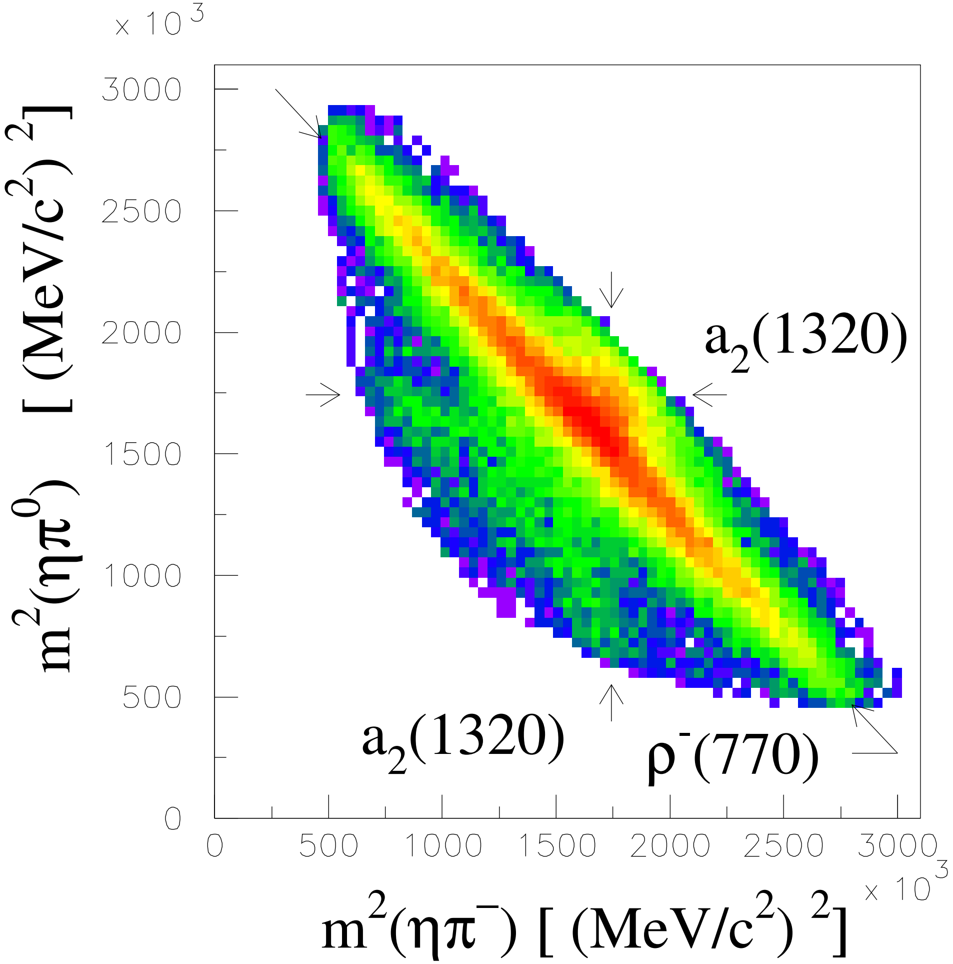
Conclusion

- No evidence for $\eta(1295)$ in $\mathrm{p}\bar{\mathrm{p}}$ reactions

  $\Rightarrow$ Does it exist ? Possibly not a $\mathrm{q}\bar{\mathrm{q}}$ state !

PhD thesis Jörg Reinnarth, Bonn 2003

Observation of an exotic $J^{PC} = 1^{-+}$ state



Most prominent candidate for an exotic hybrid state: $\pi_1(1400)$

52567 events in the Dalitz plot

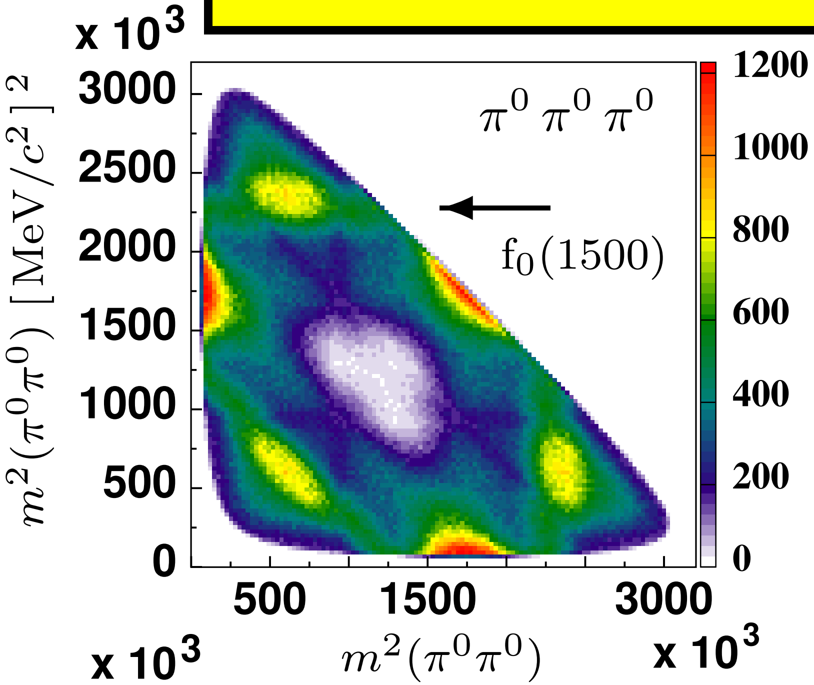
$$PWA \begin{cases} {}^3\mathrm{S}_1 & \rho^-(770),\ \rho^-(1450),\ \mathrm{a}_2(1320) \\ {}^1\mathrm{P}_1 & \mathrm{a}_0(980),\ \mathrm{a}_0(1450) \end{cases}$$

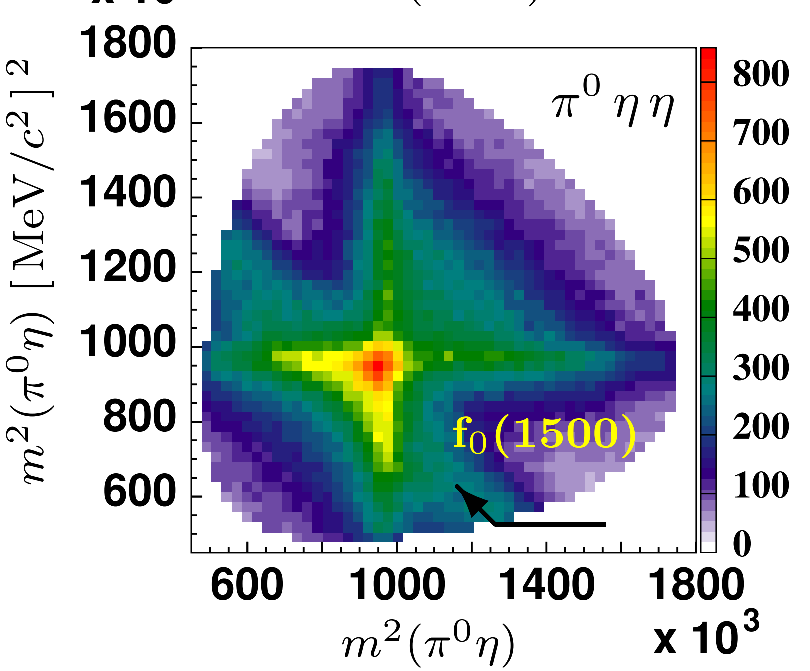
$\Rightarrow$ confirmation of exotic state in analysis of $\bar{\mathrm{p}}\mathrm{p} \rightarrow \pi^0 \boxed{\pi^0\eta}$ (PhD thesis Mario Herz, Bonn 1997)

Dalitz plot from: Abele et al., Phys.Lett. **B423** (1998) 175
Exotic $\eta\pi$ state in $\bar{p}d$ annihilation at rest into $\pi^-\pi^0\eta\, p_{\mathrm{spectator}}$

in agreement with D.R. Thompson et al. (E852 collaboration)

The search for the scalar glueball in $p\bar{p}$ annihilation





[1] C. Amsler, F.E. Close,
PL **B353** (1995) 385, PR **D53** (1996) 295.

[2] W. Lee, D. Weingarten, PR **D61** (2000) 014015.

[3] P. Minkowski, W. Ochs, EPJ **C9** (1999) 283.

[4] B.C. Metsch, C.R. Münz, H.R. Petry,
PL **B361** (1995) 160.

Ref.	[1]	[2]	[3]	[4]
$f_0(980)$	$K\overline{K}$	$K\overline{K}$	$q\bar{q}$	$q\bar{q}$
$a_0(980)$	$K\overline{K}$	$K\overline{K}$	$q\bar{q}$	$K\overline{K}$
$f_0(1000)$	ρ ex. in t	ρ ex. in t	Glueball	ρ ex.
$f_0(1370)$	$q\bar{q}$ [1]	$q\bar{q}$ [1]	Glueball	in t [2]
$f_0(1500)$	Glueball [1]	$q\bar{q}$ [1]	$q\bar{q}$	$q\bar{q}$
$f_0(1750)$	$q\bar{q}$ [1]	Glueball [1]	-	2^3P_0

Is $f_0(1500)$ a glueball ?

[1] strongly mixed

[2] possibly $\rho\rho$ molecule

There are many indications for gluonic excitations
⇒ however, most candidates are questionable

As yet little theoretical guidance on the masses of hybrid states:

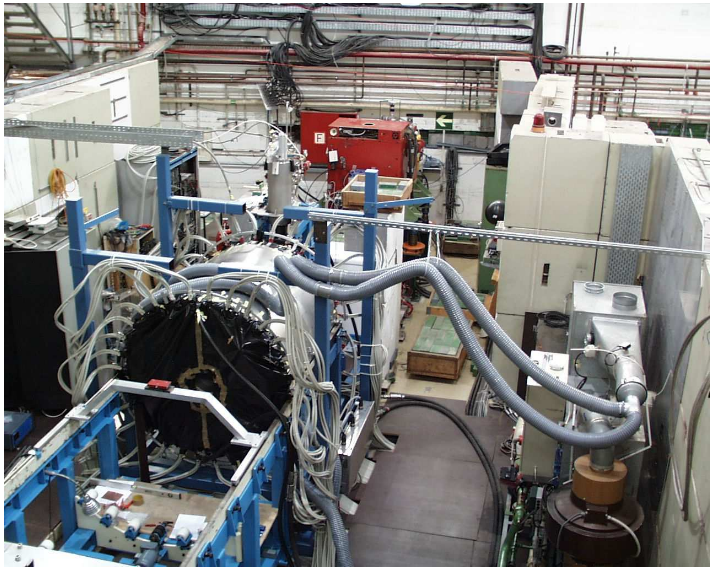
- Mass–range predictions for light–quark hybrids from 1.5 to 2.5 GeV/c^2 with the lightest exotic state ($J^{PC} = 1^{-+}$) having a mass about 2 GeV/c^2 (lattice QCD and flux–tube models)
- However, the observed masses of the most prominent exotic candidates ($\pi_1(1400), \pi_1(1600)$) are much too low
  ⇒ in addition: neither of the discussed pseudoscalar or vector candidate with non–exotic quantum numbers has a mass as predicted for hybrids

No hybrid assignment yet to any observed state in the baryon spectrum

↓

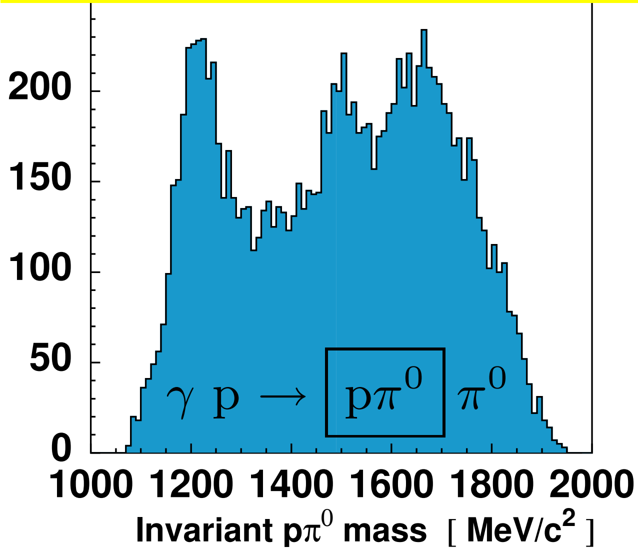
Do hybrids really exist ?

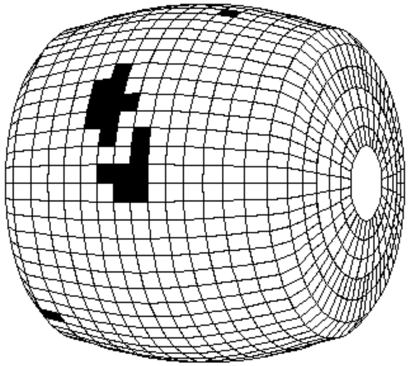
Photoproduction with the Crystal–Barrel Detector at ELSA



Photoproduction

$2.0 < m_{p\pi^0\pi^0} < 2.1$ (in GeV/c^2)





Spectroscopy

Baryon spectrosopy

- Search for missing resonances

General Physical Motivation

⇒ Search for *missing* resonances

Quark models predict many more baryons than have been observed

	****	***	**	*
N spectrum	11	3	6	2
Δ spectrum	7	3	6	6

⇒ according to PDG

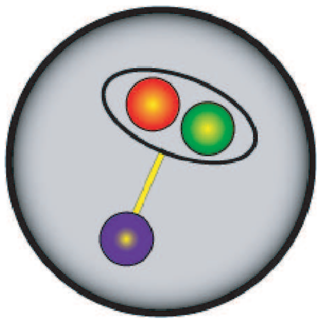
(Phys. Rev. **D66** (2002) 010001)

⇒ little known

(many open questions left)

Possible solutions:

a) Quark-diquark structure



one of the internal degrees of freedom is frozen

b) They have not been observed, yet

Nearly all existing data result from πN scattering experiments

⇒ If the missing resonances did not couple to Nπ, they would not have been discovered!!

(supported by theory)

Quark models and experimental overview

Effective theories and models necessary to make spectroscopic predictions

Basic assumption: linear confinement potential + residual short–range interaction

- Goldstone–boson (pion) exchange
  (L.Y. Glozman, W. Plessas, K. Varga and R.F. Wagenbrunn, Phys. Rev. **D58** (1998) 094030)
- One–gluon exchange (S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809)
  (*relativized* quark model)
  1. wrong spin–orbit couplings
  2. no explanation for parity doublets
- Instanton–induced interaction
  (relativistic quark model)
  1. acceptable Regge trajectories
  2. natural explanation for parity doublets

Which is the right model?
⇒ Do we have a correct model? Is there really one interaction that dominates?

Symmetries and classification

$$|\,qqq\,\rangle \;=\; |\,\mathrm{colour}\,\rangle_A \cdot |\,\mathrm{space;\ spin,\ flavour}\,\rangle_S$$

$$\mathrm{O(6)} \quad \mathrm{SU(6)} \rightarrow \mathrm{SU(2)}|_{spin} \otimes \mathrm{SU(3)}|_{flavour}$$

$\Rightarrow$ Total wave function antisymmetric with respect to exchange of two quarks

SU(6) symmetry: (Notation: $^{2S+1}$multiplet)

$$6 \otimes 6 \otimes 6 \;=\; 56_S \oplus 70_M \oplus 70_M \oplus 20_A$$

$$\Rightarrow \quad 56 \;=\; {}^4 10 \oplus {}^2 8$$

$$70 \;=\; {}^2 10 \oplus {}^4 8 \oplus {}^2 8 \oplus {}^2 1$$

$$20 \;=\; {}^2 8 \oplus {}^4 1$$

Notation for baryon resonances:

(example)

$$\mathrm{S}_{11}(1535) \quad \Longleftrightarrow \quad \mathrm{N}_{\frac{1}{2}^-}(1535)$$

Classification of multiplets $(\mathbf{D}, \mathbf{L}_N^P)$:

ground state $(\mathbf{56}, 0_0^+)$:

$\Delta_{\frac{3}{2}^+}(1232) \quad \epsilon\ {}^4 10$

$\mathrm{N}_{\frac{1}{2}^+}(939) \quad \epsilon\ {}^2 8$

1. excited state $(\mathbf{70}, 1_1^-)$:

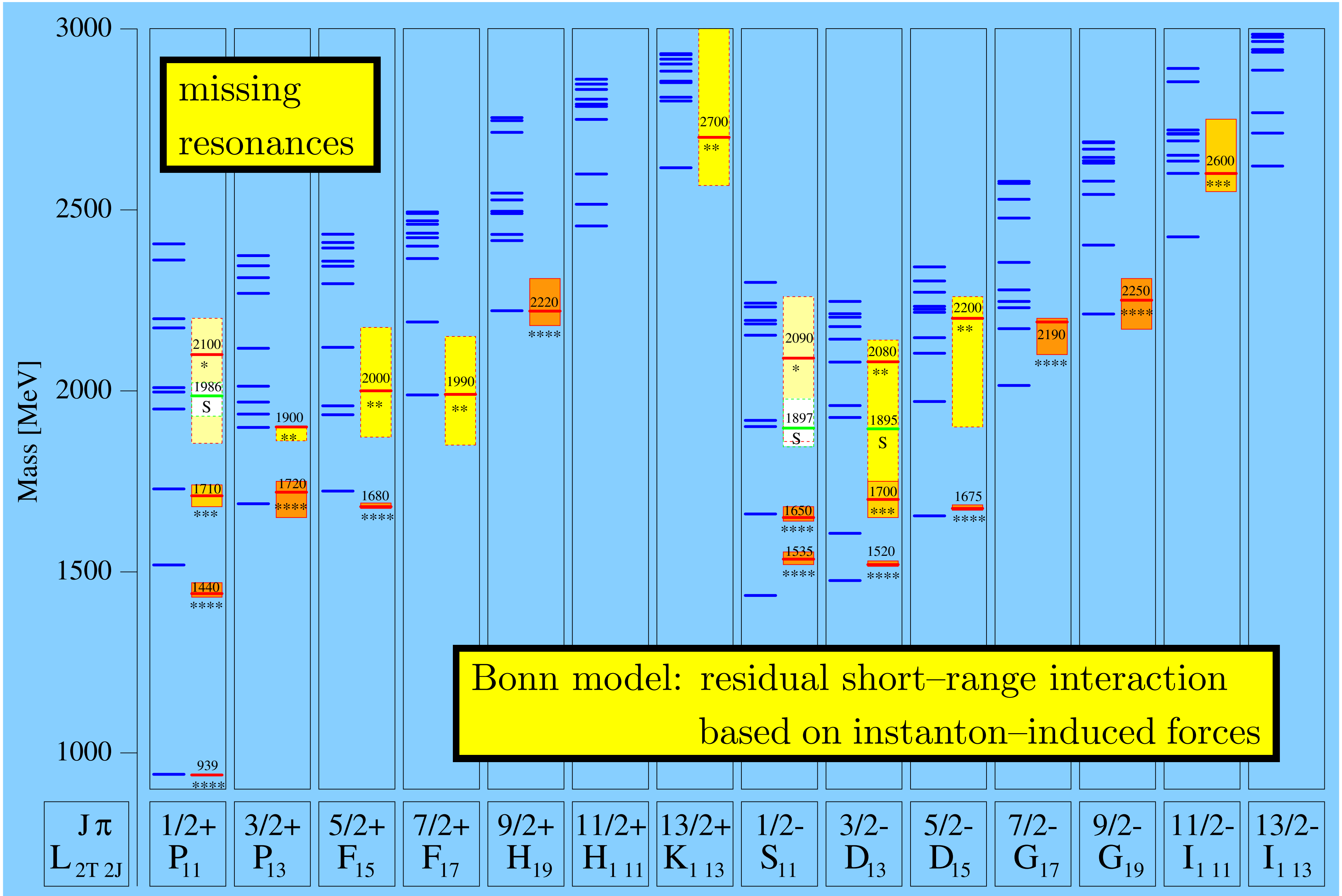
$\Delta_{\frac{1}{2}^-}(1620)$, $\Delta_{\frac{3}{2}^-}(1700)$ $\quad \epsilon\ {}^2 10$

$\mathrm{N}_{\frac{1}{2}^-}(1535)$, $\mathrm{N}_{\frac{3}{2}^-}(1520)$ $\quad \epsilon\ {}^2 8$

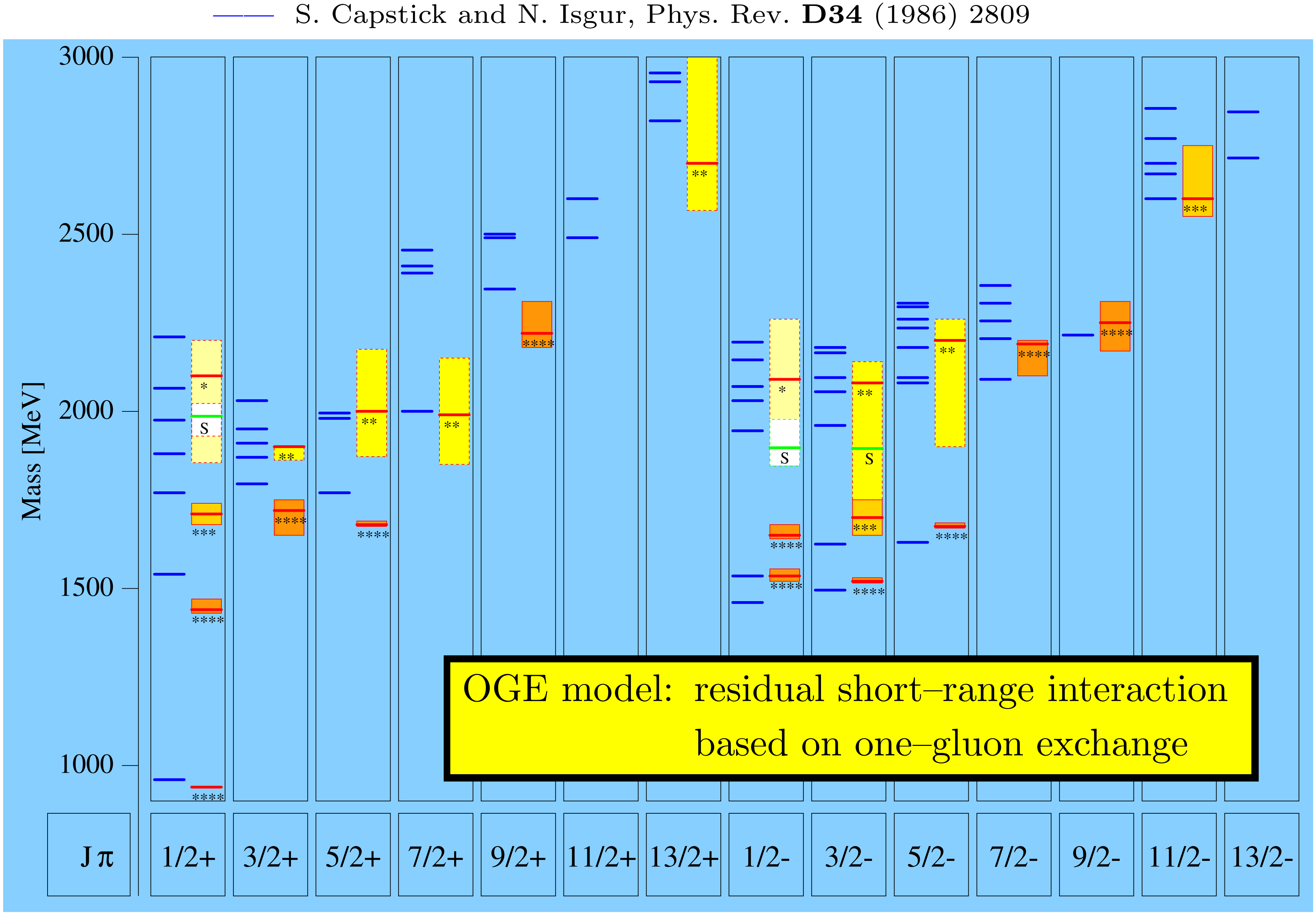
$\mathrm{N}_{\frac{1}{2}^-}(1650)$, $\mathrm{N}_{\frac{3}{2}^-}(1700)$, $\mathrm{N}_{\frac{5}{2}^-}(1675)$ $\quad \epsilon\ {}^4 8$

Nucleon resonances

—— U. Löhring, B.C. Metsch and H.R. Petry, Eur. Phys. J. A**10**, 395-446 (2001)

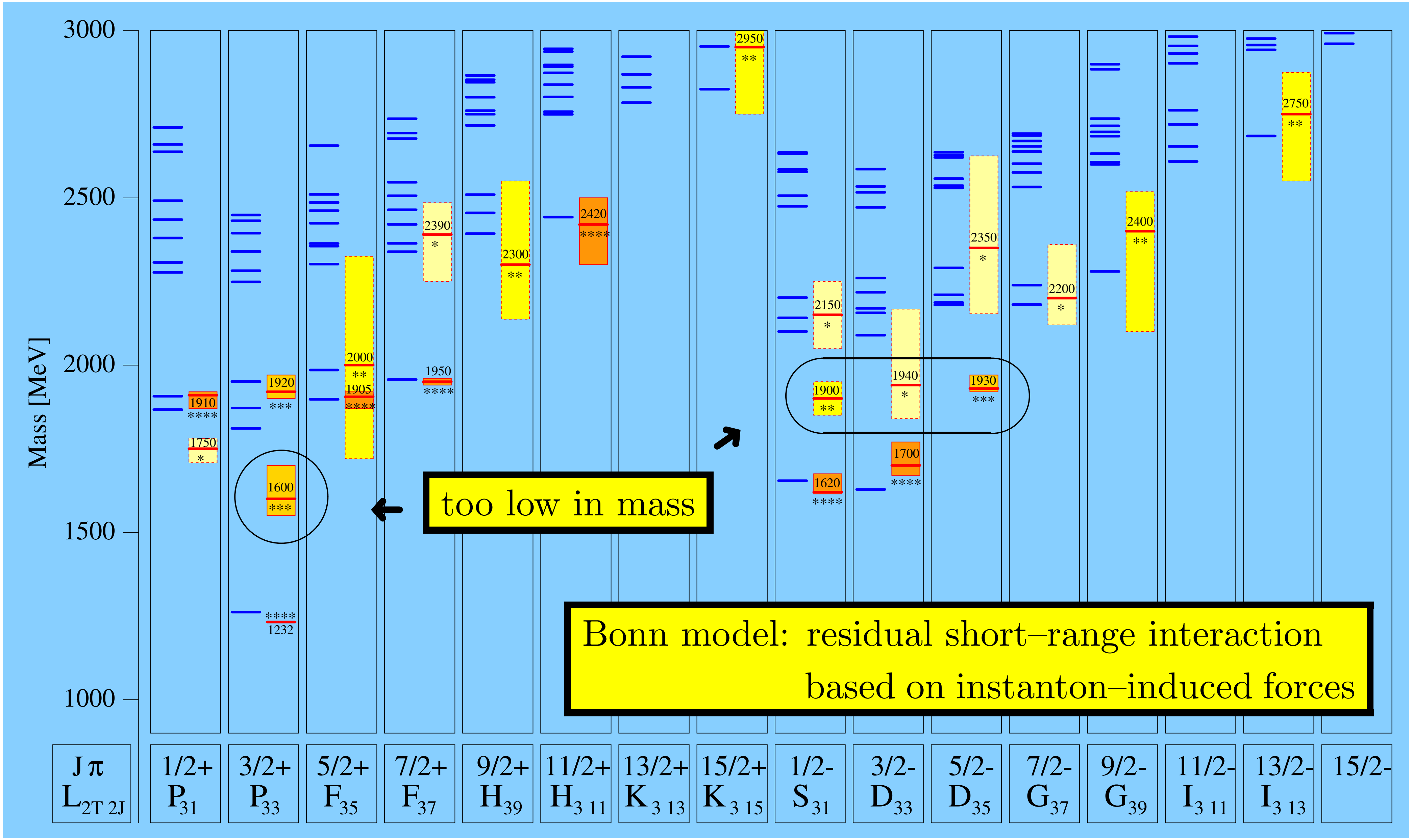


Nucleon resonances

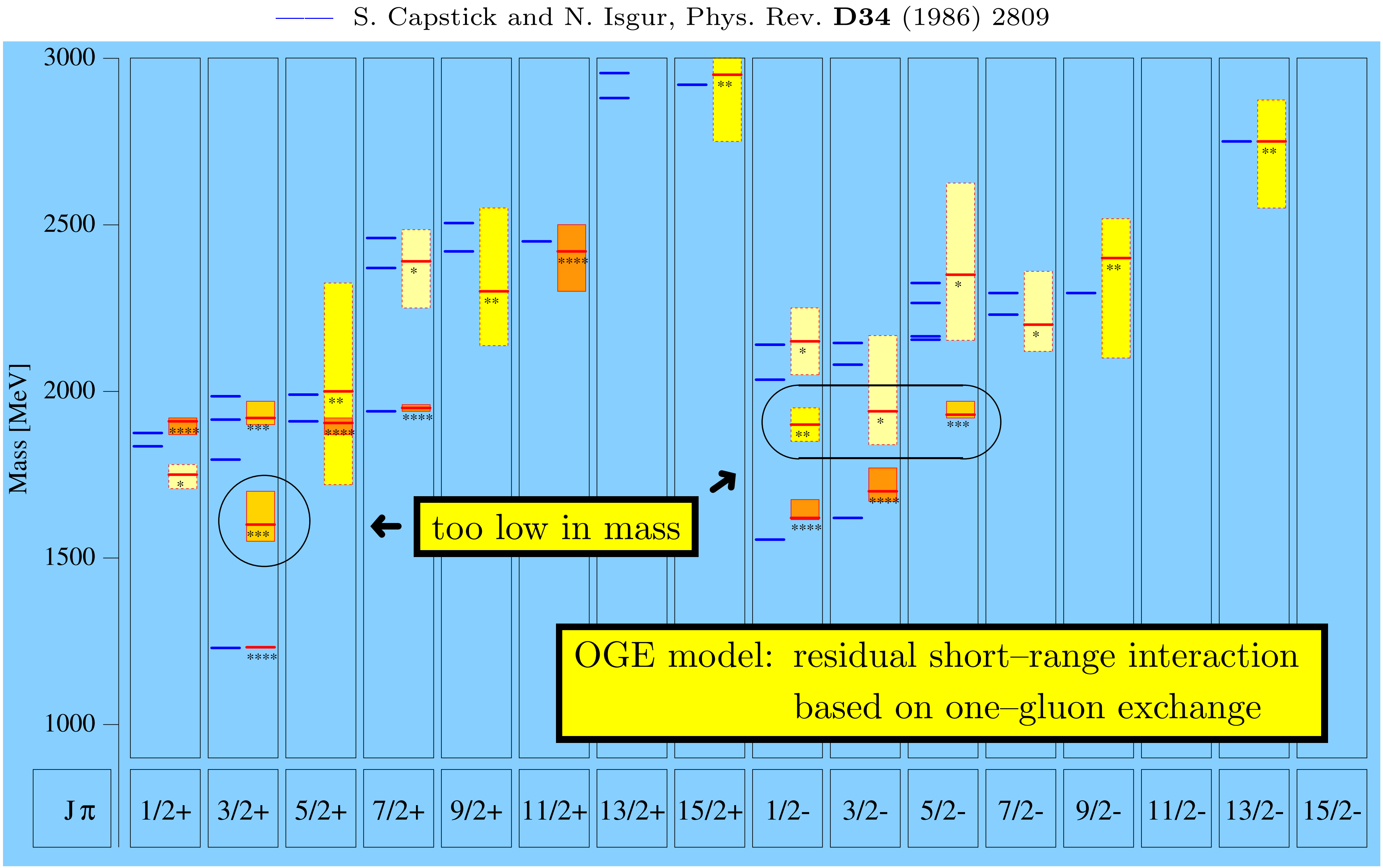


Δ-resonances

—— U. Löhring, B.C. Metsch and H.R. Petry, Eur. Phys. J. A**10**, 395-446 (2001)

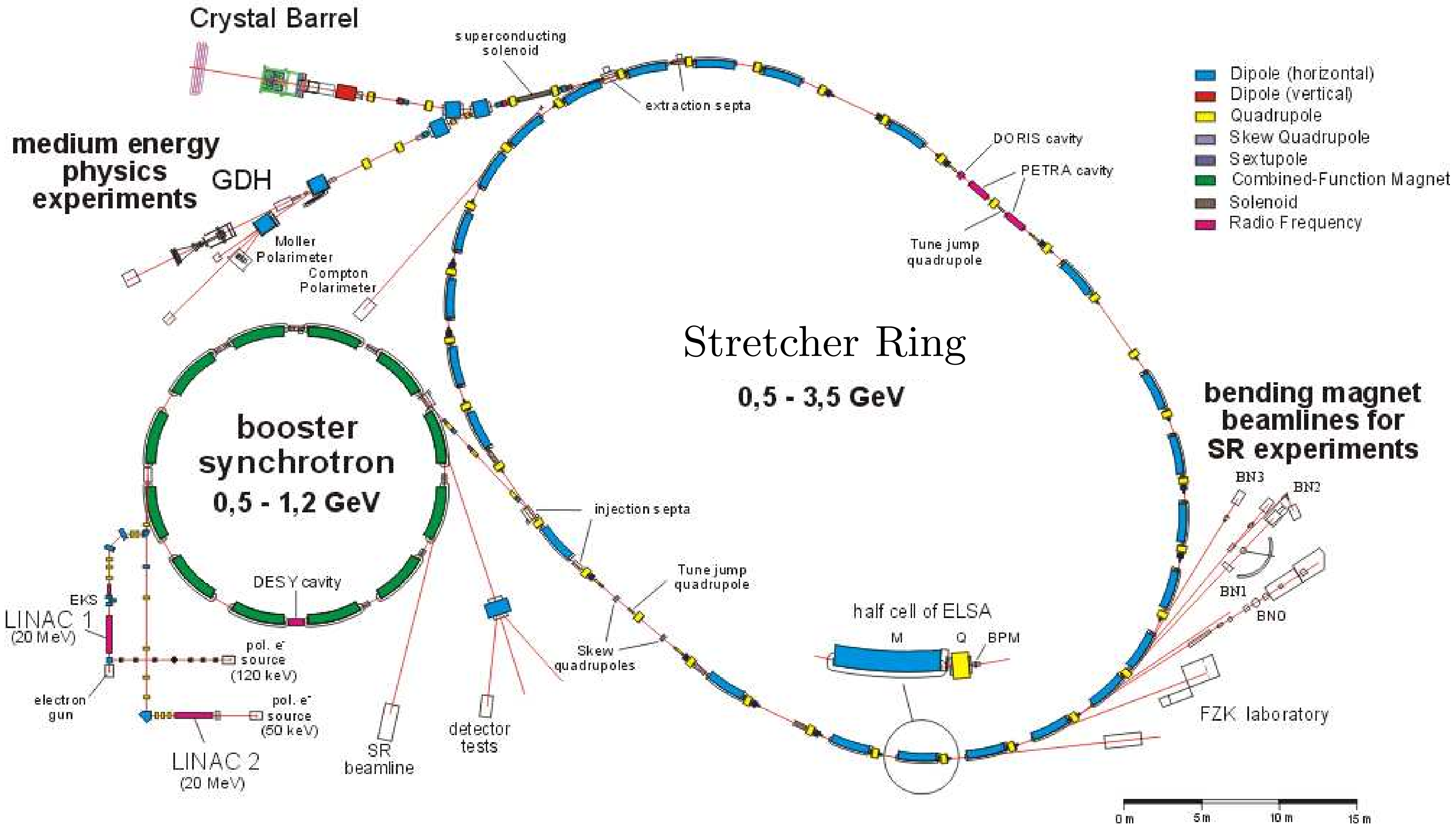


Δ resonances



The Electron Stretcher Ring ELSA

Investigation of the nucleon structure with a 4π high-resolution photon detector at the Electron Stretcher Accelerator ELSA in Bonn



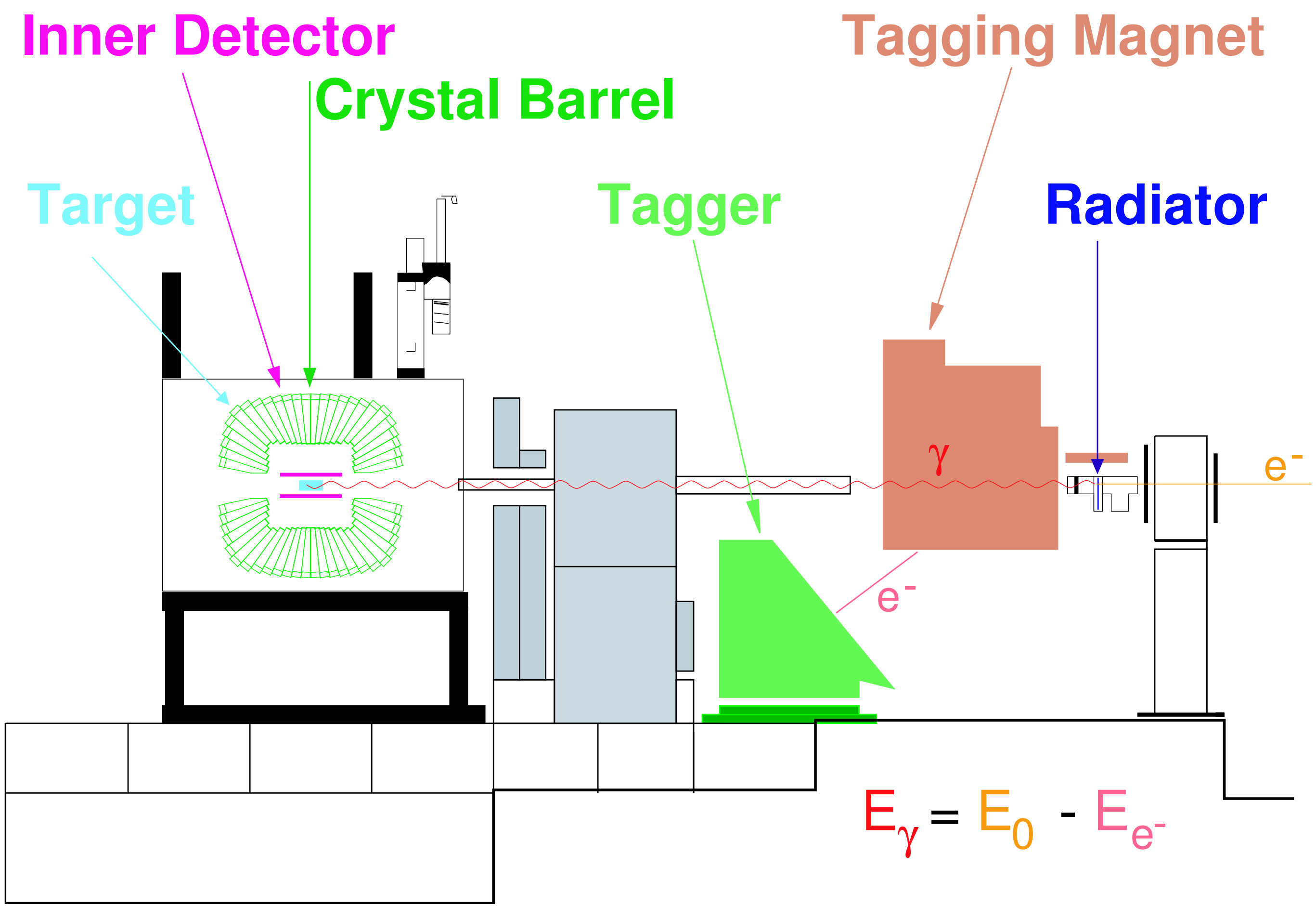
Collaboration of

- Basel
- Bochum
- Bonn
- Dresden
- Erlangen
- Gatchina
- Gießen
- Groningen
- Münster

The Crystal–Barrel Experiment at ELSA

Photoproduction experiment using a liquid H_2 target

(unpolarized in a first series of experiments → 2000/2001)



Tagging range:

25 % – 93 % of incoming E_{e^-}

$E_{e^-} = 1.4$ GeV

0.35 GeV $\leq E_\gamma \leq$ 1.3 GeV

1.2 GeV$/c^2 \leq \sqrt{s} \leq$ 1.8 GeV$/c^2$

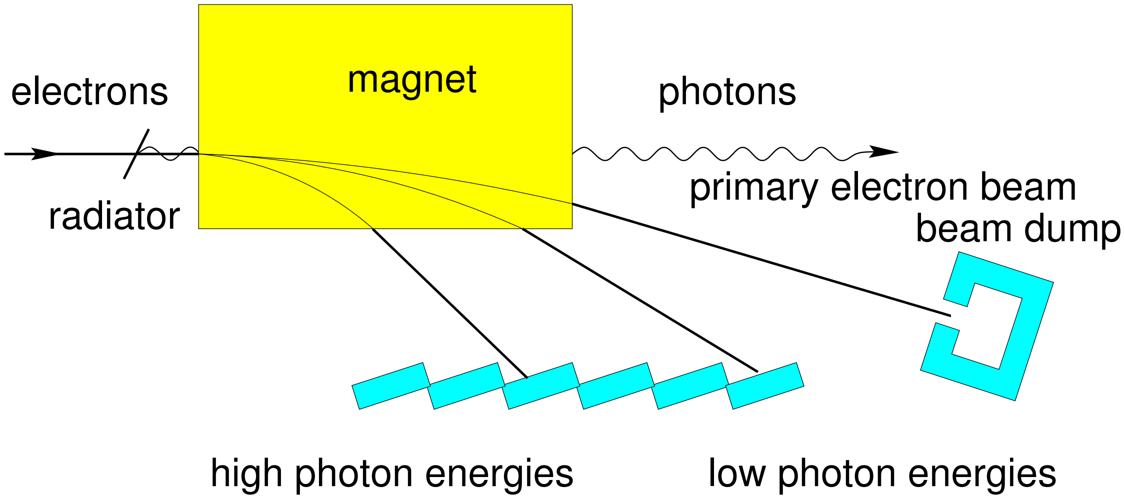
$E_{e^-} = 3.2$ GeV

0.8 GeV $\leq E_\gamma \leq$ 3.0 GeV

1.5 GeV$/c^2 \leq \sqrt{s} \leq$ 2.6 GeV$/c^2$

The tagging system

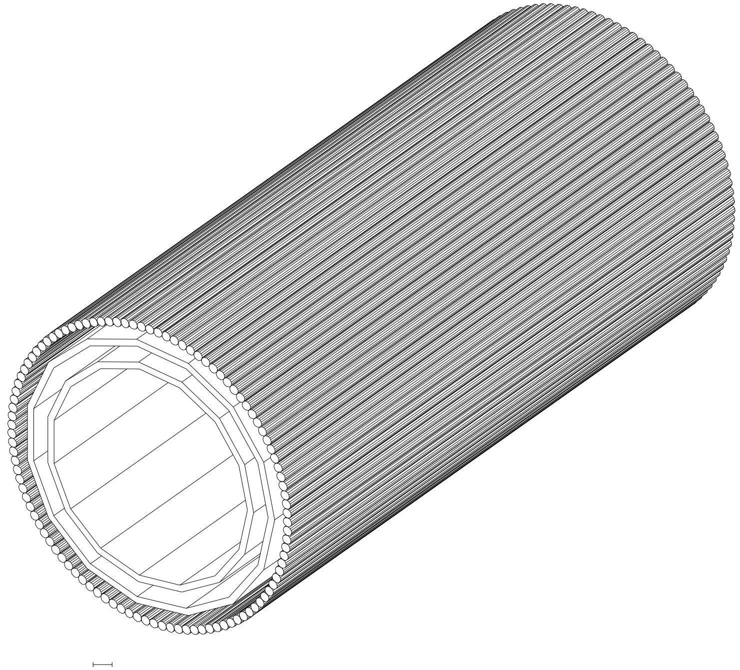
- 14 scintillation counters
- 2 wire chambers (352 wires)
- tagging range: 25 % – 92 %

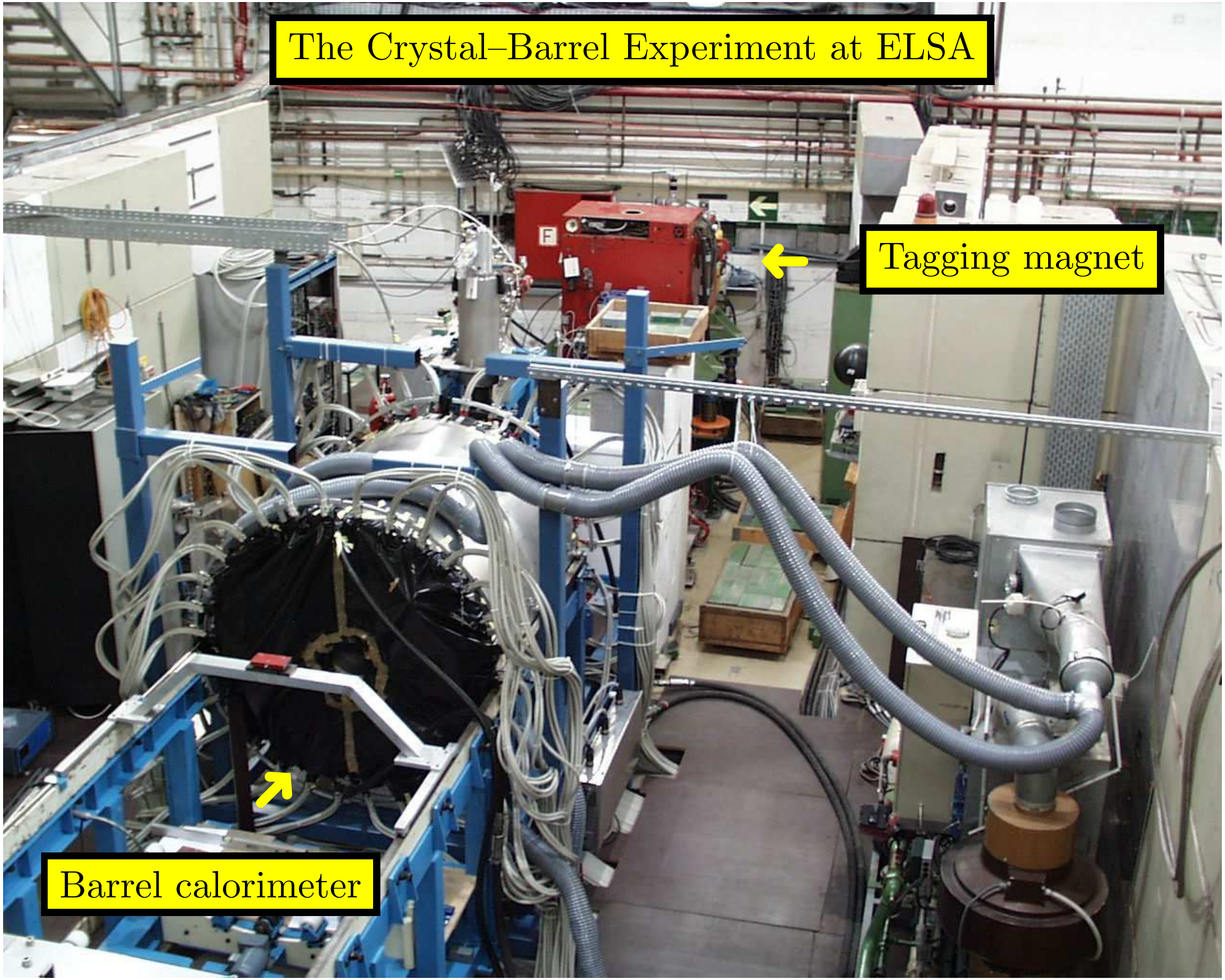


Target and inner detector

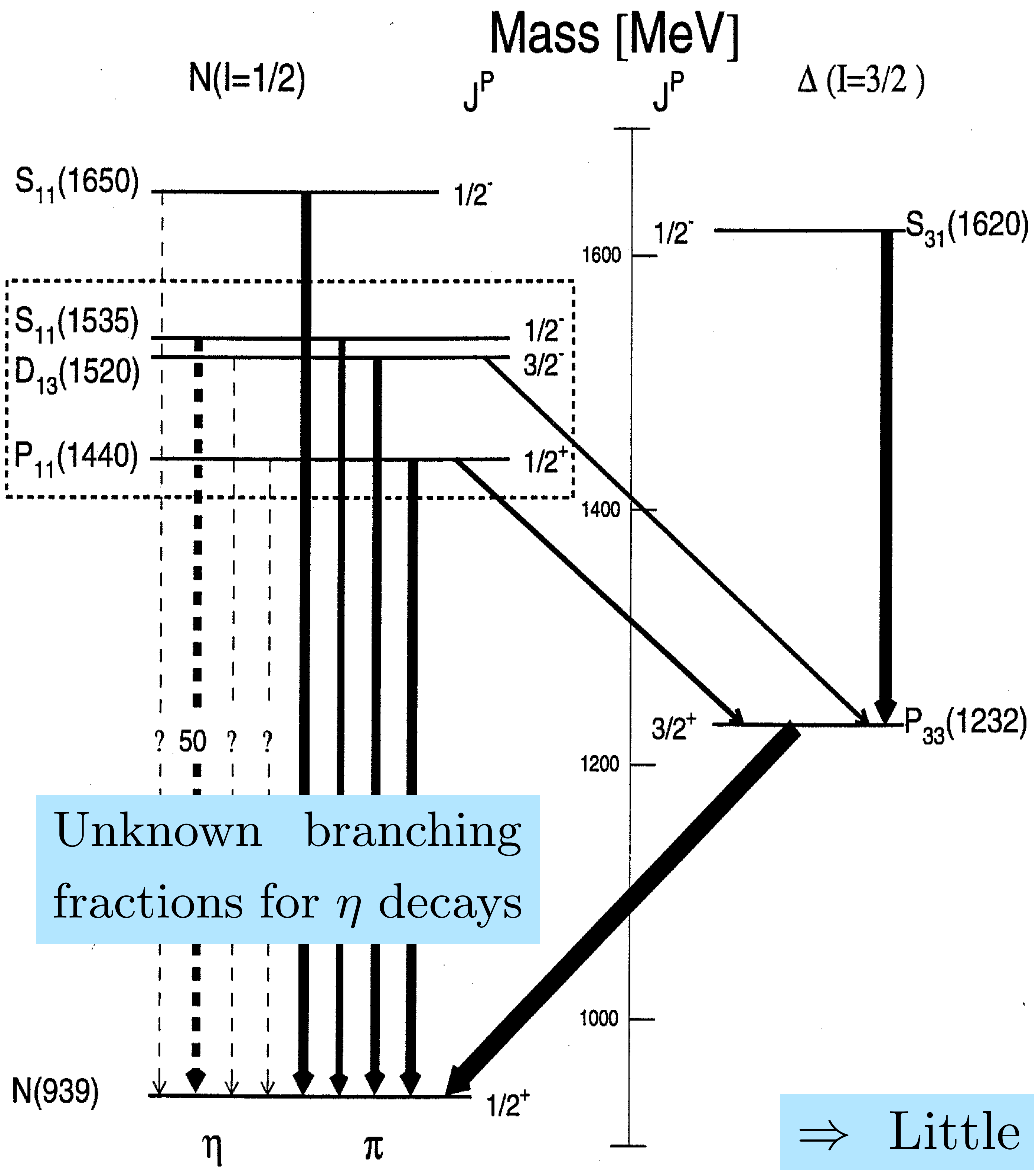
The inner detector:

- 3 layers of scintillating fibres
  (⇒ additional reconstruction point)
- Trigger on charged tracks




The Crystal–Barrel Experiment at ELSA
Tagging magnet
Barrel calorimeter

Photoproduction of π^0 / η mesons



Unknown branching fractions for η decays

Excitation spectra and quantum numbers alone do not provide very sensitive tests of hadron models

➜

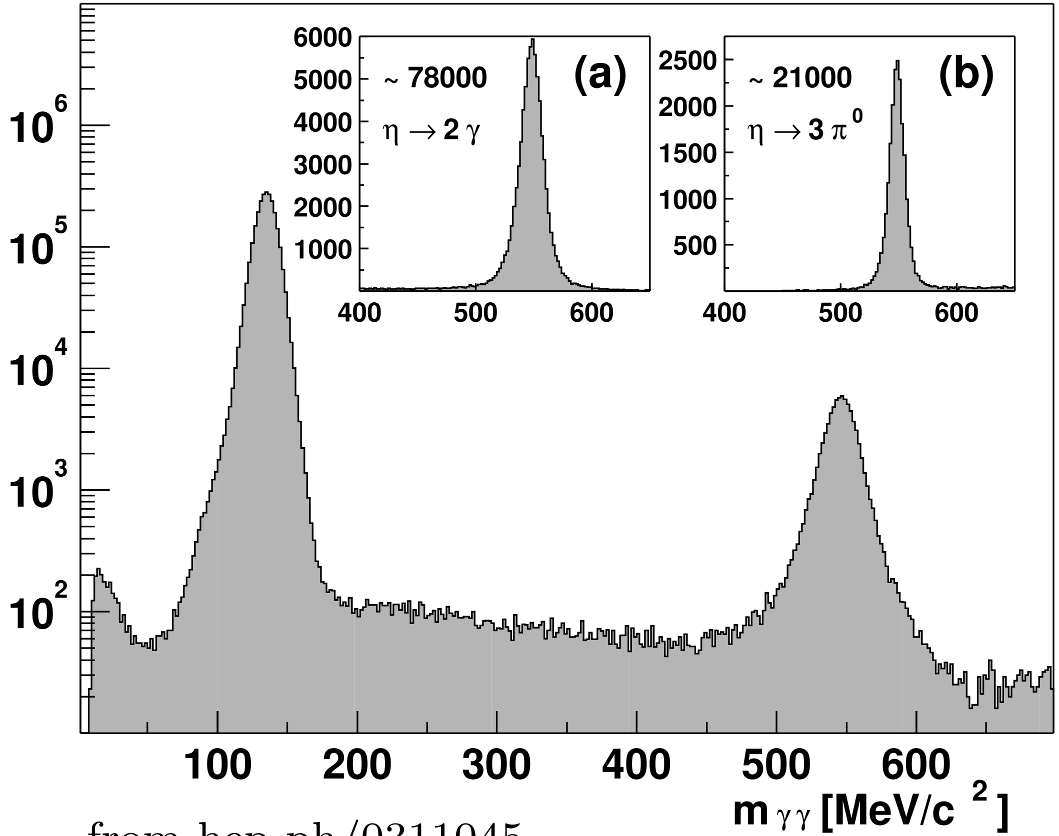
Models also have to ...

- predict transitions between states
- link observables to fundamental questions

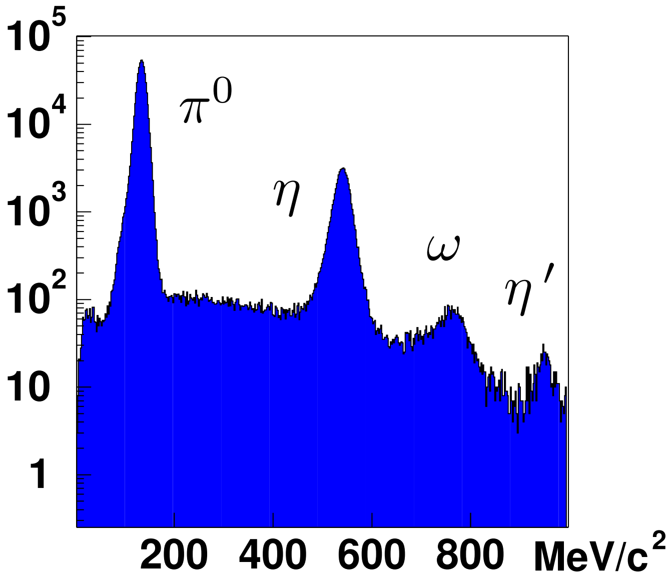
$\Rightarrow$ Little known on η decays !

Reconstruction

- Selection according to the number of clusters in the Crystal Barrel
- Identification of protons via inner scintillating fibre detector
- Kinematic fitting (e.g. $3\pi^0$ and *missing* proton)

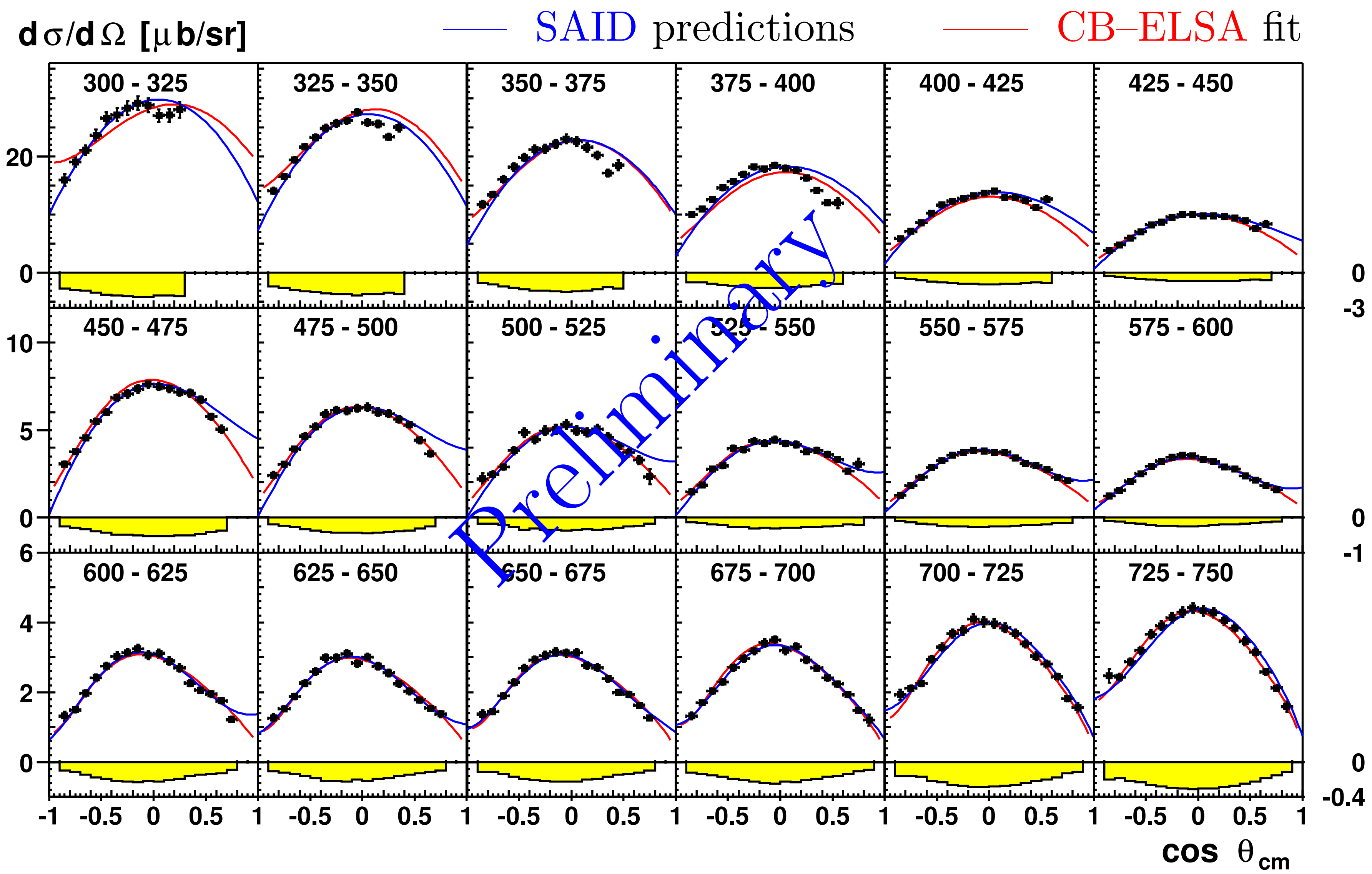


from hep-ph/0311045
on eta photoproduction



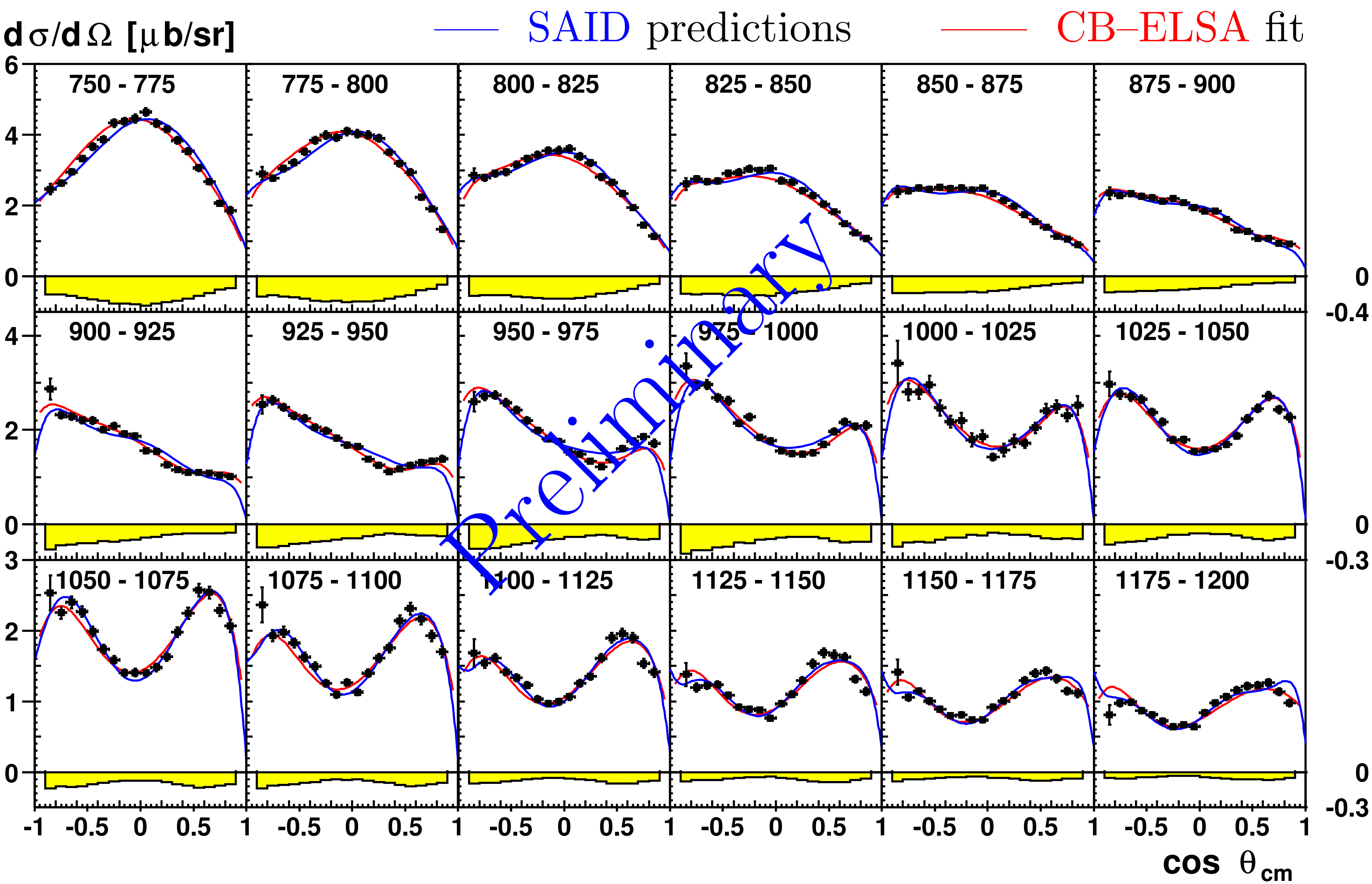
← Invariant $\gamma\gamma$ mass ↗

Differential cross sections for the reaction $\gamma\, p \;\rightarrow\; p\, \pi^0$



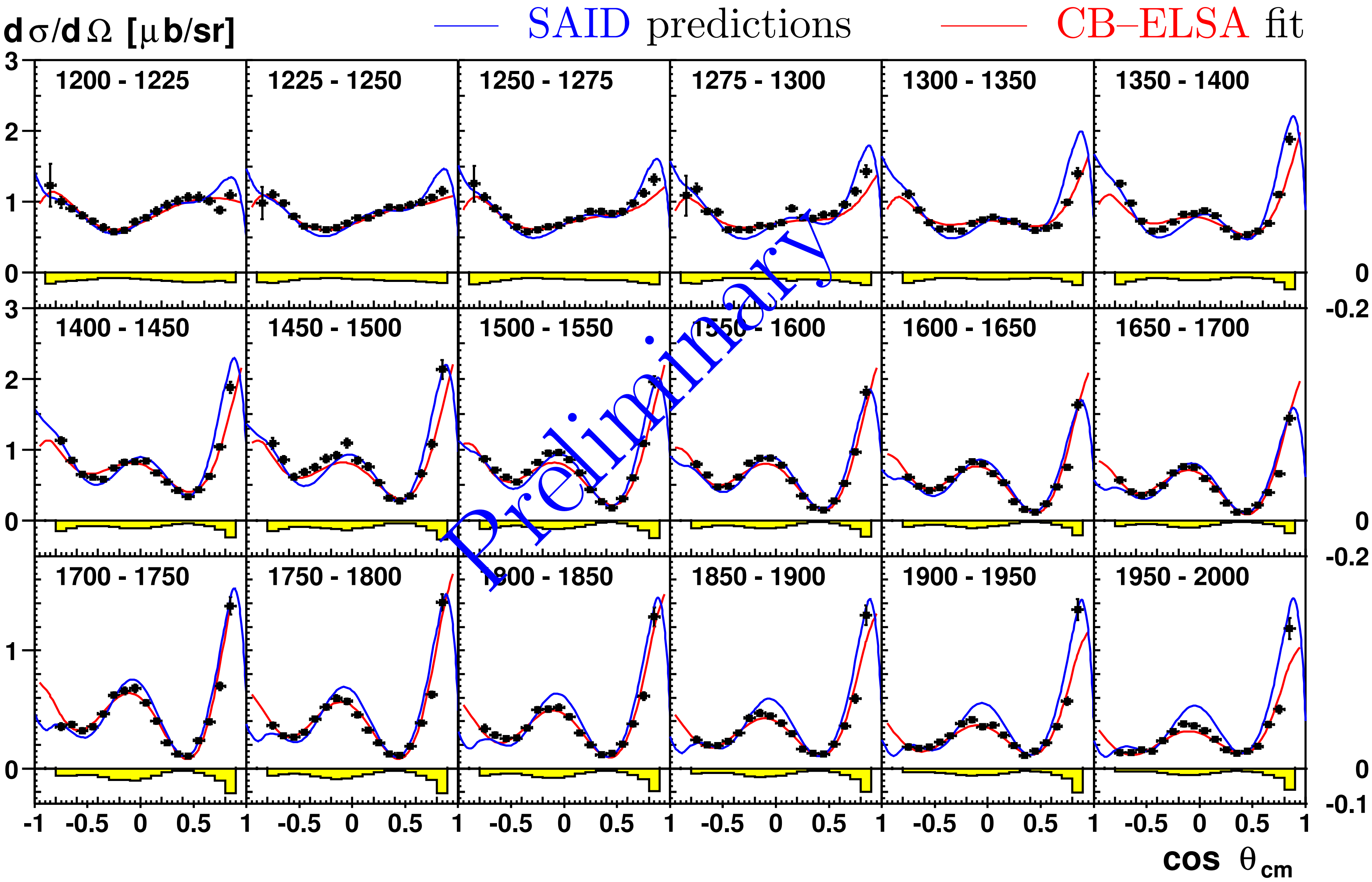
PhD thesis Harald van Pee, Bonn 2003

Differential cross sections for the reaction $\gamma\, p \rightarrow p\, \pi^0$



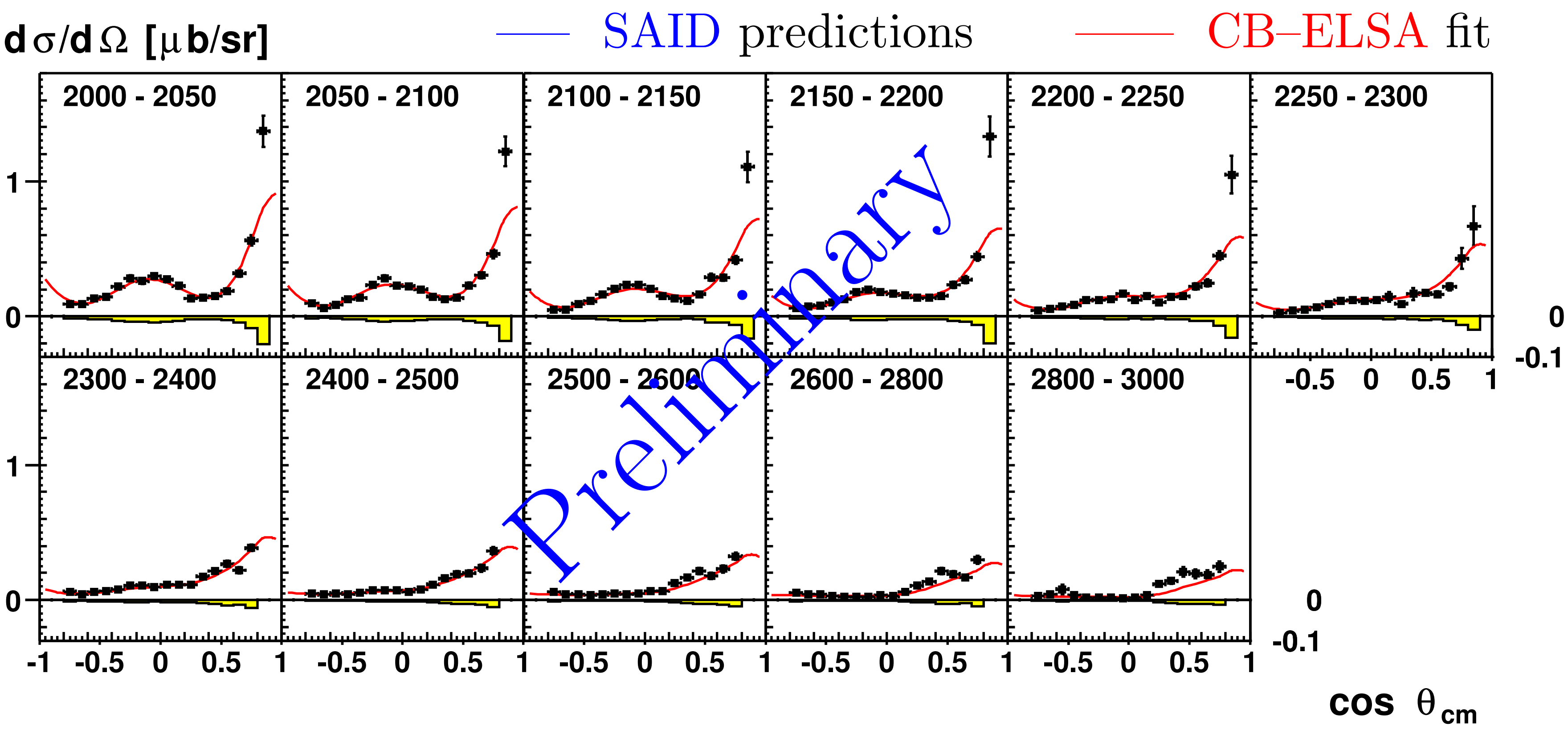
PhD thesis Harald van Pee, Bonn 2003

Differential cross sections for the reaction $\gamma\, p \;\rightarrow\; p\, \pi^0$



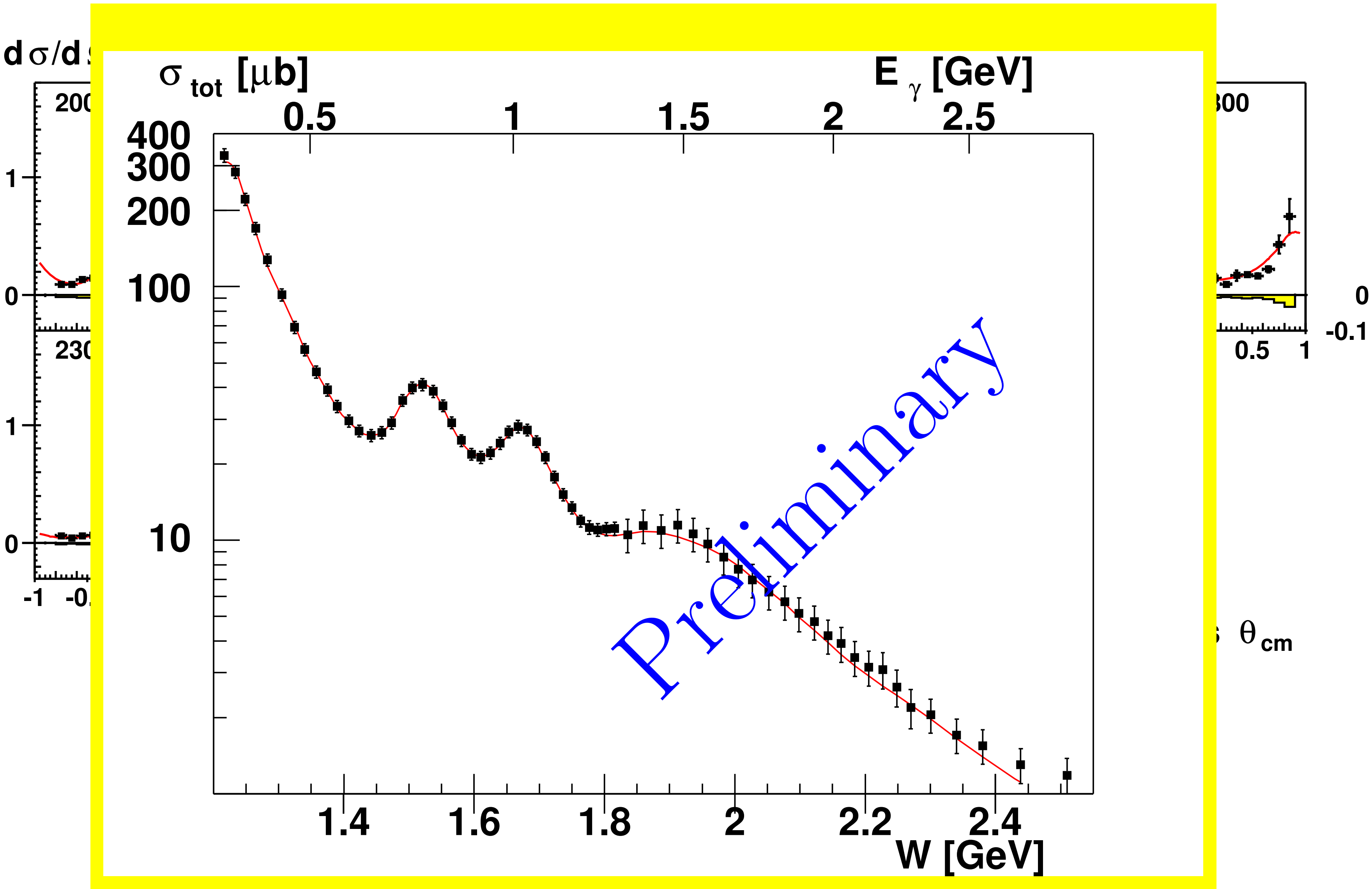
PhD thesis Olivia Bartholomy, Bonn 2004

Differential cross sections for the reaction $\gamma\, p \;\to\; p\,\pi^0$



PhD thesis Olivia Bartholomy, Bonn 2004

Total cross section for the reaction $\gamma\, p \;\to\; p\, \pi^0$



PhD thesis Olivia Bartholomy, Bonn 2004

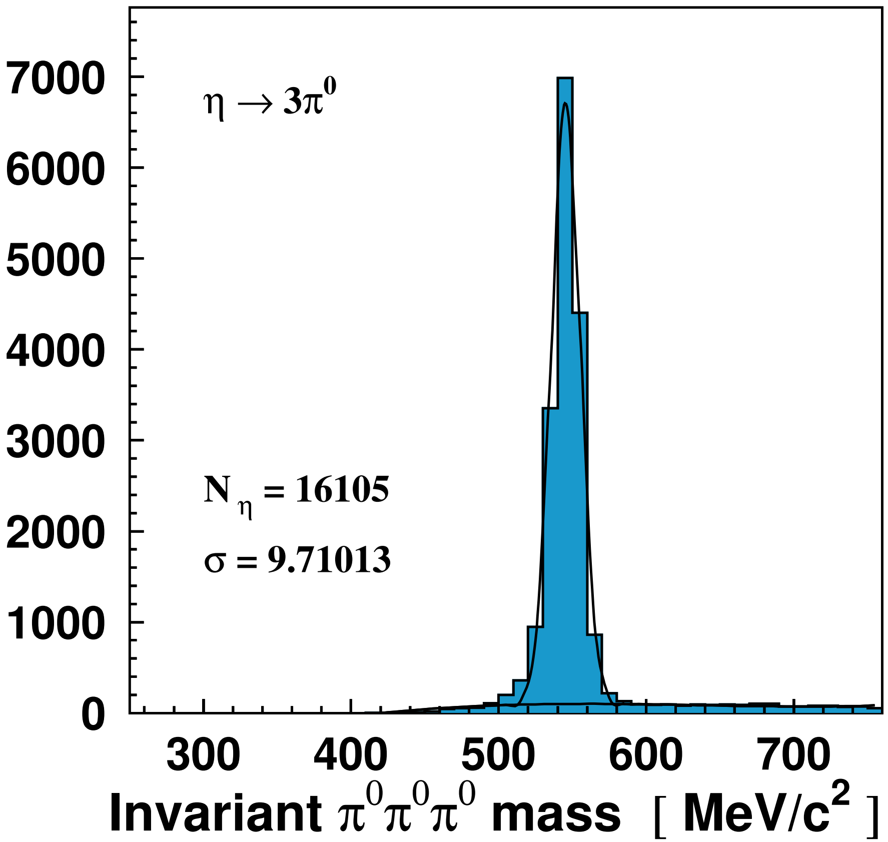
Investigation of the reaction $\gamma\, p \;\rightarrow\; p\, \pi^0$

Aspects of pion production for CB-ELSA

- Understanding of detector acceptances in preparation for partial wave analyses also for other channels ($\gamma\, p \;\rightarrow\; p\, \pi^0\, \pi^0$, $\gamma\, p \;\rightarrow\; p\, \pi^0\, \eta$, etc.)
- Normalisation (photon flux) by fitting angular distributions to known SAID predictions ➜ cross check with hardware measurements
- Better understanding of high-energy behaviour
  $\Rightarrow$ $E_\gamma > 2$ GeV:
  t–channel vector–meson exchanges are better described in terms of Regge trajectories ➜ allows extrapolation towards lower energies

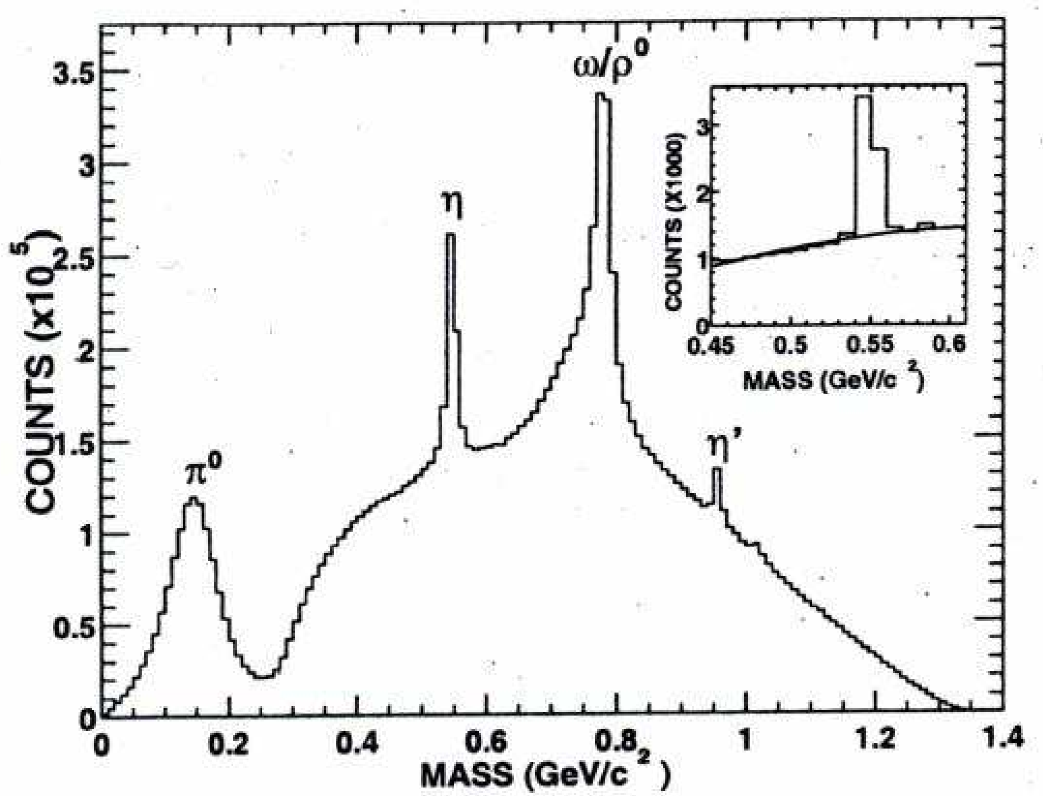
Resonances are excited up to the highest available photon energies, however, strong production of pions in the forward direction is observed above 2.4 GeV (presumably exchange of mesons in the t–channel)

Investigation of the reaction $\gamma\, \mathrm{p} \;\rightarrow\; \mathrm{p}\, \eta$

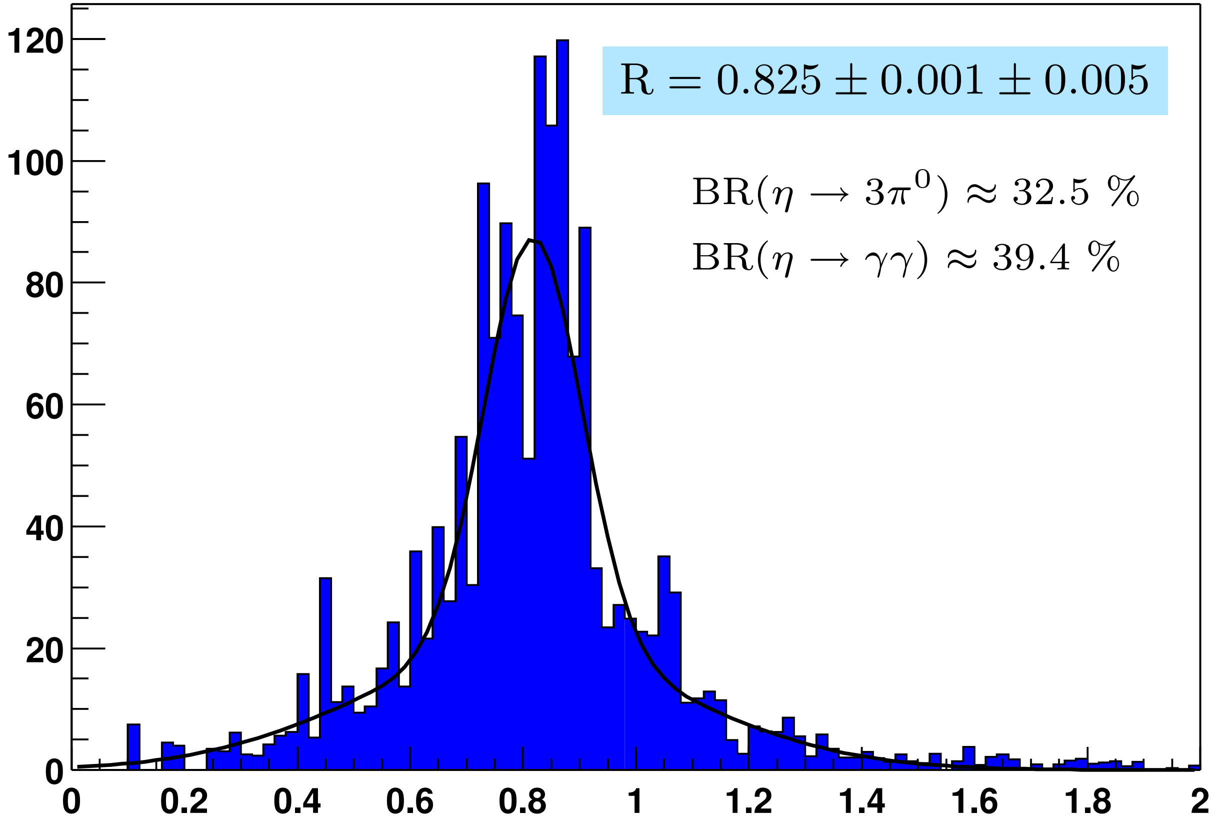


$\left\{ \begin{array}{l} \eta \;\rightarrow\; 3\pi^0 \\ \text{(CB – ELSA)} \end{array} \right.$

$\left. \begin{array}{l} \gamma\, \mathrm{p} \;\rightarrow\; \mathrm{p}\, \mathrm{X} \text{ (missing mass)} \\ \text{(CLAS)} \end{array} \right\}$



Investigation of the reaction $\gamma\,p \;\rightarrow\; p\,\eta$



$$R \;=\; \frac{\mathrm{BR}\,(\eta \;\rightarrow\; 3\pi^0)}{\mathrm{BR}\,(\eta \;\rightarrow\; 2\gamma)}$$

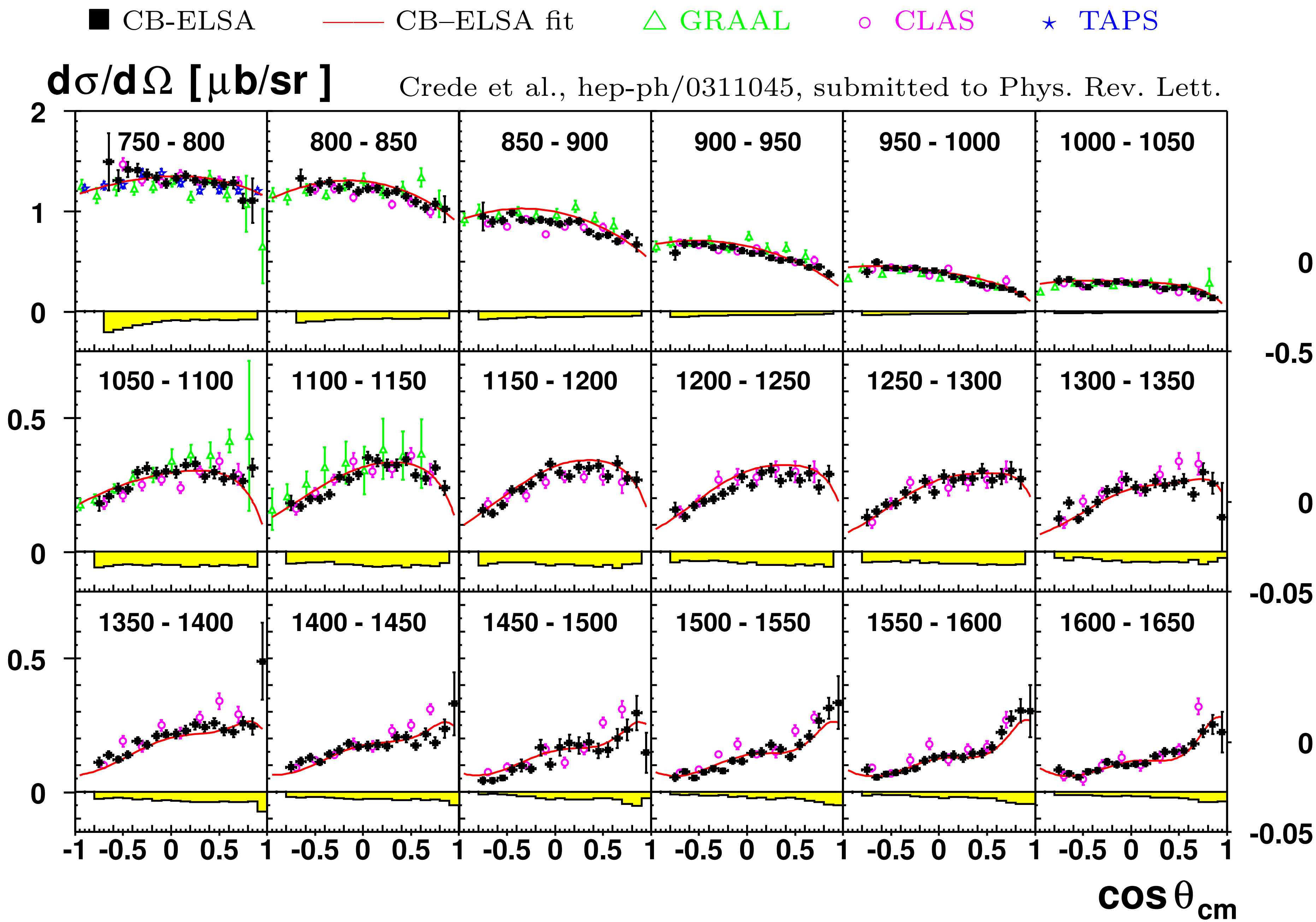
for each bin in $d\sigma/d\Omega$
weighted by $1/\sigma^2$

PDG:

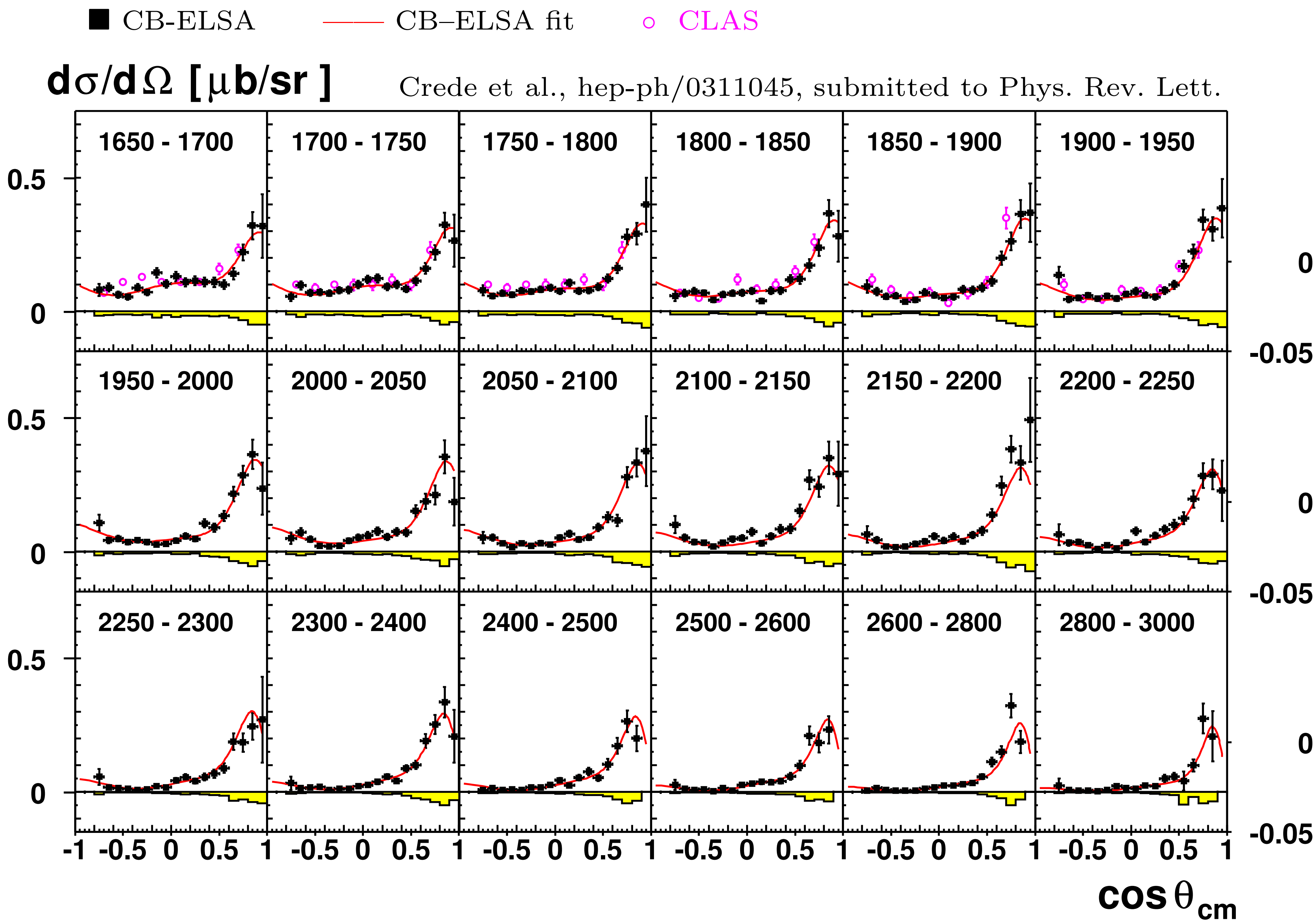
- $0.826 \;\pm\; 0.024$ **SND**
- $0.832 \;\pm\; 0.013$ **TAPS**
- $0.841 \;\pm\; 0.037$ **CBAR**

$\Rightarrow$ Data for $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0$ can be added up !

Differential cross sections for the reaction $\gamma\, p \;\rightarrow\; p\, \eta$



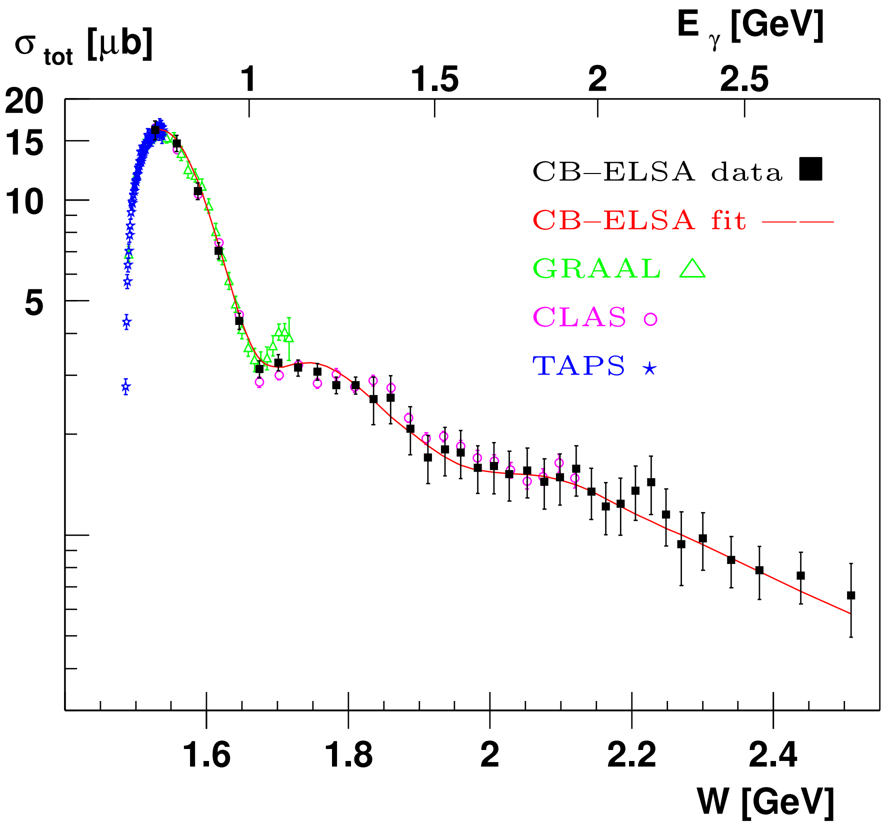
Differential cross sections for the reaction $\gamma\, p \;\rightarrow\; p\, \eta$



Models describing differential cross sections for $\gamma\, p \;\rightarrow\; p\, \eta$

- Multipole analysis (L. Tiator et al.: PRC **60** (1999) 035210)
  Bonn as well as Mainz cross section data,
  Graal beam polarization up to 1100 MeV
  $\Rightarrow$ $S_{11}(1535)$, $D_{13}(1520)$, $S_{11}(1650)$, $D_{15}(1675)$, $P_{11}(1440)$, $F_{15}(1680)$
- Isobar model (ETA-MAID by W.T. Chiang, L. Tiator)
  $\Rightarrow$ $S_{11}(1535)$, $D_{13}(1520)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $P_{11}(1710)$, $P_{13}(1720)$ + (ρ, ω) exchange in the t–channel
- *Coupled–channel* analysis (C. Bennhold et al.: PRC **58** (1998), 457 PRC **59** (1999), 460)
  $\Rightarrow$ all known spin–1/2 and spin–3/2 resonances included up to 2 GeV + (ρ, ω) exchange in the t–channel
  $\Rightarrow$ only $S_{11}(1535)$, $D_{13}(1520)$, $S_{11}(1650)$, $D_{13}(1700)$ of importance
- Chiral constituent quark model (B. Saghai and Z. Li: proceedings of N^* conference 2002)
  $\Rightarrow$ all known *** and **** resonances included, no t–exchange contributions !
  $\Rightarrow$ third S_{11} (m = 1780 MeV, Λ = 280 MeV): CLAS data up to E_γ = 2 GeV

Total cross section for the reaction $\gamma\, p \rightarrow p\, \eta$



← The angular coverage of new CB–ELSA data allows determination of the total cross section

CB-ELSA: Hint for N^* resonance $(2080)D_{15}$ (hep-ph/0311045)

$\Rightarrow$ Needs confirmation !

$\Rightarrow$ No need for third S_{11}

Remaining questions:

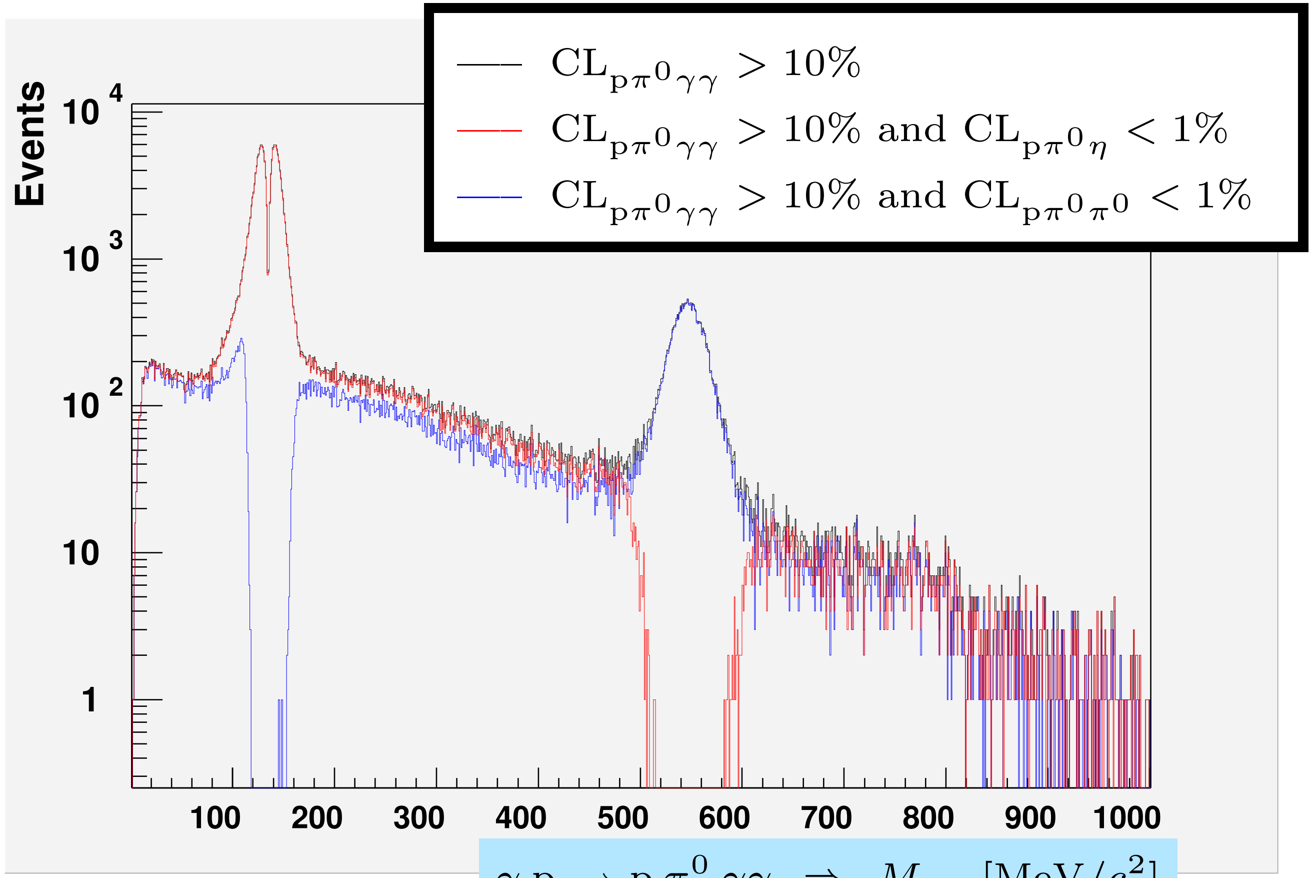
- How do baryon resonances couple to η mesons ?
- Is there evidence for a **third** S_{11} at 1780 MeV ?
- How are η mesons produced at high energies ?

Hidden symmetry for η decays ?

			J=1/2	J=3/2	J=5/2	J=7/2	J=9/2
L=3							
	S=3/2			ND_{13}	N(2200)D_{15}	N(2190)G_{17}	N(2250)G_{19}
	S=1/2				N(2080)D_{15}	N(2080)G_{17}	
L=2							
	S=3/2		N(2100)P_{11}	N(1900)P_{13}	N(2000)F_{15}	N(1990)F_{17}	
	S=1/2			N(1720)P_{13}	N(1680)F_{15}		
L=1							
	S=3/2		N(1650)S_{11}	N(1700)D_{13}	N(1675)D_{15}		
	S=1/2		N(1535)S_{11}	N(1520)D_{13}			

Investigation of the reaction $\gamma\, \mathrm{p} \rightarrow \mathrm{p}\, \pi^0\, \eta$

Data comprises full statistics of a 2001 production run with $E_{e^-} = 3.2$ GeV:



$\gamma\, \mathrm{p} \rightarrow \mathrm{p}\, \pi^0\, \gamma\gamma \;\Rightarrow\; M_{\gamma\gamma}$ [MeV/c^2]

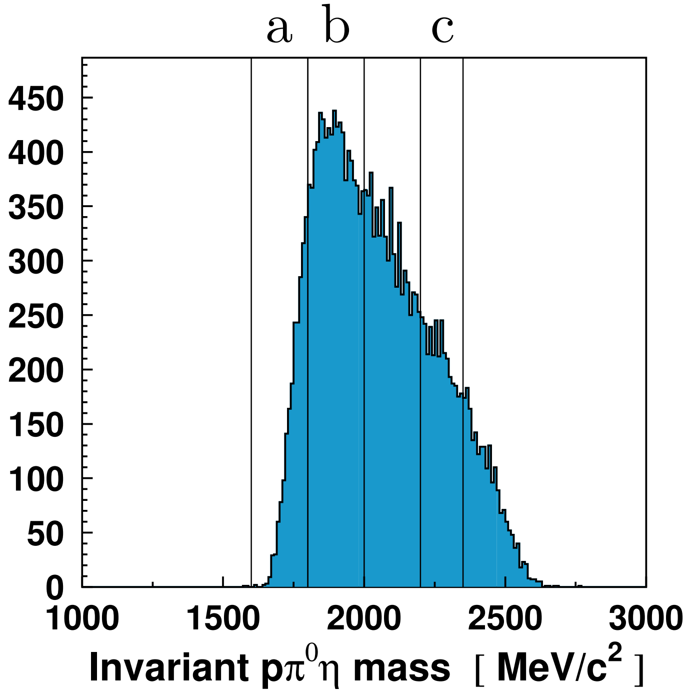
Selection

- 5-particle final states
- proton identification: inner detector
- kinematic fitting
  - energy as well as momentum conservation
  - mass constraints

$\Rightarrow$ Signal to background ratio for mesons:

- for η meson in the reaction $\gamma\, \mathrm{p} \rightarrow \mathrm{p}\, \pi^0\, \eta$: $\approx$ 16 : 1
- for π^0 meson in the reaction $\gamma\, \mathrm{p} \rightarrow \mathrm{p}\, \pi^0\, \pi^0$: $\approx$ 30 : 1

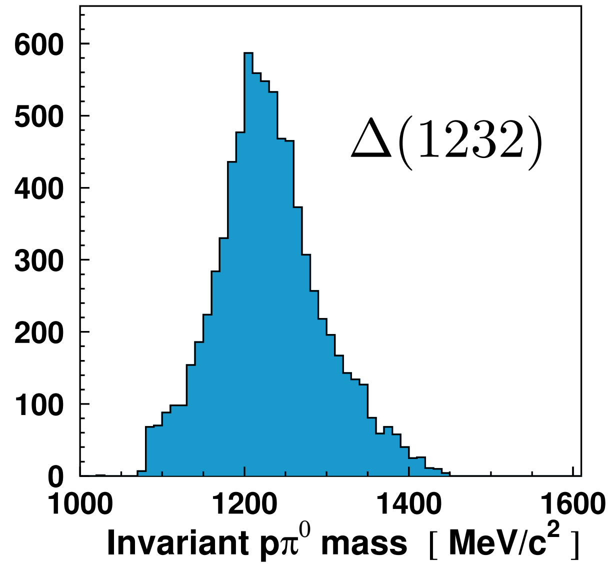
Mass plots for the reaction $\gamma\,\mathbf{p} \;\rightarrow\; \mathbf{p}\,\pi^0\,\eta$ ($E_{\mathrm{e}^-} = 3.2$ GeV)



$1.8 < \sqrt{s} < 2.0$ (in GeV/c^2)

forming invariant $p\pi^0$ mass for (b)

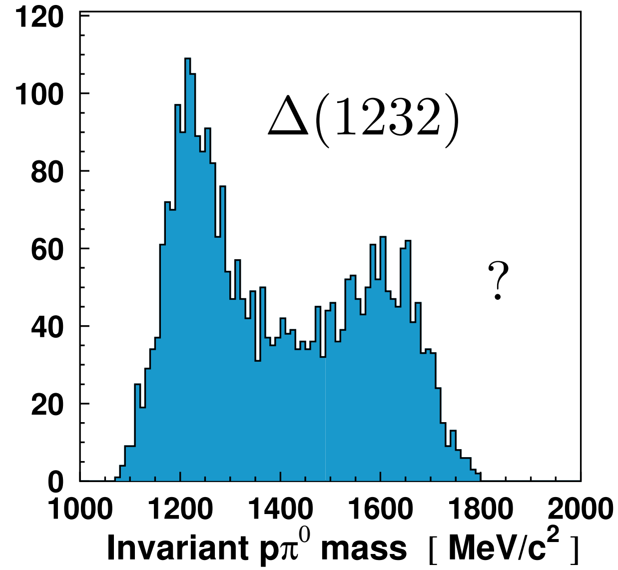
➜



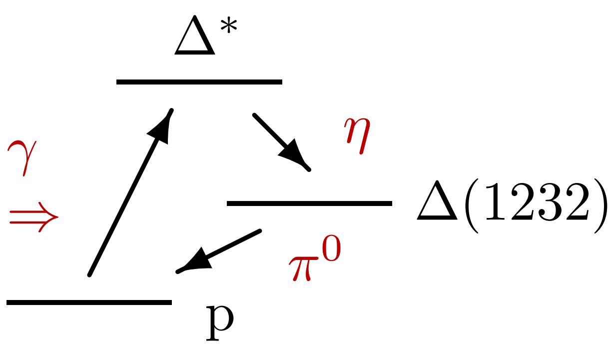
$2.2 < \sqrt{s} < 2.35$ (in GeV/c^2)

forming invariant $p\pi^0$ mass for (c)

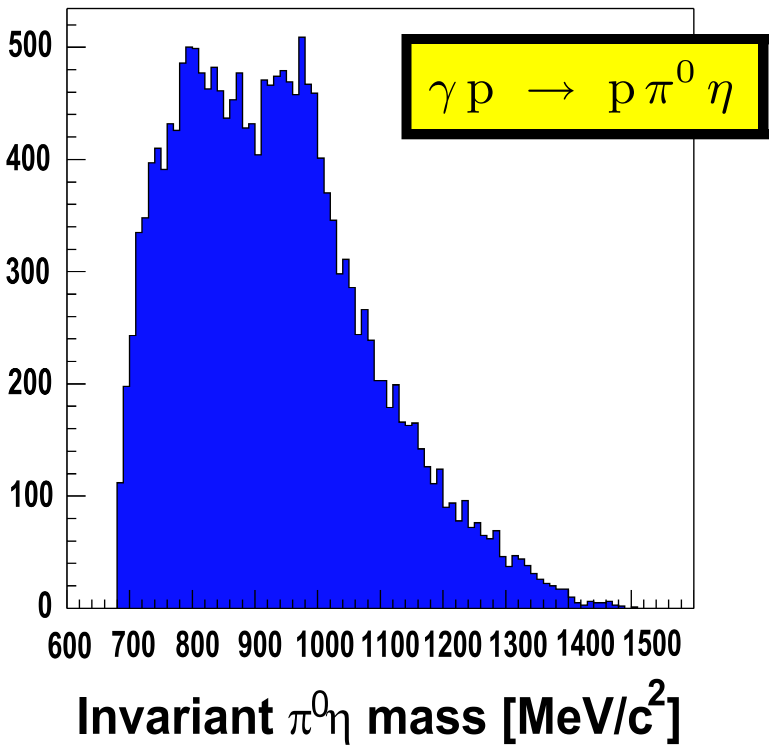
➜



Do we observe $\Delta^* \rightarrow \Delta(1232)\eta$?

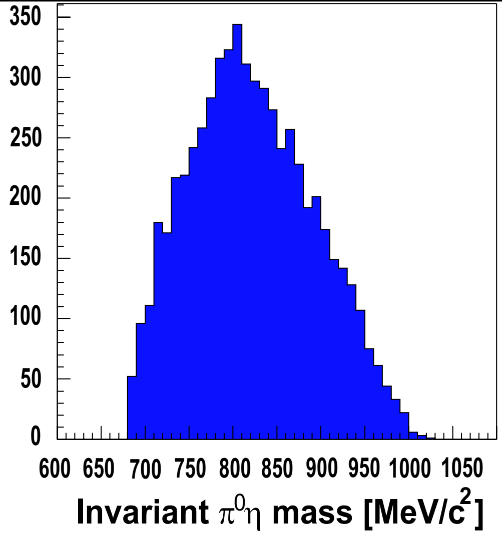


Mass plots for the reaction $\gamma\, \mathrm{p} \;\rightarrow\; \mathrm{p}\, \pi^0\, \eta$ ($E_{\mathrm{e}^-} = 3.2$ GeV)



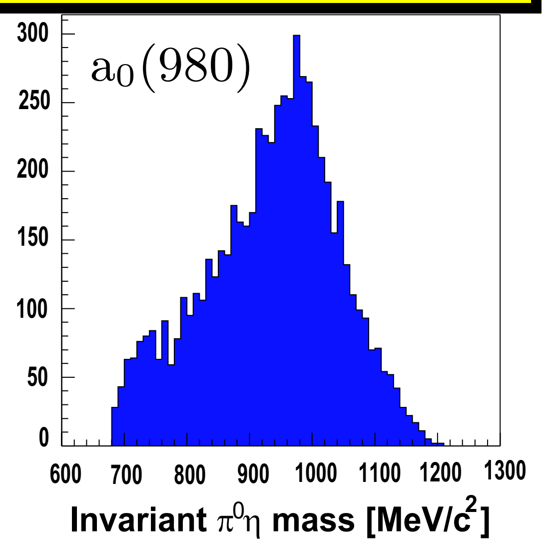
forming invariant $\pi^0\eta$ mass ➜

$1.8 < \sqrt{\mathrm{s}} < 2.0$ (in GeV/c^2)



forming invariant $\pi^0\eta$ mass ➜

$2.0 < \sqrt{\mathrm{s}} < 2.2$ (in GeV/c^2)

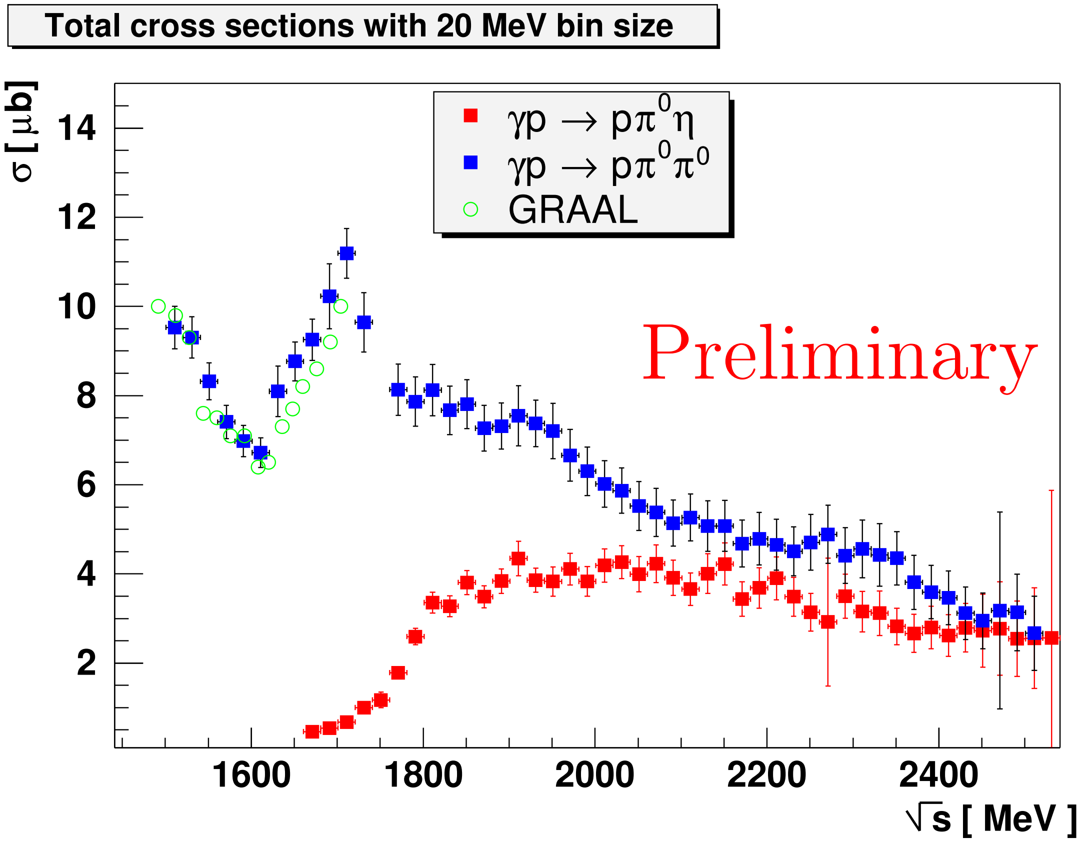


Parameters for $\mathrm{a}_0(980)$ production:

- $E_{\mathrm{threshold}} \approx 1490$ MeV
  $\Rightarrow \sqrt{s} \approx 1920$ MeV$/c^2$

Do we observe $\gamma\, \mathrm{p} \rightarrow \Delta^* \rightarrow \mathrm{a}_0(980)\mathrm{p}$?

Total cross section of $\gamma\, \mathrm{p} \;\rightarrow\; \mathrm{p}\, \pi^0\, \eta$
Performing a PWA: first results

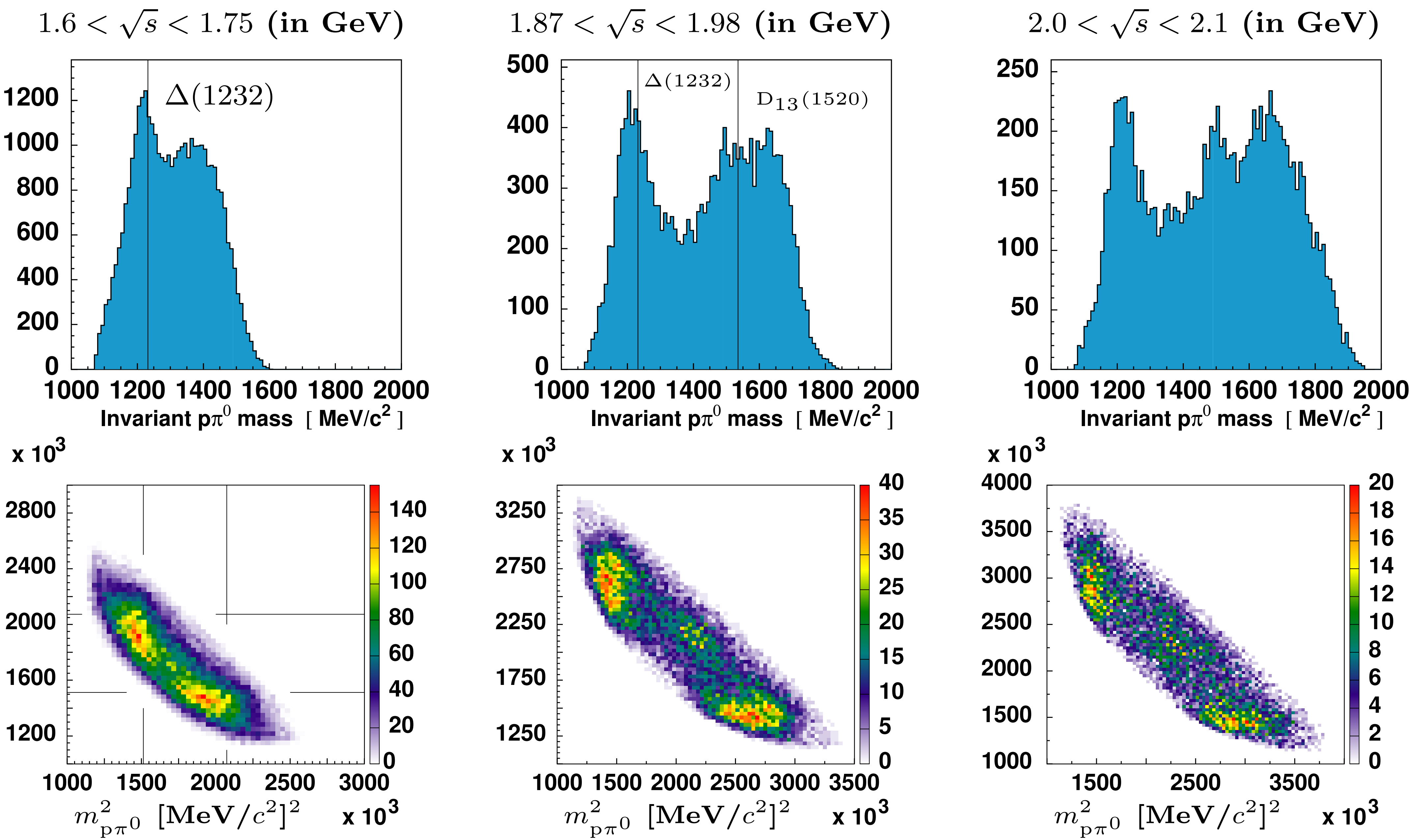


Unbinned maximum likelihood fit:

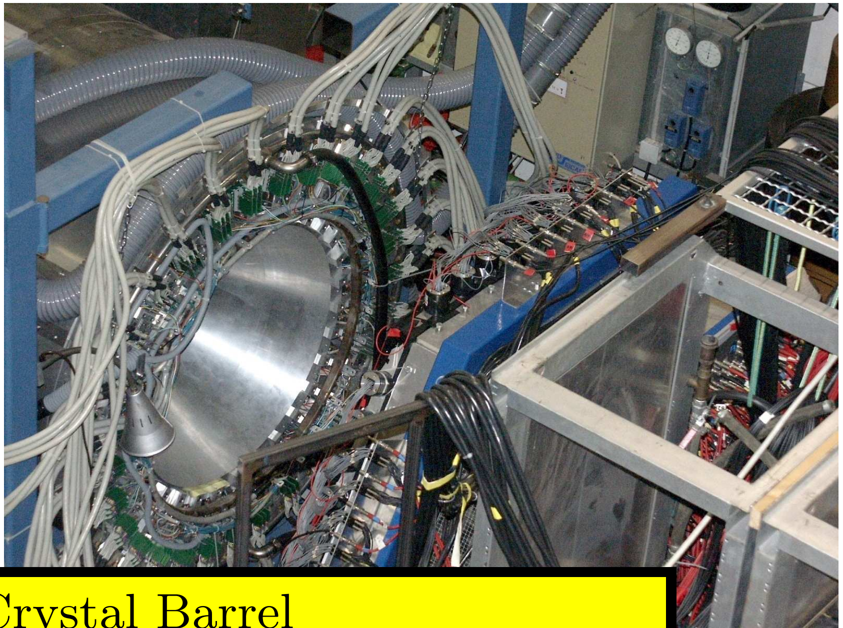
- event-based fit (important for #particles ≥ 3)
- takes all correlations properly into account (5 independent variables)

- New resonances necessary in order to describe data:
  $\Rightarrow$ evidence for $(I = \frac{3}{2}^-, J = \frac{3}{2}^-)$ at ≈ 2.2 GeV
- Hints for contributions from the reaction $\Delta^* \rightarrow \mathrm{a}_0(980)\mathrm{p}$
- Question of negative–parity Δ states around 1900 MeV:
  $\Rightarrow$ solutions ambiguous (polarization necessary)
  $\Rightarrow$ CB/TAPS

Investigation of the reaction $\gamma\, p \;\to\; p\, \pi^0\, \pi^0$ ($E_{e^-} = 3.2$ GeV)



New challenges: linear polarization and CB–TAPS



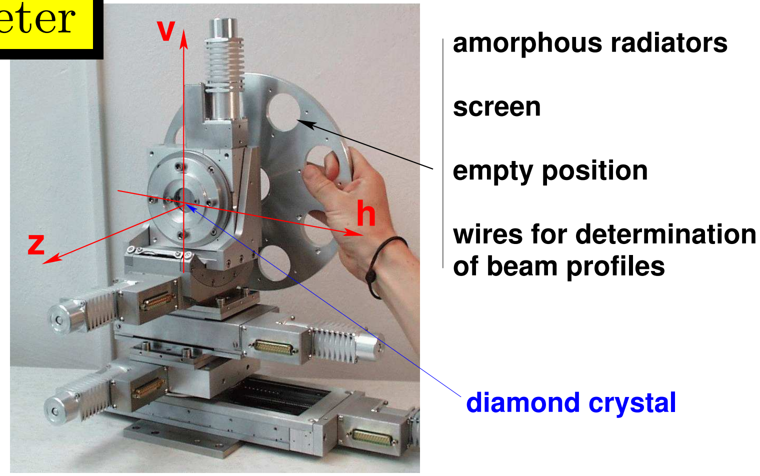
Crystal Barrel

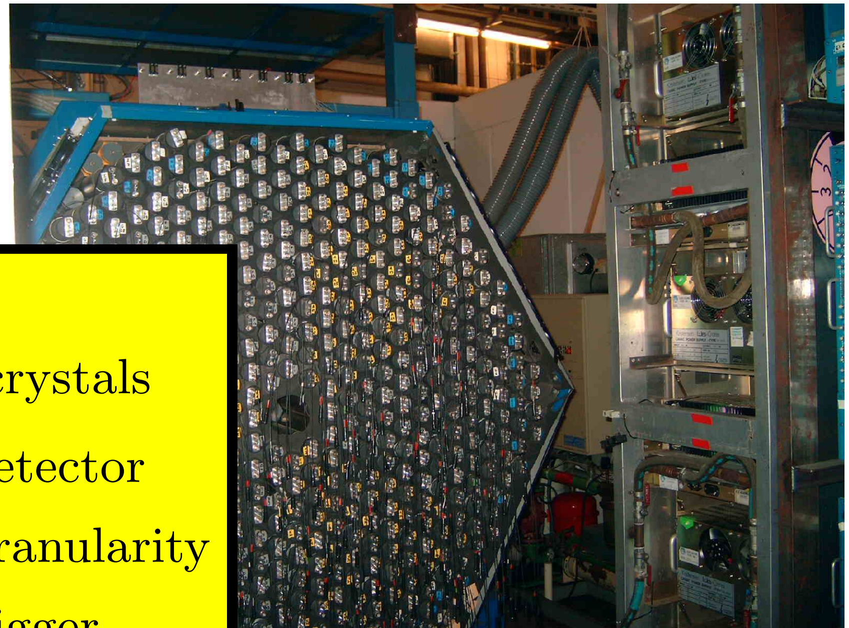
- 180 CsI crystals removed in the forward direction

Data taking: Sep. 2002 – Dec. 2003

- (un)polarized photon beam
- liquid H_2, deuterium
- solid targets

Goniometer





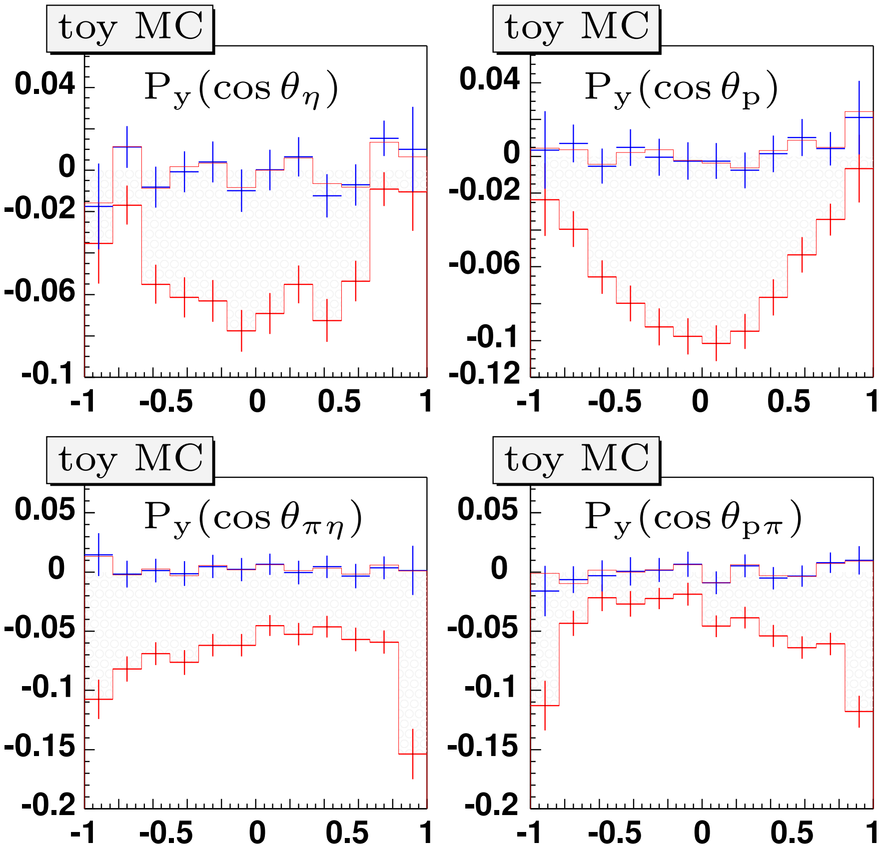
TAPS

- 512 BaF crystals
- forward detector
  - high granularity
  - fast trigger

CB–TAPS: $\vec{\gamma}\,\mathrm{p} \longrightarrow \mathrm{p}\,\pi^0\,\eta$

Polarization observables provide additional pieces of information
$\Rightarrow$ Results of PWA for the reaction $\gamma\,\mathrm{p} \;\longrightarrow\; \mathrm{p}\,\pi^0\,\eta$ are ambiguous

Calculation $\rightarrow$ $(P_T = 100\ \%)$



Example for 2-body final state (E fixed):

$$N(\phi) = N_0(1 + P_T \cdot \Sigma \cdot cos(2\phi))$$

P_T: transversal photon polarization

Σ: photon asymmetry of the reaction

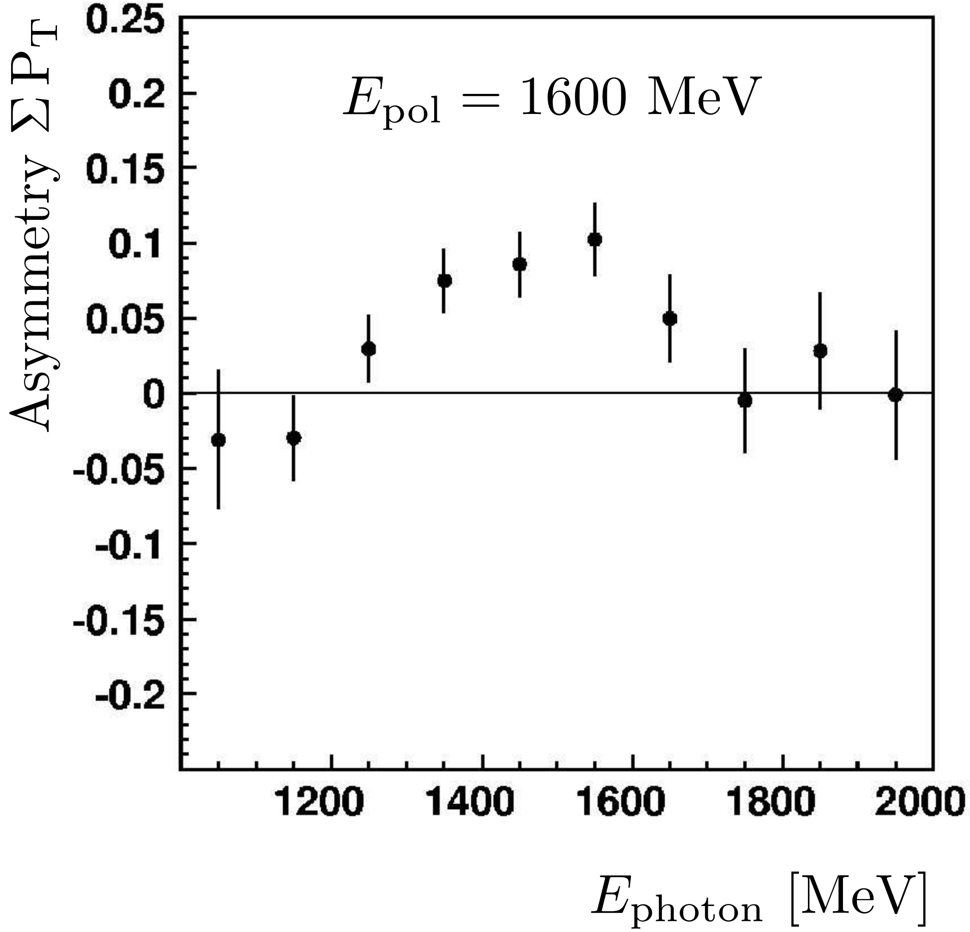
$\mathrm{P_y}$: $P_T \cdot \Sigma$ (one for 2-body decay)

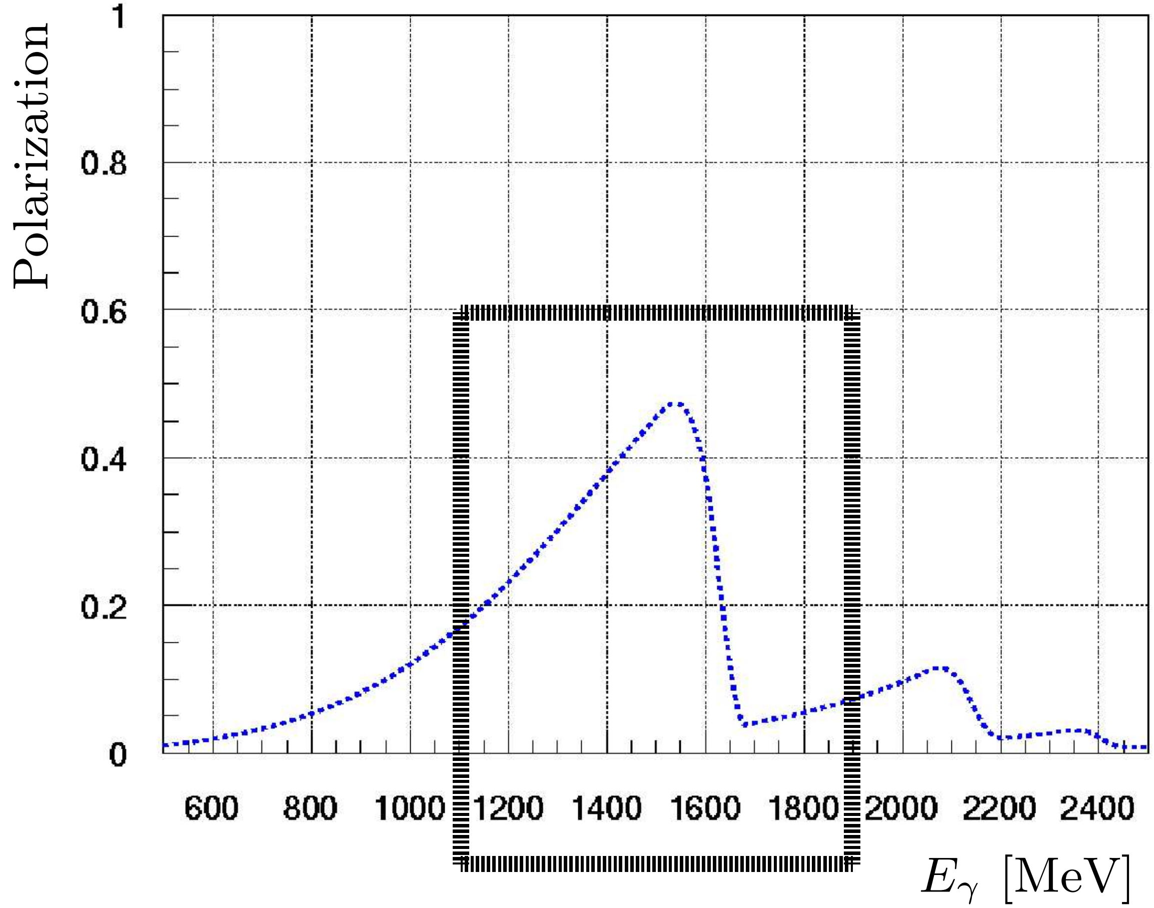
$\Rightarrow$ more for 3-body decay

$$\left\{\begin{array}{l} J^P = 1/2^+ \text{ (polarized and unpolarized)} \\ J^P = 3/2^- \text{ (unpolarized)} \\ J^P = 3/2^- \text{ (polarized)} \end{array}\right.$$

Polarization and observed asymmetries

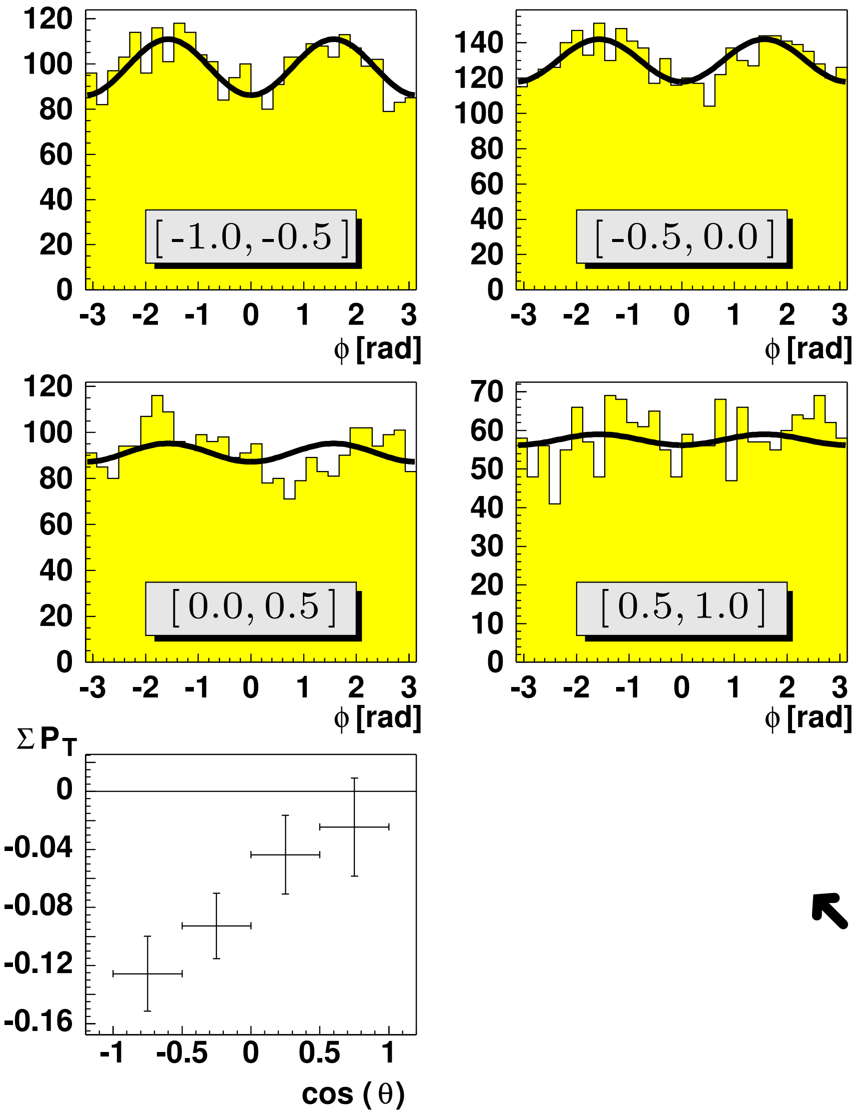
Diamond crystal used to create coherent bremsstrahlung





⇒ Agreement between polarization and observed asymmetry very good !

CB–TAPS (2003 data): $\vec{\gamma}\,\mathrm{p} \rightarrow \mathrm{p}\,\pi^0\,\eta$



Discrimination of ambiguous solutions in the PWA of the unpolarized data
$\rightarrow$ higher sensitivity
(small contributions may have a big effect in certain polarization variables)

170 000 events of the type $\vec{\gamma}\,\mathrm{p} \rightarrow \mathrm{p}\,\pi^0\,\eta$
(30 % of total statistics)

Φ_{π^0} for different $\cos\Theta_{\pi^0}$ bins
(data is not yet acceptance corrected !)
(1440 MeV $\leq E_\gamma \leq$ 1640 MeV)

Summary and conclusion

A: Baryon spectroscopy: Touching upon the question of *missing resonances*

- Observation of baryon cascades in $\gamma\,\mathrm{p} \;\rightarrow\; \mathrm{p}\,\pi^0\,\pi^0$ as well as $\gamma\,\mathrm{p} \;\rightarrow\; \mathrm{p}\,\pi^0\,\eta$
- Hint for new N* resonance $\mathrm{N(2080)D_{15}}$ observed in its decay to pη
  (V. Credé et al., submitted to Phys. Rev. Lett.)
- Hints for further states: $\Delta_{\frac{3}{2}^-}$ around 2.2 GeV/c^2 (in the reaction $\gamma\,\mathrm{p} \;\rightarrow\; \mathrm{p}\,\pi^0\,\eta$)

There is yet a lot more to be discovered!
$\Rightarrow$ Polarization (beam and target)

$\left\{ \begin{array}{l} \text{Crystal Barrel at ELSA} \\ \text{CLAS at JLab, etc.} \end{array} \right.$

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B: Meson spectroscopy: The search for new forms of matter

There are certainly striking observations ($\Rightarrow\;\mathrm{J}^{\mathrm{PC}} = 1^{-+}$) ! ($\Rightarrow$ However, our knowledge is far from solid !) $\Bigg\{$ CLAS at JLab, CLEO-c at Cornell, GlueX at JLab