Статус и перспективы экспериментов с детектором Crystal Ball

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План:

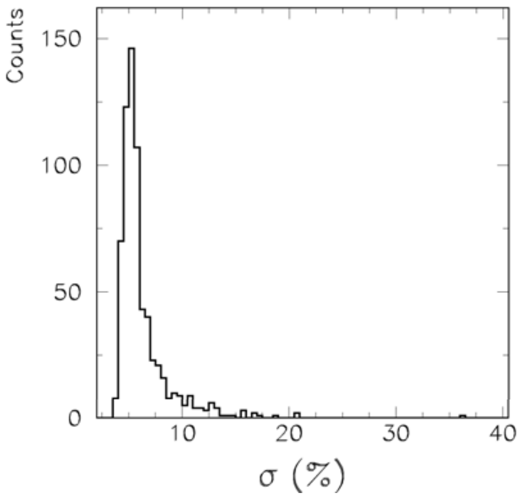
- Введение: детектор Crystal Ball
- Спектроскопия легких барионов
- Некоторые результаты эксперимента в BNL
- CB@MAMI: на пути к “полному набору” измерений
- Физика распадов псевдоскалярных мезонов
- Возможности применения Crystal Ball в JLab
- Заключение

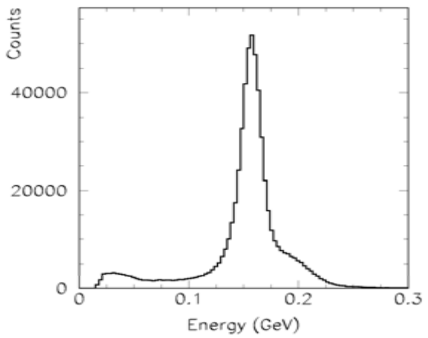
Спектрометер Crystal Ball

- Crystal Ball фотонный спектрометер состоящий из 672 кристаллов NaI и выполненный в форме двух полусфер
- Полусферы герметичны и откачены, вакуум обеспечивает механическую прочность полусфер и низкую влажность вокруг кристаллов.
- Среднее разрешение детектора: $\sigma(E)/E \approx 0.02/\sqrt{E(GeV)}$, $\sigma(\Theta) \approx 2°$

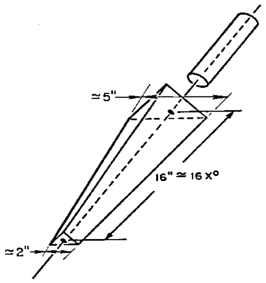
История спектрометра Crystal Ball:

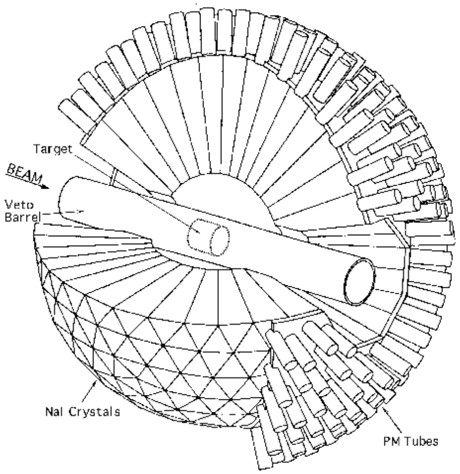
1976: Crystal Ball заложен
1978-1981: SPEAR, e+e- collider (Ecm = 3-7 GeV)
1982-1986: DORIS, e+e- collider (Ecm = 9-10 GeV)
1987-1996: CB на хранении в SLAC
1996-2002: BNL-AGS $\pi^{\pm}$, $K^{\pm}$ (Ecm = 1.2-1.53 GeV)
2002: CB перевезен в MAMI (Ecm = 1.2-2.0 GeV)





The peak is from the monochromatic μ+ from $K^+ \to \mu^+ \nu$ stopped in the middle of the BAll



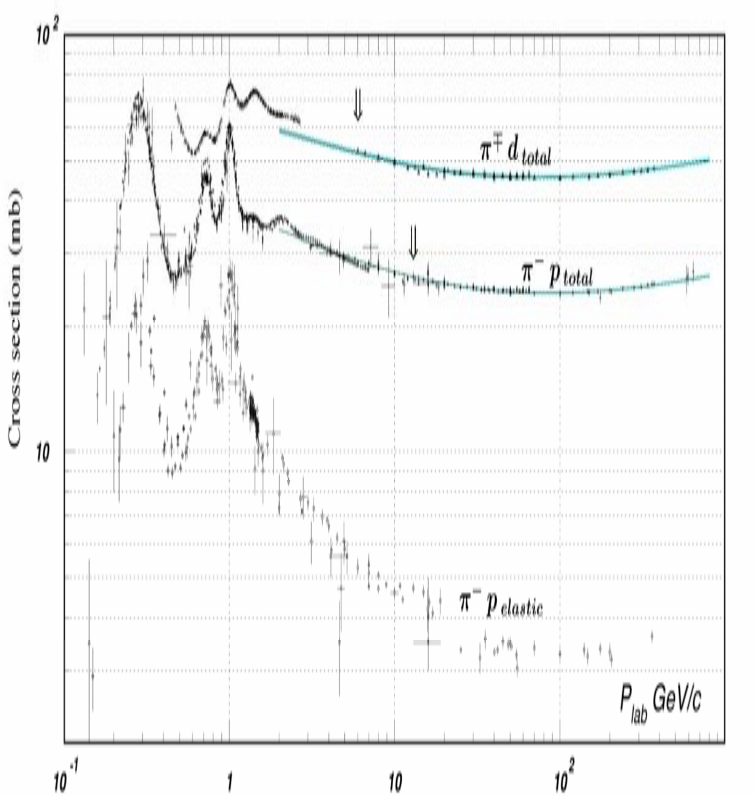


Сильное взаимодействие при низких энергиях

- Problems of hadron physics:
  - Nature and properties of the confinement
  - Relations between QCD and the CQM and other models of hadrons
  - Correlations of color and role of glue in light hadrons
  - Structure of the nucleon
- Tools of non-perturbative QCD:
  - Lattice QCD: significant progress is made, but reliable predictions are matter of the distant future.
  - Hadron models:
    - The constituent quark model
    - Bag/Chiral Bag models
    - Algebraic models
    - Soliton models
    - Color-dielectric models
    - Skyrme models

Задачи и проблемы барионной спектроскопии

- Spectrum and properties of the excited states
- Mystery of missing resonances
- Existence of exotic states: pentaquarks, meson-baryon molecules, *etc*



- N* and Δ* (*uud, udd*) resonances are wide (~100 MeV) and overlapping, the data sets are incomplete, therefore the results of PWA ambiguous, accuracy is not sufficient, the states are too light to be calculated reliably on lattice
- Λ* and Σ* (*uus, uds, dds*) are much narrower, however the existing data set is limited and inconsistent (particularly for Σ*)
- Known Ξ* are very narrow (~10 MeV), the rest of Ξ* is expected to be narrow as well, reliable lattice calculations are possible, however the available data are very limited, quantum numbers are not well known

Детектор Crystal Ball в BNL/AGS

AGS Proposal #913 3 March 1995

Baryon Spectroscopy with the Crystal Ball

Participants: L. D. Isenhower, M. E. Sadler and students, Abilene Christian University

M. Clajus, S. McDonald, T. Moriwaki, B. M. K. Nefkens, W. B. Tippens, D. B. White and students, UCLA

W. J. Briscoe, T. Morrison, Z. Papandreou and students, George Washington University

A. Efendiev and others, Joint Institute for Nuclear Research, Russia

D. M. Manley and students, Kent State University

V. Abaev, V. Bekrenev, N. Kozlenko, S. Kruglov, I. Lopatin, and A. Starostin, Petersburg Nuclear Physics Institute, Russia

M. Batinic, A. Marusic, I. Slaus, I. Supek and A. Svarc, Rudjer Boskovic Institute, Croatia

February 1995

AGS *Proposal*

Title: *Neutral Hyperon Spectroscopy*

Participants: M. Clajus, S. McDonald, T. Moriwaki, B.M.K. Nefkens, W.B. Tippens, D.B. White, students, UCLA

L.D. Isenhower, M.E. Sadler, students, Abilene Christian University

W.J. Briscoe, T. Morrison, students, George Washington University

D.M. Manley, students, Kent State University

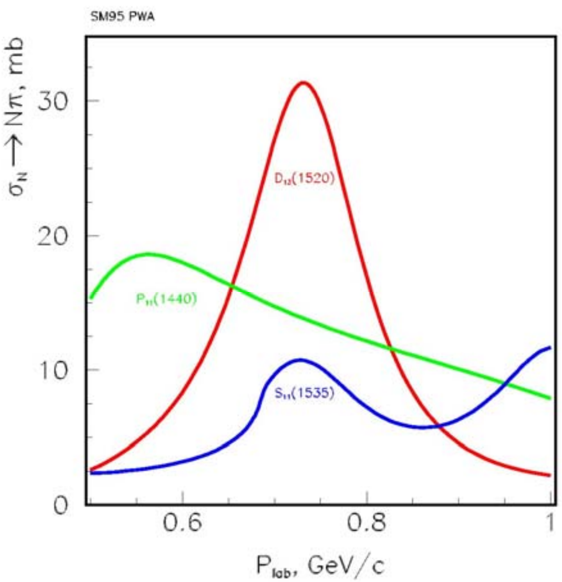
I. Šlaus, A. Švarc, M. Batinić, A. Marušić, Ruder Bošcović, Institute, Zagreb

A. Efendiev and others, JINR, Dubna

V. Abaev, V. Bekrenev, N. Kozlenko, S. Kruglov, I. Lopatin, A. Starostin, St. Petersburg Nuclear Physics Institute, Gatchina

- Properties of P11(1440), S11(1535), D13(1520) from reactions $\pi^- p \to \gamma n$, $\pi^- p \to \pi^0 n$, $\pi^- p \to 2\pi^0 n$, , $\pi^- p \to 3\pi^0 n$, $\pi^- p \to \eta n$
- Properties of hyperon resonances: $\Lambda(1405)$, $\Lambda(1670)$, $\Sigma^0(1385)$ in reactions $K^- p \to \pi^0 \Lambda$, $K^- p \to \pi^0 \Sigma$, $K^- p \to \eta \Lambda$, $K^- p \to 2\pi^0 \Lambda$, $K^- p \to 2\pi^0 \Sigma$, etc

Свойства резонансов P11(1440) и S11(1535)



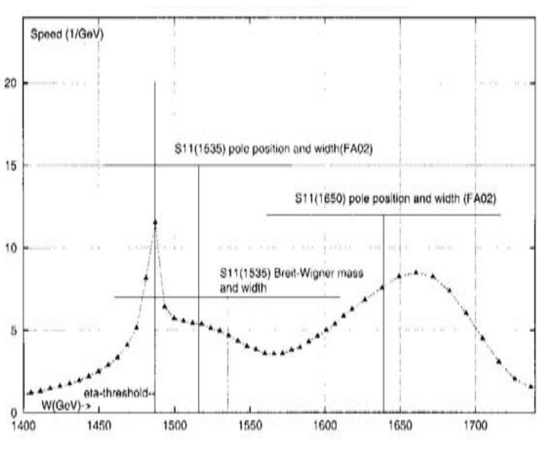


Figure 5: Speedplots near S11(1535) and S11(1650)

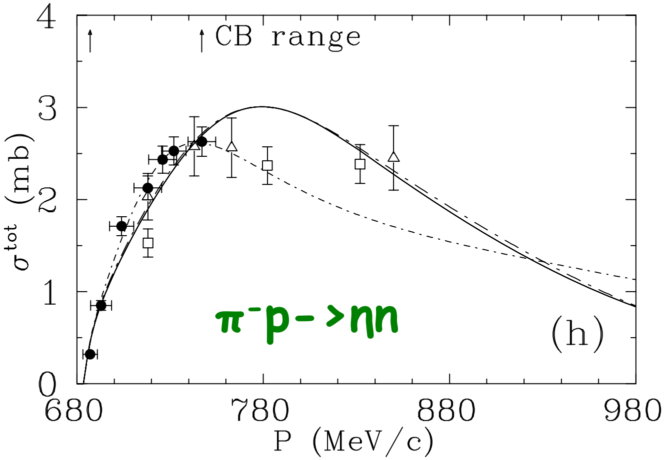
N(1535)S11

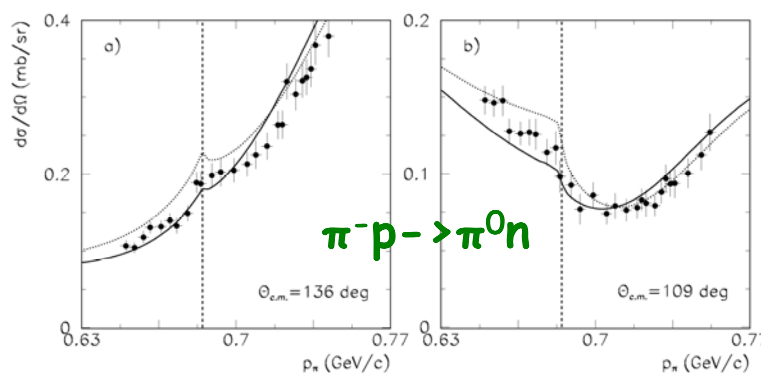
- Unusual properties:
  - Large BR(S11(1535)->ηN) ~ 60%
  - Unusual speed plot
- Suggested interpretations:
  - "cusp" at the threshold of π-p->ηn (Hoehler)
  - KΣ molecule (Kaiser)
  - πN bound state (Oset)

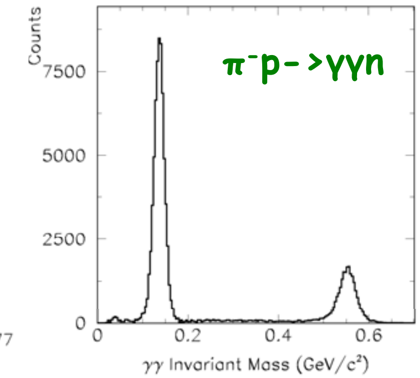
N(1440)P11

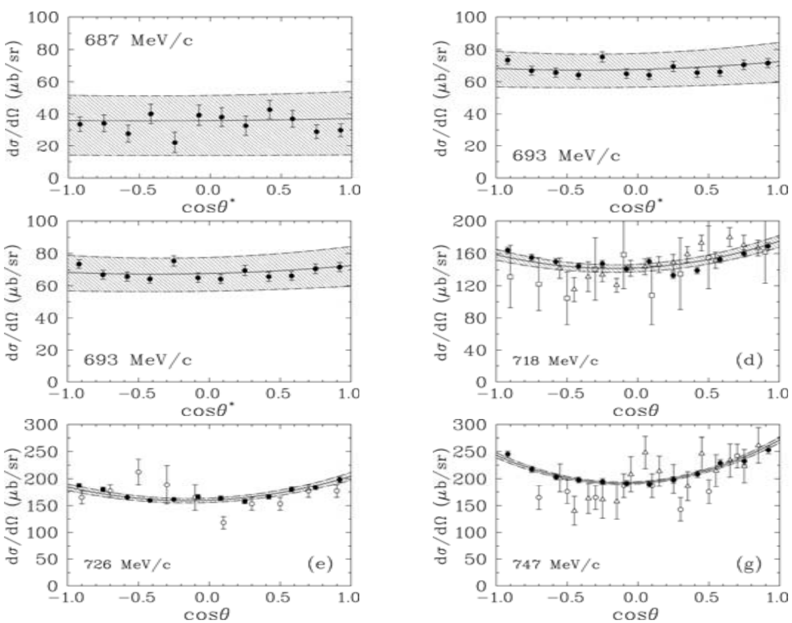
- In the bag model and in the Skyrme model the Roper resonance is surface oscillation ("breathing mode")
- In the CQM two low-mass scalar excitations predicted. For OGE:
  - The mass of the first $\frac{1}{2}+$ exceeds the mass of the $\frac{1}{2}-$ by 80 MeV (experimentally ~100 below)
  - The spacing between the two $\frac{1}{2}+$ resonances is predicted to be ~220 MeV (experimentally ~270 MeV)

Реакции $\pi^- p \to \pi^0 n$ и $\pi^- p \to \eta n$ в области S11(1535)







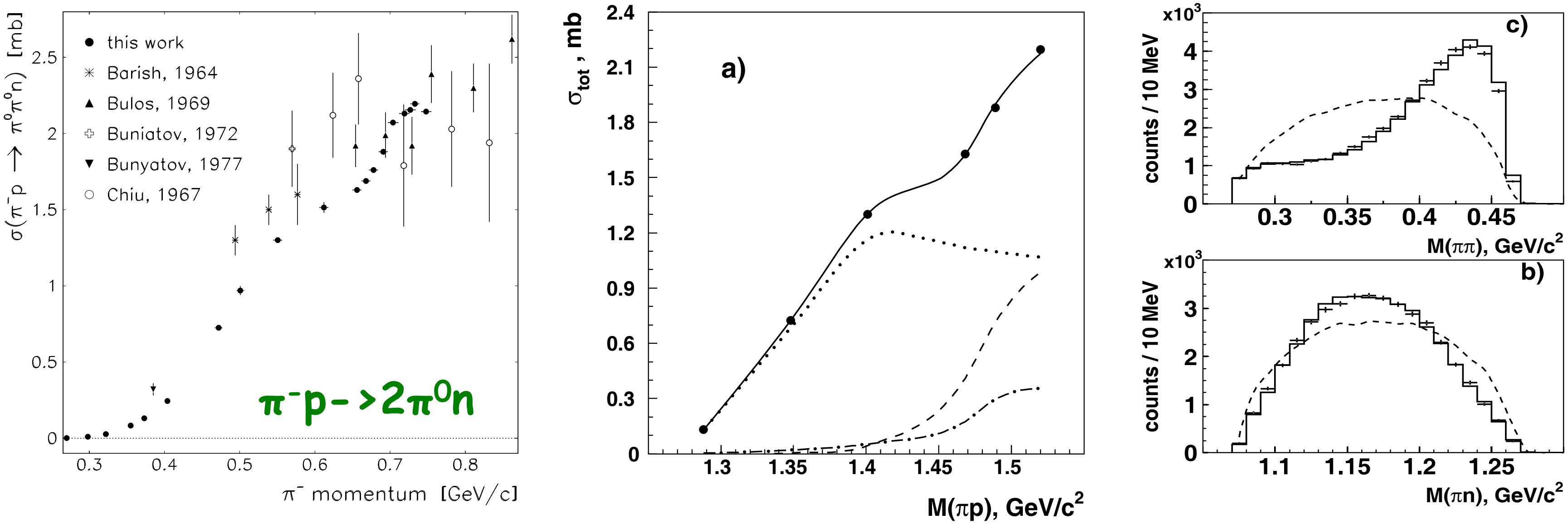


$\pi^- p \to \eta n$

- About 800 new data points for the $\pi^- p \to \pi^0 n$ and $\pi^- p \to \eta n$ diff. cross sections in the region of the S11(1535)
- New parameters for the S11(1535) from the SAID SP06 solution which includes the CB data: M=1502 MeV, Γ=95 MeV (the lower mass is consistent with the latest Bonn PWA)
- Observed cusp on CEX diff. cross sesctions at the opening of the $\pi^- p \to \eta n$ channel
- The total cross section for $\pi^- p \to 3\pi^0 n$ was used to calculated the BR(S11(1535)->P11(1440))$\pi^0 \approx 0.08$

A.Starostin et al., PRC **72**, 015205, 2005
A.Starostin et al., PRC **67**, 068201, 2003
S.Prakhov et al., PRC **72**, 025201, 2005

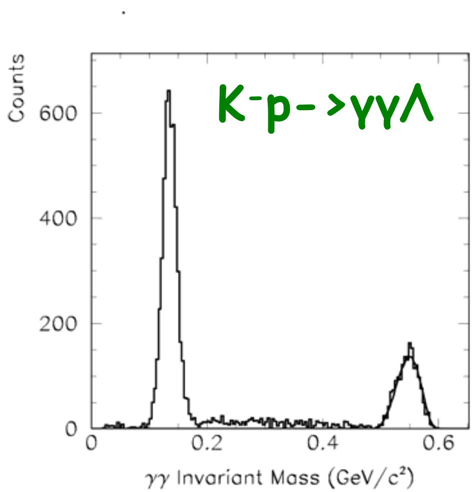
Свойства P11(1440) и $\pi^- p \to 2\pi^0 n$

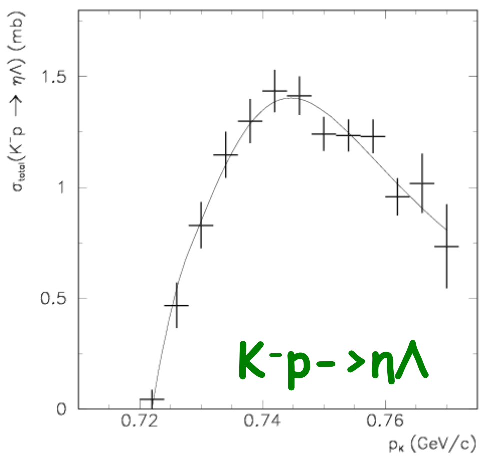


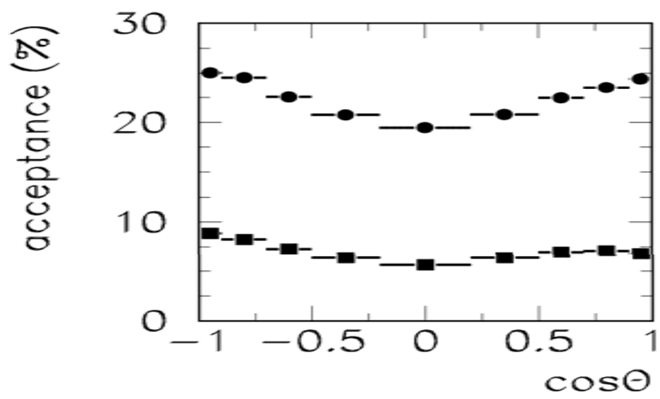
- High statistics Dalitz plot for 15 beam momenta
- Direct observation of the P11(1440) in the total cross section
- Important input to the Bonn-Gatchina analysis (Phys. Lett. B 659:94-100, 2008.)
- New parameters of the Roper:
  - M = 1436 ± 15MeV (Mpole = 1371 ± 7MeV)
  - Γ = 335 ± 40MeV (Γpole = 192 ± 20MeV)
  - ΓπN = 205 ± 25MeV; ΓσN = 71 ± 17MeV; ΓπΔ= 59 ± 15MeV

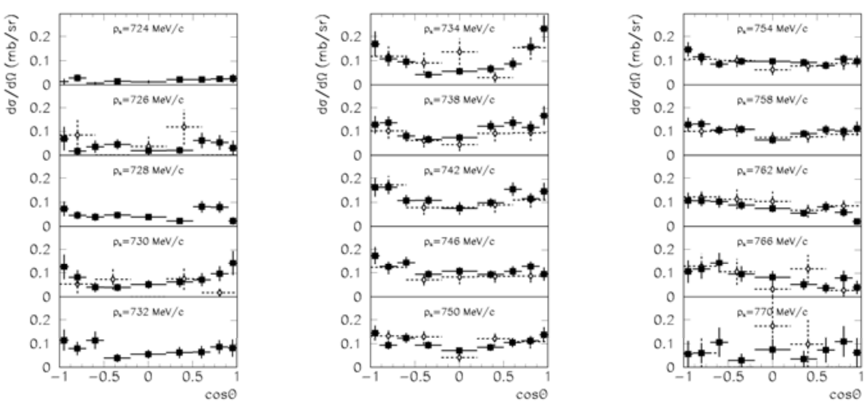
S.Prakhov et al., Phys. Rev. C **69**, 045202, 2004; K.Craig et al., PRC **69**, 045202, 2004

Свойства $\Lambda(1670)$ и $K^- p \to \eta\Lambda$







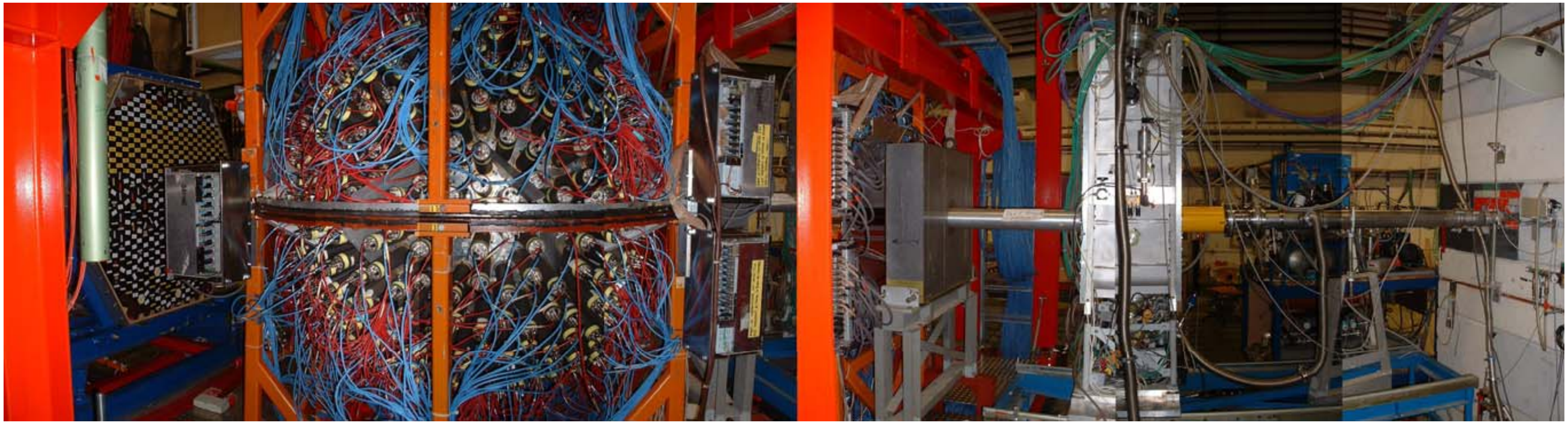


$K^- p \to \eta\Lambda$

- $\Lambda(1670)$ – "strange" analog of the S11(1535) in the flavor symmetry, but much narrower (only $\Gamma \sim 25$ MeV)
- $\Lambda(1670)$ dominates $K^- p \to \eta\Lambda$ near threshold, mass and the width of the resonance can be determined directly from the total c.s.
- New properties of the $\Lambda(1670)$:
  - $M = 1650 \pm 5$ MeV
  - $\Gamma = 24 \pm 4$ MeV

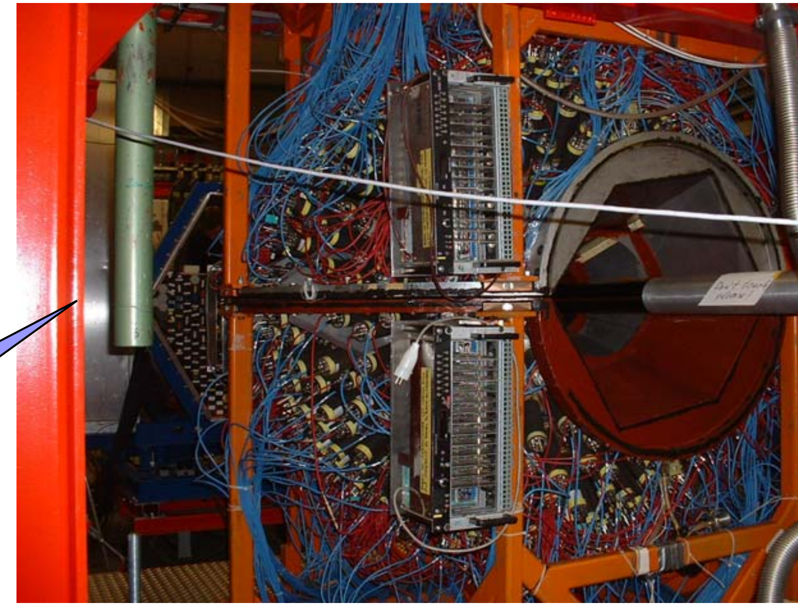
A.Starostin et al., PRC **64**, 55205, 2001

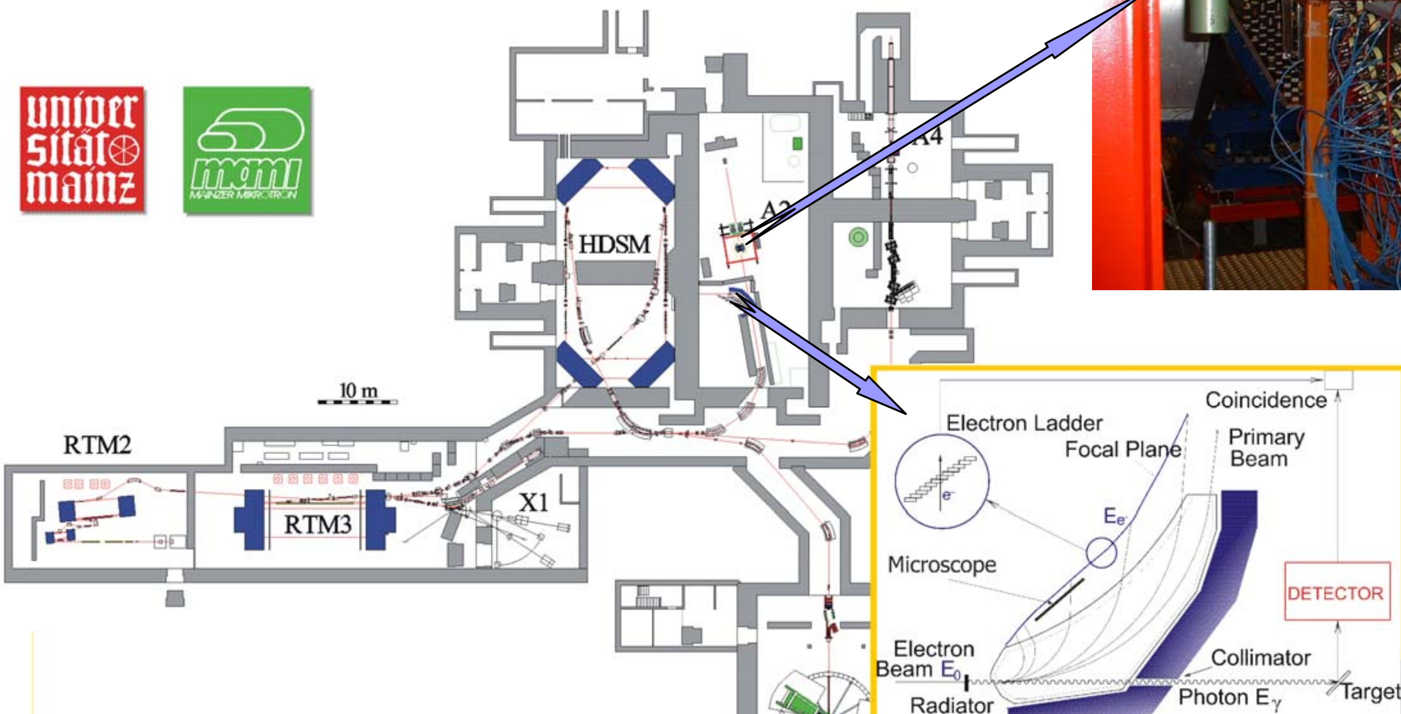
Эксперименты с Crystal Ball в MAMI



- The detector arrived to Mainz in Nov 2002, first data in Summer 2004
- Physics program:
  - Magnetic dipole moment of Δ(1232) and S11(1535) from measurements of radiative $\gamma p \to \pi^0 \gamma p$ and $\gamma p \to \eta p \gamma$
  - Measurements of the polarization and double polarization observables with linearly and circularly polarized beams and longitudinally and transversally polarized hydrogen and deuterium targets
  - Physics of η and η' decays: test of the ChPT, EM form factors, symmetries
  - Medium modification effects with the ω(782) and the pion-pion system
  - Coherent meson production on nuclei
  - Eta-mesic nuclei

Ускоритель MAMI

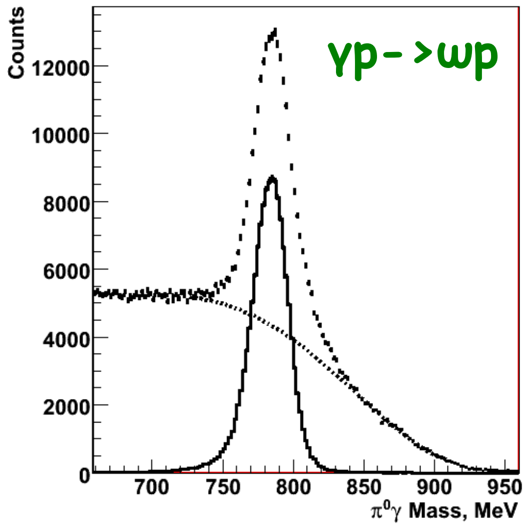


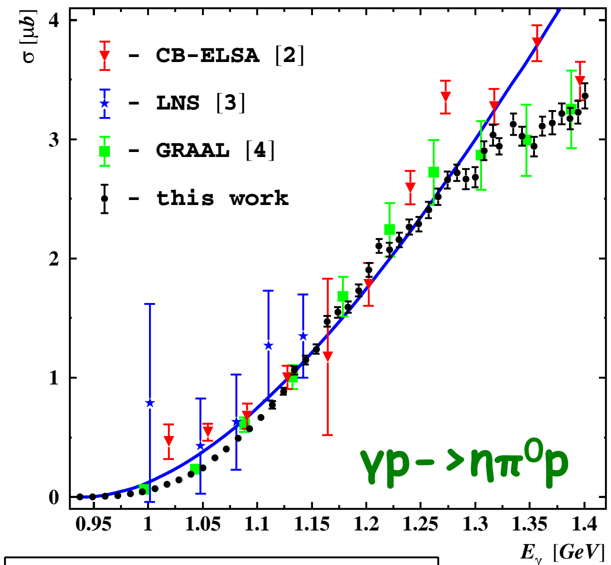


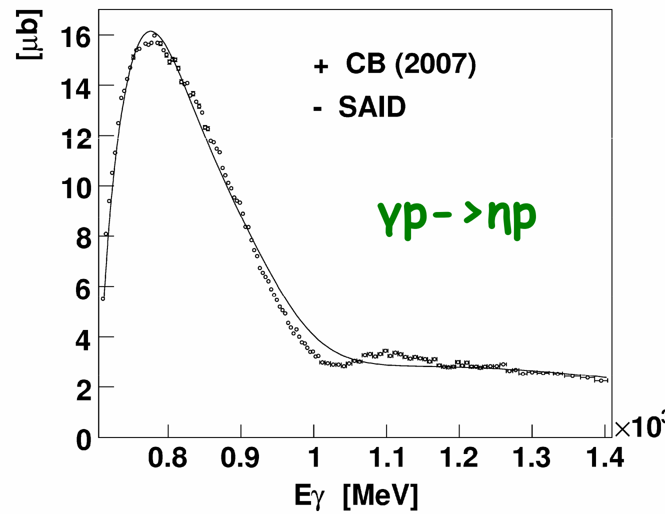
Maximum Electron Energy: 1.5 GeV
Maximum Intensity: 100 mkA
Resolution for photons : 1 MeV

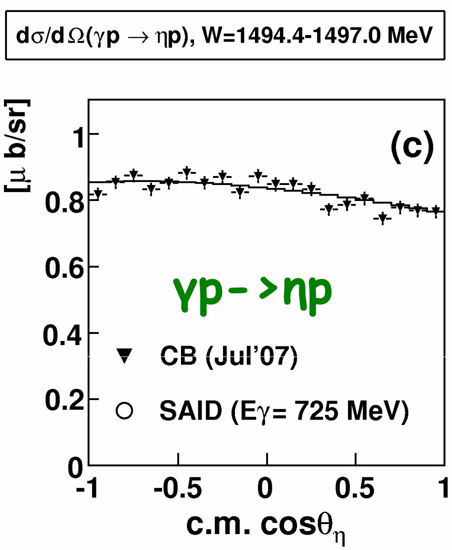
- First run with 1508 MeV beam: spring 2007
- First run with 1558 MeV beam: spring 2009
- First run with 1604 MeV beam: winter 2010?

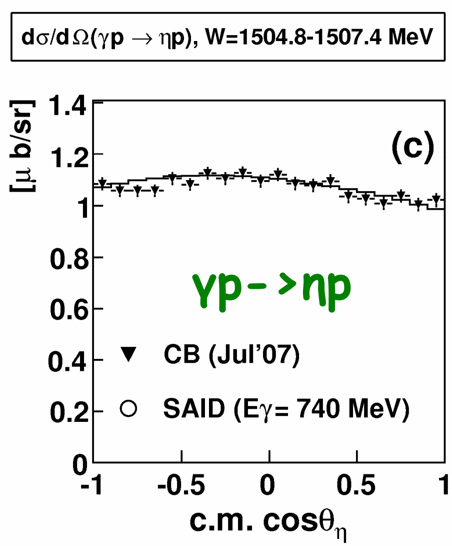
Первые результаты MAMI-C









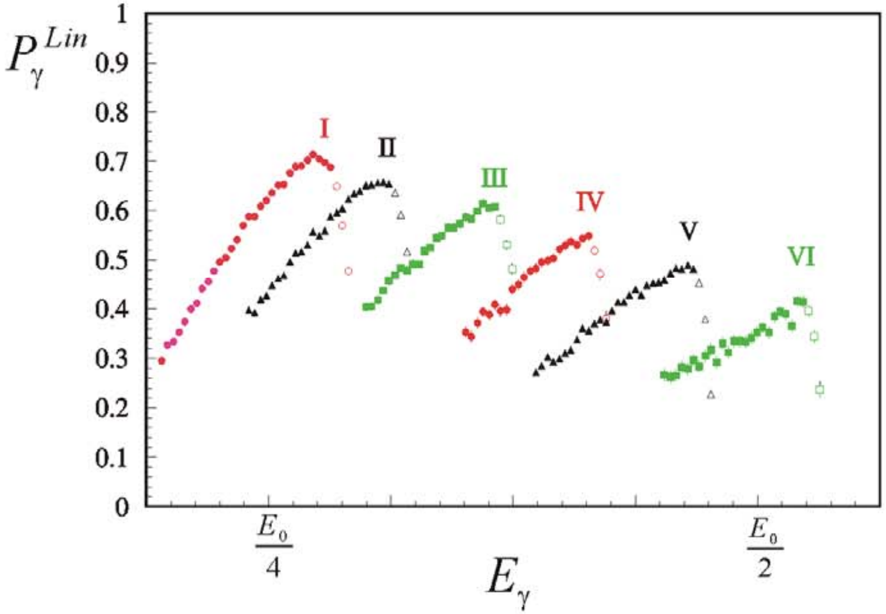


- Properties of the Δ(1700)D33 from the total and the diff. c.s. of γp->ηπ⁰p (V.Kashevarov et al., accepted to Eur. Phys. Jour. A)
- Upper limits for the C forbidden decays of ω(782) (A.Starostin et al., Phys. Rev. 79, 065201, 2009)
- The total and the diff. cross sect. γp->ηp (in preparation)

Polarized Photons @ MAMI C

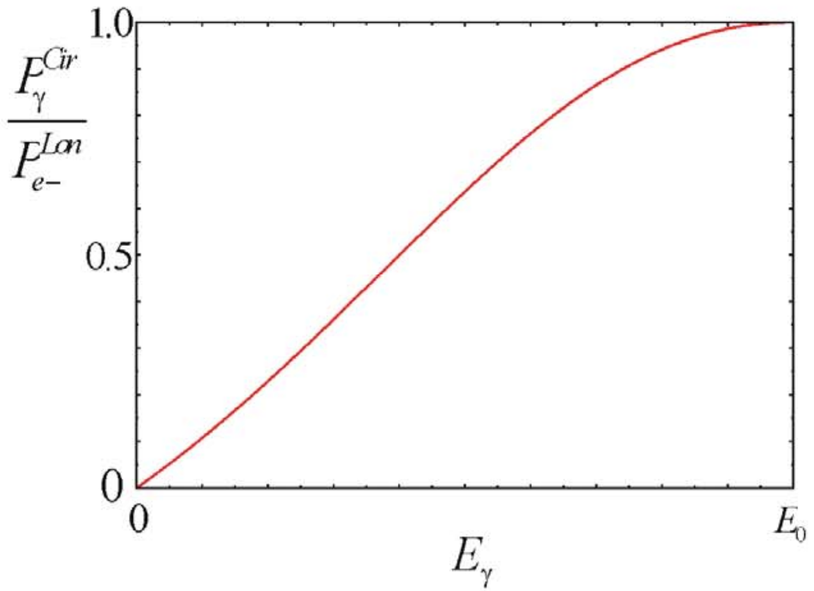
MAMI C : $E_\gamma = 75 - 1425\,MeV$ $\Delta E_\gamma = 4\,MeV$ $N_\gamma = 2 \cdot 10^5\, s^{-1} MeV^{-1}$

linearly polarized photons



$P_\gamma^{Lin} = 70\%$

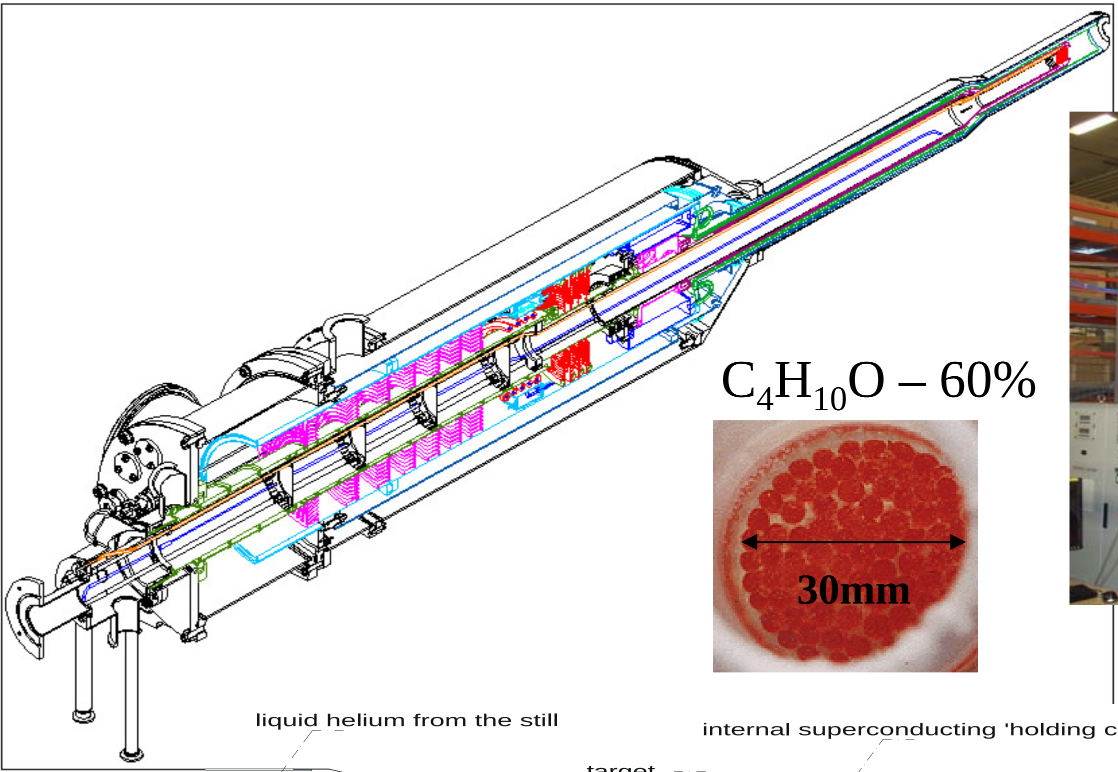
circularly polarized photons

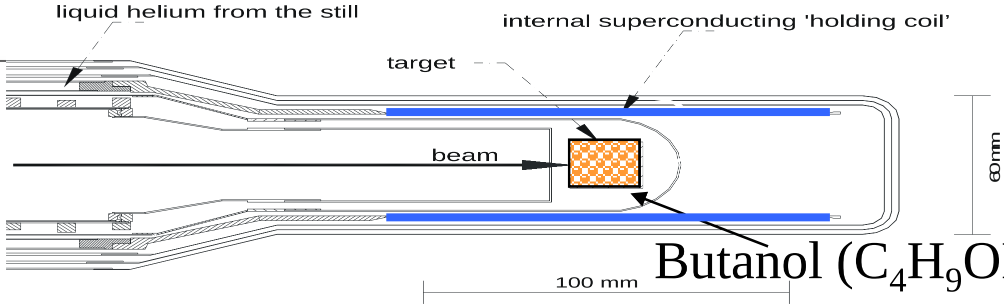


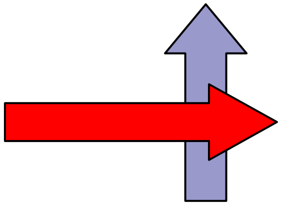
$P_{e-}^{Lon} = 80\% \rightarrow P_\gamma^{Cir} = 80\%$

- high photon flux !
- high polarization !

Поляризованая мишень MAMI





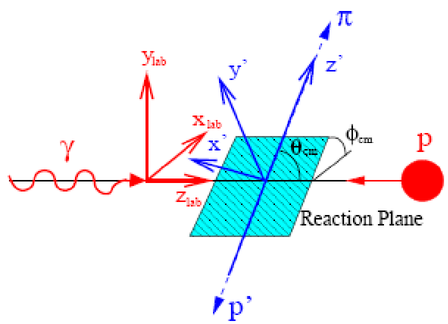


B = 0.5T

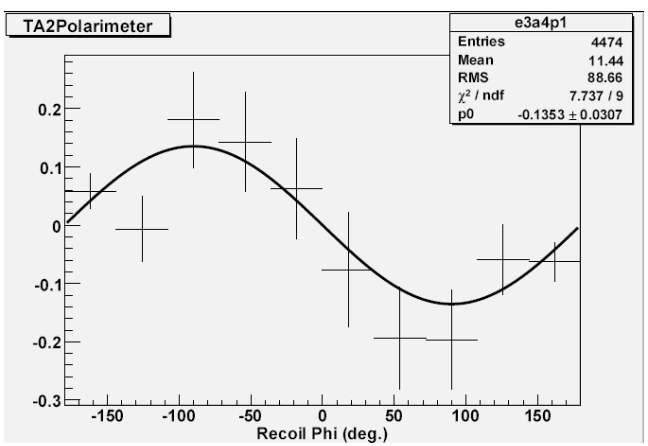
B=2.5T

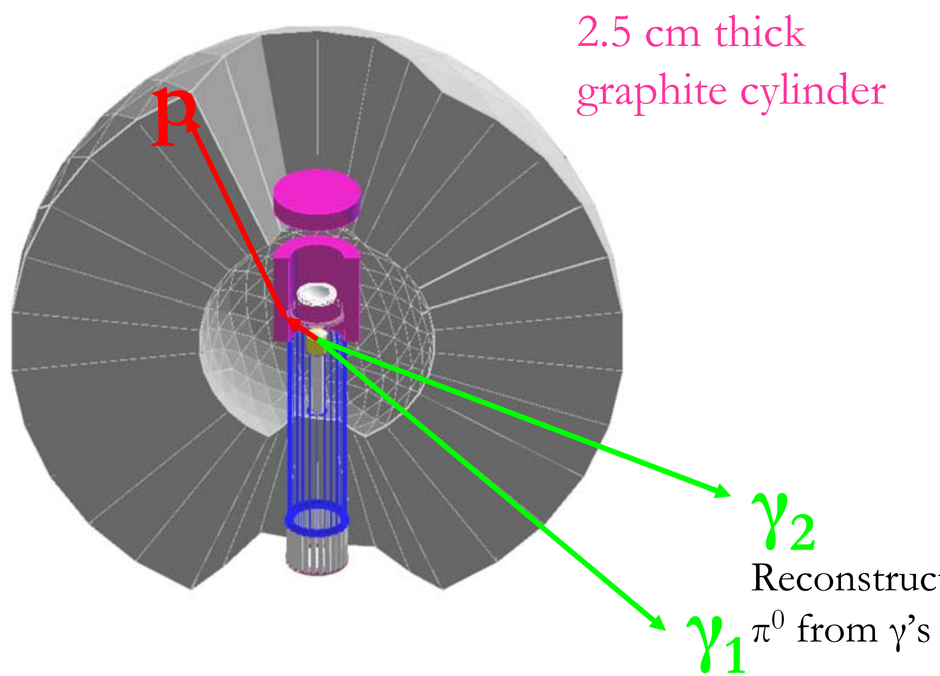
[E.Dzyubak et al., NIM A 526 (2004) 132-137, OPERA3D calculations]

Нуклонный поляриметер MAMI



$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\frac{d\sigma}{d\Omega_{un}} \{1 - P_\gamma^T \Sigma \cos 2\phi - \sigma_{x'} \left(P_\gamma^T O_x \sin 2\phi + P_\gamma^C C \right.$$
$$+\sigma_{y'} \left(P - P_\gamma^T T \cos 2\phi\right) - \sigma_{z'} \left(P_\gamma^T O_z \sin 2\phi + P_\gamma^C C \right.$$





- Initial proton asymmetry is observed for the reactions γp->πp and γp->ηp. The asymmetry is in reasonable agreement with the MAID predictions
- The analysis of a large data set is currently in progress.

“Полный набор” измерений в фоторождении псевдоскалярных мезонов

Usual symbol	Helicity representation	Transversity representation	Experiment required [a)]	Type
$d\sigma/dt$	$\|N\|^2+\|S_1\|^2+\|S_2\|^2+\|D\|^2$	$\|b_1\|^2+\|b_2\|^2+\|b_3\|^2+\|b_4\|^2$	$\{-;-;-\}$	S
$\Sigma\, d\sigma/dt$	$2\mathrm{Re}(S_1^* S_2 - ND^*)$	$\|b_1\|^2+\|b_2\|^2-\|b_3\|^2-\|b_4\|^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$ $\{-;y;y\}$	
$T\, d\sigma/dt$	$2\mathrm{Im}(S_1 N^* - S_2 D^*)$	$\|b_1\|^2-\|b_2\|^2-\|b_3\|^2+\|b_4\|^2$	$\{-;y;-\}$ $\{L(\frac{1}{2}\pi,0);0;y\}$	
$P\, d\sigma/dt$	$2\mathrm{Im}(S_2 N^* - S_1 D^*)$	$\|b_1\|^2-\|b_2\|^2+\|b_3\|^2-\|b_4\|^2$	$\{-;-;y\}$ $\{L(\frac{1}{2}\pi,0);y;-\}$	
$G\, d\sigma/dt$	$-2\mathrm{Im}(S_1 S_2^* + ND^*)$	$2\mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H\, d\sigma/dt$	$-2\mathrm{Im}(S_1 D^* + S_2 N^*)$	$-2\mathrm{Re}(b_1 b_3^* - b_2 b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	
$E\, d\sigma/dt$	$\|S_2\|^2-\|S_1\|^2-\|D\|^2+\|N\|^2$	$-2\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$	$\{c;z;-\}$	
$F\, d\sigma/dt$	$2\mathrm{Re}(S_2 D^* + S_1 N^*)$	$2\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$	$\{c;x;-\}$	
$O_x\, d\sigma/dt$	$-2\mathrm{Im}(S_2 D^* + S_1 N^*)$	$-2\mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z\, d\sigma/dt$	$-2\mathrm{Im}(S_2 S_1^* + ND^*)$	$-2\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	
$C_x\, d\sigma/dt$	$-2\mathrm{Re}(S_2 N^* + S_1 D^*)$	$2\mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$	$\{c;-;x'\}$	
$C_z\, d\sigma/dt$	$\|S_2\|^2-\|S_1\|^2-\|N\|^2+\|D\|^2$	$-2\mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$	$\{c;-;z'\}$	
$T_x\, d\sigma/dt$	$2\mathrm{Re}(S_1 S_2^* + ND^*)$	$2\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;x'\}$	TR
$T_z\, d\sigma/dt$	$2\mathrm{Re}(S_1 N^* - S_2 D^*)$	$2\mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$	$\{-;x;z'\}$	
$L_x\, d\sigma/dt$	$2\mathrm{Re}(S_2 N^* - S_1 D^*)$	$2\mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;x'\}$	
$L_z\, d\sigma/dt$	$\|S_1\|^2+\|S_2\|^2-\|N\|^2-\|D\|^2$	$2\mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$	$\{-;z;z'\}$	

a) [illegible]

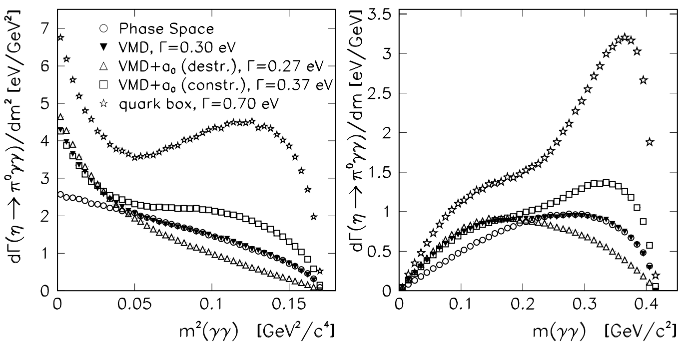
“… a necessary and sufficient condition that three measurements give complete information up to an overall phase and up to discrete ambiguities when taken together with dσ/dt, Σ, P and T is that the three measurements are not all taken from the same set.”

“To eliminate the discrete ambiguities … two further measurements will suffice, provided that of the five double polarization measurements … no four come from the same set.”

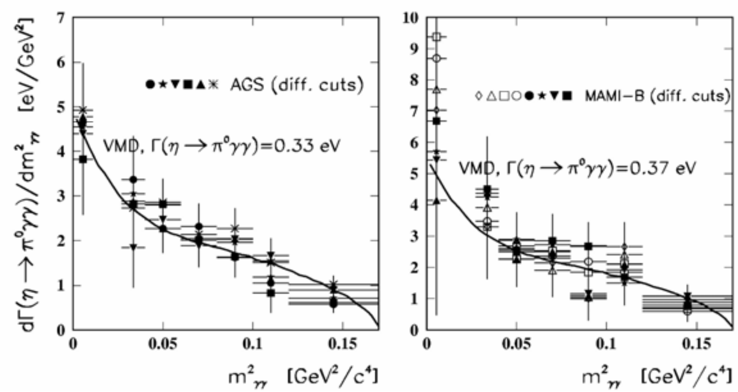
I.S.Berker, A.Donnachie, J.K.Storrow, Nucl. Phys. B95 (1975) 347

Observable	Polarisation of γ	target	recoil	
1. $\{d\sigma/d\Omega\}/\mathcal{N}$				$= \|b_1\|^2 + \|b_2\|^2 + \|b_3\|^2 + \|b_4\|^2$
Single polarization				
2. P			y'	$= \|b_1\|^2 - \|b_2\|^2 + \|b_3\|^2 - \|b_4\|^2$
3. Σ	p			$= \|b_1\|^2 + \|b_2\|^2 - \|b_3\|^2 - \|b_4\|^2$
4. T		y		$= \|b_1\|^2 - \|b_2\|^2 - \|b_3\|^2 + \|b_4\|^2$
Double polarizaton				
Beam-target				
5. E	c	z		$=2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
6. F	c	x		$=2\,\mathrm{Im}(b_1 b_3^* - b_2 b_4^*)$
7. G	t	z		$=2\,\mathrm{Im}(b_1 b_3^* + b_2 b_4^*)$
8. H	t	x		$=-2\,\mathrm{Re}(b_1 b_3^* + b_2 b_4^*)$
Beam-recoil				
9. C_x	c		x'	$=-2\,\mathrm{Im}(b_1 b_4^* - b_2 b_3^*)$
10. C_y	c		z'	$=2\,\mathrm{Re}(b_1 b_4^* + b_2 b_3^*)$
11. O_x	t		x'	$=2\,\mathrm{Re}(b_1 b_4^* - b_2 b_3^*)$
12. O_z	t		z'	$=2\,\mathrm{Im}(b_1 b_4^* + b_2 b_3^*)$
Target-recoil				
13. T_x		x	x'	$=2\,\mathrm{Re}(b_1 b_2^* - b_3 b_4^*)$
14. T_z		x	z'	$=2\,\mathrm{Im}(b_1 b_2^* - b_3 b_4^*)$
15. L_x		z	x'	$=-2\,\mathrm{Im}(b_1 b_2^* + b_3 b_4^*)$
16. L_z		z	z'	$=2\,\mathrm{Re}(b_1 b_2^* + b_3 b_4^*)$

Матричный элемент η->π°γγ

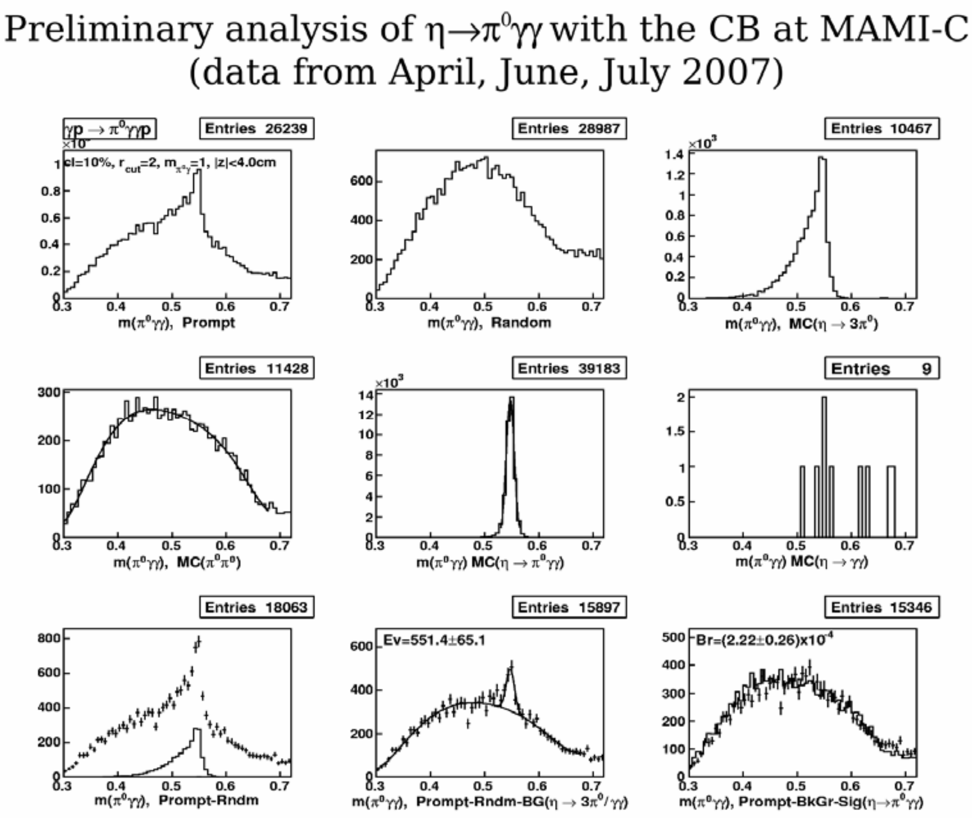


The CB (AGS and MAMI-B) results on the yield of $\eta\to\pi^0\gamma\gamma$ as a function of $m^2(\gamma\gamma)$ and comparison with the VMD prediction



- m(γγ), Dalitz plot of η->π°γγ:
  - Can be used to test quark models, VMD
- η->π°γγ in ChPT:
  - The leading order of η->π°γγ is forbidden because there is no direct γ-π⁰ and γ-η coupling
  - The tree diagram of the second order is also forbidden for the same reason
  - The loop diagram of the second order is suppressed because it violates G-parity
  - The third order is the first allowed term, there for the decay width and the Dalitz plot of the decay are sensitive to the third and higher orders of the ChPT expansion

Измерения η->π°γγ на MAMI-C

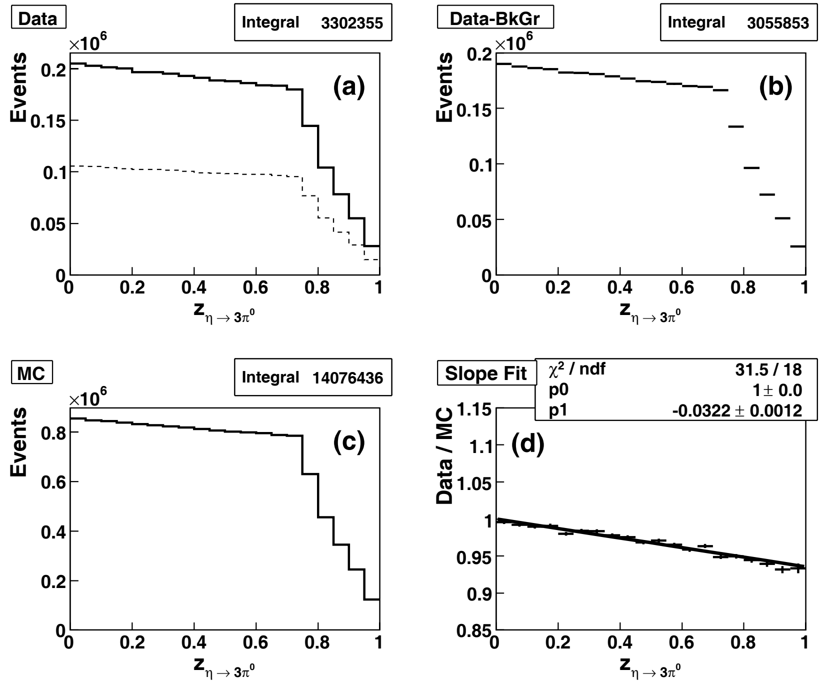


- AGS statistics: 500-1000 η->π°γγ depending on cuts (about 30M eta's total)
- Current MAMI-C statistics (2007-2009): 1000-2000 η->π°γγ depending on cuts (about 60M eta's total)
- We propose to increase statistics by factor 5: to about 10000 η->π°γγ events. This sample will be used to investigate the Dalitz plot and the matrix element

$\eta \to 3\pi^0$ Dalitz plot

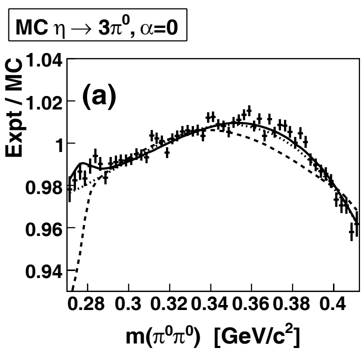
Physical motivation: tests of χPTh calculations

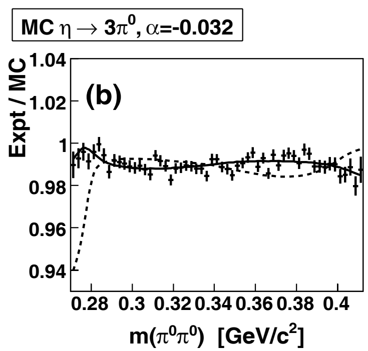
- $\eta \to 3\pi^0$ - G-parity violating strong interaction, occurring due to the m_d-m_u difference
- $A(\eta \to 3\pi^0) \sim (m_d - m_u)(1+\alpha z)$,
  $\Gamma(\eta \to 3\pi^0) \sim (m_d - m_u)^2(1+2\alpha z)$,
  $z = 6/(m_\eta - 3m_{\pi 0})^2 \Sigma_i (E^i_{\pi 0} - m_\eta/3)^2 = \rho^2/\rho^2_{max}$;
  precise measurement of α is required for a better calculation of $\Gamma(\eta \to 3\pi^0)$, needed for the m_u-m_d difference
- Analysis of the $\pi^0\pi^0$ invariant mass in the vicinity of the $\pi^+\pi^-$ threshold to search for a cusp, providing a test of the χPTh prediction for the S-wave scattering length combination a0-a2 and comparison with the $K^+ \to \pi^+\pi^0\pi^0$ results



S. Prakhov *et al.* Phys. Rev. C 79 035204 (2009)
M. Unverzagt *et al.* Eur. Phys. J. A39 169 (2009)

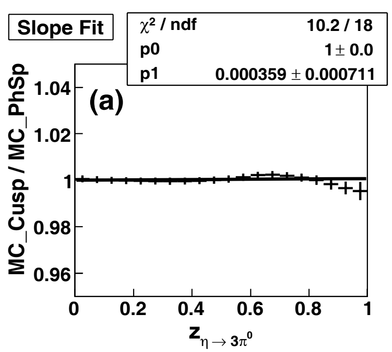
η->3π° Dalitz plot

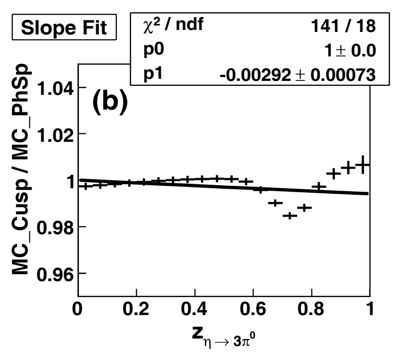




Experiment	Refs.	α
Crystal Ball at BNL	[14]	-0.031 ± 0.004
KLOE	[15]	$-0.027 \pm 0.004^{+0.004}_{-0.006}$
GAMS-2000	[17]	-0.022 ± 0.023
Crystal Barrel	[18]	$-0.052 \pm 0.017 \pm 0.010$
SND	[19]	$-0.010 \pm 0.021 \pm 0.010$
CELSIUS/WASA	[20]	$-0.026 \pm 0.010 \pm 0.010$
WASA at COSY	[21]	$-0.027 \pm 0.008 \pm 0.005$

Crystal Ball at MAMI-C -0.032 ± 0.003
Crystal Ball at MAMI-B -0.032 ± 0.002 ± 0.002





Calculation	Refs.	α
χPT $\mathcal{O}(p^2)$	[11]	0
χPT $\mathcal{O}(p^4)$	[11]	0.015
χPT $\mathcal{O}(p^6)$	[6]	0.013 ± 0.032
Dispersion	[7]	$-0.007 \ldots -0.014$
UCHPT	[9]	-0.031 ± 0.003

B.Holstein at "MAMI and beyond" workshop, 2009

Dalitz and double Dalitz decays

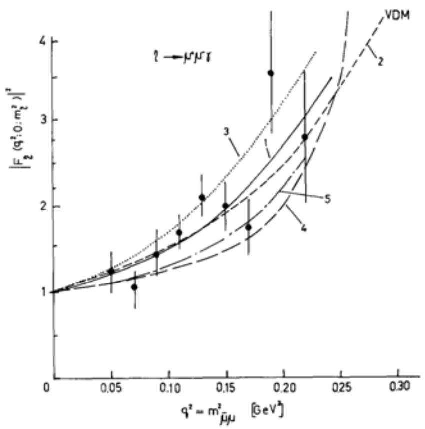
$\eta \to l^+l^-\gamma$

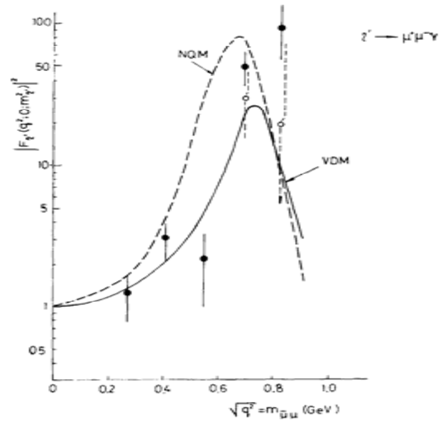
$\eta \to l^+l^-l^+l^-$

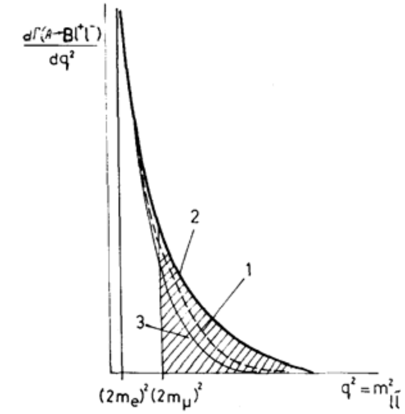
$\omega \to l^+l^-\pi^0$

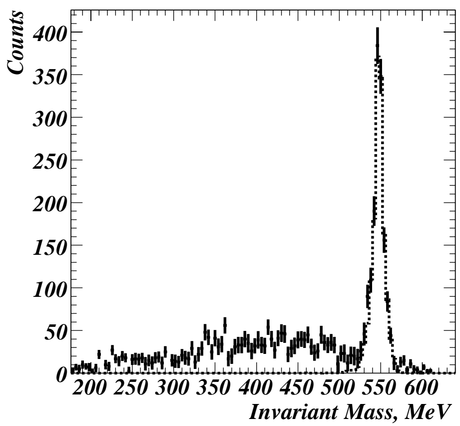
$\eta' \to l^+l^-\gamma$

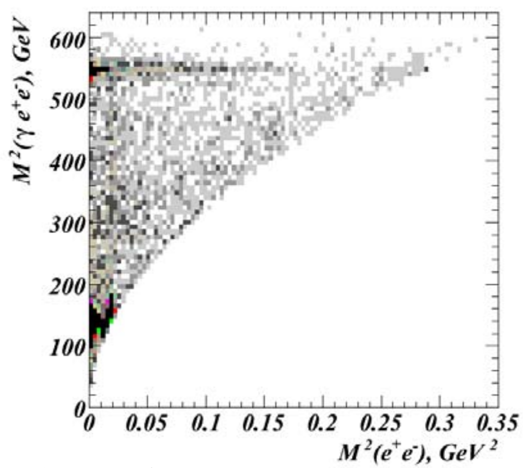
$\eta' \to l^+l^-l^+l^-$

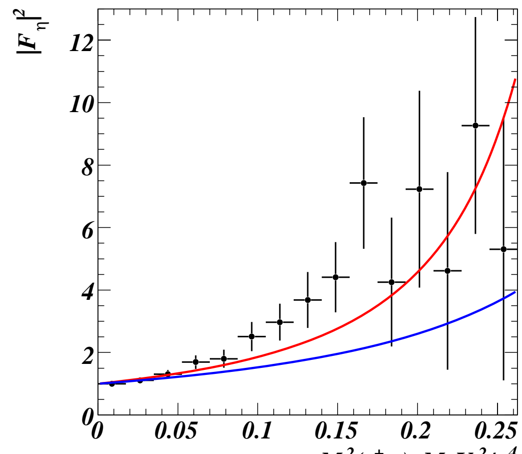












Spectrum of the l^+l^- mass in the Dalitz carries information on the EM form-factor of the decay vertex.

The form factor is an important input for the calculations of the hadronic light-by-light scattering contribution to the anomalous magnetic moment of the muon (BNL g-2 experiment).

Распады $\eta \to \mu^+\mu^-$, $\eta \to e^+e^-$ и существование лептокварков

Leptoquark – a hypothetical particle suggested by A. Salam, carries interaction between quarks and leptons, encountered in various extensions of the Standard Model, such as technicolor theories or GUTs

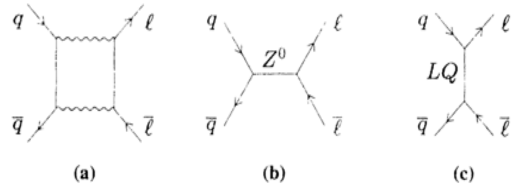


FIG. 1. Diagrams for the decay $P^0 \to \ell^+\ell^-$: (a) QED contribution, (b) weak interaction contribution, and (c) hypothetical leptoquark contribution.

$\eta \to \mu^+\mu^-$, $\eta \to e^+e^-$

- The single-photon exchange mechanism is forbidden because of conservation of angular momentum
- The decay is dominated by a two-photon intermediate state which is suppressed
- Provides lower limits of the masses of leptoquarks and axions.

$$\frac{M_{LQ}}{\left\langle g_{ue}^{L} g_{ue}^{R} \right\rangle^{1/2}} > 70GeV\left(\frac{3\times10^{-4}}{BR(\eta \to e^{+}e^{-})}\right)$$

D.Wyler, in proc. inter. workshop. "Rare decays of light mesons", Gif-sur-Yvatte, France March 29-30, 1990.

Проверка C-инвариантности

Citation: C. Amsler *et al.* (Particle Data Group), PL **B667**, 1 (2008) (URL: http://pdg.lbl.gov)

TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (*C*) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{\text{total}}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{\text{total}}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\gamma)/\Gamma_{\text{total}}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\pi^0\gamma)/\Gamma_{\text{total}}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{\text{total}}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{\text{total}}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{\text{total}}$		$<3 \times 10^{-4}$, CL = 90%
c decay parameter of $\eta'(958)$		0.015 ± 0.018
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.01 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{\text{total}}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-5}$, CL = 90%

Dalitz plot of η'-> $\eta\pi^0\pi^0$

- Substantial progress is achieved in understanding of the ππ interaction and obtaining the ππ scattering length (K(e4) decay, D decays, cusp in $K^+ \to \pi^+\pi^0\pi^0$ …). Very little is known about the ηπ scattering. η'-> ηππ is a unique system to study ηπ
- Theory predicts a substantial cusp in the $\pi^0\pi^0$ invariant mass at the opening of the $\pi^0\pi^0 \to \pi^+\pi^-$ channel (8% effect may be compared to 13% for $K^+ \to \pi^+\pi^0\pi^0$ and 2% for $\eta \to 3\pi^0$)

$$|M|^2 = (|1+\alpha y|^2 + cx^2) \times \Phi$$

$$y = \frac{(2 + m_\eta / m_\pi) \times T_\eta}{m_{\eta'} - m_\eta - 2m_\pi} - 1, \qquad x = \frac{\sqrt{3} \times (T_1 + T_2)}{m_{\eta'} - m_\eta - 2m_\pi}$$

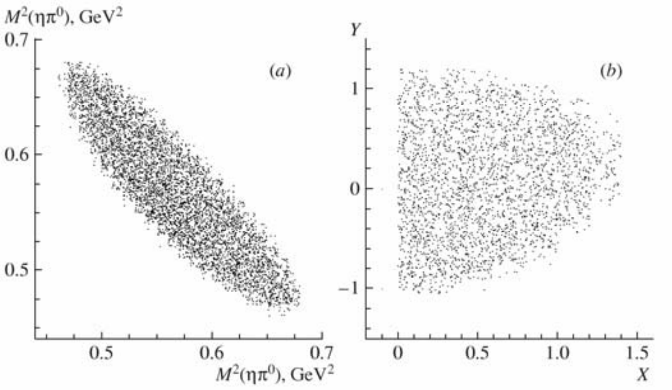


Fig. 2. The experimental form of the Dalitz diagram for the decay $\eta' \to \eta\pi^0\pi^0$ in terms of the variables (a) $M^2(\eta\pi_1^0)$ and $M^2(\eta\pi_2^0)$ (two combinations per event) and (b) X and Y.

Latest results:
GAMS-4π Collaboration, 15000 events from π-p->η'n at 32 GeV/c

A.M.Blik et al, Phys. Atom. Nucl., 72, 231 (2008)

Другие распады η′

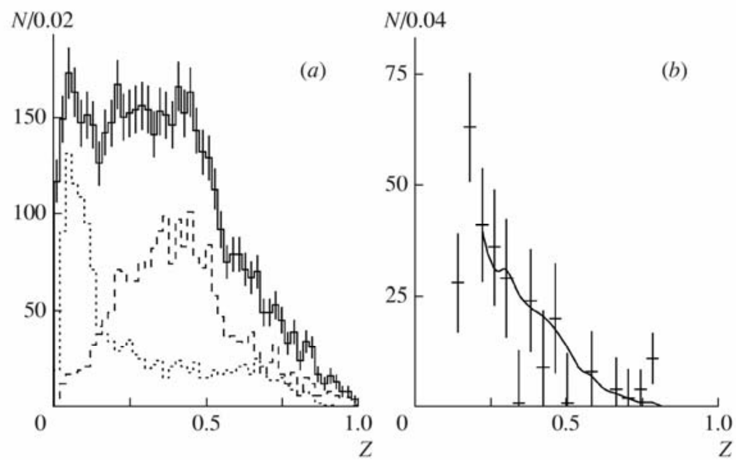


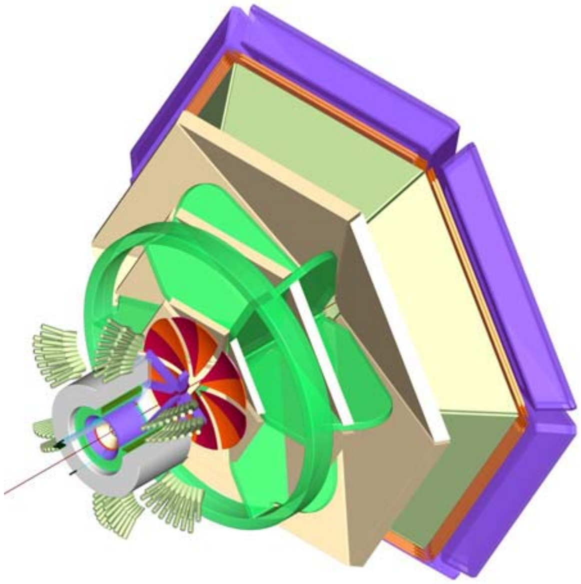
Fig. 4. (*a*) Experimental distribution with respect to Z for the case where the mass of the $3\pi^0$ system falls within the range 920–1000 MeV (solid line) before removing events associated with the (dotted line) $K^0_S\pi^0$ and (dashed line) $\eta\pi^0\pi^0$ systems; (*b*) experimental distribution with respect to Z after all selections and a fitting function.

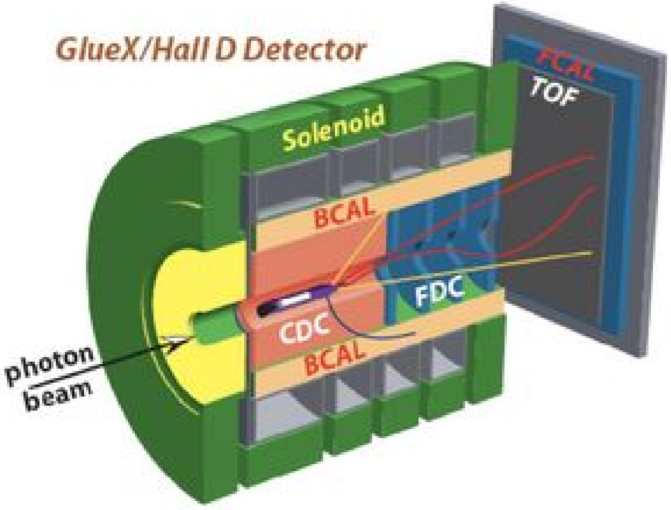
- $\eta' \to 3\pi^0$ Dalitz plot: matrix element of the Dalitz plot of $\eta' \to 3\pi^0$, carries information of the $\pi^0\pi^0$ interaction at higher (than for η) π^0 energies

- $\eta' \to \gamma\gamma$ and the octet-singlet mixing angla: $\eta \to \gamma\gamma$ and $\eta' \to \gamma\gamma$ are generated through axial anomaly, therefore are sensitive to the octet-singlet mixing angle. Current values for the absolute width (RPP average): $\Gamma(\eta \to \gamma\gamma) = (0.510 \pm 0.026)$ keV, $\Gamma(\eta' \to \gamma\gamma) = (4.30 \pm 0.19)$ keV
- Test of C and CP: $\eta' \to 4\pi^0$, $\eta' \to 3\gamma$, $\eta' \to \pi^0 e^+ e^-$, $\eta' \to \eta e^+ e^-$

JLab 12 GeV upgrade

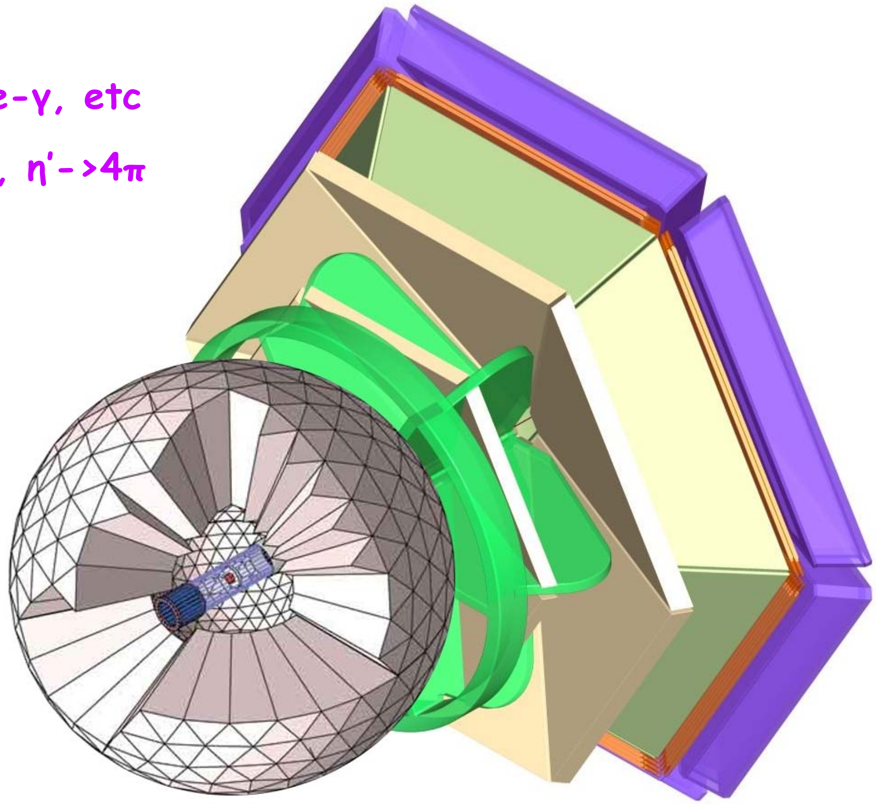
- Maximum beam energy: 12 GeV
- Major upgrade of the CLAS detecotor
- New experimental hall and new major detector – GlueX
- Physics program (Halls B and D):
  - "establish spectrum of exotic meson states" using linearly polarized photon beam with maximum energy up to 12 GeV (GlueX)
  - Baryon spectroscopy including baryon exotics (GlueX)
  - Investigation of the structure of the proton using DVCS and DVMP (electroproduction CLAS12)
  - Continuation of the photoproduction program: cascades spectroscopy, search for exotics, etc (photoproduction CLAS12)





Crystal Ball + CLAS12?

- Meson spectroscopy, search for the hybrids and other meson exotics in neutral decay modes ($\gamma\gamma$, $\pi^0\pi^0$, $3\pi^0$, $4\pi^0$, $\eta\pi^0$, $\eta\eta$, $\eta'\pi^0$, $\omega\pi^0$, etc)
- Baryon spectroscopy: Σ^*, Λ^* and Ξ^* via $\Sigma^+ \to \pi^0 p$, $\Sigma^0 \to \Lambda\gamma$, $K_s \to \pi^0\pi^0$, etc
- Physics of eta and eta' decays:
  - Tests of Chiral perturbation theory and other theories of strong interactions: $\eta \to \pi^0\pi^0\pi^0$, $\eta' \to \eta\pi^0\pi^0$
  - Tests of C invariance: $\eta \to 3\gamma$, $\eta \to \pi\gamma$, $\eta' \to e^+e^-\gamma$, etc
  - Tests of P invariance: $\eta \to 2\pi$, $\eta' \to 2\pi$, $\eta \to 4\pi$, $\eta' \to 4\pi$
  - Search for leptoquaks: $\eta \to \mu^+\mu^-$, $\eta \to e^+e^-$
- And much more…

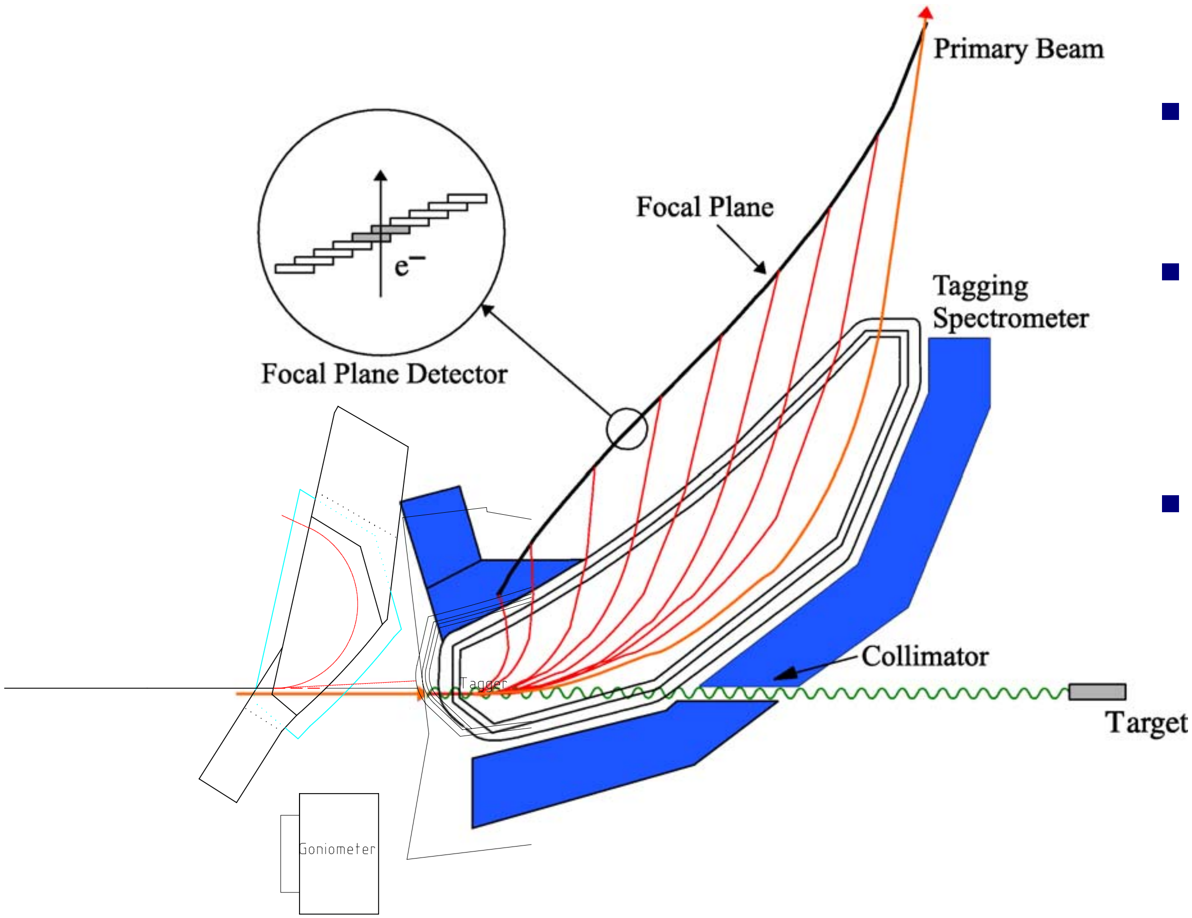


- High detection efficiency and good energy and spatial resolution for photons and electrons.
- Acceptance of CB+FEM for photons close to 4π
- Possibility to tag mesons via proton detection in the FD

Заключение

- Спектроскопия легких барионов остается важной частью адронной физики необходимой для понимания конфаймента и свойств симметрий КХД. Эта область физики частиц целиком зависит от наличия достоверных и точных экспериментальных данных для различных реакций и наблюдаемых.
- В экспериментах с детектором Crystal Ball на каонных и пионных пучках AGS были получены важные результаты для нескольких нейтральных реакций позволяющие детальное изучение свойств P11(1440), D13(1520), S11(1535), Σ(1385), Λ(1670) и других нуклонных и гиперонных резонансов.
- Эта программа была продолжена в MAMI на пучке меченых фотонов с максимальной энергией 1.6 ГэВ. Одной из целей эксперимента CB@MAMI является получение полного набора наблюдаемых необходимых для однозначного восстанавления амплитуд рассеяния в фоторождении псевдоскалярных мезонов.
- Важной частью эксперимента CB@MAMI является программа по изучению распадов η и η′ мезонов. Полученные результаты могут быть использованы для проверки адронных моделей и тестирования дискретных симметрий таких как C, P, CP.
- Программа с детектором Crystal Ball может быть продолжена на фотонном пучке JLab. Частью этой программы моги бы быть поиск гибридных мезонных состояний, изучение спектра узких Ξ резонансов, физика распадов η и η′.

Tagged Photon Beam

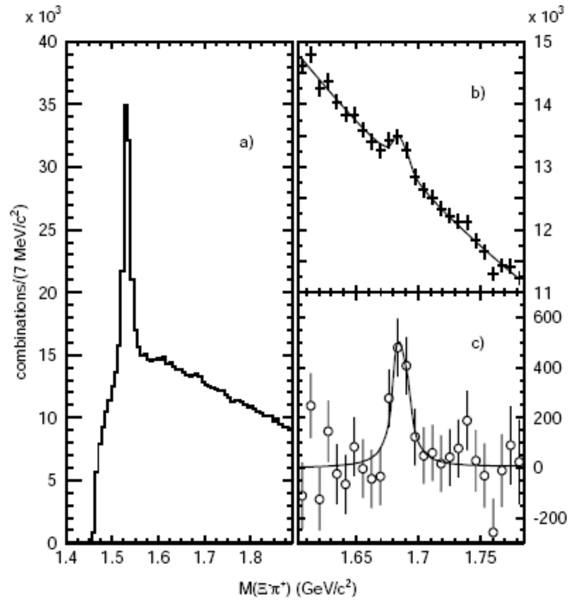


- Maximum electron energy – 1558 MeV (a test of 1600 MeV beam will be conducted)
- Maximum energy of tagged photons – 1453 MeV with the main tagger, and up to 1548 MeV with the end-point tagger (under construction)
- Energy resolution ~ 4 MeV in the main tagged ladder, ~1 MeV resolution in the microscope

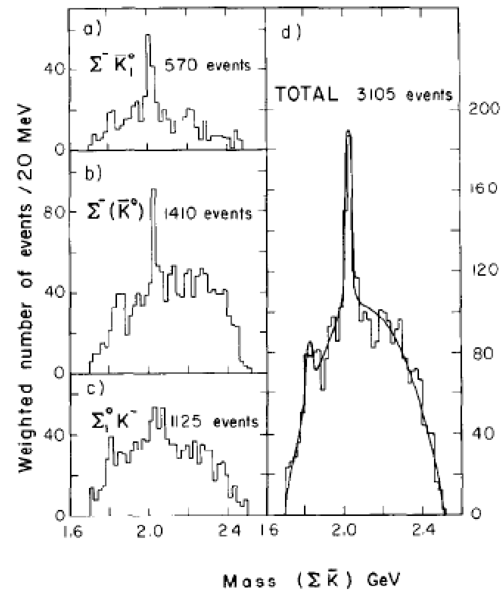
What is known about cascades?

Ξ^0 = uss, Ξ^-= dss

- Only 11 Ξ^* known; 6 "well-established"
- Those we know aren't known well: only have J^P for three states and a guess of a fourth
- SU(3) symmetry requires one Ξ I=1/2 per octet and per decuplet: $n(\Xi^*)=n(N^*)+n(\Delta^*)$



Adamovich et al., EPJ C5, 621

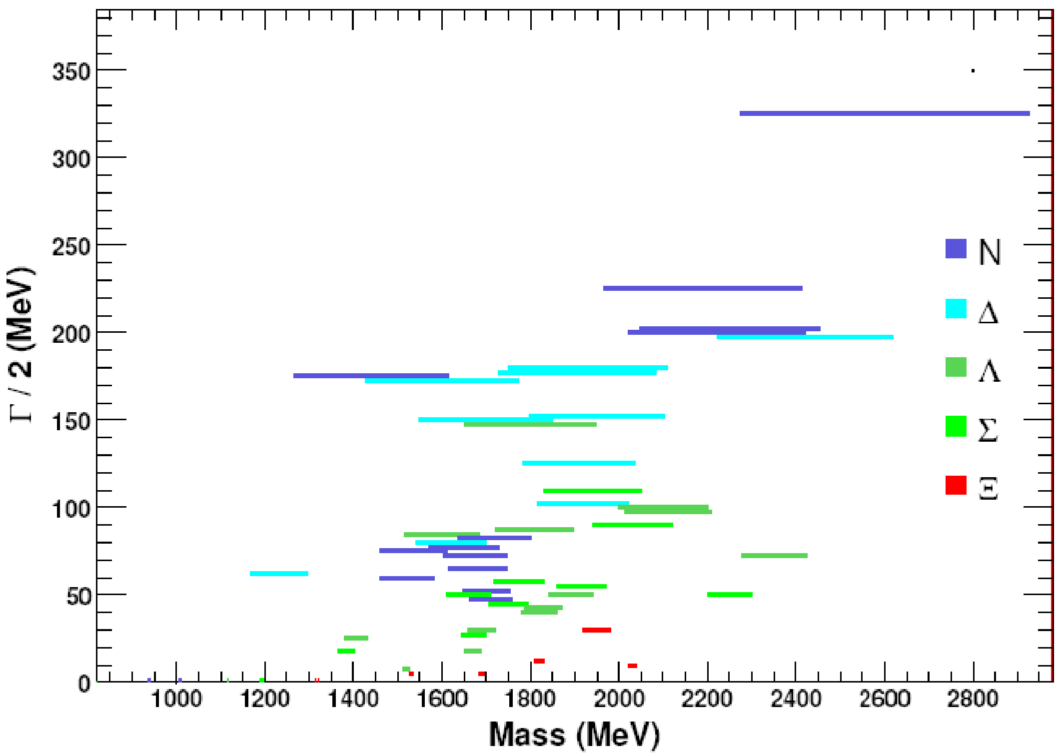


Hemingway et al., PLB 68, 1972

- CQM predicts 45 cascades with mass below 2.5 GeV (S.Capstick and N. Isgur PRD 34 2809 (1986))
- Algebraic model predicts 33 states with mass below 2.5 GeV (A.R. Bijker, F.Iachello, and A. Leviatan Ann. Phys. 284 89 (2000))

Advantages of the Cascades

3 and 4-star Baryons: mass vs. width



Riska relation: $\Gamma(N^*,\Delta^*) : \Gamma(\Lambda^*,\Sigma^*) : \Gamma(\Xi^*) \approx 3^2 : 2^2 : 1^2$

N* and Δ* resonances overlap, spectroscopy of N* and Δ* requires a complicated (and ambiguous) phase-shift analysis. Lattice calculation are not reliable for u and d quarks ($m(u,d) \approx 5$ MeV)

Calculations of the cascade spectrum in lattice gauge are much more reliable because of the two s quarks ($m(s) \approx 100$ MeV)

The known cascades are narrow. If the rest of cascades is as narrow as it is expected, the parameters of the cascade excited states can be extracted directly from the mass spectra

Many of the cascades have detached decay vertices allowing better separation from non-strange backgrounds

CI/CR Ξ states/decays (expt)

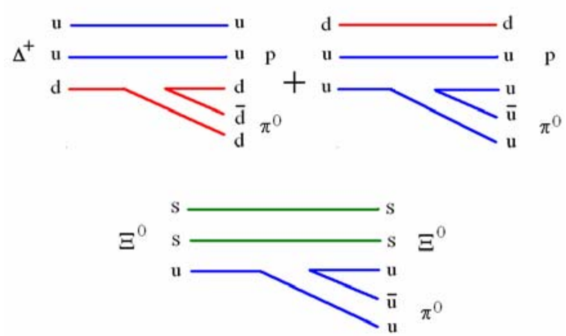
mass	state	J^P	$\|A_{\Xi\pi}\|$ $MeV^{\frac{1}{2}}$	$\|A_{\Lambda K}\|$	$\|A_{\Sigma K}\|$	$\Sigma\|A_i\|^2$ (MeV)
1755	$[S_{11}]_1$	$1/2^-$	9.3	13.6	15.3	506
1810	$[S_{11}]_2$	$1/2^-$	15.1	4.0	10.0	344
1835	$[S_{11}]_3$	$1/2^-$	2.7	4.7	12.5	186
1785	$[D_{13}]_1$	$3/2^-$	1.5 1.5	3.1 2.7	3.3 2.7	23 24
1880	$[D_{13}]_2$	$3/2^-$	2.3	1.7	2.3	13
1895	$[D_{13}]_3$	$3/2^-$	2.7	2.0	3.0	20
1900	$[D_{15}]_1$	$5/2^-$	6.5	3.3	2.7	60
1840	$[P_{11}]_2$	$1/2^+$	1.9	2.8	2.1	16
2040	$[P_{11}]_3$	$1/2^+$	5.2	5.3	5.1	81
1530	Ξ^*	$3/2^+$	3.2 3.2			10 10
2045	$[P_{13}]_2$	$3/2^+$	4.9	7.6	6.7	127
2065	$[P_{13}]_3$	$3/2^+$	1.7	5.1	10.5	110
2045	$[F_{15}]_1$	$5/2^+$	0.3	0.9	2.6	8
2165	$[F_{15}]_2$	$5/2^+$	1.4	2.1	0.2	6
2180	$[F_{17}]_1$	$7/2^+$	1.5	3.1	2.3	17
2240	$[F_{17}]_2$	$7/2^+$	5.0	0.2	0.0	25

Cascades in the CQM

S.Capstick and N.Isgur

Reasons for Ξ* to be narrow:

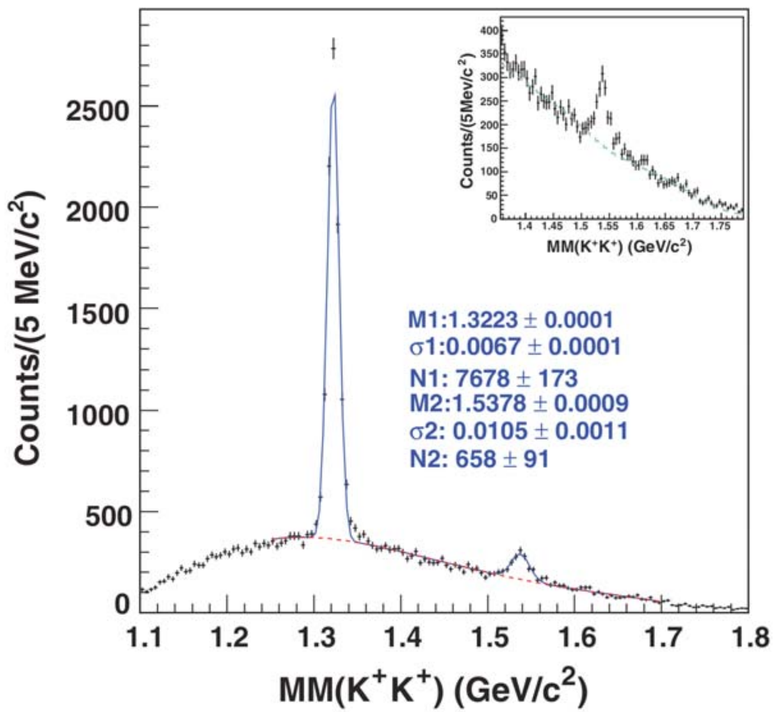
- **Phase-space factor for the decay Ξ*->Ξπ compared to N*->Nπ and Δ*->Δπ**
- **Flavor overlap factor**



Physics with Cascades

- **Spectroscopy of cascade exited states (complementary to N* and Δ*)**
- **Search for parity doubles**
- **d-u quark mass difference ($m(\Xi^-)-m(\Xi^0) \sim 6.5$ MeV, requires good energy resolution), s-d quark mass difference, test of octet-decuplet mass relations**
- **Search for exotic states: Ξ^+ and Ξ^{--}; $\Xi\Xi$ bound state**

Photoproduction of cascades



L. Guo et al. PRC 76, 025208 (2008)

J.W. Price et al. PRC 71, 058201 (2005)

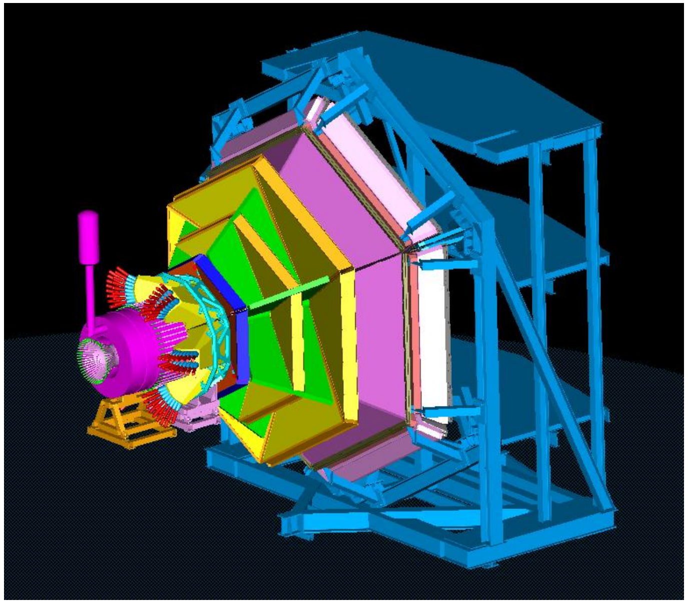
Cascades in CLAS6, run g11:

- Number of events: ground state – 7678, first exited state – 658
- maximum energy: 3.8 GeV for most of the run, some data at 4.8 GeV (production threshold ~2.4 GeV)

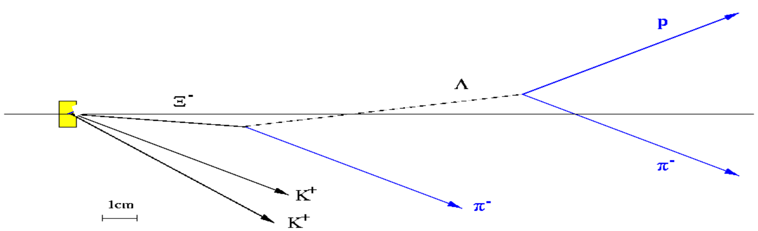
New data – run g12:

- The data were collected in spring 2008. Maximum beam energy 5.75 GeV. The setup was optimized for the high energy part of the photon spectrum
- Cooking process is in progress, scheduled to be completed by end of 2009 - early 2010

Possibilities with CLAS12



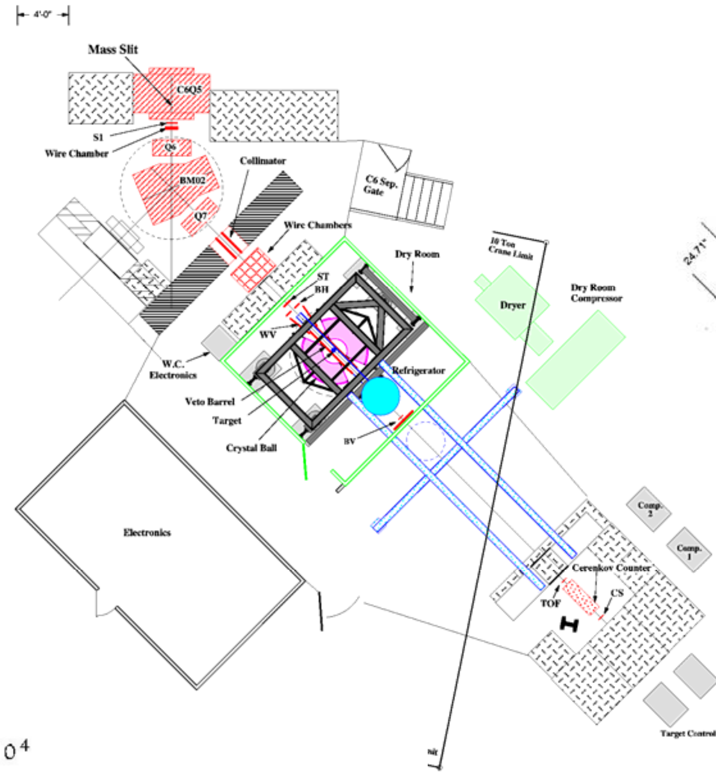
- Higher beam energies: tagged photons with energies about 6.0 GeV (available max. Ξ^* mass ~2.5 GeV), 12 GeV electron beam (available max. Ξ^* mass ~3.9 GeV)
- Advantages of the experiments with quasi-real photons:
  - Relatively high photon flux
  - Electroproduction at very low Q2 is equivalent to photo production with linearly polarized photons
- Detector requirements:
  - Good K/π separation (TOF, LTCC, HTCC at higher energies)
  - Events selection using the detached decay vertices (vertex tracker, forward drift chambers)
  - Internal tagging system (inner EM calorimeter)

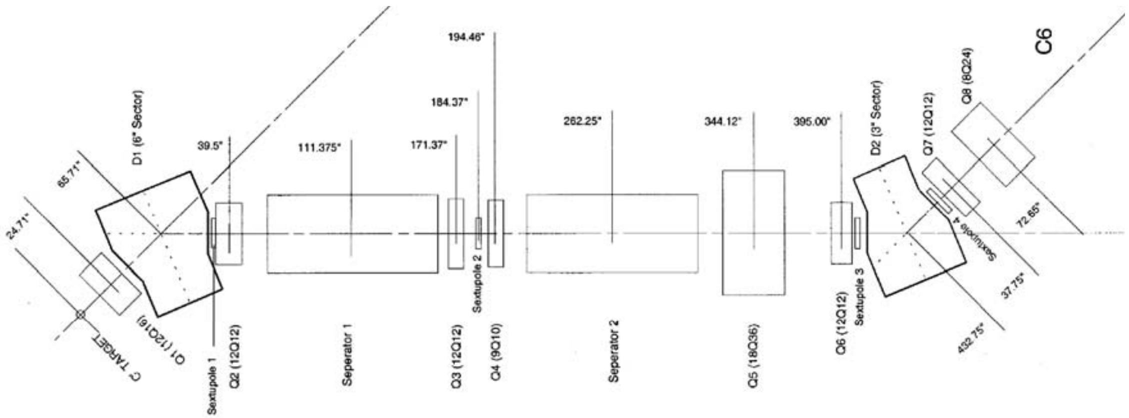


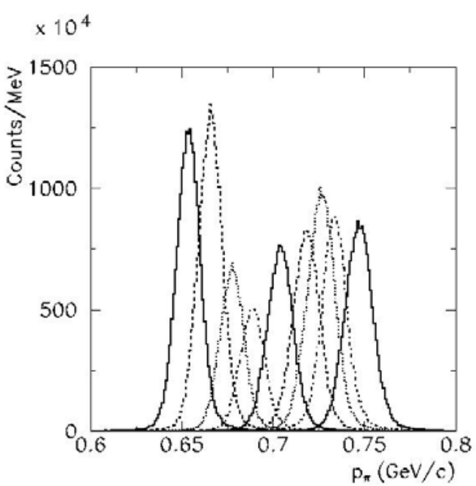
CLAS12 PID forward Detectors	$\pi - K$			$\pi - p$			$K - p$		
	p<2.6	2.6<p<5	p>5	p<2.6	2.6<p<5.6	p>5.6	p<2.6	2.6<p<5.6	p>5.6
TOF	✖	●	○	✖	✖	○	✖	✖	○
LTCC	○	●	●	○	●	●	○	○	○
HTCC	○	○	●	○	○	●	○	○	○
Result	+	+	—	+	+	—	+	+	—

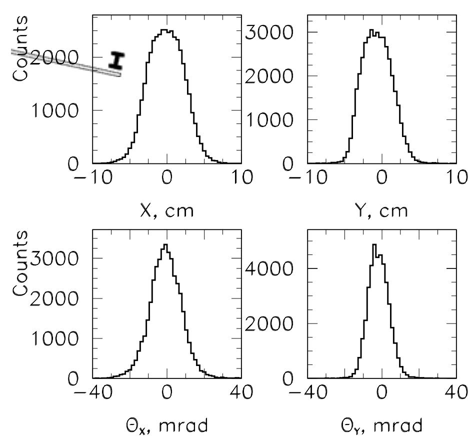
● Detector used indirectly ✖ Detector used + Separation possible ○ Detector not used
— Separation failed

Experimental Apparatus



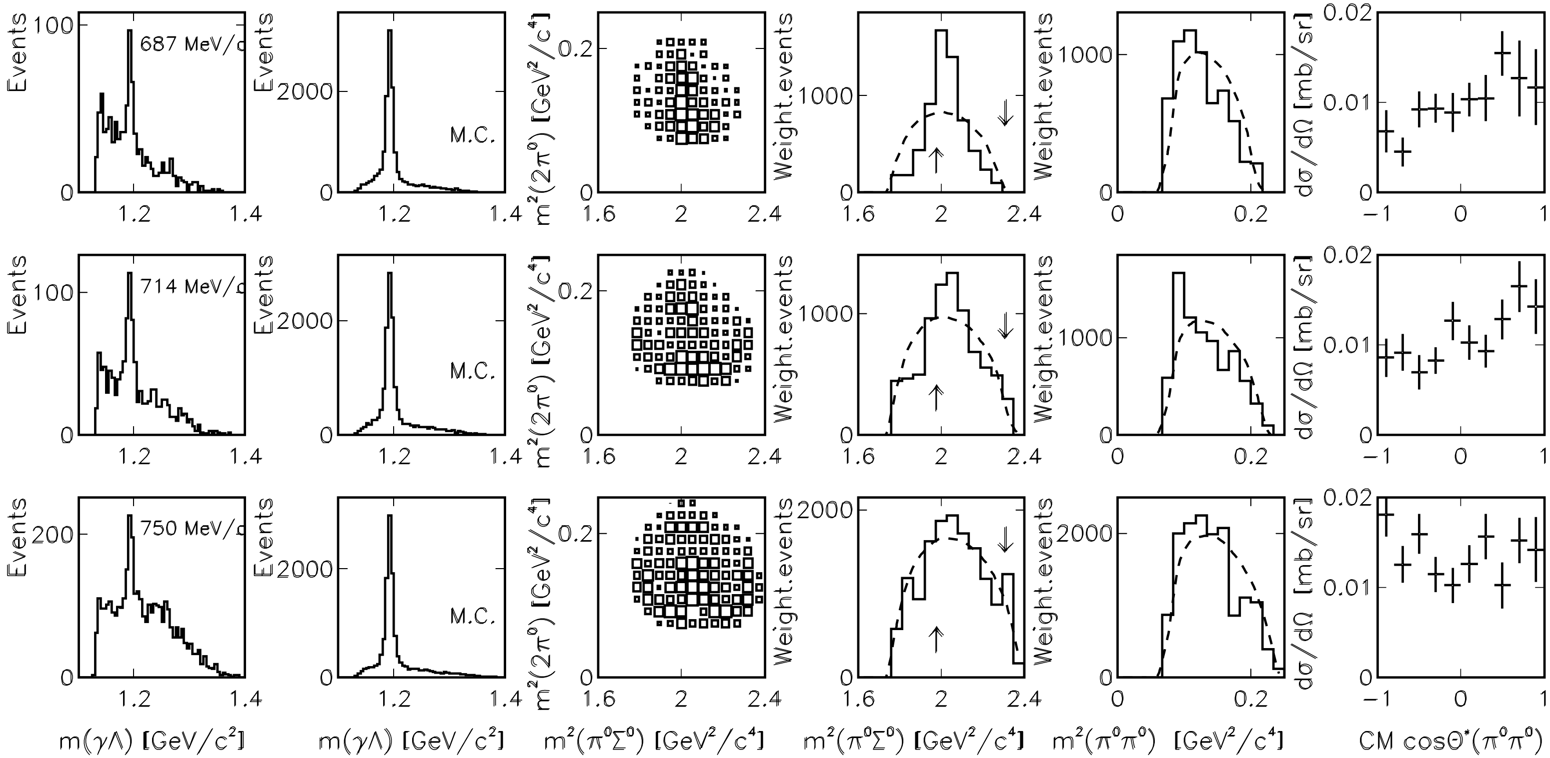






- $C6/C8$ provided a secondary beam of separated $K^{\pm}$, $\pi^{\pm}$ and antiprotons with maximum momentum ~750 MeV/c
- Intensity: ~10^6 π/sec, ~5×10^4 K/sec
- Resolution 0.1% relative to the average momentum, ±2MeV/c absolute momentum
- The Crystal Ball was installed and the C6/C8 beam line in 1996
- Engineering run: spring-summer 1996; main data: summer-fall 1998; solid target run – spring 2002

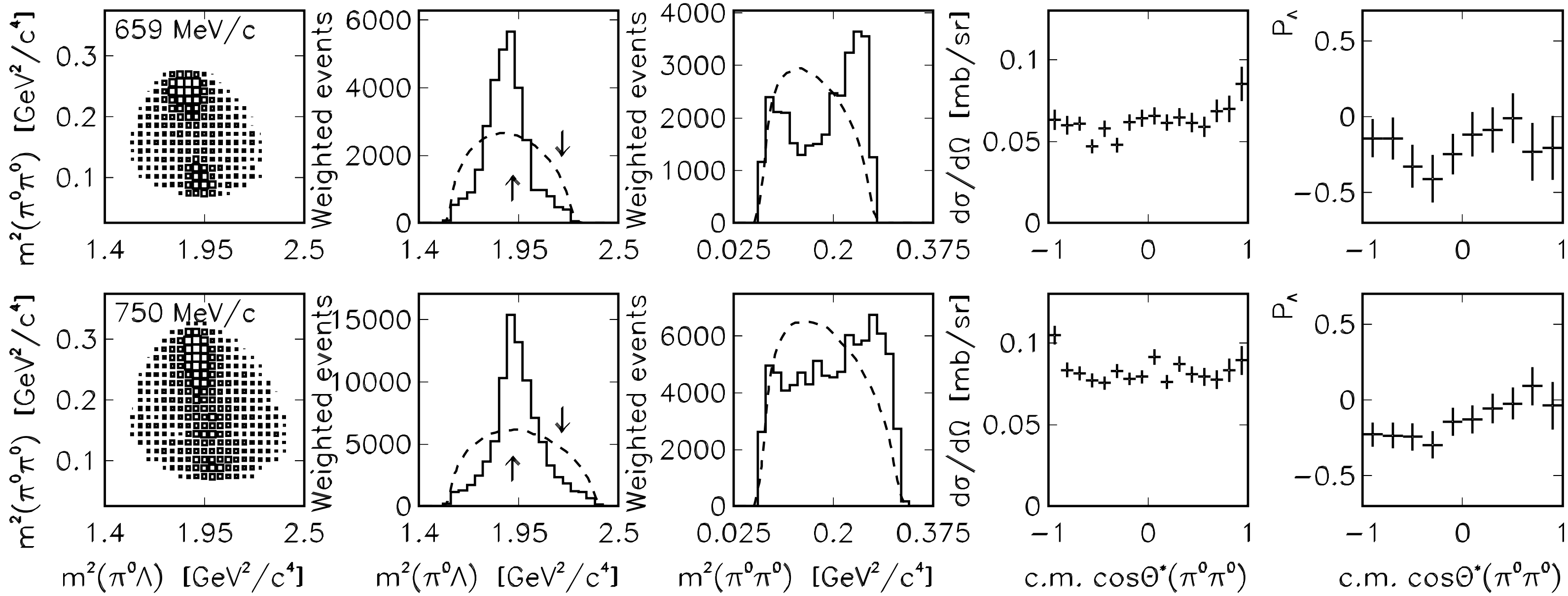
Λ(1405) and $K^- p \to \pi^0 \pi^0 \Sigma^0$



- Λ(1405) is narrow – observed directly on the $\pi^0\Sigma^0$ mass spectra
- Magas, Oset, Ramos: "Evidence for the two pole structure of the Λ(1405) resonance" (PRL 95, 052301 (2005))

S.Prakhov et al., PRC 70, 034605, 2004

$\Sigma(1385)$ and $K^-p\text{->}\pi^0\pi^0\Lambda$



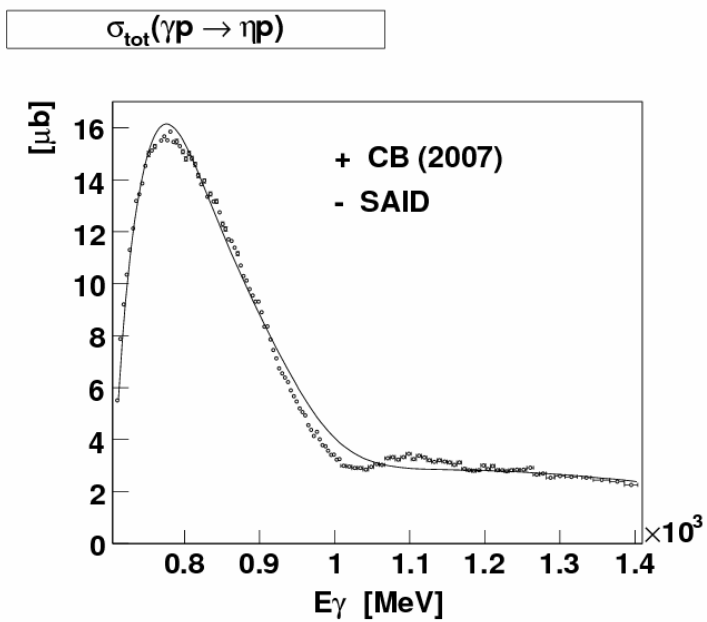
- Narrow $\Sigma(1385)$ state seen directly on the $\pi^0\Lambda$ mass spectrum
- A complete multi-channel analysis of all CB@AGS kaon data including $K^-p\text{->}\pi^0\Sigma^0$, $K^-p\text{->}\pi^0\Lambda$, $K^-p\text{->}2\pi^0\Sigma^0$, $K^-p\text{->}2\pi^0\Lambda$, $K^-p\text{->}3\pi^0\Lambda$, $K^-p\text{->}\eta\Lambda$, $K^-p\text{->}K^0n$ is in progress.

S.Prakhov et al., PRC 69, 042202, 2004

Decays of η: proposal summary

- η (A2-1/09):
  - The goal of the experiment is to produce ~3×10^8 η
  - Main physics topics: non-perturbative QCD via measuring the matrix element of $\eta\to\pi^0\gamma\gamma$, the Dalitz plot of $\eta\to3\pi^0$, the cusp in $\pi^0\pi^0\to\pi^+\pi^-$, EM form factor of PS mesons via study of the Dalitz decays ($\eta\to e^+e^-\gamma$, $\eta\to\mu^+\mu^-\gamma$, etc), test of the unitarity lower limit in $\eta\to\mu^+\mu^-$ and $\eta\to e^+e^-$, search for C and CP forbidden decays, lepton number conservation ($\eta\to\mu e$)
  - Time request: 50h setup, 900h (800h+100h) data taking
  - Setup: the Crystal Ball, TAPS, PID, 10 cm-long LH2 target
  - Beam Energy: 1558 MeV electron beam

Expected η rate



- E_{max} = 1.558 GeV, E_{thresh} = 0.710 GeV
- Photon flux (min): N_{phot} = $5x10^4$ 1/(sec*Mev)
- Target: 10 cm long, LH2: N_{prot} = 4.2* 10^{23} $1/cm^2$
- Total cross section of γp->ηp: σ_{tot}~6 μb
- Number of η per hour:

$N_\eta = N_{phot} * N_{prot} * \sigma_{tot} * \Delta E * 3600 \simeq 3x10^5$ 1/hour

- Number of η-> π° γ γ (Br=0.0002, Eff=30%, LT=70%): ≃ 10000 total

Total statistics in 800 hours: $3x10^8$ η

Decays of η': proposal summary

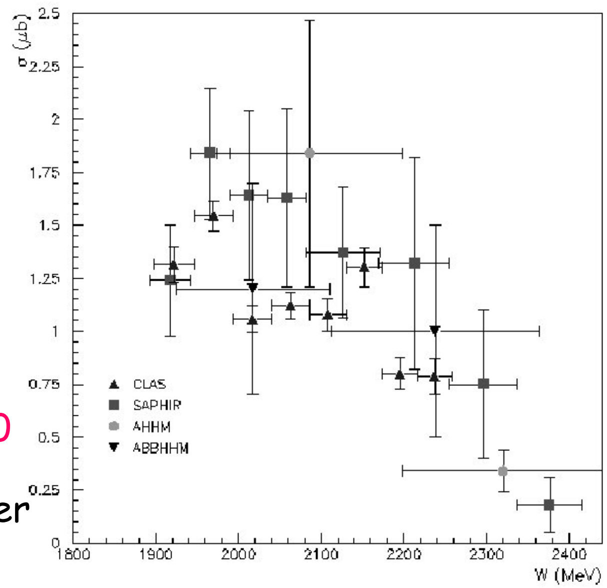
- η' (A2-2/09):
  - The goal is ~1×10^7 η' produced
  - Main physics topics: $\eta' \to \eta\pi^0\pi^0$, $\eta' \to 3\pi^0$ ($\pi\pi$ and $\eta\pi$ scattering amplitudes, study of the η' gluon component), octet/singlet mixing from the ratio $Br(\eta' \to \gamma\gamma)/Br(\eta \to \gamma\gamma)$, η' photoproduction at threshold, search for C and CP forbidden decays
  - Time requested: 50h setup, 800h (600h+200h) data
  - Setup: the Crystal Ball, TAPS, PID, 10 cm-long LH2
  - Beam requirements: **minimum** 1558 MeV electrons beam, end-point tagger required (currently we are investigating possibilities to increase the beam energy)

Expected η'(958) rate

- E_{max} = 1.547 GeV (with the end-point tagger), E_{thresh} = 1.447 GeV, ΔE = 100 MeV
- Photon flux (minimum): $N_{phot} = 10^5$ 1/(sec*Mev)
- Target: 10 cm long, LH2: $N_{prot} = 4.2 * 10^{23}$ $1/cm^2$
- Total cross section of γp->η'p: $\sigma_{tot} \sim 1 \mu b$
- Number of η'(958) per hour:

$N_{\eta'} = N_{phot} * N_{prot} * \sigma_{tot} * \Delta E * 3600 \simeq 15000$ 1/hour

- Number of η'-> $\eta\pi^0\pi^0$ (Br=21%, Eff=30%, LT=80%): $\simeq$ 700 per hour
- Number of η'-> $3\pi^0$ (Br=0.16%, Eff=30%, LT=80%): $\simeq$ 6 per hour



Total statistics in 600 hours: 10^7 η'(958)

- 4×10^5 η'-> $\eta\pi^0\pi^0$
- 4×10^3 η'-> $3\pi^0$