I. Physics Motivation

1. Light scalars are enigmatic
   ↳ interesting in their own right.

2. Understanding helps resolve the correct interpretation of 0^{++} states near 1500 MeV.

3. Distinguishing resonances from non-resonant effects is a basic requirement of any spectroscopy.

4. Their clarification may shed light on the identity of the σ - Higgs boson of χS.

1. Primary Physics Issue: the nature of the $a_0/f_0(980)$

$f_0(980)$ PDG: $\Gamma = 40 - 100$ MeV

- major decay $\pi\pi$ (S-wave) 0^{++} $(I = 0^{G=+1})$
- large threshold enhancement in $\bar{K}K$ s-wave $\Rightarrow$ strong coupling to $\bar{K}K$

$$\frac{g_{KK}}{g_{\pi\pi}} \simeq 4$$

- observed in its interference with broad $\pi\pi$ s-wave structure(s)

  $\Rightarrow$ width depends on how structures are put into the fit.

M. BUTTRAM *et al.* 1976

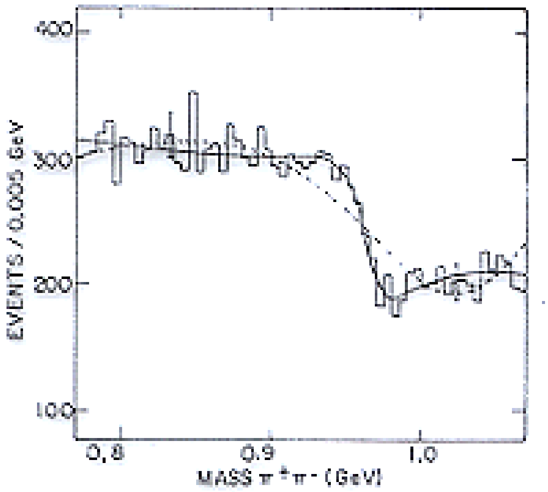


FIG. 5. The MM spectrum for events from the reaction $\pi^-p \to \pi^+\pi^-n$ where only one pion reaches the spectrometer. The solid curve is the best S^* fit to the data as described in the text. The dashed curve is the best fit if the nonresonant s-wave phase is held at 90°.

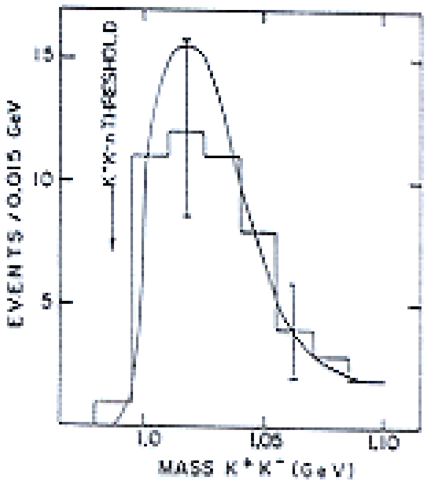


FIG. 7. The MM spectrum for $\pi^-p \to K^+K^-n$ with both kaons momentum analyzed in the spectrometer. The curve is a one-parameter (g_K) fit to the data with the S^* pole held at the $\pi^+\pi^-n$ best value.

$a_0(980)$ PDG: $\Gamma = 50 - 100$

- major decay $\eta\pi$ (s-wave) 0^{++} $(I = 1^{G=-1})$
- copiously produced in $f_1(1285)$ decays
  $f_1(1285) \to (\eta\pi)\pi$ 50% branch
  ~80% $a_0(980)$
- also seen in $f_1(1285) \to (\bar{K}K)\pi$ 10% branch
  $\Rightarrow$ strong coupling to $\bar{K}K$: $\frac{g_{KK}}{g_{\pi\pi}} \sim 1$
- large $a_0^\pm$ signal seen in photoproduction

Crystal Barrel 1994
$\bar{p}p \to \pi^0\pi^0\eta$

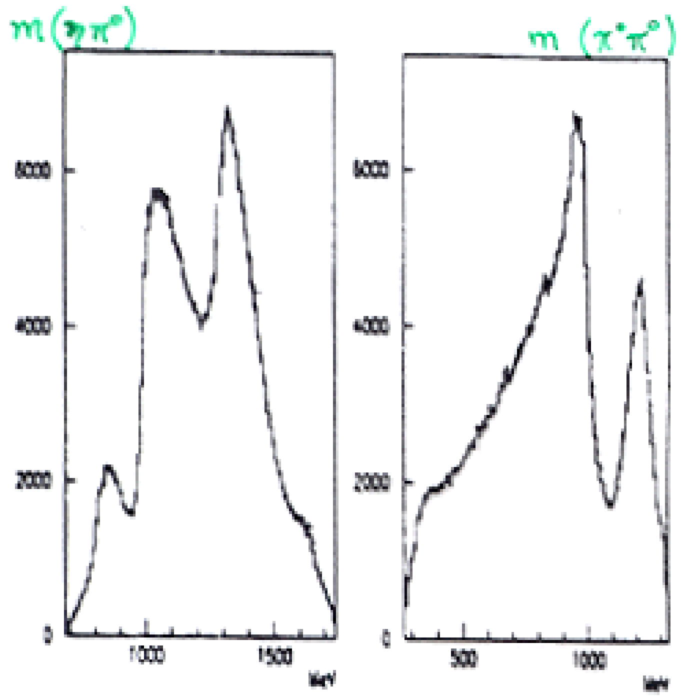
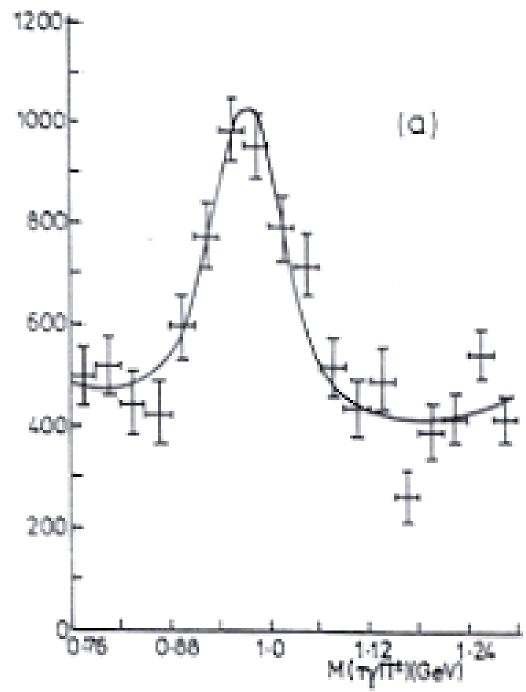


Fig. 2. Dalitz plot projections: $m(\pi\eta)$ distribution (left) and $m(\pi\pi)$ distribution (right). The dots are data and the full lines the results of the fits discussed in the text.

CERN Ω 1984
$\gamma p \to \eta\pi X$



favours $n\bar{n}$ interpretation

Important clue concerning flavour content of f_0

$$J/\psi \to V \left\{ \begin{matrix} \pi\pi \\ \bar{K}K \end{matrix} \right.$$

Mark III 1987 (review by Eigen)

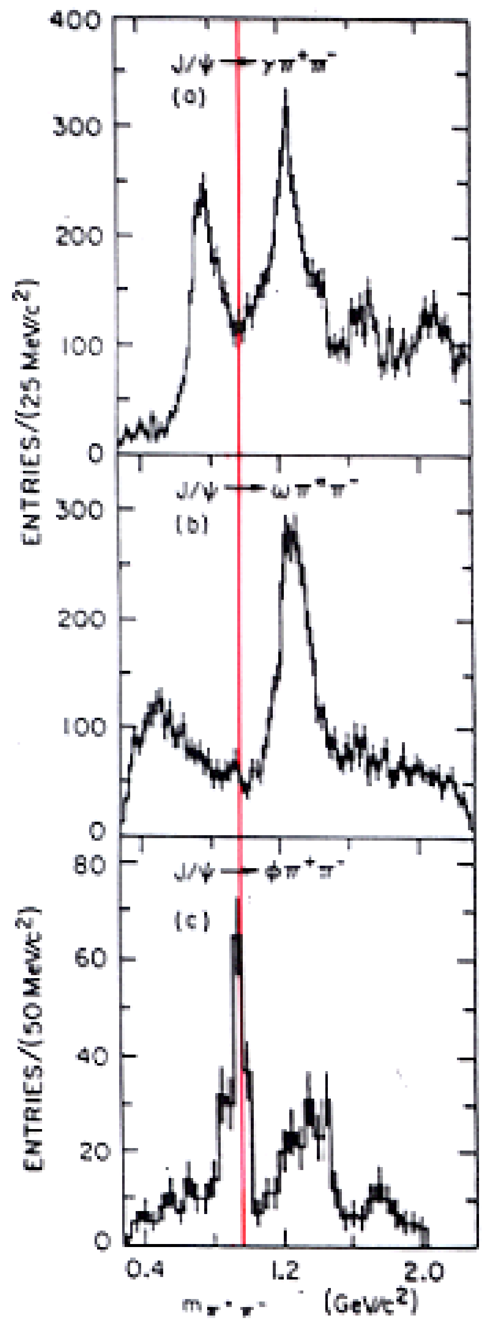


Fig.15. A comparison of the Mark III invariant mass spectra observed in the processes: a) $J/\psi \to \gamma\pi^+\pi^-$, b) $J/\psi \to \omega\pi^+\pi^-$, and c) $J/\psi \to \phi\pi^+\pi^-$.

$V = \gamma$

$V = \omega$

$V = \varphi$

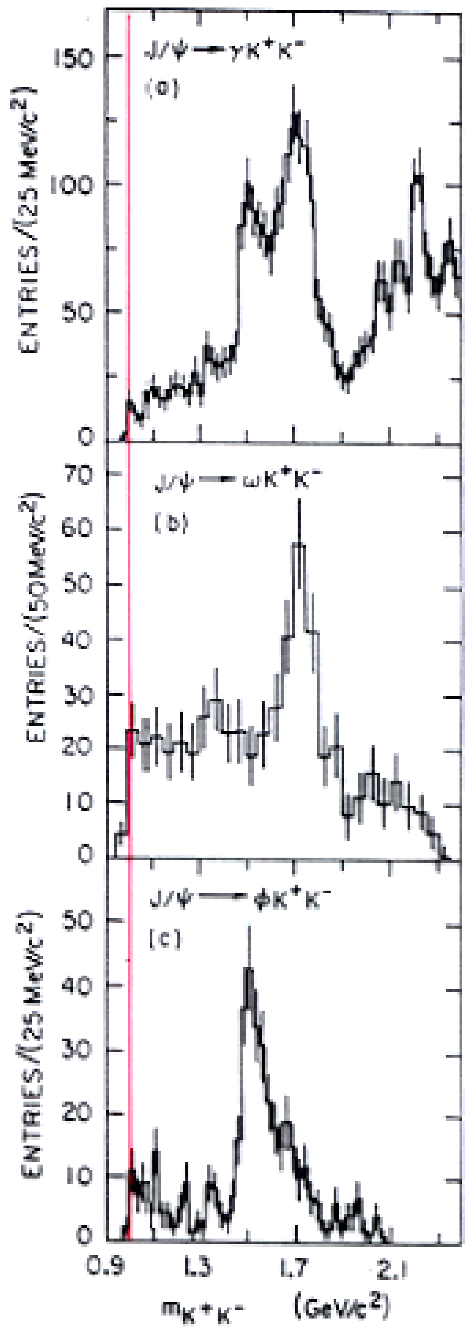
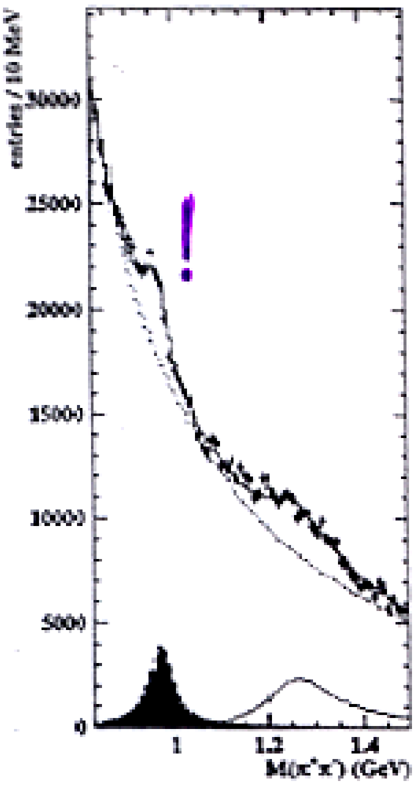
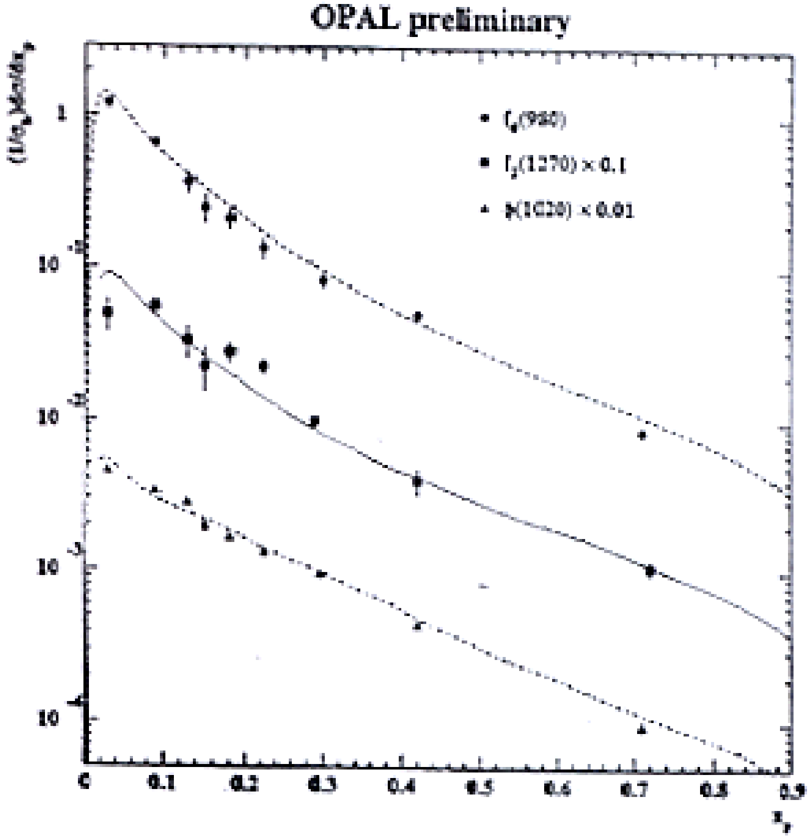


Fig.14. A comparison of the Mark III invariant mass spectra observed in the processes: a) $J/\psi \to \gamma K^+K^-$, b) $J/\psi \to \omega K^+K^-$, and c) $J/\psi \to \phi K^+K^-$.

Measurement of $f_0(980)$ production in hadronic Z^0 decay

- OPAL measure $f_0(980)$ and compare with $f_2(1270)$ and $\phi(1020)$
- Coupled channel formalism used for $f_0(980)$
- Differential cross sections compared to JETSET model





- Rates measured as functions of event multiplicity, rapidity gap
- Rates measured separately in quark and gluon jets
- All features consistent with a $u\bar{u} + d\bar{d}$ scalar meson

- $\langle N_{f_0} \rangle = 0.160 \pm 0.044$ per hadronic Z^0 decay
- $\langle N_{f_2} \rangle = 0.119 \pm 0.014$
- $\langle N_{\phi} \rangle = 0.093 \pm 0.004$

(OPAL, Contributed to EPS '97)

Parallel Session P08.02

Where do these states fit in the $^3P_0$ nonet?

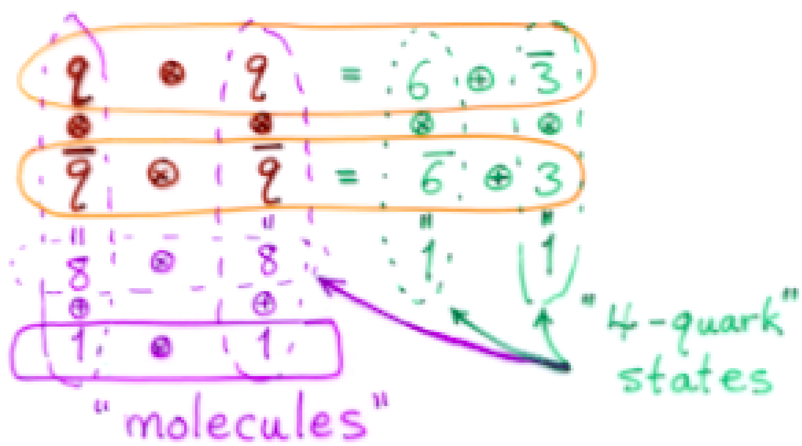
	Γ
$a_2(1320)$	107 MeV
$a_1(1260)$	400 MeV
$a_0(1250?)$	$\gtrsim$ 400 MeV
$a_0(980)$	50 MeV

With difficulty ...
- ✓ too light
- ✓ too narrow

For comparison: $K_0^*(1430)$: $\Gamma = 290$ MeV

Jaffe '77:

confine SU(3) singlets in a bag
$\Rightarrow qq\bar{q}\bar{q}$ 4-quark states



Weinstein, Isgur '83

In general 4-quark states $(qq)_{\bar{3},6}(\bar{q}\bar{q})_{3,\bar{6}}$ overlap with "molecular" colour config. $(q\bar{q})_1(q\bar{q})_1$ so that they "fall apart" into 2 mesons if possible

exceptional case: $K\bar{K}$ is bound (weakly)

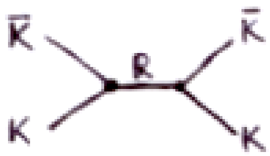
How to build a molecule

1. Potential models (Weinstein, Isgur)

a) start with constituent $q\bar{q}$ bound in potential

b) enable decays through $^3P_0$ pair creation

c) notice that decay operator also induced inter-meson potentials:



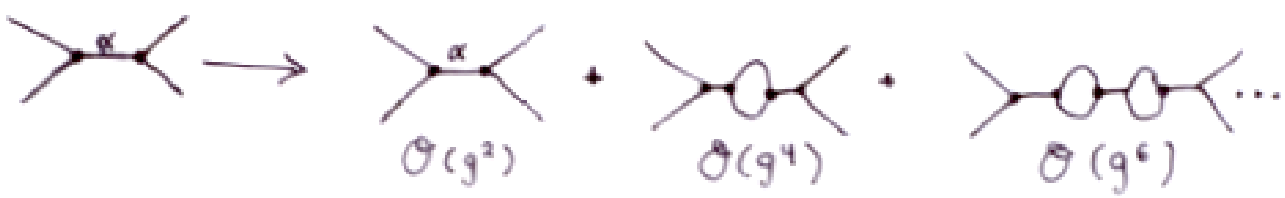
d) look for bound states in m-m potential

2. Unitarized quark models (Tornqvist, Locher)

a) start with constituent $q\bar{q}$ bound states

b) describe decays through phenomenological couplings $g_{\alpha\beta}$

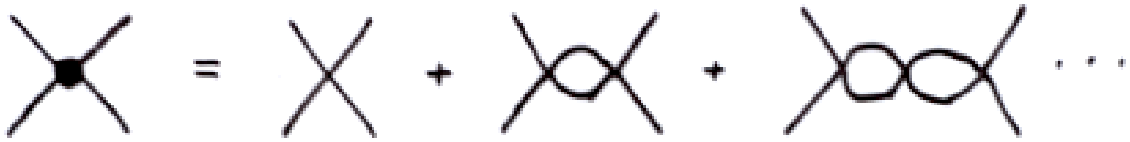
c) 'dress' bare resonances α with continuum components β by imposing unitarity in m-m scattering amplitude



3. Chiral unitary model

(Bramon, Oset, Oller, Toki ...)

- only lowest-order Lagrangian is used explicitly
- extends beyond usual scale of XSB by expanding T^{-1} instead of T
- unitarity is ensured through sum over chains



- loops in crossed channels are pushed into counter-terms
- scalar "resonances" generated automatically by summing proc.

Good description of 2P scattering up to 1.2 GeV

Question: Can the molecular picture be examined using existing data?

Answer: Yes

① Using $\gamma\gamma$ widths

Detailed calculations show $\Gamma_{\gamma\gamma}$ is much smaller for the weakly bound molecule than for a more compact $q\bar{q}$ state.

$\Gamma_{\gamma\gamma}(\eta') = 4.2\ \text{keV}$

$\Gamma_{\gamma\gamma}(f_2(1270)) = 2.4\ \text{keV}$

$\Gamma_{\gamma\gamma}(f_0(980)) \ll 1\ \text{keV}$

② Using global fits to the $\pi\pi$ and $\bar{K}K$ s-wave scattering data

★ Au, Morgan, Pennington. 1987 ...

A general coupled-channel PWA of $\pi\pi$, $\bar{K}K$ $I=0$ s-wave data, respecting constraints from Adler zeros, analyticity and unitarity.

7 poles, 4 resonances

TABLE VII. $I=0$ S-wave resonances below 1.6 GeV from our fits.

Resonance	Poles	E_R (GeV)	g_π (GeV)	g_K (GeV)	$\lvert g_\pi/g_K \rvert$
$S_1(991)$	A,C	$0.991-0.021i$	0.22	0.28	0.8
$S_2(988)$	B	0.988	0.02	0.35	0.06
$\epsilon(900)$	D,E	$0.91-0.35i$	0.52	0.27	1.9
$\epsilon'(1430)$	G,F	$1.43-0.20i$	0.58	0.16	3.6

Lessons from AMP's analysis

(in my view, not stated by the authors)

- finding the poles is data analysis.
- interpreting the poles in terms of underlying resonances is art.
- pole positions, even the number of poles can be very sensitive to the quality of the data, esp. in the vicinity of opening thresholds.

Alternative: "Unitarized quark model"

(Törnqvist)

- Underlying resonance input supplied from a model:

  ✓ $SU(3)_f$ symmetric couplings
  ✓ S.H.O. meson wave functions
  ✓ decays via quark-pair creation
  ✓ few free parameters, fit to data

  γ : overall decay constant ($S \to PP$)
  m_0 : bare mass of $n\bar{n}$ scalar
  m_s : extra bare mass per strange quark
  k_0 : cutoff for meson wave function
  δ_P : mixing angle in decay-prod. nonet

  ✓ obeys unitarity

Summary:

- There is general agreement that there are large continuum components in the f_0 and a_0
- There is no consensus about what underlies the strong $\bar{K}K$ interaction at threshold

Close, Isgur, Kumano: new input needed

Important constraint on models would come from a measurement of

$$\varphi \to \gamma \begin{cases} a_0 \\ f_0 \end{cases}$$

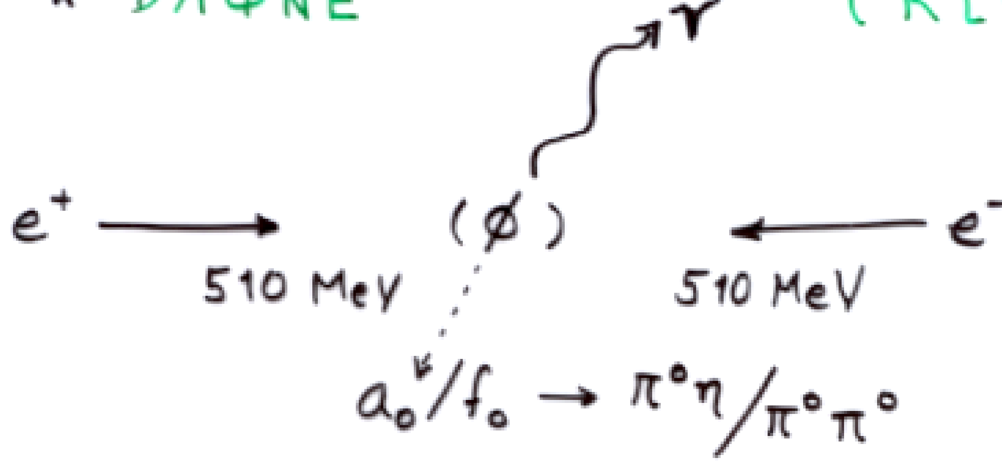
1) φ is narrow ⇒ clean selection of initial state
2) simple $s\bar{s}$ configuration
3) radiative decays are calculable
4) low B.R. expected, difficult measurement

B.R. × 10^6	B.R. $(\varphi \to \gamma a_0 \to \gamma \pi^0 \eta)$	3 · B.R. $(\varphi \to \gamma f_0 \to \gamma \pi^0 \pi^0)$	$\frac{B.R(\varphi \to \gamma a_0)}{B.R(\varphi \to \gamma f_0)}$
$^3P_0$ state	$\lesssim 0.1$	10 $(s\bar{s})$	0
		small $(u\bar{u}+d\bar{d})$	?
$K\bar{K}$ molecule			
(naive)	40	40	1
(Achasov'97)	10-20	10-20	
Bag $qq\bar{q}\bar{q}$ $(us)(\bar{u}\bar{s}) \mp (ds)(\bar{d}\bar{s})$	1 – 100 (?)		(any) 9

Basic Techniques

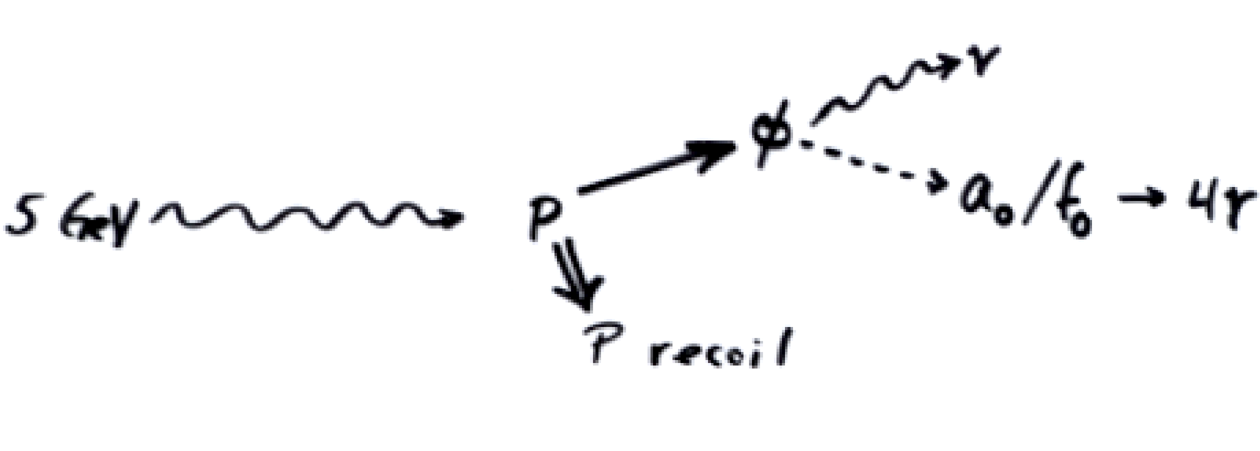
A. "ϕ Factory" e^+e^- colliders

* VEPP-2M (SND / CMD-2)
* DAΦNE (KLOE)



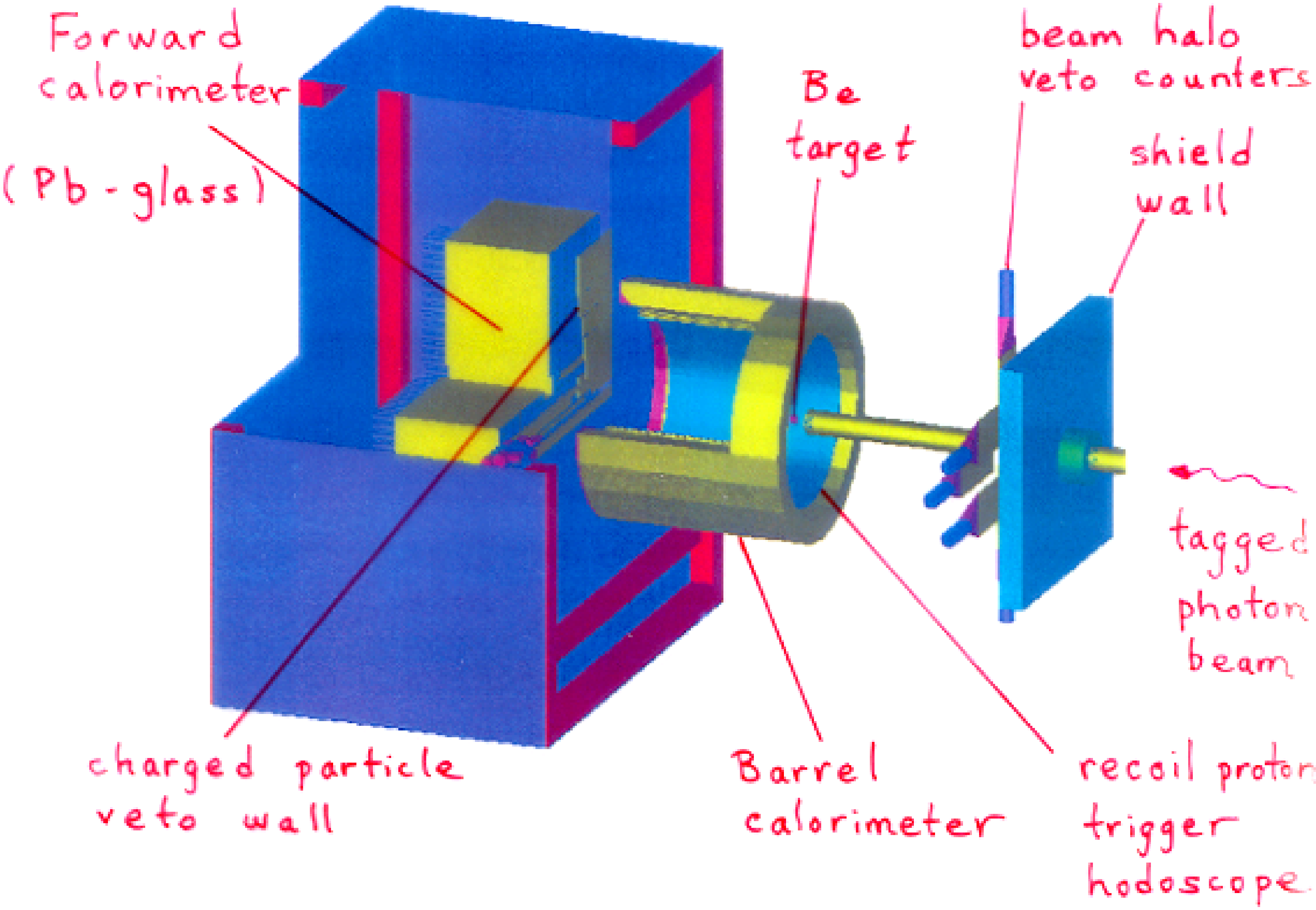
B. Fixed-target photoproduction

* Jefferson Lab (Radphi)



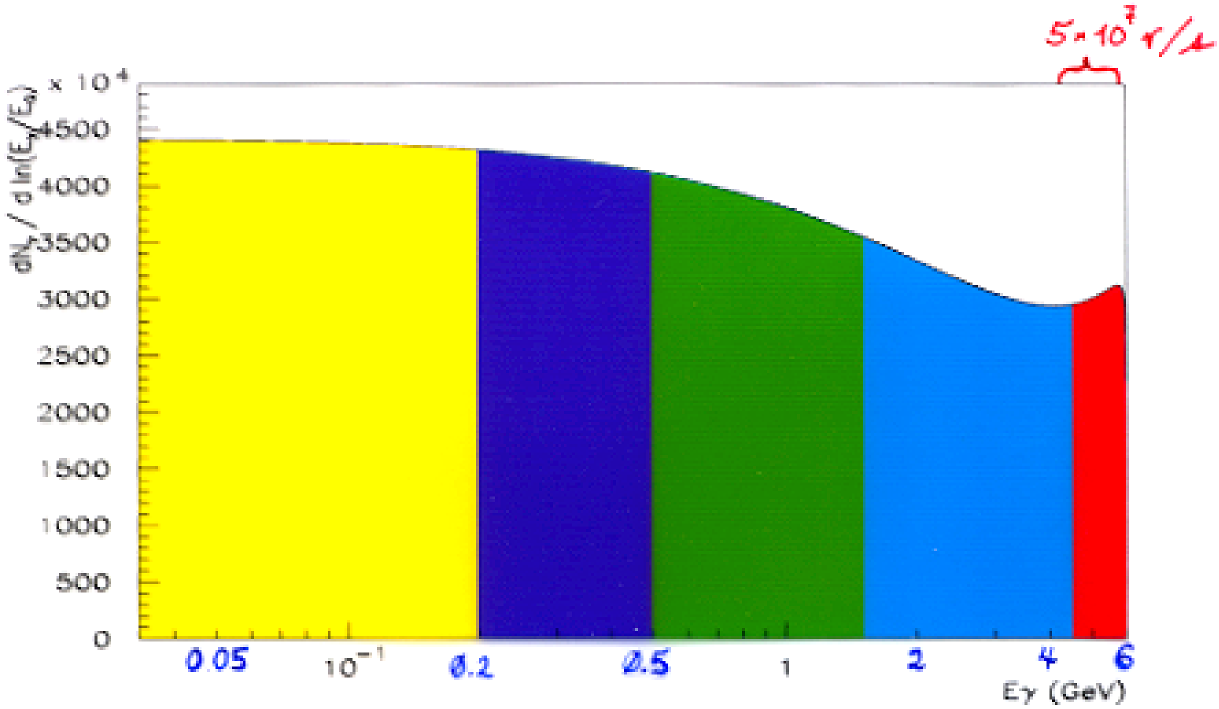
Radphi apparatus

Hall B, TJNAF



Beam:

tagged bremsstrahlung in Hall B at CEBAF



range	process	RPD·$\overline{\text{VETO}}$
50-200 MeV	giant resonances photodisintegration	20 kHz (for the first two processes, bracketed together)
200-500 MeV	$\gamma p \rightarrow \Delta^+ \rightarrow p\pi^0$ $\hookrightarrow n\pi^+$	10 kHz
500-1500 MeV	$\gamma p \rightarrow N^* \rightarrow pX$ $\hookrightarrow \pi^+ X$	10 kHz 10 kHz
1.5 - 4 GeV	$\gamma p \rightarrow p$ + neutrals	6 kHz
		56 kHz
tagged 4.5-6 GeV	$\gamma p \rightarrow p$ + neutrals	4 kHz

Acceptance estimates from Monte Carlo

1. input bremsstrahlung photon spectrum
2. $\sigma_{\gamma p \to \phi p} = 0.5 \mu b$, $\frac{d\sigma}{dt} \sim e^{-4|t|}$
3. s-channel helicity conservation
4. minimum E_γ 100 GeV, 6 cm between clusters

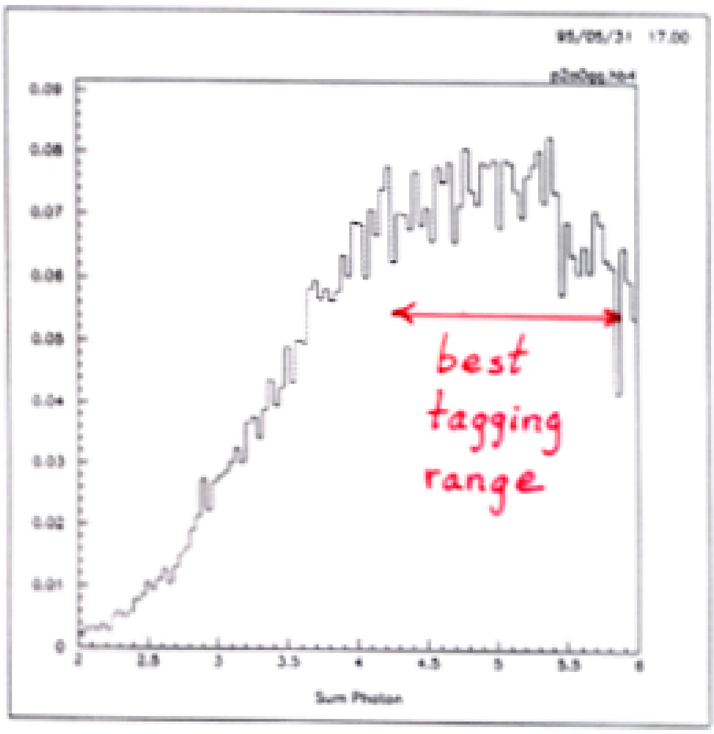


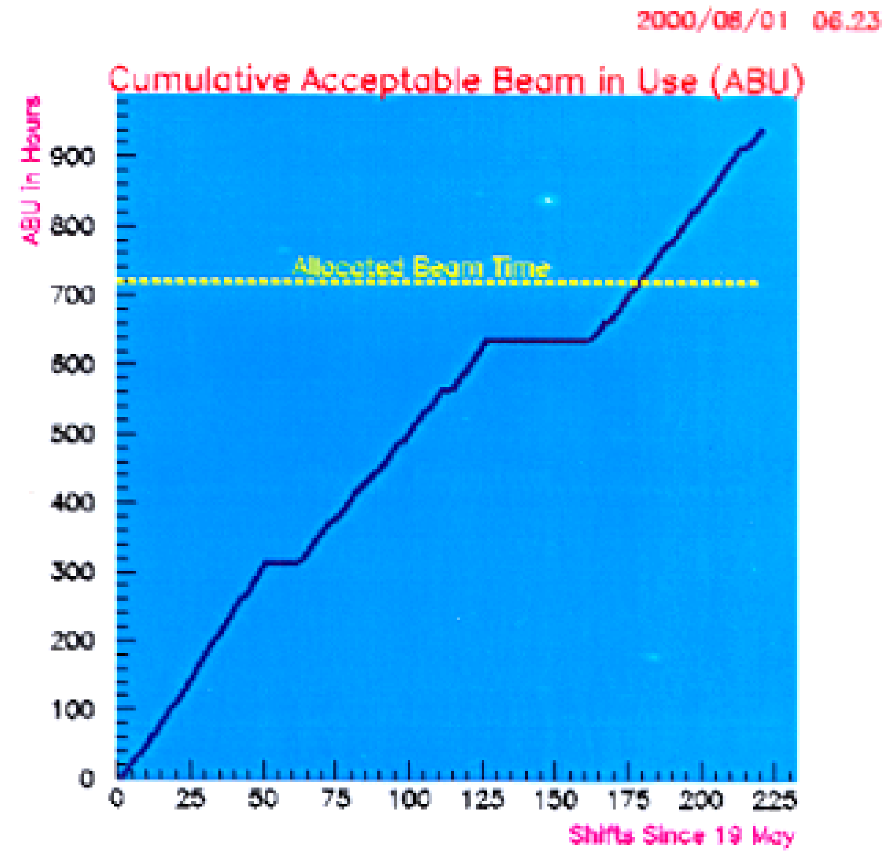
Figure 3: Acceptance for $\gamma p \to \phi p$ followed by $\phi \to a_0(980)\gamma \to 5$ photons. The incident photons are generated by bremsstrahlung from a 6 GeV primary electron beam.

Expected yields for 1000 h experiment (30 ϕ/s)

$\phi \to$	B.R. $\cdot 10^6$	(all photons)	# γ	A%	yield
$\gamma\pi^0$	1300	1300	3	35	45000
$\gamma\eta$	13000	5000	3	35	175000
$\gamma\eta'$	60	~1	3	30	40
γa_0	100	40	5	7	300
γf_0	100	30	5	10	300

Radphi experiment

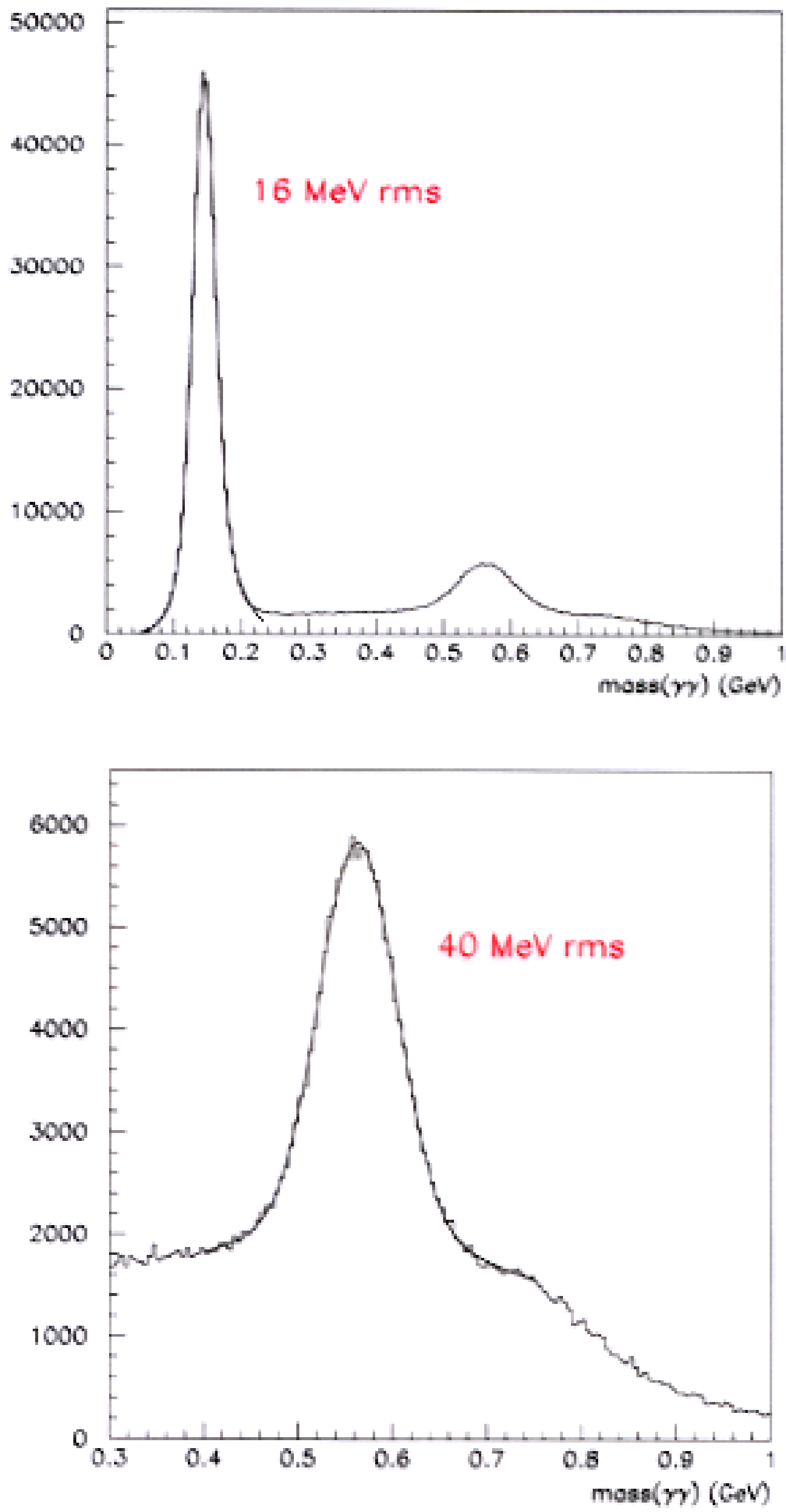
Major data-taking run summer 2000



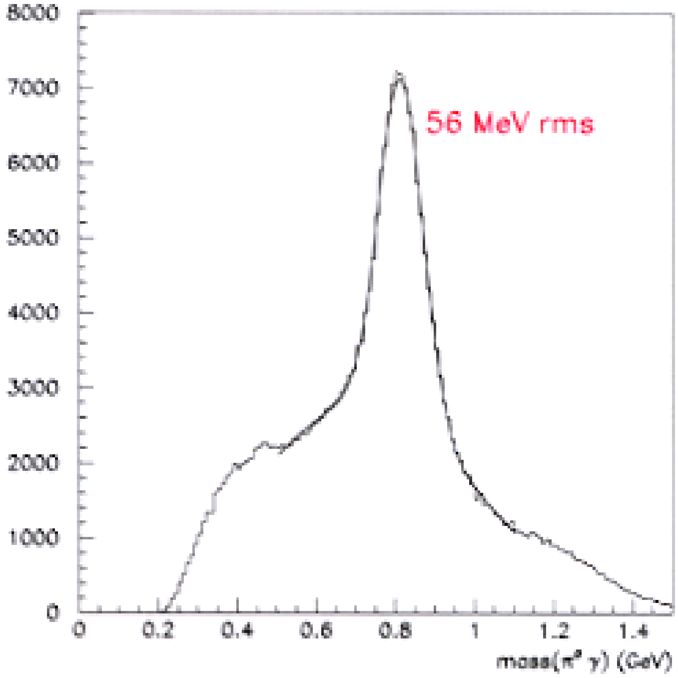
photon beam energy: 4.3-5.3 GeV
electron beam energy: 5.56 GeV
electron beam current: 80 μA

integrated luminosity: 100 pb^{-1}
total ϕ mesons from γ,p: 60 M

2γ invariant-mass spectra

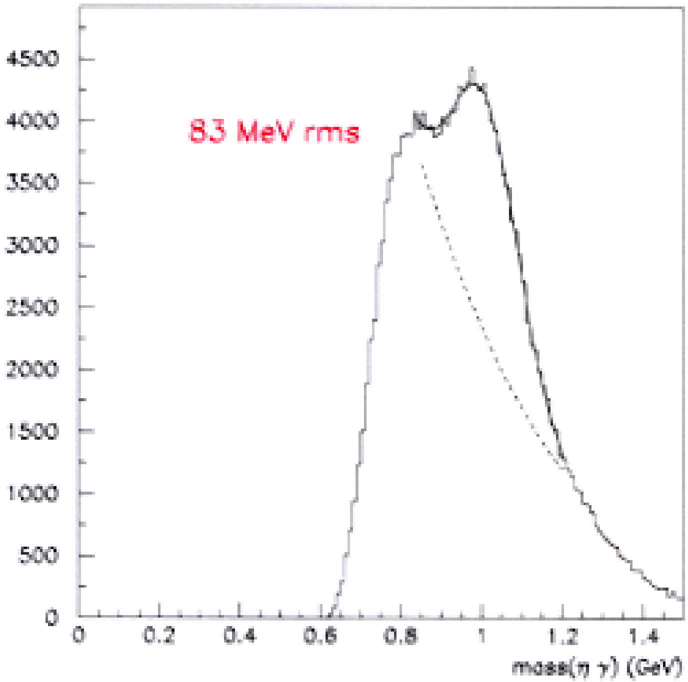


3γ invariant-mass spectra



Total sample:
4.8 M

ω(782)



Total sample:
230 K

φ(1020)

List of backgrounds under study

3γ:

$\gamma n \to p \rho^- \hookrightarrow \pi^0 (\pi^-)$

$\gamma p \to p \eta \hookrightarrow \pi^0 (\pi^+ \pi^-)$, $\eta' \hookrightarrow \eta (\pi^+ \pi^-)$

$\gamma p \to p \omega \hookrightarrow \pi^0 (\pi^+ \pi^-)$

....

$\gamma p \to p \chi \hookrightarrow \pi^0 (n \pi^\pm)$

5γ:

$\gamma p \to p \eta' \hookrightarrow 2\pi^0 \eta$

$\gamma p \to p b_1 \hookrightarrow \pi^0 \omega \hookrightarrow \begin{cases} \pi^0 \gamma \\ \pi^0 (\pi^+ \pi^-) \end{cases}$

$\gamma p \to p a_1 \hookrightarrow 3\pi^0$

$\gamma p \to p f_2 \hookrightarrow 2\pi^0 (\pi^+ \pi^-)$

$\gamma p \to p f_1 \hookrightarrow a_0 \pi^0$ or $2\pi^0 (\pi^+ \pi^-)$

$\gamma n \to p a_2^- \hookrightarrow 2\pi^0 (\pi^-)$

$\gamma n \to p a_1^- \hookrightarrow 2\pi^0 (\pi^-)$

The competition:

$$e^+e^- \to \phi \to \gamma\pi^0(\pi^0, \eta)$$

f_0, a_0

$\phi \to f_0 \gamma$, $f_0 \to \pi^0\pi^0$

VEPP-2M (Novirsibirsk)

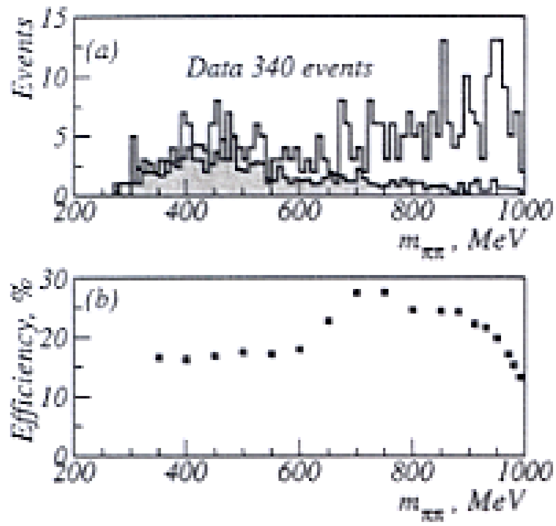


FIG. 4. a – invariant mass distribution of $\pi^0\pi^0$ pairs for selected $\pi^0\pi^0\gamma$ events without acceptance corrections. Histogram – data, shaded histogram – estimated background contribution from $e^+e^- \to \omega\pi^0$ and $\phi \to \eta\gamma$; b – detection efficiency for $\pi^0\pi^0\gamma$ events.

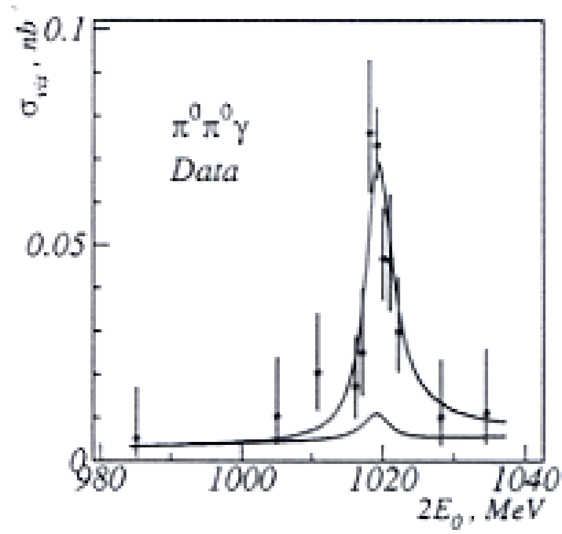


FIG. 6. Energy dependence of the visible $e^+e^- \to \pi^0\pi^0\gamma$ cross section. Points – data, solid line – fit, dotted line – estimated background contribution from $e^+e^- \to \omega\pi^0$ and $\phi \to \eta\gamma$.

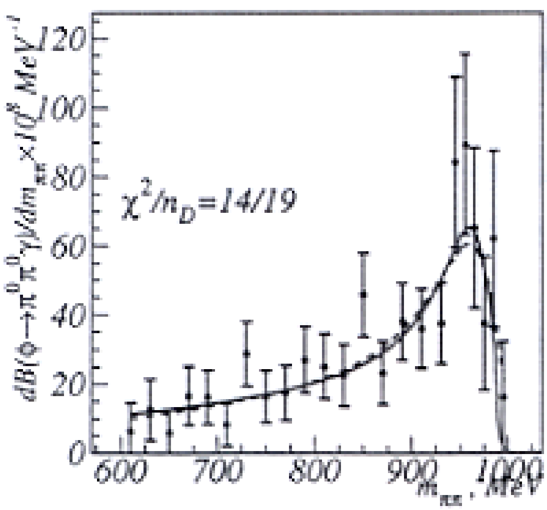


FIG. 5. The measured $\pi^0\pi^0$ invariant mass spectrur Background is subtracted and efficiency corrections applie Points – data, solid line – the result of the "broad resonanc fit, dashed line – the result of the "narrow resonance" fit.

largest background

$e^+e^- \to \pi^0\omega$, $\omega \to \pi^0\gamma$ (5γ)

B.R. $\phi \to \gamma f_0 \simeq (4.7 \pm 1.0)\cdot 10^{-4}$

how much resonant?

(30%)

VEPP - 2M

$e^+e^- \to \phi \to \gamma\pi^0\eta$

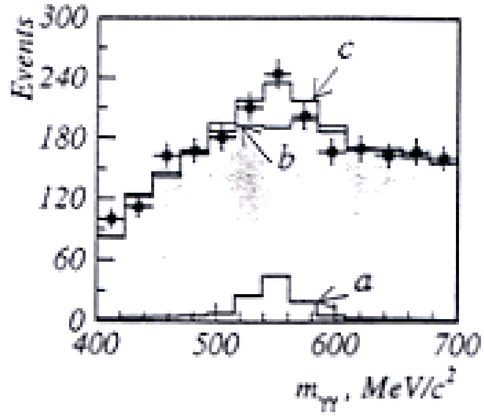


Figure 1: Invariant masses of pairs of most energetic photons: circles with error bars – experimental data, a – simulated signal from $\phi \to \eta\pi^0\gamma$ decay corresponding to a branching ratio of $0.7 \cdot 10^{-4}$, b – estimated background from the $e^+e^- \to \omega\pi^0$ and $\phi \to \eta\gamma$, $f_0(980)\gamma$ events, c – sum of a and b.

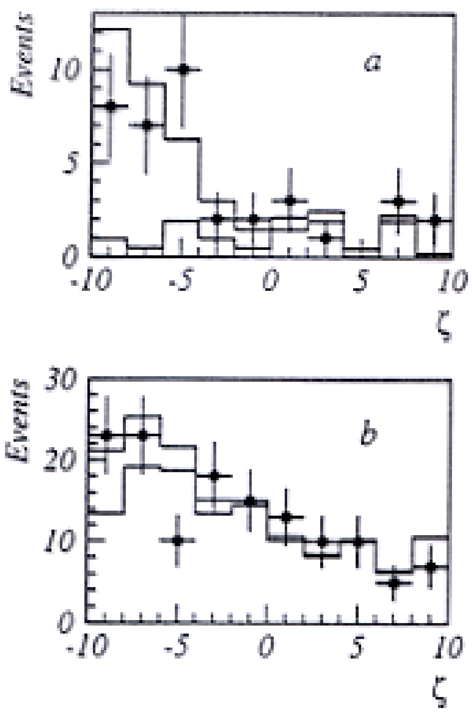


Figure 3: Distribution of events over ζ: a – events with $E_{\gamma max}/E_0 < 0.7$, b – events with $0.7 < E_{\gamma max}/E_0 < 0.8$ circles with error bars – experimental data, shaded histogram depicts simulation of the process (2) and clear histogram – simulated sum of (2) and (1) with a $BR = 10^{-4}$.

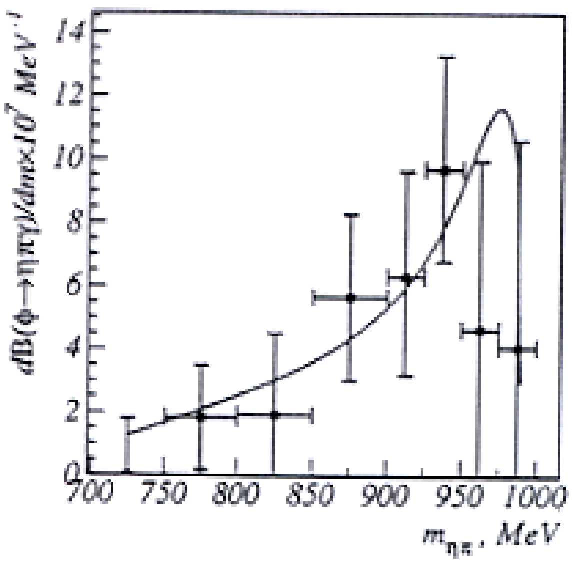


Figure 4: $\eta\pi^0$ invariant mass spectrum: points – experimental data, curve – optimal fit according to Ref. [1].

dominant background

$\phi \to \gamma\eta$
$\quad \hookrightarrow 3\pi^0$

B.R. $\sim 1.2 \times 10^{-4}$
(resonant part?)

Status and Prospects

1.) DAΦNE is now showing results

$BR(\phi \to f_0 \gamma \to \pi^0 \pi^0 \gamma) = (0.81 \pm .09 \pm .06) \cdot 10^{-4}$

$BR(\phi \to a_0 \gamma \to \pi^0 \eta \gamma) = (0.69 \pm .14 \pm .10) \cdot 10^{-4}$

→ compatible with VEPP-2M

2.) New theoretical results are coming from calculations in chiral unitary approach - called predictions

$BR(\phi \to f_0 \gamma \to \pi^0 \pi^0 \gamma) = 0.80 \times 10^{-4}$

$BR(\phi \to a_0 \gamma \to \pi^0 \eta \gamma) = 0.87 \times 10^{-4}$

3.) First results from Radphi expected by end of 2001.