Φ Rare Decays and Exotic Mesons.

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Based on recent experiments at VEPP-2M e^+e^- collider

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CONTENTS

VEPP-2M Collider Complex

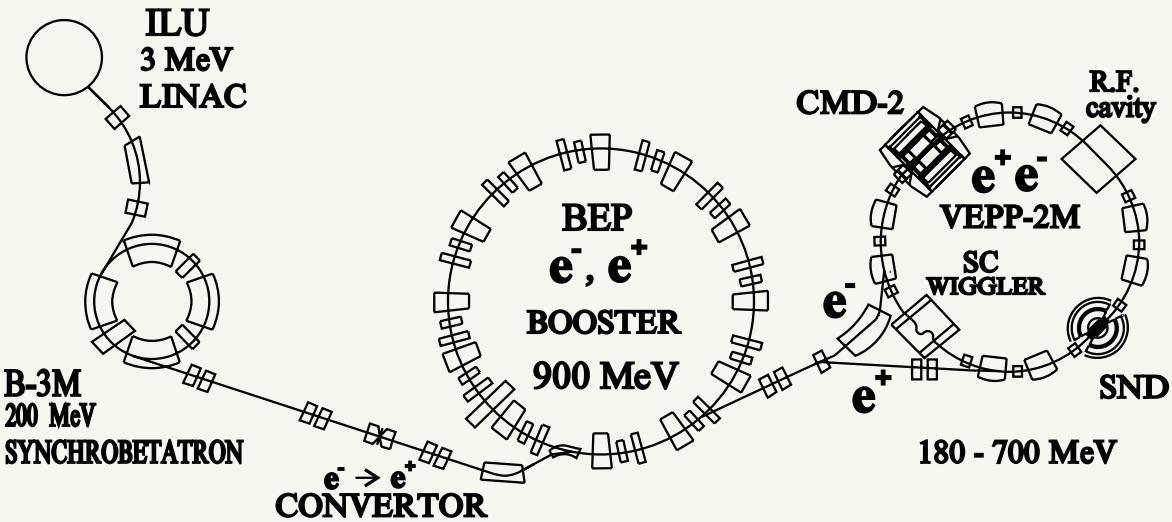


Figure 1:

- VEPP-2 - world first e^+e^- machine, operated from 1965 to 1970,
- VEPP-2M - operates since 1974,
- $2E = 0.4 \div 1.4$ GeV,
- $L_{max} = 4 \cdot 10^{30} cm^{-2} sec^{-1}$ at $E_0 = 510 MeV$,
- Total integrated luminosity $\simeq 80 pb^{-1}$.

Layout of SND

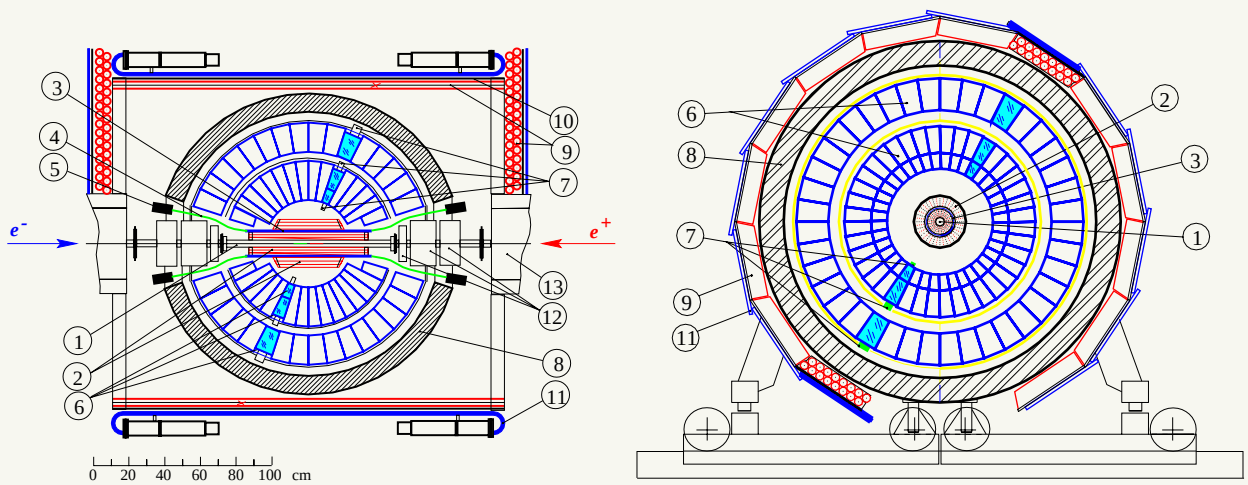


Figure 2: 1 - beam pipe, 2 - drift chambers, 3 - scintillation counter, 4 - light guides, 5 - PMTs, 6 - NaI(Tl) crystals, 7 - vacuum phototriodes 8 - iron absorber, 9 - streamer tubes, 10 - iron plates, 11 - plastic scintillators, 12 and 13 - collider magnets

SND operates since 1992,

Total integrated luminosity $\simeq 25pb^{-1}$

Number of produced $\phi \simeq 2 \cdot 10^7$

Layout of CMD-2

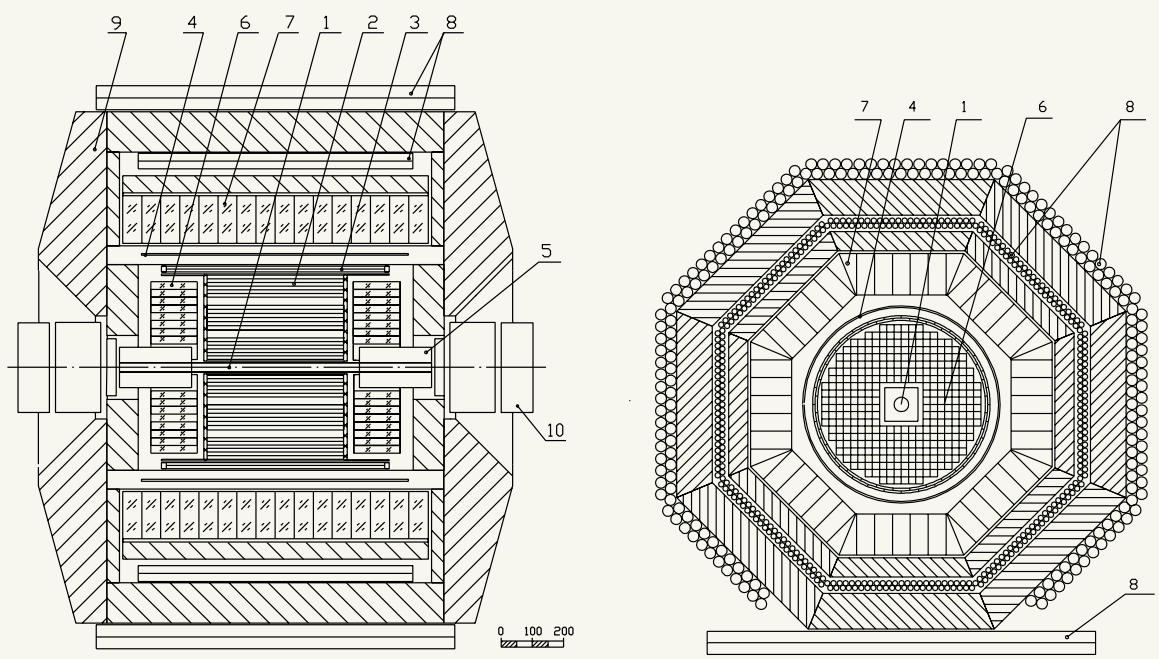
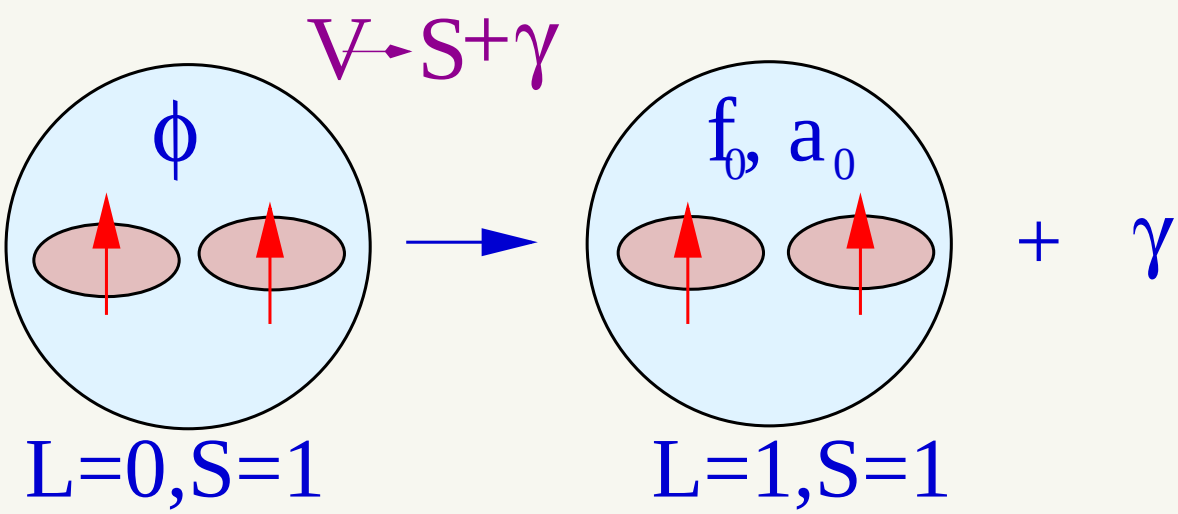


Figure 3: 1 - beam pipe; 2 - drift chamber; 3 - Z-chamber; 4 - superconductive solenoid; 5 - compensating magnet; 6 - endcap BGO calorimeter; 7 - barrel CsI(Tl)calorimeter; 8 - muon range system; 9 - yoke; 10 - quadrupole lenses

CMD-2 operates since 1992,

Total integrated luminosity $\simeq 27pb^{-1}$

Decays $\phi \to f_0\gamma,\ a_0\gamma$ in $q\bar{q}$ model



Electric dipole radiative decays are well known in heavy quarkonia e.g.

$\psi(2S) \to \chi_{c0}(1P) + \gamma$, ~9%,

$\Upsilon(2S) \to \chi_{b0}(1P) + \gamma$, ~4%,

but very few were seen in lightest quarkonia ϕ, ρ, ω.

History of $\phi \to f_0\gamma,\ a_0\gamma$ decays

1. 1984, VEPP-2M, Upper limits,
   $B(\phi \to f_0\gamma) < 2 \cdot 10^{-3}$, $B(\phi \to a_0\gamma) < 2.5 \cdot 10^{-3}$,
   Z.Phys.C37(1987)1,

2. 1987, N.Achasov, Estimates in 4-quark model:
   $B(\phi \to f_0\gamma, a_0\gamma) \sim 10^{-4}$, NP,B315(1989)465,

3. 1990-1997, Copious theoretical works in
   connection with DAFNE project,

4. 1997, VEPP-2M, SND, HADRON-97 Conference,
   First observation with
   $B(\phi \to f_0\gamma) \sim B(\phi \to a_0\gamma) \sim 10^{-4}$,

5. 1999, References for VEPP-2M data:
   PL,B440(1998)442, PL,B438(1998)441,

$\pi^0\pi^0\gamma$ and $\eta\pi^0\gamma$ Events Analysis

Background

- $e^+e^- \to \omega\pi^0 \to 5\gamma$
- $\phi \to \eta\gamma \to 3\pi^0\gamma$
- $\phi \to K_S K_L \to neutrals$

Selection Criteria

1. 5γ
2. Energy momentum balance
3. $2\pi^0$ or $\eta\pi^0$ in an event
4. $\omega\pi^0 \to 5\gamma$ and $\eta\gamma \to 3\pi^0\gamma$ suppression
5. $\zeta < 0$ - transverse shower profile

Detection Efficiency

- For $\phi \to \pi^0\pi^0\gamma$ $\epsilon \simeq 15\%$

- For $\phi \to \eta\pi^0\gamma \quad \epsilon \simeq 4\%$
- For $\phi \to \eta\gamma \quad \epsilon \simeq 0.07\%$

Check of $\pi^0\pi^0$ system spin structure.

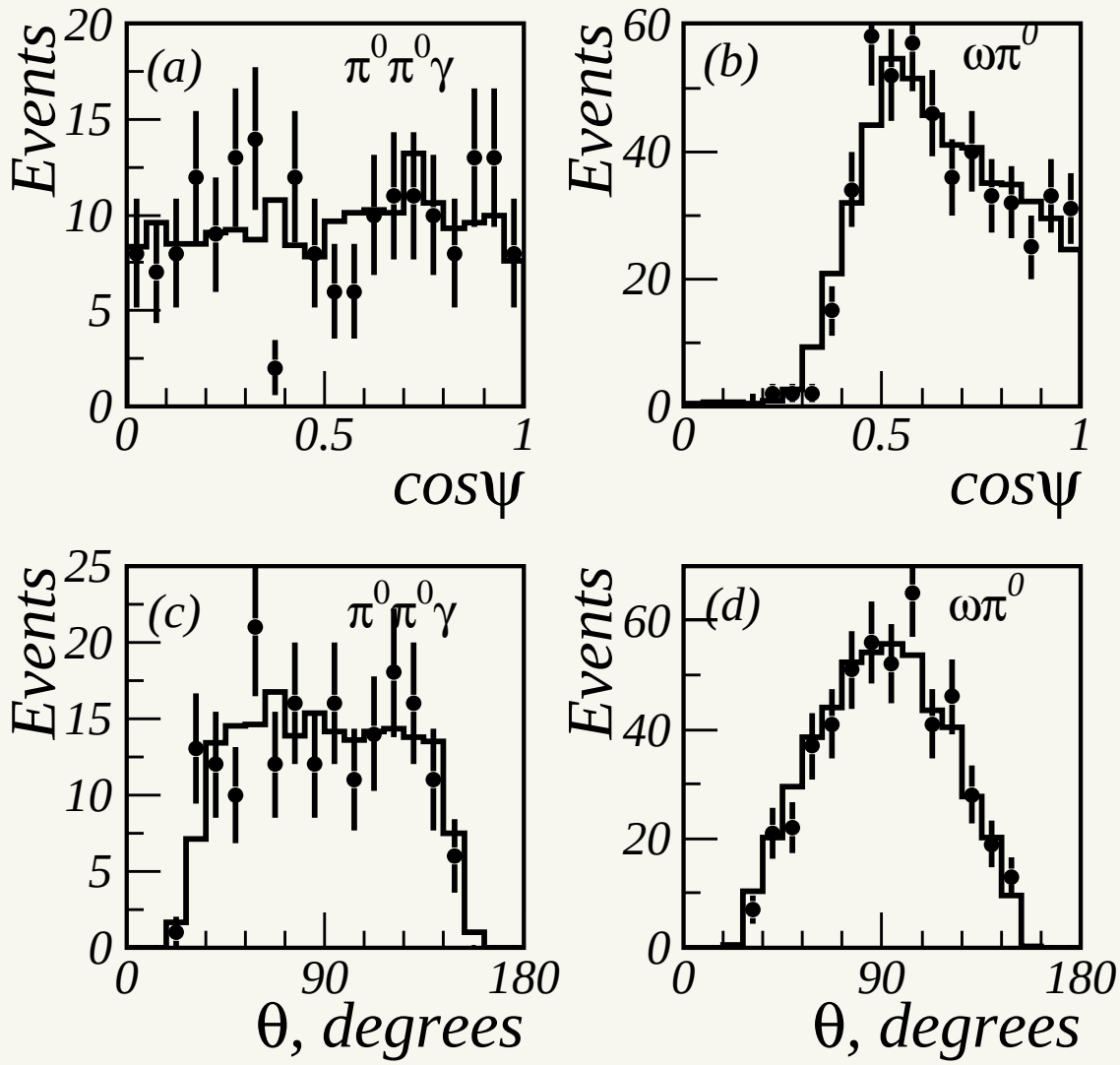


Figure 4: a, b – cosine of ψ, the angle between directions of π^0 and recoil γ in the rest frame of $\pi^0\pi^0$ system; c, d – distributions in θ, angle of the recoil γ with respect to the beam. Points – data, histogram – simulation.

Evidence of $\phi \to \eta\pi^0\gamma$ process

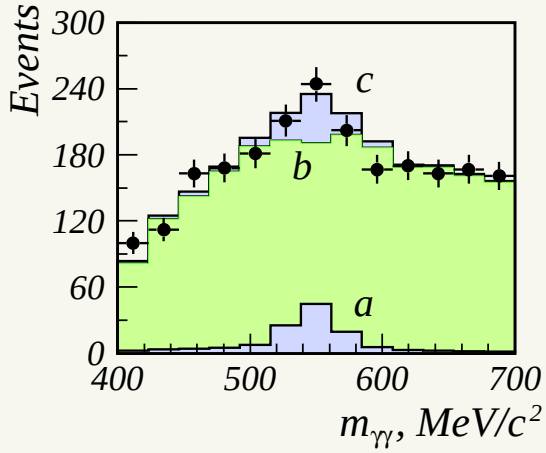


Figure 5: Two photon mass

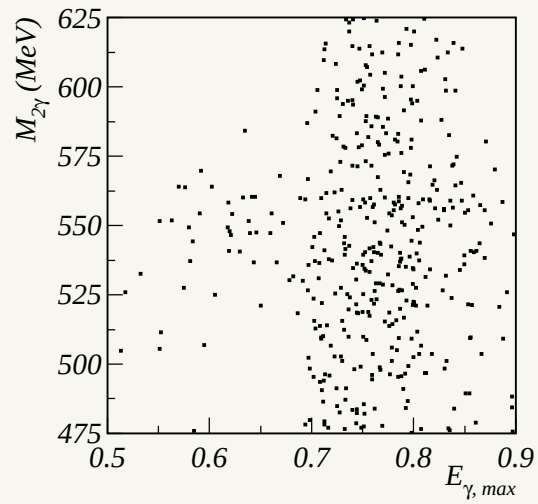


Figure 6: $M_{2\gamma}$ versus $E_{\gamma,max}$

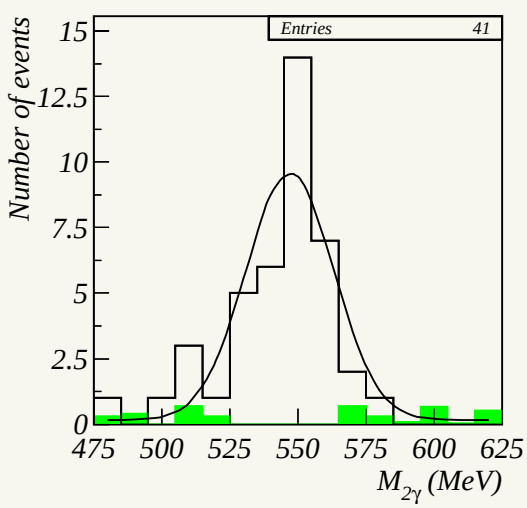


Figure 7: Two photon mass at $E_{\gamma,max} < 0.7E_0$

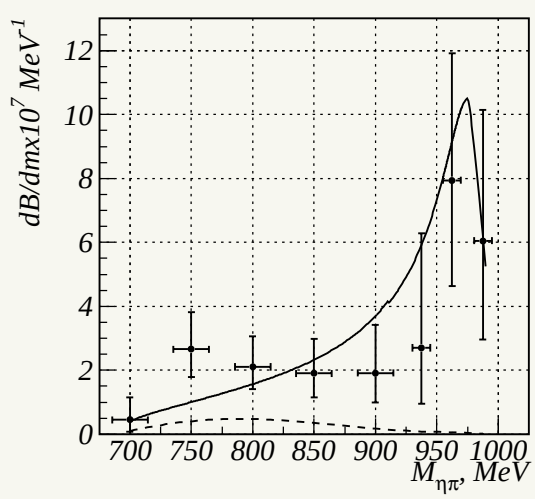


Figure 8: $\eta\pi^0$-mass

$\pi^0\pi^0$ and $\eta\pi^0$ mass spectra

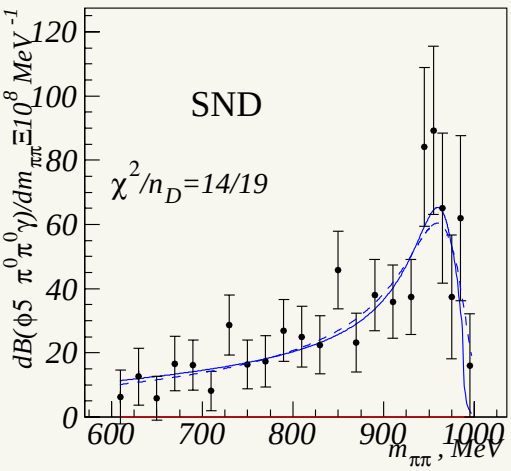


Figure 9: The $\pi^0\pi^0$ mass, SND, 1998

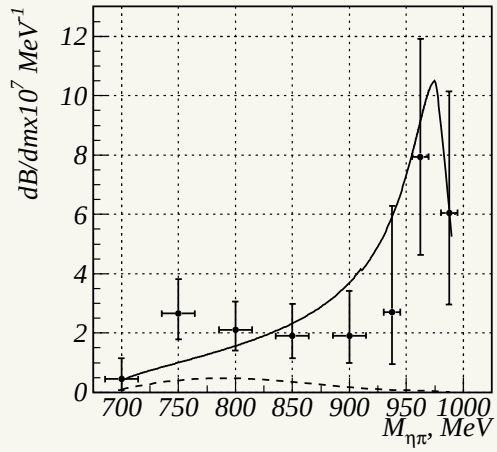


Figure 10: The $\eta\pi^0$ mass, SND, 1999

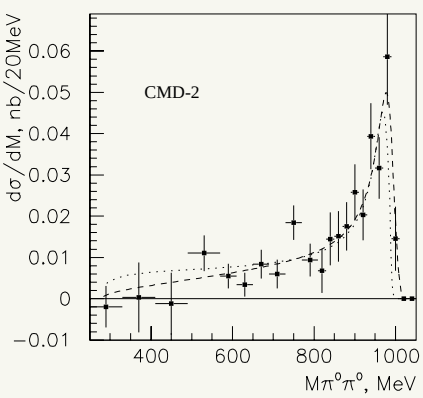


Figure 11: The $\pi^0\pi^0$ mass, CMD-2, 1999

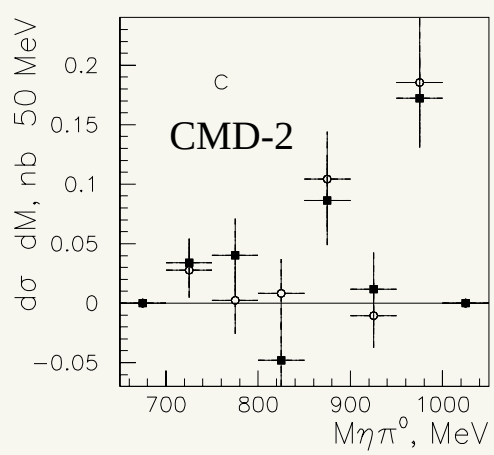


Figure 12: The $\eta\pi^0$ mass, CMD-2, 1999

Results for decays $\phi \to \pi^0\pi^0\gamma$, $\phi \to \eta\pi^0\gamma$

SND Branching Ratios

Ref.: Phys.Lett.B440(1998)442
For $m_{\pi\pi} > 900\ MeV$:
$B(\phi \to \pi^0\pi^0\gamma) = (0.50 \pm 0.06 \pm 0.06) \cdot 10^{-4}$,
For the whole mass spectrum:
$B(\phi \to \pi^0\pi^0\gamma) = (1.14 \pm 0.10 \pm 0.12) \cdot 10^{-4}$,
$B(\phi \to \pi\pi\gamma) = (3.42 \pm 0.30 \pm 0.36) \cdot 10^{-4}$,

Ref.: Phys.Lett.B438(1998)441
For $m_{\eta\pi} > 950\ MeV$:
$B(\phi \to \eta\pi^0\gamma) =\simeq 0.36 \cdot 10^{-4}$,
For the whole mass spectrum:
$B(\phi \to \eta\pi^0\gamma) = (0.89 \pm 0.14 \pm 0.06) \cdot 10^{-4}$,

CMD-2 Branching Ratios (Preliminary)

Ref.: Preprint INP 99-51

$B(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.17 \pm 0.09) \cdot 10^{-4}$,

$B(\phi \to f_0\gamma) = (3.11 \pm 0.23) \cdot 10^{-4}$,

$B(\phi \to \eta\pi^0\gamma) = (0.90 \pm 0.24 \pm 0.10) \cdot 10^{-4}$

Fitting of $\pi^0\pi^0$ and $\eta\pi^0$ mass spectra

Ref.: Phys.Rev.D56(1997)4084

$$\frac{dBr(\phi \to \pi^o\pi^o\gamma)}{dm_{\pi\pi}} = \frac{2m^2_{\pi\pi}\Gamma(\phi \to f_0\gamma)\Gamma(f_0 \to \pi^0\pi^0)}{\pi\Gamma_\phi} \times \left| \frac{1}{D_f(m_{\pi\pi})} + \frac{A_\sigma \cdot e^{i\varphi_\sigma}}{D_\sigma(m_{\pi\pi})} \right|^2 \quad (1)$$

$$\Gamma(f_0 \to \pi^0\pi^0) = \frac{g^2_{f\pi^+\pi^-}}{32\pi m_{\pi\pi}} \sqrt{1 - \frac{4m^2_{\pi^0}}{m^2_{\pi\pi}}}. \quad (2)$$

$D_x(m) = m_x^2 - m^2 - i \cdot m\Gamma_x(m)$ $A_\sigma = g_{\sigma\pi\pi}g_{\phi\sigma\gamma}/g_{f\pi\pi}g_{\phi f\gamma}$,

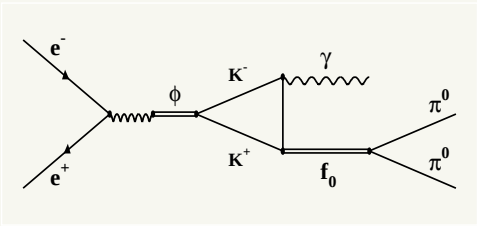
$m_\sigma = 1\ GeV$, $\Gamma_\sigma = 800\ MeV$, $\varphi_\sigma = 0$.

$\Gamma_f(m) = 3\Gamma(f_0 \to \pi^0\pi^0)$

'Narrow' Resonance Model: $\Gamma(\phi f\gamma) \sim g^2_{\phi f\gamma} \cdot \omega$

'Wide' Resonance Model: $g^2_{\phi f\gamma} \sim g_{\phi KK} \cdot g_{fKK} \cdot F(m_{\pi\pi})$

'Wide' Res. Model Diagram:



Decays $\phi \to \pi^+\pi^-\gamma$ from CMD-2.

Refs: Preprint Budker INP 99-11, 1999
E.P.Solodov, Talk for '$\phi - J/\psi$' - Conference, Novosibirsk, March 1-5,1999

Background:

- $e^+e^- \to \phi \to \pi^+\pi^-(\gamma), Br \sim 0.05 \cdot 10^{-4}$
- $e^+e^- \to \phi \to \mu^+\mu^-(\gamma), Br \sim 0.1 \cdot 10^{-4}$
- $e^+e^- \to \rho\gamma \to \pi^+\pi^-\gamma, nonresonant\ \sigma \sim 1.5nb$
- $e^+e^- \to \rho \to \pi^+\pi^-(\gamma), nonresonant\ \sigma \sim 0.7nb$

Investigated decays:

$e^+e^- \to \phi \to f_0\gamma \to \pi^+\pi^-\gamma,\ Br \sim 10^{-4}$

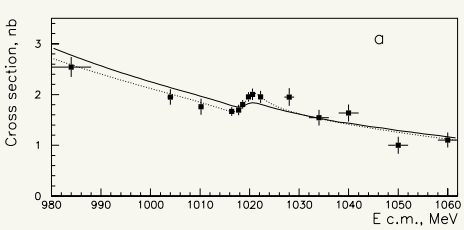


Figure 13: $e^+e^- \to \pi^+\pi^-\gamma$ cross section.

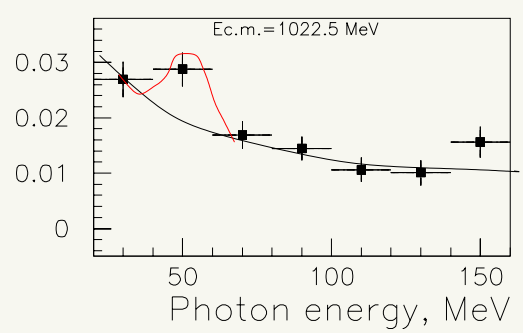


Figure 14: Recoil photon spectrum.

Model dependent branching ratio

Reference for model: NP,B315,(1989),465

$m_{f_0} = 976 \pm 5$ MeV,

$Br(\phi \to f_0\gamma) = 1.9 \pm 0.5 \cdot 10^{-4}$

ϕ decays in different f_0 and a_0 models

Refs: NP,B315,(1989),465; Phys.Rev.D56(1997)4084

$q\bar{q}$ model

$f_0 = \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$, $a_0 = \frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$

$B(\phi \to f_0\gamma \to \pi^0\pi^0\gamma) \simeq 1.5 \cdot 10^{-5}$,

$B(\phi \to a_0\gamma \to \eta\pi^0\gamma) \simeq 2.5 \cdot 10^{-5}$,

$f_0 \simeq s\bar{s}$,

$B(\phi \to f_0\gamma \to \pi^0\pi^0\gamma) \simeq 2.5 \cdot 10^{-5}$,

$K\bar{K}$ model

$f_0 = \frac{K^0\bar{K}^0+K^+\bar{K}^+}{\sqrt{2}}$, $a_0 = \frac{K^0\bar{K}^0-K^+\bar{K}^+}{\sqrt{2}}$,

$B(\phi \to f_0\gamma \to \pi^0\pi^0\gamma) \simeq 10^{-5}$,

$B(\phi \to a_0\gamma \to \eta\pi^0\gamma) \simeq 10^{-5}$

$q\bar{q}q\bar{q}$ model

$f_0 = \frac{u\bar{u}+d\bar{d}}{\sqrt{2}} \cdot s\bar{s}$, $a_0 = \frac{u\bar{u}-d\bar{d}}{\sqrt{2}} \cdot s\bar{s}$,

$B(\phi \to f_0\gamma \to \pi^0\pi^0\gamma) \simeq 8 \cdot 10^{-5}$,

$B(\phi \to a_0\gamma \to \eta\pi^0\gamma) \simeq 20 \cdot 10^{-5}$

The accuracy of model predictions $\sim 50\%$

The structure of f_0 in different models.

Refs: N.Achasov, Talk given at '$\phi - J/\psi$'-Conference, Novosibirsk, March 1-5, 1999

Model	$n\bar{n}$	$s\bar{s}$	$K\bar{K}$	$n\bar{n}s\bar{s}$	Exp.
Mass, MeV	∼1300	∼1300	∼980	∼1000	980
$J/\psi \to f_0\gamma, 10^4$	> 3.4	$> 2?$		+	< 0.14
$J/\psi \to f_0\omega$	▬				∼1.4
$D_S \to f_0\pi$	▬	+	+	+	∼1.8%
$f_0 \to \gamma\gamma$,keV	0.6÷15	< 0.05	0.6	0.3	0.3
$\phi \to f_0\gamma, 10^5$	∼4.5	∼5.5	∼1.	∼25.	≃30

The structure of a_0 in different models.

Model	$n\bar{n}$	$K\bar{K}$	$n\bar{n}s\bar{s}$	Exp.
Mass, MeV	∼ 1300	∼980	∼1000	980
$J/\psi \to a_0\rho$	▬		+	$< 4 \cdot 10^{-4}$
$a_0 \to \gamma\gamma$,keV	1.5÷6.	0.6	0.27	0.3
$\phi \to a_0\gamma, 10^5$	∼2.5	∼1	∼20	≃9

Comments to the previous slide

or why f_0 and a_0 look like exotics

Refs: N.Achasov, Talk given at '$\phi - J/\psi$'-Conference, Novosibirsk, March 1-5, 1999

- $B(\phi \to a_0\gamma \simeq B(\phi \to \eta'\gamma)$ - a_0 contains strange quarks!
  $\frac{B(J/\psi \to a_0\rho}{B(J/\psi \to a_2\rho} < 0.04 \pm 0.08$ contradicting $a_0 = \frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$.
- $B(J/\psi \to f_0\omega) \ll B(J/\psi \to f_2\omega)$,
  $B(J/\psi \to f_0\omega) < B(J/\psi \to f_0\phi)$,
  $B(J/\psi \to f_0\gamma) < 0.14 \cdot 10^{-4}$ instead of $> 3.4 \cdot 10^{-4}$,
  contradicting structure $f_0 = \frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$,
  $B(\phi \to f_0\gamma) > B(\phi \to \eta'\gamma)$ - f_0 contains strange quarks!
-

f_0 parameters from ϕ radiative decays

Decay, ref.	M_f,MeV	Γ_f,MeV	$\frac{g^2_{f\pi\pi}}{4\pi}, GeV^2$	$\frac{g^2_{fKK}}{g^2_{f\pi\pi}}$
$\phi \to \pi^0\pi^0\gamma$, narr.res.[1]	984 ± 12	74 ± 12	0.20 ± 0.03	—
$\phi \to \pi^0\pi^0\gamma$, wide.res.[1]	970 ± 6	188 ± 40	0.51 ± 0.11	4.1 ± 0.9
$\phi \to \pi\pi\gamma$, CMD-2,[2]	978 ± 7	56 ± 23	0.44 ± 0.06	3.8 ± 0.6
$f_0(980)$, PDG, 1998	980 ± 10	$40 \div 100$	—	—

a_0 parameters from ϕ radiative decays

Decay, ref.	M_a,MeV	Γ_a,MeV	$\frac{g^2_{a\eta\pi}}{4\pi}, GeV^2$	$\frac{g^2_{aKK}}{g^2_{a\eta\pi}}$
$\phi \to \eta\pi^0\gamma$, SND,[3]	986 ± 18	—	1.1 ± 0.4	1.4
$a_0(980)$, PDG, 1998	983 ± 1	$50 \div 100$	—	—

Γ_f - is a parameter of model.

A conclusion on $\phi \to f_0\gamma$, $\phi \to a_0\gamma$ decays.

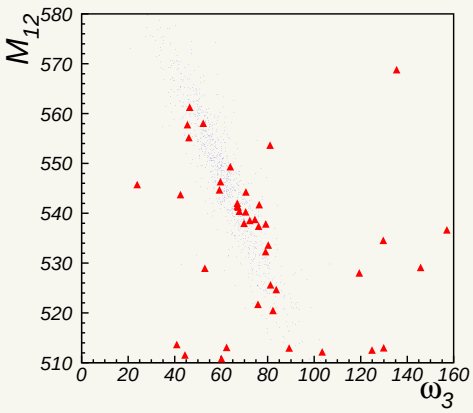
- The main troublesome point is whether the relations $BR(\phi \to \pi\pi\gamma) \simeq BR(\phi \to f_0\gamma)$, $BR(\phi \to \eta\pi\gamma) \simeq BR(\phi \to a_0\gamma)$ are correct. Our claim is, that at least $\sim 50\%$ of events (with mass $M > 900$ MeV) belong to f_0 and a_0. Furthermore, the used for fitting the data the model of N.Achasov describes the whole mass spectrum well.

- The measured branching ratios $BR(\phi \to f_0\gamma)$, $BR(\phi \to a_0\gamma)$ and coupling constants g^2_{fKK}, $g^2_{f\pi\pi}$, ... are strongly model dependent.

- The obtained data contradict conventional $q\bar{q}$ structure of f_0, a_0 scalars, but support their exotic $q\bar{q}q\bar{q}$ structure.

$\phi \to \eta'\gamma$ decay rate with CMD-2

$$e^+e^- \to \phi \to \eta'\gamma,\ \eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$$



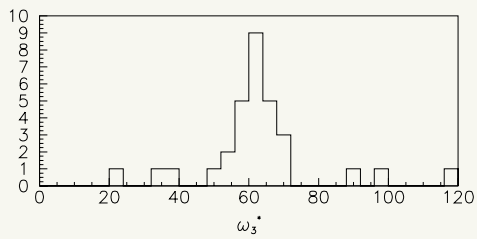


Figure 15: Two photon mass spectra versus recoil photon energy.

Figure 16: Recoil photon energy spectrum

CMD-2:1996 -	$B_{\eta'\gamma} =$	$10.1^{+5.2}_{-4.2} \cdot 10^{-5}$
CMD-2:1998 -	$B_{\eta'\gamma} =$	$8.2^{+2.1}_{-1.9} \pm 1. \cdot 10^{-5}$
SND :1998 -	$B_{\eta'\gamma} =$	$6.7^{+3.4}_{-2.9} \cdot 10^{-5}$

SND and CMD-2 Averaged Data

$$B_{aver.}(\eta'\gamma) = 7.7^{+1.8}_{-1.5} \cdot 10^{-5}$$

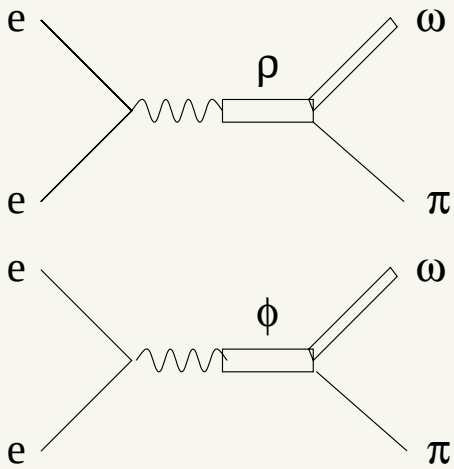
New Radiative Decay Data from VEPP-2M,

not included into PDG-1998 Tables

Process	Branch.SND	Branch,CMD	PDG-1998
$\phi \to \pi^0\pi^0\gamma$	11.4 ± 1.6	10.8 ± 1.9	$< 100.$
$\phi \to \pi^+\pi^-\gamma$	—	—	$< 3.$
$\phi \to f_0\gamma$	34.2 ± 4.33	31.1 ± 2.3	$< 100.$
$\phi \to \eta\pi^0\gamma$	8.9 ± 1.5	9.0 ± 2.6	$< 250.$
$\phi \to \eta'\gamma$	6.7 ± 3.2	8.7 ± 2.1	$12. \pm 6.$
$\rho \to \pi^0\pi^0\gamma$	4.7 ± 1.7	—	—
$\omega \to \pi^0\pi^0\gamma$	9.5 ± 5	—	7.2 ± 2.5

Branching Ratios - in units of 10^{-5}

Decay $\phi \to \omega\pi^0$.

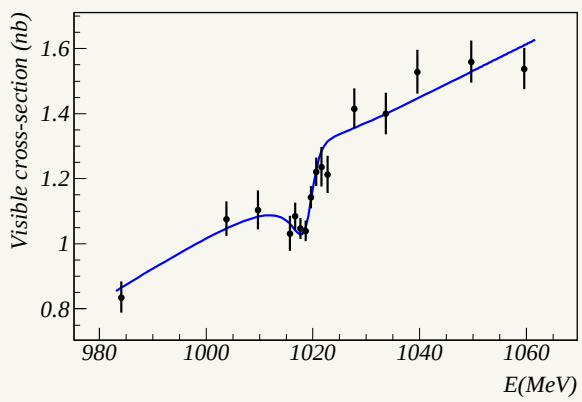


$e^+e^- \to \rho, \rho\prime \to \omega\pi^0$ $\sigma \approx 8nb$,
$\phi \to \omega\pi^0$ $B \approx 5 \cdot 10^{-5}$

$$\sigma_{\omega\pi}(E) = \sigma_0(E) \cdot \left| 1 - Z \frac{m_\phi \Gamma_\phi}{D_\phi} \right|^2$$

$$B(\phi \to \omega\pi^0) = \frac{\sigma_0 \cdot |Z|^2}{\sigma_\phi}$$

$|Z| \approx 15\%$



1996 data:

Phis.Lett. B449(1999) p.122

$B_{\phi\to\omega\pi^0} = (4.8^{+1.9}_{-1.7} \pm 0.8) \cdot 10^{-5}$

1998 data:

$B_{\phi\to\omega\pi^0} = (4.6 \pm 1.0 \pm 0.6) \cdot 10^{-5}$

$Re(Z) = 0.112 \pm 0.015$,

$Im(Z) = -0.104 \pm 0.022$

Discussion.

VDM+standard $\omega - \phi$ mixing: $(8 \div 9) \cdot 10^{-5}$

N.N.Achasov,A.A.Kozhevnikov, Int.J.Mod.Phys. A7(1992) 4825.

standard $\phi - \omega$ mixing

$Re(Z) = 0.2 \div 0.3$

$Im(Z) \approx -0.10 \div 0.20$

'weak' $\phi - \omega$ mixing

$Re(Z) = 0.1 \div 0.2$

$Im(Z) = -0.15 \div 0.25$

Summary of ϕ rare decays from VEPP-2M.

Decay	$Br(10^{-5})$		PDG
Hadronic decays.			
$\phi \to \omega\pi$	$5 \pm 1.5 \pm 0.5$	SND	
$\phi \to \pi\pi$	$7.1 \pm 1.0 \pm 1.1$	SND	8^{+5}_{-4}
	$18 \pm 2.5 \pm 1.9$	CMD	
$\phi \to \pi^+\pi^-\pi^+\pi^-$	$0.77 \pm 0.21 \pm 0.20$	CMD	< 87\$
Radiative decays.			
$\phi \to \eta'\gamma$	$6.7^{+3.4}_{-2.9}$	SND	12^{+7}_{-5}
	$8.2^{+2.1}_{-1.9}$	CMD	
$\phi \to \pi^0\pi^0\gamma$	$11.4 \pm 1.0 \pm 1.2$	SND	< 100
	$10.8 \pm 1.7 \pm 0.9$	CMD	
$\phi \to \eta\pi^0\gamma$	$8.9 \pm 1.4 \pm 0.6$	SND	< 250
	$9.0 \pm 2.4 \pm 1.0$	CMD	
Other electromagnetic decays.			
$\phi \to \mu\mu$	$31.4 \pm 2.2 \pm 1.4$	SND	25 ± 4
	$28 \pm 3.0 \pm 4.6$	CMD	
$\phi \to \mu\mu\gamma$	1.3 ± 0.6	CMD	2.3 ± 1.0
$\phi \to \eta e^+e^-$	$14.2 \pm 3.9 \pm 2.3$	SND	13^{+8}_{-6}
	$11.2 \pm 1.7 \pm 1.7$	CMD	
$\phi \to \pi^0 e^+e^-$	$1.29 \pm 0.29 \pm 0.19$	CMD	< 12

Decays $\rho, \omega \to \pi^0\pi^0\gamma$.

Old VEPP-2M data on the decay $\rho \to \pi^+\pi^-\gamma$.

Ref: Phys.Rep, v.202 No.3 (1991) 99

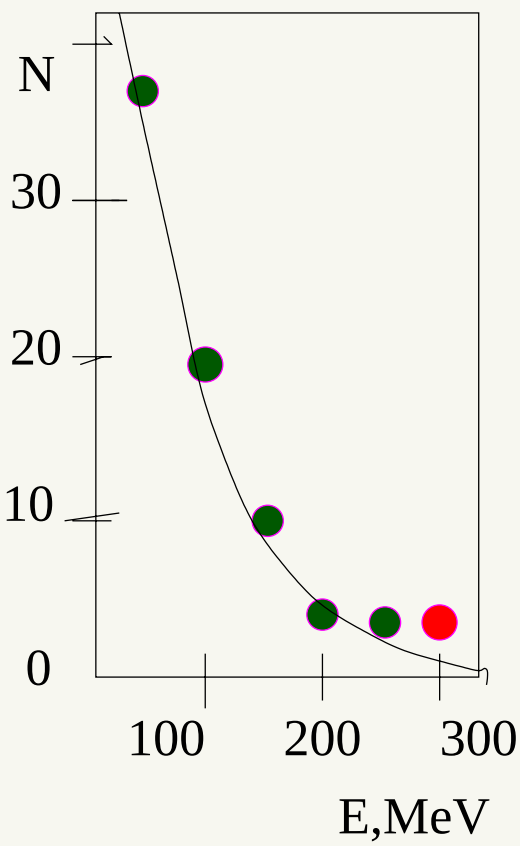


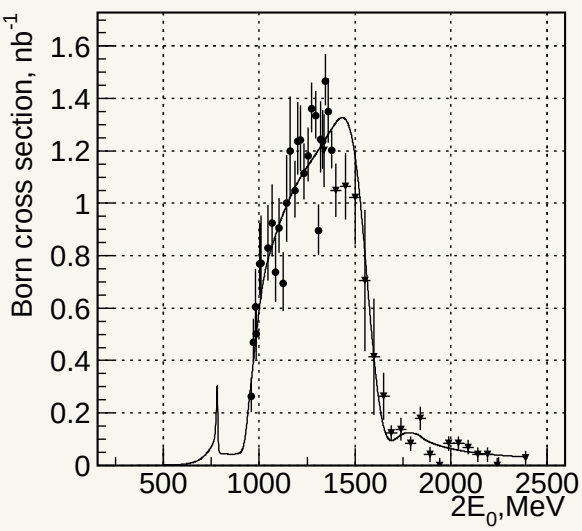
Figure 17: $\rho \to \pi^+\pi^-\gamma$ photon spectrum. Points - experiment, solid line - bremsstrahlung (M.C.)

$B(\rho \to \pi^+\pi^-\gamma) = 0.99 \pm 0.04 \pm 0.15\%$, $E_\gamma > 50 MeV$ - bremsstrahlung

$B(\rho \to \pi^+\pi^-\gamma) = 1.3 \pm 0.6 \cdot 10^{-4}$, $E_\gamma > 200 MeV$ - structural radiation, due to a possible scalar resonance σ in $\pi^+\pi^-$ -system. $\Gamma(\rho\sigma\gamma) \simeq$ 20 KeV

Decays $\rho, \omega \to \pi^0\pi^0\gamma$. New SND Data.

PDG(1998): $BR(\omega \to \pi^0\pi^0\gamma) = 7.2 \pm 2.5 \cdot 10^{-5}$



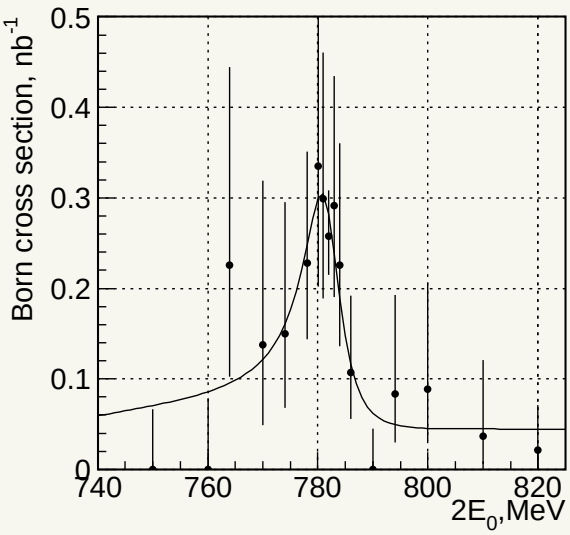


Figure 18: Born cross section. Figure 19: Born cross section.

The fit at $2E < 900\ MeV$ included ρ, ω (VMD) and and their decays via a scalar σ state.

$BR(\rho \to \omega\pi^0 \to \pi^0\pi^0\gamma) \simeq 10^{-5}$, $\Gamma \simeq 1.5 KeV$ — VMD

$BR(\omega \to \rho\pi^0 \to \pi^0\pi^0\gamma) \simeq 2.6 \cdot 10^{-5}$, $\Gamma \simeq 0.2 KeV$, — VMD

The fitting results:

$BR(\omega \to \pi^0\pi^0\gamma) = 9.5^{+7}_{-4} \cdot 10^{-5}$, - (total)

$BR(\rho \to \sigma\gamma \to \pi^0\pi^0\gamma) = 4.7^{+1.9}_{-1.6} \cdot 10^{-5}$,

$\Gamma(\rho \to \sigma\gamma \to \pi^0\pi^0\gamma) = \simeq 7 KeV$,

$\Gamma(\omega \to \pi^0\pi^0\gamma) = 0.8^{+0.6}_{-0.3} KeV$, - (total)

Decays $\rho, \omega \to \pi^0\pi^0\gamma$

The main results:

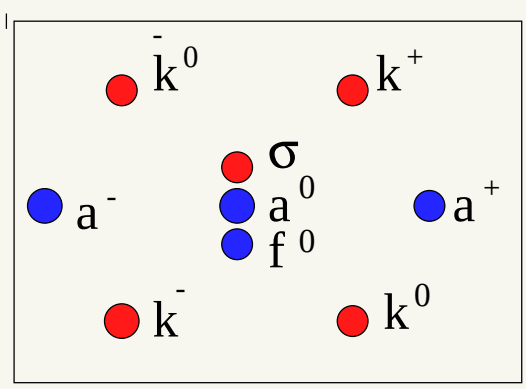
1 - The indications of the $\rho \to \pi^+\pi^-\gamma$ via a scalar state were seen $\simeq$ 10 years ago,

2 - The mesured width of $\rho \to \pi^0\pi^0\gamma$ decay agrees with ND results for $\rho \to \pi^+\pi^-\gamma$ decay,

3 - The measured widths $\Gamma(\rho \to \pi^0\pi^0\gamma)$, $\Gamma(\omega \to \pi^0\pi^0\gamma)$ exceed VMD predictions, what could be a manifestation of $\pi^0\pi^0$ bound state, possibly $\sigma(400 - 1200)$.

4 - $\Gamma(\rho \to \pi^0\pi^0\gamma) \gg \Gamma(\omega \to \pi^0\pi^0\gamma)$ in agreement with VMD.

5 -Four quark model of the lightest scalars, Jaffe(1977):



$\sigma = ud\bar{u}\bar{d}$, $k^+ = ud\bar{d}\bar{s}$, $k^- = ds\bar{u}\bar{d}$, $k^0 = ud\bar{u}\bar{s}$, $\bar{k^0} = us\bar{u}\bar{d}$, $a_0^+ = us\bar{d}\bar{s}$, $a_0^- = ds\bar{u}\bar{s}$, $a_0^0 = \frac{us\bar{u}\bar{s} - ds\bar{d}\bar{s}}{\sqrt{2}}$, $f^0 = \frac{us\bar{u}\bar{s} + ds\bar{d}\bar{s}}{\sqrt{2}}$,

Figure 20: Four-quark nonet, σ is the lowest state with the structure $qq\bar{q}\bar{q}$

$e^+e^- \to \pi^+\pi^-\pi^0$ Cross Section

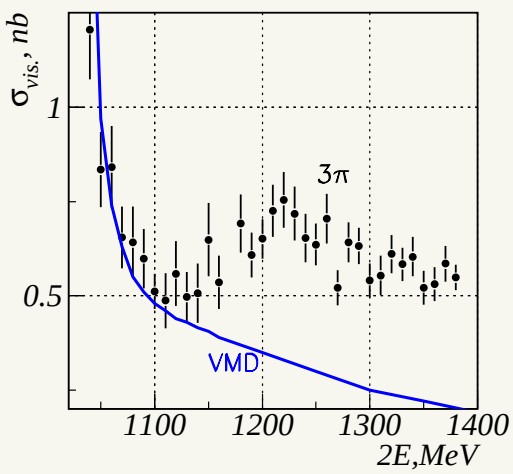


Figure 21: Visible cross section

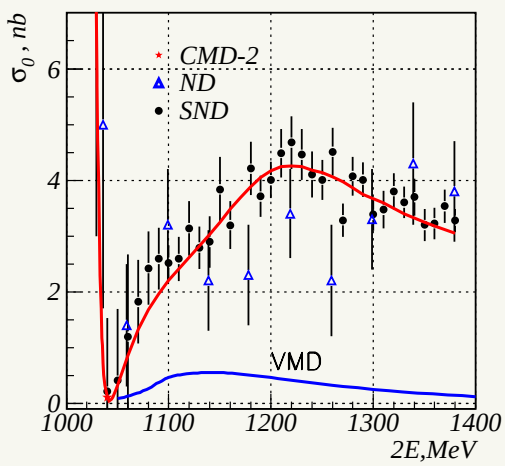


Figure 22: Total cross section

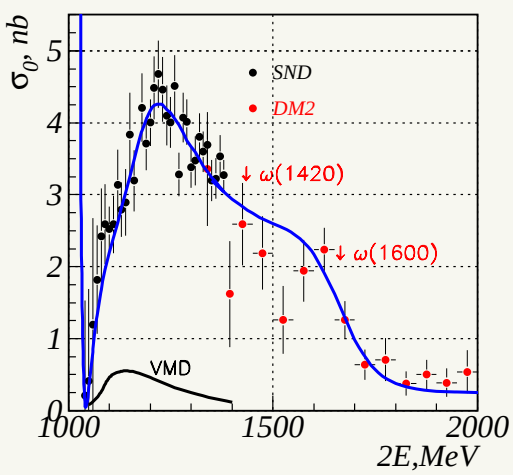


Figure 23: Total cross section

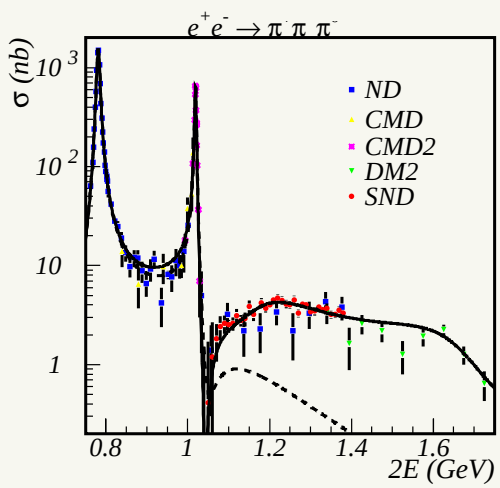


Figure 24: Total cross section

$e^+e^- \to \pi^+\pi^-\pi^0$ Cross Section

Fitting by a sum of B.W. amplitudes

$$\sigma_0(e^+e^- \to \pi^+\pi^-\pi^0) = \frac{W_{\rho\pi}(s)}{s^{3/2}} \cdot \left| \sum_V \sqrt{\frac{\sigma_V \cdot m_V^3}{W_{\rho\pi}(m_V^2)}} \cdot \frac{e^{i\phi_V}\Gamma_V m_V}{s - m_V^2 - i m_V \Gamma_V(s)} \right|^2, \quad (3)$$

$$\sigma_V = \frac{12\pi B_{Vee} B_{V\rho\pi}}{m_V^2}.$$

$W_{\rho\pi}(s)$ is a phase space factor of the final state,
the following 4 resonances were included in the fitting:
$\omega(783)$, $\phi(1020)$, $\omega(1600)$ and $\omega(1200)$,
phases: $\phi_{\omega(783)} = 0$; $\phi_{\phi(1020)} = \pi$; $\phi_{\omega(1200)} = \pi$ and $\phi_{\omega(1600)} = 0$,
$\Gamma_V(s)$=const for $\omega(1200)$ and $\omega(1600)$

Table 1: Fitted parameters of high mass ω-states

Parameter	$\omega(1200)$	$\omega(1600)$
M_{eff}, MeV	1170 ± 10	1643 ± 14
Γ_{eff}, MeV	187 ± 15	272 ± 29
σ_{max},nb	7.8 ± 0.2 $\pm 1.0(syst.)$	0.54 ± 0.13
$\Gamma_{\omega ee} \cdot B_{\omega 3\pi}$, eV	137 ± 3 $\pm 15(syst.)$	27 ± 7

In case of other interference phases the range of parameters is:

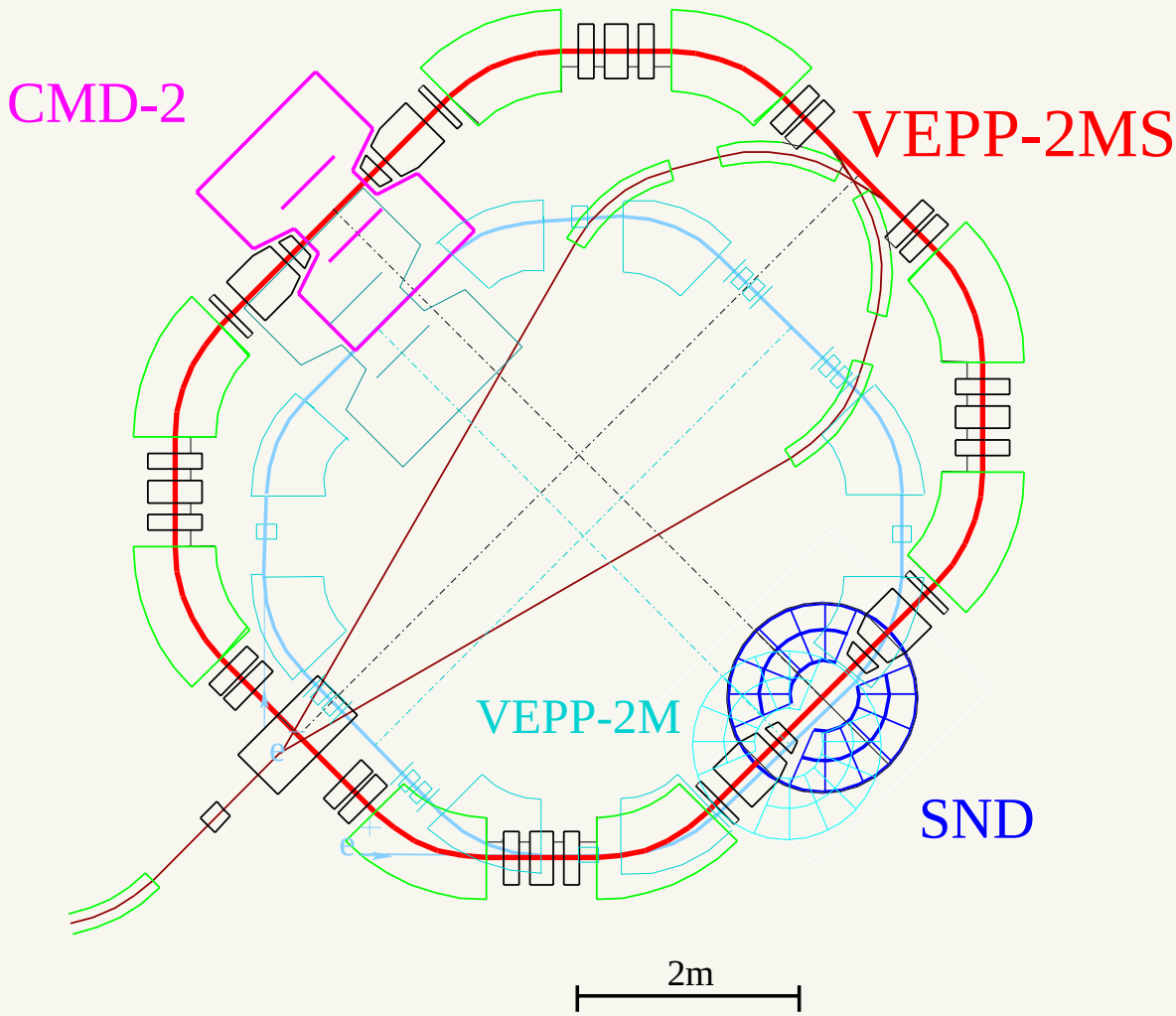
$M_{eff} = 1170 \div 1250\ MeV$, $\Gamma_{eff} = 190 \div 550\ MeV$

Conclusions on $\omega(1200)$.

- The fitting with $\Gamma_V(s)$=const gives $\omega(1200)$ parameters, strongly dependent on interference phase choise. The fitted mass M_{eff} in this case is close to the visible peak position M_{vis}.
- The observed $\omega(1200)$ could be $\omega(783)$ radial excitation 2^3S_1 or orbital excitation 1^3D_1 (D-wave), ...
- New data for the process $e^+e^- \to \pi^+\pi^-\pi^0$ are expected soon from CMD-2 and SND detectors at VEPP-2M.

VEPP-2M UPGRADE

2E=1.4 GeV → 2E=2000 MeV



VEPP-2M & VEPP-2000 parameters

	VEPP-2M $E_m = 700$ MeV	VEPP-2000 $E_m = 1000$ MeV	
E (MeV)	510	510	900
Π (cm)	1788	2235	2235
$\mathcal{I}^+, \mathcal{I}^-$ (mA)	40	34	200
$\varepsilon \cdot 10^5$ (cm · rad)	3	0.5	1.6
β_x (cm)	40	6.3	6.3
β_z (cm)	5	6.3	6.3
ξ_x	0.016	0.075	0.075
ξ_z	0.050	0.075	0.075
$\mathcal{L}$ ($cm^{-2}s^{-1}$)	$3 \cdot 10^{30}$	$1 \cdot 10^{31}$	$1 \cdot 10^{32}$

Contributed Papers

Search for Exotic Baryons with Hidden Strangeness...

hep-ex/9907025

SPHINKS Collaboration, IHEP, Protvino, Russia

Author: L.G.Landsberg, $p + N \to (\Sigma_0 K^+) + N$

1 - diffractive production, $M = 1989 \pm 6 MeV, \Gamma = 91 \pm 20 MeV$,

X(2000) is a candidate for exotic $qqqs\bar{s}$ baryon

2 - produced at small $p_t^2 \ll 0.01 GeV^2$: X(1810) candidate:

$M = 1807 \pm 7 MeV, \Gamma = 62 \pm 19 MeV$,

The new data agree with earlier results (1994-98) and are supported by SELEX experiment (FNAL)

The radiative Decays of Vector Mesons

hep-ph/9907233

Authors: T.L.Zhuang, M.L.Yan, X.J.Wang,(China)

$\rho \to \pi\pi\gamma, B \sim 10^{-5}, \phi \to KK\gamma, B \sim 10^{-7}$,

Calculations in chiral quark model, agree with previous results,

General Conclusions

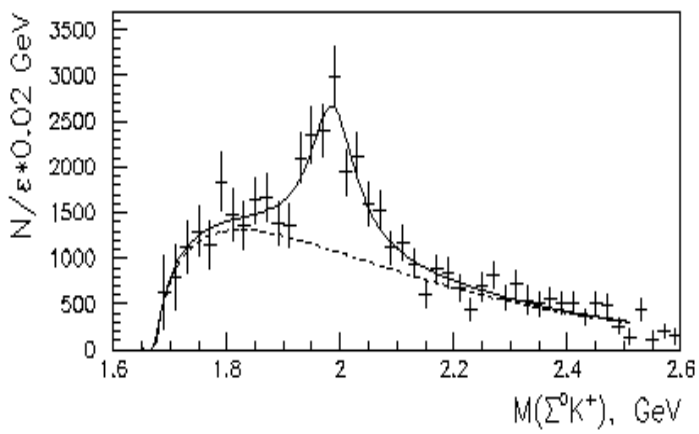
- Experiments were carried out in Novosibirsk at VEPP-2M e^+e^- collider with two collider detectors SND and CMD-2 with total integrated luminosity $\simeq 50pb^{-1}$ and total number of produced ϕ mesons $\sim 4 \cdot 10^7$.
- Electric dipole radiative decays $\phi \to \pi\pi\gamma, \eta\pi^0\gamma$ were observed with branching ratios $\sim 10^{-4}$, indicated for the exotic 4-quark structure of lightest scalars $f_0(980), a_0(980)$.
- Several new rare ϕ-decays were observed with branching fractions $\sim 10^{-4} \div 10^{-5}$, e.g., $\phi \to \omega\pi^0$, $\phi \to \eta'\gamma$, $\phi \to 4\pi$, $\phi \to \pi^0 e^+e^-$,...
- A resonance like structure in $e^+e^- \to \pi^+\pi^-\pi^0$ cross section near $2E \simeq$1.2 GeV was observed, which might be a manifestation of the lightest excited ω state,
- The decays $\rho, \omega \to \pi^0\pi^0\gamma$ were seen. Their width exceed VMD level, which might be a manifestation of lightest scalar state σ(400-1200), decaying into $\pi^0\pi^0$.
- Design and construction of a new VEPP-2000 e^+e^- machine with round beam for replacement of the VEPP-2M ring is started in Novosibirsk. The maximum designed energy of the new machine is 2E=2000 MeV, designed luminosity - $L = 1 \cdot 10^{32}$.

General Conclusions (Cont'd)

- In SPHINX experiment, Protvino, the X(2000) state with narrow width $\Gamma \simeq 90$ Mev was found, which is proposed as a candidate for exotic pentaquark baryon $nnns\bar{s}$ with hidden strangeness.

Search for exotic pentaquark baryons with hidden strangeness $|\mathrm{qqqs\bar{s}}\rangle$ in diffractive production reactions $\mathrm{p + N \to Y^{*}K + N}$

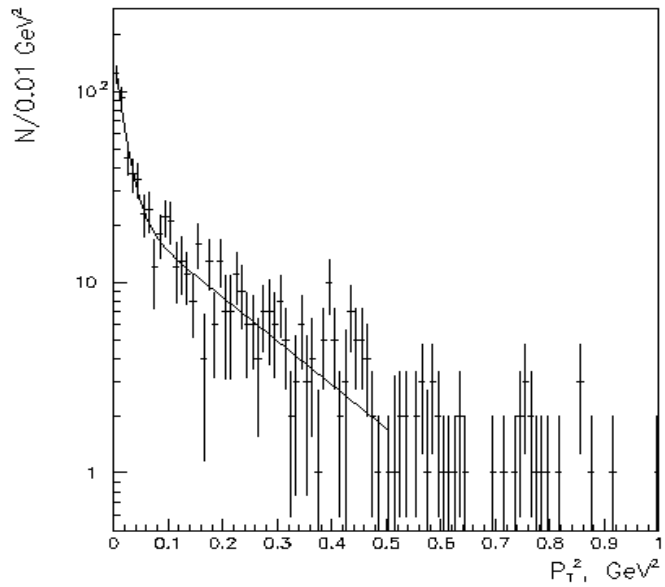
Experiment SPHINX at proton beam of IHEP accelerator with $E_p = 70\,\mathrm{GeV}$. Reaction $p + N \to [\Sigma^0 K^+] + N; \Sigma^0 \to \Lambda\gamma$ was separated (N-nucleon or C nucleus for coherent reaction).



$M(\Sigma^0 K^+)$ for all P_T^2 weighted with efficiency of the setup.

$X(2000) \to \Sigma^0 K^+ \left\} \begin{array}{lcl} M & = & 1989 \pm 6\,\mathrm{MeV} \\ \Gamma & = & 91 \pm 20\,\mathrm{MeV} \end{array} \right.$

This state is seen with high statistical level (> 10 s.d.).



dN/dP_T^2 – strong coherent production on C nuclei is observed ($b = 63 \pm 10\,\mathrm{GeV}^{-2}$)

Cross sections

$$\sigma[p + N \to X(2000) + N] \cdot BR[X(2000) \to \Sigma^0 K^+] = 95 \pm 20\,\mathrm{nb/nucleon}$$
$$\sigma[p + C \to X(2000) + C]_{\mathrm{coh.}} \cdot BR[X(2000) \to \Sigma^0 K^+] = 260 \pm 60\,\mathrm{nb}/C \text{ nucleus}$$

($\pm 20\%$ (system.) – Monte Carlo + absolute normalization)

Unusual dynamic properties of $\mathrm{X(2000)}$ state

a) $R = \frac{BR[X(2000) \to \Sigma K]}{BR[X(2000) \to \Delta(1232)\pi; p\pi^+\pi^-]} \gtrsim 1$

b) $\Gamma[X(2000)] \lesssim 100\,\mathrm{MeV}$

For usual $|\mathrm{qqq}\rangle$ isobars:

a) $R \lesssim (\mathrm{few}) \cdot 10^{-2}$

b) $\Gamma(M \gtrsim 2000\,\mathrm{MeV}) \sim 300 \div 400\,\mathrm{MeV}$

$\Big\}$ X(2000) is serious candidate for pentaquark exotic baryon with hidden strangeness $|X(2000)\rangle = |uuds\bar{s}\rangle$

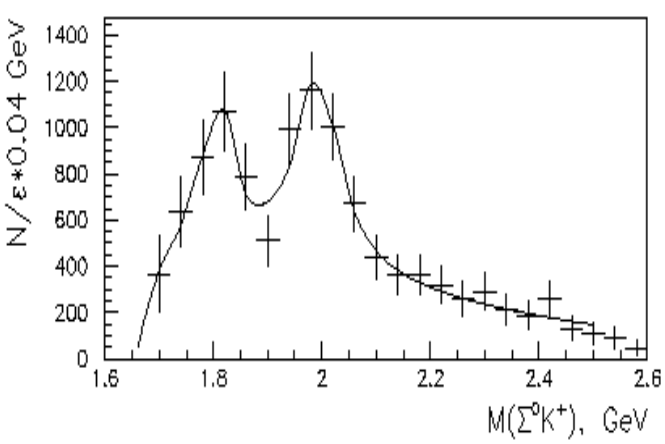
Study of coherent reaction
$\mathrm{p + C \to [\Sigma^0 K^+] + C \ \ (P_T^2 < 0.1\,GeV^2)}$

In the $M(\Sigma^0 K^+)$ for this P_T^2 region the $X(2000)$ state and some threshold structure with $M \sim 1810$ MeV are clearly seen (this structure is practically not seen in mass spectrum for all P_T^2 due to difficult background conditions). Study of the yield of $X(1810)$ as function of P_T^2 demonstrate that this state is produced only in the region of very small P_T^2 ($\lesssim 0.01\,\mathrm{GeV}^2$) where it is well defined:

$$X(1810) \to \Sigma^0 K^+ \left\{ \begin{array}{lcl} M & = & 1807 \pm 7\,\mathrm{MeV} \\ \Gamma & = & 62 \pm 19\,\mathrm{MeV} \end{array} \right.$$

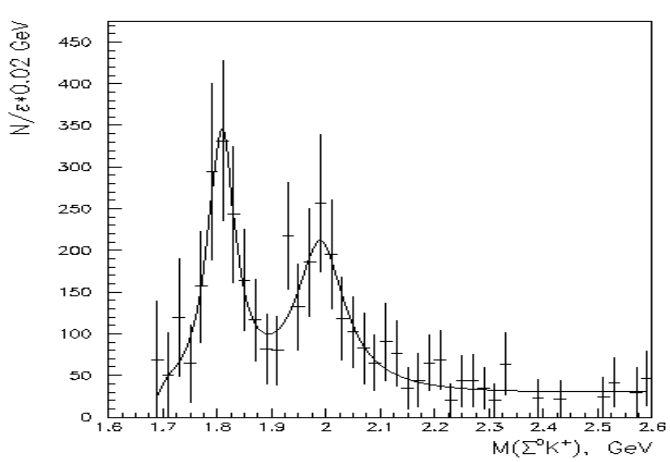
$$\sigma[p+C \to X(1810)+C]_{P_T^2<0.01\,\mathrm{GeV}^2} \cdot BR[X(1810) \to \Sigma^0 K^+] = 215 \pm 44\,\mathrm{nb}(\pm 30\%\ \mathrm{syst.})$$

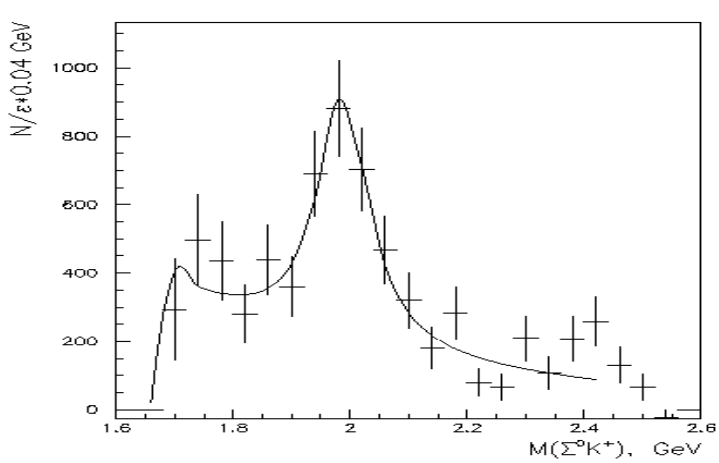
Possible explanation of unusual production properties of $X(1810)$: may be this is a Coulomb production process ? The value of the coherent cross section is not in contradiction with this hypothesis which is also supported by observation of $\Delta(1232)^+$ Coulomb production in the SPHINX experiment.



In the "restricted coherent region" $0.02 < P_T^2 < 0.1\,\mathrm{GeV}^2$ (without the influence of $X(1810)$ in $M(\Sigma^0 K^+)$ $X(2000)$ baryon is observed in the clearest way.

$\Downarrow$





Reality of $\mathrm{X}(2000)$ state, candidate for exotic baryon $|\mathrm{uuds\bar{s}}\rangle$

The data on $X(2000)$ baryon state with unusual dynamical properties (large decay BR with strange particle emission, limited decay width Γ) were obtained with a good statistical significance in the different SPHINX runs with widely different experimental conditions and in several kinematical regions for reaction $p + N \to [\Sigma^0 K^+] + N$. Due to its anomalous dynamical properties the $X(2000)$ state can be considered as a serious candidate for pentaquark exotic baryon with hidden strangeness: $|X(2000)\rangle = |uuds\bar{s}\rangle$.

New preliminary data in support of the reality of $X(2000)$ state:

a) The SPHINX experiment (IHEP): in the study of the reaction
$$p + N \quad \to \quad [\underset{\hookrightarrow\, p\pi^0}{\Sigma^+} \qquad \underset{\hookrightarrow\, \pi^+\pi^-}{K^0}] + N$$
The decay $X(2000) \to \Sigma^+ K^0$ was also observed. These data are in a good agreement with a previous SPHINX result ($X(2000) \to \Sigma^0 K^+$).

b) The SELEX experiment in Fermilab: in the study of $M(\Sigma^- K^+)$ in the diffractive production reaction $\Sigma^- + N \to [\Sigma^- K^+ K^-] + N$ at $E_{\Sigma^-} \simeq 600\,\mathrm{GeV}$. The peak has parameters which are very close to $X(2000)$ ($M = 1962 \pm 12\,\mathrm{MeV}; \Gamma = 96 \pm 32\,\mathrm{MeV}$).

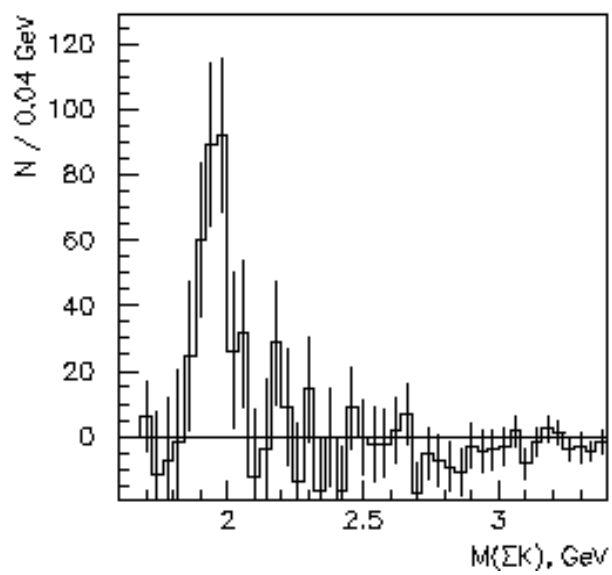
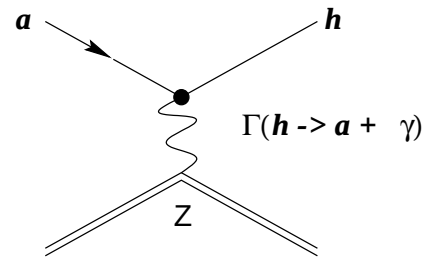


Figure: Mass spectrum $M(\Sigma^- K^+)$ after background subtraction

Now more than an order of magnitude increase of statistics for diffractive proton reactions was obtained with the totally upgraded SPHINX setup.
The analysis of this statistics is in progress.

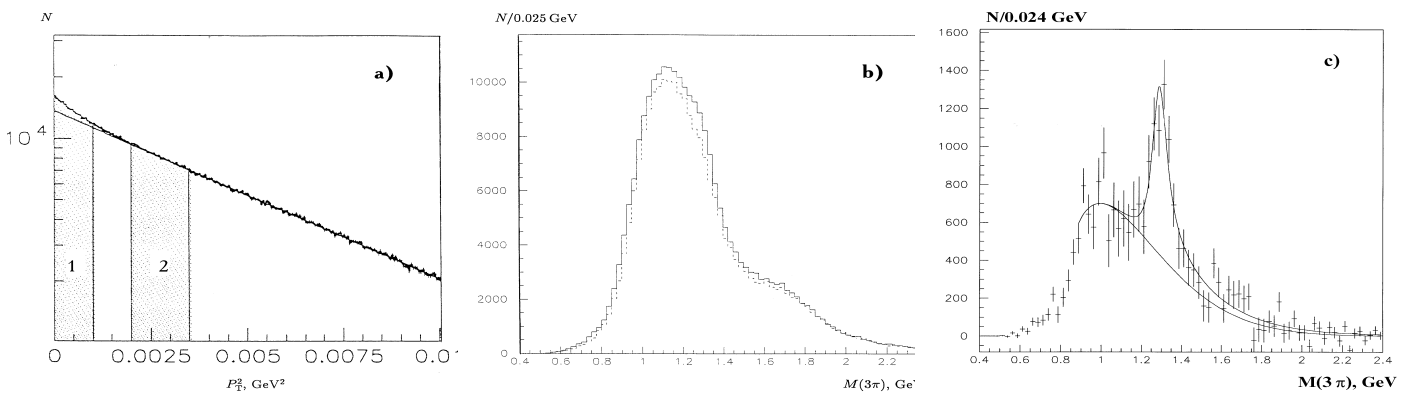
Study of Coulomb production reactions with the SELEX setup

$$\sigma_{\text{Coulomb}} = \underbrace{\sigma_0}_{\text{from QED}} \Gamma(h \to a + \gamma)$$



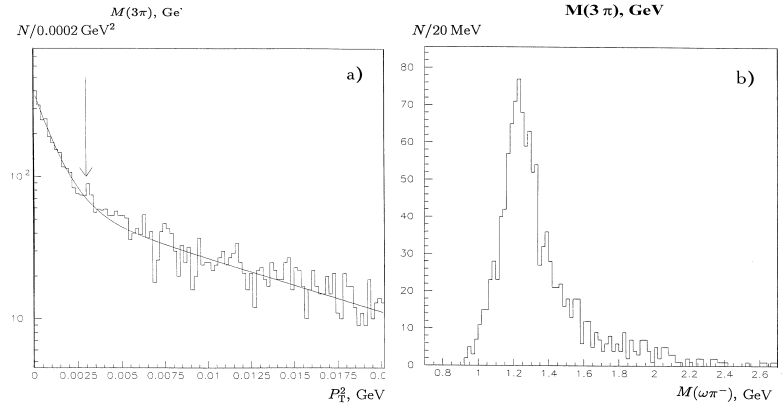
- Measurements were done on the Fermilab's Tevatron. The negative beam momentum $P \simeq 600\,\text{GeV}$ ($\simeq 50\%\,\Sigma^-; \simeq 50\%\,\pi^-$)

- $\pi^- + (\mathbf{C}; \mathbf{Cu}; \mathbf{Pb}) \to (\pi^+\pi^-\pi^-) + (\mathbf{C}; \mathbf{Cu}; \mathbf{Pb})$
  The Coulomb production is separated at $P_T^2 < 0.001\,\text{GeV}^2$ (after diffractive background subtruction)
  $$\left.\begin{array}{l} \pi^- + Z \to \quad a_2(1320) + Z \\ \qquad\qquad\quad \hookrightarrow 3\pi \end{array}\right\} \quad \Gamma \quad \begin{array}{l} (a_2(1320)^- \to \pi^- + \gamma) = \\ = (225 \pm 20 \pm 45)\,\text{KeV} \end{array}$$



- $\pi^- + \mathbf{Z} \to \pi^+\pi^-\pi^-\pi^0 + \mathbf{Z}$
  - $\pi^- + Z \to \quad b_1(1235) + Z$
    $\hookrightarrow \omega\pi^-$
  - $\pi^- + Z \to \quad a_2(1320) + Z$
    $\hookrightarrow \eta\pi^-$

  These Coulomb production reactions were well separated. Results for radiative widths are in progress.



- Search for $\Sigma^- + Z \to \quad \Sigma^{*-}(1325) + Z$
  $\hookrightarrow \Lambda\pi^-$

  Very low upper bound for SU(3) forbidden radiative decay width is obtained: $\Gamma(\Sigma^*(1385)^- \to \Sigma^- + \gamma) < 7\,\text{KeV}$ (95% c.l.)
  Theoretical expectations: $\sim 1 \div 10\,\text{KeV}$