Vector Mesons of Light Quarks

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Outline

1. Why are they interesting?
2. How do we study them?
3. ρ', ω', ϕ'
4. Conclusions

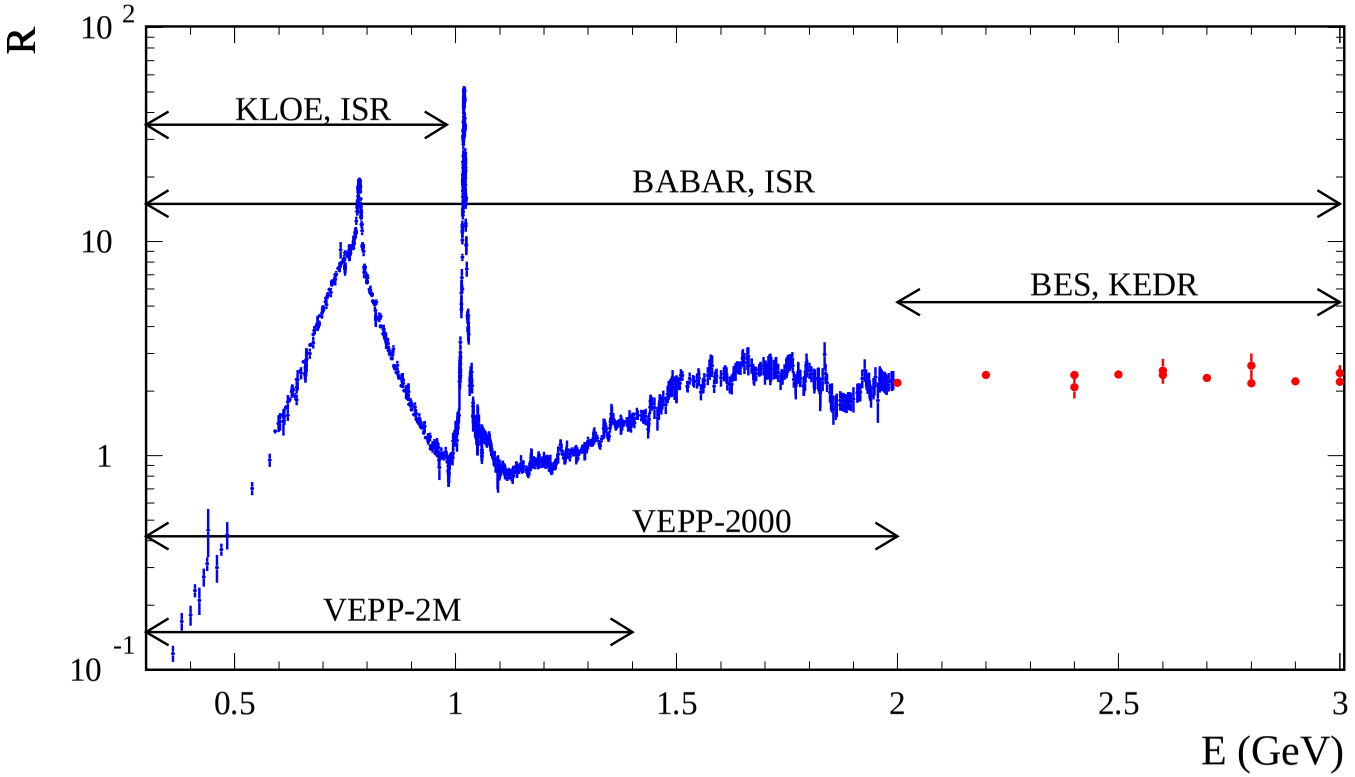
What Can We Learn From Vectors?

- $J^{PC} = 1^{--} \Rightarrow$ directly produced in one-photon e^+e^-
- Observed as resonances in cross sections of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
- Their properties (M, Γ, Γ_{ee}, $\mathcal{B}$) provide information on interactions of light (u, d, s) quarks
- Test of models and input to theory (ChPT, Vector Dominance, CVC relations between e^+e^- and τ, search for hybrids $(q\bar{q}g)$ and glueballs, QCD)
- High-precision measurements of various cross sections are important for the determination of fundamental physical quantities ($(g_\mu - 2)/2$, $\alpha(M_Z^2)$, α_s, quark and gluon condensates)

e^+e^- Low Energy Colliders and R

Two possible methods – scan and ISR (radiative return)

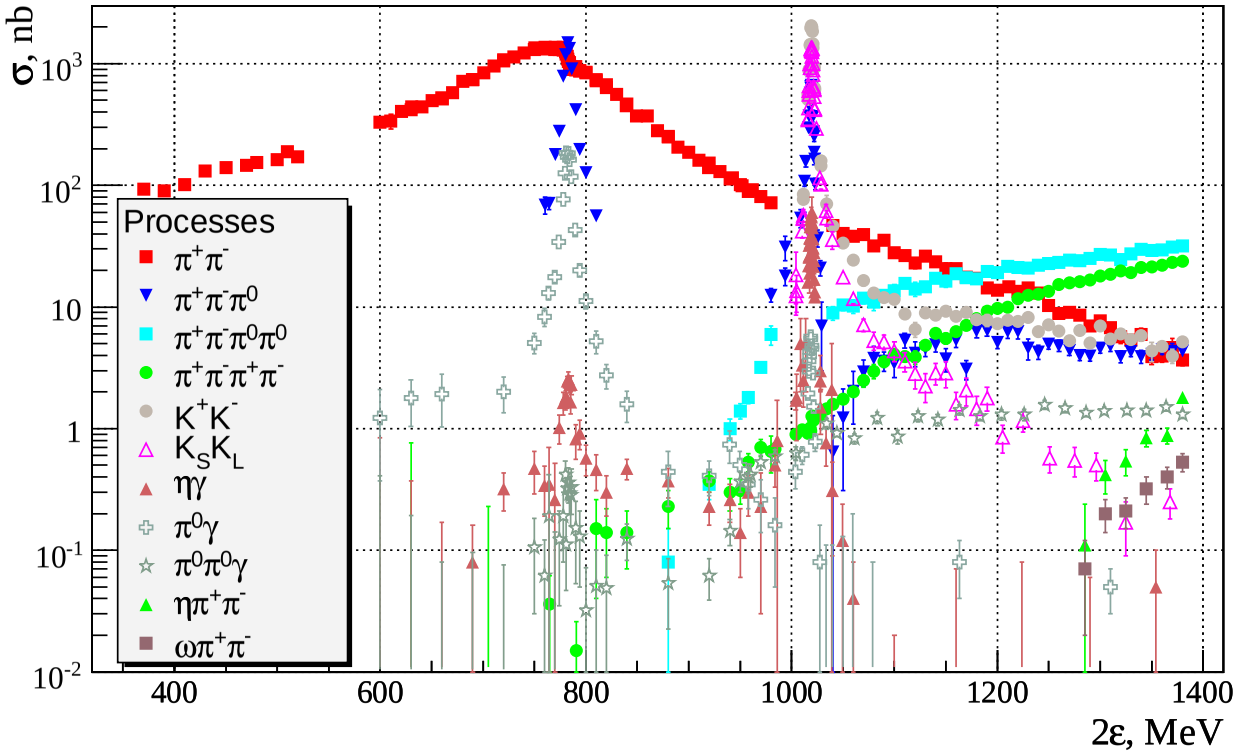
Below 2 GeV R is determined as a sum of exclusive cross sections



Hadronic Cross Sections At Low Energies

Below 1.4 GeV detailed results on the ρ, ω, ϕ and continuum from CMD-2 and SND detectors at the VEPP-2M collider

High-statistics measurements of the ϕ and ρ mesons at KLOE



Properties of Higher Vector Mesons

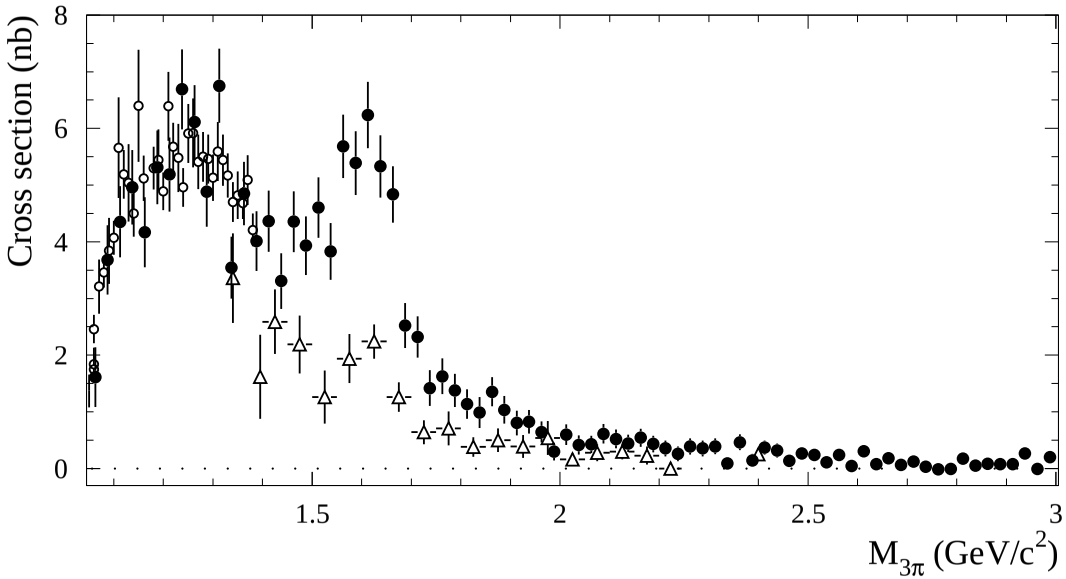
2^3S_1	Mass, MeV Width, MeV	1^3D_1	Mass, MeV Width, MeV
$\rho(1450)$	1250 - 1500 60 - 550	$\rho(1700)$	1550 - 1780 100 - 600
$\omega(1420)$	1370 - 1450 175 - 360	$\omega(1650)$	1620 - 1750 100 - 370
$\phi(1680)$	1620 - 1750 100 - 300	–	–

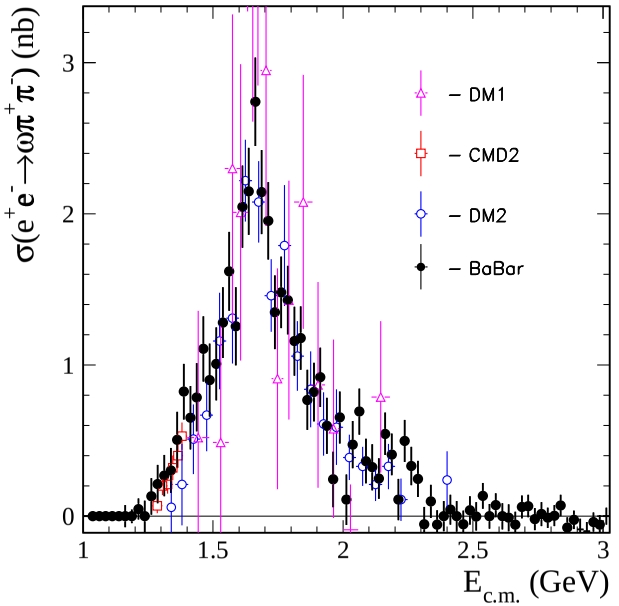
- Isospin-specific: $\rho' \to \pi^+\pi^-, 4\pi, 6\pi$, $\omega\pi^0$; $\omega'(\phi') \to \rho\pi, \omega\pi\pi, \omega\eta$
- Common: $K\bar{K}$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$, $\pi^0(\eta,\eta')\gamma$
- Γ_{ee} badly known, few modes observed
- The model of Godfrey, Isgur predicts 2 sets of states from 1 to 2 GeV

Final States and Intermediate Mechanisms

- $\pi^+\pi^-\pi^0$ – $\rho\pi$
- $\pi^+\pi^-\pi^+\pi^-$ – $a_1\pi$, $f_0\rho^0$, $a_2\pi$, $\pi'\pi$
- $\pi^+\pi^-\pi^0\pi^0$ – $a_1\pi$, $\omega\pi$, $f_0\rho^0$
- $\pi^+\pi^-\pi^+\pi^-\pi^0$ – $\omega\pi^+\pi^-$, $\eta\pi^+\pi^-$, $\phi\pi^+\pi^-$, $\rho^0\pi^+\pi^-\pi^0$
- $3\pi^+3\pi^-$ – $\rho^0(4\pi)^0$, $2\pi^+2\pi^-2\pi^0$ – $\rho^0 f_2(1270)$, $\omega\pi^+\pi^-\pi^0$, $\eta\pi^+\pi^-\pi^0$, ...
- $K^+K^-\pi^0$ – $\phi\pi^0$, $K^{*\pm}K^{\mp}$; $K^0_S K^{\pm}\pi^{\mp}$ – ,$K^{*0}K^0$, $K^{*\pm}K^{\mp}$
- $K^+K^-\pi^+\pi^-$ – $K^{*0}K^{\pm}\pi^{\mp}$, $\phi\pi^+\pi^-$, $(K\rho)K$
- Other final states observed: $K^+K^-\eta$, $K^+K^-\pi^0\pi^0$, $K^+K^-K^+K^-$, $K^+K^-2(\pi^+\pi^-)$, ...
- Interference effects should be taken into account

Study of $e^+e^- \to \pi^+\pi^-\pi^0$ and $e^+e^- \to \omega\pi^+\pi^-$





$\pi^+\pi^-\pi^0$: BaBar and SND agree. BaBar's points much higher than at DM2

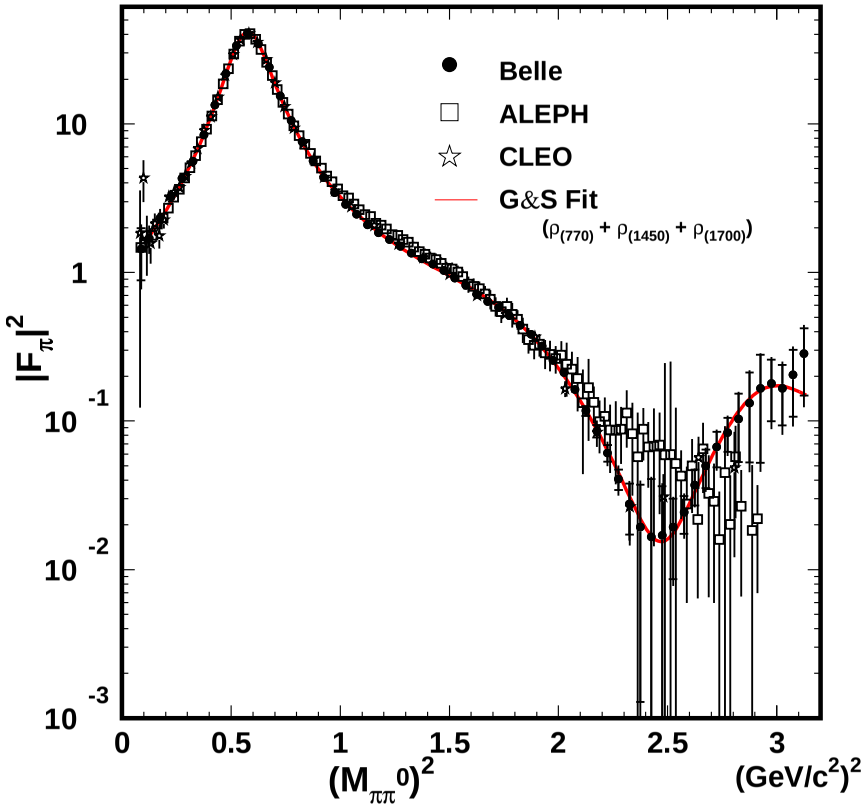
Two ω' observed in $\pi^+\pi^-\pi^0(\rho\pi)$ and $2\pi^+2\pi^-\pi^0(\omega\pi^+\pi^-)$

Parameters of the ω' Mesons

Source	PDG–2004	BaBar, $\pi^+\pi^-\pi^0$	BaBar, $\omega\pi^+\pi^-$
M, MeV	$1400 \pm 50 \pm 130$	$1350 \pm 20 \pm 20$	$1382 \pm 23 \pm 70$
Γ, MeV	$870^{+500}_{-300} \pm 450$	$450 \pm 70 \pm 70$	$133 \pm 48 \pm 100$
$\mathcal{B}_{ee}\mathcal{B}_{3\pi}, 10^{-6}$	$0.65 \pm 0.13 \pm 0.21$	$0.82 \pm 0.05 \pm 0.06$	–
$\mathcal{B}_{ee}\mathcal{B}_{5\pi}, 10^{-6}$	–	–	0.13 ± 0.04

Source	PDG–2004	BaBar, $\pi^+\pi^-\pi^0$	BaBar, $\omega\pi^+\pi^-$
M, MeV	$1770 \pm 50 \pm 60$	$1660 \pm 10 \pm 2$	$1667 \pm 13 \pm 6$
Γ, MeV	$490^{+200}_{-150} \pm 130$	$230 \pm 30 \pm 20$	$222 \pm 25 \pm 20$
$\mathcal{B}_{ee}\mathcal{B}_{3\pi}, 10^{-6}$	$1.2^{+0.4}_{-0.1} \pm 0.8$	$1.3 \pm 0.1 \pm 0.1$	–
$\mathcal{B}_{ee}\mathcal{B}_{5\pi}, 10^{-6}$	$0.41 \pm 0.09 \pm 0.13$	–	0.47 ± 0.04

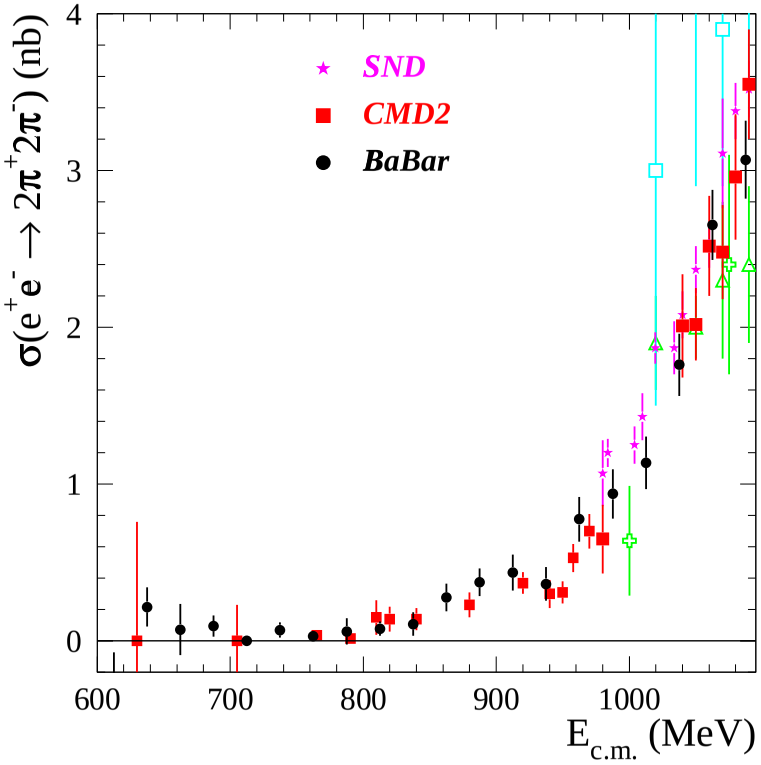
ρ Excitations from $\tau^- \to \pi^-\pi^0\nu_\tau$ at Belle

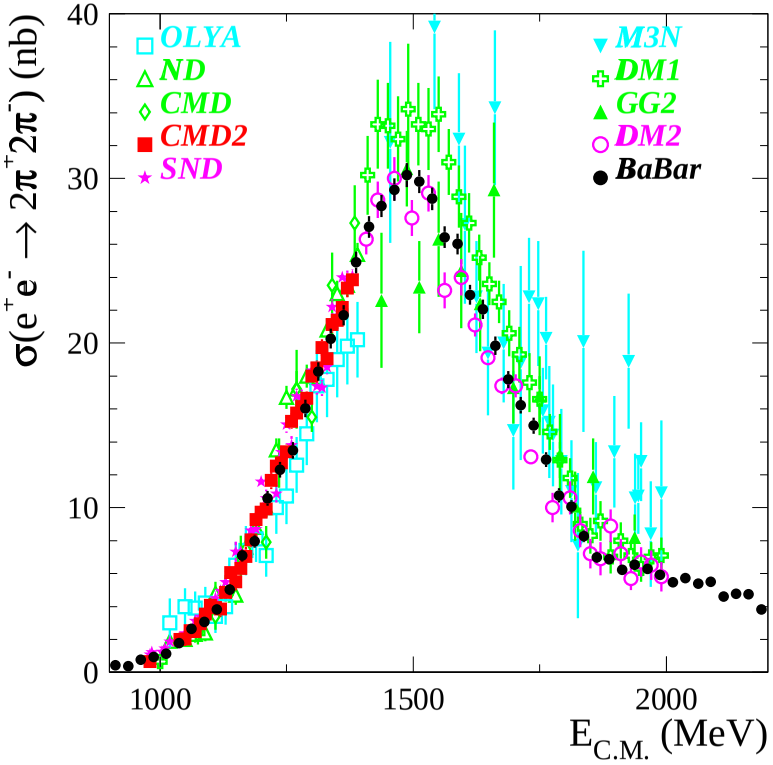


H. Hayashii, this Workshop

72 fb^{-1}, $5.6 \cdot 10^6$ events, ρ, $\rho(1450)$, $\rho(1700)$ clearly seen

How Many ρ Excitations are in the $2\pi^+2\pi^-$ Mode?

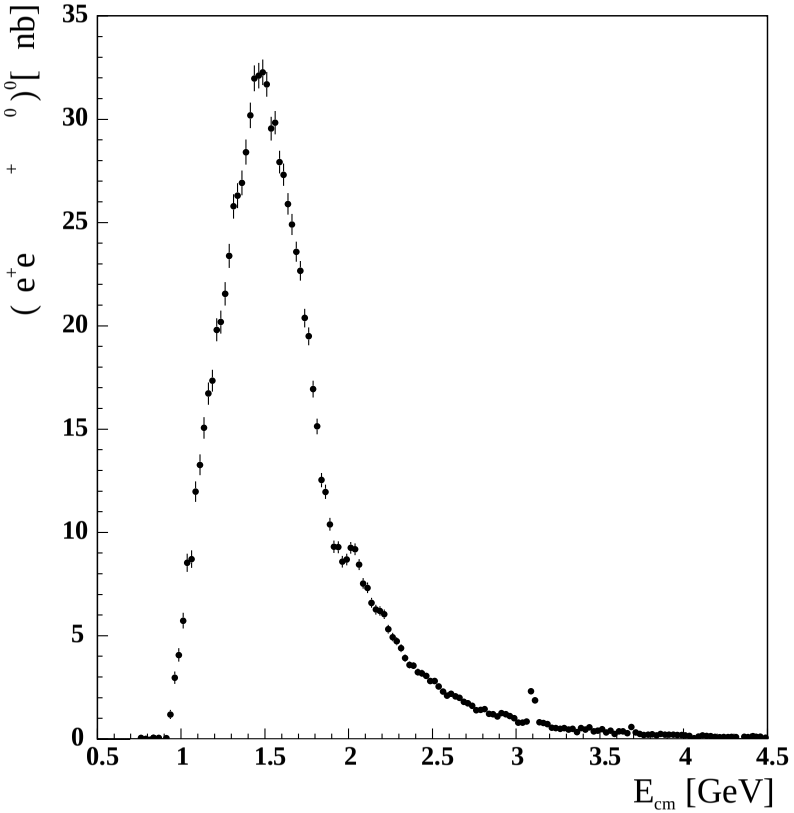


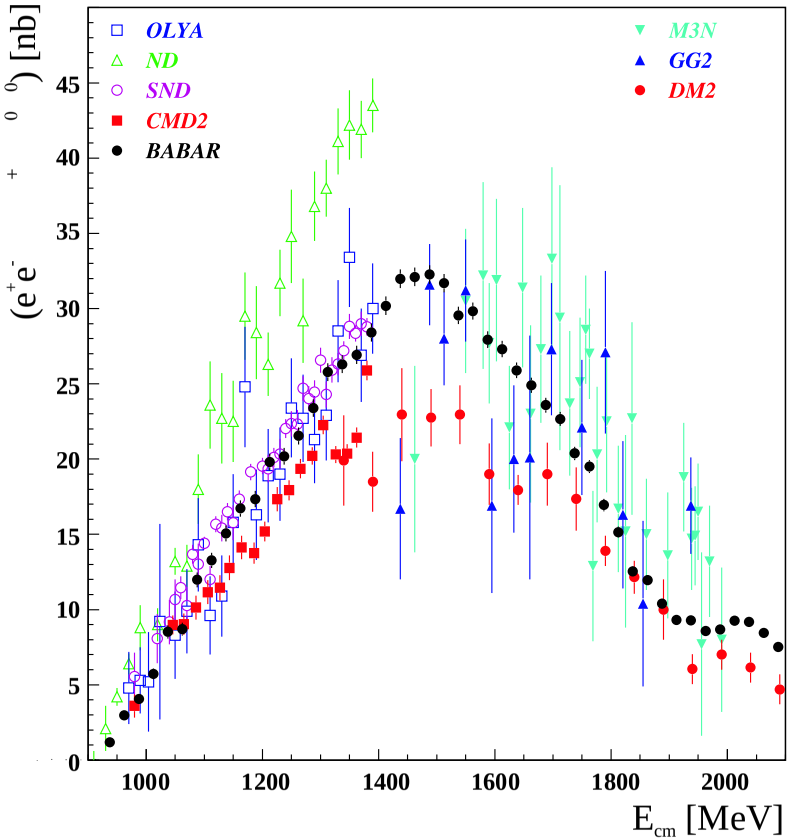


One broad state seen!

Separation of different channels ($a_1\pi$, $a_2\pi$, $\pi'\pi$) needed

$\pi^+\pi^-2\pi^0$ Mode

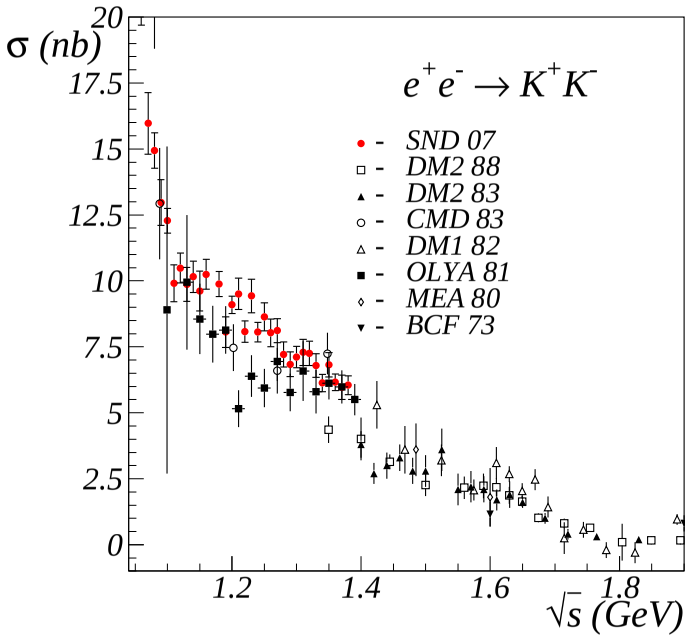


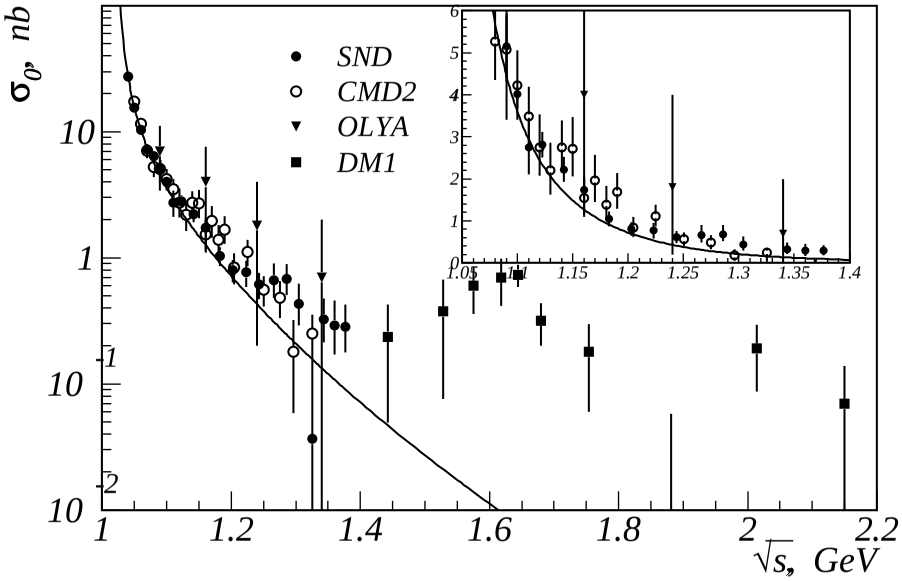


One broad state seen similar to $2\pi^+2\pi^-$!

Separation of different channels may reveal more complicated structure

$e^+e^- \to K^+K^-,\ K^0_SK^0_L$





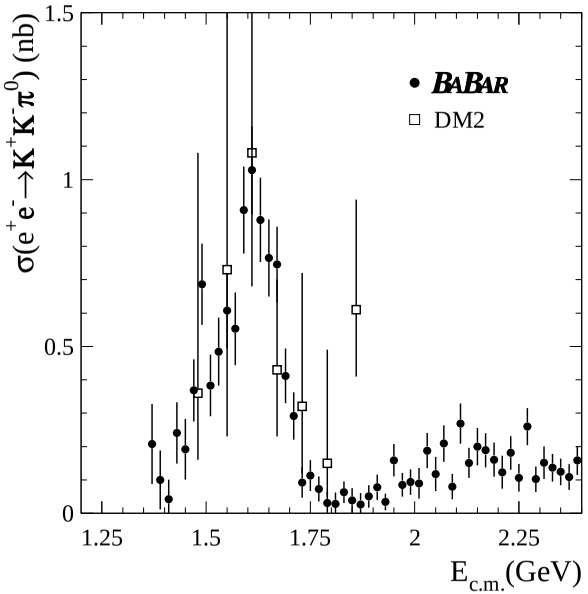
No prominent structures observed in K^+K^-,

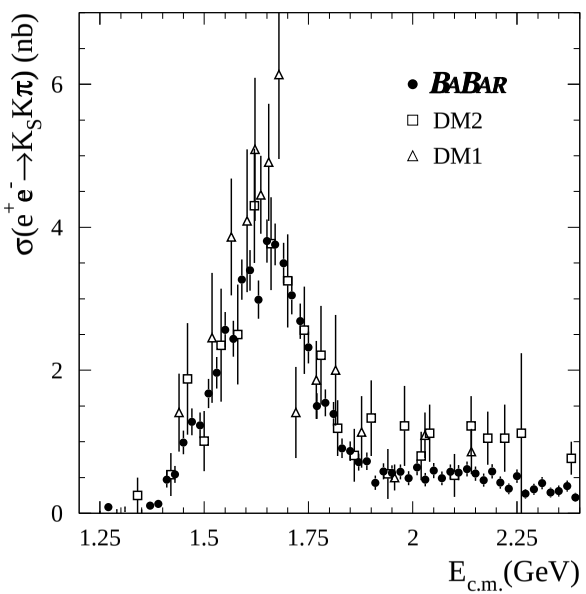
Some evidence for the ϕ' in $K^0_SK^0_L$

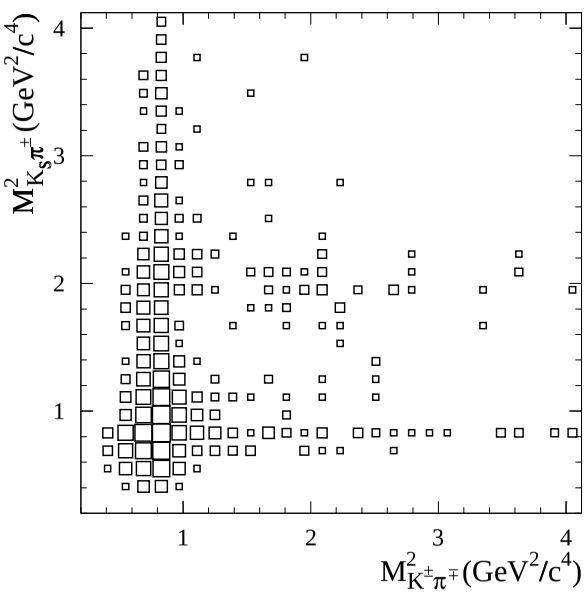
More precise experiments needed studying both modes with isospin analysis

$e^+e^- \to K\bar{K}\pi$ at BaBar (ISR)

$e^+e^- \to K^\pm\pi^\mp K^0_S,\ K^+K^-\pi^0$ studied



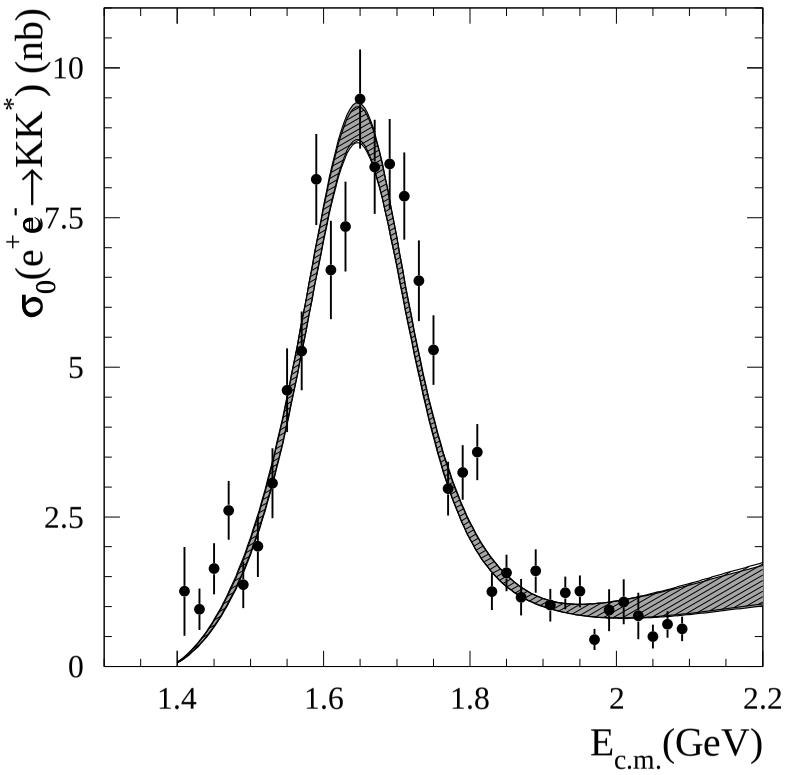


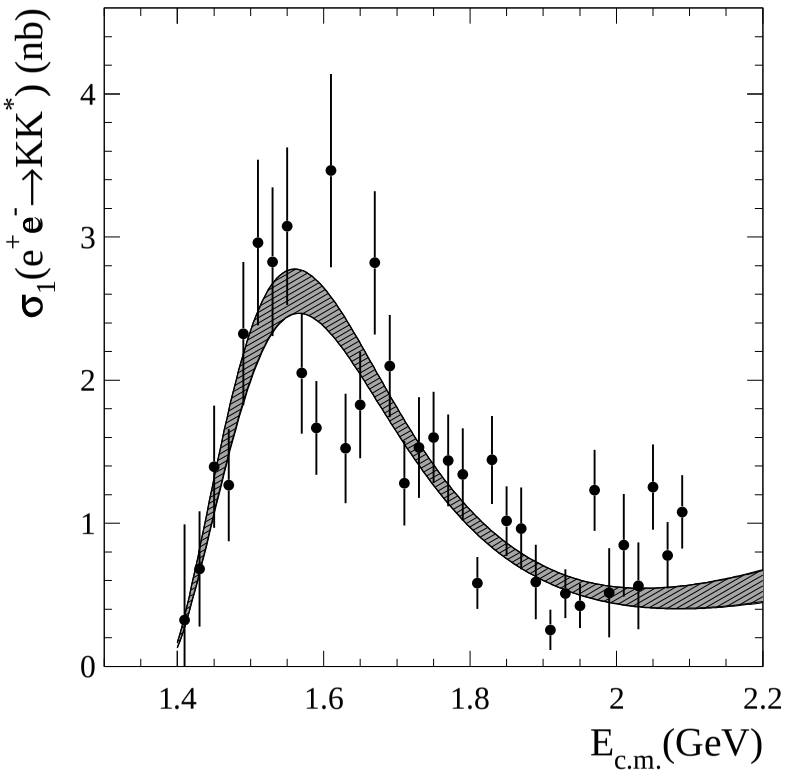


From Dalitz analysis: $K^{*0}\bar{K}^0$ dominates, $K^{*\pm}\bar{K}^\mp$ seen

Isospin 0 and 1 components are separated

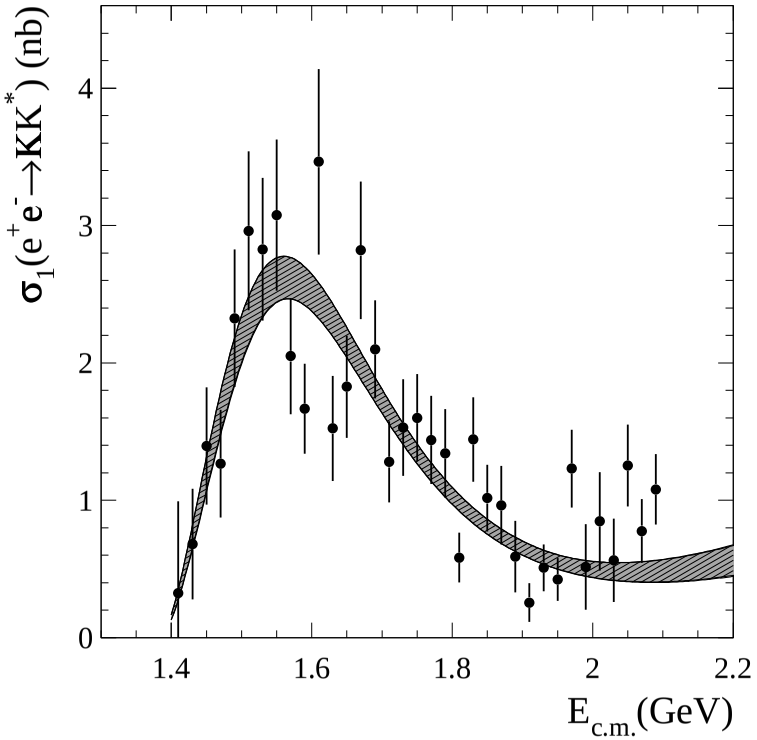
Isospin Structure of $e^+e^- \to K\bar{K}\pi$

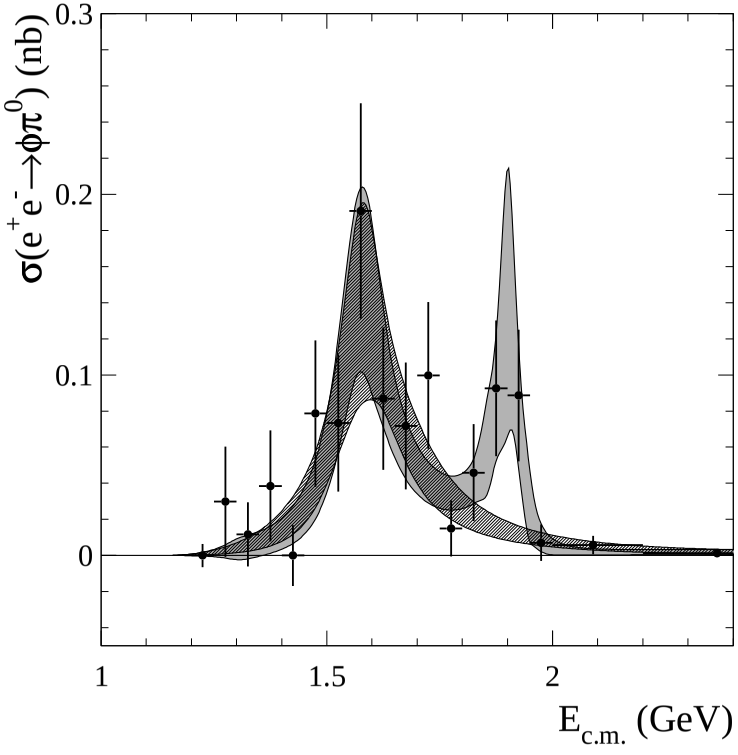




The I=0 fraction is notably bigger than the I=1 (Wess-Zumino)
with ϕ' in I=0 and ρ' in I=1
Phase difference between I=0 and I=1 important

$\rho'(1450)$ – I


σ1(e+e-→KK*) (nb)
4
3
2
1
0
1.4
1.6
1.8
2
2.2
Ec.m.(GeV)


σ(e+e-→φπ0) (nb)
0.3
0.2
0.1
0
1
1.5
2
Ec.m. (GeV)

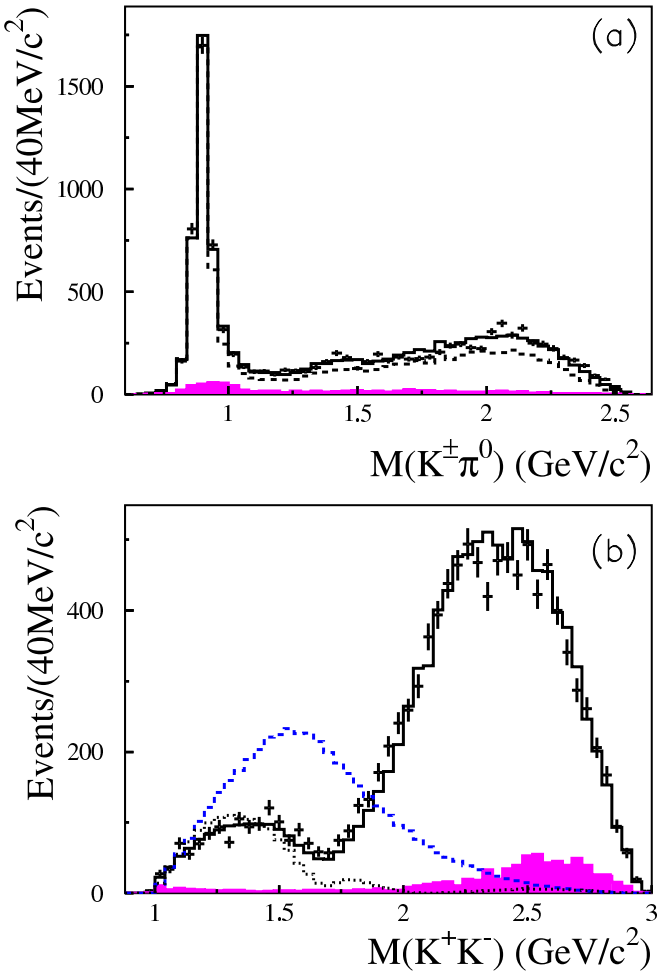
$\rho'(1450)$ – II

M, MeV	Γ, MeV	$\Gamma_{ee}\mathcal{B}_{KK^*}$, eV	$\Gamma_{ee}\mathcal{B}_{\phi\pi^0}$, eV
$1506 \pm 16 \pm 7$	$437 \pm 24 \pm 4$	$135 \pm 12 \pm 6$	–
$1570 \pm 36 \pm 62$	$144 \pm 75 \pm 43$	–	$3.5 \pm 0.9 \pm 0.3$

Is the second ρ' the same as $C(1480)$ observed in $\pi^- p \to \phi\pi^0 n$ with mass 1480 ± 40 MeV and width 130 ± 60 MeV?

Do we have two different resonances very close to each other?

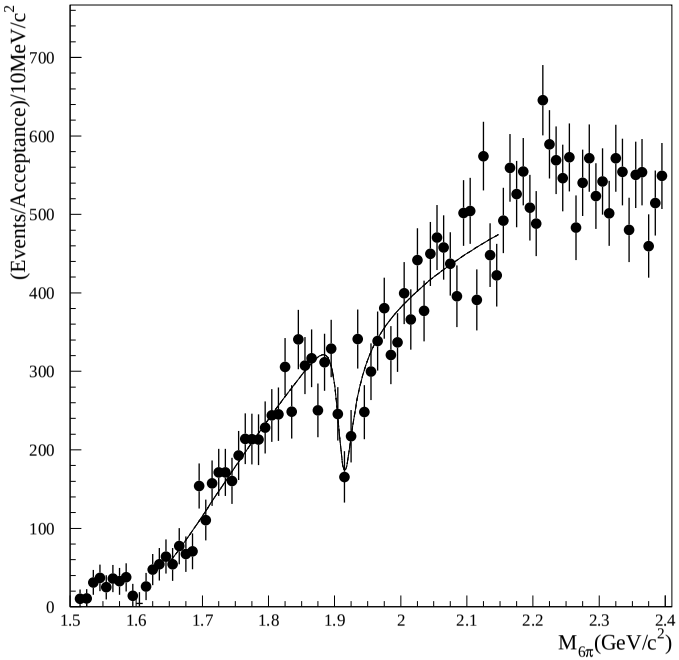
ρ' at BES?

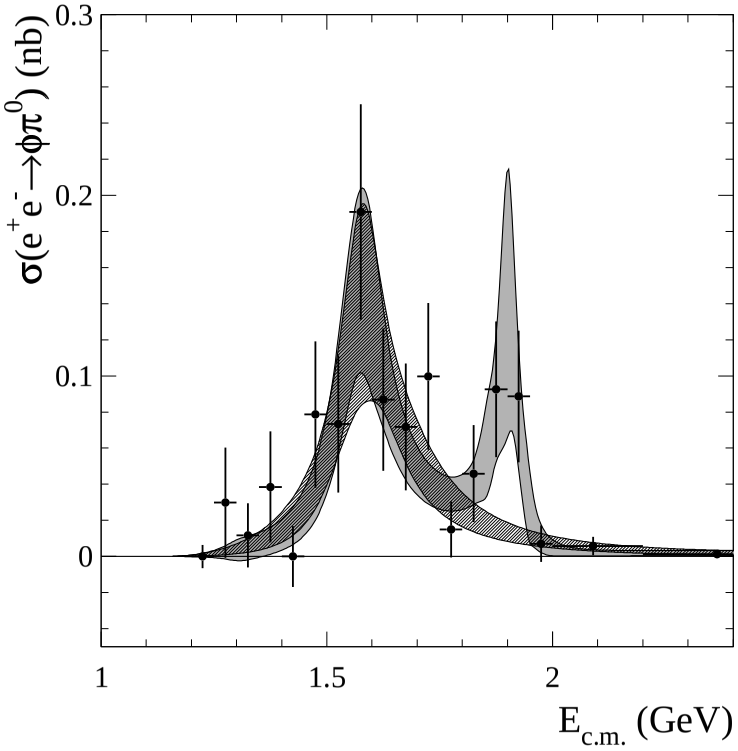


An $X(1570) = K^+K^-$ state
observed by BES
in $J/\psi \to K^+K^-\pi^0$
$M = 1576^{+49+98}_{-55-91}$ MeV,
$\Gamma = 409^{+14+32}_{-12-67}$ MeV
PWA $\Rightarrow J^{PC} = 1^{--}$

Is it a mixture of
$\rho'(1450)$ and $\rho'(1700)$?
Not in line with
$e^+e^- \to K^+K^-$, $K^0_S K^0_L$

New $\rho(1900)$ – I

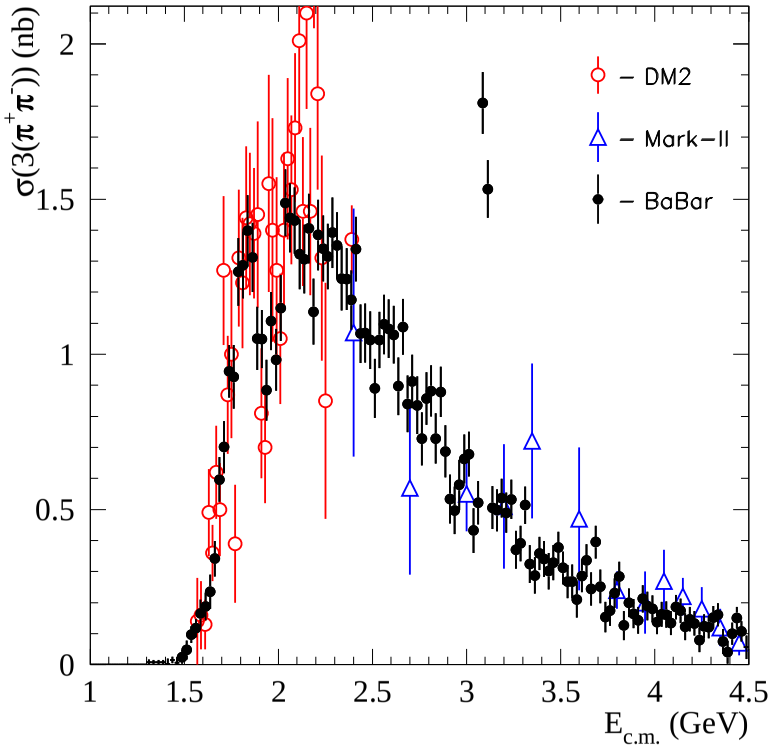


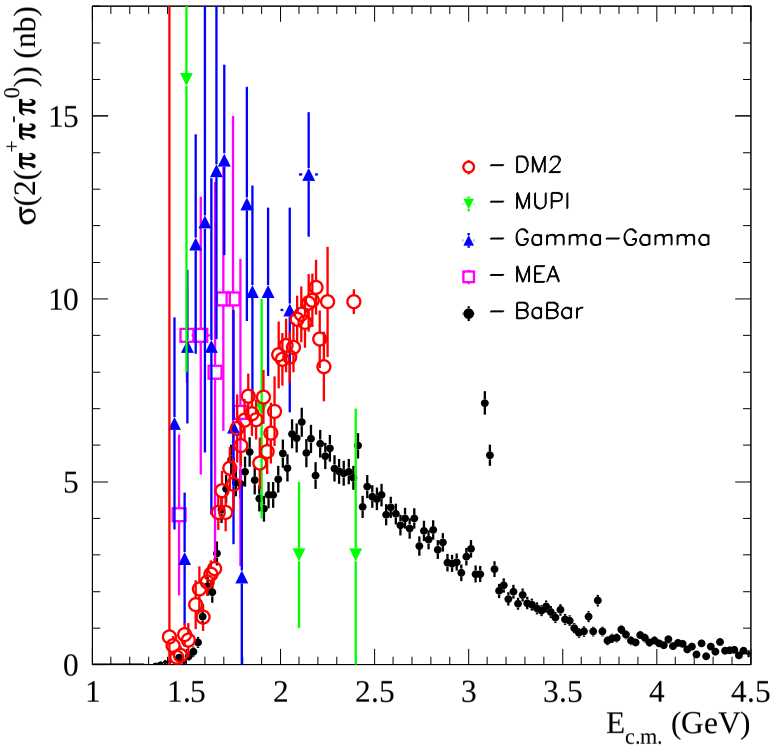


A dip at 1.9 GeV is observed in photoproduction of $3(\pi^+\pi^-)$

Some structures are seen by BaBar in $e^+e^- \to \phi\pi^0$

$\rho(1900)$ – II





BaBar sees a dip at 1.9 GeV in both 6π modes

$\rho(1900)$ – III

Source	M, MeV	Γ, MeV	$\Gamma_{ee}\mathcal{B}_f$, eV
FENICE, $e^+e^- \to$ hadrons	1870 ± 10	10 ± 5	–
E687, $\gamma p \to 3\pi^+3\pi^- p$	1910 ± 10	37 ± 13	–
BaBar, $e^+e^- \to 3\pi^+3\pi^-$	1880 ± 30	130 ± 30	–
BaBar, $e^+e^- \to 2(\pi^+\pi^-\pi^0)$	1860 ± 20	160 ± 20	–
BaBar, $e^+e^- \to \phi\pi^0$	$1909 \pm 17 \pm 25$	$48 \pm 17 \pm 2$	$2.0 \pm 0.6 \pm 0.4$

In all final states but $\phi\pi$ a dip seen

Low width $\Rightarrow$ non $q\bar{q}$, but mass small for a glueball

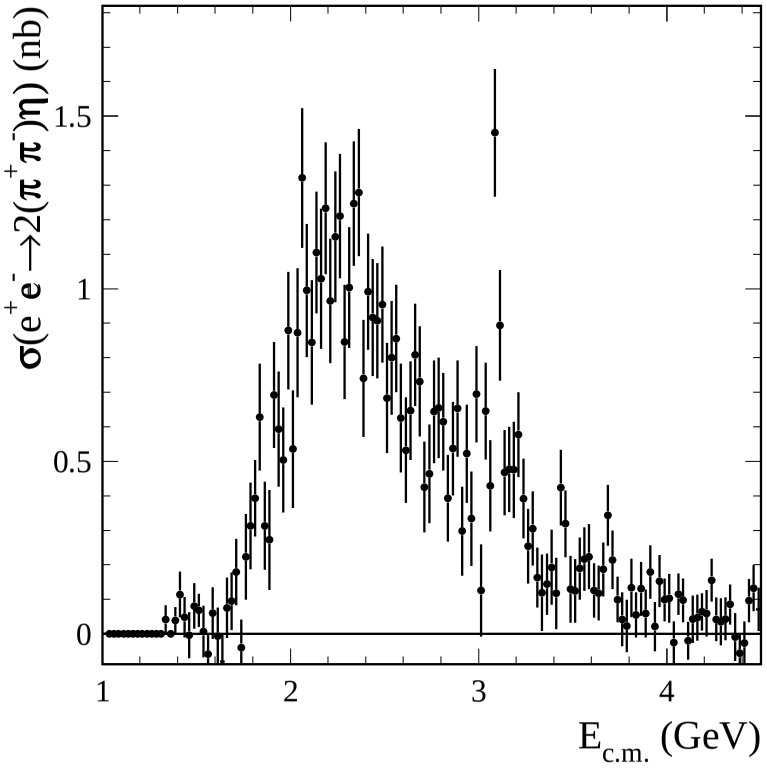
A hybrid (lattice) or a bound $N\bar{N}$ state

$\rho(2150)$ – I

First claims in 1970 in $\bar{p}p$

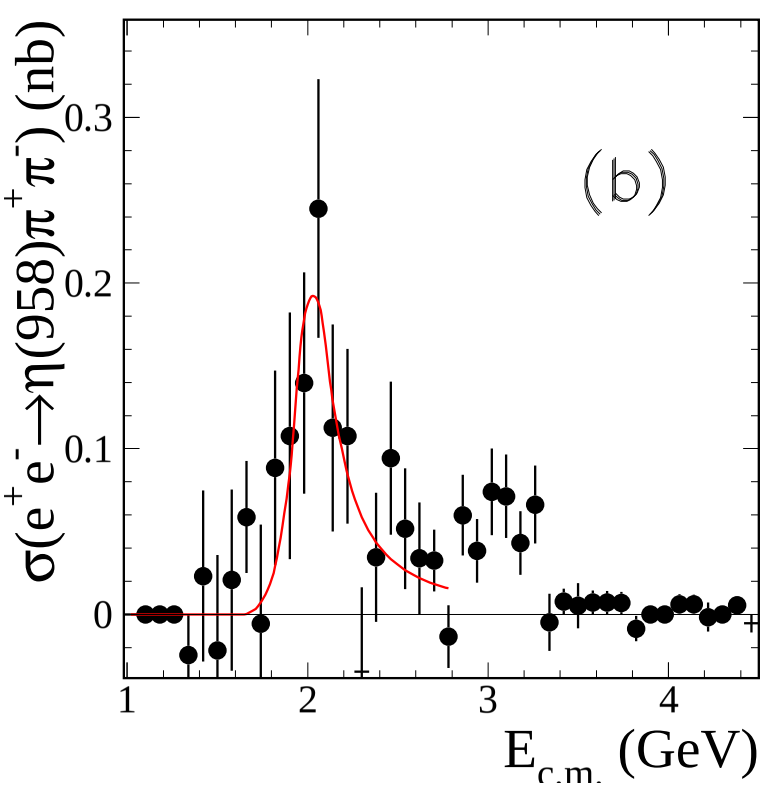
In 90-ies in $\bar{p}p$, e^+e^-, π^-p with
$\pi^+\pi^-$, K^+K^-, $\omega\pi^0$, 6π final states

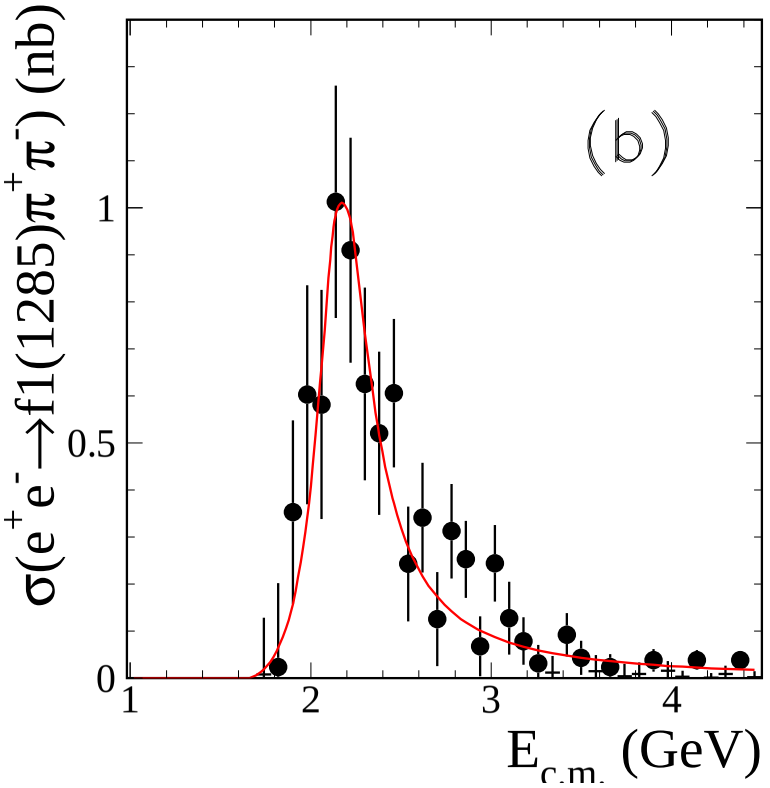
Mass 2000-2200 MeV,
width 300-400 MeV



In the $\eta\pi^+\pi^-$ mass
$\eta'(958)$ and $f_1(1285)$ are observed

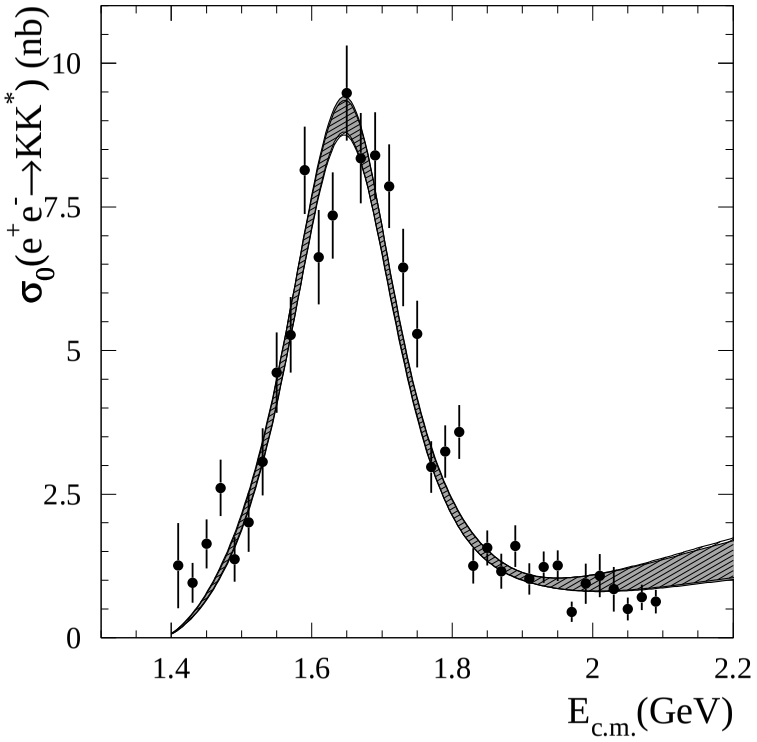
$\rho(2150)$ – II

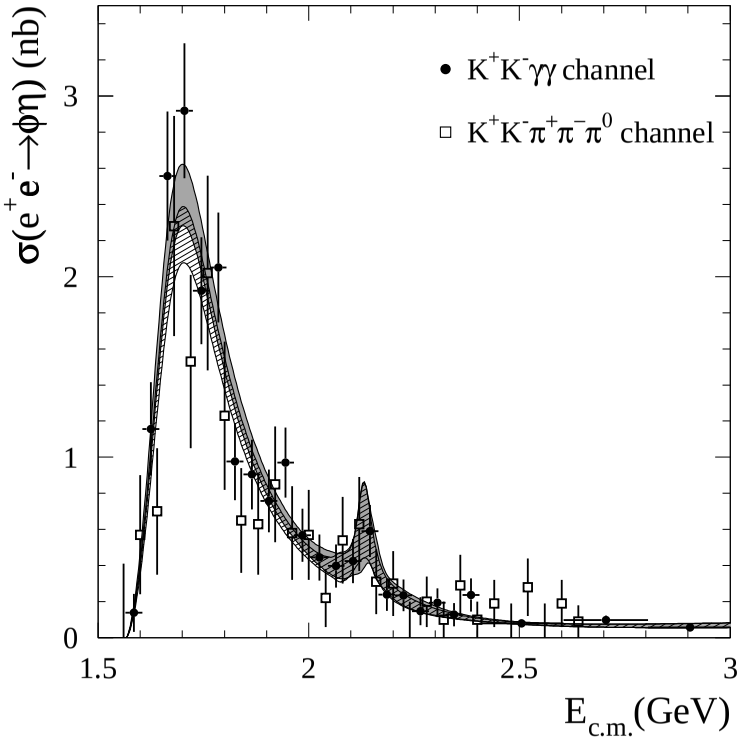




Mode	$\eta'\pi^+\pi^-$	$f_1(1285)\pi^+\pi^-$
Mass, GeV	1.99 ± 0.08	$2.15 \pm 0.04 \pm 0.05$
Width, GeV	0.31 ± 0.14	$0.35 \pm 0.04 \pm 0.05$

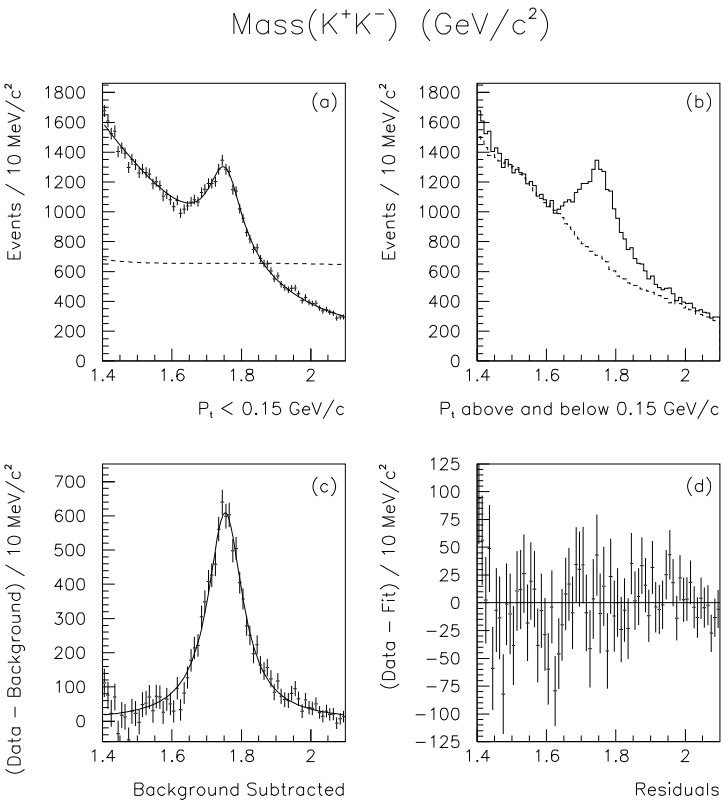
$\phi'(1680)$





M, MeV	Γ, MeV	$\Gamma_{ee}\mathcal{B}_{KK^*}$, eV	$\Gamma_{ee}\mathcal{B}_{\phi\eta}$, eV
$1723 \pm 24 \pm 43$	$371 \pm 90 \pm 160$	409 ± 53	156 ± 35

ϕ' at FOCUS?



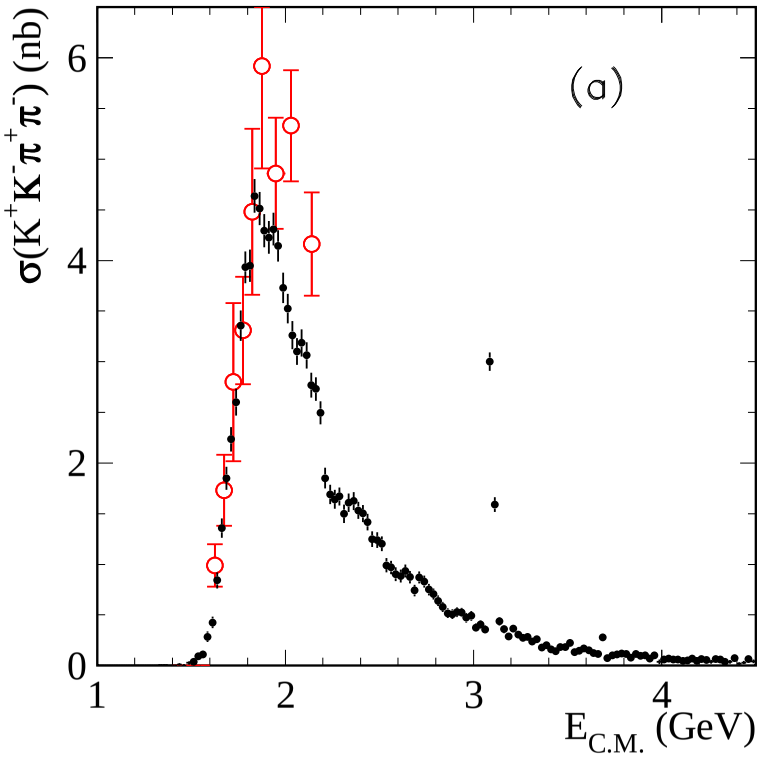
An $X(1750) = K^+K^-$ state
observed by FOCUS
in $\gamma p \to K^+K^- p$
$M = 1753.5 \pm 1.5 \pm 2.3$ MeV,
$\Gamma = 122.2 \pm 6.2 \pm 8.0$ MeV

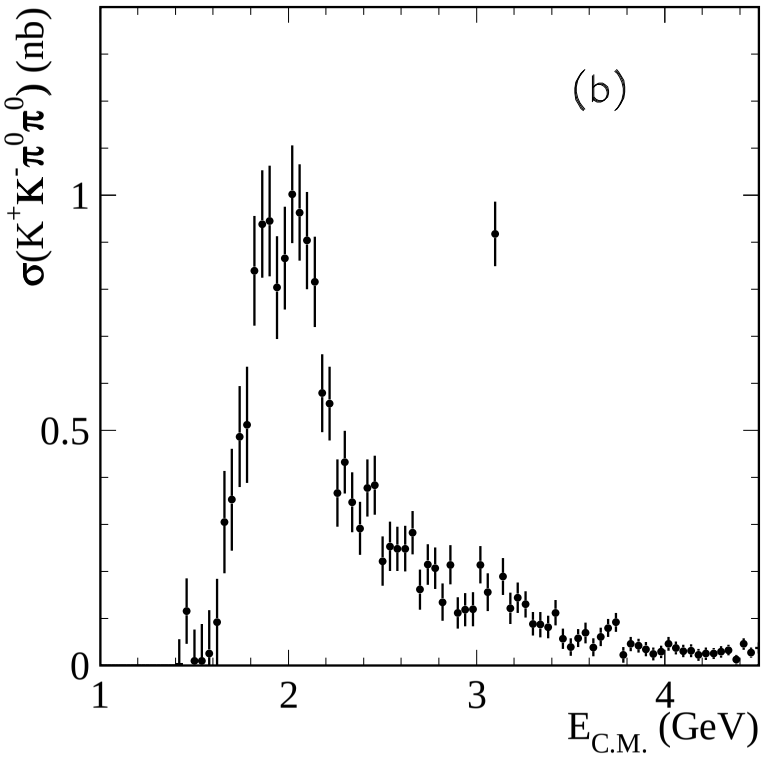
Not seen in $K^*\bar{K} \to K^\pm \pi^\mp K^0_S$:
$\mathcal{B}(\bar{K}^{*0}K^0)/\mathcal{B}(K^+K^-) < 0.065$
$\mathcal{B}(\bar{K}^{*\pm}K^\mp)/\mathcal{B}(K^+K^-) < 0.183$

Is it ϕ'?

Not in line with e^+e^-
with $\phi' \to \bar{K}^*K$, not to $K\bar{K}$

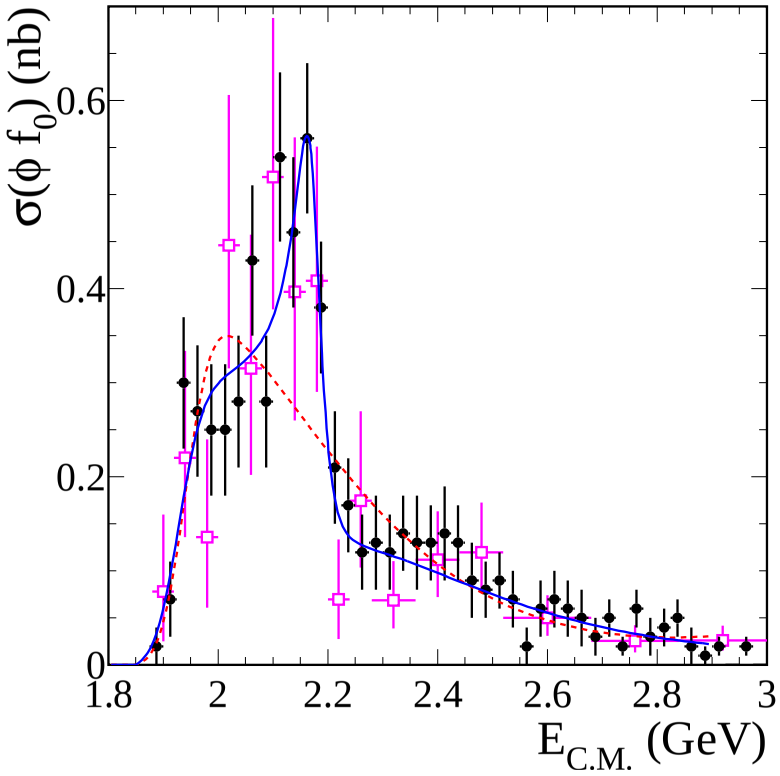
$\phi(2170)$ – I

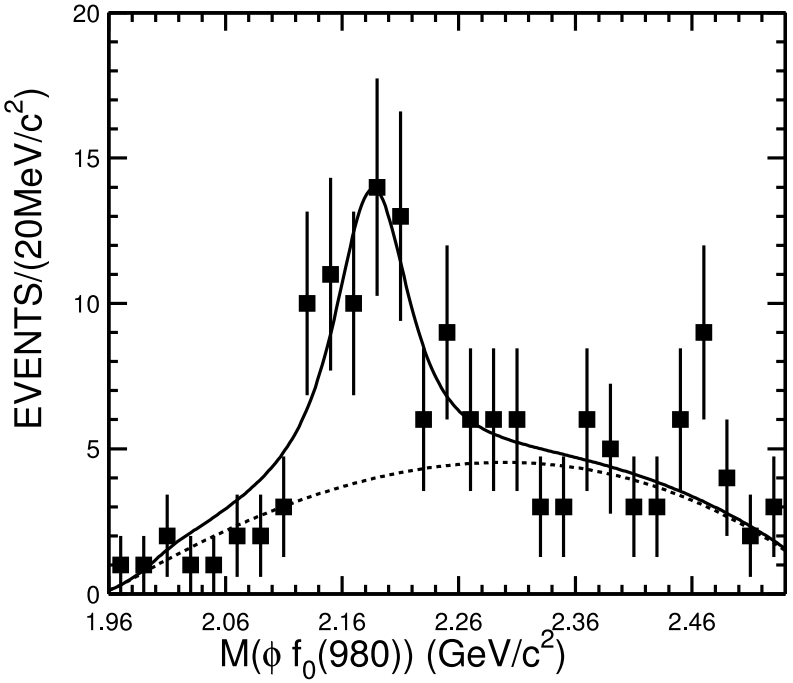




BaBar selects events with $\phi \to K^+K^-$ and $f_0(980) \to \pi^+\pi^-,\ \pi^0\pi^0$

$\phi(2170)$ – II





A new $\phi f_0(980)$ state is observed by both BaBar and BES

$\phi(2170)$ Parameters

Source	M, MeV	Γ, MeV	$\Gamma_{ee}\mathcal{B}_f$, eV
BES, ϕf_0	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$	–
BaBar, ϕf_0	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$	$2.5 \pm 0.8 \pm 0.4$
BaBar, $\phi\eta$	2139 ± 35	76 ± 62	1.9 ± 1.0

Conclusions

- A big number of vector mesons made of light quarks are observed above the $\phi(1020)$
- Their properties can be studied by measuring various final states with intermediate resonances
- Experimental evidence exists for two ω', four ρ' and two ϕ'
- There are still many puzzles and unknown things $\Rightarrow$ Complete understanding will require more theory and experiment
- Many final states (2π, 4π, $\omega\pi$, ...) can be confronted to τ decays
- Vectors are readily produced in ISR – BaBar and Belle, VEPP-2000 and DAPHNE-II are badly needed