

Vector Mesons of Light Quarks

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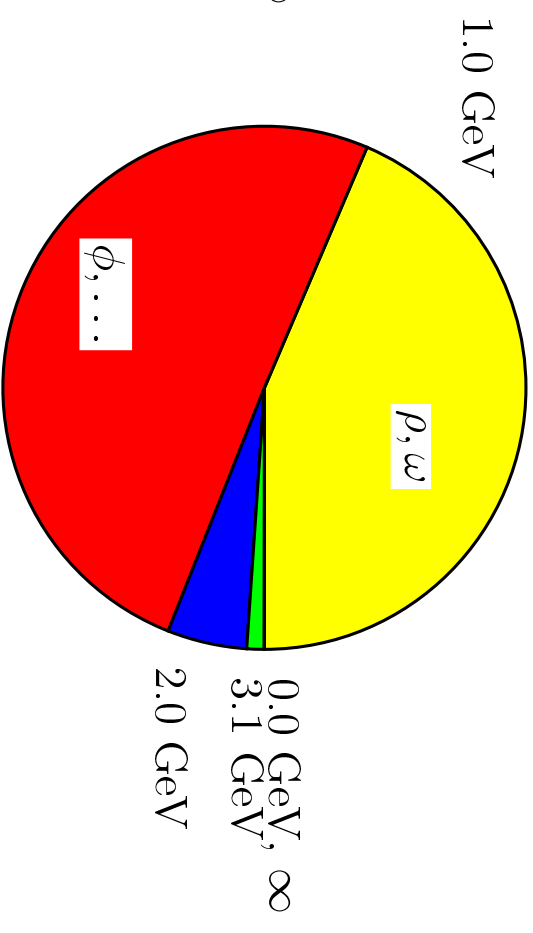
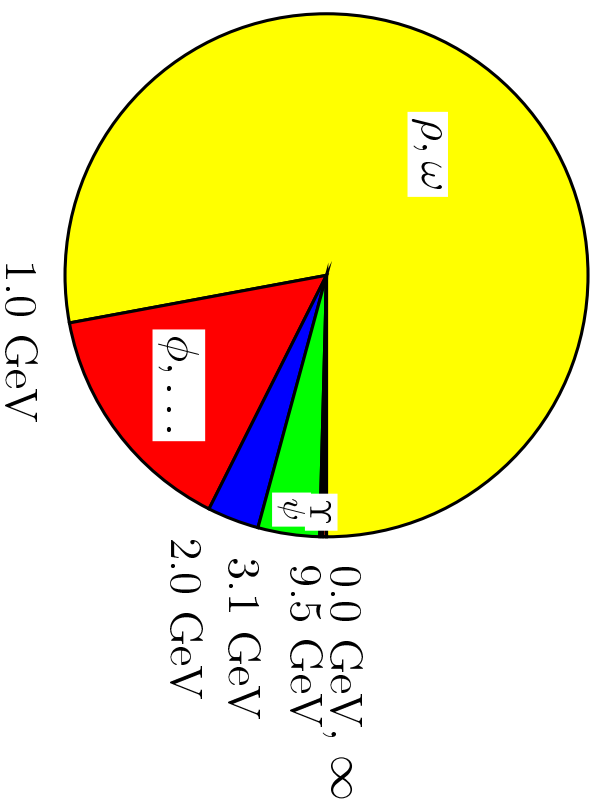
Outline

1. Why are they interesting?
2. From ρ , ω , ϕ to ρ' , ω' , ϕ'
3. Prospects
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 $e^+e^- \rightarrow (2-7)h, h = \pi, K, \eta, p, \dots$
- Their properties ($M, \Gamma, \Gamma_{ee}, \mathcal{B}$) 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 ($(g_\mu - 2)/2, \alpha(M_Z^2), \alpha_s$, quark and gluon condensates)

Contributions of Various Energy Ranges to $a_\mu^{\text{had,LO}}$

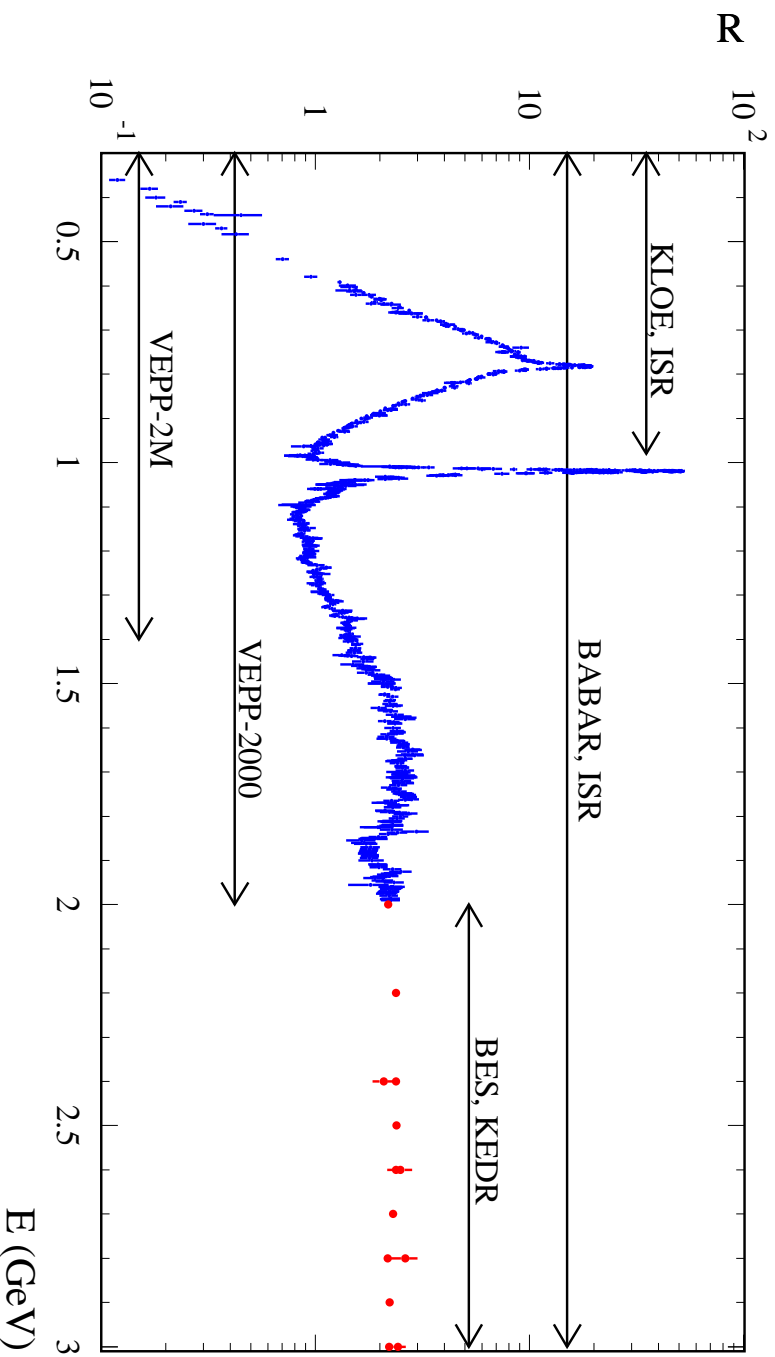


a_μ shows a more than 3σ deviation from the Standard Model prediction. Is it New Physics?

e^+e^- Low Energy Colliders and R

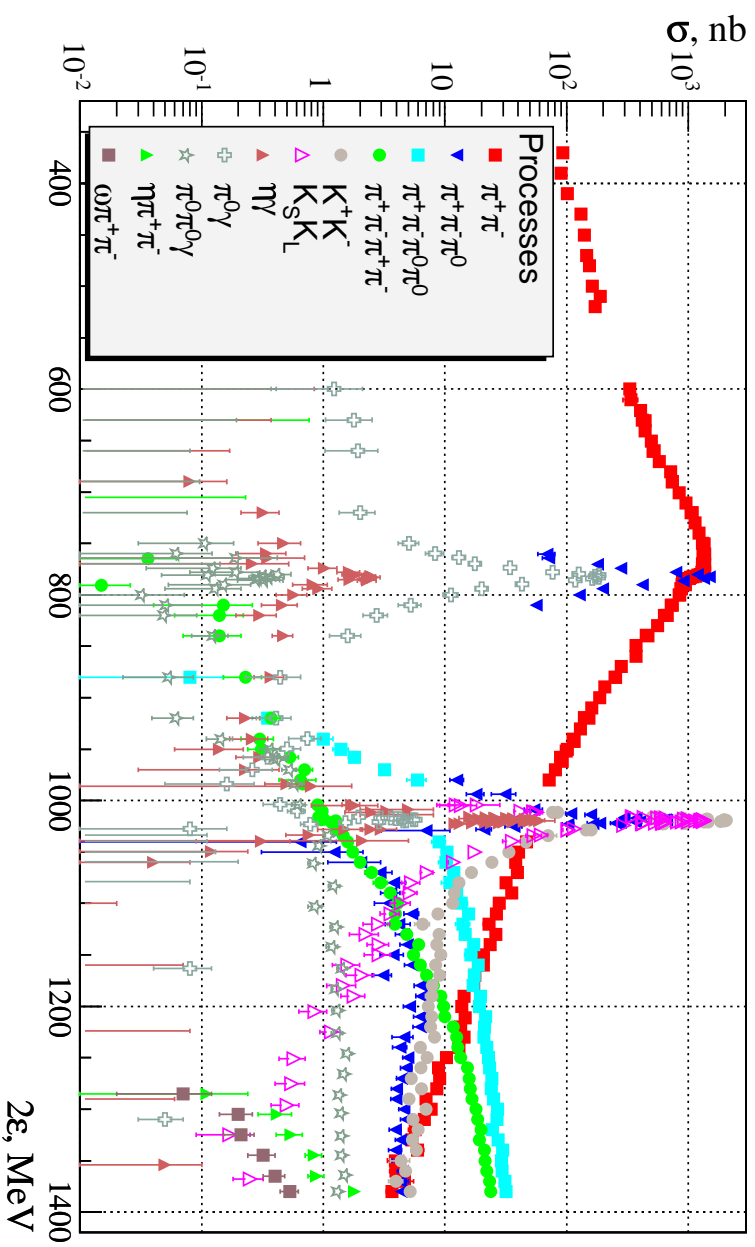
Two possible methods – scan and ISR (radiative return)

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

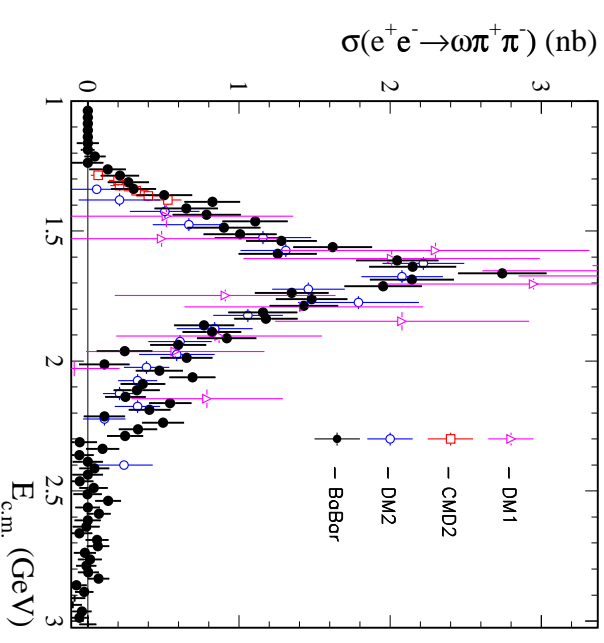
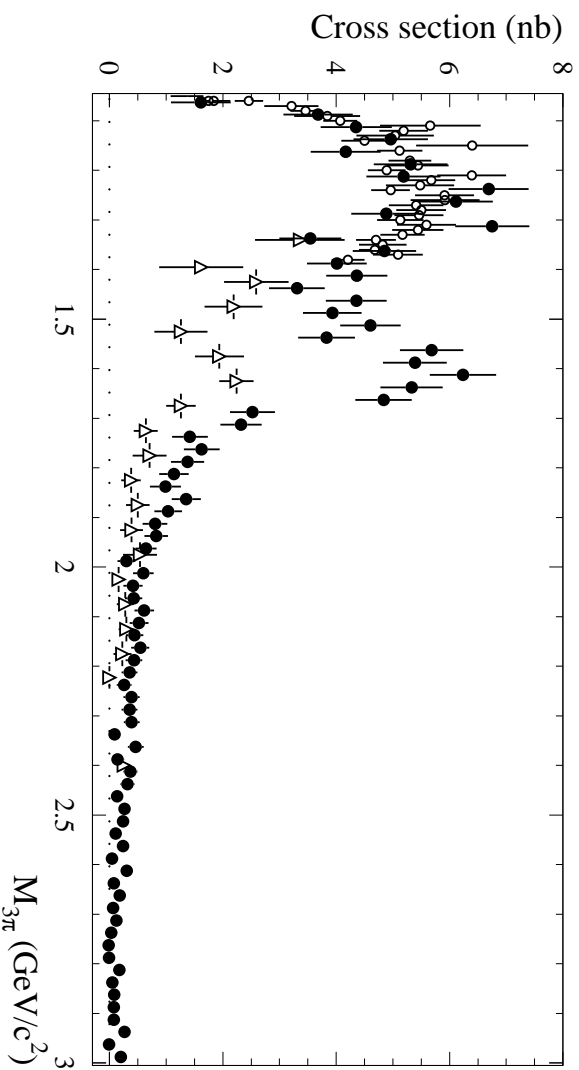
2^3S_1	Mass, MeV Width, MeV	1^3D_1	Mass, MeV Width, MeV
$\rho(1450)$	1250 - 1500 60 - 550	$\rho(1700)$	1550 - 1780 100 - 600
$\omega(1420)$	1370 - 1450 175 - 360	$\omega(1650)$	1620 - 1750 100 - 370
$\phi(1680)$	1620 - 1750 100 - 300	—	—

- Isospin-specific: $\rho' \rightarrow \pi^+ \pi^-$, 4π , 6π , $\omega\pi^0$; $\omega'(\phi') \rightarrow \rho\pi$, $\omega\pi\pi$, $\omega\eta$
- 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

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

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



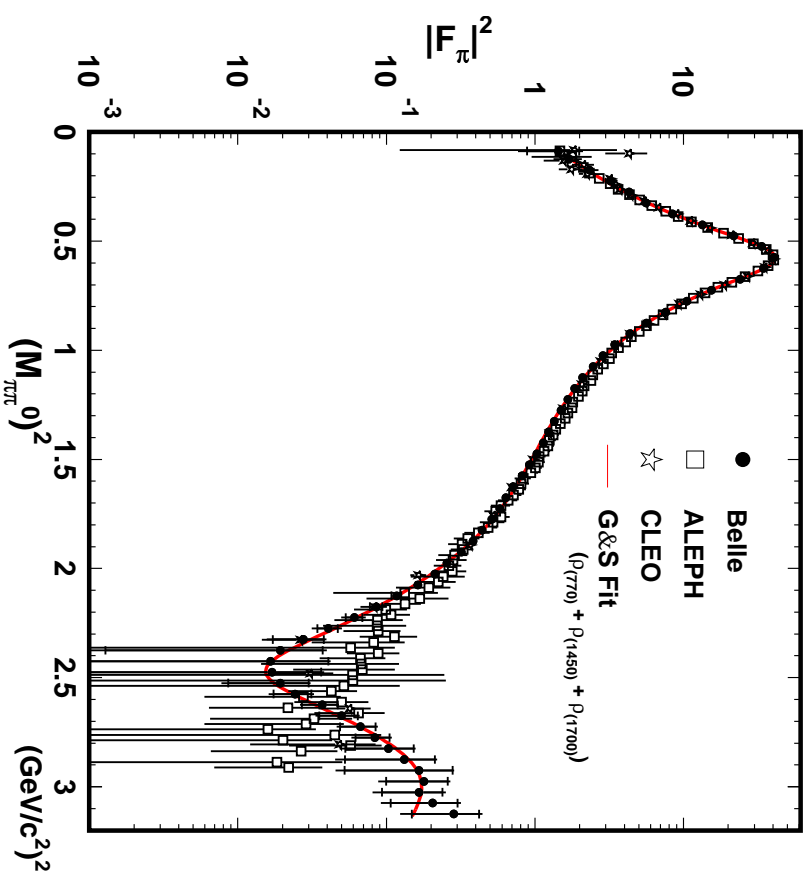
$\pi^+\pi^-\pi^0$: BaBar and SND agree. BaBar's points much higher than at DM2
 Two ω' observed in $\pi^+\pi^-\pi^0(\rho\pi)$ and $2\pi^+2\pi^-\pi^0(\omega\pi^+\pi^-)$

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	$870_{-300}^{+500} \pm 450$	$450 \pm 70 \pm 70$	$133 \pm 48 \pm 100$
$\mathcal{B}_{ee}\mathcal{B}_{3\pi}$, 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

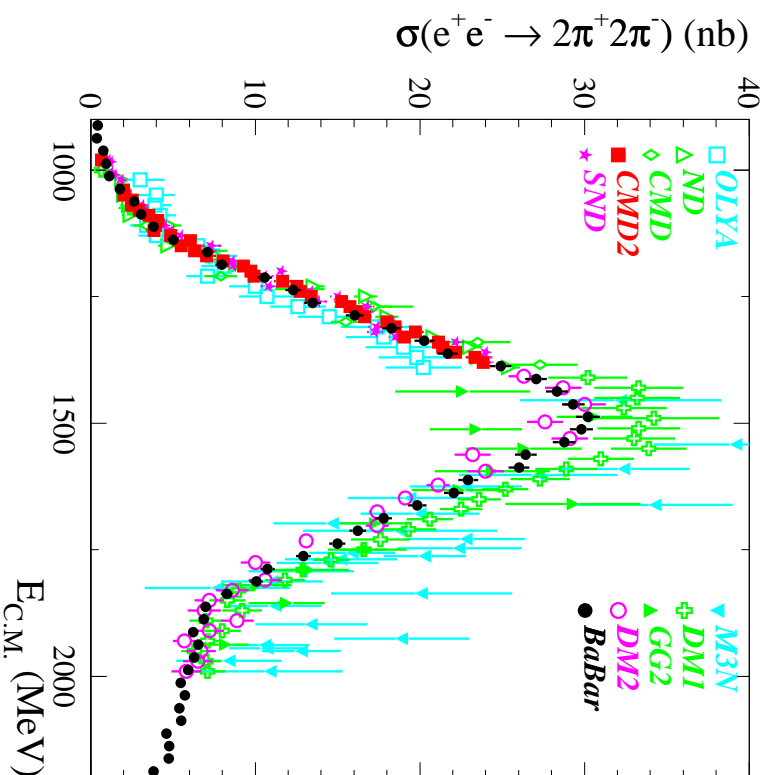
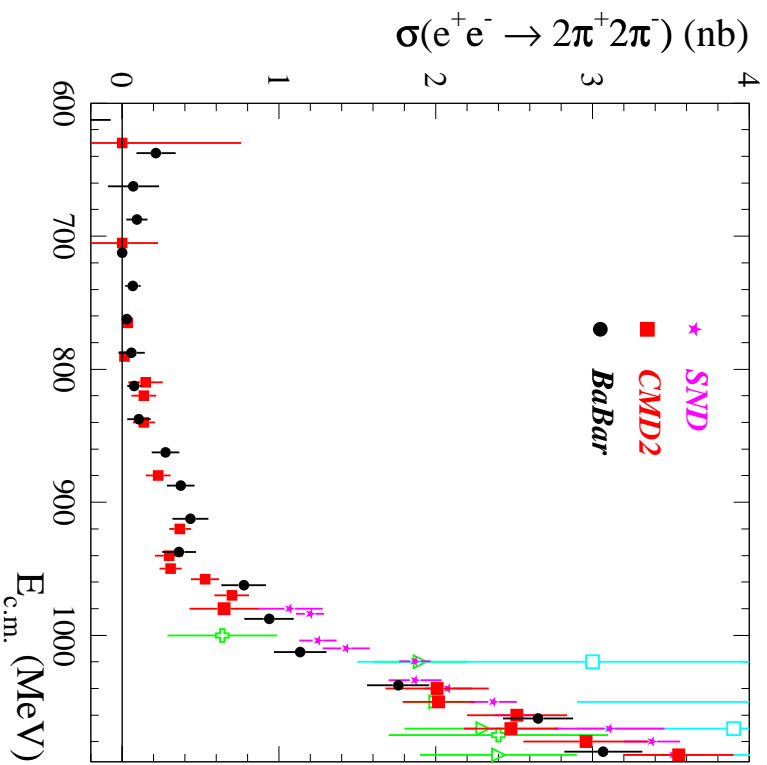
Source	PDG-2004	BaBar, $\pi^+\pi^-\pi^0$	BaBar, $\omega\pi^+\pi^-$
M , MeV	$1770 \pm 50 \pm 60$	$1660 \pm 10 \pm 2$	$1667 \pm 13 \pm 6$
Γ , MeV	$490_{-150}^{+200} \pm 130$	$230 \pm 30 \pm 20$	$222 \pm 25 \pm 20$
$\mathcal{B}_{ee}\mathcal{B}_{3\pi}$, 10^{-6}	$1.2_{-0.1}^{+0.4} \pm 0.8$	$1.3 \pm 0.1 \pm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

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



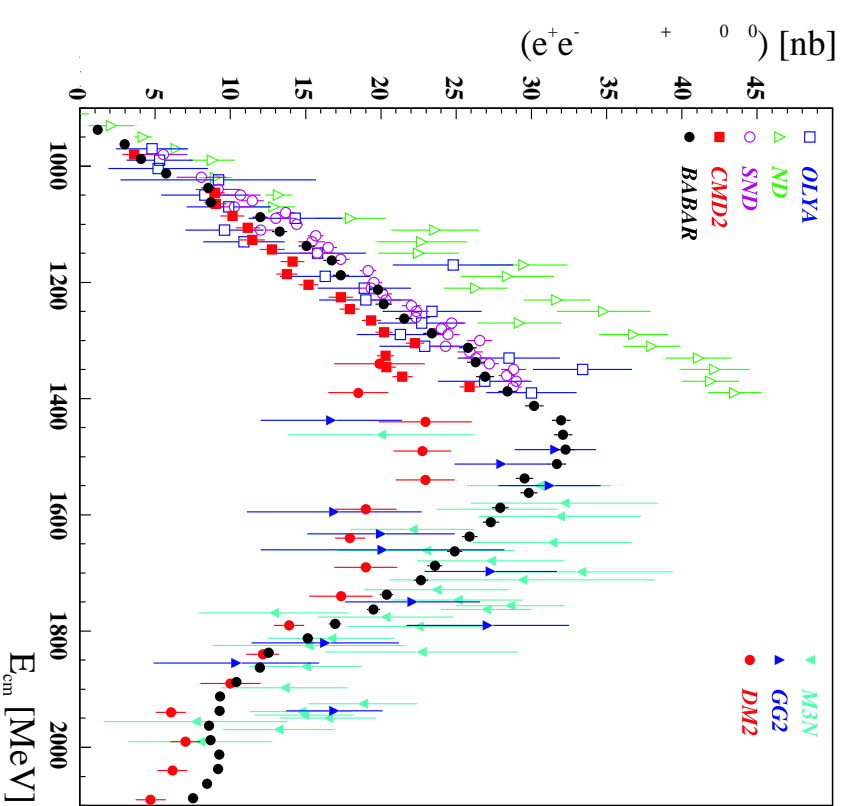
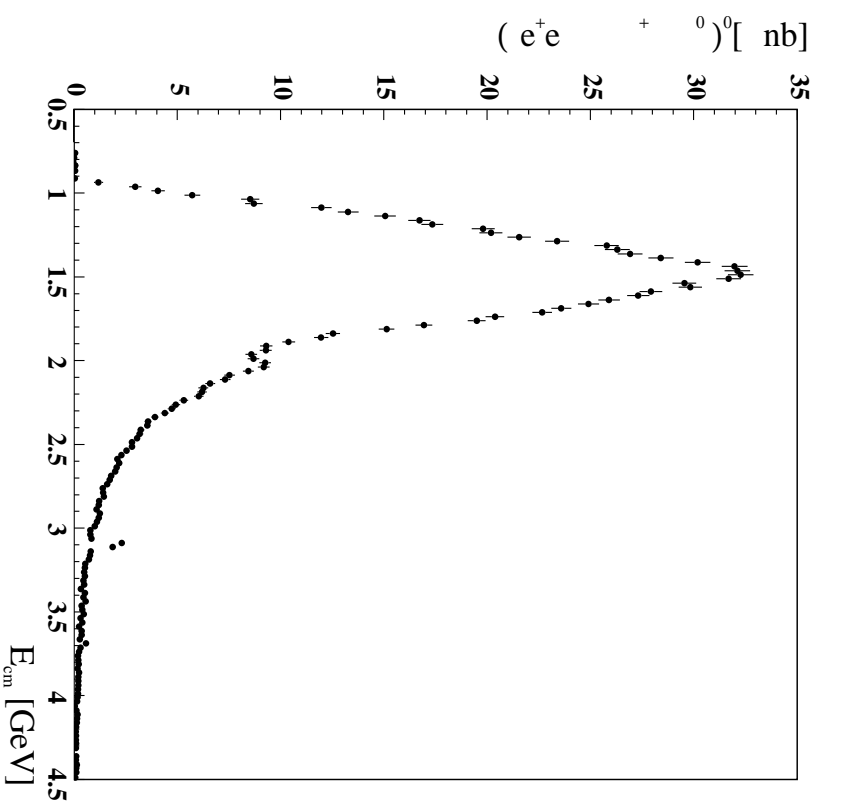
72 fb⁻¹, 5.6 · 10⁶ events, ρ , $\rho(1450)$, $\rho(1700)$ clearly seen,
 their parameters determined

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

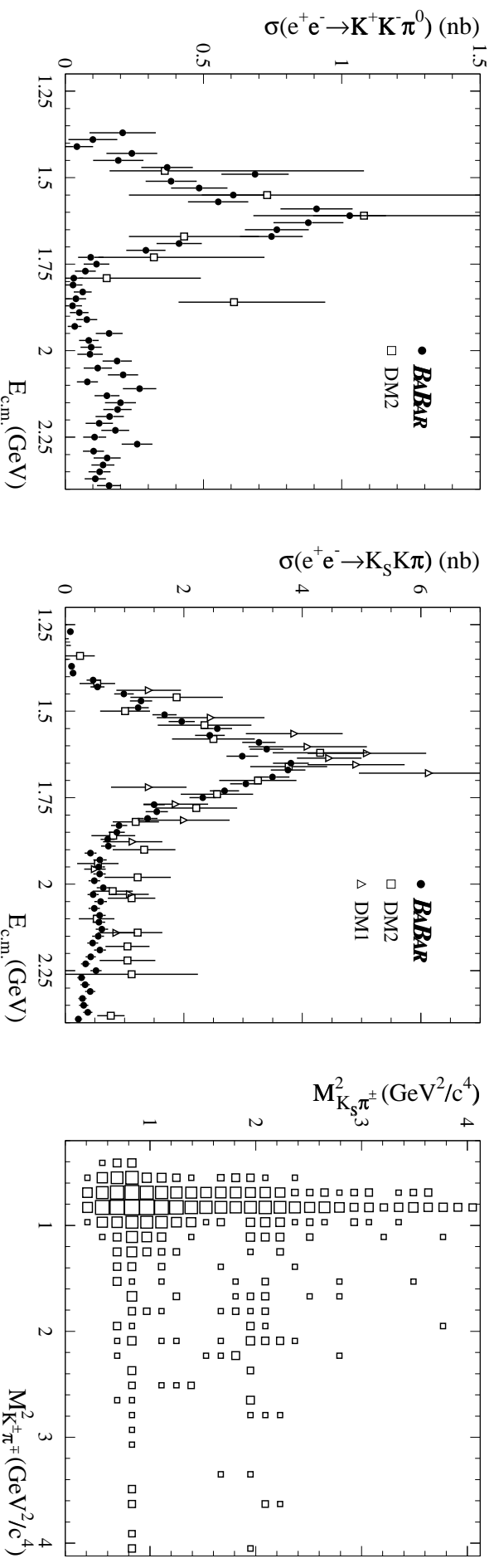
$\pi^+\pi^-\pi^0$ Mode


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

Separation of different channels may reveal more complicated structure

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

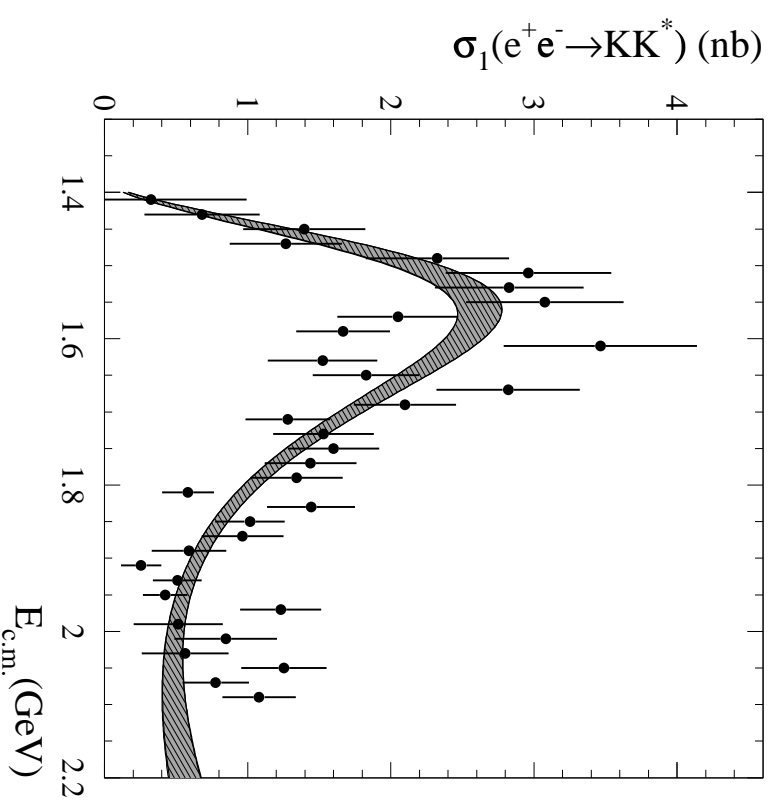
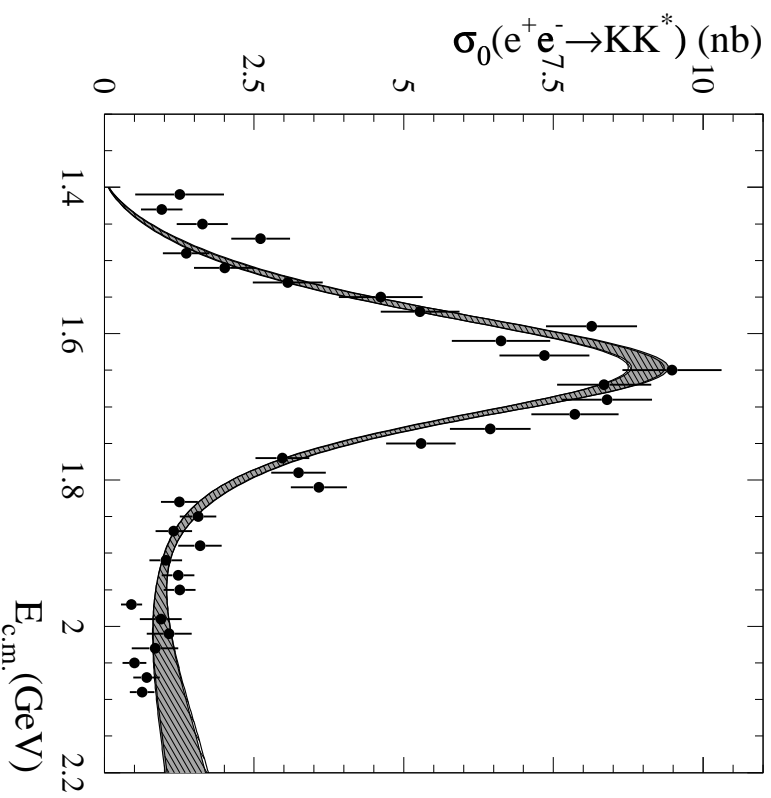
$e^+e^- \rightarrow K^\pm\pi^\mp K_S^0, K^+K^-\pi^0$ studied



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

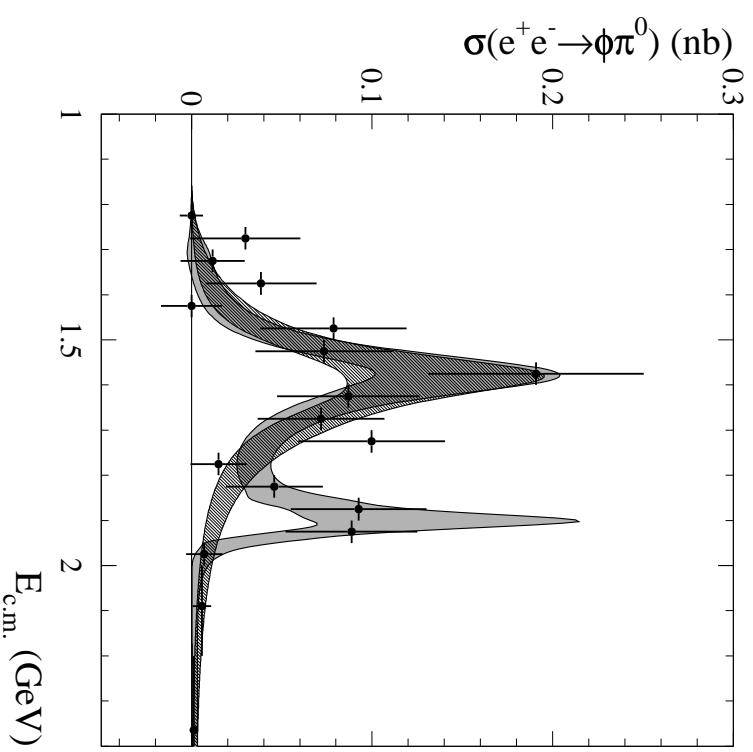
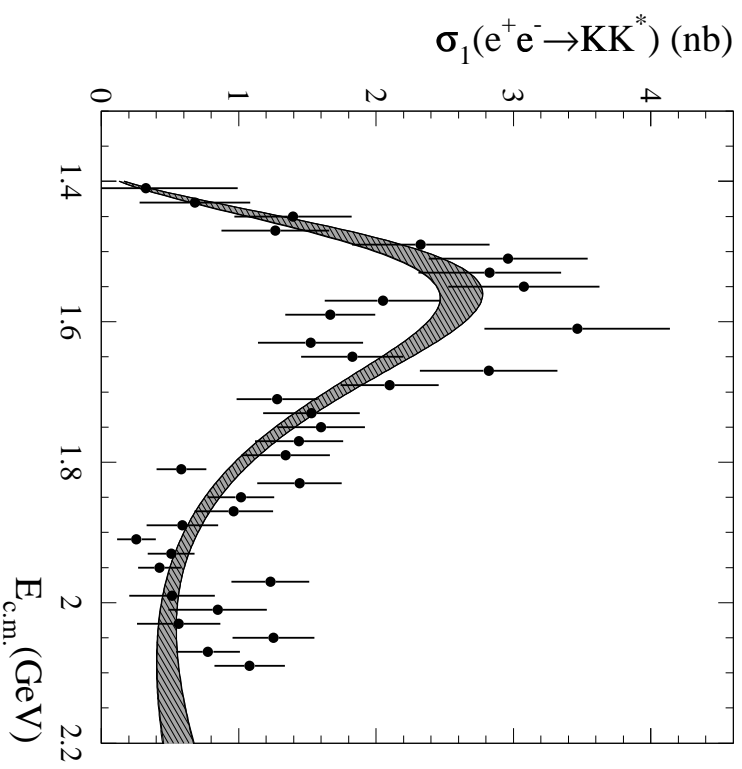
Isospin 0 and 1 components are separated

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



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

$\rho'(1450) - I$ 

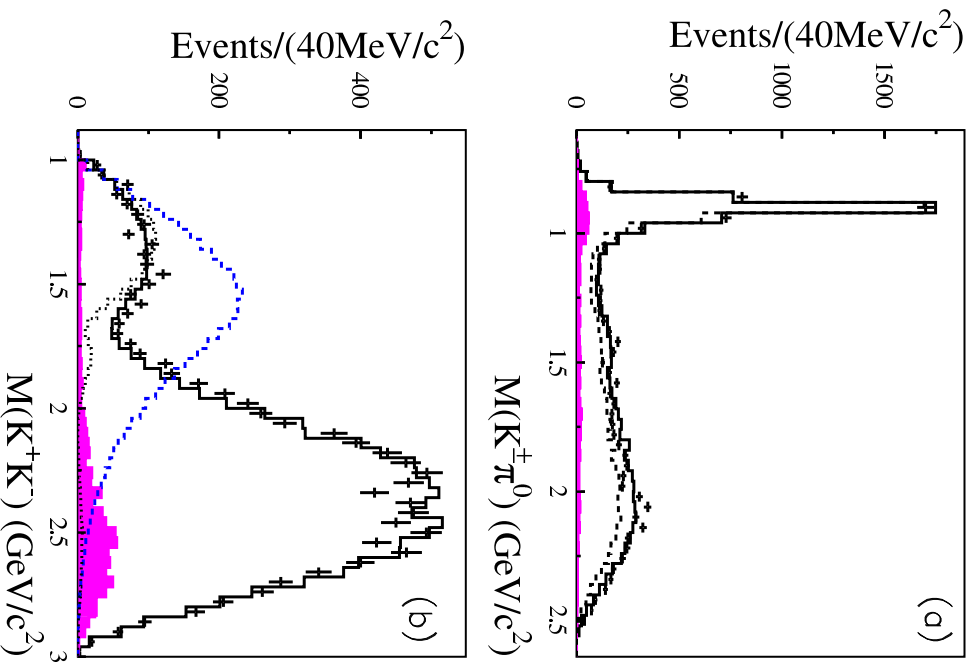
$\rho'(1450) - \text{II}$

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

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

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

ρ' at BES?



An $X(1570) = K^+K^-$ state

observed by BES

in $J/\psi \rightarrow K^+K^-\pi^0$

$M = 1576^{+49+98}_{-55-91}$ MeV,

$\Gamma = 409^{+14+32}_{-12-67}$ MeV

PWA $\Rightarrow J^{PC} = 1^{--}$

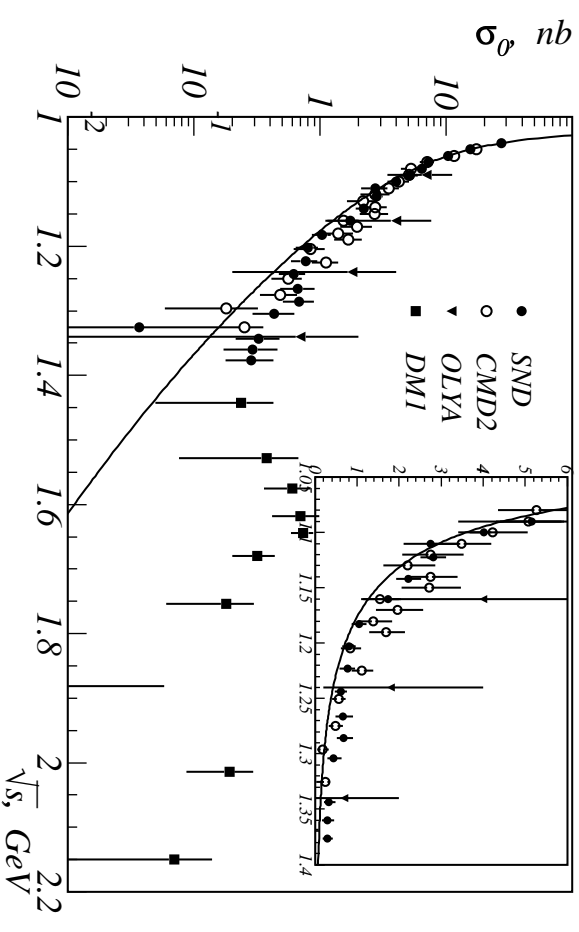
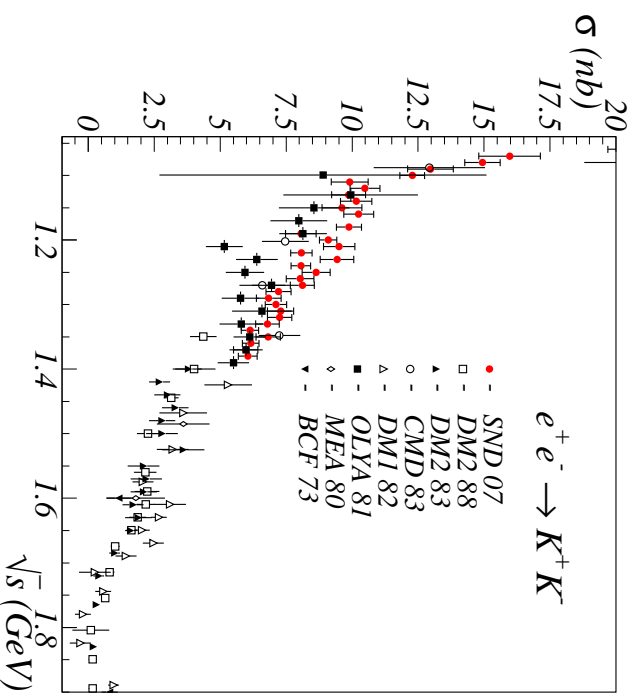
Is it a mixture of

$\rho'(1450)$ and $\rho'(1700)$?

Not in line with

$e^+e^- \rightarrow K^+K^-$, $K_S^0K_L^0$

$$e^+e^- \rightarrow K^+K^-, K_S^0K_L^0$$

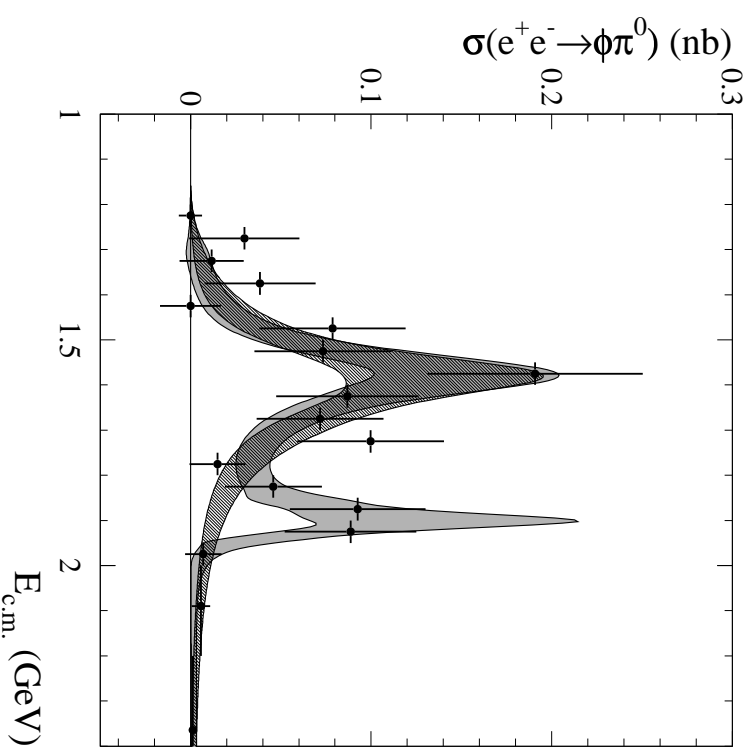
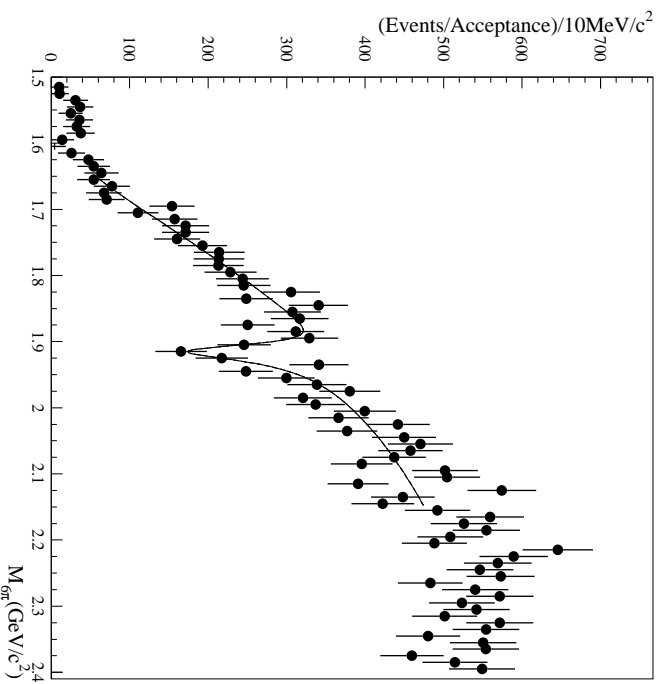


No prominent structures observed in K^+K^- ,

Some evidence for the ϕ' in $K_S^0K_L^0$

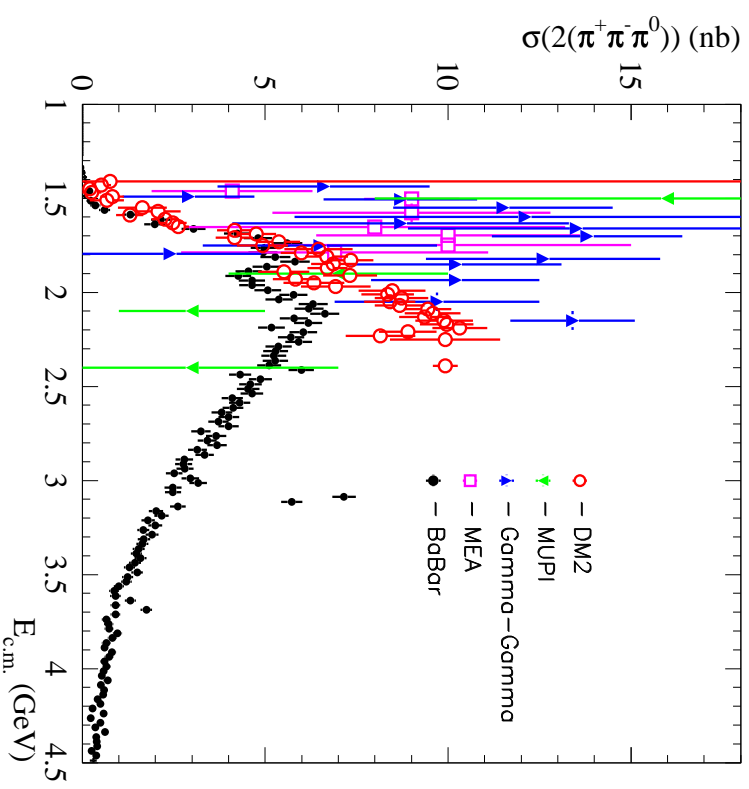
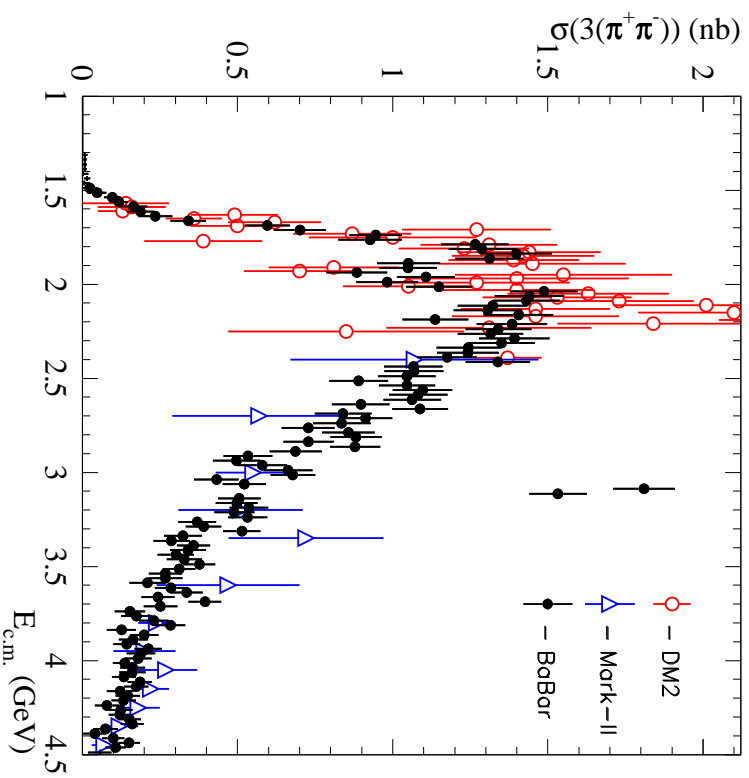
More precise experiments needed studying both modes with isospin analysis

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 $e^+e^- \rightarrow \phi\pi^0$

$\rho(1900) - II$



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

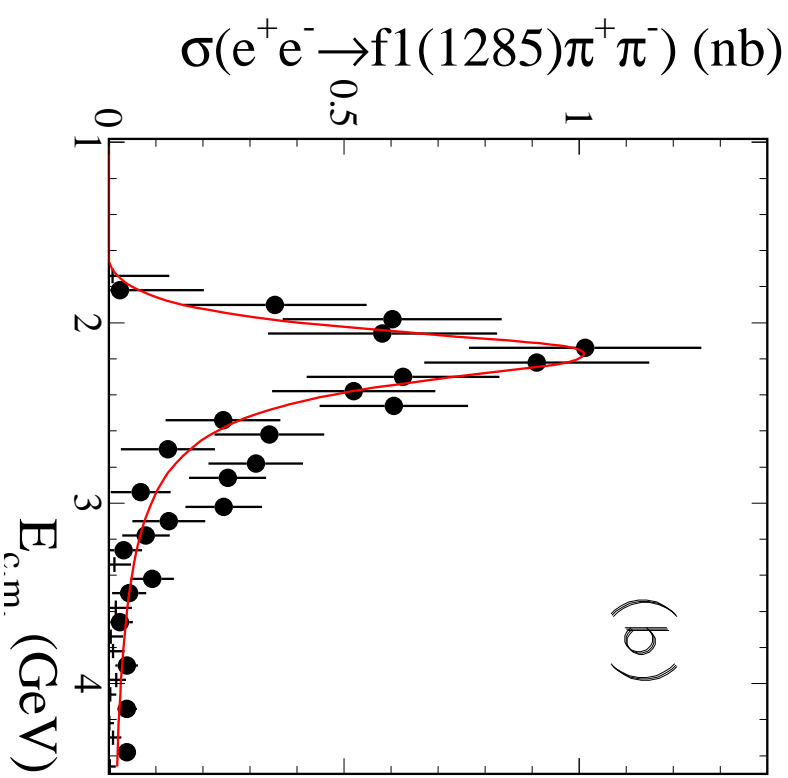
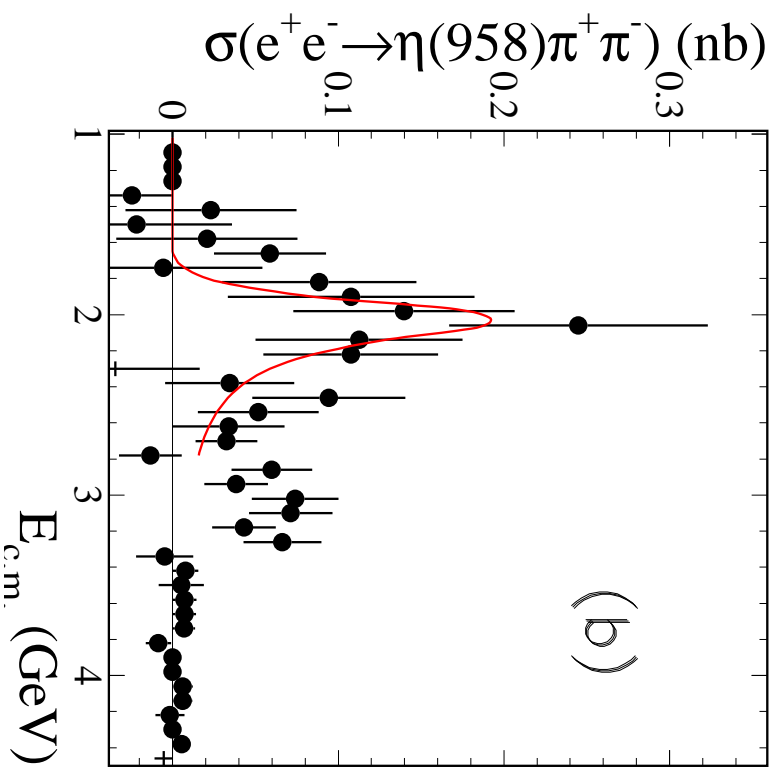
$\rho(1900) - III$

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

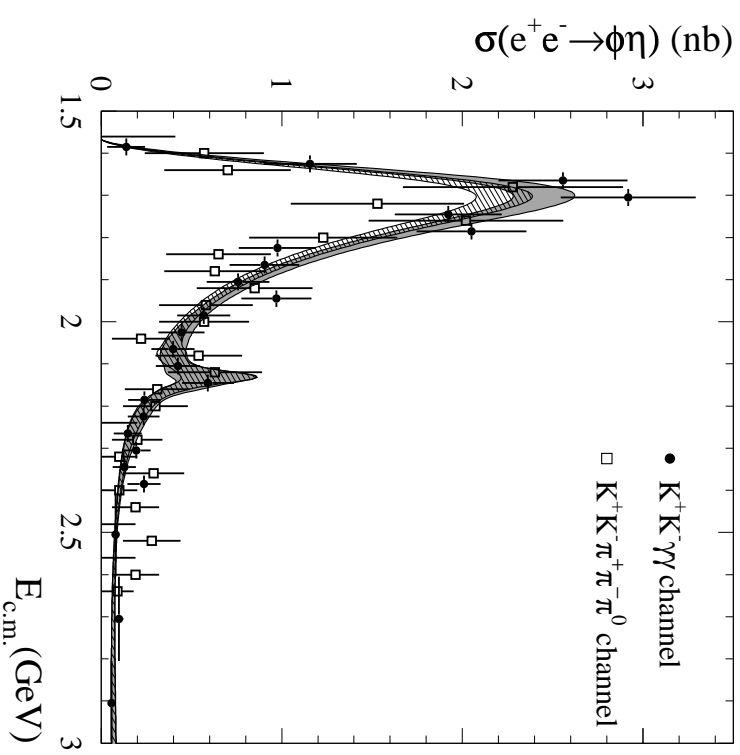
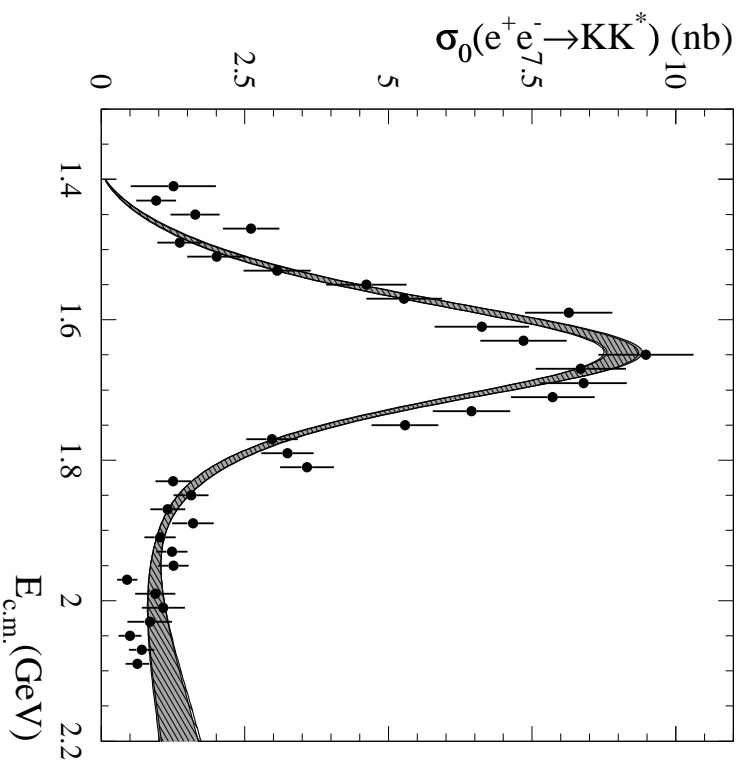
In all final states but $\phi\pi$ a dip seen

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

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

$\rho(2150)$ 

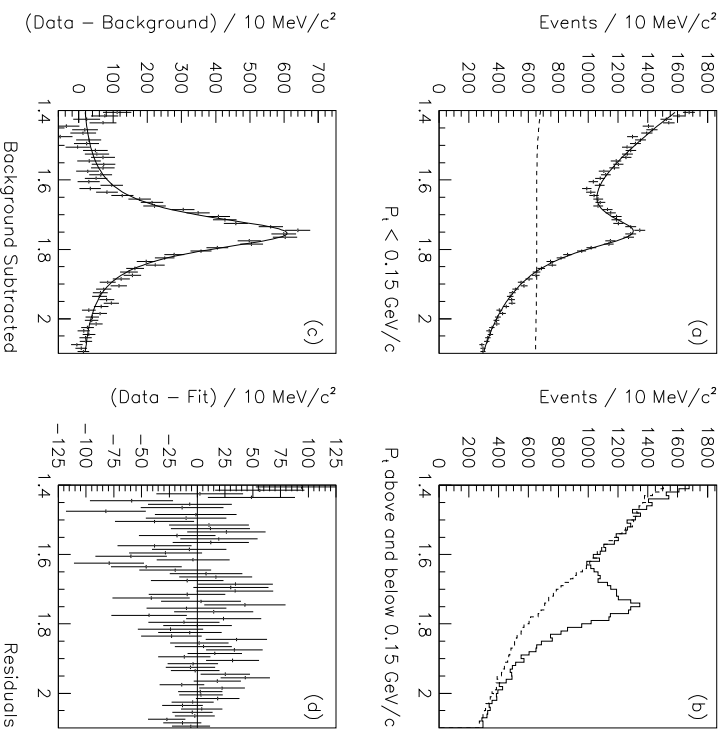
Mode	$\eta' \pi^+ \pi^-$	$f_1(1285) \pi^+ \pi^-$
Mass, GeV	1.99 ± 0.08	$2.15 \pm 0.04 \pm 0.05$
Width, GeV	0.31 ± 0.14	$0.35 \pm 0.04 \pm 0.05$

$\phi'(1680)$ 

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

ϕ' at FOCUS?

Mass(K^+K^-) (GeV/c^2)



An $X(1750) = K^+K^-$ state

observed by FOCUS

in $\gamma p \rightarrow K^+K^-p$

$M = 1753.5 \pm 1.5 \pm 2.3 \text{ MeV}$,

$\Gamma = 122.2 \pm 6.2 \pm 8.0 \text{ MeV}$

Not seen in $K^* \bar{K} \rightarrow K^\pm \pi^\mp K_S^0$:

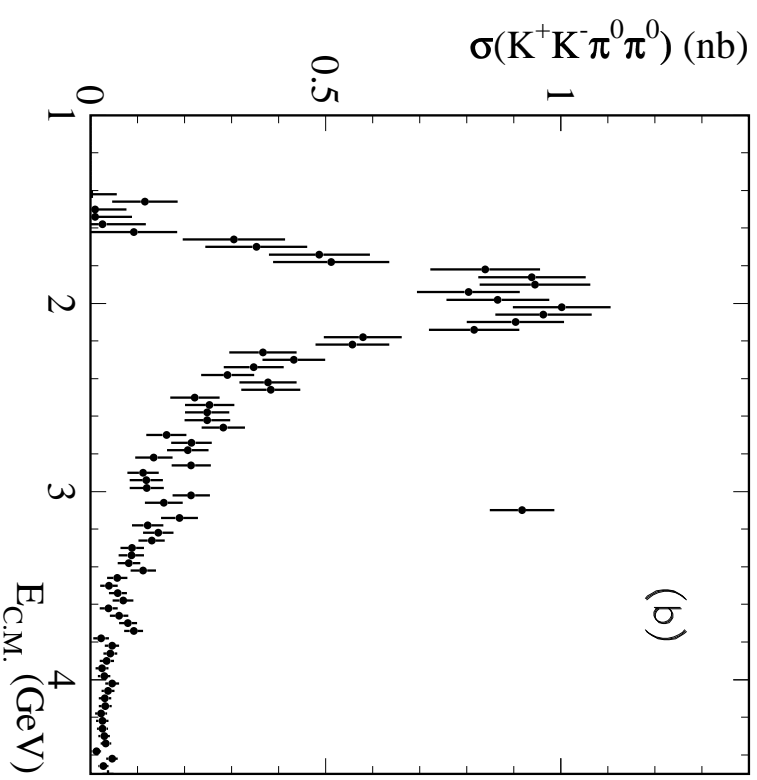
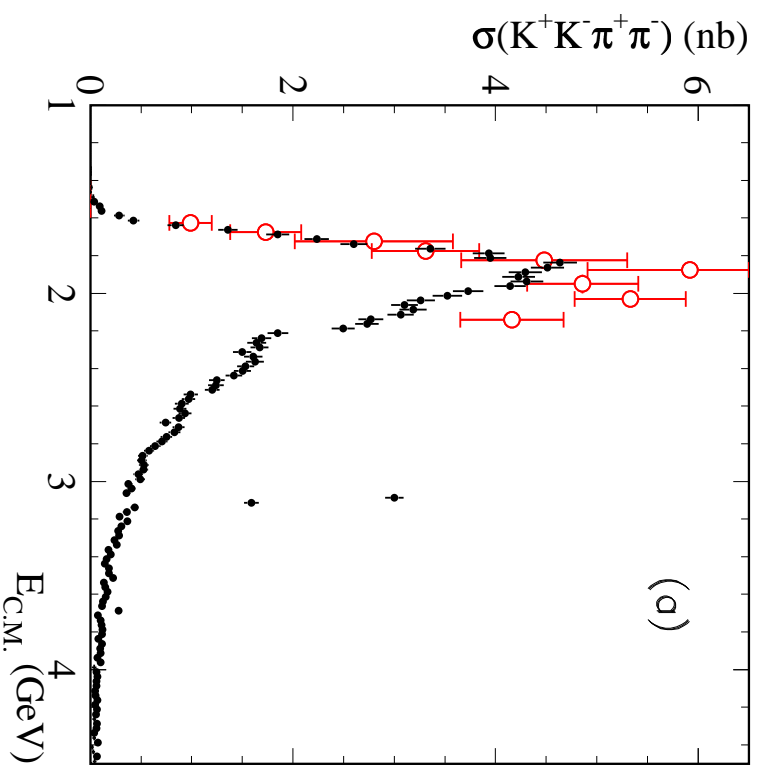
$\mathcal{B}(\bar{K}^{*0} K^0) / \mathcal{B}(K^+ K^-) < 0.065$

$\mathcal{B}(\bar{K}^{*\pm} K^\mp) / \mathcal{B}(K^+ K^-) < 0.183$

Is it ϕ' ?

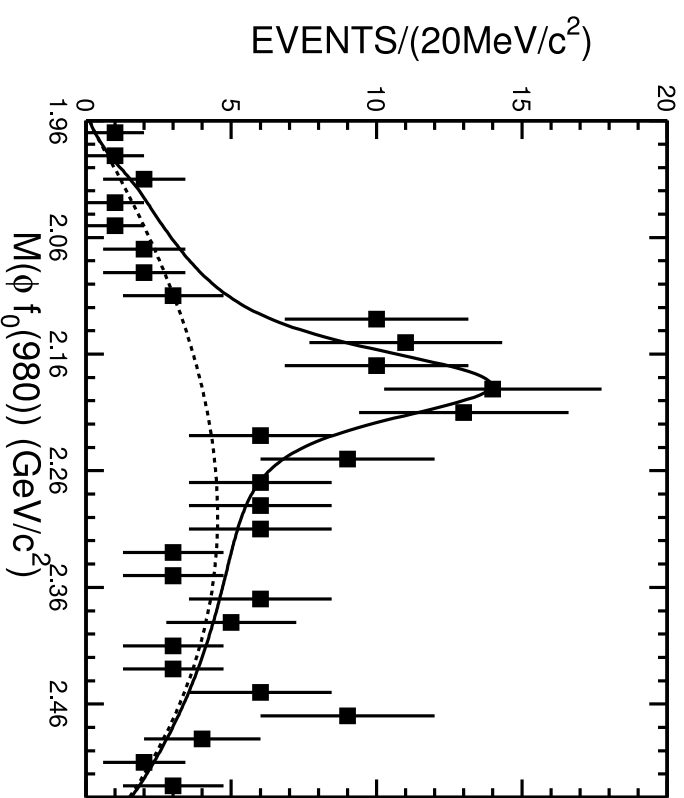
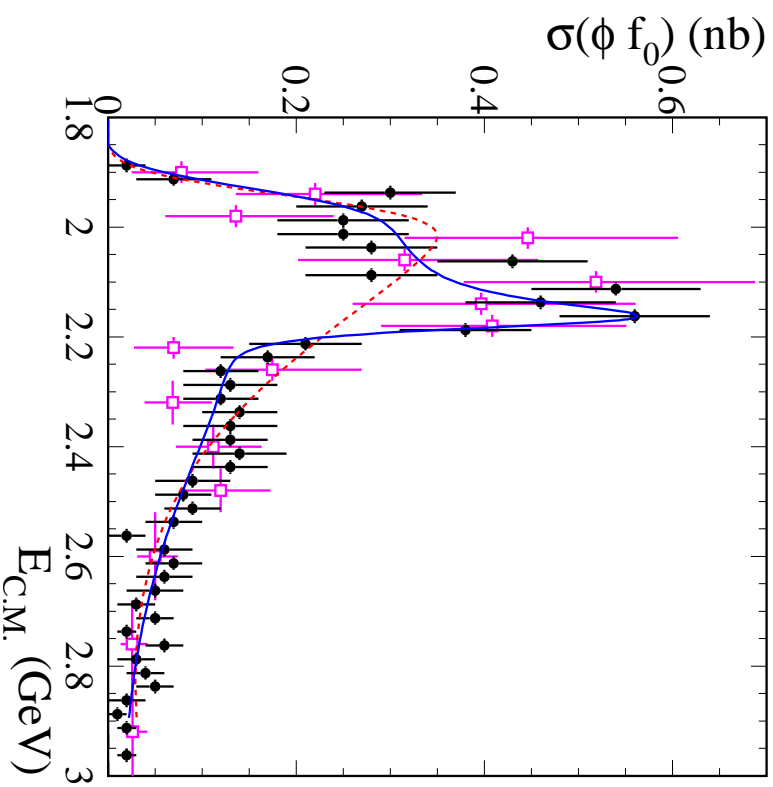
Not in line with e^+e^-

with $\phi' \rightarrow \bar{K}^* K$, not to $K\bar{K}$

$\phi(2170) - I$ 

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

$\phi(2170) - II$



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

Prospects

- A new low energy collider VEPP-2000 in Novosibirsk: the design luminosity $\mathcal{L} = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, maximum c.m.energy 2.0 GeV, commissioning started. Physical runs with two detectors at the end of 2008
- A similar collider with maximum c.m.energy $\sim 2.5 \text{ GeV}$ is discussed in Frascati – DAΦNE-II
- The τ -charm factory in Beijing started running, good coverage of the $3.0 < \sqrt{s} < 5.0 \text{ GeV}$
- BaBar has interesting ISR results with $\int \mathcal{L} dt = 232 \text{ fb}^{-1}$ below 2 GeV, often statistically and systematically limited, Belle can hopefully produce results with a 3-4 times higher data sample
- SuperBelle with $5\text{-}10 \text{ fb}^{-1}$ opens unique possibilities for high-precision measurements of vectors, R , R_c , and R_b

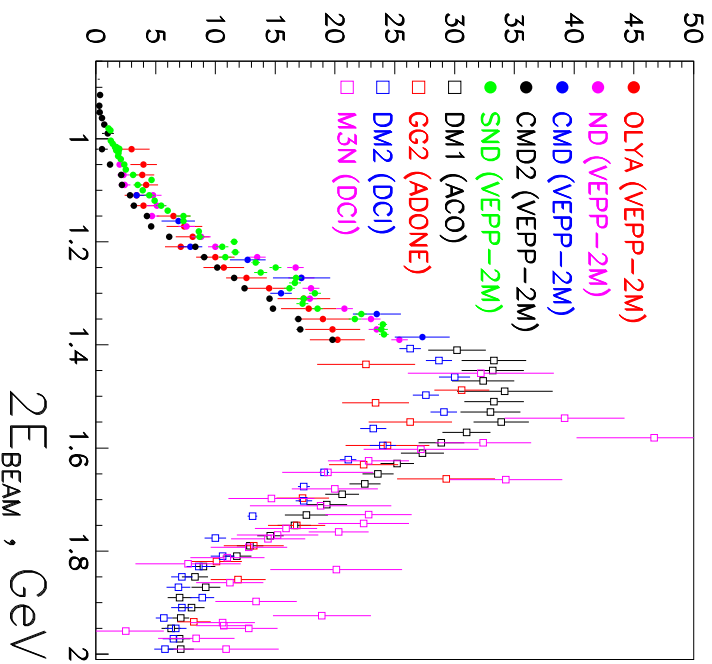
Conclusions

- 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, good prospects for SuperBelle

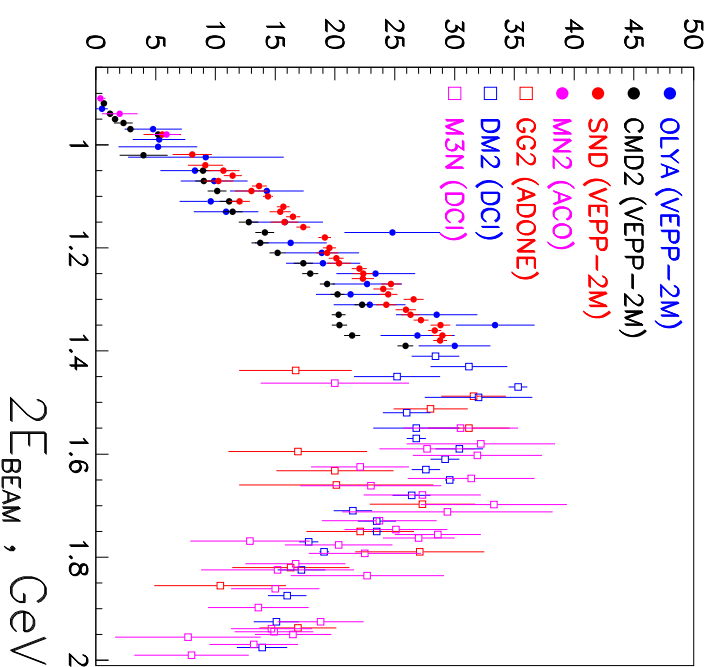
Back-up Slides

Study of $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

$$e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$$



$$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$$



Large data scatter above 1.4 GeV!

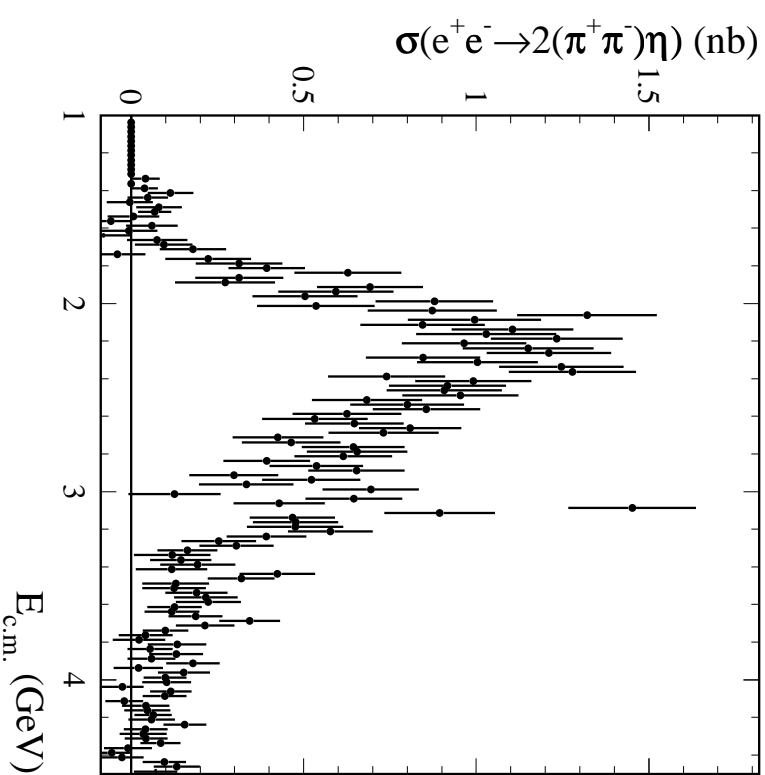
Are there two ρ 's?

$\rho(2150) - I$

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

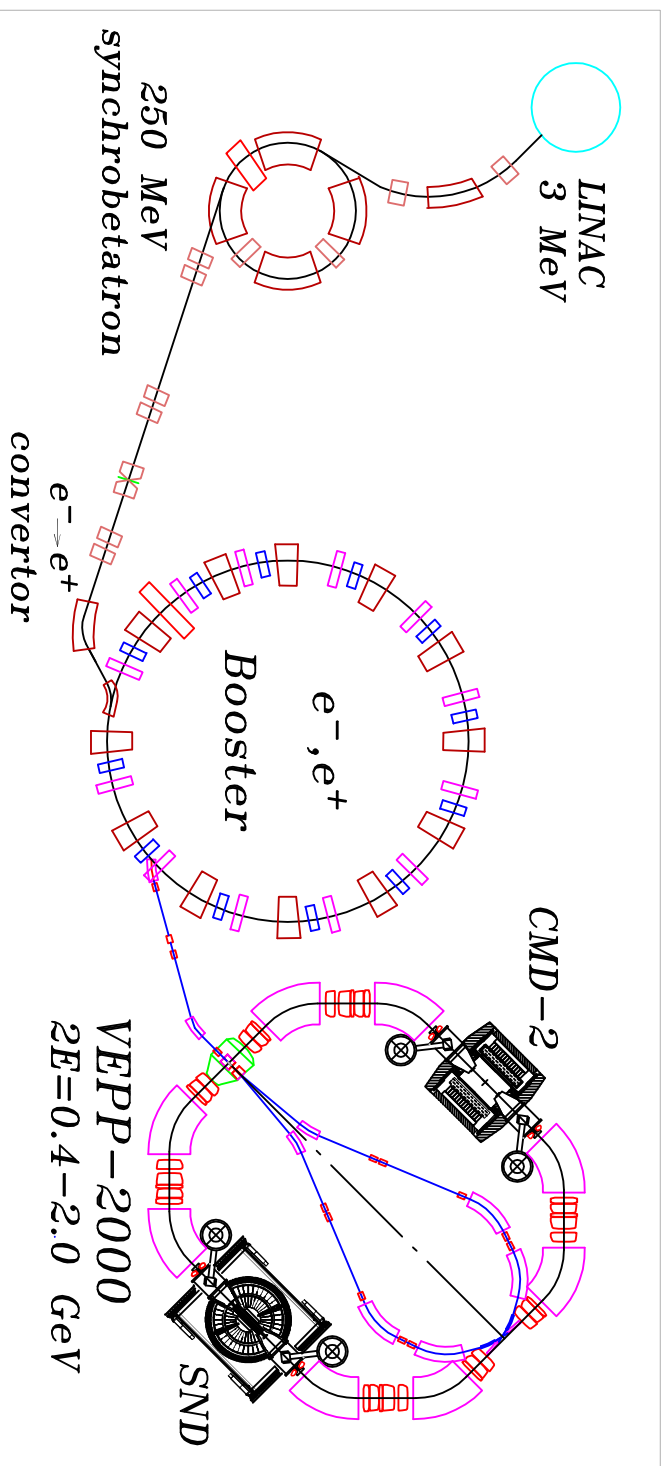
Mass 2000-2200 MeV,
 width 300-400 MeV



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

VEPP-2000

Layout of the VEPP-2000 complex



The design luminosity $\mathcal{L} = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, maximum c.m.energy 2.0 GeV, Commissioning started. Physical runs with two detectors at the end of 2008

A similar collider with maximum c.m.energy ~ 2.5 GeV is discussed in Frascati – DAΦNE-II