R Measurement below 2.5 GeV: Status and Future

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Outline

1. What can we learn?
2. Status of R measurements
3. Experimental requirements
4. Future
5. Conclusions

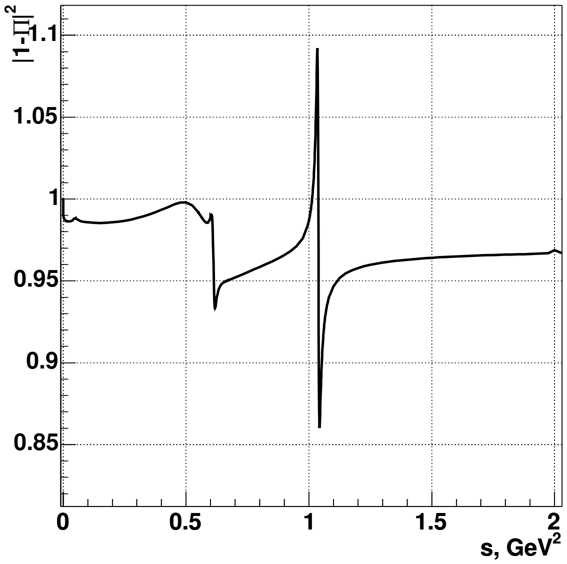
What Can We Learn?

1. Detailed study of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
   - Test of models and input to theory (ChPT, Vector Dominance, QCD, . . .)
   - Properties of vector mesons $(\rho', \omega', \phi', \ldots)$
   - Search for hybrids $(q\bar{q}g)$ and glueballs
   - Test of CVC relations between e^+e^- and τ-lepton
   - Interactions of light (u, d, s) quarks
2. High precision determination of $R = \sigma(e^+e^- \to \text{ hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at low energies and fundamental quantitites
   - $(g_\mu - 2)/2$
   - $\alpha(M_Z^2)$
   - QCD sum rules (α_s, quark and gluon condensates)

How Is R Measured Below 2.5 GeV?

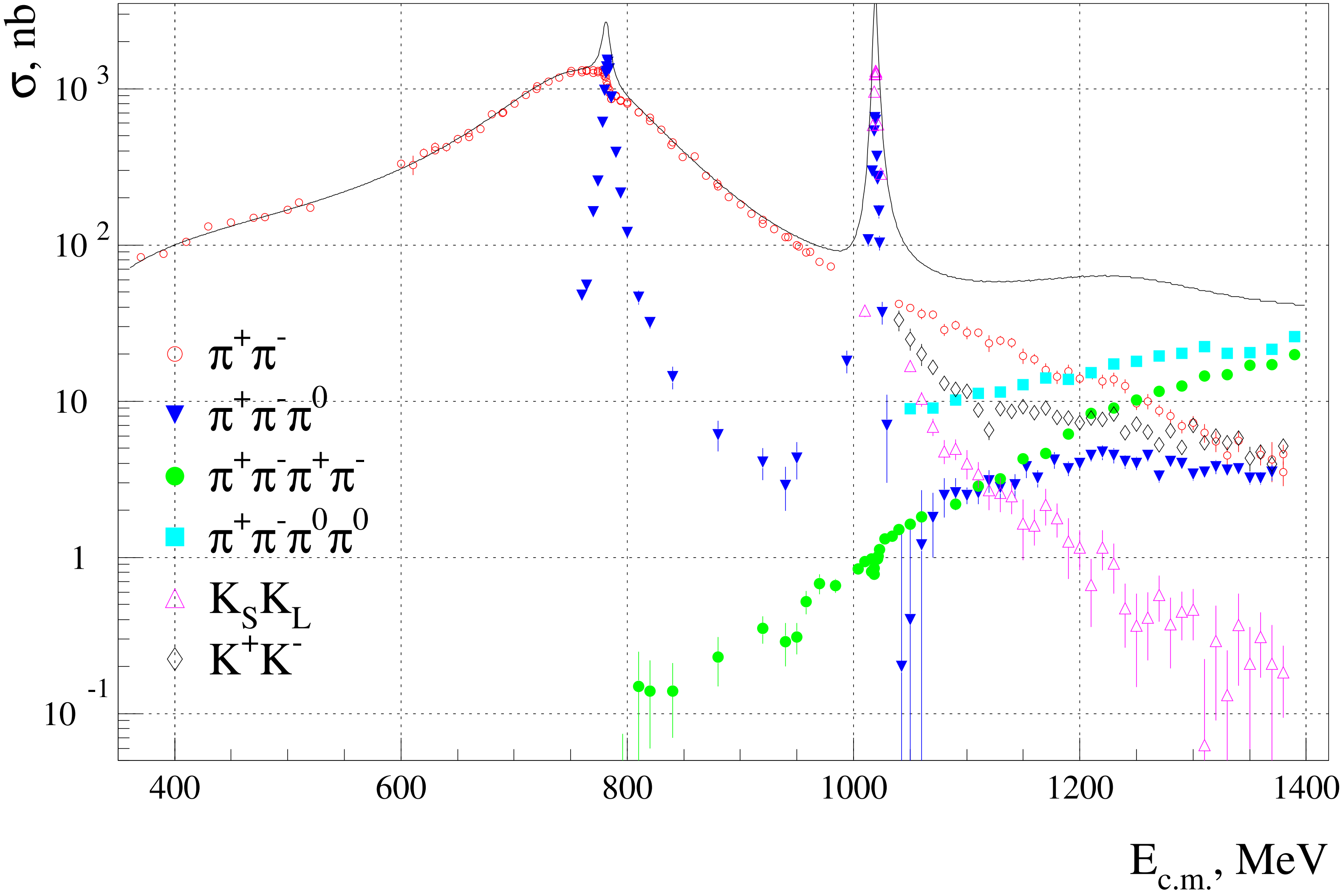
- $\sqrt{s} < 2$–2.2 GeV – exclusive modes $(\pi^+\pi^-, \pi^+\pi^-\pi^0, \ldots, K\bar{K}, \ldots)$
- Possibly missing (small σ, undetected) final states
- Above 2 GeV – total R (all multihadronic events)
- Radiative corrections: Initial state radiation (ISR), vacuum polarization (VP), final state radiation (FSR): M. Drees, K. Hikasa, 1990
- Radiative return

- $\sigma_{\text{bare}} = \sigma_{\text{dressed}}|1-\Pi(s)|^2$
- $\sigma_{\text{dressed}} = \frac{N}{\int Ldt\ \varepsilon\ (1+\delta_{\text{ISR}})}$
- $\Pi(s) = \Pi_{\text{lep}}(s) + \Pi_{\text{had}}(s)$



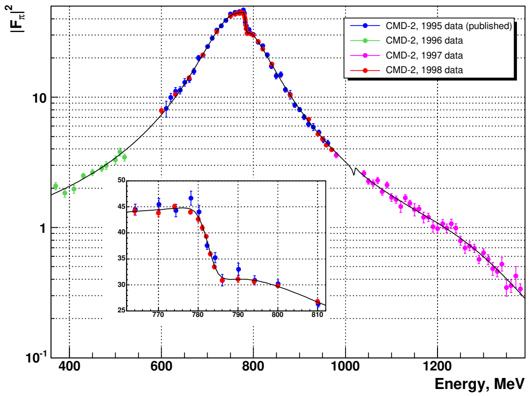
$|1-\Pi(s)|^2$

Exclusive Cross Sections at CMD-2

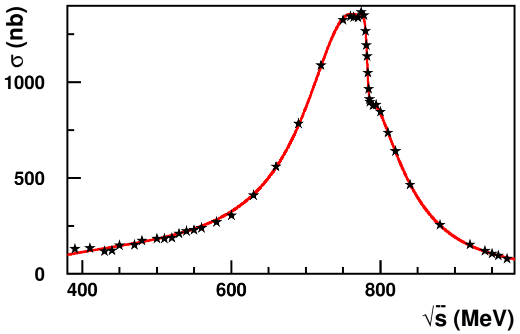


$e^+e^- \to \pi^+\pi^-$

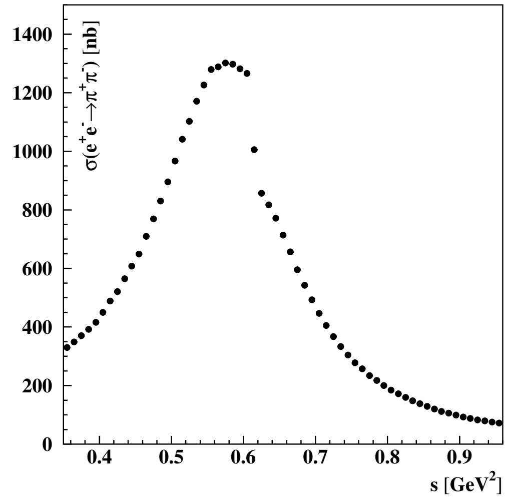
CMD-2



SND



KLOE



Systematic errors:

CMD-2 – 0.7%, 0.6(0.8)%, (1.2-4.2)% for (370-520),(600-960), (980-1380) MeV

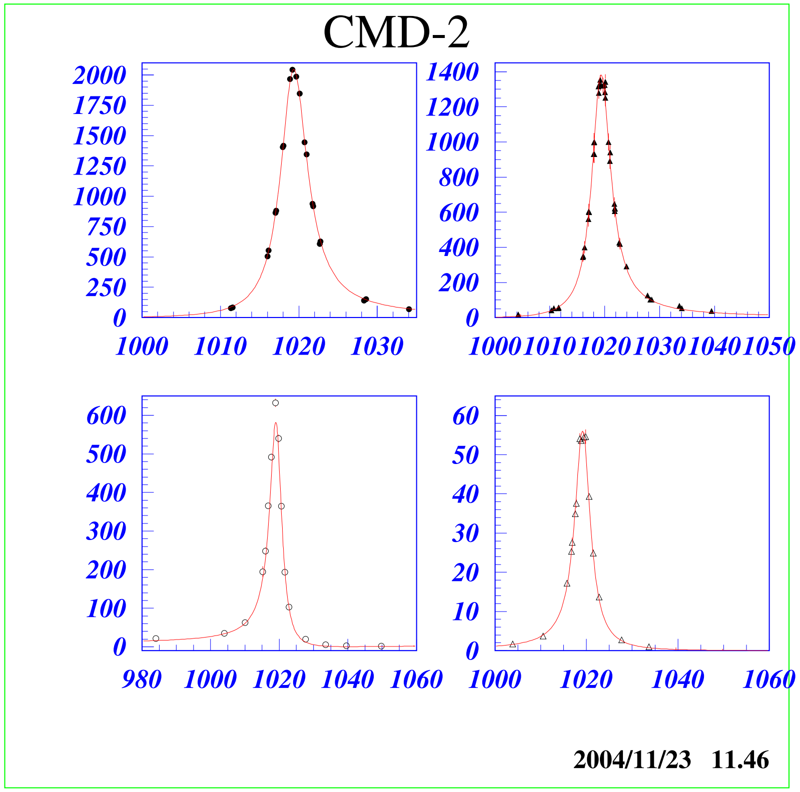
SND – 1.3% from 400 to 1000 MeV

KLOE – 1.3% from 590 to 900 MeV

Properties of Basic Vector Mesons

Meson	ρ	ω	ϕ
Mass, MeV	775.8 ± 0.5	782.65 ± 0.12	1019.460 ± 0.019
Width, MeV	146.4 ± 1.5	8.49 ± 0.08	4.26 ± 0.05
$\mathcal{B}_{ee}, 10^{-5}$	4.67 ± 0.09	7.18 ± 0.12	29.7 ± 0.4
Modes studied	12 $(2-4)\pi$, $\pi^0(\eta)\gamma$, $e^+e^-(\mu^+\mu^-)$, $\pi^0(\eta)l^+l^-$, $\pi^0\pi^0(\eta)\gamma$	17 $(2-4)\pi$, $\pi^0(\eta)\gamma$, $e^+e^-(\mu^+\mu^-)$, $\pi^0(\eta)l^+l^-$, $\pi^0\pi^0(\eta)\gamma$	27 $K\bar{K}$, $(2-5)\pi$, $\pi^0(\eta)\gamma$, $e^+e^-(\mu^+\mu^-)$, $\pi^0(\eta)l^+l^-$, $\pi^0\pi^0(\eta)\gamma$
Min $\mathcal{B}$	$2 \cdot 10^{-5}$	$7 \cdot 10^{-5}$	$4 \cdot 10^{-6}$

ϕ Parameters from 4 Main Decay Modes at CMD-2



CMD-2	$1019.444 \pm 0.007 \pm 0.025$
PDG-2006	1019.460 ± 0.019

Mass, MeV

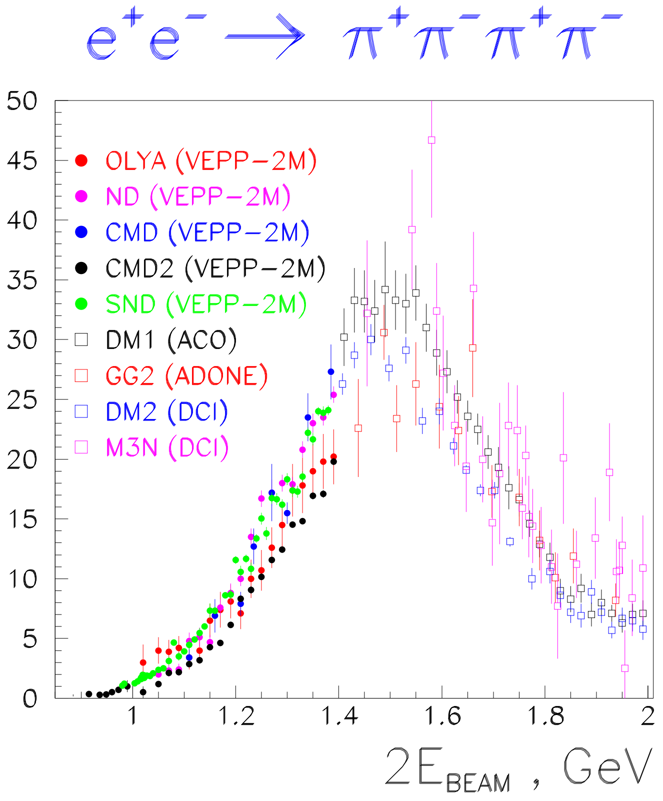
CMD-2	$4.256 \pm 0.019 \pm 0.025$
PDG-2006	4.26 ± 0.05

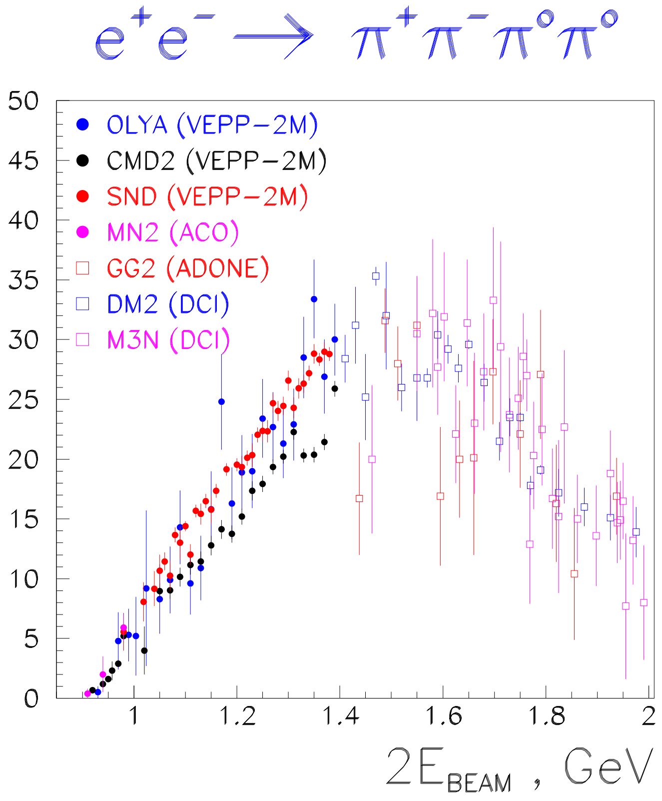
Width, MeV

CMD-2	$2.86 \pm 0.01 \pm 0.05$
PDG-2006	2.97 ± 0.04

$\mathcal{B}(\phi \to e^+e^-), 10^{-4}$

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





Large data scatter above 1.4 GeV!

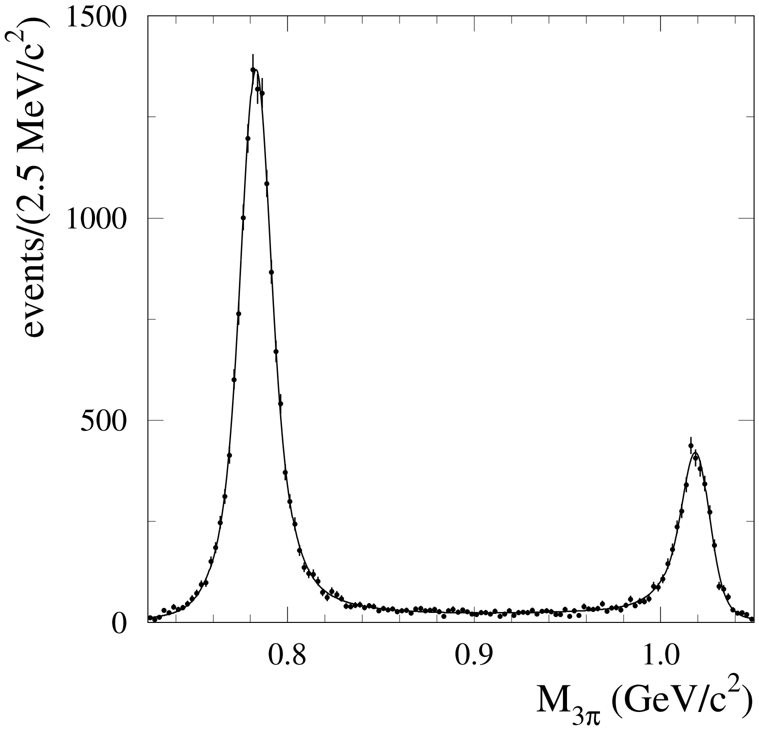
Are there two ρ'?

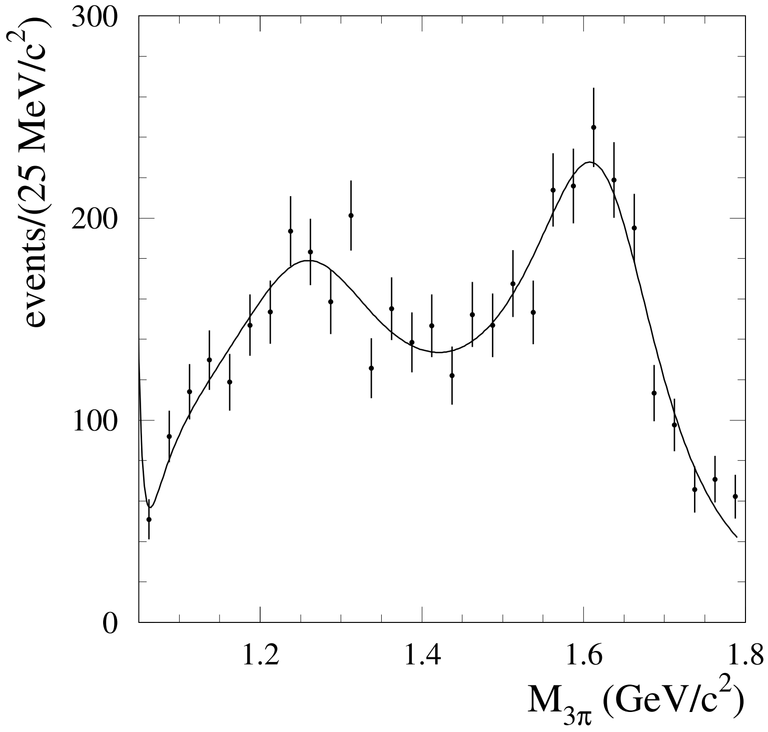
Properties of Higher Vector Mesons

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	–	–

- $\rho' \to \pi^+\pi^-, K\bar{K}, 4\pi, 6\pi,\ \pi^0(\eta,\eta')\gamma$ — Γ_{ee} badly known
- $\omega' \to K\bar{K}, \rho\pi, \omega\pi\pi, \omega\eta,\ \pi^0(\eta,\eta')\gamma$ — 1-2 modes observed
- $\phi' \to K\bar{K}, K\bar{K}\pi, K\bar{K}\pi\pi,\ \pi^0(\eta,\eta')\gamma$ — ISR helping!

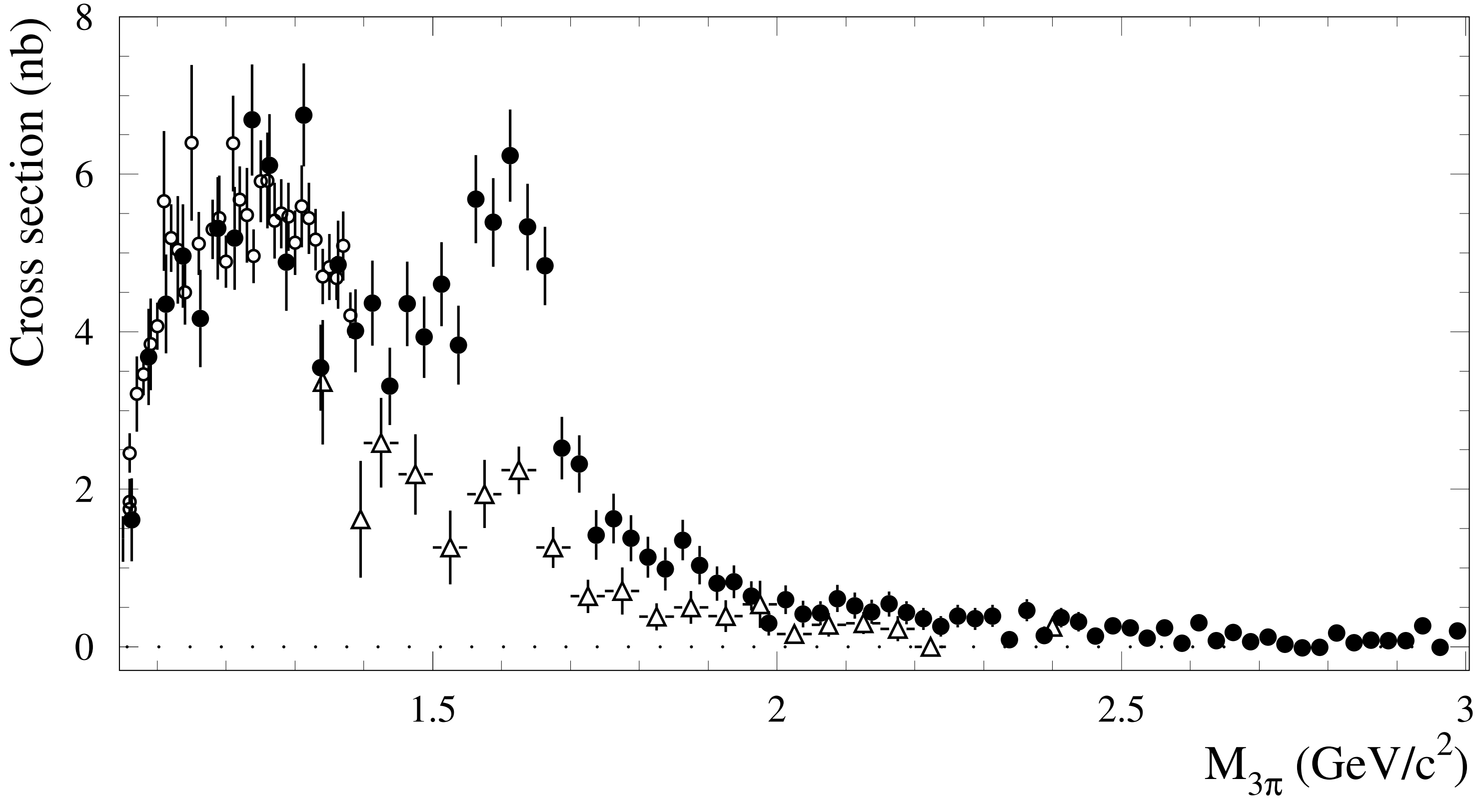
$e^+e^- \to \pi^+\pi^-\pi^0\gamma$ at BaBar





The final $\pi^+\pi^-\pi^0$ state is dominated by $\rho^+\pi^- + \rho^0\pi^0 + \rho^-\pi^+$

Parameters of $\omega(1420)$ and $\omega(1650)$ – I



SND, CMD-2 and BaBar consistent below 1.4 GeV

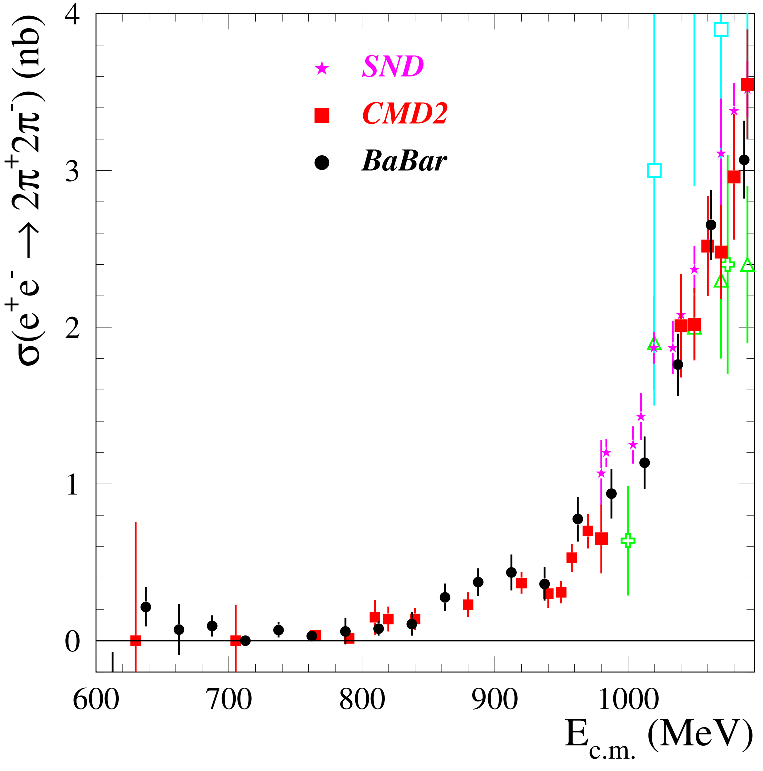
BaBar higher than DM2 above 1.4 GeV

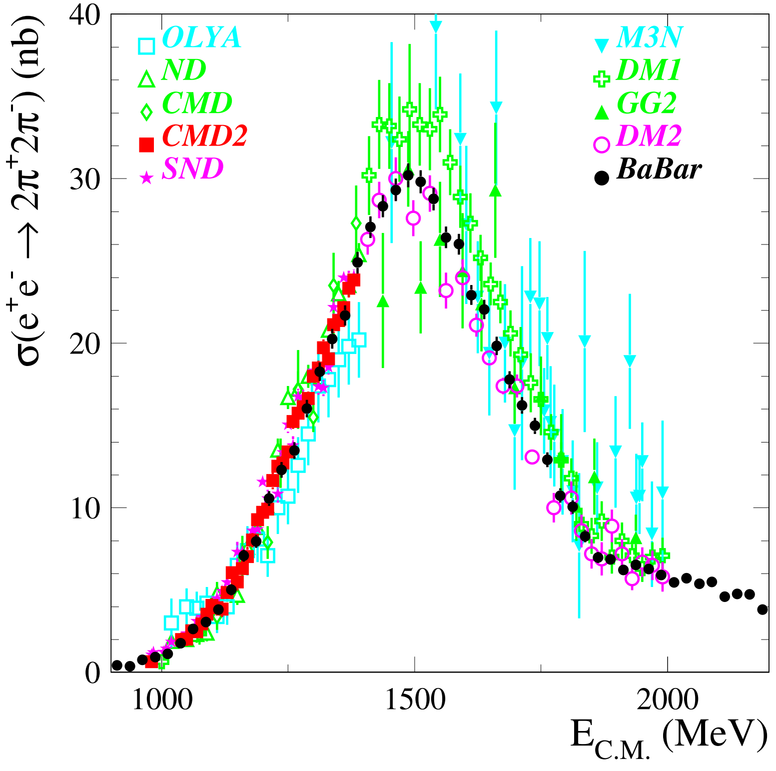
Parameters of $\omega(1420)$ and $\omega(1650)$ – II

State	Mass, MeV	Width, MeV	$\Gamma_{e^+e^-}$, eV
$\omega(782)$	782.65 ± 0.12	8.49 ± 0.08	600 ± 20
$\omega(1420)$	$1350 \pm 20 \pm 20$	$450 \pm 70 \pm 70$	~ 370
$\omega(1650)$	$1660 \pm 10 \pm 2$	$230 \pm 30 \pm 20$	~ 570

The $\Gamma_{e^+e^-}$ pattern in contradiction to the quark model,
S. Godfrey and N. Isgur, 1985

Can We See ρ Excitations in the $2\pi^+2\pi^-$ Mode?

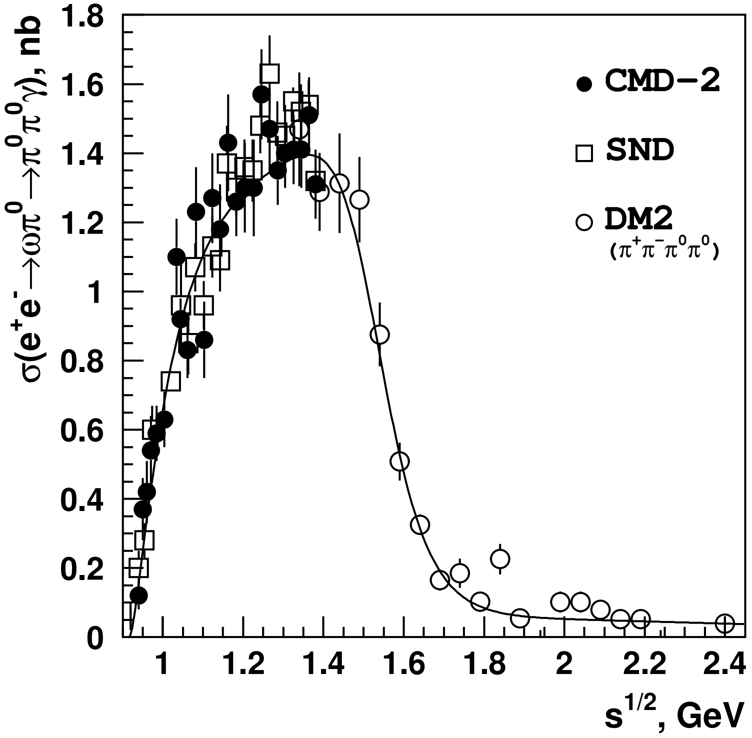


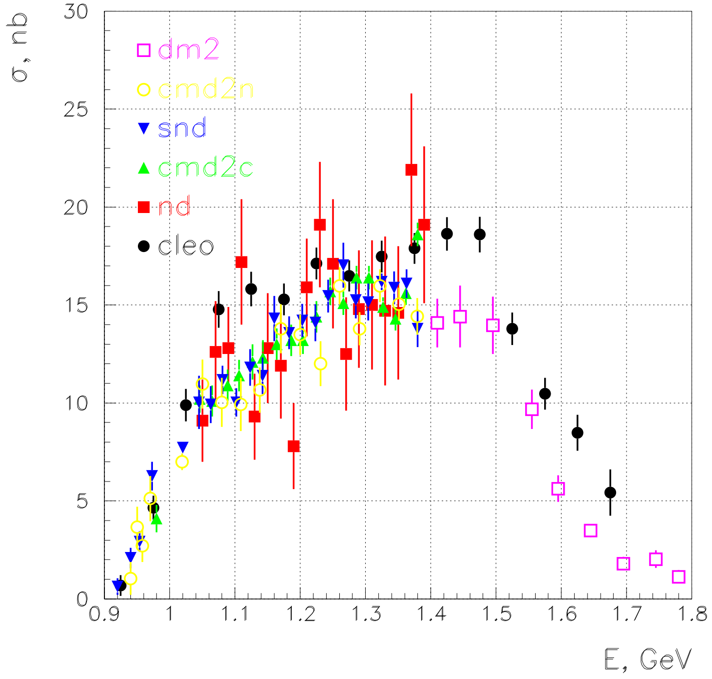


One broad state seen!

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

Can We See ρ Excitations in the $\omega\pi$ Mode?

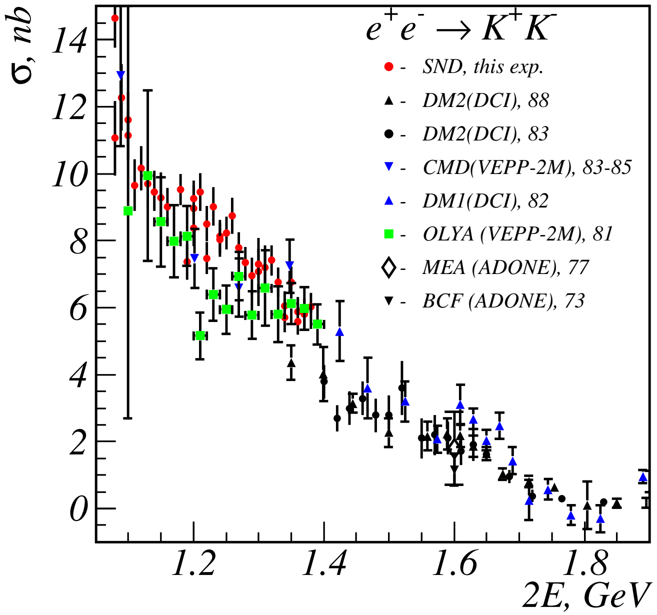


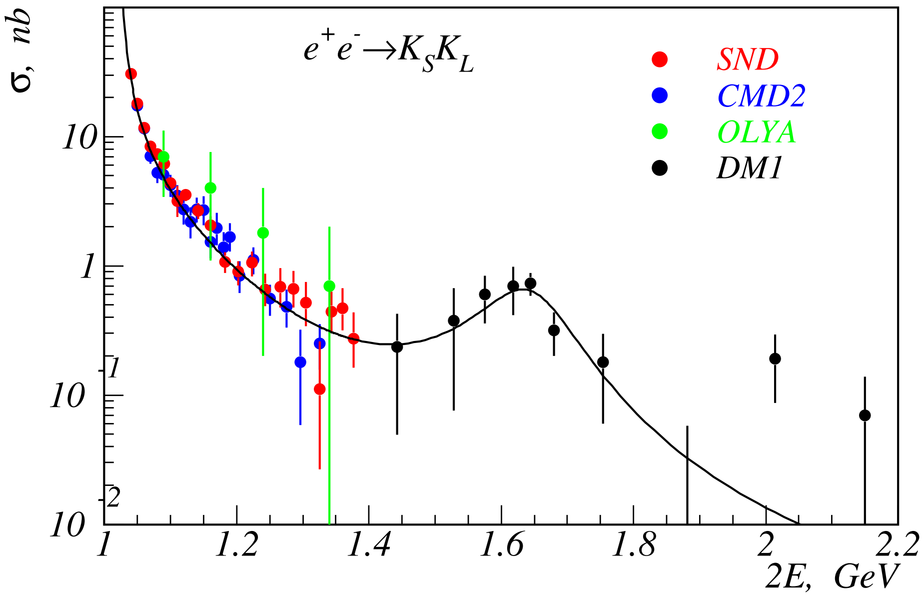


$\rho(1450)$ only needed.

Confirmed by CLEO in τ and B decays.

$e^+e^- \to K^+K^-, \quad K^0_S K^0_L$ at SND

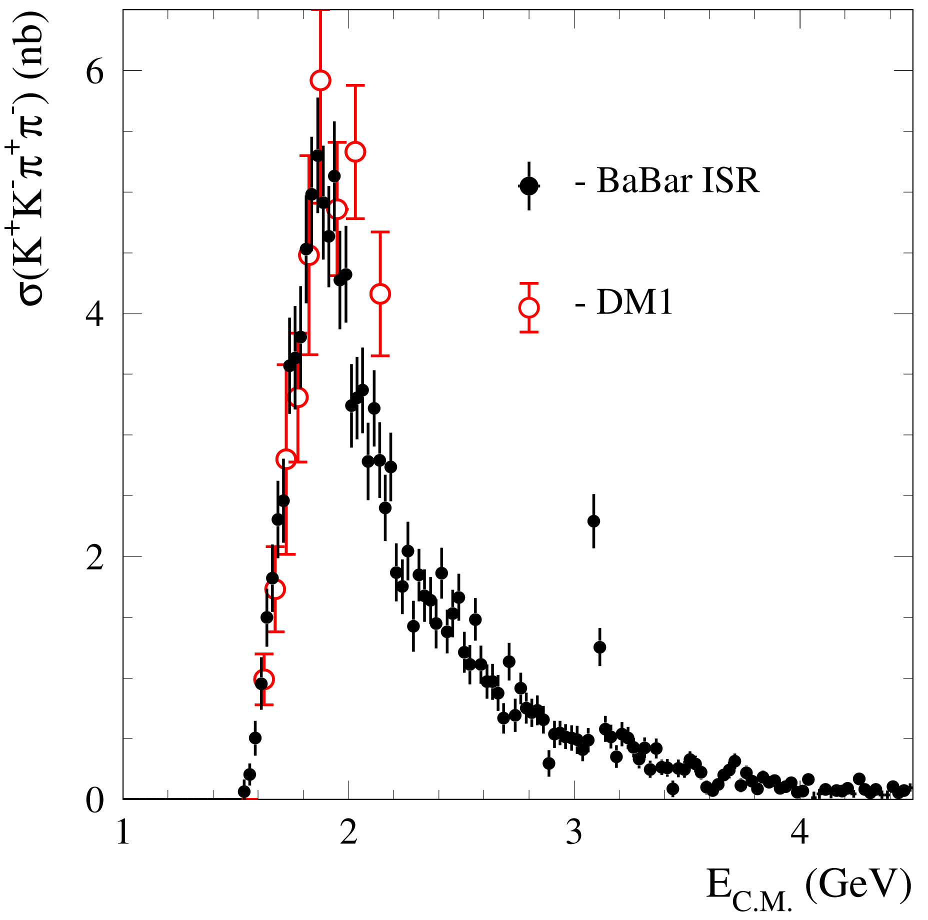




- SND data above OLYA
- No evidence for the ϕ'

- SND data consistent with CMD-2
- Evidence for the ϕ'

$K^+K^-\pi^+\pi^-$ from BaBar



One broad state or threshold?

“Zoo” of Decays and Hybrids

Below 1.1 GeV $\pi^+\pi^-$, K^+K^-, K_SK_L, $\pi^+\pi^-\pi^0$ dominate,
above 1.1 GeV – 4π ($2\pi^+2\pi^-$, $\pi^+\pi^-\pi^0\pi^0$),
5π ($2\pi^+2\pi^-\pi^0$, $\pi^+\pi^-\pi^0\pi^0\pi^0$),
6π ($3\pi^+3\pi^-$, $2\pi^+2\pi^-2\pi^0$, $\pi^+\pi^-4\pi^0$),
$K\bar{K}\pi$ ($K^+K^-\pi^0$, $K^0\bar{K^0}\pi^0$, $K^\pm K^0\pi^\mp$),
$K\bar{K}\pi\pi$ ($K^+K^-\pi^+\pi^-$, $K^+K^-\pi^0\pi^0$, $K^0\bar{K^0}\pi^+\pi^-$, $K^0\bar{K^0}\pi^0\pi^0$, $K^\pm K^0\pi^\mp\pi^0$).

Various intermediate mechanisms are possible:
4π ($\omega\pi$, $a_1^\pm\pi^\mp$, $a_2^\pm\pi^\mp$, $\rho^+\rho^-$, $\ldots$),
6π ($\rho f_0(1370)$, $\rho f_2(1270)$, $\omega 3\pi$, $\eta 3\pi$, $\ldots$),
$K\bar{K}\pi$ ($\rho(\omega,\phi)\pi$, $K^*\bar{K}$)

Theory can't exclude exotic states – hybrids ($q\bar{q}g$) with close masses and peculiar decays ($\omega\pi$, $a_1\pi$, $h_1\pi$)

New $\rho(1900)$?

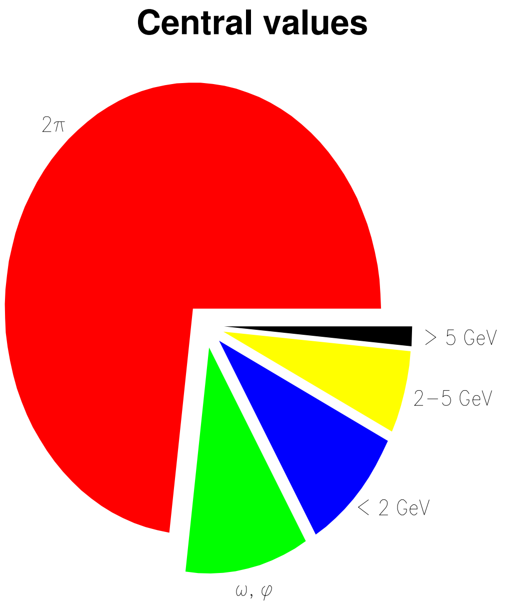
- 2001: E687 (Fermilab) dip at 1.9 GeV in $\gamma N \to 3\pi^+ 3\pi^- N$
- 1996: FENICE (Frascati) dip at $2m_{N\bar{N}}$ in $e^+e^- \to$ hadrons
- 1988: DM2 (Orsay) peculiarity at 1.9 GeV in $e^+e^- \to 6\pi$
- 2002: OBELIX (CERN) not observed in $\bar{n}p \to 3\pi^+ 2\pi^- \pi^0$

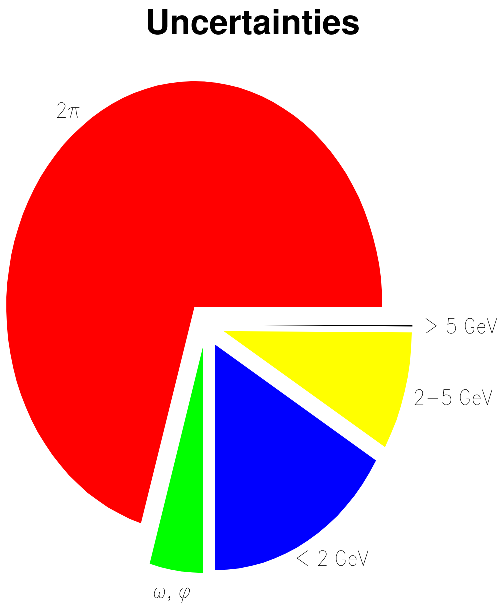
Group	Mass, GeV	Width, GeV
E687	$1911 \pm 4 \pm 1$	$29 \pm 11 \pm 4$
FENICE	1870 ± 10	10 ± 5

Possible interpretation:

- Low width $\Rightarrow$ non $q\bar{q}$
- Small mass for a glueball
- Vector hybrid?
- Bound $N\bar{N}$ state

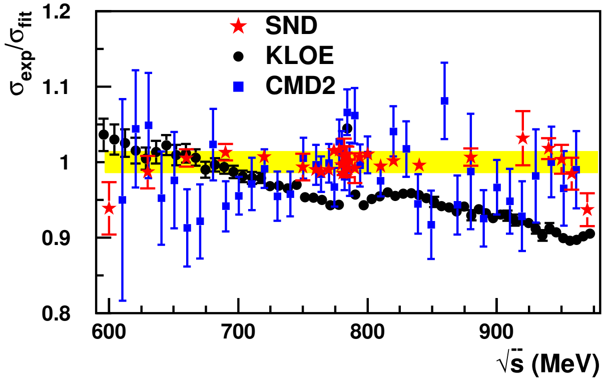
Hadronic Contribution to $a_\mu^{\mathrm{had,LO}}$





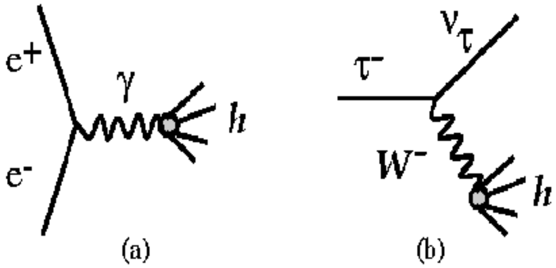
About 73% from 2π, $\sim$ 93% from $\sqrt{s} < 2$ GeV

$a_\mu^{\pi\pi,\mathrm{LO}}$ from 600 to 960 MeV



Group	$a_\mu, 10^{-10}$
CMD-2 (old)	$378.6 \pm 2.7 \pm 2.3$ (3.6)
CMD-2 (new)	$382.3 \pm 1.9 \pm 3.1$ (3.6)
CMD-2	$380.4 \pm 1.6 \pm 2.3$ (2.8)
KLOE	$375.6 \pm 0.8 \pm 4.9$ (5.0)
SND	$385.6 \pm 1.4 \pm 5.0$ (5.2)

CVC. $e^+e^- \to X^0$ and $\tau^- \to \nu_\tau X^-$



Allowed $I^G J^P = 1^+1^-$:
$X^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-, \eta\pi^-\pi^0, K^-K^0, (6\pi)^-, \ldots$

$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ud}|^2 S_{EW}}{32\pi^2 m_\tau^3} f_{kin} v_1(q^2)$ with
$v_1(q^2) = \frac{q^2 \sigma^{I=1}_{e^+e^-}(q^2)}{4\pi\alpha^2}$.

CVC tests showed good agreement of the τ branchings predicted from e^+e^- with τ data (N. Kawamoto and A. Sanda, 1978, F. Gilman and D. Miller, 1978, S. Eidelman and V. Ivanchenko, 1991, 1997).

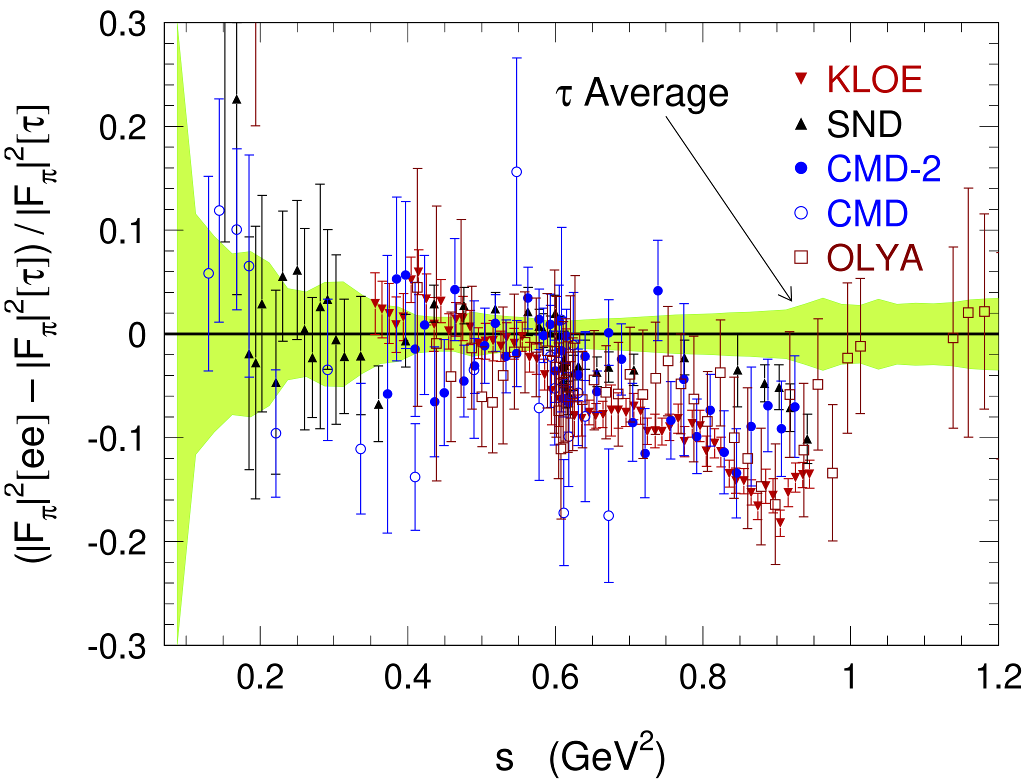
The very first application of τ data to $a_\mu^{\mathrm{had,LO}}$ improved the accuracy by a factor of 1.5 (R. Alemany, M. Davier, A. Höcker, 1998)!

τ Lepton Branchings from CVC

Hadronic State X	Experiment, 2002	CVC Prediction	$\mathcal{B}_{\rm exp} - \mathcal{B}_{\rm CVC}$
$\pi^-\pi^0$	25.31 ± 0.18	24.76 ± 0.25	0.55 ± 0.31
$\pi^-3\pi^0$	1.08 ± 0.10	1.07 ± 0.05	0.01 ± 0.11
$2\pi^-\pi^+\pi^0$	4.19 ± 0.23	3.84 ± 0.17	0.35 ± 0.29
$\omega\pi^-$	1.94 ± 0.07	1.82 ± 0.07	0.12 ± 0.10
$6\pi^-$	0.023 ± 0.004	0.134 ± 0.023	-0.111 ± 0.024
$\eta\pi^-\pi^0$	0.174 ± 0.024	0.13 ± 0.02	0.044 ± 0.030
K^-K^0	0.154 ± 0.016	0.12 ± 0.03	0.034 ± 0.016
Total	31.59 ± 0.31	30.28 ± 0.34	1.31 ± 0.46

With more accurate data some deviations have been observed.

2π Spectral Functions in e^+e^- and τ



The puzzle remains unsolved $\Rightarrow$ τ data not used

Other Problems

1. Study of hadronic states X with $J^{PC} \neq 1^{--}$ in $e^+e^- \to X\pi, XK$: smaller combinatorial BG and pure initial state, e.g., $e^+e^- \to a_1(1260)\pi \to 4\pi$, $e^+e^- \to \pi_1(1600)\pi$
2. Two-photon processes
   - Leptonic width of C-even resonances ($e^+e^- \to \pi^0\pi^0, \eta\pi^0$ via $f_2(1270)$, $a_2(1320), \ldots$, $\sigma \sim 1$ pb)
   - 2γ width of π^0, η, $\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
3. $\pi\pi$ scattering phase from charge asymmetry in $e^+e^- \to \pi^+\pi^-$ (interference with $f_2(1270), \ldots$)
4. Baryon form factors from $e^+e^- \to p\bar{p}, n\bar{n}, \Lambda\bar{\Lambda}$
5. Higher-order QED tests in $e^+e^- \to 4, 5$ leptons

Experimental Requirements

- High detector hermeticity to provide good acceptance
- Good $e^\pm/\mu^\pm/\pi^\pm$ separation for two-body channels
- γ, $\pi^\pm(K^\pm)$, $p(n)$ identification, reconstruction of $\pi^0, \eta, K^0_S, \Lambda$
- $\bar{L}$=10^{31} cm^{-2} s^{-1}, ε =10%
- Broad resonances, $\Gamma \sim$ (150–300) MeV, possible Δ_{2E}=25 MeV
- At 2 GeV $\sigma_{\rm min} \sim 0.2$ nb (K^+K^-, K_SK_L). Its 10% measurement $\Rightarrow$ 5 pb^{-1} per point. Most probable $(4\pi, 6\pi)$ processes have $\sigma \sim 5$ nb, at 5 pb^{-1} per point stat. precision $\sim 2\%$.
- At lower energies dominant channels have larger σ
- At 60 points from 1 to 2.5 GeV about 300 pb^{-1} needed – 1 year of continuous running

Systematic Uncertainties – I

The cross section of the dominant two-body process ($e^+e^- \to \pi^+\pi^-$) can be measured with accuracy better than 1% due to the normalization to the two-body QED process (large angle Bhabha or $e^+e^- \to \mu^+\mu^-$) and excellent particle ID

CMD-2 Source,	Error, %
PID	0.2
Acceptance	0.3
π losses	0.2
Beam energy	0.1
Total exper.	0.5
Rad. corrections	0.4
Total	0.6

KLOE Source,	Error, %
Total exper.	0.9
Total theor.	0.9
Total	1.3

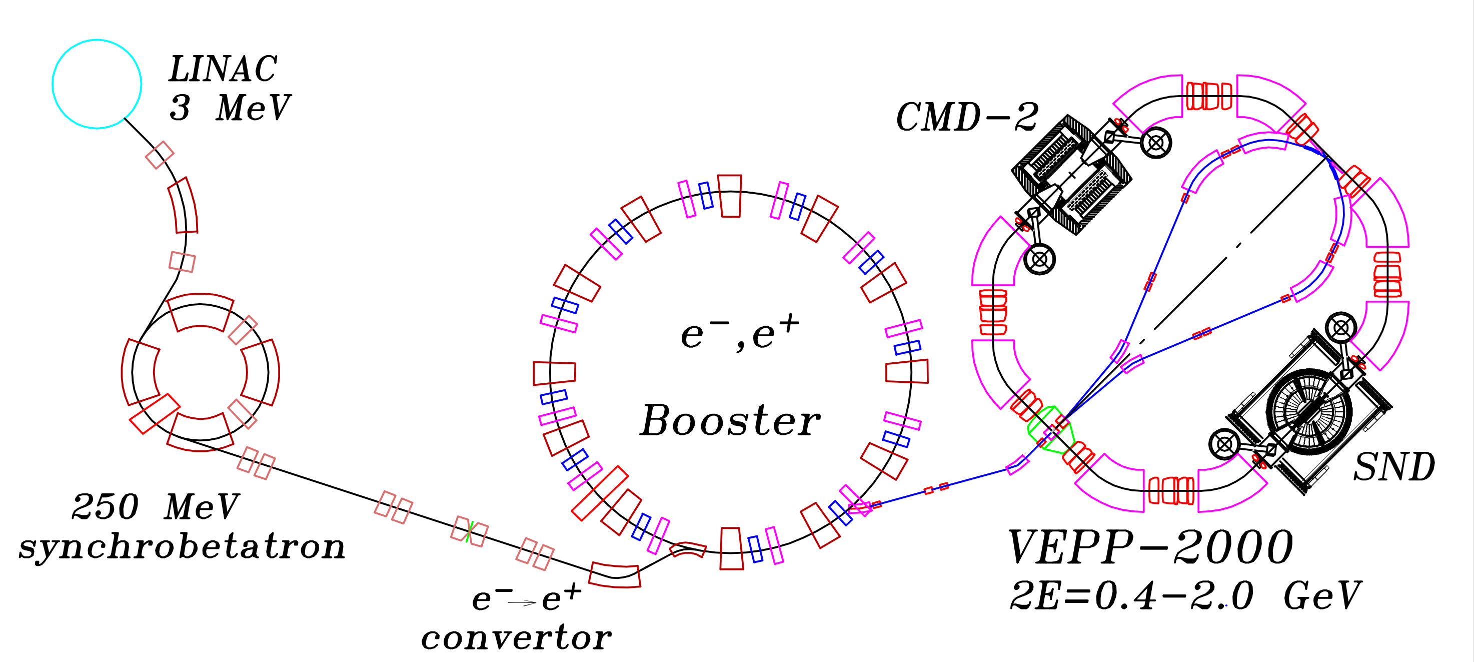
- Are errors realistic?
- Can they be improved?

Systematic Uncertainties – II

1. Luminosity determination with 1% accuracy $\Rightarrow$ MC QED generators, cross-checks with $e^+e^- \to e^+e^-, \mu^+\mu^-, \gamma\gamma$.
2. Radiative effects should be included to the MC generators $\Rightarrow$ a problem for multihadronic final states, FSR
3. Specificity of exclusive measurements:
   - Variety of mechanisms $\Rightarrow$ careful reconstruction
   - Precise and comlicated MC generators taking into account interference of various mechanisms and identical particles, form factors
   - Exclude missing final states
   - Background is small ($e^+e^- \to p\bar{p}(\pi^0)$ an exception?)
4. $\delta\sigma_{\rm syst}/\sigma \sim (2-3)\%$ if there are no correlations

VEPP-2000 in Novosibirsk

Layout of the VEPP−2000 complex



Physics with $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}: exclusive channels, vector excitations, precise R, applications to $(g_\mu - 2)/2$, $\alpha(M_Z^2)$ and CVC tests, two-photon physics, nucleon form factors, tests of higher order QED $(2 \to 4, 5)$, radiative return studies

Possible Progress for $a_\mu^{\rm LO,had}$

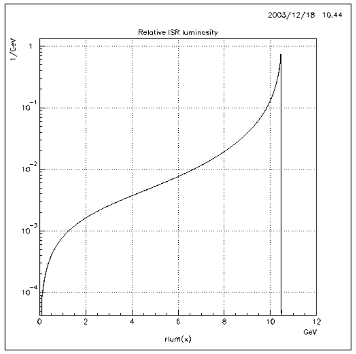
Experiments are planned at the new machine VEPP-2000 (VEPP-2M upgrade) with 2 detectors (CMD-3 and SND) up to $\sqrt{s}$=2 GeV with $L_{\rm max} = 10^{32}$ cm^{-2}s^{-1}.

A similar machine (DAΦNE-II) is discussed in Frascati.

$\sqrt{s}$, GeV	$a_\mu^{\rm LO,had}$ in 2004 (2006), 10^{-10}	2008 (pes./opt.), 10^{-10}
$2\pi, < 2$	508.4 ± 5.5 (3.5)	2.5/1.5
ω	38.0 ± 1.1 (0.8)	0.4/0.3
ϕ	35.7 ± 0.9 (0.4)	0.3/0.2
0.6–2.0	62.9 ± 2.5 (1.3)	1.2/0.7
Total	645.0 ± 6.2 (3.8)	2.8/1.7

The total error of $a_\mu^{\rm had,LO}$ falls from $6.9 \cdot 10^{-10}$ to $4.2(3.5) \cdot 10^{-10}$. Other measurements are welcome (DAΦNE-II, ISR)!

Comparison of Scan and ISR



$$\frac{dl}{Ldm} = \frac{2\alpha m}{\pi s}\left\{\frac{s+m^4}{s(s-m^2)}(\ln\frac{s}{m_e^2}-1)\right\}$$

Comparison to VEPP-2000 project, e^+e^- up to 2 GeV

(under construction at BINP)

	KEKB	VEPP-2000
Luminosity, см$^{-2}$ s^{-1}	10^{34}	10^{32}
Integrated lum. (per 10^7 s)	100 fb^{-1}	1 fb^{-1}
Integrated in the range [1-2] GeV	0.1 fb^{-1}	1 fb^{-1}

15.09.2004 **TAU-04, NARA** 4

Conclusions

- $\sqrt{s} < 2.5$ GeV is a source of interesting information, but strong competition from ISR at B factories requires $\mathcal{L} \sim 10^{32}$; another competitor - VEPP-2000
- Rare decays of the ρ, ω, ϕ with $\mathcal{B} \sim 10^{-6} - 10^{-7}$, precise Γ_{ee}
- Studies of the ρ', ω', ϕ' and search for hybrids
- High precision R $\Rightarrow$ better knowledge of $(g_\mu - 2)/2, \alpha(M_Z^2)$, CVC tests
- Two-photon physics
- Baryon form factors near threshold
- Various phenomena with effects of electroweak and strong interactions