Search for $\eta' \to e^+e^-$ Decay at CMD-3

and Review of $P \to e^+e^-$ Measurements

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Outline

1. General
2. $\eta' \to e^+e^-$ at CMD-3
3. Status of $P \to e^+e^-$
4. Conclusions

General

Why are $P \to l^+l^-$ decays interesting?

1. Comparison to theory, test of various models
   See the talk of P. Masjuan
2. Information on $P\gamma^{(*)}\gamma^{(*)}$ form factors is important
   for the hadronic light-by-light contribution,
   new dispersive approach by G. Colangelo et al., JHEP 09 (2014) 091
   See the talks of M. Hoferichter, B. Kubis and A. Wirzba
3. All previous model calculations predict that
   the largest contribution to $a_\mu^{\rm LBL}$ comes from the $\pi^0,\ \eta,\ \eta'$

Status of $P \to l^+l^-$ Studies

Helicity suppression $\Rightarrow$

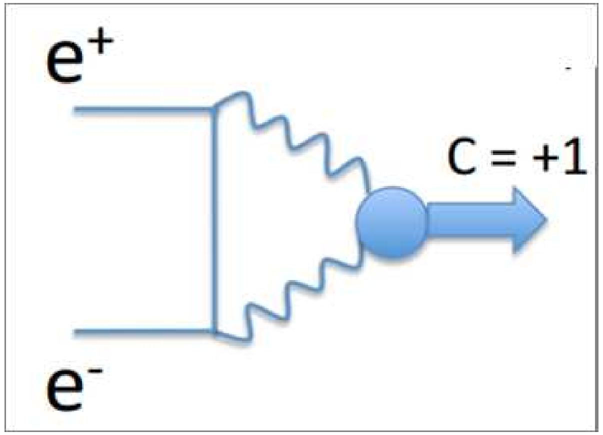
$$\Gamma_{e^+e^-}/\Gamma_{\mu^+\mu^-} \propto M_e^2\Phi_{e^+e^-}/M_\mu^2\Phi_{\mu^+\mu^-} = 2.3 \cdot 10^{-5}\Phi_{e^+e^-}/\Phi_{\mu^+\mu^-}$$

Decay mode	$\mathcal{B}_{\rm exp}$	Events	Group	$\mathcal{B}_{\rm unit.bound}$
$\pi^0 \to e^+e^-$	$(6.46 \pm 0.33) \cdot 10^{-8}$	794	KTEV, 2008	$4.8 \cdot 10^{-8}$
$\eta \to e^+e^-$	$< 5.6 \cdot 10^{-6}$	–	HADES, 2012	$1.8 \cdot 10^{-9}$
$\eta \to \mu^+\mu^-$	$(5.7 \pm 0.9) \cdot 10^{-6}$	114	SATURNEII, 1994	$4.3 \cdot 10^{-6}$
$\eta' \to e^+e^-$	$< 2.1 \cdot 10^{-7}$	–	ND, 1988	$3.75 \cdot 10^{-11}$
$K_L^0 \to e^+e^-$	$(9^{+6}_{-4}) \cdot 10^{-12}$	4	B871, 1998	$3.0 \cdot 10^{-12}$
$K_L^0 \to \mu^+\mu^-$	$(6.84 \pm 0.11) \cdot 10^{-9}$	6210	B871, 2000	$6.8 \cdot 10^{-9}$

Photon virtualities and transition f/f can enhance the unitarity bound $\mathcal{B}$

Search for C-even resonances in e^+e^- – I

Direct production of C-even resonances in e^+e^- collisions is possible via a $\gamma\gamma$ intermediate state.



The unitarity bound assuming 2 real photons is

$$\mathcal{B}_{P\to l^+l^-} = \mathcal{B}_{P\to\gamma\gamma}\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_P}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2, \beta = \sqrt{1-4\left(\frac{m_e}{m_P}\right)^2}.$$

For η' the unitarity bound is $\mathcal{B} = 3.75 \cdot 10^{-11}$

"Standard" mechanism via $e^+e^- \to e^+e^-P$ involves two almost real photons and provides $\Gamma(P\to\gamma\gamma)$ only

Search for C-even resonances in e^+e^- – II

$\eta'(958)$, $f_0(980)$, $a_0(980)$, $f_2(1270)$, $a_2(1320)$ and $f_0(1370)$ mesons were studied with the ND (1988) and SND (2000) detectors at the VEPP-2M collider.

State	Mode	$\Gamma(e^+e^-)_{\rm exp}$, eV	Group	$\Gamma(e^+e^-)_{\rm unit.bound}$, eV
$\eta'(958)$	$\eta\pi^+\pi^-$	< 0.06	ND	$7.5 \cdot 10^{-6}$
$f_0(980)$	$\pi^0\pi^0$	< 8.4	ND	
$a_0(980)$	$\eta\pi^0$	< 1.5	ND	
$f_2(1270)$	$\pi^0\pi^0$	< 0.11	SND	0.03
$a_2(1320)$	$\eta\pi^0$	< 0.56	SND	0.01
$f_0(1370)$	$\pi^0\pi^0$	< 20	ND	

ND, P.V. Vorobyev et al., Sov. J. Nucl. Phys. 48 (1988) 273

SND, M.N. Achasov et al., Phys. Lett. 492 (2000) 8

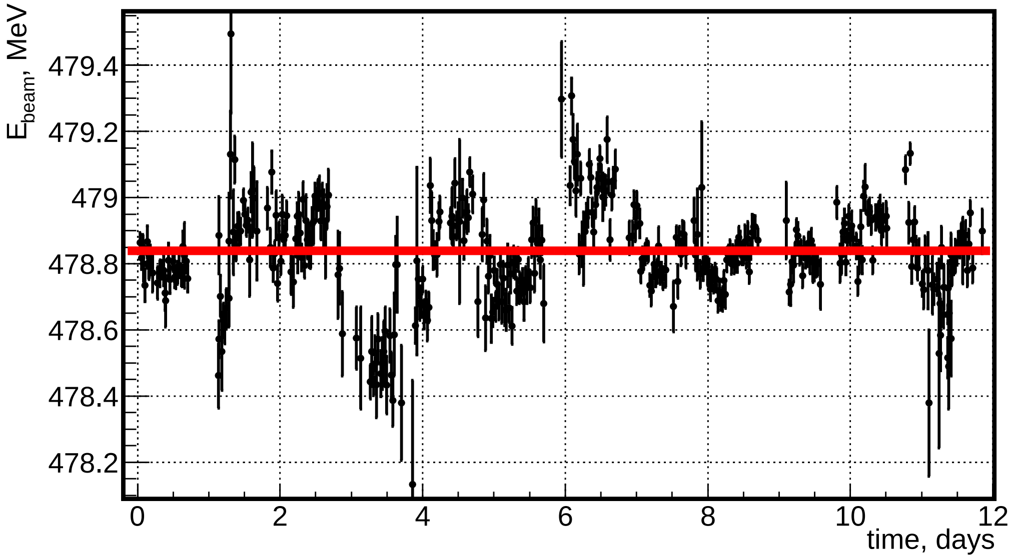
Search for $e^+e^- \to \eta'$ with CMD-3 – I

CMD-3 repeated a search for the process $e^+e^- \to \eta'(958) \to \eta\pi^+\pi^-,\ \eta \to 2\gamma$ using $\int Ldt = 2.69$ pb^{-1} collected with the CMD-3 detector at the VEPP-2000 c.m. energy $E_{\rm c.m.} \approx m_{\eta'} = 957.78 \pm 0.06$ MeV$/c^2$

The total width of the η' is rather small, (198 ± 9) keV,
it is very important to have c.m. energy close to this value.
The collider beam energy was continuously monitored during
the whole period of data taking (12 days) using
the Back-Scattering-Laser-Light system providing the accuracy of $6 \cdot 10^{-5}$

R.R. Akhmetshin et al., arXiv:1409.1664, submitted to Phys. Lett. B

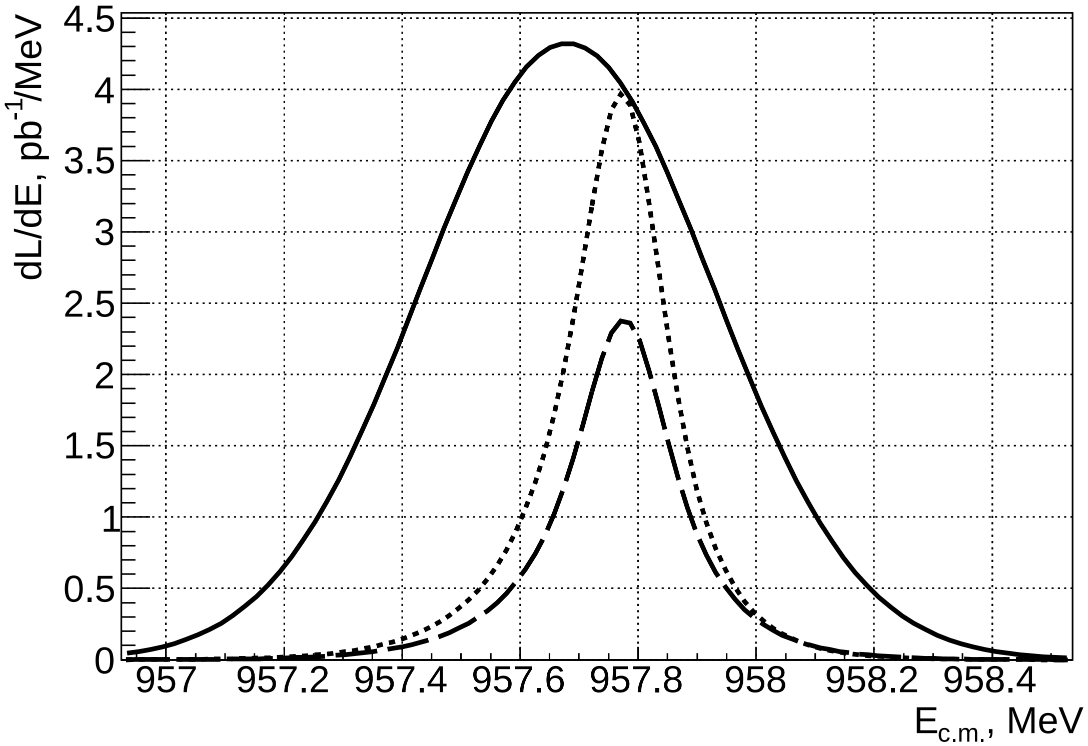
Search for $e^+e^- \to \eta'$ with CMD-3 – II



Measurements of the beam energy show good stability of the collider energy. The average value of the c.m. energy is $E^{av.}_{c.m.} = 957.678 \pm 0.014$ MeV with a few deviations of up to 0.2 MeV, corresponding to less than 5% of the integrated luminosity, which are still within an energy spread of the collider

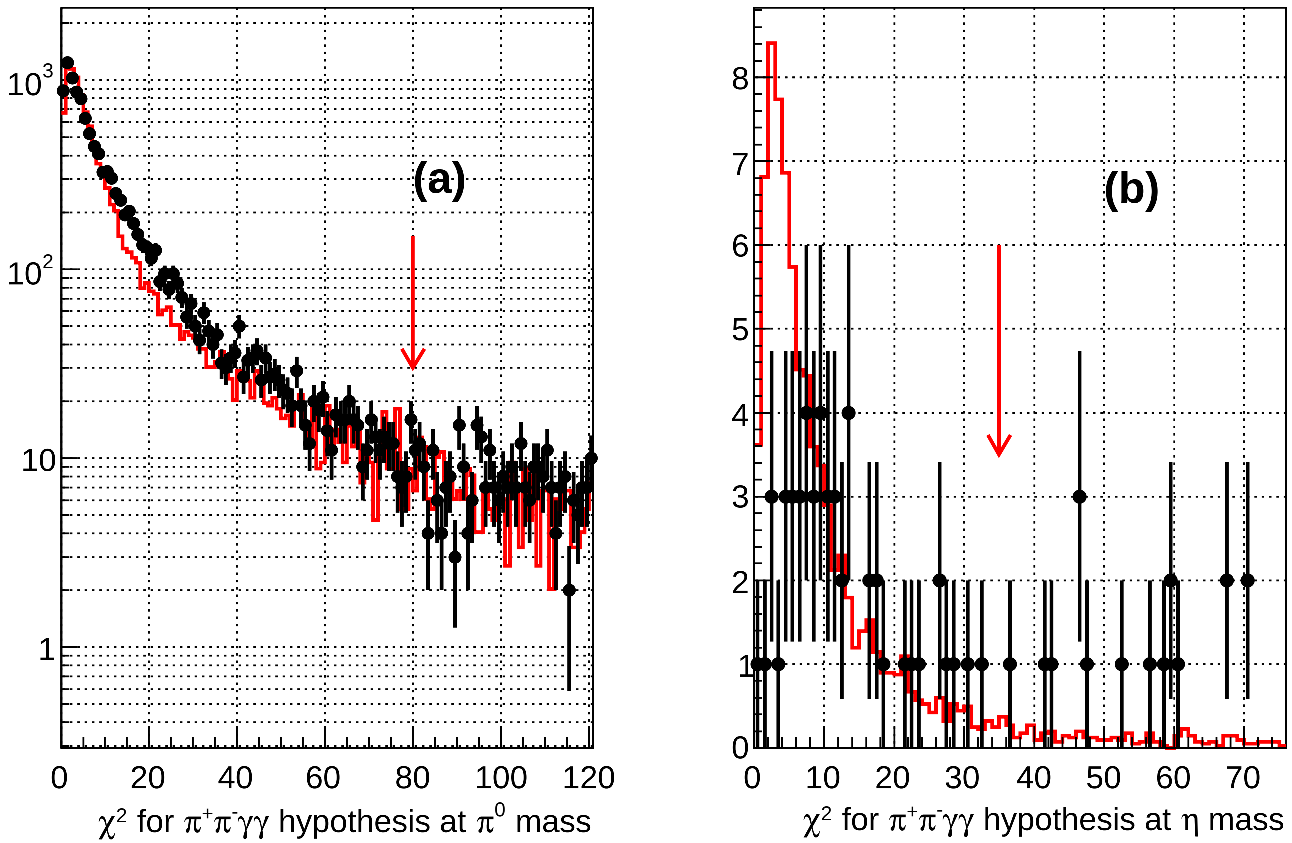
The collider beams have an energy spread mainly due to the quantum effects. For VEPP-2000 the c.m. energy spread $\sigma_{E_{c.m.}} = (0.246 \pm 0.030)$ MeV

Search for $e^+e^- \to \eta'$ with CMD-3 – III

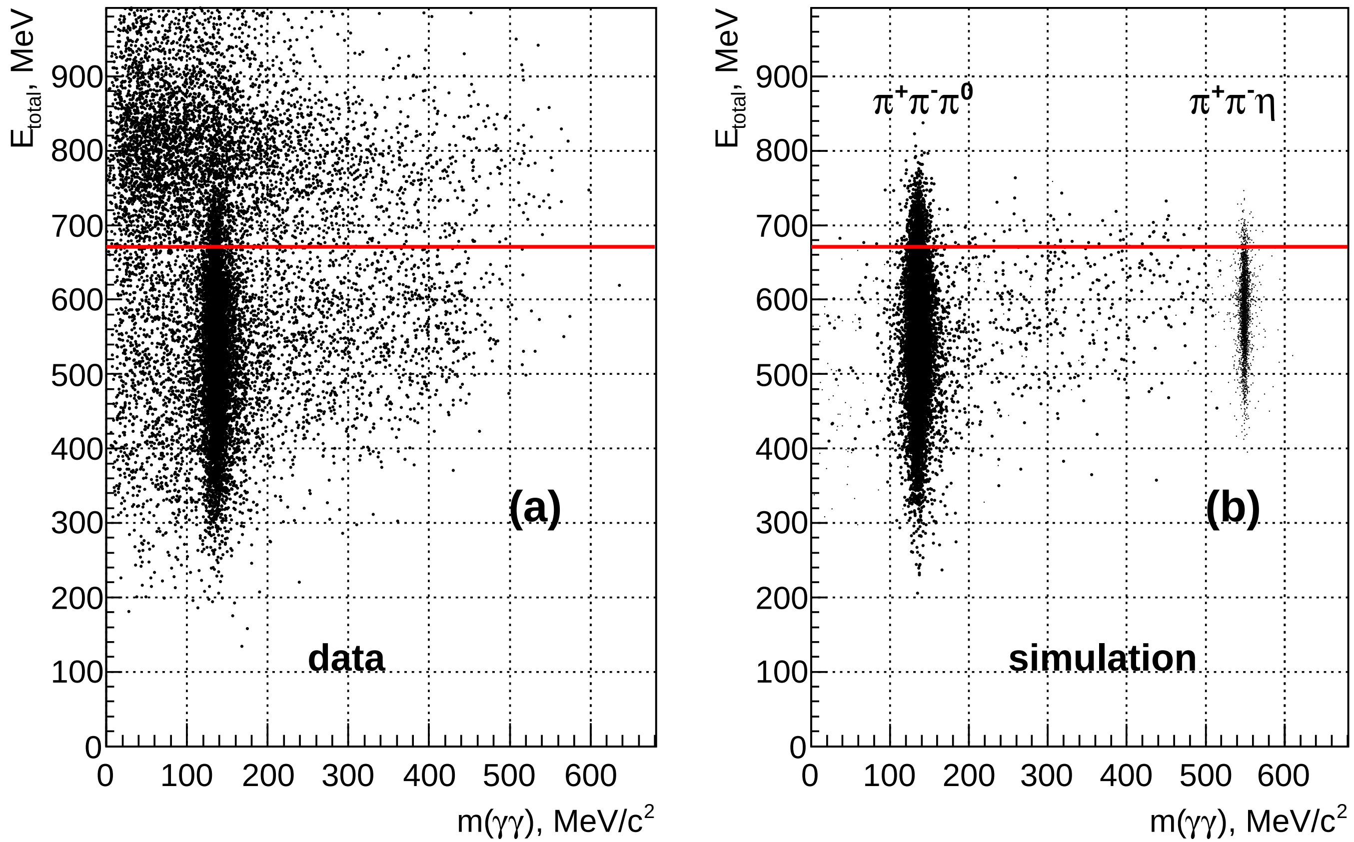


Energy spread (FWHM = 0.590 MeV) is much larger than $\Gamma_{\eta'}$. The differential luminosity distribution dL/dE versus the $E_{\rm c.m.}$ normalized to the $\int Ldt = 2.69\ \mathrm{pb}^{-1}$ should be convolved with a Breit-Wigner (BW) for the η' line shape and a radiator

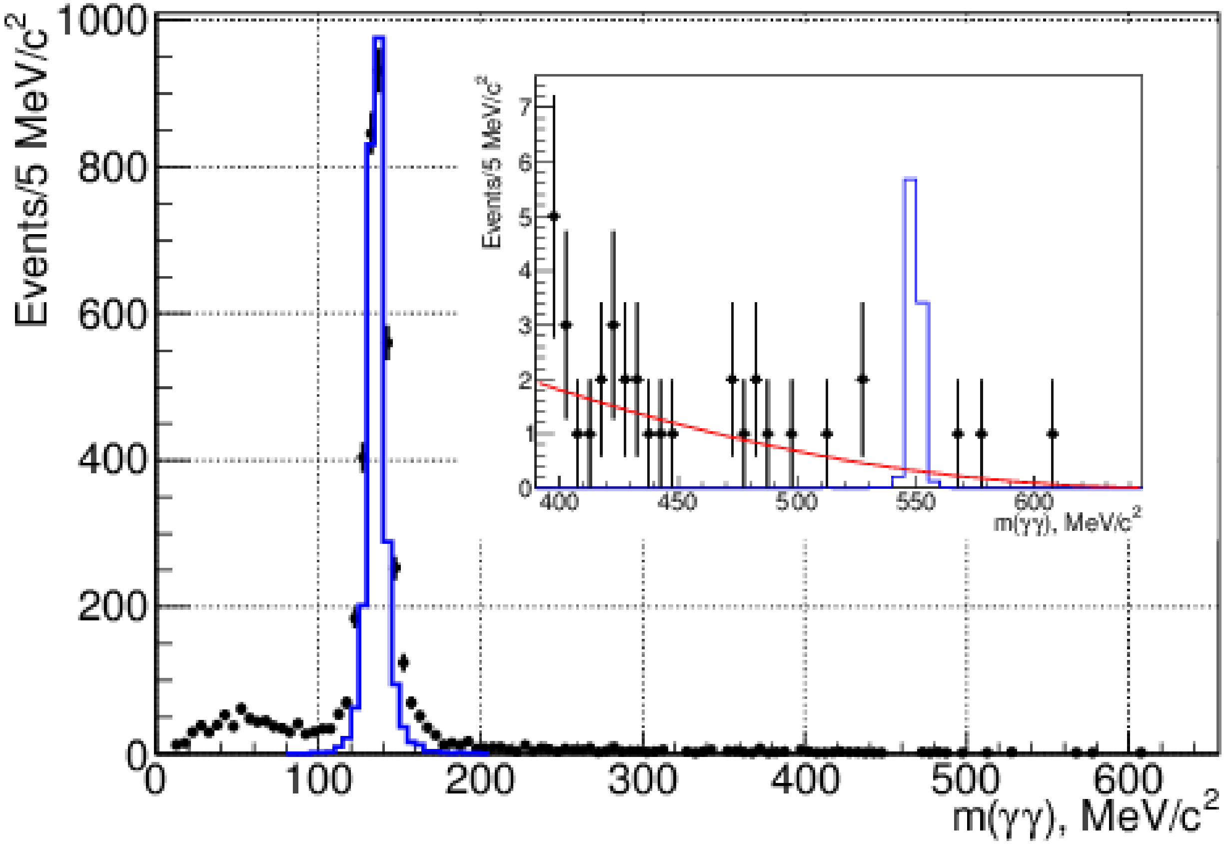
Search for $e^+e^- \to \eta'$ with CMD-3 – IV



Search for $e^+e^- \to \eta'$ with CMD-3 – V



Search for $e^+e^- \to \eta'$ with CMD-3 – VI



Search for $e^+e^- \to \eta'$ with CMD-3 – VII

From the absence of the signal

$$\Gamma_{\eta' \to e^+e^-} \mathcal{B}_{\eta' \to \pi\pi\eta} \mathcal{B}_{\eta \to \gamma\gamma} < 0.00041 \text{ eV at } 90\% \text{ C.L.}.$$

and with $\mathcal{B}_{\eta' \to \pi\pi\eta}$ and $\mathcal{B}_{\eta \to \gamma\gamma}$ from PDG:

$$\Gamma_{\eta' \to e^+e^-} < 0.0024 \text{ eV}$$

Group	ND, 1988	CMD-3, 2014
$\Gamma_{\eta' \to e^+e^-}$, eV	< 0.06	< 0.0024
$\Gamma_{\eta'}$, keV	~ 300	198 ± 9
$\mathcal{B}_{\eta' \to e^+e^-}, 10^{-8}$	< 21	< 1.2

Much more stringent than that of ND, but
still 300 times higher than the unitarity bound

Search for $e^+e^- \to \eta'$ with CMD-3 – VIII

Can we reach the unitarity bound?

Possible (realistic) improvements include:

- Higher luminosity ($4 \cdot 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$) – 4
- More decay channels of η' and η – 2
- Longer data taking period (2 weeks) – 12
- The total gain ~ 100

Less realistic, but not completely excluded, is an option of a new collider in one of the existing BINP tunnels with much higher luminosity making observation possible

Search for $e^+e^- \to \eta'$ with CMD-3 – IX

A chance for the Super-tau-charm factory in Novosibirsk to get funding ($\sim 200 \cdot 10^6$ Euro) looks currently unlikely, the alternative suggestions based on crab waist include:

A machine in the VEPP-4 tunnel (360 m circumference):

$E_{\rm beam}$, GeV	0.5	1.0	1.5	2.1
L, $10^{35}{\rm cm}^{-1}{\rm s}^{-1}$	0.92	0.92	1.3	1.3

A less ambitious project considers a machine in the VEPP-3 tunnel (80 m circumference):

$E_{\rm beam}$, GeV	0.5	0.75	1.0	1.2	1.55
L, $10^{34}{\rm cm}^{-1}{\rm s}^{-1}$	0.954	1.49	1.81	1.86	1.60

This increases the number of the ϕ by 2-3 and J/ψ by 1-2 orders

Revised Status of $P \to l^+l^-$ Decay Searches

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$\eta' \to e^+e^-$	$< 1.2 \cdot 10^{-8}$	–	CMD-3, 2014	$3.75 \cdot 10^{-11}$
$K_L^0 \to e^+e^-$	$(9^{+6}_{-4}) \cdot 10^{-12}$	4	B871, 1998	$3.0 \cdot 10^{-12}$
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HADES improved the upper limit for $\mathcal{B}(\eta \to e^+e^-)$ by a factor of 6

CMD-3 improved the upper limit for $\mathcal{B}(\eta' \to e^+e^-)$ by a factor of 18

Future Possibilities – I

- ϕ meson decays at KLOE-2,
  ω mesons are more readily produced at COSY, JLAB etc.
- J/ψ and $\psi(2S)$ meson decays at BES-III,
  but $\psi(2S)$ are not promising
- π^0 mesons from $K^\pm \to \pi^\pm \pi^0$ decays, NA48/2 collected $2 \cdot 10^{11}$ $K^\pm$ decays corresponding to 10^{10} completely reconstructed π^0's,
  NA62 will have 50 times more, but downscaled (E. Goudzovski),
  a few thousands expected (KTEV ~ 800 from $K_L^0 \to 3\pi^0$ decays)
- Promising numbers of π^0, η, η' can come from
  hadronic collisions (Crystal Ball at MAMI, Crystal Barrel at ELSA,
  GLUEX and CLAS at JLAB)

Future Possibilities – II

Decay	ϕ	J/ψ	$\psi(2S)$
$\pi^0\gamma$	$1.3 \cdot 10^{-3}$ (10^7)	$3.5 \cdot 10^{-5}$ $(3.5 \cdot 10^5)$	$1.6 \cdot 10^{-6}$
$\eta\gamma$	$1.3 \cdot 10^{-2}$ (10^8)	$1.1 \cdot 10^{-3}$ (10^7)	$1.4 \cdot 10^{-6}$
$\eta'\gamma$	$6.2 \cdot 10^{-5}$ $(6 \cdot 10^5)$	$5.2 \cdot 10^{-3}(5 \cdot 10^7)$	$1.2 \cdot 10^{-4}$

It is clear that $\psi(2S)$ mesons can't compete with the J/ψ

The numbers in () correspond to the numbers of PS mesons produced in radiative decays. We assume 10^{10} of both ϕ and J/ψ available (about 5 fb^{-1} at KLOE-2 and $\times 7$ at BESIII)

Conclusions

- $\mu^+\mu^-$ decays of the η and η' have been observed with $\mathcal{B}$ consistent with the unitarity bound
- The most precise measurement for $\pi^0 \to e^+e^-$ has $\mathcal{B}$ significantly higher than the unitarity bound
- Most probable improvement for $\pi^0 \to e^+e^-$ can come from NA62
- ϕ factories with luminosity 2-3 orders higher than today will allow observation of all $P \to l^+l^-$ decays
- Searches for $e^+e^- \to R$ seem feasible for scalars and tensors
- Many thanks again to A. Kupść for encouragement and support!