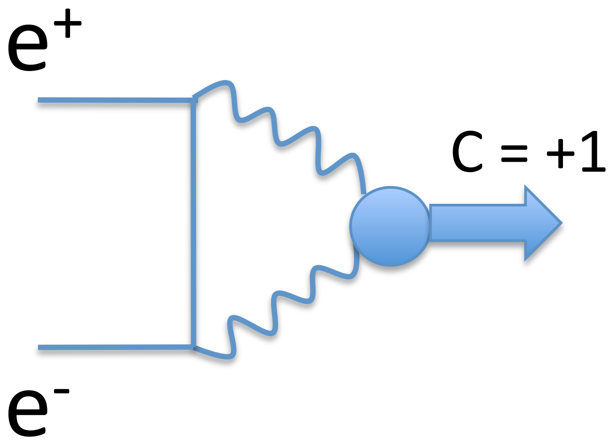
Search for e^+e^- -> η(958) reaction (at VEPP-2000)

E. Solodov

CMD-3 Collaboration

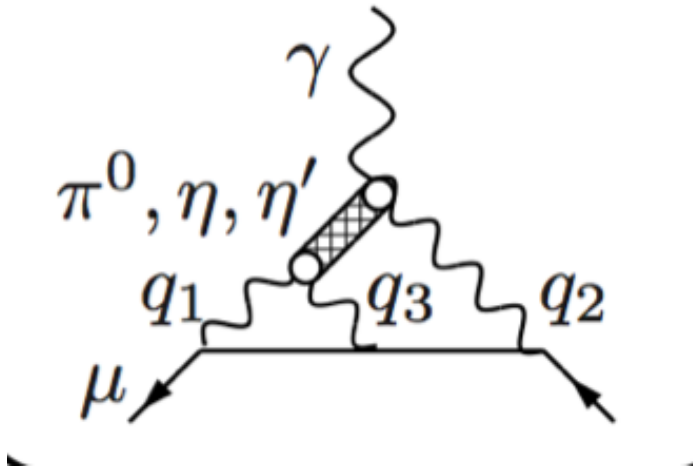
Why



C-even states can be produced in e^+e^- collision via two-photon reaction.

(π^0, $\eta(547)$, $\eta(958)$, $f_0(980)$, $a_0(980)$, $f_2(1270)$, $f_0(1500)$…)

Observation of these reactions could help to calculate light-by-light contribution to g-2 of muon.



Theory (η’)

In unitarity limit, when two photons are real, the electronic width of C-even state is in α^2 lower, than two-photon width, but for pseudo-scalars there is additional helicity suppression:

$$Br(\eta' \to e^+e^-) = Br(\eta' \to \gamma\gamma)\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_{\eta'}}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2,$$

$$\beta = \sqrt{1-4\left(\frac{m_e}{m_{\eta'}}\right)^2}$$

$Br(\eta' \to \gamma\gamma) = 0.0218 \pm 0.0008$

Unitarity limit $B_{unit}(\eta' \to e^+e^-) = 3.75 \times 10^{-11}$

For $\Gamma_{\eta'} = 0.199 \pm 0.009$ MeV, $\Gamma_{unit}(\eta' \to e^+e^-) = 7.5 \times 10^{-6}$ eV

Photons virtuality and form factor can significantly (3-5-10?) increase this number

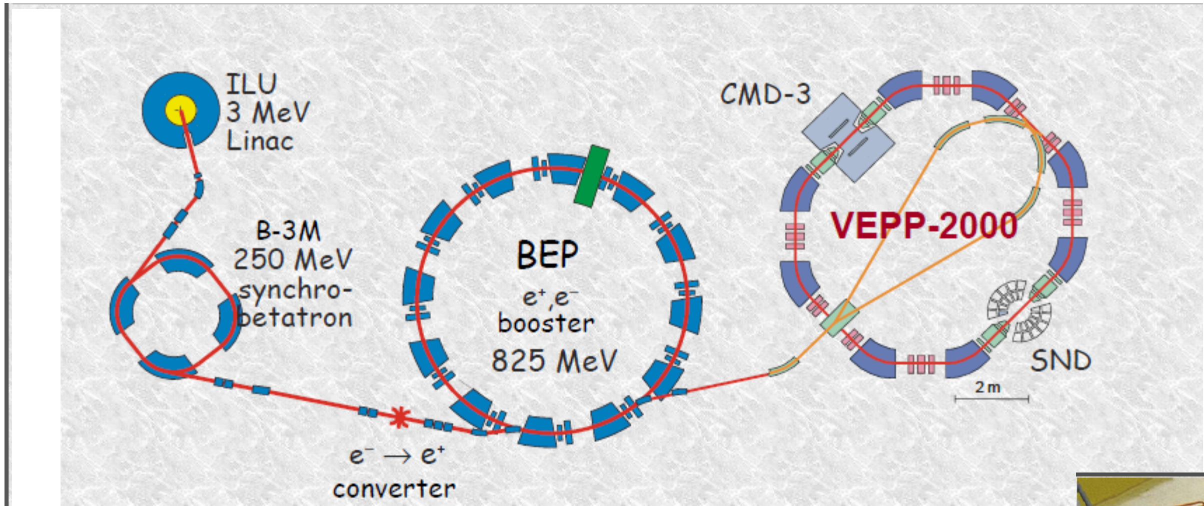
Previous measurements

Only data from ND at VEPP-2M (1985) are available.
No candidate events were found and upper limits:

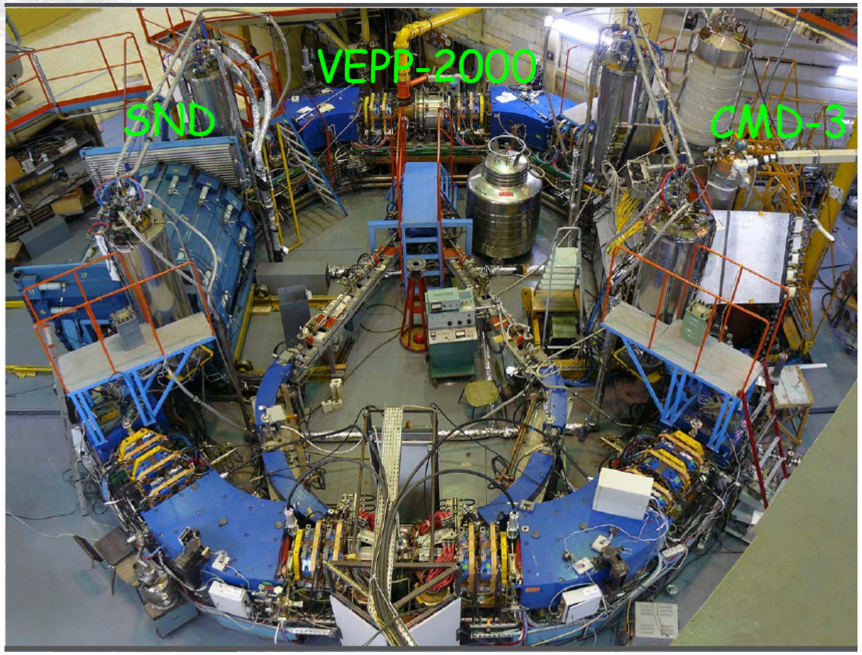
$\Gamma(\eta'(958) \to e^+e^-) < 0.06$ eV
$\Gamma(f_0(980) \to e^+e^-) < 8.4$ eV
$\Gamma(a_0(980) \to e^+e^-) < 1.5$ eV
$\Gamma(f_2(1270) \to e^+e^-) < 1.7$ eV (updated by SND to <0.11 eV)
$\Gamma(f_0(1300) \to e^+e^-) < 20$ eV
$\Gamma(a_2(1320) \to e^+e^-) < 25$ eV (updated by SND to < 0.56 eV)

ND (1985) ~1% efficiency, ~0.7 pb^{-1} luminocity.

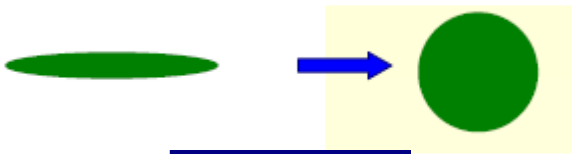
VEPP-2000 Collider (2010-2013)

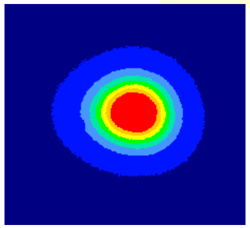


	VEPP-2M	VEPP-2000	
E (MeV)	510	510	900
Π (cm)	1788	2235	2235
$\mathcal{I}^+, \mathcal{I}^-$ (mA)	40	34	200
$\varepsilon \cdot 10^5$ (cm · rad)	3	0.5	1.6
β_x (cm)	40	6.3	6.3
β_z (cm)	5	6.3	6.3
ξ_x	0.016	0.075	0.075
ξ_z	0.050	0.075	0.075
$\mathcal{L}(\text{cm}^{-2}\text{s}^{-1})$	$3 \cdot 10^{30}$	$1 \cdot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



Main idea: Round Beams

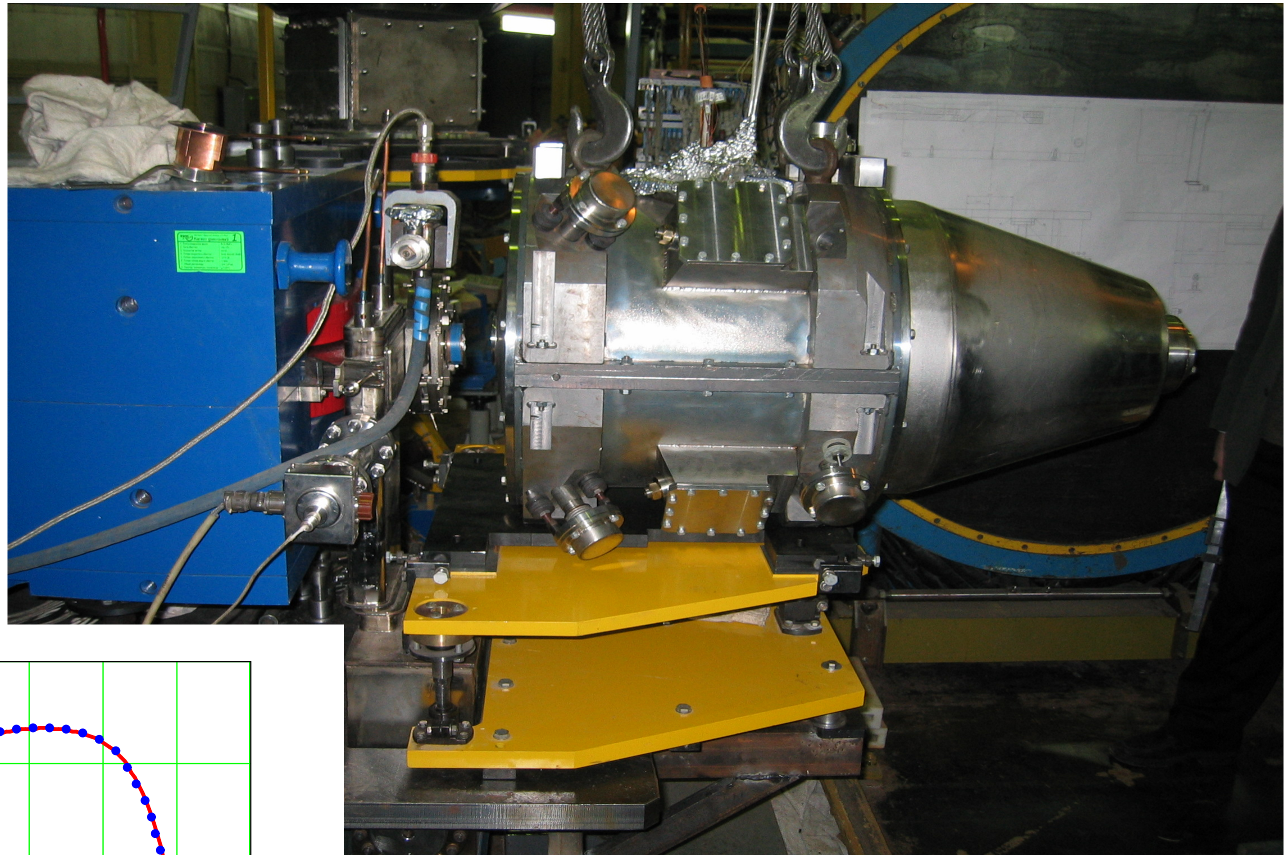


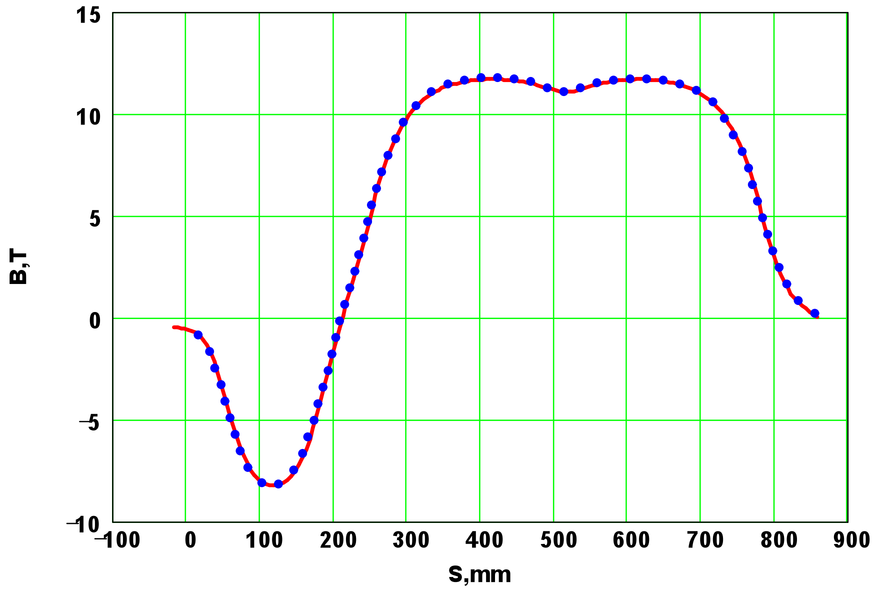


$$L = \frac{\pi \gamma^2 \xi_x \xi_y \varepsilon_x f}{r_e^2 \beta_y^*}\left(1 + \frac{\sigma_y}{\sigma_x}\right)^2 \Longrightarrow L = \frac{4\pi\gamma^2 \xi^2 \varepsilon f}{r_e^2 \beta^*} \quad \text{(x4)}$$

reduce beam-beam effects $\xi_{x,y} \geq 0.1$ (x4)

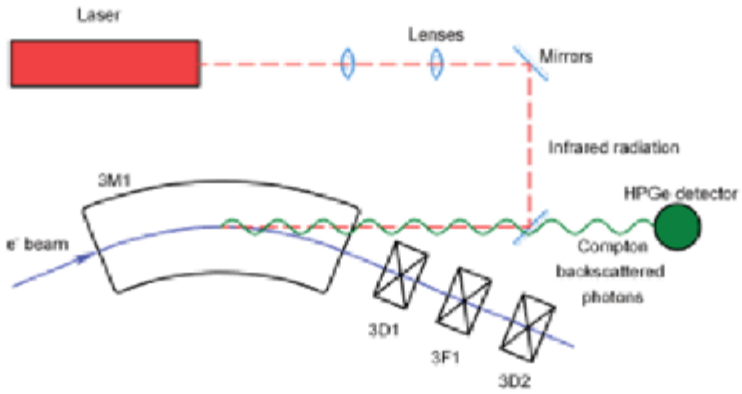
Solenoid 13.0 T at VEPP-2000

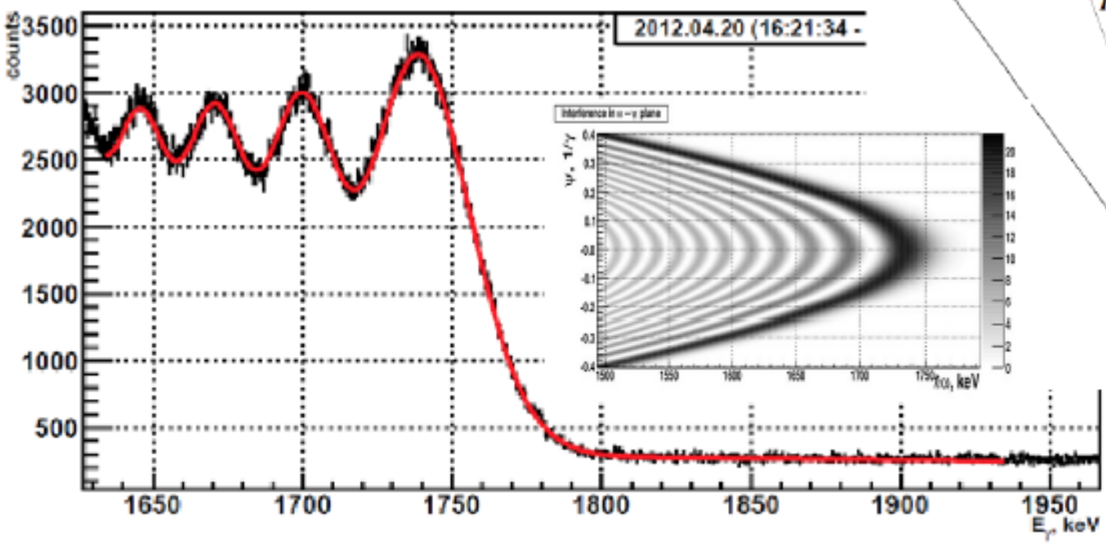


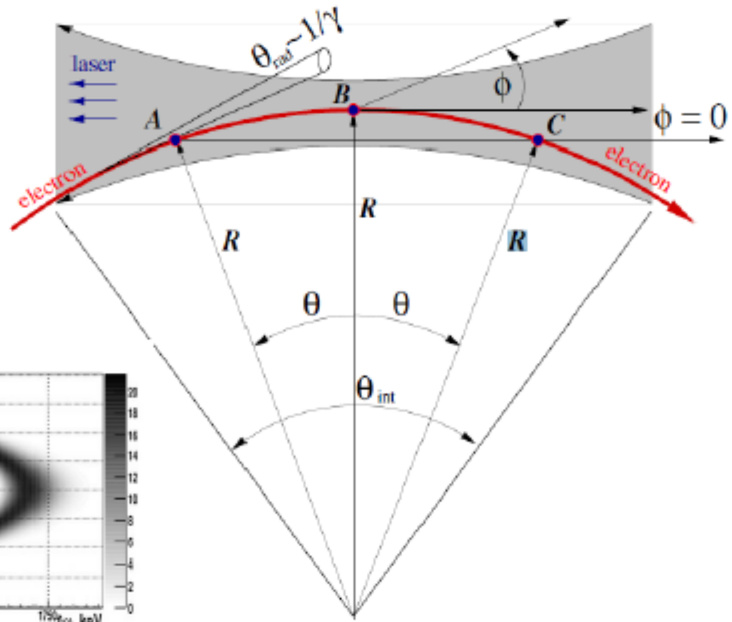


Compton backscattering beam energy measurement

$\lambda_0 = 5.426468 \pm 0.000005$ µm



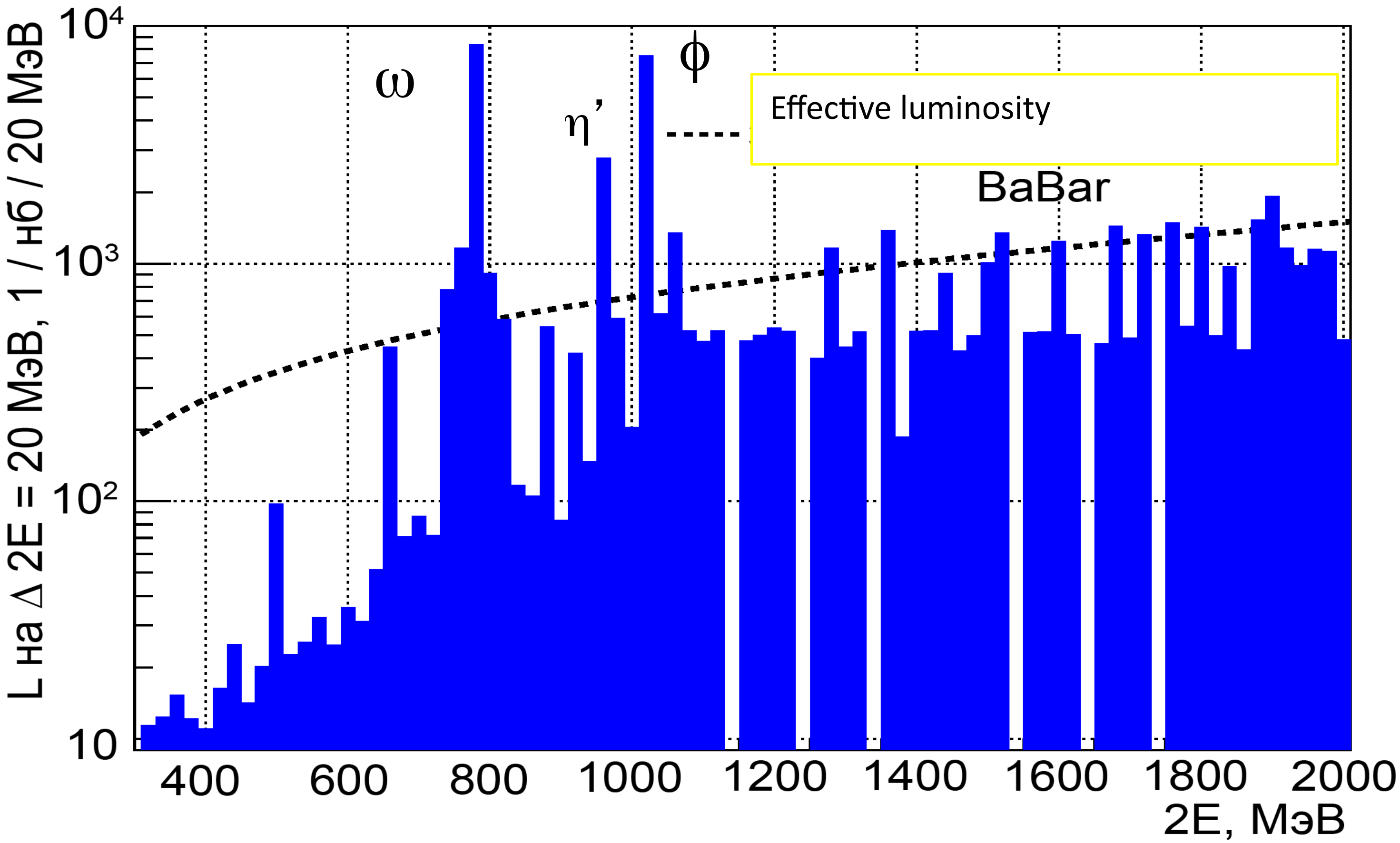




E = 993.662 ± 0.016 МэВ

E.V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

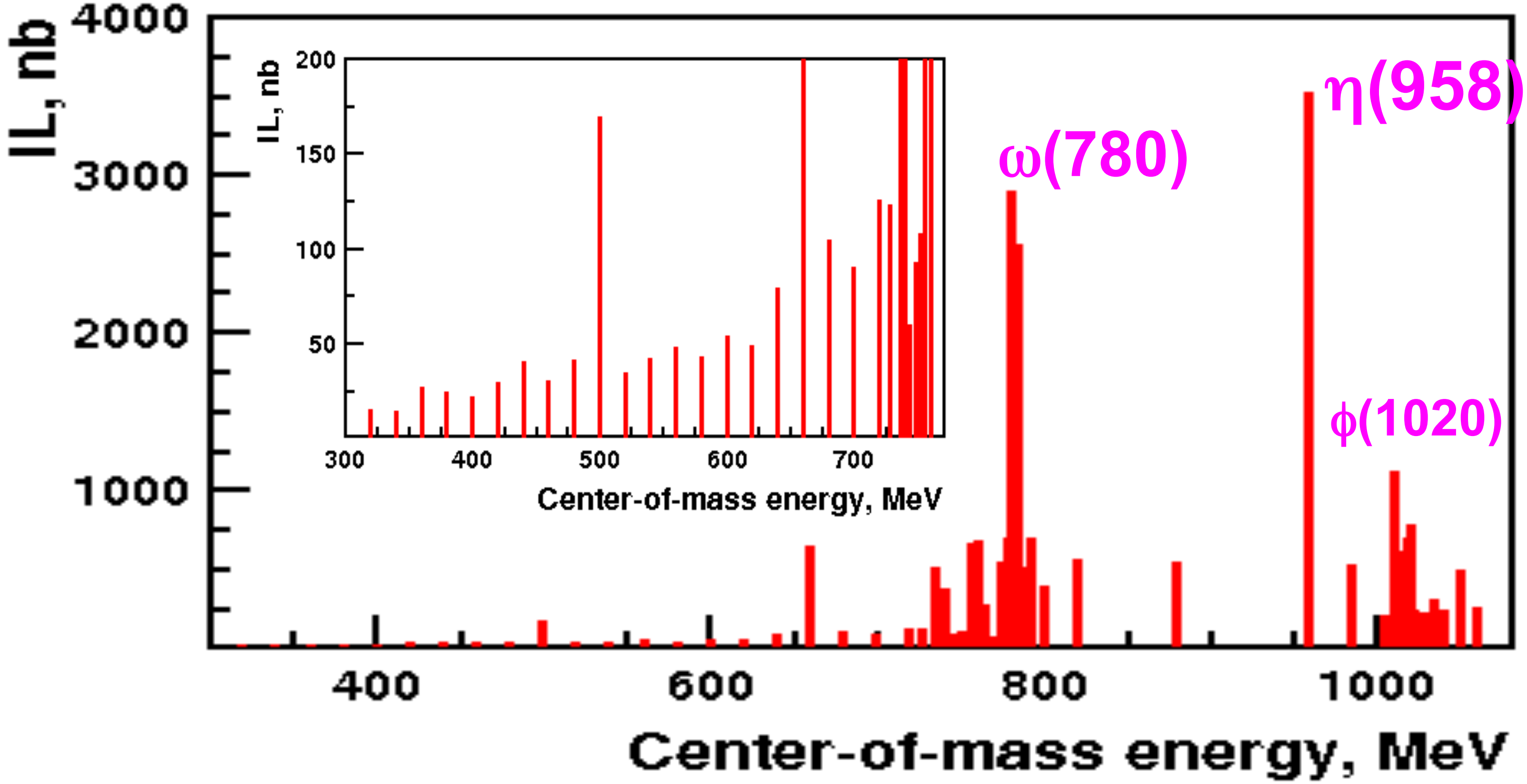
VEPP-2000 experiment (2010-2013)



Energy distribution of collected integrated luminosity of CMD-3

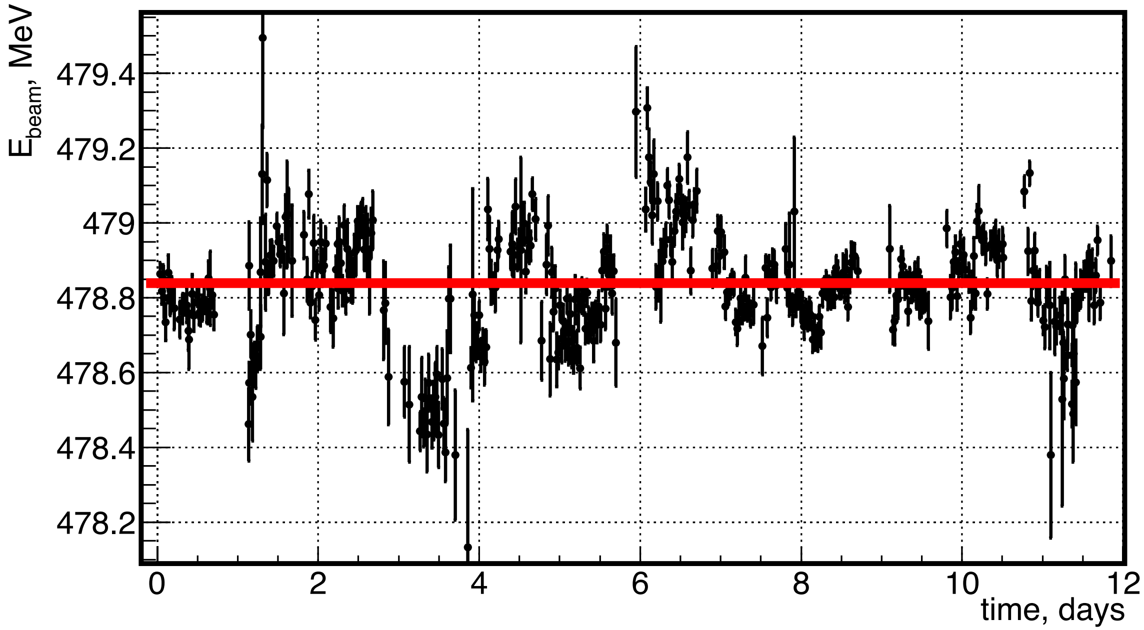
L = 2.69 pb^{-1} used for this analysis

VEPP-2000 experiment (2013)



Energy distribution of collected integrated luminosity

Beam energy control



Beam energy was continuously monitored with Laser-Back-Scattering System.

Ec.m. = 957.678 ± 0.014 MeV, to be compared with m(η’) = 957.78 ± 0.06 MeV
Deviations are at the level of beam energy spread.

$E_{c.m.}$ energy spread

For VEPP-2000 collision energy spread is related to longitudinal collision points distribution σ_Z and RF voltages on the cavity V_{cav} as

$$\sigma_{E_{c.m.}} = 4.05\sigma_Z \sqrt{V_{cav} E_{c.m.} \sin(a\cos(63.2 E^4_{c.m.} / V_{cav}))} = 0.246 \pm 0.030 MeV$$

For this experiment σ_Z = 2.3 cm (using BhaBha events) and V_c = 15 kV (monitored).

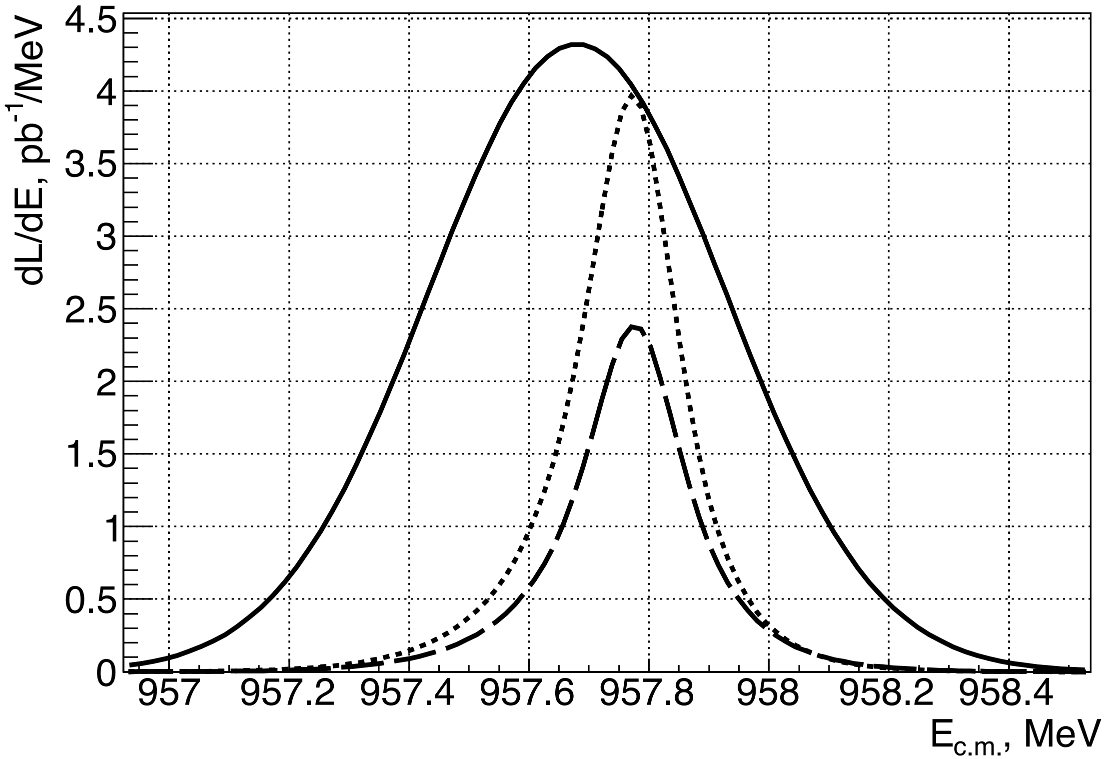
FWHM = 0.59 MeV is significantly larger, compare to $\Gamma_{\eta'} = 0.199 \pm 0.009$ MeV , and integrated (over width) cross section is calculated as

$$\sigma^f_{\text{int}} = \int_0^{E_{\text{beam}}} dE \int_0^1 \frac{1}{\sqrt{2\pi}\sigma_{\text{E}_{\text{c.m.}}}} e^{-\frac{(\text{E}_{\text{c.m.}}{}^{\text{av.}} - \text{E})^2}{2\sigma^2_{\text{E}_{\text{c.m.}}}}} \cdot F(x, E) \cdot \sigma^f(E(1-x)) dx$$

where *x* is fraction of energy taken by soft photons according to radiator function F(x, E), and $\sigma^f(E)$ is a Breit-Wigner for η'

$$\sigma(E) = 4\pi \frac{C\Gamma_{\eta'}\Gamma_{\eta' \to e^+e^-}}{(m^2_{\eta'} - E^2)^2 + E^2\Gamma^2_{\eta'}}$$

Integrated cross section



σ^{f}_{int} = (6.38 ± 0.23) • $\Gamma_{\eta' \to e+e-}$(eV) • $B_{\eta' \to f}$ nb

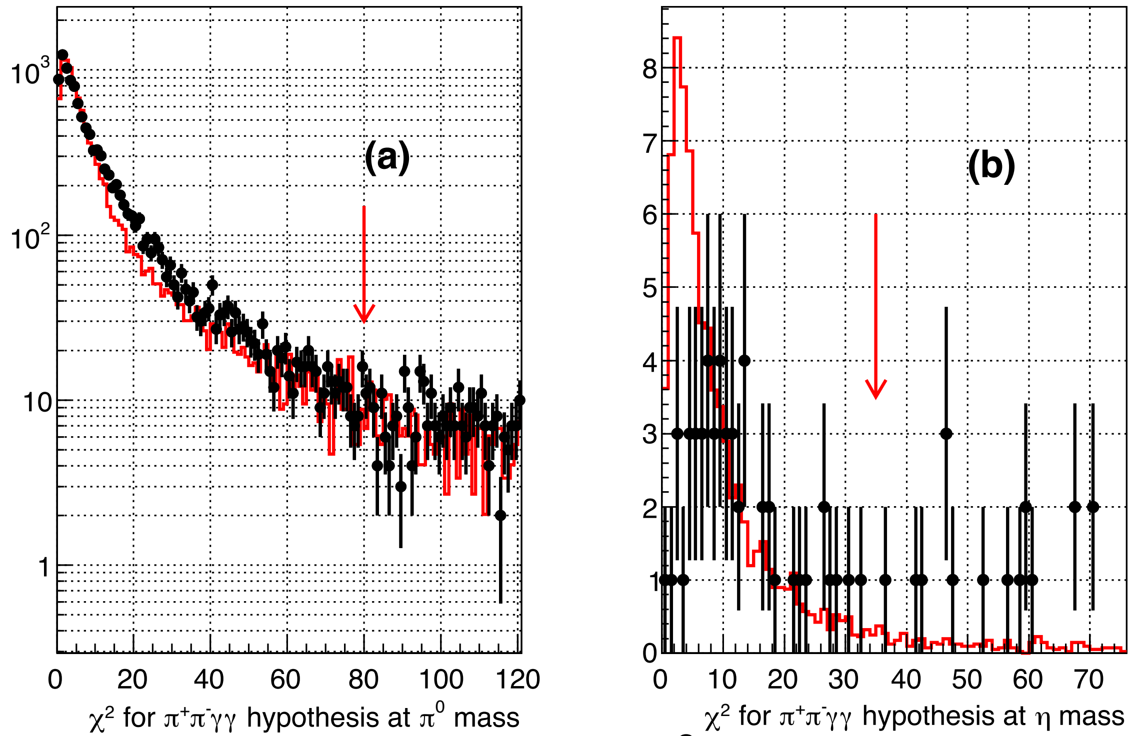
For unitarity limit and $B_{\eta' \to f}$ = 1 $\sigma_{int}^{unit} = 4.8 \times 10^{-5}$ nb.

If we observe N events, we measure $\Gamma_{\eta' \to e^+e^-} = \frac{N}{6.38 \cdot \epsilon \cdot L} eV.$

Event selection – CMD-3

We search for the reaction: $e^+e^- \rightarrow \eta(958) \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$

- we select events with two “good” tracks and >2 photons
- we perform a kinematic fit in the $e+e- \rightarrow \pi+\pi-\gamma\gamma$ hypothesis
- if more than 2 photons, the best $\chi2$ combination is used

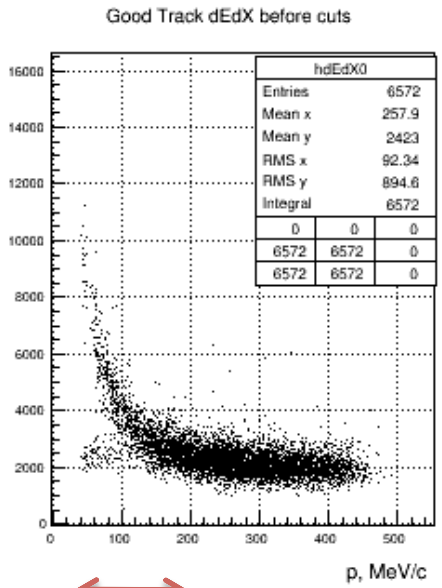


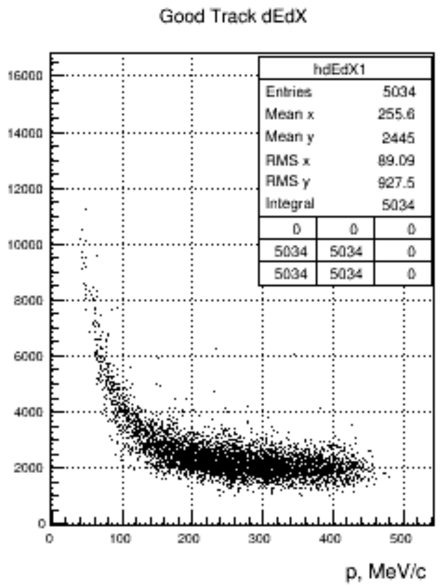
Events from ± 35 MэВ around π^0 mass(a) и η mass (b)

Histograms are simulation

Event selection (example)

dE/dX

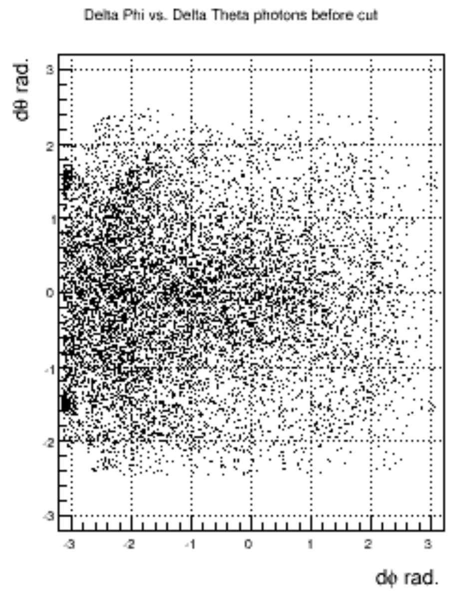


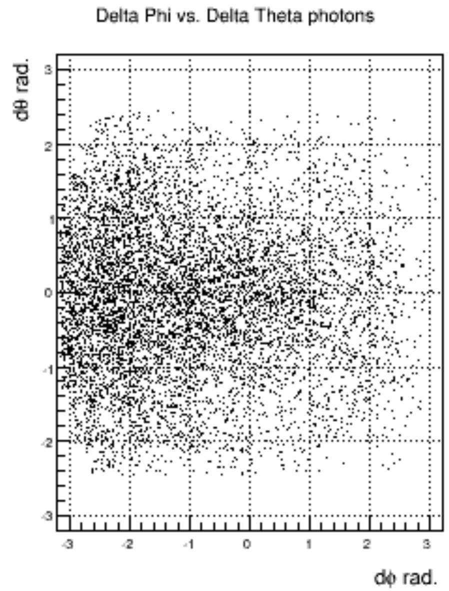


Tracks

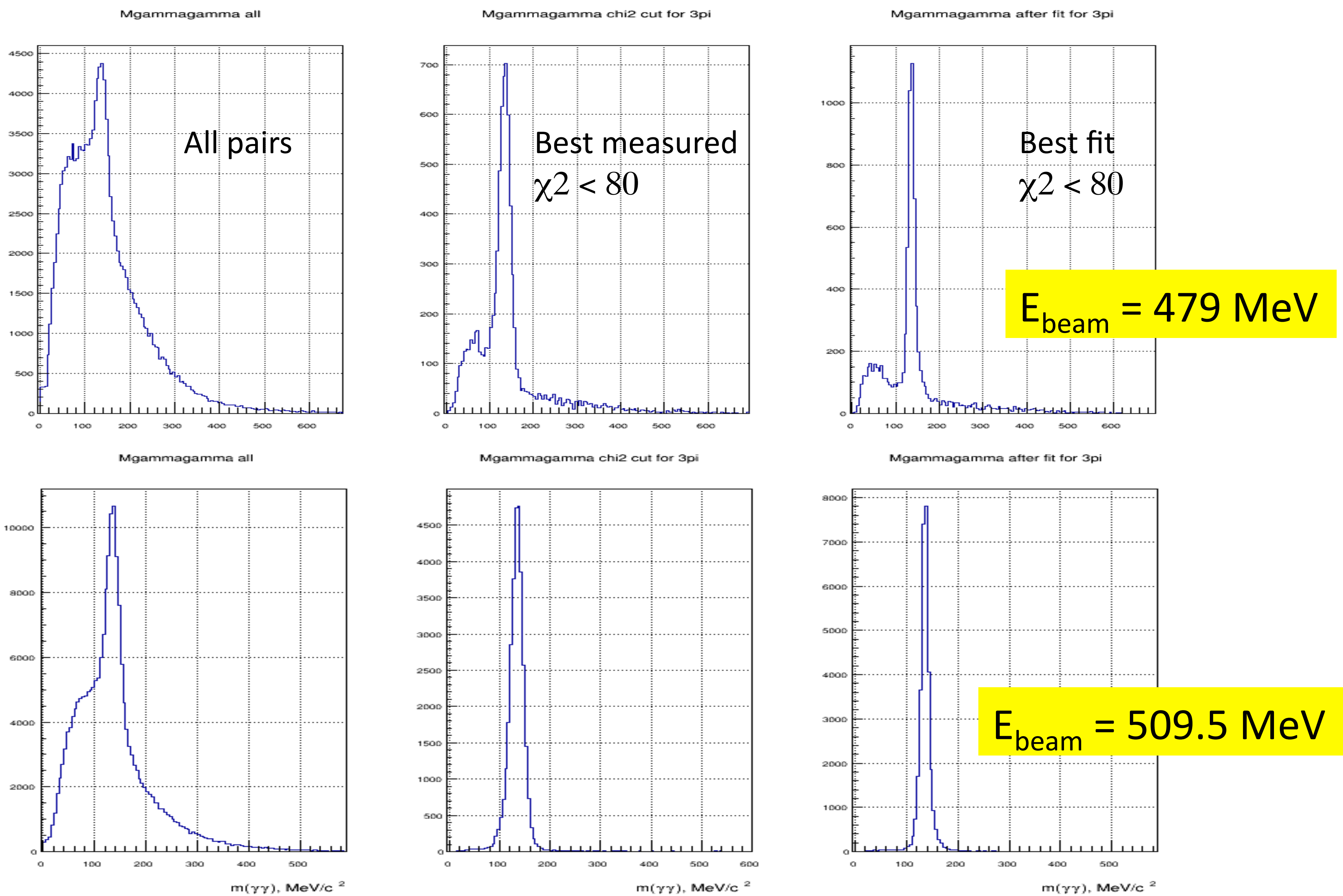
Momentum range for $\pi^+\pi^-\eta$

Photons

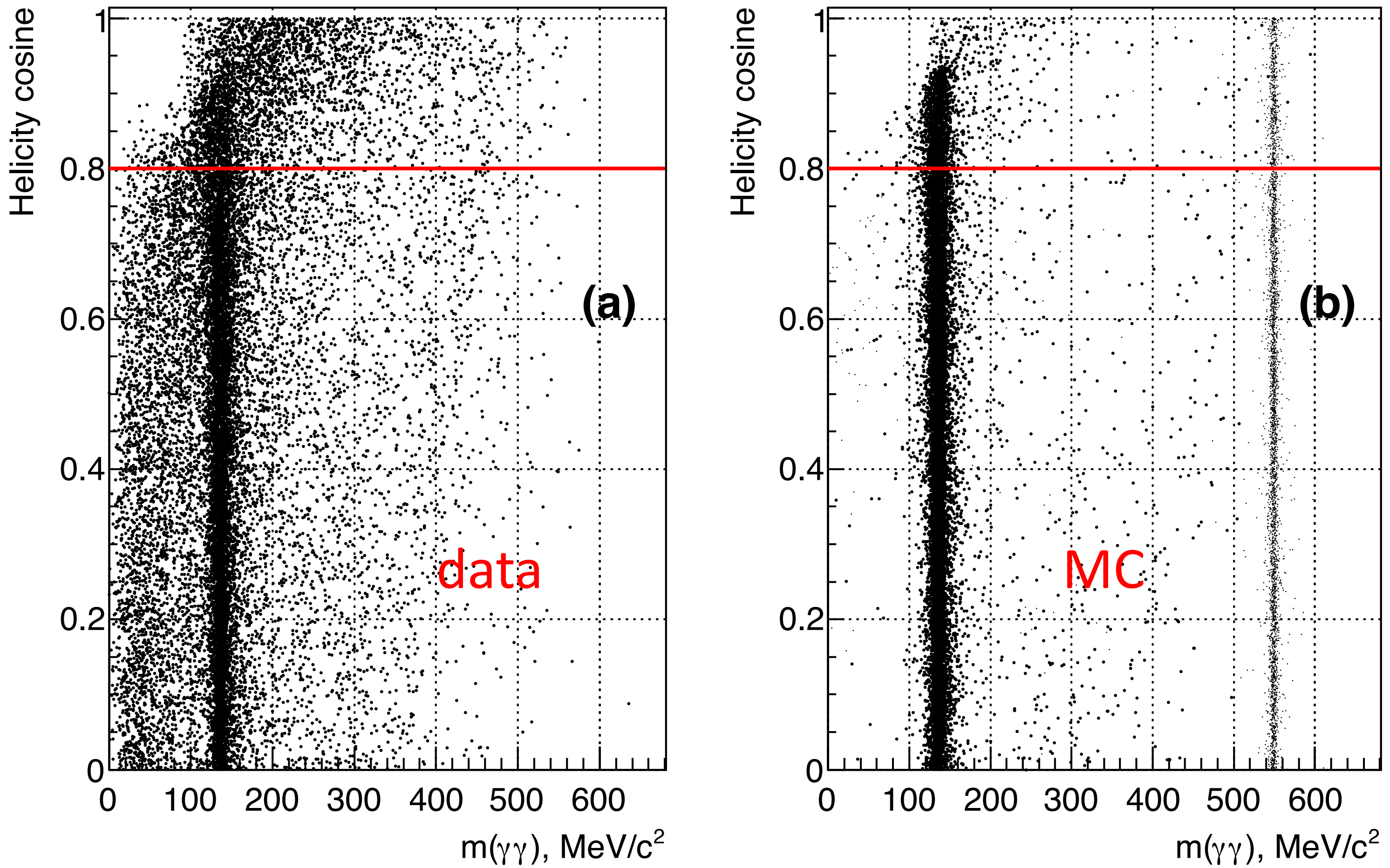




How m(γγ) looks like ?

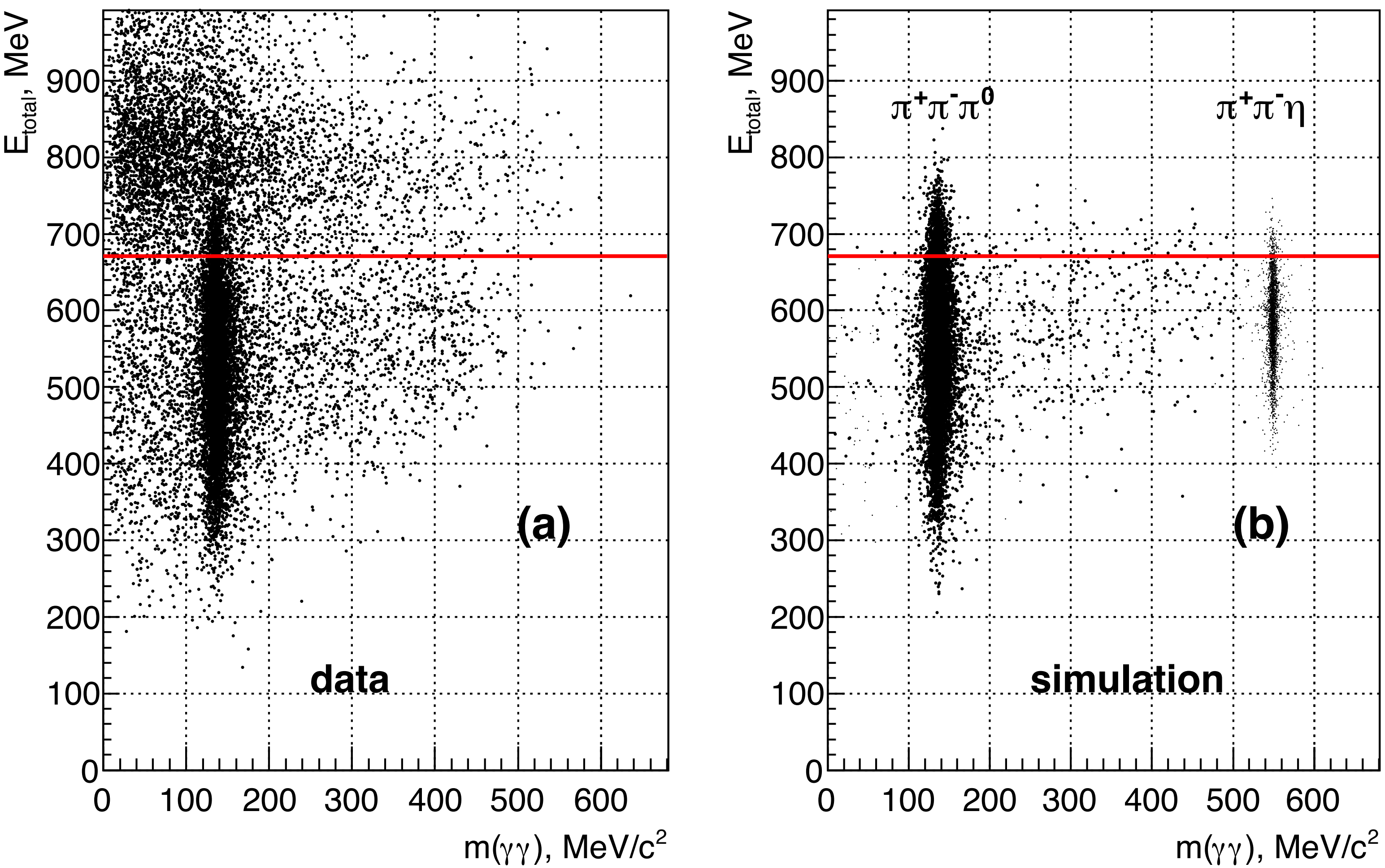


Additional cut on photon pair



|cos(H)| < 0.8 : Efficiency reduced by 20 %

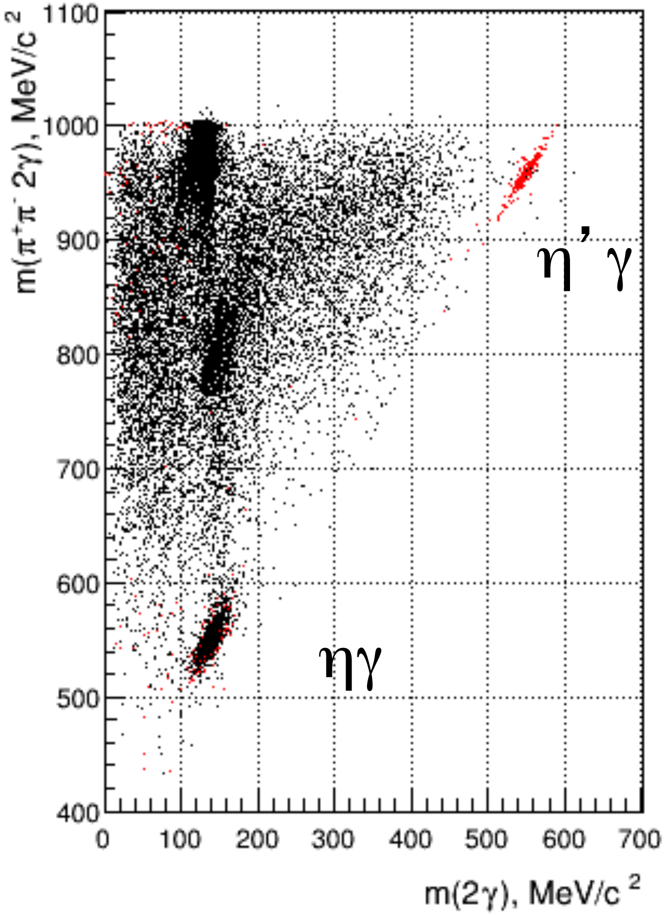
Background from QED



$E_{total} < 1.4\ E_{beam}$: Efficiency reduced by 13 %

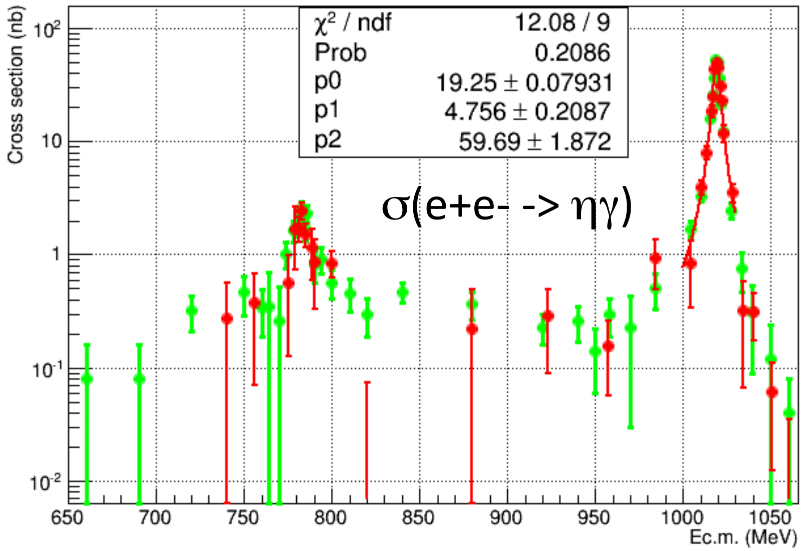
Check with $\pi^+\pi^-\pi^0(\eta)\gamma$

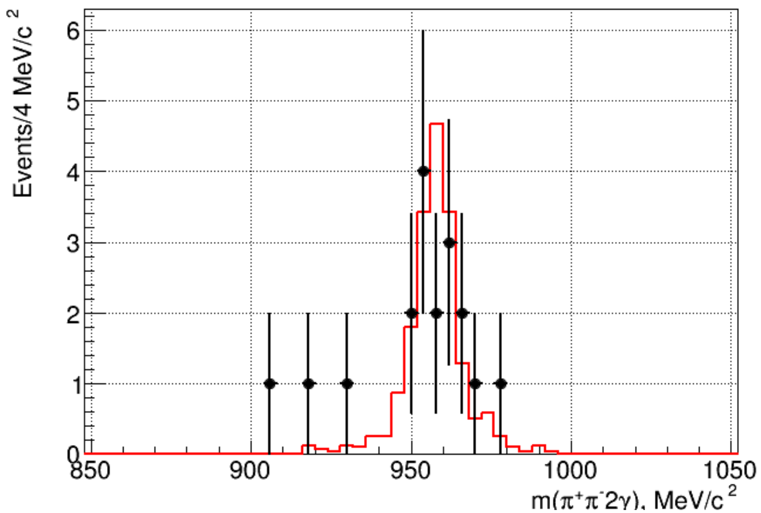
$E_{beam} = 509.5$



red points - simulation

Green – CMD-2, red – CMD-3 (part of data)

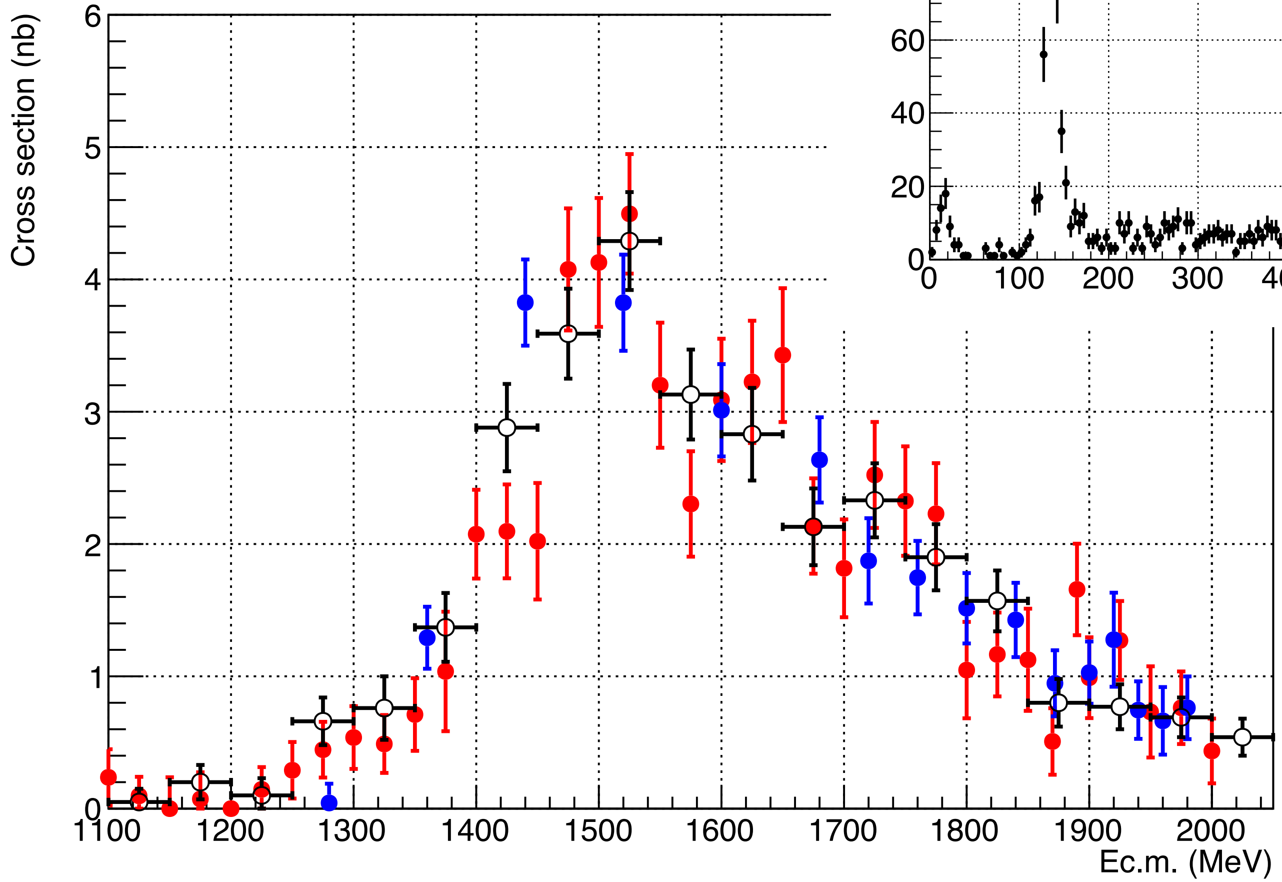


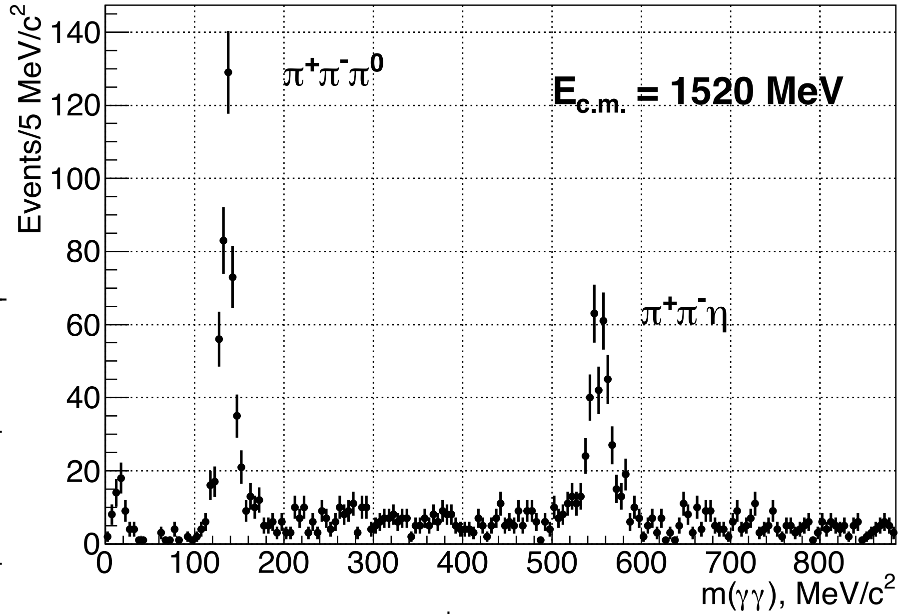


η′ signal

Check with $\pi^+\pi^-\eta \rightarrow \pi^+\pi^-2\gamma$

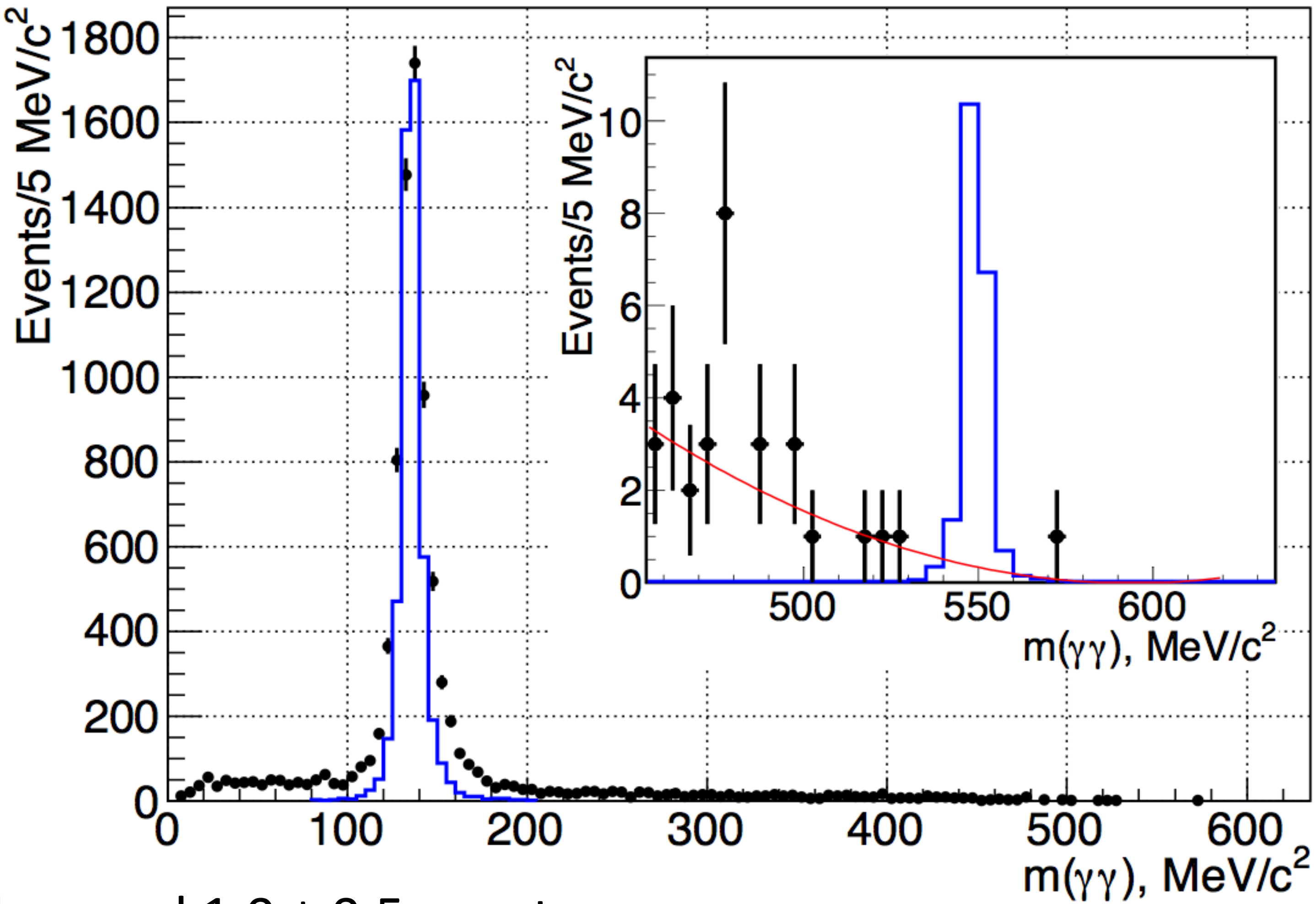
black – BaBar, red, blue – CMD-3





How large it is at Ec.m. = 958 MeV?

NO signal at Ec.m. = 958 MeV



Background 1.0 ± 0.5 events

```
root [0] TFeldmanCousins f
root [1] f.CalculateUpperLimit(0,0.5)
(Double_t)1.93999999999999995e+00
```

We take N < 2.0 at 90% C.L.

Result

Efficiency for e+e- -> η(958) -> π+π−η -> π+π−γγ - 31.1%, L = 2690 nb-1

Systematic unsertainties:

2% - luminosity, 5% - energy instability, 5% - efficiency

Our result is:

$$\Gamma_{\eta' \to e^+e^-} \mathcal{B}_{\eta' \to \pi^+\pi^- \eta} \mathcal{B}_{\eta \to \gamma\gamma} < \frac{2.0}{6.38 \cdot 0.311 \cdot 2690} = 0.00037 \text{ eV at } 90\% \text{ C.L.}$$

With systematics

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

Calculate $\Gamma_{\eta' \to e^+e^-} < 0.0024$ eV or $\mathcal{B}_{\eta' \to e^+e^-} < 1.2 \times 10^{-8}$

Compare to old ND: $\Gamma_{\eta' \to e+e-} < 0.06$ eV $Br_{\eta' \to e+e-} < 2.1 \times 10^{-7}$

(ND used ~0.3 MeV в PDG 1985)

Unitarity limit is $\Gamma_{unit}(\eta' \to e^+e^-) = 7.5 \times 10^{-6}$ eV - still ~300 lower

$B_{unit}(\eta' \to e^+e^-) = 3.75 \times 10^{-11}$

Analysis has been published at Phys. Lett. B740(2015) 273.

In our experiment we can also set a limit on the cross section for the process

$e^+e^- \to \pi^+\pi^-\eta$ at $E_{c.m.}$ = 957.7 MeV, which is found to be

$$\sigma = N/(\varepsilon L) < 6.1 \text{ pb}$$ for 90 C.L.,

where $\varepsilon B(\eta \to 2\gamma) = 0.122$ is a detection efficiency for this process.

How large it is? KLOE can measure it NOW!

SND analysis (Phys. Rev. D 91, 092010 (2015))

- Same time data taking
- Using five decay chains of η(958)

$e^+e^- \to \eta(958) \to \pi^+\pi^-\eta \to \pi^+\pi^-\gamma\gamma$

$\to \pi^+\pi^-\pi^0\pi^0\pi^0$

$e^+e^- \to \eta(958) \to \pi^0\pi^0\eta \to \pi^0\pi^0\gamma\gamma$

$\to \pi^0\pi^0\pi^0\pi^0\pi^0$

$\to \pi^0\pi^0\pi^+\pi^-\pi^0$

NO non-resonant background!

$\Gamma(\eta'\to e^+e^-) < 0.0024$ eV (90%CL) - CMD-3
$\Gamma(\eta'\to e^+e^-) < 0.0020$ eV (90%CL) - SND
$B(\eta'\to e^+e^-) < 5.6\times10^{-9}$ (90%CL) - SND+CMD-3
$B(\eta'\to e^+e^-) = 3.7\times10^{-11}$ – Theory (no FF)

Only DAFNE-KLOE can make it!

$\eta'(958)$ DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ± 0.7) %		232
$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ± 0.5) %		165
$\pi^0\pi^0\eta$	(22.3 ± 0.8) %		239
$\omega\gamma$	(2.62 ± 0.13) %		159
ωe^+e^-	$(2.0 \pm 0.4) \times 10^{-4}$		159
$\gamma\gamma$	(2.21 ± 0.08) %		479

η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes			
neutral modes	(72.12 ± 0.34) %	S=1.2	–
2γ	(39.41 ± 0.20) %	S=1.1	274
$3\pi^0$	(32.68 ± 0.23) %	S=1.1	179
$\pi^0 2\gamma$	$(2.56 \pm 0.22) \times 10^{-4}$		257
$2\pi^0 2\gamma$	$< 1.2 \times 10^{-3}$	CL=90%	238
4γ	$< 2.8 \times 10^{-4}$	CL=90%	274
invisible	$< 1.0 \times 10^{-4}$	CL=90%	–
Charged modes			
charged modes	(28.10 ± 0.34) %	S=1.2	–
$\pi^+\pi^-\pi^0$	(22.92 ± 0.28) %	S=1.2	174
$\pi^+\pi^-\gamma$	(4.22 ± 0.08) %	S=1.1	236

If energy spread is similar to VEPP2000:

σ_{int} = 5.8x10^{-5} x BR(η'->f) nb

Using BR(η'->$\pi^0\pi^0\eta$) = 0.223 and all η decay modes with 50% efficiency (?) we need

L_{int} = 160 pb-1 to reach unitarity limit: FF~5-10 is expected (?).

~0.5 fb^{-1} at $E_{c.m.}$ = 958 MeV could also be used for ISR $\pi+\pi-$ and $\gamma\gamma$ physics out of ϕ.

Energy control at the level of ~100 keV is required!