γγ interactions with KLOE

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for the KLOE Collaboration

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Outline

- motivations for studying $\gamma\gamma$ events:

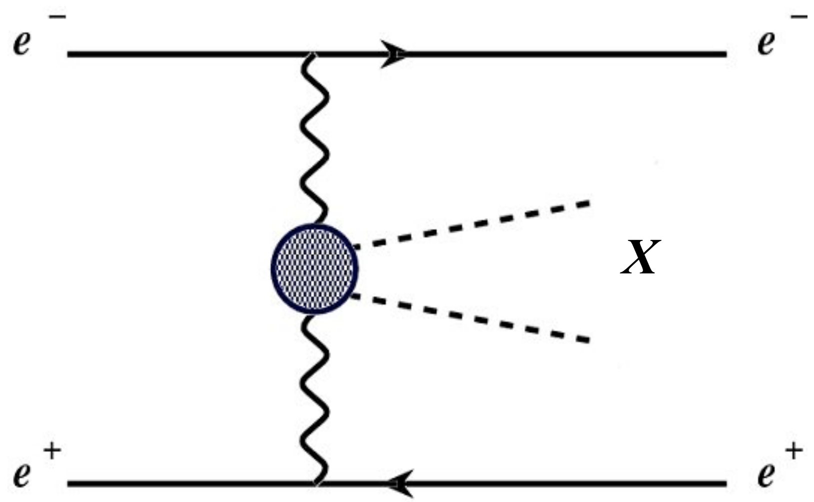
assessment of scalar and pseudoscalar mesons through electromagnetic properties

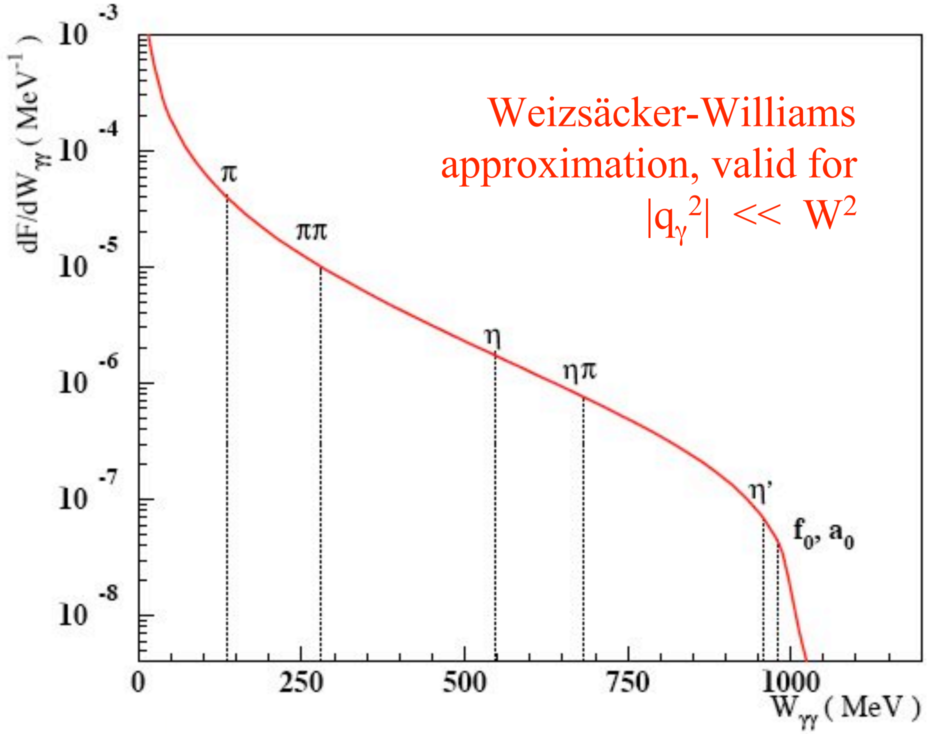
- observation of $\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$ events at DAΦNE

- study of $\gamma\gamma \to \pi^0\pi^0$ events, search for $\gamma\gamma \to \sigma$

- conclusions

$e^+e^- \to e^+ e^- X$ or $\gamma\gamma$ interactions





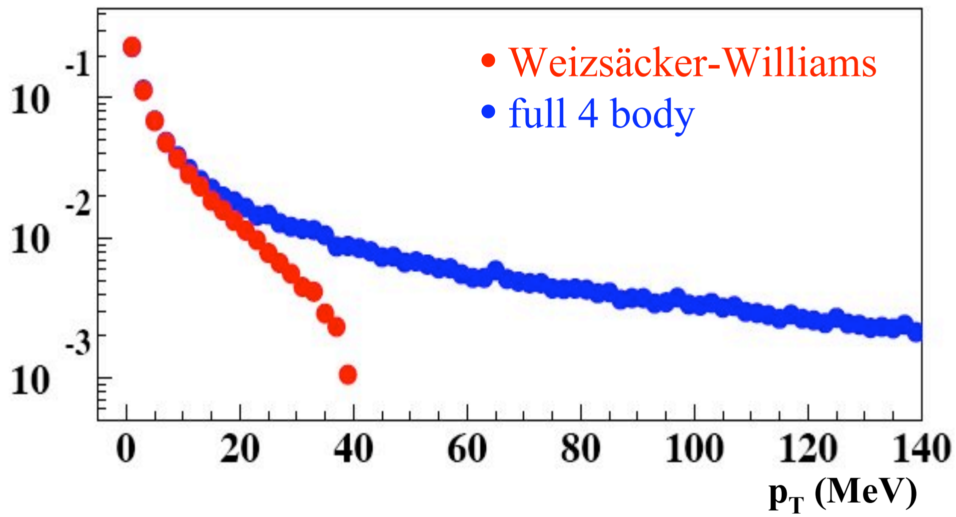
$$N_{e^+e^-\to e^+e^-X} = L_{ee}\int \frac{dF_{\gamma\gamma}}{dW_{\gamma\gamma}}\sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})dW_{\gamma\gamma}$$

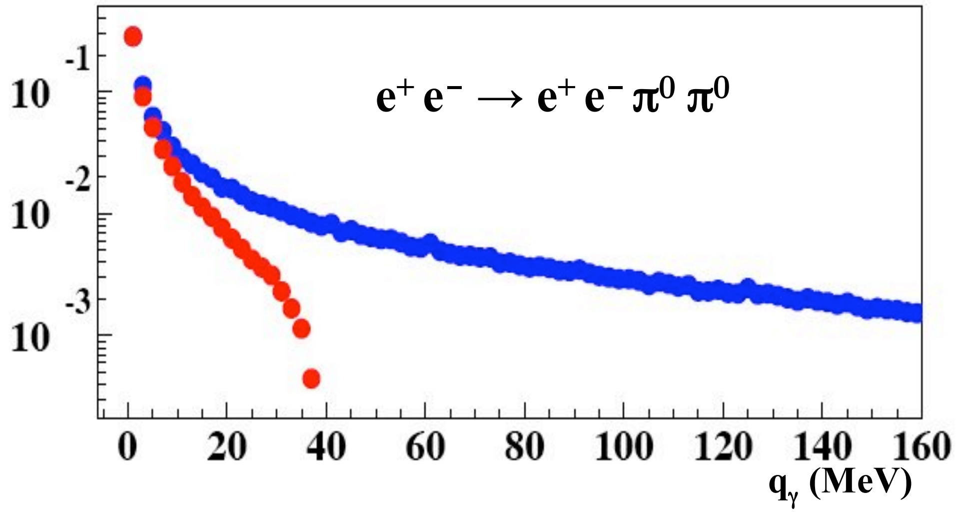
$$\sigma_{e^+e^-\to e^+e^-X} = \frac{16\alpha^2\Gamma_{X\gamma\gamma}}{m_X^3}\left(\ln\frac{E_b}{m_e}\right)^2\left((y^2+2)^2\ \ln\frac{1}{y} - (1-y^2)\ (3+y^2)\right)$$

$$y = m_X/(2E_b)$$

$\sqrt{s}$ (GeV)	1
$\sigma\,(e^+e^- \to e^+e^-\pi^0)$ (pb)	266
$\sigma\,(e^+e^- \to e^+e^-\eta)$ (pb)	43
$\sigma\,(e^+e^- \to e^+e^-\eta')$ (pb)	3.3

Comparison btw W.W. and phase space



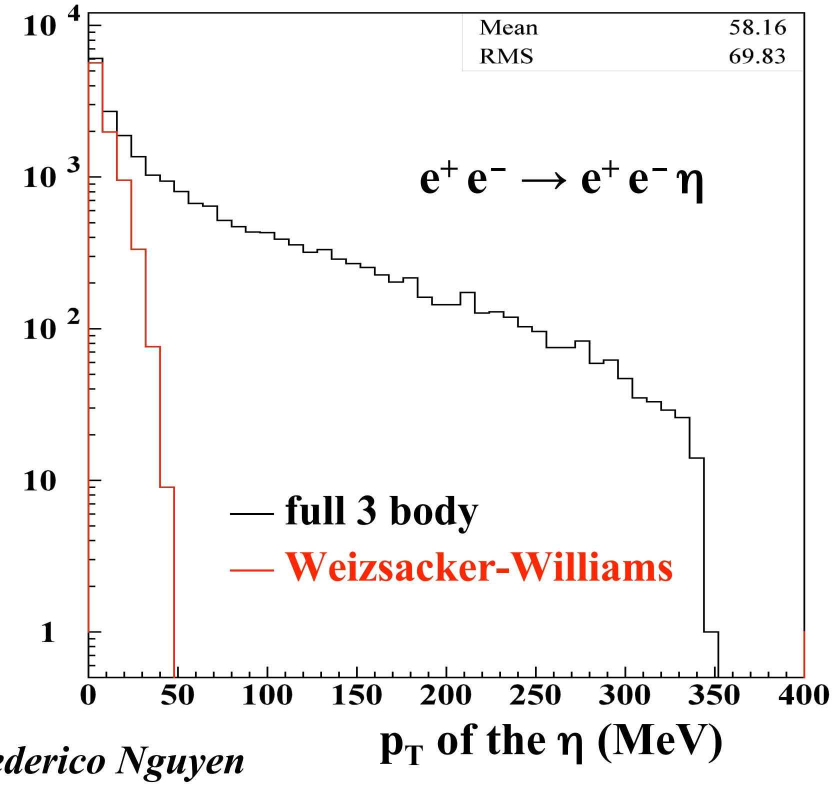


1) W.W. is reproduced with a cut

$\theta < 5^o$ for final state e^+e^-

2) impact at the % level within cuts

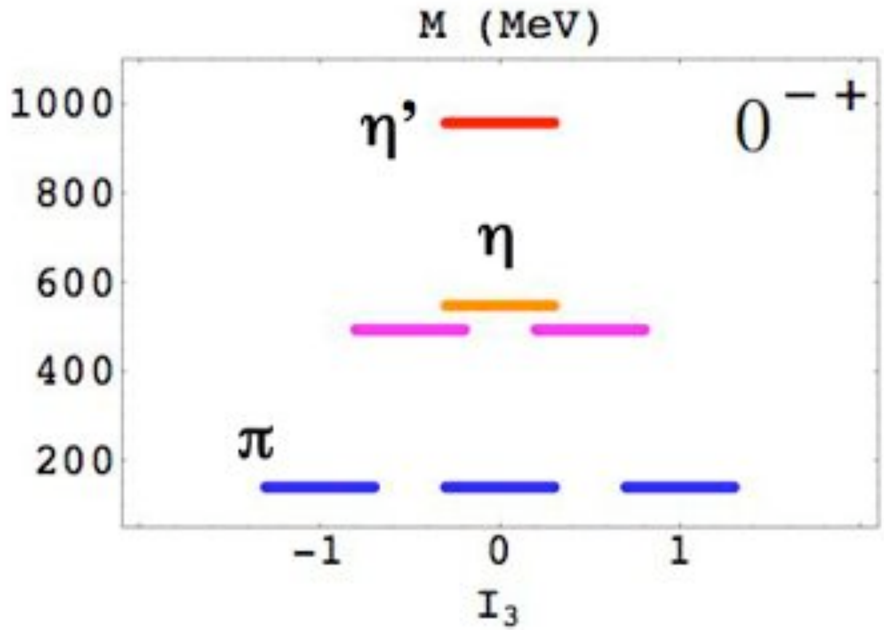
(p_T < 80 MeV)

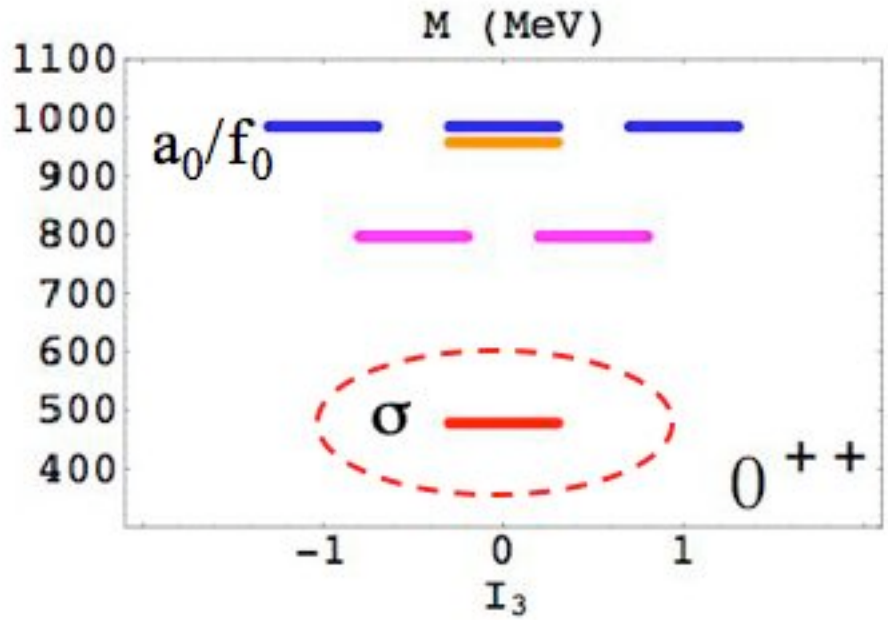


F.N., F. Piccinini & A. Polosa
Eur.Phys.J.C47(2006)65

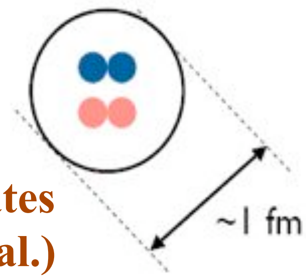
Federico Nguyen
14-10-2009

Pseudoscalar and scalar mesons



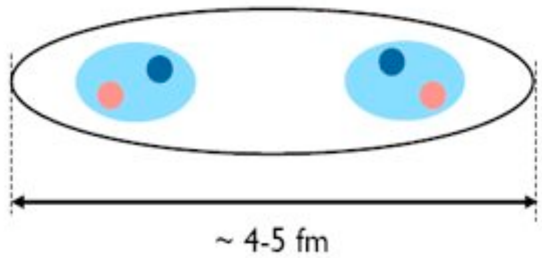


- **Is σ(600) the lightest scalar meson?**
- **What structure?**



$qq\bar{q}\bar{q}$ **states**
(Jaffe, Achasov et al., Maiani et al.)

vs.



$K\bar{K}$ **molecules**
(Weinstein-Isgur, Close et al., Kalashnikova et al.)

The $f_0(600)$ or σ case

data come from Dalitz plot analyses, using Breit-Wigner or T-matrix fits

$f_0(600)$ BREIT-WIGNER MASS OR K-MATRIX POLE PARAMETERS

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–1200) OUR ESTIMATE			
513 ± 32	[26] MURAMATSU 02	CLEO	$e^+e^- \approx 10$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$478^{+24}_{-23} \pm 17$	AITALA 01B	E791	$D^+ \to \pi^-\pi^+\pi^+$
563^{+58}_{-29}	[27] ISHIDA 01		$\Upsilon(3S) \to \Upsilon\pi\pi$
555	[28] ASNER 00	CLE2	$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$
540 ± 36	ISHIDA 00B		$p\bar{p} \to \pi^0\pi^0\pi^0$

CLEO 02: $D^0 \to K_S \pi^+\pi^-$ Dalitz analysis

$f_0(600)$ BREIT-WIGNER WIDTH

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(600–1000) OUR ESTIMATE			
335 ± 67	[37] MURAMATSU 02	CLEO	$e^+e^- \approx 10$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$324^{+42}_{-40} \pm 21$	AITALA 01B	E791	$D^+ \to \pi^-\pi^+\pi^+$
372^{+229}_{-95}	[38] ISHIDA 01		$\Upsilon(3S) \to \Upsilon\pi\pi$
540	[39] ASNER 00	CLE2	$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$
372 ± 80	ISHIDA 00B		$p\bar{p} \to \pi^0\pi^0\pi^0$

$f_0(600)$ T-MATRIX POLE $\sqrt{s}$

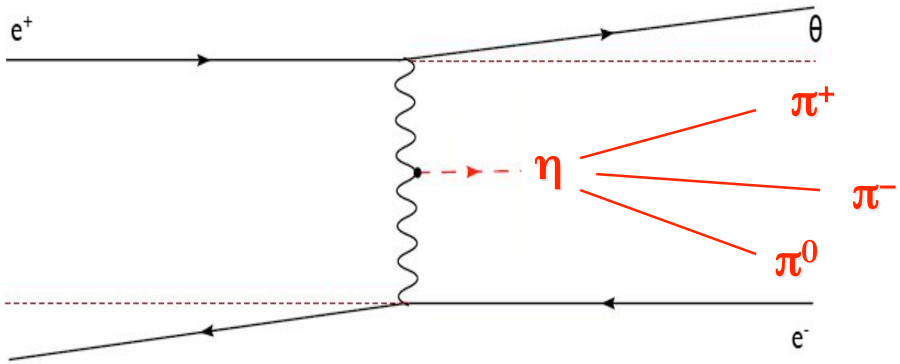
Note that $\Gamma \approx 2\,\mathrm{Im}(\sqrt{s_{\rm pole}})$.

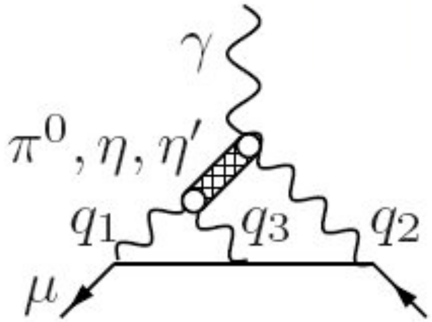
VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–1200)−i(250–500) OUR ESTIMATE			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$(455 \pm 6^{+31}_{-13}) - i(278 \pm 6^{+34}_{-43})$	[1] CAPRINI 08	RVUE	Compilation
$(463 \pm 6^{+31}_{-17}) - i(259 \pm 6^{+33}_{-34})$	[2] CAPRINI 08	RVUE	Compilation
$(552^{+84}_{-106}) - i(232^{+81}_{-72})$	[3] ABLIKIM 07A	BES2	$\psi(2S) \to \pi^+\pi^- J/\psi$
$(466 \pm 18) - i(223 \pm 28)$	[4] BONVICINI 07	CLEO	$D^+ \to \pi^-\pi^+\pi^+$
$(484 \pm 17) - i(255 \pm 10)$	GARCIA-MAR..07	RVUE	$Ke4$
$(441^{+16}_{-8}) - i(272^{+9}_{-12.5})$	[5] CAPRINI 06	RVUE	$\pi\pi \to \pi\pi$
$(470 \pm 50) - i(285 \pm 25)$	[6] ZHOU 05	RVUE	
$(541 \pm 39) - i(252 \pm 42)$	[7] ABLIKIM 04A	BES2	$J/\psi \to \omega\pi^+\pi^-$
$(528 \pm 32) - i(207 \pm 23)$	[8] GALLEGOS 04	RVUE	Compilation
$(440 \pm 8) - i(212 \pm 15)$	[9] PELAEZ 04A	RVUE	$\pi\pi \to \pi\pi$
$(533 \pm 25) - i(247 \pm 25)$	[10] BUGG 03	RVUE	
$532 - i272$	BLACK 01	RVUE	$\pi^0\pi^0 \to \pi^0\pi^0$
$(470 \pm 30) - i(295 \pm 20)$	[5] COLANGELO 01	RVUE	$\pi\pi \to \pi\pi$
$(535^{+48}_{-36}) - i(155^{+76}_{-53})$	[11] ISHIDA 01		$\Upsilon(3S) \to \Upsilon\pi\pi$
$610 \pm 14 - i620 \pm 26$	[12] SUROVTSEV 01	RVUE	$\pi\pi \to \pi\pi, K\bar{K}$
$(558^{+34}_{-27}) - i(196^{+32}_{-41})$	ISHIDA 00B		$p\bar{p} \to \pi^0\pi^0\pi^0$

The case of $e^+e^- \to e^+e^-\eta$

$\Gamma(\gamma\gamma)$

VALUE (keV)	EVTS	DOCUMENT ID		TECN	COMMENT	√s (GeV)
0.510±0.026 OUR FIT						
0.510±0.026 OUR AVERAGE						
0.51 ±0.12 ±0.05	36	BARU	90	MD1	$e^+e^- \to e^+e^-\eta$	**7.2-10.4**
0.490±0.010±0.048	2287	ROE	90	ASP	$e^+e^- \to e^+e^-\eta$	**29**
0.514±0.017±0.035	1295	WILLIAMS	88	CBAL	$e^+e^- \to e^+e^-\eta$	**9.4-10.6**
0.53 ±0.04 ±0.04		BARTEL	85E	JADE	$e^+e^- \to e^+e^-\eta$	**34.6**





BR($\eta \to \pi^+\pi^-\pi^0$) = 22.73%
major issue:
e+e- -> ηγ background

interests on the transition form factors for LbyL contributions (A. Nyffeler, J.Prades) to g-2…but need more statistics
→ KLOE-2 (see G. Venanzoni)

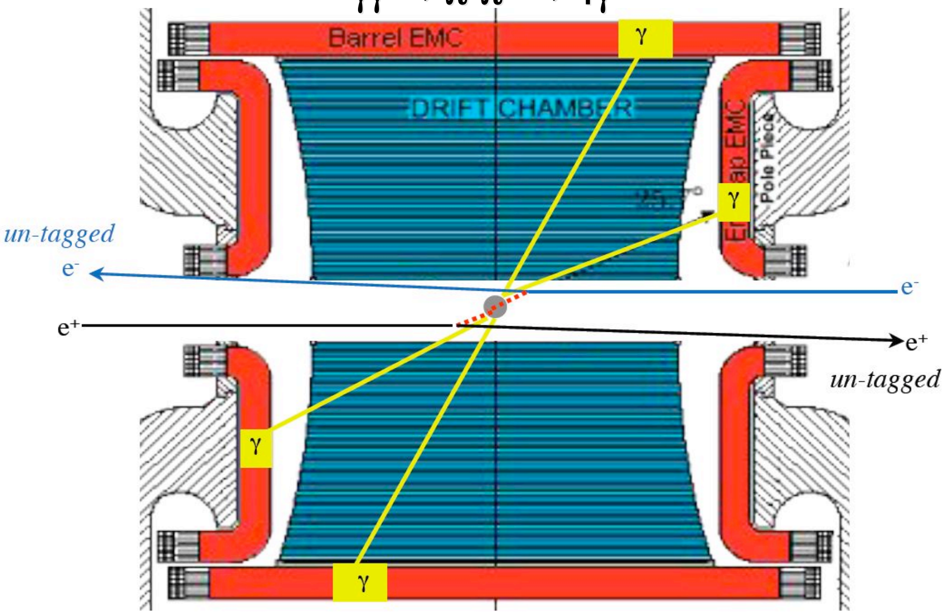
$$\sigma_{\gamma\gamma\to R}(q_1,q_2) \propto \Gamma_{R\to\gamma\gamma}\frac{8\pi^2}{M_R}\delta((q_1+q_2)^2 - M_R^2)\left|F(q_1^2,q_2^2)\right|^2$$

$\gamma\gamma$ interactions at DAΦNE

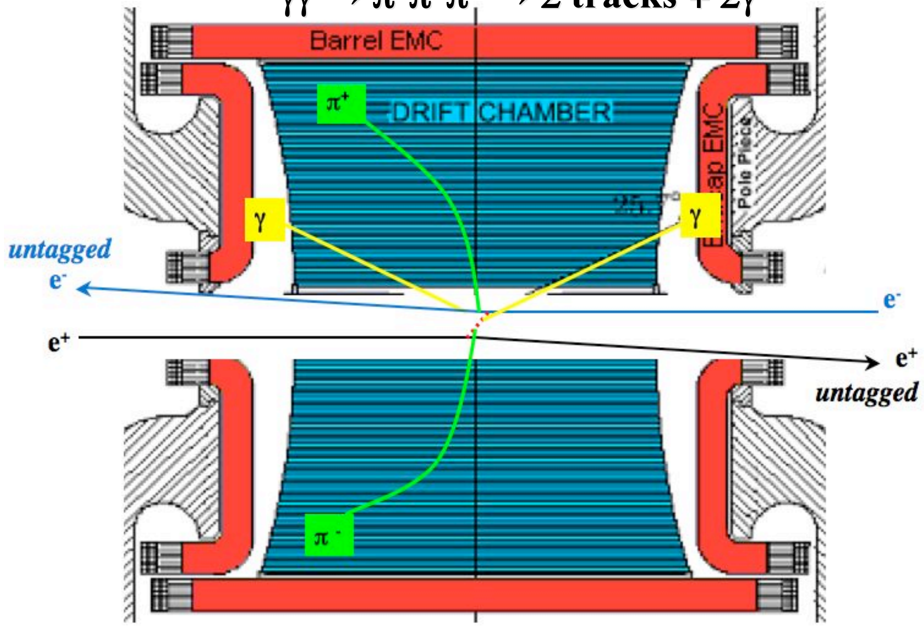
- ✓ data collected at $\sqrt{s}$ = 1 GeV (see S. Müller), suppressed ϕ decays
- ✓ instant luminosity = 7×10^{31} cm^{-2} s^{-1}, $\int L dt \sim 250$ pb^{-1}
- ✓ data processing with dedicated filter:

- at least 2 photons with energy > 15 MeV, acceptance 20°-160°
- the most energetic photon with energy > 50 MeV
- total calorimetric energy 200 MeV < E_{calo} < 900 MeV
- $R = (\sum_\gamma E_\gamma) / E_{calo} > 0.3$

$\gamma\gamma \to \pi^0\pi^0 \to 4\gamma$



$\gamma\gamma \to \pi^+\pi^-\pi^0 \to$ 2 tracks + 2γ



Selection of $e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$ events

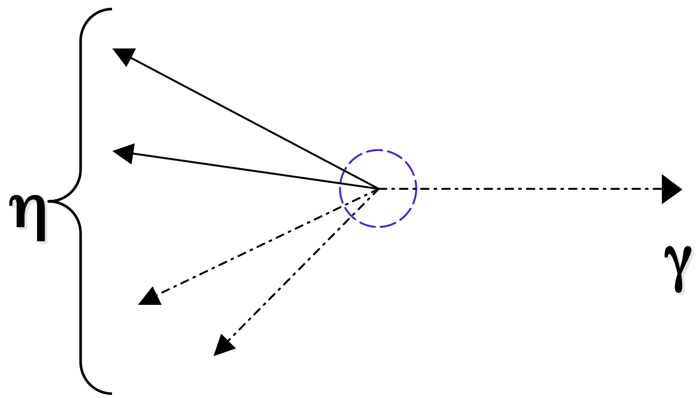
- ✓ 2 tracks w/ opposite charge
- ✓ 2 and only 2γ from the π^0 decay $\rightarrow$ imposes the $\eta\gamma$ photon ($E_\gamma \sim 350$ MeV) to be lost in the beam pipe
- ✓ kinematic fit χ^2_η based on Lagrange multipliers
- ✓ for $\eta\gamma$ events, η system constrained in a small cone around $p_L \sim 350$ MeV and with $M_{miss} \sim 0$

$$M^2_{miss} \approx s + M^2_\eta - 2E_T\sqrt{s} - \frac{p_L^2}{E_T}\sqrt{s}$$

$$E_T = \sqrt{p_T^2 + M_\eta^2} \approx M_\eta$$

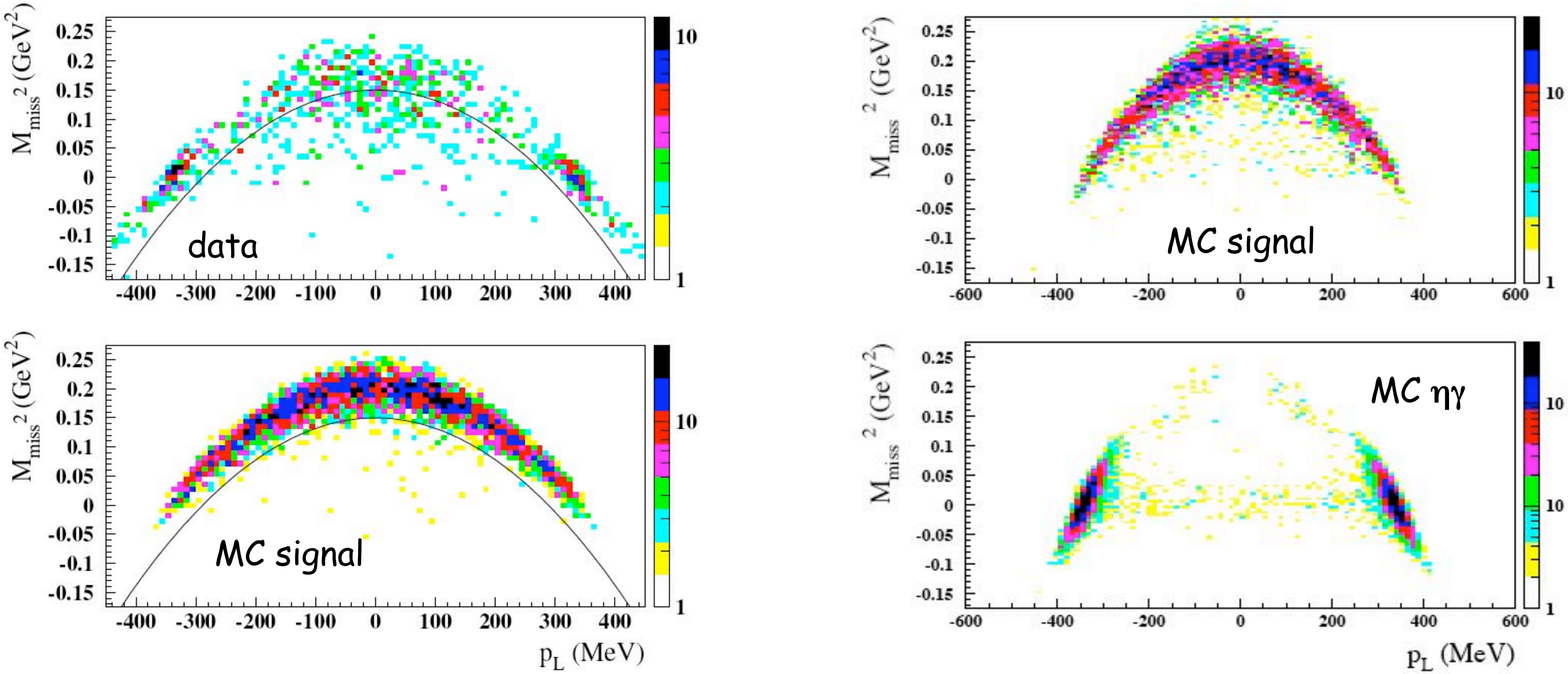
χ^2_η: **5 variables × 2γ**
4 constraints

$$m^2_{\gamma\gamma} = m^2_{\pi 0}$$
$$m^2_{\pi+\pi-\gamma\gamma} = m^2_\eta$$
$$t_\gamma - |\underline{r}_\gamma| / c = 0 \quad \text{for } 2\gamma$$



from 239.6 pb^{-1}
1576 events survive selection

$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$: efficiencies and background



	$\eta\gamma$ $\eta \to \pi^+\pi^-\pi^0$	$\omega\pi^0$ $\omega \to \pi^+\pi^-\pi^0$	$\pi^+\pi^-\pi^0$	K^+K^- $\mu\nu,\ \pi^\pm\pi^0$	$K_S K_L$	$e^+e^-\gamma$
σ (nb)	0.23	5.7	30	8.6	2.0	400
ε	9.2×10^{-3}	6.3×10^{-5}	1.5×10^{-5}	1.9×10^{-5}	1.7×10^{-5}	$\mathcal{O}(10^{-7})$

signal: $\sigma = 0.043$ **nb**

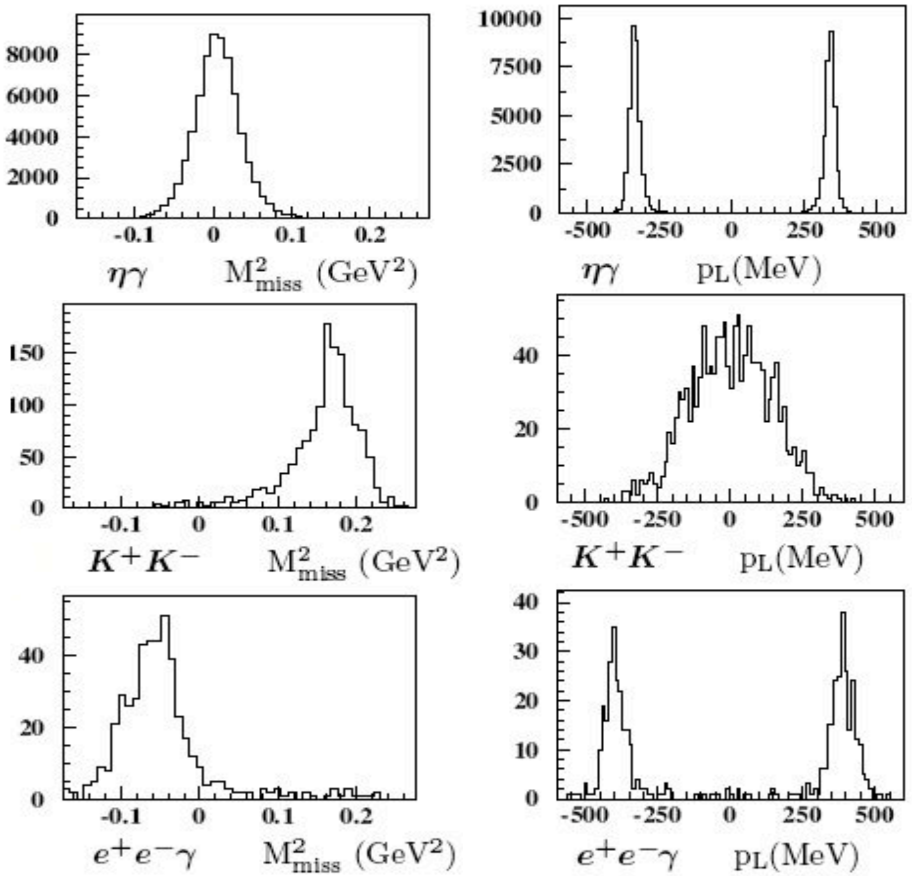
signal: $\varepsilon_{global} = 20\%$

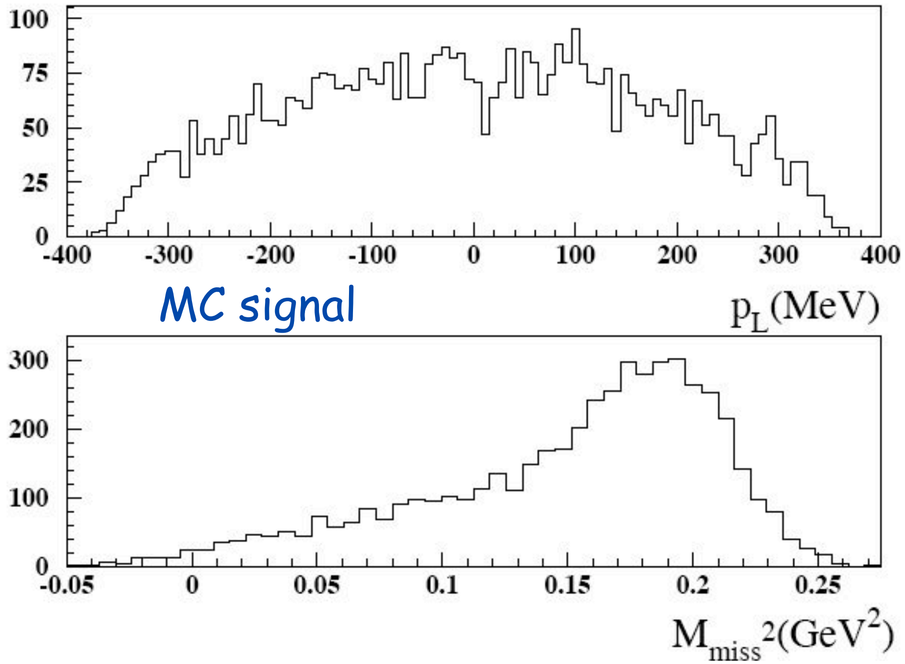
$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^0$: fit method

$$L = \Pi_i \, P(d_i|w_S S_i + w_B B_i) \, P(s_i|S_i) \, P(b_i|B_i) \;\rightarrow\; \chi_{fit}^2 = -2 \ln L$$

parameters — *generated MC statistics*

background yields constrained by present knowledge on cross sections

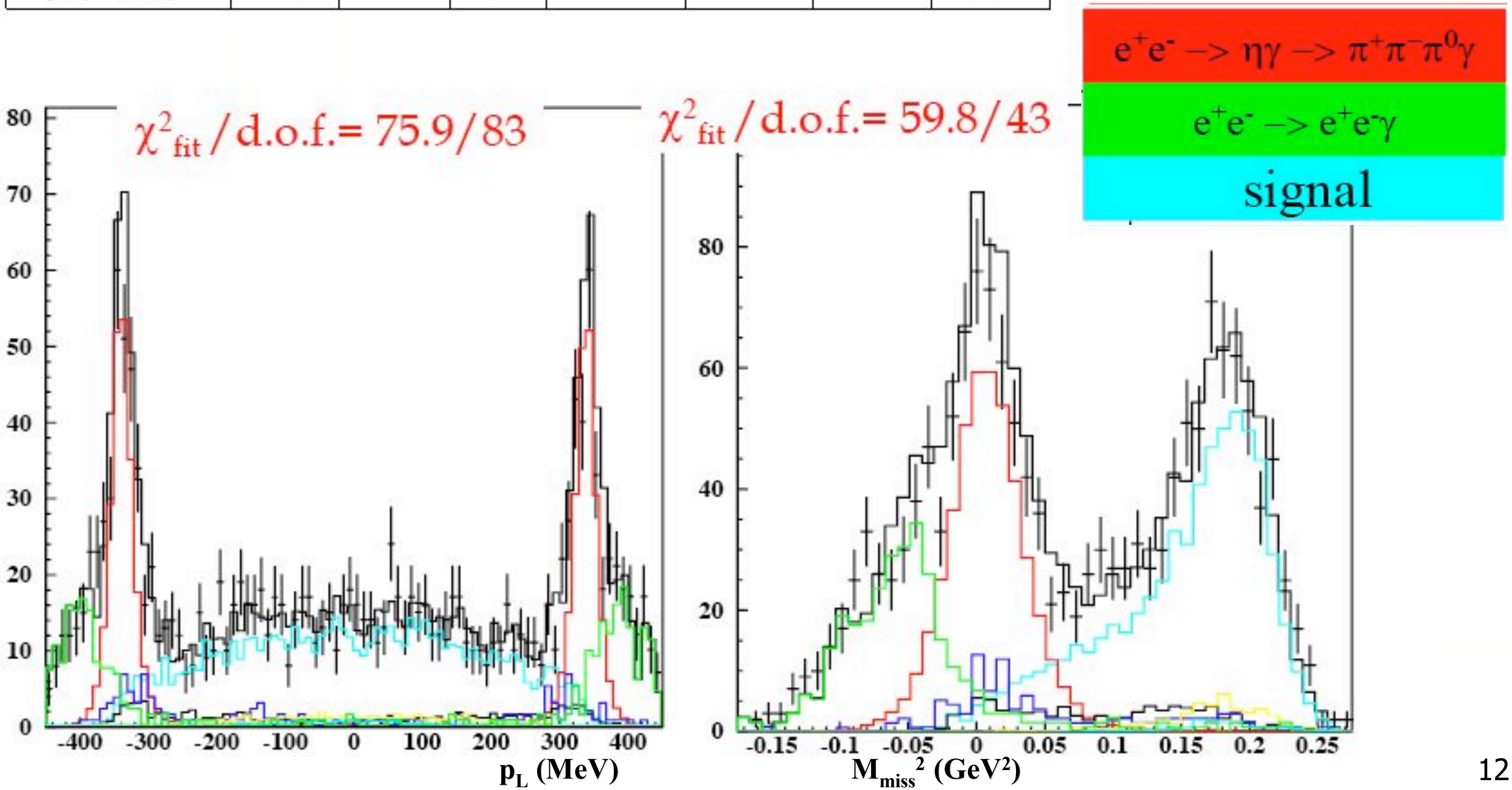




$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$: preliminary result

observation of
γγ collisions @ 1 GeV

	signal	$\eta\gamma$	$\omega\pi^0$	$\pi^+\pi^-\pi^0$	K^+K^-	$K_S K_L$	$e^+e^-\gamma$
range variation	free	±15%	±1%	±7%	±25%	±15	free
$N_{fit}(p_L)$	646	442	87	101	46	14	286
$N_{fit}(M^2_{miss})$	625	442	87	101	46	14	303



$e^+e^- \to e^+e^-\pi^+\pi^-\pi^0$: preliminary result

observation of
$\gamma\gamma$ collisions @ 1 GeV

	signal	$\eta\gamma$	$\omega\pi^0$	$\pi^+\pi^-\pi^0$	K^+K^-	K_SK_L	$e^+e^-\gamma$
range variation	free	±15%	±1%	±7%	±25%	±15	free
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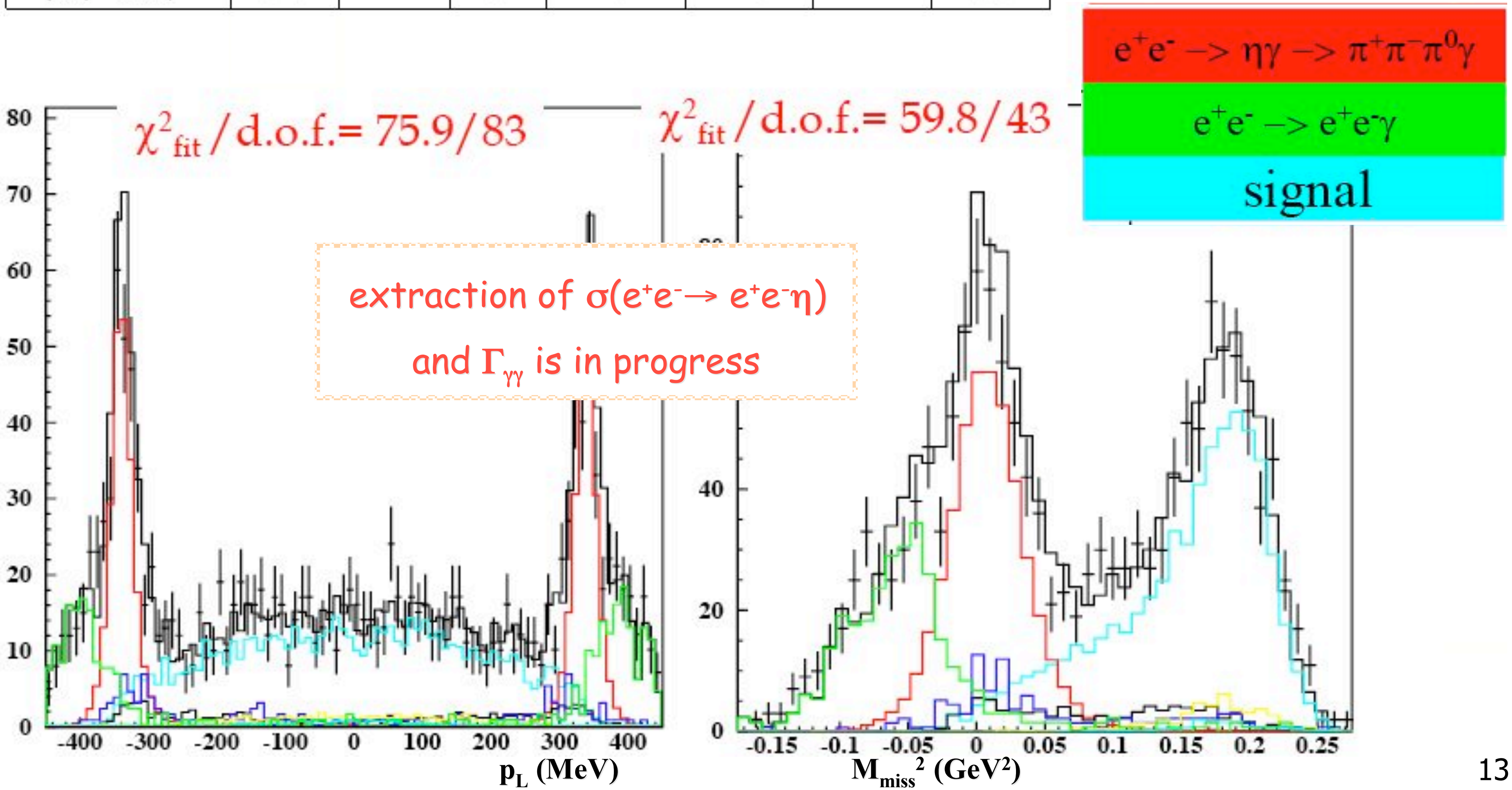
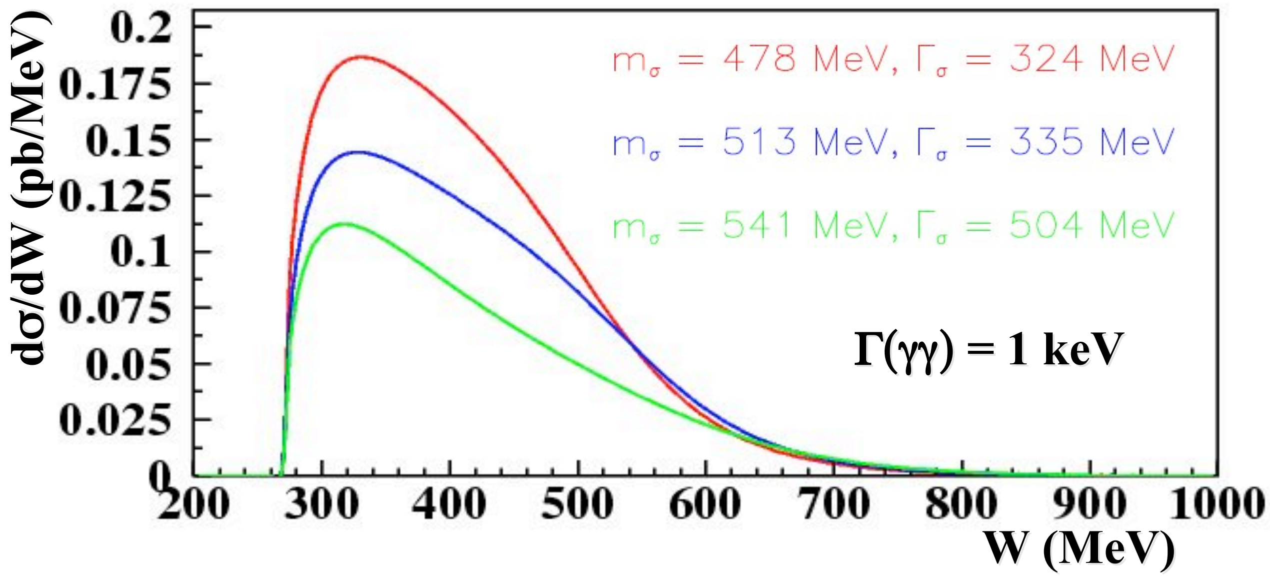


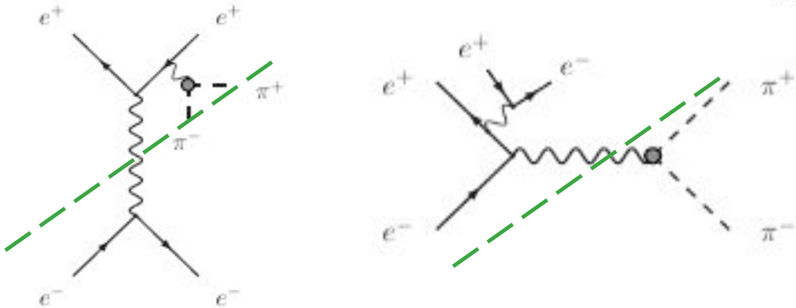
Search for $e^+e^- \to e^+e^-\pi^0\pi^0$

✓only process to measure directly the $\sigma\gamma\gamma$ coupling
→ infer structure

✓ $\pi^0\pi^0$ preferred wrt $\pi^+\pi^-$
→ vector states exchange switched off

BW shape folded with γγ flux function





and no background from $e^+e^- \to e^+e^-\mu^+\mu^-$

$f_0(600)$ PARTIAL WIDTHS

$\Gamma(\gamma\gamma)$

VALUE (keV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.2±0.4	[48] BERNABEU	08	RVUE	
3.9±0.6	[49] MENNESSIER	08	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
4.1±0.3	[50] PENNINGTON	06	RVUE	$\gamma\gamma \to \pi^0\pi^0$
3.8±1.5	[51,52] BOGLIONE	99	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
5.4±2.3	[51] MORGAN	90	RVUE	$\gamma\gamma \to \pi^+\pi^-, \pi^0\pi^0$
10 ±6	COURAU	86	DM1	$e^+e^- \to \pi^+\pi^-e^+e^-$

Identification of the $2\pi^0$ signal

- **4 γ with energy > 15 MeV, in acceptance**
- **no tracks**

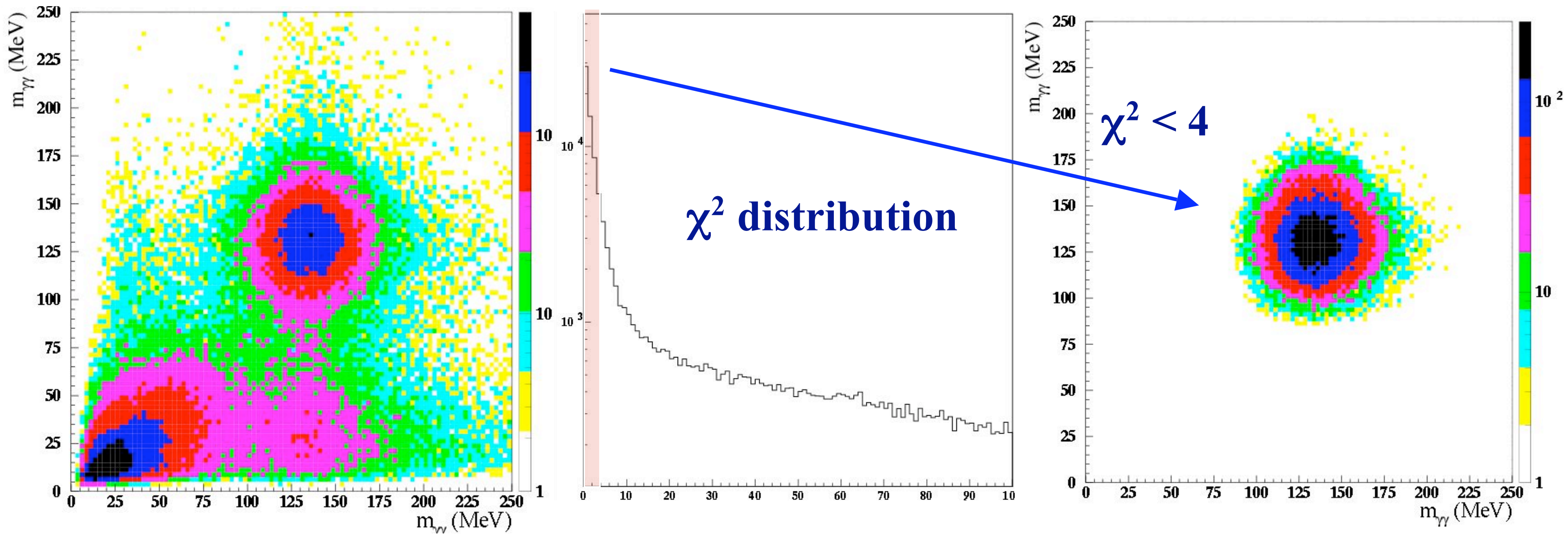
$$\chi^2_{pair} = \left(\frac{M_{ij} - m_{\pi 0}}{\sigma(E_i, E_j)}\right)^2 + \left(\frac{M_{lk} - m_{\pi 0}}{\sigma(E_l, E_k)}\right)^2$$

$$\frac{\sigma_E}{E} \sim \frac{0.06}{\sqrt{E(GeV)}}$$

$$\frac{\sigma(E_i, E_j)}{M_{ij}} = \frac{1}{2}\left(\frac{\sigma_{E_i}}{E_i} \oplus \frac{\sigma_{E_j}}{E_j}\right)$$

$$M_{ij}^2 = 2E_iE_j(1 - \cos\theta_{ij})$$

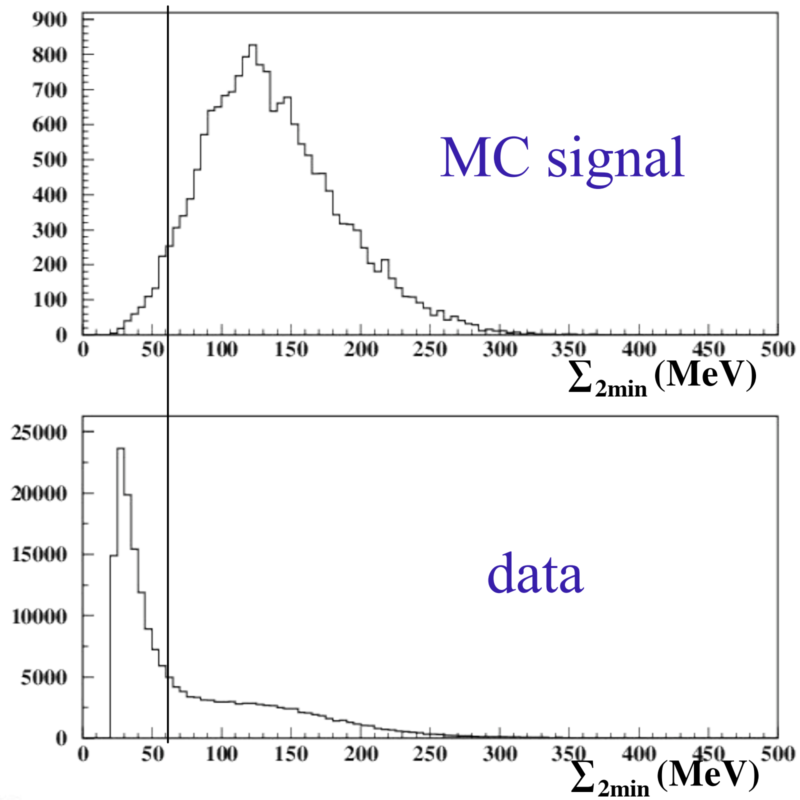
$m_{\gamma1\gamma2}$ vs. $m_{\gamma3\gamma4}$

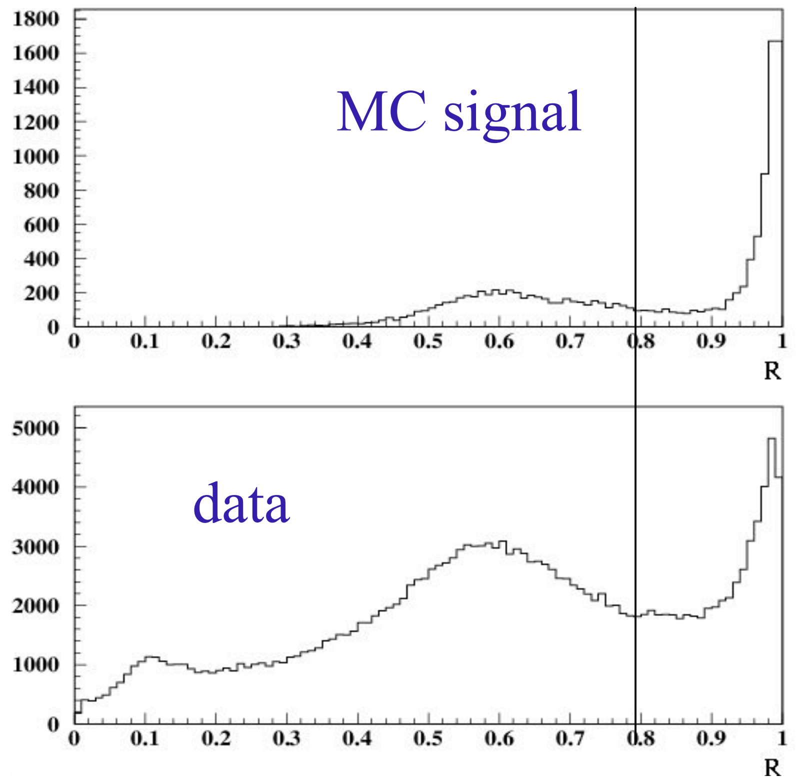


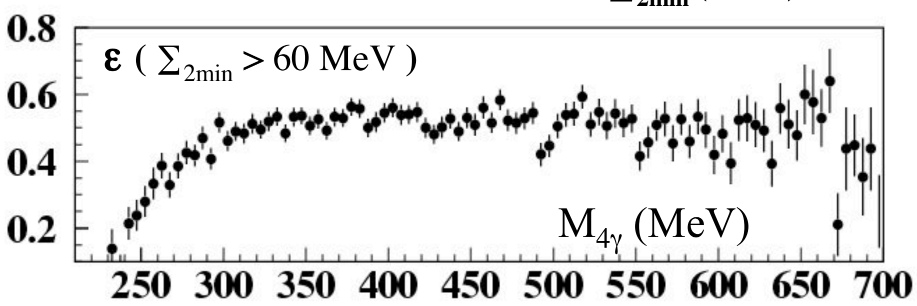
$e^+e^- \to e^+e^-\pi^0\pi^0$: analysis cuts

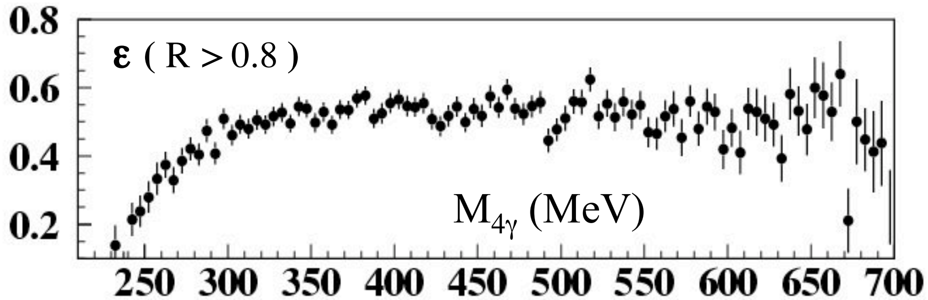
$\sum_{2min}$: sum of the energies of the two least energetic clusters

$$R = \frac{\sum_{i=1}^{4} E_i}{E_{calo}}$$









$e^+e^- \to e^+e^-\pi^0\pi^0$: background shapes

4 and only 4 γ

$\chi^2 < 4$

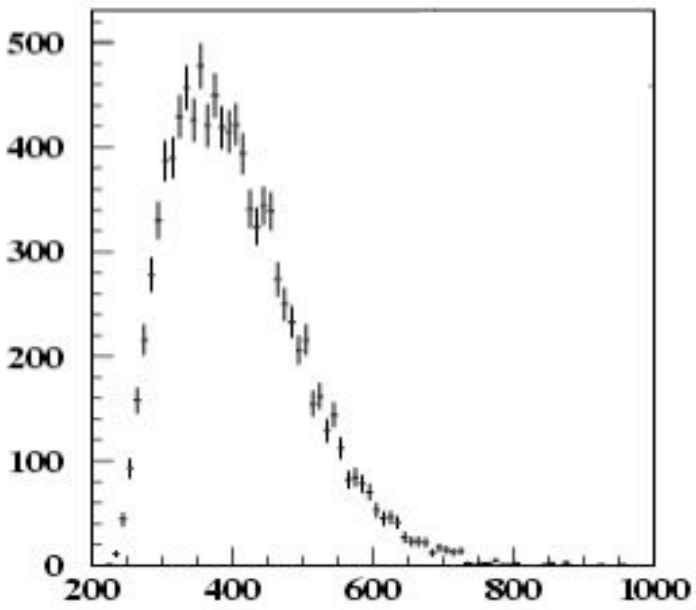
$R > 0.8$

$\sum_{2min} > 60$ MeV

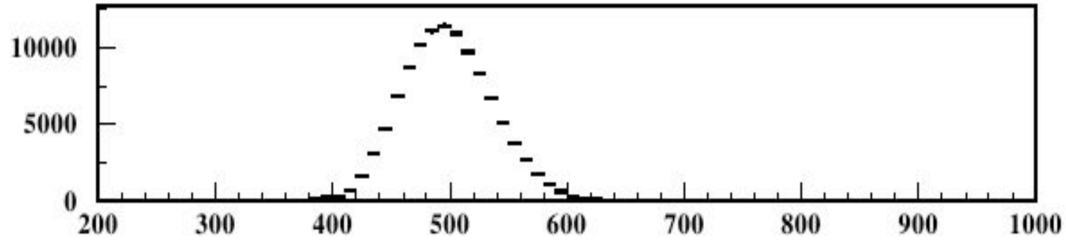
$p_T < 80$ MeV

no tracks

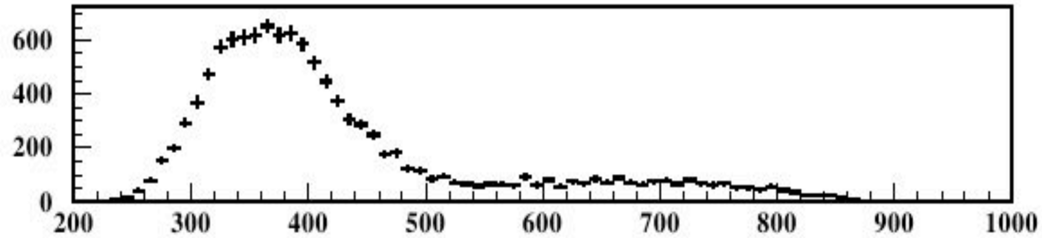
signal: $\varepsilon_{global} \sim 0.23\text{-}0.29$



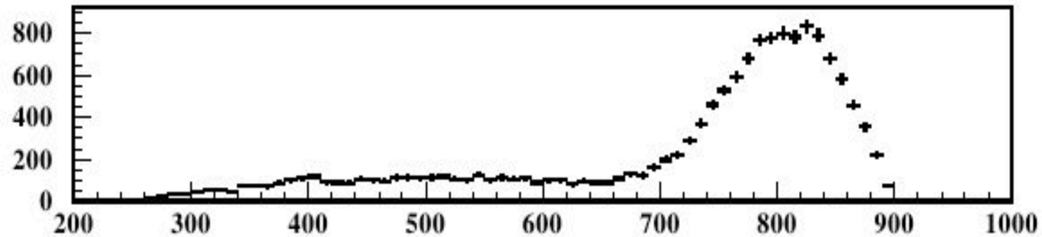
signal



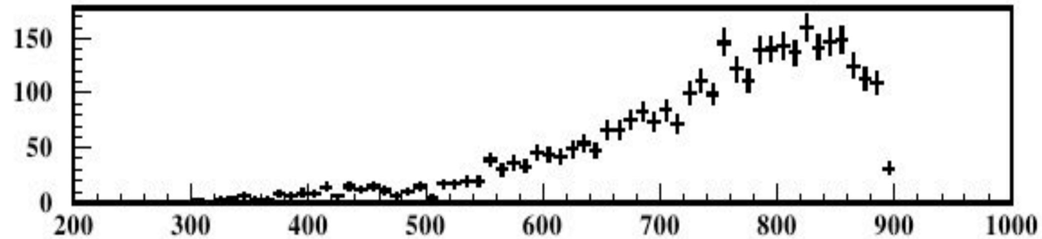
$K_S K_L \to \pi^0\pi^0 K_L$



$\eta \to 3\pi^0$



$\omega\pi^0 \to \gamma\pi^0\pi^0$



$f_0 \to 2\pi^0$

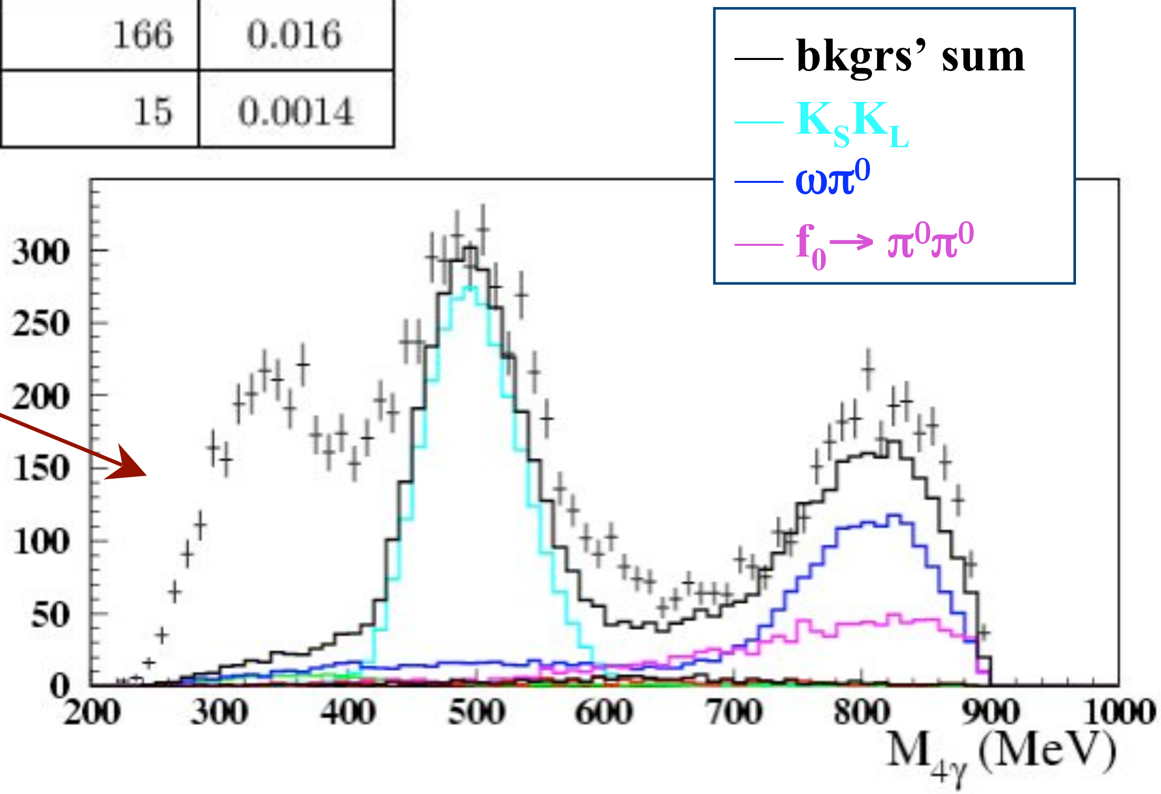
$e^+e^- \to e^+e^-\pi^0\pi^0$: expected background yields

	ϵ	σ (nb)	$n = \epsilon L \sigma$	$n/10188$
$K_S K_L$	5.60×10^{-3}	2.0	2 682	0.26
$\eta \to 3\pi^0$	1.79×10^{-3}	0.33	142	0.014
$\omega\pi^0$	1.55×10^{-2}	0.55	2 045	0.2
$f_0 \to 2\pi^0$	2.58×10^{-2}	0.17	1 052	0.10
$a_0 \to \eta\pi^0$	4.55×10^{-3}	0.11	120	0.012
$e^+e^- \to \gamma\gamma$	1.92×10^{-5}	360	166	0.016
$\eta \to \gamma\gamma$	1.57×10^{-4}	0.39	15	0.0014

from 239.6 pb^{-1}
10188 events after selection

we observe a clear evidence of $e^+e^- \to e^+e^-\pi^0\pi^0$ events at low $M_{4\gamma}$

the precise yield estimate depends on assumptions for the background processes



$e^+e^- \to e^+e^-\pi^0\pi^0$: expected background yields

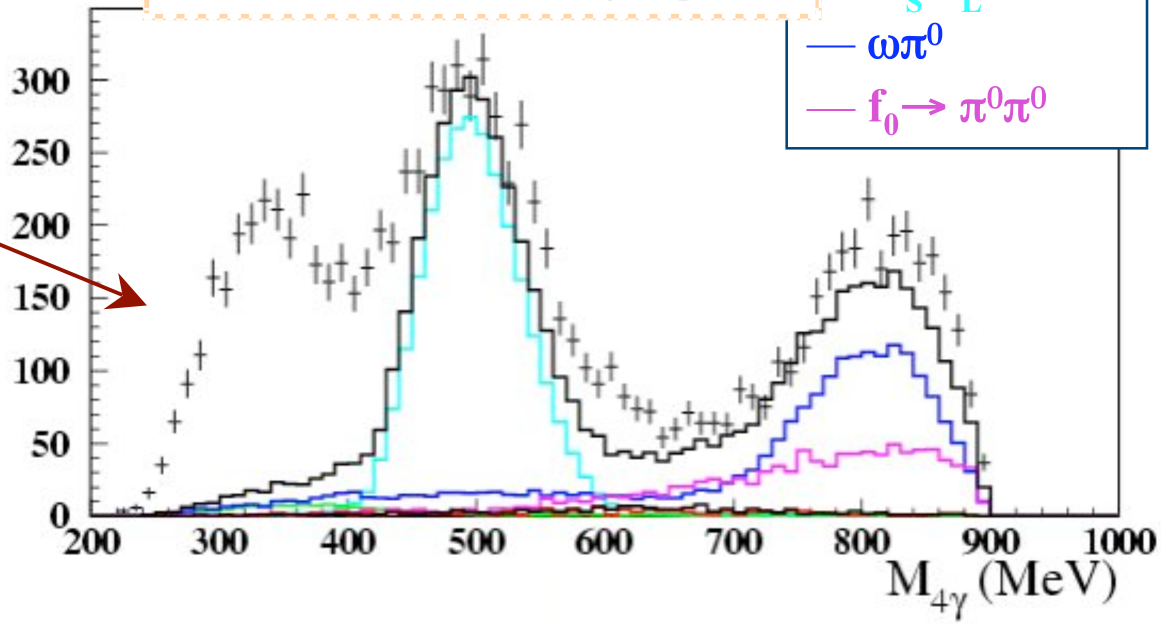
	ϵ	σ (nb)	$n = \epsilon L \sigma$	$n/10188$
$K_S K_L$	5.60×10^{-3}	2.0	2 682	0.26
$\eta \to 3\pi^0$	1.79×10^{-3}	0.33	142	0.014
$\omega\pi^0$	1.55×10^{-2}	0.55	2 045	0.2
$f_0 \to 2\pi^0$	2.58×10^{-2}	0.17	1 052	0.10
$a_0 \to \eta\pi^0$	4.55×10^{-3}	0.11	12[illegible]	[illegible]
$e^+e^- \to \gamma\gamma$	1.92×10^{-5}	360	16[illegible]	[illegible]
$\eta \to \gamma\gamma$	1.57×10^{-4}	0.39	1[illegible]	[illegible]

from 239.6 pb^{-1}
10188 events after selection

subtraction of backgrounds
and study of differential
cross section are in progress

we observe a clear evidence of $e^+e^- \to e^+e^-\pi^0\pi^0$ events at low $M_{4\gamma}$

the precise yield estimate depends on assumptions for the background processes



Conclusions

✓ unambiguous signature of both $\gamma\gamma \to \eta$ and $\gamma\gamma \to \pi^0\pi^0$ events, without any tagger and at $\sqrt{s}$ = 1 GeV

✓ $\gamma\gamma \to \eta$ observed through the $e^+e^- \to e^+e^- \eta$ process, with the $\eta \to \pi^+\pi^-\pi^0$ channel

✓ collected statistics allows to measure $\Gamma_{\gamma\gamma}(\eta)$ with accuracy comparable with existing measurements

✓ an exploratory research shows a structure (~ 4000 events) in the 4 γ invariant mass, where the process $e^+e^- \to e^+e^-\sigma \to e^+e^- \pi^0\pi^0$ is expected

✓ studies are under way to describe the $e^+e^- \to e^+e^- \pi^0\pi^0$ differential cross section to understand the σ meson contribution

KLOE and DAΦNE

✓ data collected at $\sqrt{s}$ = 1 GeV, suppressed ϕ decays

✓ instant luminosity = 7×10^{31} cm^{-2} s^{-1}, $\int L dt$ = 239.6 pb^{-1}

Calorimeter, EmC:

Pb/Scint. Fiber, 4880 PMTs

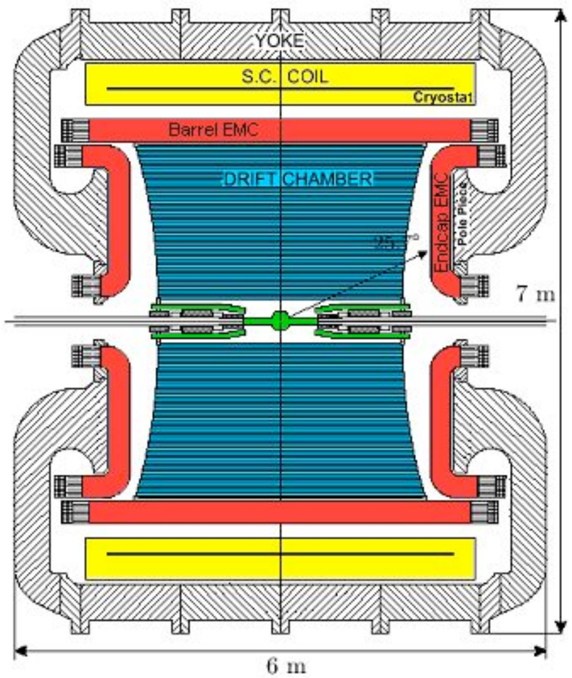
98% of solid angle

$\sigma_E / E = 0.057/\sqrt{E}$ (GeV)

$\sigma_t = 57$ ps / $\sqrt{E}$ (GeV) $\oplus$ 50 ps

$\sigma_\perp = 1.3$ cm

both detectors
w/ trigger decision



Drift Chamber, DC:

4 m Ø × 3.3 m length

90% He, 10% i-C_4H_{10}

12582 stereo sense wires

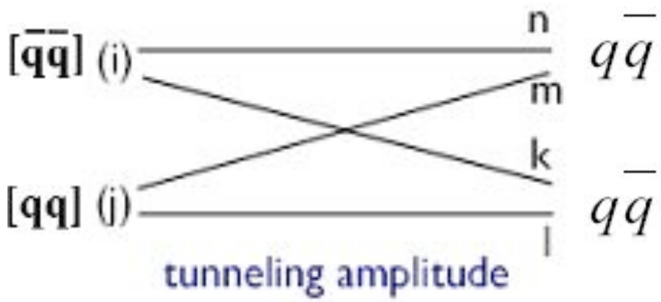
$\sigma_p / p = 0.4\%$ for $\theta > 45°$

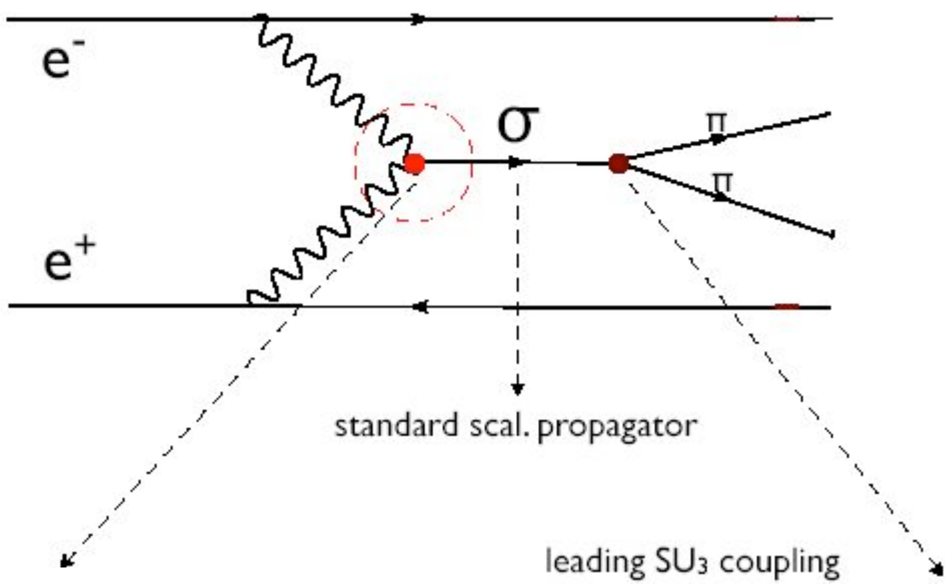
$\sigma_{r\varphi} = 0.150$ mm, $\sigma_z = 2$ mm

$\sigma(m_{\pi\pi}) \sim 1$ MeV

✓ no $e^\pm$ tagging device

The model for the σ produced in γγ (I)





$$\frac{\mathcal{A}}{M_\sigma^2}\phi_\sigma F^{\mu\nu}F_{\mu\nu}$$

$$\mathcal{A}\epsilon_{jlm}\epsilon^{ikn}S_i^j\Pi_k^l\Pi_n^m$$

1) the σ is a bound state made up of 2 diquarks, each diquark being a $[qq]_{\mathbf{\bar{3}_c},\mathbf{1_s},\mathbf{\bar{3}_f}}$

$$S=\begin{pmatrix}\frac{f_0+a^0}{\sqrt{2}} & a^+ & \kappa^+\\ a^- & \frac{f_0-a^0}{\sqrt{2}} & \kappa^0\\ \kappa^- & \bar{\kappa}^0 & \sigma_0\end{pmatrix}$$

2) the decay into 2 mesons is described by the probability of breaking each diquark shell, the coupling *A*

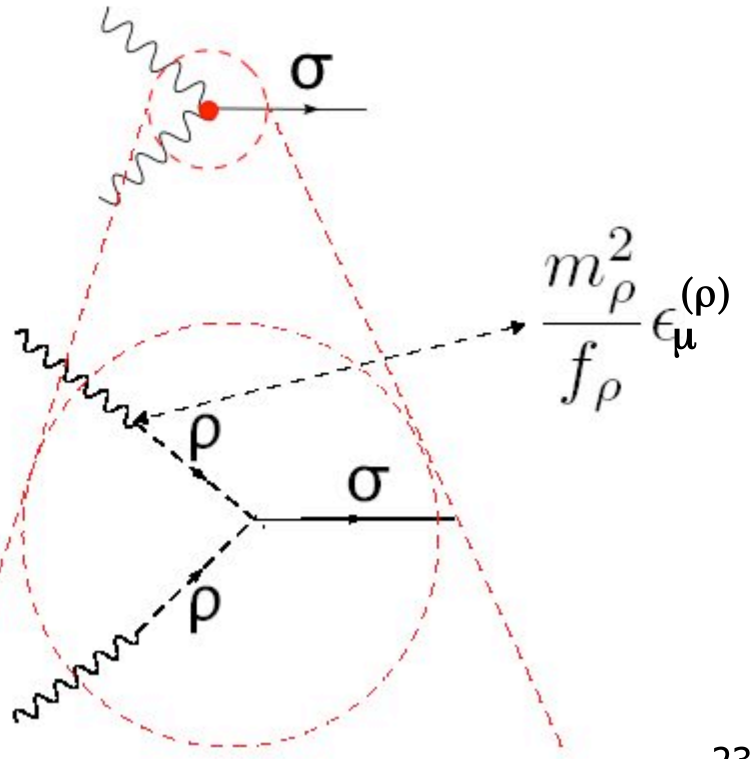
$$\Pi=\begin{pmatrix}\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+\\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta_8 & K^0\\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8\end{pmatrix}$$

The model for the σ produced in γγ (II)

$$\mathbf{V} = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}$$

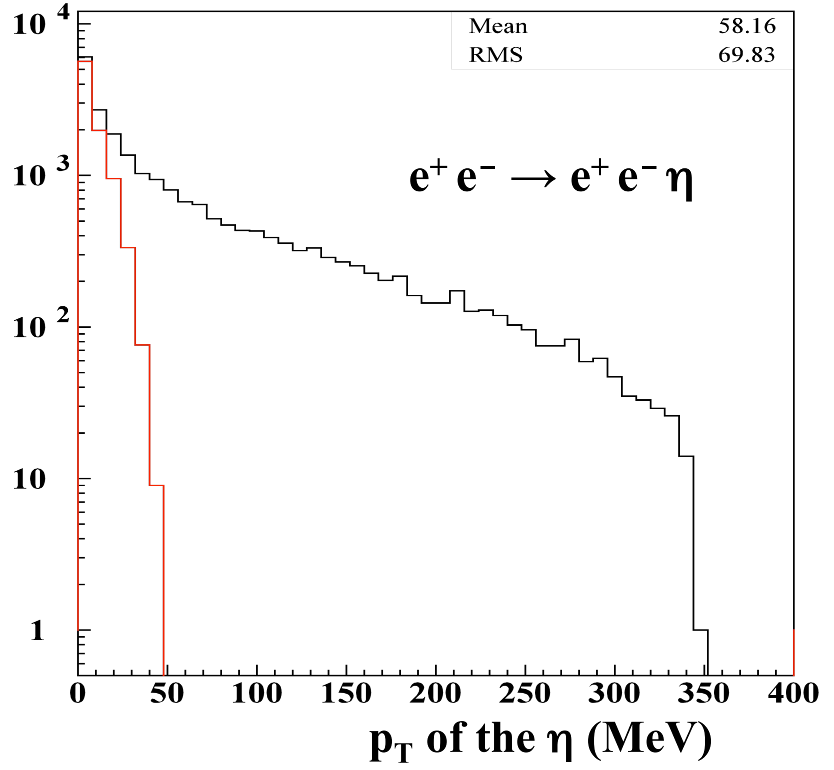
1) the σγγ coupling is parameterized by a similar dynamics, i. e. the breaking of the diquark shells into 2 ordinary $q\bar{q}$, but <u>vector</u> mesons, again the coupling *A*

2) the vector meson-photon transition is described by the standard VMD



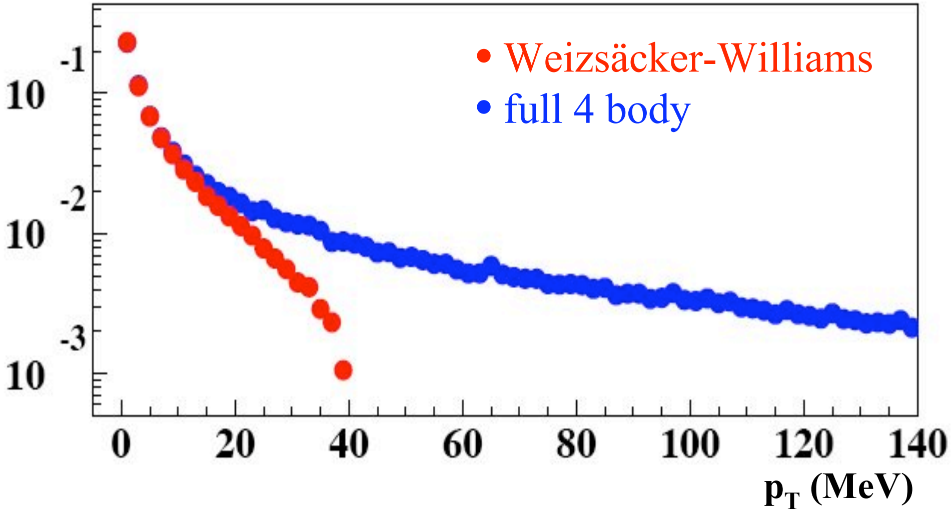
This is why we use again A on the 2-photon vertex.
The SU3 of vectors V^i_j is assumed to be controlled by the same coupling

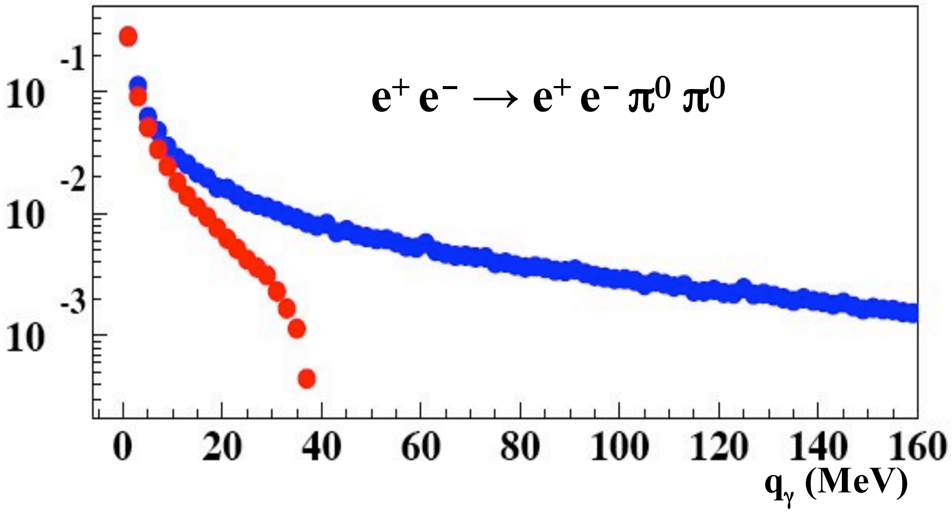
Spares

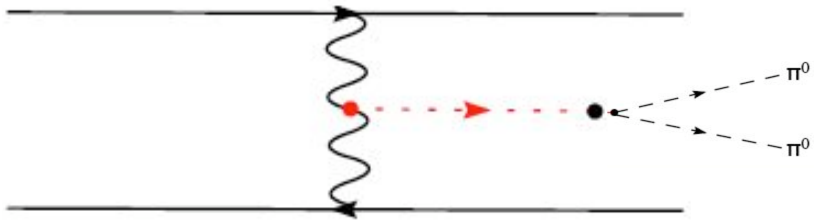


Mean 58.16
RMS 69.83
$e^+ e^- \to e^+ e^- \eta$
10^4
10^3
10^2
10
1
0
50
100
150
200
250
300
350
400
p_T of the η (MeV)

Comparison btw W.W. and phase space







1) the σ is a bound state made up of 2 diquarks, each diquark being a $[qq]_{\bar{3}_c, 1_s, \bar{3}_f}$

2) the decay into 2 mesons or 2 photons is described by the probability of breaking each diquark shell

F.N., F. Piccinini & A. Polosa
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W.W. is reproduced with a cut
$\theta < 5^o$ for both e^+e^- in the final state