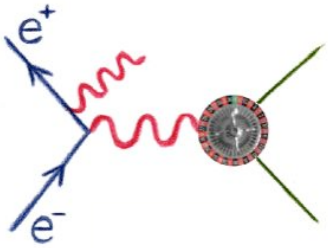


Working Group on Radiative Corrections and Generators for Low Energy Hadronic Cross Section and Luminosity

Two-Photon Physics Results at KLOE

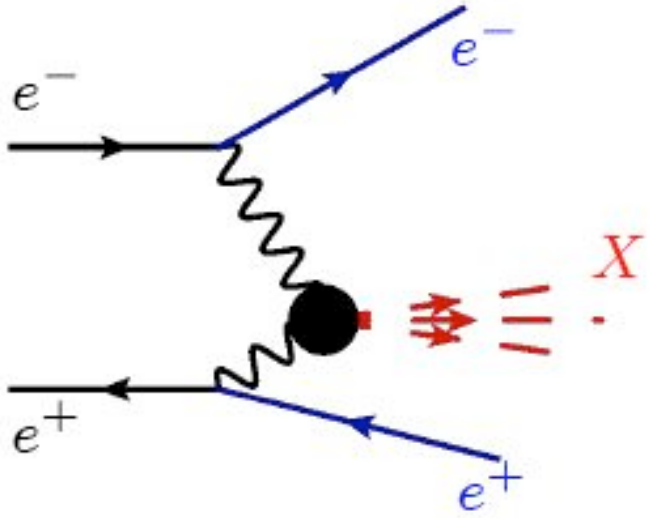
Federico Nguyen
for the KLOE/KLOE-2 Collaborations
LNF - *April, 17th 2012*

INFN ROMA Tre

Outline

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$$

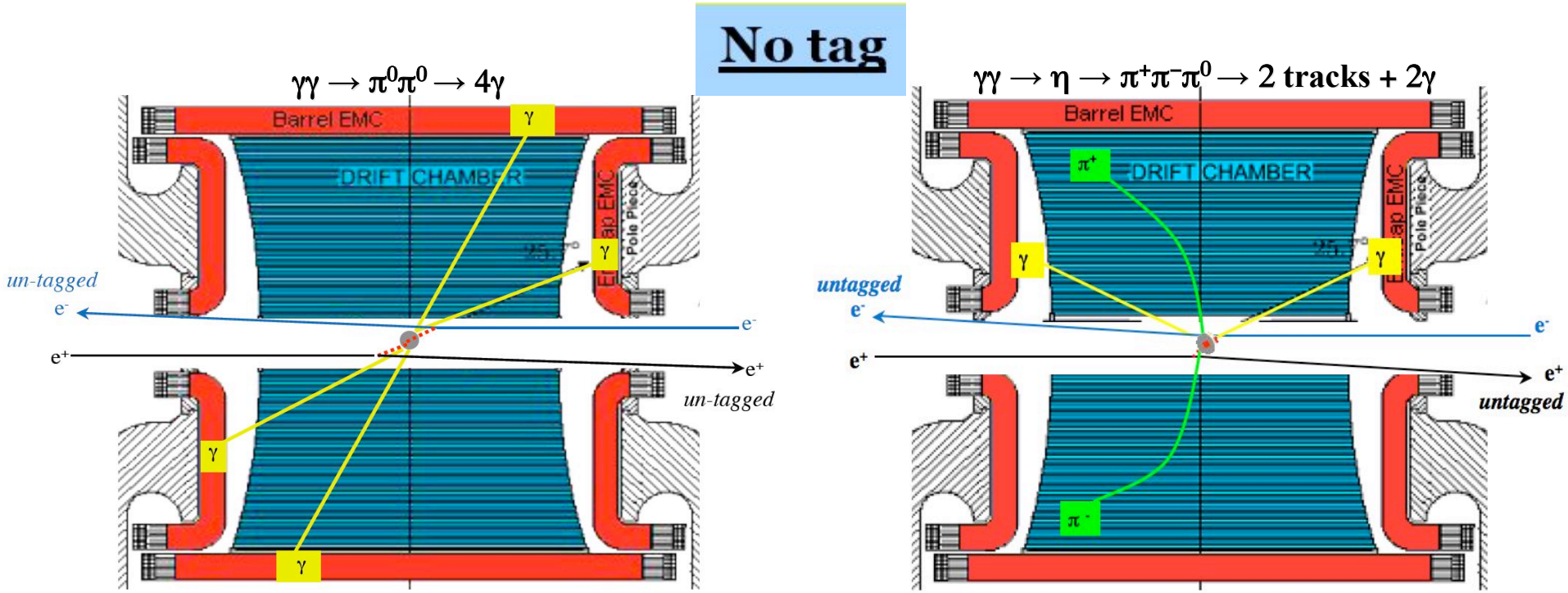
- $\gamma\gamma$ physics with KLOE: introduction
- 1st observation of $\gamma\gamma \to \eta$ at $\sqrt{s}$ = 1 GeV: $\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$ and $\gamma\gamma \to \eta \to \pi^0\pi^0\pi^0$
- spectrum study of $\gamma\gamma \to \pi^0\pi^0$
- outlook and conclusions



γγ interactions with KLOE

240 pb^{-1} taken @ $\sqrt{s}$ = 1 GeV, to suppress background from φ decays

No tag



B=0.52 T

Calorimeter, EmC:
Pb/Scint. Fiber, 4880 PMTs
$\sigma_E/E = 0.057/\sqrt{E\ (GeV)}$
$\sigma_t = 57\ ps/\sqrt{E\ (GeV)} \oplus 100\ ps$

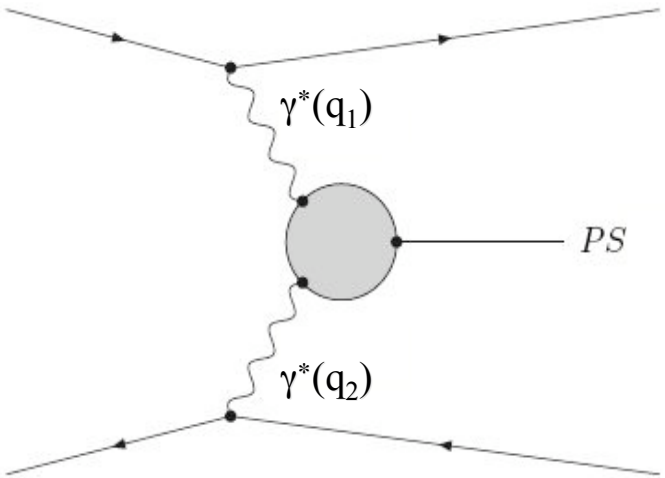
Drift Chamber, DC:
90% He, 10% C_4H_{10}
$\sigma_p/p = 0.4\%$ for $\theta > 45°$
$\sigma_{r\phi} = 0.15\ mm$, $\sigma_z = 2\ mm$

Pseudoscalar mesons: γγ widths

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

for narrow pseudoscalar mesons (e.g. π^0, η, η', etc…):

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



absolute measurement: either your decay channel is X → γγ or must know BR(X→f) for a certain final state f

spectrum measurement, as a function of a single momentum transfer, fixing or integrating over the other one, 2-dim PDF not yet measured

PS form factors: from models to the $(g-2)_\mu$

important to test phenomenological models, more or less QCD/ChPT inspired…, but impacts also on the $(g-2)_\mu$

e.g.

$$F(k_1^2, k_2^2) = \frac{m_\rho^2}{(m_\rho^2 - k_1^2 - k_2^2)}$$

$$F(k_1^2, k_2^2) = \frac{m_\rho^4 - \frac{4\pi^2 F_\pi^2}{N_c}(k_1^2 + k_2^2)}{(m_\rho^2 - k_1^2)(m_\rho^2 - k_2^2)}$$

from F.Jegerlehner & A.Nyffeler, Phys. Rept,477(2009)1

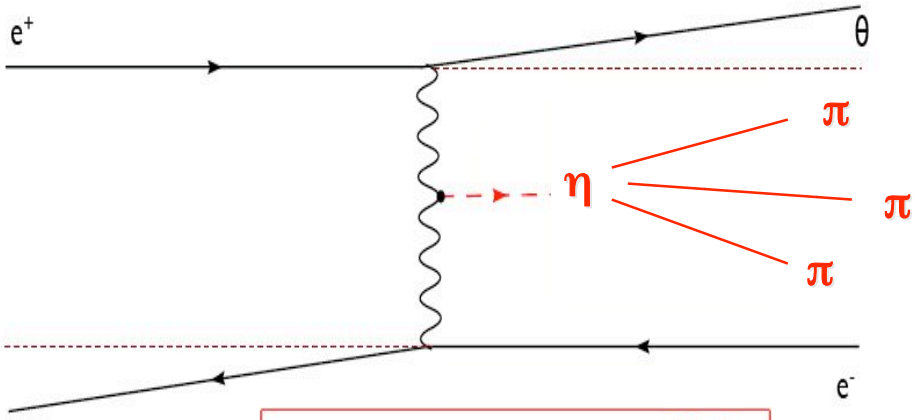
Standard model theory and experiment comparison [in units 10^{-11}].

Contribution	Value	Error
QED incl. 4-loops + LO 5-loops	116584718.1	0.2
Leading hadronic vacuum polarization	6903.0	52.6
Subleading hadronic vacuum polarization	−100.3	1.1
Hadronic light-by-light	116.0	39.0
Weak incl. 2-loops	153.2	1.8
Theory	116591790.0	64.6
Experiment	116592080.0	63.0
Exp. - The. 3.2 standard deviations	290.0	90.3

Present situation on the η meson

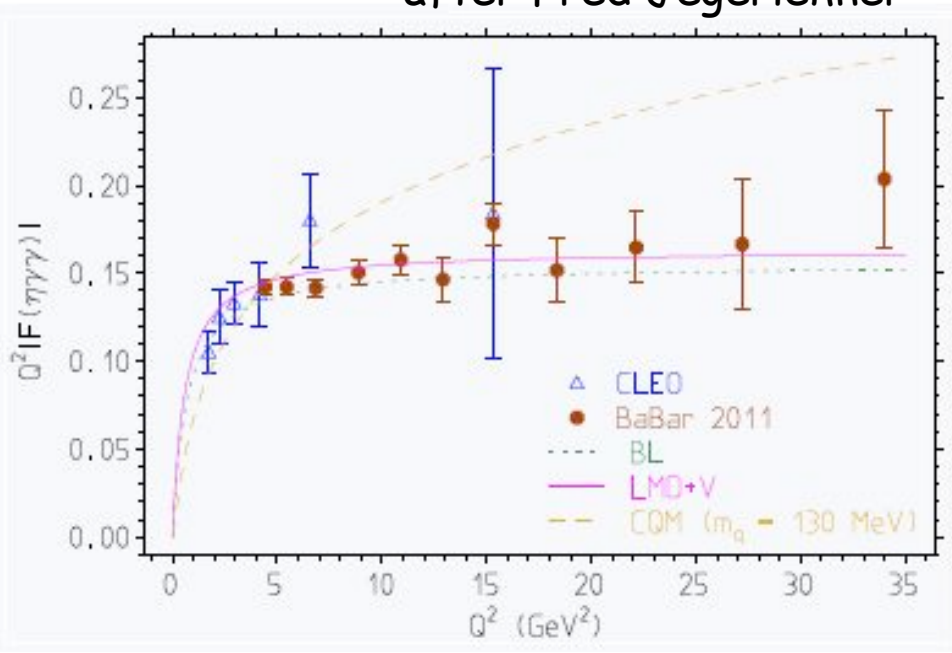
$\Gamma(\gamma\gamma)$

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**



η branching ratios [%]	
$\pi^+\pi^-\pi^0$	22.74 ± 0.28
$\pi^0\pi^0\pi^0$	32.57 ± 0.23

after Fred Jegerlehner



$e^+e^- \to \eta\gamma$ background:
not only an issue...

Search for $\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$

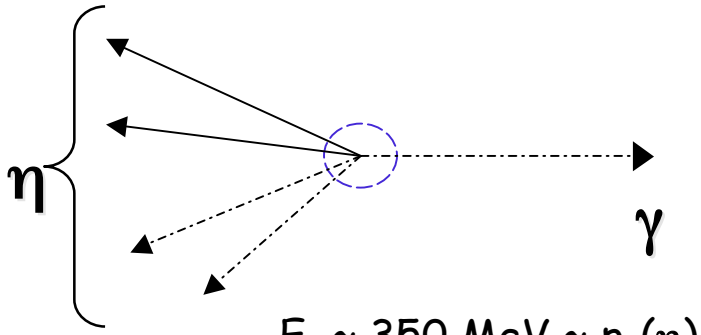
BR($\eta \to \pi^+\pi^-\pi^0$) = 22.73%

2 photons + 2 tracks with opposite charge

$$\chi^2_\eta = \sum \frac{(P_i - P_i^{meas})^2}{\sigma_i^2} + \sum \lambda_j^k C_j(P_1^k \ldots P_N^k)$$

- $\gamma\gamma$ pairing
- charged pion ID
- p_T < 100 MeV
- kinematic fit, χ^2_η

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



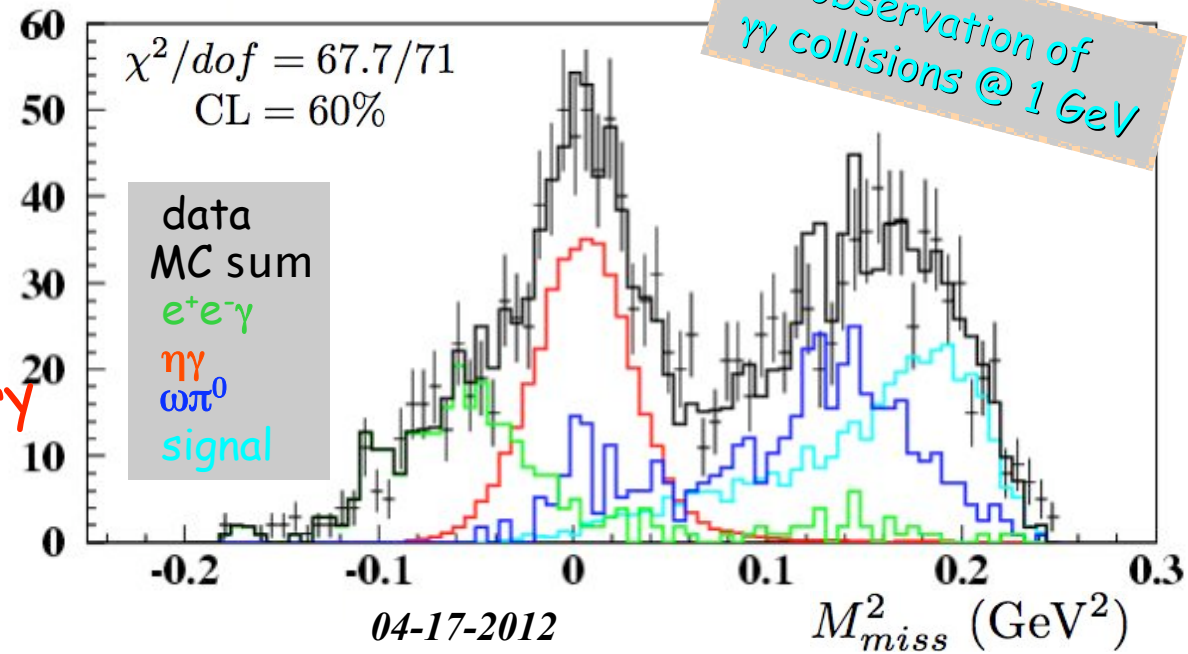
$E_\gamma \sim 350$ MeV ~ $p_L(\eta)$

only irreducible background is $e^+e^- \to \eta(\to \pi^+\pi^-\pi^0)\,\gamma_{lost}$

1500 data events,
signal fraction ~ 26%
efficiency ε ~ 17%

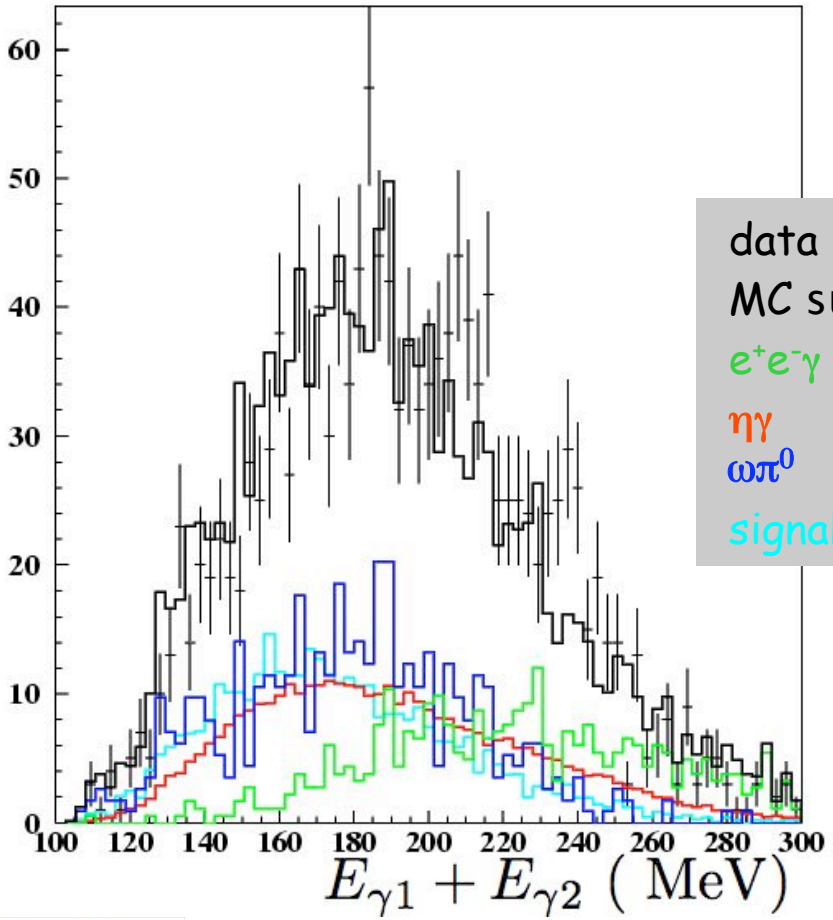
preliminary

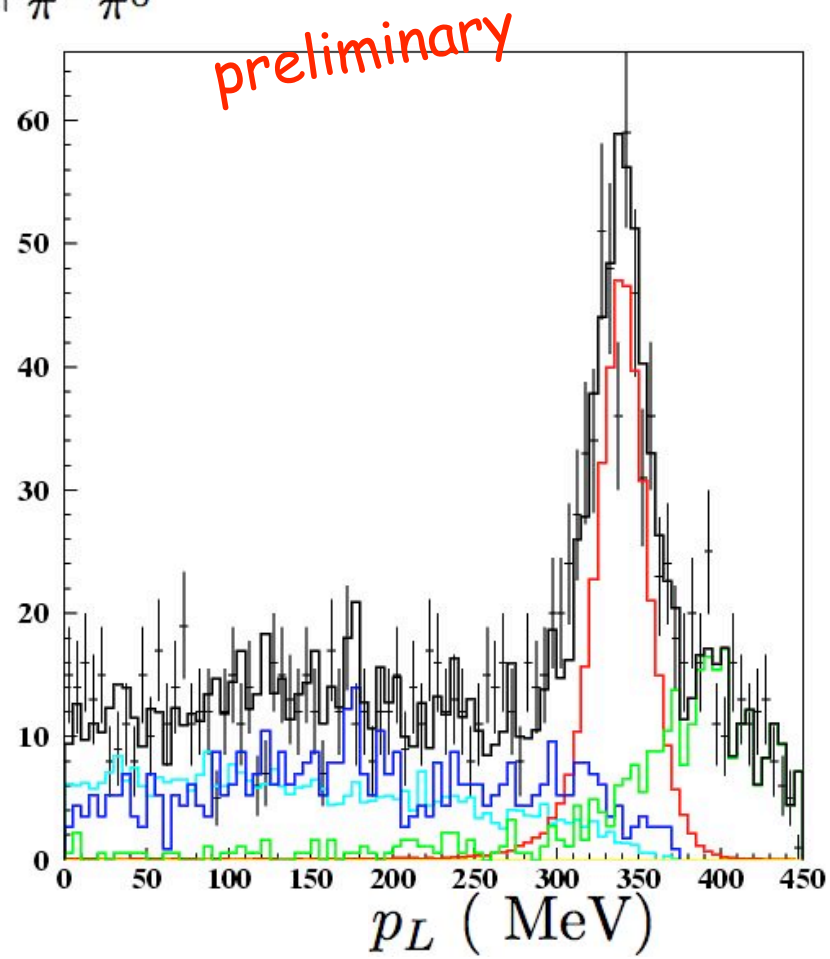
observation of $\gamma\gamma$ collisions @ 1 GeV



Search for $\gamma\gamma \to \eta \to \pi^+\pi^-\pi^0$

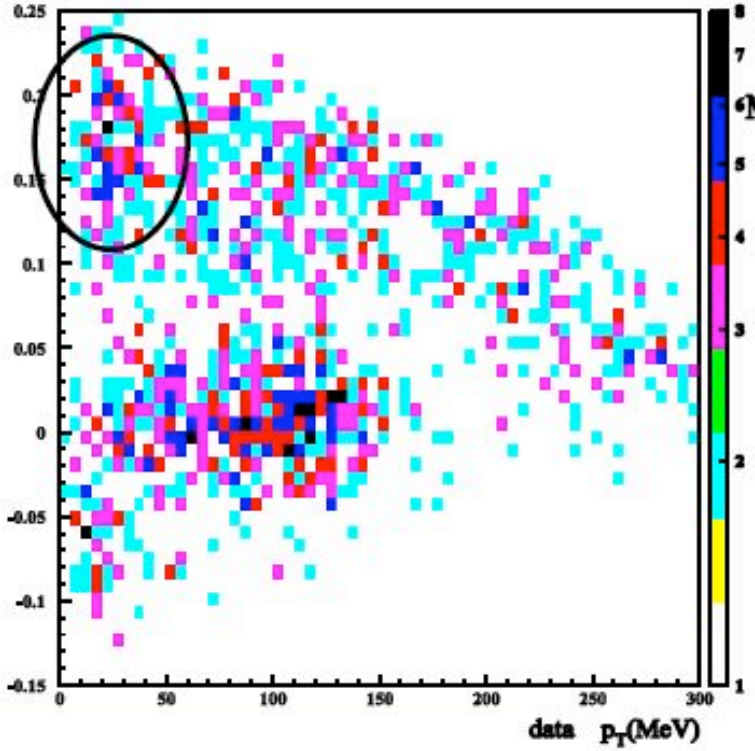
$$\sigma_{e^+e^-\to e^+e^-\eta} = \frac{\%\, N_{data}}{\mathcal{L}\,\varepsilon}\,\frac{1}{\mathrm{BR}_{\eta\to\pi^+\pi^-\pi^0}} = (41.7 \pm 4_{\mathrm{stat}})\ \mathrm{pb}$$



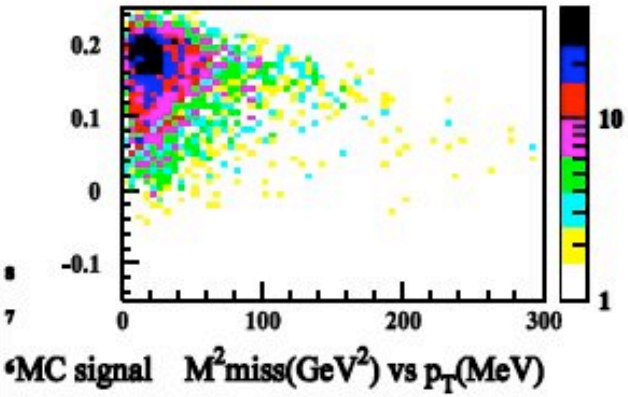


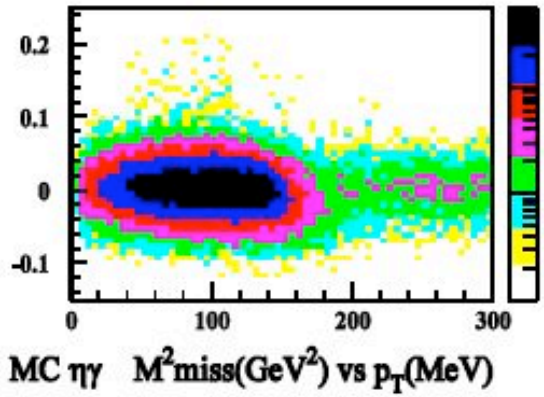
Improvements for $\gamma\gamma \rightarrow \eta \rightarrow \pi^+\pi^-\pi^0$

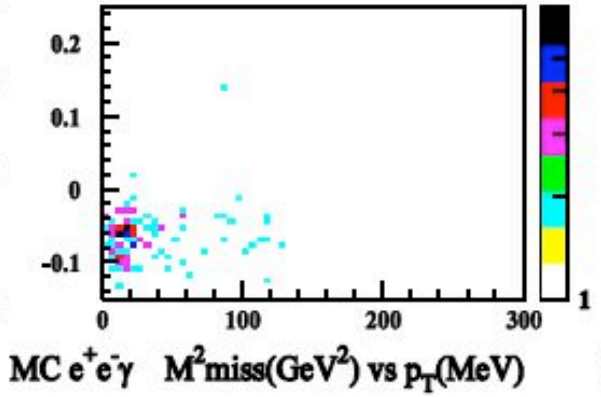
2D distributions to fit,
M^2_{miss} vs p_T

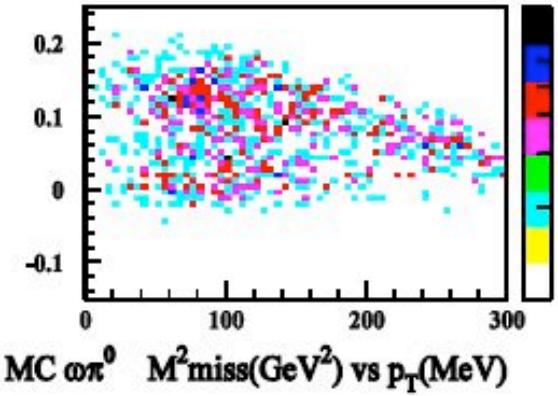


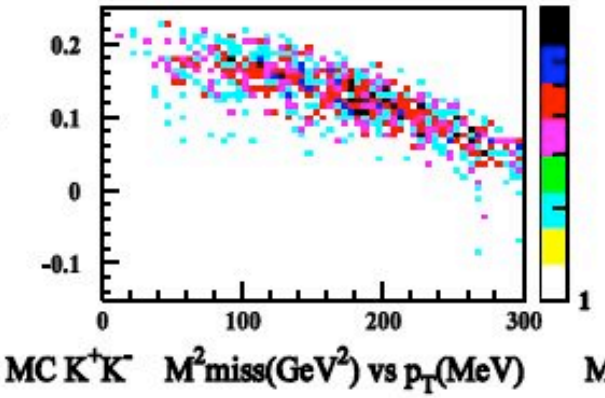
fit in the 2D distributions including p_T, instead of cut

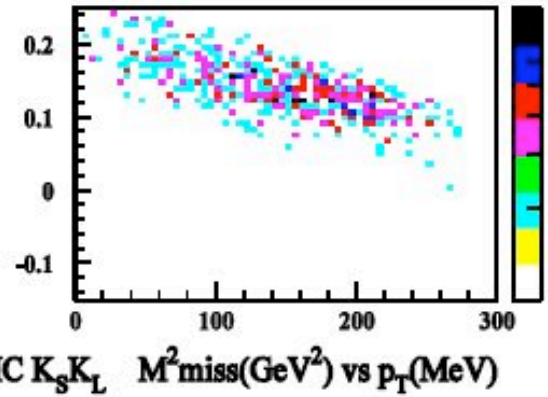










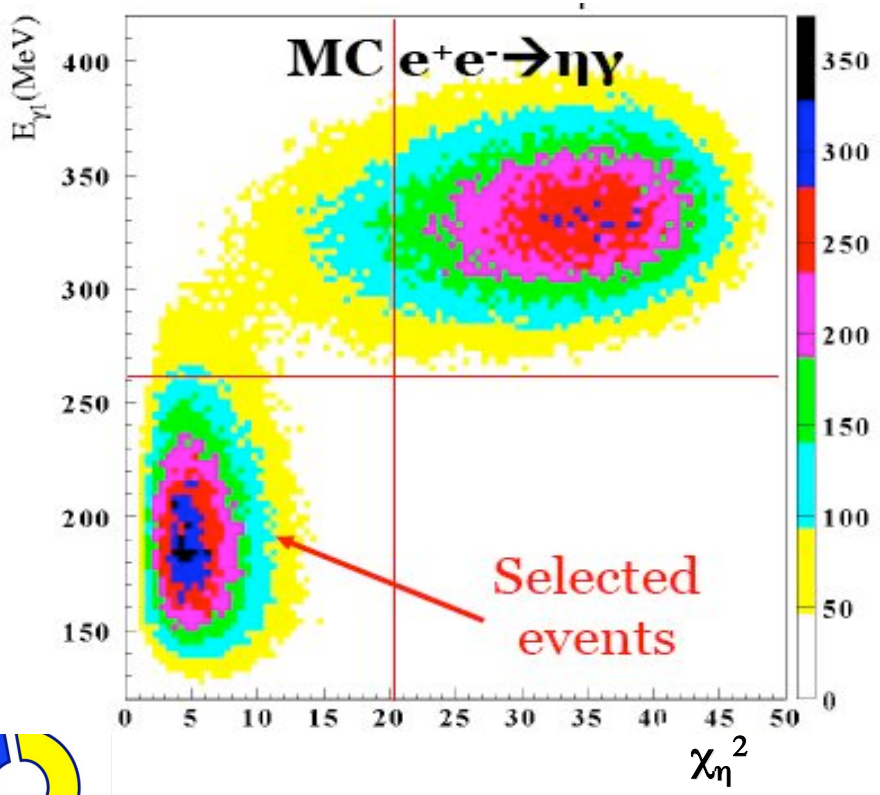


Search for $\gamma\gamma \rightarrow \eta \rightarrow 3\pi^0$

$BR(\eta \rightarrow 3\pi^0) = 32.57\%$

6 photons and NO tracks

- $\gamma\gamma$ pairing to 3 pions
- kinematic fit, χ_η^2
- most energetic γ E<260 MeV



$$\chi^2_\eta = \sum \frac{(P_i - P_i^{meas})^2}{\sigma_i^2} + \sum \lambda_j^k C_j(P_1^k \ldots P_N^k)$$

$$m^2_{6\gamma} = m^2_\eta$$

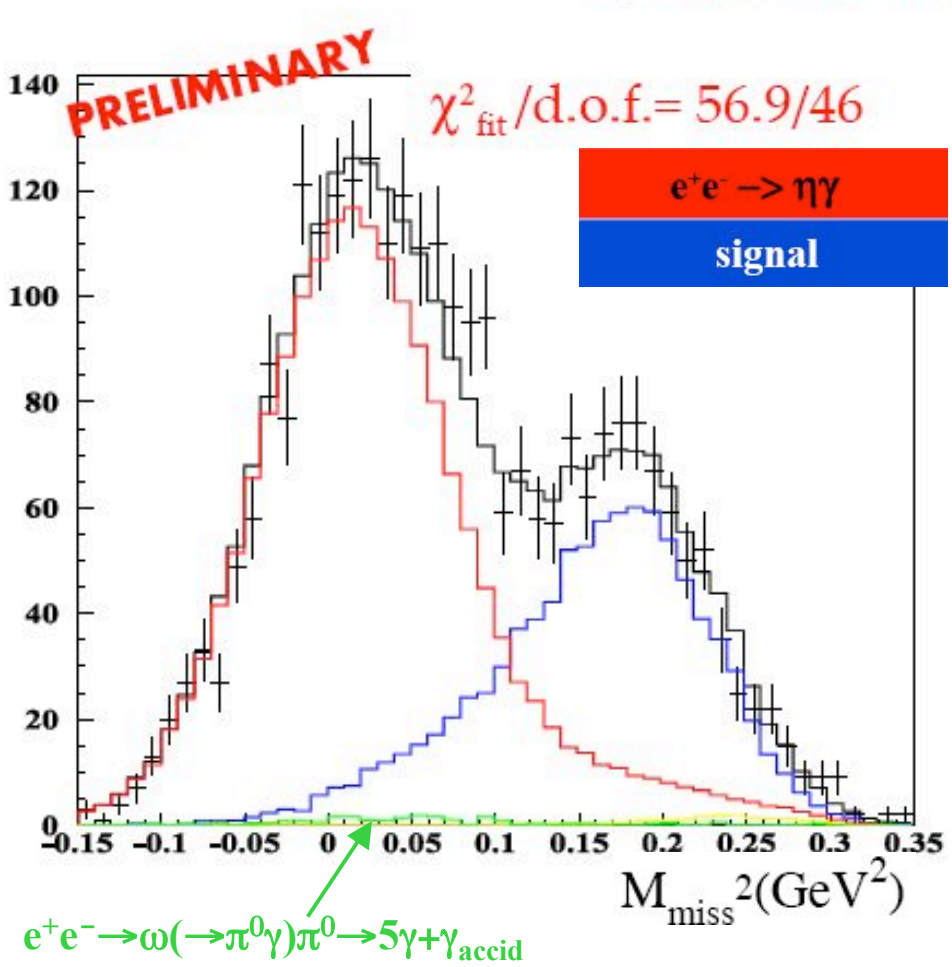
$$t_\gamma - |\underline{r}_\gamma| / c = 0 \quad \text{for } 6\gamma$$

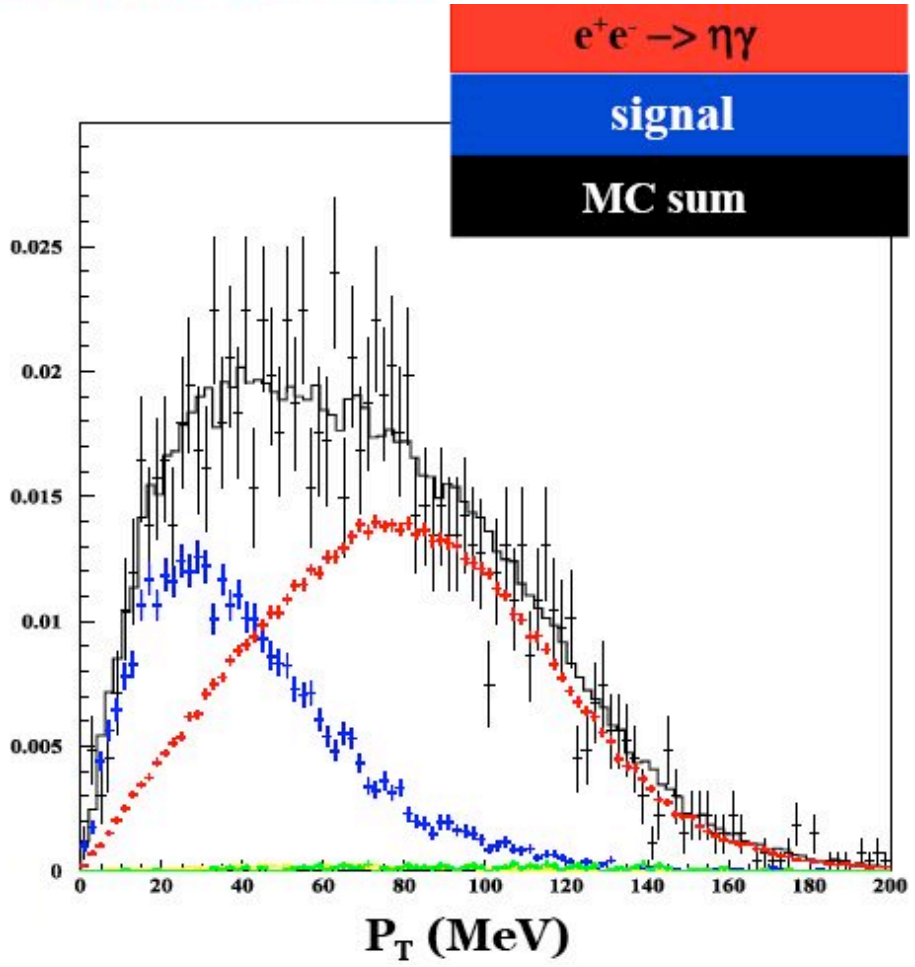
only ~~irreducible~~ background

is $e^+e^- \rightarrow \eta(\rightarrow \pi^0\pi^0\pi^0)\,\gamma_{lost}$

Search for $\gamma\gamma \rightarrow \eta \rightarrow 3\pi^0$

2725 data events after all cuts

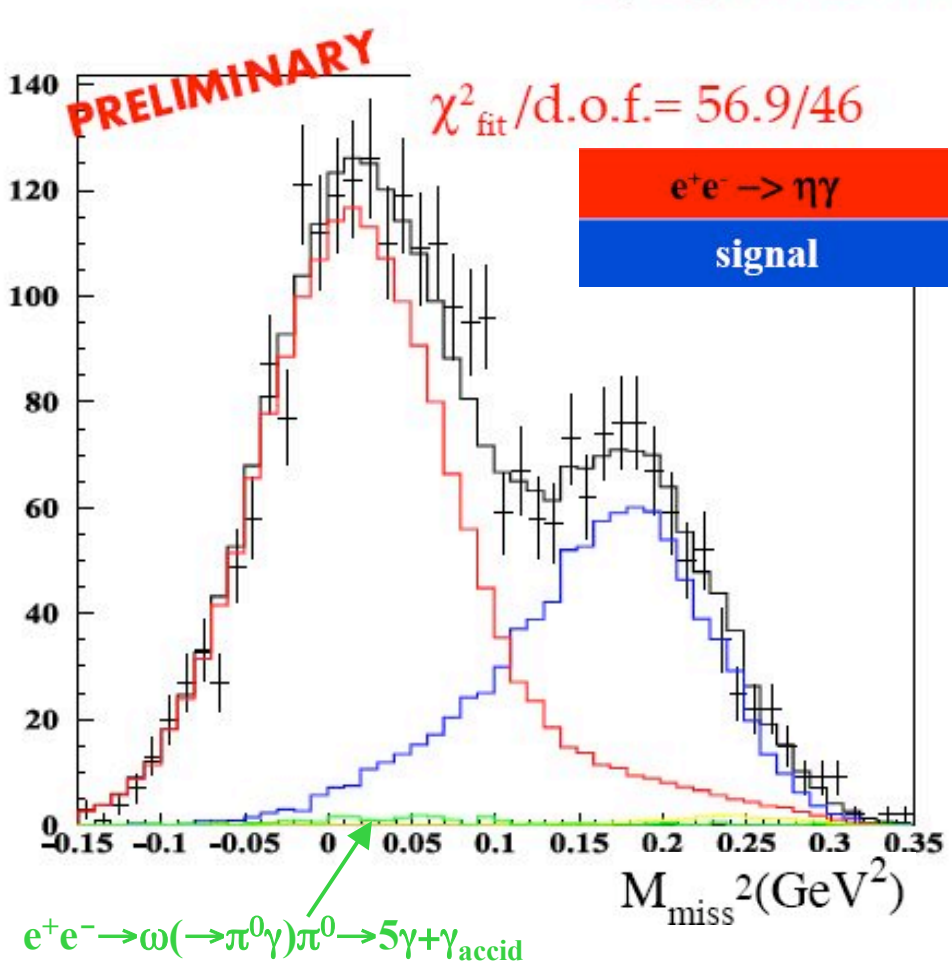


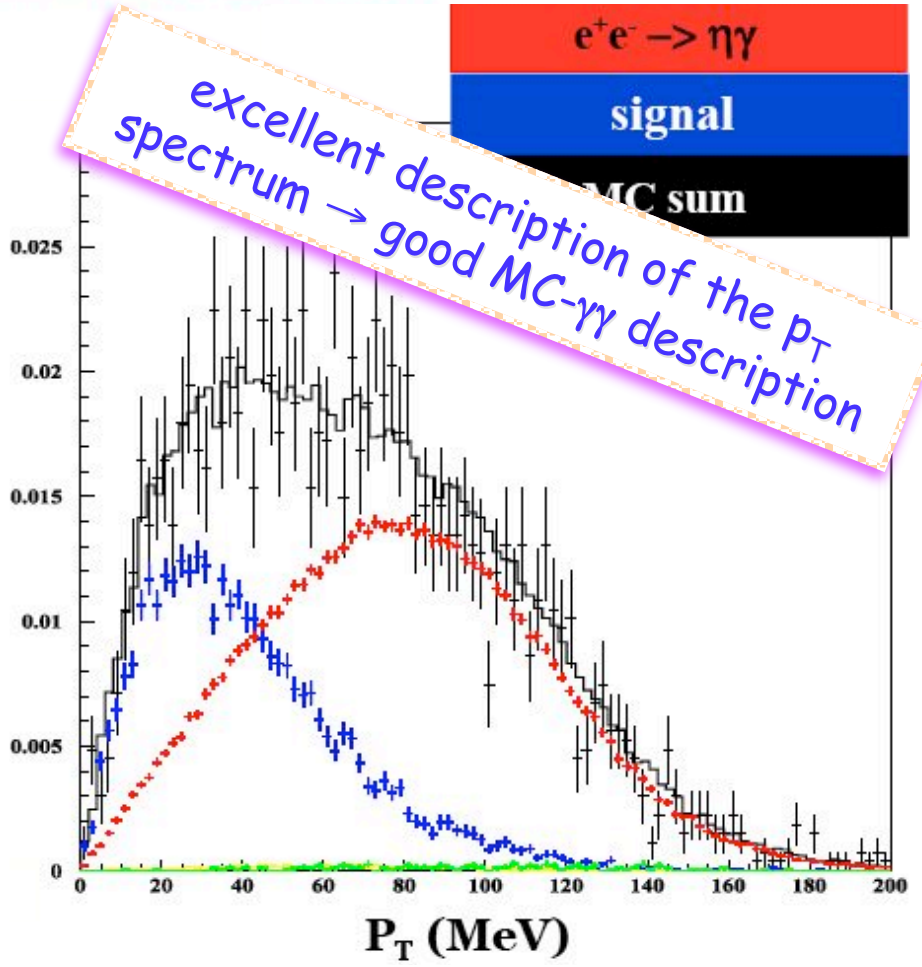


$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s}=1\ \text{GeV}) = (37.0 \pm 1.4_{stat} \pm 2.2_{syst})\ \text{pb}$$

Search for $\gamma\gamma \rightarrow \eta \rightarrow 3\pi^0$

2725 data events after all cuts





excellent description of the p_T spectrum → good MC-$\gamma\gamma$ description

$$\sigma(e^+e^- \rightarrow e^+e^-\eta, \sqrt{s}=1\ \text{GeV}) = (37.0 \pm 1.4_{stat} \pm 2.2_{syst})\ \text{pb}$$

Status of $\gamma\gamma \rightarrow \eta$

Charged channel:

$$\sigma\,(e^+e^- \rightarrow e^+e^-\eta,\ \sqrt{s}=1\ \mathrm{GeV}) = (41.7 \pm 4.0_{\mathrm{stat}} \pm ??_{\mathrm{syst}})\ \mathrm{pb}$$

1st channel where we had signal evidence, looser selection to be < 10% stat. error

Neutral channel:

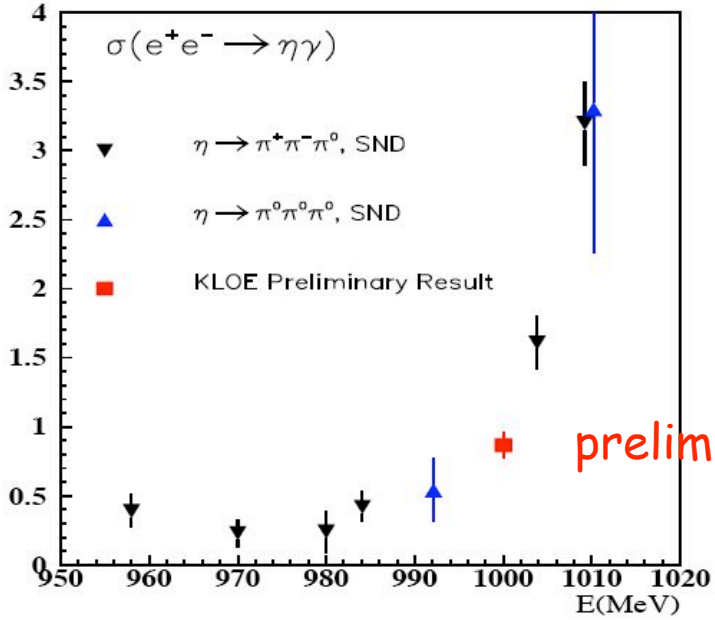
$$\sigma\,(e^+e^- \rightarrow e^+e^-\eta,\ \sqrt{s}=1\ \mathrm{GeV}) = (37.0 \pm 1.4_{\mathrm{stat}} \pm 2.2_{\mathrm{syst}})\ \mathrm{pb}$$

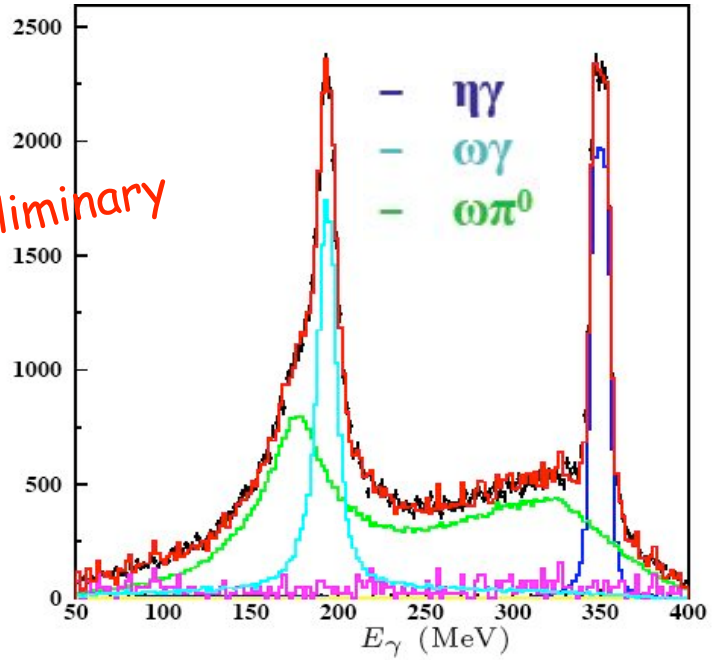
background free measurement, a bit tighter selection to have syst. < stat. errors
($\eta\gamma$ tail affecting the measurement stability, due to photon resolution)

Measurement of $\sigma(e^+e^- \to \eta\gamma)$ @ 1 GeV

- $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$: 3 photons + 2 tracks
  - pion ID
  - kinematic cuts to suppress background from kaons
  - kinematic fit

$\sigma(e^+e^- \to \eta\gamma, 1\ \text{GeV}) = (0.866 \pm 0.009 \pm 0.093)$ nb





- In agreement with the result from $\eta \to \pi^0\pi^0\pi^0$: 6γ with imposed π^0,η + miss. E

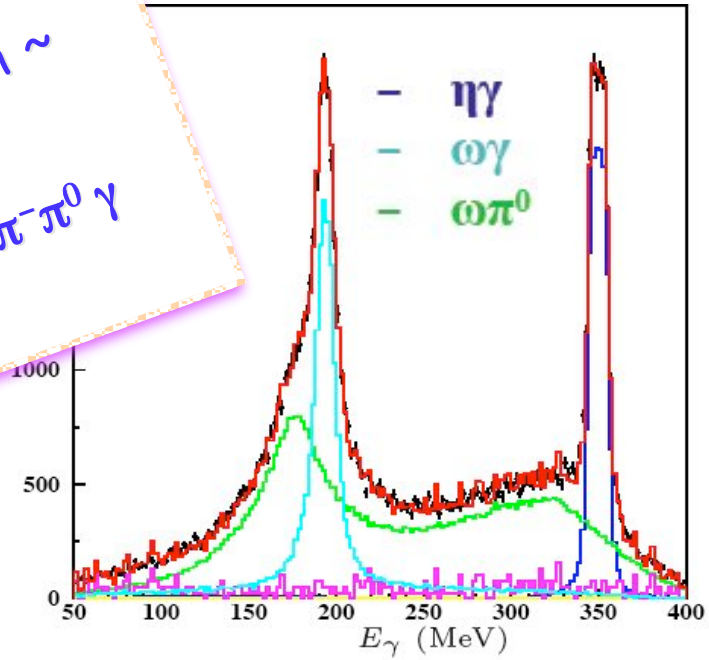
$\sigma(e^+e^- \to \eta\gamma, 1\ \text{GeV}) = (0.875 \pm 0.018 \pm 0.035)$ nb

background for $\gamma\gamma \to \eta$ most accurately measured from the same 240 pb^{-1} sample

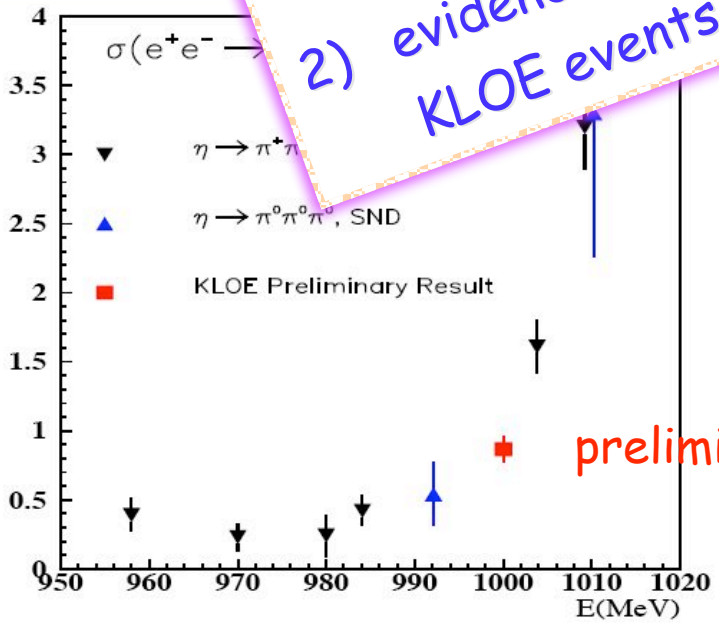
Measurement of $\sigma(e^+e^- \to \eta\gamma)$ @ 1 GeV

- $e^+e^- \to \eta\gamma \to \pi^+\pi^-\pi^0\gamma$: 3 photons + ?
  - pion ID
  - kinematic cuts t…
  - from k…
  - kin…

1) we have energy scan data with $\sqrt{s}$ ~ 1010-1030 MeV, each point with ~ 10 pb^{-1} int. luminosity
2) evidence of ISR-produced $\pi^+\pi^-\pi^0\gamma$ KLOE events peaking at ω



$\sigma(e^+e^- \to \eta$…



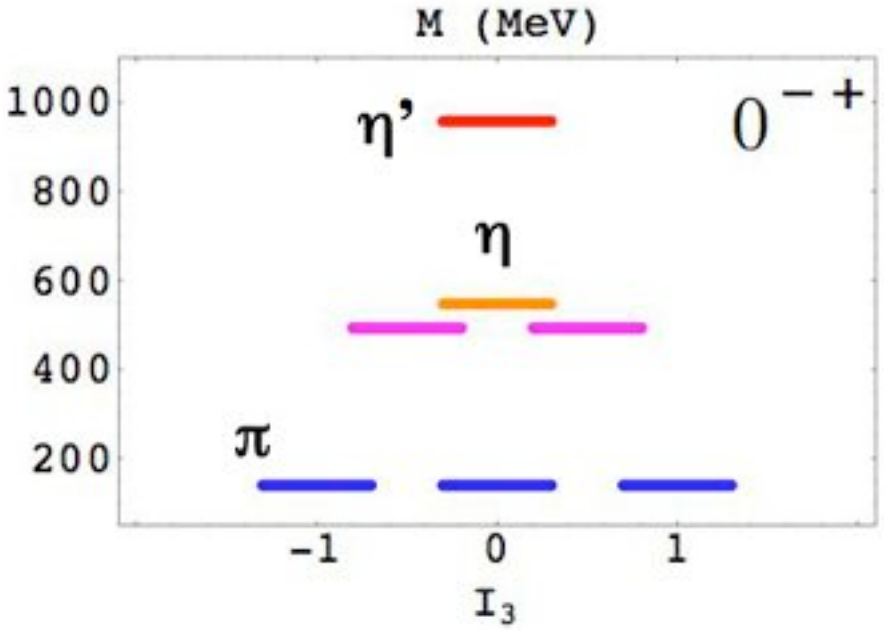
preliminary

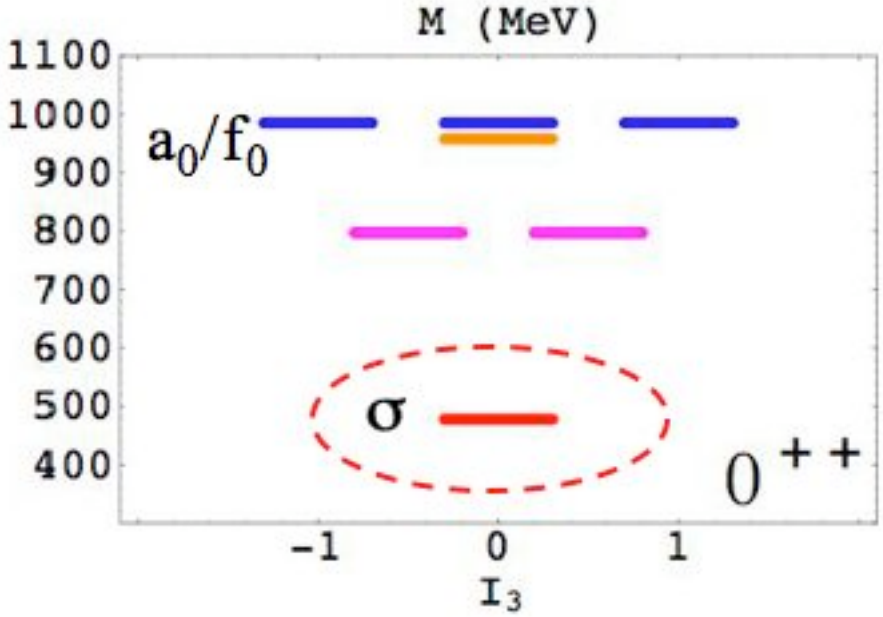
- In agreement with the result from $\eta \to \pi^0\pi^0\pi^0$: 6γ with imposed π^0,η + miss. E

$\sigma(e^+e^- \to \eta\gamma, 1\ \text{GeV}) = (0.875 \pm 0.018 \pm 0.035)$ nb

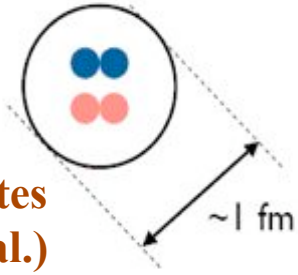
background for $\gamma\gamma \to \eta$ most accurately measured from the same 240 pb^{-1} sample

Scalar mesons: γγ widths to infer structure



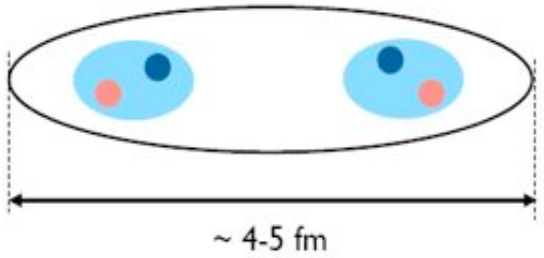


- **Is σ(600) the lightest scalar meson?**
- **What structure?**



qqq̄q̄ states
(Jaffe, Achasov et al., Maiani et al.)

vs.



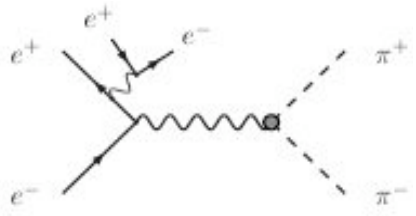
K$\bar{K}$ molecules
(Weinstein-Isgur, Close et al., Kalashnikova et al.)

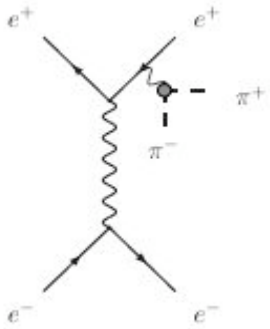
Searching for $\gamma\gamma \to \sigma(600) \to 2\pi^0$

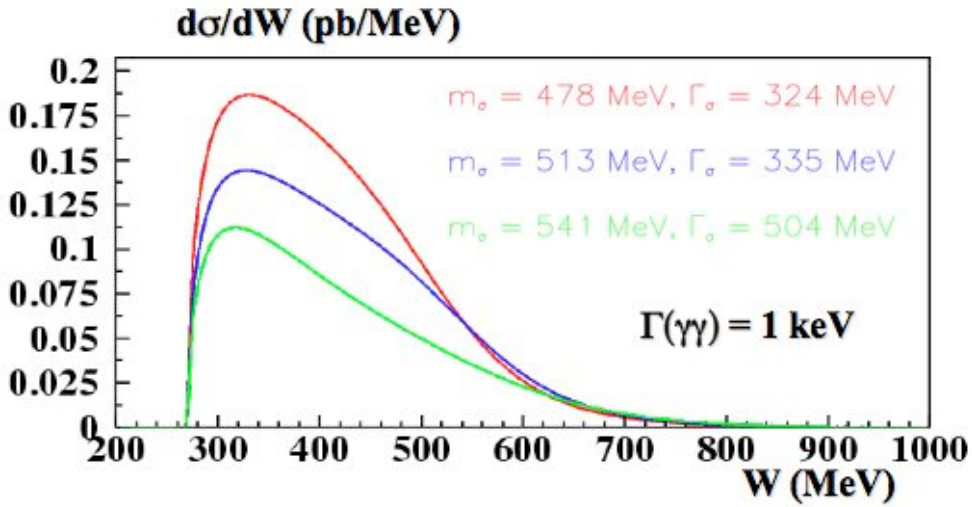
$\pi^+\pi^-$ harder than $\pi^0\pi^0$ channel:

1) $\gamma\gamma \to \mu^+\mu^-$ background (need robust particle ID)

2) background from vector states







F.Nguyen, F.Piccinini & A.Polosa

$\Gamma(\gamma\gamma)$ keV		
composition	predictions	author(s)
$(\bar{u}u + \bar{d}d)/\sqrt{2}$	4.0	Babcock & Rosner [73]
$\bar{s}s$	0.2	Barnes [74]
$\overline{[ns]}[ns]$, $n = (u, d)$	0.27	Achasov *et al.* [75]
$\bar{K}K$	0.6 0.22	Barnes [76] Hanhart *et al.* [77]

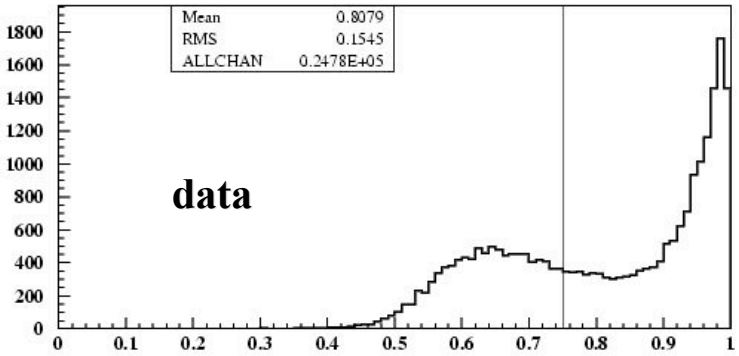
$$\sigma(\gamma\gamma \to \sigma(600)) \propto \Gamma(\sigma(600) \to \gamma\gamma)$$

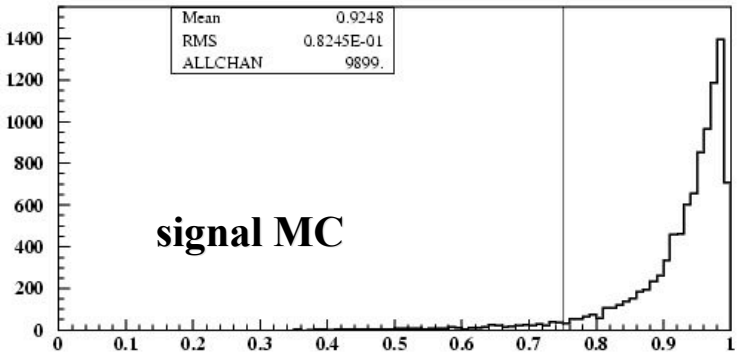
from the radiative width

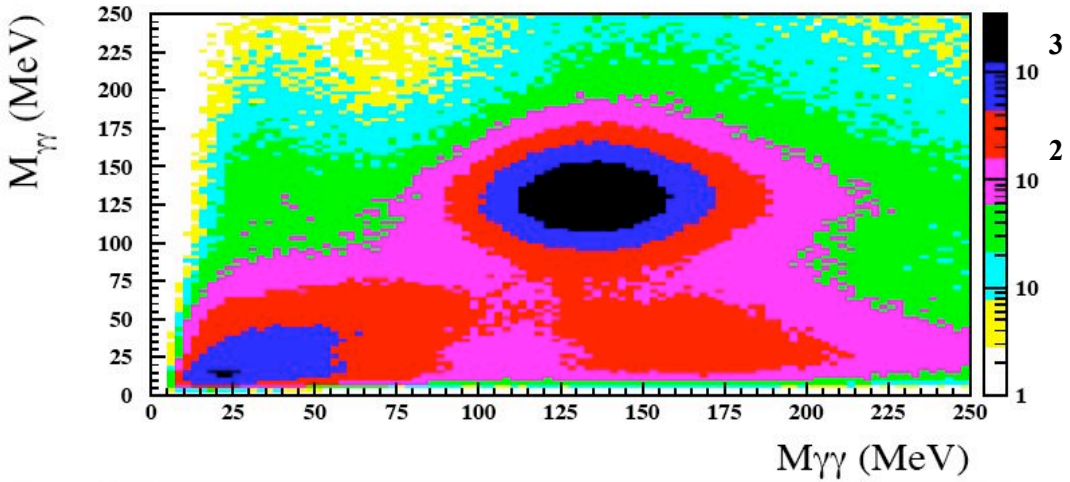
→ infer the structure

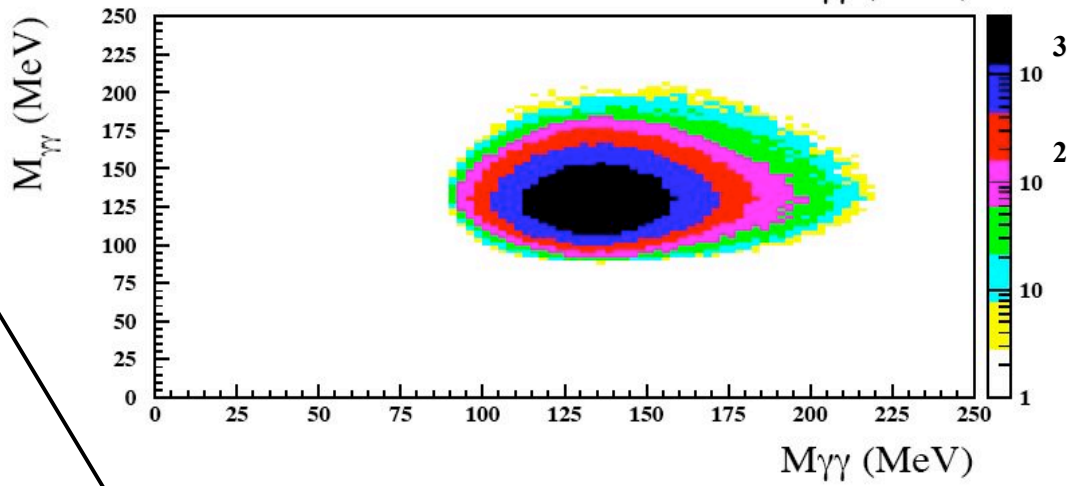
Search for $\gamma\gamma \rightarrow 2\pi^0$

- $\gamma\gamma$ pairing to 2 pions, $\chi_{\pi\pi}^2 < 4$
- 4 photons and NO tracks
- $p_T(4\gamma) < 120$ MeV
- $\Sigma_{4\gamma} / \Sigma_{CALO} > 0.75$
- promptness enforced (t_γ cuts)



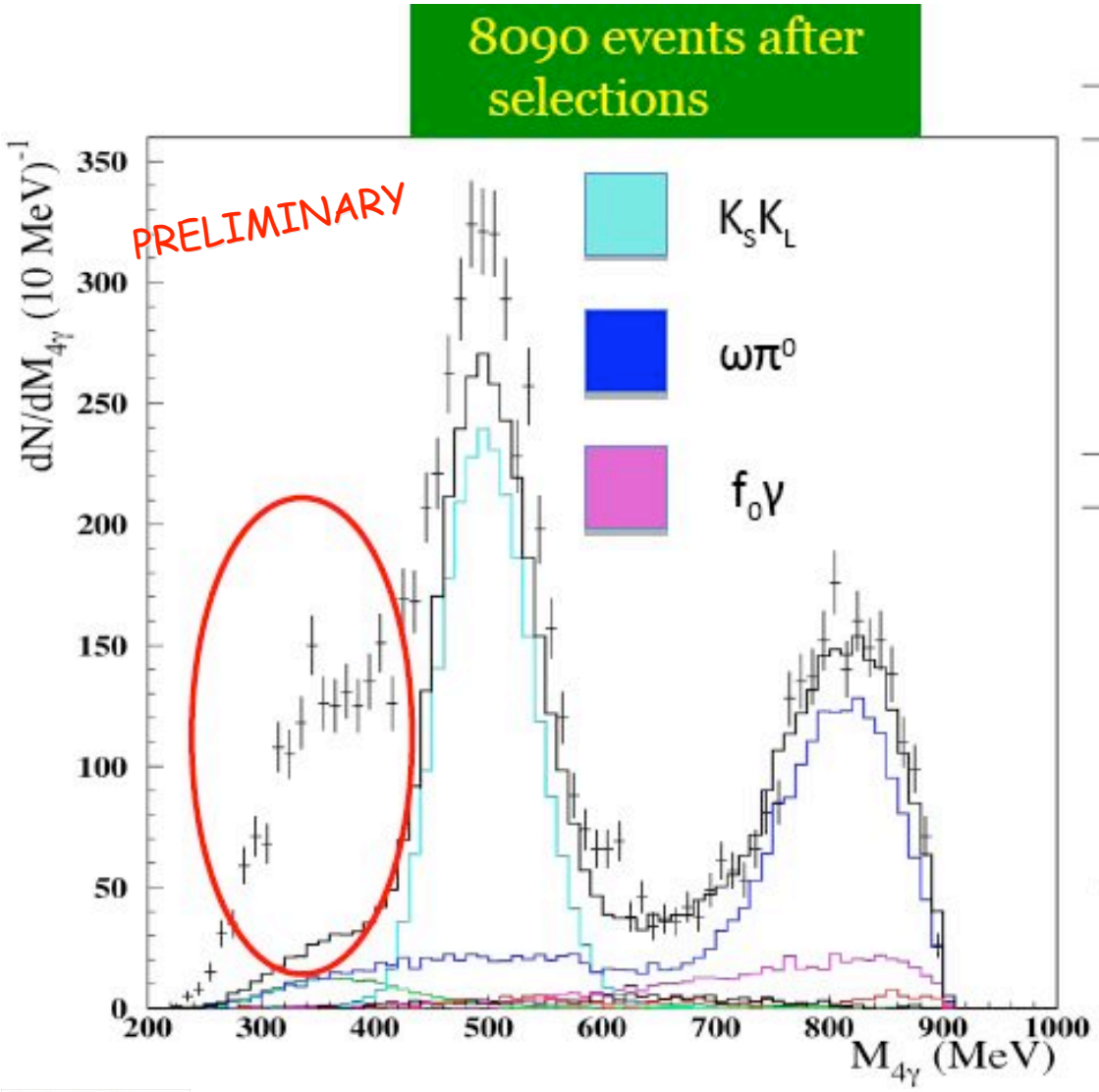






$\Sigma_{4\gamma} / \Sigma_{CALO}$

Search for $\gamma\gamma \to 2\pi^0$



	ϵ	σ (nb)	$n = \mathcal{L}\sigma\epsilon$
K_SK_L	7.5×10^{-3}	1.28	2328
$\eta \to 3\pi^0$	2.8×10^{-3}	0.284	193
$\omega\pi^0$	1.4×10^{-2}	0.55	1867
$f_0\gamma$	2.9×10^{-2}	0.17	1204
$a_0\gamma$	5.8×10^{-3}	0.11	155
$\gamma\gamma$	2×10^{-6}	360	175
			5922
Data			8090

Expected values

O(2000) candidate events of $\gamma\gamma \to \pi^0\pi^0$, evaluation and interpretation of the cross section is in progress…

efforts focussed on checking the K_SK_L peak on data

Control of $K_L(\rightarrow \text{escape})\ K_S(\rightarrow 2\pi^0)$

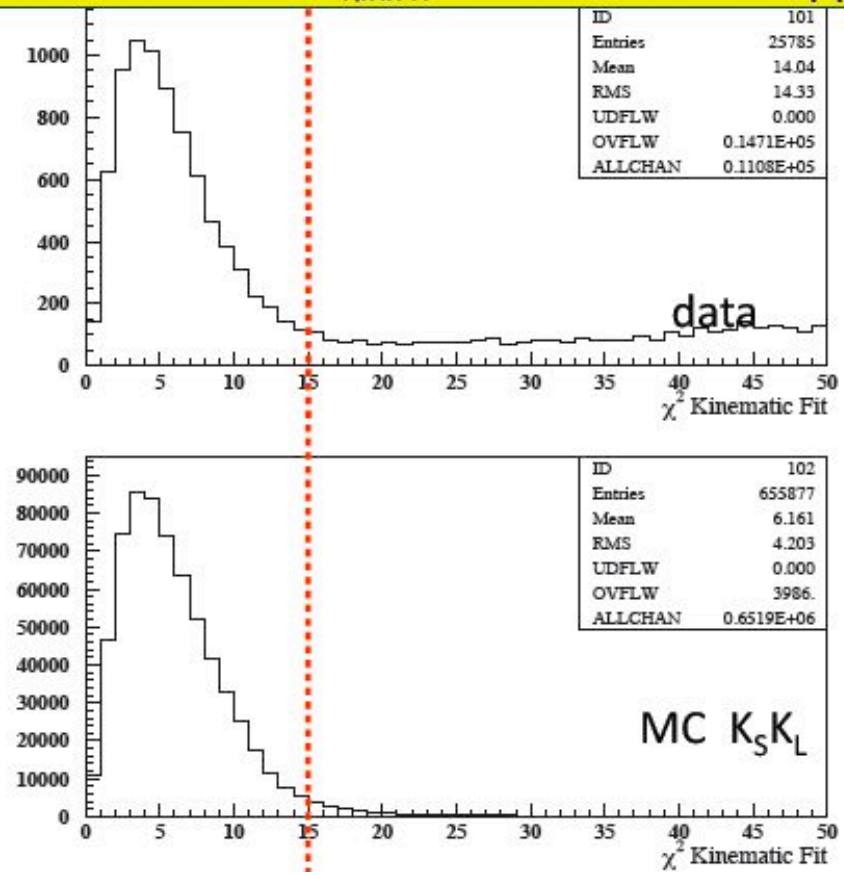
A clean data sample is obtained performing a kinematic fit with the 6 constraints and cutting on the resulting χ^2:

- $M_{4\gamma} = M_{Ks} = 497.614$ MeV
- $M_{miss} = M_{Kl}$
- $R_\gamma = ct_\gamma$ for each gamma

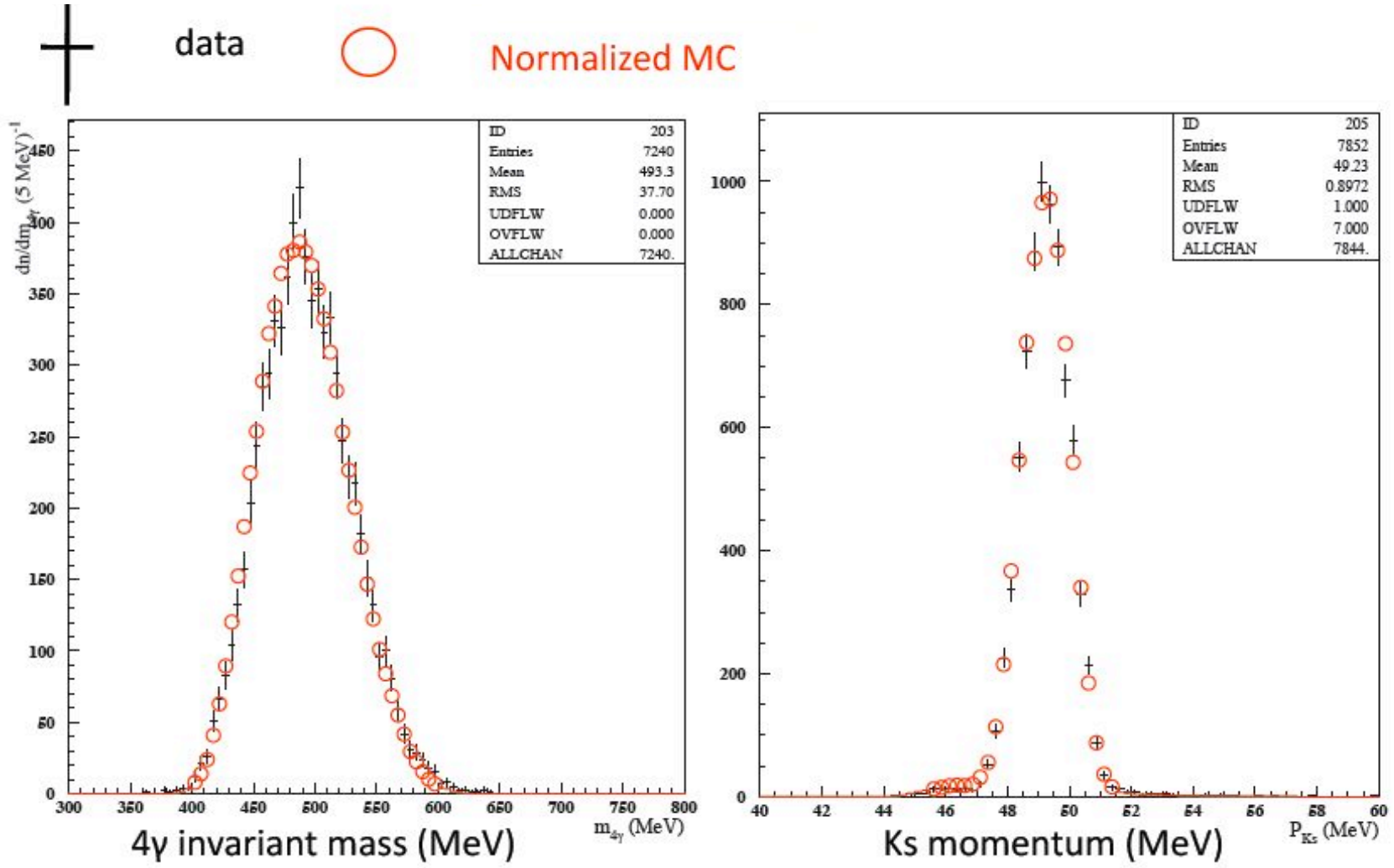
Selections:

- ✓ $\chi^2_t < 12$
- ✓ $\chi^2_{\pi\pi} < 4$
- ✓ 4 γ only and no tracks
- ✓ $48 < P_{Ks} < 51$ MeV
- ✓ $\chi^2_{kin.fit} < 15$

Distributions in $\chi^2_{kin.fit}$ (all other cuts applied)



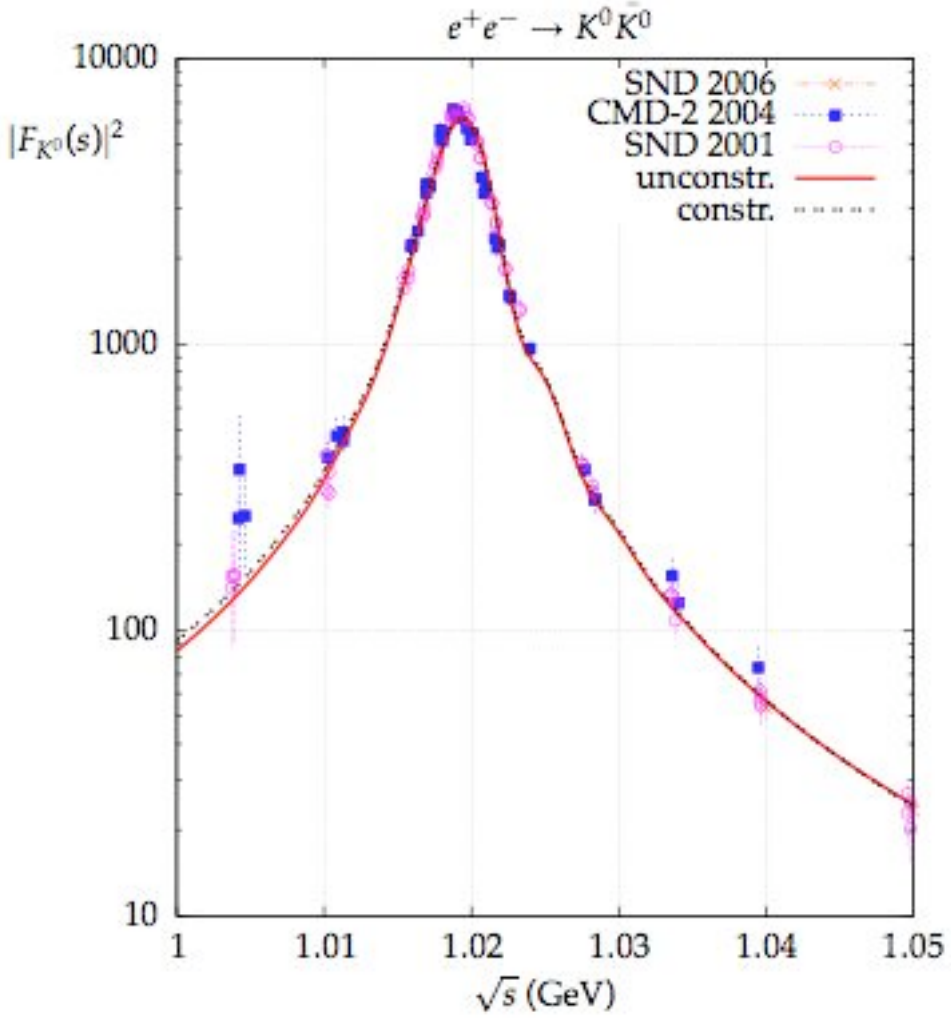
Control of $K_L(\rightarrow \text{escape})$ $K_S(\rightarrow 2\pi^0)$



Control of $K_L(\rightarrow \text{escape})$ $K_S(\rightarrow 2\pi^0)$

1) we are finalizing estimating evaluation of the $\sigma(K_S K_L)$ @ 1 GeV (not presently available) and the data/MC correction factors

2) as a by-product, we are able to measure $\sigma(K_S K_L)$ at different energy scan KLOE points with int. luminosity O(10 pb^{-1}) each one



H.Czyz et al., PRD 81 (2010) 094014

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 $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to 3\pi^0$ channels, preliminary results agree within 1 standard deviation

✓ an exploratory research shows a structure (~ 2000 events) in the 4γ invariant mass, where the process $e^+e^- \to e^+e^-\sigma \to e^+e^- \pi^0\pi^0$ is expected

✓ tools ready also to measure the TFF $|F_\eta(\sqrt{s})|$ and the neutral kaon electromagnetic FF $|F_{K\bar{K}}(\sqrt{s})|$

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 ... cess, with the $\eta \to \pi^+\pi^-\pi^0$ ... inary results ac...

we are very close to submit for publication, we even checked carefully all cable connections...

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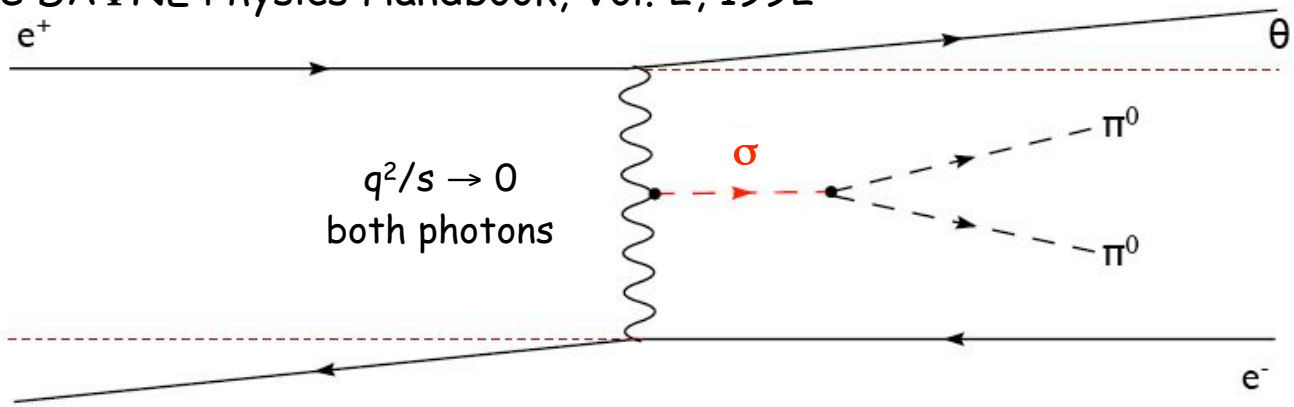
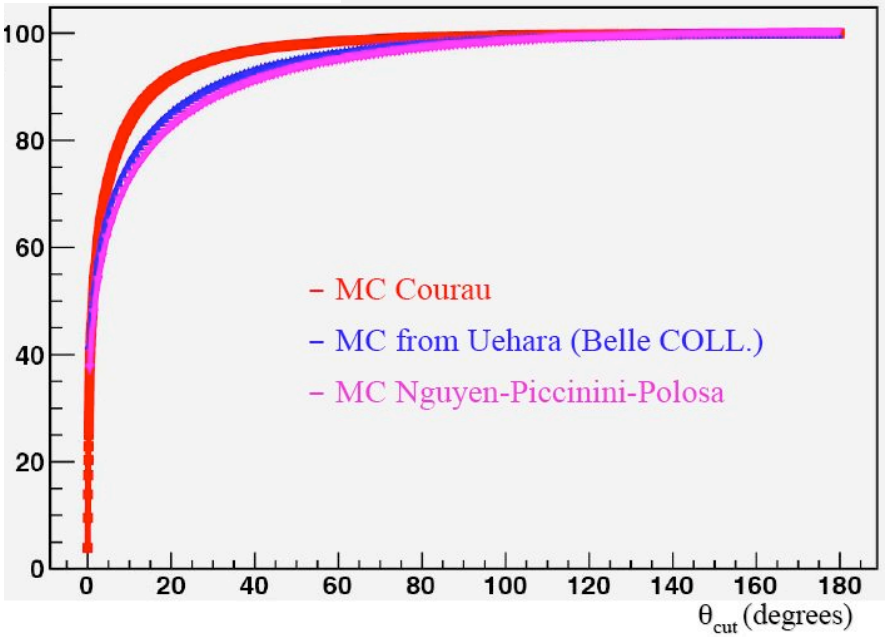
Monte Carlo simulation

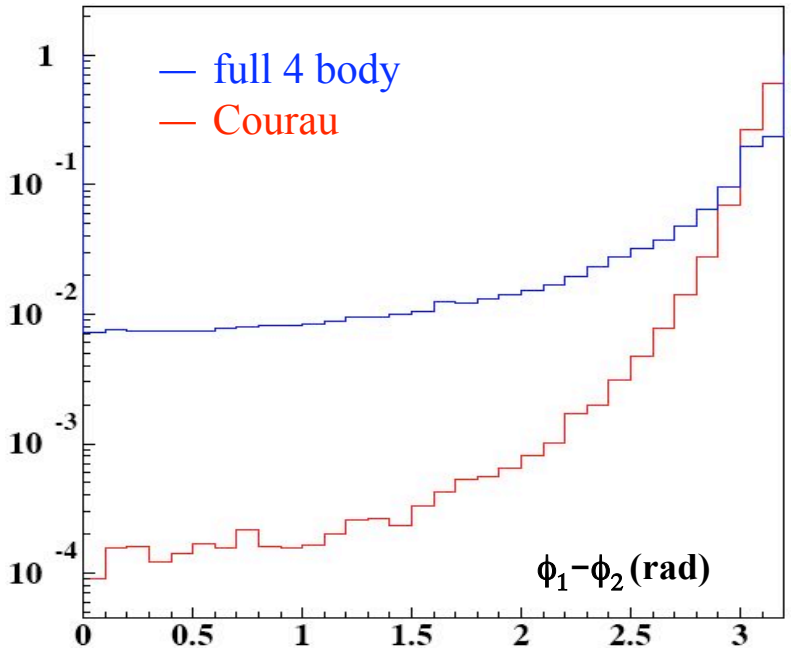
the complete 4 body simulation, EPJC47 (2006) 65, is compared with the Weizsäcker-Williams approx. (head on collision of 2 quasi-real γγ)

A. Courau & G. Pancheri, The DAΦNE Physics Handbook, Vol. 2, 1992



$$F(\theta_{cut}) = \int_0^{\theta_{cut}} \frac{dn}{d\theta} d\theta$$





Medium term plans for $\sigma(e^+e^- \rightarrow \eta\gamma)$