# Perspectives on $\eta - \eta'$ physics

**S. Giovannella**
(INFN–LNF)

**F. Ambrosino**
(Università e Sezione INFN, Napoli)

# Expected data sample

Working hypothesis: 20 $fb^{-1}$ of integrated luminosity
(a factor 10 more w.r.t. the expected KLOE final data sample)

$$\left.\begin{array}{l} \sigma_\phi = 3.3\ \mu b \\ BR(\phi\rightarrow\eta\gamma) = (\ 1.295 \pm 0.025\ )\% \end{array}\right\} \quad \mathbf{N_\eta(20\ fb^{-1}) \approx 8.6 \times 10^8}$$

$$\left.\begin{array}{l} \sigma_\phi = 3.3\ \mu b \\ BR(\phi\rightarrow\eta'\gamma) = (6.2 \pm 0.7)\times 10^{-5} \end{array}\right\} \quad \mathbf{N_{\eta'}(20\ fb^{-1}) \approx 4 \times 10^6}$$

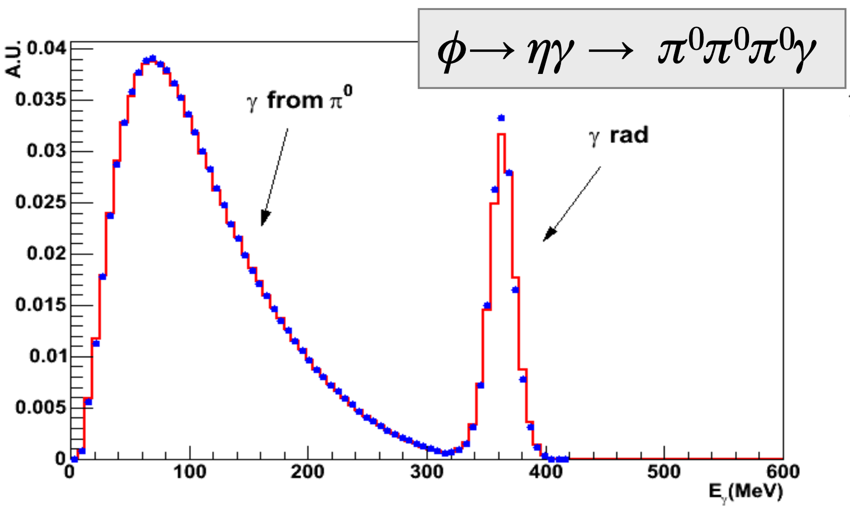
# $\eta$ identification

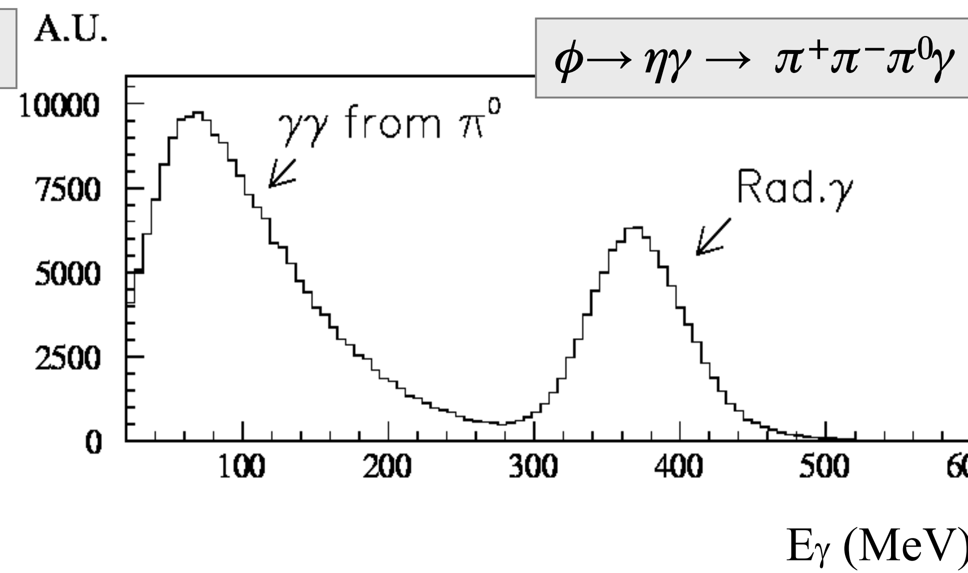
$\eta$ produced through $\phi \to \eta\gamma$ ➡

**Identified by the monochromatic recoil photon**

$E_{recoil}(\eta) = 363$ MeV

**Very clean and tagged $\eta$ sample**



# Main η decay channels

| Decay | BR (PDG04) | $\varepsilon_{ana}$ (KLOE) | $N_{exp}$ |
|---|---|---|---|
| $\eta \to \gamma\gamma$ | ( 39.43 ± 0.26 ) % | 70% | $2.4\times 10^8$ |
| $\eta \to \pi^0\pi^0\pi^0$ | ( 32.51 ± 0.29 ) % | 45% | $1.3\times 10^8$ |
| $\eta \to \pi^+\pi^-\pi^0$ | ( 22.6 ± 0.4 ) % | 36.5% | $0.7\times 10^8$ |
| $\eta \to \pi^+\pi^-\gamma$ | ( 4.68 ± 0.11 ) % | 46% | $1.8\times 10^7$ |

- PDG fit needs to scale BRs of main η decay modes from 1.2 to 1.3
- Main BRs known with *O(%)* precision. Further improvement requires a complete measurement of all main decay channels
- All these decays already studied @ KLOE
  By tagging the recoil photon, it is possible to overcome the normalization problem

# Main η decay channels

| Decay | BR (PDG04) | $\varepsilon_{ana}$ (KLOE) | $N_{exp}$ |
|---|---|---|---|
| $\eta \to \gamma\gamma$ | ( 39.43 ± 0.26 ) % | 70% | $2.4\times 10^8$ |
| $\eta \to \pi^0\pi^0\pi^0$ | ( 32.51 ± 0.29 ) % | 45% | $1.3\times 10^8$ |
| $\eta \to \pi^+\pi^-\pi^0$ | ( 22.6 ± 0.4 ) % | 36.5% | $0.7\times 10^8$ |
| $\eta \to \pi^+\pi^-\gamma$ | ( 4.68 ± 0.11 ) % | 46% | $1.8\times 10^7$ |

- PDG fit needs to scale BRs of main η decay mo…
- Main BRs known with $O(\%)$ pr… …ement requires a complete me… …ecay channels
- All the… …ed @ KLOE … photon, it is possible to overcome the … problem

**Probably not too much to say on main decay channels after the analysis of the final KLOE data sample (2.5 fb$^{-1}$)**

# $\eta \rightarrow \pi^+\pi^-\gamma$

**At the moment just poor experimental data from the 70's**

1. **Dalit plot: left–right asymmetry parameter**
2. Shape of the $E_\gamma$ spectrum to test ChPT predictions
   - Resonant contribution:
     1. $\rho$ production whit its subsequent decay to a pion pair (VDM)
     2. existence of a small non-VDM contribution
   - Anomalous contribution:

     box anomaly (similar to the classical triangle anomaly), responsible for $\eta/\eta' \rightarrow \pi^+\pi^-\gamma$ decays predicted by PCAC and by the Wess-Zumino-Witten chiral lagrangian

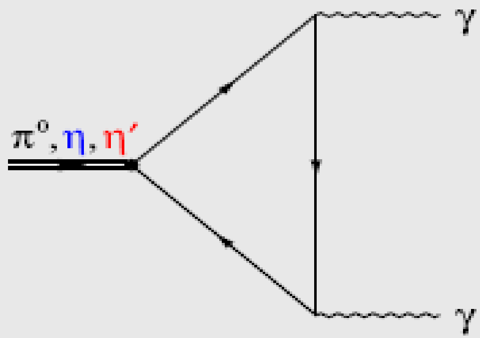
# $\eta \to \pi^+\pi^-\gamma$ : box anomaly

**Anomalies in QCD**

*Wess-Zumino-Witten Lagrangian*

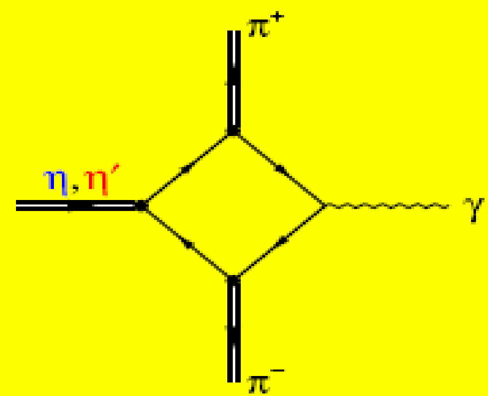
J. Wess, B. Zumino, Phys. Lett. B 37 (1971) 95
E. Witten, Nucl. Phys. B 223 (1983) 422

$$L_{WZW} = L_{AVV} + L_{AAAV} + \ldots$$




*triangle anomaly*

S. L. Adler, Phys. Rev. 117 (1969) 2426
J. S. Bell, R. Jackiw, Nuovo Cim. A 60 (1969) 47
G. M. Shore, G. Veneziano, Nucl. Phys. B 381 (1992) 3




*box anomaly*

M. S. Chanowitz, Phys. Rev. Lett. 35 (1975) 977
J. Gasser, H. Leutwyler, Nucl. Phys. B 250 (1985) 465
J. F. Donoghue, B. R. Holstein, Y. R. Lin, Phys. Rev. Lett. 55 (1985) 2766

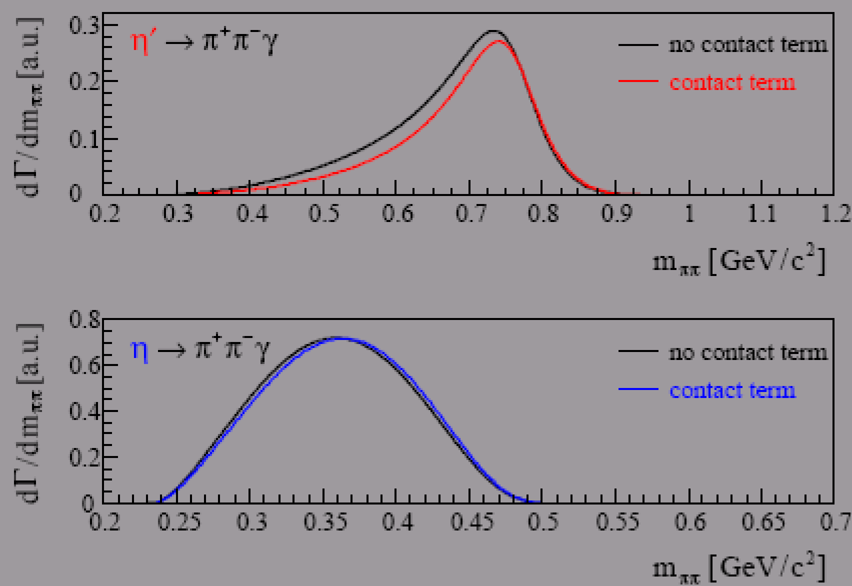
# $\eta \to \pi^+\pi^-\gamma$ : $M_{\pi\pi}$ spectrum

**Box Anomaly and $\eta/\eta' \to \pi^+\pi^-\gamma$**

$$BW(\rho) = \frac{1}{(m_{\pi\pi}^2 - m_\rho^2) - i m_{\pi\pi}\Gamma_\rho} + \frac{\xi}{m_{\eta/\eta'}^2} e^{i\phi}$$

*EChPT, HLS model*

*M. Benayoun et al., Eur. Phys. J. C31 (2003) 525*

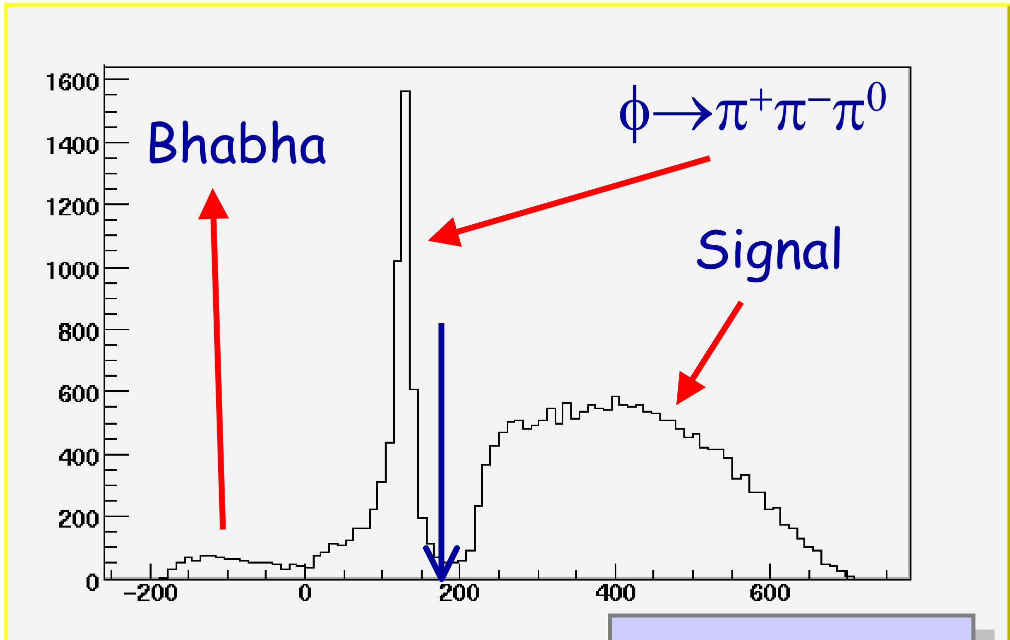



Unfortunately $\eta \to \pi^+\pi^-\gamma$ not sensitive to the box anomaly contribution

# $\eta \to \pi^+\pi^-\gamma$ @ KLOE

Preliminary KLOE analysis looks promising…

First sample analyzed:
**29 pb$^{-1}$ of 2001 data**




$M_{miss}$ (MeV)

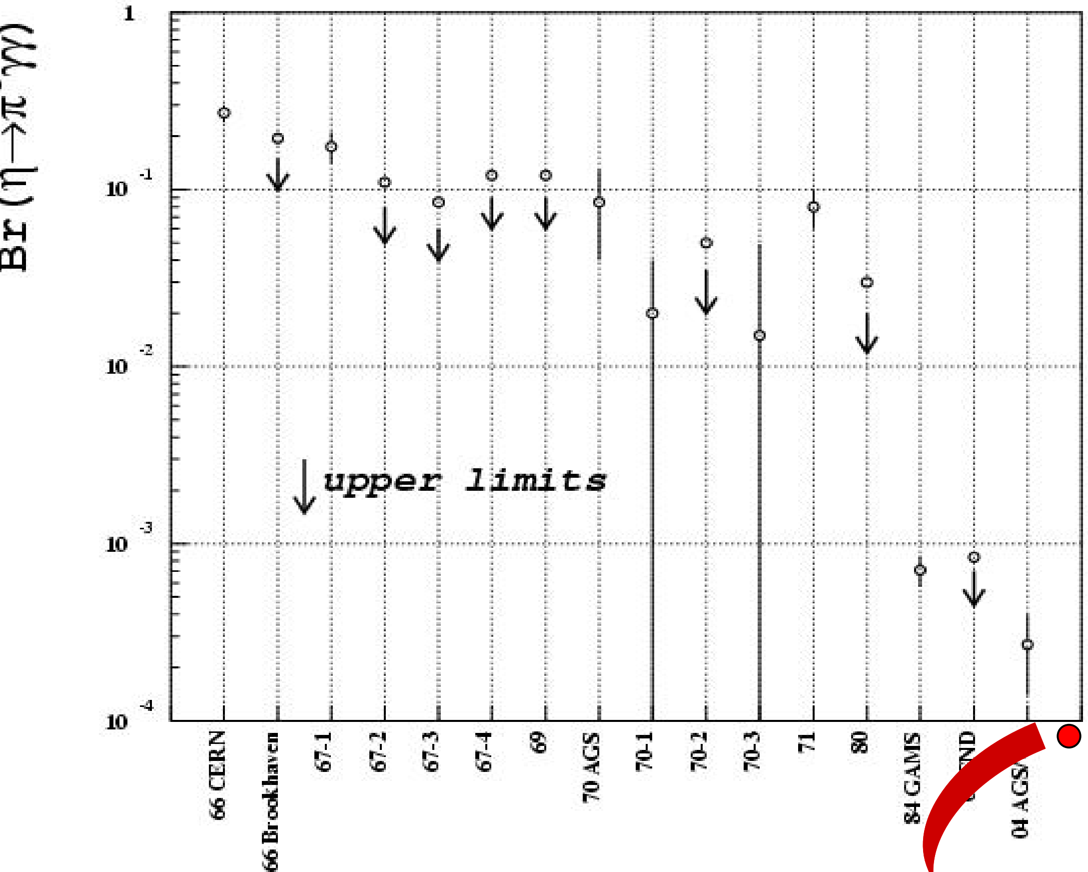
Analysis scheme:

- 1 vtx with 2 tracks
- 2 prompt neutral clusters
- Kin fit: $P(\chi^2) > 10^{-4}$
- $357.8 < E_{\gamma\ recoil} < 368.2$ MeV
- $M^{miss}(\pi^+\pi^-) > 160$ MeV

**S/B ~ 460**

# $\eta \rightarrow \pi^0\gamma\gamma$

Interesting from the theoretical point of view because the bigger contribution comes from $p^6$ in $\chi_{PT}$




$\pi^- + p \rightarrow \eta + n$
(CERN, Brookhaven, GAMS, Crystal Ball)

$\pi^+ + d \rightarrow p + p + \eta$ (67)

$\pi^+ + p \rightarrow \pi^+ + p + \eta$ (67,69)

$K^- + p \rightarrow \Lambda + \eta$ (70 AGS)

$\pi^+ + n \rightarrow \eta + p$ (71)

$\pi^- + n \rightarrow \pi^- + n + \eta$ (80)

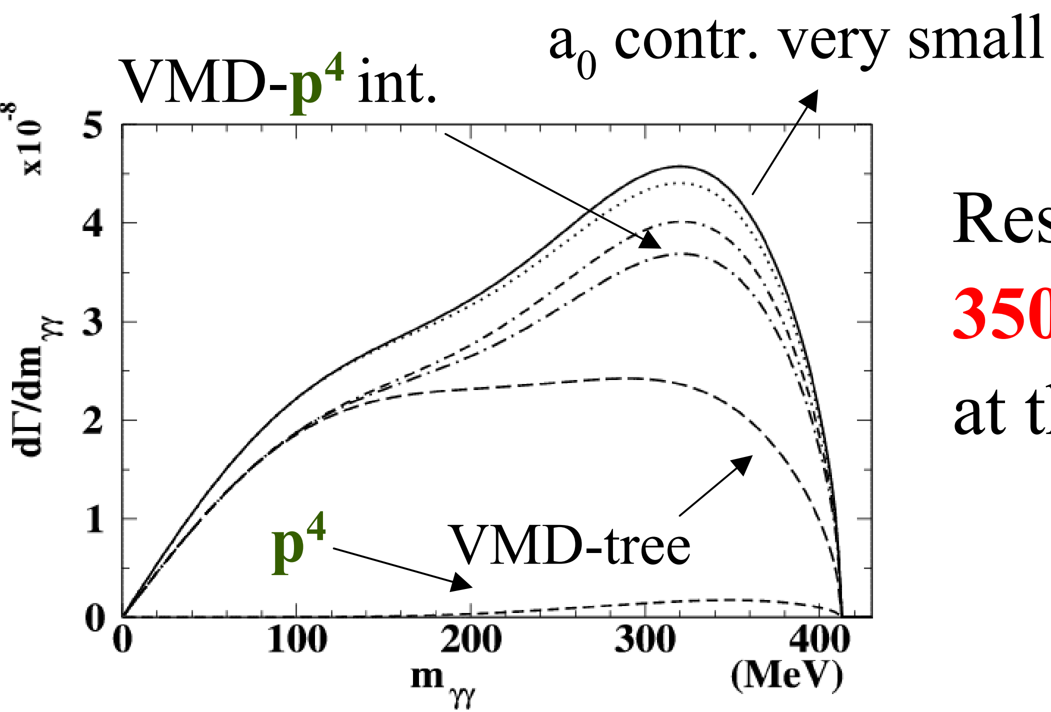
$\phi \rightarrow \eta\gamma$ (SND 01)

**Prel. KLOE measuremen**

# $\eta\to\pi^0\gamma\gamma$ : mass spectrum measurement

A further improvement on BR is expected with 20 fb$^{-1}$, but more interesting is the shape of the $\gamma\gamma$ mass spectrum

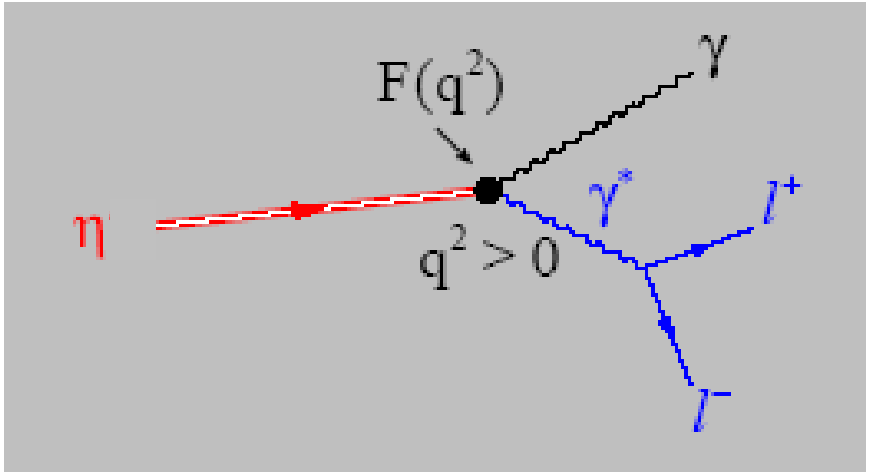
E.Oset, J.R.Pelaez, L.Roca, PRD67 (2003) 073013




Rescaling KLOE results:
**3500 events expected**
at the end of the analysis

# Dalitz decays

The study of the e.m. structure of neutral mesons can be done through the $\eta \to \gamma l^+ l^-$




A transition form factor $f\,(q^2)$ arising in the vertex provides information on the meson structure

$$\frac{d\Gamma}{dm^2_{ll}} = \frac{d\Gamma}{dq^2} = \underbrace{\left[\frac{d\Gamma}{dq^2}\right]_{pointlike}}_{\Uparrow\ QED} \cdot \left|F_{\eta'\gamma}(q^2)\right|^2$$

✓ Observable: $l^+l^-$ invariant mass

✓ $F(q^2)$ calculations: (1) VMD (2) Quark triangle loop (3) ChPT

# η Dalitz decays

Dalitz and double Dalitz decay can be easily reached with 20 $\mathrm{fb}^{-1}$

| Decay | BR (PDG04) |
|---|---|
| $\eta \to e^+e^-\gamma$ | $(6.0 \pm 0.8) \times 10^{-3}$ |
| $\eta \to \mu^+\mu^-\gamma$ | $(3.1 \pm 0.4) \times 10^{-4}$ |
| $\eta \to e^+e^-e^+e^-$ | $< 6.9 \times 10^{-5}$ |
| $\eta \to \pi^+\pi^-e^+e^-$ | $(4.0^{+14.0}_{-2.7}) \times 10^{-4}$ |

Bckgs: $\phi \to \pi^+\pi^-\pi^0$

$\eta \to \pi^+\pi^-\gamma$

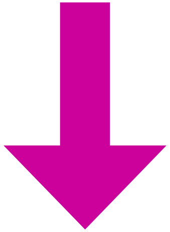
≈ 60,000 produced

All these measurements can be significantly improved and a first observation of $e^+e^-e^+e^-$ can be achieved ( theoretical expectations: $BR(\eta \to e^+e^-e^+e^-) = 6.5 \times 10^{-5}$ [PR 98 (1955) 1355] )

# $\eta \to \pi^+\pi^- e^+ e^-$ : test of CP violation beyond CKM

- Standard model: source of CP violation is a single phase in CKM mixing matrix describing quark flavor changing weak interaction couplings

- Test CP simmetry in flavour conserving process, where Standard Model predictions are vanishingly small

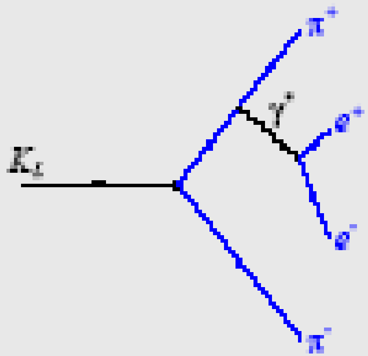


TEST OF NEW PHYSICS BEHOND THE STANDARD MODEL

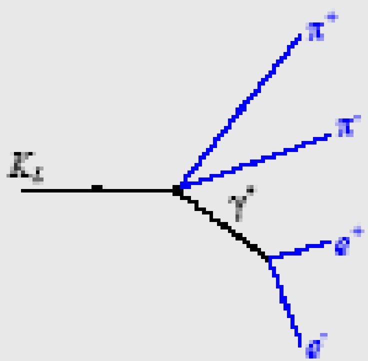
# CP violation in $K_L \to \pi^+\pi^- e^+ e^-$

*dominant amplitudes*

*CP violating bremsstrahlung*




*CP conserving M1 $\gamma$ emission*




*interference of amplitudes*

$\Rightarrow$ *CP violating circular photon polarisation*

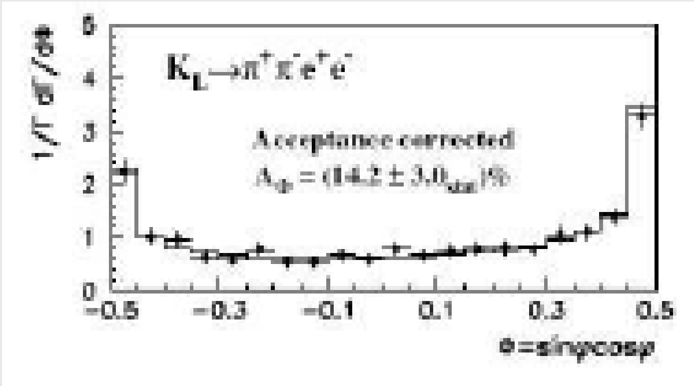
$\Rightarrow$ *CP violating asymmetry in $\sin\varphi\cos\varphi$*

L. M. Sehgal, M. Wanninger, PR D46 (1992) 1035,
P. Heiliger, L. M. Sehgal, PR D48 (1993) 4146

$\varphi = \angle\, (\pi^+\pi^-), (e^+e^-)$ planes in $K_L$ cms

$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

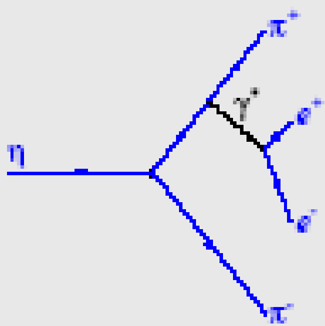
*NA48 result* (A. Lai et al., EPJC 30 (2003) 33 )



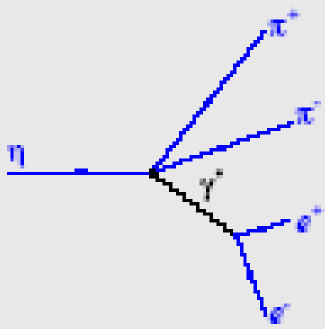
# CP violation in $\eta \to \pi^+\pi^- e^+e^-$

*amplitudes*

*CP violating bremsstrahlung*




*CP conserving M1 γ emission*




*interference of amplitudes*

⇒ *CP violating asymmetry in* $\sin\varphi\cos\varphi$

$\varphi = \angle\,(\pi^+\pi^-), (e^+e^-)$ planes in $\eta$ cms

⇒ *construct operators, that do not contribute directly to* $\eta \to \pi^+\pi^-$ *and* $K^0$ *decays*

⇒ *flavor conserving CP violating four-fermion operators involving two s-quarks*

C.Q. Geng, J.N. Ng, T.H. Wu, MPLA 17 (2002) 1489,
D.N. Gao, MPLA 17 (2002) 1583

$A_\phi$ *up to 2%*

# $\eta \to e^+e^- / \mu^+\mu^-$

| **Decay** | **BR (PDG04)** | **Prediction** |
|---|---|---|
| $\eta \to e^+e^-$ | $< 7.7 \times 10^{-5}$ | $6 \times 10^{-9}$ |
| $\eta \to \mu^+\mu^-$ | $(5.8 \pm 0.8) \times 10^{-6}$ | $4 \times 10^{-6}$ |

A large improvement on U.L. expected from the statistical point of view for $\eta \to e^+e^-$

However… large background from $e^+e^- \to e^+e^-(\gamma)$ expected

1. Kinematic fit imposing $\eta$ mass
2. Study of angular and momentum distributions of the decay products

# C, P, CP, LF violating η decays

Already measured with KLOE 2001/2002 data:

| Decay | BR (KLOE) | Violation |
|---|---|---|
| $\eta \to \pi^+\pi^-$ | $< 1.3\times10^{-5}$ | P , CP |
| $\eta \to \gamma\gamma\gamma$ | $< 1.6\times10^{-5}$ | C |

**Upper limits on $\pi^+\pi^-/\gamma\gamma\gamma$, background limited, will improve with $\sqrt{(L_{NEW}/L_{OLD})}$**

Other decays:

| Decay | BR (PDG04) | Violation |
|---|---|---|
| $\eta \to \pi^0\pi^0$ | $< 4.3\times10^{-5}$ | P , CP |
| $\eta \to \pi^0\pi^0\pi^0\pi^0$ | $< 6.9\times10^{-7}$ | P , CP |
| $\eta \to \pi^0 e^+e^-$ | $< 4\times10^{-5}$ | C |
| $\eta \to \pi^0\mu^+\mu^-$ | $< 5\times10^{-6}$ | C |
| $\eta \to \mu^+e^-, \mu^-e^+$ | $< 6\times10^{-6}$ | LF |

Too much bckg: $\phi \to S\gamma$, $\phi \to K_S K$

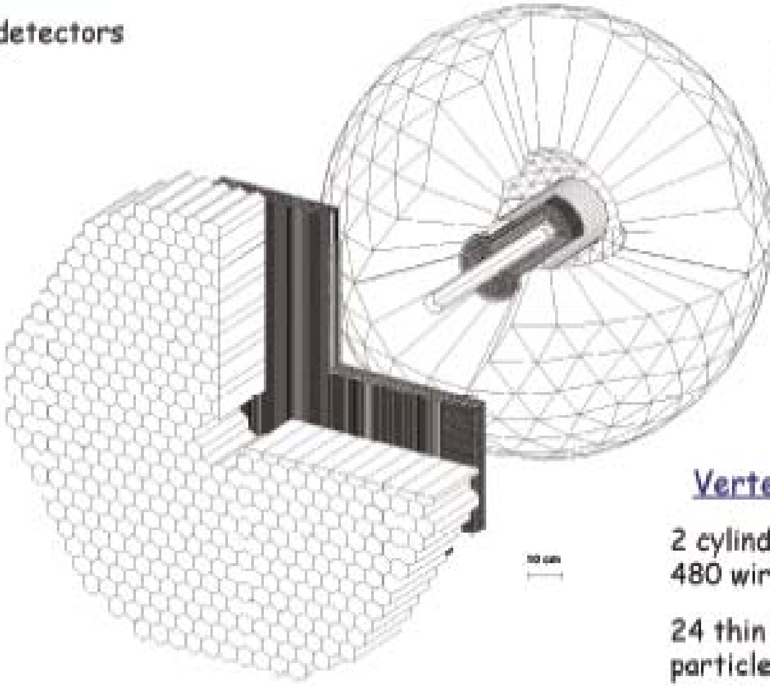
$\pi^+\pi^-\pi^0$ bckg to be removed

Similar search of $\phi \to \eta\gamma$ with $\eta \to \mu^+\mu^-$

# Competitors: Crystall Ball @ MAMI

**TAPS:**

510 $BaF_2$-detectors



**Crystal Ball:**

672 NaI-detectors

- ❖ $\sigma_E/E = 2\%/\sqrt[4]{E(\mathrm{GeV})}$
- ❖ $\sigma_\theta = 2–3$ degrees

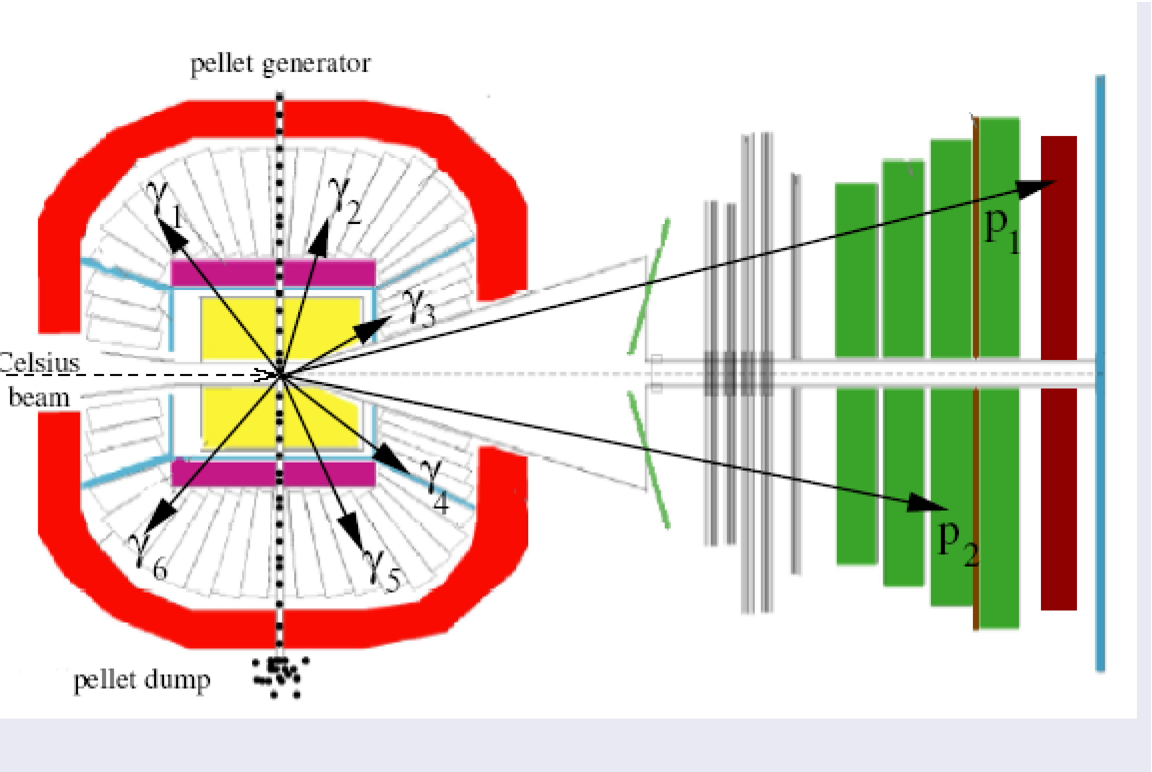
**Vertex Detectors:**

2 cylindrical wire chambers
480 wires, 320 strips

24 thin plastic counters
particle separation

- ✓ 30M $\eta$ acquired @ AGS (BNL) [$\pi^-(720\ \mathrm{MeV}/c)p \rightarrow n\eta$]
- ✓ 30M $\eta$ acquired @ MAMI (MAINZ) in 2004, 300 hours run [$\gamma(180–820\ \mathrm{MeV})p \rightarrow p\eta$]
- ✓ MAMI upgrade in progress: next run $E_\gamma$ up to 1.5 GeV
  300M $\eta$ expected + $\eta'$ sample

# Competitors: WASA @ COSY




- ❖ CsI calorimeter
- ❖ Plastic scintillator barrel
- ❖ Mini drift chamber
- ❖ Forward detector

✓ Production mechanism: $pp \rightarrow pp\eta(\eta')$

✓ Expected rate : **2500 $\eta$/s   30 $\eta'$/s**

✓ Expected start-up: January 2007

# $\eta'$ decays

**$N_{\eta'}(20\ fb^{-1}) \approx 4 \cdot 10^6$**

**DAFNE2 is an η' factory!**
**But beware: WASA@ COSY claims $2 \cdot 10^6$ η'/day ….**

| Decay | BR (PDG04) |
|---|---|
| $\eta' \to \pi^+\pi^-\eta$ | ( 44.3 ± 1.5 ) % |
| $\eta' \to \pi^+\pi^-\gamma$ | ( 29.5 ± 1.0 ) % |
| $\eta' \to \pi^0\pi^0\eta$ | ( 20.0 ± 1.2 ) % |
| $\eta' \to \omega\gamma$ | ( 3.03 ± 0.31 ) % |
| $\eta' \to \gamma\gamma$ | ( 2.12 ± 0.14 ) % |

✓ $\eta'$ main BRs known with an error of 3–10%

✓ We can probably improve the situation on the less frequent decay by measuring ratio of BRs (sth already @ KLOE/DAFNE)

✓ For the others, we need **tagged measurement of all the decay chain** **Hard,** but this **could reduce the systematic error in the measurement of $R = BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma)$** which dominates already its error

# $\eta' \rightarrow \gamma\gamma$

✓BR currently known at 7%.

✓BR is the main uncertainty in the extraction of the $\eta$' full width

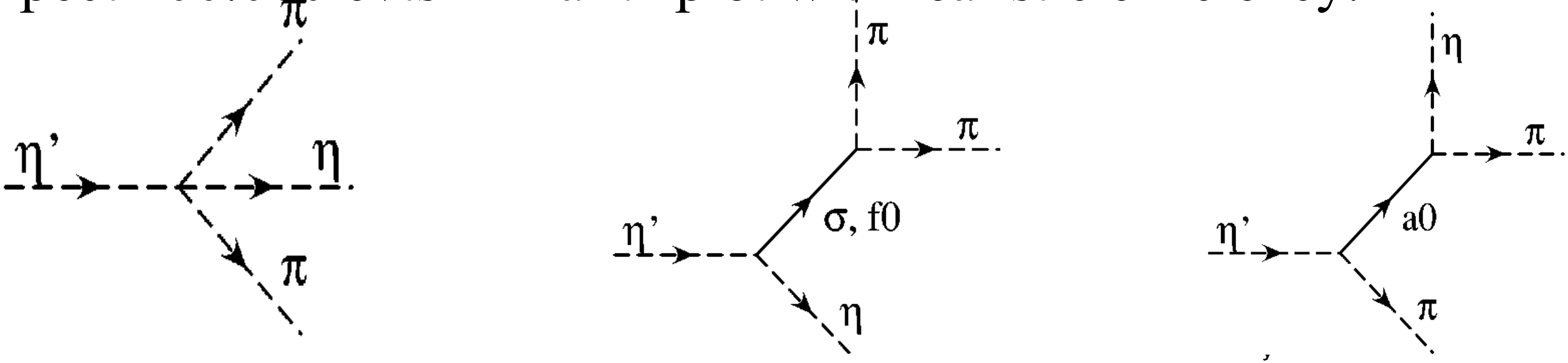
✓ $8 \cdot 10^4$ events produced. With 10 % efficiency can improve BR accuracy to about 4%. But hard from the exp. point of view (QED bkg

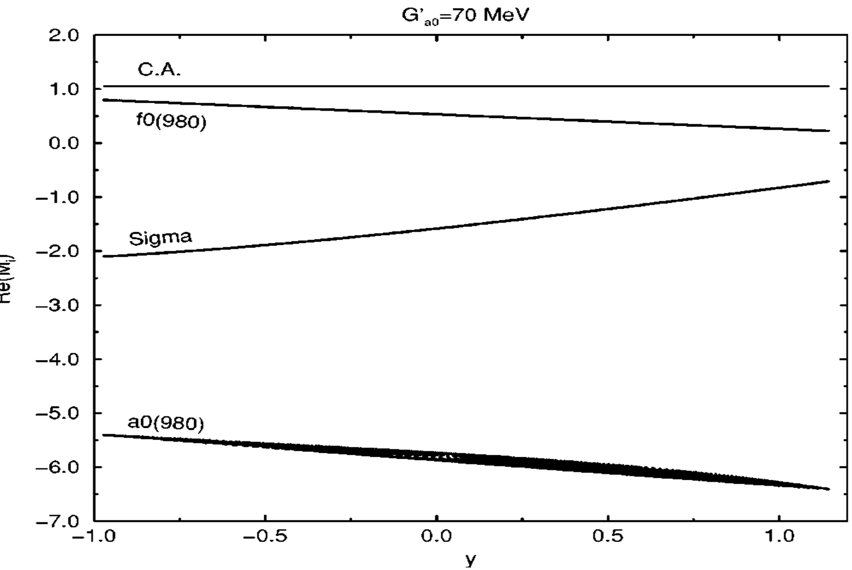
✓$\Gamma\gamma\gamma$ is already known to 3% thus no improvement for $\eta-\eta$' mixing parameters.

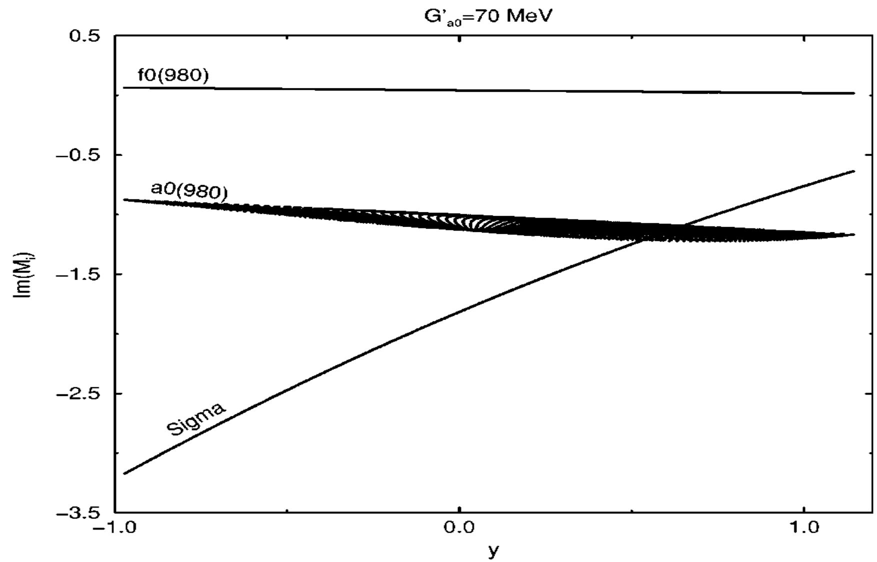
✓…not a big issue….

# $\eta' \to \eta\pi\pi$ : Dalitz plot analysis

- Interesting to study scalar mesons (no tree contributions from VMD)
- Sensitive to $\sigma(600)$ (PRD 60, 034002)
- Expect 200.000 evts in Dalitz plot with realistic efficiency.



# $\eta' \to \pi^+\pi^-\pi^0$ : first observation ?

✓Interesting, because is sensitive to isospin violating part of strong Lagrangian, and proportional to $m_d$-$m_u$

✓Currently only upper limit @ 5% (!)

✓Expected at $O(10^{-3})$ i.e. 4000 evts produced

✓With realistic efficiency can expect to measure BR @ some % level

# $\eta' \to \pi^+\pi^-\gamma$ : asymmetry and spectrum

✓Interesting, because $\gamma$ energy spectrum is sensitive to the "box anomaly" term of the WZW chiral Lagrangian

✓Asymmetry related to possible C violation in strong interactions

✓Difficult background from $\rho\pi$ ( but we know we can deal with it reasonably for the $\eta$ )

✓More than 1 million events produced

# Other $\eta'$ decays

✓With an expected BR of $2 \cdot 10^{-4}$ the Dalitz decay could be observed wit[h] order 10% accuracy or less (transition form factor, light by light scattering etc.)

✓$4\pi$ decays could possibly be observed… but we could not find theoretical prediction for that….

✓Reasonably one could slightly improve limits on C, CP violating decays down to $10^{-4}$ level.