# KLOE results on light meson properties


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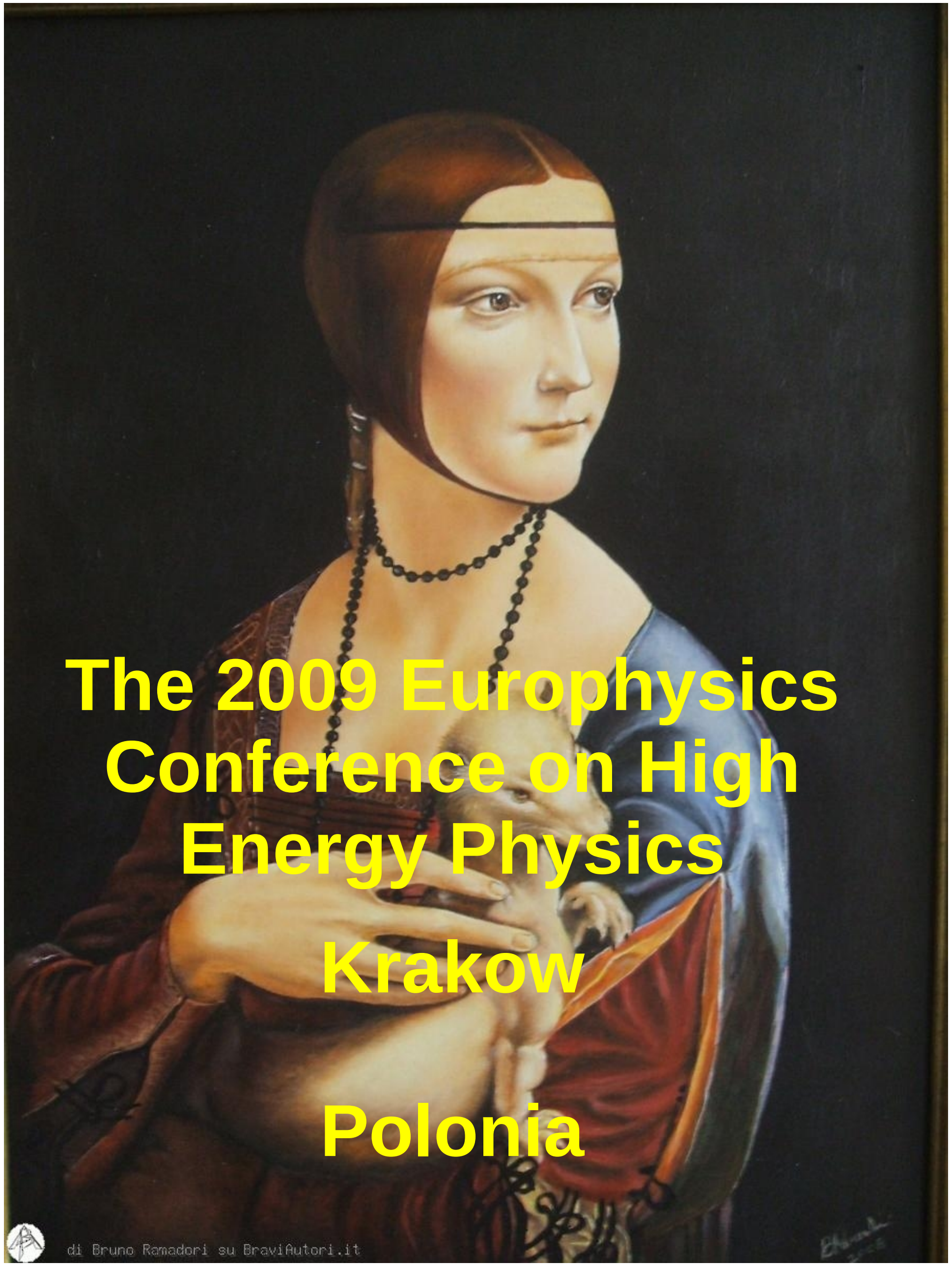
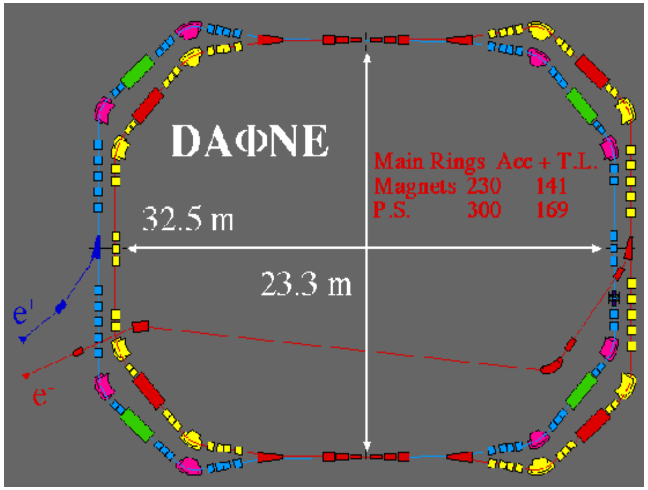
**Istituto Nazionale di Fisica Nucleare sez. Roma Tre**

**on the behalf of the KLOE collaboration**

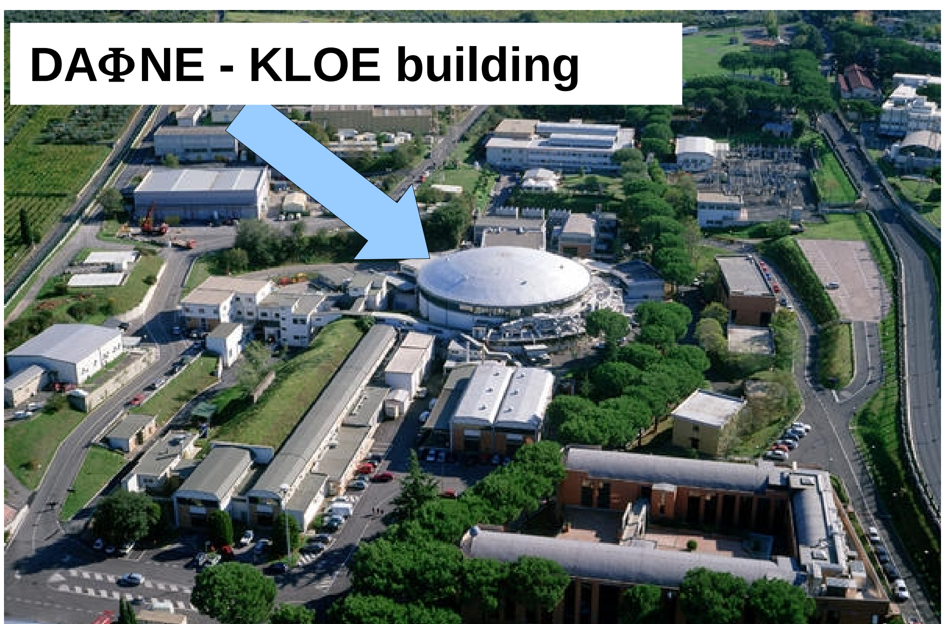
# DAΦNE and KLOE

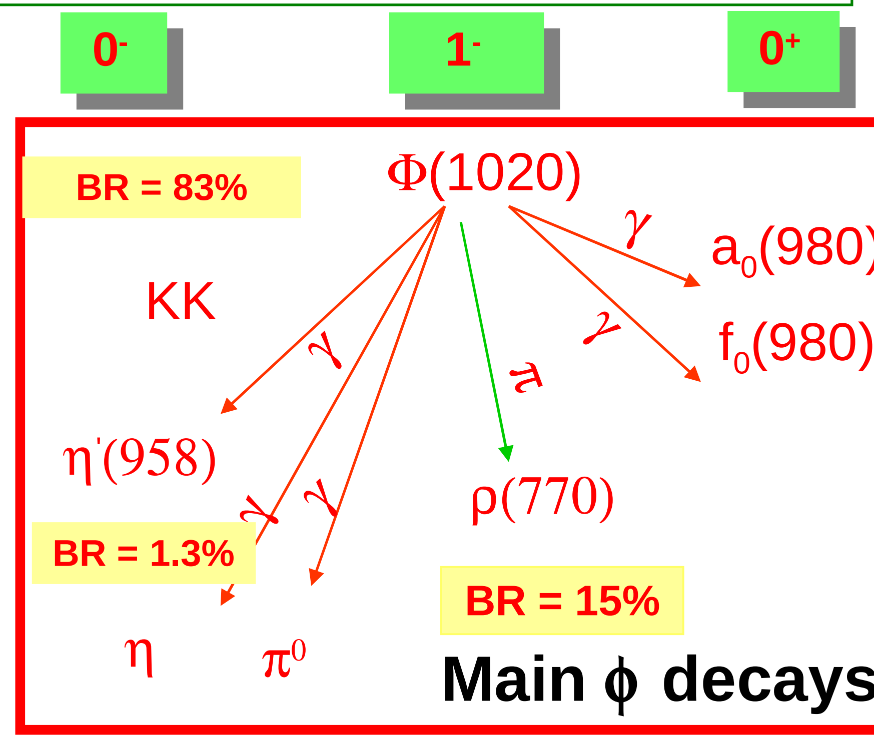
## Collected luminosity (2.5 $fb^{-1}$)




## High luminosity $e^+e^-$ collider

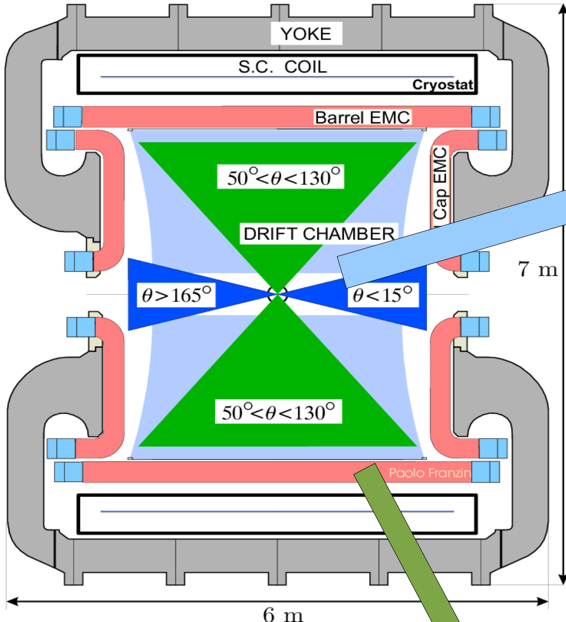
- $\sigma(e^+e^- \to \phi) \sim 3\ \mu\beta$ $\quad \sqrt{s} = m(\phi) = 1\,019.4\,MeV$
- Independent $e^+e^-$ rings to reduce beam-beam interactions
- crossing angle: 25 mrad, $p_x(\phi) \sim 12.6$ MeV/c
- Bunch crossing every 2.7 ns
- injection during acquisition

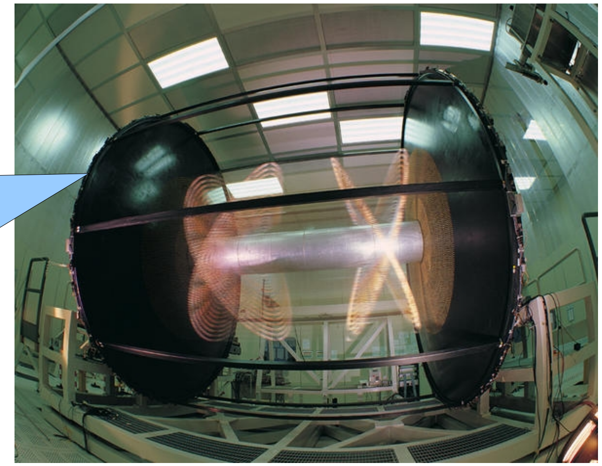


# The KLOE Detector

## Detector scheme



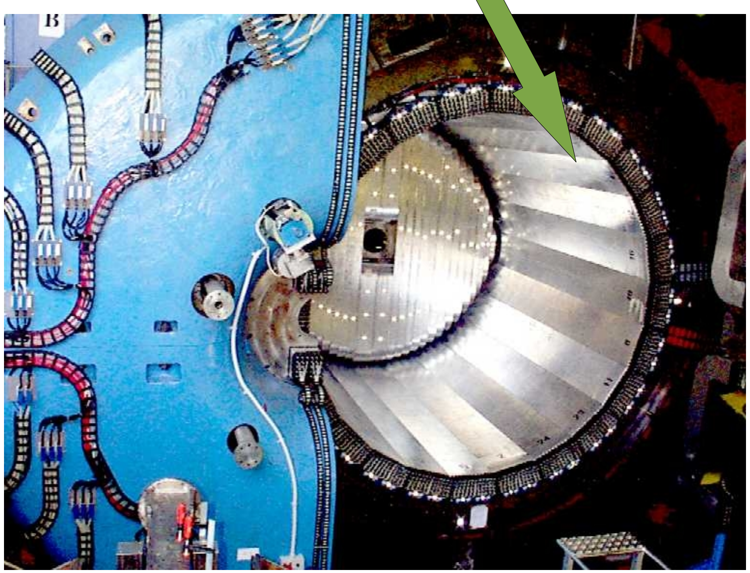
**Cylindrical Drift Chamber**

Stereo wires structure to reconstruct longitudinal position

52140 wires – 12582 drift cell
90% He 10% $iC_4H_{10}$
0.5 T Magnetic field

$\sigma_v = 1$ mm $\qquad \sigma_{pt}/p_t = 0.5\%$

$\sigma_{r,\phi} = 200\ \mu$m $\qquad \sigma_z = 2$ mm



**Electromagnetic calorimeter**

- 1 barrel + 2 end-caps
- 98% solid angle coverage
- Fine sampling Pb / Scintillating Fibers
- Hermetical coverage
- High efficiency for low energy photons
- two side PM read out, longitudinal position from arrival time

$$\sigma_E/E = 5.7\%/\sqrt{E(\mathrm{GeV})}$$

$$\sigma_t = 54\,\mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 140\ \mathrm{ps}$$

# Outline

- $\phi$ decays to scalars, the $a_0$ parameters, the scalar structure and the instanton model;

- Search for $\phi \to (f_0 + a_0)\gamma \to \overline{K}^0 K^0 \gamma \to K_S K_S \gamma$

- Measurement of the $e^+e^- \to \omega\pi^0$ cross section and determination of the Br($\omega \to \pi^0\gamma$)

- The determination of the $\eta'$ gluonium content;

- Measurement of the Br($\eta \to \pi^+ \pi^- e^+ e^- (\gamma)$) and looking for unconventional CP violation in the decay.

# Scalar physics

**Still open questions on the nature of the light scalars:**

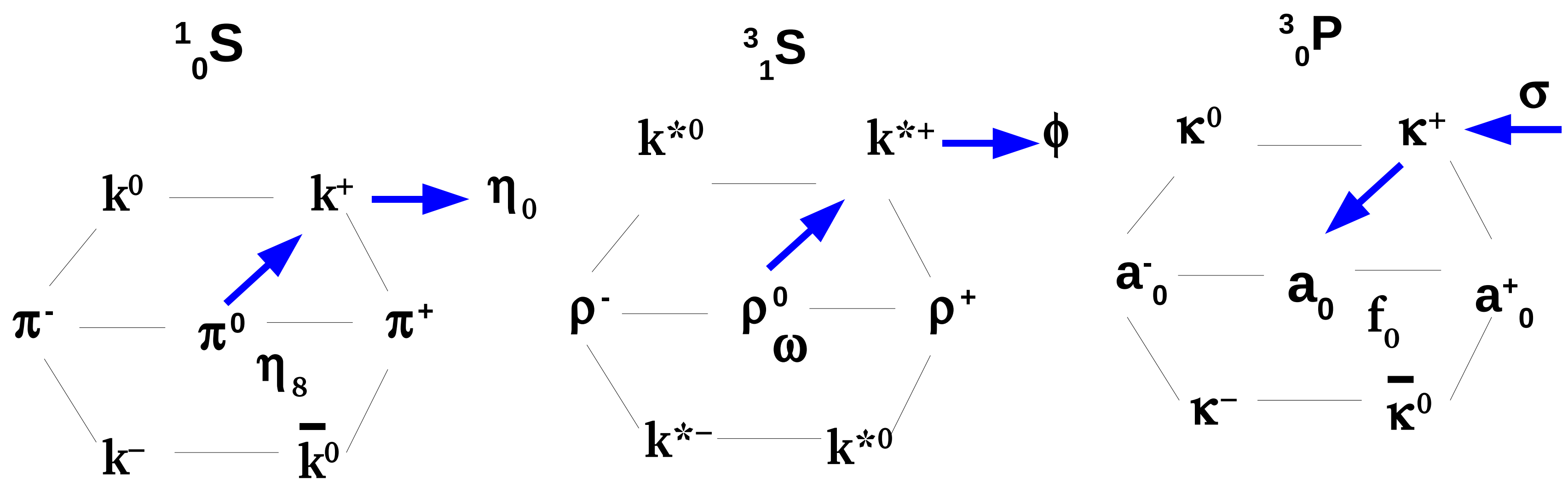
$a_0$ $f_0$ $\sigma$ $\kappa$

**The natural answer (2 quarks states in $^3_0P$ configuration) cannot explain the inverted hierarchy.**

Increasing mass arrow

$q\bar{q}$

nonets




Why scalars show an inverted mass spectrum respect to the pseudoscalar and vector partners?

Natural explanation in the 4q hypothesys Jaffe

$f_0$ $a_0$ ssdd ssuu $\sigma$ uudd

# Scalar study in $\phi$ decays

**Scalars nature can be studied with the $\phi$ decays**

$e^+e^- \rightarrow \phi \rightarrow (f_0+\sigma)\gamma \rightarrow \pi^0\pi^0\gamma,\ \pi^+\pi^-\gamma$

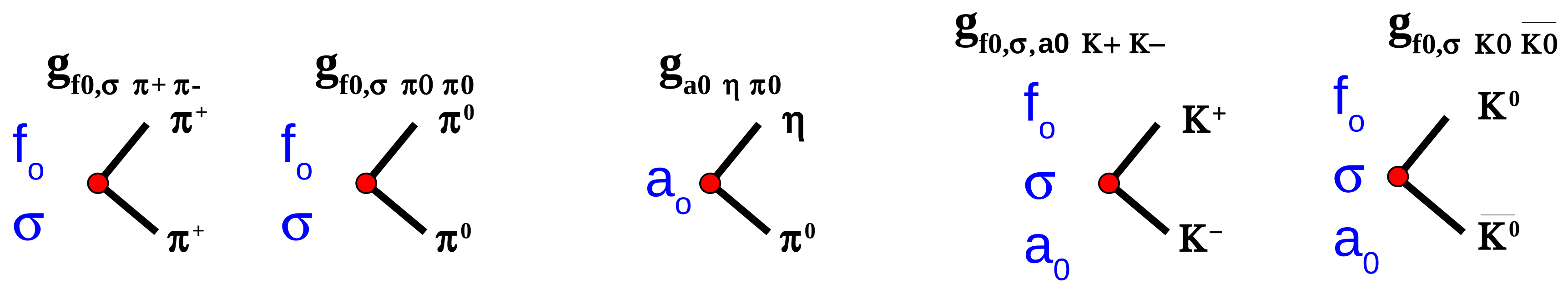
**Eur. Phys. J. C49 (2007) 473**
**Phys. Lett. B 634 (2006) 148**

$e^+e^- \rightarrow \phi \rightarrow a_0\gamma \rightarrow \eta\pi^0\gamma$

**Sensitive to the scalar structure**

$e^+e^- \rightarrow \phi \rightarrow (a_0 + f_0)\ \gamma \rightarrow K^0\overline{K^0}\gamma \rightarrow K_sK_s\gamma$ Sensitive to the $a_0$-$f_0$ interference.

**The couplings to the pseudoscalar mesons ($\pi\pi$, $K^+K^-$, $\eta\pi$) are sensitive to the quark structure.**

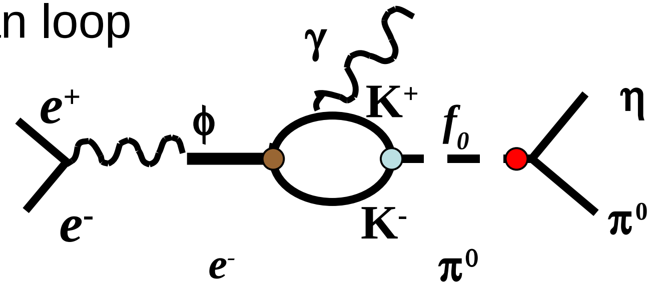



**Isospin symmetry:** $g_{f0,\sigma\ \pi+\pi-} = 2\, g_{f0,\sigma\ \pi0\ \pi0}$

# $M_{\eta\pi 0}$ fit to $\eta\pi^0\gamma$ events at KLOE

Submitted to PLB
arXiv:0904.2539

Koan loop



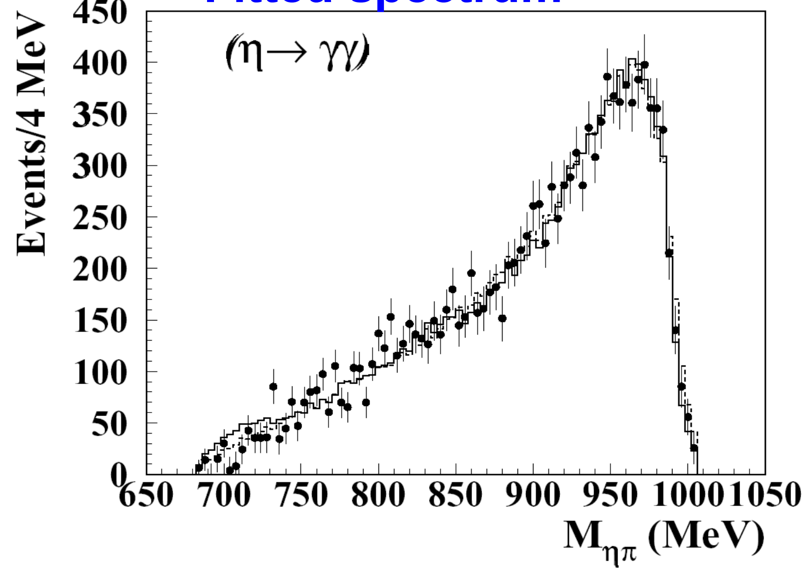

- $g_{\phi K^+K^-}$
- $g_{SK^+K^-}$
- $g_{S K^0K^0}$

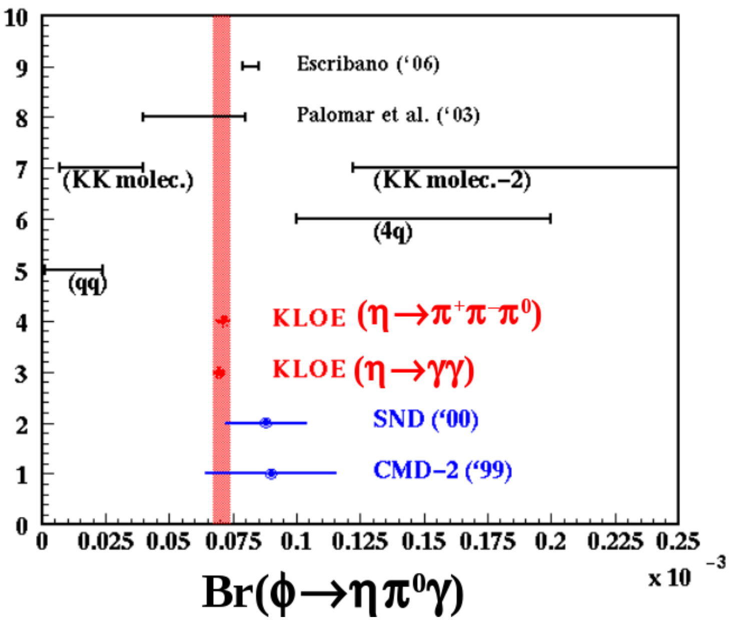
extraction of Br($\phi\to\eta\pi^0\gamma$)
from event counting (model independent).

$\eta\to\gamma\gamma$ – Br($\phi\to\eta\pi^0\gamma$) = $(7.01 \pm 0.10_{stat} \pm 0.20_{syst}) \times 10^{-5}$

$\eta\to\pi^+\pi^-\pi^0$ – Br($\phi\to\eta\pi^0\gamma$) = $(7.12 \pm 0.13_{stat} \pm 0.22_{syst}) \times 10^{-5}$

**Fitted spectrum**




| | | | |
|---|---|---|---|
| $M_{a0}$ | $982.5 \pm 1.6 \pm 1.1$ MeV | $g_{a0\eta\pi}$ | $2.82 \pm 0.03 \pm 0.04$ GeV |
| Br($\phi\to\rho\pi\to\eta\gamma\pi$) | $(0.92 \pm 0.40 \pm 0.15)\times 10^{-6}$ | | |
| $\delta(\phi\to\rho\pi\to\eta\gamma\pi)$ | $(222 \pm 13 \pm 3)^\circ$ | $g_{a0K+K-}$ | $2.15 \pm 0.06 \pm 0.06$ GeV |

qq: Achasov-Ivanchenko NPB315(1989)
Close et al., NPB389(1993)
4q: Achasov-Ivanchenko NPB315(1989)
KK molec.: Close et al., NPB389(1993)
Achasov et al., PRD56(1997)
KK molec.-2: Kalashnikova et al., EPJA24(2005)
Palomar et al., NPA729(2003): UχPT
Escribano, PRD74(2006): Linear σ model

# Scalar couplings to pseudoscalars 2q versus 4q

Couplings compatible with a 2 quarks hypothesys with $f_0 = s\bar{s}$

4q cannot fit the small value of $g_{a0KK}$.

| | KLOE | SU(3) | | |
|---|---|---|---|---|
| | | 4q | $q\bar{q}$ | |
| $(g_{aK+K-}/g_{a\eta\pi})^2$ | 0.6 – 0.7 | 1.2 – 1.7 | 0.4 q (u,d) | |
| $(g_{f0K+K-}/g_{f0\pi+\pi-})$ | 4.6 – 4.8 | >>1 | >>1 ($f_0=s\bar{s}$) | 1/4 ($f_0=q\bar{q}$) |
| $^{2}(g_{f0K+K-}/g_{aK+K-})^2$ | 4 - 5 | 1 | 2 ($f_0=s\bar{s}$) | 1 ($f_0=q\bar{q}$) |

# Scalar couplings to pseudoscalars 2q versus 4q

Couplings compatible with a 2 quarks hypothesys with $f_0 = s\bar{s}$

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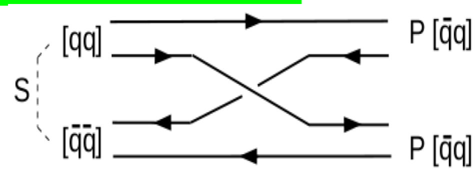
| $(g_{f0K^+K^-}/g_{aK^+K^-})^2$ | 4 - 5 | 1 | 2 ($f_0=s\bar{s}$) | 1 ($f_0=q\bar{q}$) |

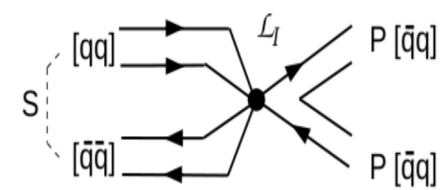
New model from T'Hooft, Isidori, Maiani, Polosa and Riquer (Phys. Lett. B662 (2008) 424

Standard interaction (quark exchange)




Interference allows small a0KK coupling

Instanton interaction




allows $f_0 \to \pi\pi$

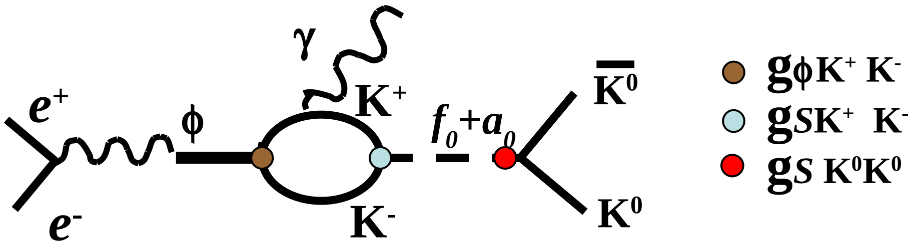
inputs: $g_{f0KK}$, $g_{f0\pi\pi}$, $m_{f0}$, $m_{a0}$, $\psi_P$

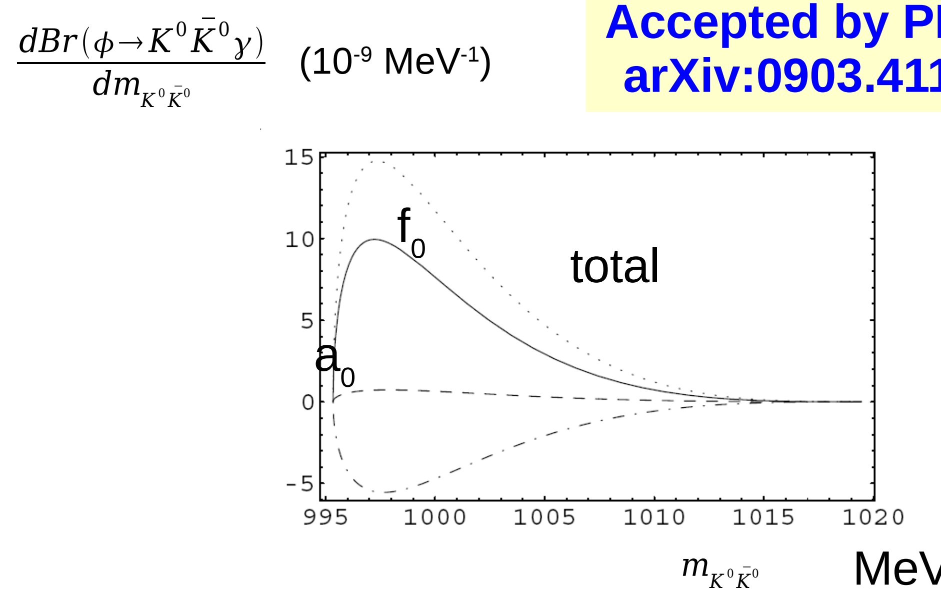
outputs: $g_{a0KK}$, $g_{a0\eta\pi}$

| | KLOE (KL) | | $[qq][\bar{q}\bar{q}]$ | $q\bar{q}$ |
|---|---|---|---|---|
| $g_{f0K^+K^-}$ (GeV) | 3.97 — 4.74 | } | $c_I$ = - 2.8 — - 3.4 GeV$^{-1}$ | $c_I$ = - 3.9 — - 4.8 GeV$^{-1}$ |
| $g_{f0\pi^+\pi^-}$ (GeV) | -1.82 — -2.23 | | $c_f$ = 20.5 — 24.5 GeV$^{-1}$ | $c_f$ = 16.5 — 19.7 GeV$^{-1}$ |
| | | | ⇓ | ⇓ |
| $g_{a0K^+K^-}$ (GeV) | 2.01 — 2.15 | | 2.1 — 2.5 | 2.4 — 2.9 |
| $g_{a0\eta\pi}$ (GeV) | 2.46 — 2.82 | | 3.3 — 3.9 | 6.6 — 7.9 |

very good agreement in the 4 quarks hypothesis

# $\phi \to (f_0 + a_0)\gamma \to \bar{K}^0 K^0 \gamma \to K_S K_S \gamma \to \pi^+ \pi^- \pi^+ \pi^- \gamma$




**Accepted by PLB**
**arXiv:0903.4115**

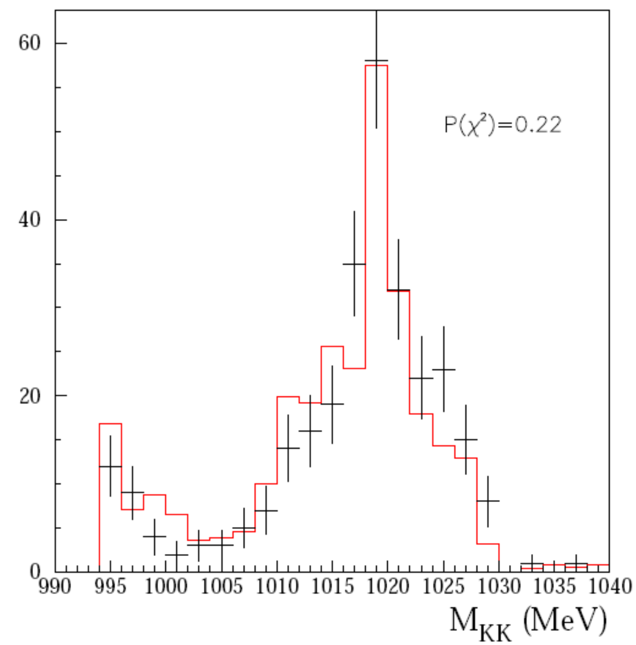
Isospin symmetry relates the couplings

$g\, f_0\pi^+ \pi^- = 2\, g\, f_0\pi^0\pi^0$

$g\, f_0K^0K^0 = g\, f_0K^+K^-$

$g\, a_0K^0K^0 = -g\, a_0K^+K^-$

strong destructive interference between $a_0$ and $f_0$ is expected in the KK channel



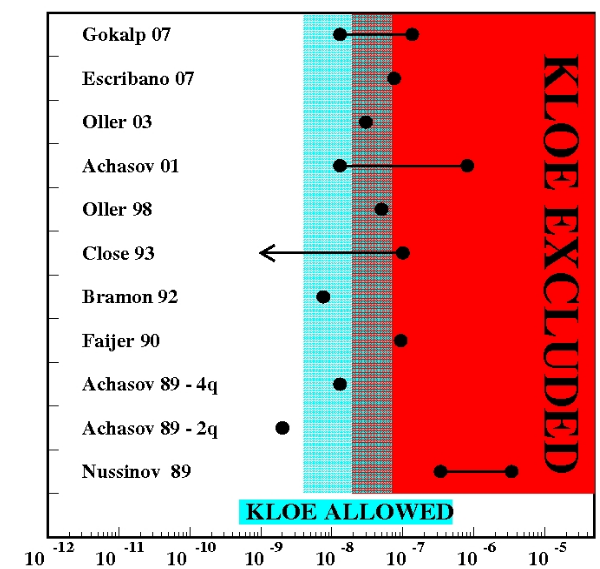

**Dataset: 2.2 fb$^{-1}$**

**5 events in data** (ε = 24%)

**3.2 ± 0.7 exp. background**

**First experimental result**

**BR($\phi \to \bar{K}^0 K^0 \gamma$) < 1.9 × 10$^{-8}$ 90% C.L.**



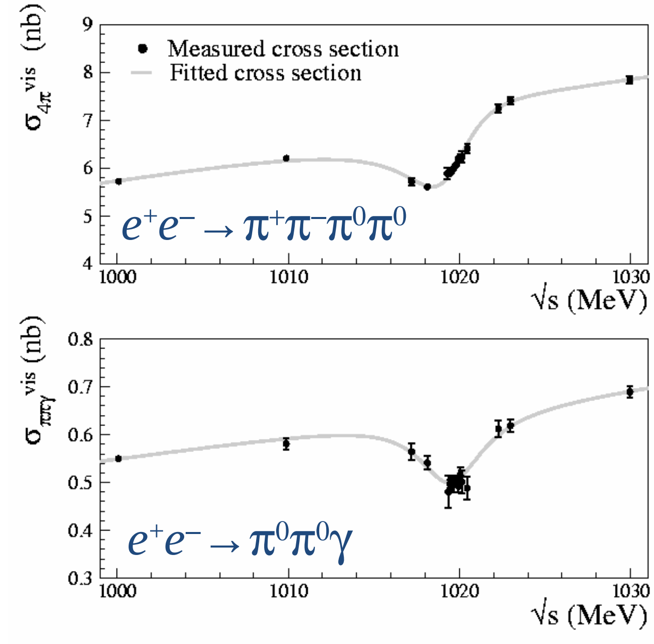
# $\sigma(e^+e^- \rightarrow \omega\pi^0)$

KLOE PLB 669 (2008) 223

## Interference pattern between non-resonant $e^+e^- \rightarrow \omega\pi^0$ and $\phi$ decays:

$$\sigma(\sqrt{s}) = \sigma_0(\sqrt{s}) \cdot \left| 1 - Z \frac{M_\phi \Gamma_\phi}{D_\phi} \right|^2$$

model independent $\Rightarrow$ $\sigma_0(\sqrt{s}) = \sigma_0 + \sigma'(\sqrt{s} - M_\phi)$

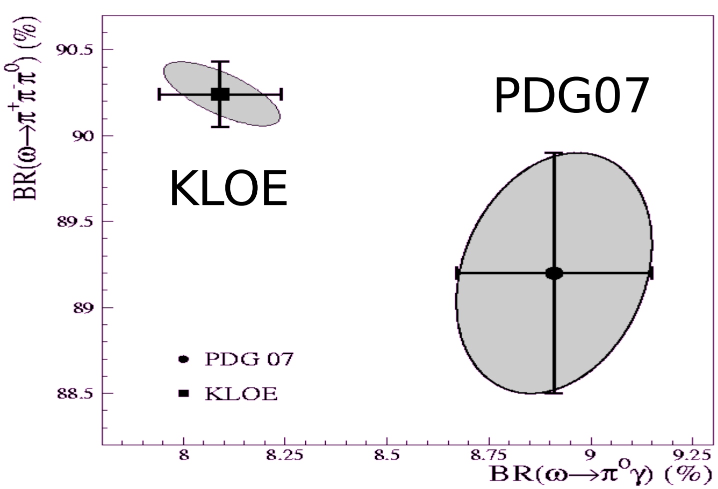



$\Gamma(\omega \rightarrow \pi^0\gamma)/\Gamma(\omega \rightarrow \pi^+\pi^-\pi^0)$ & assuming

$\Sigma_i \mathrm{Br}_i = 1$ $\mathrm{Br}(\omega \rightarrow \pi^+\pi^-)$ from PDG average

$\mathrm{BR}(\omega \rightarrow \pi^+\pi^-\pi^0) = (90.24 \pm 0.19)\%$

$\mathrm{BR}(\omega \rightarrow \pi^0\gamma) = (8.09 \pm 0.14)\%$




OZI + G-parity violating

$$BR(\phi \rightarrow \omega\pi^0) = \frac{\sigma_0^{\omega\pi} |Z_{4\pi}|^2}{\sigma_\phi} = (5.63 \pm 0.70) \times 10^{-5}$$

$$\mathrm{SND(2000)}: \mathrm{BR}(\phi \rightarrow \omega\pi^0) = (5.2^{+1.3}_{-1.1}) \times 10^{-5}$$

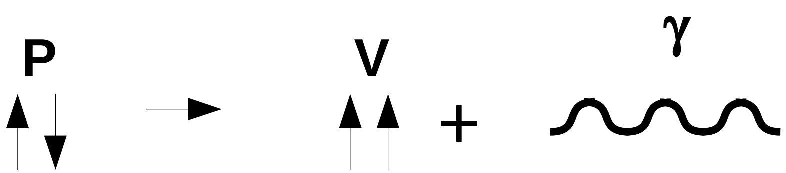
# $\eta,\eta'$: mixing and gluonium

**The $\eta,\eta'$ mesons wave function can be decomposed in the quark mixing base as in the folowing (J. L. Rosner, Phys. Rev. D 27 (1983) 1101. ).**

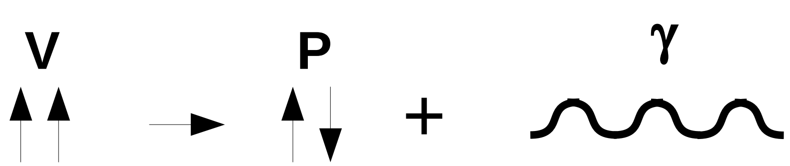
$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|G\rangle \qquad |\eta\rangle = \cos\psi_P|q\bar{q}\rangle - \sin\psi_P|s\bar{s}\rangle \qquad |q\bar{q}\rangle = \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$$

$$X_{\eta'} = \sin\psi_P \cos\psi_G$$
$$Y_{\eta'} = \cos\psi_P \cos\psi_G$$
$$Z_{\eta'} = \sin\psi_G$$

**The $\phi \to \eta,\eta'\gamma$ transition is modelled according a spin flip transition**




$$\Gamma(P \to V\gamma) = \frac{g^2}{4\pi}|p_\gamma|^3$$




$$\Gamma(V \to P\gamma) = \frac{1}{3}\frac{g^2}{4\pi}|p_\gamma|^3$$

**Only quarks participate to the electromagnetic transition, gluonium is spectator.**
**It appears in the $\eta'$ decay amplitudes only through the normalisation to 1 ($Y_{\eta'} \sim \cos\psi_G$)**

# KLOE past fit

**KLOE [Phys. Lett. B648 (2007) 267] has fitted:**

$$\frac{\Gamma(\eta'\to\rho\gamma)}{\Gamma(\omega\to\pi^0\gamma)} = \frac{z_q^2}{\cos^2\psi_V}\cdot 3\left(\frac{m_{\eta'}^2-m_\rho^2 m_\omega}{m_\omega^2-m_\pi^2 m_{\eta'}}\right)^3 X_{\eta'}^2$$

$$\frac{\Gamma(\eta'\to\omega\gamma)}{\Gamma(\omega\to\pi^0\gamma)} = \frac{1}{3}\left(\frac{m_{\eta'}^2-m_\omega^2 m_\omega}{m_\omega^2-m_\pi^2 m_{\eta'}}\right)^3 \left[z_q X_{\eta'}+2\frac{m_s}{\bar{m}} z_s\cdot\tan\psi_V\cdot Y_{\eta'}\right]^2$$

**taken from a global fit without gluonium**

A. Bramon, R. Escribano, M.D. Scadron
Phys. Lett. B503 (2001) 271

## Using KLOE measured branching ratio:

$$R_\phi = \frac{Br(\phi\to\eta'\gamma)}{Br(\phi\to\eta\gamma)} = \cot^2\psi_P\cdot\cos^2\psi_G\left(1-\frac{m_s}{\bar{m}}\frac{z_q}{z_s}\cdot\frac{\tan\psi_V}{\sin 2\psi_P}\right)^2\cdot\left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$R_\phi = (4.77 \pm 0.09 \pm 0.19)\times 10^{-3}$

$\phi\to\eta'\gamma$ 
$\eta'\to\pi^+\pi^-\eta$, $\eta\to3\pi^0$
$\eta'\to\pi^0\pi^0\eta$, $\eta\to\pi^+\pi^-\pi^0$
$\phi\to\eta\gamma$, $\eta\to3\pi^0$

**and the ratio:**

$$\frac{\Gamma(\eta'\to\gamma\gamma)}{\Gamma(\pi^0\to\gamma\gamma)} = \frac{1}{9}\left(\frac{m_{\eta'}}{m_\pi}\right)^3\left(5\frac{f_\pi}{f_q}X_{\eta'}+\sqrt{2}\frac{f_\pi}{f_s}Y_{\eta'}\right)^2$$

E. Kou, Phys. Rev. D 63 (2001) 54027

# KLOE new fit

Accepted by JHEP
arXiv:0906.3819

New global fit with more free parameters: $Z_N$, $Z_{NS}$, $\psi_V$, $m_s/m$

Other input are needed $\frac{\Gamma(\omega\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)}, \frac{\Gamma(\rho\to\pi^0\gamma)}{\Gamma(\omega\to\pi^0\gamma)}, \frac{\Gamma(\phi\to\eta\gamma)}{\Gamma(\omega\to\pi^0\gamma)}, \frac{\Gamma(\phi\to\pi^0\gamma)}{\Gamma(\omega\to\pi^0\gamma)}, \frac{\Gamma(K^{*+}\to K^+\gamma)}{\Gamma(K^{*0}\to K^0\gamma)}$

**From PDG06**

| Parameter | KLOE published | KLOE New fit | K. New fit (no Pγγ) | R.Escribano, J. Nadal JHEP 05 (2007) 6 |
|---|---|---|---|---|
| $Z^2_{\eta'}$ | 0.14 ± 0.04 | 0.105 ± 0.037 | **0.03 ± 0.06** | **0.04 ± 0.09** |
| $\psi_P$ | ( 39.7 ± 0.7 )° | ( 40.7 ± 0.7 )° | **( 41.6 ± 0.8 )°** | **( 41.4 ± 1.3 )°** |
| $Z_{NS}$ | 0.91 ± 0.05 | 0.866 ± 0.025 | **0.85 ± 0.03** | **0.86 ± 0.03** |
| $Z_S$ | 0.89 ± 0.07 | 0.79 ± 0.05 | **0.78 ± 0.05** | **0.79 ± 0.05** |
| $\psi_V$ | 3.2° | ( 3.15 ± 0.10 )° | **( 3.16 ± 0.10 )°** | **( 3.2 ± 0.1 )°** |
| $m_s/m$ | 1.24 ± 0.07 | 1.24 ± 0.07 | **1.24 ± 0.07** | **1.24 ± 0.07** |
| $P(\chi^2)$ | 49% | 17% | **41%** | **38%** |

**Gluonium content @ ~3σ level confirmed** ($Z_{\eta'} = 0$: $\psi_P = (41.6\pm0.5)°$, $P(\chi^2)=1\%$)

**$\eta'\to\gamma\gamma$ is the only measurement sensitive to the gluonium**

# USING PDG-08 and KLOE $\omega\to\pi^0\gamma$

$$\frac{\Gamma(\eta'\to\gamma\gamma)}{\Gamma(\pi^0\to\gamma\gamma)}=\frac{1}{9}\left(\frac{m_{\eta'}}{m_\pi}\right)^3\left(5\frac{f_\pi}{f_q}X_{\eta'}+\sqrt{2}\frac{f_\pi}{f_s}Y_{\eta'}\right)^2$$

exact isospin symmetry limit

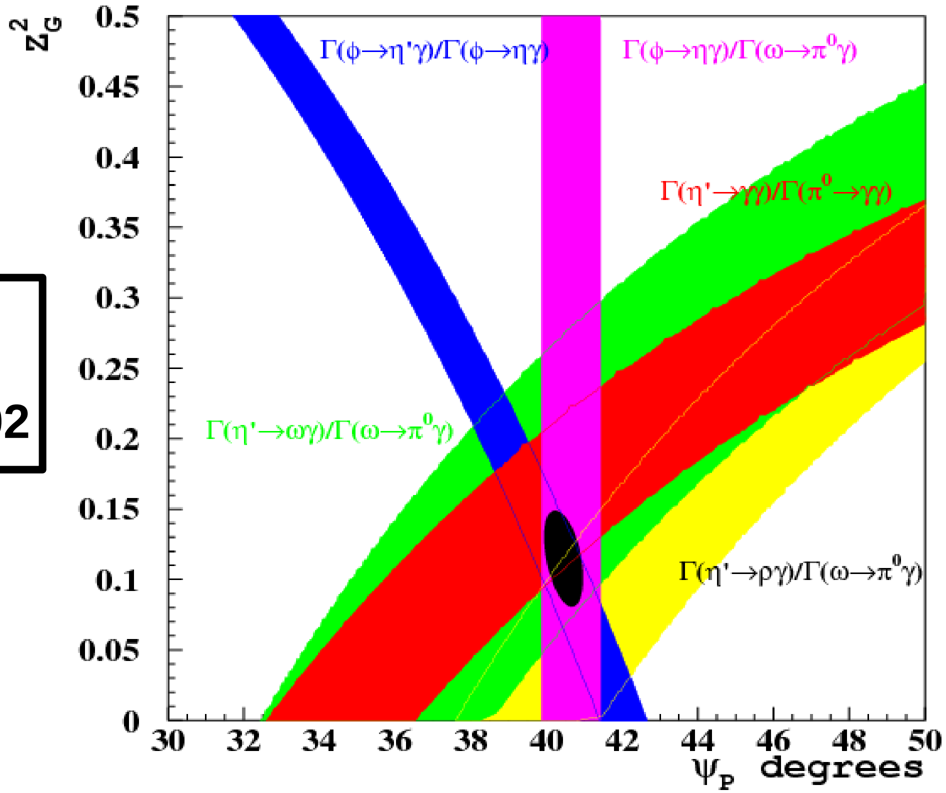
$$f_q/f_\pi=1 \qquad f_s/f_\pi=\sqrt{2f_K^2/f_\pi^2-1}$$

| | |
|---|---|
| $f_K/f_\pi$ | from lattice (UKQCD)<br>**E.Follana *et a l.***<br>**Phys. Rev. Lett. 100 (2008) 062002** |

$\chi^2$/ndof = 4.6/3

P($\chi^2$) = 20%

| | |
|---|---|
| $(Z_G)^2$ | 0.115 ± 0.036 |
| $\psi_P$ | (40.4 ± 0.6)° |
| $Z_q$ | 0.94 ± 0.03 |
| $Z_s$ | 0.83 ± 0.05 |
| $\psi_V$ | (3.32 ± 0.09)° |
| $m_s/m$ | 1.24 ± 0.07 |




**$Z_G$ can be interpreted as a mixing with a glue ball. The mass of this glue ball has been determined using KLOE fit [ Hai-Yang Cheng, Phys. Rev. D79 (2009) 014024]**

$m_G$ = (1.41 ± 0.1) GeV

**The glue-ball is identified as η(1405)**

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

- Poorly measured (4 events CMD-2, 16 events CELSIUS-WASA)
- Br predicted by ChPT and VMD models $(26 \div 36) \cdot 10^{-5}$
- η structure using virtual photon

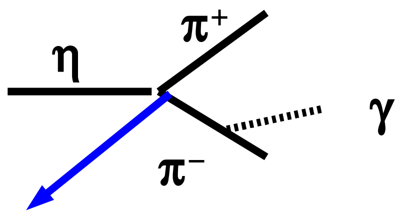
D. N. Gao, Mod. Phys. Lett. A17(2002) 1583

**CP violation source not constrained by CKM measurements and neutron elecrìtrc dipole moment**

$$\mathcal{O} = \frac{1}{m_\eta^3} G \bar{s} i \sigma_{\mu\nu} \gamma_5 (p-q)^\nu s \bar{\psi} \gamma^\mu \psi$$

} asymmetry in the particle decay angle

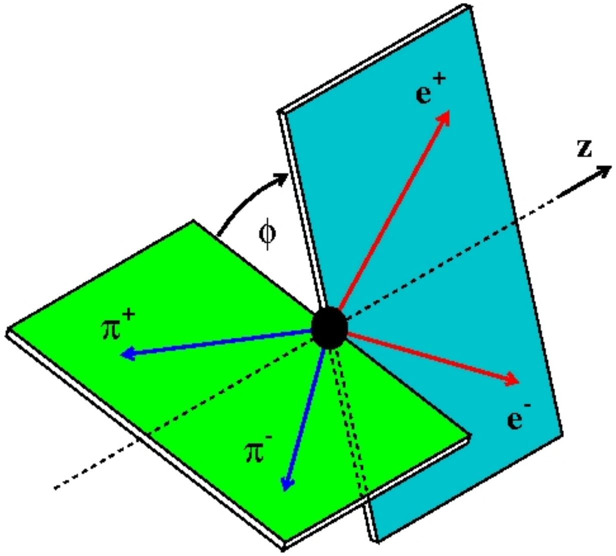
Within the SM:




**$Br(\eta \to \pi^+\pi^-) < 1.3\times10^{-5}$**
**KLOE, Phys. Lett. B606 (2005) 276**

$A_\phi < 10^{-4}$ **SM** $A_\phi \sim 10^{-15}$

**The unconventional CPV term can increase $A_\phi$ up to $10^{-2}$**



# Results: BR and $A_\phi$

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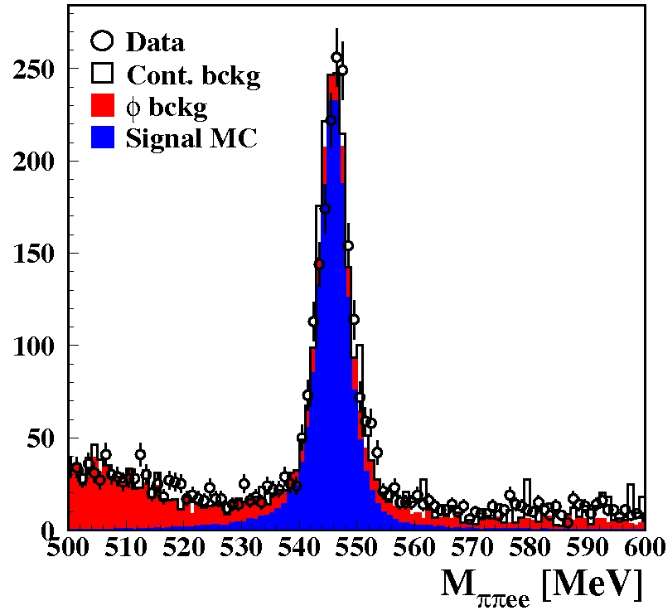
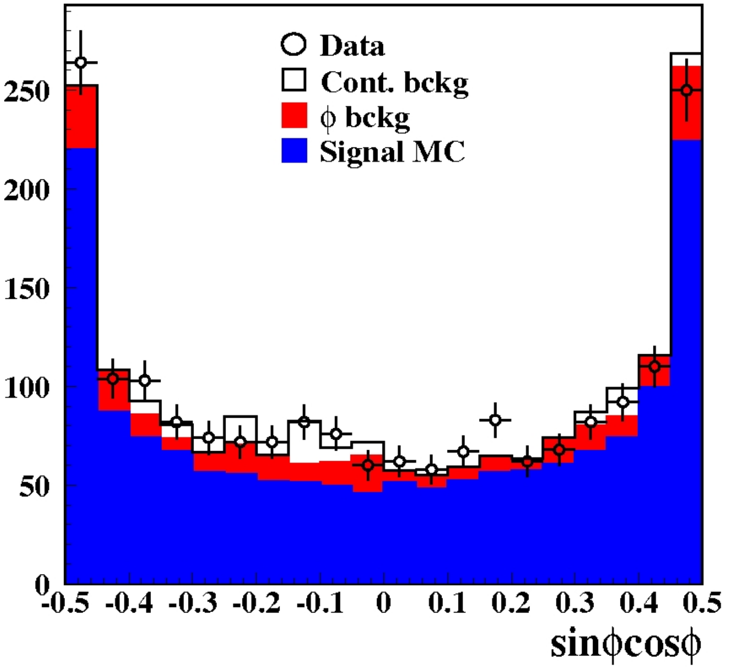
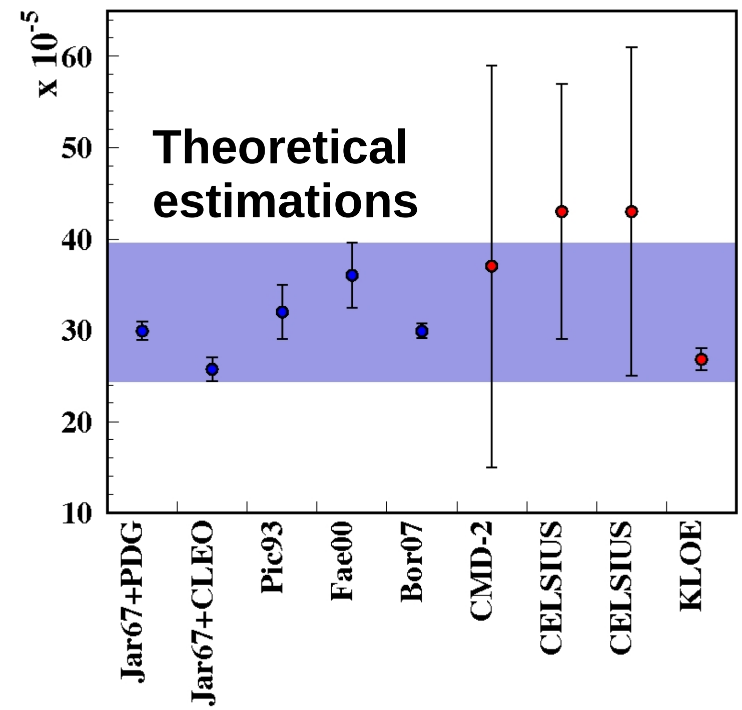



**$BR(\eta \to \pi^+ \pi^- e^+ e^- (\gamma))$**

**$(26.8 \pm 0.9_{Stat.} \pm 0.7_{Syst.}) \cdot 10^{-5}$**




**$A_\phi = (-0.6 \pm 2.5_{Stat.} \pm 1.8_{Syst.}) \cdot 10^{-2}$**

**$|G| < 1.8$**

First measurment of the CP asymmetry and attempt to constraint |G|.

# Conclusion & Outlook

- New KLOE data on $a_0$ together with the old $f_0$ results nicely agree with the 4 quark hypothesis in the instanton model;

- First upper limit on $\phi \rightarrow (f_0 + a_0)\gamma \rightarrow K^0 \bar{K}^0 \gamma \rightarrow K_S K_S \gamma$, sensitivity near the obsevation threshold;

- Refit of the $\eta'$ gluonium content confirms the $3\sigma$ KLOE claim, the main sensitive measurement has been identified with the $\eta' \rightarrow \gamma\gamma$;

- Precise measurement of the $\eta \rightarrow \pi^+ \pi^- e^+ e^- (\gamma)$ branching ratio and first measurement of the CP violating asymmetry.

**OUTLOOK: see next talk of P. Gauzzi**