"Study of ϕ meson radiative decays at KLOE, η/η' mixing angle and η' gluonium content."

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Talk outline

- Do we have evidence of states beyond the quark model predicitions?
- What's the present status of light scalar mesons?
- Kloe results on the 4 quark candidate f_0 and a_0
- Do we have evidence of bound states of gluons?
- KLOE results on $\phi\to\eta\gamma/\phi\to\eta'\gamma$;
- The vector and pseudoscalar mixing angle and the gluonium content in the η';
- 4q, 2q, meson molecules?

The quark model

Ordinary hadrons are since '60 classified from the quark model as $q\bar{q}$ (mesons) and qqq (baryons)

Quarks are bound by strong force in its non perturbative regime.

Analytical predictions for possible quark states from QCD are impossible to obtain, some progress with numerical computation through QCD on lattice.

The only guiding rule in thinking to possible quark states is the requirement that the states are colorless.
Color is an exact SU(3) symmetry, the quark belonging to the fundamental representation 3. All the quark bound states have to be in a singlet representation of $SU(3)_{color}$

1 q is colored, 3 representation
1 $\bar{q}$ $\bar{3}$ representation

Mesons

$q\bar{q}$ pair $3\otimes\bar{3} = 8 \oplus \mathbf{1}$

color singlet

qq pair $3\otimes 3 = 6 \oplus \bar{3}$ is colored

Baryons

qqq have a color singlet $3 \otimes 3 \otimes 3 = (6 \oplus \bar{3})\otimes 3 = 10 \oplus \bar{8} \oplus 3 \otimes \bar{3} = 10 \oplus \bar{8} \oplus 8 \oplus \mathbf{1}$

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Nice!! just with a bit of algebra we see that only $q\,\bar{q}$ and qqq states are allowed the main part of all particles we produce at our colliders.

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1 $\bar{q}$ $\bar{3}$ representation

Mesons

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Baryons

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"Let's add another quark..."

$qqqq$ $(10 \oplus \overline{8} \oplus 8 \oplus 1) \otimes 3$

$qqq\bar{q}$ $(10 \oplus \overline{8} \oplus 8 \oplus 1) \otimes 3$

→ No color singlets can come out from these combination

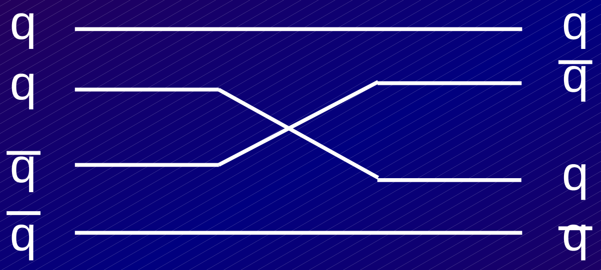
Let's go back to qq..

qq pair $3 \otimes 3 = 6 \oplus \overline{3}$ $\bar{q}\bar{q}$ pair $\overline{3} \otimes \overline{3} = \overline{6} \oplus 3$

$qq\bar{q}\bar{q}$ $(6 \oplus \overline{3}) \otimes (\overline{6} \oplus 3) = (3 \otimes \overline{3})_1 \oplus (6 \otimes \overline{6})_1$

We can have a color singlet from colored quark pairs. In this case we say we have a 4 quark state. Jaffe (1974).

quark exchange



colored pair

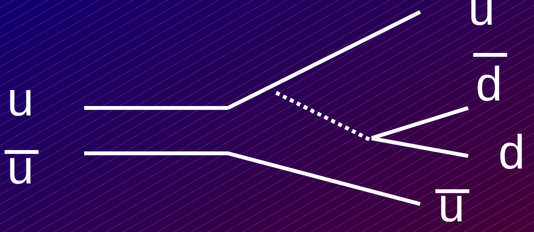
colored pair

singlet meson

singlet meson

Due to quark exchange these states have high decay probability to meson pairs, large width Γ, **in** some cases $\Gamma \sim m$

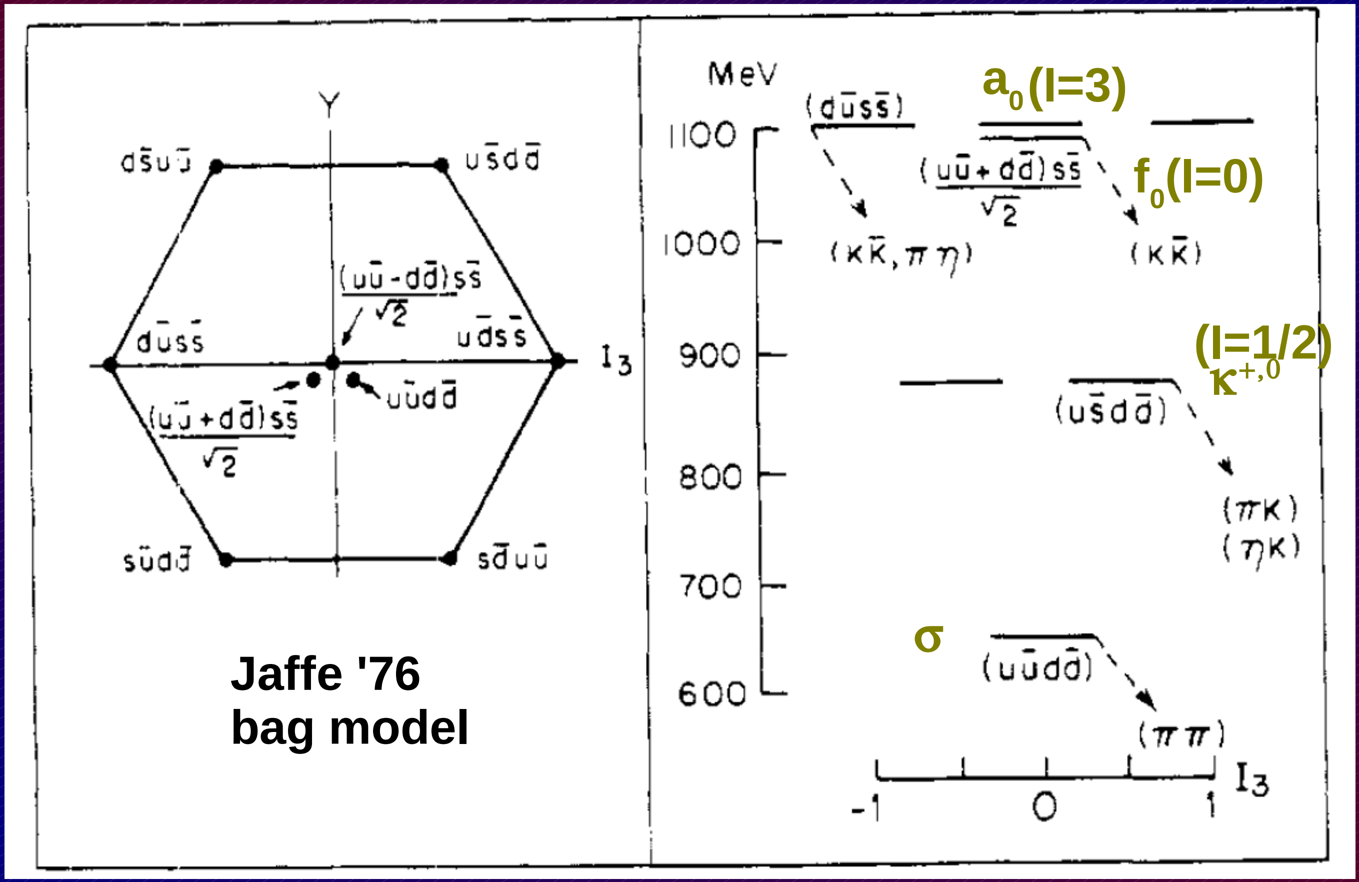
In contrast $\rho \to \pi^+\pi^-$



4q Phenomenology

1) Large decay rates to meson pairs.

2) Large widths.



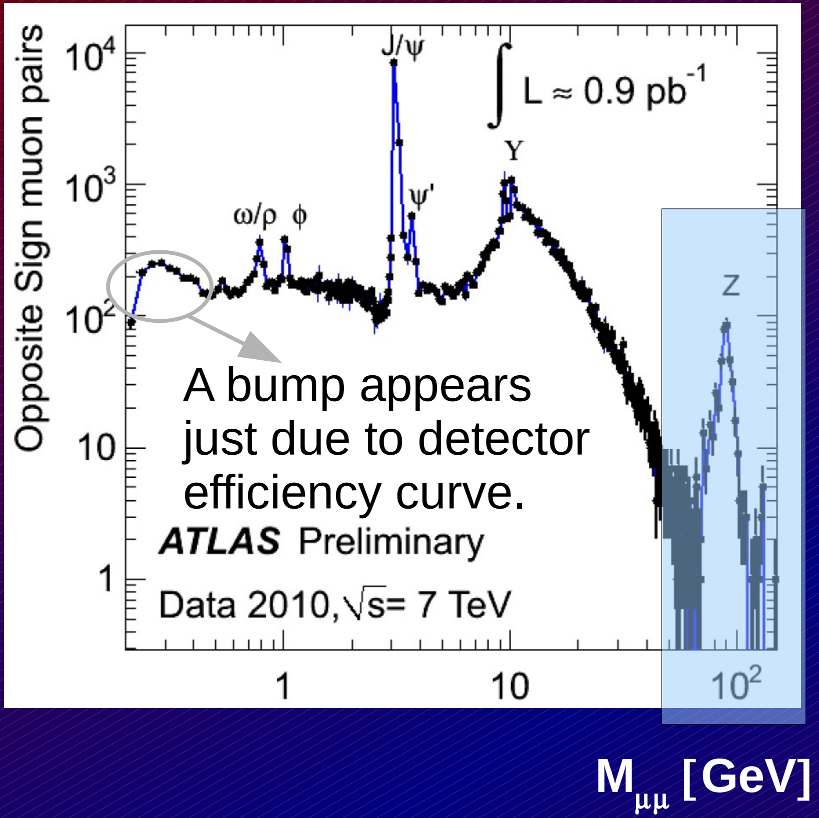
Four quark states

Jaffe '76
bag model

A complete nonet of states is predicted with quantum number $J^{PC} = 0^{++}$

Why are we still talking about them?

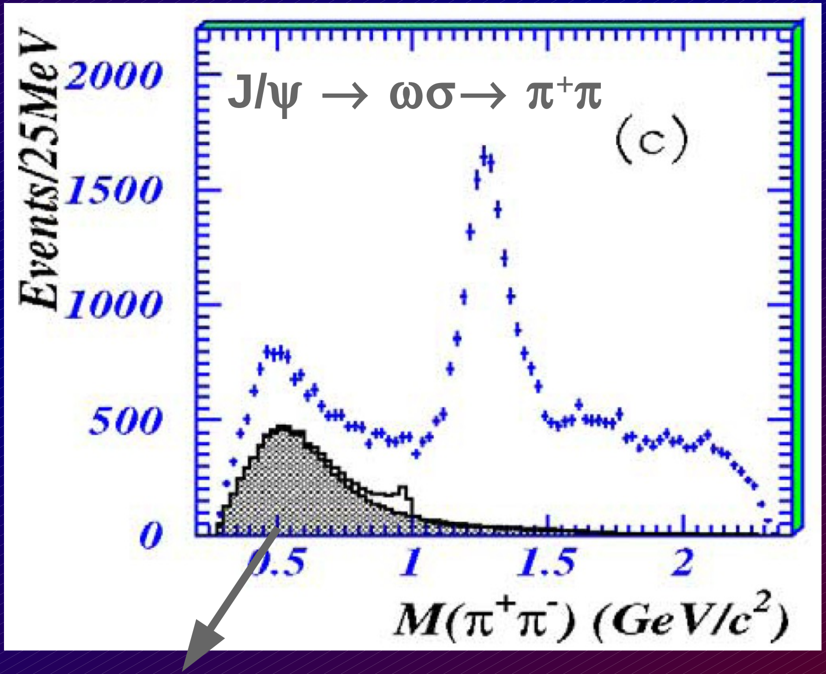
di-muon resonance spectrum in pp collisions



A bump appears just due to detector efficiency curve.

This guy is out of the game

BESII-$J/\psi \rightarrow \omega\pi^+\pi^-$



0^{++} contribution from partial wave analysis

Broad resonance can be easily interpreted as continuum background + efficiency of the detector at threshold and vice versa.

m = 541 ± 39 MeV
Γ = 504 ± 84 MeV

Why are we still talking about them?

Even when clearly established we can doubt about their nature

Meson-Meson molecules:
bound states just like pn in deuteron.

meson (color singlet)   meson (color singlet)

q .... q

$\bar{q}$ .... $\bar{q}$

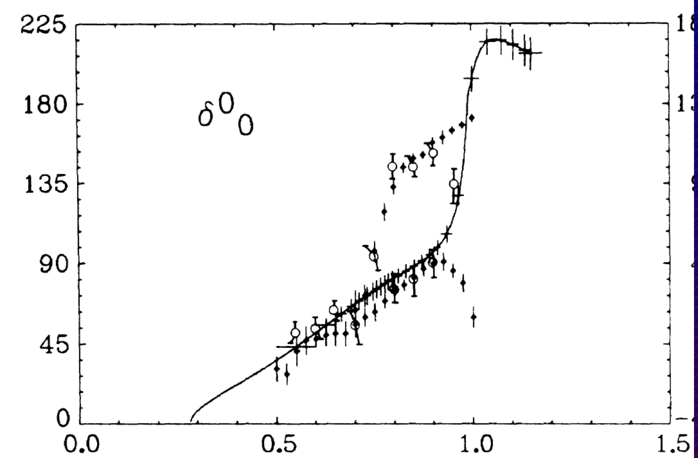
Ordinary $q\bar{q}$ states in $^3P_0$ configuration

0^{++} quantum numbers can be obtained by two quarks in triplet spin state and orbital angular momentum 1.

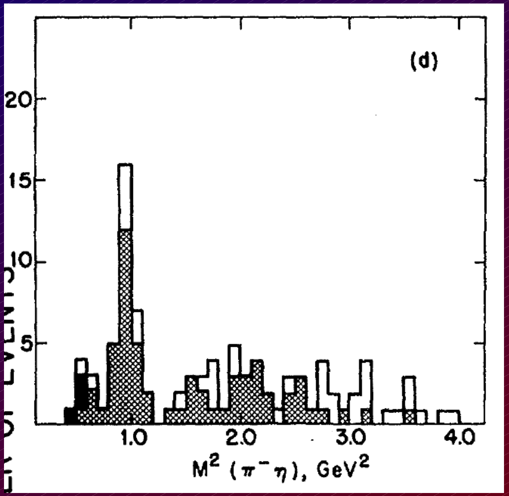
a_0 and f_0 mesons, well established since '68 and '73 in $\pi^-\eta$ invariant mass and $\pi^+\pi^-$ scattering. Candidates for KK molecules being m = 980 MeV <~ $2m_K$ = 997 MeV (K^0), 987 ($K^\pm$), 991 ($K^0K^\pm$)

S.D. Protopopescu, Phys. Rev. D7, 1279

I = 0, L = 0 phase shift



R. Ammar, Phys. Rev. Lett 21, 1832



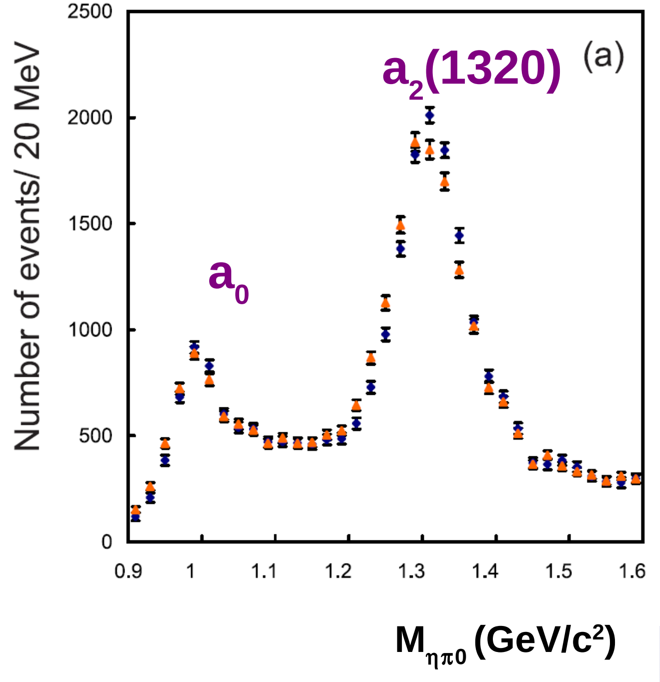
The a_0 isospin triplet

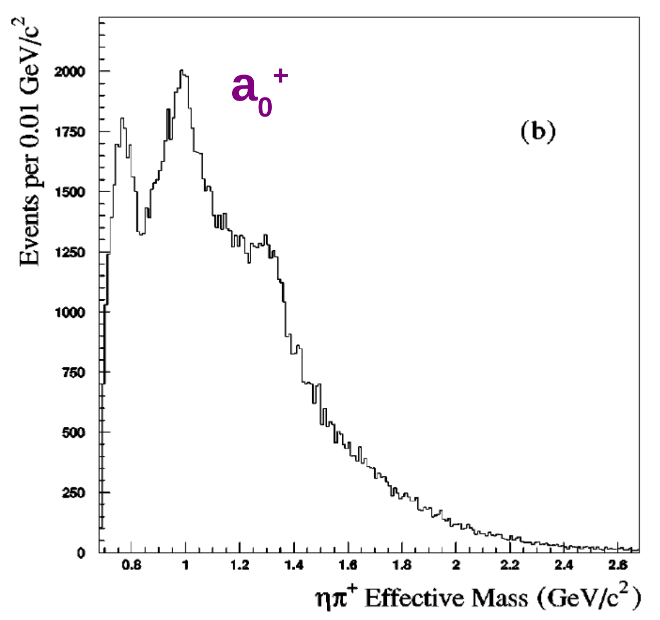
Belle, $e^+e^- \to (\gamma^*\gamma^*) \to a_0 \to \eta\pi^0$

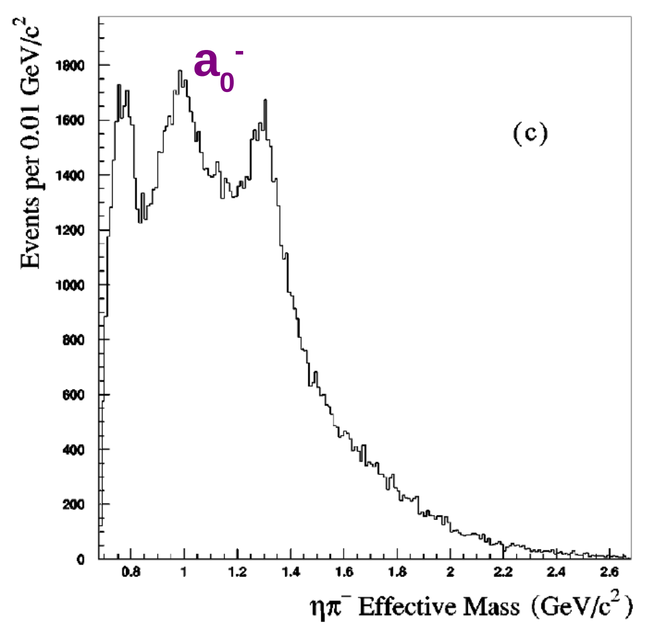
Phys. Rev. D 80 (2009) 032001

BNL E852, $\pi^- p \to n\eta\pi^+\pi^-$

Phys. Rev. D59 (1999) 012001

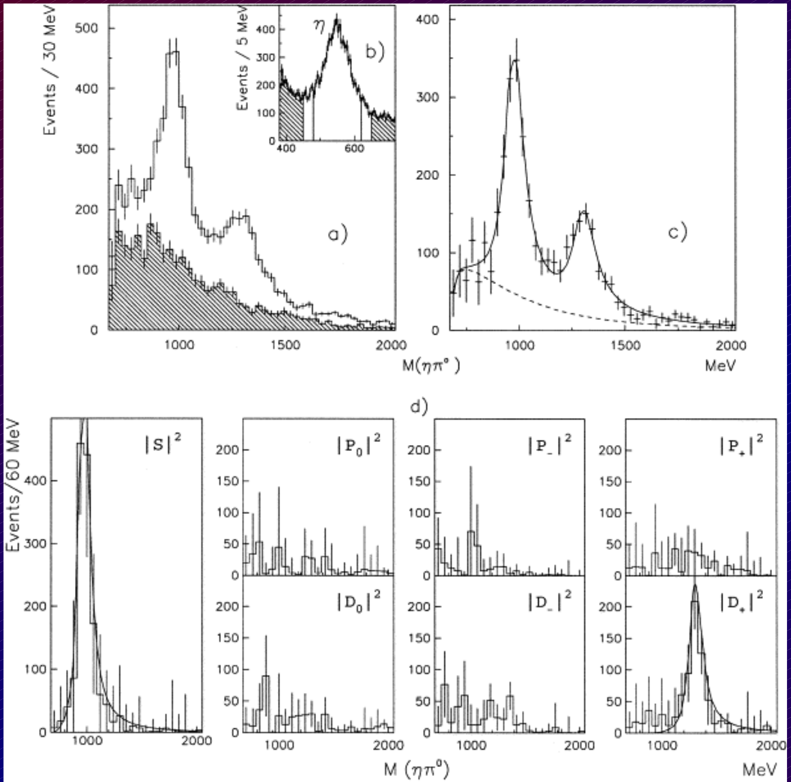




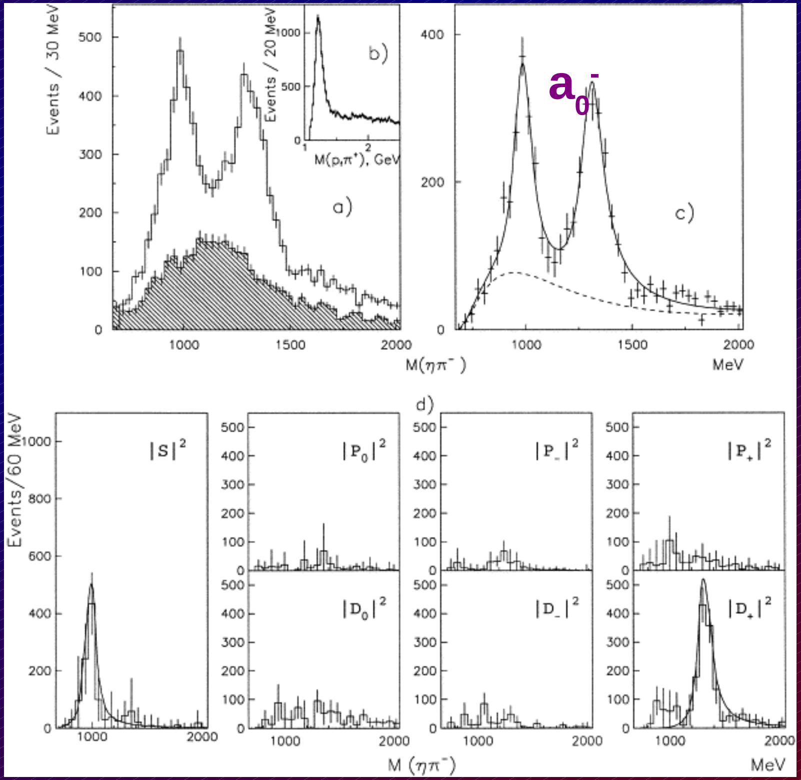


The a_0 isospin triplet in pp interaction

D. Barberis, et al. Phys. Lett. B488 (2000) 225
WA102 pp $\to \eta\pi^0 pp$



WA102 pp $\to \eta\pi^- p\Delta^{++}$



The mass values

$m_\sigma = 541$ MeV > $2m_\pi = 270–280$ MeV, cannot be interpreted as $\pi\pi$ molecules

Same argument applies to κ, cannot be a $K\pi$ molecules.

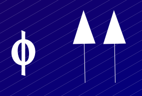
The 2 quark states build a full spectrum as well.

The f_0 meson has I=0, it can be $u\bar{u} + d\bar{d}$ or $s\bar{s}$

like the ρ, but with higher mass and the $\pi^0\pi^0$ channel open, so we would expect $\Gamma_{f0} >> \Gamma_\rho$, while $\Gamma_{f0} < \Gamma_\rho$

If f_0 were $s\bar{s}$, it would be an angular excitation of the ϕ meson

$s\bar{s}$



spin 1
L = 0

m_ϕ = 1020 MeV

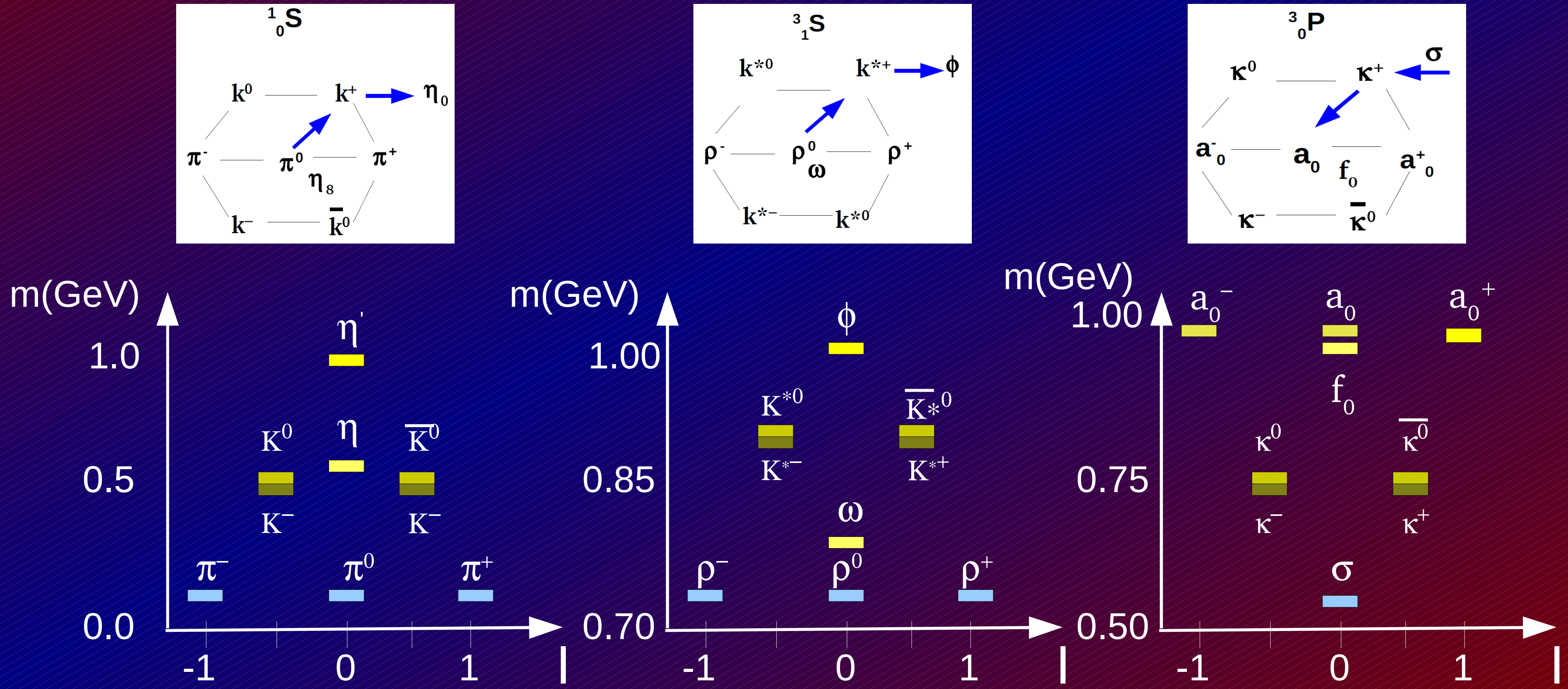
spin 1
L = 1

$m_{f0} > m_\phi$

Already Jaffe prediction of $^3P_0$ states had to lie in the m>1 GeV region

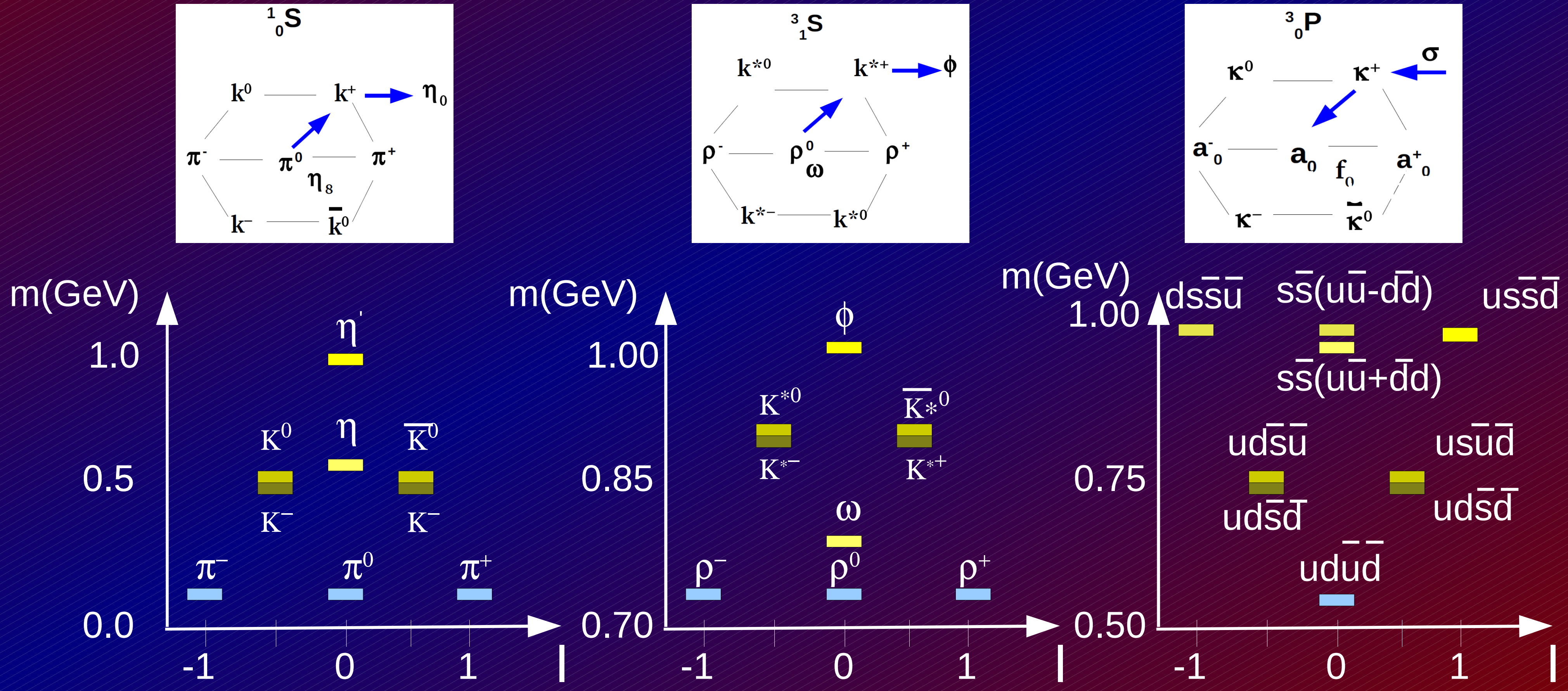
The nonet mass hierarchy

Even if we don't consider the absolute value of the mass, the mass pattern among them cannot be explained in the 2q hypothesis



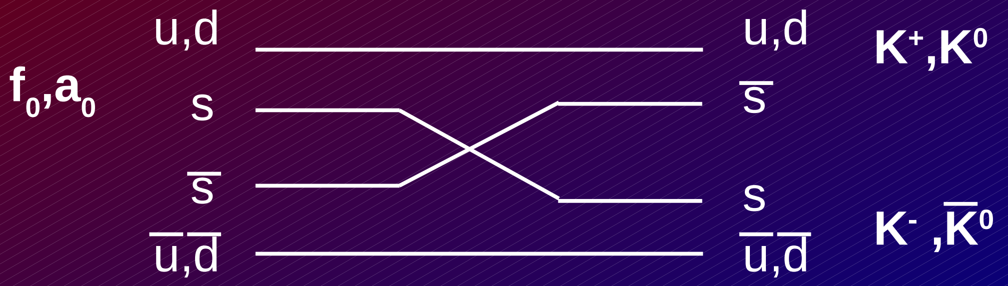
The nonet mass hierarchy

Natural explanation in the 4q hypothesis thanks to the increasing number of s quark, also the degeneracy in mass of f_0 and a_0 gets explained



The decays...

In principle large widths and decay rate to pseudoscalars are expected due to the quark exchange process, that's surely true for σ and κ



f_0,a_0

u,d
s
$\bar{s}$
$\bar{u},\bar{d}$

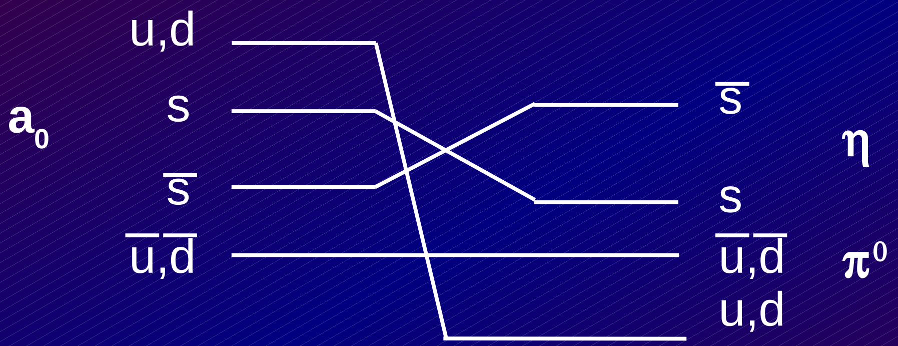
u,d
$\bar{s}$
s
$\bar{u},\bar{d}$

K^+,K^0

K^- ,$\bar{K}^0$

the process is kinematically suppressed being m_{f0a0} < $2m_{K.}$ Anyway a large coupling to KK is expected.

$f_0 \rightarrow \pi\pi$ **Should vanish unless it mixes with σ**



a_0

u,d
s
$\bar{s}$
$\bar{u},\bar{d}$

$\bar{s}$
s
$\bar{u},\bar{d}$
u,d

η

π^0

Large coupling is expected.

KLOE scalar study in ϕ decays

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

Eur. Phys. J. C49 (2007) 473

Phys. Lett. B 634 (2006) 148

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

Phys. Lett. B 681 (2009) 5

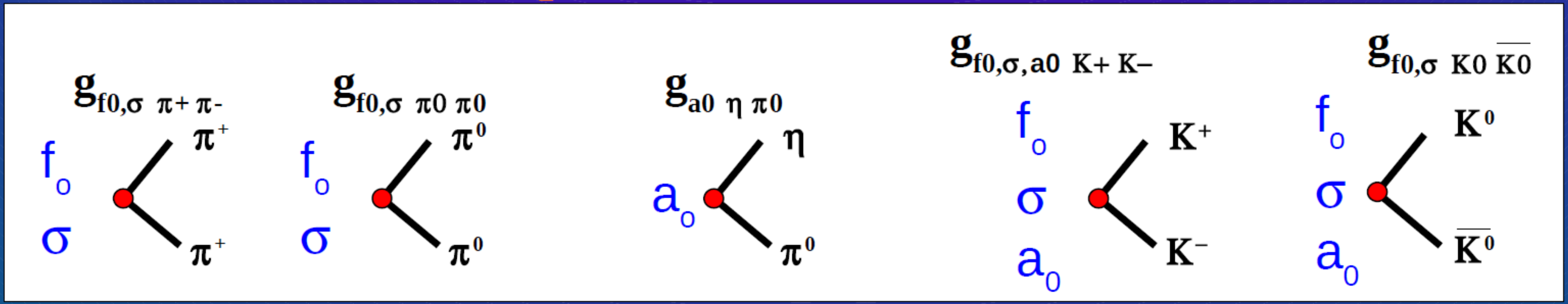
Sensitive to the scalar structure

$e^+e^- \to \phi \to (a_0 + f_0)\gamma \to K^0\overline{K^0}\gamma \to K_sK_s\gamma$

Phys. Lett. B 681 (2009) 5

Sensitive to the a_0-f_0 interference.

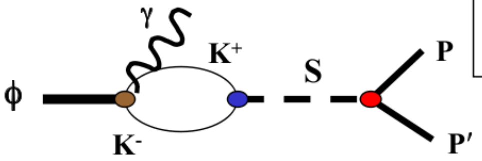
Allow the measurement of the following couplings



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

Phenomenological parametrisations

Kaon Loop



Fit params:
M_S, $g_{SPP'}$, g_{SKK}

[N.N.Achasov, V.N.Ivanchenko, NPB315 (1989) 465]
[N.N.Achasov, V.V.Gubin, PRD 56 (1997) 4084]
[N.N.Achasov, A.V.Kiselev, PRD 68 (2003) 014006]

For the a_0 case:

$$\frac{d\Gamma_{\text{scal}}}{dm} = \frac{2|g_{\phi K^+K^-}\, g(m)|^2\, p_{\eta\pi^0}(M_\phi^2 - m^2)}{3(4\pi)^2 M_\phi^3}\left|\frac{g_{a_0K^+K^-}\, g_{a_0\eta\pi^0}}{D_{a_0}(m)}\right|^2$$

$$D_{a_0}(m) = M_{a_0}^2 - m^2 + \sum_{ab}\left[\operatorname{Re}\Pi_{ab}(M_{a_0}) - \Pi_{ab}(m)\right]$$

The propagator has a variable width as a function of √s taking into account the opening of the ππ and KK channels

$$\Gamma_{a_0}(m) = \frac{\sum_{ab}\operatorname{Im}\Pi_{ab}(m)}{m} = \frac{\sum_{ab} g_{a_0ab}^2\,\rho_{ab}(m)}{16\pi m}$$

Propagator withfinite width corrections

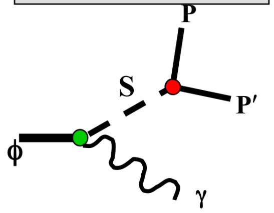
$$\begin{pmatrix} \pi\pi, K^+K^-, K^0\overline{K}^0, \eta\eta, \eta\eta', \eta'\eta' \text{ for } f_0(980) \\ \eta\pi^0, K^+K^-, K^0\overline{K}^0, \eta'\pi^0 \text{ for } a_0(980) \end{pmatrix}$$

Channel opening threshold
$m > m_a + m_b$.

$$\rho_{ab}(m) = \sqrt{\left(1 - \frac{(m_a+m_b)^2}{m^2}\right)\left(1 - \frac{(m_a-m_b)^2}{m^2}\right)}$$

Alternative model
Direct coupling to the ϕ

No Structure

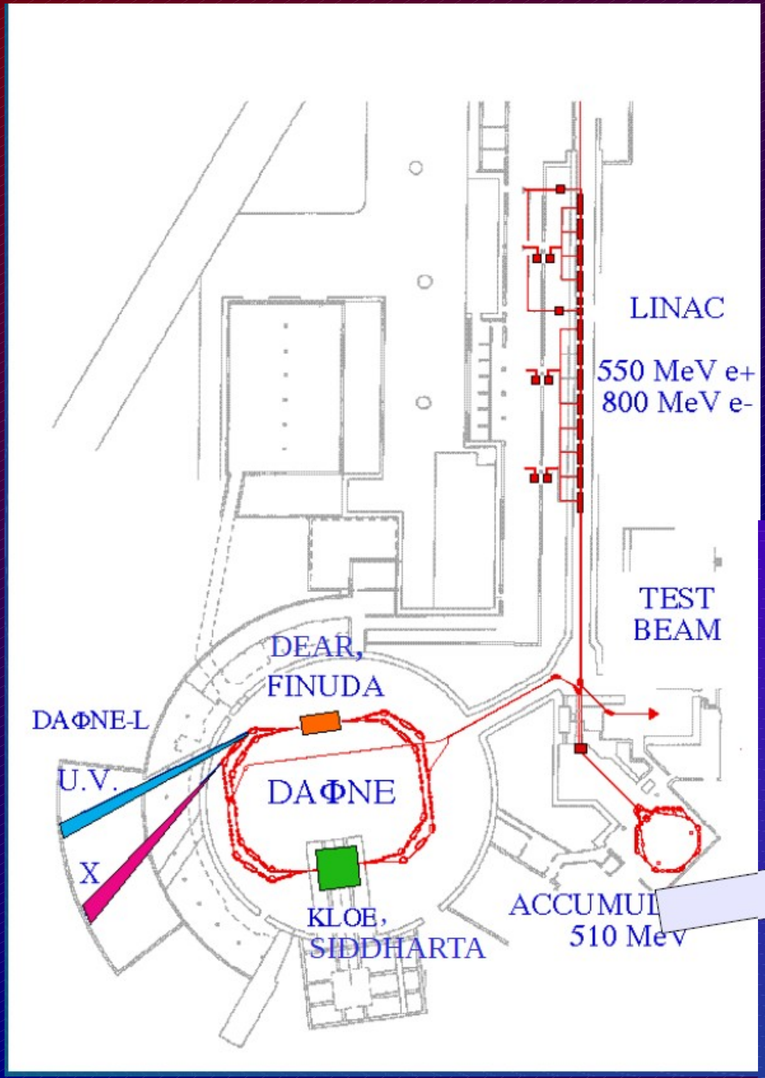


Fit params:
M_S, g_{fSg}, $g_{SPP'}$, g_{SKK},
continuum (polynomial)

[G.Isidori, L.Maiani, M.Nicolaci, S.Pacetti, JHEP 05 (2006) 049]

The DAFNE ϕ factory

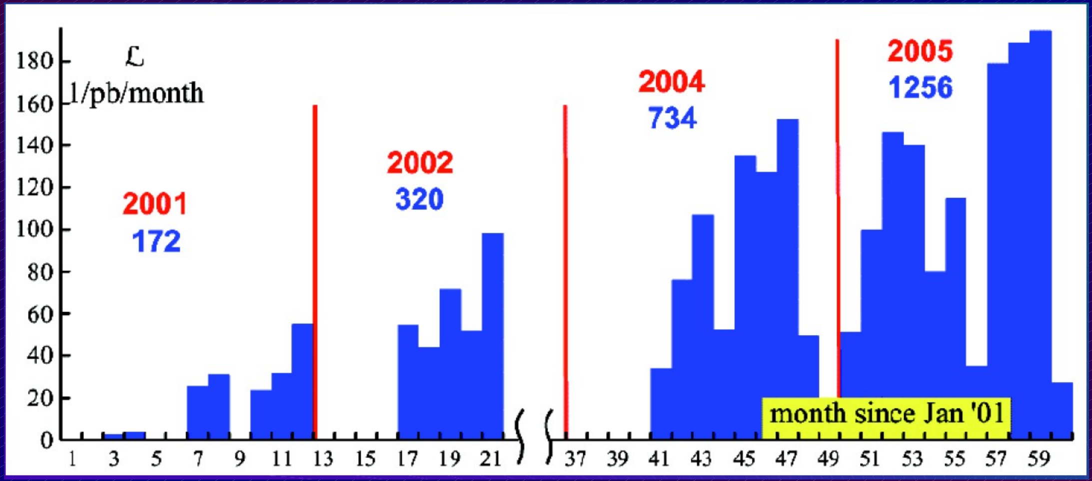
- $\sqrt{s} = m_\phi = 1019.4$ MeV, $\sigma(e^+e^- \to \phi) \sim 3\mu b$
- Separate e^+e^- rings to reduce beam-beam interaction
- Crossing angle: 25 mrad, $p_x\phi \sim 12.6$ MeV
- 105 + 105 bunches, 2.7 ns inter bunch time
- Acquisition also during the injection
- Maximum currents $I(e^+)$ 2.4 A $I(e^-) = 1.5$ A

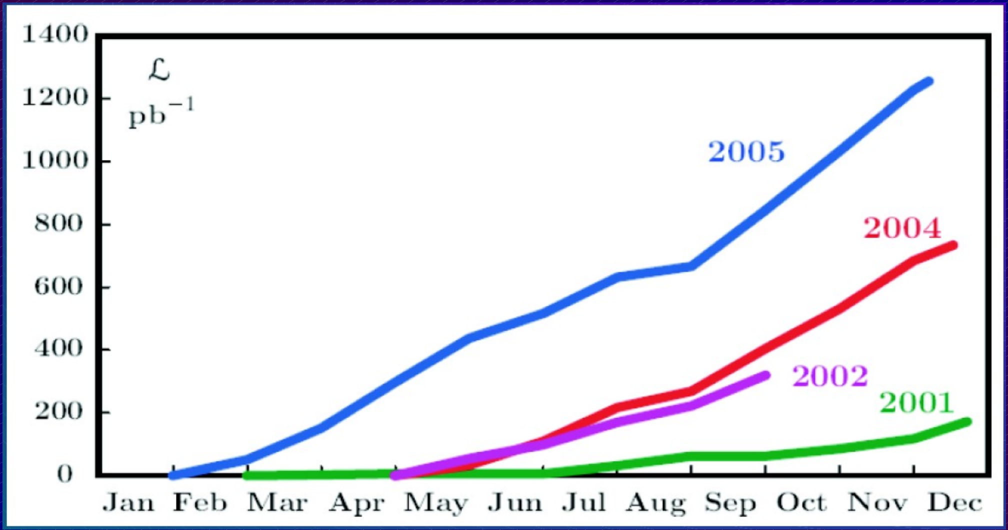


Machine performance and data sample

Collected data

- Last run- March 2006
- Max luminosity 1.3×10^{32} cm^{-2}s^{-1}
- Tot. Integrated 2.5 fb^{-1}
- 200 pb^{-1} @ $\sqrt{s}$ = 1000 MeV





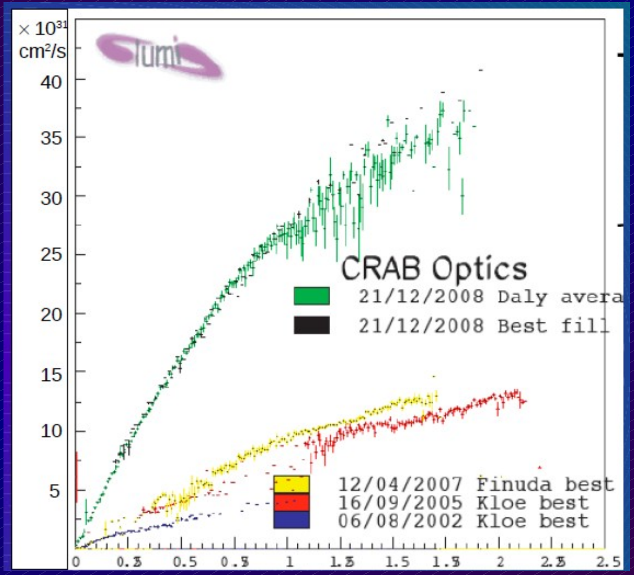
Events on tape
8 billions of ϕ decays

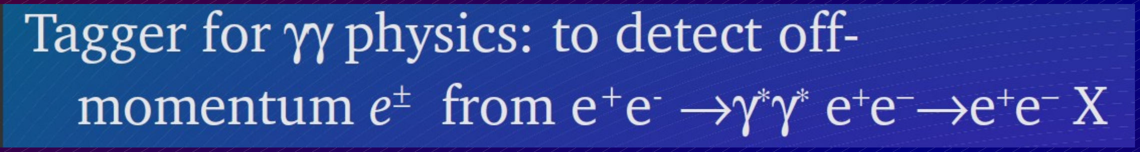
K^+K^-	4×10^9	$\pi^0\gamma$	10×10^6
$K^0\overline{K^0}$	3×10^9	$f_0\gamma$	2.6×10^6
$\pi^+\pi^-\pi^0$	1.2×10^9	$a_0\gamma$	6.3×10^5
$\eta\gamma$	100×10^6	$\eta'\gamma$	5.4×10^5

KLOE-2, new run starting...

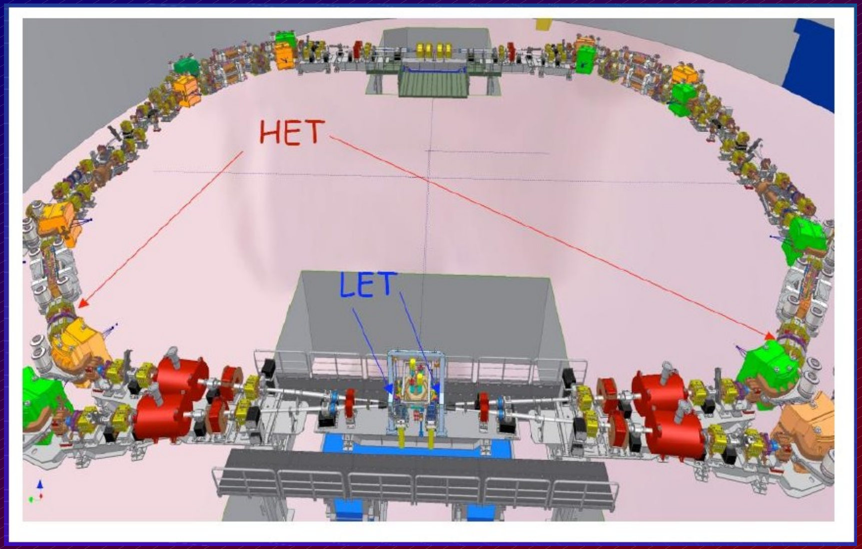
New interaction region

- New interaction region and sextupoles have bin designed to apply the crab waist technique;
- The β function is minimized along a large region of beams intersection.

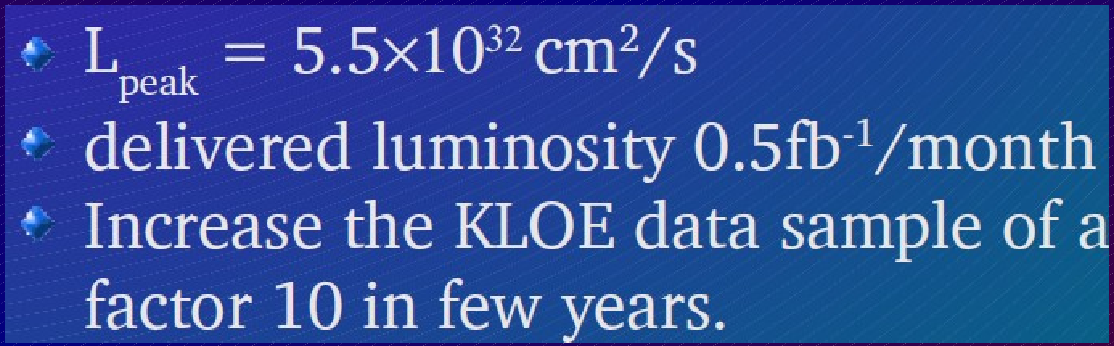




Tagger for γγ physics: to detect off-momentum $e^{\pm}$ from $e^+e^- \to \gamma^*\gamma^*\, e^+e^- \to e^+e^- X$



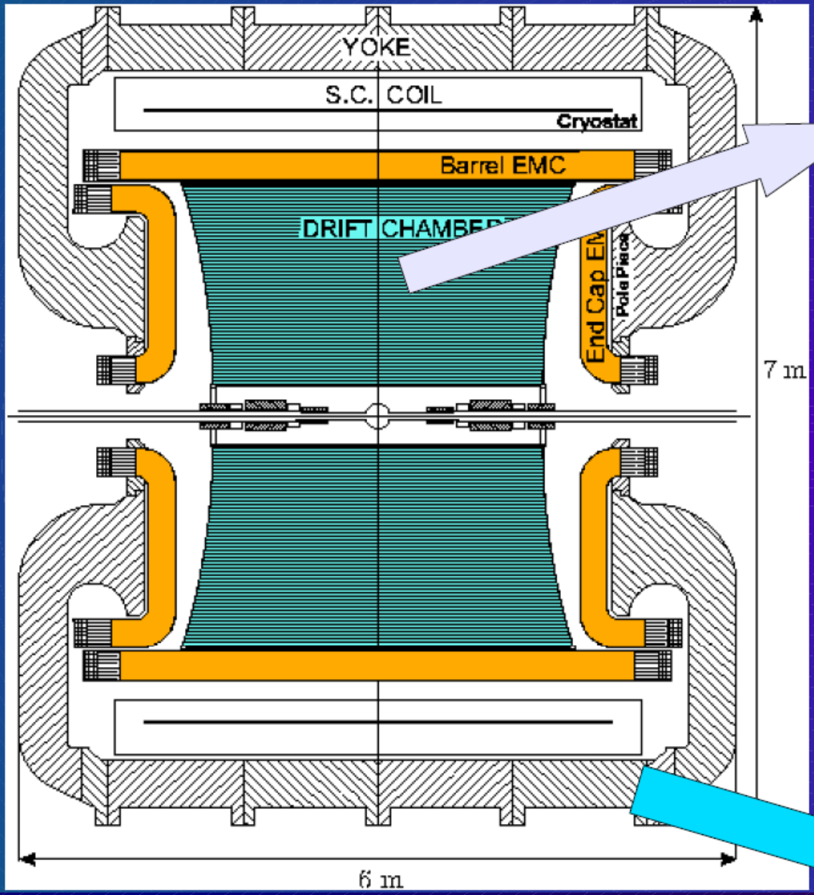
Expected performances



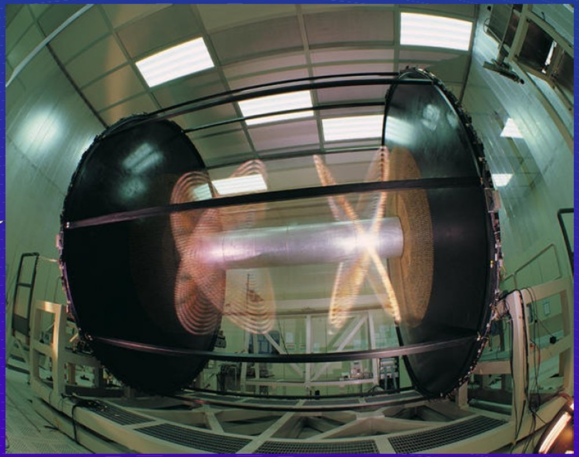
- $L_{peak} = 5.5\times10^{32}$ cm²/s
- delivered luminosity 0.5fb^{-1}/month
- Increase the KLOE data sample of a factor 10 in few years.

The KLOE detector - the tracker

Detector scheme



Cylindrical Drift Chamber



- Stereo wires structure to reconstruct longitudinal position
- 52140 wires – 12582 drift cell
- 90% He 10% iC_4H_{10}

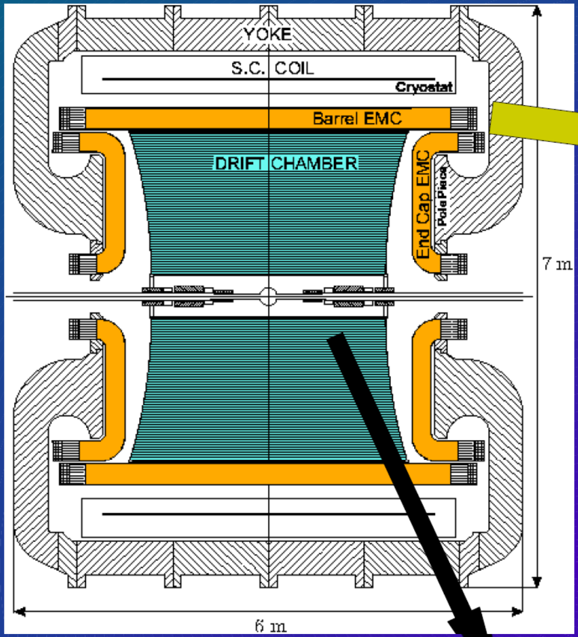
σ_{vtx} = 1 mm σ_{pt}/p_t = 0.5%

$\sigma_{r\phi}$ =200μm σ_z = 2 mm

Magnetic system.

- 0.5 T magnetic field
- Cryogenic coil working at 4.2 °K
- Coil current 2300 A

The KLOE detector - the calorimeter



Main 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

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

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

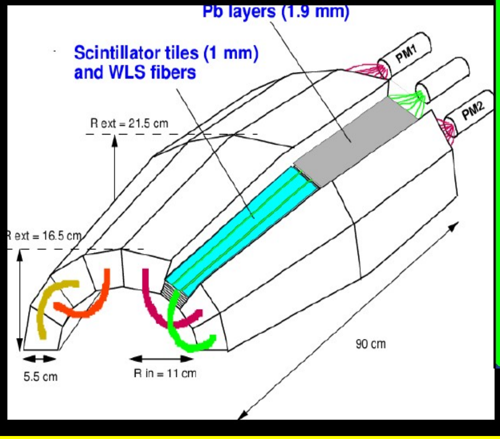
Small angle veto calorimeter

Efficiency 20 – 90 %

E 26-125 MeV

σ_t = 240 ps/√E (GeV)

covered angle 23°



The $\phi \to a_0 \gamma \to \eta\pi^0\gamma \to 5\gamma$

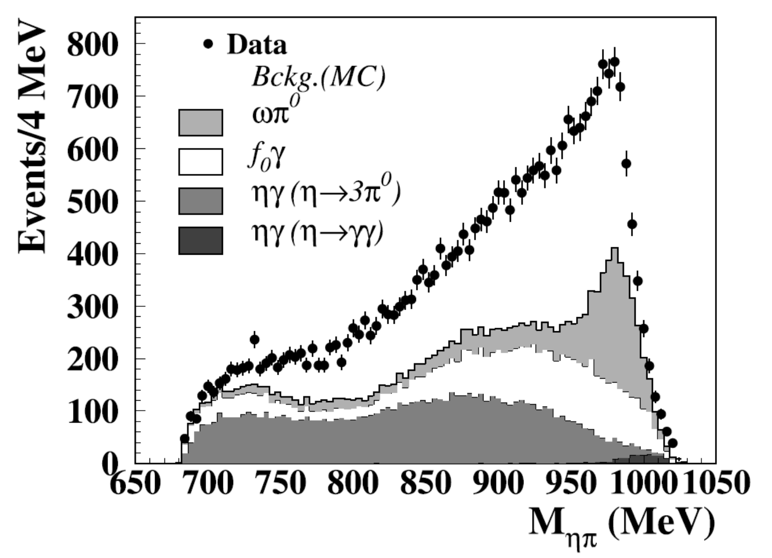
Analysis selection

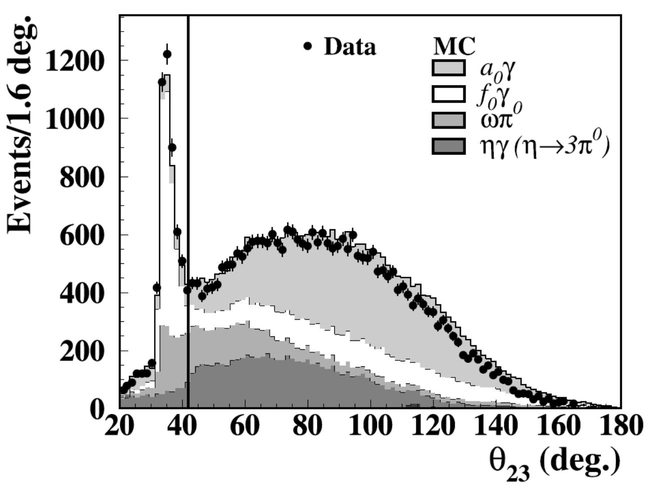
1) 5 energy deposits in calo;
2) TOF identification of photons using cluster times;
3) Kinematic fit constrained to the ϕ momentum;
4) Pairing of the photons to π^0 and η;
5) 2' kinematic fit imposing π^0 and η masses;
Selection using the χ^2 of the fits;
6) kinematic rejection of background channel

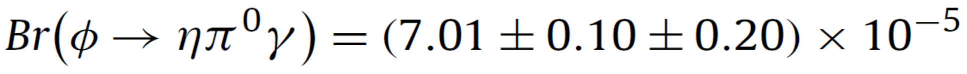
S/B bef. sel. 0.05, after selection 1

MC prediction corrected using enriched background samples on data, fitting discriminant variables.

Selection efficiency 38.5%

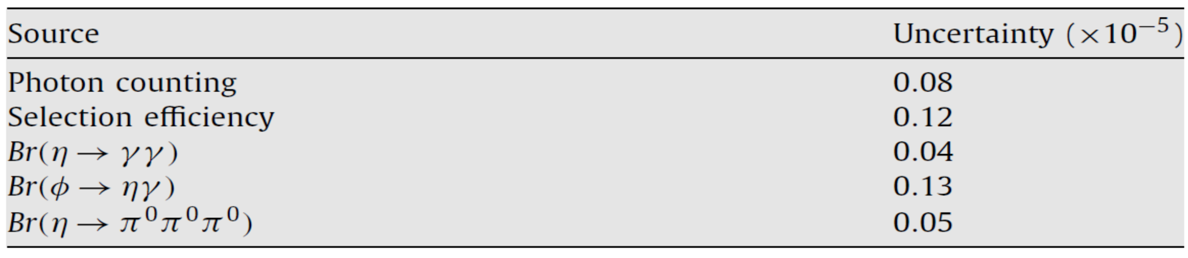






$$Br(\phi \to \eta\pi^0\gamma) = (7.01 \pm 0.10 \pm 0.20) \times 10^{-5}$$

Systematic error

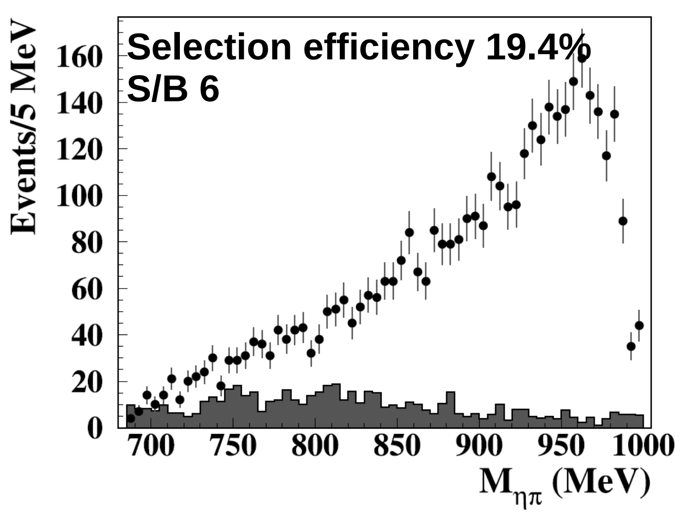


Source	Uncertainty $(\times 10^{-5})$
Photon counting	0.08
Selection efficiency	0.12
$Br(\eta \to \gamma\gamma)$	0.04
$Br(\phi \to \eta\gamma)$	0.13
$Br(\eta \to \pi^0\pi^0\pi^0)$	0.05

The $\phi \to a_0 \gamma \to \eta\pi^0\gamma \to \pi^+\pi^-\pi^0\pi^0\ \gamma \to \pi^+\pi^- 5\gamma$

Analysis selection

1) 5 energy deposits in calo;
2) TOF identification of photons using cluster times;
3) 2 track in one vertex close to the I.P.
3) Kinematic fit constrained to the ϕ momentum;
4) Pairing of the photons to π^0 and η;
5) 2' kinematic fit imposing π^0 and η masses;
Selection using the χ^2 of the fits;
6) $|p_{\pi+}| + |p_{\pi-}| < 418$ MeV, $|p_{\pi+}| + |p_{\pi-}| > 430$ MeV
to reject $K_s \to \pi^+\pi^-$ background
7) $E_{\gamma\phi} > 20$ MeV (to remove fake photons)


Selection efficiency 19.4%
S/B 6

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

Systematic error from bkg estimate and efficiency.

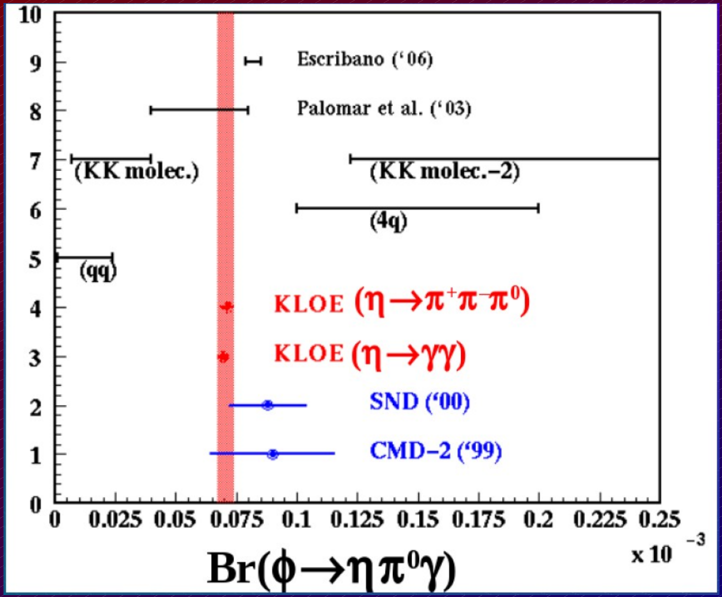
Background contribution

$e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\ 2\pi^0 \to \pi^+\pi^- 4\gamma$ + 1 fake
$\phi \to K_S K_L \to \pi^+\pi^-\ 3\pi^0 \to \pi^+\pi^-\ 6\gamma$ 1 lost
$\phi \to K_S K_L \to 2\pi^0\pi^+\pi^-\ \pi^0 \to \pi^+\pi^-\ 6\gamma$ 1 lost
$\phi \to K_S K_L \to 2\pi^0\pi^+\pi^-\ \pi^0 \to \pi^+\pi^-\ 6\gamma$ 1 lost

Combined result

$$Br(\phi \to \eta\pi^0\gamma) = (7.06 \pm 0.22) \times 10^{-5}$$

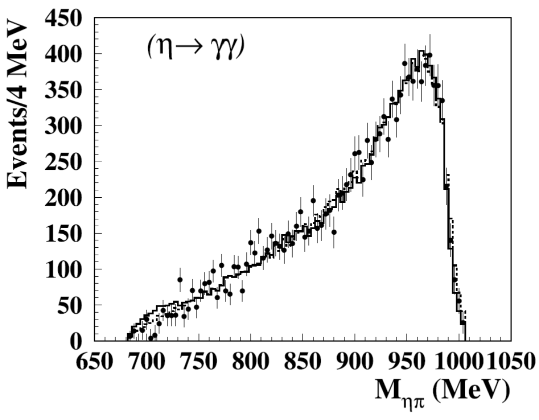
Spectral shape and results

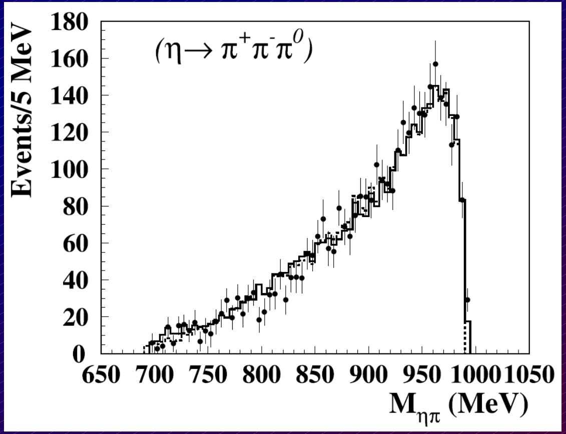


qq: Achasov-Ivanchenko NPB315(1989)
Close et al., NPB389(1993)
4q: Achasov-Ivanchenko NPB315(1989)
KK molec.: Close et al., NPB389(1993)
Achasov et al., PRD56(1997)
KK molec.-2: Kalashnikova et al., EPJA24(2005)
Palomar et al., NPA729(2003): UχPT
Escribano, PRD74(2006): Linear σ model

Combined fit to the Kaon Loop model

$Br(\phi \to \rho\pi \to \eta\gamma\pi)$ $(0.92 \pm 0.40 \pm 0.15) \times 10^{-6}$





g_{a0K+K-} 2.15 ± 0.06 ± 0.06 GeV

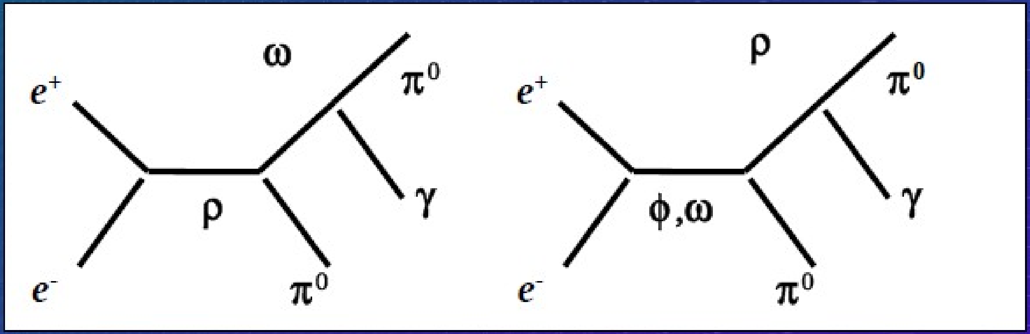
$g_{a0\eta\pi}$ 2.82 ± 0.03 ± 0.04 GeV

$\delta(\phi \to \rho\pi \to \eta\gamma\pi)$ $(222 \pm 13 \pm 3)^\circ$

M_{a0} 982.5 ± 1.6 ± 1.1 MeV

The $\phi \to f_0 \gamma \to \pi^0 \pi^0 \gamma \to 5\gamma$

Irreducible background fitted in the amplitude



Model parameters: M_{f0}, g_{f0K+K-}, $g_{f0\,\pi+\pi-}$ $(=\sqrt{2}\ \ g_{f\pi0\pi0})$

Background parameters:

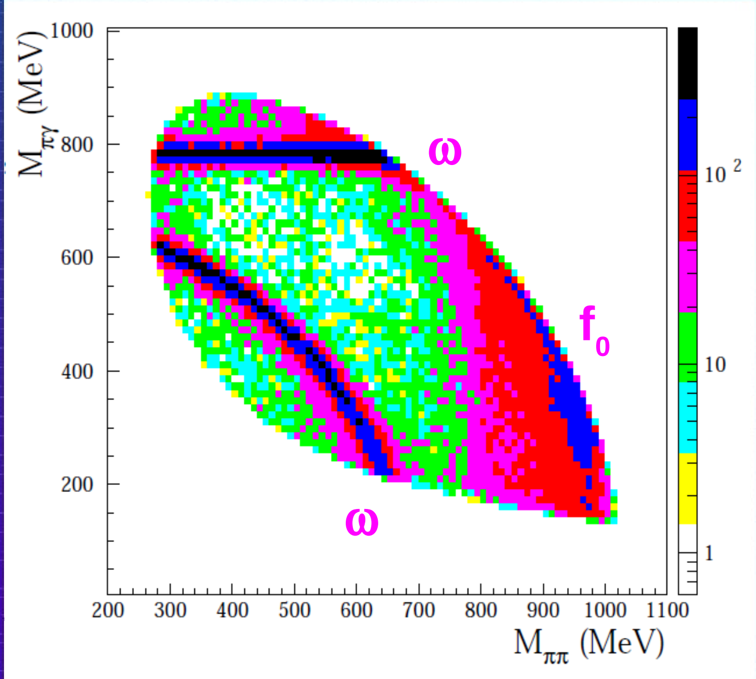
$\phi_{\omega\pi0}, \phi_{\rho\pi0}, C_{\omega\pi0}, C_{\rho\pi0}, \alpha_{\rho\pi}, M_{\omega}, \delta_{b\rho}$

Interference phase with the scalar amplitude

- $\delta_B = \delta_B^{\pi\pi} + \delta_B^{KK}$ (Background from elastic scattering)
- and σ(600) parameters fixed

[Achasov-Kiselev, PRD73 (2006) 054029 with PRD 74 (2006) 059902 (E)

+ private comunication for $C_{f0\sigma}$]



Fit result

M_{f0} = 984.7 ± 1.9 MeV

g_{f0K+K-} = 3.97 ± 0.43 GeV

g_{f0p+p-} = -1.82 ± 0.19 GeV

The σ needed in the fit. $P(\chi^2) \sim 10^{-4}$ without σ

Systematic dominated by fixed parameters.

10 sets of parameters available

8 with $P(\chi^2) > 1\%$

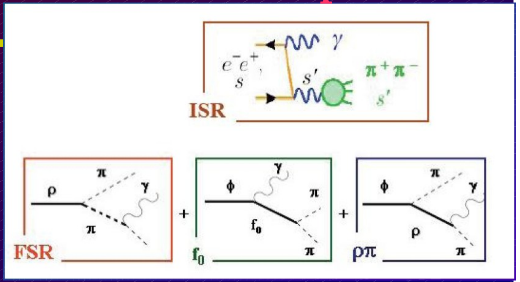
Values are the mean and the RMS of the fit results.

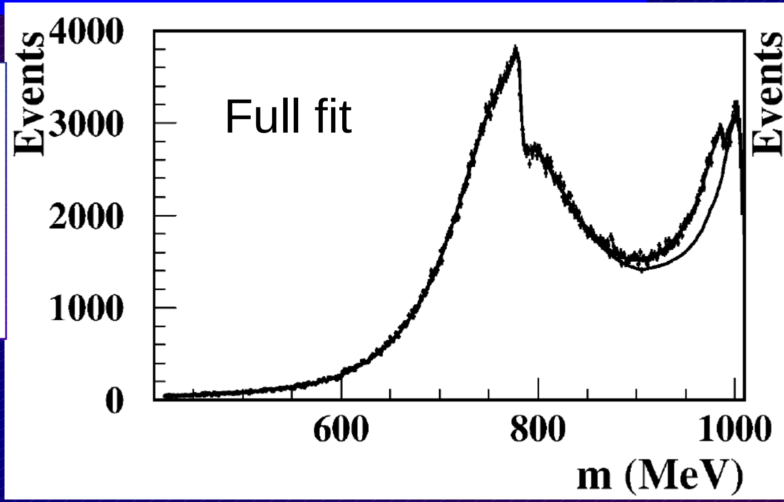
The $\phi \to f_0\, \gamma \to \pi^+ \pi^- \gamma$

Analysis selection

1) 2 track vertex close to the IP;
2) $\theta_{\pi\pm} > 45^o$, $\theta_\gamma > 45^o$
3) π ID against e using TOF and shower profile;
4) Cut on the track mass in $tr^+tr^-\gamma$ hypothesis;
5) Calorimeter cluster in the direction pointed by the missing charged track momentum;
6) TOF and charged track veto for γ ID;
7) $E_\gamma > 10$ MeV

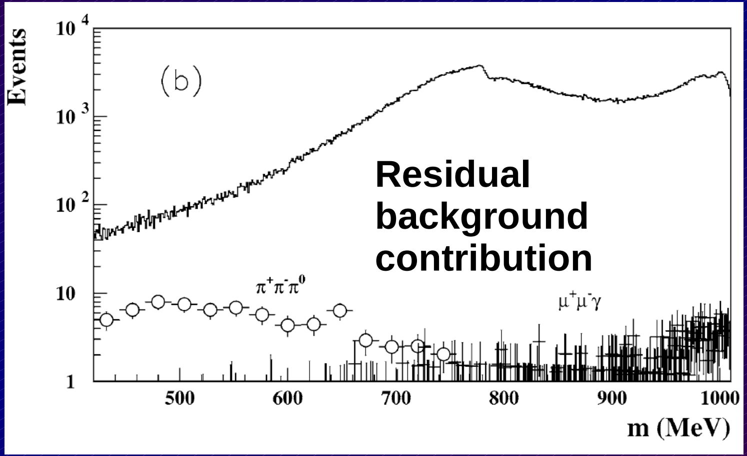
Fitted amplitude



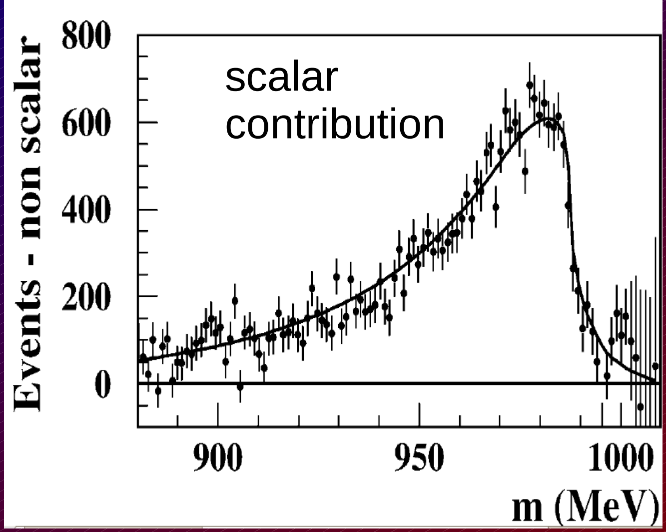


Reducible background

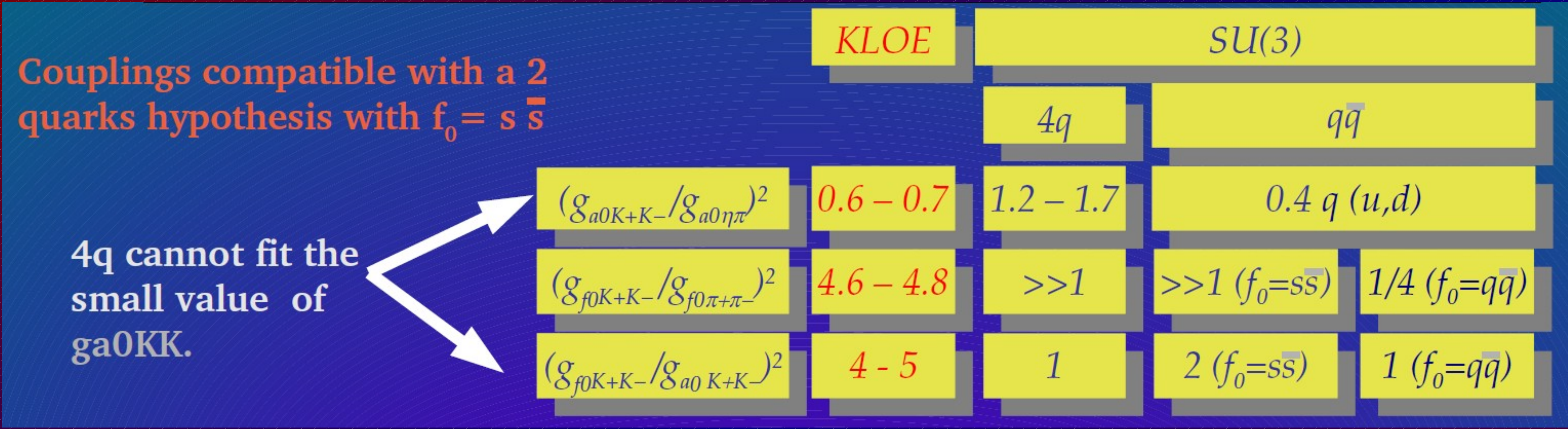
$e^+e^- \to e^+e^-\gamma$ $e^+e^- \to \mu^+\mu^-\gamma$ $\phi \to \pi^+\pi^-\pi^0$



M_{f0} = 983.7 MeV
g_{f0K+K-} = 4.74 GeV
g_{f0p+p-} = -2.22 GeV



What's the structure?



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

4q cannot fit the small value of ga0KK.

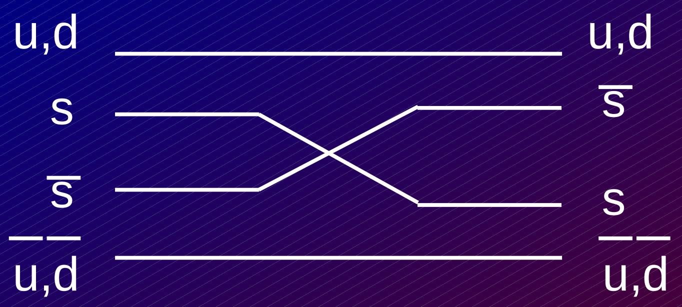
	KLOE	SU(3)		
		4q	$q\bar{q}$	
$(g_{a0K^+K^-}/g_{a0\eta\pi})^2$	0.6 – 0.7	1.2 – 1.7	0.4 q (u,d)	
$(g_{f0K^+K^-}/g_{f0\pi^+\pi^-})^2$	4.6 – 4.8	>>1	>>1 ($f_0=s\bar{s}$)	1/4 ($f_0=q\bar{q}$)
$(g_{f0K^+K^-}/g_{a0\,K^+K^-})^2$	4 - 5	1	2 ($f_0=s\bar{s}$)	1 ($f_0=q\bar{q}$)

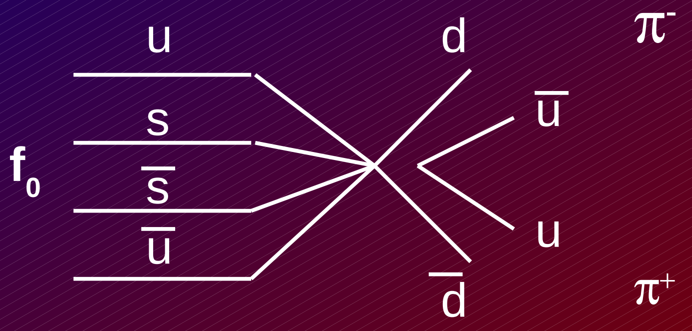
We would expect nearly same coupling of f_0 and a_0 to KK in the 4q hypothesis,

And a null coupling of f_0 to $\pi^+ \pi^-$.

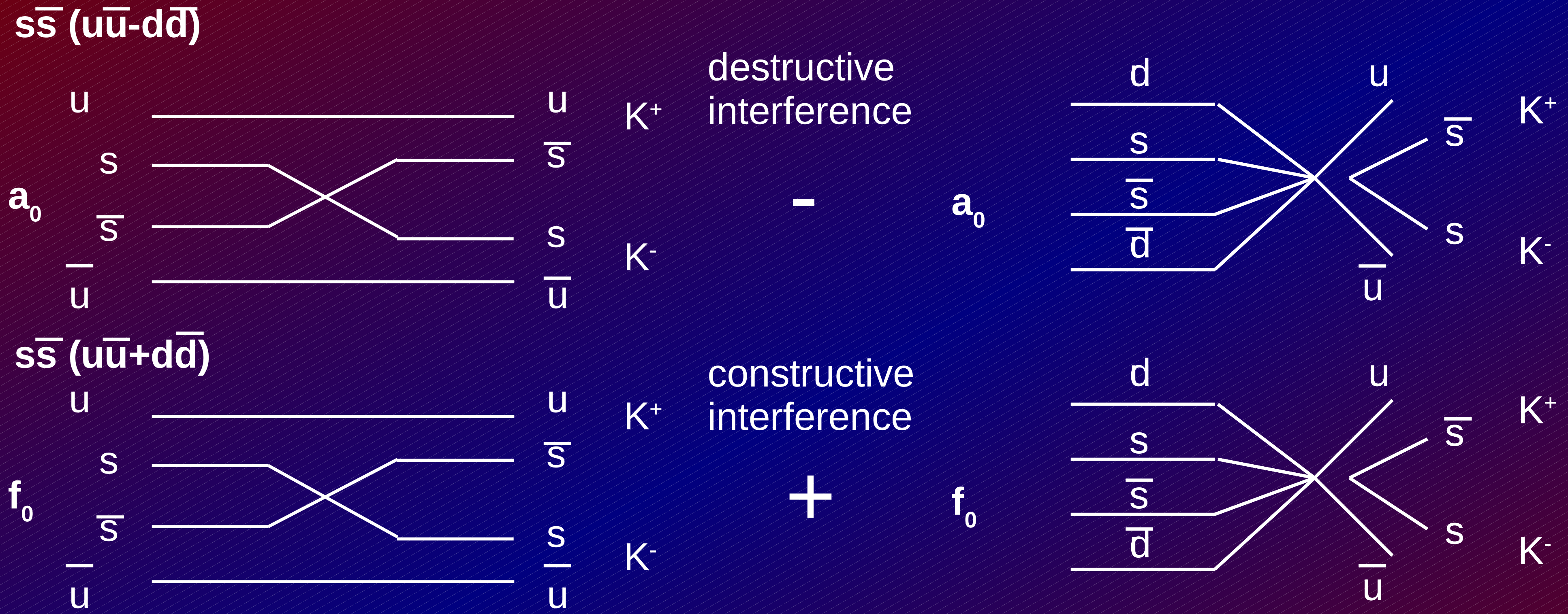
New amplitude,
Instanton mediated interaction

T'Hooft et al.
Phys. Lett. B 662 (2008) 424





The instanton amplitude and the a_0 , $f_0 \rightarrow K^+K^-$



$s\bar{s}\,(u\bar{u}-d\bar{d})$

destructive interference

-

$s\bar{s}\,(u\bar{u}+d\bar{d})$

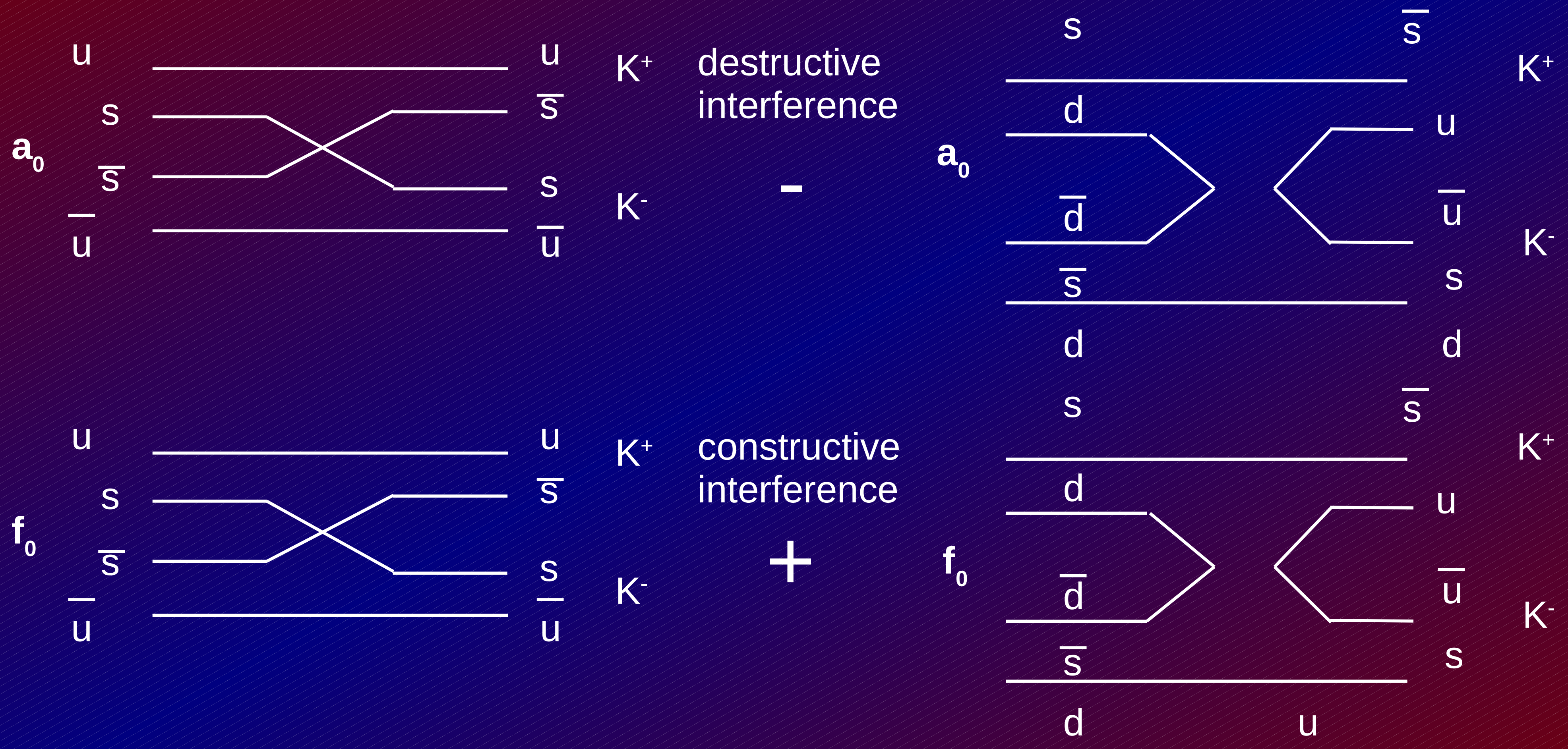
constructive interference

+

Different couplings of a_0 and f_0 to KK are possible

The same without instanton

F. Giacosa, N. Pagliara, Nuclear Physics A 833 (2010) 138–155



a_0: u, s, $\bar{s}$, $\bar{u}$ → u, $\bar{s}$ (K^+); s, $\bar{u}$ (K^-)

destructive interference

-

a_0: s, d, $\bar{d}$, $\bar{s}$, d → $\bar{s}$, u (K^+); $\bar{u}$, s (K^-); d

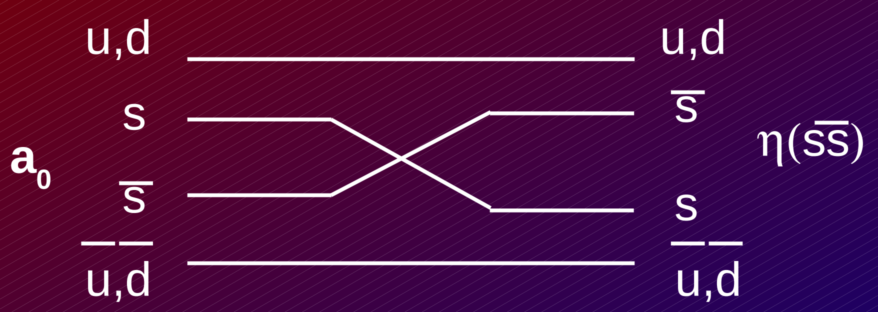
f_0: u, s, $\bar{s}$, $\bar{u}$ → u, $\bar{s}$ (K^+); s, $\bar{u}$ (K^-)

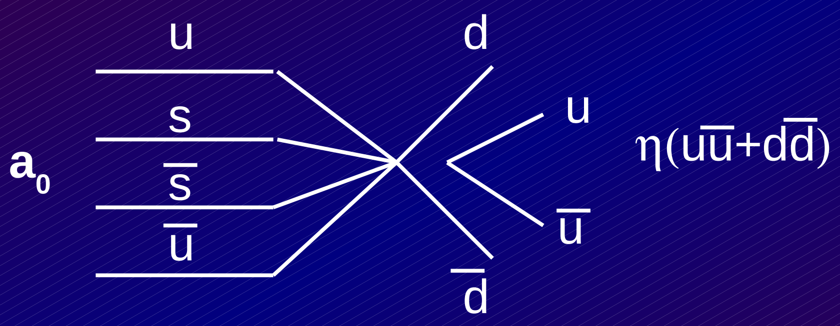
constructive interference

+

f_0: s, d, $\bar{d}$, $\bar{s}$, d → $\bar{s}$, u (K^+); $\bar{u}$, s (K^-); u

The $a_0 \to \eta\pi^0$





The a_0 couples to the $s\bar{s}$ and $u\bar{u}+d\bar{d}$ component of the η meson in different ways.

$$|q\bar{q}\rangle = \frac{|u\bar{u}\rangle + |d\bar{d}\rangle}{\sqrt{2}}$$

$$|\eta\rangle = \cos\psi_P |q\bar{q}\rangle - \sin\psi_P |s\bar{s}\rangle$$

**η' is almost SU(3) singlet, without flavor quantum numbers,
it can mix with states without quarks.**

$$|\eta'\rangle = X_{\eta'}|q\bar{q}\rangle + Y_{\eta'}|s\bar{s}\rangle + Z_{\eta'}|G\rangle$$

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

|G> is called gluonium,
It can be interpreted as
a mixing with a pure
gluon state.

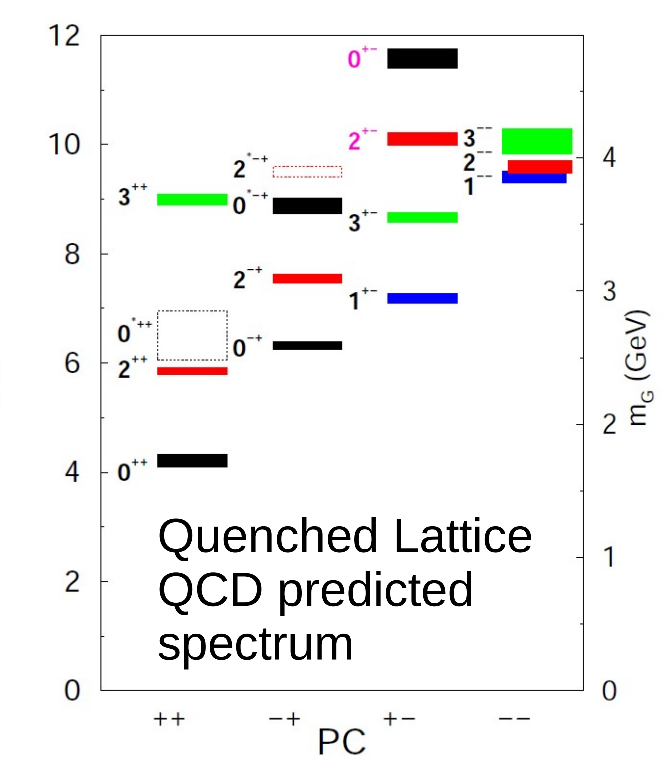
The glue balls

Gluons carry color charge like quarks, color singlets can be built just using gluons, gluons belong to the 8 representation of SU(3)

GG $$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$ **A singlet term is present**

A 2 gluon singlet states has a total symmetric color component.
Lattice QCD predicts the following quantum numbers and masses:

C.J. Morningstar, M. Peardon Phys. Rev. D60 (1999) 034509



Potential models dealing with massive gluons (the constituent mass is acquired by the confinement into the potential), predict also quantum numbers 1^{-+}

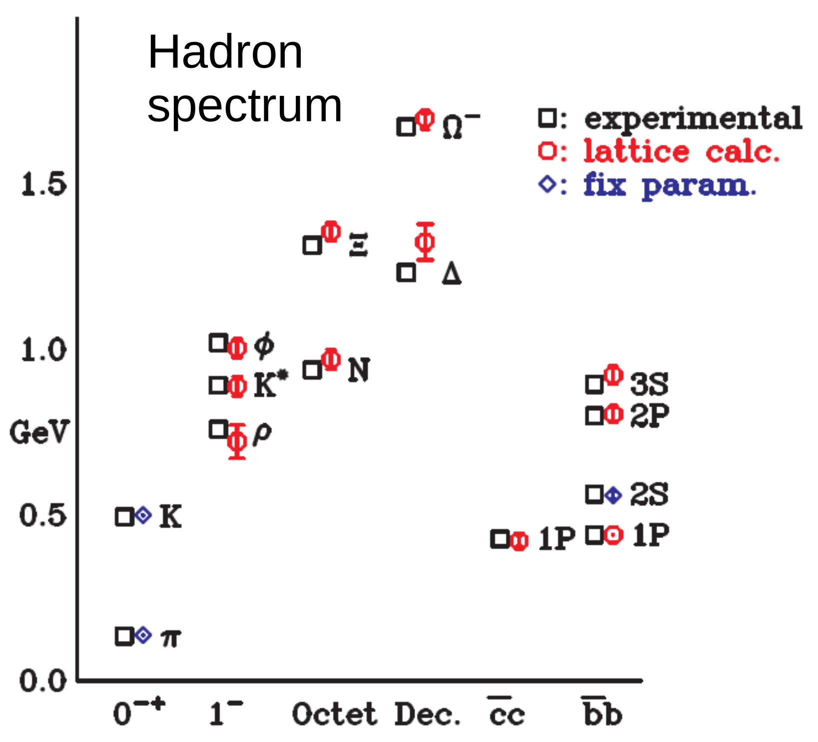
In V. Mathieu et al., Phys. Rev. D 77 (2008) 11402
using mass-less gluons all J = 1 states are missing.

Pseudoscalar glue-ball predicted with high mass. m> 2GeV.

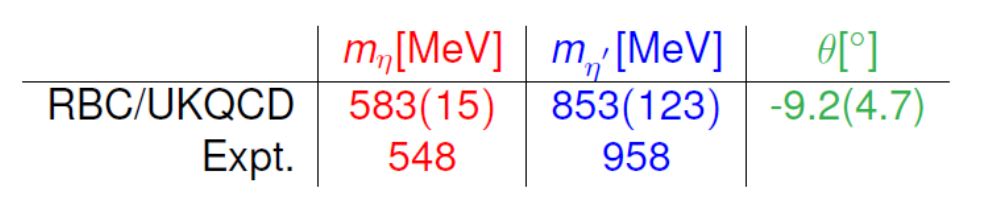
Is the lattice predicted spectrum reliable?

Ch. Hoebling, Lattice 2010
MILC collaboration

η,η' states are out of the computation, difficult to obtain



Results from unquenched calculations



	m_η[MeV]	$m_{\eta'}$[MeV]	θ[°]
RBC/UKQCD	583(15)	853(123)	-9.2(4.7)
Expt.	548	958	

Glue ball mass 0^{-+} from UKQCD
m_G = 1 -1.5 GeV
A. Hart, M. Teper, Phys. Rev. D65 (2002) 034502

M_G = 2.4 GeV C. M. Richards et al., Phys. Rev. D82 (2010) 034501

Computational problems when treating SU(3) singlets states.

QCD vacuum fluctuation enters in the computation making difficult to evaluate the masses.

The model used to evaluate the mixing JHEP 07 (2009), 105

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

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

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

Decay width:

Quark charge

$$\Gamma(V \to P\gamma) = \frac{2}{3}\alpha\omega^3\left(\frac{E_P}{m_V}\right)\sum\left|\left\langle V\left|\frac{\mu_q e_q \sigma_q}{e}\right|P\right\rangle\right|^2$$

Pauli matrices

$$|\rho\rangle = \frac{|u\bar{u}> - |d\bar{d}>}{\sqrt{2}}$$

In the exact isospin symmetry $m_u = m_d = \bar{m}$

$$\langle u\bar{u}_\rho|u\bar{u}_\eta\rangle = \langle d\bar{d}_\rho|d\bar{d}_\eta\rangle = \langle q\bar{q}_\rho|q\bar{q}_\eta\rangle$$

$$\langle\rho|\frac{\mu_q e_q \sigma_q}{e}|\eta\rangle = \frac{e}{m_u}\cos(\psi_P)\frac{2}{3}\langle u\bar{u}_\rho|u\bar{u}_\eta\rangle + \frac{e}{m_d}\cos(\psi_P)\frac{1}{3}\langle d\bar{d}_\rho|d\bar{d}_\eta\rangle = \frac{e}{\bar{m}}\cos(\psi_P)\langle q\bar{q}_\rho|q\bar{q}_\eta\rangle$$

The following constants are defined:

$$C_q = \langle q\bar{q}_\eta|\, q\bar{q}_\omega\rangle = \langle q\bar{q}_\eta|\, q\bar{q}_\rho\rangle\,, \quad C_s = \langle s\bar{s}_\eta|\, s\bar{s}_\phi\rangle\,, \quad C_\pi = \langle q\bar{q}_\pi|\, q\bar{q}_\omega\rangle = \langle q\bar{q}_\pi|\, q\bar{q}_\rho\rangle$$

$$Z_q = C_q/C_\pi$$

$$Z_s = C_s/C_\pi$$

V→Pγ decays

ρ, ω mixing angle

$$R_\phi = \frac{Br(\phi\rightarrow\eta'\gamma)}{Br(\phi\rightarrow\eta\gamma)}$$

$$R_\phi = \cot^2\psi_P \cos^2\psi_G \left(1 - \frac{m_s}{\bar{m}}\frac{Z_q}{Z_s}\frac{\tan\psi_V}{\sin 2\psi_P}\right)^2 \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

$$\frac{\Gamma(\omega\rightarrow\eta\gamma)}{\Gamma(\omega\rightarrow\pi^0\gamma)} = \frac{1}{9}\left[Z_q\cos\psi_P - 2\frac{\bar{m}}{m_s}Z_s\tan\psi_V\sin\psi_P\right]^2\left(\frac{m_\omega^2-m_\eta^2}{m_\omega^2-m_{\pi^0}^2}\right)^3$$

$$\frac{\Gamma(\rho\rightarrow\eta\gamma)}{\Gamma(\omega\rightarrow\pi^0\gamma)} = Z_q^2\frac{\cos^2\psi_P}{\cos^2\psi_V}\left(\frac{m_\rho^2-m_\eta^2}{m_\omega^2-m_{\pi^0}^2}\frac{m_\omega}{m_\rho}\right)^3$$

$$\frac{\Gamma(\phi\rightarrow\eta\gamma)}{\Gamma(\omega\rightarrow\pi^0\gamma)} = \frac{1}{9}\left[Z_q\tan\psi_V\cos\psi_P + 2\frac{\bar{m}}{m_s}Z_s\sin\psi_P\right]^2\left(\frac{m_\phi^2-m_\eta^2}{m_\omega^2-m_{\pi^0}^2}\frac{m_\omega}{m_\phi}\right)^3$$

$$\frac{\Gamma(\phi\rightarrow\pi^0\gamma)}{\Gamma(\omega\rightarrow\pi^0\gamma)} = \tan^2\psi_V\cdot\left(\frac{m_\phi^2-m_{\pi^0}^2}{m_\omega^2-m_{\pi^0}^2}\frac{m_\omega}{m_\phi}\right)^3$$

$$\frac{\Gamma(K^{*+}\rightarrow K^+\gamma)}{\Gamma(K^{*0}\rightarrow K^0\gamma)} = \left(\frac{2\frac{m_s}{\bar{m}}-1}{1+\frac{m_s}{\bar{m}}}\right)^2\cdot\left(\frac{m_{K^{*+}}^2-m_{K^+}^2}{m_{K^{*0}}^2-m_{K^0}^2}\cdot\frac{m_{K^{*0}}}{m_{K^{*+}}}\right)^3$$

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

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

We perform a fit to branching ratios and decay widths.
Using KLOE data for R_ϕ, η mass, $Br(\omega\rightarrow\pi^0\gamma)$ and PDG 2008 η', ρ, K^* branching ratios and correlation matrix.

Measurement of R_ϕ = Br($\phi\to\eta'\gamma$)/Br($\phi\to\eta\gamma$)

Signal topology

$\phi \to \eta'\gamma \to \pi^+\pi^- \eta\gamma \to \pi^+\pi^- 3\pi^0\gamma \to \pi^+\pi^- 7\gamma$

$\phi \to \eta'\gamma \to \pi^0\pi^0 \eta\gamma \to \pi^0\pi^0 \pi^+\pi^-\pi^0\gamma \to \pi^+\pi^- 7\gamma$

Analysis selection

1) 2 track vertex close to the IP;
2) 7 energy deposits in calo (E_γ > 10 MeV, 21° < θ_γ < 169°);
3) TOF identification of photons using cluster times;
4) Kinematic fit constrained to the ϕ momentum;
5) selection using the χ^2 of the fits;
6) kinematic rejection of background channel;
7) Rejection of K_S decays using $m_{\pi+\pi-}$;

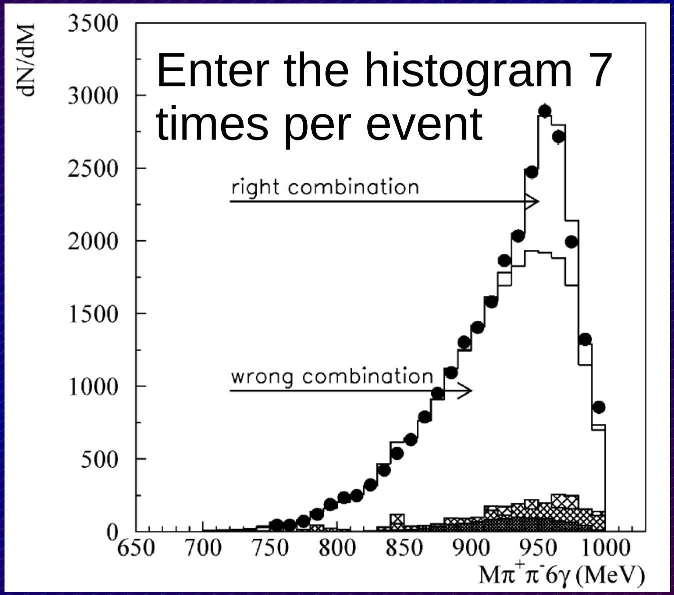
Background channels

$\phi \to K_S K_L \to \pi^+\pi^- 3\pi^0 \to \pi^+\pi^- 6\gamma$ +1 fake

$\phi \to K_S K_L \to 2\pi^0\pi^+\pi^- \pi^0 \to \pi^+\pi^- 6\gamma$ +1 fake

$\phi \to K_S K_L \to \pi^+\pi^-\gamma\, 3\pi^0 \to \pi^+\pi^- 7\gamma$

Residual background contamination 9%.

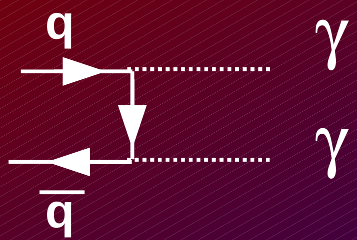


No pairing applied to the photons.

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

Systematic is dominated by the error on the $\eta' \to \pi\pi\eta$ branching fractions.

The two photon width and experimental correlation

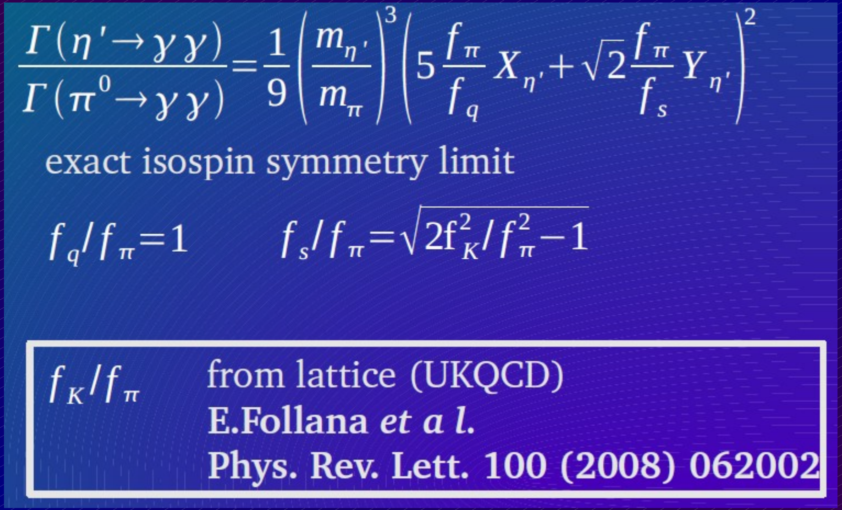


E. Kou, , Phys. Rev. D 63 (2001) 054027

$$i f_q p^\mu = \langle 0 | u \gamma^\mu \gamma_5 \bar{u} + d \gamma^\mu \gamma_5 \bar{d} | \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} \rangle$$

$$i f_s p^\mu = \langle 0 | s \gamma^\mu \gamma_5 \bar{s} \rangle$$

$$i f_\pi p^\mu = \langle 0 | u \gamma^\mu \gamma_5 \bar{u} + d \gamma^\mu \gamma_5 \bar{d} | \frac{u\bar{u} - d\bar{d}}{\sqrt{2}} \rangle$$



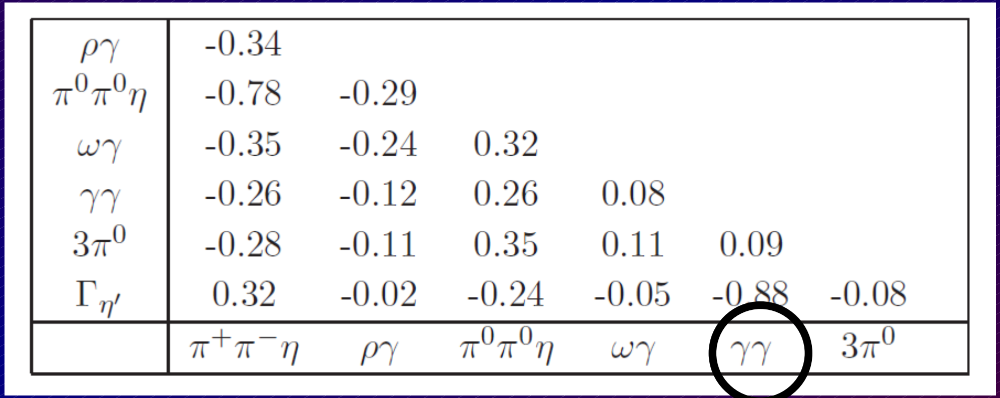
$$\frac{\Gamma(\eta' \to \gamma\gamma)}{\Gamma(\pi^0 \to \gamma\gamma)} = \frac{1}{9} \left(\frac{m_{\eta'}}{m_\pi} \right)^3 \left(5 \frac{f_\pi}{f_q} X_{\eta'} + \sqrt{2} \frac{f_\pi}{f_s} Y_{\eta'} \right)^2$$

exact isospin symmetry limit

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

f_K / f_π from lattice (UKQCD)
E.Follana *et a l.*
Phys. Rev. Lett. 100 (2008) 062002

Correlation matrix of the η' branching fractions



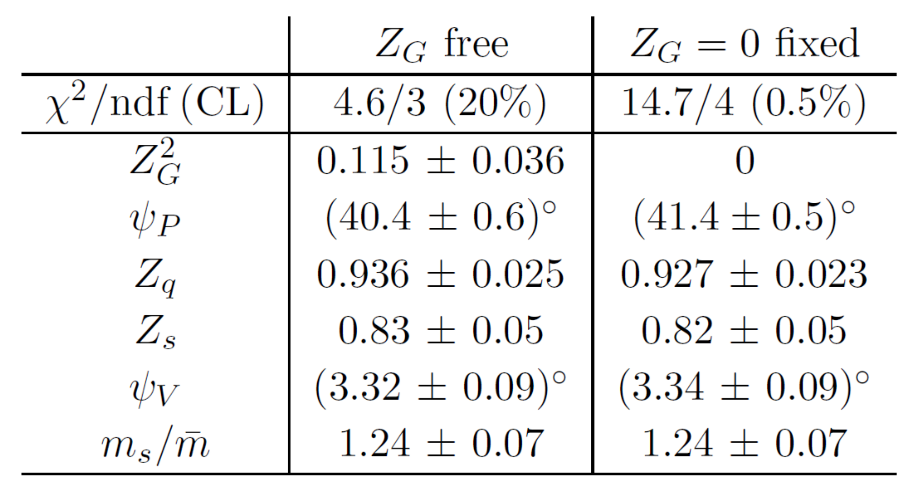
$\rho\gamma$	-0.34					
$\pi^0\pi^0\eta$	-0.78	-0.29				
$\omega\gamma$	-0.35	-0.24	0.32			
$\gamma\gamma$	-0.26	-0.12	0.26	0.08		
$3\pi^0$	-0.28	-0.11	0.35	0.11	0.09	
$\Gamma_{\eta'}$	0.32	-0.02	-0.24	-0.05	-0.88	-0.08
	$\pi^+\pi^-\eta$	$\rho\gamma$	$\pi^0\pi^0\eta$	$\omega\gamma$	$\gamma\gamma$	$3\pi^0$

Br and Γ strongly correlated (above all Γ(η'→γγ))

the Γ is measured using:

$$e^+e^- \to \eta' e^+e^-$$

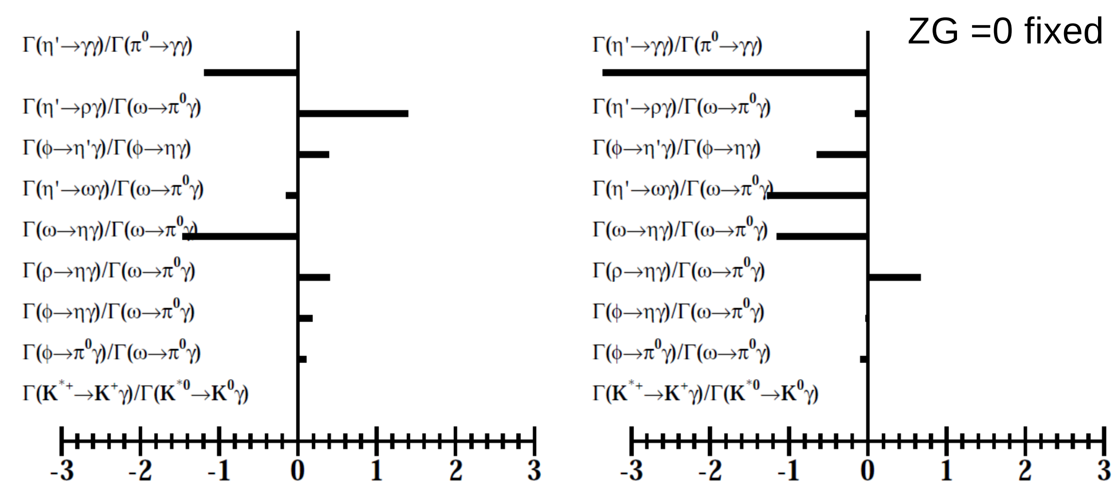
Fit results



	Z_G free	$Z_G = 0$ fixed
χ^2/ndf (CL)	4.6/3 (20%)	14.7/4 (0.5%)
Z_G^2	0.115 ± 0.036	0
ψ_P	$(40.4 \pm 0.6)°$	$(41.4 \pm 0.5)°$
Z_q	0.936 ± 0.025	0.927 ± 0.023
Z_s	0.83 ± 0.05	0.82 ± 0.05
ψ_V	$(3.32 \pm 0.09)°$	$(3.34 \pm 0.09)°$
$m_s/\bar{m}$	1.24 ± 0.07	1.24 ± 0.07

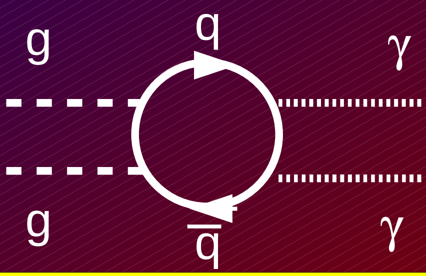
Good fit allowing for gluonium component. Stable value of the pseudoscalar mixing angle respect to the gluonium hypothesis.

Fit pulls



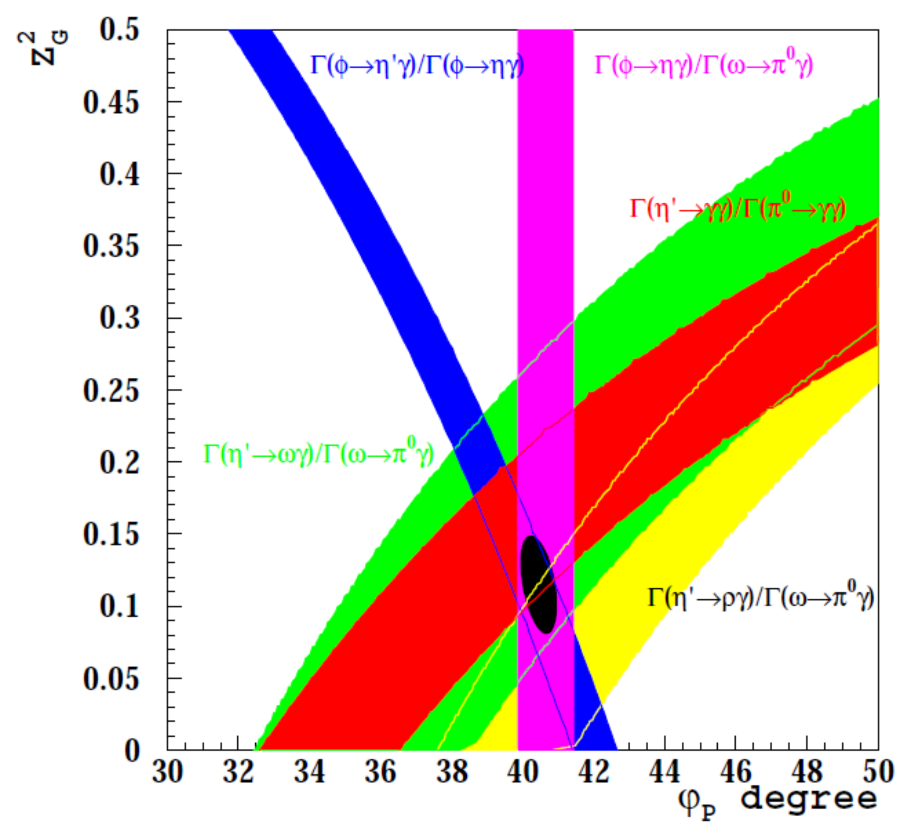
The 2 photon decay width of the η' is too low if gluonium is not present.

The glue balls have small branching fractions to γγ, the coupling being mediated by a qaurk loop.

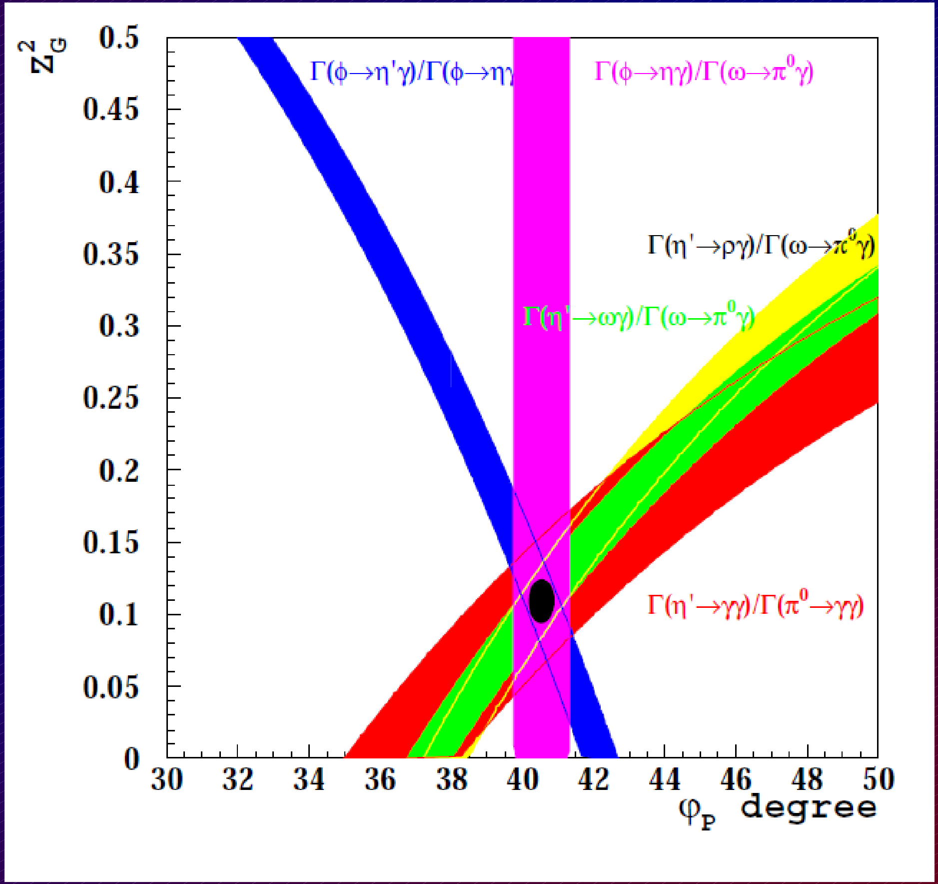


Graphical view of the fit

Present result



Expected result with 1% accuracy at KLOE-2

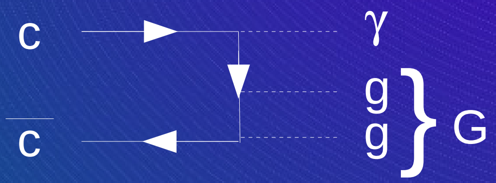


The glue ball mass relation

$Z_{\eta'}$ can be interpreted as a mixing with a glue ball.
The mass of this glue ball has been determined
[Hai-Yang Cheng, Phys. Rev. D79 (2009) 014024]

$\theta_i = 54.7^\circ$ $\phi \rightarrow \psi_P$ $\phi_G \rightarrow \psi_G$

$$\frac{c\theta(s\phi - c\theta s\theta_i\Delta_G)m_{\eta'}^2 - s\theta(c\phi + s\theta s\theta_i\Delta_G)^2 m_\eta^2 - s\theta_i c\phi_G m_G^2}{c\theta(c\phi - c\theta c\theta_i\Delta_G)m_{\eta'}^2 + s\theta(s\phi - s\theta c\theta_i\Delta_G)^2 m_\eta^2 - c\theta_i c\phi_G m_G^2} = \frac{\sqrt{2}f_s}{f_q},$$

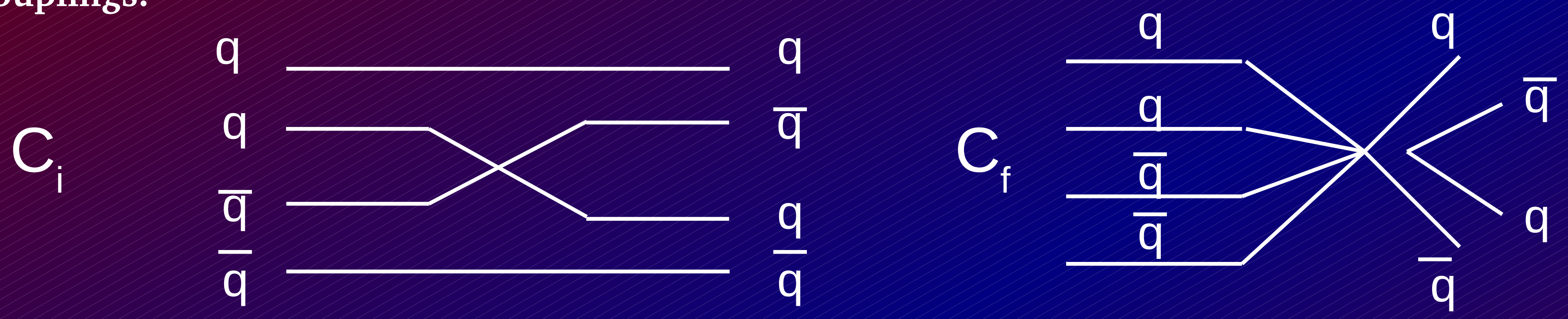


$m_G = (1.41 \pm 0.1)$ GeV

The glue-ball is identified as η(1405)
copiously produced in J/ψ→η(1405)γ
It is not observed in γγ production.
Prediction Br(η(1405) →γγ) = $6 \pm 1 \times 10^{-5}$
Decay never observed

Let's come back to the scalar structure...

Using the model from T'Hooft, the pseudoscalar mixing angle and the f_0 $\pi\pi$ couplings from KLOE as well meson masses, we calculate the strength of the quark exchange and instanton amplitude and the predicted a_0 couplings.



A coherent picture in terms of 4q structure is obtained.

	KLOE (KL)		4q	2q
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

The role of the σ

	m_σ MeV	Γ_σ MeV	$g_{\sigma\pi+\pi-}$ GeV^{-1}
Caprini PRL 96, 132001 (2006)	441	544	3.5
CLEO Phys. Rev. D76 012001	466	446	3.5
BES2 Phys. Lett. B645 19 $J/\psi \rightarrow \omega\pi^+\pi^-$	541	504	3.2

Sigma needs further studies to have a definitive answer.

	KLOE (KL)		4q	2q
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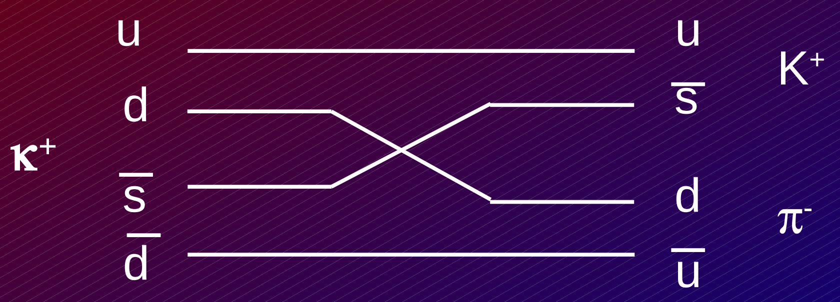
$g_{a0\eta\pi}$ (GeV)	2.46 — 2.82		3.3 — 3.9	6.6 — 7.9
$g_{\sigma\pi+\pi-}$ (GeV)	m_σ 441 MeV		1.6 - 2.0	1.8 - 2.2
$g_{\sigma\pi+\pi-}$ (GeV)	m_σ 541 MeV		2.6 - 3.2	2.9 - 3.6

κ the missing guy

Still outside from the PDG summary table, it's a very broad resonance, needed to complete the nonet.

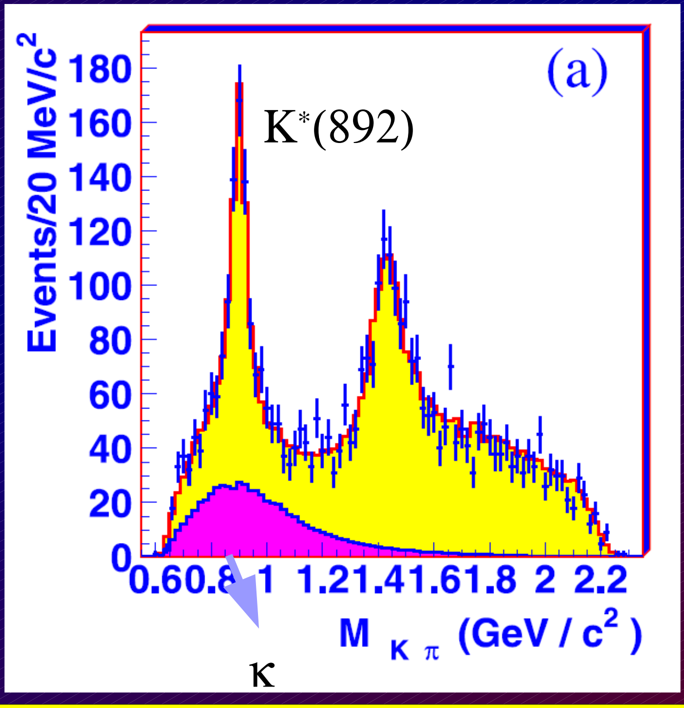


$m_\kappa = 800$ MeV $> m_{K+}+m_\pi$

$\Gamma_\kappa = 600$ MeV

The last determination from J/ψ decays

Article in press: PLB:26968



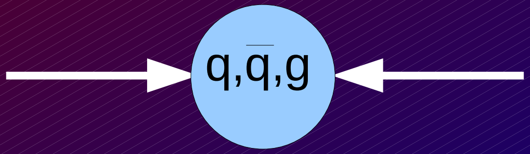
The result comes out as a continuum distribution under a dominant K^* background.

Still far from clear evidence.

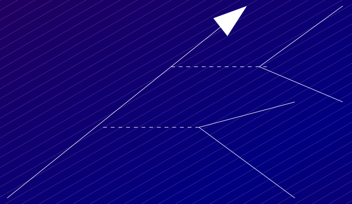
The quark content studied in heavy ion collision

L. Maiani et al.,
Phys. Lett. B 645 (2007) 138

Recombination of quarks
In the soft spectrum, independent
from number of quarks



Fragmentation of hard quarks



Standard Production

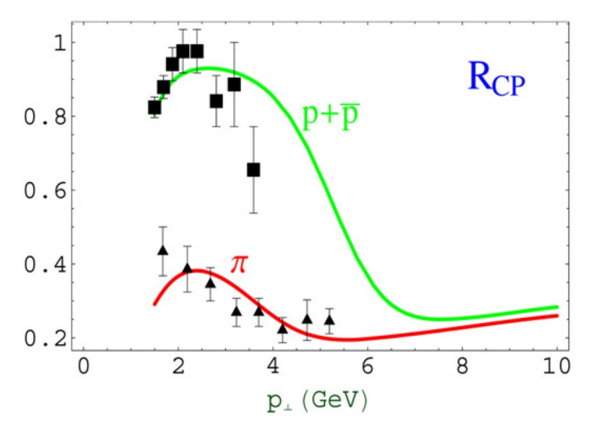
Less probable with
increasing number
of quarks.

The recombination is higher in central ion-ion collision respect to peripheral collision or p+p collision, an higher yield in central interaction is expected respect to p+p.

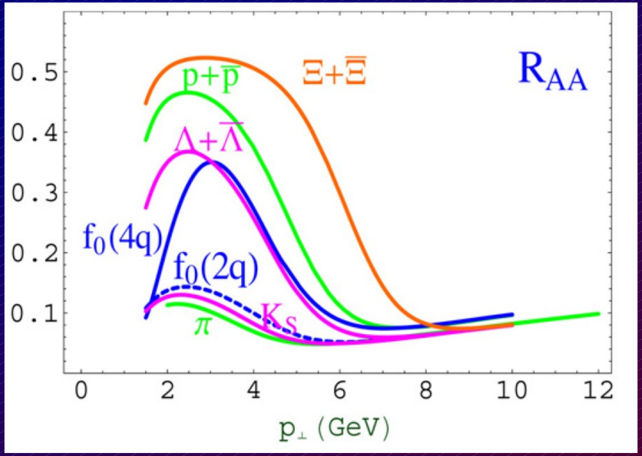
$$R_{AA} = \frac{d^2N_{\mathrm{Au+Au}}(b=0)/dP_\perp^2}{N_{\mathrm{coll}}(b=0)\, d^2N_{p+p}/dP_\perp^2}$$

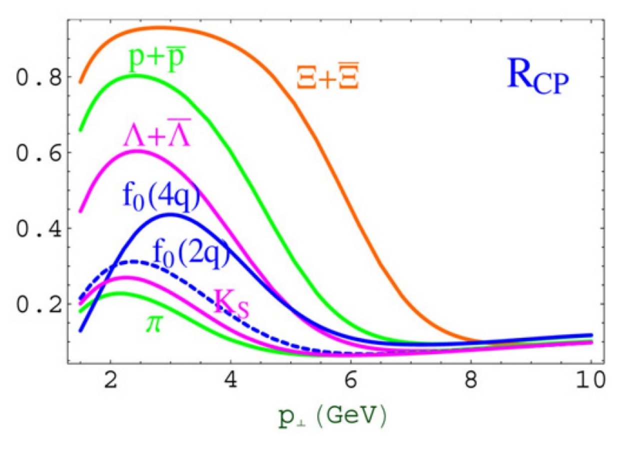
$$R_{CP} = \frac{N_{\mathrm{coll}}(b)\, d^2N_{\mathrm{Au+Au}}(b=0)/dP_\perp^2}{N_{\mathrm{coll}}(b=0)\, d^2N_{\mathrm{Au+Au}}(b)/dP_\perp^2}$$

$p\bar{p}$ and π^0 production
(RHIC)



Expectation at LHC





Conclusions

- The high statistics of f_0 and a_0 meson at KLOE gives important constraint on their nature;
- A second process (instanton or gluon mediation) is needed to giustify the KK couping of the a_0;
- A coherent picture of a_0, f_0, σ meson is obtained justifying their masses and couplings;
- Recent measurements of $\gamma\gamma$ coupling are also in favour of a 4q structure
- Measurement and possible observation of σ in $\gamma\gamma$ collision will be possible at KLOE-2
- A gluonium component is needed to describe radiative decays of vector meson to psudoscalars meson, and $\gamma\gamma$ decay width.
- A natural candidate is $\eta(1405)$ mixing with η', even if its mass is too light for lattice calculations.