Radiative decays involving a nonet of light scalar mesons

Deirdre Black, Jefferson Lab

in collaboration with

M. Harada and J. Schechter

Outline

- Brief overview of the scalar mesons
- Recent radiative ϕ decay experiments
- Implications of a light scalar nonet: Chiral Lagrangian approach
- Discussion & future directions

Scalar Mesons

Scalar ($J^P = 0^+$) mesons - from 2002 PDG:

State	Isospin
$f_0(600)[``\sigma'']$	0
$?\kappa(900)?$	$\frac{1}{2}$
$f_0(980)$	0
$a_0(980)$	1
$f_0(1370)$	0
$K_0^*(1430)$	$\frac{1}{2}$
$a_0(1450)$	1
$f_0(1500)$	0
$f_0(1710)$	0

Examples of "typical" $q\bar{q}$ meson multiplets

Vector($J^P = 1^-$)	Tensor($J^P = 2^+$)	Isospin
$\omega(782)$	$f_2(1270)$	$I = 0$
$\rho(770)$	$a_2(1320)$	$I = 1$
$K^*(892)$	$K_2^*(1430)$	$I = \dfrac{1}{2}$
$\phi(1020)$	$f_2'(1525)$	$I = 0$

- p-wave states are heavier than s-wave states
- states occur in multiplets with nine members (nonets) and their mass differences are consistent with counting the number of strange quarks
- Note that in constituent quark model $\mathrm{L} \cdot \mathrm{S}$ forces make the scalars lighter than other p-wave states

Scalar Mesons - questions and ideas

Scalar ($J^P = 0^+$) mesons - from 2002 PDG:

State	Isospin
$f_0(600)[``\sigma"]$	0
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PUZZLES

- Some controversy still surrounds existence/interpretation of σ and κ - related to problem of arriving at a theoretical description of experimental $\pi\pi$ and πK scattering amplitudes at energies above threshold
- Too many states for one SU(3) nonet (octet + singlet)
- Certain states seem too light to be like simple quark model $q\bar{q}$ scalars (may not be so in other approaches)
- Are any of the observed states the chiral partners of the pseudoscalar octet?

Scalar Mesons - questions and ideas

THEORETICAL UNDERSTANDING

- Lattice QCD: calculations of scalar glueball masses and mixing with $q\bar{q}$ states, of masses of I=1 ground state scalar mesons [$a_0(980)$ or $a_0(1450)$?] and of multiquark scalar states
- Interpretation of experiment: σ and κ should not be considered as meson resonances (e.g. "σ" as correlated $\pi\pi$ ...)
- $K\bar{K}$ threshold: $a_0(980)$ and $f_0(980)$ as $K\bar{K}$ threshold effects, $K\bar{K}$ molecules ...
- Light scalar mesons below 1 GeV are "generated" by unitarizing pseudoscalar meson scattering amplitudes: $\frac{\mathrm{N}}{\mathrm{D}}$, K-matrix ...
- Below 2 GeV there are two nonets of scalar mesons (maybe $qq\bar{q}\bar{q}$ and $q\bar{q}$) + one scalar glueball, presumably mixed ...
- Many approaches: Potential models, Effective Lagrangians, Schwinger-Dyson formalism, QCD sum rules ...

Scalar Mesons - recent experimental advances

D decays at Fermilab [E791 2000-2002, FOCUS (upcoming)]

$$\begin{aligned} \sigma : &\qquad D^+ \to \pi^-\pi^+\pi^+ \\ f_0 : &\qquad D_s^+ \to \pi^-\pi^+\pi^+ \\ \kappa : &\qquad D^+ \to K^-\pi^+\pi^+ \end{aligned}$$

Other experiments:

- Role in chiral symmetry breaking/restoration, finite (nuclear) density effects: TAPS, A2, CHAOS
- $\tau \to 3\pi$ (CLEO), $B \to K\pi\pi, KKK$ (Belle, Babar)
- Scalar meson production in $p\bar{p}$ annihilation (Crystal Barrel)
- Proposal to measure isospin-violating $a_0 - f_0$ mixing at COSY

Radiative ϕ decays at Novosibirsk, Frascati & JLab . . .

Focus on $a_0(980)$ and $f_0(980)$

In 2002 PDG there are two $J^P = 0^+$ scalar mesons at ~ 980 MeV:

State	Mass	Width
$f_0(980)$	$980 \pm 10\,\mathrm{MeV}$	$40 - 100\,\mathrm{MeV}$
$a_0(980)$	$984.7 \pm 1.2\,\mathrm{MeV}$	$50 - 100\,\mathrm{MeV}$

- Well-established experimentally
- Both states close to the $K\bar{K}$ threshold
- Dominant decay modes are (I=0) $f_0 \longrightarrow \pi\pi$ and (I=1) $a_0(980) \longrightarrow \pi\eta$
- Both states are also seen to decay to $K\bar{K}$
- Both states are lighter than candidates for quark model $q\bar{q}$ p-wave states $\sim 1.3 - 1.4$ GeV.

How can we understand the properties of $a_0(980)$ and $f_0(980)$?

Radiative ϕ Decays: $\phi \to \pi\eta\gamma, \pi\pi\gamma$

Nussinov and Truong, Lucio and Pestieau & Close, Isgur and Kumano predicted that (possible $K\bar{K}\gamma$ background for $\phi \to K_{\mathrm{L}}K_{\mathrm{S}}$ at DaΦne):

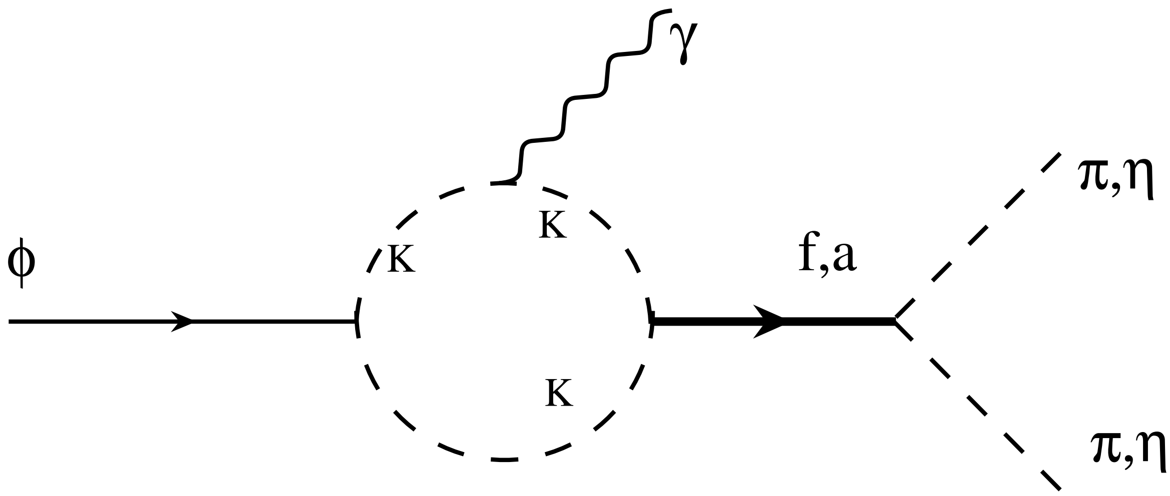
$$\mathrm{BR}(\phi \to a_0\gamma, f_0\gamma) \sim 10^{-5} - 10^{-6} \text{ for } q\bar{q} \text{ statess}$$

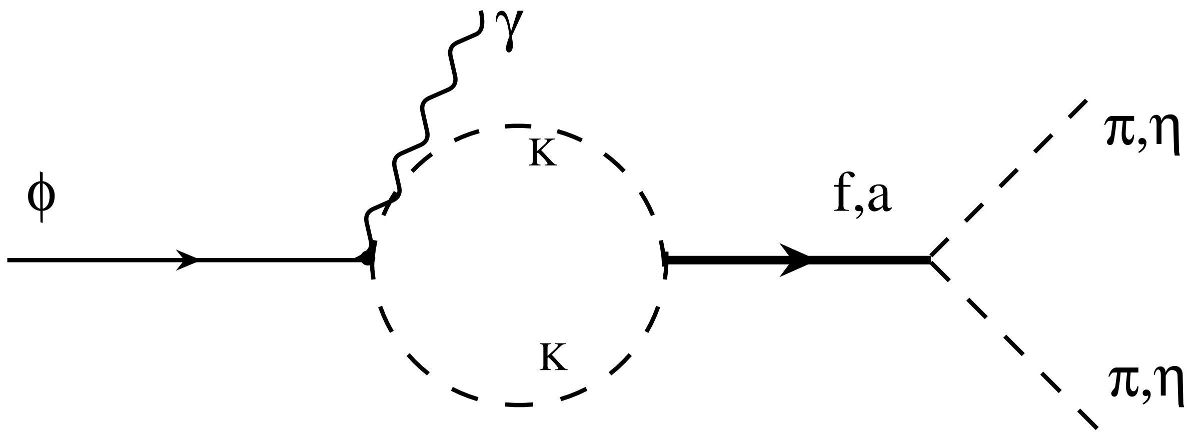
In 1989 Achasov and Ivanchenko did an analysis predicting that $\mathrm{BR}(\phi \to \pi^0\eta\gamma)$ and $\mathrm{BR}(\phi \to \pi\pi\gamma)$ both vary between $\sim 10^{-5}$ and $\sim 10^{-4}$ depending on whether a_0 and f_0 treated as $q\bar{q}$ or $qq\bar{q}\bar{q}$ states.

Bramon, Grau and Pancheri ('92) found that $\phi \to \pi\pi\gamma \sim 0.6 \times 10^{-4}$ MeV using Chiral Perturbation Theory to calculate $P^+P^- \to P^0P^0$ rescattering amplitudes.

Radiative ϕ Decays: $\phi \to \pi\eta\gamma, \pi\pi\gamma$

Achasov and Ivanchenko proposed looking at decays $\phi \to \pi^0\eta\gamma$ and $\phi \to \pi\pi\gamma$ to study $a_0(980)$ and $f_0(980)$. Predicted decay, via charged kaon loops, dominated by a_0 and f_0 resonances - e.g.

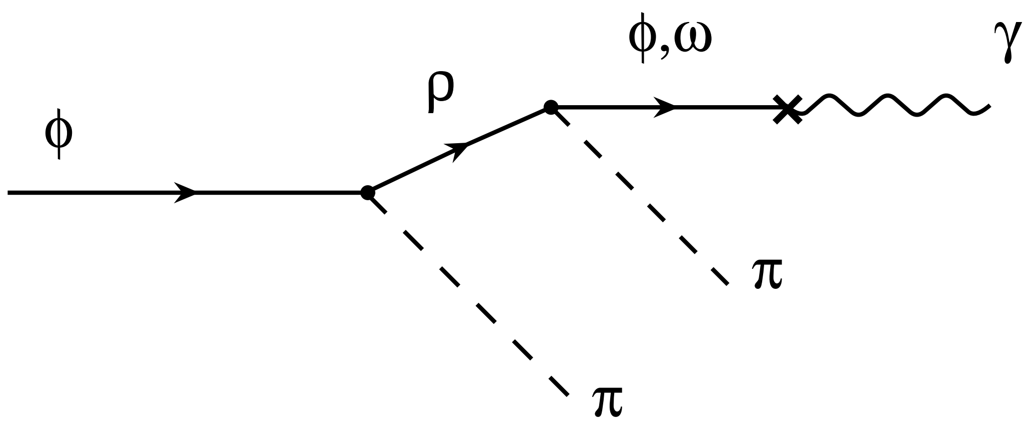




(Also at least one more diagram for gauge invariance.)

Radiative ϕ Decays: $\phi \to \pi\eta\gamma, \pi\pi\gamma$

There is also a non-resonant background which various authors find to be small e.g.:



Radiative ϕ Decays: $\phi \to \pi\eta\gamma, \pi\pi\gamma$

Measurements of BR($\phi \to \pi^0\pi^0\gamma$) and BR($\phi \to \eta\pi^0\gamma$) from SND '00 and KLOE '02 are consistent with each other (see experimental data plots).

BR($\phi \to a_0\gamma$) extracted from experimental values of BR($\phi \to \eta\pi^0\gamma$). Best fits by SND and KLOE using theoretical parameterisations of BR($\phi \to \eta\pi^0\gamma$) as sum of non-resonant background and resonant $a_0(980)$ kaon loop contribution:

$$\begin{aligned} \text{SND}: &\quad \text{BR}(\phi \to a_0\gamma) = (0.88 \pm 0.14) \times 10^{-4} \\ \text{KLOE}: &\quad \text{BR}(\phi \to a_0\gamma) = (0.74 \pm 0.07) \times 10^{-4} \end{aligned}$$

BR($\phi \to f_0\gamma$) extracted from $\phi \to \pi^0\pi^0\gamma$. Best fits by SND and KLOE:

$$\begin{aligned} \text{SND}: &\quad \text{BR}(\phi \to f_0\gamma) = (3.5 \pm 0.3 \pm 1.3) \times 10^{-4} \\ \text{KLOE}: &\quad \text{BR}(\phi \to f_0\gamma) = (4.47 \pm 0.21) \times 10^{-4} \end{aligned}$$

Radiative ϕ Decays: Questions

Both collaborations measure BR($\phi \to P^0 P'^0 \gamma$) $\sim 10^{-4}$. Theoretical predictions ranged from $10^{-6} - 10^{-5}$ for $q\bar{q}$ $a_0(980)$ and $f_0(980)$ states. Can we conclude that a_0 and f_0 are NOT pure $q\bar{q}$ states?

How model-dependent are the extracted branching ratios for $\phi \to a_0\gamma$ and $\phi \to f_0\gamma$? (Note that ratios obtained from SND and DaΦne are somewhat different.)

How do the rare radiative ϕ decays fit in with observations of other processes involving the light scalar mesons?

Possibility of two nonets of scalar mesons

Reminder: Scalar ($J^P = 0^+$) mesons - from 2002 PDG:

State	Isospin
$f_0(600)[``\sigma"]$	0
$?\kappa(900)?$	$\frac{1}{2}$
$f_0(980)$	0
$a_0(980)$	1
$f_0(1370)$	0
$K_0^*(1430)$	$\frac{1}{2}$
$a_0(1450)$	1
$f_0(1500)$	0
$f_0(1710)$	0

- All of these states could be accounted for if there are two nonets + one scalar glueball below 2 GeV
- If $\sigma, \kappa, f_0(980), a_0(980)$ are members of an SU(3) nonet the mass spectrum is inverted compared to what we would expect - I=1 state is heaviest (compare with ρ and ω)
- The states will occur as resonances in $\pi\pi$, πK and $\pi\eta$ scattering. Included explicitly in for example Linear Sigma Model. "Integrated out" in Chiral Perturbation Theory.

Chiral Lagrangian description of $\pi\pi$, πK and $\pi\eta$ scattering

- Leading order pseudoscalar meson Lagrangian:

$$\mathcal{L}_{p.s.} = -\frac{{\mathrm{F}_\pi}^2}{8}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \mathrm{Tr}\left[B\left(U + U^\dagger\right)\right]$$

where U is the chiral field

$$U = \exp(\frac{2i\phi}{F_\pi}) \longrightarrow U_L U U_R^\dagger$$

Calculating using $\mathcal{L}_{p.s.}$ reproduces usual low energy results, e.g. Weinberg $\pi\pi$ scattering amplitude.

- Vector mesons can be introduced by "gauging" $\mathcal{L}_{p.s.}$ (or equivalently Hidden Local Symmetry approach):

$$U \equiv \xi^2 \longrightarrow U_L \xi^2 {U_R}^\dagger = U_L \xi K^\dagger K \xi U_R^\dagger$$

$$\Rightarrow \xi \longrightarrow U_L \xi K[\phi(x), U_L, U_R]^\dagger \equiv K[\phi(x), U_L, U_R]\xi U_R^\dagger$$

Under chiral group vector meson multiplet V_μ transforms as:

$$V_\mu \longrightarrow K V_\mu K^\dagger + \frac{i}{g} K \partial_\mu K^\dagger$$

Introducing scalar meson multiplet $[\sigma, \kappa, a_0, f_0]$

DB, Fariborz, Sannino and Schechter, PRD 59 074026 (1999)

$$\mathrm{S} = \begin{bmatrix} \mathrm{S}_1^1 & a_0^+ & \kappa^+ \\ a_0^- & \mathrm{S}_2^2 & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & \mathrm{S}_3^3 \end{bmatrix} \longrightarrow KSK^\dagger$$

with

$$\begin{pmatrix} \sigma \\ f_0 \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_s & -\sin\theta_s \\ \sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} S_3^3 \\ \frac{S_1^1+S_2^2}{\sqrt{2}} \end{pmatrix}$$

Trilinear part of general chiral invariant Lagrangian which gives tree-level interaction of scalar nonet with two pseudoscalars is:

$$\begin{aligned} \mathcal{L}_{S\phi\phi} &= a\epsilon^{abc}\epsilon_{def}S_a^d\partial_\mu\phi_b^e\partial_\mu\phi_c^f + b\mathrm{Tr}\left(S\right)\mathrm{Tr}\left(\partial_\mu\phi\partial_\mu\phi\right) \\ &+ c\mathrm{Tr}\left(S\partial_\mu\phi\right)\mathrm{Tr}\left(\partial_\mu\phi\right) + d\mathrm{Tr}\left(S\right)\mathrm{Tr}\left(\partial_\mu\phi\right)\mathrm{Tr}\left(\partial_\mu\phi\right) \end{aligned}$$

- Contains $\mathrm{Tr}(S\partial_\mu\phi\partial^\mu\phi)$ term. Actually first term would be the OZI-preserving term for multiquark scalars (see next transparency).

- We get good fits to $\pi\pi$, πK scattering and $\eta' \to \eta\pi\pi$ decay data. Fitting parameters are scalar masses, widths and coupling constants and also $\sigma - f_0$ mixing angle θ_s.

- Different processes related - we predict for example $\eta\pi$ scattering and $\eta \to 3\pi$ decay. Best fit found for $\theta_s \approx -20^o$.

Possible clue about quark substructure

$$\mathrm{S} = \begin{bmatrix} \mathrm{S}_1^1 & a_0^+ & \kappa^+ \\ a_0^- & \mathrm{S}_2^2 & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & \mathrm{S}_3^3 \end{bmatrix}$$

with

$$\begin{pmatrix} \sigma \\ f_0 \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_s & -\sin\theta_s \\ \sin\theta_s & \cos\theta_s \end{pmatrix} \begin{pmatrix} S_3^3 \\ \frac{S_1^1+S_2^2}{\sqrt{2}} \end{pmatrix}$$

$\theta_s = \frac{\pi}{2} \longrightarrow$ Usual ideal mixing with $S_a^b \sim q_a \bar{q}^b$:

$$f_0 = S_3^3 \sim s\bar{s} \qquad\qquad \sigma \sim \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$$

$\theta_s = 0 \longrightarrow$ "Dual" Ideal mixing natural for nonet $S_a^b \sim Q_a \bar{Q}^b$:

$$Q_a \sim \epsilon_{abc}\bar{q}^b\bar{q}^c \qquad\qquad \bar{Q}^a \sim \epsilon^{abc} q_b q_c$$

An ideally mixed "dual" nonet would correspond to:

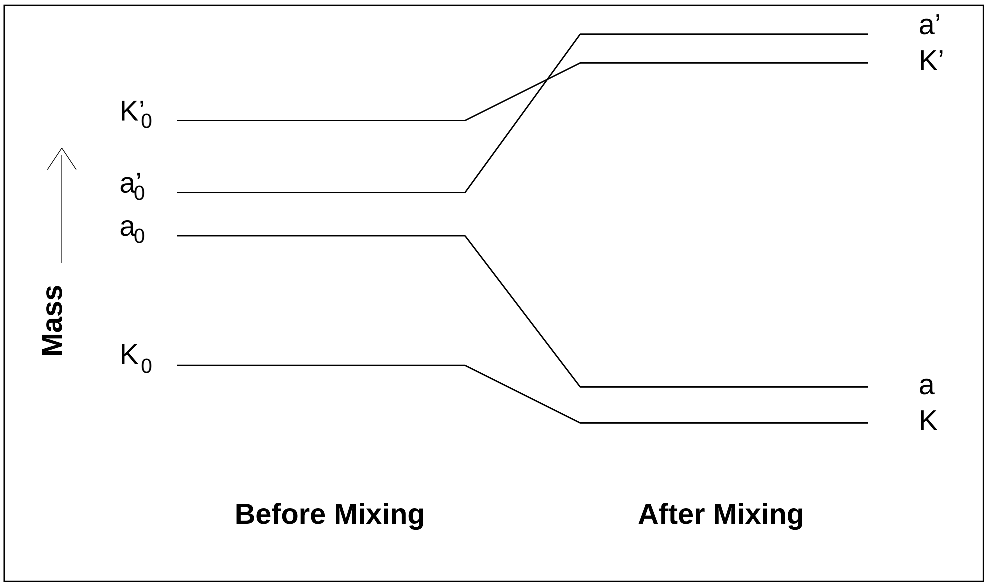
$$\begin{aligned} \sigma &\sim ud\bar{u}\bar{d} & \qquad f_0 &\sim s\bar{s}\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right) \\ \kappa^+ &\sim ud\bar{d}\bar{s} & \qquad a_0^+ &\sim us\bar{d}\bar{s} \end{aligned}$$

Fit $\theta_s \approx -20^o$ mixing pattern is closer to "dual" ideal mixing. Suggests that light scalar mesons have non-trivial four-quark component (c.f. Jaffe).

Mixing of $q\bar{q}$ scalar nonet with lighter scalar nonet

DB, Fariborz and Schechter, PRD 61, 074001 (2000)

Idea is that the $a_0(980)$, $a_0(1450)$, $\kappa(900)$ & $K_0^*(1430)$ are mixtures of $qq\bar{q}\bar{q}$ (for example) and $q\bar{q}$ states:



Mixing of scalar $qq\bar{q}\bar{q}$ states a_0 & K_0 with $q\bar{q}$ states a_0' & K_0' to produce observed isoscalar and isospinor states labelled K, a, K' & a'.

Reminder: $K_0^+ \sim ud\bar{d}\bar{s}$, $a_0^+ \sim us\bar{d}\bar{s}$.

Simplest mixing terms for two nonets S and S':

$$\mathcal{L}_{mixing} = \gamma \mathrm{Tr}\,(SS')$$

Fitting the masses of the physical states, there are values of γ for which we can we recover the $qq\bar{q}\bar{q}$ and $q\bar{q}$ states with expected ordering of their masses prior to mixing. Decays can also be understood.

Radiative Decays - A first approach

Can we extend chiral Lagrangian framework that succesfully describes strong processes involving the scalar mesons in order to study radiative decays like $\phi \longrightarrow \pi\pi\gamma$?

So far:

- Vector meson multiplet introduced by "gauging" the lowest order chiral Lagrangian of pseudoscalar mesons. (Gauge invariance then broken by vector meson mass terms.)

- We included interactions of pseudoscalar mesons with an SU(3) nonet of scalar mesons in a chiral invariant way.

Radiative Decays - A first approach

DB, Harada and Schechter, PRL 88 (2002)

- We need to figure out general chiral invariant coupling between scalar and vector mesons. Trilinear Scalar-Vector-Vector interaction is:

$$\mathcal{L}_{SVV} = \beta_A \, \epsilon_{abc}\epsilon^{a'b'c'} \left[F_{\mu\nu}(V)\right]_{a'}^{a} \left[F_{\mu\nu}(V)\right]_{b'}^{b} S_{c'}^{c} + \beta_B \,\mathrm{Tr}\left[S\right] \mathrm{Tr}\left[F_{\mu\nu}(V)F_{\mu\nu}(V)\right]$$
$$+ \beta_C \,\mathrm{Tr}\left[SF_{\mu\nu}(V)\right] \mathrm{Tr}\left[F_{\mu\nu}(V)\right] + \beta_D \,\mathrm{Tr}\left[S\right] \mathrm{Tr}\left[F_{\mu\nu}(V)\right] \mathrm{Tr}\left[F_{\mu\nu}(V)\right]$$

$$F_{\mu\nu}(V) = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu].$$

- Electromagnetism: Vector meson dominance emerges naturally because, if we introduce again local U(1) invariance, photon coupling to charged pseudoscalar mesons becomes:

$$eA^\mu \Big[kgF_\pi^2 \mathrm{Tr}(QV_\mu) + i(1 - \frac{k}{2}) \mathrm{Tr}(Q\phi \overleftrightarrow{\partial_\mu} \phi) \Big]$$

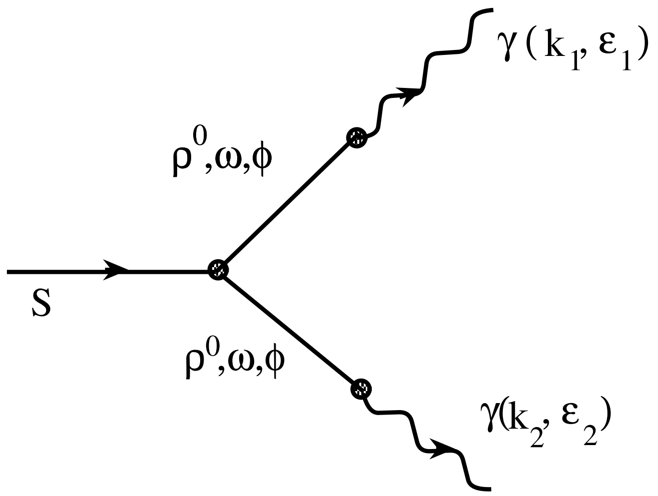
$$k = \left(\frac{m_v}{gF_\pi}\right)^2 \approx 2 \qquad \text{KSRF relation}$$

Radiative decays - a first approach

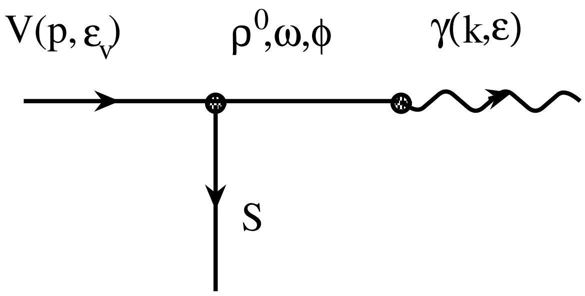
General trilinear Scalar-Vector-Vector chiral invariant interaction:

$$\mathcal{L}_{SVV} = \beta_A\,\epsilon_{abc}\epsilon^{a'b'c'}\,[F_{\mu\nu}(V)]^a_{a'}\,[F_{\mu\nu}(V)]^b_{b'}\,S^c_{c'} + \beta_B\,\mathrm{Tr}\,[S]\,\mathrm{Tr}\,[F_{\mu\nu}(V)F_{\mu\nu}(V)] \\ + \beta_C\,\mathrm{Tr}\,[SF_{\mu\nu}(V)]\,\mathrm{Tr}\,[F_{\mu\nu}(V)] + \beta_D\,\mathrm{Tr}\,[S]\,\mathrm{Tr}\,[F_{\mu\nu}(V)]\,\mathrm{Tr}\,[F_{\mu\nu}(V)]\ .$$

Radiative decays occur at tree level: e.g.



(a)



(b)

Many processes given in terms of the four new parameters β in $\mathcal{L}_{SVV}$:

$$\phi \to a_0\gamma,\ f_0\gamma \qquad \rho,\ \omega,\ \phi \to \sigma\gamma$$

$$a_0,\ f_0,\ \sigma \to \gamma\gamma \qquad a_0,\ f_0 \to \rho\gamma,\ \omega\gamma$$

Radiative decays - a first approach

New feature - many processes are related:

$$\phi \to a_0\gamma,\ f_0\gamma \qquad \rho,\ \omega,\ \phi \to \sigma\gamma$$

$$a_0,\ f_0,\ \sigma \to \gamma\gamma \qquad a_0,\ f_0 \to \rho\gamma,\ \omega\gamma$$

Model is now constrained. For example, using experimental values for $a_0 \to \gamma\gamma$, $f_0 \to \gamma\gamma$, and $\phi \to a_0\gamma$ to solve for β_A, β_B and β_C we predict nine other processes.

However, our best prediction for $\phi \to f_0\gamma$ is:

$$\left[\frac{\mathrm{BR}(\phi \to f_0\gamma)}{\mathrm{BR}(\phi \to a_0\gamma)}\right]_{\mathrm{VMD}} \sim 0.46$$

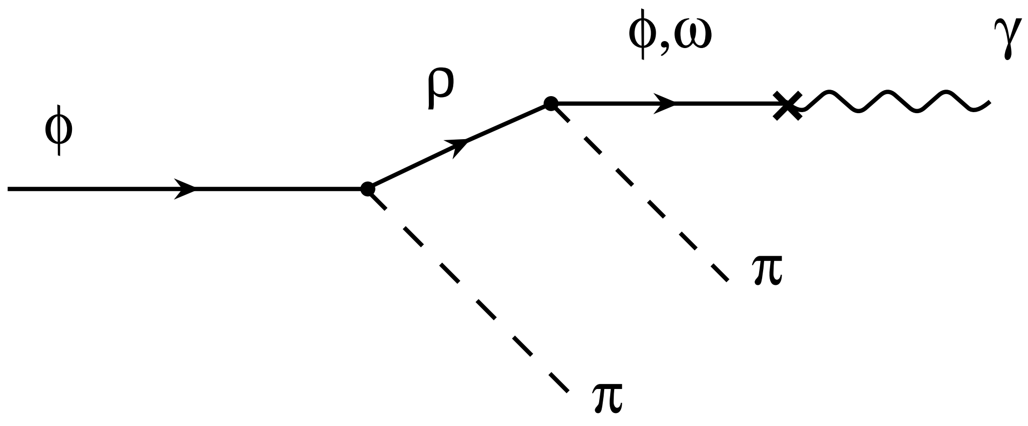
Central values, extracted from different models, from SND and KLOE measurements of $\phi \to \pi\pi\gamma$ and $\phi \to \pi\eta\gamma$ were:

$$\left[\frac{\mathrm{BR}(\phi \to f_0\gamma)}{\mathrm{BR}(\phi \to a_0\gamma)}\right]_{\mathrm{SND}} = 3.9 \qquad \left[\frac{\mathrm{BR}(\phi \to f_0\gamma)}{\mathrm{BR}(\phi \to a_0\gamma)}\right]_{\mathrm{KLOE}} = 6.0$$

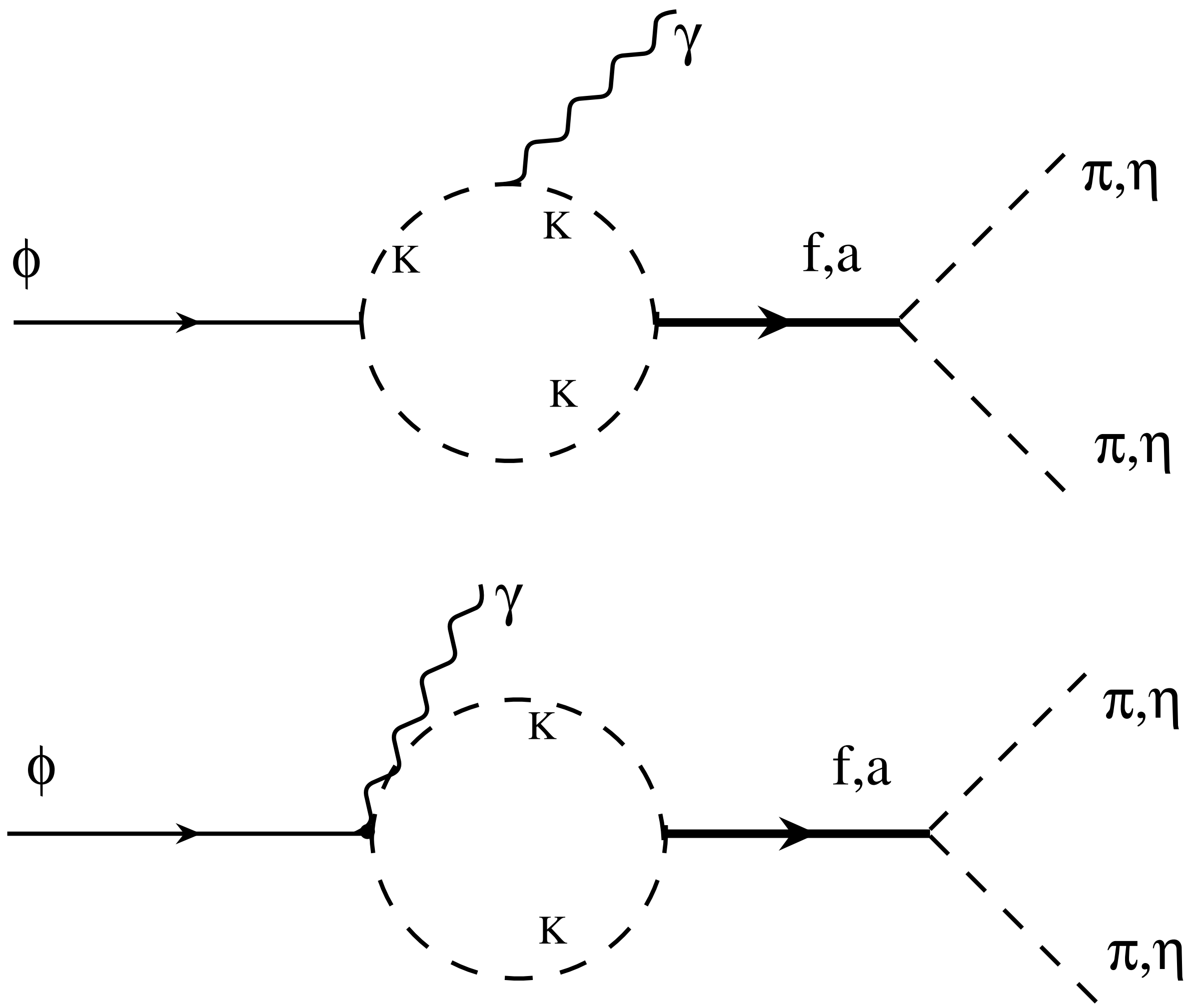
Also if we try and fit only $\phi \to \pi\pi\gamma$ and $\phi \to \pi\eta\gamma$ we do not reproduce the high end of the experimental spectrum with this simple tree-level picture.

Radiative decays - the next steps

- We include the Kaon loop corrections to our picture (found to be important by original authors).
- We need to calculate $\phi \to \pi\pi\gamma$ and $\phi \to \pi\eta\gamma$ and see how to extract $\mathrm{BR}(\phi \to f_0, a_0\gamma)$.
- Study of backgrounds/interference - e.g. σ, contact diagrams and other non-resonant background such as:



Radiative decays - the next steps



In principle all couplings are related to those found previously in fits to processes such as $\pi\pi$ and πK scattering. If we allow the scalar-pseudoscalar-pseudoscalar couplings to be free parameters we get a good fit to the radiative phi decay data using tree diagrams + kaon loops (see fits).

Discussion

- Pseudoscalar meson-meson scattering and decays consistent with non-linear chiral Lagrangian treatment using light nonet of scalar mesons. Mixing pattern which emerges is natural for a $qq\bar{q}\bar{q}$ nonet.

- Recent experiments by SND and CMD-2 at Novosibirsk and KLOE at Frascati have measured the rare radiative $\phi \rightarrow \pi^0\eta\gamma$ and $\phi \rightarrow \pi^0\pi^0\gamma$ decays for the first time.

- We extend our chiral model to include all radiative decays involving a nonet of scalar mesons. Fitting $a_0 \rightarrow \gamma\gamma$, $f_0 \rightarrow \gamma\gamma$ and $\phi \rightarrow a_0\gamma$ we predict $\phi \rightarrow f_0\gamma$ and eight other processes.

- Tree-level approximation seems too simple for describing $\phi \rightarrow \pi\pi\gamma$ and $\pi\eta\gamma$ - difficult to get the detailed spectrum shape correct.

- We calculate $\phi \rightarrow \pi\pi\gamma$ and $\pi\eta\gamma$ including Kaon loop corrections and get a reasonable fit. However at this stage the parameters are not constrained to agree with strong scattering and decay data.

- Ongoing: Inclusion of all effects due to chiral symmetry - e.g gives rise to interference, even at tree level between f_0, σ, contact diagram and "non-resonant background". Include effect of mixing between light scalar nonet and heavier conventional scalar mesons and glueball. Eventually, test whether radiative decay experiments can be described in framework consistent with chiral Lagrangian description of strong processes involving (possibly exotic) scalar mesons.