MC event generator for π^0, η and η' production via Primakoff scattering $e^-\gamma \to e^-\mathcal{P}$

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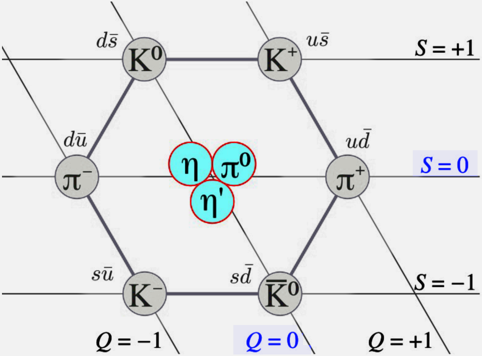
- ✓ Introduction, motivation
- ✓ Width: theory
- ✓ Width: experiments
- ✓ Elementary Primakoff
- ✓ MC generator
- ✓ Conclusions

Flavor $SU(3)$ symmetry pattern



meson properties are “driven” by underlying quark symmetries

Pseudoscalar nonet

Following the approach of Feldmann

[Th.Feldmann, Int.J.Mod.Phys., A15, 159 (2000)]

$$\psi(x) = \frac{1}{f_\pi} \begin{pmatrix} \frac{\pi^0 + C_q\eta + C'_q\eta'}{\sqrt{2}} & \pi^+ & \frac{f_\pi}{f_K} K^+ \\ \pi^- & \frac{-\pi^0 + C_q\eta + C'_q\eta'}{\sqrt{2}} & \frac{f_\pi}{f_K} K^0 \\ \frac{f_\pi}{f_K} K^- & \frac{f_\pi}{f_K} \bar{K}^0 & -C_s\eta + C'_s\eta' \end{pmatrix}$$

$f_\pi \approx 92.4$ MeV, $f_K \approx 1.22\ f_\pi$.
$C_q \approx 0.720$, $C_s \approx 0.471$, $C'_q \approx 0.590$ and $C'_s \approx 0.576$
(provided $f_8 = 1.26\ f_\pi$, $f_0 = 1.17\ f_\pi$, $\theta_8 = -21.2^{\rm o}$ and $\theta_0 = -9.2^{\rm o}$)

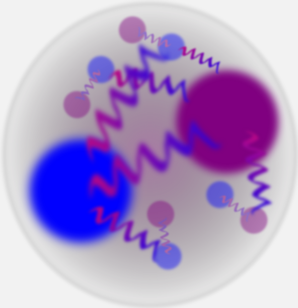
Flavor symmetry breaking in the is accounted here, as well as the $\eta - \eta'$ mixing

Discovering the internal structure

- “bound states” of quark and anti-quark

light quarks: u, d, s

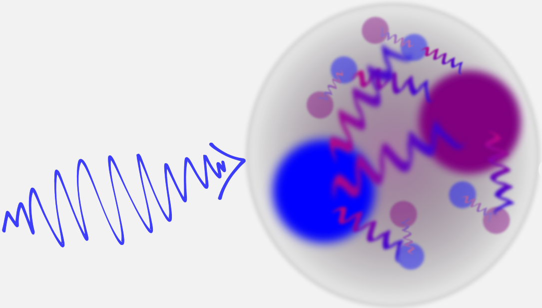
- different scales of experiments — different "structure"



how can we "touch" the meson?

Discovering the internal structure

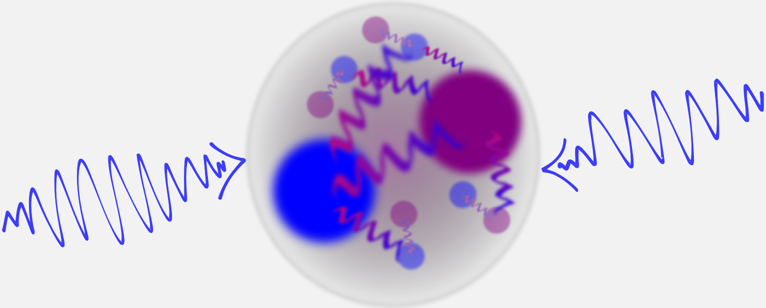
- generic approach — “electromangetic probe”



…but if the particle is neutral?

Discovering the internal structure

- two-photon interactions of π^0, η, η' mesons



guided by Wess-Zumino-Witten type of interaction

Wess-Zumino-Witten Lagrangian

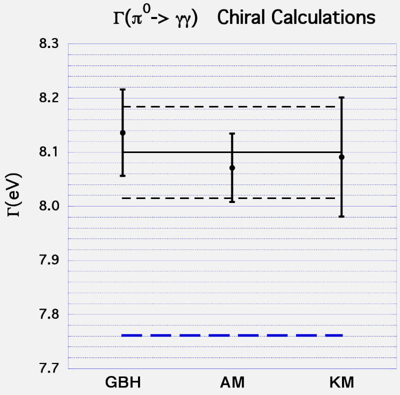
At the lowest order:

$$\mathcal{L}_{\gamma\gamma P} = -\frac{\sqrt{2}e^2 N_c}{8\pi^2}\epsilon^{\mu\nu\alpha\beta}\partial_\mu B_\nu \partial_\alpha B_\beta \langle \mathcal{Q}^2 \psi \rangle$$

$N_c = 3$ is the number of quark colors,
quark charges are given by $\mathcal{Q} \equiv diag(2/3,\ -1/3,\ -1/3)$ and
the electromagnetic field is denoted by B_ν.

In terms of physical fields:

$$\begin{aligned}\mathcal{L}_{\gamma\gamma P} = & - \frac{e^2 N_c}{24\pi^2 f_\pi}\epsilon^{\mu\nu\alpha\beta}\partial_\mu B_\nu \partial_\alpha B_\beta \\ & \times \left[\pi^0 + \eta\left(\frac{5}{3}C_q - \frac{\sqrt{2}}{3}C_s\right) + \eta'\left(\frac{5}{3}C'_q + \frac{\sqrt{2}}{3}C'_s\right)\right].\end{aligned}$$

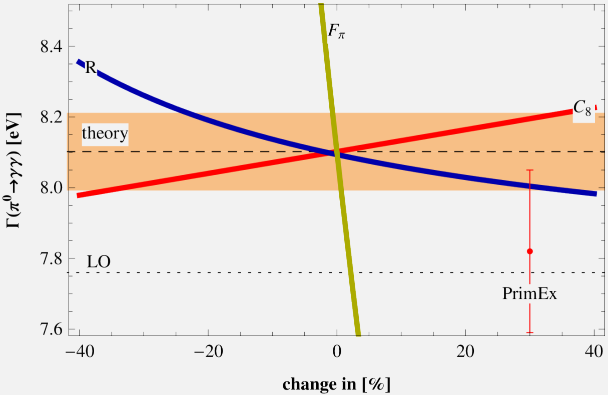


lower dashed — chiral anomaly (Adler, Bell, Jackiw)

upper solid — NLO ChPT average, dotted — estimated 1% theory uncertainty

[J. Goity, A. Bernstein, and B. Holstein, Phys.Rev. **D66** (2002) 076014]
[K. Kampf and B. Moussallam, Phys.Rev. **D79** (2009) 076005]
[B. Ananthanarayan and B. Moussallam, JHEP **0205** (2002) 052]

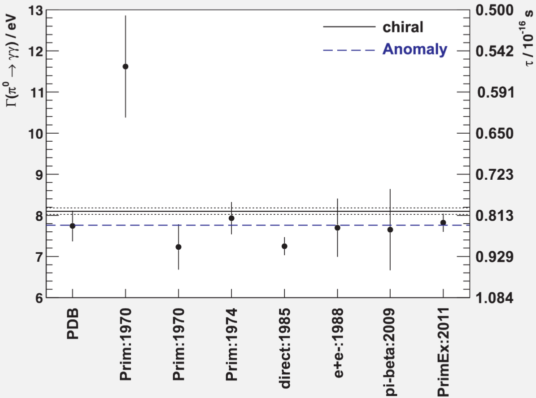
Dependence of $\pi^0 \to \gamma\gamma$ width on $N_f = 3$ ChPT LECs



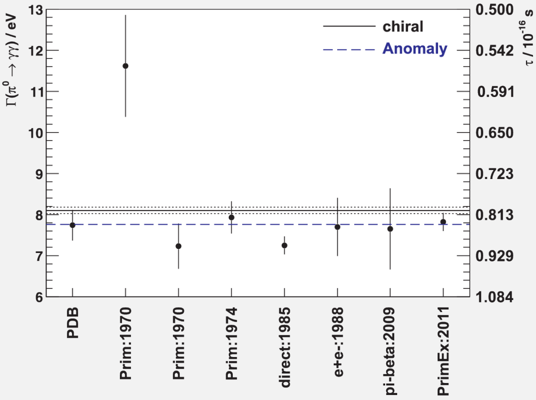
F_π pion decay constant

C_8^W reflects the $\eta - \eta'$ process

$R = (m_s - \hat{m})/(m_d - m_u)$ reflects the flavor breaking



1 particle data group average;
2,3,4 Primakoff experiments (1970-1974) Browman:1974, Bellettini:1970, Kryshkin:1970;
5 direct method (1985) Atherton;
6 e^+e^- (1988) Williams;
7 $\pi\beta$ experiment (2009) Bychkov;
8 PrimEx (2011) Larin



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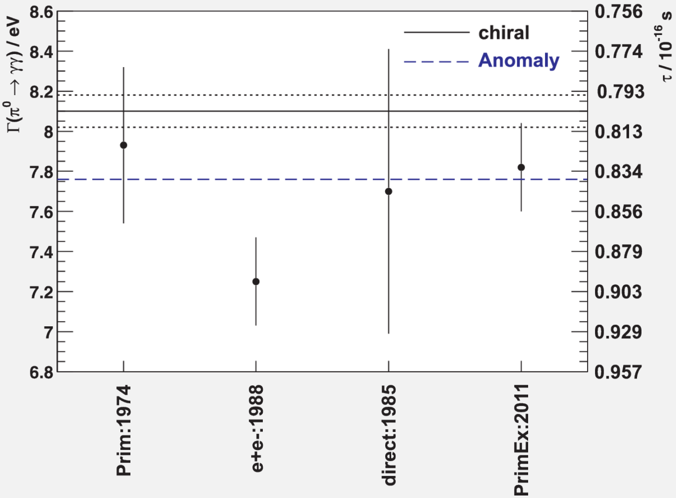
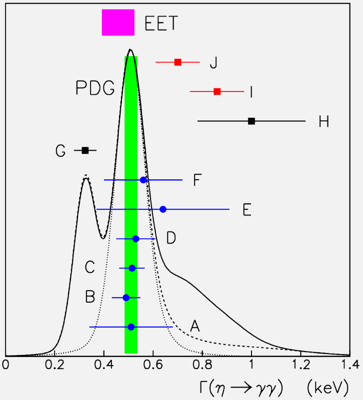


Four most precise measurements vs. theory

Extraction of $\eta \to \gamma\gamma$ width utilizing the Primakoff effect



- I, J — A. Sibirtsev et al.: $\gamma p \to \eta p$ Primakoff, reanalysis (2010) based on W. Braunschweig et al. (1970) and J. Dewire et al. (1971)
- H — C. Bemporad et al., Phys. Lett. B 25, 380 (1967).
- G — A. Browman et al., Phys. Rev. Lett. 32, 1067 (1974).
- F — A.J. Weinstein et al., Phys. Rev. D 28, 2896 (1983).
- E — H. Aihara et al., Phys. Rev. D 33, 844 (1986).
- D — W. Bartel et al., Phys. Lett. B 160, 421 (1985).
- C — D.A. Williams et al., Phys. Rev. D 38, 1365 (1988).
- B — N.A. Roe et al., Phys. Rev. D 41, 17 (1990).
- A — S.E. Baru et al., Z. Phys. C 48, 581 (1990).

Blue circles — $e^+e^- \to e^+e^-\eta$

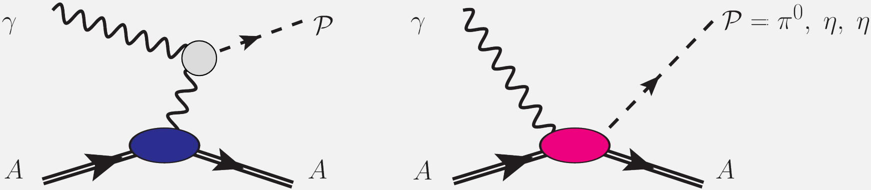
Squares — Primakoff effect

Green band — PDG average

" In reality the interference of the Primakoff amplitude with the nuclear coherent amplitude contaminates the signal.
Furthermore, the conversion of photons to mesons deep inside the nucleus distorts the signal by FSI and photon shadowing in ISI.
The data analysis and width extraction thus have to be based on a model which is able to describe the different production mechanisms reliably. "

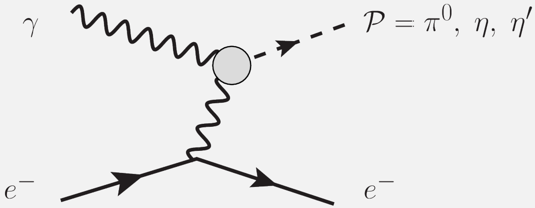
Primakoff: $A\gamma \to A\mathcal{P}$

- $\mathcal{P}$ mesons can be produced via Primakoff effect
  [H.Primakoff, Phys.Rev. 81 (1951) 899]
- typically, it is done on a nuclear target: $A\gamma$ collision
  $\Rightarrow Z^2$ factor in the cross section

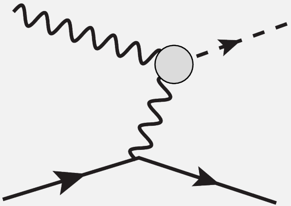


Goal: precise measurement of $\gamma\gamma$ width

- we consider a less intense, but much cleaner option "elementary Primakoff": $e^-\gamma$ collision



Amplitude: $e^- \gamma \to e^- \mathcal{P}$



$$\mathcal{M} \;=\; \frac{i\,\alpha\,e}{\pi\,f_\pi}\,\frac{F(0,t)}{t}\,\bar{u}(q)\gamma^\beta u(p)\,\epsilon_{\mu\nu\sigma\beta}\,k^\mu\,l^\nu\,\varepsilon^\sigma$$

$\alpha = \frac{e^2}{4\pi}$
k - real photon momentum
ϵ - real photon polarization vector
l - virtual photon momentum
$t = l^2$
$F(t_1, t_2)$ - two-photon form factor of $\mathcal{P}$

Cross section: $e^-\gamma \to e^-\mathcal{P}$

$$\frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\Omega} = \frac{1}{32\,\pi^2}\,\frac{\lambda^{1/2}(s, m_e^2, m_{\mathcal{P}}^2)}{2s(s-m_e^2)}\,\overline{|\mathcal{M}|^2}$$

$$\overline{|\mathcal{M}|^2} = \frac{2\,\alpha^3}{\pi\ f_\pi^2}\,\frac{|F(0,t)|^2}{t^2}\,\mathcal{T}$$

$$\mathcal{T} = \frac{1}{2}t(s-u)^2 + 2m_e^2(u+s)^2 - 8m_e^4(u+s-m_e^2) + 2q_X^2(s-m_e^2)^2$$

$$q_X^2 = \frac{\lambda(s, m_{\mathcal{P}}^2, m_e^2)}{4s}\ \sin^2\theta\ \cos^2\phi$$

θ is the polar angle of the final lepton (w.r.t z-axis)

ϕ is the azimutal angle of the final lepton in xy plane (w.r.t x-axis)

The above formula accounts for the sum over the initial electron helicity states and for $1/2$ averaging factor.

The photon is linearly polazrized in xz plane ($\vec{\varepsilon} = (1, 0, 0)$).

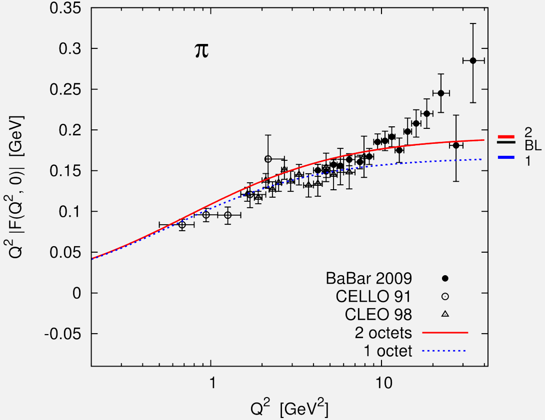
Monte carlo: $e^- \gamma \to e^- \mathcal{P}$

- Stand-alone program in FORTRAN90
- Leading order matrix element
- Polarized photon beam (linear polarization)
- Draft histogramming out-of-box
- $\mathcal{P} \to \gamma\gamma$ decay is included
- π^0, η and η' are in the narrow-width approximation (to be improved)

Form factor $\gamma^*\gamma\pi^0$

If necessary, we can include the transition form fators, which are also used in EKHARA MC generator

[H. Czyz, S. Ivashyn, A. Korchin and O. Shekhovtsova, Phys.Rev.**D 85** (2012) 094010]



- good agreement with CELLO 1991, CLEO 1998
- discrepancy with BaBar 2009

Form factor $\gamma^*\gamma\eta$ and $\gamma^*\gamma\eta'$

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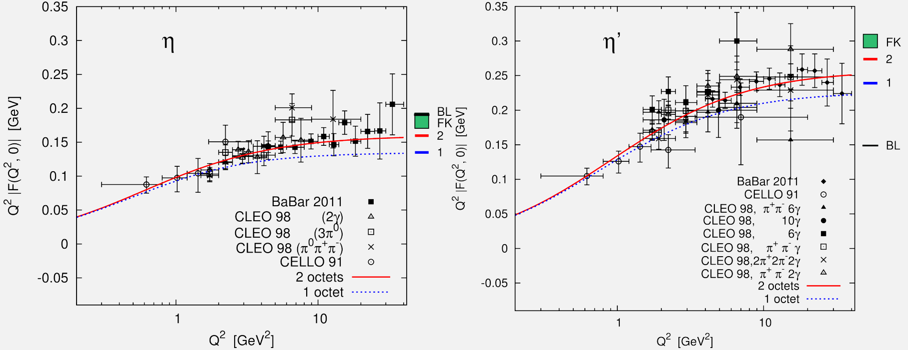
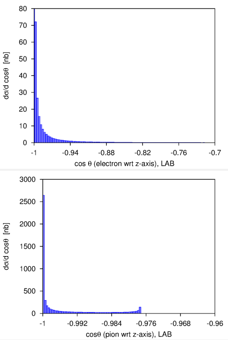


- agreement with CELLO 1991, CLEO 1998 and with BaBar 2011

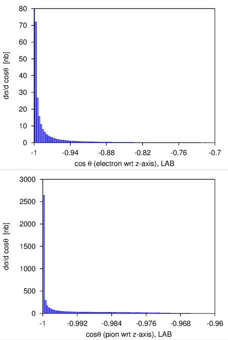
Simulation: $e^-\gamma \to e^-\pi^0$

- $E_\gamma = 20$ MeV, $E_{e^-} = 750$ MeV
- beam spread: $E_\gamma \pm 10\%$, $E_{e^-} \pm 0.1\%$

no beam spread



with beam spread



Conclusions

- Interesting physics program
  for a high-luminosity $e^-\gamma$ collider

- Precise measurement of the two-photon widths of light pseudoscalars

  - ✓ solving a puzzle of Primakoff vs. e^+e^- data for η meson
  - ✓ ChPT tests, determination of LECs
  - ✓ quark mass ratio
  - ✓ flavor symmetry breaking and meson mixing

- Beam polarization and spread are included in MC.

- Ready to perform simple MC simulations

Spare parts

$e^- \gamma \to e^- \pi^0$ Simulation

$e^-\gamma \to e^-\pi^0$ cross section

"low-energy option"	"high-energy option"
$E_\gamma = 20$ MeV	$E_\gamma = 270$ MeV
$E_{e^-} = 750$ MeV	$E_{e^-} = 4000$ MeV
$\sigma \approx 2.1$ nb	$\sigma \approx 5.8$ nb

- In order to be competitive, one must perform a $\sim 1\%$ precision measurement
  - KLOE-2 feasibility study [Eur.Phys.J. C72 (2012) 1917]
  - the most recent measurement by PRIMEX [Phys.Rev.Lett. 106 (2011) 162303]

- $E_\gamma = 270$ MeV, $E_{e^-} = 4000$ MeV
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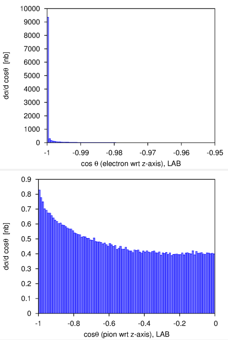
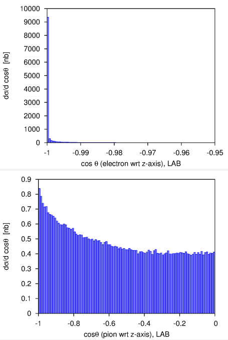


with beam spread



Odd-intrinsic-parity Lagrangian, $\eta - \eta'$ issues

WZW Lagrangian

- LO ChPT Lagrangian (odd-intrinsic-parity)

  [J. Gasser and H. Leutwyler, Nucl. Phys. B 250 (1985) 465]

  [R. Kaiser, Phys. Rev. D 63 (2001) 076010]

- NLO ChPT Lagrangian (odd-intrinsic-parity)

  [T. Ebertshauser, H. W. Fearing and S. Scherer, Phys. Rev. D 65 (2002) 054033]

  [J. Bijnens, L. Girlanda and P. Talavera, Eur. Phys. J. C 23 (2002) 539]

$\eta \to \gamma\gamma$ in ChPT

Calculation of $\eta \to \gamma\gamma$:

[B. Borasoy and R. Nissler, Eur. Phys. J. A 19 (2004) 367]

[J. Bijnens and K. Kampf, Nucl. Phys. Proc. Suppl. 207-208 (2010) 220]

Explaining the motivation for the NLO ChPT calculation of $\eta \to \gamma\gamma$:

[J. Bijnens, K. Kampf, Nucl. Phys. Proc. Suppl. 207-208 (2010) 220-223]

$\eta - \eta'$ mixing

Recent advances:

[R. Escribano, P. Masjuan, J.J. Sanz-Cillero, JHEP 1105 (2011) 094]

[P. Kroll, Mod.Phys.Lett. A20 (2005) 2667-2684]

[B. Borasoy and R. Nissler, Eur. Phys. J. A 19 (2004) 367]

[Th. Feldmann, Int.J.Mod.Phys., A15, 159 (2000)]