A first prediction of the e-m. rare decays $\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$

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Purpose:

To present for the first time a calculation of the electromagnetic rare decays $\eta' \to \pi^0 \gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ with the aim of extracting some relevant information on the properties of the lowest-lying scalar mesons

Motivations:

- To complement other analyses based on $V \to P^0 P^0 \gamma$ decays, D and J/ψ decays, central production...
- To complete the existing predictions for $\eta \to \pi^0 \gamma\gamma$ in view of the ongoing and forthcoming experiments @ ELSA, MAMI, WASA, KLOE2 and BES-III

Outline:

- *Experimental data*
- *Theory predictions: seminal work and recent analysis*
- *Our proposal*
- $\eta \rightarrow \pi^0\gamma\gamma$ *as a test of our approach*
- $\eta' \rightarrow \pi^0\gamma\gamma$
- $\eta' \rightarrow \eta\gamma\gamma$
- *Conclusions*

In collab. with Renata Jora (NIPNE, Bucharest)

- *Experimental data*
  - ✦ $\eta \to \pi^0 \gamma\gamma$

GAMS-2000: $\Gamma=0.84\pm0.18$ eV

D. Alde *et al.*, ZPC 25 (1984) 225 $\pi^- p \to \eta n$

CB@AGS: $\Gamma=0.45\pm0.12$ eV

S. Prakhov *et al.*, PRC 72 (2005) 025201 $\pi^- p \to \eta n$

CB@AGS: $\Gamma=0.285\pm0.031\pm0.049$ eV

S. Prakhov *et al.*, PRC 76 (2008) 015206

KLOE@DAPHNE: $\Gamma=0.109\pm0.035\pm0.018$ eV

B. Di Micco *et al.*, APS 56 (2006) 403 $\phi \to \eta \gamma$

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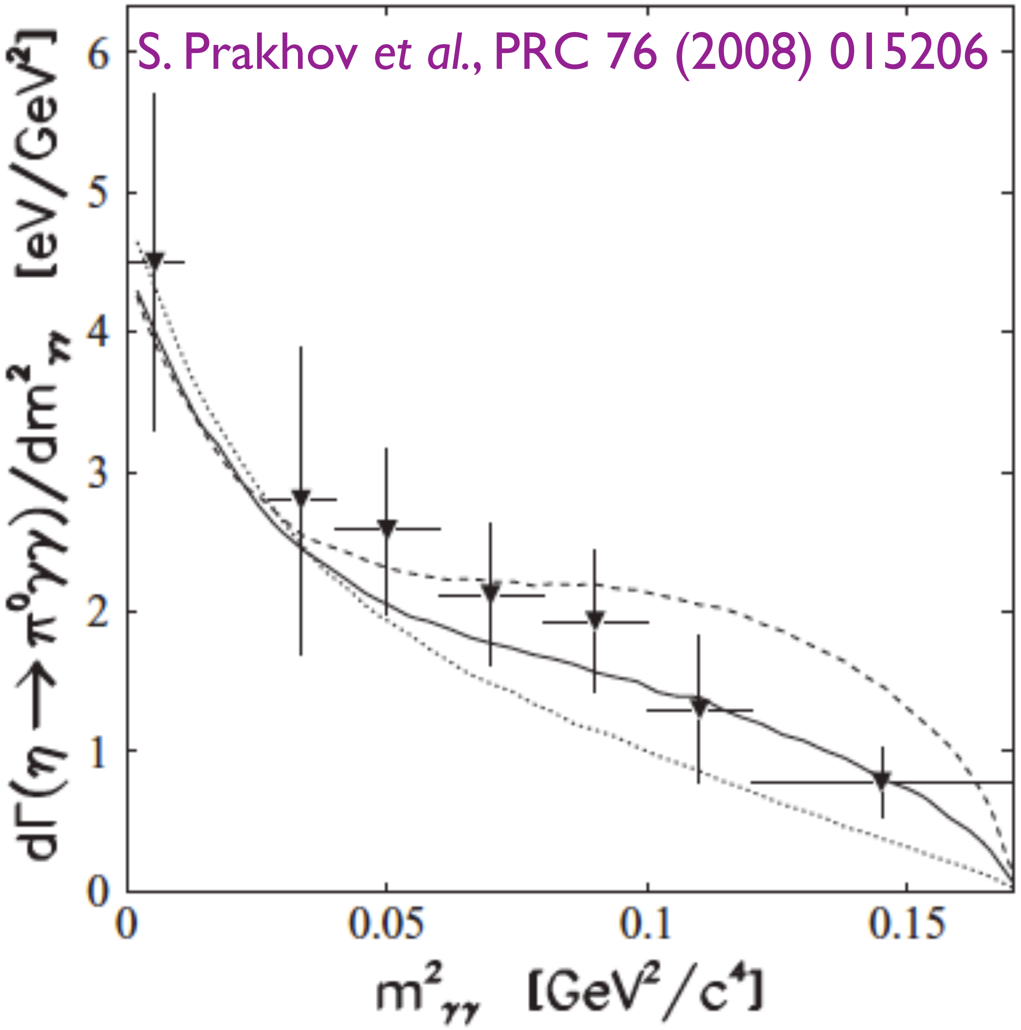

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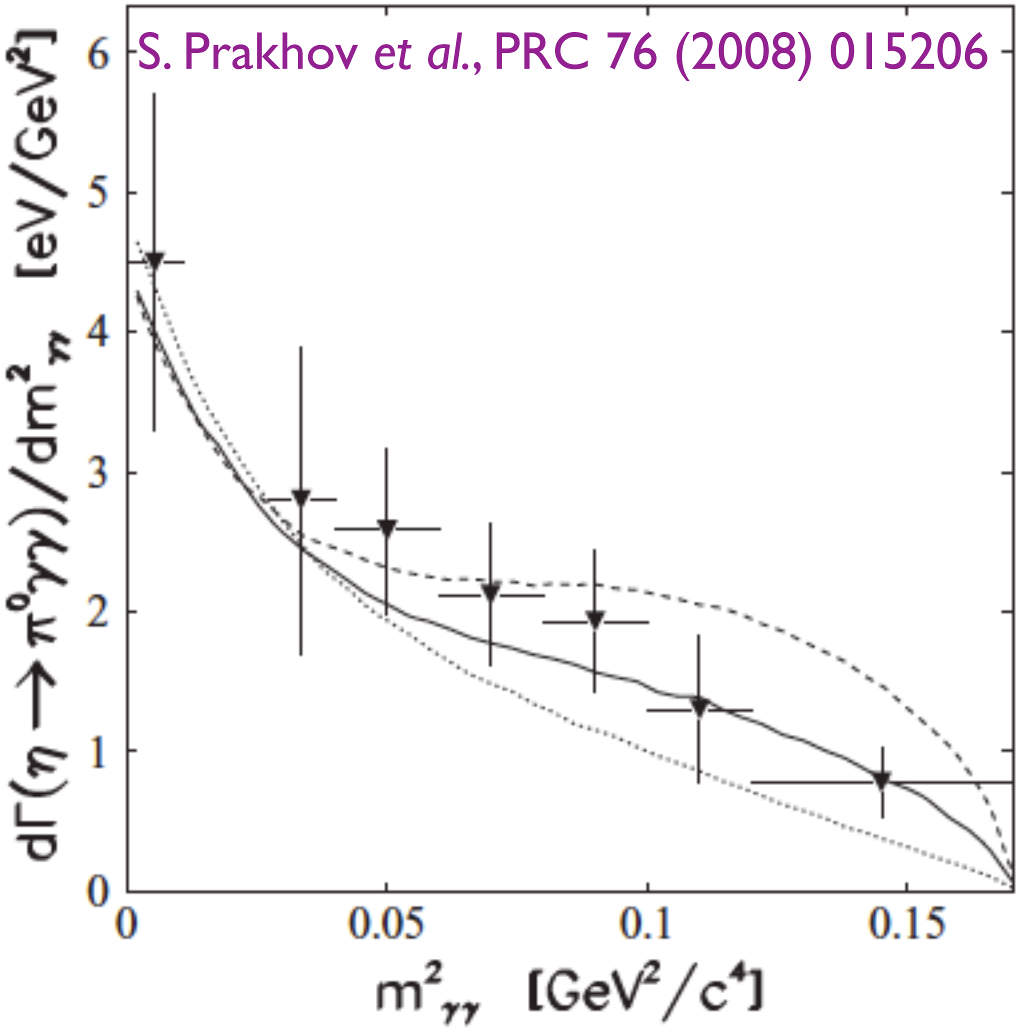
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  - $\eta'\rightarrow\pi^0\gamma\gamma$

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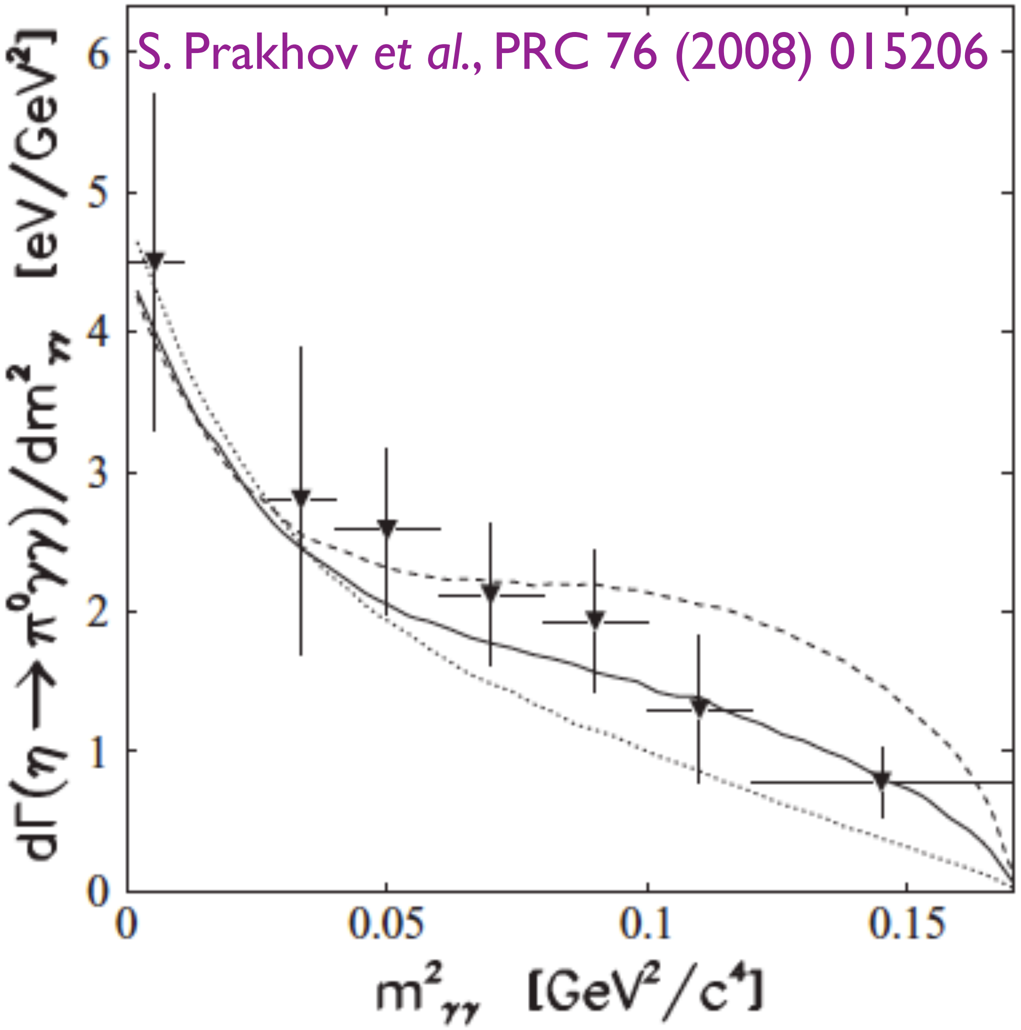
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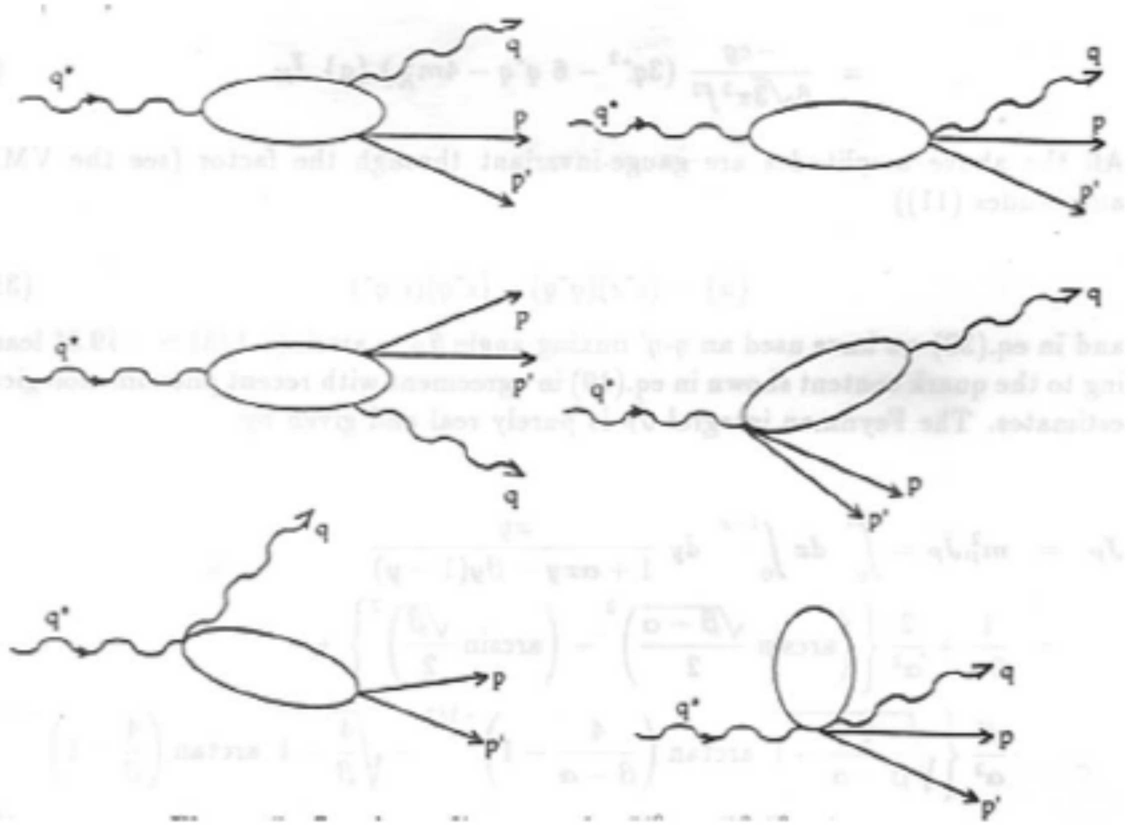
✦ $\eta'\rightarrow\eta\gamma\gamma$

Theory predictions: seminal work

Ll. Ametller, J. Bijnens, A. Bramon and F. Cornet, PLB 276 (1992) 185

Chiral-loop prediction:

- no tree level contributions
- θ_P=arcsin(-1/3)≃-19.5°
- only the η_8 contribution is taken into account



pion loops, isospin breaking contr.

$$a_4^\pi = \frac{-4\sqrt{2}\alpha}{3\sqrt{3}\pi f^2}\Delta m_K^2 \left(1+\frac{3s-m_\eta^2-3m_\pi^2}{m_\eta^2-m_\pi^2}\right) H(s,m_\pi^2)$$

$$a_4^K = \frac{2\sqrt{2}\alpha}{3\sqrt{3}\pi f^2}\left(3s-m_\eta^2-\frac{1}{3}m_\pi^2-\frac{8}{3}m_K^2\right) H(s,m_K^2)$$

kaon loops

$$\Gamma_\pi^{(4)}(\eta\to\pi^0\gamma\gamma) = 0.84\times 10^{-3}\ \mathrm{eV}$$

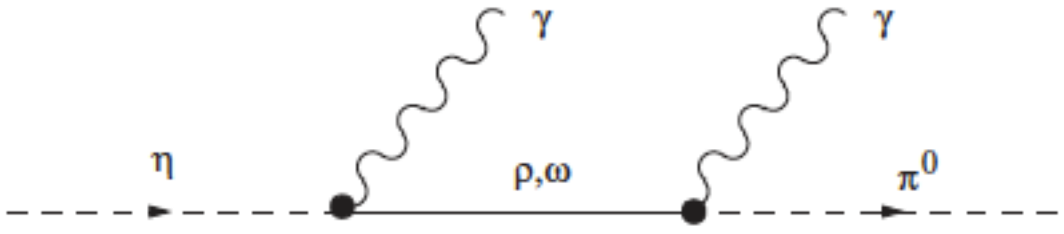
$$\Gamma_K^{(4)}(\eta\to\pi^0\gamma\gamma) = 2.45\times 10^{-3}\ \mathrm{eV}$$

$$\Gamma_{\pi,K}^{(4)}(\eta\to\pi^0\gamma\gamma) = 3.89\times 10^{-3}\ \mathrm{eV}$$

• *Theory predictions: seminal work*

Ll. Ametller, J. Bijnens, A. Bramon and F. Cornet, PLB 276 (1992) 185

Vector meson contributions:



- ✦ equal ρ and ω contributions
- ✦ no vector meson decay widths

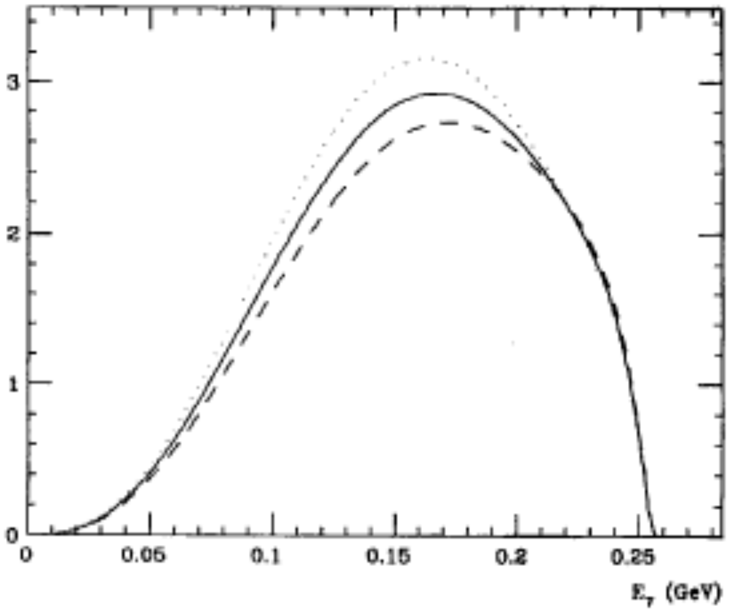
$$M_{VMD} = \frac{2\sqrt{2}}{3\sqrt{3}} g^2_{\omega\pi^0\gamma}\left\{\left[\frac{P\cdot q_2 - m_\eta^2}{M_V^2 - t} + \frac{P\cdot q_1 - m_\eta^2}{M_V^2 - u}\right] A - \left[\frac{1}{M_V^2 - t} + \frac{1}{M_V^2 - u}\right] B\right\}$$

→ $\Gamma_{VMD}(\eta \to \pi^0\gamma\gamma) = 0.31 \text{ eV}$ → $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.42 \text{ eV}$

Scalar meson effects:

$$L_{S\gamma\gamma} = g_S F_{\mu\nu} F^{\mu\nu} tr(Q^2 S) \qquad L_{SPP} = g'_S tr(S\partial_\mu P \partial^\mu P)$$

→ $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.42 \pm 0.20 \text{ eV}$

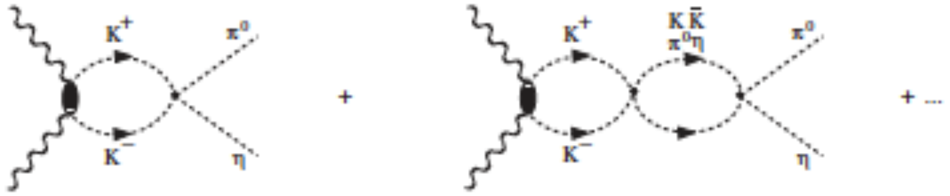


- *Theory predictions: recent analysis*

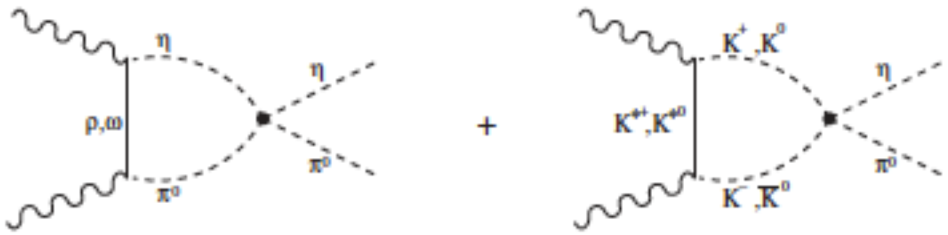
E. Oset, J. R. Peláez and L. Roca, PRD 67 (2003) 073013 and PRD 77 (2008) 073001

Other mechanisms:

- ✦ unitarized chiral loops



- ✦ loops for vector meson contr.



- ✦ diagrams with two anomalous vertices

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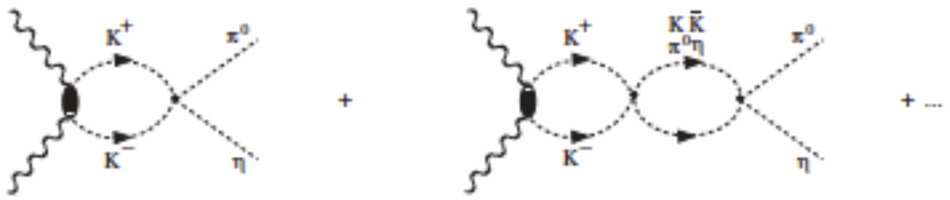
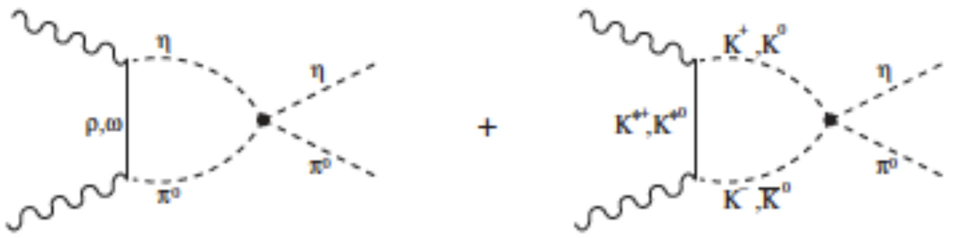


✦ loops for vector meson contr.



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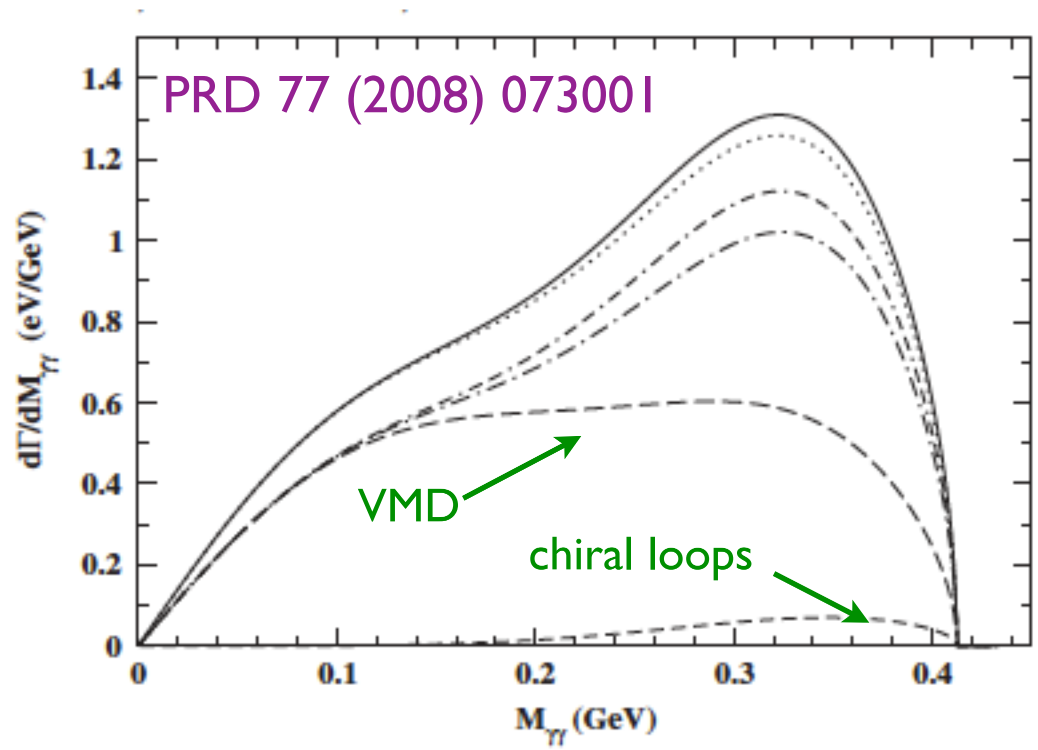


FIG. 6. Contributions to the two-photon invariant mass distribution. From bottom to top, the short-dashed line is for chiral loops, the long-dashed line shows only tree-level VMD, the dashed-dotted line shows the coherent sum of the previous mechanisms, the double dashed-dotted line is the same but with the resummed VMD loops, and the solid line is the same but with the anomalous terms of Fig. 5, which is the full model presented in this work (we are also showing as a dotted line the full model but substituting the full $t_{K^+K^-,\eta\pi^0}$ amplitude by its lowest order).

$$\Gamma = 0.33 \pm 0.08 \text{ eV}$$

- *Our proposal*

To calculate the scalar meson effects within the framework of the LσM

The LσM is a well-defined U(3)xU(3) chiral model which incorporates *ab initio* both the pseudoscalar nonet together with its chiral partner the scalar nonet

The complementarity between ChPT and the LσM will be used for including the scalar meson poles while keeping the correct behaviour at low energies expected from ChPT

✦ $\eta^{(\prime)} \to \pi^0 \gamma\gamma$: $a_0(980)$

✦ $\eta' \to \eta\gamma\gamma$: $\sigma(600)$ & $f_0(980)$

- *Our proposal*

The combination of the LσM together with VMD for the scalar and vector meson contributions, respectively, has been successfully applied to $V \to P^0P^0\gamma$ decays

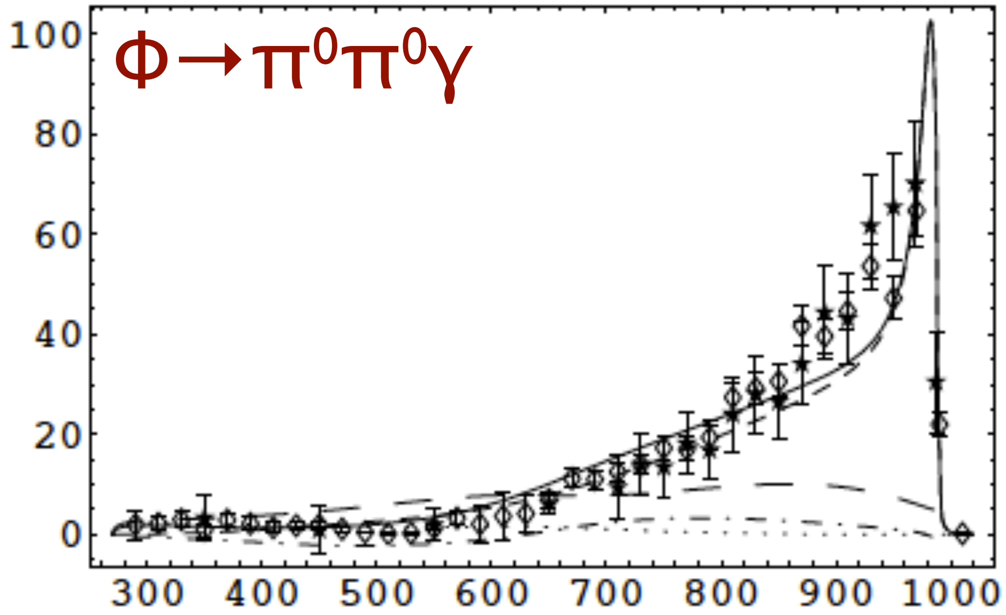


Figure 1: $dB(\phi \to \pi^0\pi^0\gamma)/dm_{\pi^0\pi^0} \times 10^8$ (in MeV^{-1}) *versus* $m_{\pi^0\pi^0}$ (in MeV). The dashed, dotted and dot-dashed lines correspond to the contributions from the LσM, VMD and their interference, respectively. The solid line is the total result. The long-dashed line is the chiral loop prediction. Experimental data are taken from SND (solid star) and KLOE (open diamond).

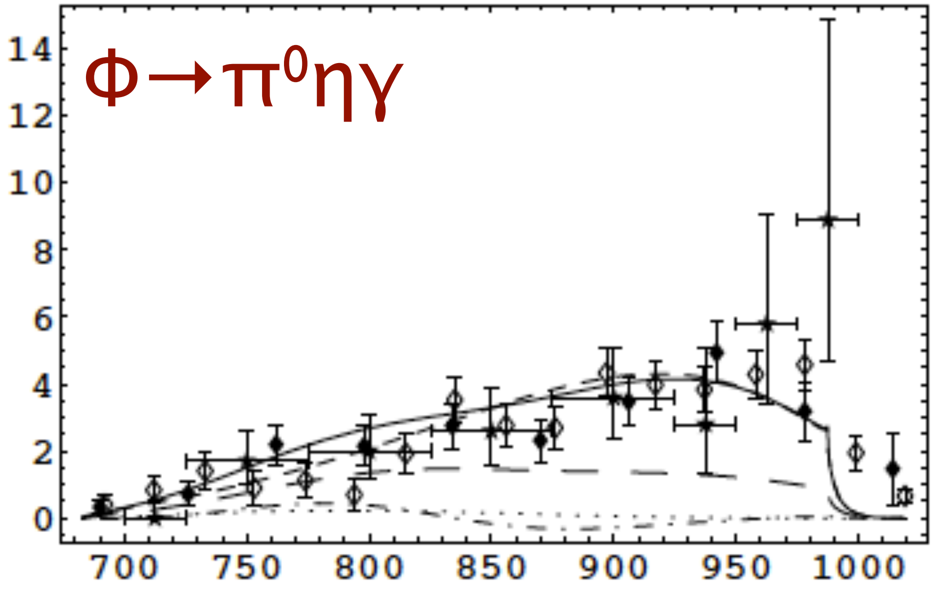


Figure 2: $dB(\phi \to \pi^0\eta\gamma)/dm_{\pi^0\eta} \times 10^7$ (in MeV^{-1}) *versus* $m_{\pi^0\eta}$ (in MeV). Experimental data are taken from SND (solid star) and KLOE: (open diamond) from $\eta \to \gamma\gamma$ and (solid diamond) from $\eta \to \pi^+\pi^-\pi^0$.

R. Escribano, PRD 74 (2006) 114020

• η→π⁰γγ *as a test of our approach*

Chiral-loop prediction:

Lorentz structure Loop function

$$\mathcal{A}^{\chi}_{\eta\to\pi^0\gamma\gamma} = \frac{2\alpha}{\pi} A\, H(s, m_K^2) \times \mathcal{A}^{\chi}_{K^+K^-\to\pi^0\eta}$$

$$\mathcal{A}^{\chi}_{K^+K^-\to\pi^0\eta} = \frac{1}{4F_\pi F_K}\left[\left(s - \frac{m_\eta^2}{3} - \frac{8m_K^2}{9} - \frac{m_\pi^2}{9}\right)(\cos\varphi_P + \sqrt{2}\sin\varphi_P) + \frac{4}{9}(2m_K^2 + m_\pi^2)\left(\cos\varphi_P - \frac{\sin\varphi_P}{\sqrt{2}}\right)\right]$$

octet contribution

singlet contribution

- ✦ $\varphi_P = \theta_P + \arctan\sqrt{2} = (41.4 \pm 0.5)^\circ$ F.Ambrosino *et al.*, JHEP 07 (2009) 105
- ✦ both the η_8 and η_0 contributions are taken into account

➡ $$\Gamma^{\chi}_{\eta\to\pi^0\gamma\gamma} = 1.24 \times 10^{-3}\ \mathrm{eV}$$

➡ a factor of 2 *smaller* than the original chiral loop prediction

• $\eta\to\pi^0\gamma\gamma$ *as a test of our approach*

Scalar meson effects:

+ t and u channels driven by the κ

$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta}=\frac{s-m_\eta^2}{2F_\pi F_K}\frac{m_K^2-m_{a_0}^2}{D_{a_0}(s)}\cos\varphi_P+\left(\mathcal{A}^{\chi}_{K^+K^-\to\pi^0\eta}-\frac{s-m_\eta^2}{2F_\pi F_K}\cos\varphi_P\right)$$

resonant contribution

non-resonant contribution

- ✦ correct low-energy behaviour
- ✦ 2nd term mimics the contribution of the κ driven channels

$$\Gamma^{\mathrm{L}\sigma\mathrm{M}}_{\eta\to\pi^0\gamma\gamma}=4.5\times10^{-4}\ \mathrm{eV}$$

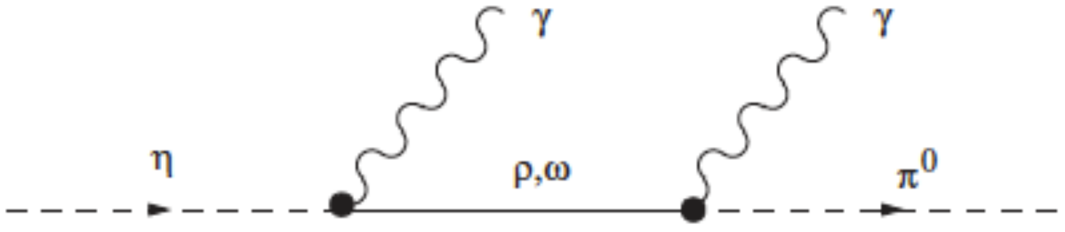
a factor of 3 *smaller* than the chiral loop prediction

• $\eta \to \pi^0 \gamma\gamma$ *as a test of our approach*

Vector meson contributions:

$$\mathcal{L}_{\mathrm{VVP}} = \frac{G}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \partial_\mu V_\nu \partial_\alpha V_\beta P \rangle,$$

$$\mathcal{L}_{\mathrm{V}\gamma} = -4 f^2 e g A_\mu \langle Q V^\mu \rangle,$$

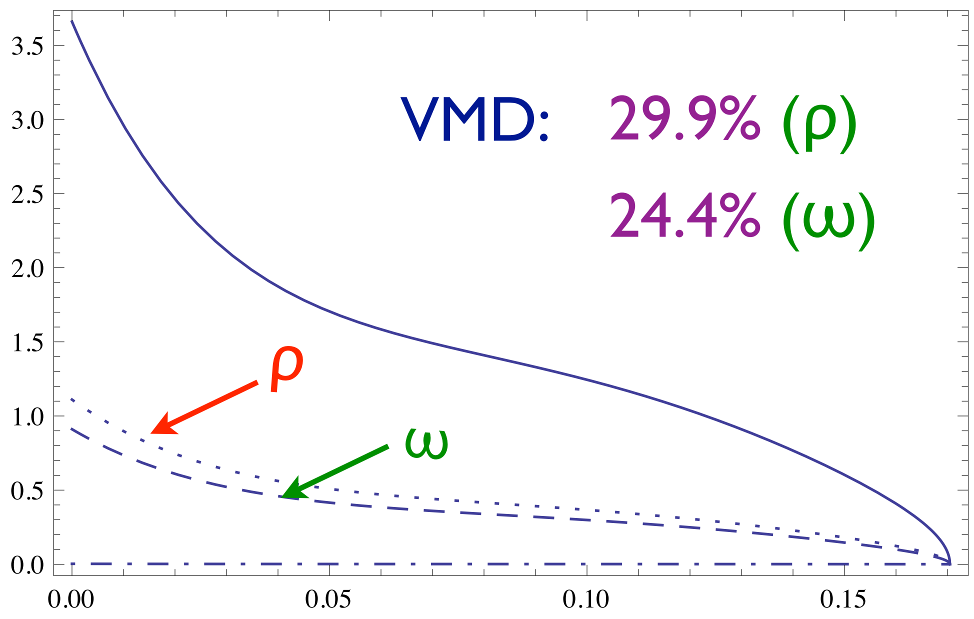


Lorentz str's

⇨ $$\mathcal{A}^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = g_{\rho\eta\gamma} g_{\rho\pi^0\gamma} \left[\left(\frac{P\cdot q_2 - m_\eta^2}{D_\rho(t)} + \frac{P\cdot q_1 - m_\eta^2}{D_\rho(u)} \right) A - \left(\frac{1}{D_\rho(t)} + \frac{1}{D_\rho(u)} \right) B \right] + (\rho \leftrightarrow \omega)$$

$$g_{\rho\eta\gamma} g_{\rho\pi^0\gamma} = g^2_{\omega\pi^0\gamma} \frac{1}{3} \cos\varphi_P \simeq g_{\omega\eta\gamma} g_{\omega\pi^0\gamma}$$

$d\Gamma(\eta \to \pi^0\gamma\gamma)/dm^2_{\gamma\gamma}$ [eV/GeV^2]



VMD: 29.9% (ρ)
24.4% (ω)

✦ different ρ and ω contributions

✦ vector meson decay widths included

⇨ $$\Gamma^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.25 \text{ eV}$$

• η→π⁰γγ *as a test of our approach*

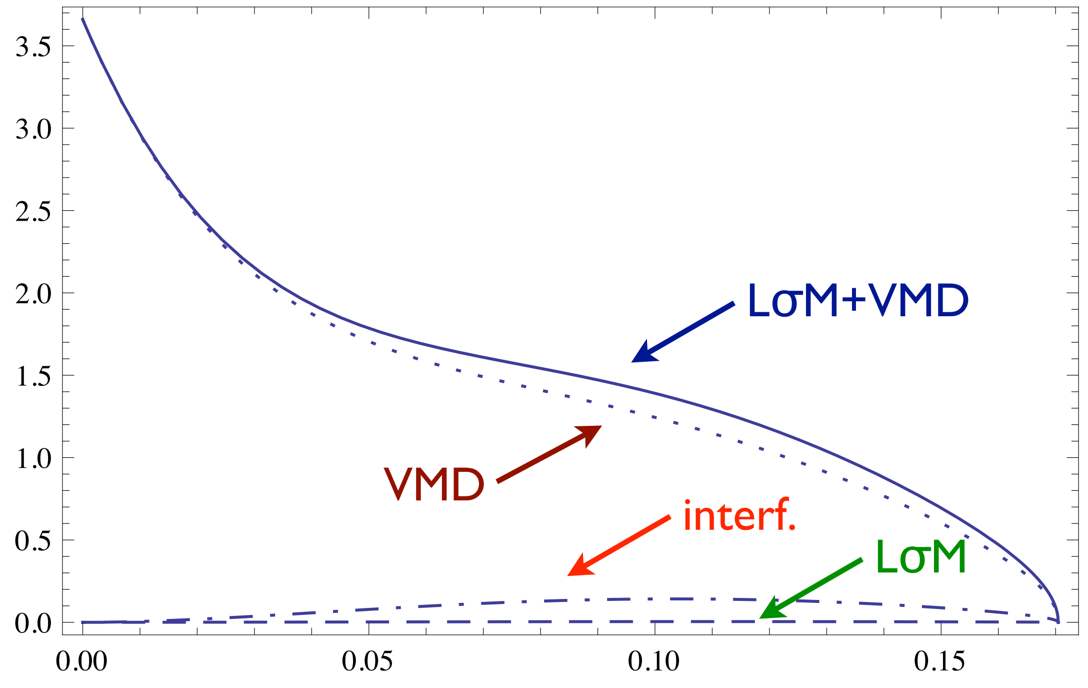
Preliminary results:

$$\Gamma^{\mathrm{L}\sigma\mathrm{M}}_{\eta\to\pi^0\gamma\gamma} = 4.5 \times 10^{-4}\ \mathrm{eV}$$

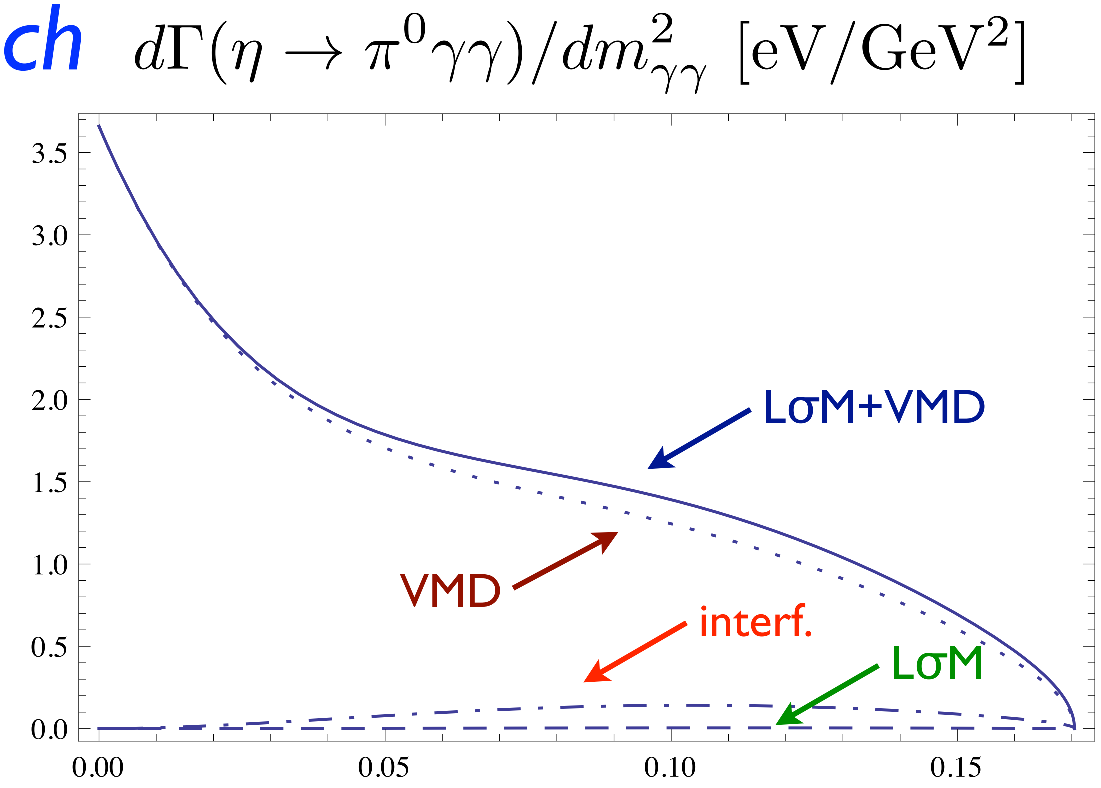
$$\Gamma^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.25\ \mathrm{eV}$$

➡ $$\Gamma^{\mathrm{L}\sigma\mathrm{M+VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.26\ \mathrm{eV}$$

➡ $$B = 2.0 \times 10^{-4}$$



- η→π⁰γγ *as a test of our approach*



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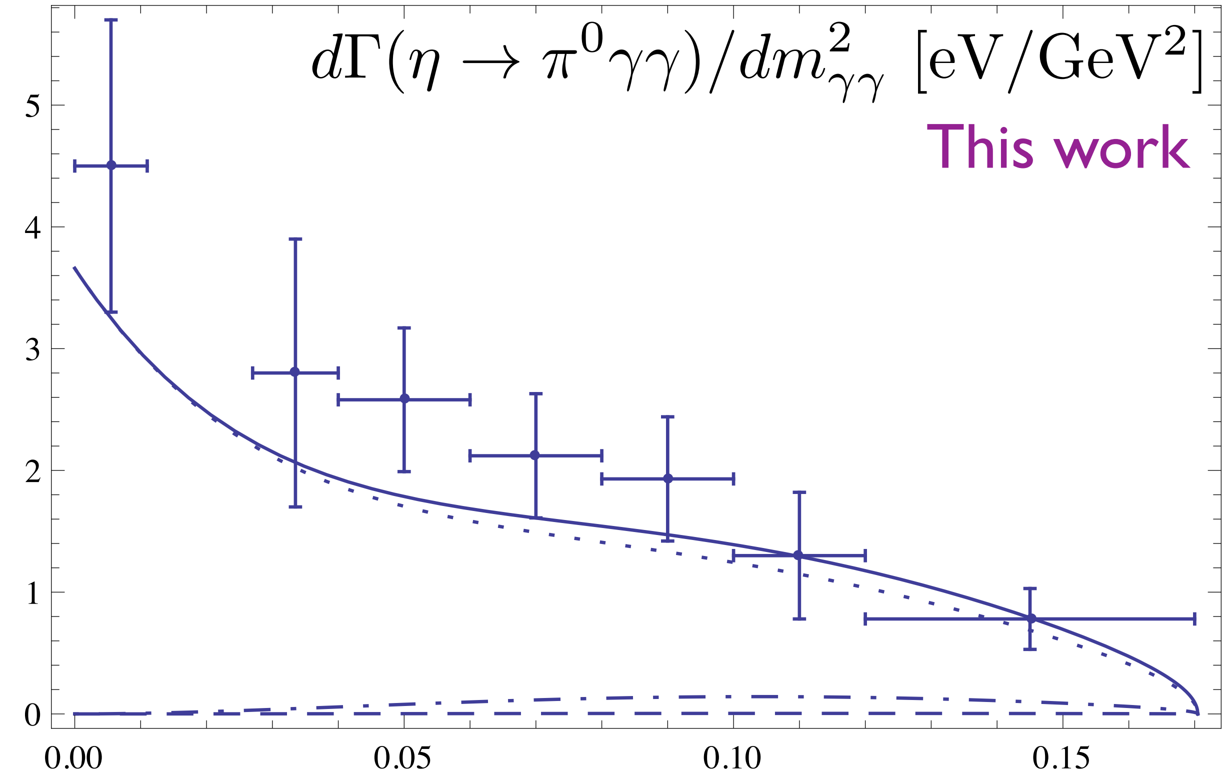
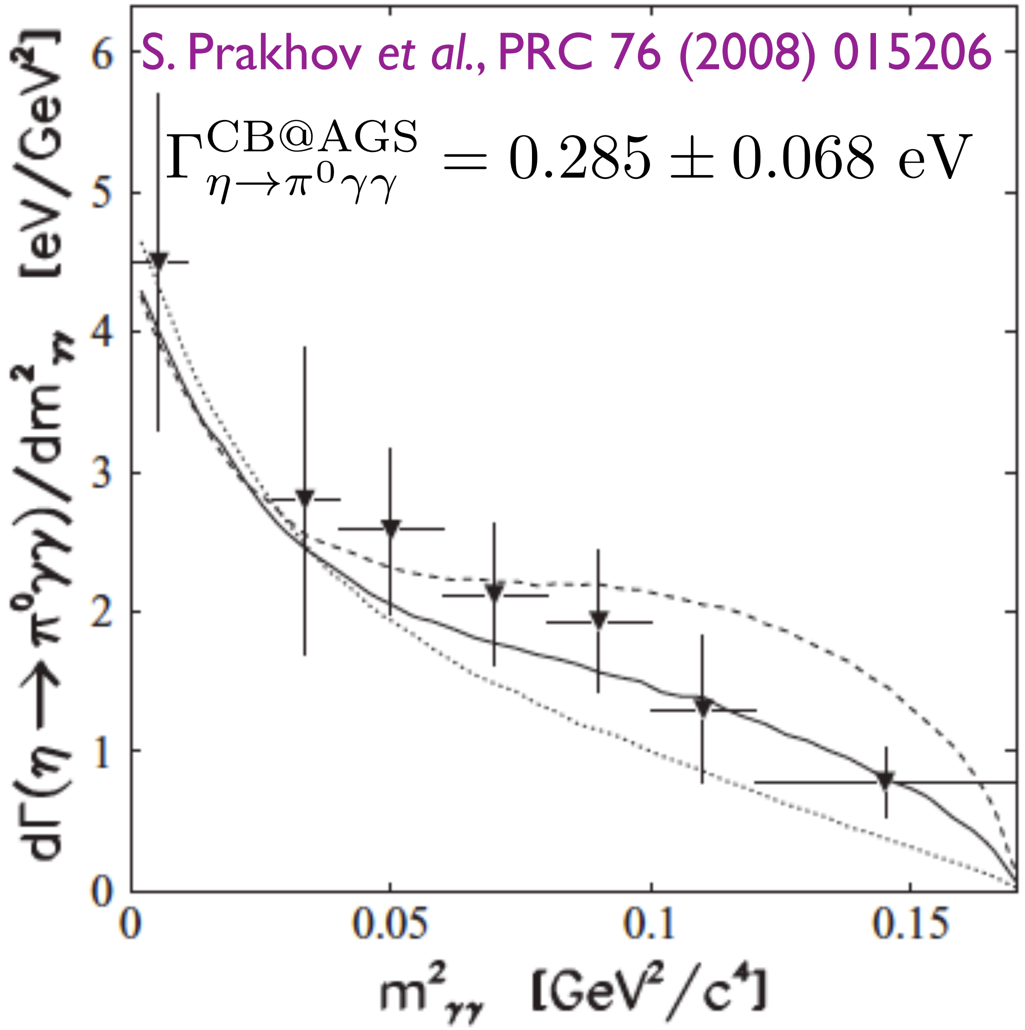



S. Prakhov *et al.*, PRC 76 (2008) 015206

$$\Gamma^{\mathrm{CB@AGS}}_{\eta\to\pi^0\gamma\gamma} = 0.285 \pm 0.068\ \mathrm{eV}$$

- η’→π⁰γγ

Chiral-loop prediction:

$$\mathcal{A}^{\chi}_{K^+K^-\to\pi^0\eta'} = \frac{1}{4F_\pi F_K}\left[\left(s-\frac{m^2_{\eta'}}{3}-\frac{8m^2_K}{9}-\frac{m^2_\pi}{9}\right)(\sin\varphi_P-\sqrt{2}\cos\varphi_P)\right.$$
$$\left.+\frac{4}{9}(2m^2_K+m^2_\pi)\left(\sin\varphi_P+\frac{\cos\varphi_P}{\sqrt{2}}\right)\right]$$

Scalar meson effects:

$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta'} = \frac{s-m^2_{\eta'}}{2F_\pi F_K}\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\sin\varphi_P+\mathcal{A}^{\chi}_{K^+K^-\to\pi^0\eta'}-\frac{s-m^2_{\eta'}}{2F_\pi F_K}\sin\varphi_P$$

Vector meson contributions:

$$\mathcal{A}^{\mathrm{VMD}}_{\eta'\to\pi^0\gamma\gamma} = g_{\rho\eta'\gamma}g_{\rho\pi^0\gamma}\left[\left(\frac{P\cdot q_2-m^2_{\eta'}}{D_\rho(t)}+\frac{P\cdot q_1-m^2_{\eta'}}{D_\rho(u)}\right)A-\left(\frac{1}{D_\rho(t)}+\frac{1}{D_\rho(u)}\right)B\right]+(\rho\leftrightarrow\omega)$$

$$g_{\rho\eta'\gamma}g_{\rho\pi^0\gamma} = g^2_{\omega\pi^0\gamma}\frac{1}{3}\sin\varphi_P \simeq g_{\omega\eta'\gamma}g_{\omega\pi^0\gamma}$$

- # $\eta' \to \pi^0\gamma\gamma$

Preliminary results:

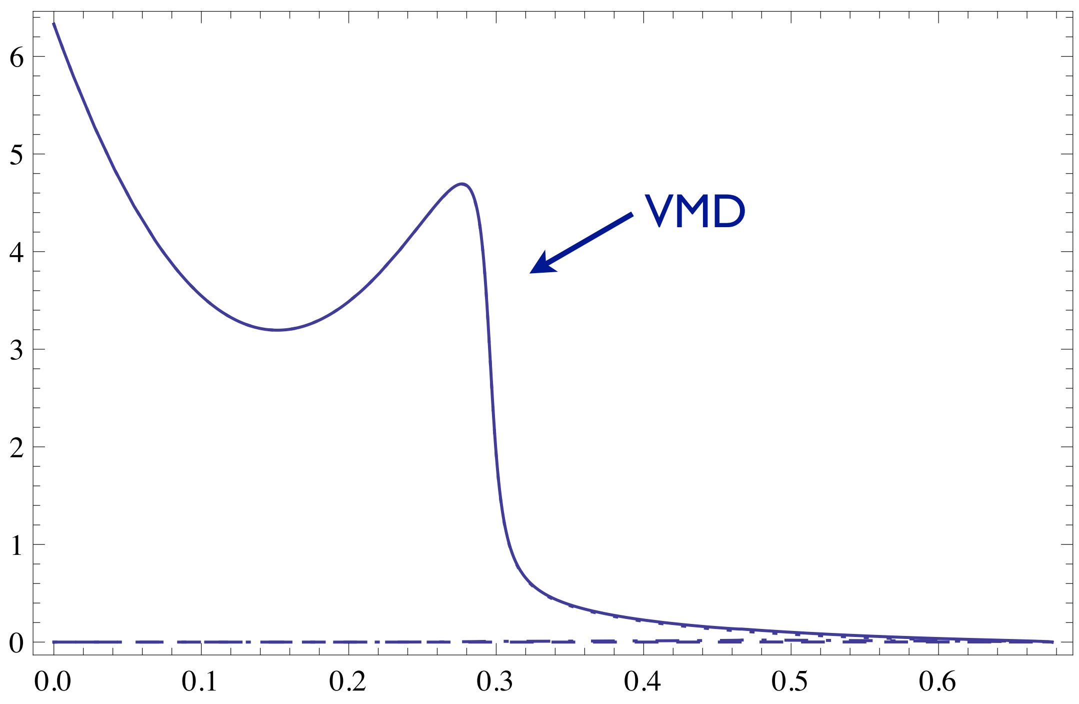
$$\Gamma^{\chi}_{\eta\prime\to\pi^0\gamma\gamma} = 7.7\times 10^{-5}\ \mathrm{keV}$$

$$\Gamma^{\mathrm{L}\sigma\mathrm{M}}_{\eta\prime\to\pi^0\gamma\gamma} = 2.7\times 10^{-4}\ \mathrm{keV}$$

a factor of 3 *bigger* than the chiral loop pred.

$$\Gamma^{\mathrm{VMD}}_{\eta\prime\to\pi^0\gamma\gamma} = 1.28\ \mathrm{keV}$$

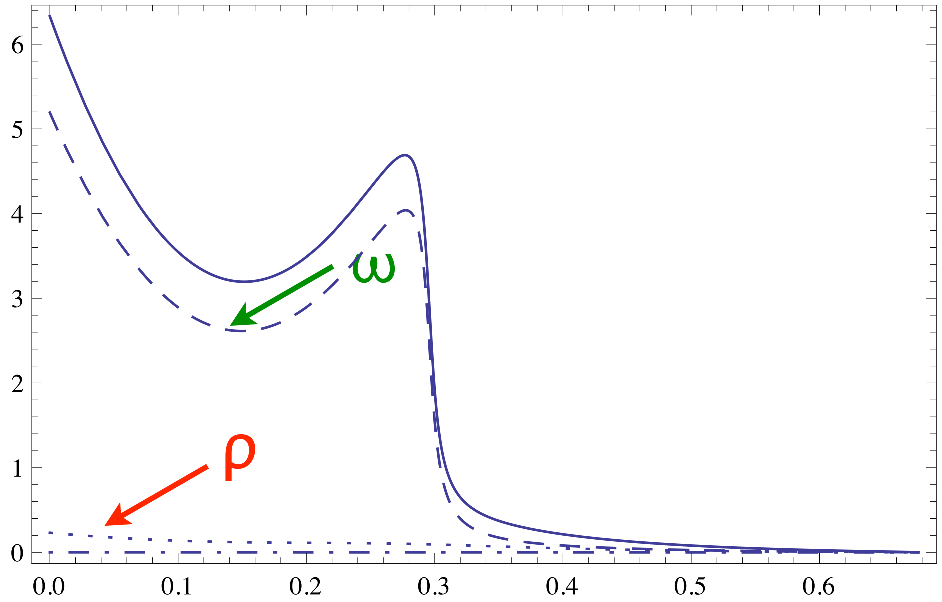
$d\Gamma(\eta\prime\to\pi^0\gamma\gamma)/dm^2_{\gamma\gamma}\ [\mathrm{keV/GeV^2}]$



$$\Gamma^{\mathrm{L}\sigma\mathrm{M+VMD}}_{\eta\prime\to\pi^0\gamma\gamma} = 1.28\ \mathrm{keV}$$

$$B = 6.4\times 10^{-3}$$

GAMS-2000: BR<8 10^{-4} CL=90%



VMD: 4.1% (ρ)

81.2% (ω)

- η’→ ηγγ

Chiral-loop prediction:

kaon loops

$$\mathcal{A}^{\chi}_{K^+K^-\to\eta\eta'} = \frac{1}{4F_\pi^2}\frac{3}{2}\left[\left(s-\frac{m_\eta^2+m_{\eta'}^2}{3}-\frac{8m_K^2}{9}-\frac{2m_\pi^2}{9}\right)\sin(2\theta_P)-4\sqrt{2}\,\frac{4}{9}(2m_K^2-m_\pi^2)\cos(2\theta_P)\right]$$

pion loops

$$\mathcal{A}^{\chi}_{\pi^+\pi^-\to\eta\eta'} = \frac{m_\pi^2}{6F_\pi^2}\left[2\sqrt{2}\cos(2\theta_P)-\sin\cos(2\theta_P)\right]$$

Scalar meson effects:

resonant σ and f_0 contributions in the s-channel

Vector meson contributions:

$$\mathcal{A}^{\mathrm{VMD}}_{\eta'\to\eta\gamma\gamma} = g_{\rho\eta'\gamma}g_{\rho\eta\gamma}\left[\left(\frac{P\cdot q_2-m_{\eta'}^2}{D_\rho(t)}+\frac{P\cdot q_1-m_{\eta'}^2}{D_\rho(u)}\right)A-\left(\frac{1}{D_\rho(t)}+\frac{1}{D_\rho(u)}\right)B\right]+(\rho\leftrightarrow\omega)+(\rho\leftrightarrow\phi)$$

$$g_{\rho\eta'\gamma}g_{\rho\eta\gamma} = g_{\omega\eta'\gamma}g_{\omega\eta\gamma} = -\frac{1}{4}g_{\phi\eta'\gamma}g_{\phi\eta\gamma} = g^2_{\omega\pi^0\gamma}\frac{1}{9}\cos\varphi_P\sin\varphi_P$$

- $\eta' \to \eta\gamma\gamma$

Preliminary results:

$$\Gamma^{\chi}_{\eta\prime\to\eta\gamma\gamma} = 1.4 \times 10^{-2}\ \mathrm{eV}$$

$$\Gamma^{\mathrm{L}\sigma\mathrm{M}}_{\eta\prime\to\eta\gamma\gamma} = 2.7 \times 10^{-2}\ \mathrm{eV}$$

$$\Gamma^{\mathrm{VMD}}_{\eta\prime\to\eta\gamma\gamma} = 49.8\ \mathrm{eV}$$

→ $\Gamma^{\mathrm{L}\sigma\mathrm{M+VMD}}_{\eta\prime\to\eta\gamma\gamma} = 48.3\ \mathrm{eV}$ → $B = 2.4 \times 10^{-4}$

- *Summary and Conclusions*

We have calculated for the first time the electromagnetic rare decays $\eta' \rightarrow \pi^0\gamma\gamma$ and $\eta' \rightarrow \eta\gamma\gamma$

The LσM and VMD have been used to obtain the corresponding scalar and vector meson contributions

Our preliminary results seem to indicate that scalar meson effects are negligible in both decays

In any case, invariant mass spectra and decay widths have been given for the sake of comparison