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
(not a detailed calculation but rather an estimate)
of the electromagnetic rare decays
$\eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$

Motivations:

- To complete the existing predictions for $\eta \to \pi^0\gamma\gamma$ in view of the ongoing and forthcoming experiments @ MAMI, WASA, KLOE2 and BES-III

- To extract, if possible, some relevant information on the lowest-lying scalar mesons, thus complementing other analyses based on $V \to P^0P^0\gamma$ decays, D and J/ψ decays, central production...

Outline:

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

In collab. with Renata Jora (NIPNE, Bucharest)

- *Experimental data*

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

    GAMS-2000: Γ=0.84±0.18 eV

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

    CB@AGS: Γ=0.45±0.12 eV

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

    CB@AGS: Γ=0.285±0.031±0.049 eV

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

    KLOE@DAPHNE: Γ=0.109±0.035±0.018 eV

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

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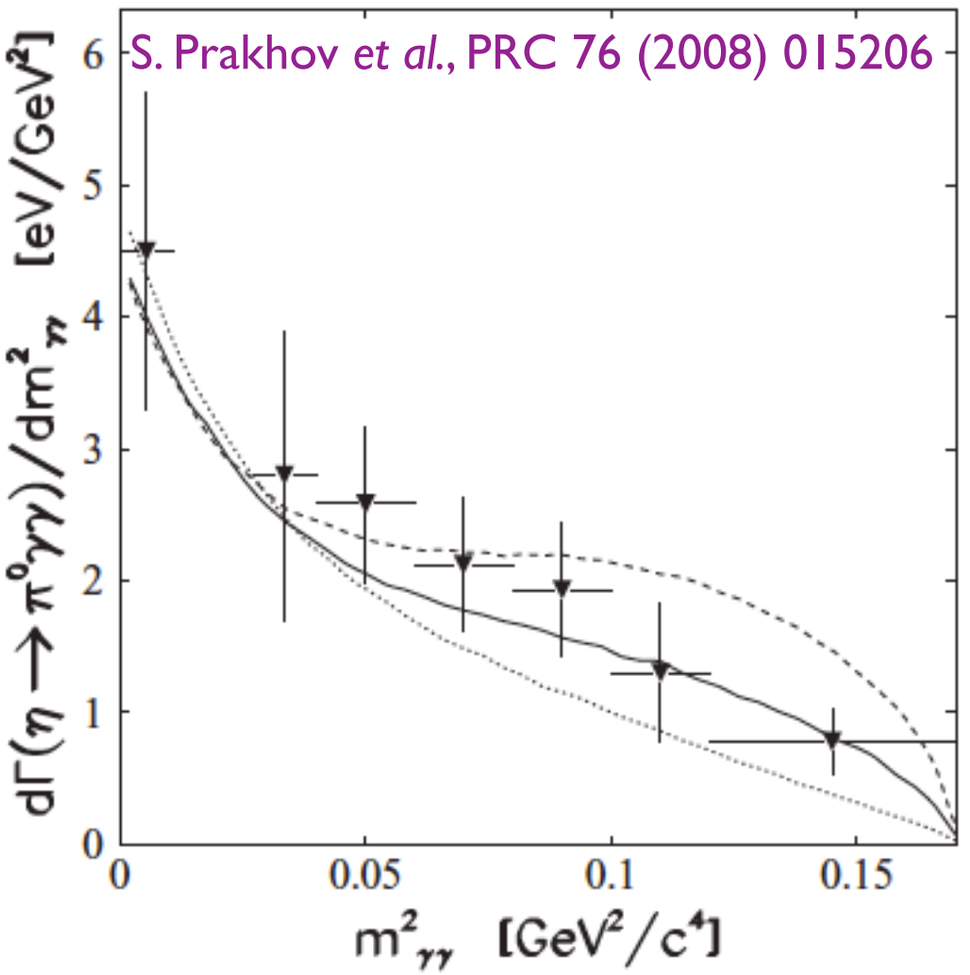

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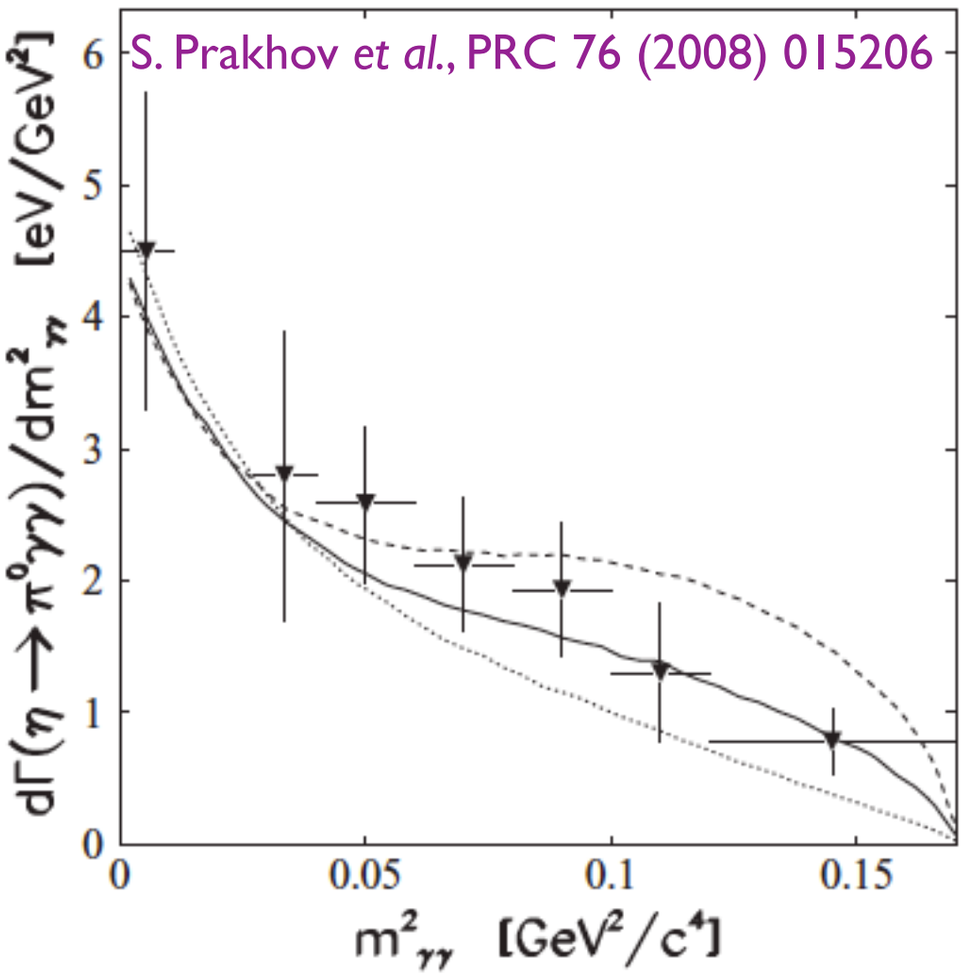

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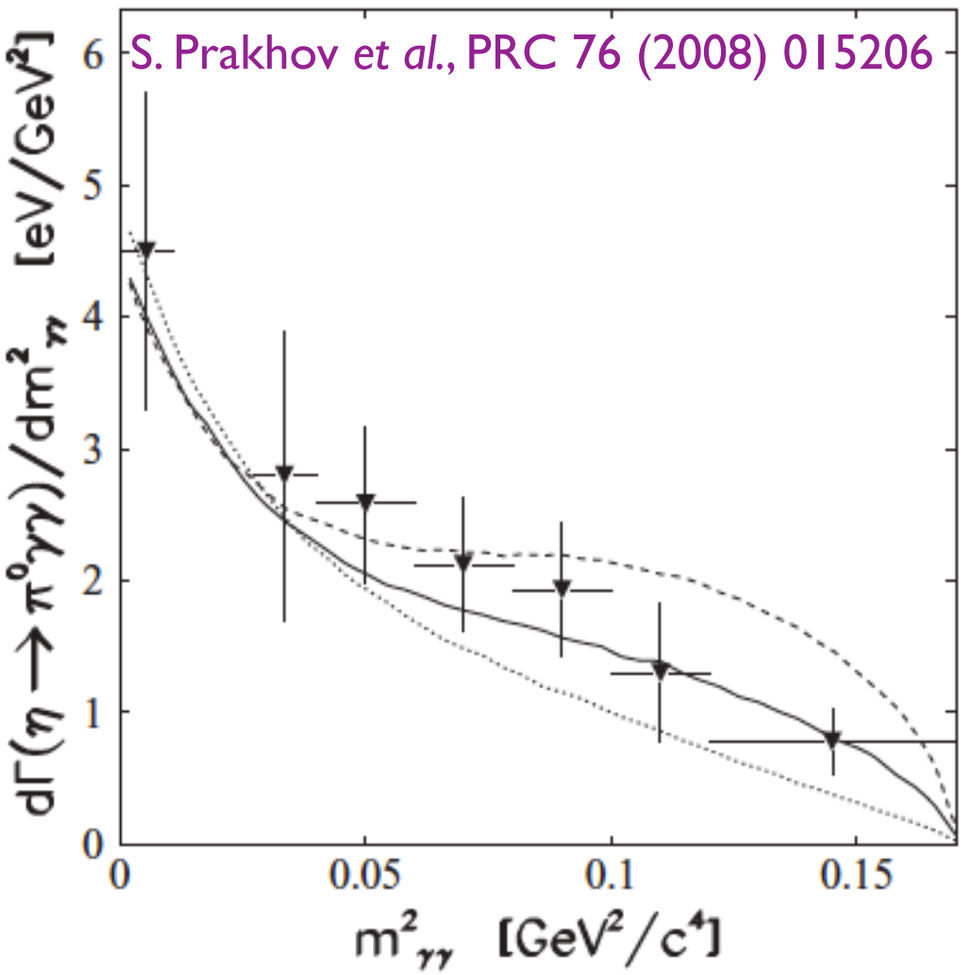

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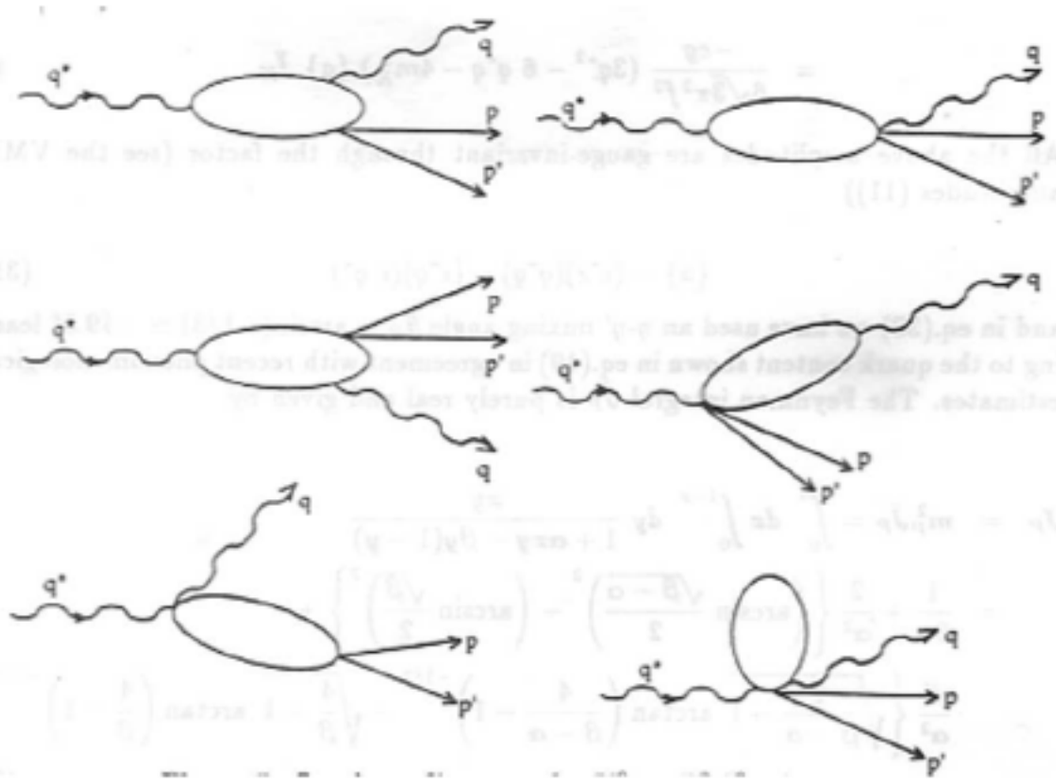
- *Theory predictions: seminal work*

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

Chiral-loop prediction:

- ✦ no tree level contributions at $O(p^2)$ and $O(p^4)$ → finite one-loop calculation
- ✦ only the η_8 contribution is taken into account
- ✦ $\theta_P = \arcsin(-1/3) \simeq -19.5°$



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

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

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

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

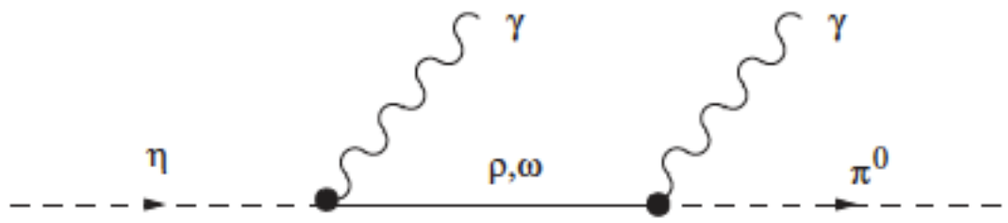
- *Theory predictions: seminal work*

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

- ✦ tree level contributions at $O(p^6)$, saturated by resonances, but not enough...
- ✦ loop contributions at $O(p^8)$ from anomalous vertices, again very small

Vector meson contributions:

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



$$L_{VP\gamma} = \frac{1}{2} g_{\omega\pi^0\gamma} \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu}\ tr[Q(V_\alpha \partial_\beta P + \partial_\beta P V_\alpha)] \quad \text{VMD}$$

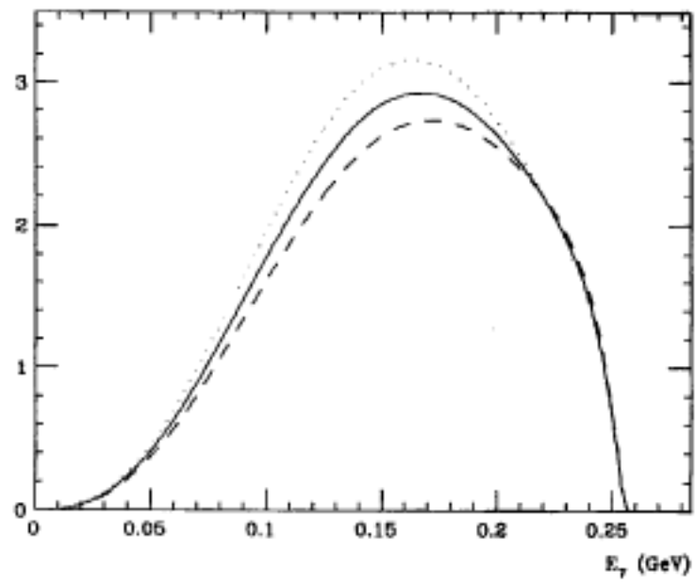
$$\Gamma_{VMD}(\eta \to \pi^0\gamma\gamma) = 0.31 \text{ eV} \quad \Rightarrow \quad \Gamma(\eta \to \pi^0\gamma\gamma) = 0.42 \text{ eV}$$

Scalar meson effects:

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

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

sign of the interference not fixed

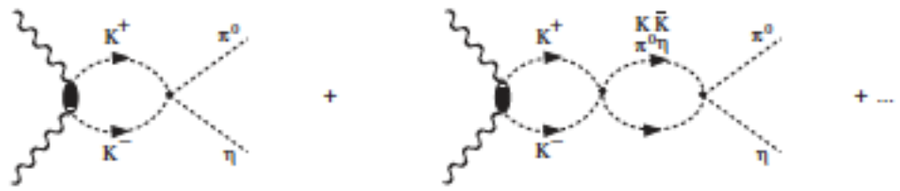


- *Theory predictions: recent analysis*

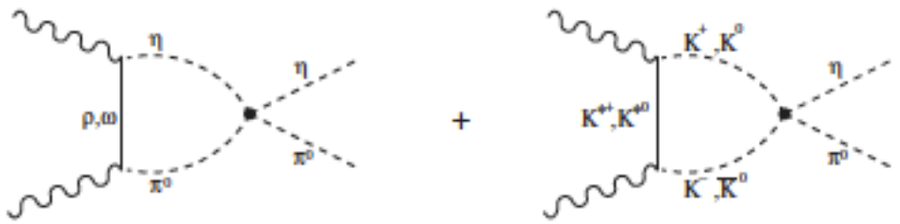
E. Oset, J. R. Peláez and L. Roca, PRD 67 (2003) 073013 and PRD 77 (2008) 073001

Other mechanisms:

✦ unitarized chiral loops



✦ loops for vector meson contr.



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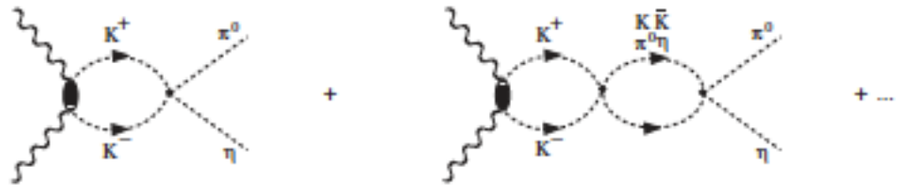

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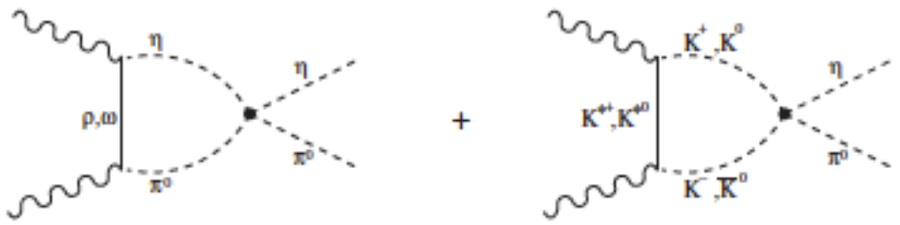


✦ ...

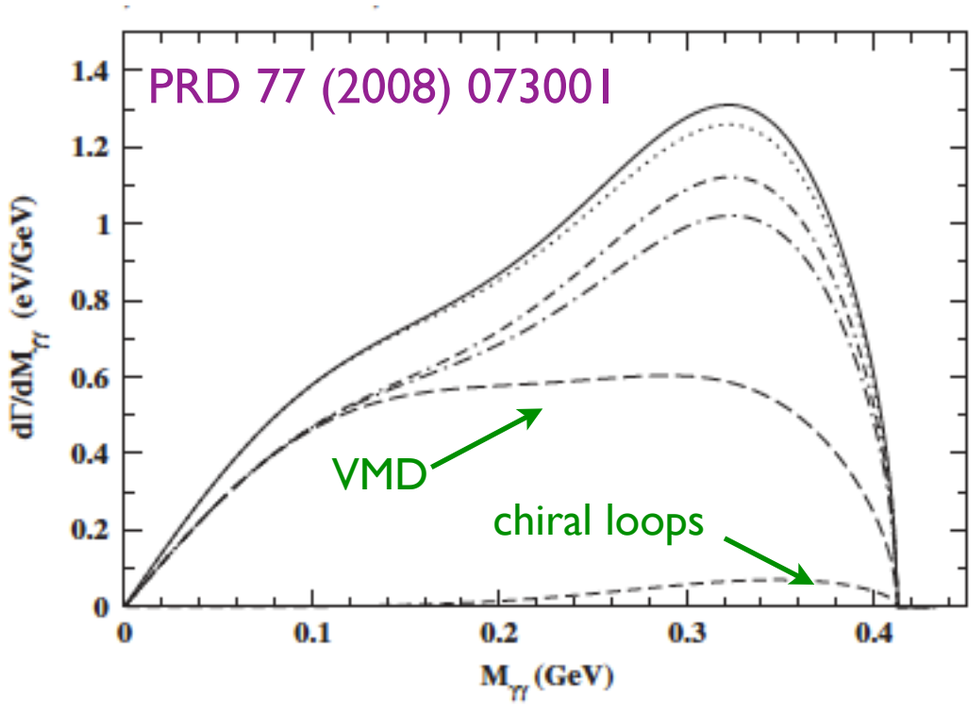


FIG. 6. Contributions to the two-photon invariant mass distribution. From bottom to top, the short-dashed line is for chiral loops, the long-dashed line shows only tree-level VMD, the dashed-dotted line shows the coherent sum of the previous mechanisms, the double dashed-dotted line is the same but with 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

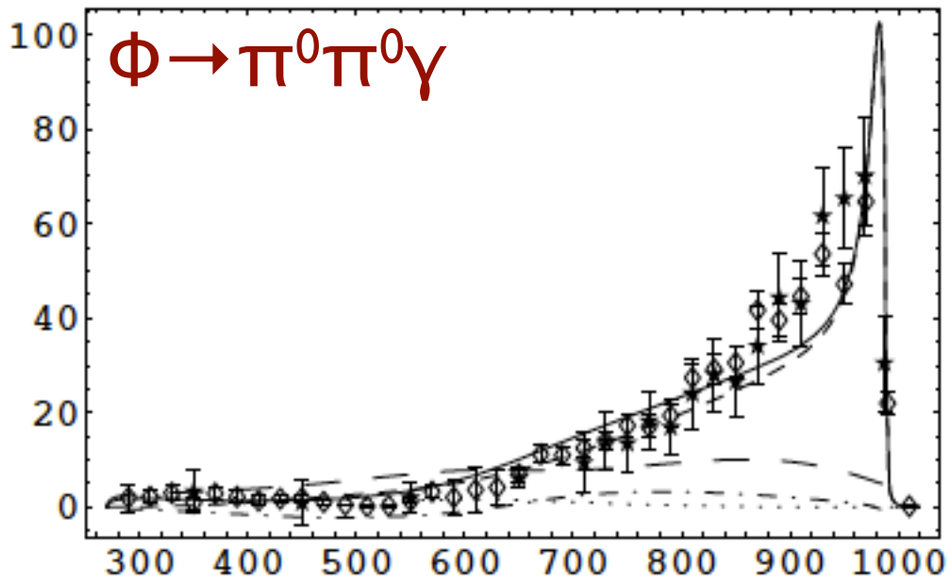


Figure 1: $dB(\phi \to \pi^0\pi^0\gamma)/dm_{\pi^0\pi^0} \times 10^8$ (in MeV^{-1}) *versus* $m_{\pi^0\pi^0}$ (in MeV). The dashed, dotted and dot-dashed lines correspond to the contributions from the LσM, VMD and their interference, respectively. The solid line is the total result. The long-dashed line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

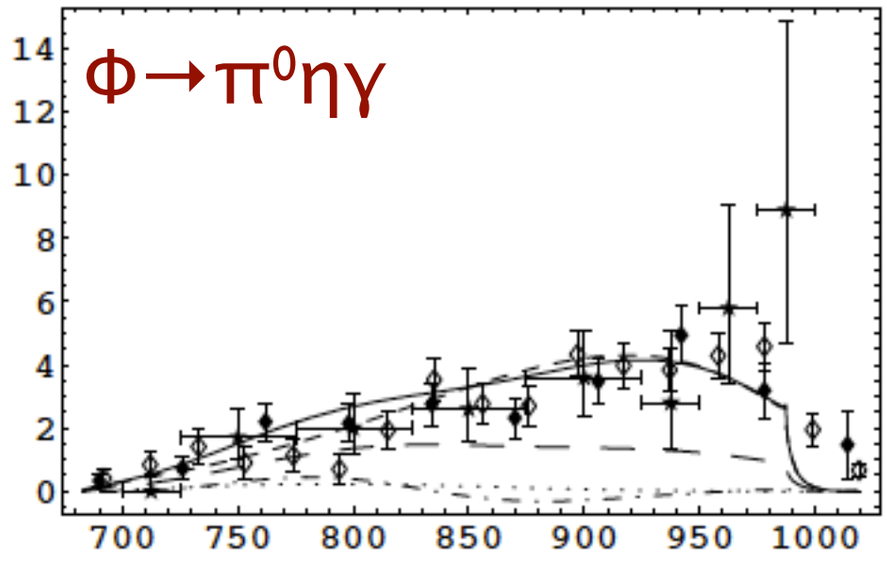


Figure 2: $dB(\phi \to \pi^0\eta\gamma)/dm_{\pi^0\eta} \times 10^7$ (in MeV^{-1}) *versus* $m_{\pi^0\eta}$ (in MeV). Experimental data are taken from SND (solid star) and KLOE: (open diamond) from $\eta \to \gamma\gamma$ and (solid diamond) from $\eta \to \pi^+\pi^-\pi^0$.

R. Escribano, PRD 74 (2006) 114020

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

Chiral-loop prediction:

4-pseudoscalar amplitude (not a scattering amplitude)

Lorentz structure

Loop function

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

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

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

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

→ 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

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

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

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

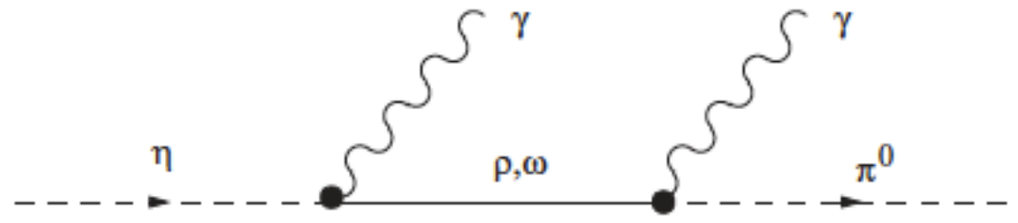
→ a factor of 3 *smaller* than the chiral loop prediction

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

Vector meson contributions:

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

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



Lorentz str's

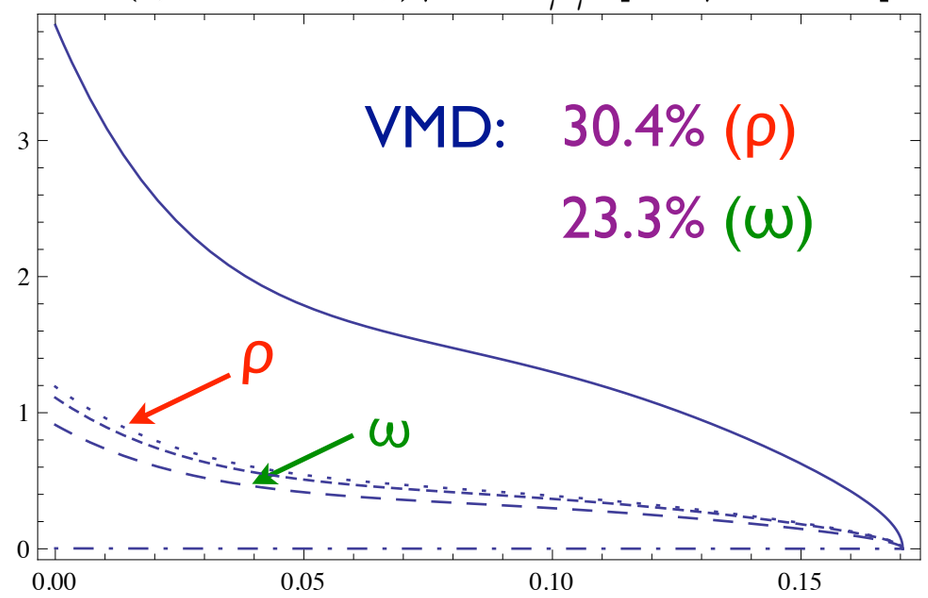
$$\mathcal{A}^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = g_{\rho\eta\gamma}g_{\rho\pi^0\gamma}\left[\left(\frac{P\cdot q_2 - m_\eta^2}{D_\rho(t)} + \frac{P\cdot q_1 - m_\eta^2}{D_\rho(u)}\right)A - \left(\frac{1}{D_\rho(t)} + \frac{1}{D_\rho(u)}\right)B\right] + (\rho \leftrightarrow \omega)$$

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

- ✦ different ρ and ω contributions
- ✦ vector meson decay widths included

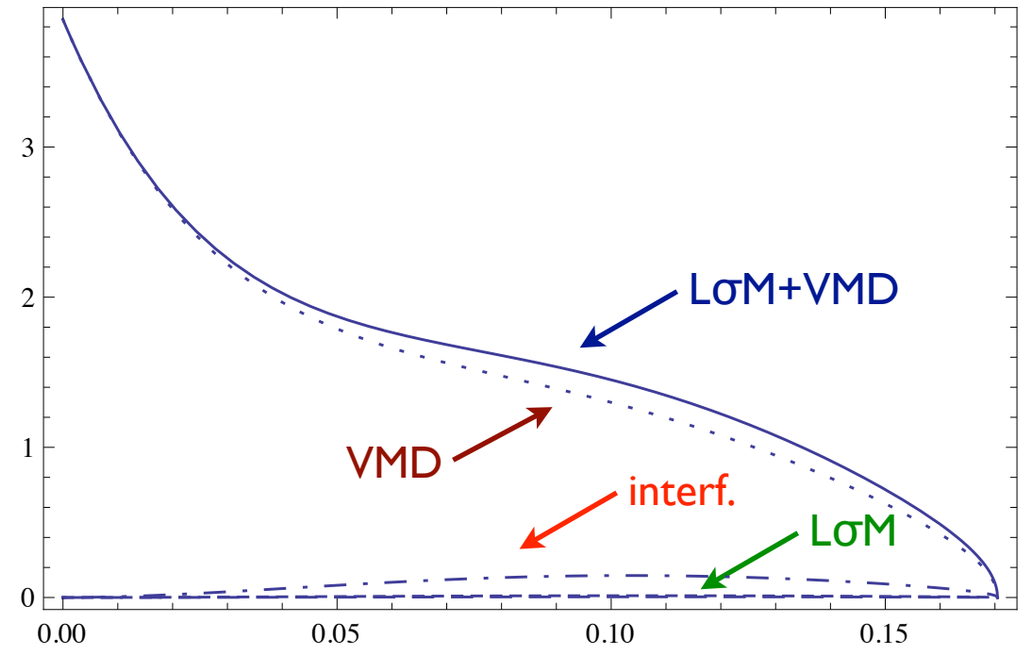
$$\Gamma^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.26\ \mathrm{eV}$$

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



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

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



Preliminary results:

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

$$\Gamma^{\mathrm{VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.26\ \mathrm{eV}$$

$$\Gamma^{\mathrm{L}\sigma\mathrm{M+VMD}}_{\eta\to\pi^0\gamma\gamma} = 0.28\ \mathrm{eV}$$

$$B = 2.1 \times 10^{-4}$$

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

Preliminary results:

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

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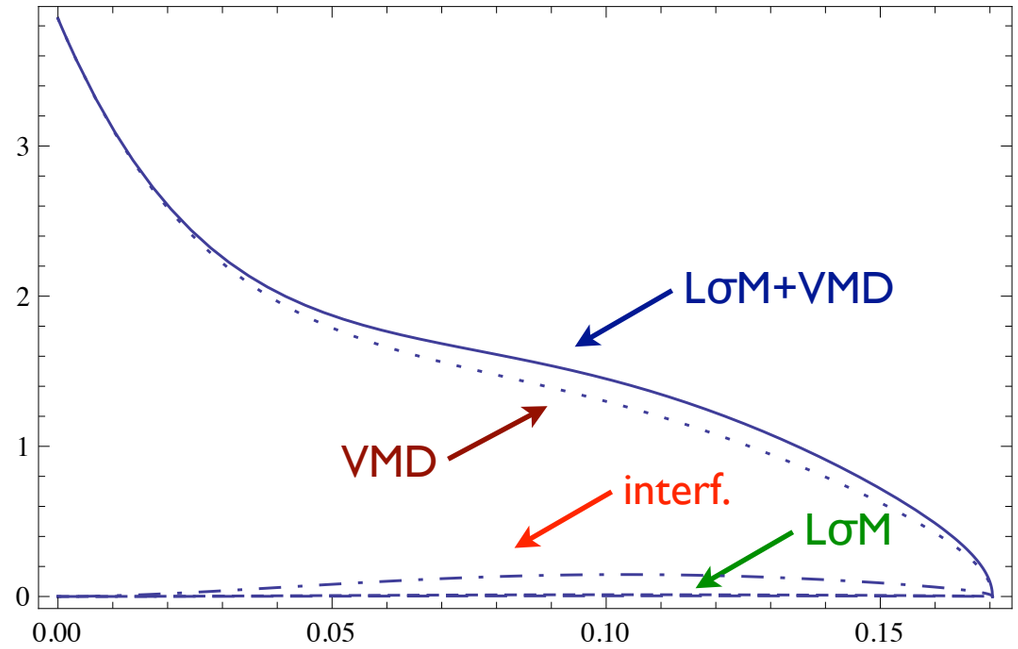
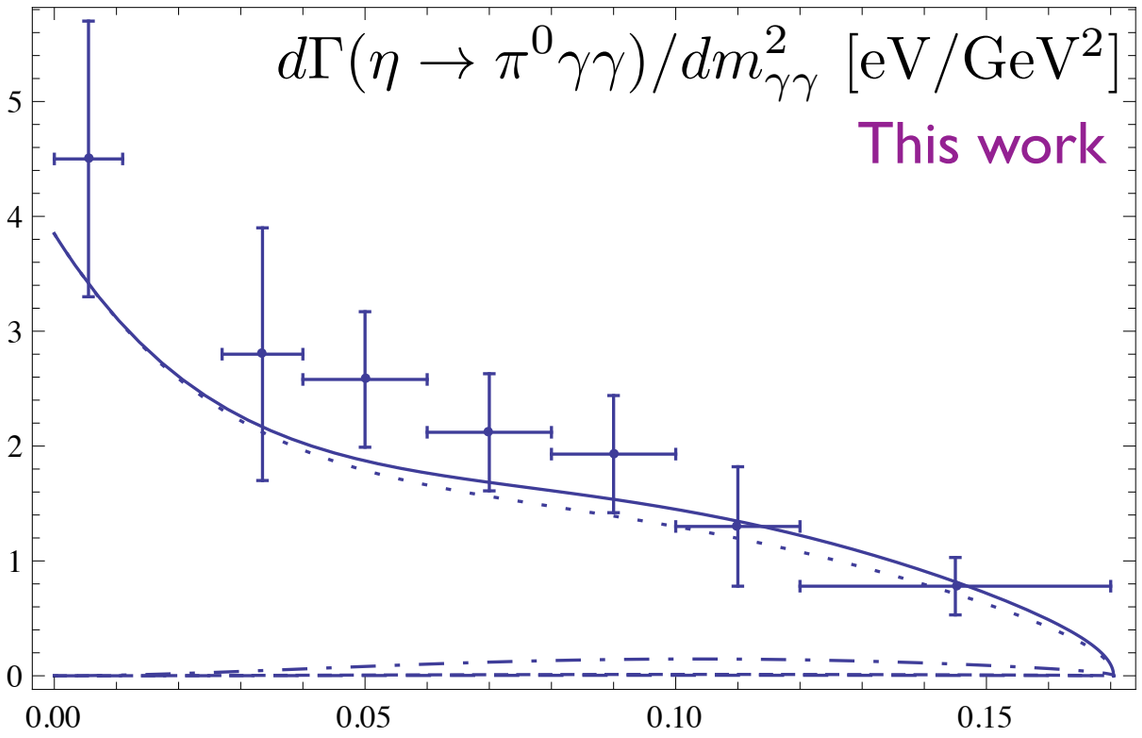
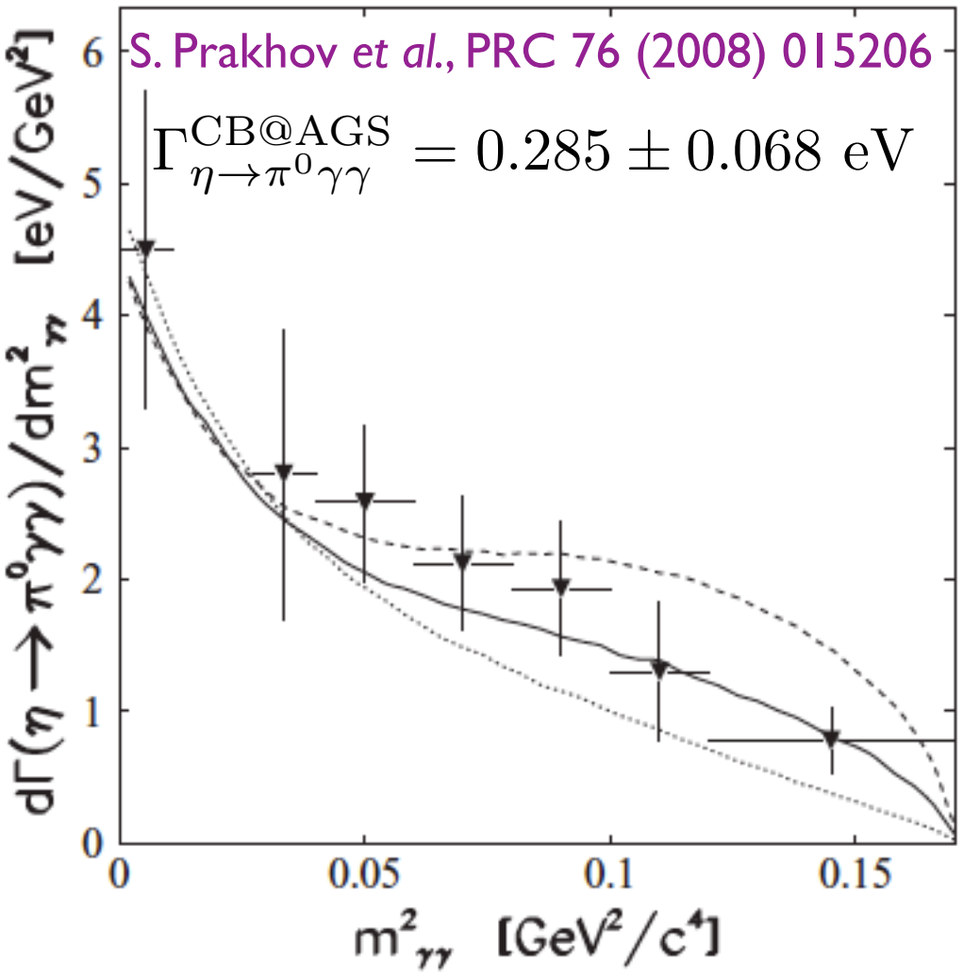






- $\eta' \to \pi^0\gamma\gamma$

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:

$$\Gamma^{\chi}_{\eta\prime\to\pi^0\gamma\gamma} = 7.7\times10^{-5}\ \text{keV}$$

$$\Gamma^{\mathrm{L}\sigma\mathrm{M}}_{\eta\prime\to\pi^0\gamma\gamma} = 1.3\times10^{-4}\ \text{keV}$$

a factor of 2 *bigger* than the chiral loop pred.

$$\Gamma^{\mathrm{VMD}}_{\eta\prime\to\pi^0\gamma\gamma} = 1.29\ \text{keV}$$

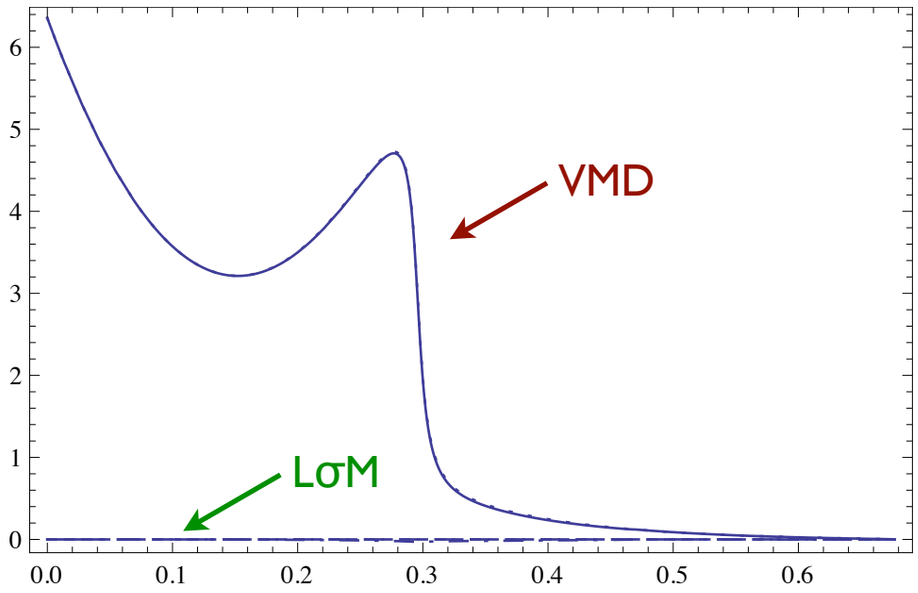
$$\Gamma^{\mathrm{L}\sigma\mathrm{M+VMD}}_{\eta\prime\to\pi^0\gamma\gamma} = 1.29\ \text{keV}$$

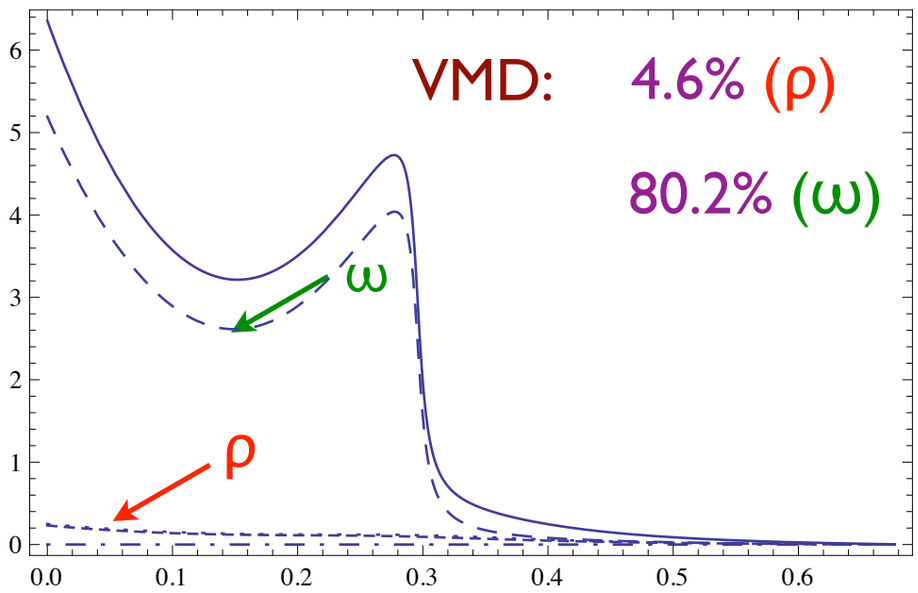
$$B = 6.5\times10^{-3}$$

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

new measurement would be welcome!

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





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

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

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

not suppressed by G-parity → dominant!

Scalar meson effects:

resonant σ and f_0 contributions in the s-channel → important σ effects

Vector meson contributions:

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

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

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

Preliminary results:

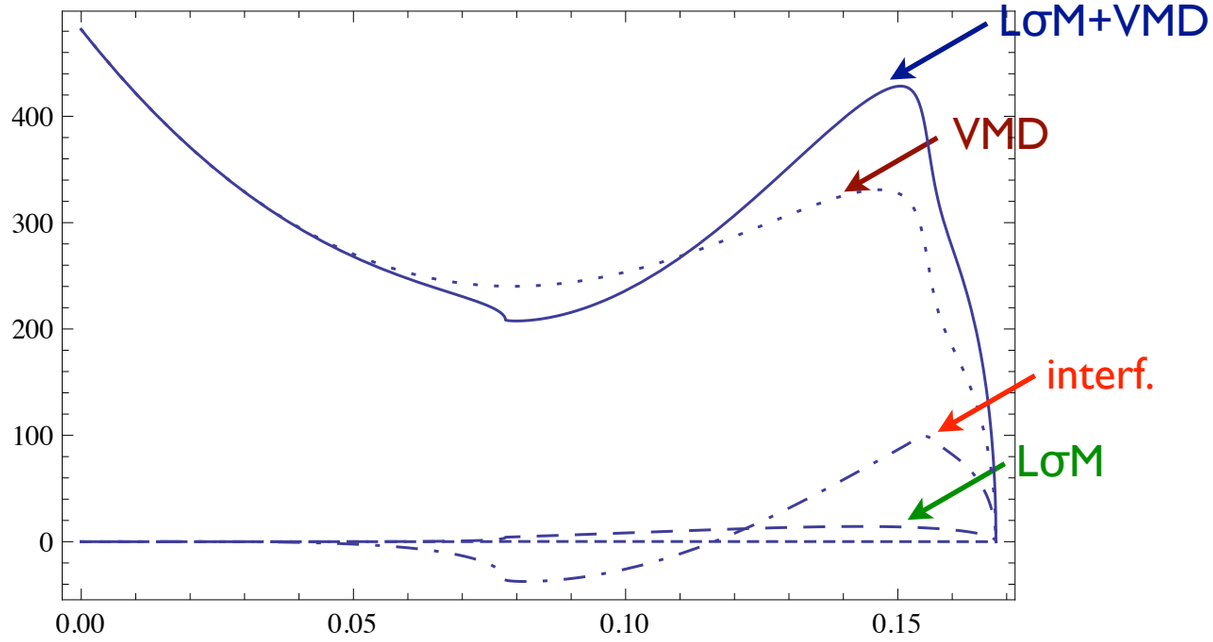
$$\Gamma^{\chi}_{\eta'\to\eta\gamma\gamma} = 1.4\times10^{-2}\ \text{eV}$$

$$\Gamma^{\mathrm{L\sigma M}}_{\eta'\to\eta\gamma\gamma} = 0.96\ \text{eV}$$

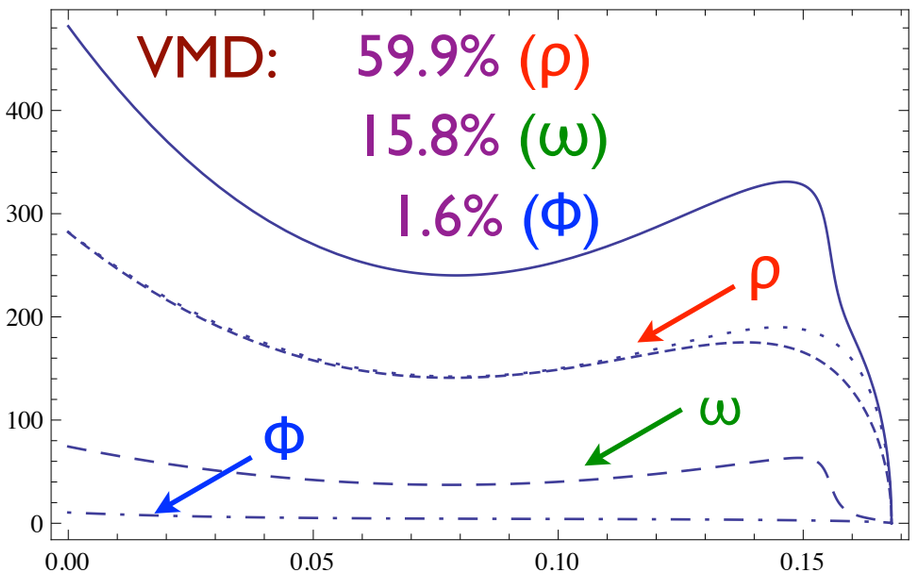
70 times bigger!

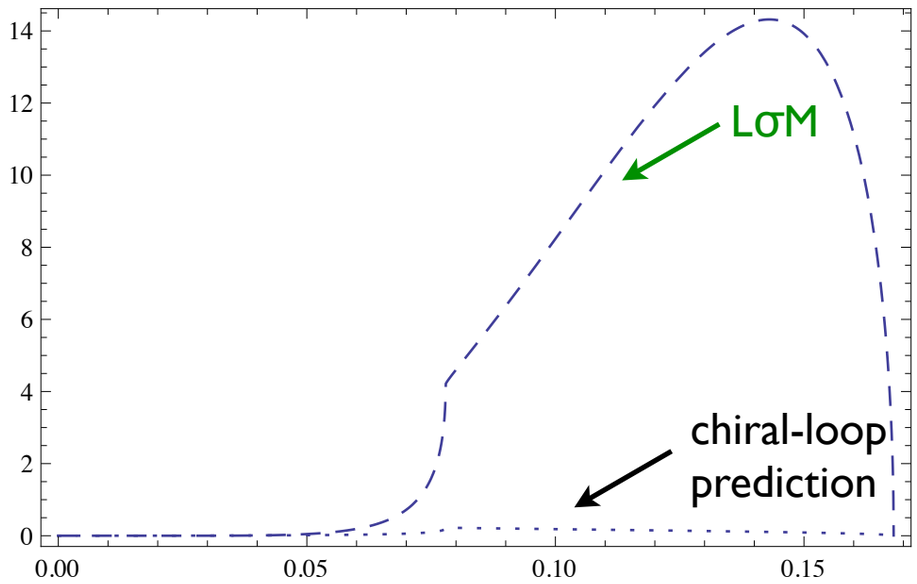
$$\Gamma^{\mathrm{VMD}}_{\eta'\to\eta\gamma\gamma} = 48.8\ \text{eV}$$

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



$$\Gamma^{\mathrm{L\sigma M+VMD}}_{\eta'\to\eta\gamma\gamma} = 51.2\ \text{eV} \quad\Rightarrow\quad B = 2.6\times10^{-4}$$





- *Summary and Conclusions*

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

invariant mass spectra and decay widths have been given for the sake of comparison

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 $\eta' \to \pi^0\gamma\gamma$ but significant in $\eta' \to \eta\gamma\gamma$

	chiral loops	LσM	VMD	Γ	$BR_{th} \times 10^4$	$BR_{exp} \times 10^4$
$\eta \to \pi^0\gamma\gamma$ (eV)	1.24×10^{-3}	4.5×10^{-4}	0.26	0.28	2.1	2.7 ± 0.5
$\eta' \to \pi^0\gamma\gamma$ (keV)	7.7×10^{-5}	1.3×10^{-4}	1.29	1.29	65	<8 (90% CL)
$\eta' \to \eta\gamma\gamma$ (eV)	1.4×10^{-2}	0.96	48.8	51.2	2.6	—