η AND η' DECAYS: A THEORY PERSPECTIVE

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η AND η' PROPERTIES AND METHODS

- The η/η' mesons are **special**:
  - The η is a pseudo-Goldstone boson
  - The η' is largely influenced by the $U(1)$ anomaly
  - The η/η' are eigenstates of the C, P, CP and G operators: $I^G J^{PC} = 0^+0^{-+}$
  - Flavour conserving decays
  - All their strong and EM decays are forbidden at lowest order
- η and η' decays offer **fantastic opportunities** to:

  • test low-energy QCD • search for New Physics
- Theoretical **methods**:
  - ChPT and its extensions (large-N_c)
  - Vector-meson dominance
  - Dispersion theory

(Selected) η/η' decays

- **High priority** $\eta^{(\prime)}$ decays for experiment and theory

  (L. Gan, B. Kubis, E. Passemar and S. Tulin, 2007.00664)

Decay channel	Standard Model	Discrete symmetries	BSM particles
$\eta^{(\prime)} \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons
$\eta^{(\prime)} \to \gamma\gamma$	η-η' mixing, width	—	—
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$	—	Z', dark photon
$\eta^{(\prime)} \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$	higher-order χPT, scalar dynamics	—	$U(1)_B$ boson, scalar boson
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	—
$\eta^{(\prime)} \to \pi^0\ell^+\ell^-$	—	C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$	—	ALP, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$	—	C violation	ALP

- **Important** experimental activities: A2, Belle-II, BESIII, GlueX, LHCb, KLOE-II, WASA-at-COSY

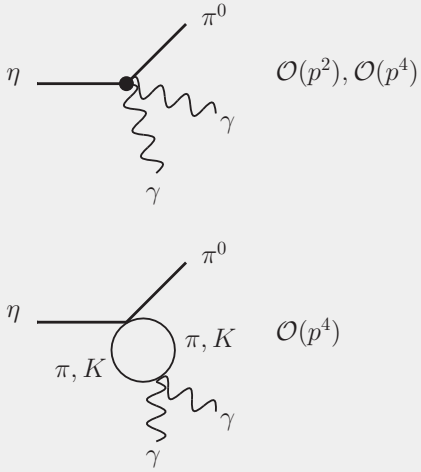
- **Forthcoming** experiments: JLab Eta Factory and REDTOP

  (talks by Gan and Gatto)

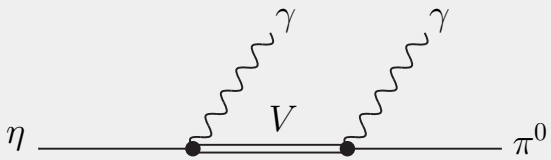
$\eta \to \pi^0\gamma\gamma$ DECAYS: THEORETICAL MOTIVATION

- **SM motivation**:

Reference	$\Gamma(\eta \to \pi^0\gamma\gamma)$ [eV]
$\mathcal{O}(p^2)$, $\mathcal{O}(p^4)$ tree-level χPT	0
$\pi + K$ loops at $\mathcal{O}(p^4)$	1.87×10^{-3}
Experimental value (pdg)	0.34(3)



  - 1st sizable contribution comes at $\mathcal{O}(p^6)$, but LEC's are not well known
  - To **test ChPT** and a wide range of chiral models, *e. g.* VMD and LσM

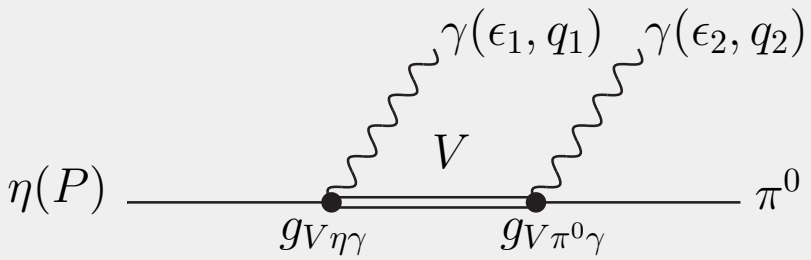


- **BSM motivation**: search for a B boson via $\eta \to B\gamma \to \pi^0\gamma\gamma$

(talk by Gan)

$\eta \to \pi^0\gamma\gamma$ DECAYS: VMD CALCULATION

- Six **diagrams** corresponding to the exchange of $V = \rho^0, \omega, \phi$



$$\mathcal{A}^{\rm VMD}_{\eta\to\pi^0\gamma\gamma} = \sum_{V=\rho^0,\omega,\phi} g_{V\eta\gamma} g_{V\pi^0\gamma} \left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right] ,$$

- $g_{VP\gamma}$ **couplings**:
  - Effective Lagrangian

$$\mathcal{L}_{VVP} = \frac{G}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \mathrm{tr}\left[\partial_\mu V_\nu \partial_\alpha V_\beta P\right] , \quad \mathcal{L}_{V\gamma} = -2egf_\pi^2 A^\mu \mathrm{tr}\left[QV_\mu\right] ,$$

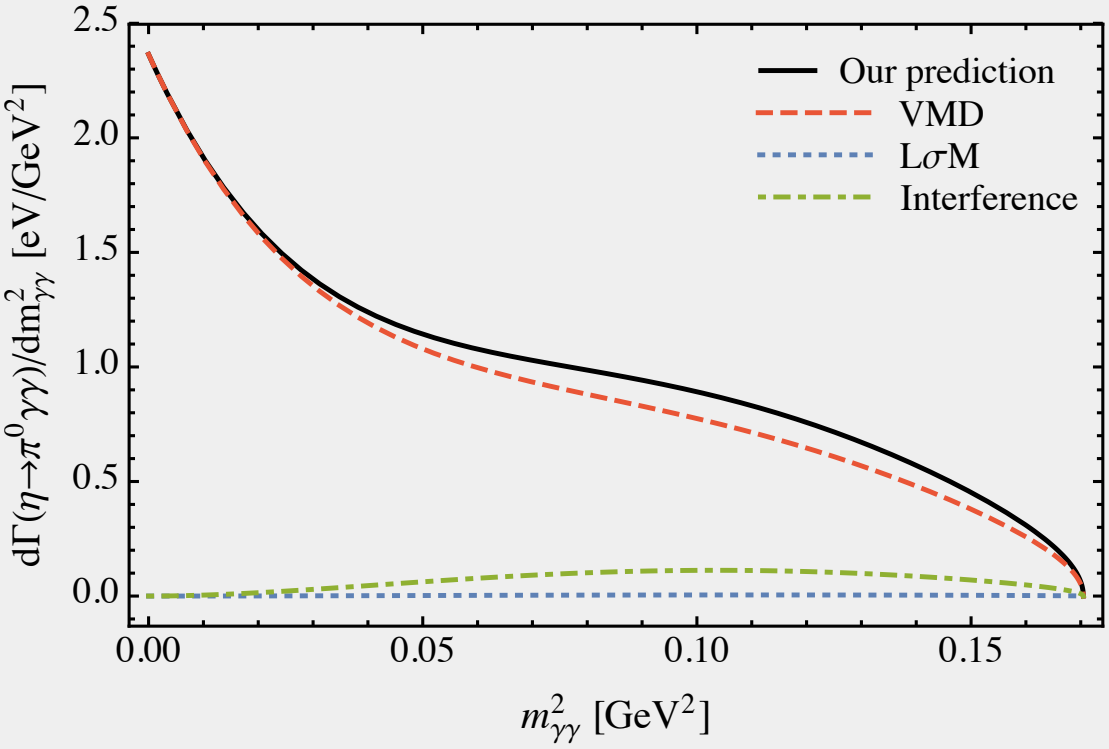
  - Measured $\Gamma^{\rm exp}_{V(P)\to P(V)\gamma}$ widths (this work)

- The decays $\eta' \to \{\pi^0, \eta\}\gamma\gamma$ are formally identical, with:

$$g_{V\eta\gamma} g_{V\pi^0\gamma} \to g_{V\eta'\gamma} g_{V\{\pi^0,\eta\}\gamma}$$

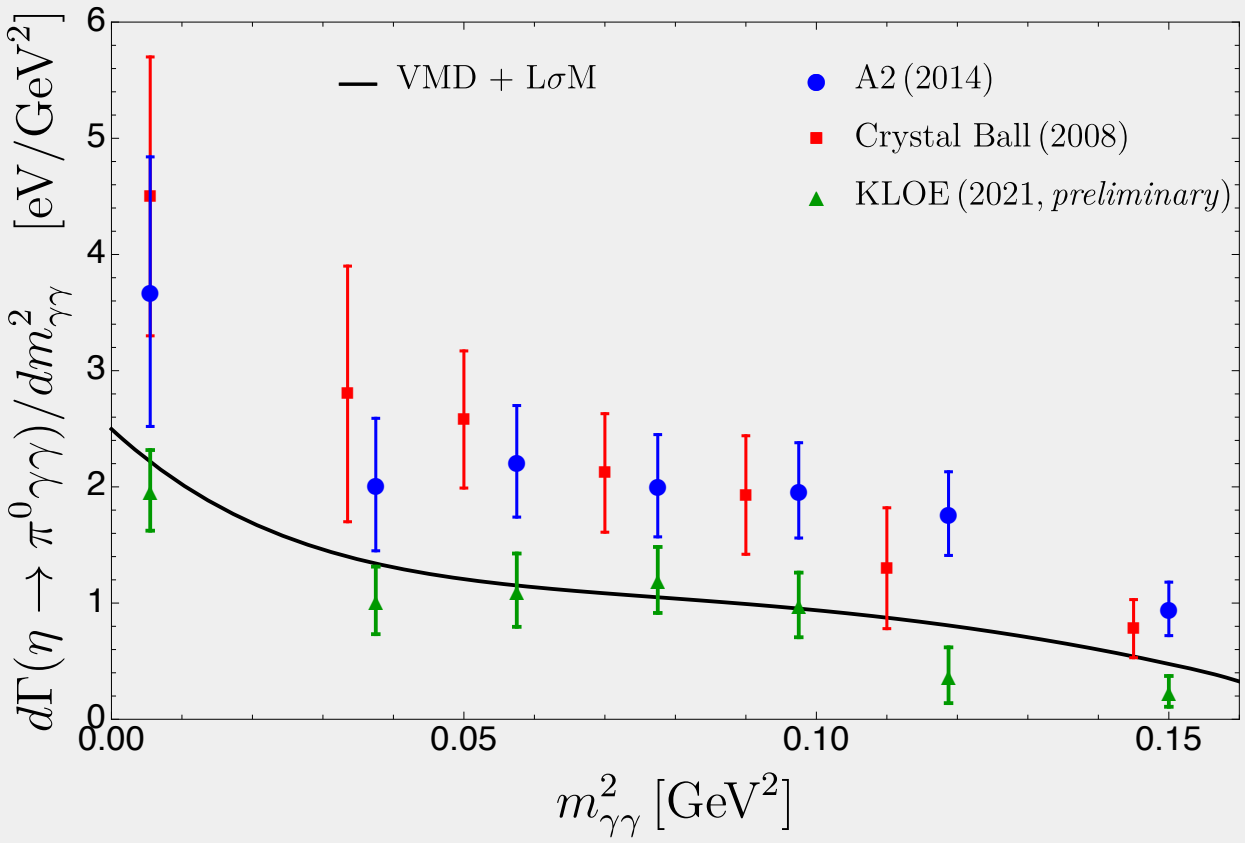
$\eta \to \pi^0\gamma\gamma$ PREDICTIONS

- Our theoretical prediction $BR = 1.35(8) \times 10^{-4}$
  (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD dominates:
  - ρ: 27% of the signal
  - ω: 21% of the signal
  - ϕ: 0% of the signal
  - interference between ρ-ω-ϕ: 52%
  - interference between scalar and vector mesons: 7%



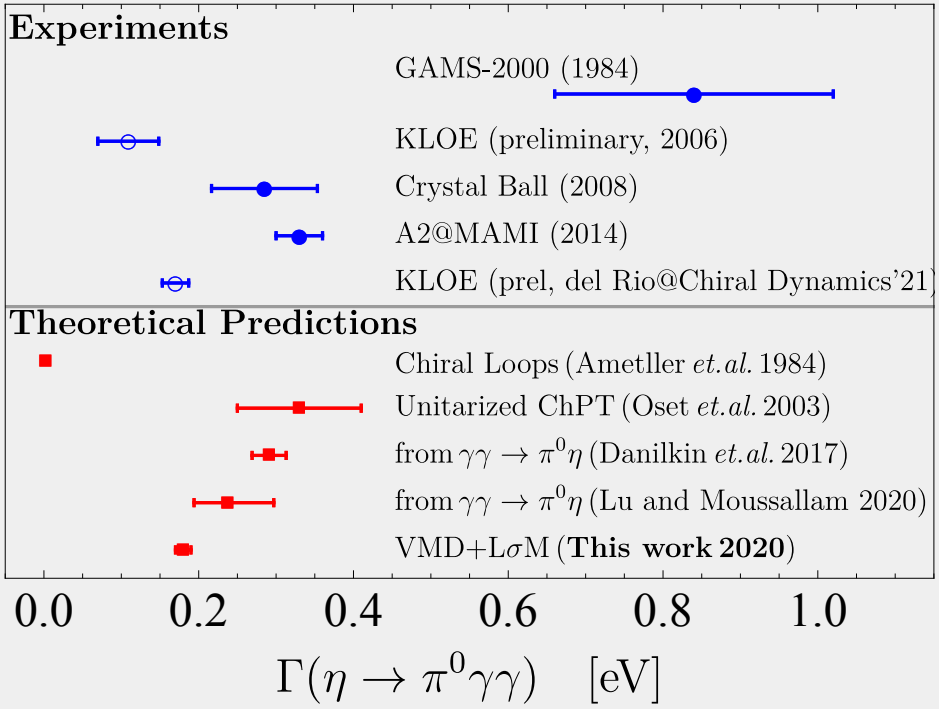
$\eta \to \pi^0\gamma\gamma$ PREDICTIONS VS DATA

- VMD comparison with A2 and CB data
  (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - Shape of the A2 and Crystal Ball spectra is captured well
  - Normalization offset
  - Good agreement with KLOE data (preliminary)



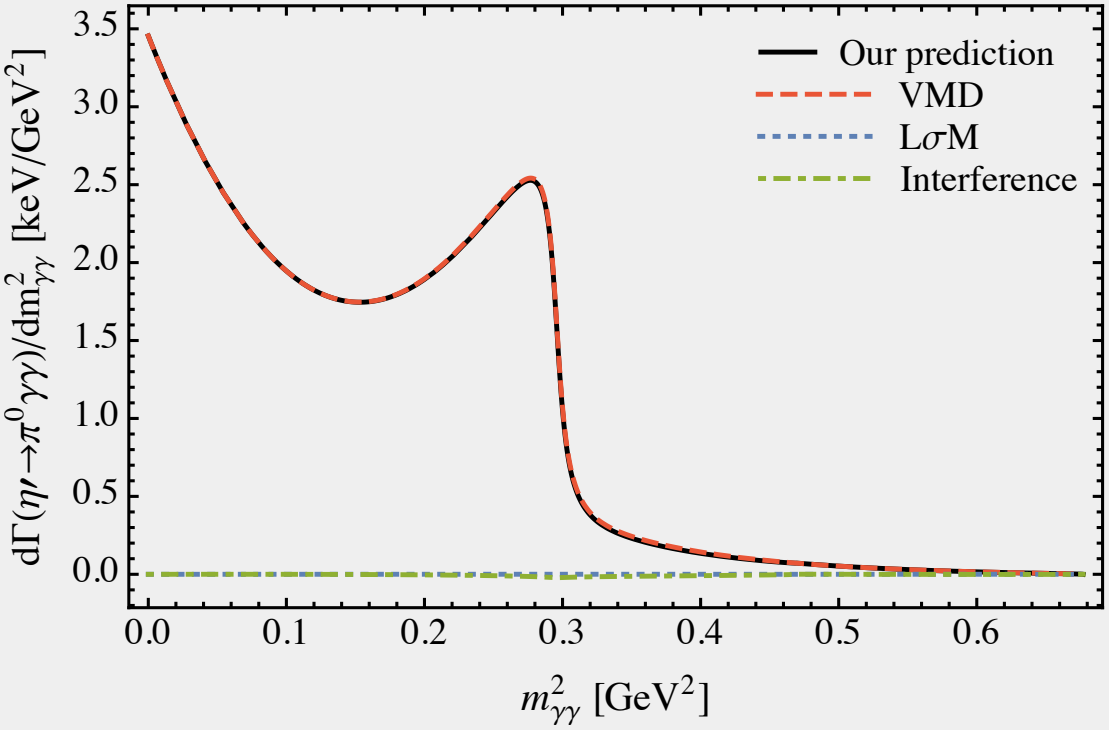
$\eta \to \pi^0\gamma\gamma$ PREDICTIONS VS DATA (BR)

- Our prediction, BR$= 1.35(8) \times 10^{-4}$, agrees with BR$= 1.30(13) \times 10^{-4}$ (KLOE prel, del Rio@Chiral dynamics'21)
- KLOE-II final measurement is forthcoming
- JEF experiment: (talk by Gan)
  - BR and Dalitz distribution with $\sim 5\%$ precision
  - Improved understanding of the interplay of meson resonances
  - $\mathcal{O}(p^6)$ LEC's determination



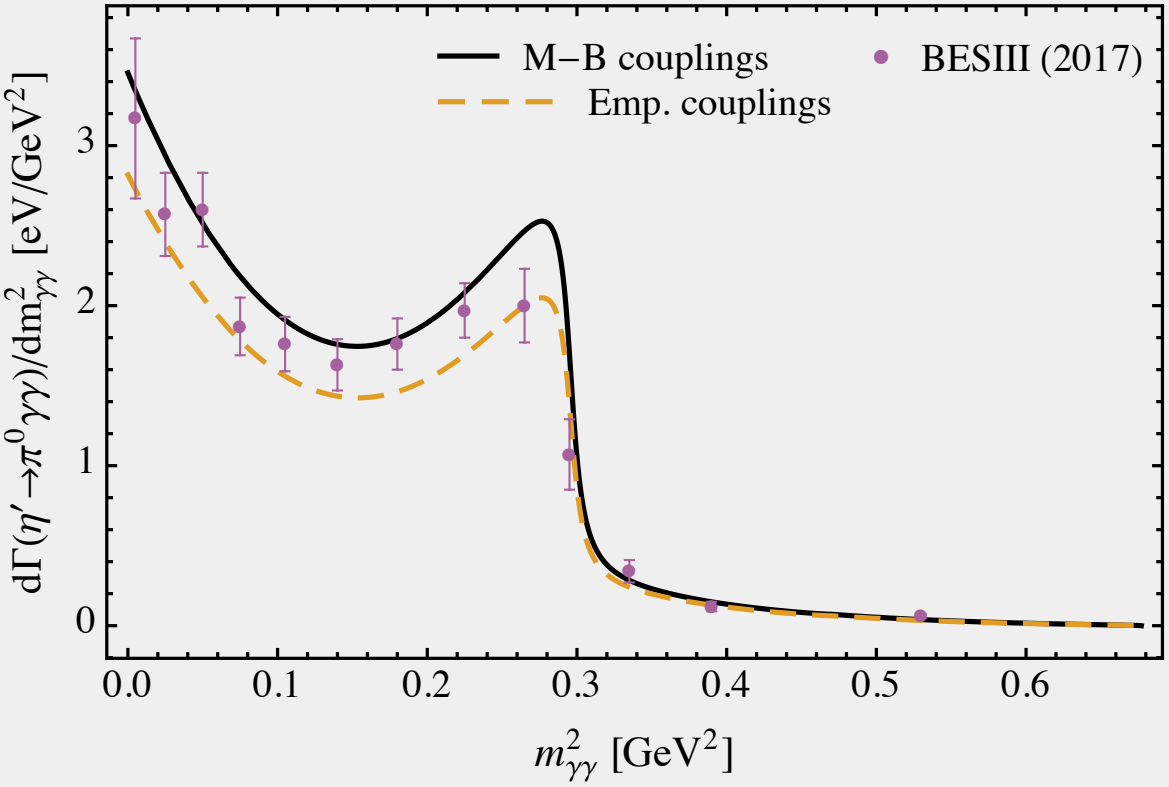
$\eta' \to \pi^0\gamma\gamma$ DECAYS

- Our theoretical predictions $BR = [2.91(21), 3.57(25)] \times 10^{-3}$
  (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD completely dominates:
  - ω: 78% of the signal
  - ρ: 5% of the signal
  - ϕ: 0% of the signal
  - interference: 17%



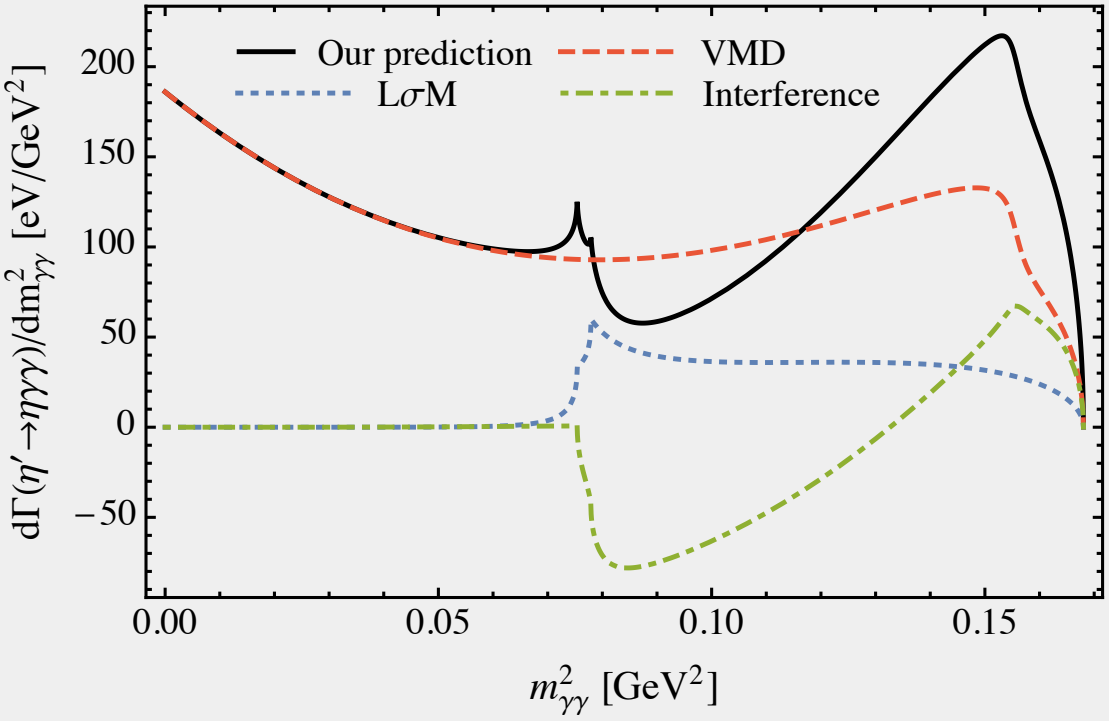
$\eta' \to \pi^0\gamma\gamma$ DECAYS

- Our theoretical predictions $BR = [2.91(21), 3.57(25)] \times 10^{-3}$ (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
- First time $m_{\gamma\gamma}$ invariant mass distribution by the BESIII coll.; $BR = 3.20(7)(23) \times 10^{-3}$ (Ablikim *et al.* Phys.Rev.D 96, 012005 (2017))



$\eta' \to \eta\gamma\gamma$ DECAYS

- 1st BR measurement by BESIII, $BR = 8.25(3.41)(0.72) \times 10^{-5}$ or $BR < 1.33 \times 10^{-4}$ at 90% C.L. (Ablikim *et al.* Phys.Rev.D 100, 052015 (2019))
- Our theoretical predictions $BR = [1.07(7), 1.17(8)] \times 10^{-4}$ (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))
  - VMD predominates (91% of the signal)
  - Substantial scalar meson effects (16%)
  - Interference between scalar and vector mesons (7%)



- We look forward to the release of the $m_{\gamma\gamma}$ spectrum

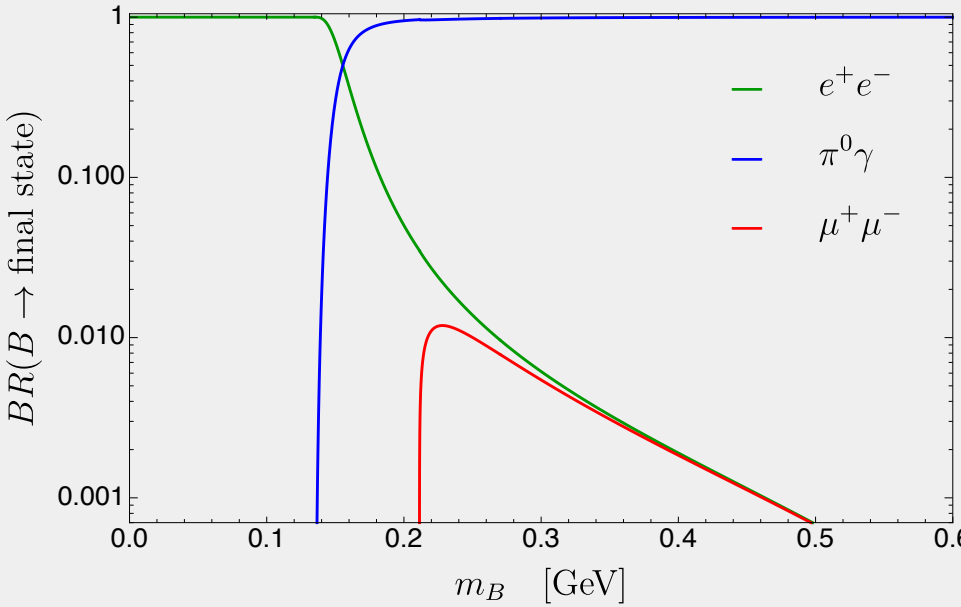
Leptophobic B boson model

- New boson that (predominantly) couples to quarks (Tulin'14)

$$\mathcal{L}_{\rm int} = \left(\frac{1}{3} g_B + \varepsilon Q_q e\right) \bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu \,,$$

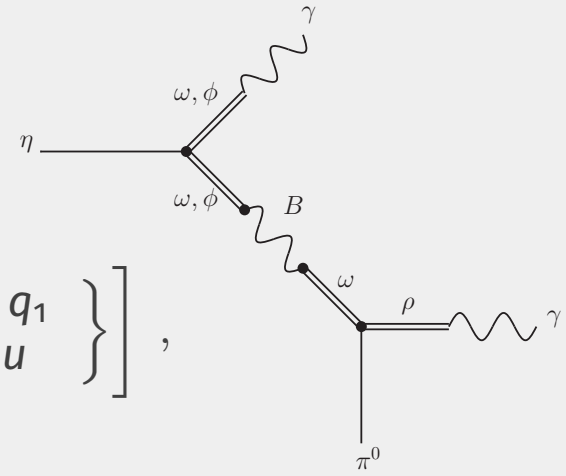
  - g_B new gauge (universal?) coupling, $\alpha_B = g_B^2/4\pi$
  - Preserves QCD symmetries (C, P, T)
  - $\varepsilon = e g_B/(4\pi)^2$: (subleading) γ-like coupling to fermions
  - Effective Lagrangian:

$$\begin{aligned}
\mathcal{L}_{VB} &= -2\frac{1}{3} g_B g f_\pi^2 B^\mu \,\mathrm{tr}\,[V^\mu] \,, \\
\Gamma_{B\to\pi^0\gamma} &= \frac{\alpha_B \alpha_{em} m_B^3}{96\pi^3 f_\pi^2}\left(1 - \frac{m_\pi^2}{m_B^2}\right)^3 |F_\omega(m_B^2)|^2 \,, \\
\Gamma_{B\to\ell^+\ell^-} &= \frac{\alpha_{em}\varepsilon^2 m_B}{3}\left(1 + 2\frac{m_\ell^2}{m_B^2}\right)\sqrt{1 - 4\frac{m_\ell^2}{m_B^2}} \,,
\end{aligned}$$



$\eta \to \pi^0\gamma\gamma$ DECAYS: B BOSON CALCULATION

- Two diagrams corresponding to the exchange of a B **boson**



$$\mathcal{A}^{B\,\mathrm{boson}}_{\eta\to\pi^0\gamma\gamma} = g_{B\eta\gamma}(t)g_{B\pi^0\gamma}(t)\left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)} + \left\{\begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array}\right\}\right],$$

- $g_{BP\gamma}$ **couplings**:

$$g_{B\pi^0\gamma}(t) = \frac{\sqrt{2}eg_B}{4\pi^2 f_\pi}F_\omega(t)\,, \quad g_{B\eta\gamma}(t) = \frac{eg_B}{12\pi^2 f_\pi}\frac{1}{\sqrt{3}}\left[(c_\theta - \sqrt{2}s_\theta)F_\omega(t) + (2c_\theta + \sqrt{2}s_\theta)F_\phi(t)\right],$$

- Energy-dependent **width**

$$\Gamma_B(t) = \frac{\tilde{\gamma}_{B\to\ell^+\ell^-}(t)}{\tilde{\gamma}_{B\to\ell^+\ell^-}(m_B^2)}\Gamma_{B\to\ell^+\ell^-}\theta(t-4m_\ell^2) + \frac{\tilde{\gamma}_{B\to\pi^0\gamma}(t)}{\tilde{\gamma}_{B\to\pi^0\gamma}(m_B^2)}\Gamma_{B\to\pi^0\gamma}\theta(t-m_{\pi^0}^2)\,,$$

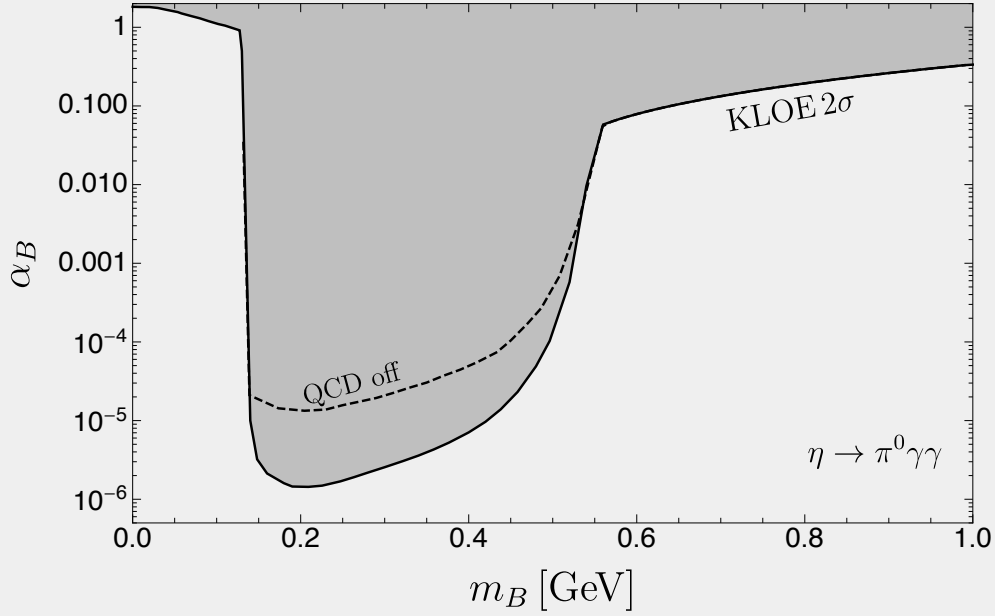
$\eta \to \pi^0\gamma\gamma$ SENSITIVITY TO A B BOSON

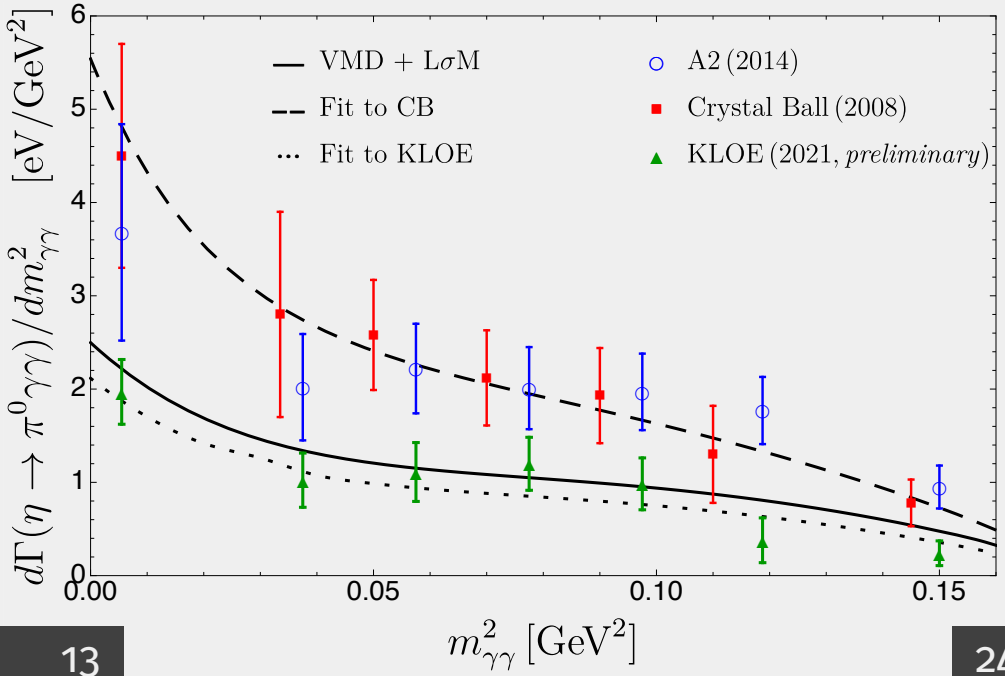
- *Preliminary results (Escribano, G-S, Royo)*
- Fit to Crystal Ball:

$$\alpha_B = 0.39(15),$$
$$m_B = 581(50)\,\mathrm{MeV}$$

- Fit to KLOE:

$$\alpha_B = 0.056(34),$$
$$m_B = 142^{+1}_{-60}\,\mathrm{MeV}$$





$\eta \to \pi^0\gamma\gamma$ SENSITIVITY TO A B BOSON

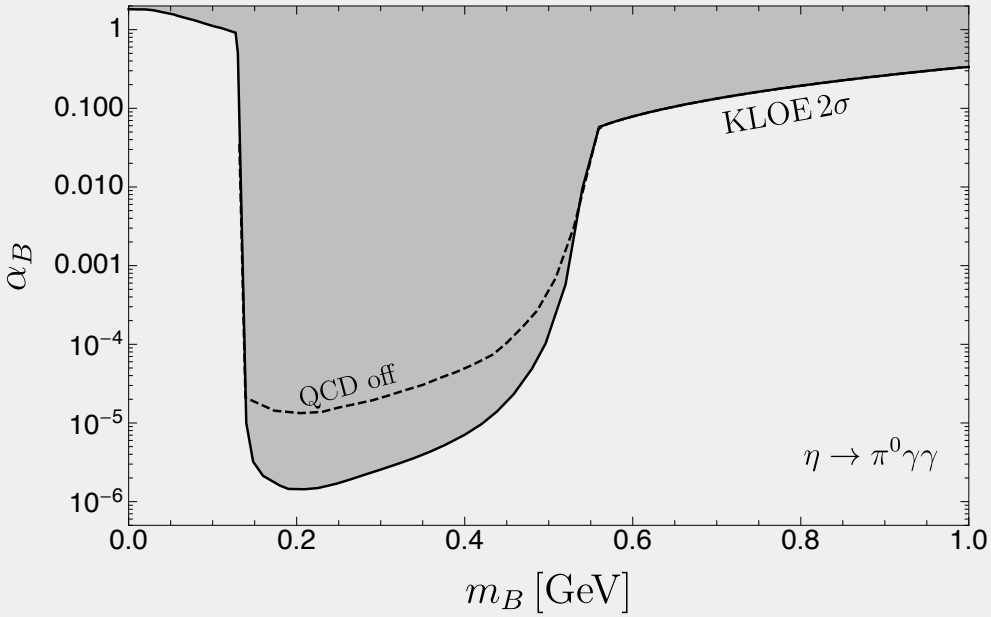
- *Preliminary results (Escribano, G-S, Royo)*
- Fit to Crystal Ball:

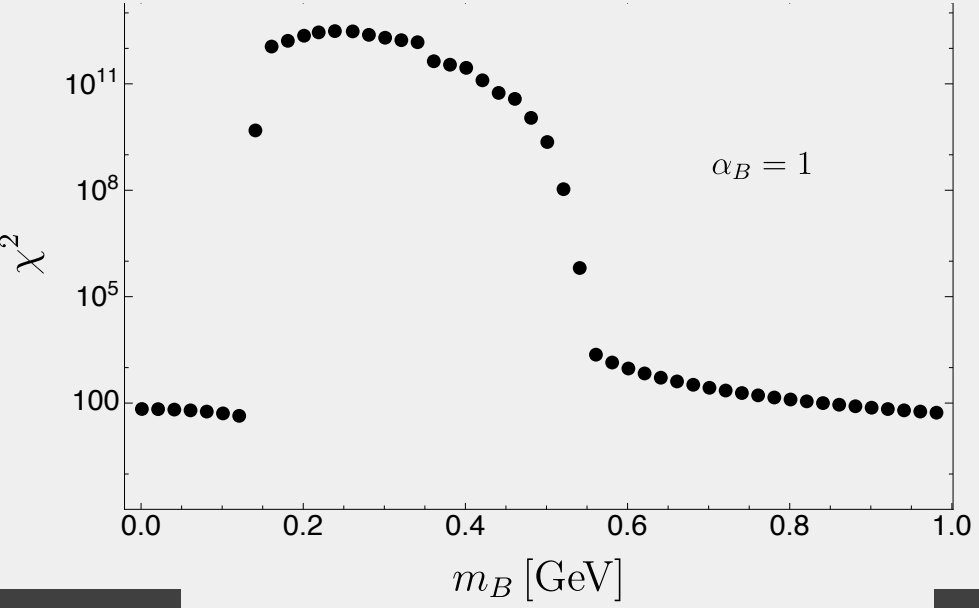
$$\begin{aligned} \alpha_B &= 0.39(15), \\ m_B &= 581(50)\,\mathrm{MeV} \end{aligned}$$

- Fit to KLOE:

$$\begin{aligned} \alpha_B &= 0.056(34), \\ m_B &= 142^{+1}_{-60}\,\mathrm{MeV} \end{aligned}$$

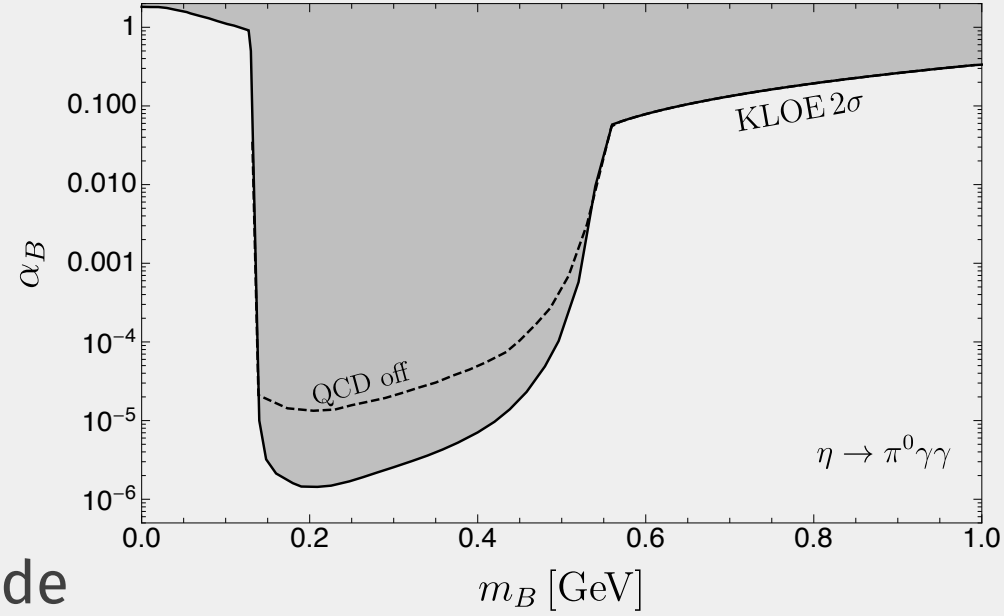
- Extremely narrow resonance
- $m_\pi^0 \lesssim m_B \lesssim m_\eta$ not allowed?
  - No signal in $\eta \to \gamma B \to \gamma\gamma\pi^0$

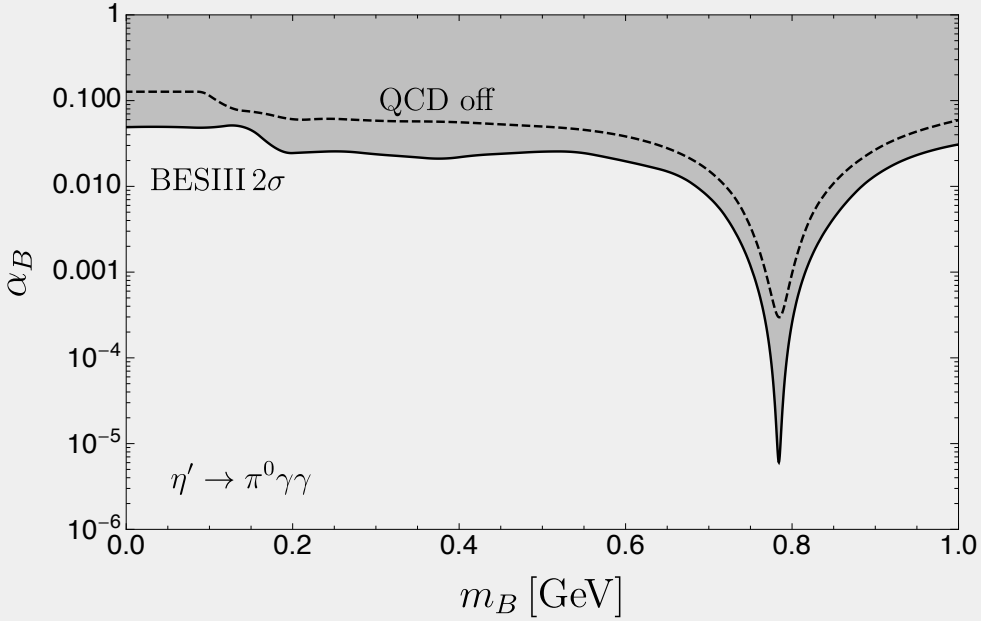




$\eta' \to \pi^0\gamma\gamma$ SENSITIVITY TO A B BOSON

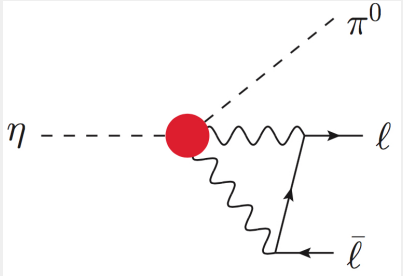
- *Preliminary results (Escribano, G-S, Royo)*
- Sharp dip when $m_B \sim m_\omega$
- Bounds 4 orders of magnitude weaker than $\eta \to \pi^0\gamma\gamma$
- $\eta' \to \pi^0\gamma\gamma$ not as useful as $\eta \to \pi^0\gamma\gamma$ for constraining B bosons





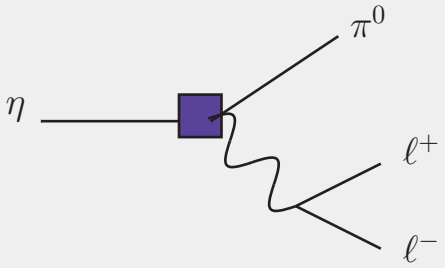
$\eta^{(\prime)} \to \{\pi^0, \eta\}\ell^+\ell^-$ DECAYS ($\ell = e, \mu$)

- In the SM:
  - $\eta \to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$ forbidden by *C* and *CP*
  - $\eta \to \pi^0\ell^+\ell^-$ proceed via *C*-conserving two-photon intermediate state



Decay channel	$BR_{\rm th}$ (Escribano&Royo 2007.12467)	$BR_{\rm exp}$ (pdg)
$\eta \to \pi^0 e^+e^-$	$2.1(1)(2) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)
$\eta \to \pi^0 \mu^+\mu^-$	$1.2(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)
$\eta' \to \pi^0 e^+e^-$	$4.6(3)(7) \times 10^{-9}$	$< 1.4 \times 10^{-3}$ (CL=90%)
$\eta' \to \pi^0 \mu^+\mu^-$	$1.8(1)(2) \times 10^{-9}$	$< 6.0 \times 10^{-5}$ (CL=90%)
$\eta' \to \eta e^+e^-$	$3.9(3)(4) \times 10^{-10}$	$< 2.4 \times 10^{-3}$ (CL=90%)
$\eta' \to \eta \mu^+\mu^-$	$1.6(1)(2) \times 10^{-10}$	$< 1.5 \times 10^{-5}$ (CL=90%)

- Background for BSM searches, *e.g.* *C*-violating virtual photon exchange or new scalar mediators
- REDTOP can improve the experimental state



Other interesting η and η' decays

- Standard Model decays:
  - $\eta \to 3\pi$: Dalitz plot measurements with improved precision (GlueX, REDTOP) $\Rightarrow$ more precise extraction of Q
  - $\eta' \to 3\pi$: theoretical advances $\Rightarrow$ extraction of Q also possible
  - $\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$: detailed differential information $\Rightarrow$ access to the doubly-virtual transition form factors $\Rightarrow (g-2)_\mu$
- Discrete symmetry tests:
  - $\eta \to \mu^+\mu^-$: high-precision experimental test (REDTOP) can probe *CP* violation
  - $\eta^{(\prime)} \to \pi\pi$: improved experimental bounds are welcome
  - $\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$: test of *C*-violation
- New light BSM particles:
  - dark photon appears as a resonance in $\eta^{(\prime)} \to \ell^+\ell^-\gamma$ (REDTOP)
  - Axion-like particles searches in $\eta^{(\prime)}$ decays, *e.g.* $\eta^{(\prime)} \to 2\pi a$

Outlook

- A lot of **interesting physics** to be done in the η/η' sector
- Within the VMD and LσM frameworks **we have described**
  - $\eta \to \pi^0\gamma\gamma$: the situation is **not conclusive**

$$BR = 1.35(8)\times 10^{-4} \begin{cases} \sim 1/2 \text{ of } BR = 2.54(27) \times 10^{-4} & \text{(A2, 2014)} \\ \sim 1.6\sigma \text{ from } BR = 2.21(24)(47) \times 10^{-4} & \text{(CB, 2008)} \\ \text{agrees with } BR = 1.30(13) \times 10^{-4} & \text{(prel. KLOE, del Rio CD'21)} \end{cases}$$

  - $\eta' \to \pi^0\gamma\gamma$: **in fair agreement** with BESIII data
  - $\eta' \to \eta\gamma\gamma$: **in line** with BESIII data
- *B* **boson searches** in $\eta/\eta' \to \pi^0\gamma\gamma$ out of the game?
  - requires robust SM predictions and precise experiments
- **Important experimental activity**: A2, Belle-II, BESIII, KLOE-II, GlueX, WASA. The contribution of **new experiments** (JEF, REDTOP), will be very welcome!

Phenomenological $VP\gamma$ couplings

$$
\begin{aligned}
g_{\rho^0\pi^0\gamma} &= \frac{1}{3} g\,, \\
g_{\rho^0\eta\gamma} &= g z_{\mathrm{NS}} \cos\varphi_P\,, \\
g_{\rho^0\eta'\gamma} &= g z_{\mathrm{NS}} \sin\varphi_P\,, \\
g_{\omega\pi^0\gamma} &= g \cos\varphi_V\,, \\
g_{\omega\eta\gamma} &= \frac{1}{3} g \left(z_{\mathrm{NS}} \cos\varphi_P \cos\varphi_V - 2\frac{\overline{m}}{m_s} z_{\mathrm{S}} \sin\varphi_P \sin\varphi_V \right), \\
g_{\omega\eta'\gamma} &= \frac{1}{3} g \left(z_{\mathrm{NS}} \sin\varphi_P \cos\varphi_V + 2\frac{\overline{m}}{m_s} z_{\mathrm{S}} \cos\varphi_P \sin\varphi_V \right), \\
g_{\phi\pi^0\gamma} &= g \sin\varphi_V\,, \\
g_{\phi\eta\gamma} &= \frac{1}{3} g \left(z_{\mathrm{NS}} \cos\varphi_P \sin\varphi_V + 2\frac{\overline{m}}{m_s} z_{\mathrm{S}} \sin\varphi_P \cos\varphi_V \right), \\
g_{\phi\eta'\gamma} &= \frac{1}{3} g \left(z_{\mathrm{NS}} \sin\varphi_P \sin\varphi_V - 2\frac{\overline{m}}{m_s} z_{\mathrm{S}} \cos\varphi_P \cos\varphi_V \right),
\end{aligned}
$$

Input for the $g_{VP\gamma}$ couplings

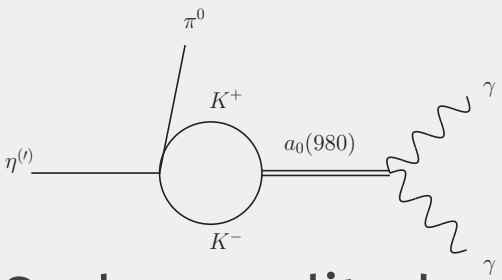
- $g_{VP\gamma}$ couplings fixed from the measured widths ($P = \pi^0, \eta, \eta'$)

$$\Gamma^{\rm exp}_{V\to P\gamma} = \frac{1}{3}\frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_V^2 - m_P^2}{m_V}\right)^3 , \quad \Gamma^{\rm exp}_{P\to V\gamma} = \frac{g^2_{VP\gamma}}{32\pi}\left(\frac{m_P^2 - m_V^2}{m_P}\right)^3 ,$$

Decay	**Branching ratio** (pdg)	$\lvert g_{VP\gamma}\rvert$ GeV^{-1}
$\rho^0 \to \pi^0\gamma$	$(4.7 \pm 0.6) \times 10^{-4}$	0.22(1)
$\rho^0 \to \eta\gamma$	$(3.00 \pm 0.21) \times 10^{-4}$	0.48(2)
$\eta' \to \rho^0\gamma$	$(28.9 \pm 0.5)\%$	0.40(1)
$\omega \to \pi^0\gamma$	$(8.40 \pm 0.22)\%$	0.70(1)
$\omega \to \eta\gamma$	$(4.5 \pm 0.4) \times 10^{-4}$	0.135(6)
$\eta' \to \omega\gamma$	$(2.62 \pm 0.13)\%$	0.127(4)
$\phi \to \pi^0\gamma$	$(1.30 \pm 0.05) \times 10^{-3}$	0.041(1)
$\phi \to \eta\gamma$	$(1.303 \pm 0.025)\%$	0.2093(20)
$\phi \to \eta'\gamma$	$(6.22 \pm 0.21) \times 10^{-5}$	0.216(4)

LσM FOR THE SCALAR RESONANCE CONTRIBUTIONS

- χPT loops complemented by the exchange of scalar resonances, $a_0(980), \kappa, \sigma, f_0(980)$, e.g.:



$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{\eta^{(\prime)}\to\pi^0\gamma\gamma} = \frac{2\alpha}{\pi}\frac{1}{m^2_{K^+}}L(s_K)\{a\}\times\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}}\,,$$

- Scalar amplitudes:

$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta^{(\prime)}} = \frac{1}{2f_\pi f_K}\Bigg\{(s-m^2_{\eta^{(\prime)}})\frac{m^2_K-m^2_{a_0}}{D_{a_0}(s)}\cos\varphi_P + \frac{1}{6}\Big[(5m^2_{\eta^{(\prime)}}+m^2_\pi-3s)\cos\varphi_P - \sqrt{2}(m^2_{\eta^{(\prime)}}+4m^2_K+m^2_\pi-3s)\sin\varphi_P\Big]\Bigg\}\,,$$

- Complete one-loop propagator for the scalar resonances:

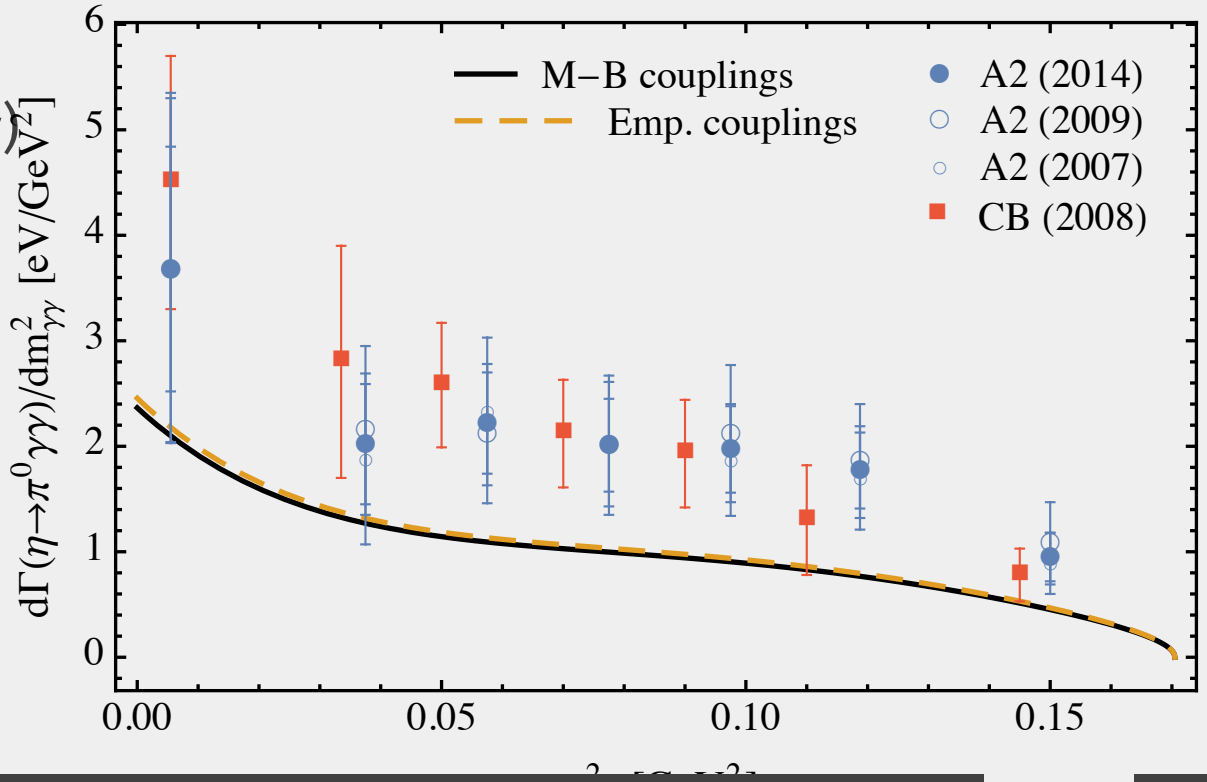
$$D_R(s) = s - m^2_R + \mathrm{Re}\Pi(s) - \mathrm{Re}\Pi(m^2_R) + i\mathrm{Im}\Pi(s)\,,$$

$\eta \to \pi^0\gamma\gamma$ PREDICTIONS VS DATA

- VMD comparison with A2 and CB data

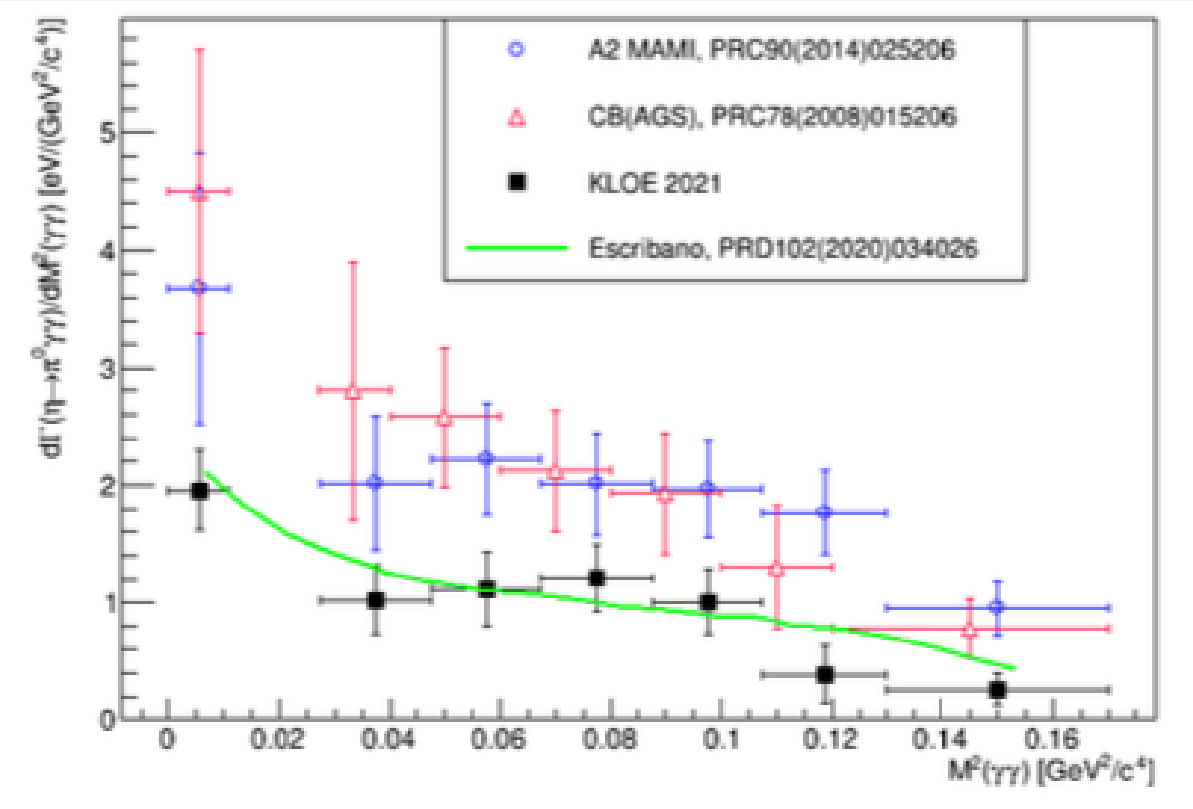
  (R. Escribano, S. G-S, R. Jora, E. Royo, Phys.Rev.D 102, 034026 (2020))

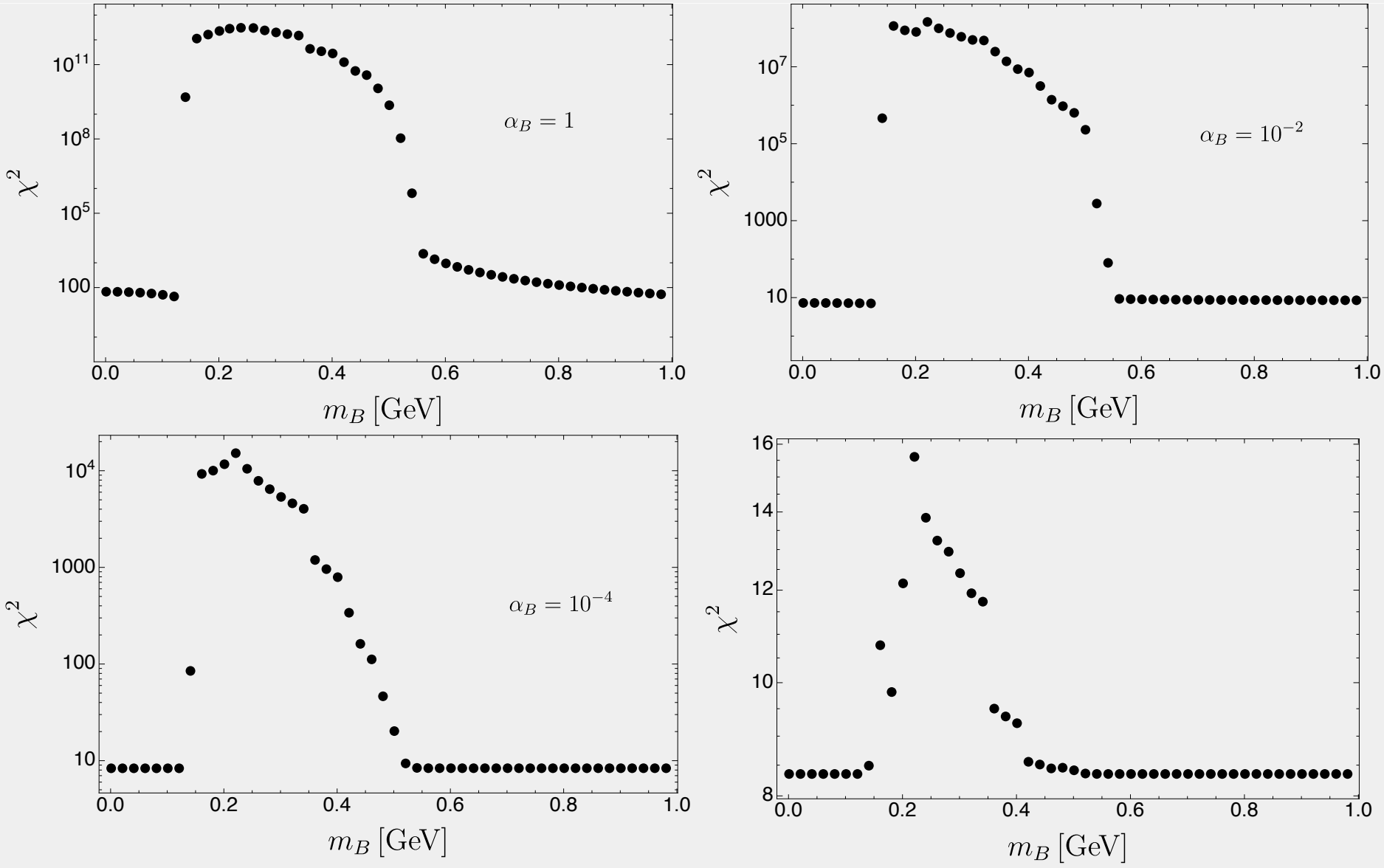
  - Shape of the spectra is captured well
  - Normalization offset
  - Good agreement with the (preliminary) KLOE data



$\eta \to \pi^0\gamma\gamma$ PREDICTIONS VS DATA (SPECTRA)

- Comparison with KLOE preliminary results (See talk by Elena P. del Rio, figure taken from her talk)
  - Good agreement



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

R. Escribano, S. Gonzàlez-Solís, E. Royo in progress