Universitat Autònoma de Barcelona

QNP 2024

Institut de Física d'Altes Energies

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Search for a leptophobic U(1) B boson using $\eta \to \pi^0 \gamma\gamma$ and $\phi \to \pi^0 \eta\gamma$ decays

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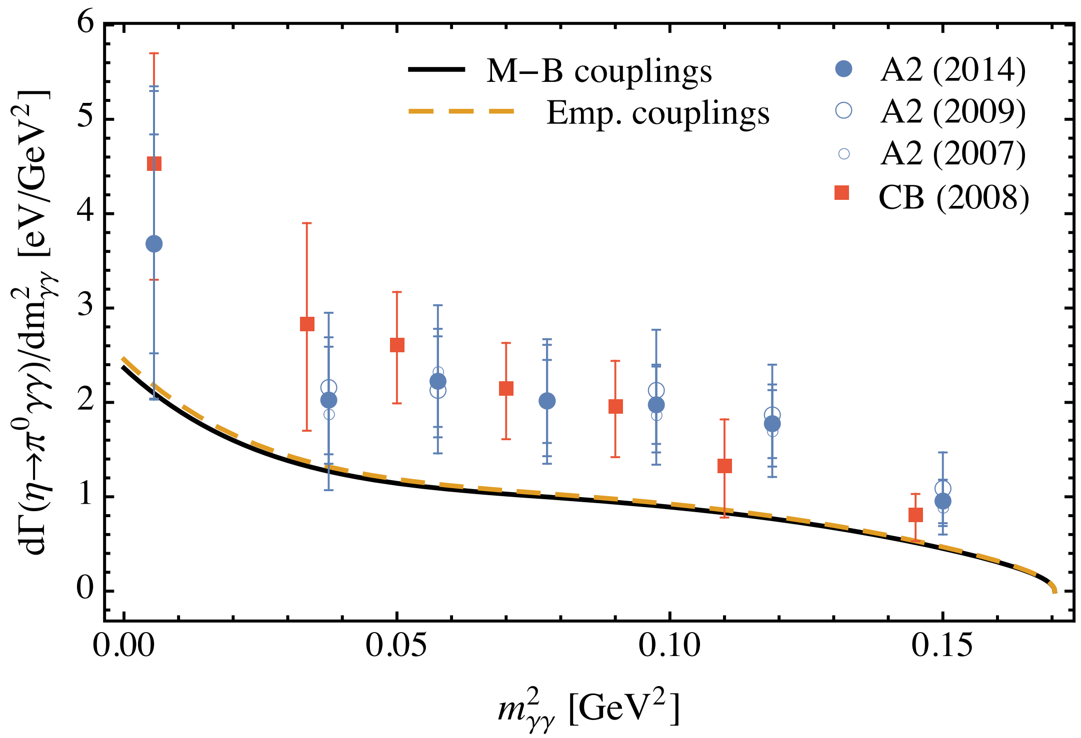
What's the motivation for this analysis?

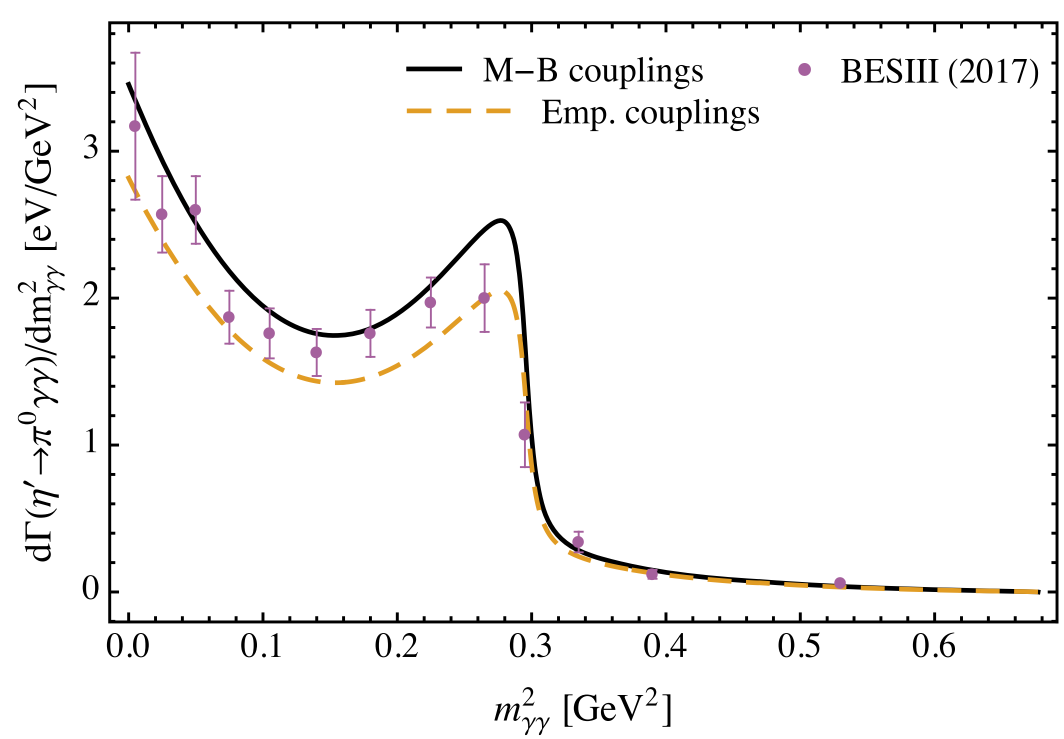
Theoretical analysis of the doubly radiative decays

$\eta, \eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$

Decay	Couplings	Chiral loop	LσM	VMD	Γ	BR$_{th}$	BR$_{exp}$ [14]
$\eta \to \pi^0\gamma\gamma$ (eV)	Empirical	1.87×10^{-3}	5.0×10^{-4}	0.16(1)	0.18(1)	$1.35(8) \times 10^{-4}$	$2.56(22) \times 10^{-4}$
	Model-based	1.87×10^{-3}	5.0×10^{-4}	0.16(1)	0.17(1)	$1.30(1) \times 10^{-4}$	
$\eta' \to \pi^0\gamma\gamma$ (keV)	Empirical	1.1×10^{-4}	1.3×10^{-4}	0.57(3)	0.57(3)	$2.91(21) \times 10^{-3}$	$3.20(7)(23) \times 10^{-3}$
	Model-based	1.1×10^{-4}	1.3×10^{-4}	0.70(4)	0.70(4)	$3.57(25) \times 10^{-3}$	
$\eta' \to \eta\gamma\gamma$ (eV)	Empirical	1.4×10^{-2}	3.29	21.2(1.2)	23.0(1.2)	$1.17(8) \times 10^{-4}$	$8.25(3.41)(0.72) \times 10^{-5}$
	Model-based	1.4×10^{-2}	3.29	19.1(1.0)	20.9(1.0)	$1.07(7) \times 10^{-4}$	

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





What's a leptophobic U(1) B boson?

It is a new gauge boson coupled to the baryon number

$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu \qquad \alpha_B \equiv g_B^2/(4\pi)$$

The low-energy symmetries of QCD are preserved

C and P are conserved

B does not transform under SU(3) flavour symmetry

B is a singlet under isospin

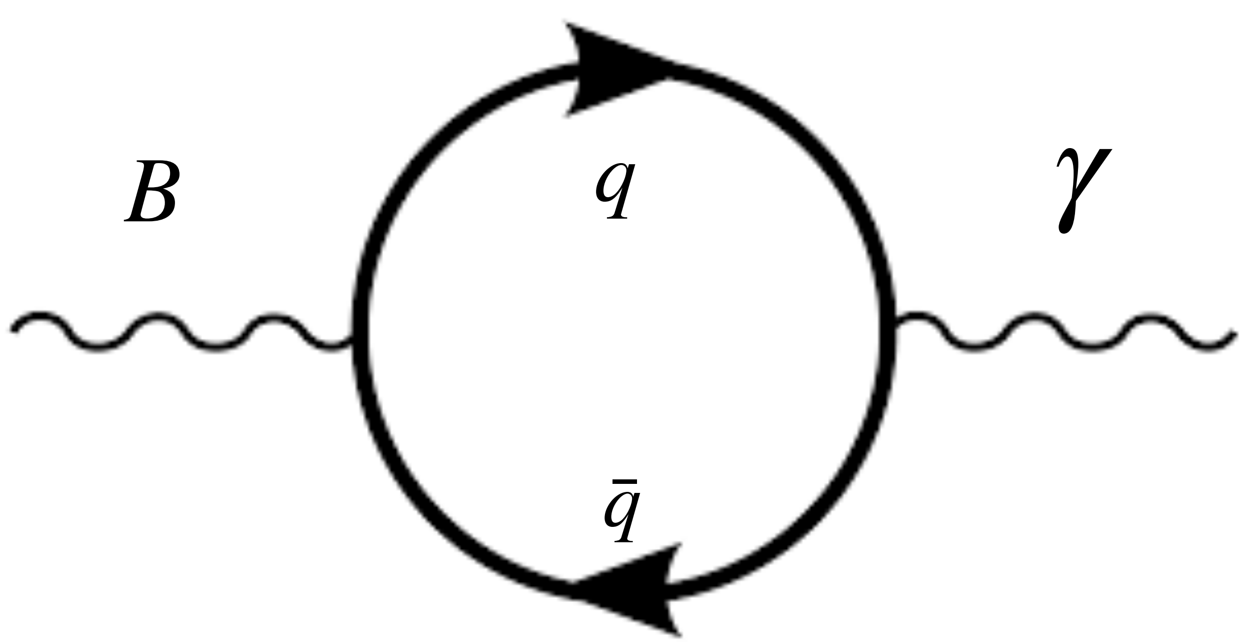
➡ $I^G(J^{PC}) = 0^-(1^{--})$ ➡ **B is ω meson like!**

What's a leptophobic U(1) B boson?

B is not completely decoupled from leptons

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

with a "natural"-sized $\varepsilon = e g_B/(4\pi)^2$ **induced radiatively**



What's the motivation for a U(1) B boson?

- The baryon number symmetry may be related to dark matter (it is stabilised since it carries a conserved baryon number charge)

- Natural framework for the Peccei-Quinn solution to the strong CP problem

- …

How are hadronic processes calculated?

Using the hidden local symmetry (HLS) for VMD

$$\mathscr{L}_{VVP} = \frac{G}{\sqrt{2}} \varepsilon^{\mu\nu\alpha\beta} \mathrm{tr}\left[\partial_\mu V_\nu \partial_\alpha V_\beta P\right] \quad \textbf{with} \quad G = \frac{3g^2}{4\pi^2 f_\pi}$$

P is the pseudoscalar meson nonet

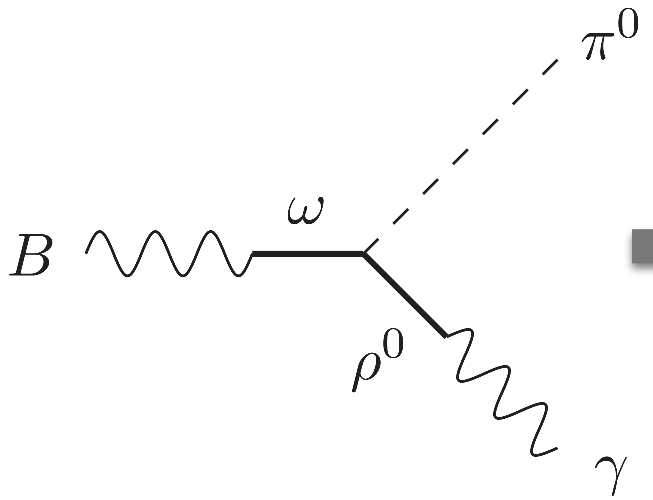
V is the vector meson nonet
(gauge bosons of a hidden $U(3)_V$ symmetry)

In conventional VMD:

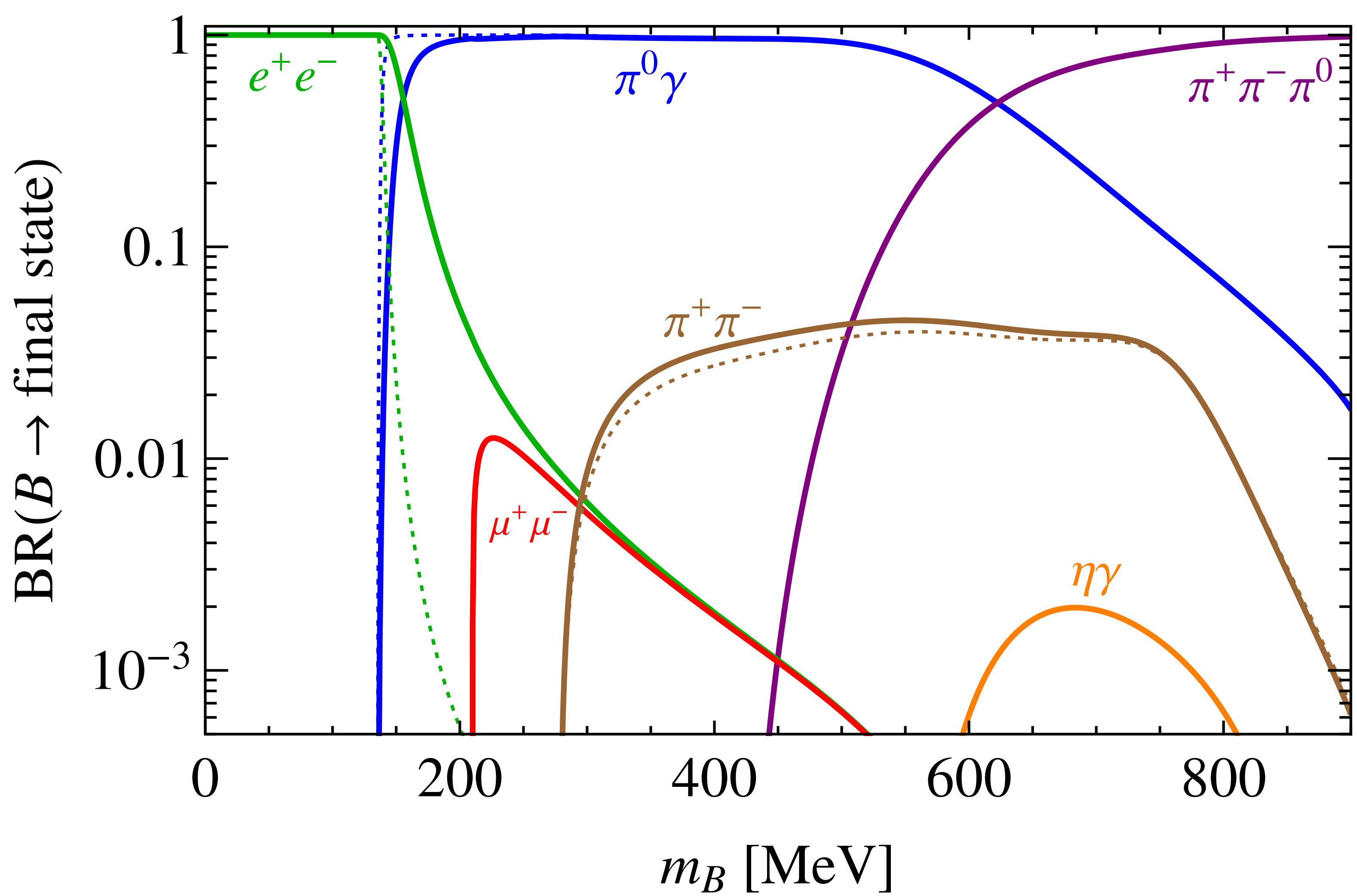
$$\mathscr{L}_{V\gamma} = -4eg f_\pi^2 A^\mu \mathrm{tr}\left[Q V_\mu\right]$$

$$\mathscr{L}_{VB} = -4\frac{1}{3} g_B g f_\pi^2 B^\mu \mathrm{tr}\left[V^\mu\right]$$

How are hadronic processes calculated?



$$\Gamma_{B\to\pi^0\gamma} = \frac{\alpha_{\rm em}\alpha_B m_B^3}{96\pi^3 f_\pi^2}\left(1-\frac{m_\pi^2}{m_B^2}\right)^3 |F_\omega(m_B^2)|^2$$



S. Tulin, Phys. Rev. D 89 (2014) 114008

Previous estimates

Assuming the Narrow Width Approximation (NWA):

$$\mathrm{BR}(\eta \to \pi^0\gamma\gamma) = \mathrm{BR}(\eta \to B\gamma) \times \mathrm{BR}(B \to \pi^0\gamma)$$

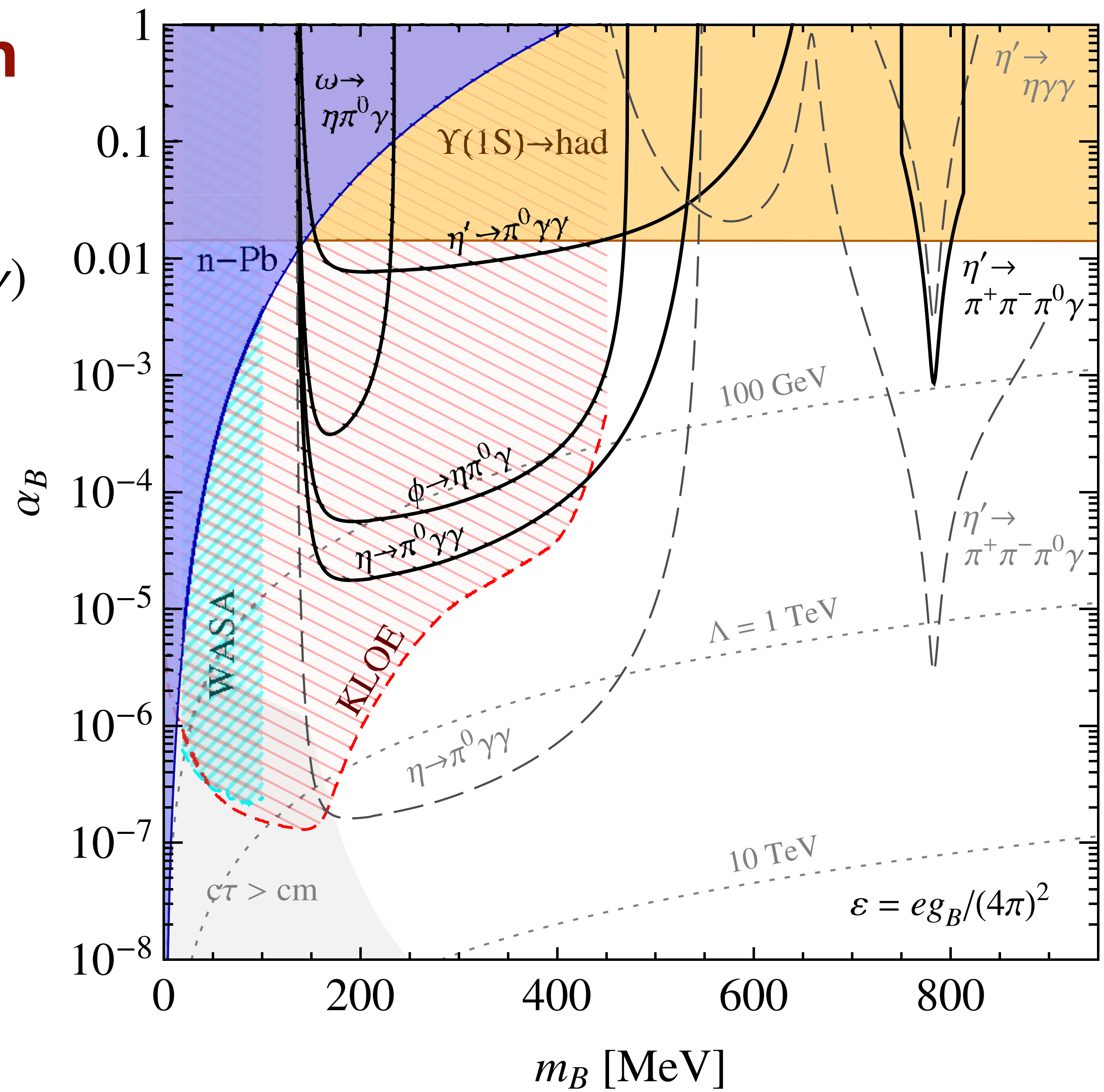
and

$$\mathrm{BR}(B \to \pi^0\gamma) = 1$$

and QCD contribution off

and

$$\mathrm{BR}(\eta \to \pi^0\gamma\gamma) < \mathrm{BR}_{\mathrm{exp}} \text{ at } 2\sigma$$



S. Tulin, Phys. Rev. D 89 (2014) 114008

Present estimates from this analysis

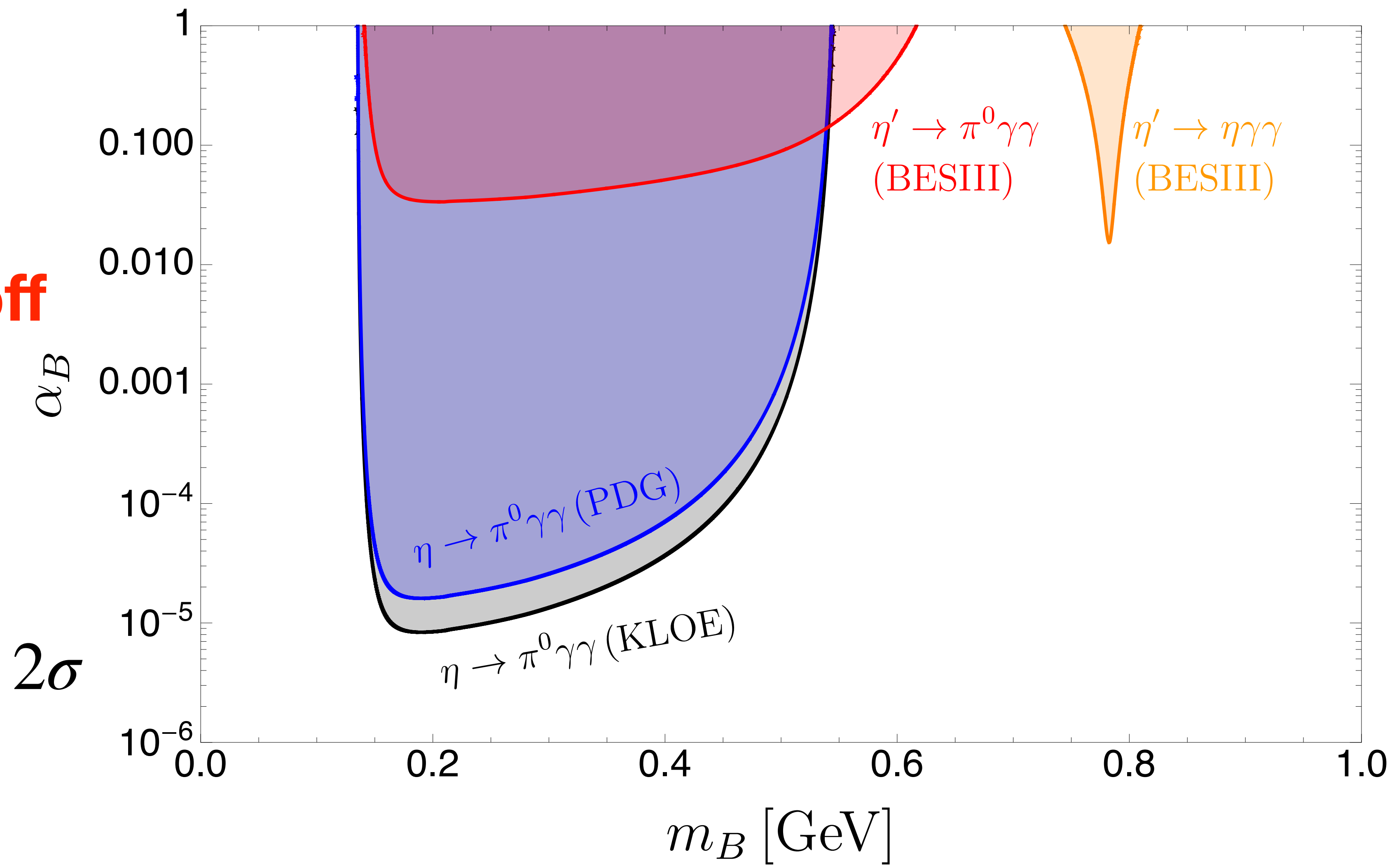
Assuming the NWA

and QCD contribution off

and

$\mathrm{BR}(\eta \to \pi^0\gamma\gamma) < \mathrm{BR}_{\mathrm{exp}}$ at 2σ

and including the latest experimental BRs



R. Escribano, S. Gonzàlez-Solís and E. Royo, Phys. Rev. D 106 (2022) 114007

However, a lot more can be done nowadays!

Using the new BR value and spectrum from KLOE for

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

B. Cao [KLOE-2], PoS EPS-HEP2021 (2022) 409

E. Pérez del Rio, CD21

Using the recent BR value and spectrum from BESIII for

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

M. Ablikim *et. al.* [BESIII], Phys. Rev. D 96 (2017) 012005

Using the recent BR value from BESIII for

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

M. Ablikim *et. al.* [BESIII], Phys. Rev. D 100 (2019) 052015

How are these processes calculated?

VMD:

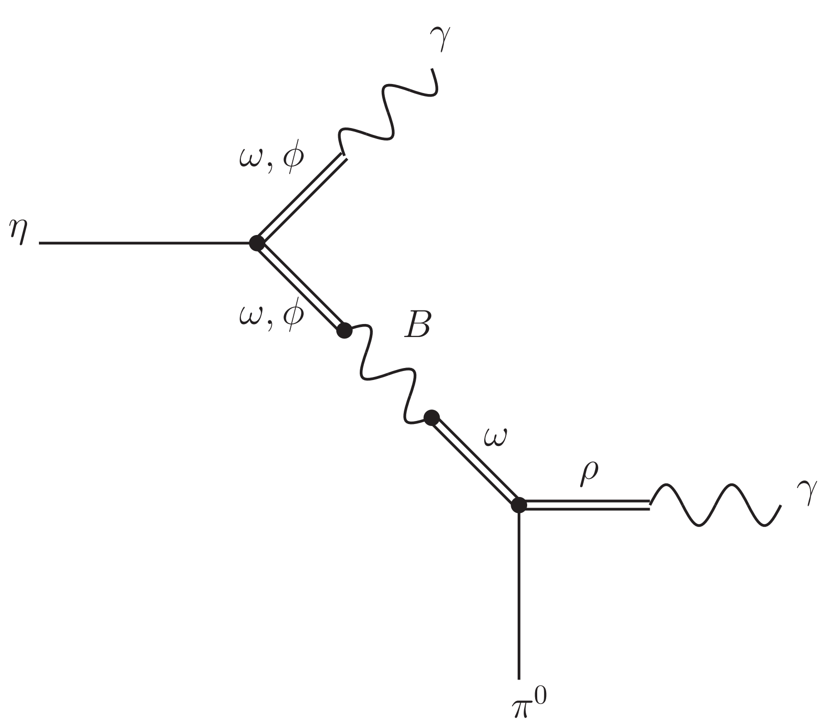
$$\mathscr{A}^{\text{VMD}}_{\eta\to\pi^0\gamma\gamma} = \sum_{V=\rho^0,\omega,\phi} g_{V\eta\gamma} g_{V\pi^0\gamma} \left[\frac{(P\cdot q_2 - m_\eta^2)\{a\} - \{b\}}{D_V(t)} + \left\{ \begin{array}{c} q_2 \leftrightarrow q_1 \\ t \leftrightarrow u \end{array} \right\} \right]$$

LσM:

$$\mathscr{A}^{\text{L}\sigma\text{M}}_{\eta\to\pi^0\gamma\gamma} = \frac{2\alpha_{em}}{\pi} \frac{1}{m_{K^+}^2} L(s_K)\{a\} \times \mathscr{A}^{\text{L}\sigma\text{M}}_{K^+K^-\to\pi^0\eta}$$

B boson:

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



$$g_{B\pi^0\gamma}(t) = \frac{e g_B}{4\pi^2 f_\pi} F_\omega(t) \qquad F_V(s) = \frac{m_V^2}{m_V^2 - s - i m_V \Gamma_V}$$

$$g_{B\eta\gamma}(t) = \frac{e g_B}{12\pi^2 f_\pi} \left[\cos\varphi_P F_\omega(t) + \sqrt{2}\sin\varphi_P F_\phi(t) \right]$$

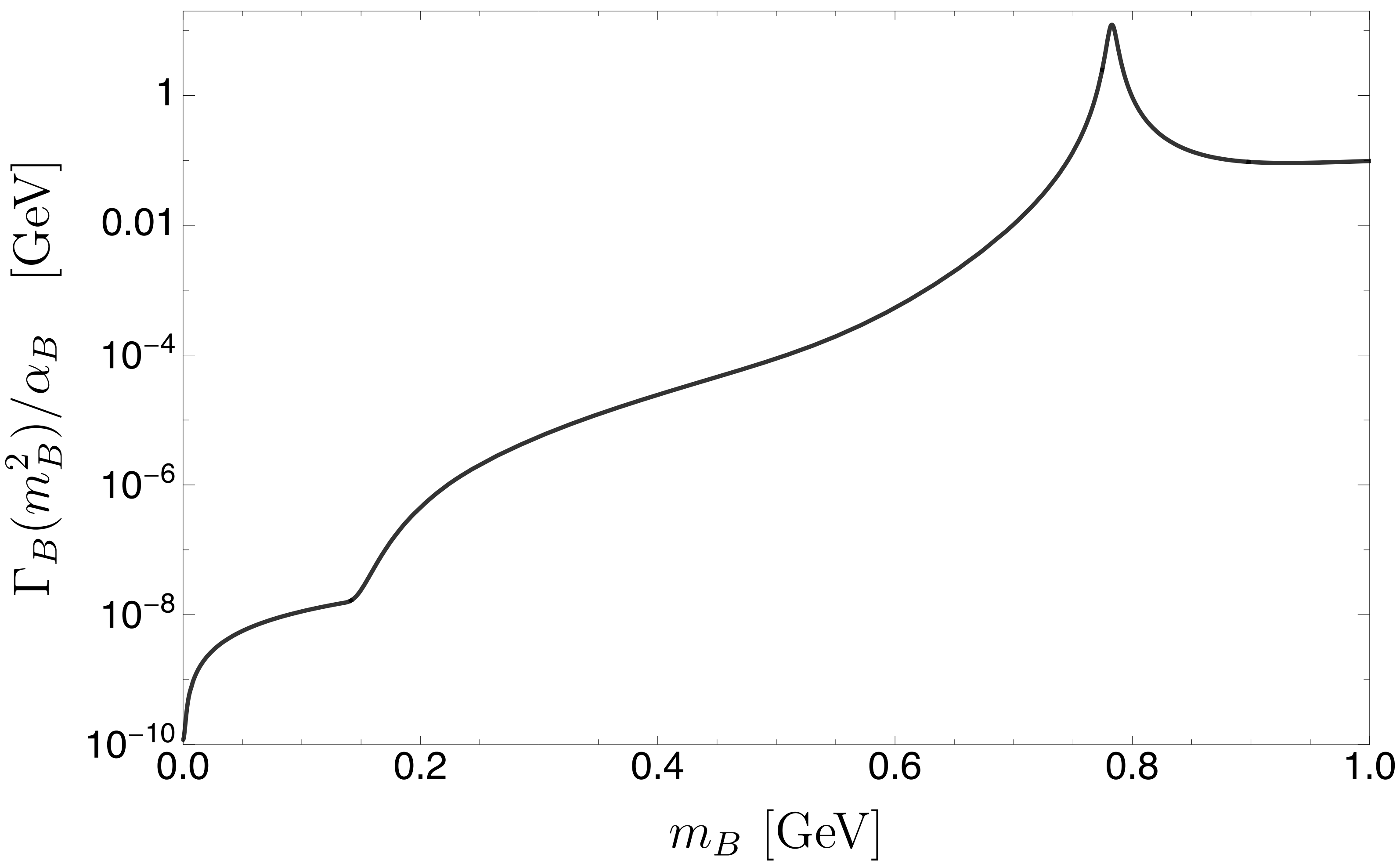
$$D_B(t) = m_B^2 - t - i\sqrt{t}\,\Gamma_B(t)$$

How are these processes calculated?

B boson width:

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

$$+ \frac{\tilde{\gamma}_{B\to\pi^+\pi^-}(t)}{\tilde{\gamma}_{B\to\pi^+\pi^-}(m_B^2)}\Gamma_{B\to\pi^+\pi^-}\theta(t-4m_\pi^2) + \frac{\tilde{\gamma}_{B\to\pi^+\pi^-\pi^0}(t)}{\tilde{\gamma}_{B\to\pi^+\pi^-\pi^0}(m_B^2)}\Gamma_{B\to\pi^+\pi^-\pi^0}\theta(t-9m_\pi^2),$$



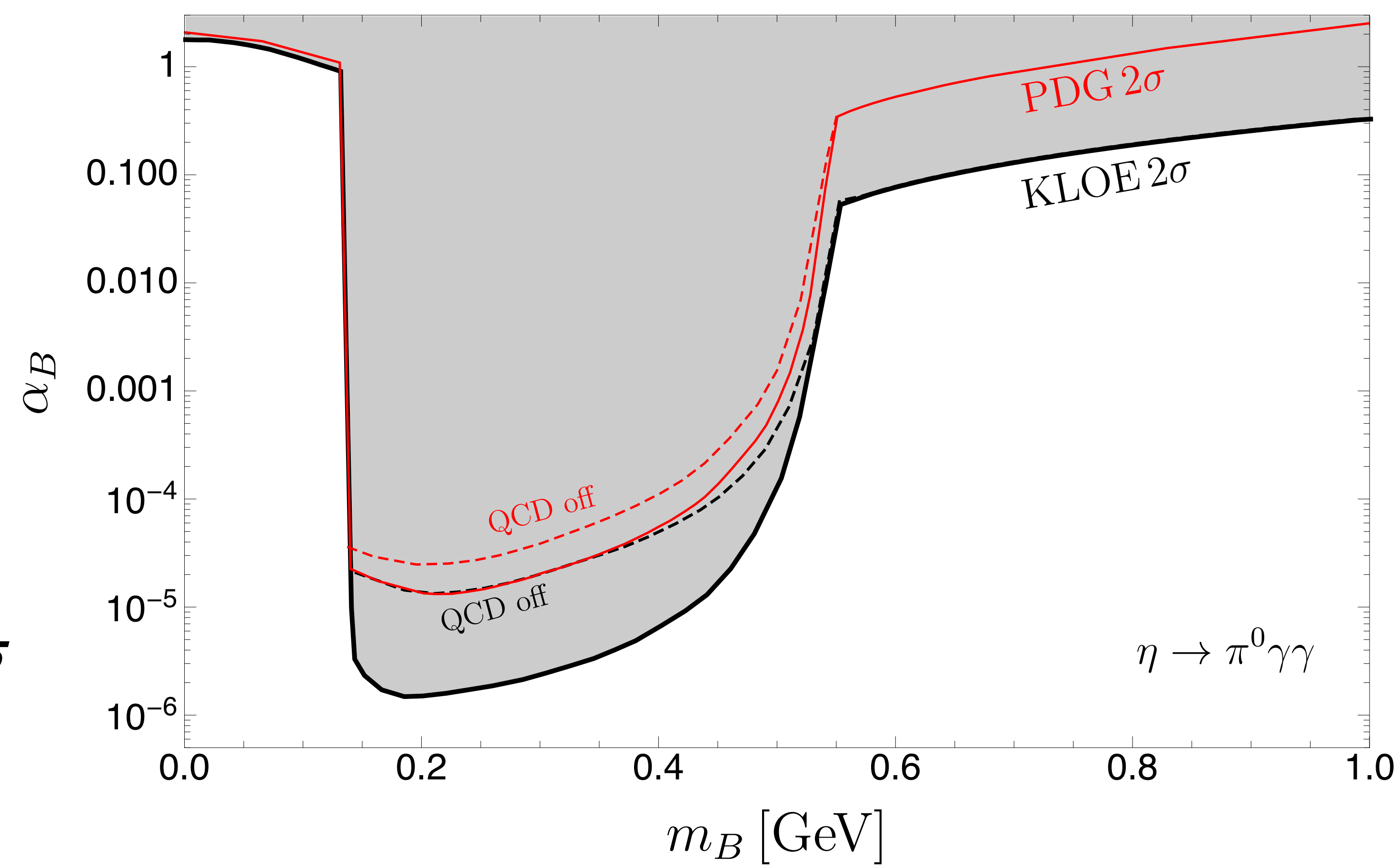
New exclusion plots

Not assuming the NWA

and QCD contribution on

and

$\mathrm{BR}(\eta \to \pi^0\gamma\gamma) < \mathrm{BR}_{\mathrm{exp}}$ at 2σ



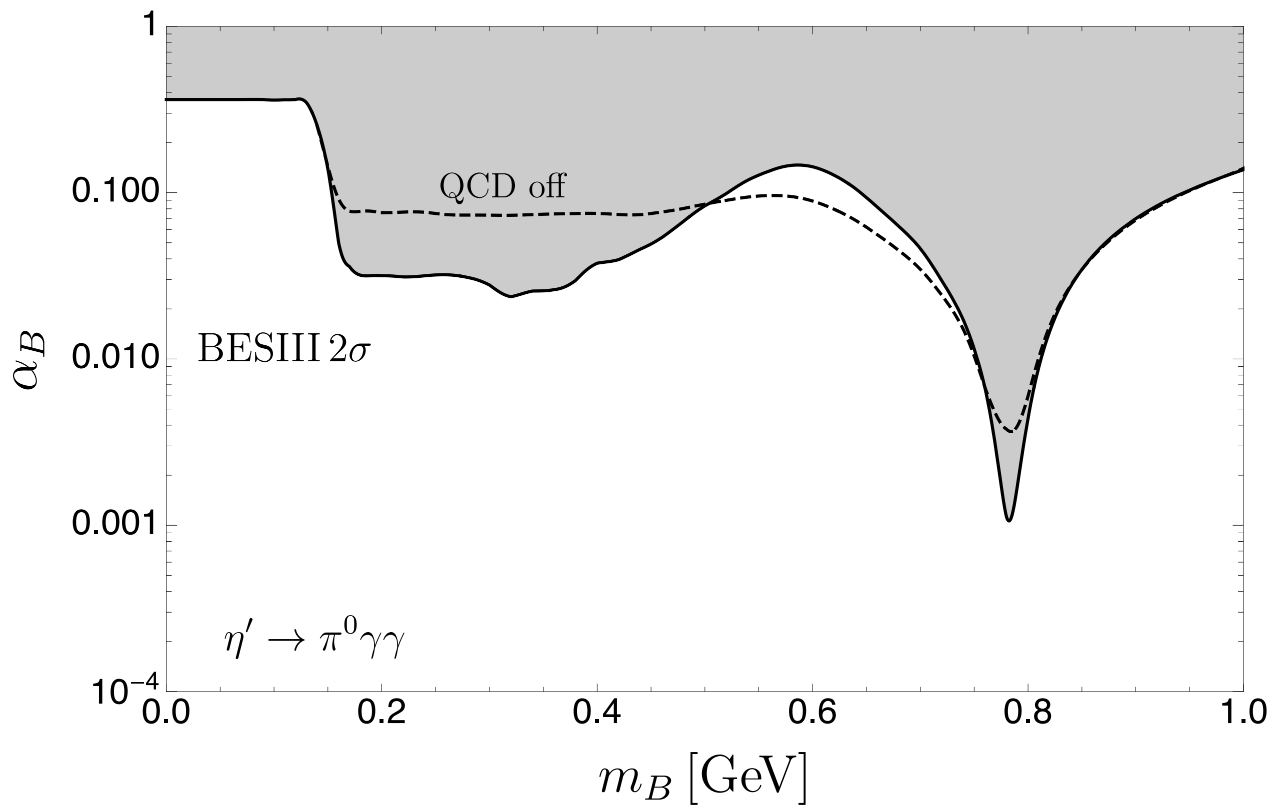
$\mathrm{BR(PDG)} = (2.56 \pm 0.22) \times 10^{-4}$ **P. A. Zyla *et.* Al. [PDG], PTEP 2020 (2020) 093C01**

$\mathrm{BR(KLOE)} = (1.23 \pm 0.14) \times 10^{-4}$ **B. Cao [KLOE-2], PoS EPS-HEP2021 (2022) 409**

R. Escribano, S. Gonzàlez-Solís and E. Royo, Phys. Rev. D 106 (2022) 114007

New exclusion plots

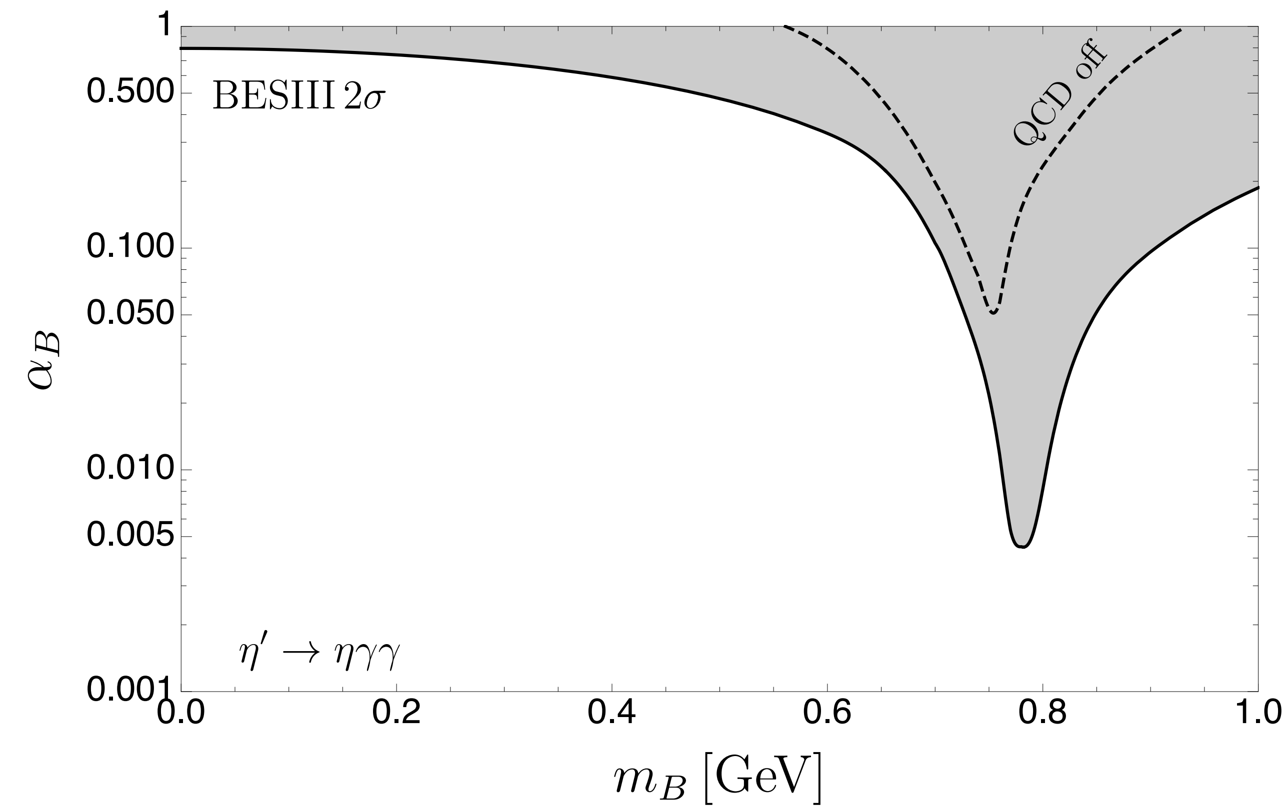
$$\eta' \to \pi^0\gamma\gamma$$



$$\text{BR(BESIII)} = (3.20 \pm 0.07 \pm 0.23) \times 10^{-3}$$

M. Ablikim et. al. [BESIII], Phys. Rev. D 96 (2017) 012005

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

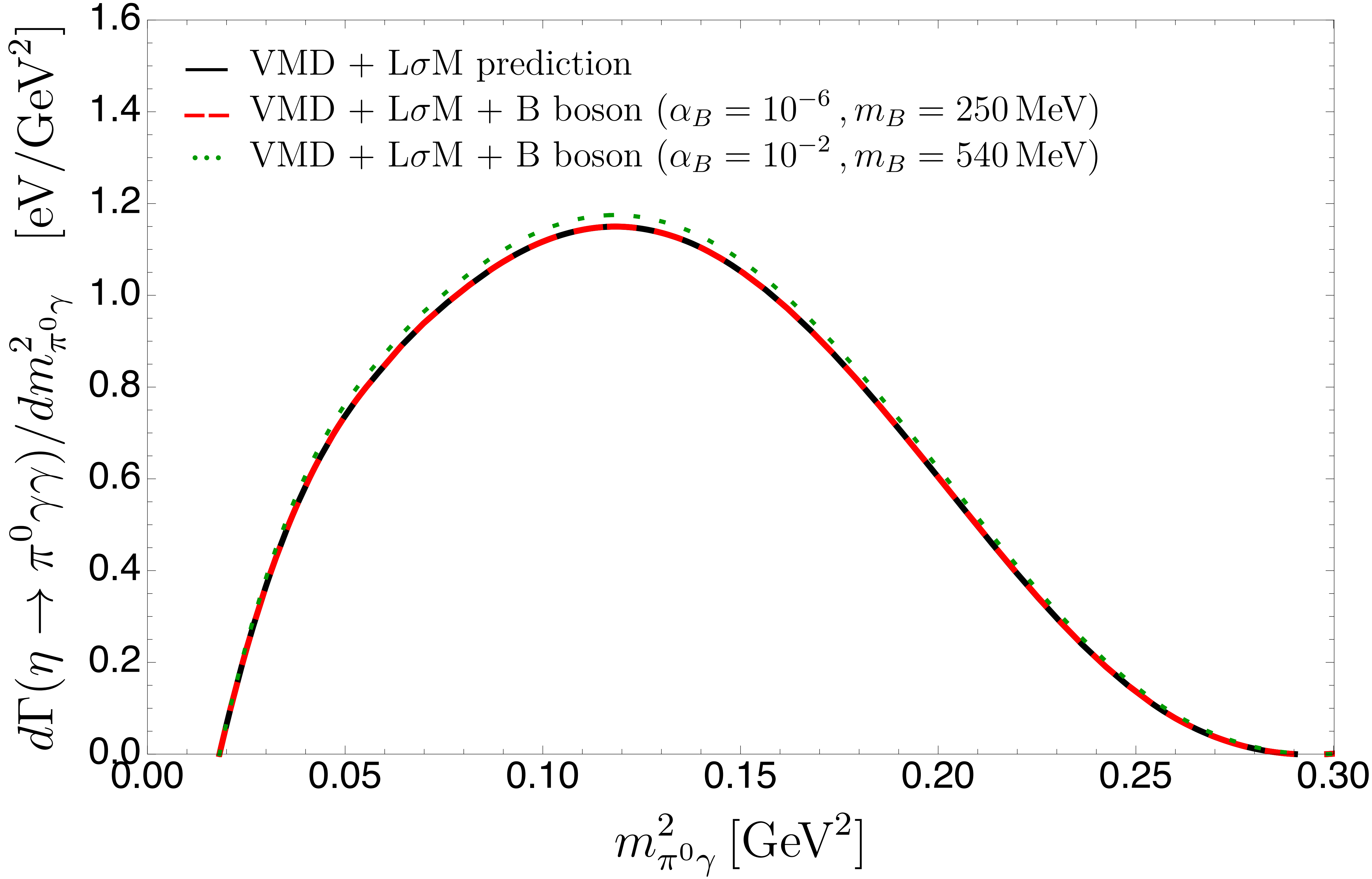


$$\text{BR(BESIII)} = (8.25 \pm 3.41 \pm 0.72) \times 10^{-3}$$

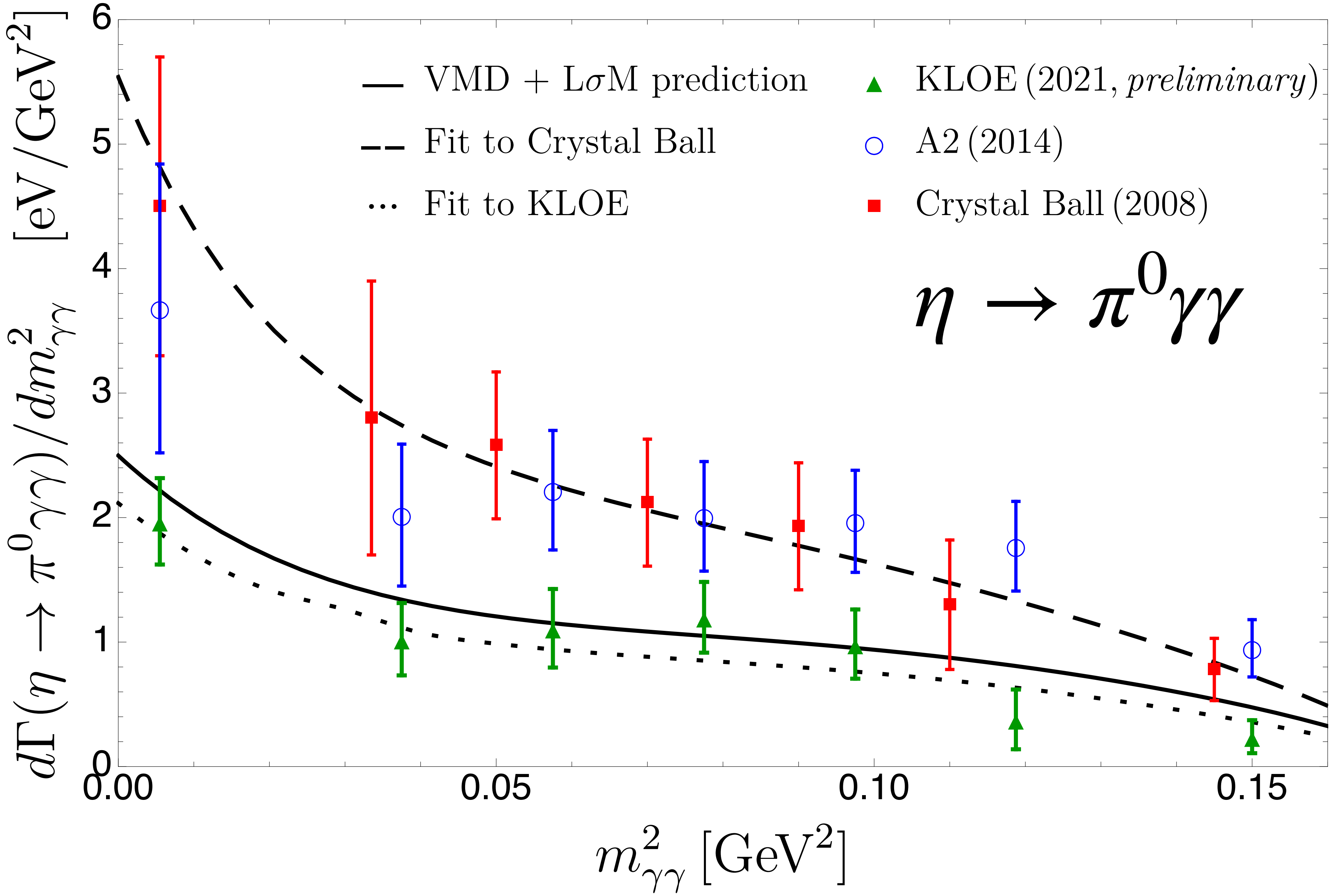
M. Ablikim et. al. [BESIII], Phys. Rev. D 100 (2019) 052015

R. Escribano, S. Gonzàlez-Solís and E. Royo, Phys. Rev. D 106 (2022) 114007

Are peaks in the $\pi^0\gamma$ mass distribution see



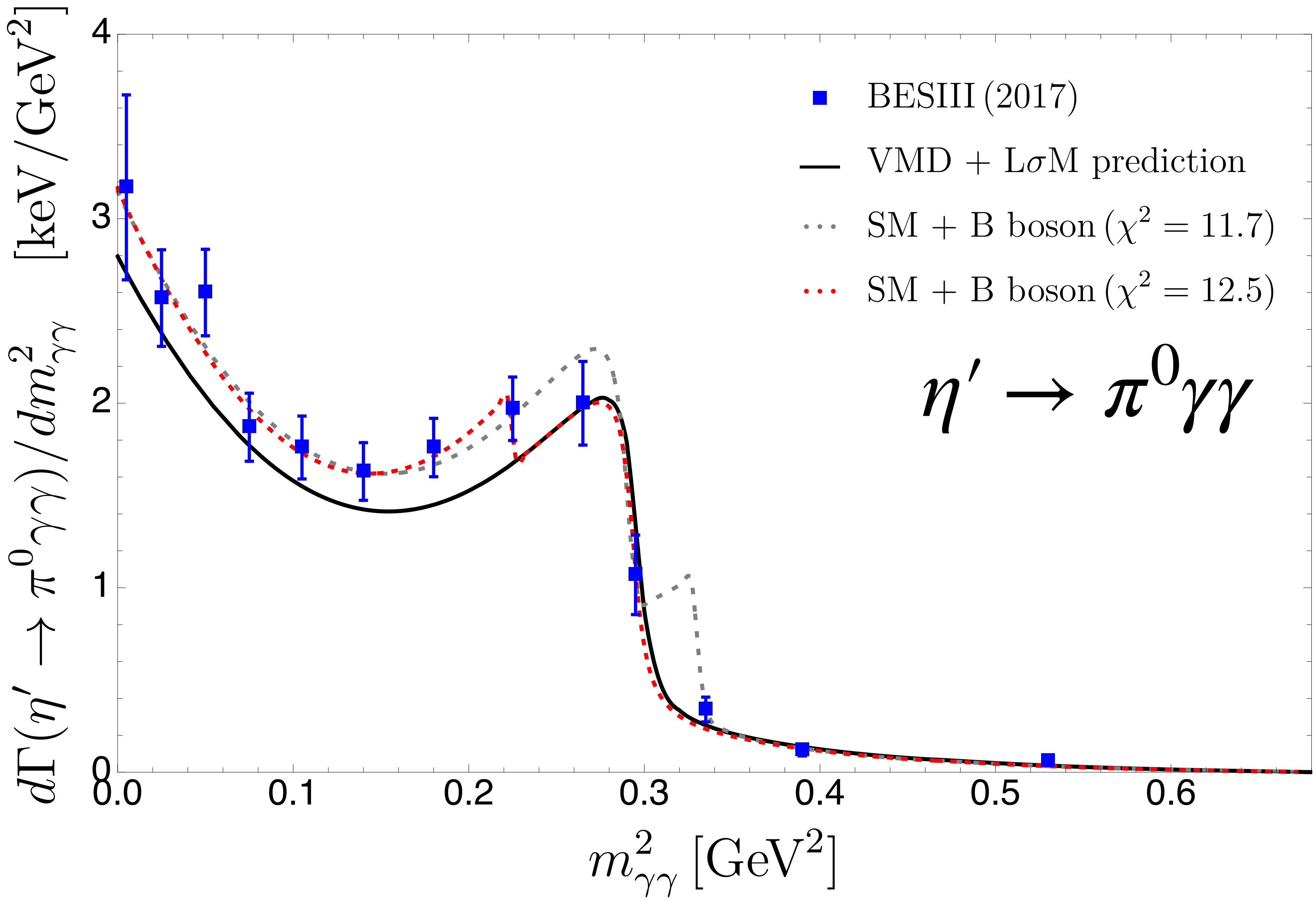
Fits to the γγ mass distribution



Crystal Ball: $\alpha_B = 0.40^{+0.07}_{-0.08}\,, \quad m_B = 583^{+32}_{-20}$ MeV $\quad \chi^2_{\rm min}/{\rm dof} = 0.4/5 = 0.1$

KLOE: $\alpha_B = 0.049^{+40}_{-27}\,, \quad m_B = 135^{+1}_{-135}$ MeV $\quad \chi^2_{\rm min}/{\rm dof} = 4.5/5 = 0.9$

Fits to the γγ mass distribution

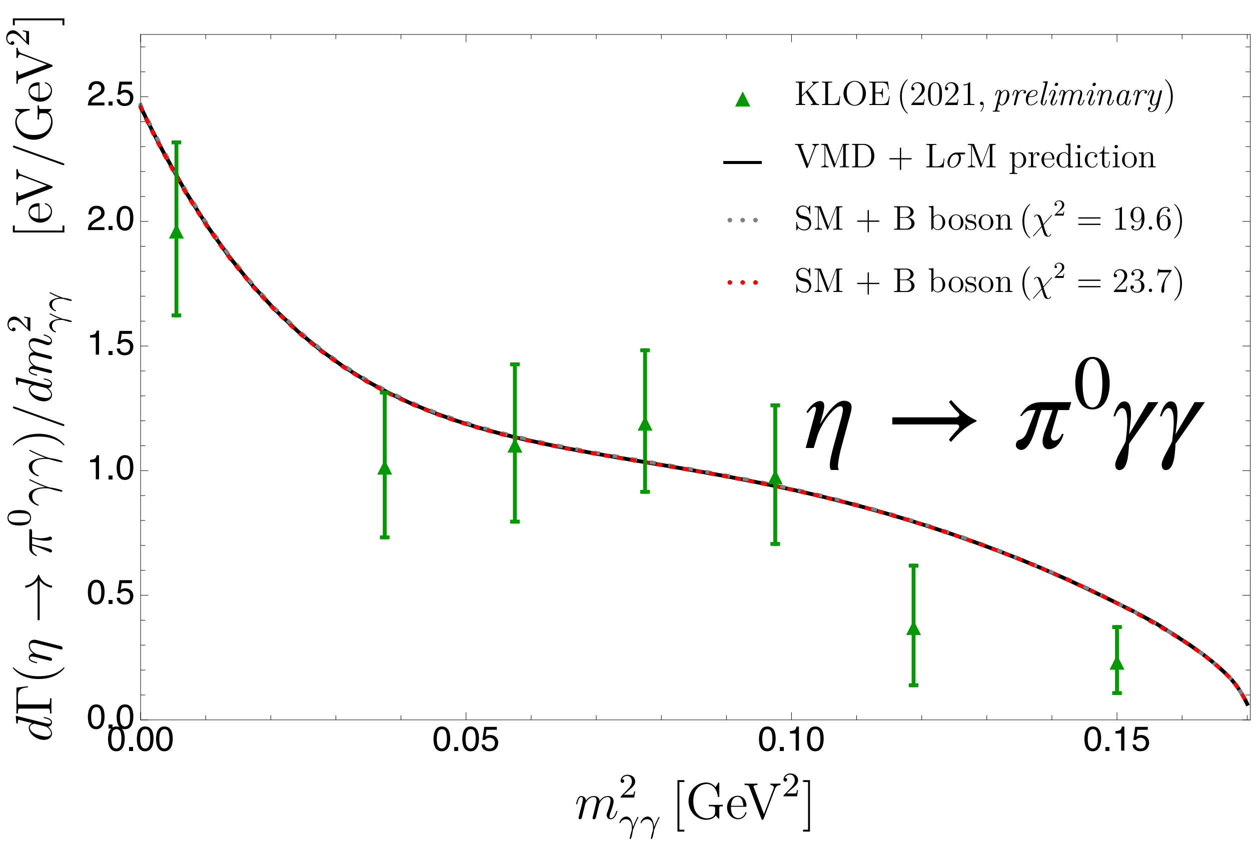


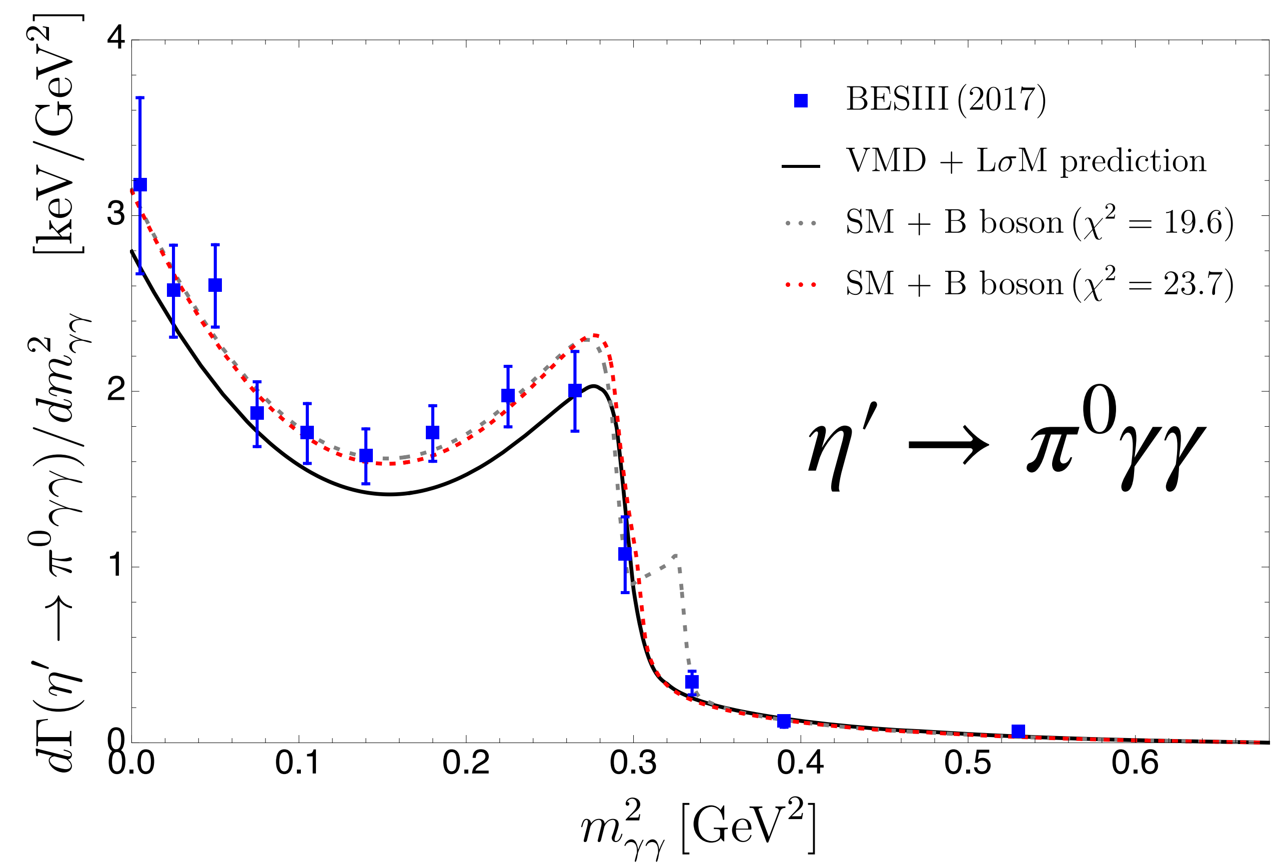
BESIII: $\alpha_B = 0.005(1)\,, \quad m_B = 759(1)$ MeV $\quad \alpha_B = 0.018(5)\,, \quad m_B = 156^{+5}_{-1}$ MeV

$\chi^2_{\rm min}/\text{dof} = 11.7/11 = 1.1 \qquad \chi^2_{\rm min}/\text{dof} = 12.5/11 = 1.1$

Fits to the γγ mass distribution

Joint Fit





$$\alpha_B = 0.005(1)\,, \quad m_B = 759(1)\text{ MeV}$$

$$\chi^2_{\text{min}}/\text{dof} = 19.6/18 = 1.1$$

$$\alpha_B = 5(2)\times 10^{-4}\,, \quad m_B = 780^{+3}_{-4}\text{ MeV}$$

$$\chi^2_{\text{min}}/\text{dof} = 23.7/18 = 1.3$$

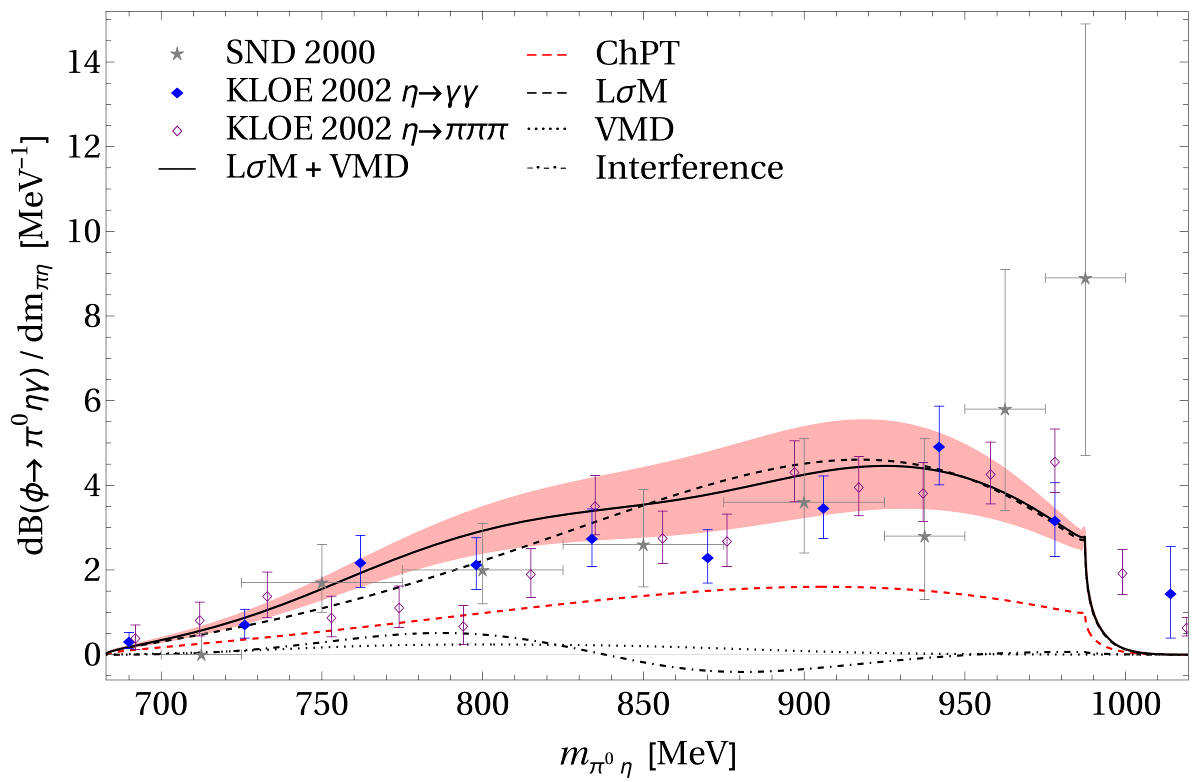
BESIII data dominates the fit

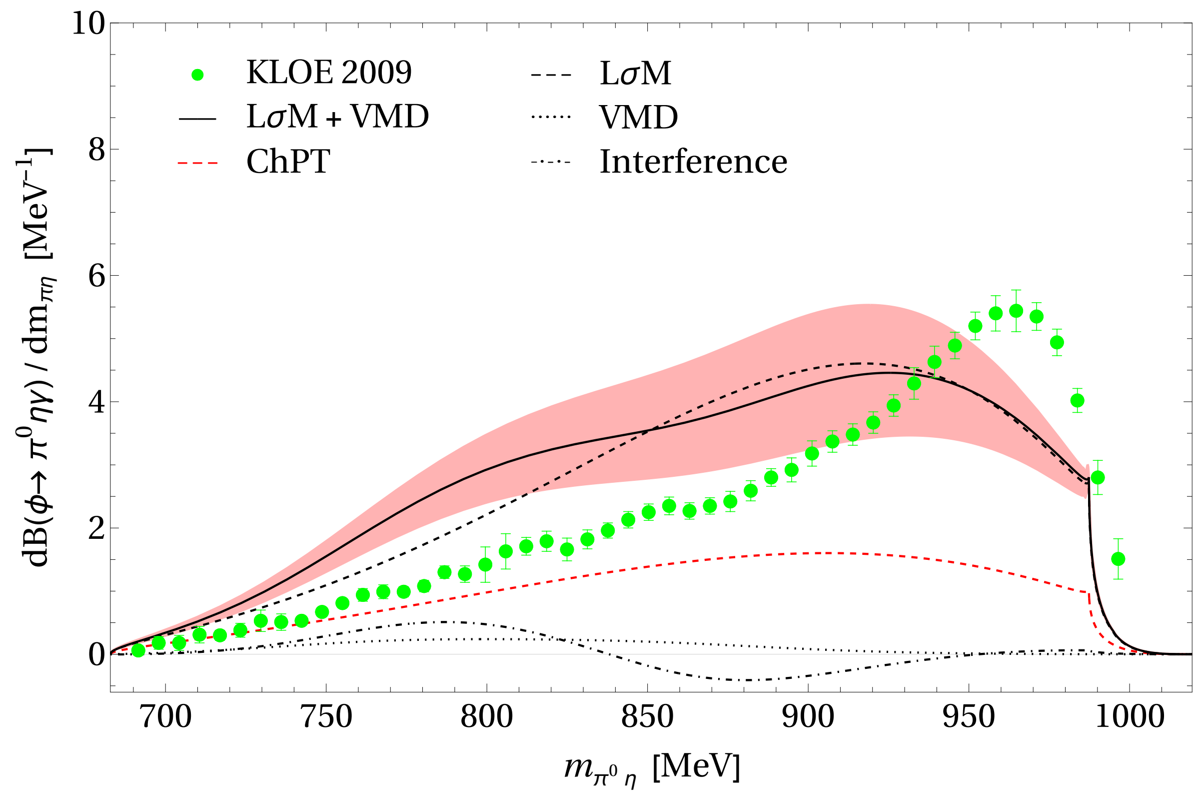
In preparation: $\phi \to \pi^0 \eta \gamma$

R. Escribano, A. Miranda, in preparation

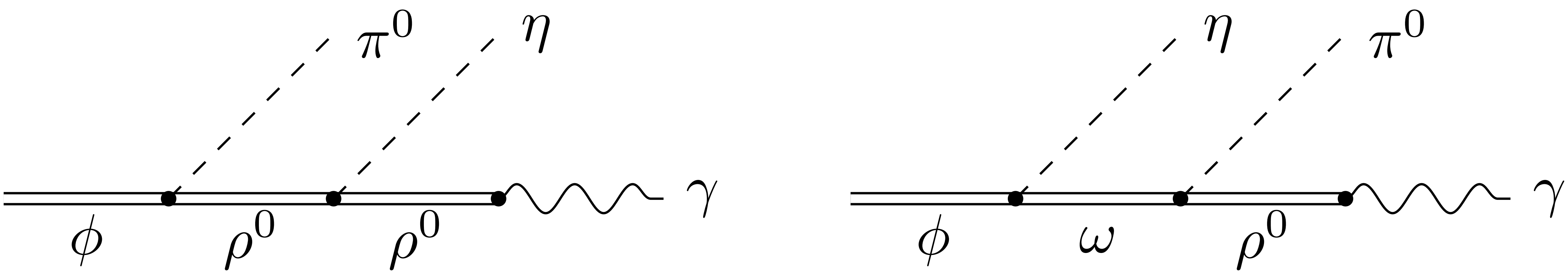
Much more statistics from KLOE

Scalar contribution dominates, vector contributions subdominate



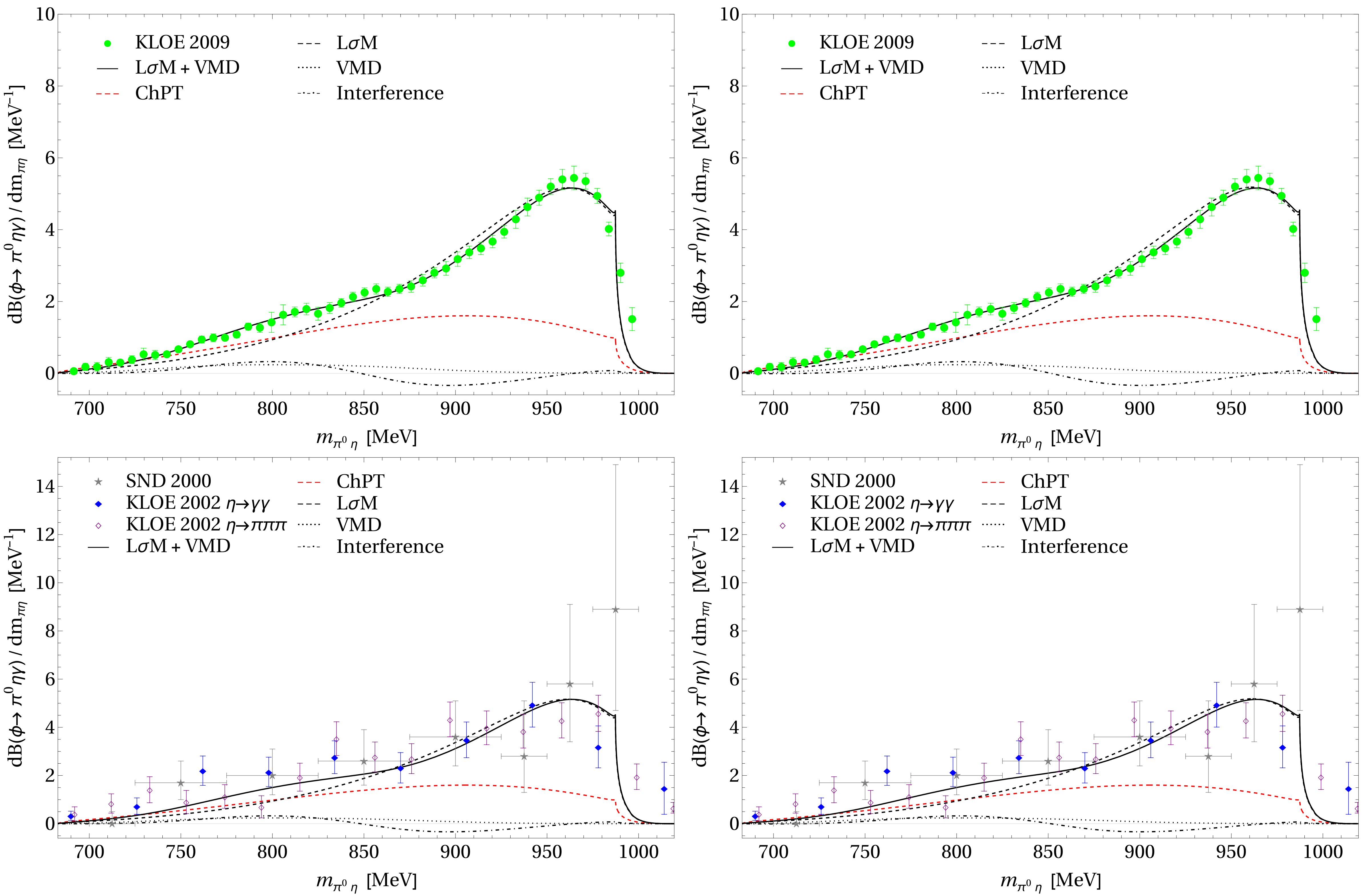


In preparation: $\phi \to \pi^0 \eta \gamma$

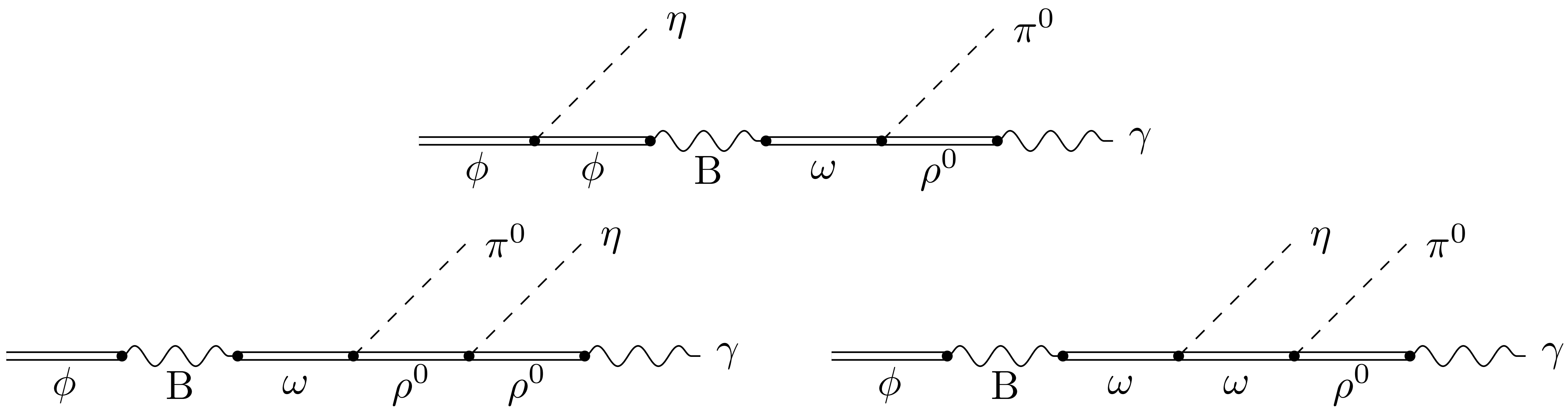


	Fit 1	Fit 2
$\chi^2/d.o.f$	$69.3/46 \sim 1.5$	$68.0/45 \sim 1.5$
m_{a_0}	$986.6^{+0.7}_{-1.2}$	$986.6^{+0.7}_{-1.1}$
$g_{a_0 K\bar{K}}$	$\pm(2838.2^{+80.7}_{-77.8})$	$\pm(2844.6^{+81.9}_{-79.0})$
$g_{a_0 \pi\eta}$	$\pm(3692.0^{+56.5}_{-55.1})$	$\pm(3691.3^{+57.1}_{-55.7})$
δ_{+0}	$0^{\dagger}$	0.12 ± 0.10

In preparation: $\phi \to \pi^0 \eta \gamma$

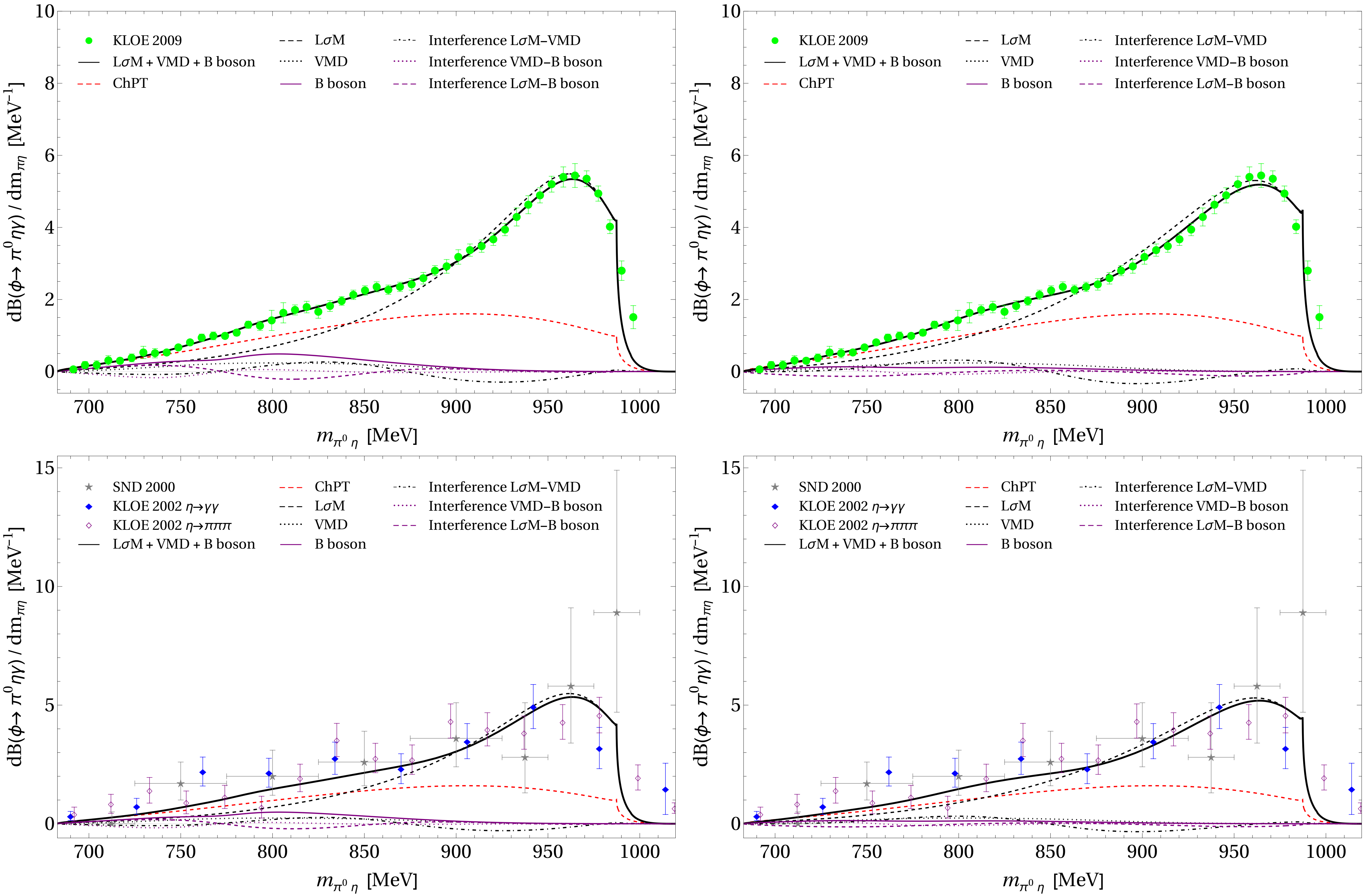


In preparation: $\phi \to \pi^0 \eta \gamma$

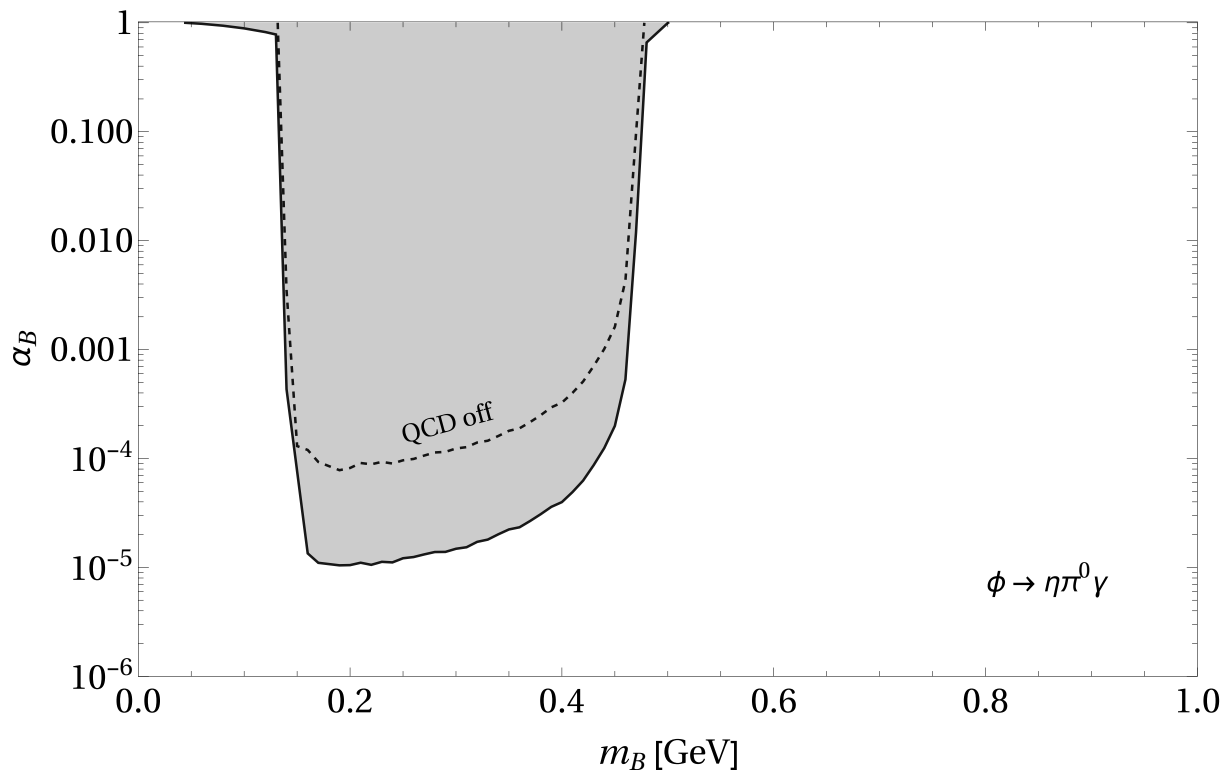


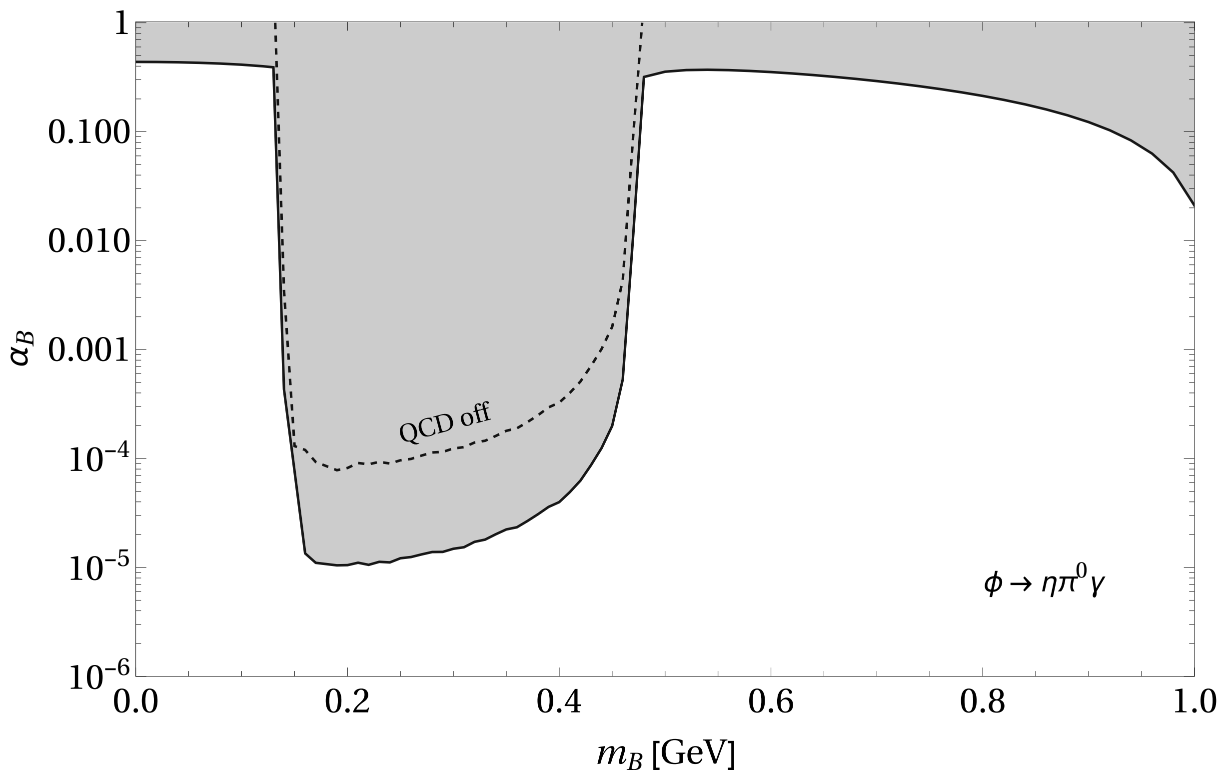
	V. R	V. A
$\chi^2/d.o.f$	$63.1/43 \sim 1.5$	$58.2/42 \sim 1.4$
m_{a_0}	985.16 ± 1.87	980.14 ± 2.68
$g_{a_0 K\bar{K}}$	$\pm(2743.2 \pm 130.5)$	$\pm(2401.3 \pm 146.6)$
$g_{a_0 \pi\eta}$	$\pm(3570.9 \pm 122.8)$	$\pm(3190.1 \pm 174.8)$
δ_{+0}	$0^\dagger$	$(48.1 \pm 29.7)^\circ$
m_B	496.3 ± 34.6	475.4 ± 4.4
α_B	0.45 ± 0.24	0.35 ± 0.07
δ_B	$(311.3 \pm 8.7)^\circ$	$(165.8 \pm 13.3)^\circ$

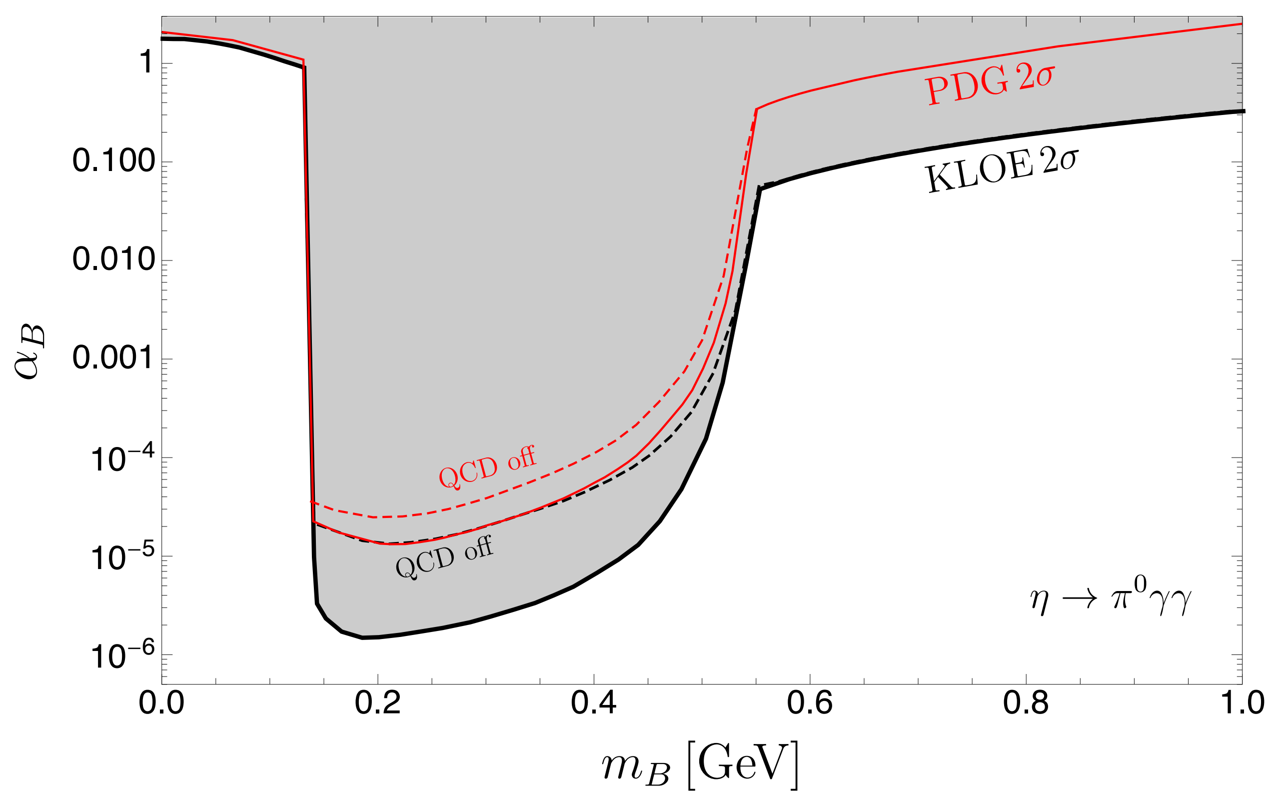
In preparation: $\phi \to \pi^0\eta\gamma$



In preparation: $\phi \to \pi^0 \eta \gamma$



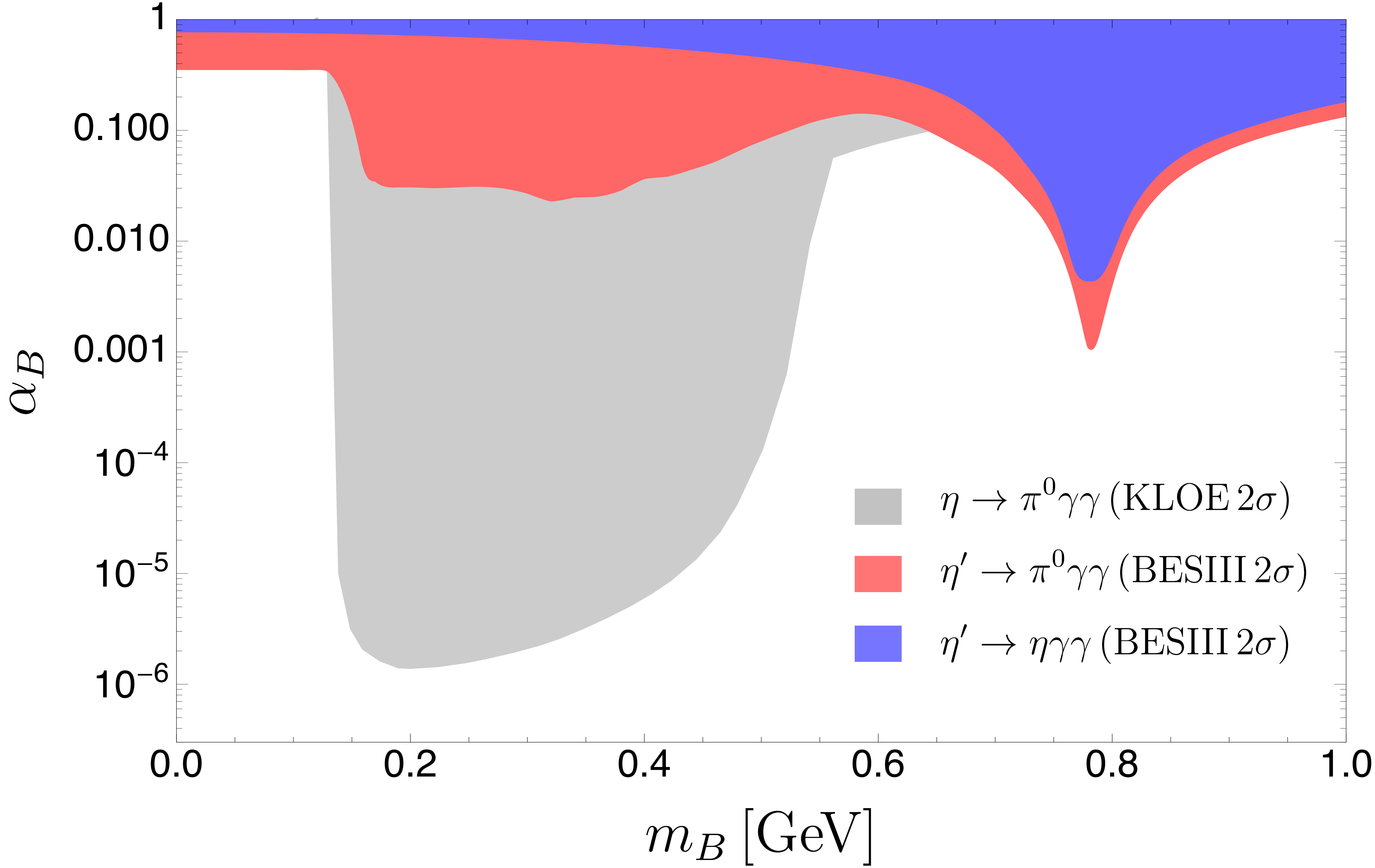




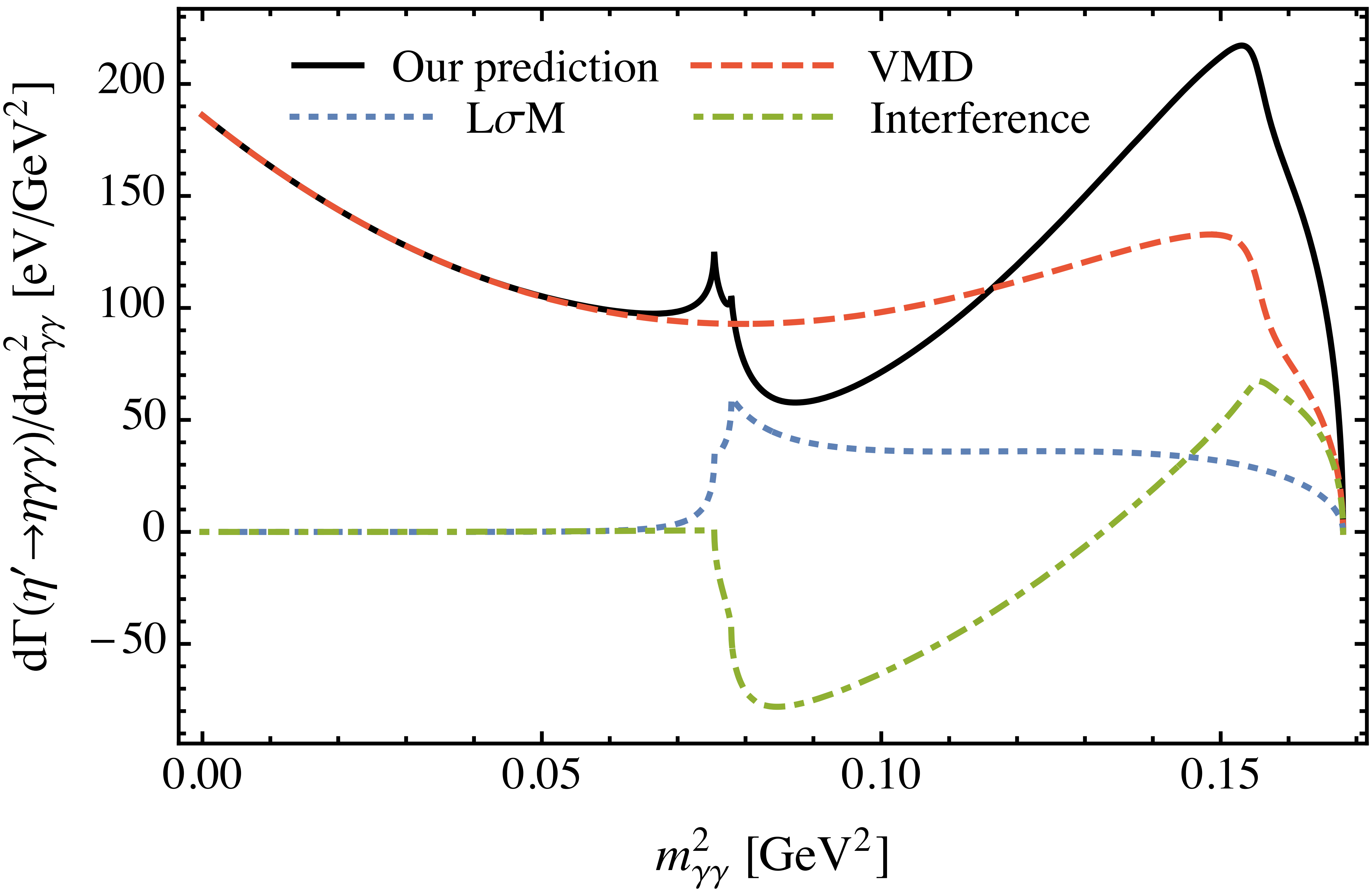
Conclusions

- The sensitivity of the rare decays $\eta, \eta' \to \pi^0\gamma\gamma$ and $\eta' \to \eta\gamma\gamma$ to a leptophobic U(1) B boson in the mass range MeV-GeV has been analysed in detail
- Stringent limits on the B boson parameters m_B and α_B have been found
- The current constraints have been strengthened by one order of magnitude from $\eta \to \pi^0\gamma\gamma$
- These constraints would make a B-boson signature strongly suppressed

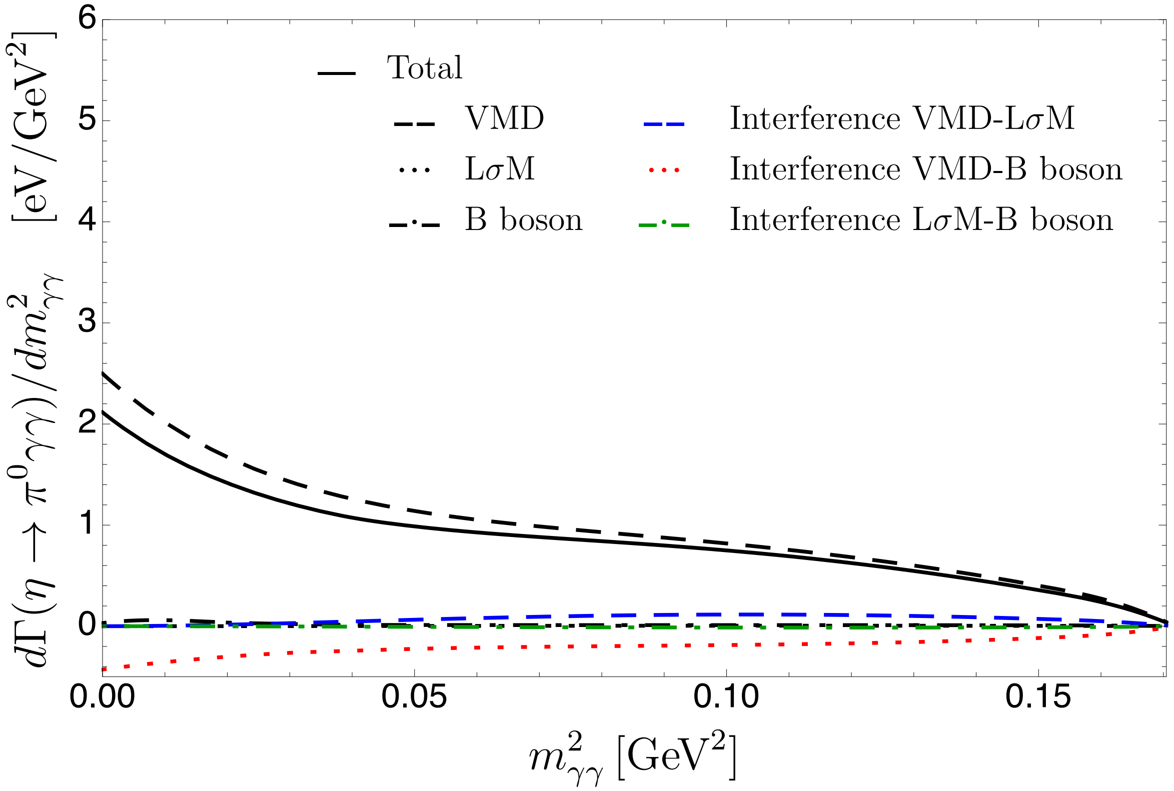
Conclusions

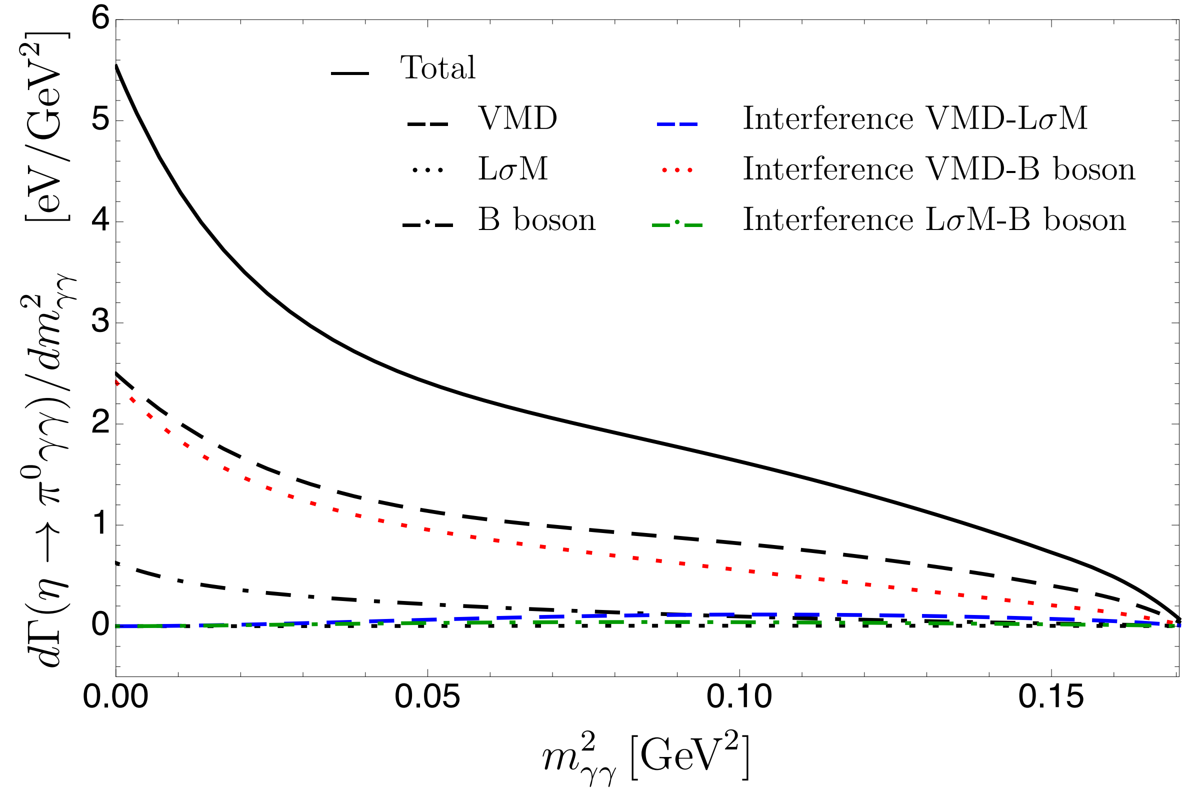


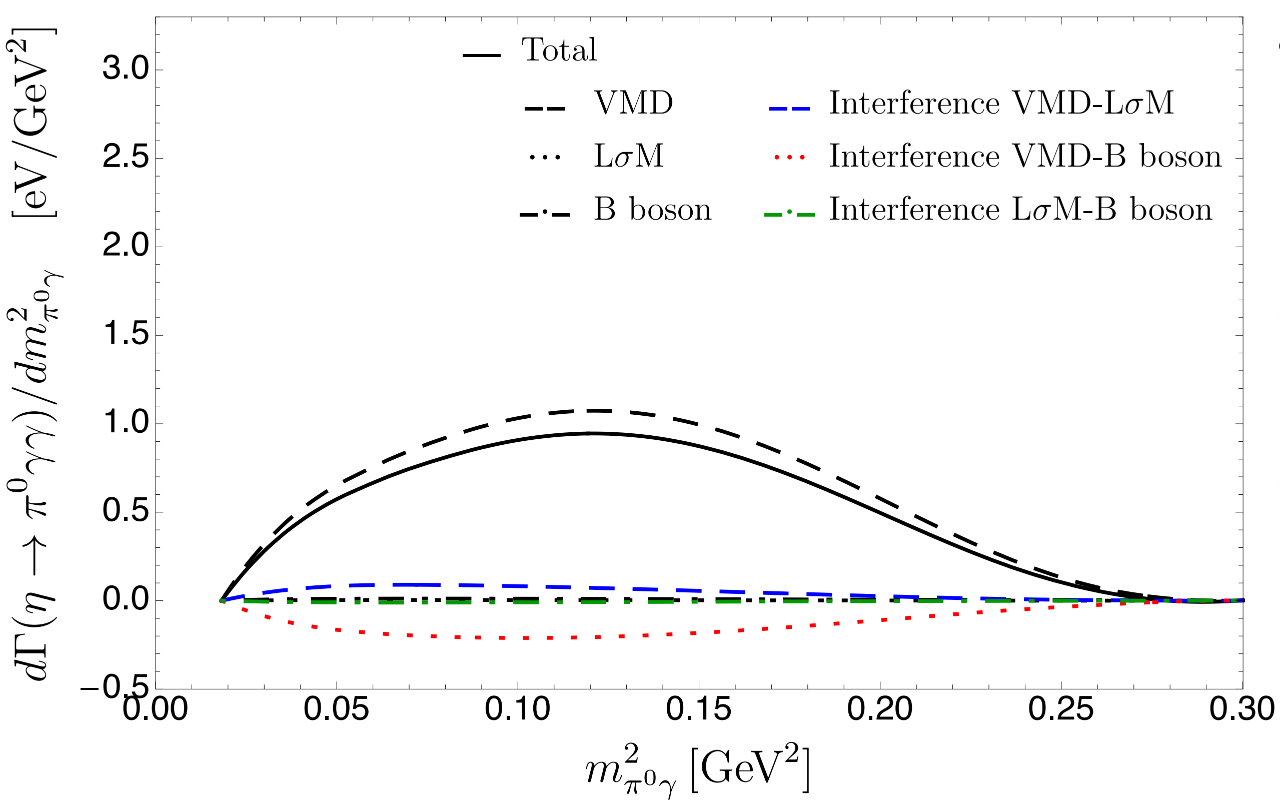
Backup slides

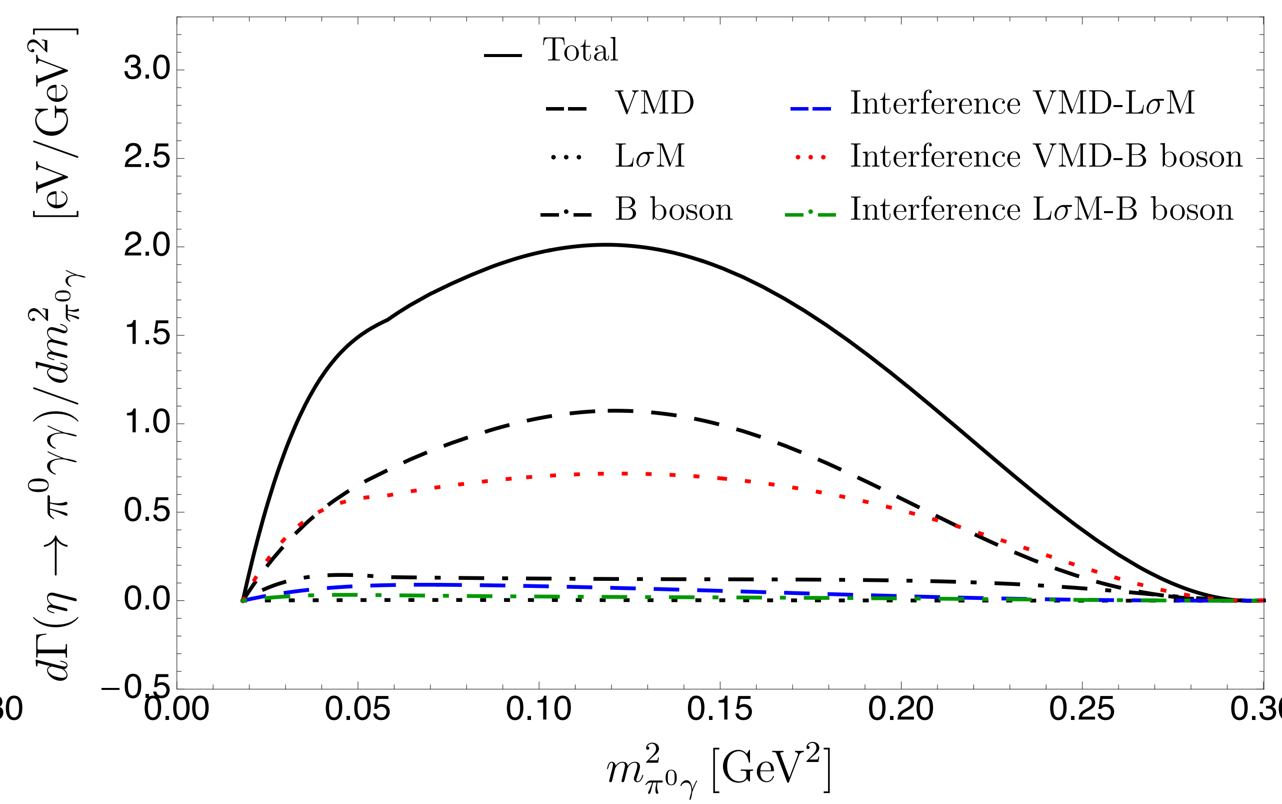


Backup slides

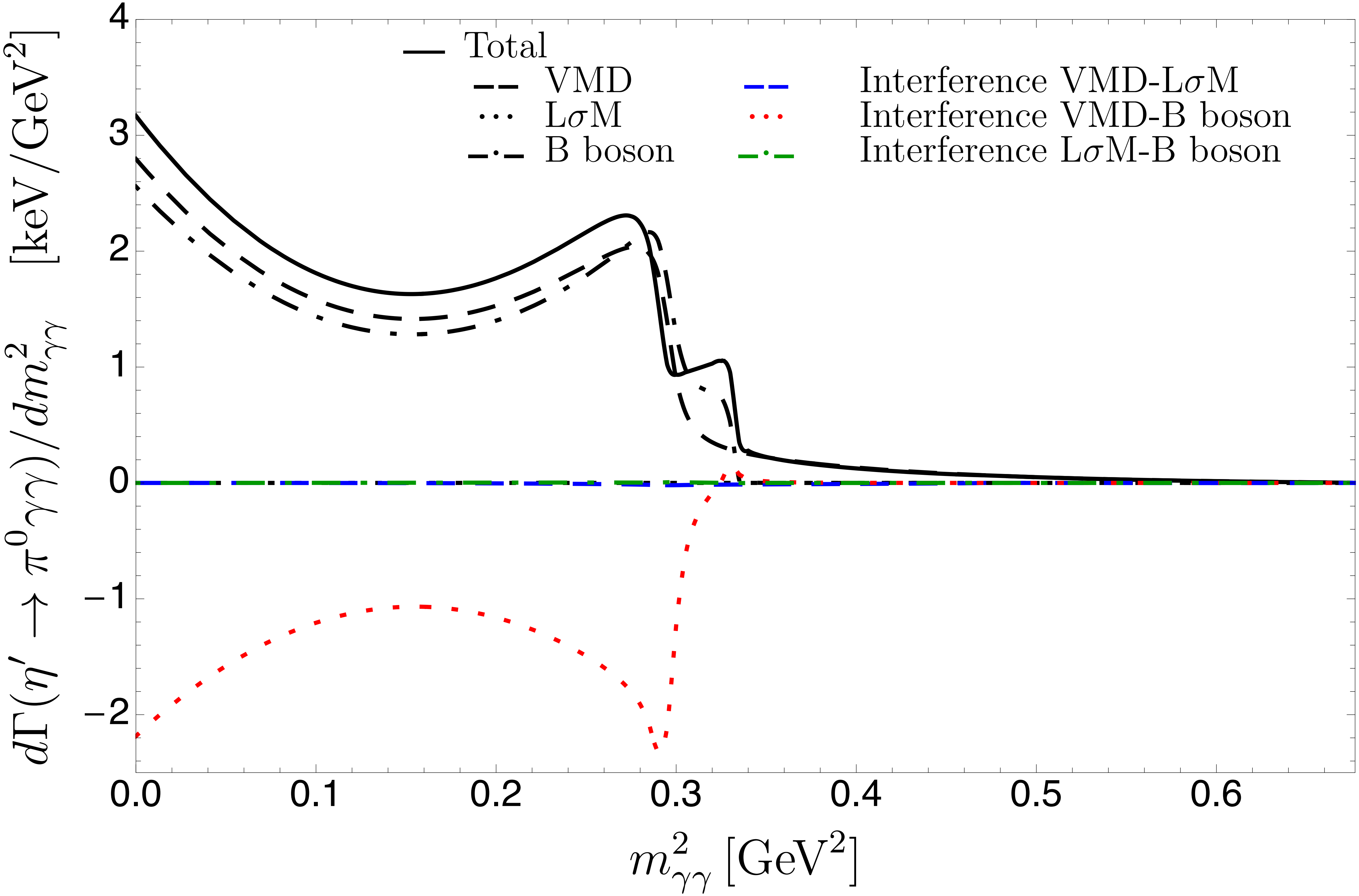








Backup slides



Backup slides

Contribution	LσM	Fit 1	Fit 2
Scalar	$8.29^{+1.78}_{-1.74}$	$6.52(^{24}_{20})(^{23}_{22})(1)$	$6.54(^{22}_{20})(23)(1)$
Vector		0.36(0)	
Interference	0.13(2)	0.02(0)(0)(0)	0.01(0)(0)(0)(1)
Total	$8.78^{+1.78}_{-1.74}$	$6.90(^{33}_{30})$	$6.91(^{32}_{31})$
PDG [14]		7.27 ± 0.30	

Table 2: Contributions to $\mathcal{B}(\phi \to \pi^0\eta\gamma)$ in units of 10^{-5}.

Contribution	$\mathcal{B}(\phi \to \pi^0\eta\gamma) \times 10^5$			
LσM	6.52			
VMD	0.36			
Interference SV	+0.02			
Contribution	Set 1		Set 2	
	V. R	V. A	V. R	V. A
$B-$boson	0.08	0.08	$4.0 \cdot 10^{-5}$	$2.8 \cdot 10^{-4}$
Interference SB	$+5.4 \cdot 10^{-7}$	$+5.8 \cdot 10^{-7}$	$-1.2 \cdot 10^{-3}$	$-7.0 \cdot 10^{-4}$
Interference VB	$+4.8 \cdot 10^{-7}$	$+1.8 \cdot 10^{-6}$	$+8.4 \cdot 10^{-4}$	+0.02

Table 3: Contributions to $\mathcal{B}(\phi \to \pi^0\eta\gamma)$ in units of 10^{-5}. Set 1: $\alpha_B = 10^{-6}$, $m_B =$ 250 MeV. Set 2: $\alpha_B = 10^{-2}$, $m_B = 540$ MeV. These values are taken from Ref. [19].