# XIX Mexican Workshop on Particles and Fields

**October 21, 2025**

# Sub-GeV leptophobic B-boson exchange in $\Phi \to \eta \pi^0 \gamma$ decays


Alejandro Miranda
Cinvestav, México

**In collaboration with:**
**Rafel Escribano (IFAE, UAB, Spain)**


Institut de Física d'Altes Energies

Cinvestav

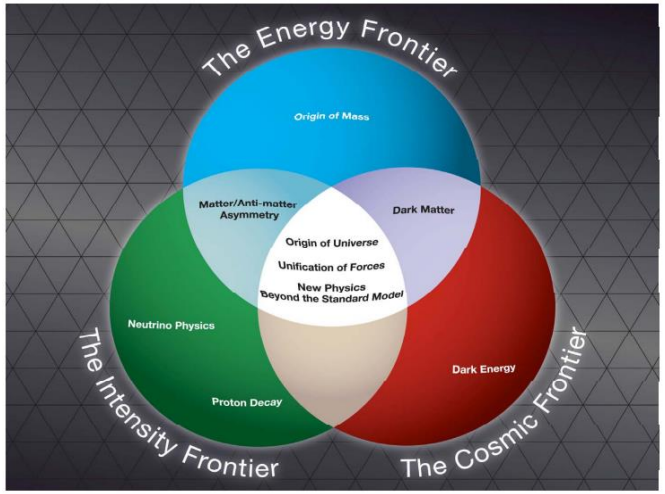
BIST Barcelona Institute of Science and Technology

Generalitat de Catalunya
Departament de Recerca i Universitats

# Exploring Weakly Coupled New Physics

- **Energy Frontier:** Direct searches
- **Intensity Frontier:** High-luminosity, rare process detection

**2008 Frontiers of Particle Physics**




**2023 Science Drivers**


Report of the P5 Panel

- **Key Research Themes:**
  - **Hidden Sector Particles:** axions, axion-like, dark photons, heavy neutral leptons
  - **Dark Matter Candidates:** WIMPs, dark sector particles

# Searches of a leptophobic B boson

- What if a **new force couples** predominantly to **quarks** over leptons?
  - **Simplest model:** A new gauge boson **B** that couples to the baryon number

$$\mathcal{L}_{\rm int} = \left(\frac{1}{3}g_B + \varepsilon Q_q e\right)\bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu \quad \Longrightarrow \quad \varepsilon \sim e g_B/(4\pi)^2 \qquad \alpha_B = \frac{g_B^2}{4\pi}$$

  - It **preserves** the low-energy symmetries of QCD: **C, P, SU(3)$_F$**
  - **B** is a **singlet** under isospin
  - $I^G(J^{PC}) = 0^-(1^{--})$ ⟹ **B** is **ω meson like!** $m_\pi \lesssim m_B \lesssim \text{GeV}$

| | Dark-photon like | $m_B$ [MeV] | | Novel signatures |
|---|---|---|---|---|
| Decay → <br> Production ↓ | $B \to e^+e^-$ <br> $m_B \sim 1 - 140$ MeV | $B \to \pi^0\gamma$ <br> 140 – 620 MeV | $B \to \pi^+\pi^-\pi^0$ <br> 620 – 1000 MeV | $B \to \eta\gamma$ |
| $\pi^0 \to B\gamma$ | $\pi^0 \to e^+e^-\gamma$ | ⋯ | ⋯ | ⋯ |
| $\eta \to B\gamma$ | $\eta \to e^+e^-\gamma$ | $\eta \to \pi^0\gamma\gamma$ | ⋯ | ⋯ |
| $\eta' \to B\gamma$ | $\eta' \to e^+e^-\gamma$ | $\eta' \to \pi^0\gamma\gamma$ | $\eta' \to \pi^+\pi^-\pi^0\gamma$ | $\eta' \to \eta\gamma\gamma$ |
| $\omega \to \eta B$ | $\omega \to \eta e^+e^-$ | $\omega \to \eta\pi^0\gamma$ | ⋯ | ⋯ |
| $\phi \to \eta B$ | $\phi \to \eta e^+e^-$ | $\phi \to \eta\pi^0\gamma$ | ⋯ | |

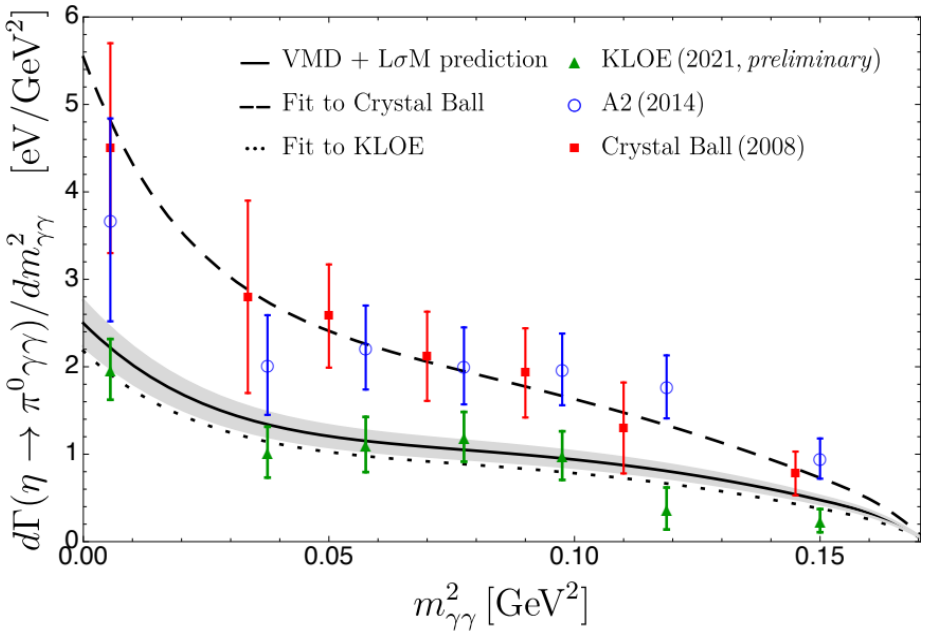
S. Tulin. Phys.Rev.D 89 (2014) 11, 114008

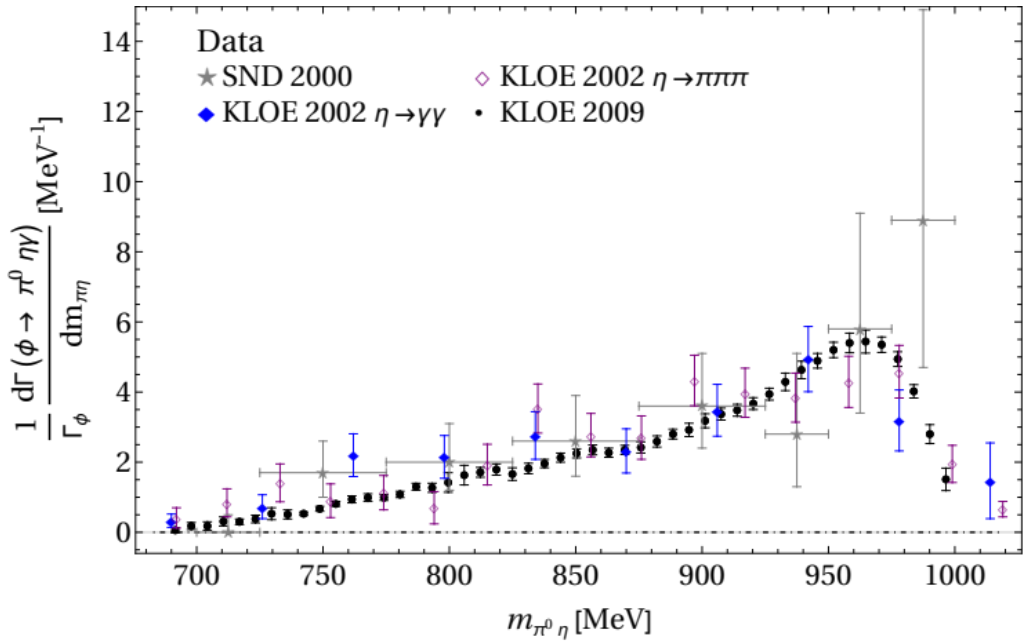
Escribano, Gonzàlez Solís, Royo. Phys.Rev.D 106, 114007 (2022)

Escribano, Miranda. To appear.

# Motivation

- **Tensions between measurements** of the **γγ spectrum** for the **η → π⁰γγ** decay.
- **Higher statistics** for the **ηπ⁰ invariant mass distribution** for the **ϕ → π⁰ηγ** decays from **KLOE**.
- **Better agreement** between different datasets from **SND00**, **KLOE02** and **KLOE09**.




R. Escribano et al. Phys.Rev.D 106 (2022) 11, 114007

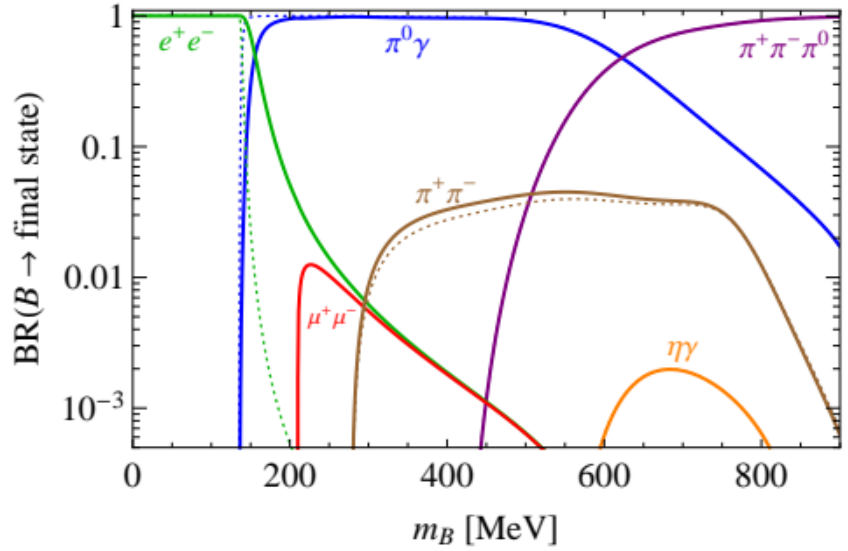
# Previous estimates

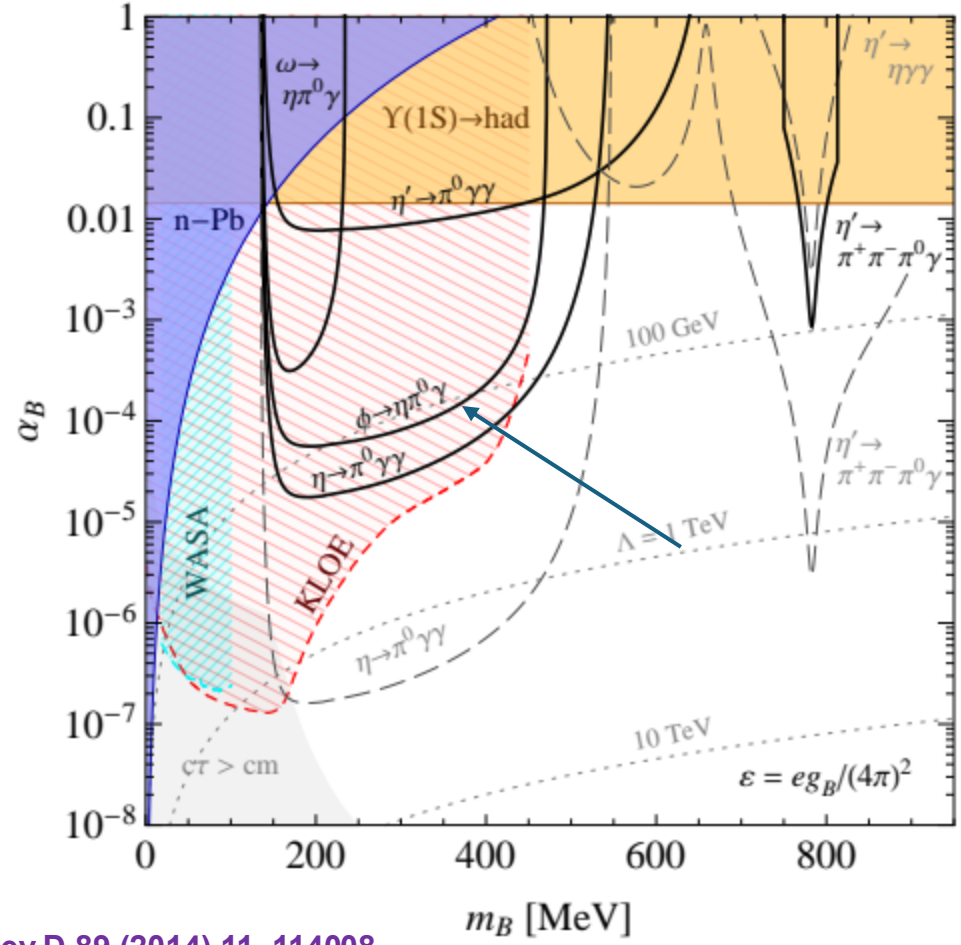
- Assuming the **Narrow Width Approximation (NWA)**:

$$\mathrm{Br}(\phi \to \pi^0\eta\gamma) = \mathrm{Br}(\phi \to B\eta) \times \mathrm{Br}(B \to \pi^0\gamma)$$
$$\mathrm{Br}(B \to \pi^0\gamma) = 1$$

- **QCD** contribution **off**

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

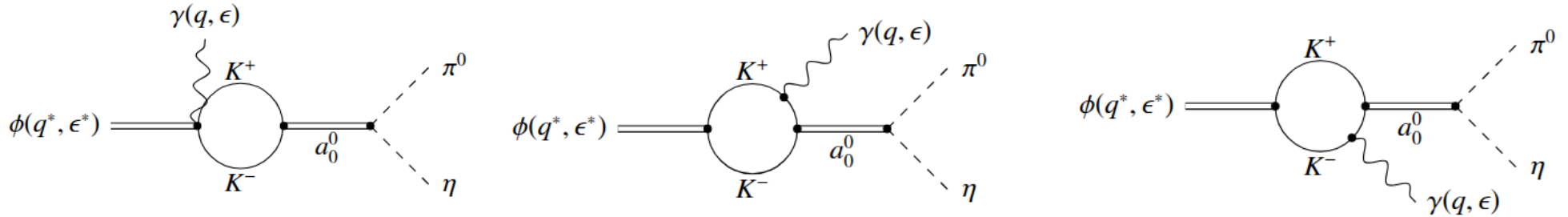



S. Tulin. Phys.Rev.D 89 (2014) 11, 114008

# Scalar meson exchange contributions

- In the **LσM** framework, the **$\phi \to \pi^0\eta\gamma$ decay** proceed through the **exchange** of intermediate **scalar mesons**




$$\mathcal{A}^{L\sigma M}_{\phi\to\pi^0\eta\gamma} = \frac{eg}{2\pi^2 m^2_{K^+}}\{a\}L(m^2_{\pi^0\eta})\,\mathcal{A}^{L\sigma M}_{K^+K^-\to\pi^0\eta}$$

$$\mathcal{A}^{\mathrm{L}\sigma\mathrm{M}}_{K^+K^-\to\pi^0\eta} = \frac{s-m_\eta^2}{D_{a_0}(s)}\frac{g_{a^0K^+K^-}\,g_{a^0\pi^0\eta}}{m_\eta^2-m_{a^0}^2} + \frac{m_\eta^2+m_\pi^2-s}{4f_\pi f_K}(c\varphi_P - \sqrt{2}s\varphi_P)$$

$$g_{a_0\pi^0\eta} = \frac{m_\eta^2-m_{a_0}^2}{f_\pi}c\varphi_P,$$

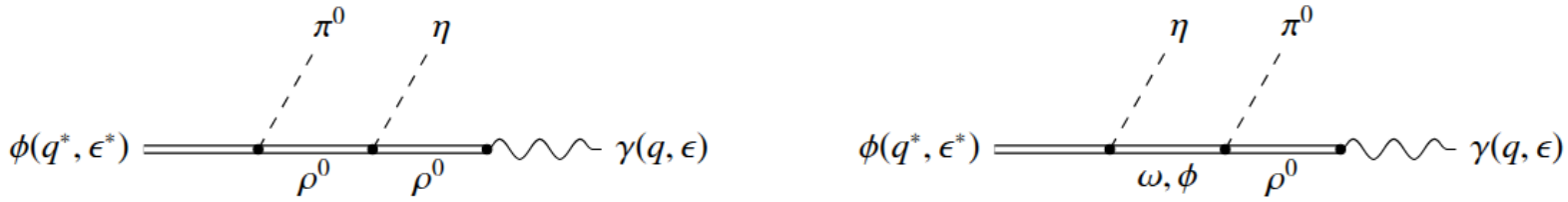
$$g_{a_0K^+K^-} = -g_{a_0K^0\bar{K}^0} = \frac{m_K^2-m_{a_0}^2}{2f_K}$$

A. Bramon et al. Phys.Lett.B 494 (2000) 221-228

$$D(s) = s - m_R^2 + \mathrm{Re}\Pi(s) - \mathrm{Re}\Pi(m_R^2) + i\mathrm{Im}\Pi(s)$$

# Vector meson exchange contributions

- In the **VMD** framework, the **$\phi \to \pi^0\eta\gamma$ decay** proceed through the **exchange** of intermediate **vector mesons**



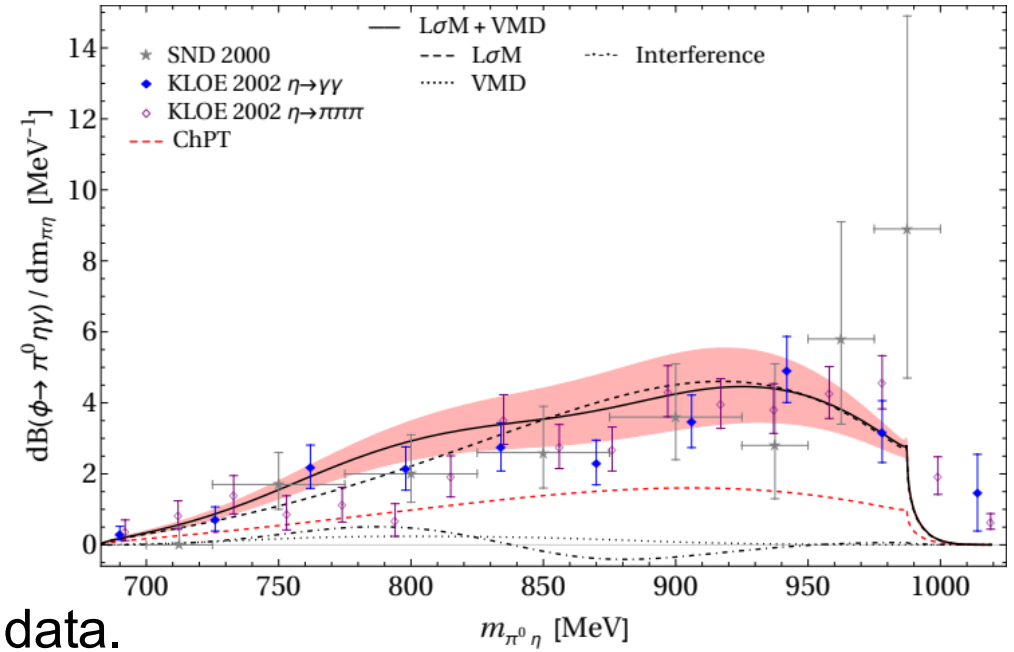

$$\mathcal{A}^{\mathrm{VMD}}_{\phi\to\pi^0\eta\gamma} = \frac{\epsilon e G^2}{\sqrt{2}g}\left\{c\varphi_P\left(\frac{P'^2\{a\}+\{b(P')\}}{D_\rho(P'^2)}+\frac{P^2\{a\}+\{b(P)\}}{D_\omega(P^2)}\right)+\sqrt{2}s\varphi_P\left(\frac{P^2\{a\}+\{b(P)\}}{D_\omega(P^2)}-\frac{P^2\{a\}+\{b(P)\}}{D_\phi(P^2)}\right)\right\}$$

A. Bramon et al. Phys.Lett.B 283 (1992) 416-420

$$\{a\} = (\epsilon^*\epsilon)(q^*q) - (\epsilon^*q)(\epsilon q^*)$$
$$\{b(P)\} = (\epsilon^*q)(\epsilon P)(q^*P) + (\epsilon q^*)(\epsilon^*P)(qP) - (\epsilon^*\epsilon)(q^*P)(qP) - (\epsilon^*P)(\epsilon P)(q^*q)$$

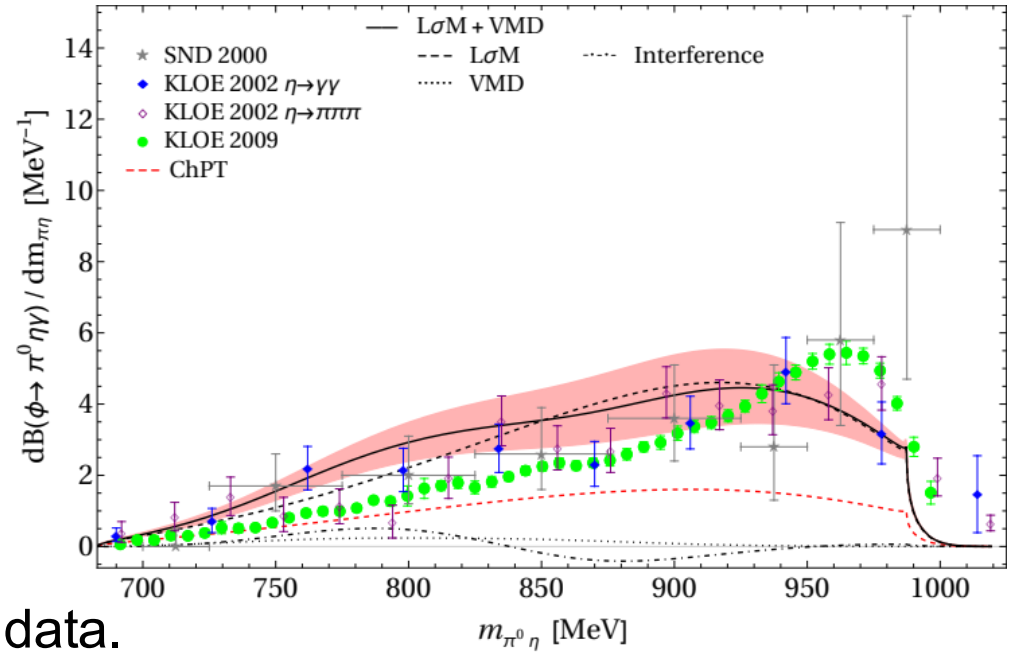
# $\phi \rightarrow \pi^0\eta\gamma$ predictions

- In **LσM**, the theoretical prediction is ***BR*=8.78(1.76) x10$^{-5}$**
  - **Scalar** contribution dominates:
    - $a_0$: **95%**
  - **VMD** contribution:
    - ρ, ω, and ϕ: **1%**
  - **Interference**:
    - S-V: **4%**
- **Compatible** with the present available **data**:
  - ***BR*=7.27(30) x10$^{-5}$** **PDG 2024**
- Comparison with **experimental data**:
  - **Good agreement** with **SND'00** and **KLOE'02** data.



# $\phi \rightarrow \pi^0\eta\gamma$ predictions

- In **LσM**, the theoretical prediction is ***BR*=8.78(1.76) x10$^{-5}$**
  - **Scalar** contribution dominates:
    - $a_0$: **95%**
  - **VMD** contribution:
    - ρ, ω, and ϕ: **1%**
  - **Interference**:
    - S-V: **4%**
- **Compatible** with the present available **data**:
  - ***BR*=7.27(30) x10$^{-5}$** **PDG 2024**
- Comparison with **experimental data**:
  - **Good agreement** with **SND'00** and **KLOE'02** data.
  - **Fails** to the describe the **KLOE'09** data.

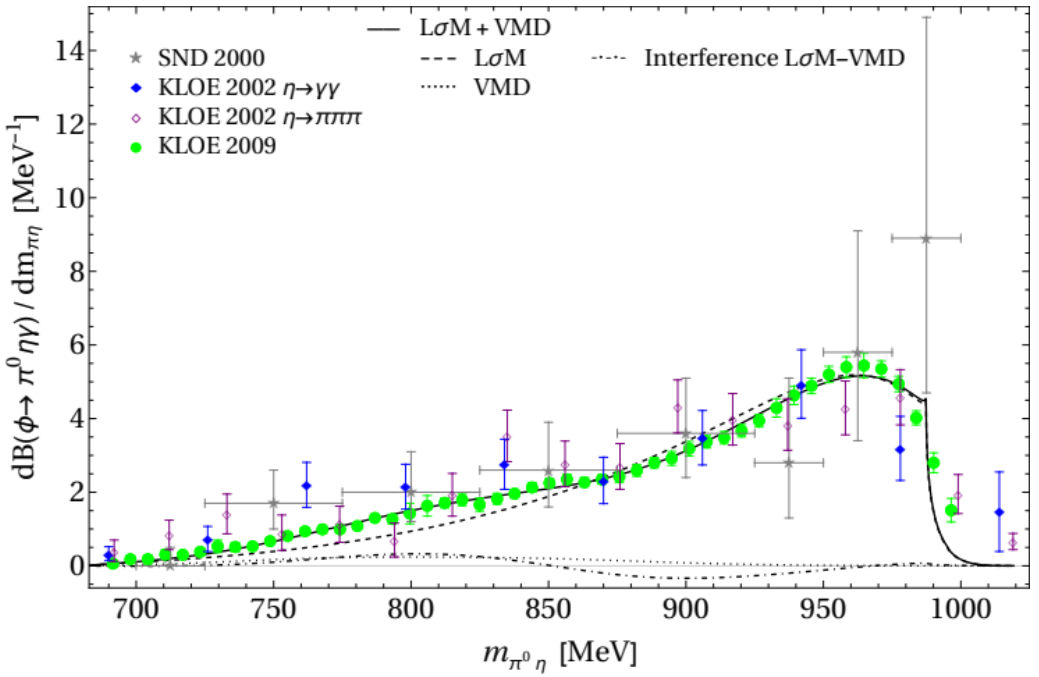


# $\phi \rightarrow \pi^0\eta\gamma$ predictions

- **Advantages** of our model:
  - Incorporation of **scalar resonances** in an explicit way.
  - Includes the **constraints** required by **chiral symmetry.**
- We relax the **theoretical framework:**
  - **Three parameters:** $m_{a_0}$, $g_{a_0\pi^0\eta}$ and $g_{a_0K^+K^-}$
- We perform a **fit** to the **experimental data:**

| | Fit 1 | Fit 2 |
|---|---|---|
| $\chi^2/d.o.f$ | 69.3/46 = 1.5 | 68.0/45 = 1.5 |
| $m_{a_0}$ | $986.6^{+0.7}_{-1.2}$ | $986.6^{+0.7}_{-1.1}$ |
| $g_{a_0K\bar{K}}$ | $\pm(2838.2^{+80.7}_{-77.8})$ | $\pm(2844.6^{+81.9}_{-79.0})$ |
| $g_{a_0\pi\eta}$ | $\pm(3692.0^{+56.5}_{-55.1})$ | $\pm(3691.3^{+57.1}_{-55.7})$ |
| $\delta_{+0}$ | $0^{\dagger}$ | $0.12 \pm 0.10$ |

Vector-Scalar interference




**This approach improves the agreement between theory and experiment.**

# SM contribution to the branching ratio

| Contribution | L$\sigma$M | 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 [15] | | $7.27 \pm 0.30$ | |

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

**Good agreement between theory and experiment.**

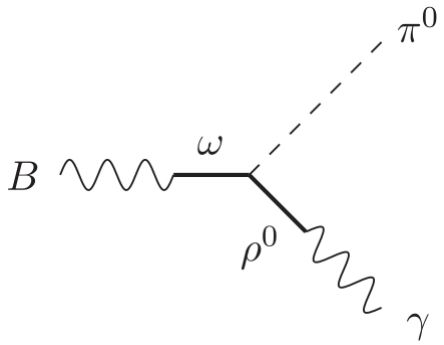
# Calculation of hadronic processes

- Using the **hidden local symmetry** (HLS) for **VMD**

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

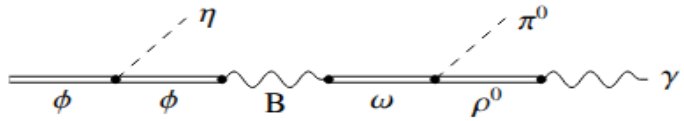
- **P** is the pseudoscalar meson nonet
- **V** is the vector meson nonet (**gauge boson** of a hidden **$U(3)_V$ symmetry**)
- In conventional **VMD:** $A^\mu \to B^\mu, \quad e \to g_B, \quad Q = \frac{1}{3}$

$$\mathcal{L}_{V\gamma} = -4egf_\pi^2 A^\mu \mathrm{tr}\left[QV_\mu\right] \longrightarrow \mathcal{L}_{VB} = -4\frac{1}{3}g_B g f_\pi^2 B^\mu \mathrm{tr}\left[V_\mu\right]$$



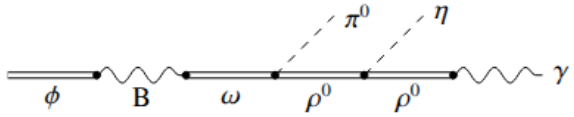

$$\Gamma_{B\to\pi^0\gamma} = \frac{\alpha_{\mathrm{em}}\alpha_B m_B^3}{96\pi^3 f_\pi^2}\left(1-\frac{m_\pi^2}{m_B^2}\right)^3 |F_\omega(m_B^2)|^2$$

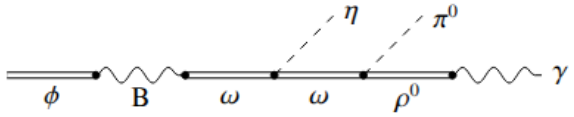
# $\phi \to \pi^0\eta\gamma$ decays: B boson calculation




- **Three diagrams** corresponding to the exchange of a **B boson:**

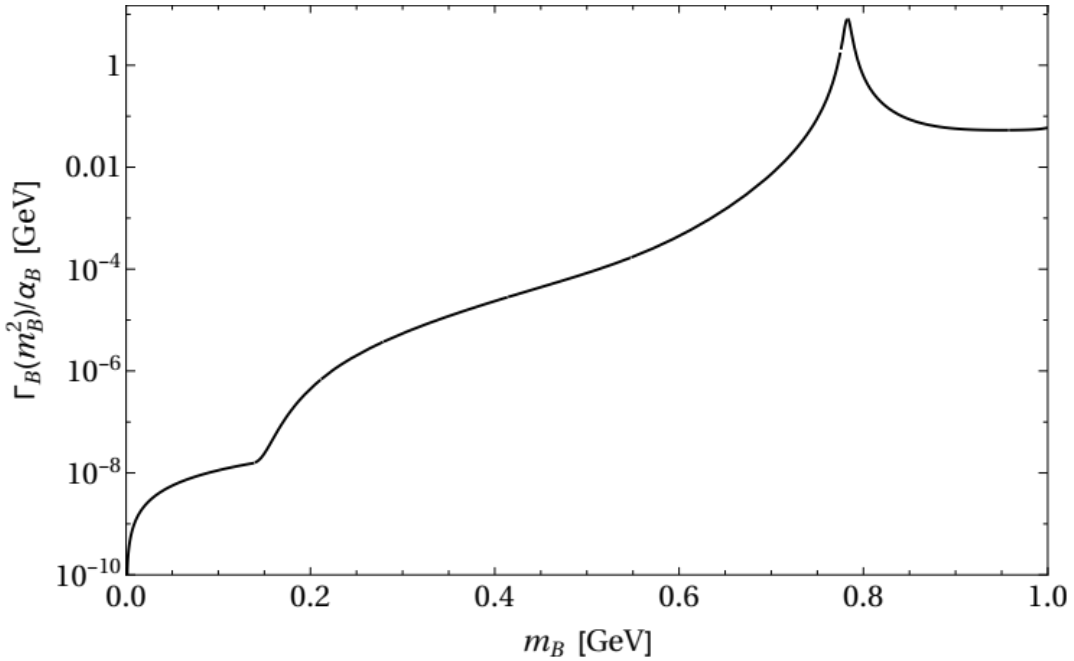
$$\mathcal{A}^{\text{B-boson}}_{\phi\to\pi^0\eta\gamma} = \frac{egg_B^2 m_\rho^4}{16\pi^4 f_\pi^2}\left\{-\sqrt{2}s\varphi_P \frac{P^2\{a\}+\{b(P)\}}{D_\phi[P^2]\,D_B[P^2]\,D_\omega[P^2]} + \frac{c\varphi_P}{D_B\left[m_\phi^2\right]D_\omega\left[m_\phi^2\right]}\left(\frac{P'^2\{a\}+\{b(P')\}}{D_\rho[P'^2]} + \frac{P^2\{a\}+\{b(P)\}}{D_\omega[P^2]}\right)\right\}$$




- **B boson width:**

$$\Gamma_B(s) = \frac{\gamma_{B\to\pi^0\gamma}(s)}{\gamma_{B\to\pi^0\gamma}(m_B^2)}\Gamma_{B\to\pi^0\gamma}\,\theta(s-m_\pi^2) + \frac{\gamma_{B\to e^+e^-}(s)}{\gamma_{B\to e^+e^-}(m_B^2)}\Gamma_{B\to e^+e^-}\,\theta(s-4m_e^2)$$
$$+ \frac{\gamma_{B\to\mu^+\mu^-}(s)}{\gamma_{B\to\mu^+\mu^-}(m_B^2)}\Gamma_{B\to\mu^+\mu^-}\,\theta(s-4m_\mu^2) + \frac{\gamma_{B\to\pi^+\pi^-}(s)}{\gamma_{B\to\pi^+\pi^-}(m_B^2)}\Gamma_{B\to\pi^+\pi^-}\,\theta(s-4m_\pi^2)$$
$$+ \frac{\gamma_{B\to\pi^+\pi^-\pi^0}(s)}{\gamma_{B\to\pi^+\pi^-\pi^0}(m_B^2)}\Gamma_{B\to\pi^+\pi^-\pi^0}\,\theta(s-9m_\pi^2),$$

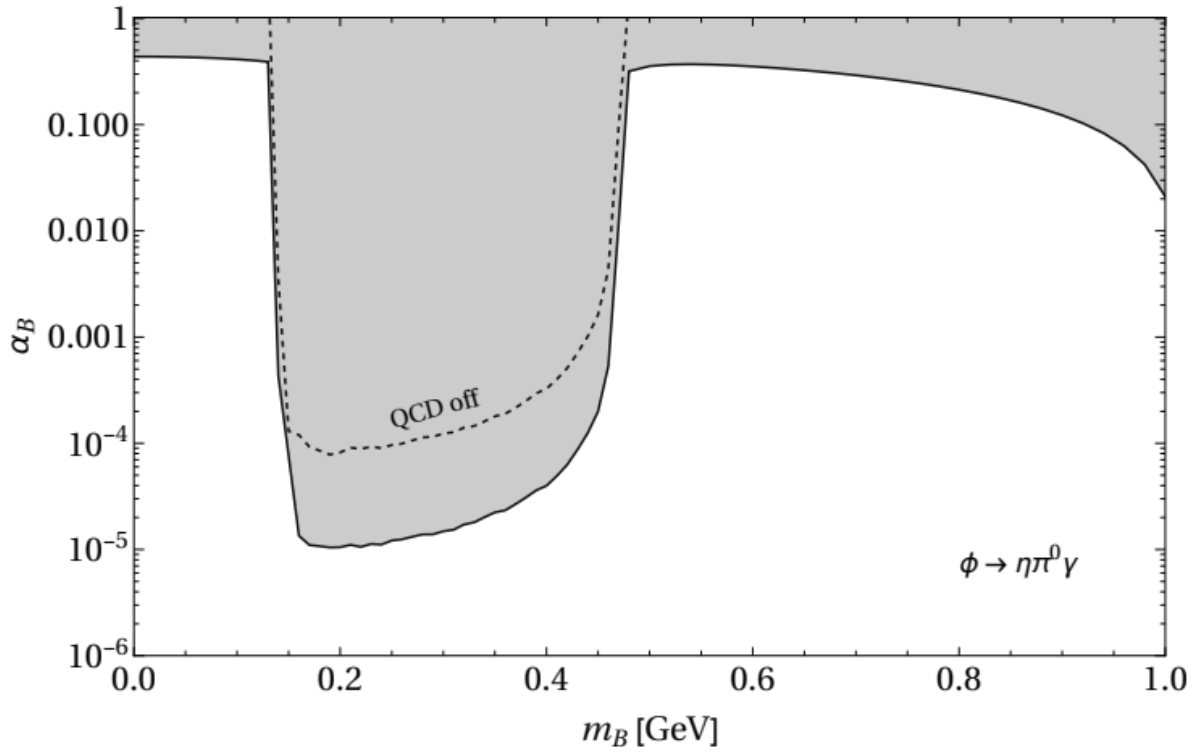


# New limits on $\alpha_B$ and $m_B$

- **Not** assuming the **NWA**
- **QCD** contribution **on**
- $\mathrm{Br}(\phi \to \pi^0\eta\gamma) < \mathrm{Br}_{\mathrm{exp}}$ at $2\sigma$

$$\mathrm{Br}(\phi \to \pi^0\eta\gamma)^{\mathrm{PDG}}_{\mathrm{exp}} = (7.27 \pm 0.30) \times 10^{-5}$$

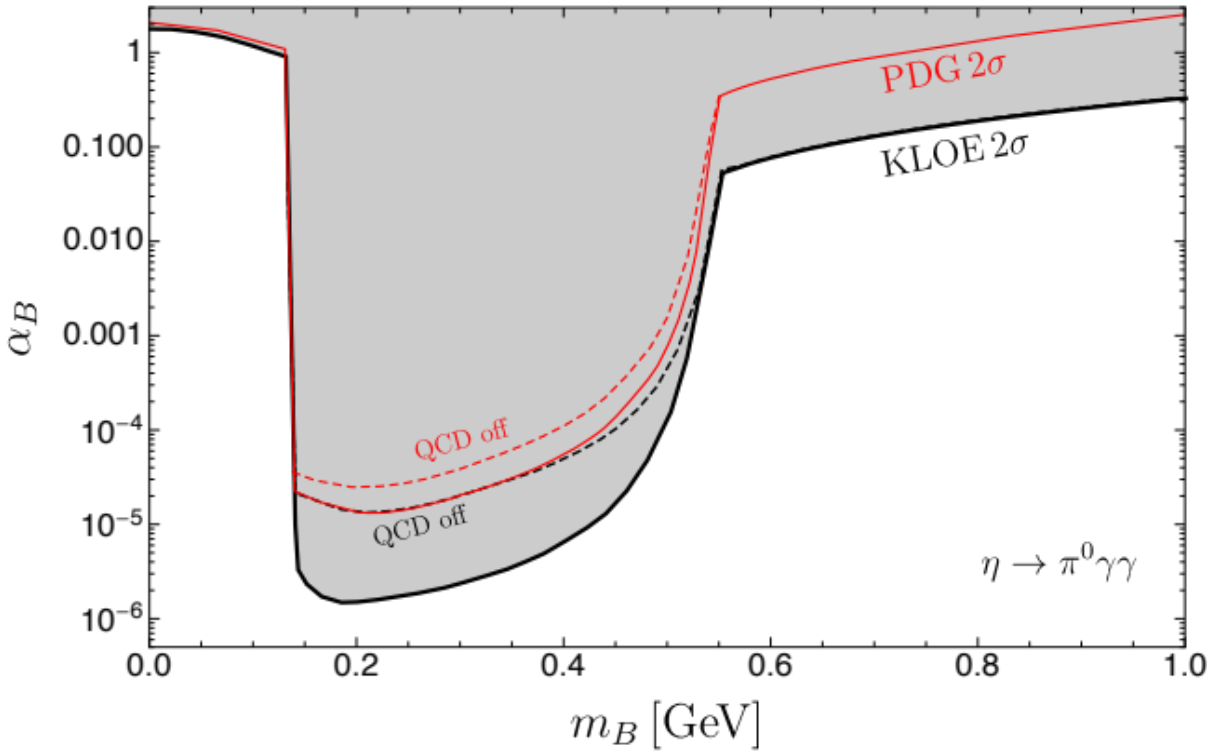
S. Navas et al. [PDG], Phys. Rev. D 110, 03001 (2024)

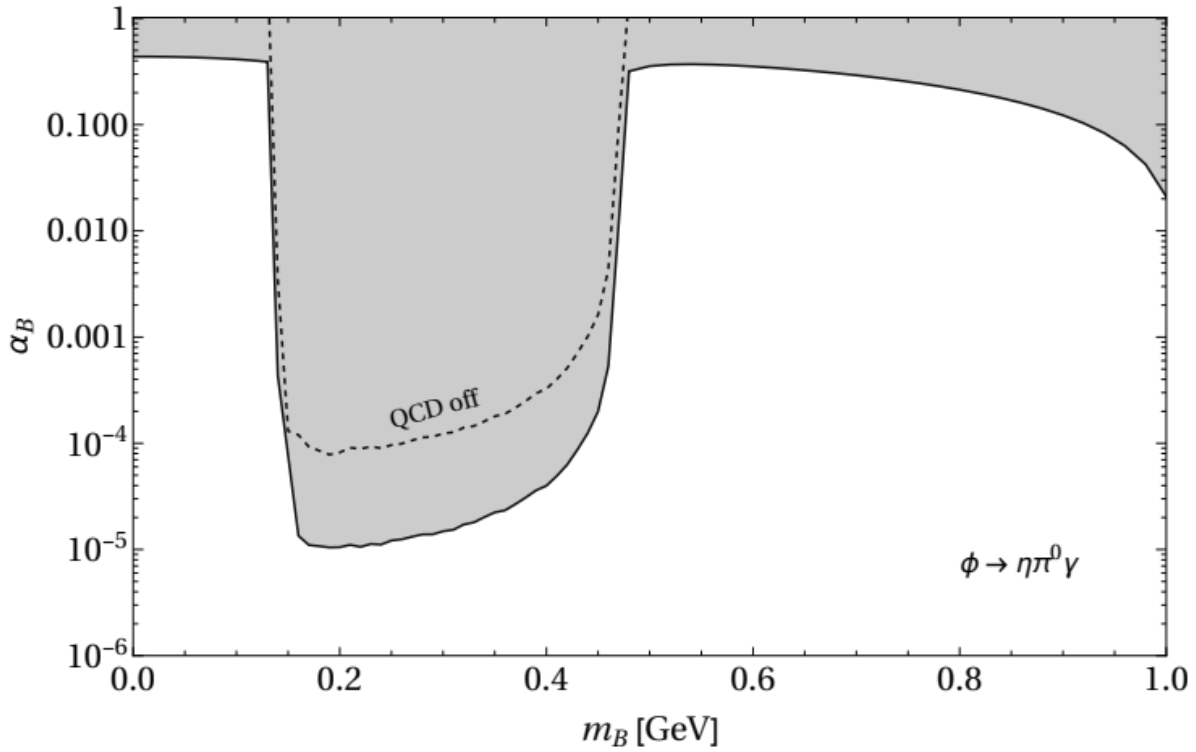



- **Limits** on the **B boson** parameters **improved by an order of magnitude** compared to previous analysis.

S. Tulin. Phys.Rev.D 89 (2014) 11, 114008

# New limits on $\alpha_B$ and $m_B$




- **Limits** on the **B boson** parameters **improved by an order of magnitude,**
- But **weaker than** those from **$\eta \to \pi^0\gamma\gamma$ decays.**

**R. Escribano et al. Phys.Rev.D 106 (2022) 11, 114007**

# B boson contributions to the branching ratio

| Contribution | $\mathcal{B}(\phi \to \pi^0\eta\gamma) \times 10^5$ | |
|---|---|---|
| L$\sigma$M | 6.52 | |
| VMD | 0.36 | |
| Interference SV | +0.02 | |
| Contribution | Set 1 | Set 2 |
| $B$–boson | 0.08 | $2.8 \cdot 10^{-4}$ |
| Interference SB | $+5.8 \cdot 10^{-7}$ | $-7.0 \cdot 10^{-4}$ |
| Interference VB | $+1.8 \cdot 10^{-6}$ | +0.02 |

→ **Results from Fit 1**

$\alpha_B = 10^{-6}$, $m_B = 250$ MeV

$\alpha_B = 10^{-2}$, $m_B = 540$ MeV.

**B-boson signature strongly suppressed.**

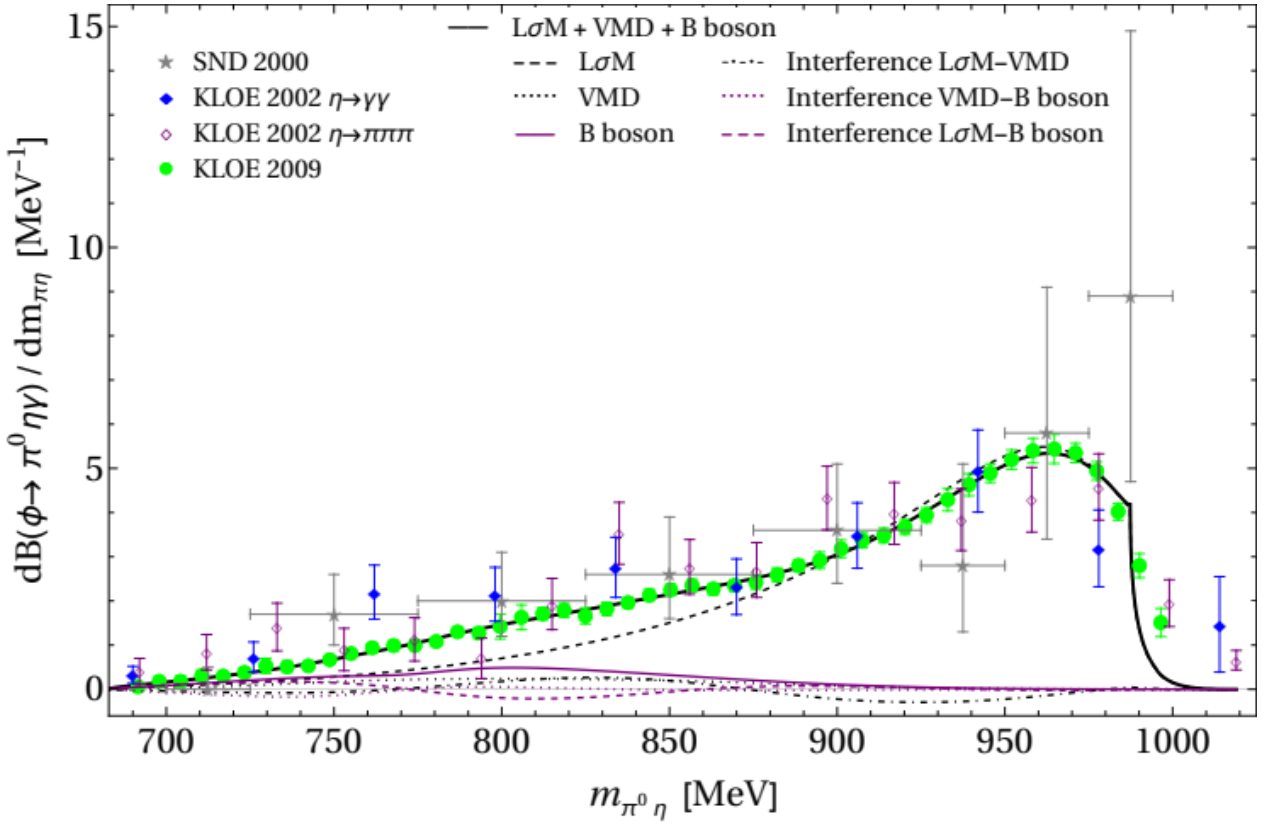
# Fits to $\phi \to \pi^0\eta\gamma$ decays

- Much **more statistics** from **KLOE**

| $\chi^2/d.o.f$ | $58.2/42 = 1.4$ |
|---|---|
| $m_{a_0}$ | $980.14 \pm 2.68$ |
| $g_{a_0 K\bar{K}}$ | $\pm(2401.3 \pm 146.6)$ |
| $g_{a_0 \pi\eta}$ | $\pm(3190.1 \pm 174.8)$ |
| $\delta_{+0}$ | $(48.1 \pm 29.7)^\circ$ |
| $m_B$ | $475.4 \pm 4.4$ |
| $\alpha_B$ | $0.35 \pm 0.07$ |
| $\delta_{0B}$ | $(165.8 \pm 13.3)^\circ$ |

- Signatures outside may be visible

$$m_{\pi^0} \lesssim m_B \lesssim m_\phi - m_\eta$$



# Summary

- **Scalar** contribution **dominates**, **vector** contributions **subdominate.**
- **LσM fails** to accurately describe the data from **KLOE.**
- Allowing the parameters to **vary freely**, the SM description is **improved**.
- **Sensitivity to B boson** has been **analyzed**.
- **Limits on $\alpha_B$ and $m_B$** have been **strengthened** by **an order of magnitude**.
- The **$\phi \rightarrow \pi^0\eta\gamma$ decays** provide **weaker constraints** on the B-boson parameters compared to **$\eta \rightarrow \pi^0\gamma\gamma$** below the mass of the η meson.