A theoretical analysis of the semileptonic decays $\eta^{(\prime)} \to \pi^0 \ell^+ \ell^-$ and $\eta' \to \eta \ell^+ \ell^-$

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Presentation based on:

- Escribano, Royo,
  Eur. Phys. J. C (2020) 80: 1190, arXiv:2007.12467
- Escribano, Royo, Sanchez-Puertas,
  JHEP 05 (2022) 147, arXiv:2202.04886

Outline

1. Motivation
2. SM Calculations & Results
3. Potential *CP* Violation
4. Summary

1. Motivation

- Standard Model of particle physics is *too* successful!

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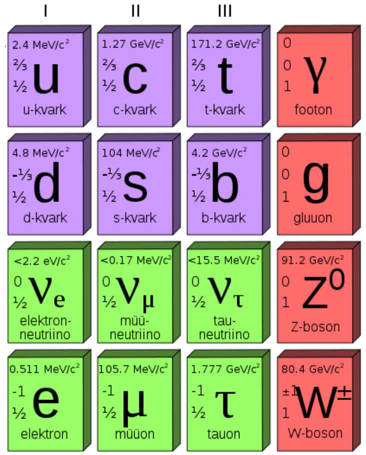

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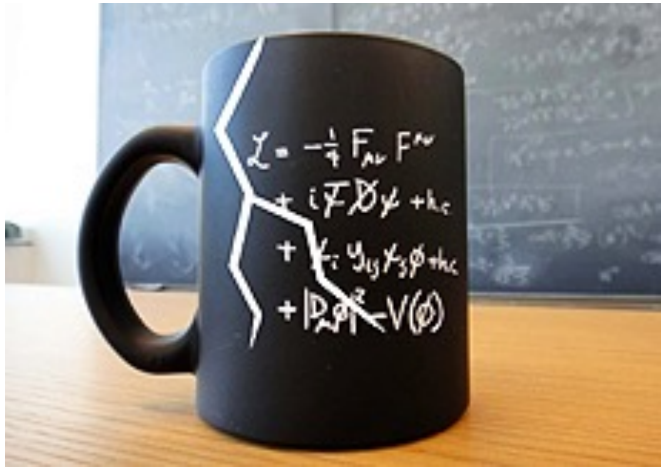

1. Motivation

- A number of low-energy precision measurements are sensitive to BSM Physics
  - SM prediction for the measured quantity is precisely known
  - SM background is small
- Experiments currently underway
  - Muon g – 2
  - nEDMs
  - Neutron decays
  - Etc.

1. Motivation

- The η and η' mesons are special:
  - The η is a pseudo-Goldstone boson
  - The η' is largely influenced by the $U(1)_A$ anomaly
  - The η and η' are eigenstates of the *C*, *P*, *CP* and *G* operators: $I^G J^{PC} = 0^+ 0^{-+}$
  - All their additive quantum numbers are zero: flavour conserving decays
  - All their strong and EM decays are forbidden at lowest order
  - Decays are mostly free from SM background

→ **Perfect laboratory to stress-test the SM in search of physics BSM**

2. Calculations

Eur. Phys. J. C (2020) 80: 1190, arXiv:2007.12467

- The semileptonic decays $\eta^{(\prime)} \to \pi^0 \ell^+ \ell^-$ and $\eta' \to \eta \ell^+ \ell^-$ ($\ell = e$ or μ) can be used as fine probes to assess physics BSM.
  - SM contributes through the *C*-conserving exchange of two photons that is highly suppressed (no contribution at tree-level, only corrections at one-loop and higher orders)
- Latest theoretical estimations for $\eta \to \pi^0 \ell^+ \ell^-$ date back to the 90s
- No theoretical studies for $\eta' \to \pi^0 \ell^+ \ell^-$ or $\eta' \to \eta \ell^+ \ell^-$ to the best of our knowledge

2. Calculations

Eur. Phys. J. C (2020) 80: 1190, arXiv:2007.12467

- Calculations performed within the Vector Meson Dominance (VMD) framework
  - Decay processes dominated by the exchange of vector resonances
- VMD coupling constants parametrised using an existing phenomenological model
  - Numerical values obtained from an optimisation fit to $V \to P\gamma$ and $P \to V\gamma$ radiative decays ($V = \rho^0,\omega,\phi$ and $P = \pi^0,\eta,\eta'$)
  - See *Phys. Lett. B* 807 (2020) 135534, arXiv:2003.08379 for details

2. Calculations

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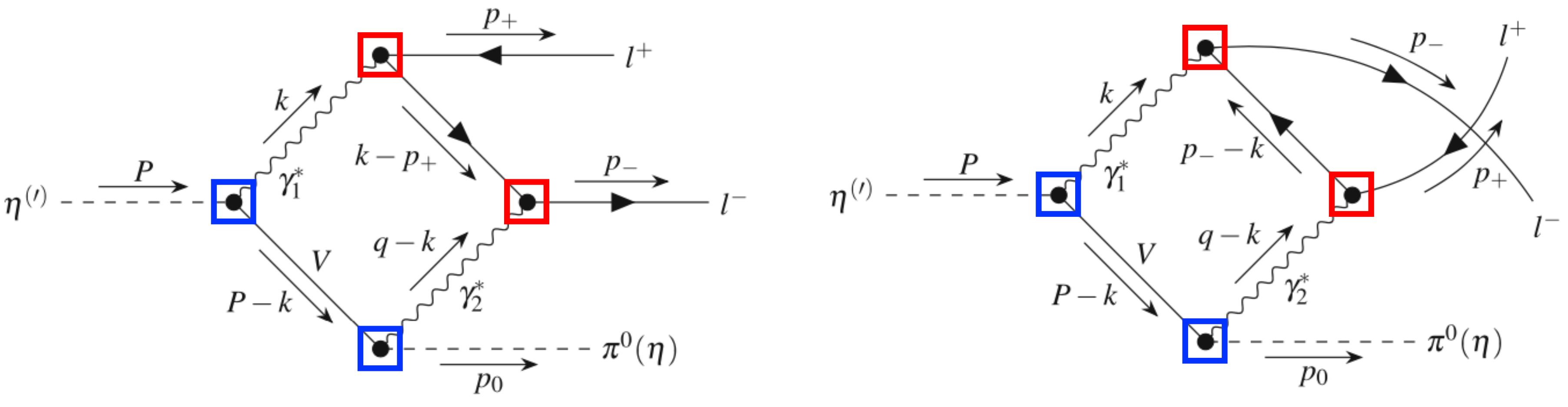
- Contributing Feynman diagrams

QED vertex
VMD vertex



(a) *t*-channel Feynman diagram

(b) *u*-channel Feynman diagram

Fig. 1 Feynman diagrams contributing to the *C*-conserving semileptonic decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ ($l = e$ or μ). Note that $q = p_+ + p_-$ and $V = \rho^0, \omega, \phi$

2. Calculations

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- *VPγ* interaction amplitude consistent with Lorentz, *C*, *P* and EM gauge invariance can be written as

$$\mathscr{M}(V \to P\gamma) = g_{VP\gamma}\,\varepsilon_{\mu\nu\alpha\beta}\,\varepsilon^{\mu}_{(V)}\,p^{\nu}_{V}\,\varepsilon^{*\alpha}_{(\gamma)}\,q^{\beta}\,\hat{F}_{VP\gamma}(q^2)\ ,$$

where $g_{VP\gamma}$ is the coupling constant for the $VP\gamma$ transition involving on-shell photons, $\varepsilon_{\mu\nu\alpha\beta}$ is the totally antisymmetric Levi-Civita tensor, $\varepsilon_{(V)}$ and p_V are the polarisation and 4-momentum vectors of the initial V, $\varepsilon^{*}_{(\gamma)}$ and q are the corresponding ones for the final γ, and $\hat{F}_{VP\gamma}(q^2) \equiv F_{VP\gamma}(q^2)/F_{VP\gamma}(0)$ is a normalised form factor to account for off-shell photons mediating the transition

2. Calculations

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- Invariant decay amplitude

$$\mathcal{M} = ie^2 \sum_{V=\rho^0,\omega,\phi} g_{V\eta^{(\prime)}\gamma}\, g_{V\pi^0(\eta)\gamma} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2+i\varepsilon} \frac{1}{(k-q)^2+i\varepsilon} \varepsilon_{\mu\nu\alpha\beta} \left[\frac{k^\mu (P-k)^\alpha (k-q)^\rho (P-k)^\delta}{(P-k)^2 - m_V^2 + i\varepsilon} \right] \varepsilon_{\rho\sigma\delta}{}^{\beta}$$

$$\bar{u}(p_-) \left[\gamma^\sigma \frac{\not{k} - \not{p}_+ + m_l}{(k-p_+)^2 - m_l^2 + i\varepsilon} \gamma^\nu + \gamma^\nu \frac{\not{p}_- - \not{k} + m_l}{(k-p_-)^2 - m_l^2 + i\varepsilon} \gamma^\sigma \right] v(p_+) \,,$$

where $q = p_+ + p_-$ is the sum of lepton-antilepton pair 4-momenta, e is the electron charge, and $g_{V\eta^{(\prime)}\gamma}$ and $g_{V\pi^0(\eta)\gamma}$ are the corresponding VMD coupling constants

Vector current — Scalar current

$$\mathcal{M} = \sum_{V=\rho^0,\omega,\phi} \mathcal{M}_{1_V} + \mathcal{M}_{2_V} = \underbrace{\Omega\left[\bar{u}(p_-)\not{P} v(p_+)\right]}_{\text{Vector current}} + \underbrace{m_l \Sigma\left[\bar{u}(p_-) v(p_+)\right]}_{\text{Scalar current}}$$

2. Calculations

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with

$$\Omega = \sum_{V=\rho^0,\omega,\phi} \alpha_V + \sigma_V \ ,$$

$$\Sigma = \sum_{V=\rho^0,\omega,\phi} \beta_V + \tau_V \ ,$$

$$\alpha_V = e^2 \frac{g_{V\eta^{(\prime)}\gamma} g_{V\pi^0(\eta)\gamma}}{16\pi^2} \int dxdydz \left[\frac{2A_1}{\Delta_{1V} - i\varepsilon} - \frac{B_1}{(\Delta_{1V} - i\varepsilon)^2} \right]$$

$$\beta_V = e^2 \frac{g_{V\eta^{(\prime)}\gamma} g_{V\pi^0(\eta)\gamma}}{16\pi^2} \int dxdydz \left[\frac{2C_1}{\Delta_{1V} - i\varepsilon} - \frac{D_1}{(\Delta_{1V} - i\varepsilon)^2} \right]$$

$$\sigma_V = e^2 \frac{g_{V\eta^{(\prime)}\gamma} g_{V\pi^0(\eta)\gamma}}{16\pi^2} \int dxdydz \left[\frac{2A_2}{\Delta_{2V} - i\varepsilon} - \frac{B_2}{(\Delta_{2V} - i\varepsilon)^2} \right]$$

$$\tau_V = e^2 \frac{g_{V\eta^{(\prime)}\gamma} g_{V\pi^0(\eta)\gamma}}{16\pi^2} \int dxdydz \left[\frac{2C_2}{\Delta_{2V} - i\varepsilon} - \frac{D_2}{(\Delta_{2V} - i\varepsilon)^2} \right]$$

2. Calculations

Phys. Lett. B 807 (2020) 135534, arXiv:2003.08379

- VMD couplings parametrisation

$$g_{\rho^0\pi^0\gamma} = \frac{1}{3}g ,$$
$$g_{\rho^0\eta\gamma} = g z_{NS} \cos\phi_P ,$$
$$g_{\rho^0\eta'\gamma} = g z_{NS} \sin\phi_P ,$$
$$g_{\omega\pi^0\gamma} = g \cos\phi_V ,$$
$$g_{\phi\pi^0\gamma} = g \sin\phi_V ,$$

$$g_{\omega\eta\gamma} = \frac{1}{3}g\left(z_{NS}\cos\phi_P\cos\phi_V - 2\frac{\overline{m}}{m_s}z_S\sin\phi_P\sin\phi_V\right) ,$$
$$g_{\omega\eta'\gamma} = \frac{1}{3}g\left(z_{NS}\sin\phi_P\cos\phi_V + 2\frac{\overline{m}}{m_s}z_S\cos\phi_P\sin\phi_V\right) ,$$
$$g_{\phi\eta\gamma} = \frac{1}{3}g\left(z_{NS}\cos\phi_P\sin\phi_V + 2\frac{\overline{m}}{m_s}z_S\sin\phi_P\cos\phi_V\right) ,$$
$$g_{\phi\eta'\gamma} = \frac{1}{3}g\left(z_{NS}\sin\phi_P\sin\phi_V - 2\frac{\overline{m}}{m_s}z_S\cos\phi_P\cos\phi_V\right) ,$$

where g is a generic electromagnetic constant, ϕ_P is the pseudoscalar η-η' mixing angle in the quark-flavour basis, ϕ_V is the vector ω-ϕ mixing angle in the same basis, $\overline{m}/m_s$ is the quotient of constituent quark masses, and z_{NS} and z_S are the *non-strange* and *strange* multiplicative factors accounting for the relative meson wave-function overlaps

2. Calculations

Phys. Lett. B 807 (2020) 135534, arXiv:2003.08379

- Numerical values from optimisation fit to *VP*γ radiative decays

$$g = 0.70 \pm 0.01\ \text{GeV}^{-1}, \quad z_S \overline{m}/m_s = 0.65 \pm 0.01\ ,$$
$$\phi_P = (41.4 \pm 0.5)^\circ, \quad \phi_V = (3.3 \pm 0.1)^\circ\ ,$$
$$z_{NS} = 0.83 \pm 0.02\ .$$

2. Results

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- Decay widths and branching ratios

Decay	Γ_{th}	BR_{th}	BR_{exp}	
$\eta \to \pi^0 e^+ e^-$	$2.7(1)(1)(2) \times 10^{-6}$ eV	$2.0(1)(1)(1) \times 10^{-9}$	$< 7.5 \times 10^{-6}$ (CL=90%)	WASA-at-COSY
$\eta \to \pi^0 \mu^+ \mu^-$	$1.4(1)(1)(1) \times 10^{-6}$ eV	$1.1(1)(1)(1) \times 10^{-9}$	$< 5 \times 10^{-6}$ (CL=90%)	PDG
$\eta' \to \pi^0 e^+ e^-$	$8.7(5)(6)(6) \times 10^{-4}$ eV	$4.5(3)(4)(4) \times 10^{-9}$	$< 1.4 \times 10^{-3}$ (CL=90%)	PDG
$\eta' \to \pi^0 \mu^+ \mu^-$	$3.3(2)(4)(3) \times 10^{-4}$ eV	$1.7(1)(2)(2) \times 10^{-9}$	$< 6.0 \times 10^{-5}$ (CL=90%)	PDG
$\eta' \to \eta e^+ e^-$	$8.3(0.5)(0.1)(3.5) \times 10^{-5}$ eV	$4.3(0.3)(0.2)(1.8) \times 10^{-10}$	$< 2.4 \times 10^{-3}$ (CL=90%)	PDG
$\eta' \to \eta \mu^+ \mu^-$	$3.0(0.2)(0.1)(1.1) \times 10^{-5}$ eV	$1.5(1)(1)(5) \times 10^{-10}$	$< 1.5 \times 10^{-5}$ (CL=90%)	PDG

Table 1: Decay widths and branching ratios for the six C-conserving decays $\eta^{(\prime)} \to \pi^0 l^+ l^-$ and $\eta' \to \eta l^+ l^-$ ($l = e$ or μ). First error is experimental, second is down to numerical integration and third is due to model dependency.

2. Results

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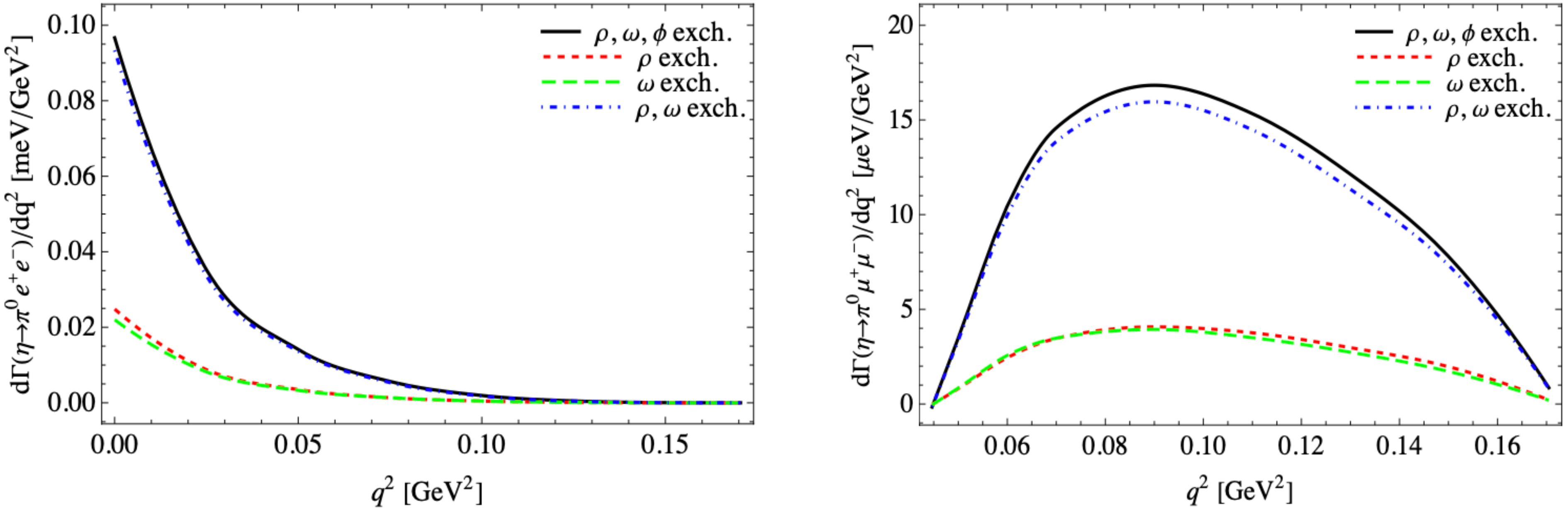
- $\eta \to \pi^0 \ell^+ \ell^-$ dilepton spectra



(a) $\eta \to \pi^0 e^+ e^-$ (b) $\eta \to \pi^0 \mu^+ \mu^-$

2. Results

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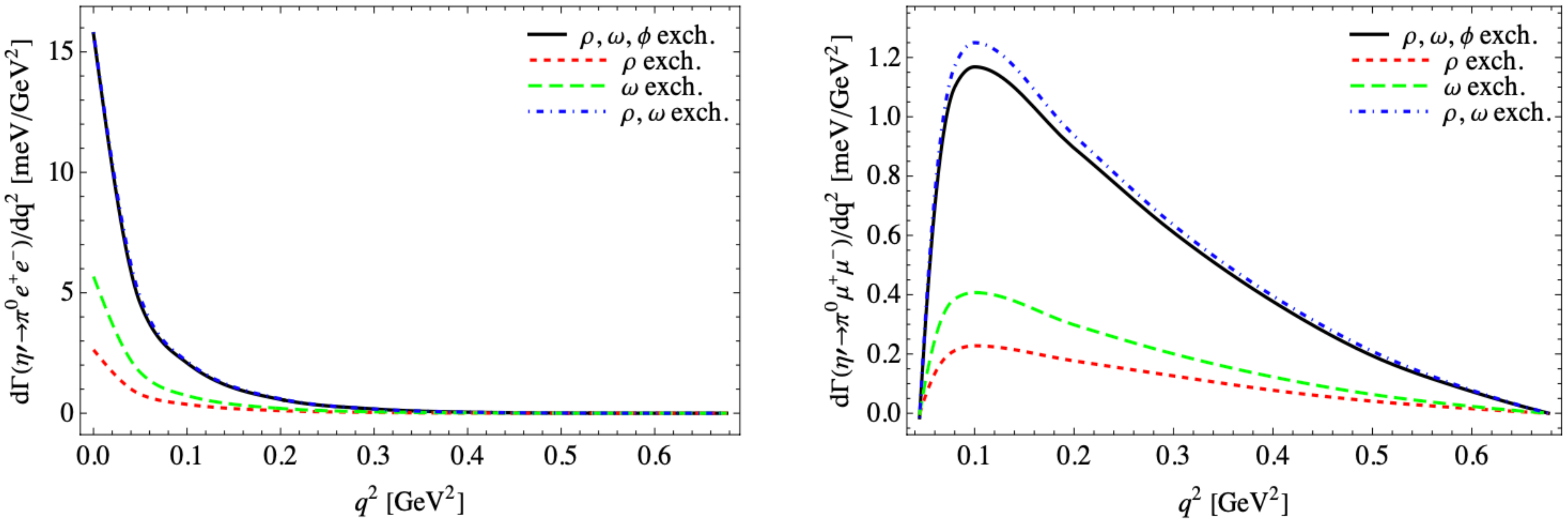
- $\eta' \to \pi^0 \ell^+ \ell^-$ dilepton spectra

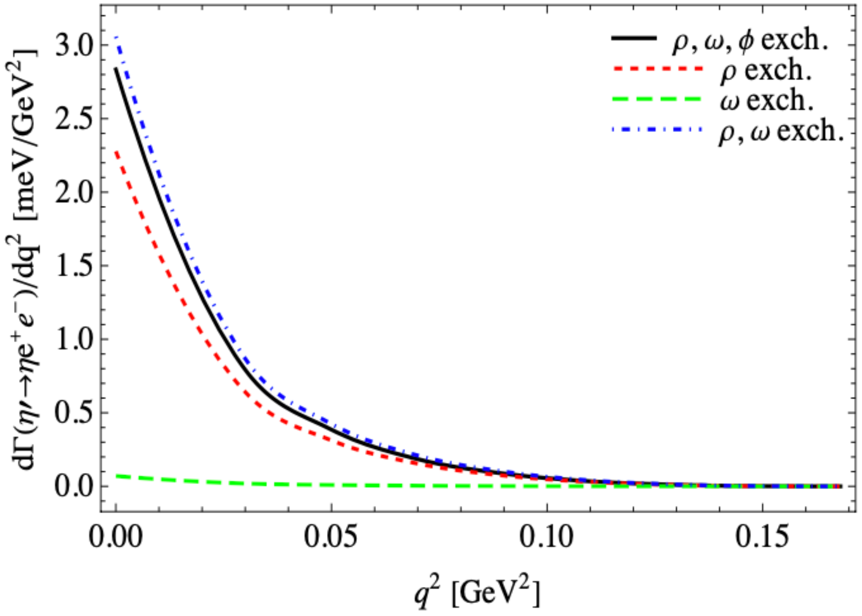


(c) $\eta' \to \pi^0 e^+ e^-$ (d) $\eta' \to \pi^0 \mu^+ \mu^-$

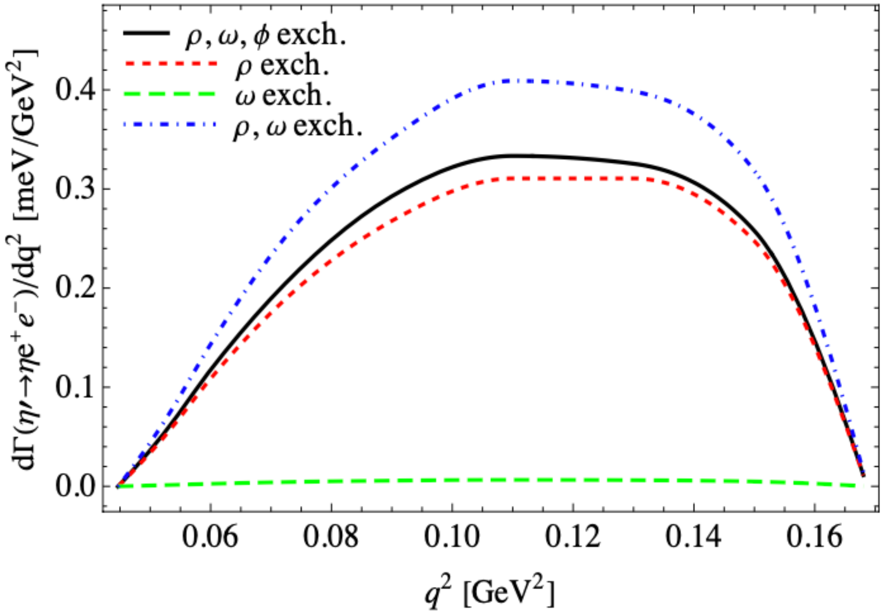
2. Results

Eur. Phys. J. C (2020) 80: 1190, arXiv:2007.12467

- $\eta' \to \eta \ell^+\ell^-$ dilepton spectra



(e) $\eta' \to \eta e^+e^-$



(f) $\eta' \to \eta \mu^+\mu^-$

2. Results

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- REDTOP is a new Fermilab project that belongs to the high intensity class of experiments
  - It aims at detecting small variations from the SM by looking at a large number of events produced with very intense beams
- 1.8 GeV continuous proton beam impinging on a target made with 10 foils of beryllium to produce about $2.5 \times 10^{13} \frac{\eta}{year}$ and $2.5 \times 10^{11} \frac{\eta'}{year}$
- REDTOP may be able measure these BRs with significantly improved accuracy!
- More information about REDTOP can be found in https://redtop.fnal.gov and arXiv:2203.07651

3. *CP* violation

- The results from the previous section are used to fix the SM background

3. *CP* violation

JHEP 05 (2022) 147, arXiv:2202.04886

- The SMEFT is a consistent EFT generalization of the SM constructed out of a series of $SU_c(3) \times SU_L(2) \times U_Y(1)$ invariant higher dimensional operators, built out of SM fields*

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \underbrace{\sum_i \frac{c_i}{\Lambda}\mathcal{O}_i^{d=5} + \boxed{\sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6}} + \mathcal{O}(\Lambda^{-3})}_{\text{BSM effects}}$$

- Relevant operators for our study

$$\mathcal{O}_{\ell edq}^{prst} = (\bar{\ell}_p^i e_r)(\bar{d}_s q_t^i), \qquad \mathcal{O}_{\ell equ}^{(1)prst} = (\bar{\ell}_p^i e_r)(\bar{q}_s^j u_t)\epsilon_{ij}$$

* Phys. Rept. 793 (2019) 1-98, arXiv:1706.08945

3. *CP* violation

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- The most general form factor decomposition for the three $\eta^{(\prime)} \to \pi^0\mu^+\mu^-$ and $\eta' \to \eta\mu^+\mu^-$ processes

$$\langle \mu^+\mu^-|iT|\eta^{(\prime)}\pi^0(\eta)\rangle = i\mathcal{M}(2\pi)^4\delta(p_{\mu^+} + p_{\mu^-} - p_{\eta^{(\prime)}} - p_{\pi(\eta)})$$

is

$$\mathcal{M} = m_\ell(\bar{u}v)F_1 + (\bar{u}i\gamma^5 v)F_2 + (\bar{u}\not{k}v)F_3 + i(\bar{u}\not{k}\gamma^5 v)F_4,$$

where

$$k = p_{\eta^{(\prime)}} - p_{\pi(\eta)}$$

3. *CP* violation

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- Noting that
  - within the SM only $F_{1,3}$ terms contribute if one neglects electroweak effects,
  - contributions to F_4 within the SM arise via electroweak loops which are negligible,
  - within the SMEFT contributions to F_4 can appear at higher orders and, thus, are irrelevant for this study,

one arrives at

$$F_1 = \Sigma \qquad \text{(cf. slide 11)}$$

$$F_2 = \Big[\mathrm{Im}\, c_{\ell edq}^{2211} \langle 0|\, \bar{d}d\, |\eta^{(\prime)}\pi^0(\eta)\rangle + \mathrm{Im}\, c_{\ell edq}^{2222} \langle 0|\, \bar{s}s\, |\eta^{(\prime)}\pi^0(\eta)\rangle - \mathrm{Im}\, c_{\ell equ}^{(1)2211} \langle 0|\, \bar{u}u\, |\eta^{(\prime)}\pi^0(\eta)\rangle\Big]/v^2$$

$$F_3 = \tfrac{1}{2}\Omega \qquad \text{(cf. slide 11)}$$

$$F_4 = 0$$

3. *CP* violation

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- At NLO in LN_c χPT, the matrix elements in F_2 can be expressed as

$$\langle 0|\, \bar{u}u/\bar{d}d\, |\eta\pi^0\rangle = \pm B_0 \left[\left(1-\frac{m_\eta^2-m_\pi^2}{M_S^2}\right)(c\phi_{23}\pm\epsilon_{13}s\phi_{23}) - \left(c\phi_{23}-\frac{s\phi_{23}}{\sqrt{2}}\right)\frac{\tilde{\Lambda}}{3}\right]\left(\frac{M_S^2}{M_S^2-s}\right)$$

$$\langle 0|\, \bar{s}s\, |\eta\pi^0\rangle = -2B_0\epsilon_{13} \left[\left(1-\frac{m_\eta^2+3m_\pi^2-4m_K^2}{M_S^2}\right)s\phi_{23} + \frac{\tilde{\Lambda}}{3}\left(\frac{c\phi_{23}}{\sqrt{2}} - s\phi_{23} - \frac{\epsilon_{12}s\phi_{23}}{\sqrt{2}\epsilon_{13}}\right)\right]\left(\frac{M_S^2}{M_S^2-s}\right)$$

The corresponding expressions for $\eta \to \eta'$ can be found by substituting $\begin{cases} c\phi_{23} \to s\phi_{23} \\ s\phi_{23} \to -c\phi_{23} \\ m_\eta \to m_{\eta'} \end{cases}$

3. *CP* violation

JHEP 05 (2022) 147, [arXiv:2202.04886]

- At NLO in LN_c χPT, the matrix elements in F_2 can be expressed as

$$\langle 0|\,\bar{u}u/\bar{d}d\,|\eta'\eta\rangle = B_0\left[\left(1-\frac{m_{\eta'}^2+m_\eta^2-2m_\pi^2}{M_S^2}\right)\left(\frac{s2\phi_{23}}{2}\mp\epsilon_{13}c2\phi_{23}\right)-\left(\frac{c2\phi_{23}}{\sqrt{2}}+s2\phi_{23}\right)\frac{\tilde{\Lambda}}{3}\right]\left(\frac{M_S^2}{M_S^2-s}\right)$$

$$\langle 0|\,\bar{s}s\,|\eta'\eta\rangle = -B_0\left[\left(1-\frac{m_{\eta'}^2+m_\eta^2+2m_\pi^2-4m_K^2}{M_S^2}\right)s2\phi_{23}+\left(\sqrt{2}c2\phi_{23}-s2\phi_{23}\right)\frac{\tilde{\Lambda}}{3}\right]\left(\frac{M_S^2}{M_S^2-s}\right)$$

where we have introduced the scale invariant parameter $\tilde{\Lambda}=\Lambda_1-2\Lambda_2$, ϕ_{23} is the η-η' mixing angle in the quark-flavour basis, ϵ_{12} and ϵ_{13} are first order approximations to the corresponding ϕ_{12} and ϕ_{13} isospin-breaking mixing angles in the π^0-η and π^0-η' sectors, respectively, and M_S is the mass of a generic scalar resonance.

3. *CP* violation

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- Differential decays widths for $\eta^{(\prime)} \to \pi^0(\eta)\mu^+\mu^- \to \pi^0(\eta)e^+\nu_e\bar{\nu}_\mu e^-\bar{\nu}_e\nu_\mu$

$$d\Gamma = \sum_{\lambda\bar{\lambda}} \underbrace{\frac{ds\,dc\theta}{64(2\pi)^3}\frac{\lambda_K^{1/2}\beta_\mu}{m^3_{\eta^{(\prime)}}}|\mathcal{M}(\lambda\boldsymbol{n},\bar{\lambda}\bar{\boldsymbol{n}})|^2}_{\eta^{(\prime)} \to \pi^0(\eta)\mu^+\mu^-} \underbrace{\left[\frac{d\Omega}{4\pi}dx\; n(x)\left(1-\lambda b(x)\boldsymbol{\beta}\cdot\boldsymbol{n}\right)\right]}_{\mu^+ \to e^+\nu_e\bar{\nu}_\mu} \underbrace{\left[\frac{d\bar{\Omega}}{4\pi}d\bar{x}\; n(\bar{x})\left(1+\bar{\lambda}b(\bar{x})\bar{\boldsymbol{\beta}}\cdot\bar{\boldsymbol{n}}\right)\right]}_{\mu^- \to e^-\bar{\nu}_e\nu_\mu}$$

$$d\Gamma = \frac{ds\,dc\theta}{64(2\pi)^3}\frac{\lambda_K^{1/2}\beta_\mu}{m^3_{\eta^{(\prime)}}}\left[\frac{d\Omega}{4\pi}dx\; n(x)\right]\left[\frac{d\bar{\Omega}}{4\pi}d\bar{x}\; n(\bar{x})\right]\Big[\tilde{c}_1|F_1|^2 + \tilde{c}_3|F_3|^2 + \tilde{c}^R_{13}\,\mathrm{Re}\,F_1F_3^* + \tilde{c}^I_{13}\,\mathrm{Im}\,F_1F_3^*$$
$$+\tilde{c}_2|F_2|^2 + \tilde{c}^R_{12}\,\mathrm{Re}\,F_1F_2^* + \tilde{c}^I_{12}\,\mathrm{Im}\,F_1F_2^* + \tilde{c}^R_{23}\,\mathrm{Re}\,F_2F_3^* + \tilde{c}^I_{23}\,\mathrm{Im}\,F_2F_3^*\Big]$$

3. *CP* violation

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- Longitudinal and transverse asymmetries:

$$A_L = \frac{N(c\theta_{e^+} > 0) - N(c\theta_{e^+} < 0)}{N(c\theta_{e^+} > 0) + N(c\theta_{e^+} < 0)} = -\frac{2}{3}\frac{\int dsdc\theta\lambda_K^{1/2}\beta_\mu m_\mu\left[\beta_\mu s\,\mathrm{Im}\,F_1F_2^* + 2\lambda_K^{1/2}c\theta\,\mathrm{Im}\,F_3F_2^*\right]}{64(2\pi)^3 m_{\eta^{(\prime)}}^3\int d\Gamma}$$

$$A_T = \frac{N[s(\bar{\phi}-\phi) > 0] - N[s(\bar{\phi}-\phi) < 0]}{N[s(\bar{\phi}-\phi) > 0] + N[s(\bar{\phi}-\phi) < 0]} = \frac{\pi}{18}\frac{\int dsdc\theta\lambda_K^{1/2}\beta_\mu m_\mu\left[\beta_\mu s\,\mathrm{Re}\,F_1F_2^* + 2\lambda_K^{1/2}c\theta\,\mathrm{Re}\,F_3F_2^*\right]}{64(2\pi)^3 m_{\eta^{(\prime)}}^3\int d\Gamma}$$

where the polar angles $\theta_{e^\pm}$ refer to those of the $e^\pm$ in the $\mu^\pm$ rest frames, $\phi(\bar{\phi})$ correspond to the azimuthal $e^\pm$ angles in the $\mu^\pm$ rest frames, and N refers to the number of $\eta^{(\prime)}$ decays.

3. *CP* violation

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- Results @NLO in LN_c χPT for $\eta^{(\prime)} \to \pi^0(\eta)\mu^+\mu^-$

$$
\begin{aligned}
A_L^{\eta\to\pi^0\mu^+\mu^-} &= -0.19(6)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} - 0.19(6)\,\mathrm{Im}\,c_{\ell edq}^{2211} - 0.020(9)\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,\\
A_T^{\eta\to\pi^0\mu^+\mu^-} &= 0.07(2)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} + 0.07(2)\,\mathrm{Im}\,c_{\ell edq}^{2211} + 7(3)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,\\
A_L^{\eta'\to\pi^0\mu^+\mu^-} &= -0.04(8)\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} - 0.04(8)\,\mathrm{Im}\,c_{\ell edq}^{2211} + 10(3)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,\\
A_T^{\eta'\to\pi^0\mu^+\mu^-} &= 3(6)\times10^{-3}\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} + 3(6)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2211} - 7(2)\times10^{-4}\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,\\
A_L^{\eta'\to\eta\mu^+\mu^-} &= -5(39)\times10^{-3}\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} + 5(46)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2211} - 0.08(1)\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,\\
A_T^{\eta'\to\eta\mu^+\mu^-} &= 7(50)\times10^{-5}\,\mathrm{Im}\,c_{\ell equ}^{(1)2211} - 6(65)\times10^{-5}\,\mathrm{Im}\,c_{\ell edq}^{2211}\\
&\quad + 1(19)\times10^{-3}\,\mathrm{Im}\,c_{\ell edq}^{2222}\,,
\end{aligned}
$$

where the error quoted accounts for both the numerical integration and the model-dependence uncertainties

3. *CP* violation

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- REDTOP is currently studying the implementation of muon polarimetry, cf. arXiv:2203.07651
- A total production of $2.5 \times 10^{13} \frac{\eta}{year}$ and $2.5 \times 10^{11} \frac{\eta'}{year}$ is expected, with assumed reconstruction efficiencies of approximately 20%
- The expected SM asymmetry noise for the $\eta^{(\prime)} \to \pi^0\mu^+\mu^-$ and $\eta' \to \eta\mu^+\mu^-$ is

$$\sigma_{\eta\to\pi^0\mu^+\mu^-} = 1.29 \times 10^{-2}$$
$$\sigma_{\eta'\to\pi^0\mu^+\mu^-} = 0.105$$
$$\sigma_{\eta'\to\eta\mu^+\mu^-} = 0.354$$

3. *CP* violation

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- Sensitivity to new physics at REDTOP

Process	Asymmetry	$\text{Im}\, c_{\ell equ}^{(1)2211}$	$\text{Im}\, c_{\ell edq}^{2211}$	$\text{Im}\, c_{\ell edq}^{2222}$
$\eta \to \pi^0 \mu^+ \mu^-$	A_L	0.0695	0.0720	0.686
	A_T	0.194	0.203	1.93
$\eta' \to \pi^0 \mu^+ \mu^-$	A_L	2.36	2.56	10.96
	A_T	33.1	35.8	154
$\eta' \to \eta \mu^+ \mu^-$	A_L	67.5	78.5	4.46
	A_T	5264	5549	328
$\eta \to \mu^+ \mu^-$	A_L	0.007	0.007	0.005
nEDM	—	≤ 0.001	≤ 0.002	≤ 0.02

Table 1. Summary of REDTOP sensitivities to (the imaginary parts of) the Wilson coefficients associated to the SMEFT *CP*-violating operators in eq. (2.2) for the processes studied in this work, as well as the $\eta \to \mu^+\mu^-$ decay analysed in ref. [4]. In addition, the upper bounds from nEDM experiments are given in the last row for comparison purposes.

4. Summary

- The study of the η and η' phenomenology may provide a very effective window to find physics BSM
- Theoretical predictions within the SM framework have been presented for the the six $\eta^{(\prime)} \to \pi^0 \ell^+ \ell^-$ and $\eta' \to \eta \ell^+ \ell^-$ semileptonic processes
- Theoretical estimations for the longitudinal and transverse asymmetries of the three $\eta^{(\prime)} \to \pi^0 \mu^+ \mu^-$ and $\eta' \to \eta \mu^+ \mu^-$ processes have been presented. The predicted statistics at REDTOP would fall short to detect *CP*-violating effects in these decays