

A theoretical analysis of the semileptonic decays

$\eta^{(')} \rightarrow \pi^0 \ell^+ \ell^-$ and $\eta' \rightarrow \eta \ell^+ \ell^-$



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Presentation based on:

- Escribano, Royo,
Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)
- Escribano, Royo, Sanchez-Puertas,
JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)



**Universitat Autònoma
de Barcelona**



Outline

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

1. Motivation

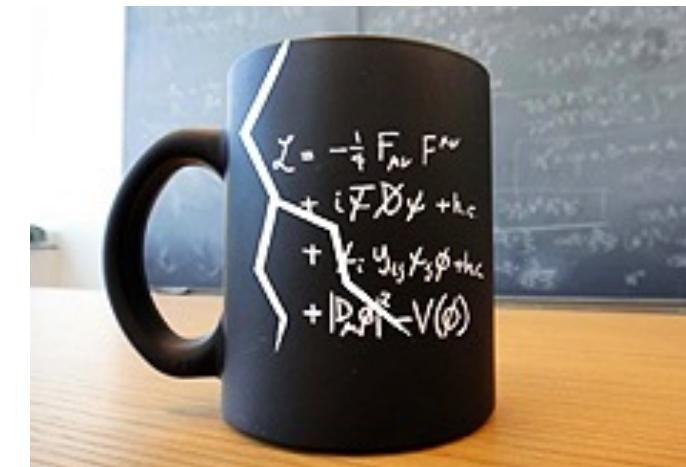
- Standard Model of particle physics is *too* successful!



+

	II	III	IV
2.4 MeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ u-kvark	12.7 GeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ c-kvark	171.2 GeV/c^2 $\frac{2}{3}$ $\frac{1}{2}$ t-kvark	0 0 1 footon
4.8 MeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ d-kvark	104 MeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ s-kvark	4.2 GeV/c^2 $-\frac{1}{3}$ $\frac{1}{2}$ b-kvark	0 0 1 gluon
$<2.2 \text{ eV/c}^2$ $\frac{0}{2}$ elektron-neutrino	$<0.17 \text{ MeV/c}^2$ $\frac{0}{2}$ muon-neutrino	$<15.5 \text{ MeV/c}^2$ 0 $\frac{1}{2}$ tau-neutrino	91.2 GeV/c^2 0 1 Z-boson
0.511 MeV/c^2 -1 $\frac{1}{2}$ elektron	105.7 MeV/c^2 -1 $\frac{1}{2}$ muon	1.777 GeV/c^2 -1 $\frac{1}{2}$ tauon	80.4 GeV/c^2 ± 1 1 W-boson

1



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
 - Violation of SM symmetries
- 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](https://arxiv.org/abs/2007.12467)

- The semileptonic decays $\eta^{(')} \rightarrow \pi^0 \ell^+ \ell^-$ and $\eta' \rightarrow \eta \ell^+ \ell^-$ ($\ell = e$ 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 $\eta \rightarrow \pi^0 \ell^+ \ell^-$ date back to the 90s
- No theoretical studies for $\eta' \rightarrow \pi^0 \ell^+ \ell^-$ or $\eta' \rightarrow \eta \ell^+ \ell^-$ to the best of our knowledge

2. Calculations

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

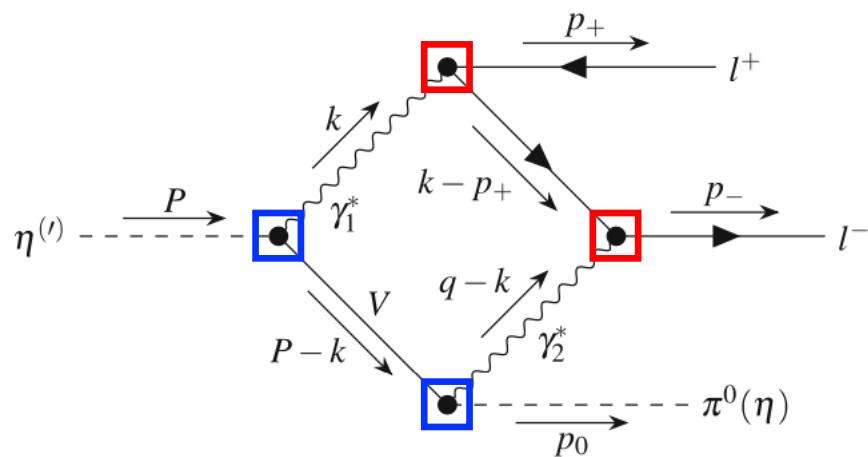
- Calculations performed within the Vector Meson Dominance (VMD) framework
 - Decay processes dominated by the exchange of vector resonances
- VMD coupling constants parametrised using an existing phenomenological model
 - Numerical values obtained from an optimisation fit to $V \rightarrow P\gamma$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

2. Calculations

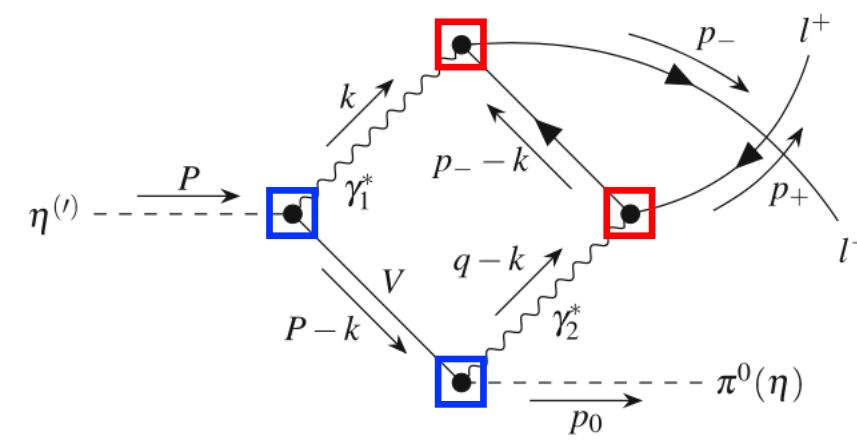
Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

- 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 $\eta^{(\prime)} \rightarrow \pi^0 l^+ l^-$ and $\eta' \rightarrow \eta l^+ l^-$ ($l = e$ or μ). Note that $q = p_+ + p_-$ and $V = \rho^0, \omega, \phi$

2. Calculations

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

- $VP\gamma$ interaction amplitude consistent with Lorentz, C , P and EM gauge invariance can be written as

$$\mathcal{M}(V \rightarrow P\gamma) = g_{VP\gamma} \epsilon_{\mu\nu\alpha\beta} \epsilon_{(V)}^\mu p_V^\nu \epsilon_{(\gamma)}^{*\alpha} q^\beta \hat{F}_{VP\gamma}(q^2) ,$$

where $g_{VP\gamma}$ is the coupling constant for the $VP\gamma$ transition involving on-shell photons, $\epsilon_{\mu\nu\alpha\beta}$ is the totally antisymmetric Levi-Civita tensor, $\epsilon_{(V)}$ and p_V are the polarisation and 4-momentum vectors of the initial V , $\epsilon_{(\gamma)}^*$ 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

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

- Invariant decay amplitude

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

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

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

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

2. Calculations

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

with

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

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

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

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

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

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

2. Calculations

Phys. Lett. B 807 (2020) 135534, [arXiv:2003.08379](https://arxiv.org/abs/2003.08379)

- VMD couplings parametrisation

$$g_{\rho^0 \pi^0 \gamma} = \frac{1}{3} g ,$$

$$g_{\rho^0 \eta \gamma} = g z_{\text{NS}} \cos \phi_P ,$$

$$g_{\rho^0 \eta' \gamma} = g z_{\text{NS}} \sin \phi_P ,$$

$$g_{\omega \pi^0 \gamma} = g \cos \phi_V ,$$

$$g_{\phi \pi^0 \gamma} = g \sin \phi_V ,$$

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

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

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

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

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, \bar{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 wavefunction overlaps

2. Calculations

Phys. Lett. B 807 (2020) 135534, [arXiv:2003.08379](https://arxiv.org/abs/2003.08379)

- Numerical values from optimisation fit to $VP\gamma$ radiative decays

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

2. Results

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

- Decay widths and branching ratios

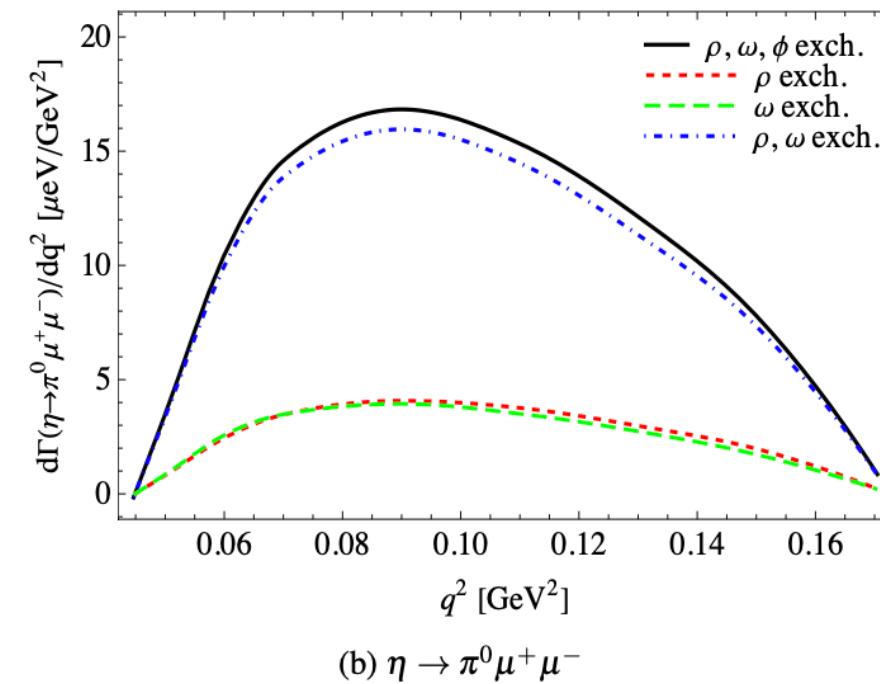
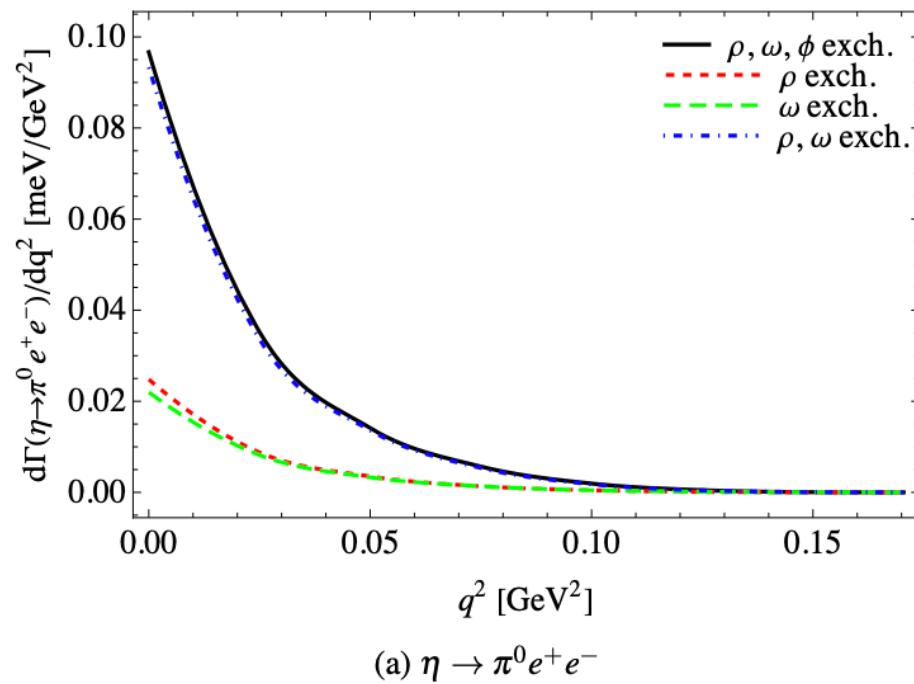
Decay	Γ_{th}	BR_{th}	BR_{exp}	
$\eta \rightarrow \pi^0 e^+ e^-$	$2.7(1)(1)(2) \times 10^{-6} \text{ eV}$	$2.0(1)(1)(1) \times 10^{-9}$	$< 7.5 \times 10^{-6} (\text{CL}=90\%)$	WASA-at-COSY
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	$1.4(1)(1)(1) \times 10^{-6} \text{ eV}$	$1.1(1)(1)(1) \times 10^{-9}$	$< 5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

Table 1: Decay widths and branching ratios for the six C -conserving decays $\eta^{(\prime)} \rightarrow \pi^0 l^+ l^-$ and $\eta' \rightarrow \eta l^+ l^-$ ($l = e$ 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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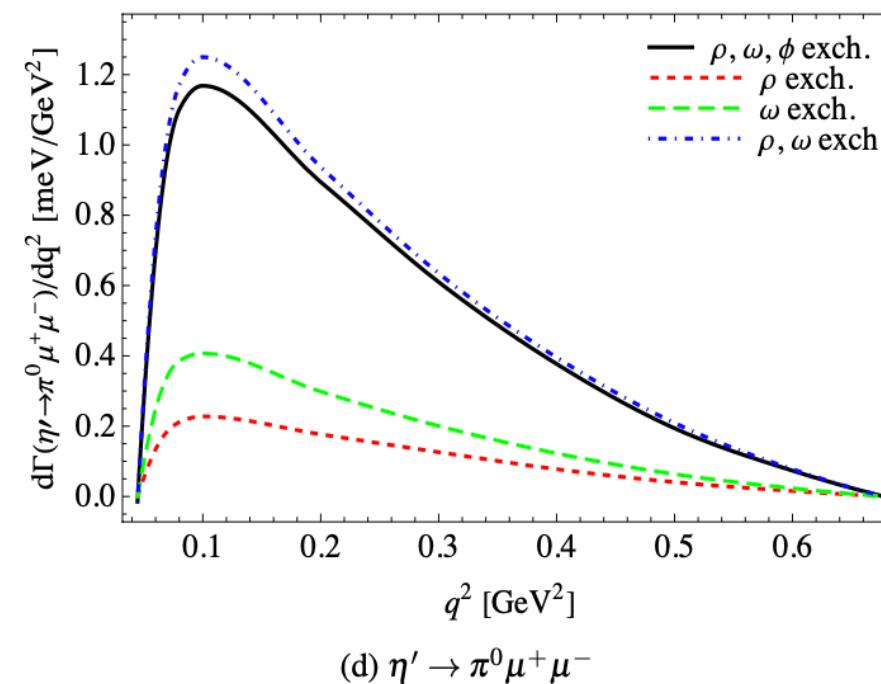
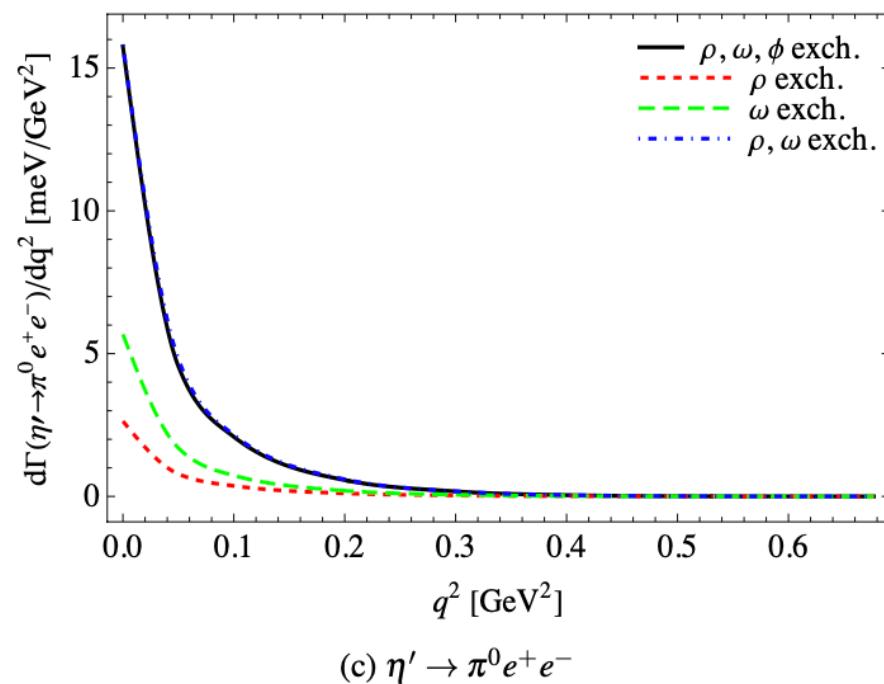
- $\eta \rightarrow \pi^0 \ell^+ \ell^-$ dilepton spectra



2. Results

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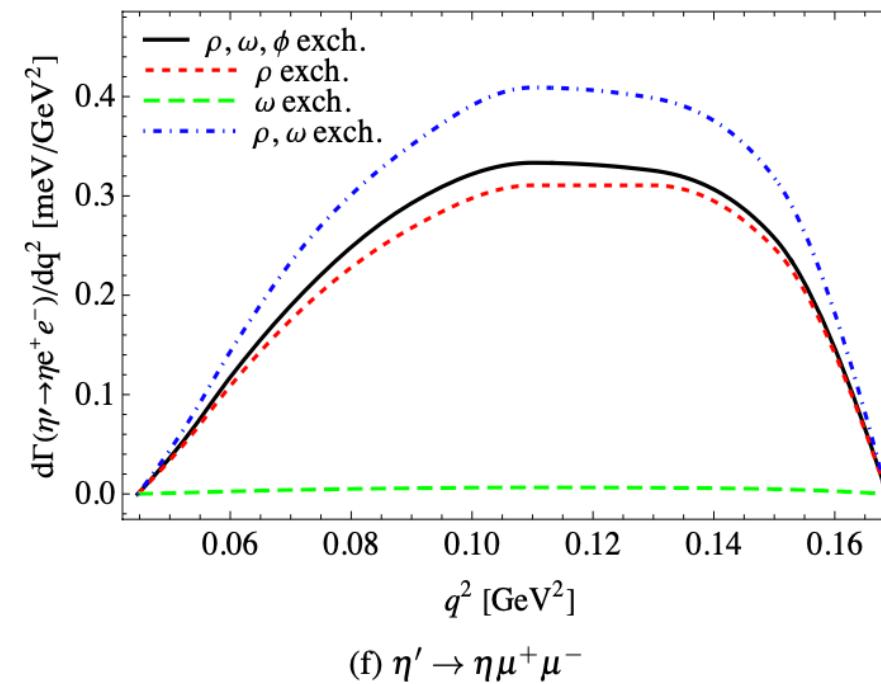
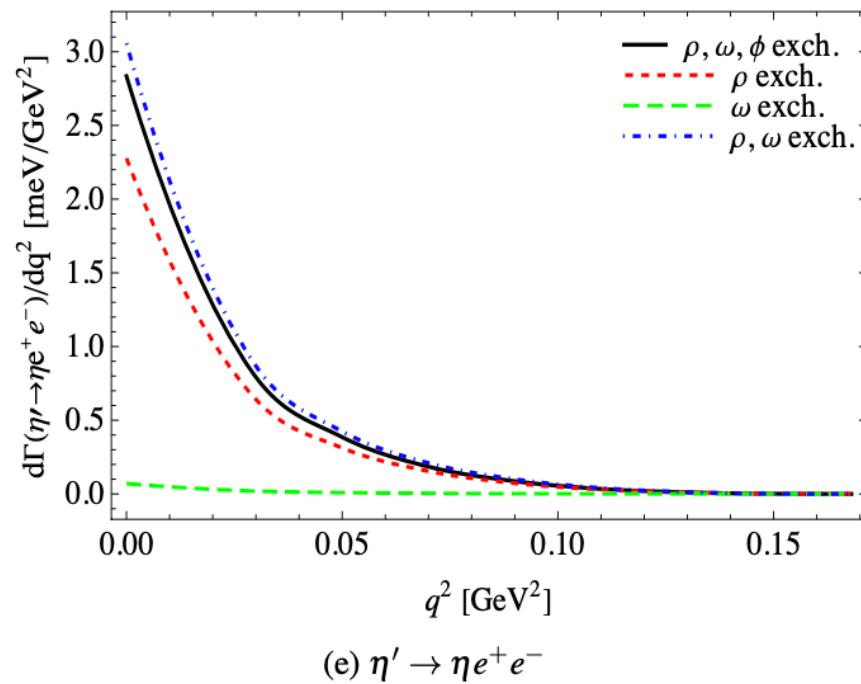
- $\eta' \rightarrow \pi^0 \ell^+ \ell^-$ dilepton spectra



2. Results

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



2. Results

Eur. Phys. J. C (2020) 80: 1190, [arXiv:2007.12467](https://arxiv.org/abs/2007.12467)

- 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 $2.5 \times 10^{13} \frac{\eta}{\text{year}}$ and $2.5 \times 10^{11} \frac{\eta'}{\text{year}}$
- 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](https://arxiv.org/abs/2203.07651)

3. CP violation

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

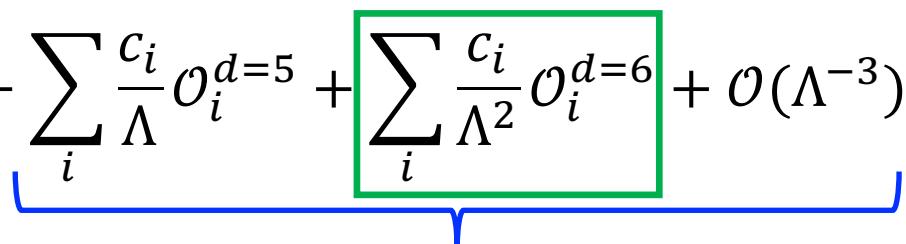


3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/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*

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


BSM effects

- Relevant operators for our study

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

* Phys. Rept. 793 (2019) 1-98, [arXiv:1706.08945](https://arxiv.org/abs/1706.08945)

3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

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

$$\mathcal{M} = m_\ell(\bar{u}v)F_1 + (\bar{u}i\gamma^5 v)F_2 + (\bar{u}k v)F_3 + i(\bar{u}k\gamma^5 v)F_4,$$

where

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

3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

- 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

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

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

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

$$F_4 = 0$$

3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

- At NLO in $\text{LN}_c \chi\text{PT}$, 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 $\eta \rightarrow \eta'$ can be found by substituting

$$\begin{cases} c\phi_{23} \rightarrow s\phi_{23} \\ s\phi_{23} \rightarrow -c\phi_{23} \\ m_\eta \rightarrow m_{\eta'} \end{cases}$$

3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

- At NLO in $\mathcal{LN}_c \chi\text{PT}$, 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

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

- Differential decays widths for $\eta^{(\prime)} \rightarrow \pi^0(\eta) \mu^+ \mu^- \rightarrow \pi^0(\eta) e^+ v_e \bar{v}_\mu e^- \bar{v}_e v_\mu$

$$d\Gamma = \sum_{\lambda \bar{\lambda}} \frac{dsdc\theta}{64(2\pi)^3} \frac{\lambda_K^{1/2} \beta_\mu}{m_{\eta^{(\prime)}}^3} |\mathcal{M}(\lambda \mathbf{n}, \bar{\lambda} \bar{\mathbf{n}})|^2 \left[\frac{d\Omega}{4\pi} dx n(x) (1 - \lambda b(x) \boldsymbol{\beta} \cdot \mathbf{n}) \right] \left[\frac{d\bar{\Omega}}{4\pi} d\bar{x} n(\bar{x}) (1 + \bar{\lambda} b(\bar{x}) \bar{\boldsymbol{\beta}} \cdot \bar{\mathbf{n}}) \right]$$

$\eta^{(\prime)} \rightarrow \pi^0(\eta) \mu^+ \mu^-$ $\mu^+ \rightarrow e^+ v_e \bar{v}_\mu$ $\mu^- \rightarrow e^- \bar{v}_e v_\mu$

$$d\Gamma = \frac{dsdc\theta}{64(2\pi)^3} \frac{\lambda_K^{1/2} \beta_\mu}{m_{\eta^{(\prime)}}^3} \left[\frac{d\Omega}{4\pi} dx n(x) \right] \left[\frac{d\bar{\Omega}}{4\pi} d\bar{x} n(\bar{x}) \right] \left[\tilde{c}_1 |F_1|^2 + \tilde{c}_3 |F_3|^2 + \tilde{c}_{13}^R \operatorname{Re} F_1 F_3^* + \tilde{c}_{13}^I \operatorname{Im} F_1 F_3^* \right. \\ \left. + \tilde{c}_2 |F_2|^2 + \tilde{c}_{12}^R \operatorname{Re} F_1 F_2^* + \tilde{c}_{12}^I \operatorname{Im} F_1 F_2^* + \tilde{c}_{23}^R \operatorname{Re} F_2 F_3^* + \tilde{c}_{23}^I \operatorname{Im} F_2 F_3^* \right]$$

3. CP violation

JHEP 05 (2022) 147, [arXiv:2202.04886](https://arxiv.org/abs/2202.04886)

- Longitudinal and transverse asymmetries:

$$A_L = \frac{N(c\theta_{e^+} > 0) - N(c\theta_{e^+} < 0)}{N(c\theta_{e^+} > 0) + N(c\theta_{e^+} < 0)} = -\frac{2}{3} \frac{\int ds d\phi \lambda_K^{1/2} \beta_\mu m_\mu [\beta_\mu s \operatorname{Im} F_1 F_2^* + 2\lambda_K^{1/2} c\phi \operatorname{Im} F_3 F_2^*]}{64(2\pi)^3 m_{\eta^{(\prime)}}^3 \int d\Gamma}$$

$$A_T = \frac{N[s(\bar{\phi} - \phi) > 0] - N[s(\bar{\phi} - \phi) < 0]}{N[s(\bar{\phi} - \phi) > 0] + N[s(\bar{\phi} - \phi) < 0]} = \frac{\pi}{18} \frac{\int ds d\phi \lambda_K^{1/2} \beta_\mu m_\mu [\beta_\mu s \operatorname{Re} F_1 F_2^* + 2\lambda_K^{1/2} c\phi \operatorname{Re} F_3 F_2^*]}{64(2\pi)^3 m_{\eta^{(\prime)}}^3 \int d\Gamma}$$

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

3. CP violation

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- Results @NLO in $\mathcal{LN}_c \chi\text{PT}$ for $\eta^{(\prime)} \rightarrow \pi^0(\eta)\mu^+\mu^-$

$$A_L^{\eta \rightarrow \pi^0 \mu^+ \mu^-} = -0.19(6) \text{Im } c_{\ell equ}^{(1)2211} - 0.19(6) \text{Im } c_{\ell edq}^{2211} - 0.020(9) \text{Im } c_{\ell edq}^{2222},$$

$$A_T^{\eta \rightarrow \pi^0 \mu^+ \mu^-} = 0.07(2) \text{Im } c_{\ell equ}^{(1)2211} + 0.07(2) \text{Im } c_{\ell edq}^{2211} + 7(3) \times 10^{-3} \text{Im } c_{\ell edq}^{2222},$$

$$A_L^{\eta' \rightarrow \pi^0 \mu^+ \mu^-} = -0.04(8) \text{Im } c_{\ell equ}^{(1)2211} - 0.04(8) \text{Im } c_{\ell edq}^{2211} + 10(3) \times 10^{-3} \text{Im } c_{\ell edq}^{2222},$$

$$A_T^{\eta' \rightarrow \pi^0 \mu^+ \mu^-} = 3(6) \times 10^{-3} \text{Im } c_{\ell equ}^{(1)2211} + 3(6) \times 10^{-3} \text{Im } c_{\ell edq}^{2211} - 7(2) \times 10^{-4} \text{Im } c_{\ell edq}^{2222},$$

$$A_L^{\eta' \rightarrow \eta \mu^+ \mu^-} = -5(39) \times 10^{-3} \text{Im } c_{\ell equ}^{(1)2211} + 5(46) \times 10^{-3} \text{Im } c_{\ell edq}^{2211} - 0.08(1) \text{Im } c_{\ell edq}^{2222},$$

$$\begin{aligned} A_T^{\eta' \rightarrow \eta \mu^+ \mu^-} = & 7(50) \times 10^{-5} \text{Im } c_{\ell equ}^{(1)2211} - 6(65) \times 10^{-5} \text{Im } c_{\ell edq}^{2211} \\ & + 1(19) \times 10^{-3} \text{Im } c_{\ell edq}^{2222}, \end{aligned}$$

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](https://arxiv.org/abs/2203.07651)
- A total production of $2.5 \times 10^{13} \frac{\eta}{\text{year}}$ and $2.5 \times 10^{11} \frac{\eta'}{\text{year}}$ is expected, with assumed reconstruction efficiencies of approximately 20%
- The expected SM asymmetry noise for the $\eta^{(')} \rightarrow \pi^0 \mu^+ \mu^-$ and $\eta' \rightarrow \eta \mu^+ \mu^-$ is

$$\sigma_{\eta \rightarrow \pi^0 \mu^+ \mu^-} = 1.29 \times 10^{-2}$$

$$\sigma_{\eta' \rightarrow \pi^0 \mu^+ \mu^-} = 0.105$$

$$\sigma_{\eta' \rightarrow \eta \mu^+ \mu^-} = 0.354$$

3. CP violation

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- Sensitivity to new physics at REDTOP

Process	Asymmetry	$\text{Im } c_{\ell equ}^{(1)2211}$	$\text{Im } c_{\ell edq}^{2211}$	$\text{Im } c_{\ell edq}^{2222}$
$\eta \rightarrow \pi^0 \mu^+ \mu^-$	A_L	0.0695	0.0720	0.686
	A_T	0.194	0.203	1.93
$\eta' \rightarrow \pi^0 \mu^+ \mu^-$	A_L	2.36	2.56	10.96
	A_T	33.1	35.8	154
$\eta' \rightarrow \eta \mu^+ \mu^-$	A_L	67.5	78.5	4.46
	A_T	5264	5549	328
$\eta \rightarrow \mu^+ \mu^-$	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 $\eta \rightarrow \mu^+ \mu^-$ 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 six $\eta^{(')} \rightarrow \pi^0 \ell^+ \ell^-$ and $\eta' \rightarrow \eta \ell^+ \ell^-$ semileptonic processes
- Theoretical estimations for the longitudinal and transverse asymmetries of the three $\eta^{(')} \rightarrow \pi^0 \mu^+ \mu^-$ and $\eta' \rightarrow \eta \mu^+ \mu^-$ processes have been presented. The predicted statistics at REDTOP would fall short to detect CP -violating effects in these decays