Flavor-changing neutral currents in tau decays

Alexey A. Petrov
University of South Carolina

Table of Contents:

- Introduction: neutrinos
- Effective Lagrangians for tau decays
- Examples: leptoquarks, FCNC scalars, …
- Conclusions and outlook

Prologue: ν electromagnetic interactions

- Neutrino electromagnetic interactions: signs of New Physics?
  - ν electromagnetic interactions are described by operators of dim ≥ 5

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{C^{(5)}_{1,ij}}{\Lambda} \frac{e}{8\pi^2} (\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu}$$

dipole moment

$$+ \sum_{i,j} \frac{C^{(6)}_{F,ij}}{\Lambda^2} \bar{\nu}_i \gamma^\mu \gamma_5 \nu_j \partial^\nu F_{\mu\nu}$$

anapole moment

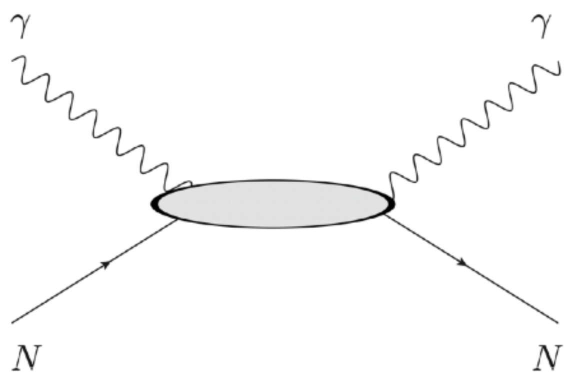
$$+ \frac{1}{2} \sum_{i,j} \left[\frac{C^{(7)}_{1,ij}}{\Lambda^3} \frac{\alpha}{12\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3} \frac{\alpha}{8\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \cdots$$

polarizability

  - For Majorana neutrinos the flavor conserving dipole moments vanish because the dipole is antisymmetric in flavor indices $(\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) = -(\bar{\nu}_j \sigma^{\mu\nu} P_L \nu_i)$
  - The dim-7 Rayleigh operators are symmetric: flavor diagonal transition possible

Neutrino polarizability

- Polarizability: reaction to external EM field
  - Example: nucleon polarizabilities are extensively studied in Compton scattering



$$H_{scal} = -2\pi \left(\alpha_{E1} \vec{E}^2 + \beta_{M1} \vec{H}^2 \right)$$

Hagelstein, Miskimen, Pascalutsa

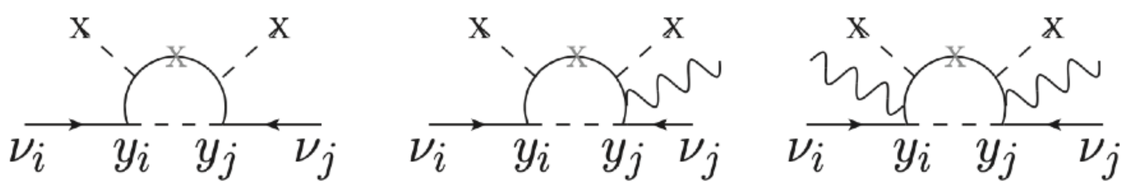
- Neutrino polarizability
  - neutrino polarizability is encoded in dim-7 Rayleigh operators

$$\mathcal{L} = \frac{1}{2} \sum_{i,j} \left[\frac{C^{(7)}_{1,ij}}{\Lambda^3} \frac{\alpha}{12\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3} \frac{\alpha}{8\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \cdots$$

  - … which are related to polarizability, as, e.g. $F_{\mu\nu} F^{\mu\nu} = \vec{H}^2 - \vec{E}^2$

Naive dimensional analysis: masses and EM interactions

- Neutrino masses: scale of New Physics?
  - Majorana: Weinberg terms (dim-5): $y'_{\alpha\beta}\left(\bar{L}^c_\alpha H^{c\dagger} H^\dagger L_\beta\right)/\Lambda$
  - Dirac: Yukawa terms (dim-4): $y_{\alpha\beta}\left(\bar{L}_\alpha H \nu_{R\beta}\right)$
  - need experiment, e.g. neutrinoless double beta decay



- Neutrino electromagnetic interactions: scale of New Physics?
  - Dipole moment: $c_6\left(\bar{L}_\alpha H \sigma^{\mu\nu} \nu_{R\beta}\right) F_{\mu\nu}/\Lambda^2$
  - Rayleigh operators: $c_8\left(\bar{L}_\alpha H \nu_{R\beta}\right) F_{\mu\nu} F^{\mu\nu}/\Lambda^4$
  - Both types of interaction flip chirality, so we naively expect

$$c_6 v/\Lambda^2 \sim c_6 m_\nu/\Lambda^2 \quad \text{or} \quad c_8 v/\Lambda^4 \sim c_8 m_\nu/\Lambda^4$$

  - … which is tiny and unobservable (similar for Majorana). So, why bother?

Dipole moment

- Neutrino electromagnetic interactions: signs of New Physics?
  - ν electromagnetic interactions are described by operators of dim ≥ 5

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{C^{(5)}_{1,ij}}{\Lambda} \frac{e}{8\pi^2} (\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu}$$

dipole moment

  - For Majorana neutrinos the dipole operator is antisymmetric in flavor indices $(\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) = -(\bar{\nu}_j \sigma^{\mu\nu} P_L \nu_i)$, while the mass operator is symmetric
  - Then, any New Physics that is odd under the same flavor exchange will only contribute to the neutrino magnetic moments and not to the neutrino masses.

Voloshin

Neutrino electrodynamics and possible consequences for solar neutrinos

M. B. Voloshin, M. I. Vysotskiĭ, and L. B. Okun'

Institute of Theoretical and Experimental Physics
(Submitted 25 April 1986)
Zh. Eksp. Teor. Fiz. **91**, 754–765 (September 1986)

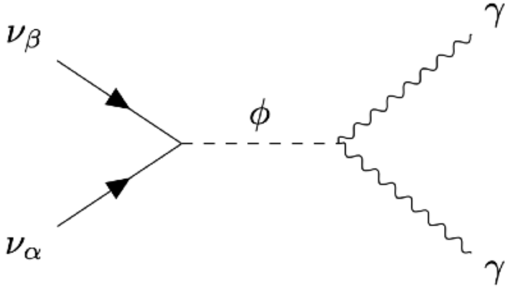
The neutrino electromagnetic moment matrix and the possibility that some of the elements of this matrix are of the order of 10^{-10} of the Bohr magneton are discussed. Flavor oscillations and spin precession are examined for a neutrino in a magnetic field in the presence of matter. The interaction between solar neutrinos and the magnetic field in the interior of the convective zone of the Sun can lead, in this case, to the 11-year and semiannual variations in the neutrino flux, shown experimentally to be correlated with the magnetic activity of the Sun.

  - Is it possible to find a similar mechanism to enhance Rayleigh operators?

- Neutrino polarizability
  - neutrino polarizability is encoded in dim-7 Rayleigh operators

$$\mathcal{L} = \frac{1}{2}\sum_{i,j}\left[\frac{C^{(7)}_{1,ij}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}\tilde{F}^{\mu\nu}\right] + \cdots$$

  - … which are also symmetric in flavor indices, just like the mass operator
  - But the smallness of the neutrino masses can be compensated:



  - A prototypical example is pNGB interactions: majoron a, which couples to $\Delta L = 2$ interaction as $\bar{\nu}^c_L \nu_L \partial_\mu a/f_a$
  - Majoron would also generically have EM couplings, aFF/Λ_γ
  - Thus, for energies below m_a: $\nu\nu FF \times (m_\nu/f_a)1/(m_a^2\Lambda_\gamma)$

We can study phenomenology of $\nu\nu FF$ interactions to probe New Physics

Phenomenology of neutrino polarizability

- Consider two separate cases
  - heavy mediator: effective operators and constraints on Wilson coefficients/New Physics scale

$$\mathcal{L} = \frac{1}{2}\sum_{i,j}\left[\frac{C^{(7)}_{1,ij}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar{\nu}_i P_L \nu_j) F_{\mu\nu}F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar{\nu}_i P_L \nu_j) F_{\mu\nu}\tilde{F}^{\mu\nu}\right] + \cdots$$

  - light mediator: constraints on a simplified model parameters

$$\mathcal{L}_{\rm int} = -\frac{\alpha}{12\pi}\frac{c_\gamma}{f_\phi}\phi F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{c'_\gamma}{f_\phi}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}c_\nu^{ij}(\bar{\nu}_i P_L \nu_j)\phi + \text{h.c.}$$

where c_γ, c'_γ and c_ν^{ij} are dimensionless couplings, while f_ϕ is a UV scale (e.g. related to pNG symmetry breaking)

  - also, $g_{\phi\gamma} \equiv \frac{\alpha}{2\pi}\frac{c'_\gamma}{f_\phi}$ and

$$\Gamma(\phi \to \gamma\gamma) = \left(\frac{\alpha}{8\pi}\right)^2 \frac{m_\phi^3}{4\pi f_\phi^2}\left[\frac{4}{9}(c_\gamma)^2 + (c'_\gamma)^2\right],$$

$$\Gamma(\phi \to \nu\nu') = \frac{m_\phi}{16\pi}\sum_{\alpha\beta}\left|c_\nu^{\alpha\beta}\right|^2,$$

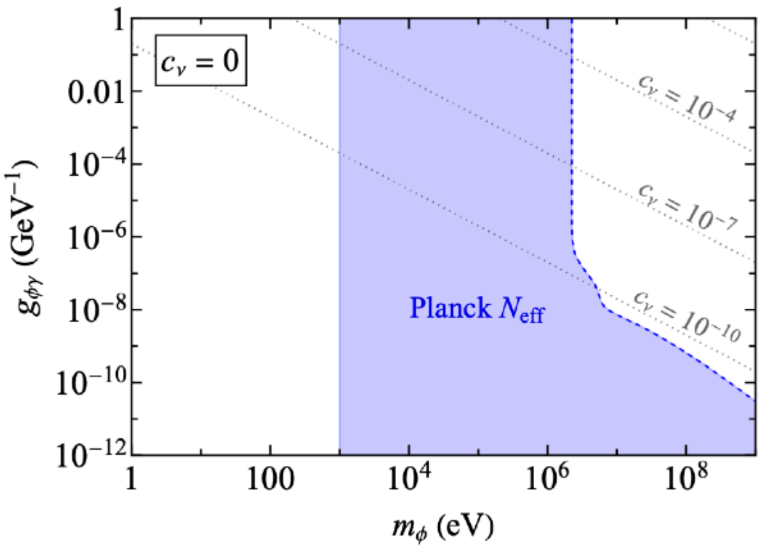
Light mediator phenomenology depends on what is larger, $\Gamma(\phi \to \gamma\gamma)$ or $\Gamma(\phi \to \nu\nu')$

Phenomenology of neutrino polarizability

- Constraints on the light resonance parameters from various sources

Process	$m_\phi = \text{eV}$	$m_\phi = \text{keV}$
BBN	$c_\nu \lesssim 4 \times 10^{-5}$	$c_\nu \lesssim 4.4 \times 10^{-6}$
ν self-interaction	$c_\nu < 2.8 \times 10^{-7}$	$c_\nu < 2.8 \times 10^{-4}$
HB star	$g_{\phi\gamma} \in [3.5 \times 10^{-3}, 10^{-11}]$	$g_{\phi\gamma} \in [3.3 \times 10^{-3}, 10^{-11}]$
SN1987a	$g_{\phi\gamma} \in [10^{-2}, 5 \times 10^{-6}]$ $c_\nu \in [10^{-3}, 1]$	$g_{\phi\gamma} \in [10^{-2}, 5 \times 10^{-6}]$ $c_\nu \in [10^{-6}, 10^{-2}]$
Borexino	$c_\nu g_{\phi\gamma} < 5.3 \times 10^{-8}$	$c_\nu g_{\phi\gamma} < 5.3 \times 10^{-8}$
Xenon-nT	$c_\nu g_{\phi\gamma} < 2.5 \times 10^{-8}$	$c_\nu g_{\phi\gamma} < 2.5 \times 10^{-8}$
MiniBoone	$c_\nu g_{\phi\gamma} < 4 \times 10^{-6}$	$c_\nu g_{\phi\gamma} < 4 \times 10^{-6}$
M/τ rare dec.	$c_\nu < 4 \times 10^{-3}$	$c_\nu < 4 \times 10^{-3}$
$0\nu 2\beta$	$c_\nu < 8 \times 10^{-6}$	$c_\nu < 8 \times 10^{-6}$
Beam dump	—	$g_{\phi\gamma} < 10^{-2}$
$e^+e^- \to 3\gamma$	—	—
$\pi^0 \to \gamma\gamma \to \nu\nu$	$c_\nu g_{\phi\gamma} < 2 \times 10^{-2}$	$c_\nu g_{\phi\gamma} < 2 \times 10^{-2}$
$B^0 \to \gamma\gamma \to \nu\nu$	$c_\nu g_{\phi\gamma} < 180$	$c_\nu g_{\phi\gamma} < 180$
BaBar	$g_{\phi\gamma} < 1.5 \times 10^{-4}$	$g_{\phi\gamma} < 1.5 \times 10^{-4}$
$h \to \gamma\gamma \to \nu\nu$	$c_\nu g_{\phi\gamma} < 2.4$	$c_\nu g_{\phi\gamma} < 2.4$

Constraints on $g_{\phi\gamma}$ from Planck bounds on N_{eff} (blue)



S. Bansal, G. Paz, AAP, M. Tammaro, and J. Zupan
JHEP 05 (2023) 142

Can we use tau decays to constrain some of the parameters?

FCNC in tau decays

- Tau FCNC electromagnetic & gluonic interactions: signs of New Physics?
  - interactions are described by operators of dim ≥ 5

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{C_{1,i}^{(\tau,5)}}{\Lambda} \frac{e}{8\pi^2} (\bar{\ell}_i \sigma^{\mu\nu} P_L \tau) F_{\mu\nu}$$

$$+\frac{1}{2}\sum_{i,j}\left[\frac{C_{1,i}^{(\tau,7)}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar{\ell}_i P_L \tau) F_{\mu\nu}F^{\mu\nu} + \frac{C_{2,i}^{(\tau,7)}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar{\ell}_i P_L \tau) F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

photonic polarizability

$$+\frac{1}{2}\sum_{i,j}\left[\frac{\widetilde{C}_{1,i}^{(\tau,7)}}{\Lambda^3}\frac{\alpha_s}{12\pi}(\bar{\ell}_i P_L \tau) G_{\mu\nu}G^{\mu\nu} + \frac{\widetilde{C}_{2,i}^{(\tau,7)}}{\Lambda^3}\frac{\alpha_s}{8\pi}(\bar{\ell}_i P_L \tau) G_{\mu\nu}\tilde{G}^{\mu\nu}\right] + \text{h.c.} + \cdots,$$

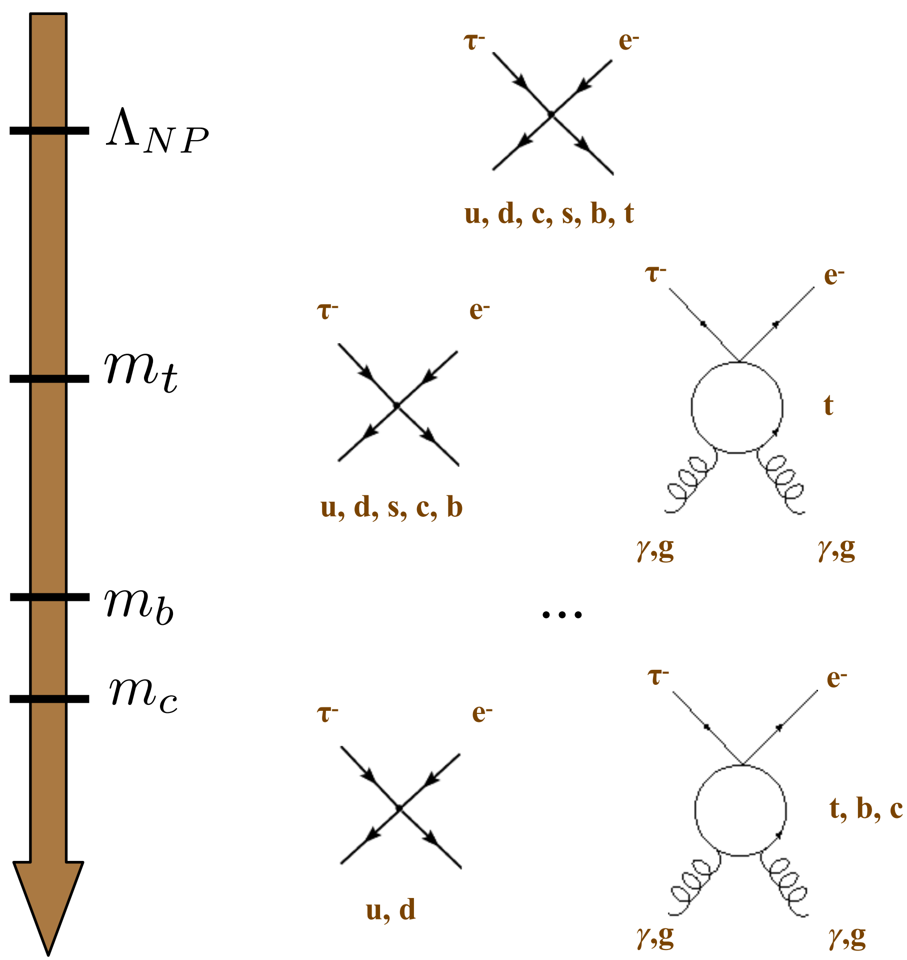
gluonic polarizability

  - Similar to neutrinos: both heavy NP and light NP is possible
  - constraints on both types of polarizability

F. Fortuna, et al
Phys.Rev.D 107 (2023) 1, 015027

Effective Interactions for taus

★ It is important to understand ALL relevant energy scales



New Physics generates lepton FCNC

SM EFT

…

heavy quarks decouple

…

Scale of the tau decay experiment

Effective Interactions for taus

★ Naive power counting: largest contribution from lowest dimensional operators

★ Can write the most general LO Lagrangian

$$\mathcal{L}^{(6)}_{\ell_1\ell_2} = \frac{1}{\Lambda^2}\sum_{i=1}^{12}\sum_q C_i^{q\ell_1\ell_2} Q_i^{q\ell_1\ell_2} + \text{H.c.},$$

- scalar operators

$$Q_1^{q\ell_1\ell_2} = (\bar\ell_{1R}\ell_{2L})\ (\bar q_R q_L),$$
$$Q_2^{q\ell_1\ell_2} = (\bar\ell_{1R}\ell_{2L})\ (\bar q_L q_R),$$
$$Q_3^{q\ell_1\ell_2} = (\bar\ell_{1L}\ell_{2R})\ (\bar q_R q_L),$$
$$Q_4^{q\ell_1\ell_2} = (\bar\ell_{1L}\ell_{2R})\ (\bar q_L q_R),$$

- vector operators

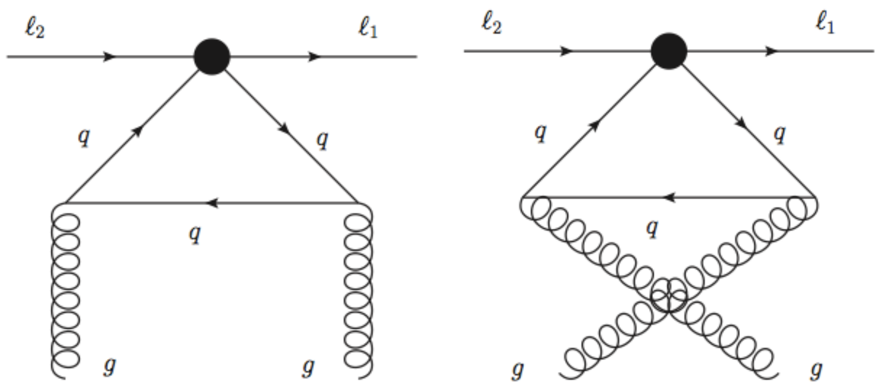
$$Q_5^{q\ell_1\ell_2} = (\bar\ell_{1L}\gamma^\mu\ell_{2L})(\bar q_L\gamma_\mu q_L),$$
$$Q_6^{q\ell_1\ell_2} = (\bar\ell_{1L}\gamma^\mu\ell_{2L})(\bar q_R\gamma_\mu q_R),$$
$$Q_7^{q\ell_1\ell_2} = (\bar\ell_{1R}\gamma^\mu\ell_{2R})(\bar q_L\gamma_\mu q_L),$$
$$Q_8^{q\ell_1\ell_2} = (\bar\ell_{1R}\gamma^\mu\ell_{2R})(\bar q_R\gamma_\mu q_R),$$

- tensor operators (do not contribute to considered tau decays)

Is this correct?

Effective Lagrangians: gluonic operators

★ Let's integrate out heavy quarks and concentrate on gluonic operators



$$\mathcal{L}^{(7)}_{\ell_1\ell_2} = \frac{1}{\Lambda^2}\sum_{i=1}^{4} c_i^{\ell_1\ell_2} O_i^{\ell_1\ell_2} + \text{H.c.},$$

★ we can calculate their contribution to tau decay rates!
★ c_i probe couplings of heavy quarks to New Physics

AAP and D. Zhuridov
PRD89 (2014) 3, 033005

Effective Lagrangians: gluonic operators

★ ... get an effective Lagrangian

$$\mathcal{L}^{(7)}_{\ell_1\ell_2} = \frac{1}{\Lambda^2}\sum_{i=1}^{4} c_i^{\ell_1\ell_2} O_i^{\ell_1\ell_2} + \text{H.c.},$$

AAP and D. Zhuridov
PRD89 (2014) 3, 033005

...where we defined operators

$$O_1^{\ell_1\ell_2} = \bar{\ell}_{1R}\ell_{2L}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu},$$

$$O_2^{\ell_1\ell_2} = \bar{\ell}_{1R}\ell_{2L}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu},$$

$$O_3^{\ell_1\ell_2} = \bar{\ell}_{1L}\ell_{2R}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu},$$

$$O_4^{\ell_1\ell_2} = \bar{\ell}_{1L}\ell_{2R}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu},$$

...and Wilson coefficients

$$c_1^{\ell_1\ell_2} = -\frac{2}{9}\sum_{q=c,b,t}\frac{I_1(m_q)}{m_q}\left(C_1^{q\ell_1\ell_2} + C_2^{q\ell_1\ell_2}\right),$$

$$c_2^{\ell_1\ell_2} = \frac{2\mathrm{i}}{9}\sum_{q=c,b,t}\frac{I_2(m_q)}{m_q}\left(C_1^{q\ell_1\ell_2} - C_2^{q\ell_1\ell_2}\right),$$

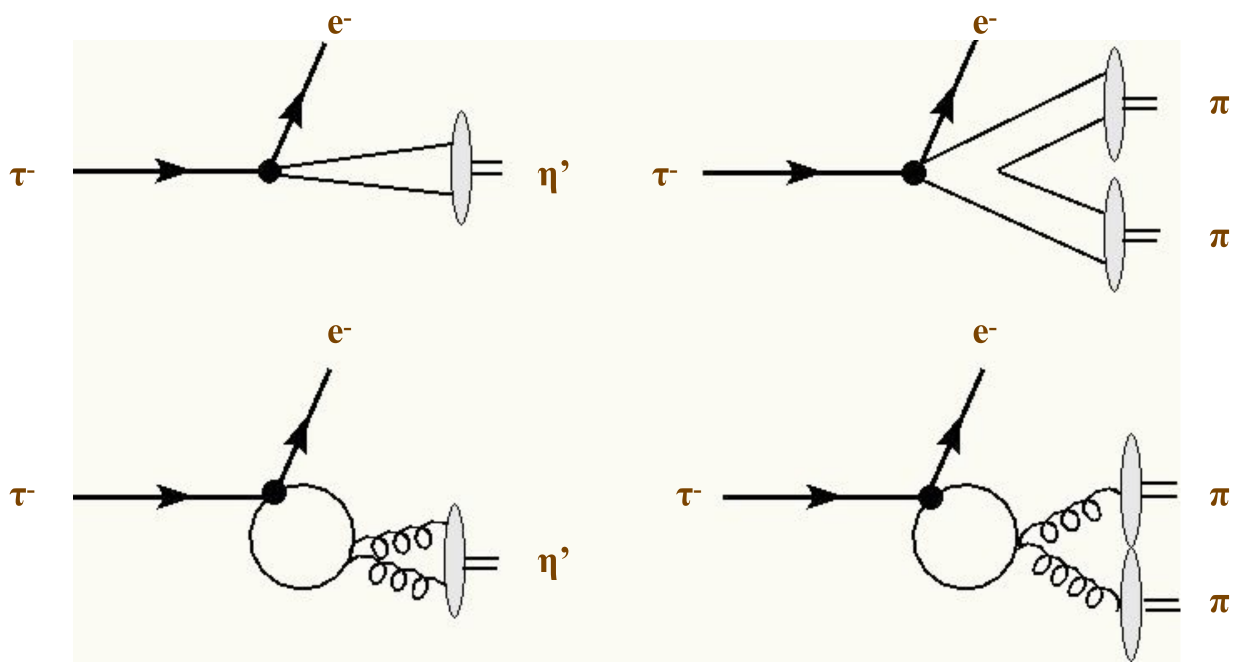
$$c_3^{\ell_1\ell_2} = -\frac{2}{9}\sum_{q=c,b,t}\frac{I_1(m_q)}{m_q}\left(C_3^{q\ell_1\ell_2} + C_4^{q\ell_1\ell_2}\right),$$

$$c_4^{\ell_1\ell_2} = \frac{2\mathrm{i}}{9}\sum_{q=c,b,t}\frac{I_2(m_q)}{m_q}\left(C_3^{q\ell_1\ell_2} - C_4^{q\ell_1\ell_2}\right),$$

$$I_1 = \frac{1}{3}, \qquad I_2 = \frac{1}{2}.$$

Constraints from FCNC tau decays

★ Gluonic polarizability constraints from FCNC tau decays to hadrons
- use designer modes to project out relevant operators



Partity-violating operators

Parity-conserving operators

★ To calculate FV tau decays we need a bit of hadronic physics

- matrix elements of parity-conserving operators

$$\langle \pi^+\pi^- | \bar{q}q | 0 \rangle = \langle K^+K^- | \bar{q}q | 0 \rangle = \delta_q^M B_0$$

$$\langle M^+M^- | \bar{q}\gamma_\mu q | 0 \rangle = \delta_q^M G_M^{(q)}(Q^2)\,(p_+ - p_-)_\mu$$

$$\langle M^+M^- | \frac{\alpha_s}{4\pi} G^{a\mu\nu} G^a_{\mu\nu} | 0 \rangle = -\frac{2}{9} q^2,$$

- ... where B_0=1.96 GeV from $m_\pi^2 = (m_u + m_d)\,B_0$

Black, Han, He, Sher

- ... and we used $\theta^\mu_\mu = -\frac{b\alpha_s}{8\pi} G^{\mu\nu a} G^a_{\mu\nu} + \sum_{q=u,d,s} m_q \bar{q}q$

Voloshin

★ Can do better on hadronic side by using data

Celis, Cirigliano, Passemar

★ To calculate FV tau decays we need a bit of hadronic physics

- matrix elements of parity-violating operators

$$
\begin{aligned}
\langle M(p)|\bar{q}\gamma^\mu\gamma_5 q|0\rangle &= -ib_q f_M^q p^\mu, \\
\langle M(p)|\bar{q}\gamma_5 q|0\rangle &= -ib_q h_M^q, \\
\langle M(p)|\frac{\alpha_s}{4\pi}G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}|0\rangle &= a_M,
\end{aligned}
$$

- ... where q=u,d,s and $b_{u,d}=1/2^{1/2}$, while $b_s=1$

- ... and in the FKS scheme of eta-eta' mixing

$$
\begin{aligned}
a_\eta &= -\frac{m_{\eta'}^2 - m_\eta^2}{2}\sin 2\phi\left(-f_q b_q \sin\phi + f_s \cos\phi\right), \\
a_{\eta'} &= -\frac{m_{\eta'}^2 - m_\eta^2}{2}\sin 2\phi\left(f_q b_q \sin\phi + f_s \cos\phi\right),
\end{aligned}
$$

★ Looking at the scalar operators only

$$\frac{d\Gamma(\tau \to \ell M^+ M^-)}{dq^2} = \frac{m_\tau}{32(2\pi)^3\Lambda^4}\left[|A_{MM}|^2 + |B_{MM}|^2\right] \times \sqrt{1 - \frac{4m_M^2}{q^2}}\left(1 - \frac{q^2}{m_\tau^2}\right)^2,$$

- ... with the following coefficients

$$A_{MM} = -\frac{2c_1^{\ell\tau}}{9}q^2 + \frac{1}{2}\sum_{q=u,d,s}\left(C_1^{q\ell\tau} + C_2^{q\ell\tau}\right)\delta_q^M B_0,$$

$$B_{MM} = -\frac{2c_3^{\ell\tau}}{9}q^2 + \frac{1}{2}\sum_{q=u,d,s}\left(C_3^{q\ell\tau} + C_4^{q\ell\tau}\right)\delta_q^M B_0.$$

Coef	Bound on $\lvert c_i^{\ell\tau}\rvert/\Lambda^2$, GeV^{-3}							
	$\mathcal{B}(\tau \to \mu\, \pi^+\pi^-)$ $< 2.1 \times 10^{-8}$	$\mathcal{B}(\tau \to e\, \pi^+\pi^-)$ $< 2.3 \times 10^{-8}$	$\mathcal{B}(\tau \to \mu K^+K^-)$ $< 4.4 \times 10^{-8}$	$\mathcal{B}(\tau \to e K^+K^-)$ $< 3.3 \times 10^{-8}$	$\mathcal{B}(\tau \to \mu\eta')$ $< 1.3 \times 10^{-7}$	$\mathcal{B}(\tau \to e\eta')$ $< 1.6 \times 10^{-7}$	$\mathcal{B}(\tau \to \mu\eta)$ $< 1.3 \times 10^{-7}$	$\mathcal{B}(\tau \to e\eta)$ $< 1.6 \times 10^{-7}$
c_1	6.8×10^{-8}	6.5×10^{-8}	9.4×10^{-8}	8.2×10^{-8}	–	–	–	–
c_2	–	–	–	–	2.3×10^{-7}	2.5×10^{-7}	1.6×10^{-7}	1.5×10^{-7}
c_3	6.8×10^{-8}	6.5×10^{-8}	9.4×10^{-8}	8.2×10^{-8}	–	–	–	–
c_4	–	–	–	–	2.3×10^{-7}	2.5×10^{-7}	1.6×10^{-7}	1.5×10^{-7}

Bounds: parity violating

★ *Again, looking at the scalar operators only*

$$\Gamma(\tau \to \mu M) = \frac{m_\tau}{8\pi\Lambda^4}\left[\left|A_M\right|^2 + \left|B_M\right|^2\right]\left(1 - \frac{m_M^2}{m_\tau^2}\right)^2$$

- ... with the following coefficients

$$A_M = -\frac{2i}{9} c_2^{\ell\tau} a_M + \sum_{q=u,d,s}\left(C_2^{q\ell\tau} - C_1^{q\ell\tau}\right)\frac{b_q h_M^q}{4m_q} + \frac{1}{2} m_\mu \sum_{q=u,d,s}\left(C_5^{q\ell\tau} - C_6^{q\ell\tau}\right) b_q f_M^q - \frac{1}{2} m_\tau \sum_{q=u,d,s}\left(C_7^{q\ell\tau} - C_8^{q\ell\tau}\right) b_q f_M^q$$

$$B_M = -\frac{2i}{9} c_4^{\ell\tau} a_M + \sum_{q=u,d,s}\left(C_4^{q\ell\tau} - C_3^{q\ell\tau}\right)\frac{b_q h_M^q}{4m_q} - \frac{1}{2} m_\tau \sum_{q=u,d,s}\left(C_5^{q\ell\tau} - C_6^{q\ell\tau}\right) b_q f_M^q + \frac{1}{2} m_\mu \sum_{q=u,d,s}\left(C_7^{q\ell\tau} - C_8^{q\ell\tau}\right) b_q f_M^q$$

Coef	Bound on $\lvert c_i^{\ell\tau}\rvert/\Lambda^2$, GeV^{-3}							
	$\mathcal{B}(\tau \to \mu\, \pi^+\pi^-)$ $< 2.1\times10^{-8}$	$\mathcal{B}(\tau \to e\, \pi^+\pi^-)$ $< 2.3\times10^{-8}$	$\mathcal{B}(\tau \to \mu K^+K^-)$ $< 4.4\times10^{-8}$	$\mathcal{B}(\tau \to eK^+K^-)$ $< 3.3\times10^{-8}$	$\mathcal{B}(\tau \to \mu\eta')$ $< 1.3\times10^{-7}$	$\mathcal{B}(\tau \to e\eta')$ $< 1.6\times10^{-7}$	$\mathcal{B}(\tau \to \mu\eta)$ $< 1.3\times10^{-7}$	$\mathcal{B}(\tau \to e\eta)$ $< 1.6\times10^{-7}$
c_1	6.8×10^{-8}	6.5×10^{-8}	9.4×10^{-8}	8.2×10^{-8}	–	–	–	–
c_2	–	–	–	–	2.3×10^{-7}	2.5×10^{-7}	1.6×10^{-7}	1.5×10^{-7}
c_3	6.8×10^{-8}	6.5×10^{-8}	9.4×10^{-8}	8.2×10^{-8}	–	–	–	–
c_4	–	–	–	–	2.3×10^{-7}	2.5×10^{-7}	1.6×10^{-7}	1.5×10^{-7}

★ Leptoquark interactions

- scalar leptoquarks

$$\mathcal{L}_S = \left(\lambda_{LS_0}\bar{q}^c_L i\tau_2 \ell_L + \lambda_{RS_0}\bar{u}^c_R e_R\right) S_0^\dagger + \left(\lambda_{LS_{1/2}}\bar{u}_R \ell_L + \lambda_{RS_{1/2}}\bar{q}_L i\tau_2 e_R\right) S_{1/2}^\dagger + \text{H.c.},$$

- vector leptoquarks

$$\mathcal{L}_V = \left(\lambda_{LV_0}\bar{q}_L \gamma_\mu \ell_L + \lambda_{RV_0}\bar{d}_R \gamma_\mu e_R\right) V_0^{\mu\dagger} + \left(\lambda_{LV_{1/2}}\bar{d}^c_R \gamma_\mu \ell_L + \lambda_{RV_{1/2}}\bar{q}^c_L \gamma_\mu e_R\right) V_{1/2}^{\mu\dagger} + \text{H.c.},$$

Davidson, Bailey, Campbell

★ Matching to the general result above, get

C_i^u/Λ^2	Expression	C_i^d/Λ^2	Expression
$\frac{C_1^u}{\Lambda^2}$	$\frac{\lambda^{\ell_1 u}_{RS_{1/2}}\lambda^{\ell_2 u}_{LS_{1/2}}}{2M^2_{S_{1/2}}}$	$\frac{C_1^d}{\Lambda^2}$	$\frac{\lambda^{\ell_2 b}_{LV_{1/2}}\lambda^{\ell_1 b}_{RV_{1/2}}}{M^2_{V_{1/2}}}$
$\frac{C_2^u}{\Lambda^2}$	$\frac{\lambda^{\ell_1 u}_{RS_0}\lambda^{\ell_2 u}_{LS_0}}{2M^2_{S_0}}$	$\frac{C_2^d}{\Lambda^2}$	$\frac{\lambda^{\ell_2 b}_{LV_0}\lambda^{\ell_1 b}_{RV_0}}{M^2_{V_0}}$
$\frac{C_3^u}{\Lambda^2}$	$\frac{\lambda^{\ell_2 u}_{RS_0}\lambda^{\ell_1 u}_{LS_0}}{2M^2_{S_0}}$	$\frac{C_3^d}{\Lambda^2}$	$\frac{\lambda^{\ell_1 b}_{LV_0}\lambda^{\ell_2 b}_{RV_0}}{M^2_{V_0}}$
$\frac{C_4^u}{\Lambda^2}$	$\frac{\lambda^{\ell_2 u}_{RS_{1/2}}\lambda^{\ell_1 u}_{LS_{1/2}}}{2M^2_{S_{1/2}}}$	$\frac{C_4^d}{\Lambda^2}$	$\frac{\lambda^{\ell_1 b}_{LV_{1/2}}\lambda^{\ell_2 b}_{RV_{1/2}}}{M^2_{V_{1/2}}}$

Explicit models: leptoquarks

★ Leptoquark interaction parameters for tau-mu transitions

$$\frac{|\lambda^{\mu t}_{RS_0}\lambda^{\tau t}_{LS_0}|}{M^2_{S_0}} = \frac{|\lambda^{\mu t}_{RS_{1/2}}\lambda^{\tau t}_{LS_{1/2}}|}{M^2_{S_{1/2}}} < 2.3\times 10^{-4}\ \mathrm{GeV}^{-2},$$

$$\frac{|\lambda^{\tau b}_{LV_0}\lambda^{\mu b}_{RV_0}|}{M^2_{V_0}} = \frac{|\lambda^{\tau b}_{LV_{1/2}}\lambda^{\mu b}_{RV_{1/2}}|}{M^2_{V_{1/2}}} < 4.4\times 10^{-6}\ \mathrm{GeV}^{-2}$$

★ … and the same for tau-e

$$\frac{|\lambda^{et}_{RS_0}\lambda^{\tau t}_{LS_0}|}{M^2_{S_0}} = \frac{|\lambda^{et}_{RS_{1/2}}\lambda^{\tau t}_{LS_{1/2}}|}{M^2_{S_{1/2}}} < 2.2\times 10^{-4}\ \mathrm{GeV}^{-2}$$

$$\frac{|\lambda^{\tau b}_{LV_0}\lambda^{eb}_{RV_0}|}{M^2_{V_0}} = \frac{|\lambda^{\tau b}_{LV_{1/2}}\lambda^{eb}_{RV_{1/2}}|}{M^2_{V_{1/2}}} < 4.2\times 10^{-6}\ \mathrm{GeV}^{-2}$$

AAP and D. Zhuridov
PRD89 (2014) 3, 033005

Epilogue

- Flavor-changing neutral current transitions provide great opportunities for studies of flavor in the SM and BSM
  - charge lepton transitions offer practically SM-background-free playground
    - large contributions from New Physics are possible, but not seen
    - EFT approach can be useful in studies of tau FCNC decays
    - ... as current methods rarely go beyond dim-6 operators
    - ... and thus do not constrain NP-heavy fermion couplings very well
- Tau decays can be used to put additional constraints on neutrino properties
- Maybe flavor physics will be the first place to see glimpses of New Physics
- ...but then again, maybe not.

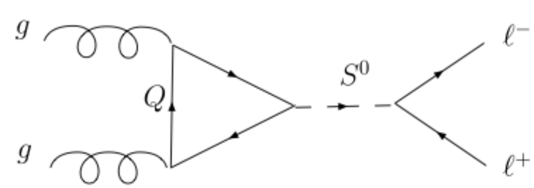
Effective Interactions for taus

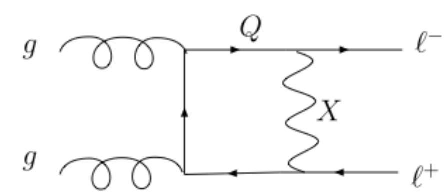
★ (Pseudo)scalar operators as given do not respect EW gauge invariance

- need to be induced by higher dimensional operators in SMEFT, e.g.

$$\frac{\overline{C}_i}{\Lambda^4}\left(\overline{\ell}_{1R} H \ell_{2L}\right)\left(\overline{q}_R H q_L\right) \Rightarrow \frac{\overline{C}_i}{\Lambda^2}\frac{v^2}{\Lambda^2}\left(\overline{\ell}_{1R}\ell_{2L}\right)\left(\overline{q}_R q_L\right)$$

- model examples? Note that we always have two scales present…





$$\overline{C}_i \sim \frac{m_\ell}{v}\tan^2\beta \qquad \Lambda^4 \sim (4\pi v)^2 M_S^2$$

$$\overline{C}_i \sim \pi\alpha_s \qquad \Lambda^4 \sim (4\pi v)^2 M_X^2$$

Potter, Valencia

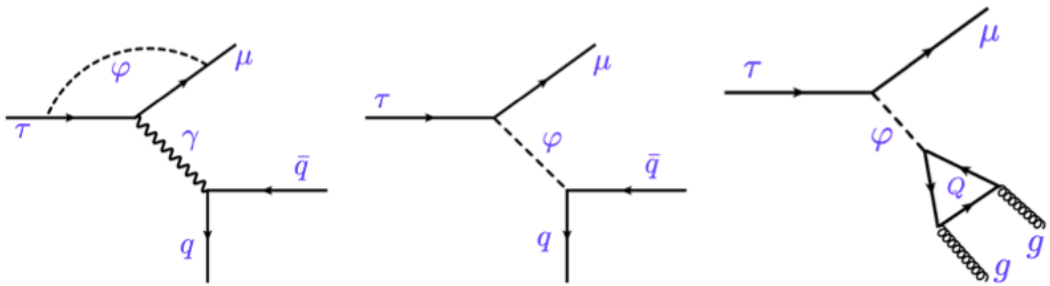
- … and for FCNC Higgs $\Lambda \sim v$

★ To simplify our discussion redefine C_i so power of Λ tracks operator's dimension

FCNC Higgs

Celis, Cirigliano, Passemar

★ FCNC Higgs gives another example



★ Constraints on FCNC Higgs Yukawa's

Process	$(BR \times 10^8)$ 90% C.L.	$\sqrt{\lvert Y^h_{\mu\tau}\rvert^2 + \lvert Y^h_{\tau\mu}\rvert^2}$	Operator(s)
$\tau \to \mu\gamma$	<4.4 [86]	<0.016	Dipole
$\tau \to \mu\mu\mu$	<2.1 [87]	<0.24	Dipole
$\tau \to \mu\pi^+\pi^-$	<2.1 [88]	<0.13	Scalar, gluon, dipole
$\tau \to \mu\rho$	<1.2 [89]	<0.13	Scalar, gluon, dipole
$\tau \to \mu\pi^0\pi^0$	$<1.4 \times 10^3$ [90]	<6.3	Scalar, gluon

Process	$(BR \times 10^8)$ 90% CL	$\sqrt{\lvert Y^h_{e\tau}\rvert^2 + \lvert Y^h_{\tau e}\rvert^2}$	Operator(s)
$\tau \to e\gamma$	<3.3 [86]	<0.014	Dipole
$\tau \to eee$	<2.7 [87]	<0.12	Dipole
$\tau \to e\pi^+\pi^-$	<2.3 [88]	<0.14	Scalar, gluon, dipole
$\tau \to e\rho$	<1.8 [89]	<0.16	Scalar, gluon, dipole
$\tau \to e\pi^0\pi^0$	$<6.5 \times 10^2$ [90]	<4.3	Scalar, gluon

Celis, Cirigliano, Passemar