Lepton-flavor violation in quarkonium decays

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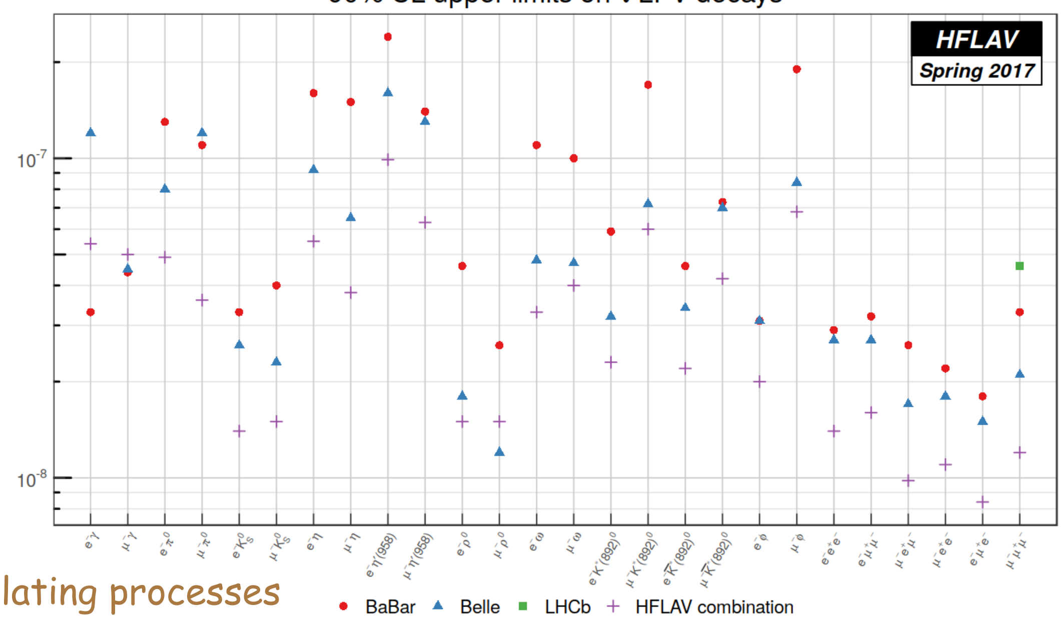
★ Why study flavor-changing neutral currents (FCNC)?

★ No trivial FCNC vertices in the Standard Model: sensitive NP tests

★ Possible experimental studies in a lepton sector

- lepton-flavor violating processes
  - $\mu \to e\gamma$, $\tau \to e\gamma$, etc.
  - $\mu \to eee$, $\tau \to \mu ee$, etc.
  - $\mu^+ e^- \to e^- \mu^+$
  - $Z^0 \to \mu e$, τe, etc.
  - $H \to \mu e$, τe, etc.
  - K^0 (B^0, D^0, ...) $\to \mu e$, τe, etc.
  - K^+ (B^+, D^+, ...) $\to \pi^+ \mu e$, $\pi^+ \tau e$, etc.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$

90% CL upper limits on τ LFV decays



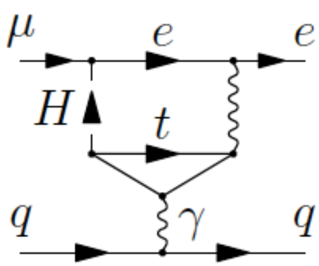
- lepton number and lepton-flavor violating processes
  - $(A, Z) \to (A, Z\pm2) + e^{\mp} e^{\mp}$
  - $\mu^- + (A, Z) \to e^+ + (A, Z-2)$

★ Highly suppressed in the Standard Model, e.g. $Br(\mu \to e\gamma) = \dfrac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \dfrac{m^2_{\nu_i}}{M^2_W} \right|^2 < 10^{-54}$

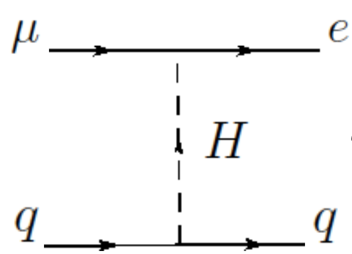
★ Leptonic FCNC could be generated by New Physics

★ E.g. FCNC Higgs decays H → μe, τe, etc.: $Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$ Harnik, Kopp, Zupan

★ FCNC Higgs model & muon conversion/quarkonium decays

e.g. 

$\sim \mathcal{O}(\alpha^2)$



$\sim \mathcal{O}(m_u \text{ or } m_d)$

Barr-Zee type

tree level

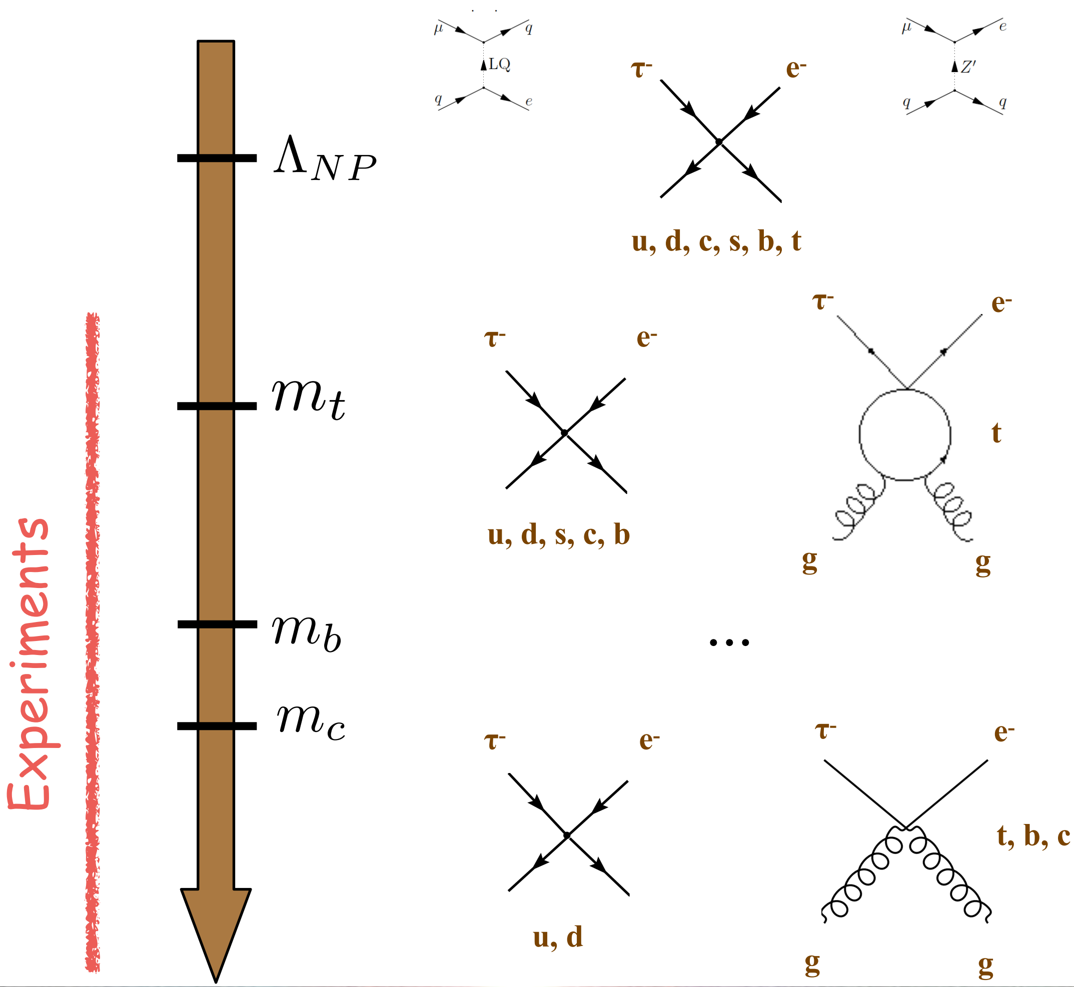
★ … but note: couplings of new physics to light quarks are suppressed

Can we correlate low energy (Belle/BESIII) and high energy (LHC) data?
(will not discuss purely leptonic LFV interactions)

2. Effective Lagrangians for LFV transitions

★ Modern approach to flavor physics calculations: effective field theories

★ It is important to understand ALL relevant energy scales for the problem at hand



New Physics generates lepton FCNC

Scales associated with heavy quarks

...

heavy
quarks
decouple

...

Scales associated with experiment

Effective Lagrangians

★ Naive power counting: largest contribution from lowest dimensional operators

★ Can write the most general LFV Lagrangian $\mathcal{L}_{LFV} = \mathcal{L}_D + \mathcal{L}_{lq} + \mathcal{L}_G + \ldots$

- dipole operators

$$\mathcal{L}_D = -\frac{m_2}{\Lambda^2}\left[\left(C_{DR}\overline{\ell}_1\sigma^{\mu\nu}P_L\ell_2 + C_{DR}\overline{\ell}_1\sigma^{\mu\nu}P_R\ell_2\right)F_{\mu\nu} + h.c.\right]$$

- four-fermion operators

$$\begin{aligned}\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\ \overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\ \overline{\ell}_1\gamma^\mu P_L\ell_2\right)\ \overline{q}\gamma_\mu q \\ & + \left(C_{AR}^{q\ell_1\ell_2}\ \overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\ \overline{\ell}_1\gamma^\mu P_L\ell_2\right)\ \overline{q}\gamma_\mu\gamma_5 q \\ & + m_2 m_q G_F\left(C_{SR}^{q\ell_1\ell_2}\ \overline{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\ \overline{\ell}_1 P_R\ell_2\right)\ \overline{q}q \\ & + m_2 m_q G_F\left(C_{PR}^{q\ell_1\ell_2}\ \overline{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\ \overline{\ell}_1 P_R\ell_2\right)\ \overline{q}\gamma_5 q \\ & + m_2 m_q G_F\left(C_{TR}^{q\ell_1\ell_2}\ \overline{\ell}_1\sigma^{\mu\nu}P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\ \overline{\ell}_1\sigma^{\mu\nu}P_R\ell_2\right)\ \overline{q}\sigma_{\mu\nu}q\ +\ h.c.\ \Big].\end{aligned}$$

- gluonic operators

$$\begin{aligned}\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[& \left(C_{GR}\overline{\ell}_1 P_R\ell_2 + C_{GL}\overline{\ell}_1 P_L\ell_2\right)G^a_{\mu\nu}G^{a\mu\nu} \\ & + \left(C_{\tilde{G}R}\overline{\ell}_1 P_R\ell_2 + C_{\tilde{G}L}\overline{\ell}_1 P_L\ell_2\right)G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} + h.c.\Big]\end{aligned}$$

Effective Lagrangians: designer states

★ There are many effective operators, so a single operator dominance hypothesis (SODH) is usually applied to get constraints on relevant Wilson coefficients.

This does not happen in most NP models!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}q \\
& + m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}\gamma_5 q \\
& + m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_R\ell_2\right)\ \bar{q}\sigma_{\mu\nu} q\ +\ h.c.\ \Big].
\end{aligned}
$$

- Can (partially) do away with SODH if designer initial/final states are used
- This can be done in case of restricted kinematics (e.g. 2-body decays)

★ Much tighter constraints on dipole operators are obtained from lepton radiative decays: drop them from quarkonium decay analyses in what follows

Effective Lagrangians: designer states

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \boxed{\left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu q} \\
& + \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}q \\
& + m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}\gamma_5 q \\
& + \boxed{m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_R\ell_2\right)\ \bar{q}\sigma_{\mu\nu} q} + \ h.c.\ \Big].
\end{aligned}
$$

also dipole operators

Vector meson decays: $\Upsilon(nS) \to \overline{\mu}\tau, \psi(nS) \to \overline{\mu}\tau, \rho \to \overline{\mu}e, \ldots$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

Effective Lagrangians: designer states

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2} \sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2} \; \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2} \; \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right) \; \bar{q}\gamma_\mu q \\
& + \boxed{\left(C_{AR}^{q\ell_1\ell_2} \; \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2} \; \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right) \; \bar{q}\gamma_\mu \gamma_5 q} \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2} \; \bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2} \; \bar{\ell}_1 P_R \ell_2 \right) \; \bar{q} q \\
& + \boxed{m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2} \; \bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2} \; \bar{\ell}_1 P_R \ell_2 \right) \; \bar{q}\gamma_5 q} \\
& + m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2} \; \bar{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2} \; \bar{\ell}_1 \sigma^{\mu\nu} P_R \ell_2 \right) \; \bar{q}\sigma_{\mu\nu} q \; + \; h.c. \Big].
\end{aligned}
$$

also gluonic operators

Pseudoscalar meson decays: $\eta_b \to \overline{\mu} e, \eta_c \to \overline{\mu}\tau, \eta^{(\prime)} \to \overline{\mu} e, \ldots$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

Effective Lagrangians: designer states

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q} q \\
& + m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q}\gamma_5 q \\
& + m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_R \ell_2 \right)\ \bar{q}\sigma_{\mu\nu} q\ +\ h.c.\ \Big].
\end{aligned}
$$

also gluonic operators

Scalar meson decays: $\chi_{b0} \to \overline{\mu}\tau,\ \chi_{c0} \to \overline{\mu}\tau,\ \ldots$

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3a. LFV vector quarkonia decays

★ Most LFV experimental data available V → μe, τe, etc.

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(\Upsilon(1S)\to\ell_1\ell_2)$	6.0×10^{-6}	$\cdots$	$\cdots$
$\mathcal{B}(\Upsilon(2S)\to\ell_1\ell_2)$	3.3×10^{-6}	3.2×10^{-6}	$\cdots$
$\mathcal{B}(\Upsilon(3S)\to\ell_1\ell_2)$	3.1×10^{-6}	4.2×10^{-6}	$\cdots$
$\mathcal{B}(J/\psi\to\ell_1\ell_2)$	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
$\mathcal{B}(\phi\to\ell_1\ell_2)$	FPS	FPS	4.1×10^{-6}
$\mathcal{B}(\ell_2\to\ell_1\gamma)$	4.4×10^{-8}	3.3×10^{-8}	5.7×10^{-13}

★ Decay amplitude:

$$\mathcal{A}(V\to\ell_1\bar{\ell}_2)=\bar{u}(p_1,s_1)\left[A_V^{\ell_1\ell_2}\gamma_\mu+B_V^{\ell_1\ell_2}\gamma_\mu\gamma_5+\frac{C_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu\right.$$
$$\left.+\frac{iD_V^{\ell_1\ell_2}}{m_V}(p_2-p_1)_\mu\gamma_5\right]v(p_2,s_2)\ \epsilon^\mu(p).$$

★ Decay rate:

$$\frac{\mathcal{B}(V\to\ell_1\bar{\ell}_2)}{\mathcal{B}(V\to e^+e^-)}=\left(\frac{m_V(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2\left[\left(|A_V^{\ell_1\ell_2}|^2+|B_V^{\ell_1\ell_2}|^2\right)\right.$$
$$+\frac{1}{2}(1-2y^2)\left(|C_V^{\ell_1\ell_2}|^2+|D_V^{\ell_1\ell_2}|^2\right)$$
$$\left.+y\mathrm{Re}\left(A_V^{\ell_1\ell_2}C_V^{\ell_1\ell_2*}+iB_V^{\ell_1\ell_2}D_V^{\ell_1\ell_2*}\right)\right].$$

Form-factors depend on vector, tensor, and dipole Wilson coefficients

LFV vector quarkonia decays

★ Most general decay rate for V → μe, τe, etc. ($V = \Upsilon(nS), \psi(nS), \rho, \phi, \dots$):

$$\frac{\mathcal{B}(V \to \ell_1 \bar{\ell}_2)}{\mathcal{B}(V \to e^+ e^-)} = \left(\frac{m_V(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 [(|A_V^{\ell_1\ell_2}|^2 + |B_V^{\ell_1\ell_2}|^2)$$
$$+ \frac{1}{2}(1-2y^2)(|C_V^{\ell_1\ell_2}|^2 + |D_V^{\ell_1\ell_2}|^2)$$
$$+ y\mathrm{Re}(A_V^{\ell_1\ell_2} C_V^{\ell_1\ell_2 *} + i B_V^{\ell_1\ell_2} D_V^{\ell_1\ell_2 *})].$$

D. Hazard and A.A.P., PRD94 (2016), 074023

… and the decay rate is

$$A_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}[\sqrt{4\pi\alpha} Q_q y^2 (C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}) + \kappa_V (C_{VL}^{q\ell_1\ell_2} + C_{VR}^{q\ell_1\ell_2})$$
$$+ 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q (C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2})],$$

$$B_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2}[-\sqrt{4\pi\alpha} Q_q y^2 (C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}) - \kappa_V (C_{VL}^{q\ell_1\ell_2} - C_{VR}^{q\ell_1\ell_2})$$
$$- 2y^2 \kappa_V \frac{f_V^T}{f_V} G_F m_V m_q (C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2})],$$

$$C_V^{\ell_1\ell_2} = \frac{f_V m_V}{\Lambda^2} y[\sqrt{4\pi\alpha} Q_q (C_{DL}^{\ell_1\ell_2} + C_{DR}^{\ell_1\ell_2}) + 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q (C_{TL}^{q\ell_1\ell_2} + C_{TR}^{q\ell_1\ell_2})],$$

$$D_V^{\ell_1\ell_2} = i\frac{f_V m_V}{\Lambda^2} y[-\sqrt{4\pi\alpha} Q_q (C_{DL}^{\ell_1\ell_2} - C_{DR}^{\ell_1\ell_2}) - 2\kappa_V \frac{f_V^T}{f_V} G_F m_V m_q (C_{TL}^{q\ell_1\ell_2} - C_{TR}^{q\ell_1\ell_2})].$$

LFV vector quarkonia decays: 4f operators

★ Constraints on Wilson coefficients of four-fermion low energy operators

	Leptons	Initial state (quark)				
Wilson coefficient [GeV^{-2}]	$\ell_1\ell_2$	$\Upsilon(1S)(b)$	$\Upsilon(2S)(b)$	$\Upsilon(3S)(b)$	$J/\psi(c)$	$\phi(s)$
$\lvert C_{VL}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	FPS
	$e\tau$	$\cdots$	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	FPS
	$e\mu$	$\cdots$	$\cdots$	$\cdots$	1.0×10^{-5}	2×10^{-3}
$\lvert C_{VR}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	5.6×10^{-6}	4.1×10^{-6}	3.5×10^{-6}	5.5×10^{-5}	FPS
	$e\tau$	$\cdots$	4.1×10^{-6}	4.1×10^{-6}	1.1×10^{-4}	FPS
	$e\mu$	$\cdots$	$\cdots$	$\cdots$	1.0×10^{-5}	2×10^{-3}
$\lvert C_{TL}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	FPS
	$e\tau$	$\cdots$	3.3×10^{-2}	3.2×10^{-2}	2.4	FPS
	$e\mu$	$\cdots$	$\cdots$	$\cdots$	4.8	1×10^{4}
$\lvert C_{TR}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	4.4×10^{-2}	3.2×10^{-2}	2.8×10^{-2}	1.2	FPS
	$e\tau$	$\cdots$	3.3×10^{-2}	3.2×10^{-2}	2.4	FPS
	$e\mu$	$\cdots$	$\cdots$	$\cdots$	4.8	1×10^{4}

D. Hazard and A.A.P., PRD94 (2016), 074023

LFV (pseudo)scalar quarkonia decays

★ Most general decay rate for P/S → μe, τe, etc ($P = \eta_b, \eta_c, \eta^{(\prime)}, \ldots$):
$S = \chi_{b0}, \chi_{c0}, \ldots$

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$$\mathcal{B}(M \to \ell_1 \bar{\ell}_2) = \frac{m_M}{8\pi\Gamma_M}\left(1-y^2\right)^2\left[\left|E_M^{\ell_1\ell_2}\right|^2 + \left|F_M^{\ell_1\ell_2}\right|^2\right]$$

… for pseudoscalar operators

$$\begin{aligned} E_P^{\ell_1\ell_2} &= y\frac{m_P}{4\Lambda^2}\left[-if_P\left[2\left(C_{AL}^{cc\ell_1\ell_2} + C_{AR}^{cc\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{cc\ell_1\ell_2} + C_{PR}^{cc\ell_1\ell_2}\right)\right]\right] \\ F_P^{\ell_1\ell_2} &= -y\frac{m_P}{4\Lambda^2}\left[f_P\left[2\left(C_{AL}^{cc\ell_1\ell_2} - C_{AR}^{cc\ell_1\ell_2}\right) - m_P^2 G_F\left(C_{PL}^{cc\ell_1\ell_2} - C_{PR}^{cc\ell_1\ell_2}\right)\right]\right] \end{aligned}$$

… and for scalar operators

$$\begin{aligned} E_S^{\ell_1\ell_2} &= iyf_S m_c\frac{m_S^2 G_F}{2\Lambda^2}\left(C_{SL}^{ccl_1l_2} + C_{SR}^{ccl_1l_2}\right) \\ F_S^{\ell_1\ell_2} &= yf_S m_c\frac{m_S^2 G_F}{2\Lambda^2}\left(C_{SL}^{ccl_1l_2} - C_{SR}^{ccl_1l_2}\right) \end{aligned}$$

Gluonic operators?

LFV pseudoscalar/scalar quarkonia decays

★ Constraints on Wilson coefficients of low energy operators

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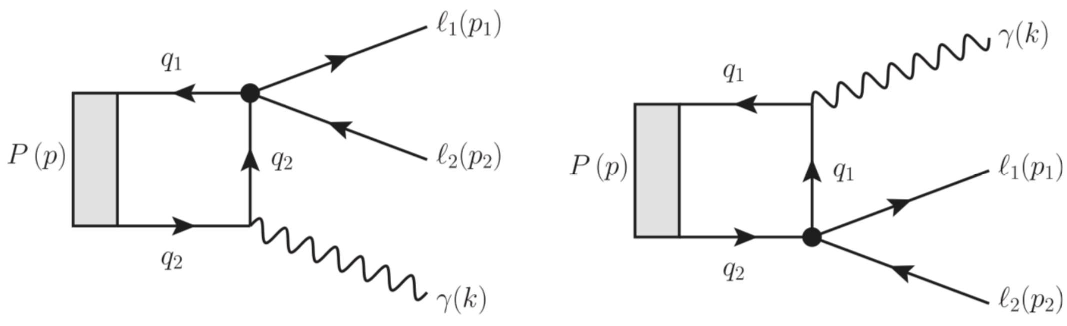
	Leptons	Initial state					
Wilson coefficient	$\ell_1\ell_2$	η_b	η_c	$\eta(u/d)$	$\eta(s)$	$\eta'(u/d)$	$\eta'(s)$
$\lvert C_{AL}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\mu$	$\cdots$	$\cdots$	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
$\lvert C_{AR}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\mu$	$\cdots$	$\cdots$	3×10^{-3}	2×10^{-3}	2.1×10^{-1}	1.9×10^{-1}
$\lvert C_{PL}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\mu$	$\cdots$	$\cdots$	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}
$\lvert C_{PR}^{q\ell_1\ell_2}/\Lambda^2\rvert$	$\mu\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\tau$	$\cdots$	$\cdots$	FPS	FPS	FPS	FPS
	$e\mu$	$\cdots$	$\cdots$	2×10^{3}	1×10^{3}	3.9×10^{4}	3.6×10^{4}

★ More data is needed: use radiative decays: $A(P(p) \to \gamma(k)\ell_1(p_1)\bar{\ell}_2(p_2))$

$$= \bar{u}(p_1,s_1)M^\mu(p,k,q)v(p_2,s_2)\varepsilon^*_\mu(k),$$



(a) (b)

★ Most general parameterization: $M^\mu(p,k,q)$

$$= \gamma^\mu(M_1^{P\ell_1\ell_2} + \not{k}M_2^{P\ell_1\ell_2}) + i\gamma_5\gamma^\mu(M_3^{P\ell_1\ell_2} + \not{k}M_4^{P\ell_1\ell_2})$$
$$+ q^\mu(M_5^{P\ell_1\ell_2} + \not{k}M_6^{P\ell_1\ell_2}) + i\gamma_5 q^\mu(M_7^{P\ell_1\ell_2} + \not{k}M_8^{P\ell_1\ell_2})$$
$$+ p^\mu(M_9^{q\ell_1\ell_2} + \not{k}M_{10}^{q\ell_1\ell_2}) + i\gamma_5 p^\mu(M_{11}^{P\ell_1\ell_2} + \not{k}M_{12}^{P\ell_1\ell_2}).$$

★ Not the most minimal set: gauge invariance? Project $P^{\mu\nu} = g^{\mu\nu} - \dfrac{p^\mu k^\nu}{(p\cdot k)}$

$$P^{\mu\nu}M_\nu = M^\mu \quad \text{and} \quad k_\mu P^{\mu\nu} = 0,$$

D. Hazard and A.A.P., PRD98 (2018), 015027

Radiative LFV decays

★ A minimal set of amplitudes can be obtained
$$A(P(p) \to \gamma(k)\ell_1(p_1)\bar{\ell}_2(p_2)) = \bar{u}(p_1, s_1)M^\mu(p,k,q)v(p_2,s_2)\varepsilon^*_\mu(k),$$

$$M^\mu(p,k,q) = \sum_i L_i^\mu(p,q,k)A_i^{P\ell_1\ell_2}(p^2,\ldots)$$

$$L_1^\mu = \gamma^\mu \not{k}, \qquad L_2^\mu = i\gamma_5\gamma^\mu\not{k},$$
$$L_3^\mu = (p\cdot k)q^\mu - (k\cdot q)p^\mu,$$
$$L_4^\mu = i\gamma_5[(p\cdot k)q^\mu - (k\cdot q)p^\mu],$$
$$L_5^\mu = (p\cdot k)\gamma^\mu - p^\mu\not{k},$$
$$L_6^\mu = i\gamma_5[(p\cdot k)\gamma^\mu - p^\mu\not{k}],$$
$$L_7^\mu = q^\mu\not{k} - (k\cdot q)\gamma^\mu,$$
$$L_8^\mu = i\gamma_5[q^\mu\not{k} - (k\cdot q)\gamma^\mu].$$

★ These amplitudes can be related to hadronic form-factors and Wilson coefficients. Complicated expression: single operator dominance again?

★ Simplification: select resonance region
$$\mathcal{B}(V \to \gamma\ell_1\bar{\ell}_2) = \mathcal{B}(V \to \gamma M)\mathcal{B}(M \to \ell_1\bar{\ell}_2)$$

$$\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}(1P)) = 9.99 \pm 0.27\%,$$
$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c0}(1P)) = 0.73 \pm 0.09\%.$$
$$\mathcal{B}(J/\psi \to \gamma\eta_c) = 1.7 \pm 0.4\%,$$
$$\mathcal{B}(\psi(2S) \to \gamma\eta_c) = 0.34 \pm 0.05\%.$$

$$\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{b0}(1P)) = 3.8 \pm 0.4\%,$$
$$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b0}(1P)) = 0.27 \pm 0.04\%,$$
$$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = 5.9 \pm 0.6\%.$$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

LFV pseudoscalar/scalar quarkonia decays

★ Very scarce LFV experimental data available P/S → μe, τe, etc.

- no data for pseudoscalar heavy-flavored meson decays
- no data for any scalar meson decays
- maybe use B-decays?

$\ell_1\ell_2$	$e\mu$
$\mathcal{B}(\eta \to \ell_1\ell_2)$	6×10^{-6}
$\mathcal{B}(\eta' \to \ell_1\ell_2)$	4.7×10^{-4}
$\mathcal{B}(\pi^0 \to \ell_1\ell_2)$	3.6×10^{-10}

$$P = \eta_b, \eta_c, \eta^{(\prime)}, \ldots$$
$$S = \chi_{b0}, \chi_{c0}, \ldots$$

★ Constraints are available for quark off-diagonal currents from B/D → μe, τe, etc.

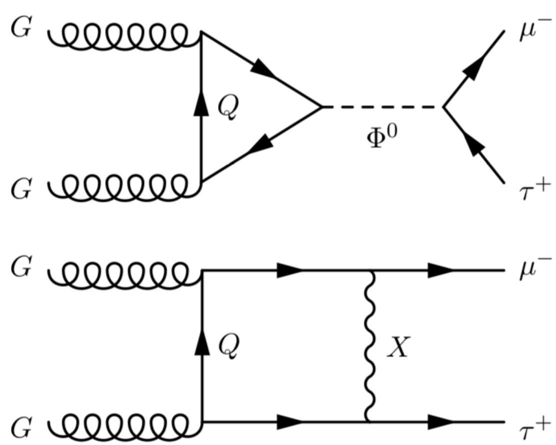
$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(B_d^0 \to \ell_1\ell_2)$	2.2×10^{-5}	2.8×10^{-5}	1.0×10^{-9}
$\mathcal{B}(B_s^0 \to \ell_1\ell_2)$	$\cdots$	$\cdots$	5.4×10^{-9}
$\mathcal{B}(\bar{D}^0 \to \ell_1\ell_2)$	FPS	$\cdots$	1.3×10^{-8}
$\mathcal{B}(K_L^0 \to \ell_1\ell_2)$	FPS	FPS	4.7×10^{-12}

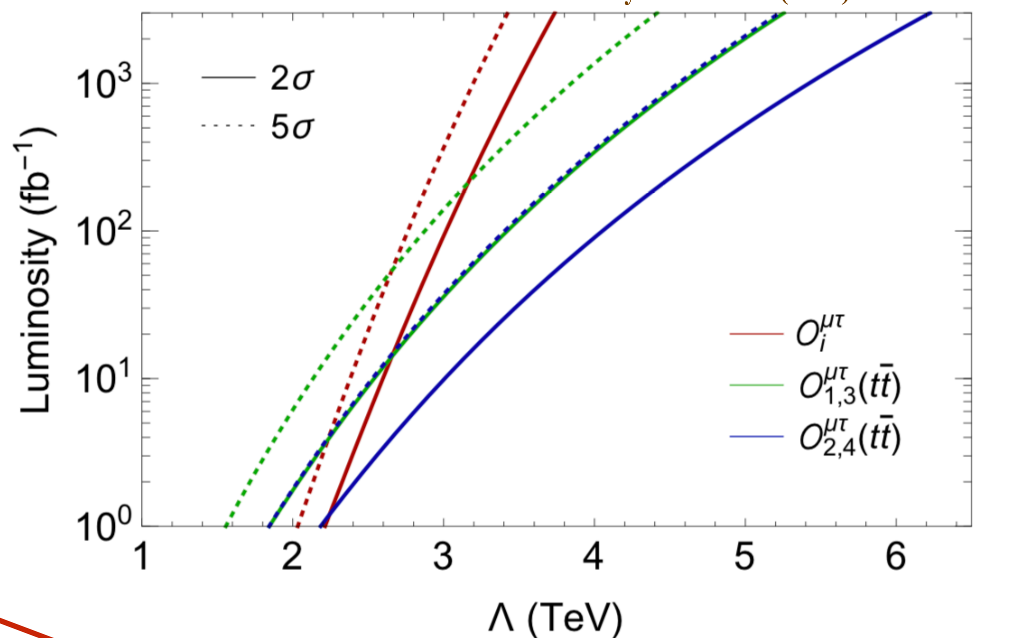
D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

3c. Probing LFV gluonic operators with LHC

★ Large gluon luminosity of the LHC makes it possible to probe gluonic operators at LHC directly

Bhattacharya, Morgan, Osborne, AAP: Phys.Lett. B785 (2018) 165-170





NP "Q"

SM "Q"

$$\mathcal{L}_{\rm eff} = \sum_{i=1}^{4} \mathcal{C}_i^{\mu\tau} \mathcal{O}_i^{\mu\tau} + \text{h.c.}\,,$$

$$\begin{aligned}
\mathcal{O}_1^{\mu\tau} &= (\overline{\mu}_L \tau_R)\, G \cdot G\,, \\
\mathcal{O}_2^{\mu\tau} &= (\overline{\mu}_L \tau_R)\, G \cdot \widetilde{G}\,, \\
\mathcal{O}_3^{\mu\tau} &= (\overline{\mu}_R \tau_L)\, G \cdot G\,, \\
\mathcal{O}_4^{\mu\tau} &= (\overline{\mu}_R \tau_L)\, G \cdot \widetilde{G}\,.
\end{aligned}$$

$$C_i^{\mu\tau} = 4\pi v\, g_s^2/\sqrt{2}\Lambda^4$$

$$\boxed{\begin{aligned}\Lambda_{2\sigma} &\approx 3000 \text{ GeV} \\ \Lambda_{5\sigma} &\approx 2800 \text{ GeV}\end{aligned}}$$

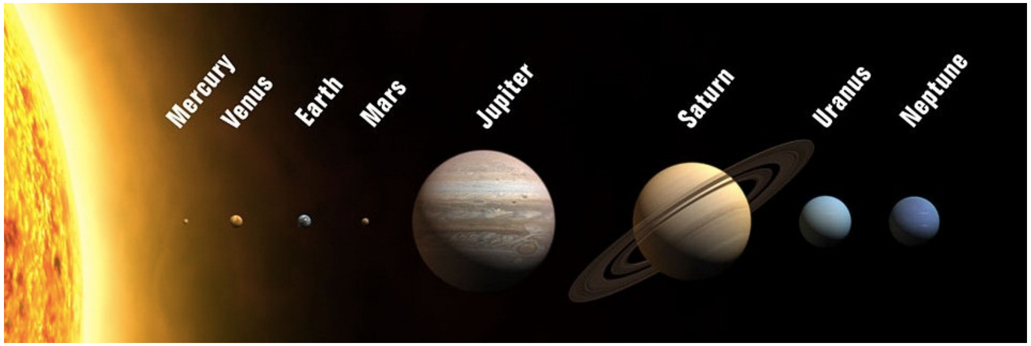
$$\mathcal{L}_{\mu\tau}^{(6)} \supset \frac{1}{\Lambda^2} \sum_{i=1}^{4} C_i^{q\mu\tau} \mathcal{O}_i^{q\mu\tau} + \text{h.c.}\,,$$

$$\begin{aligned}
\mathcal{O}_1^{q\mu\tau} &= (\overline{\mu}_L \tau_R)(\overline{q}_L q_R) \\
\mathcal{O}_2^{q\mu\tau} &= (\overline{\mu}_L \tau_R)(\overline{q}_R q_L) \\
\mathcal{O}_3^{q\mu\tau} &= (\overline{\mu}_R \tau_L)(\overline{q}_L q_R) \\
\mathcal{O}_4^{q\mu\tau} &= (\overline{\mu}_R \tau_L)(\overline{q}_R q_L)
\end{aligned}$$

Can probe LFV couplings of top quarks!

Things to take home

- Flavor-changing neutral current transitions provide great opportunities for studies of lepton 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 quarkonium/tau FCNC decays
    - ... as current methods do not constrain NP-heavy fermion couplings very well
    - LFV decays might shed some light on LFUV transitions in B-decays
- Need more data from Belle-II (or LHCb) on LFV quarkonia decays!
  - there is NO DATA for LFV radiative decays, e.g. $\psi(nS) \to \gamma \overline{\mu} e, \gamma \overline{\mu} \tau, \ldots$
- More data from ATLAS/CMS/(LHCb?) on pp $\to$ $\tau\mu$ + X
  - studies of gluonic operators from gg $\to$ $\tau\mu$ due to large gluon luminosity of LHC

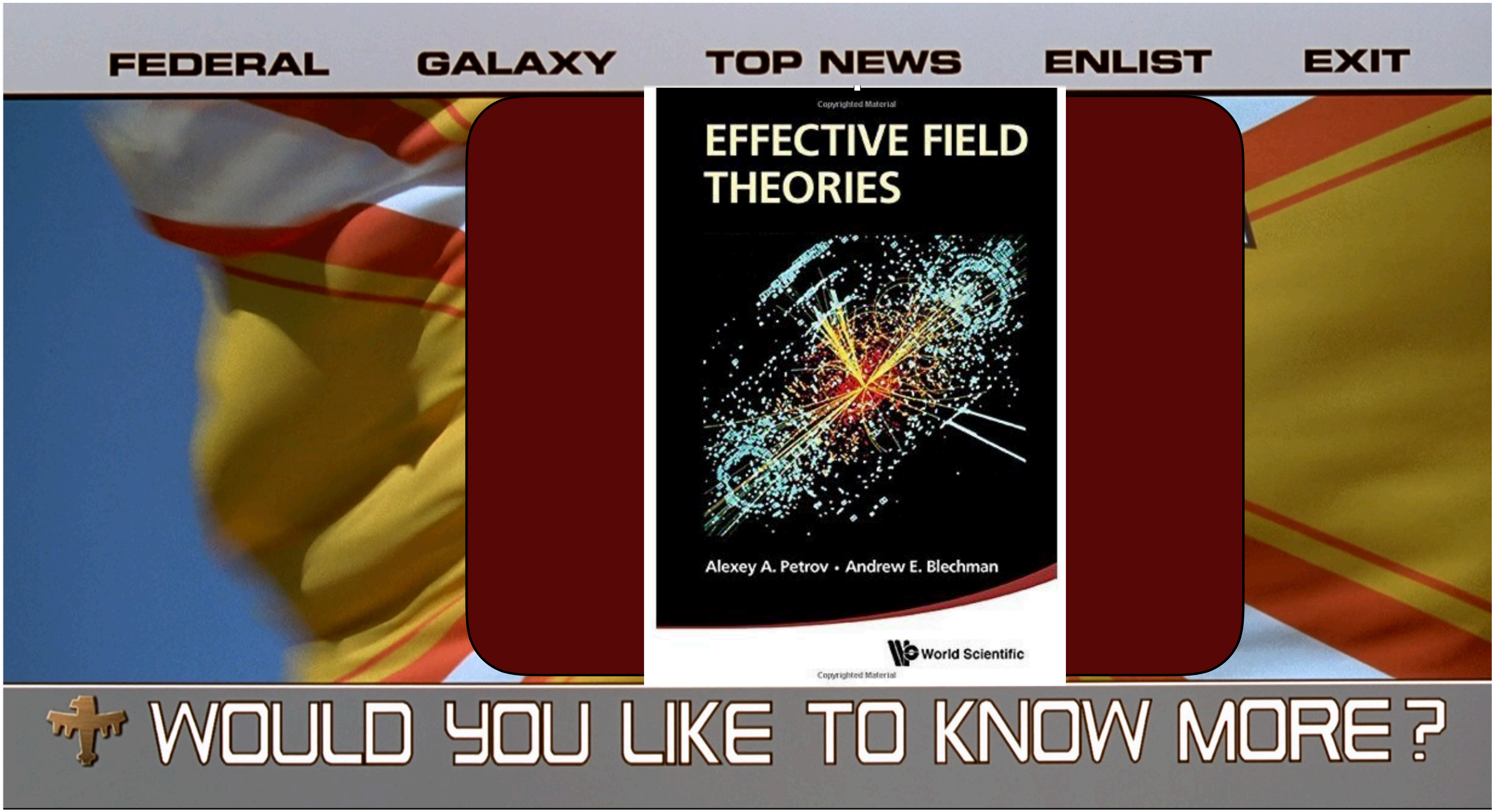


- Goal: global analysis of LFV.
- Is there a flavor problem?

Why is $m_t \gg m_u$?

Why is $M_{Jupiter} \gg M_{Mercury}$?


EXTRA!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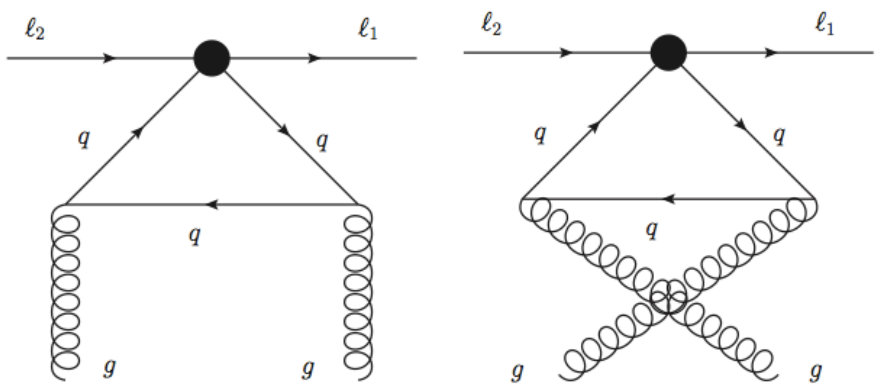
Effective Lagrangians: gluonic operators

★ Coefficients of gluonic operators depend on the number of active flavors



$$\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[\Big(C_{GR}\bar{\ell}_1 P_R \ell_2 + C_{GL}\bar{\ell}_1 P_L \ell_2\Big) G^a_{\mu\nu} G^{a\mu\nu} + \Big(C_{\tilde{G}R}\bar{\ell}_1 P_R \ell_2 + C_{\tilde{G}L}\bar{\ell}_1 P_L \ell_2\Big) G^a_{\mu\nu} \widetilde{G}^{a\mu\nu} + h.c.\Big]$$

★ we can calculate their contribution to meson or tau decay rates!
★ also relevant for muon conversion experiments
★ c_i probe couplings of heavy quarks to New Physics

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