Flavor violation in tau decays

or when leptons interact with gluons

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Based on A.A.P. & D. Zhuridov, PRD89 (2014) 3, 033005;
M. Goderinger, D. Hazard, A.A.P., to be published

Introduction: leptonic FCNC

★ 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.
  - K^0 (B^0, D^0, ...) $\to \mu e$, τe, etc.
  - K^+ (B^+, D^+, ...) $\to \pi^+\mu e$, $\pi^+\tau e$, etc.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$

Channel	Babar $\mathcal{L}$ (fb^{-1})	Babar $\mathcal{B}_{UL}$ (10^{-8})	BELLE $\mathcal{L}$ (fb^{-1})	BELLE $\mathcal{B}_{UL}$ (10^{-8})
$\tau^\pm \to e^\pm\gamma$	232	11	535	12
$\tau^\pm \to \mu^\pm\gamma$	232	6.8	535	4.5
$\tau^\pm \to \ell^\pm\ell^\mp\ell^\pm$	92	11 - 33	535	2 - 4
$\tau^\pm \to e^\pm\pi^0$	339	13	401	8.0
$\tau^\pm \to \mu^\pm\pi^0$	339	11	401	12
$\tau^\pm \to e^\pm\eta$	339	16	401	9.2
$\tau^\pm \to \mu^\pm\eta$	339	15	401	6.5
$\tau^\pm \to e^\pm\eta'$	339	24	401	16
$\tau^\pm \to \mu^\pm\eta'$	339	14	401	13

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

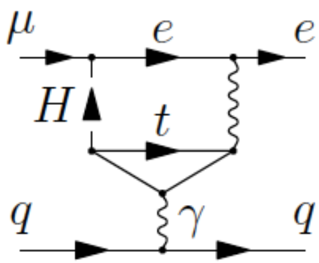
$$\mathrm{BR}\,(K_L^0 \to \mu e) < 4.7 \times 10^{-12}$$
$$\mathrm{BR}\,(B_d^0 \to \mu e) < 1.7 \times 10^{-7} \quad \text{[Belle]}$$
$$\mathrm{BR}\,(B_s^0 \to \mu e) < 6.1 \times 10^{-6} \quad \text{[CDF]}$$

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

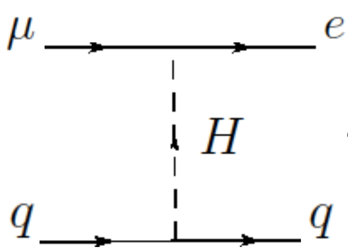
An example in a particular model:

★ Consider an example: FCNC Higgs model & muon conversion

e.g.



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

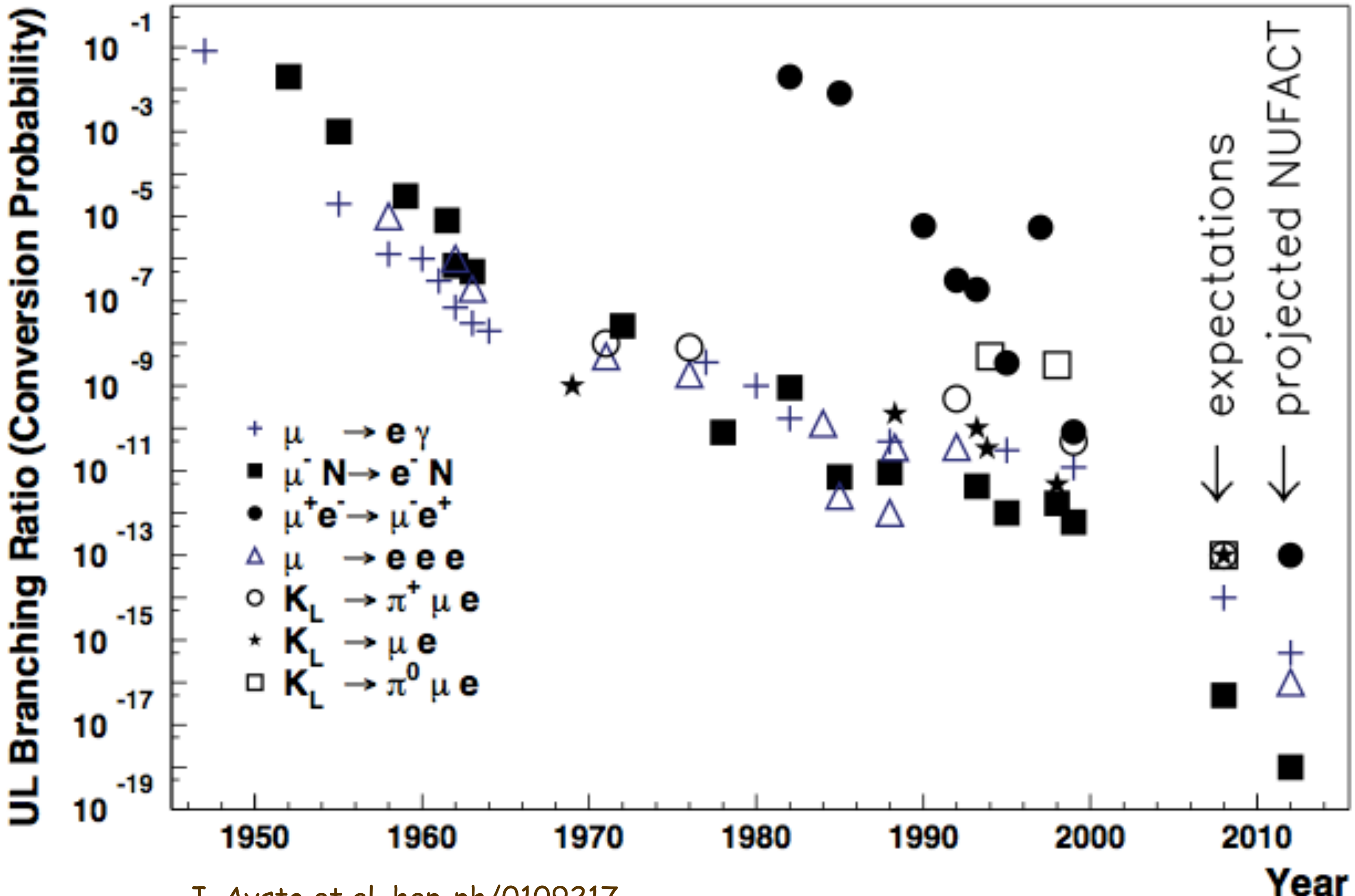


$\sim \mathcal{O}(m_u \text{ or } m_d)$

★ Couplings of new physics to light quarks are suppressed…

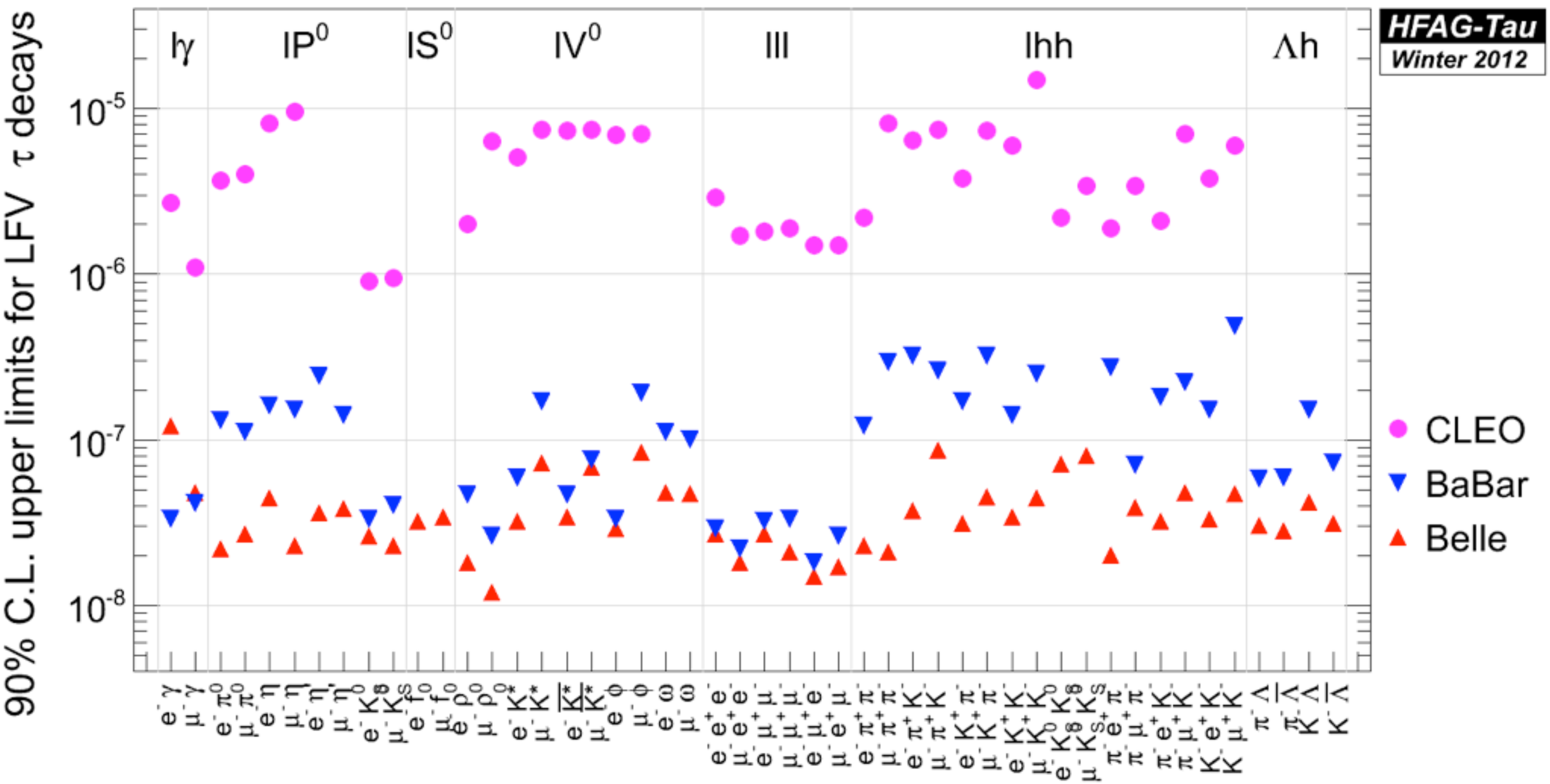
★ … same thing for tau decays

Searches for Lepton Number Violation



J. Aysto et al, hep-ph/0109217

What about taus?



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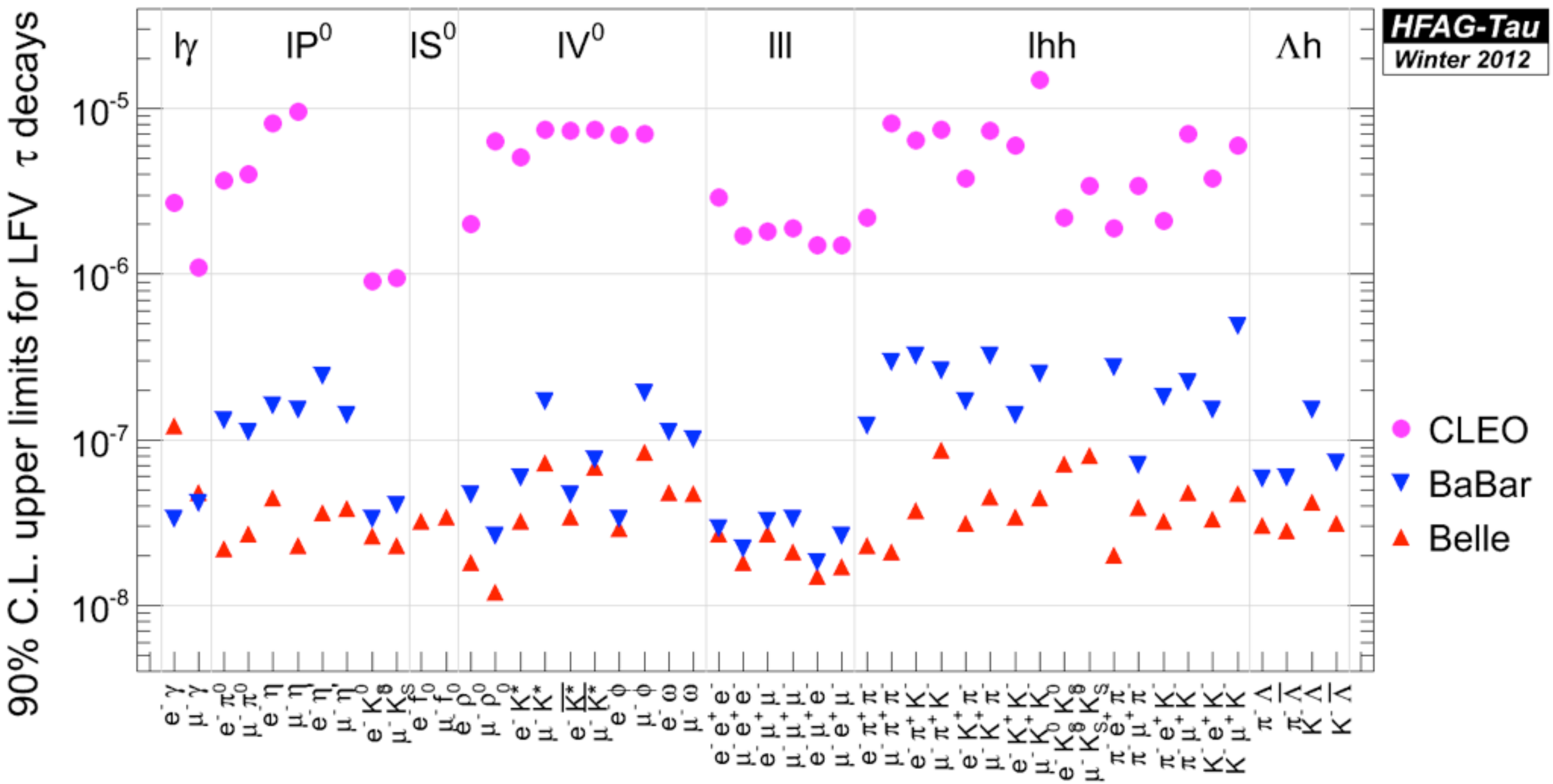

What can we learn about NP from this data?

Can leptons interact with gluons?

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Can apparent superluminal neutrino speeds be explained as a quantum weak measurement?

M V Berry[1], N Brunner[1], S Popescu[1] and P Shukla[2]

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[2] Department of Physics, Indian Institute of Technology, Kharagpur, India

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Abstract
Probably not.

PACS numbers: 03.65.Ta, 03.65.Xp, 14.60.Pq

http://arxiv.org/abs/1110.2832

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Can photons interact among themselves?

Yes, indeed!

Folgerungen aus der Diracschen Theorie des Positrons.

Von **W. Heisenberg** und **H. Euler** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 22. Dezember 1935.)

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha^2}{m_e^4} \left\{ c_1 (F_{\mu\nu} F^{\mu\nu})^2 + c_2 (F_{\mu\nu} \tilde{F}^{\mu\nu})^2 \right\} + O(m_e^{-6}) \,,$$

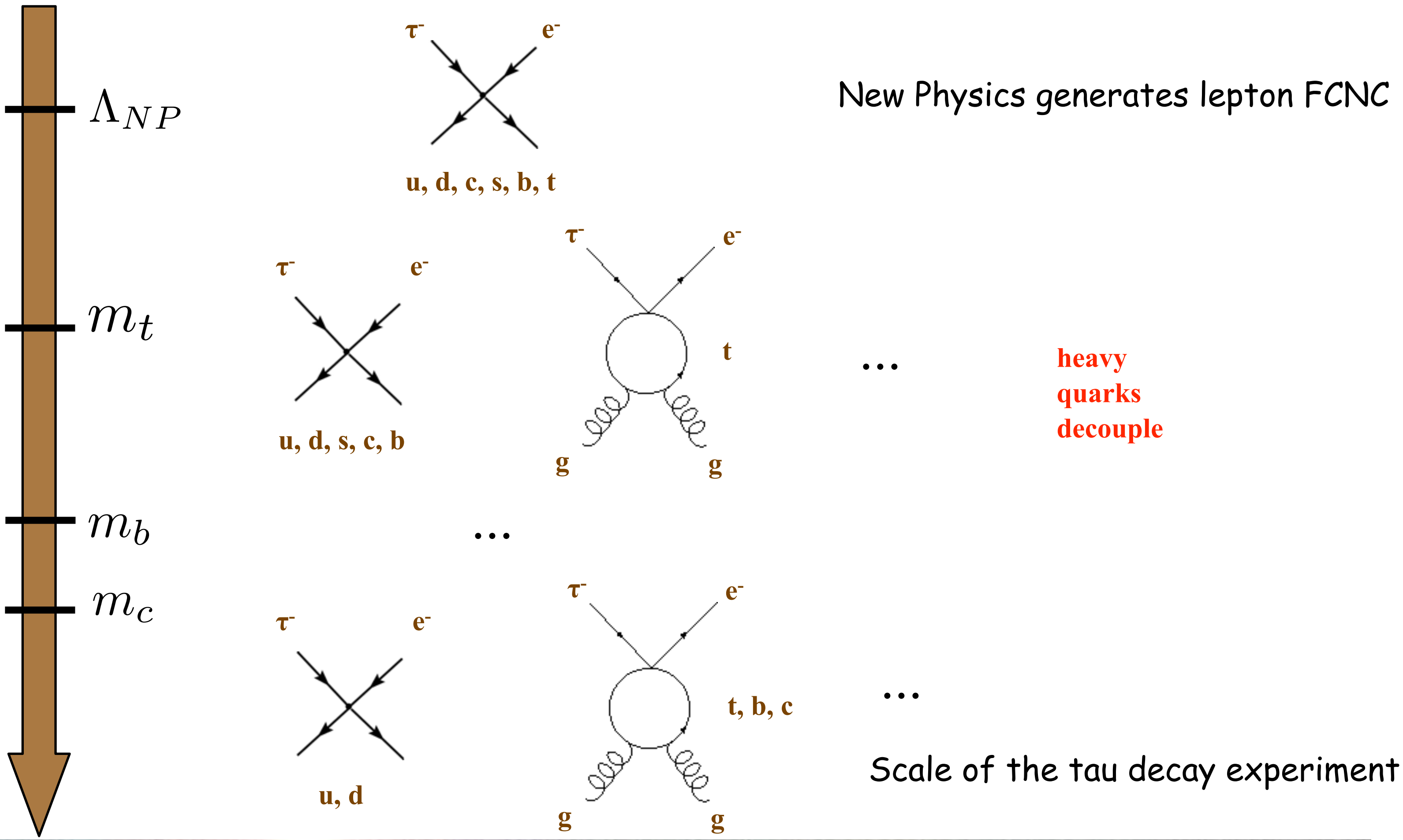
$$c_1 = \frac{1}{90} \,, \qquad c_2 = \frac{7}{360}$$

Euler-Heisenberg Lagrangian

2. Effective Lagrangians for tau decay

★ Modern approach to flavor physics calculations: effective field theories

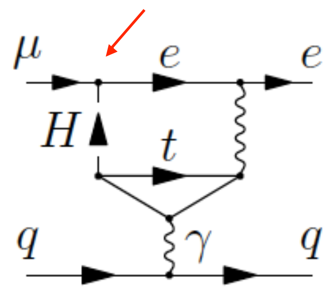
- ★ It is important to understand ALL relevant energy scales for the problem at hand



An example in a particular model:

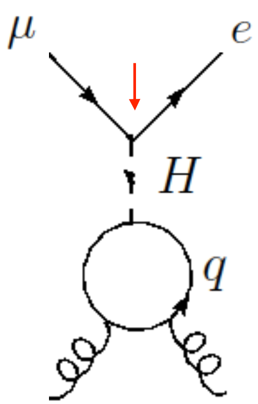
★ Contribution of heavy quarks can, in principle, be large

★ Two-loop sensitivity to NP in muon conversion experiment...



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

★ ... becomes one-loop!



➡ gluonic couplings to hadrons are not (always) suppressed!

➡ NP couplings to heavy quarks are not well constrained and could be large

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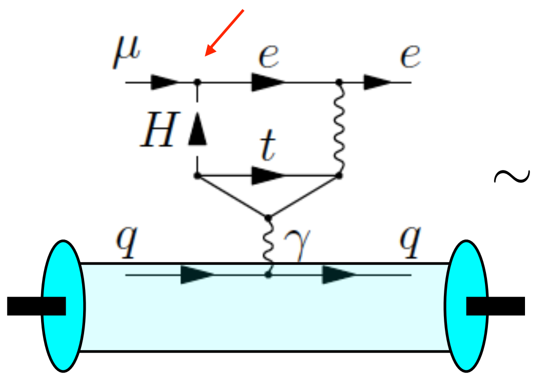

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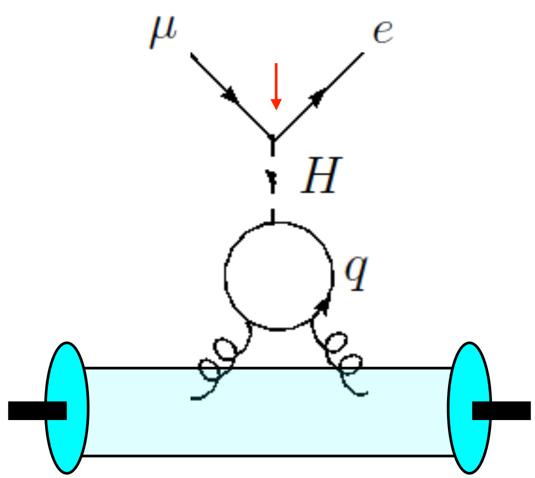

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➡ NP couplings to heavy quarks are not well constrained and could be large

Effective Lagrangians

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

- vector operators
$$\begin{aligned}
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),
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- tensor operators (do not contribute to considered tau decays)

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

Is this correct?

EW gauge invariance

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

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

$$\left(\overline{\ell}_{1R} H \ell_{2L}\right)\left(\overline{q}_R H q_L\right)$$

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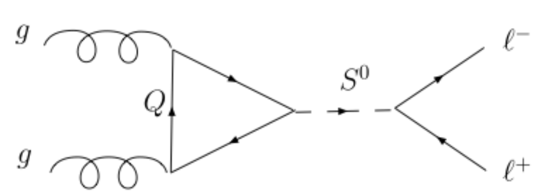
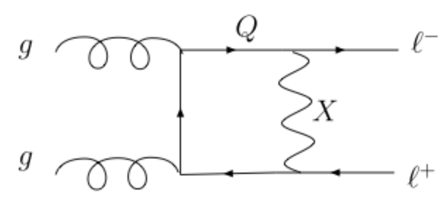
- model examples? Note that we always have two scales present…



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



$$\overline{C}_i \sim \pi\alpha_s$$
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Potter, Valencia

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

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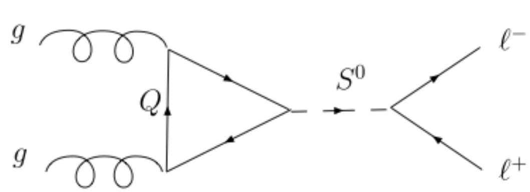

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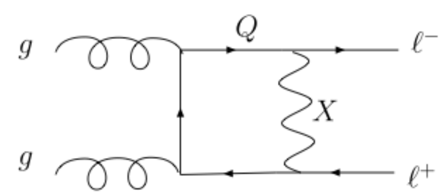


$$\overline{C}_i \sim \pi\alpha_s$$
$$\Lambda^4 \sim (4\pi v)^2 M_X^2$$

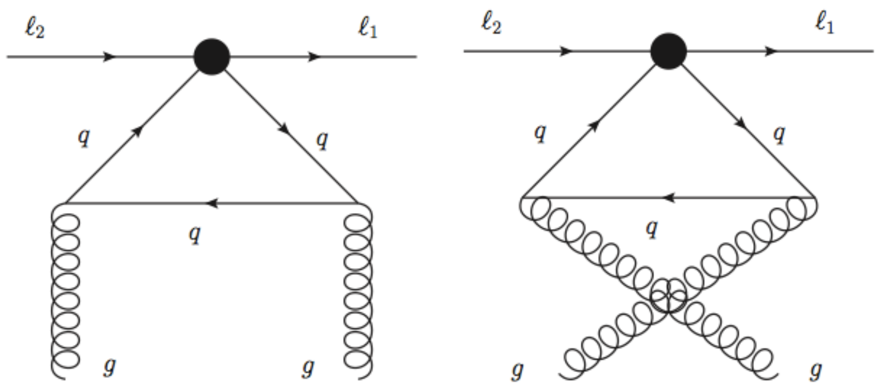
Potter, Valencia

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

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

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

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

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

...where we defined operators

$$O_1^{\ell_1\ell_2} = \bar{\ell}_{1R}\ell_{2L}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu},$$
$$O_2^{\ell_1\ell_2} = \bar{\ell}_{1R}\ell_{2L}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu},$$
$$O_3^{\ell_1\ell_2} = \bar{\ell}_{1L}\ell_{2R}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu},$$
$$O_4^{\ell_1\ell_2} = \bar{\ell}_{1L}\ell_{2R}\,\frac{\beta_L}{4\alpha_s} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu},$$

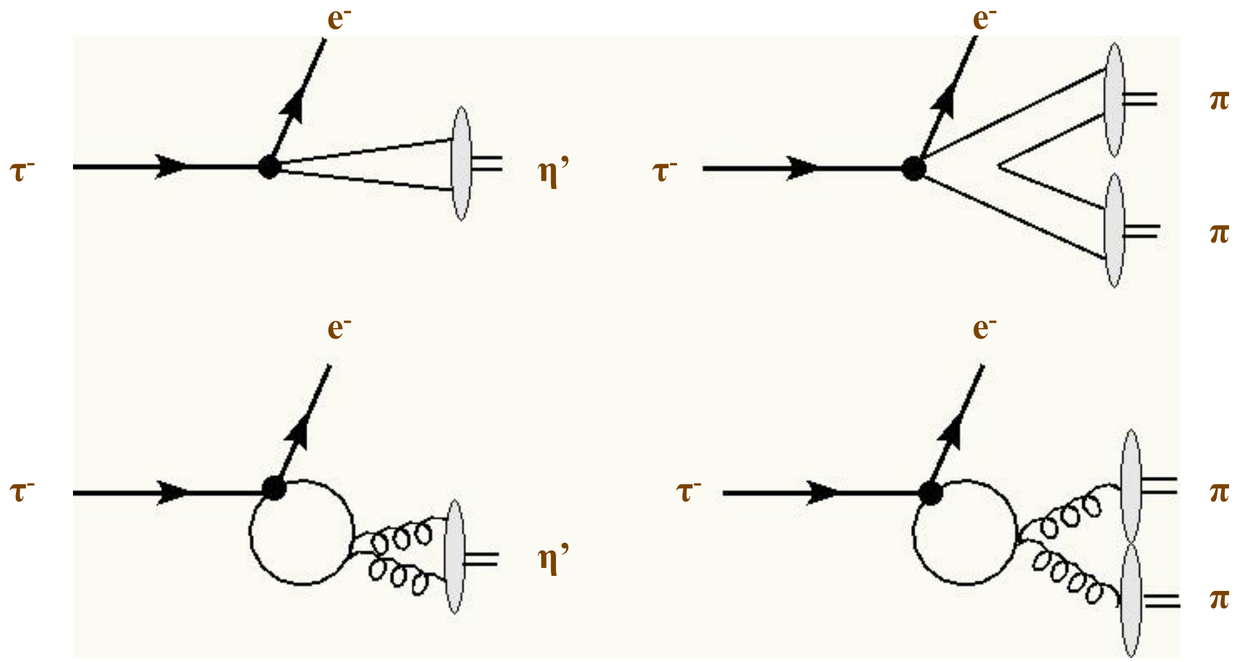
...and Wilson coefficients

$$c_1^{\ell_1\ell_2} = -\frac{2}{9}\sum_{q=c,b,t}\frac{I_1(m_q)}{m_q}\left(C_1^{q\ell_1\ell_2} + C_2^{q\ell_1\ell_2}\right),$$
$$c_2^{\ell_1\ell_2} = \frac{2\mathrm{i}}{9}\sum_{q=c,b,t}\frac{I_2(m_q)}{m_q}\left(C_1^{q\ell_1\ell_2} - C_2^{q\ell_1\ell_2}\right),$$
$$c_3^{\ell_1\ell_2} = -\frac{2}{9}\sum_{q=c,b,t}\frac{I_1(m_q)}{m_q}\left(C_3^{q\ell_1\ell_2} + C_4^{q\ell_1\ell_2}\right),$$
$$c_4^{\ell_1\ell_2} = \frac{2\mathrm{i}}{9}\sum_{q=c,b,t}\frac{I_2(m_q)}{m_q}\left(C_3^{q\ell_1\ell_2} - C_4^{q\ell_1\ell_2}\right),$$

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

Tau decays and heavy quarks

★ Let's compute FCNC tau decays



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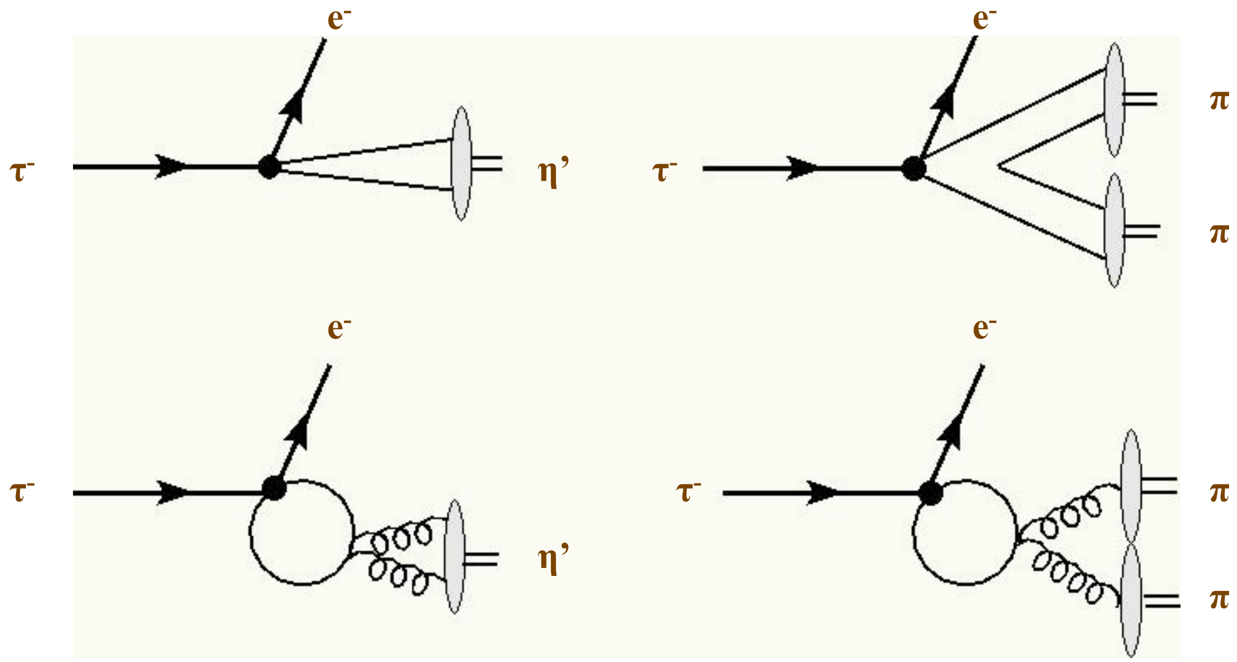


Partity-violating operators

Parity-conserving operators

Hadronic physics I

★ 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

Hadronic physics II

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

- matrix elements of parity-violating operators

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

- ... 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

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

Bounds: parity conserving

★ Looking at the scalar operators only

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

- ... 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 $\|c_i^{\ell\tau}\|/\Lambda^2$, 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

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

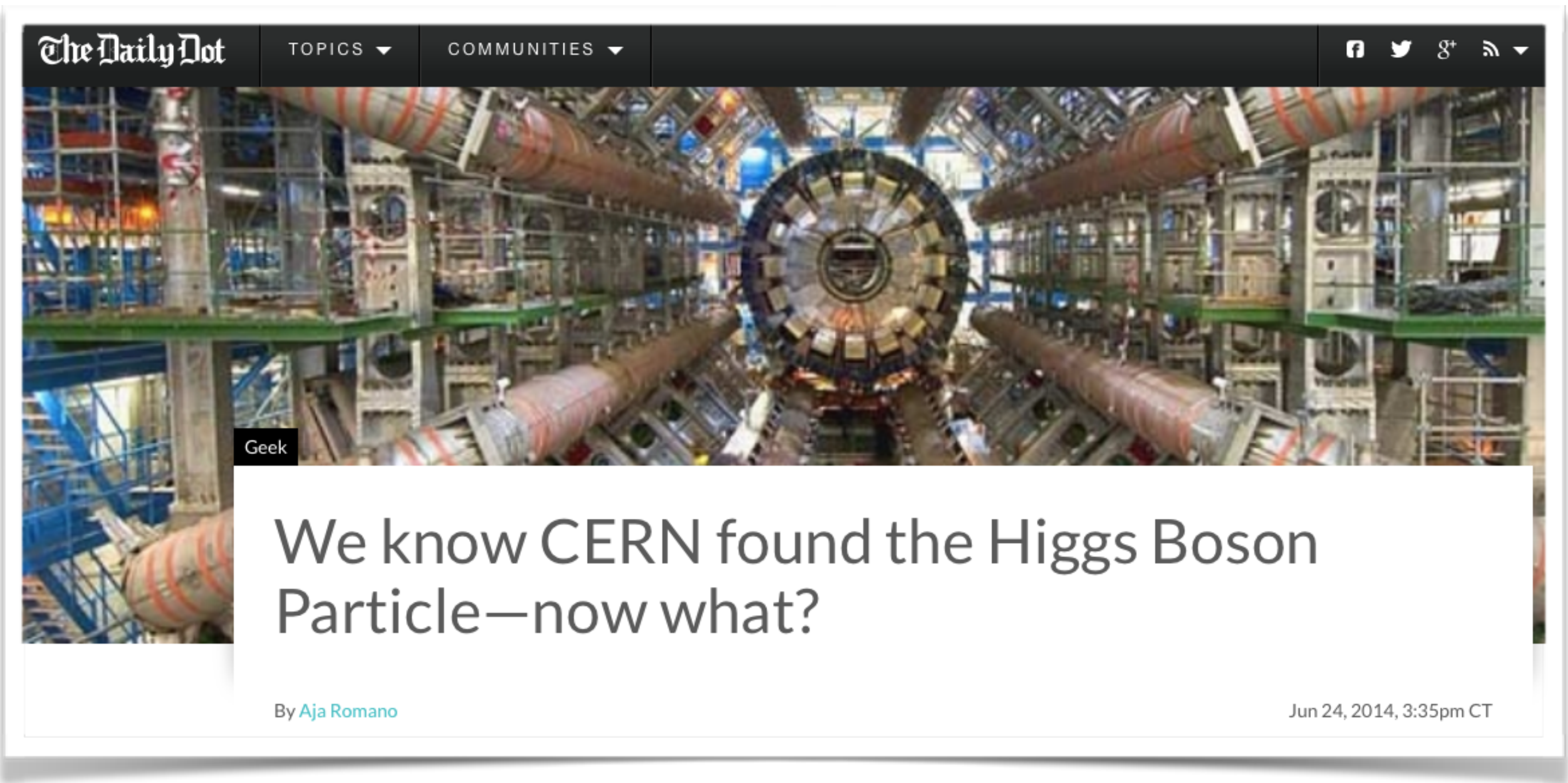
– ... with the following coefficients

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

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

Coef	Bound on $\lvert c_i^{\ell\tau}\rvert/\Lambda^2$, GeV^{-3}							
	$\mathcal{B}(\tau \to \mu\, \pi^+\pi^-)$ $< 2.1 \times 10^{-8}$	$\mathcal{B}(\tau \to e\, \pi^+\pi^-)$ $< 2.3 \times 10^{-8}$	$\mathcal{B}(\tau \to \mu K^+K^-)$ $< 4.4 \times 10^{-8}$	$\mathcal{B}(\tau \to e K^+K^-)$ $< 3.3 \times 10^{-8}$	$\mathcal{B}(\tau \to \mu\eta')$ $< 1.3 \times 10^{-7}$	$\mathcal{B}(\tau \to e\eta')$ $< 1.6 \times 10^{-7}$	$\mathcal{B}(\tau \to \mu\eta)$ $< 1.3 \times 10^{-7}$	$\mathcal{B}(\tau \to e\eta)$ $< 1.6 \times 10^{-7}$
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}

Now what?


The Daily Dot
TOPICS
COMMUNITIES
Geek
We know CERN found the Higgs Boson Particle—now what?
By Aja Romano
Jun 24, 2014, 3:35pm CT

3a. Leptoquarks as an example

★ Leptoquark interactions

- scalar leptoquarks

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

- vector leptoquarks

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

Davidson, Bailey, Campbell

★ Matching to the general result above, get

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

Leptoquarks as an example

★ 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

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

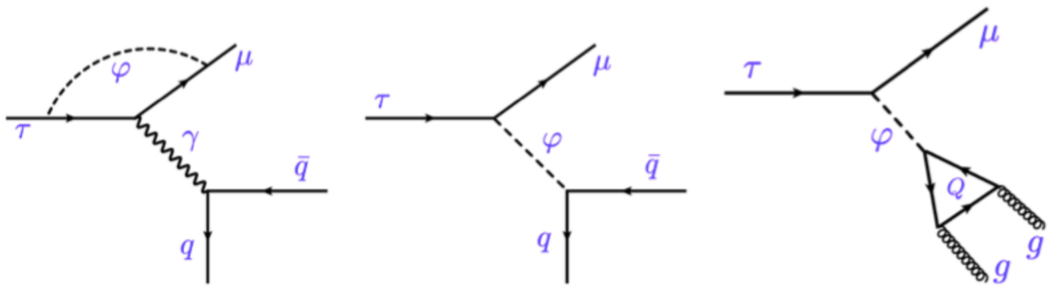
$$\frac{|\lambda^{\tau b}_{LV_0}\lambda^{eb}_{RV_0}|}{M^2_{V_0}} = \frac{|\lambda^{\tau b}_{LV_{1/2}}\lambda^{eb}_{RV_{1/2}}|}{M^2_{V_{1/2}}} < 4.2 \times 10^{-6}\ \mathrm{GeV}^{-2}$$

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

3b. FCNC Higgs as an example

Celis, Cirigliano, Passemar

★ FCNC Higgs gives another example



★ FCNC Higgs gives another example

Process	$(\mathrm{BR} \times 10^8)$ 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	$(\mathrm{BR} \times 10^8)$ 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

4. Conclusions

- 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
- New data from Belle-II on LHCb on tau decays!
- More data from ATLAS/CMS on pp $\rightarrow \tau\mu$ + X
  - possible effects from $gg \rightarrow \tau\mu$ due to large gluon luminosity of LHC

Gonderinger, Hazard, AAP

- Maybe flavor physics will be the first place to see glimpses of New Physics
- ...but then again, maybe not.

Thank you for your attention!

JOURNAL OF APPLIED BEHAVIOR ANALYSIS 1974, 7, 497 NUMBER 3 (FALL 1974)

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DENNIS UPPER

VETERANS ADMINISTRATION HOSPITAL, BROCKTON, MASSACHUSETTS

REFERENCES

[1]Portions of this paper were not presented at the 81st Annual American Psychological Association Convention, Montreal, Canada, August 30, 1973. Reprints may be obtained from Dennis Upper, Behavior Therapy Unit, Veterans Administration Hospital, Brockton, Massachusetts 02401.

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Hopefully, I did better than him...