Theoretical perspective on rare and radiative charm decays

Svjetlana Fajfer

Physics Department, University of Ljubljana and
Institute J. Stefan, Ljubljana, Slovenia

Overview

- SM in radiative and decays: LD & SD dynamics;
- New Physics in rare charm decays;
- Direct CP violation and rare charm decays;
- Lepton flavor violating decays;
- Summary.

Standard Model: short distance contributions

Effective Lagrangian $$\mathcal{L}_{\text{eff}}^{\text{SD}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i$$

perturbative QCD: Wilson coefficients

$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1 + \gamma_5) c,$$

contributes to $c \to u\gamma$ and $c \to u l^+ l^-$

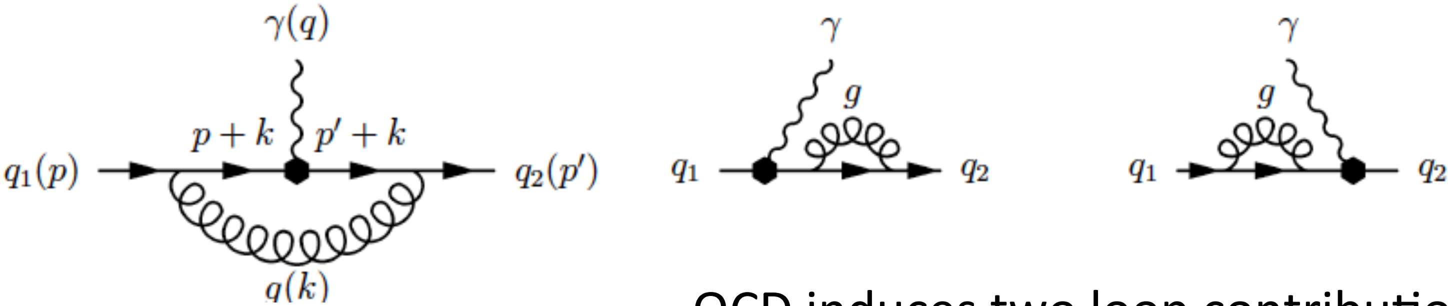
$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell,$$

all three operators contribute to $c \to u l^+ l^-$

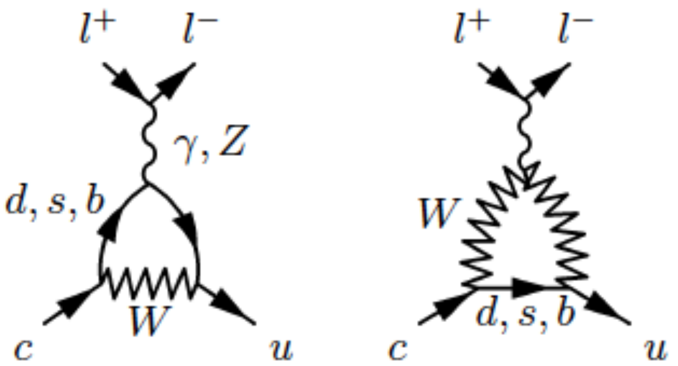
$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

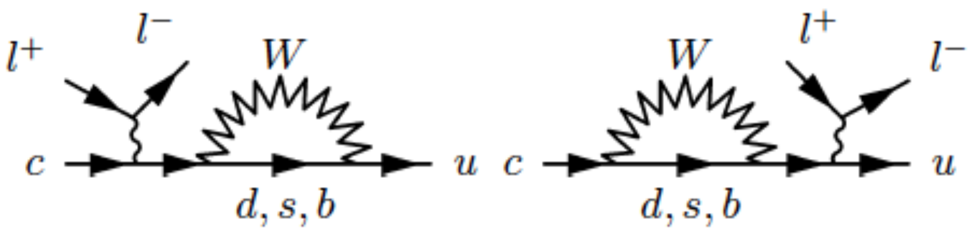
SM contribution in $c \to u\gamma$ and $c \to ul^+l^-$ transitions

$$c \to u\gamma$$

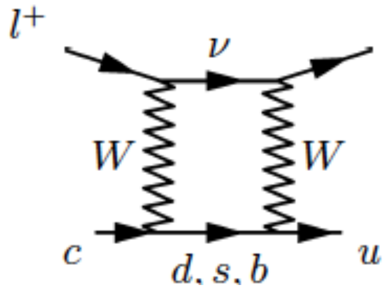


QCD induces two loop contributions





$$c \to ul^+l^-$$



FCNC effects in charm rare decays

- conspiracy: d,s, b quarks are in the loops;
- very strong GIM suppression;
- $m_{s,d} \ll \Lambda_{QCD}$

} long distance contribution dominant!

$c_7(m_c)$ at two-loop level (including RGE running for $m_W \to m_c$)

$$V_{cb}^* V_{ub} \hat{C}_7^{\rm eff} = V_{cs}^* V_{us} (0.007 + 0.020i)(1 \pm 0.2)$$

C. Greub et al., PLB 382 (1996) 415;

SM prediction

$$\Gamma(c \to u\gamma)/\Gamma_{D^0} = 2.5 \times 10^{-8}$$

SM inclusive $c \to u l^+ l^-$

$C_7(m_c), \;\; C_9(m_c), \;\; C_{10}(m_c)$

SM : C_7 and C_9 are important due to QCD corrections, while $C_{10 \text{ is QCD}}$ uncorrected

$$C_{10}^{SM} \sim m_s^2/m_W^2 \to 0$$

$$\frac{d}{d\hat{s}}\mathrm{Br}_{\mathrm{SM}}^{\mathrm{SD}}(D \to X_u l^+ l^-) = \frac{1}{\Gamma_D}\frac{G_F^2 \alpha^2 m_c^5}{768\pi^5}(1-\hat{s})^2\Big[(|C_9(\mu)|^2 +$$

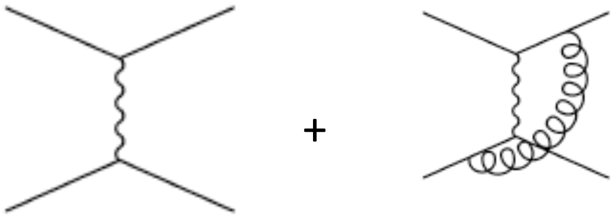
$$|C_{10}(\mu)|^2)(1+2\hat{s}) + 12\mathrm{Re}(C_7(\mu)C_9^*(\mu)) + 4\left(1+\frac{2}{\hat{s}}\right)|C_7(\mu)|^2\Big]$$

$$\mathrm{BR}_{\mathrm{SD}}^{\mathrm{SM}}(D \to X_u e^+ e^-) \sim 3.7 \times 10^{-9}$$

A. Paul et al., PRD83 (2011) 114006,
S.F., P. Singer and J. Zupan PRD 64 (2002)074008;
G. Burdman et al., PRD 66 (2002) 014009

Long distance contributions

$$\mathcal{L}_W^{|\Delta c|=1} = -\frac{G_F}{\sqrt{2}} V_{cq_i}^* V_{uq_i} [C_1(\mu) O_1^{ij}(\mu) + C_2(\mu) O_2^{ij}(\mu)]$$



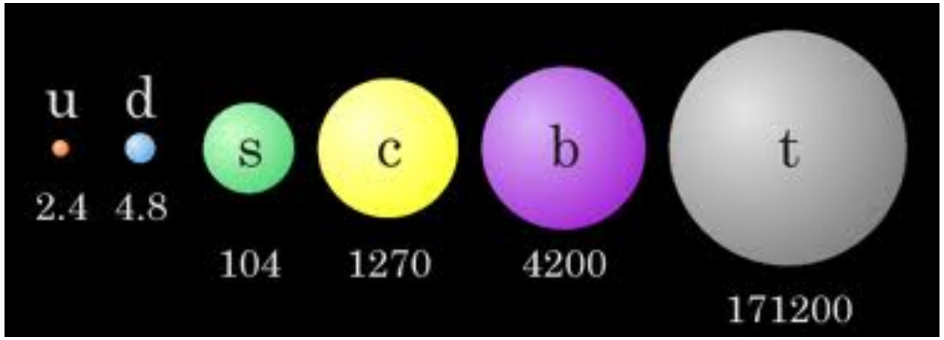
at NLO (Buras, 1998)
S. Prelovsek, 2000

$$(a_1^c)^{eff} = 1.2 \pm 0.1$$
$$(a_2^c)^{eff} = -0.5 \pm 0.1$$

perturbative QCD

Non-peturbative QCD physics:

$$\mathrm{m_s}(\Lambda_{\mathrm{QCD}}) < \mathrm{m_c} < \mathrm{m_b}$$



- charm quark not heavy enough for HQET;
- charm mesons are having masses above scale χPT.

No adequate theoretical framework!

Need for lattice QCD calculations!

Exclusive decay modes: $D \to V\gamma$

Amplitude

$$\mathcal{M}(D^0 \to V(k,\lambda^V)\gamma(q,\lambda^\gamma) = \epsilon_\mu^{\dagger V}\epsilon_\nu^{\dagger\gamma}$$
$$[A_{PV}(p^\mu p^\nu - g^{\mu\nu}(p\cdot q)) + iA_{PC}\epsilon^{\mu\nu\alpha\beta}k_\alpha p_\beta]$$

Decay width

$$\Gamma(D \to V\gamma) = \frac{|\vec{q}|^3}{4\pi}(|A_{PC}|^2 + |A_{PV}|^2)$$

Experimental results (PDG)

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = 3.27(34)\cdot 10^{-4}$$
$$\mathcal{B}(D^0 \to \phi\gamma) = 2.70(35)\cdot 10^{-5}$$

$D \to V\gamma$	BR
$D^0 \to \bar{K}^{*0}\gamma$	$[6 - 36] \times 10^{-5}$
$D_s^+ \to \rho^+\gamma$	$[20 - 80] \times 10^{-5}$
$D^0 \to \rho^0\gamma$	$[0.1 - 1] \times 10^{-5}$
$D^0 \to \omega\gamma$	$[0.1 - 0.9] \times 10^{-5}$
$D^0 \to \phi\gamma$	$[0.4 - 1.9] \times 10^{-5}$
$D^+ \to \rho^+\gamma$	$[0.4 - 6.3] \times 10^{-5}$
$D_s^+ \to K^{*+}\gamma$	$[1.2 - 5.1] \times 10^{-5}$
$D^+ \to K^{*+}\gamma$	$[0.3 - 4.4] \times 10^{-6}$
$D^0 \to K^{*0}\gamma$	$[0.3 - 2.0] \times 10^{-6}$

Recent estimates:

C. Delaunay et al, JHEP 1301 (2013) 027;
G.Isidori and J.F. Kamenik, PRL 109 (2012) 171801;
A.Paul et al, PRD 82 (2012) 094006,
A.Paul, 1308.5886
J. Lyon & Zwicky 1210.6546,

Prevoius estimates:

C. Greub et al., PLB 382 (1996) 415;
G. Burdman et al., PRD 66 (2002) 014009;
S.F. S.Prelovsek, P. Singer., PRD (2001) 114009;

Previous theoretical estimates for the rates $D^0 \to \bar{K}^{*0}\gamma$, $D^0 \to \phi\gamma$ are too large, or too small!

QCD sum rules and radiative D decays

J. Lyon & Zwicky 1210.6546;
A. Khodjamirian, G. Stoll and D. Wyler, hep-ph/9506242.

$$A(D^0 \to \bar{K}^{*0}\gamma) \simeq A(D^0 \to \rho^0\gamma)$$
$$A(D^+ \to \rho^+\gamma) \simeq A(D_s \to \rho^+\gamma)$$

holds for PC and PV amplitudes:

$$BR(D^+ \to \rho^+\gamma) \simeq 2.7 \cdot 10^{-6}$$

$$BR(D^0 \to \rho^0\gamma) \simeq 3.1 \cdot 10^{-6}$$

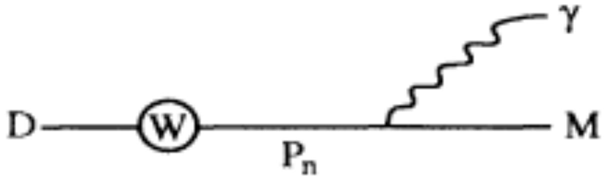
$$BR(D_s \to \rho^+\gamma) = 2.8 \times 10^{-5}$$

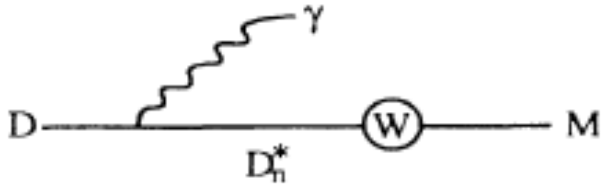
$$BR(D^0 \to \bar{K}^{*0}\gamma) = 1.5 \times 10^{-4}$$

Parity conserving amplitude

Input from the experimentally measured rates and lattice results!

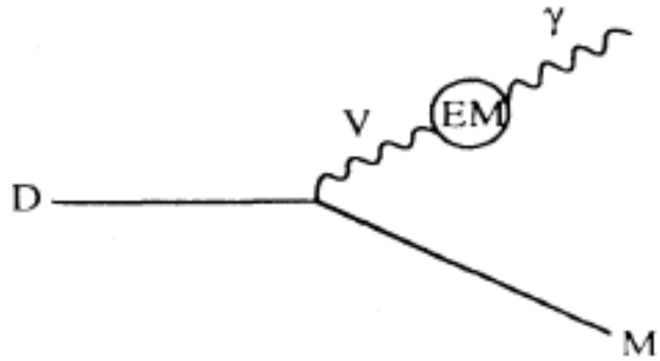
$$D^* \to D\gamma$$
$$V \to P\gamma$$





Parity violating amplitude

Simple phenomenological model, knowing measured branching ratios for $D^0 \to V_1 V_2$ and using vector meson dominance model $V_{1,2} \to \gamma$ transition (Burdman et al., PRD 52, 6383 (1995)



PDG 2014 results on $D^0 \to V_1 V_2$:

$\overline{K}^*(892)^0 \rho^0$	(1.58 ± 0.34) %	
$\overline{K}^*(892)^0 \rho^0$ transverse	(1.7 ± 0.6) %	
$\overline{K}^*(892)^0 \rho^0$ *S*-wave	(3.0 ± 0.6) %	
$\overline{K}^*(892)^0 \rho^0$ *S*-wave long.	$< 3 \times 10^{-3}$	CL=90%
$\overline{K}^*(892)^0 \rho^0$ *P*-wave	$< 3 \times 10^{-3}$	CL=90%
$\overline{K}^*(892)^0 \rho^0$ *D*-wave	(2.1 ± 0.6) %	

$2\rho^0$ total	$(1.82 \pm 0.13) \times 10^{-3}$
$2\rho^0$, parallel helicities	$(8.2 \pm 3.2) \times 10^{-5}$
$2\rho^0$, perpendicular helicities	$(4.8 \pm 0.6) \times 10^{-4}$
$2\rho^0$, longitudinal helicities	$(1.25 \pm 0.10) \times 10^{-3}$

$(\phi\rho^0)_{S-wave}$, $\phi \to K^+K^-$	$(9.3 \pm 1.2) \times 10^{-4}$
$(\phi\rho^0)_{D-wave}$, $\phi \to K^+K^-$	$(8.3 \pm 2.3) \times 10^{-5}$
$(K^{*0}\overline{K}^{*0})_{S-wave}$, $K^{*0} \to$	$(1.48 \pm 0.30) \times 10^{-4}$

Helicity formalism for $D \to V_1 V_2$

$$\mathcal{M}(D(k) \to V_1(k_1, \lambda_1 V_2(k_2, \lambda_2)) = \epsilon^{\dagger}_{\mu}(k_1, \lambda_1)\epsilon^{\dagger}_{\nu}(k_2, \lambda_2)$$
$$\left(a g_{\mu\nu} + \frac{b}{m_1 m_2} p_\mu p_{nu} - i \frac{c}{m_1 m_2} \epsilon_{\mu\nu\rho\sigma} k_1^\rho p^\sigma\right)$$

$$\mathcal{H}_{++} = a - \sqrt{x^2 - 1}c$$
$$\mathcal{H}_{--} = a + \sqrt{x^2 - 1}c$$
$$\mathcal{H}_{00} = -xa + (x^2 - 1)b$$

a is a s-wave amplitude
b is a d-wave amplitude
c is a p- wave amplitude

$$x = \frac{k_1 \cdot k_2}{m_1 m_2}$$

VMD for $D \to VV' \to V\gamma$

$$\mathcal{L}_{VDM} = \frac{e}{f_V}[\frac{1}{2}F_{\mu\nu}V^{\mu\nu} + J_\mu^{V,em}A^\mu]$$

$$< 0|J_\mu^{V,em}(0)|V(k,\lambda) >= \frac{em_V^2}{f_V}$$

- guage invariance should hold;

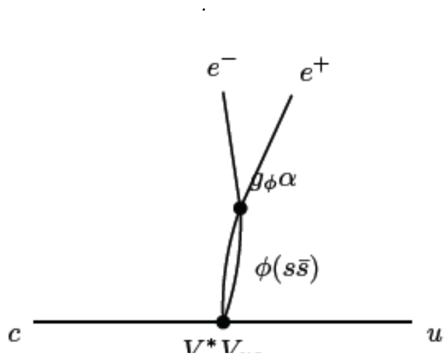
- real photon is transversely polarized; $D \to VV'$

- longitudinaly polarized amplitude does not contribute $D \to V\gamma$.

Decay mode	Branching ratio
$D^0 \to \bar{K}^{*0}\gamma$	$(2.8 - 4.9) \times 10^{-4}$
$D^0 \to \phi\gamma$	$(2.8 - 4.1) \times 10^{-5}$
$D^0 \to \rho^0\gamma$	$(0.3 - 0.78) \times 10^{-6}$

The experimental results for observed branching ratios is possible to explain by LD. However, relative phases among different contributions are not known!

Exclusive $D \to P l^+ l^-$



LD effects dominant!

$$\frac{d\Gamma_{D\to\pi V_0\to\pi l^+l^-}}{dq^2} = \Gamma_{D\to\pi V_0}(q^2)\frac{1}{\pi}\frac{\sqrt{q^2}}{(m_{V_0}^2 - q^2)^2 + m_{V_0}^2\Gamma_{V_0}^2}\Gamma_{V_0\to l^+l^-}(q^2)$$

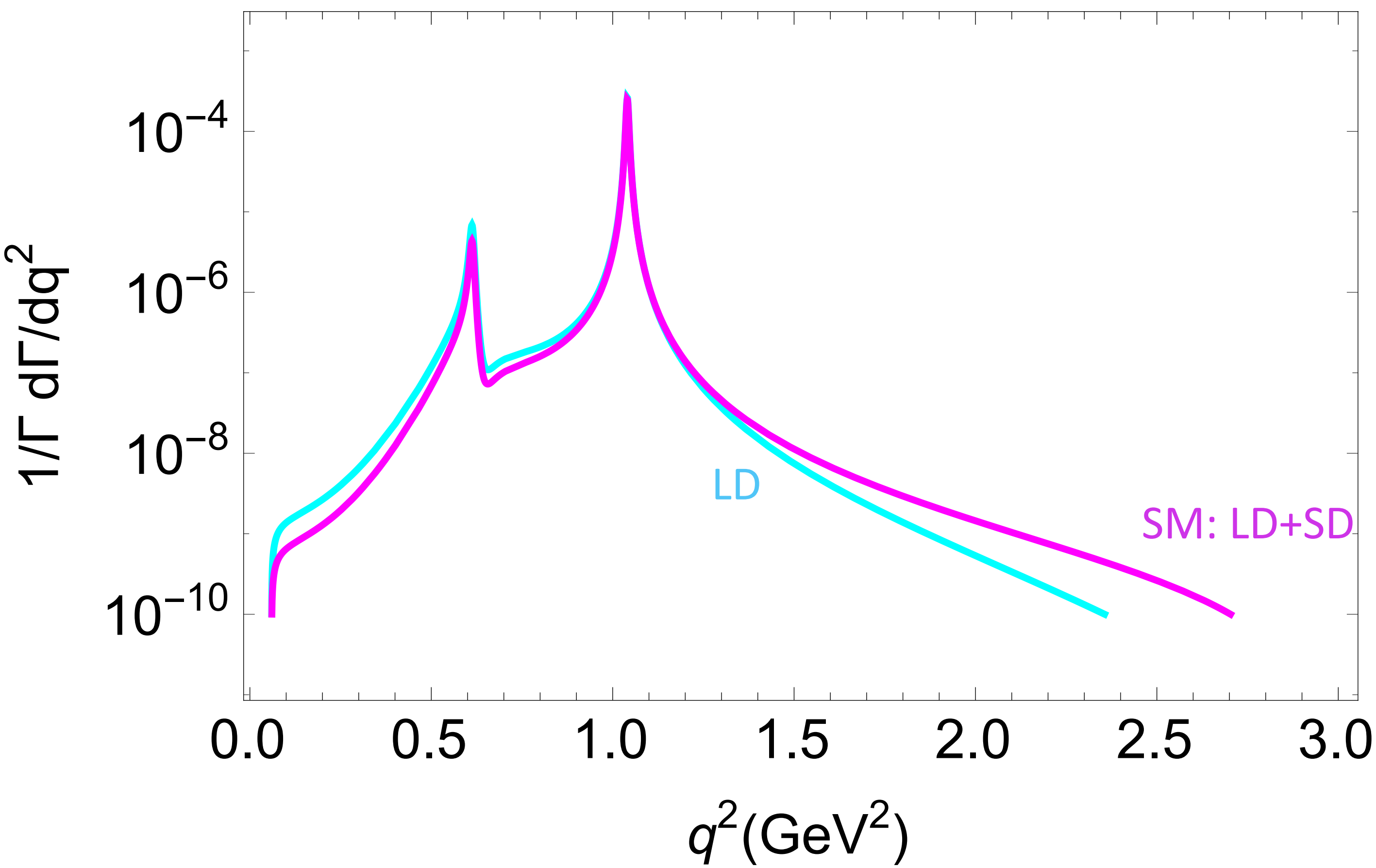
$$\mathcal{A}^{\rm LD} = \Big[a_\rho\Big(\frac{1}{q^2 - m_\rho^2 + im_\rho\Gamma_\rho} - \frac{1}{3}\frac{1}{q^2 - m_\omega^2 + im_\omega\Gamma_\omega}\Big) - \frac{a_\phi}{q^2 - m_\phi^2 + im_\phi\Gamma_\phi}\Big]\bar{u}(p_-)\not{p}v(p_+)$$

$a_{\rho,\phi}$ from experiment

VMD hypothesis!

S.F., N.Kosnik, Phys.Rev. D87 (2013) 054026;
S.F., N.Kosnik, S. Prelovsek; Phys.Rev. D76 (2007) 074010;
S.F. S. Prelovsek, Phys.Rev. D73 (2006) 054026

$D^+ \to \pi^+\mu^+\mu^-$

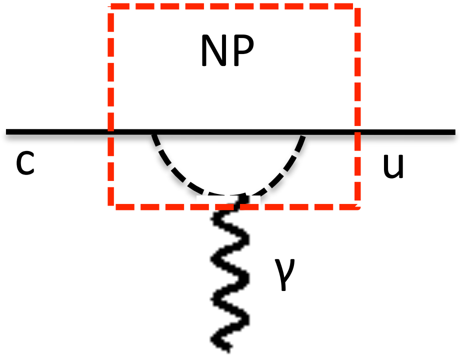


Predictions for branching ratios for rare D decays within SM

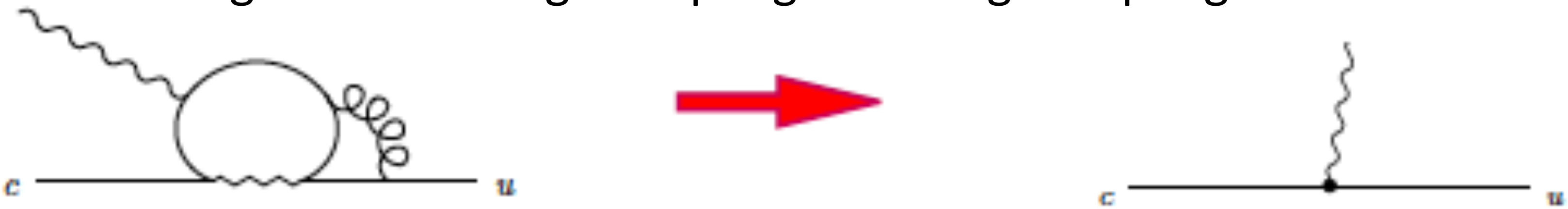
Decay mode	Branching ratio	Reference
$D \to \rho(\omega)\gamma$	0.6×10^{-5}	Isidori & Kamenik 2012
$D \to K^+K^-\gamma$	$1.35 \times 10^{-5}\,(\phi)$	Isidori & Kamenik 2012
$D \to X_u l^+l^-$	$\mathcal{O}(10^{-6})$	Paul et al, 2011
$D^+ \to \pi^+ l^+ l^-$	2×10^{-6}	Fajfer et al, 2007
$D_s^+ \to K^+ l^+ l^-$	6×10^{-6}	Fajfer et al, 2007
$D \to \pi^+ K^- l^+ l^-$	$\mathcal{O}(10^{-5})$	Cappiello et al, 2013
$D \to \pi^+ \pi^- l^+ l^-$	$\mathcal{O}(10^{-6})$	Cappiello et al, 2013
$D \to K^+ K^- l^+ l^-$	$\mathcal{O}(10^{-7})$	Cappiello et al, 2013
$D \to \pi^- K^+ l^+ l^-$	$\mathcal{O}(10^{-8})$	Cappiello et al, 2013
$D \to \gamma\gamma$	$(1-3) \times 10^{-8}$	Paul et al, 2010
$D \to \mu^+\mu^-$	$(7-8) \times 10^{-13}$	Paul et al, 2010

New physics in $c \to u\gamma$

in $c \to u\gamma$ NP contribution can appear in $C_7^{eff}(m_c)$



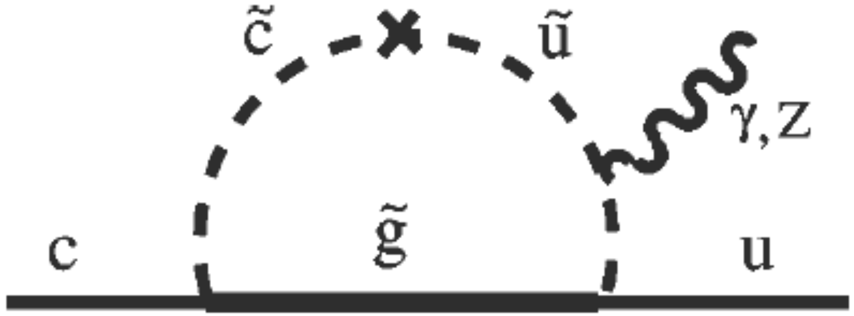
- mixing of electromagnetic penguin with gluon penguin



renormalization mixes C_7 and C_8 and C_2: (+ terms with C_2, penguins- not shown)

J.F. Kamenik & G. Isidori, Phys.Rev.Lett. 109 (2012) 171801;
G. Burdman et al., PRD 66 (2002) 014009;
S. F. P. Singer and J. Zupan, EPJC 27(2003) 201

MSSM in $c \to u\gamma$

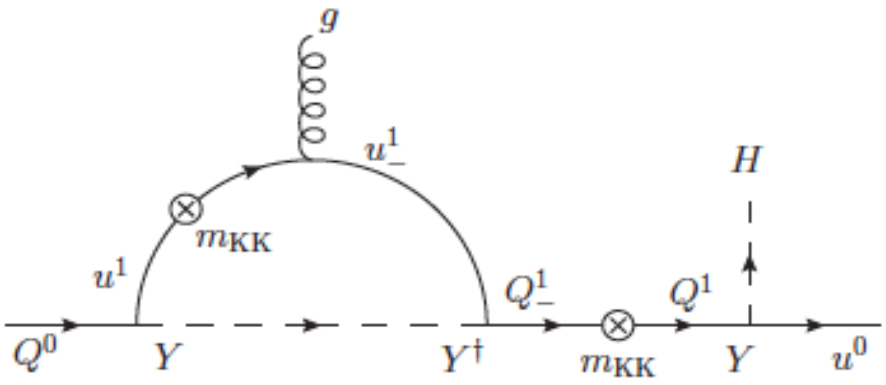


MSSM scenario by
S. Prelovsek & D. Wyler, Phys.Lett. B500 (2001) 304

the largest contribution comes $(\delta^u_{12})_{LR,RL} \leq 3m_c/m_{\tilde{q}}$

$$BR(c \to u\gamma)_{MSSM} < 10^{-7}$$

Dipole operator from Randall - Sundrum flavour anarchy



$$\mathcal{B}(D^0 \to X\gamma)^{\mathrm{RS}} \simeq 1 \times 10^{-8}$$

- Sizable contribution to chromo-magnetic operator are generated;

- The dipole operator quickly saturates as the Higgs profile approaches the IR brane;

- In 5D the coefficients are found to be finite.

C. Delaunay, J. F. Kamenik, G. Perez, L, Randall JHEP 1301 (2013) 027.

Proposal to look for C_7

NP is difficult to see in branching ratios- very small deviations!
Is there any possibility to find an observable in which NP in C_7 can be seen?

$$R = \frac{BR(D^0 \to \rho^0\gamma) - BR(D^0 \to \omega\gamma)}{BR(D^0 \to \omega\gamma)} \propto \mathrm{Re}\,\frac{A(D^0 \to u\bar{u}\gamma)}{A(D^0 \to d\bar{d}\gamma)}$$

LD dynamics originates from $d\bar{d}\gamma$ in this difference LD effects deduct

SD dynamics originates from $u\bar{u}\gamma$, therefore appropriate to look for $c \to u\gamma$

$$R \leq 5\%$$

S.F., S. Prelovsek, P. Singer, D. Wyler, Phys.Lett. B487(2000) 81

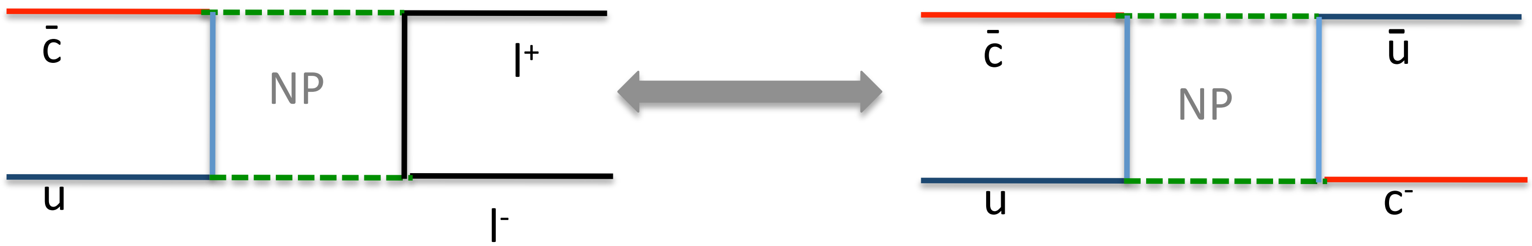
NP in $c \to u l^+ l^-$

Flavor changing NC:
- SM Higgs or new scalar;
- SM Z boson or new Z';

The same couplings immediately create contributions to $D^0 - \bar{D}^0$

NP at tree level FCNC

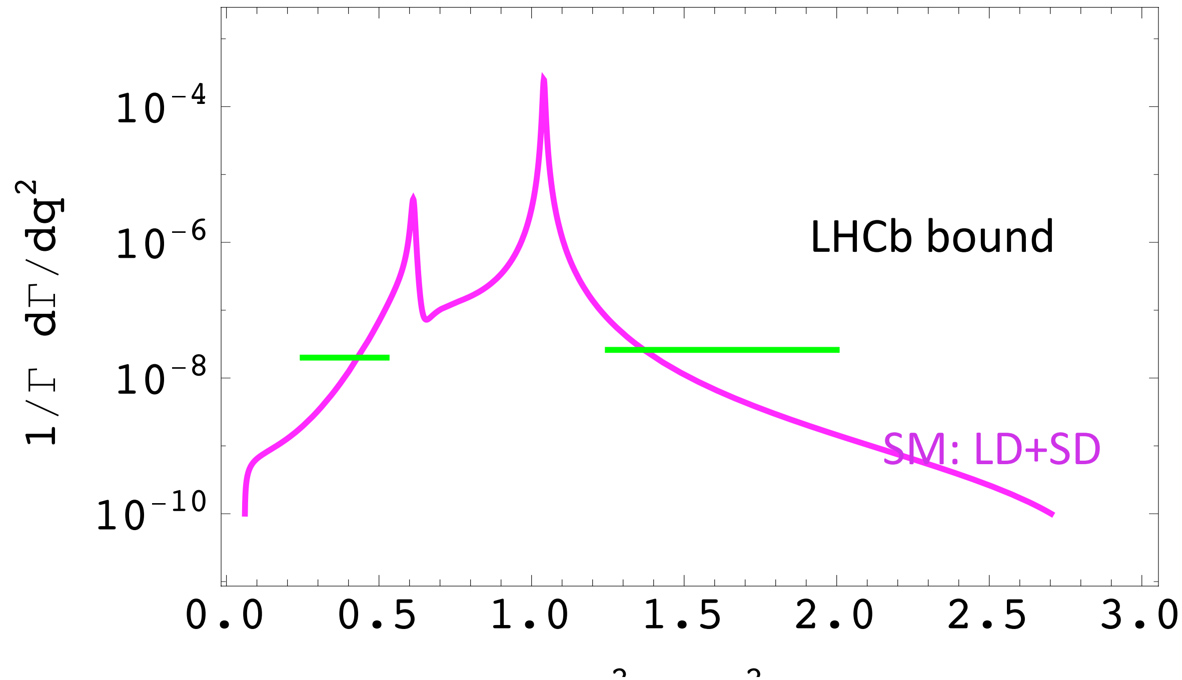
(e.g.)



$c \to u l^+ l^-$ NP at Loop level $D^0 - \bar{D}^0$

Up quark from a weak doublet "talks" to down quark via CKM!

Experimental results useful to constrain NP



$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)_{s\in[0.250,0.525]GeV^2} < 2.0 \times 10^{-8}$$

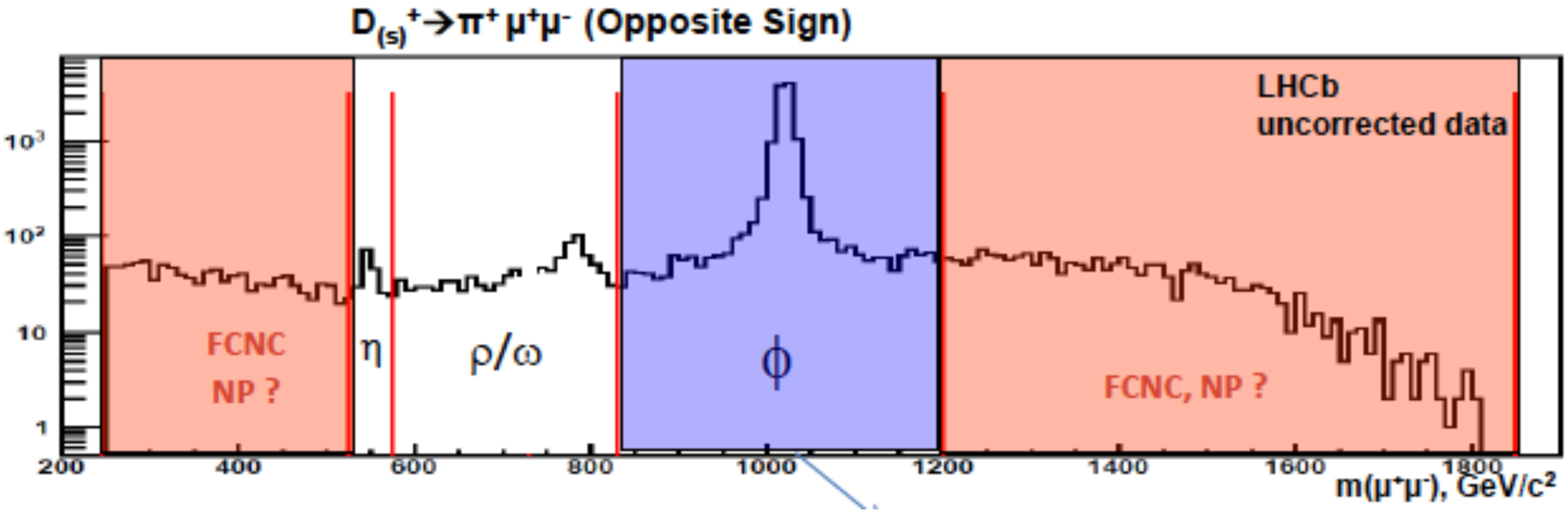
$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)_{s\in[1.250,2.000]GeV^2} < 2.6 \times 10^{-8}$$

$$\mathrm{BR}(\mathrm{D} \to \mu^+\mu^-)_{\mathrm{LHCb}} < 6.2 \times 10^{-9}$$

Exclusive $D \to P l^+ l^-$

Recent experimental result:

$D_{(s)}^+ \to \pi^+ \mu^+ \mu^-$ at LHCb



R. Aaij et al. (the LHCb collaboration), PLB 724 (2013) 203.

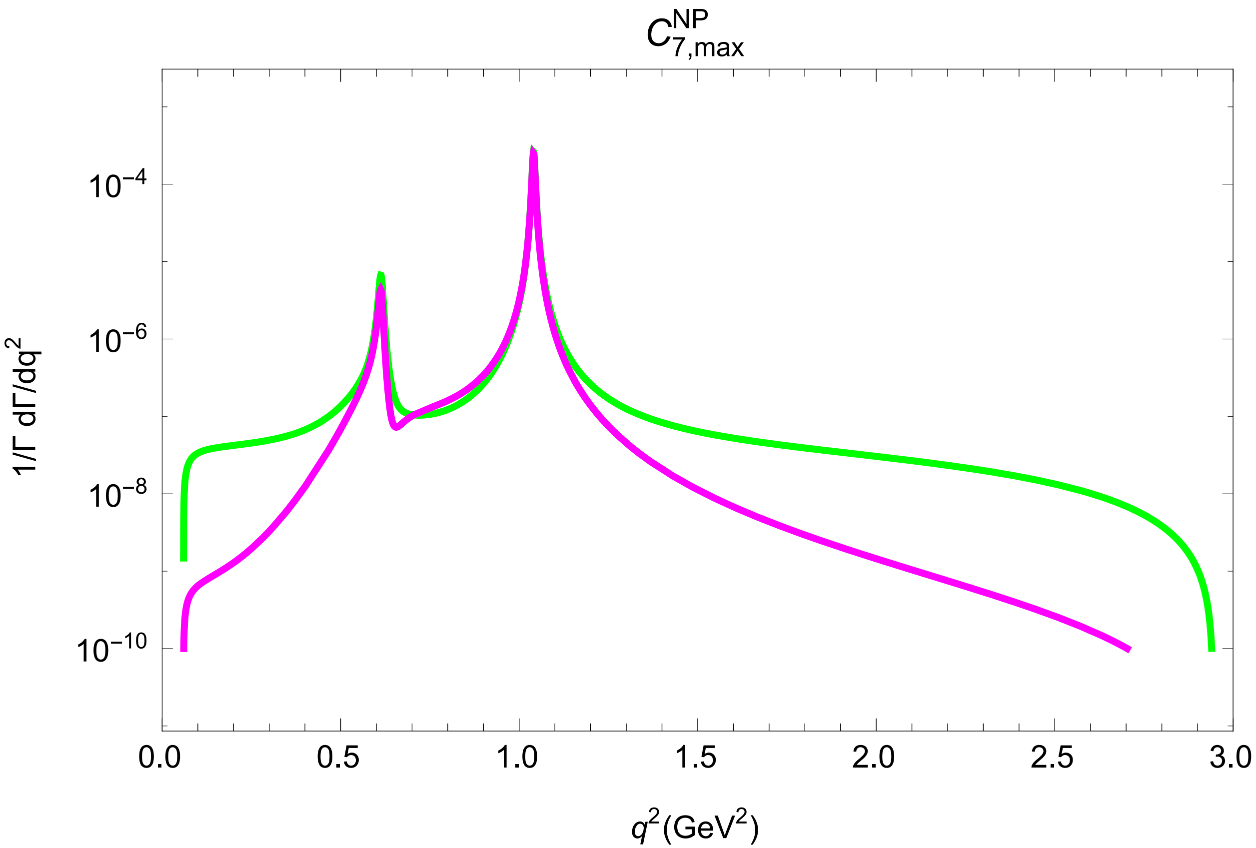
$$\mathcal{B}(D^\pm \to \pi^\pm \mu^+ \mu^-) < 8.3 \times 10^{-8}$$

$$\mathcal{B}(D_s^\pm \to \pi^\pm \mu^+ \mu^-) < 4.8 \times 10^{-7}$$

Using LHCb bound on outside resonance region, one can get upper bounds on the effective Wilson coefficients:

max: $|C_7^{eff,NP}| < 8|C_7^{eff,SM}|$

difficult to observe in $\mathrm{D} \to \mathrm{V}\gamma$



Maximal values of Wilson coefficient allowed by LHCb upper bounds are:

max: $$|V_{ub}V_{cb}^{*}C_9^{NP}| < 1.87$$

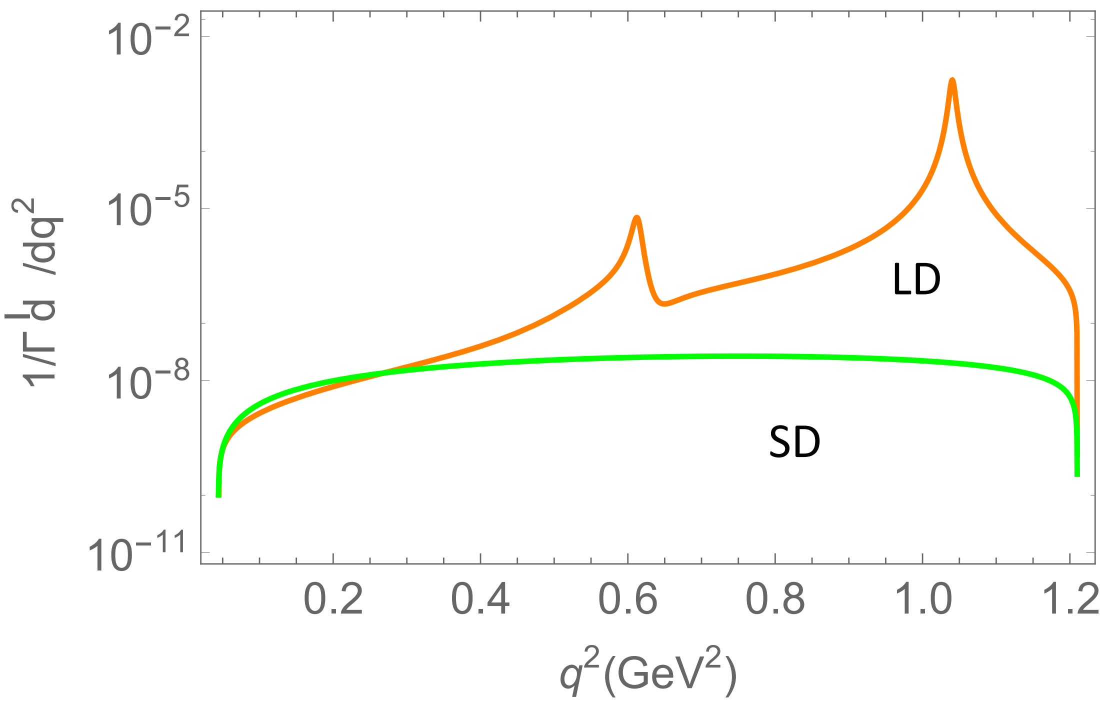
max: $$|V_{ub}V_{cb}^{*}C_{10}^{NP}| < 1.61$$

Much better bound on $V_{ub}V_{cb}^{*}C_{10}^{NP}$ can be obtained from

$$BR(D \to \mu^+\mu^-)_{LHCb} < 6.2 \times 10^{-9}$$

max: $$|V_{ub}V_{cb}^{*}C_{10}^{NP}| < 0.364$$

$$D^0 \to \rho^0 l^+ l^-$$



Long distance contribution estimated using VMD!

Forward-backward asymmetry arise if $C_{10}$is generated. Fox maximal value C_{10}

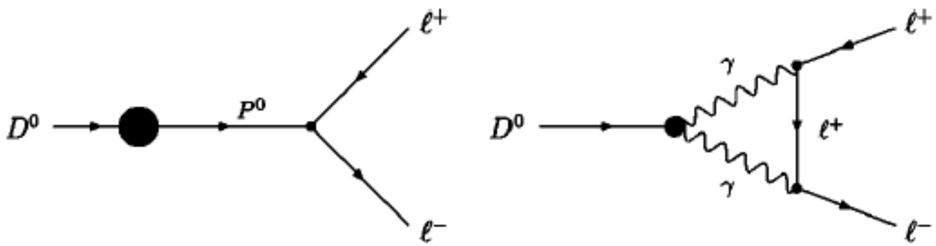
$$A_{FB}(D^0 \to \rho^0 l^+ l^-) \leq 20\%$$

$$\mathrm{D} \to \mu^+\mu^-$$

R. Aaij et al. (the LHCb collaboration), PLB 725 (2013) 15.

$$BR(D \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}$$

$$\mathrm{BR}^{\mathrm{SD}}_{\mathrm{SM}}\left(\mathrm{D}^0 \to \mu^+\mu^-\right) \sim 6 \times 10^{-19}$$



LD dominant!

$$\mathrm{BR}^{\mathrm{LD}}_{\mathrm{SM}}(D^0 \to \mu^+\mu^-) = 2.7 \times 10^{-5} \times \mathrm{BR}(D^0 \to \gamma\gamma) \simeq 2.7 - 8 \times 10^{-13}$$

A. Paul et al, PRD 82 (2012) 094006,
G. Burdman et al., PRD 66 (2002) 014009,
E. Golowich, J. Hewett, S. Pakvasa, A. Petrov, Phys.Rev. D79 (2009) 114030

Additional vector-like quarks

Vector-like quark: left and right handed component have the same color and electroweak quantum numbers.

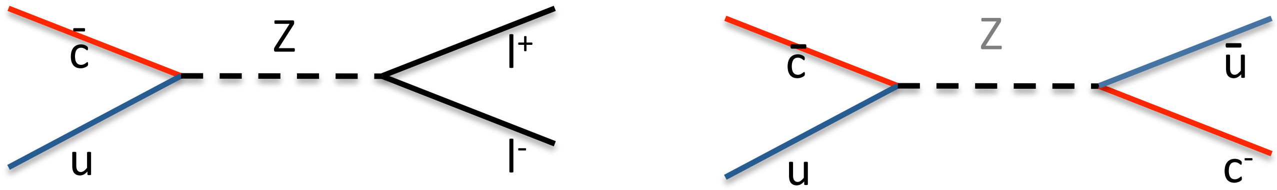
- W gets right-handed couplings;
- Z gets flavor changing couplings;
- H gets flavor changing couplings.

Known example:
- Little Higgs models : t quark has T vector-like partner
(I.Bigi et al, JHEP 0907 (2009) 097;
- Composite models.

Many constraints: from precision EW physics, Higgs physics, LHC searches, flavor physics!

e.g. S.F., A. Greljo, J.F. Kamenik , I. Mustac, JHEP 1307 (2013) 155 ;
074010 ; S.F.& Kosnik PRD87 (2013) 054026;
S.F &S.Prelovsek PRD73 (2006) 054026, S.F.& J.F.Kamenik, PRD 72 (2005)034029+
many references therein.

Tree level FCNC Z due to vectorlike quark



Coupling	Constraint
$\lvert X^u_{cu}\rvert, \lvert Y^u_{cu}\rvert$	$< 2.1 \times 10^{-4}$

$$D^0 - \bar{D}^0$$

$$\Gamma(D^0 \to \mu^+\mu^-)_{vq} \leq 4 \times 10^{-11}$$

Direct CP violation in charm decays

time integrated CP asymmetry

f – CP eigenstate

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

$$\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$$

2012 world average: $\Delta a_{CP} = -(0.67 \pm 0.16)\%$

2014 world average: (HFAG) $\Delta a_{CP} = -(0.253 \pm 0.104)\%$

Naive SM estimate: $|\Delta a_{CP}| = \left|\mathrm{Im}\left(\frac{\lambda_s}{\lambda_d}\right)\right| \frac{\alpha_s}{\pi} \ll 0.1\%$

(Y. Grossman et al. PR D75 (2007) 036008)

$$\lambda_q \equiv V_{cq}^* V_{uq}$$

Direct CP violation in rare charm decays

If there is a direct CP vioaltion in charm non-leptonic decays then it can be present in:

1) $c \to u\gamma$ → $D \to V\gamma$, $D \to P_1 P_2 \gamma$

New phase only in C_7

2) $c \to u l^+ l^-$ → $D \to P l^+ l^-$, $D \to V l^+ l^-$, $D \to P_1 P_2 l^+ l^-$

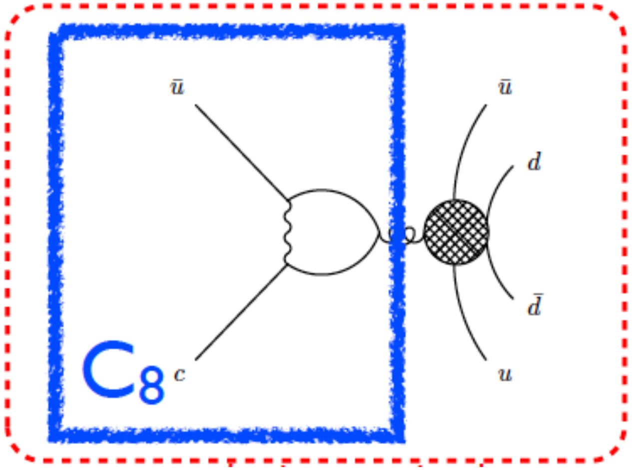
New phase(s) in one of C_7, C_9, C_{10}

C_7 induced CPV

under QCD RGE there is a mixing of

$$\mathcal{O}_8 = \frac{m_c}{(4\pi)^2}\bar{u}_L\sigma_{\mu\nu}c_R G^{\mu\nu}$$

$$\mathcal{O}_7 = \frac{m_c}{(4\pi)^2}\bar{u}_L\sigma_{\mu\nu}Q_u c_R F^{\mu\nu}$$



$$|\mathrm{Im}[\mathrm{C_7(m_c)}]| \simeq |\mathrm{Im}[\mathrm{C_8^{NP}(m_c)}]|$$

$$|\mathrm{Im}[\lambda_b \mathrm{C_7(m_c)}]| \simeq (0.1 - 0.4) \times 10^{-2}$$

G.Isidori and J.F. Kamenik,
PRL 109 (2012) 171801:
(exp. a_{CP} result (2014) considered.)

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

$$f = V\gamma$$

$$|a_{(\rho,\omega)\gamma}|^{max} = 0.027 \ |\frac{\mathrm{Im}[\mathrm{C_7(m_c)}]}{0.2 \times 10^{-2}}|[\frac{10^{-5}}{BR(D \to (\rho,\omega)\gamma)}] \leq 3\%$$

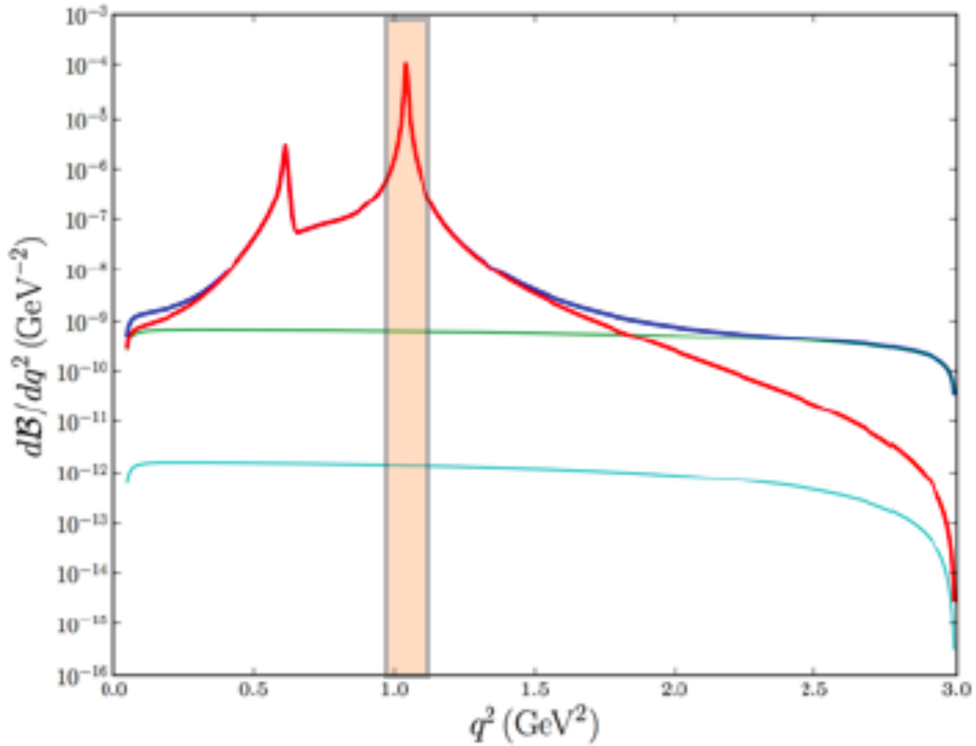
Direct CP violation in $D \to \pi l^+ l^-$

$$\mathcal{A}_{\rm LD}^{\phi}\left[D \to \pi\phi \to \pi\ell^-\ell^+\right] = \frac{iG_F}{\sqrt{2}}\lambda_s \frac{8\pi\alpha}{3} a_\phi e^{i\delta_\phi} \frac{m_\phi \Gamma_\phi}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi} \bar{u}(k_-)\not{p}\, v(k_+)$$

a_ϕ, δ_ϕ real parameters

$$\mathrm{Br}(D^+ \to \phi\pi^+) = (2.65 \pm 0.09) \times 10^{-3}\,,$$
$$\mathrm{Br}(\phi \to \mu^+\mu^-) = (0.287 \pm 0.019) \times 10^{-3}$$

$$a_\phi = 1.23 \pm 0.05$$



Φ

SF, N. Kosnik, PRD (2013) 054026

Is there any possibility to test CP on resonances?

$$|\mathcal{A}_{LD} + \mathcal{A}_{SD}|^2 \approx |\mathcal{A}_{LD}|^2 + 2\Re[\mathcal{A}_{LD}\mathcal{A}_{SD}^*]$$

In the rate this is very small contribution.

$$\mathcal{A}(D^+ \to \pi^+\ell^+\ell^-) = \mathcal{A}_{\mathrm{LD}}^{\phi} + \mathcal{A}_{\mathrm{SD}}^{\mathrm{CPV}}$$

$$\overline{\mathcal{A}}(D^- \to \pi^-\ell^+\ell^-) = \mathcal{A}_{\mathrm{LD}}^{\phi} + \overline{\mathcal{A}}_{\mathrm{SD}}^{\mathrm{CPV}}$$

$$a_{CP}(\sqrt{q^2}) \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}$$

$$= \frac{-3}{2\pi^2}\frac{f_T(q^2)}{a_\phi}\frac{m_c}{m_D + m_\pi}\mathrm{Im}\left[\frac{\lambda_b}{\lambda_s}C_7\right]\left[\cos\delta_\phi - \frac{q^2 - m_\phi^2}{m_\phi\Gamma_\phi}\sin\delta_\phi\right]$$

Differential CP asymmetries

$$a_{CP} \sim 1\%$$

Prediction for the size of CP violating asymmetries in rare charm decays

Decay mode	size	Reference
$D \to \rho(\omega)\gamma$	$\leq 3\%$	Zwicky et al, 2012
$D \to K^+K^-\gamma$	$\leq 0.7\%$	Isidori & Kamenik 2012
$D \to X_u l^+ l^-$	$\leq 3\%$	Paul et al, 2012
$D^+ \to \pi^+\mu^+\mu^-$	$\leq 1\%$	Fajfer & Košnik, 2013
$D^+ \to hh\mu^+\mu^-$	$\leq 1\%$	Cappiello et al, 2013

CP asymmetry in inclusive charm decay

A. Paul et al., PRD83 (2011) 114006 arXive 1212.4849 proposals:

$$A^c_{CP}(\hat{s}) = \frac{\frac{d}{d\hat{s}}\Gamma(D^+ \to X_u l^+ l^-) - \frac{d}{d\hat{s}}\Gamma(D^- \to X_{\bar{u}} l^+ l^-)}{\frac{d}{d\hat{s}}\Gamma(D^+ \to X_u l^+ l^-) + \frac{d}{d\hat{s}}\Gamma(D^- \to X_{\bar{u}} l^+ l^-)}$$

Integrated asymmetry in SM

$$A^c_{CP} = \frac{\Gamma(D^+ \to X_u l^+ l^-) - \Gamma(D^- \to X_{\bar{u}} l^+ l^-)}{\Gamma(D^+ \to X_u l^+ l^-) + \Gamma(D^- \to X_{\bar{u}} l^+ l^-)} \sim 3 \times 10^{-4}$$

$$A^{CP}_{\rm FB}(\hat{s}) = \frac{A^c_{\rm FB}(\hat{s}) + A^{\bar{c}}_{\rm FB}(\hat{s})}{A^c_{\rm FB}(\hat{s}) - A^{\bar{c}}_{\rm FB}(\hat{s})}$$

in the case of CP conservation

$$A^c_{FB}(\hat{s}) = -A^{\bar{c}}_{FB}(\hat{s})$$

Wrapped extra dimension RS model leads to asymmetries:

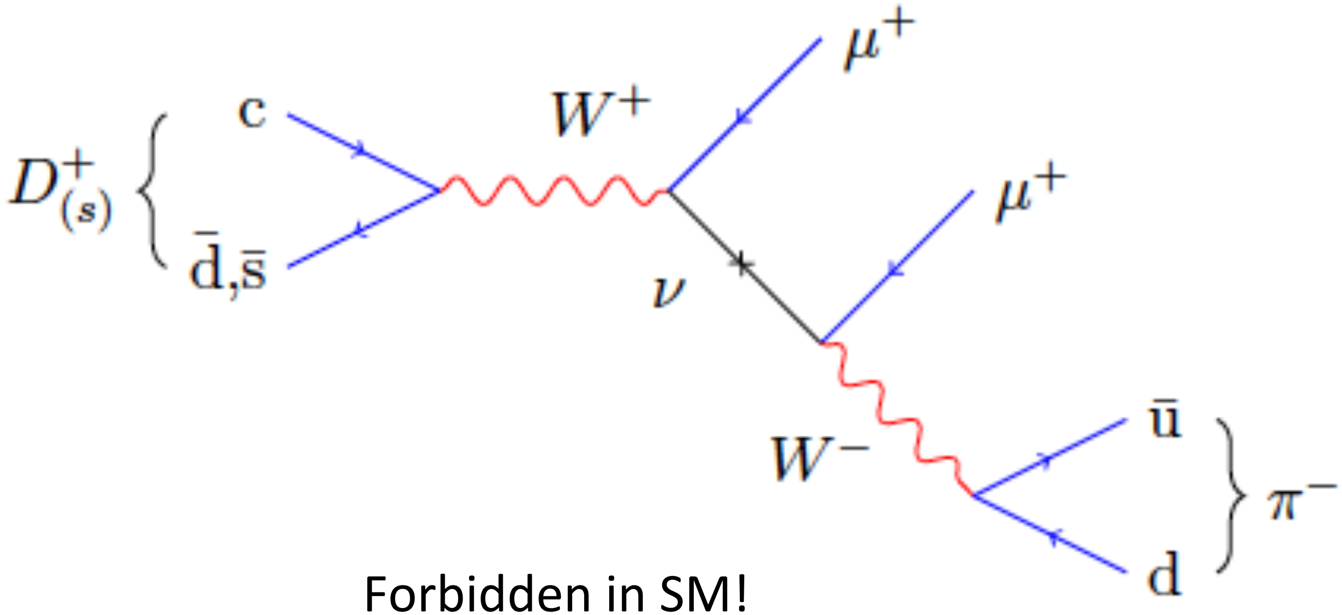
$A_{FB}^{c} \sim \mathcal{O}(5\%)$

$A_{CP}^{c} \sim \mathcal{O}(1\%)$

Lepton flavour violating decays

$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.2\,(2.5) \times 10^{-8},$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 1.2\,(1.4) \times 10^{-7}$$

R. Aaij et al. (the LHCb collaboration), PLB 724 (2013) 203.

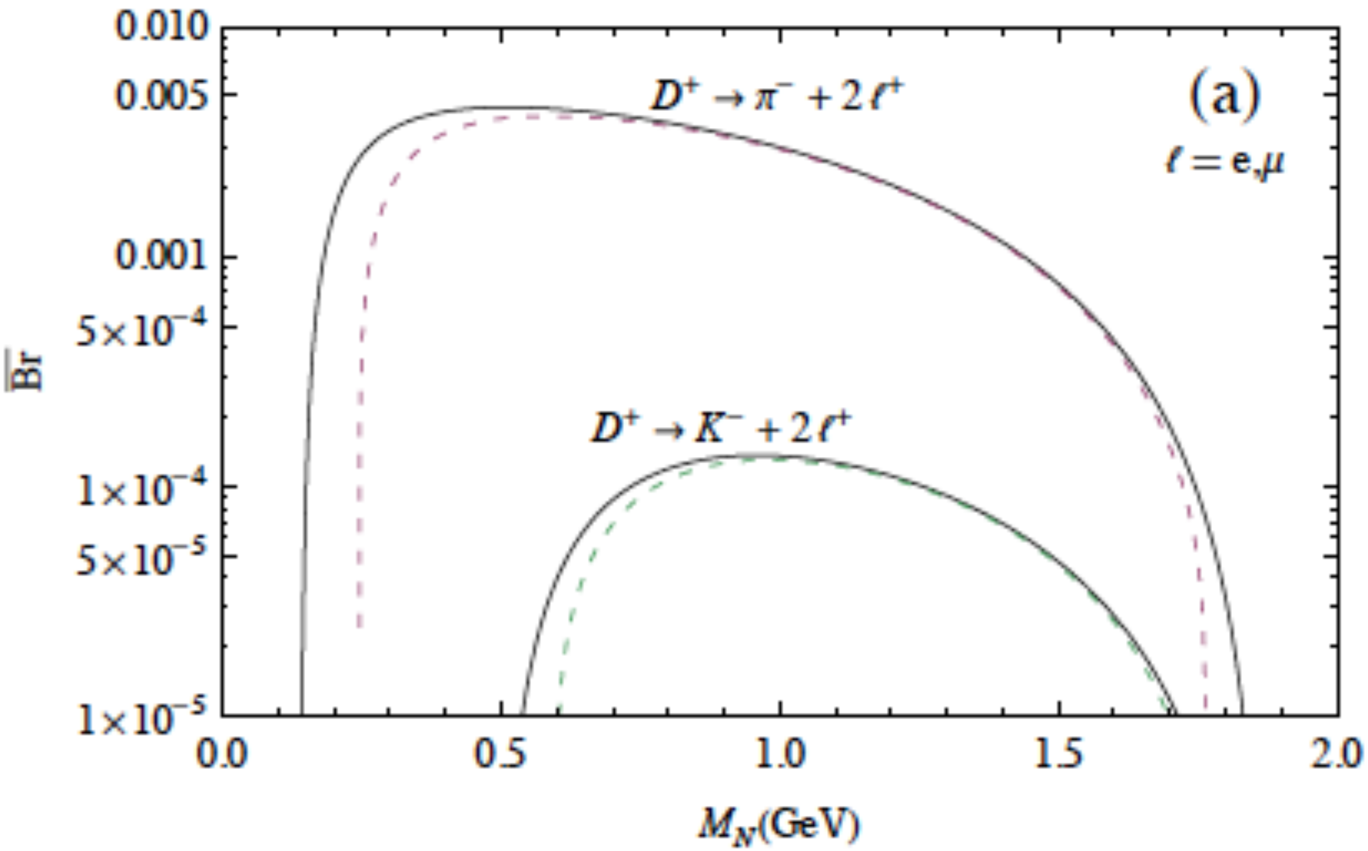


Forbidden in SM!

Mojorana nuetrino – LFV mechanisem; G. Cvetic et al, PRD 89 (2014) 093012 :

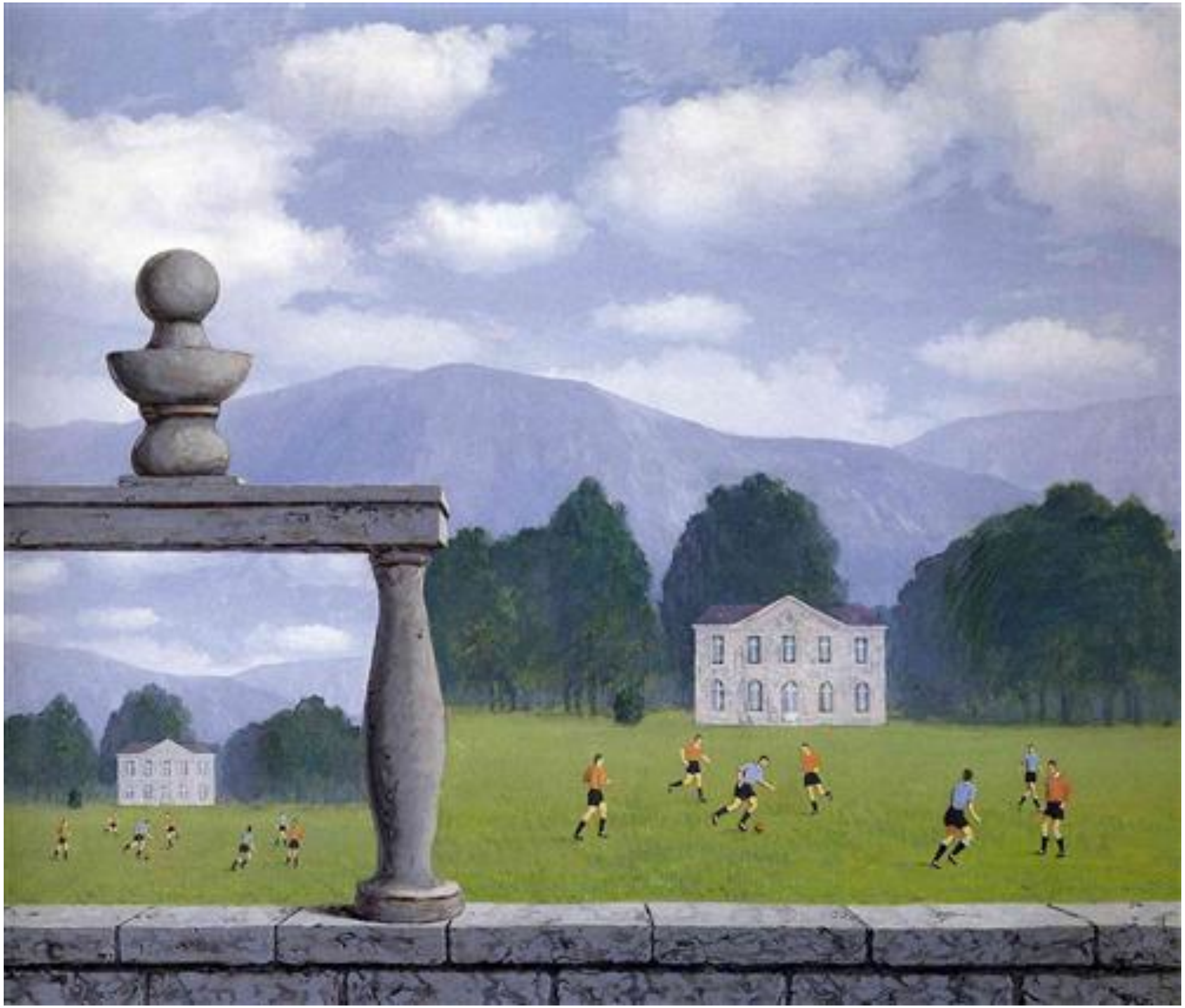
2 degenerate sterile Majorana (mass between 100 MeV and few GeV)
+ a light Majorana sterile neutrino!

G.Burdman etal, PRD 66, (2002) 014009 ;
A.Ilakovac, Phys.Rev. D62 (2000) 036010



Summary of results

- LD + SD contributions are reinvestigated within SM and NP (CPC and CPV);
- LD contribution dominant!
- LHCb measurements of non-resonant $\mathrm{BR}(\mathrm{D}^+ \to \pi^+\mu^+\mu^-)$ enables to put bounds on $\mathrm{C}_{7,\mathrm{max}}^{\mathrm{NP}}, \mathrm{C}_{9,\mathrm{max}}^{\mathrm{NP}}, \mathrm{C}_{10,\mathrm{max}}^{\mathrm{NP}}$;
- Lattice QCD might help in understanding hadronic inputs;
- New observables have been suggested to test NP violation (or CPV);
- NP induced CP violating asymmetries are of the order 1%!



Thanks!

CP violation in $D \to K^+ K^- \gamma$

(S.F. A.Prapotnik and P. Singer PRD66 (2002) 074002)

bremsstrahlung

$$\mathcal{M}(D \to P_1(p_1)P_2(p_2)\gamma(q,\epsilon)) = \frac{G_F}{\sqrt{2}} V_{ci}^* V_{uj} \{F_0 [\frac{p_1 \cdot \epsilon}{p_1 \cdot q} - \frac{p_2 \cdot \epsilon}{p_2 \cdot q}]$$

$$+F_1[(p_1 \cdot \epsilon)(p_2 \cdot q) - (p_2 \cdot \epsilon)(p_1 \cdot q)] + F_2 \epsilon^{\mu\alpha\beta\delta} \epsilon_\mu P_\alpha p_{1\beta} p_{2\delta}\}$$

electric transition

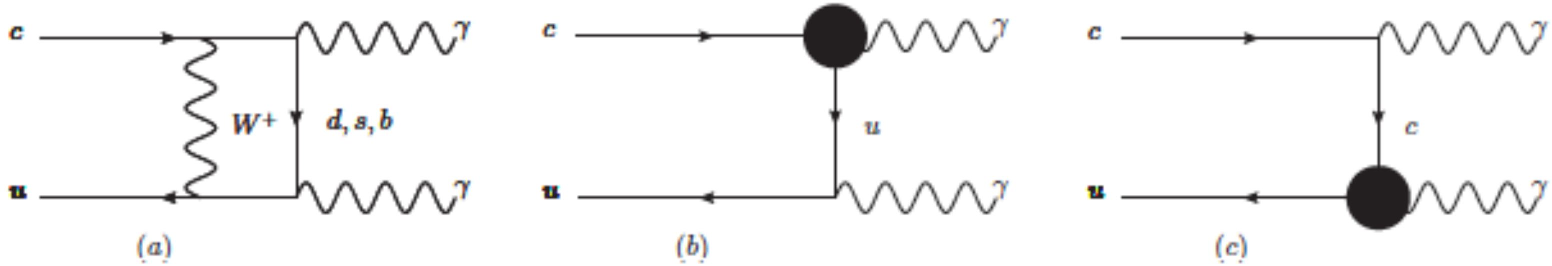
magnetic transition

G. Isidori & J.F. Kamenik, PLB 711, (2012) 46

$$|a_{K^+K^-\gamma}|^{\max} \approx 1\% , \quad 2m_K < \sqrt{s} < 1.05 \text{ GeV} ,$$

$$|a_{K^+K^-\gamma}|^{\max} \approx 3\% , \quad 1.05 \text{ GeV} < \sqrt{s} < 1.20 \text{ GeV}$$

$D \to \gamma\gamma$



- parity violating amplitude

- parity conserving amplitude

$$\mathrm{BR}_{\mathrm{SD}}^{2\text{-loop}}(D^0 \to \gamma\gamma) \simeq (3.6\text{–}8.1) \times 10^{-12}$$

$$\mathrm{BR}_{\mathrm{SM}}^{\mathrm{LD}}(D^0 \to \gamma\gamma) \sim (1\text{–}3) \times 10^{-8}$$

$$\mathrm{BR}_{\mathrm{exp}}(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}\ (90\%\ \mathrm{C.L.})$$

A.Paul et al, PRD 82 (2012) 094006, A.Paul,1308.5886
G. Burdman et al., PRD 66 (2002) 014009; S.F., P. Singer and J. Zupan PRD 64 (2002) 07400