NEW PHYSICS IN CHARM RADIATIVE DECAYS

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Outline

- Motivation
- Short Distance vs Long Distance
- QCD Enhancement in SM and in a model with a down type vector-like quark
- Left-Right Symmetric model
- Long Distance contributions
- Results-including Polarization of the photon
- Conclusions

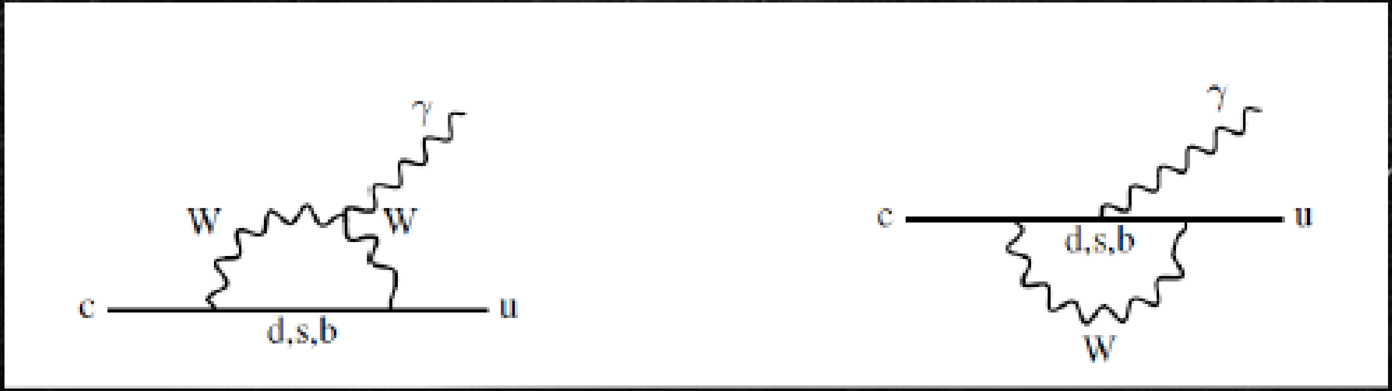
Why look at Charm Radiative Decays?

- *Direct search for BSM has been unsuccessful so far.*
- *Some anomalies in the Flavour sector.*
- *Rare meson decays, provide a path for new physics searches.*
- *Need to look at all possible avenues not only for finding New Physics, but also for pinning down 'the' model of New Physics.*

SHORT DISTANCE VS LONG DISTANCE

- While in case of B mesons, short-distance effects dominate, charm quark systems are dominated by large long-distance QCD contributions.

- Within the SM, the short distance in rare charm decays Suffers from almost complete GIM suppression, as box or penguin diagrams get contributions from down type-almost massless quarks from the weak scale perspective.



- The long distance effects can screen the presence of new physics particles that may appear in the loop of the short distance penguin contributions.

- NP short distance enhancement should be larger than the long distance contributions, to be distinguishable

Alternately, look for special observables

Measure the difference in the rates of the exclusive modes, $D^0 \to \rho\gamma$ and $D^0 \to \omega\gamma$ in which the long distance effects are expected to cancel, would indicate short distance new physics if the data reveals a difference of rates which is more than 30%.

We will demonstrate that measurement of the photon polarization can be used to signal new physics.

Explore effects of presence of a heavy-vector like down type isosinglet quark with additional L-R symmetry.

No Z-mediated FCNC in the up type quark sector.

Enhancement of rates:

with QCD Corrections

Within SM, there is an enhancement of the radiative decay rates in the presence of QCD corrections. Enhancement by a factor of 2 in $\boldsymbol{b \rightarrow s\, \gamma}$. A more dramatic enhancement expected in the case of charm radiative decays.

Hence need to evaluate the corresponding Wilson coefficients within the RG improved perturbation theory.

with NP

Need to enhance the rate above that from long distance Effects OR need signals that can be observed even in the presence of the long distance effects.

Short Distance contribution in the SM

$c \to u\gamma$

$$\mathcal{L}_{\rm int} = -\frac{4G_F}{\sqrt{2}} A^{SM} \frac{e}{16\pi^2} m_c \left(\bar{u}\sigma_{\mu\nu} P_R c\right) F^{\mu\nu}$$

$$\begin{aligned} A^{SM} &= \sum_{p=1,2} Q_p \left[V_{cb}^* V_{ub} G_p^{LL}(r_b) + V_{cs}^* V_{us} G_p^{LL}(r_s) + V_{cd}^* V_{ud} G_p^{LL}(r_d)\right] \\ &= \sum_{p=1,2} Q_p \sum_{q=d,s,b} V_{ci}^* V_{ui} G_p^{LL}(r_q), \end{aligned}$$

Short Distance QCD corrections in the SM

It was shown (Greub, Hurth, Misiak, Wyler), that there is an enhancement from $\mathcal{O}(10^{-17})$ to $\mathcal{O}(10^{-8})$ of the $\mathcal{BR}$ with NLO QCD corrections.

Missing above mb due to CKM unitarity

Hamiltonian for the scale $m_b < \mu < M_W$ is given by

$$\mathcal{H}_{eff}(m_b < \mu < M_W) = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V^*_{cq} V_{uq} [C_1(\mu) Q^q_1 + C_2(\mu) Q^q_2].$$

Effective hamiltonian at the scale $m_c < \mu < m_b$ is given by

$$\mathcal{H}_{eff}(m_c < \mu < m_b) = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V^*_{cq} V_{uq} [C_1(\mu) Q^q_1 + C_2(\mu) Q^q_2 + \sum_{i=3}^{10} C_i(\mu) Q_i]$$

Vector-like down type isosinglet quark

- Possibility of short-distance enhancement in heavy vector like fermion models discussed previously (Babu, He Li Pakvasa)

- No new operators are introduced for the $c \to u\gamma$ transition

- Above the b scale, one needs to integrate Out b' also.

- The operators $\mathcal{O}_7, \mathcal{O}_8$ contribute above the b scale, due to presence of b' quark.

- A chi-squared fit to many flavor observables was performed to obtain the preferred central values of all the elements of the measurable 3X4 quark mixing matrix.

Parameter values obtained from the fit to flavor observables

Alok, Banerjee, Kumar and S. U. Sankar,

Parameter	SM	$m_{b'} = 800$ GeV	$m_{b'} = 1200$ GeV
θ_{12}	0.2273	0.2271	0.2270
θ_{13}	0.0035	0.0038	0.0038
θ_{23}	0.0397	0.0391	0.0391
δ_{13}	1.10	1.04	1.04
θ_{14}	–	0.0151	0.0147
θ_{24}	–	0.0031	0.0029
θ_{34}	–	0.0133	0.0123
δ_{14}	–	0.11	0.11
δ_{24}	–	3.23	3.23

In addition to the 3 angles of the CKM matrix, there are 3 additional angles , $\theta_{i4}, i = 1,2,3$

Values of Wilson coefficients

Benchmark values of $800GeV$ and $1200GeV$ used for m_b'

Coefficients	LO			NLO		
	SM	NP $m_{b'} = 800$ GeV	NP $m_{b'} = 1200$ GeV	SM	NP $m_{b'} = 800$ GeV	NP $m_{b'} = 1200$ GeV
C_1	-1.0769	-1.0769	-1.0769	-0.7434	-0.7434	-0.7434
C_2	1.1005	1.1005	1.1005	1.0503	1.0503	1.0503
C_3	-0.0043	-0.0043	-0.0043	-0.0060	-0.0060	-0.0060
C_4	-0.0665	-0.0665	-0.0665	-0.1015	-0.1015	-0.1015
C_5	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003
C_6	0.0008	0.0008	0.0008	0.0009	0.0009	0.0009
C_7	0.0837	0.3324	0.3276	0.6095	0.2820	0.2778
C_8	-0.0582	-0.2259	-0.2253	-0.0690	-0.2197	-0.2192
$\|C_{7_{eff}}\|$	0.0424	0.2911	0.2863	0.0119	0.2159	0.2117

$$C_{7_{eff}} = C_7 + \sum_{i=1}^{6} y_i C_i$$

Branching Ratios in SM and in a model with Vector like quark

QCD corrections	$\mid A \mid$			$BR(c \to u\gamma)$		
	SM	**VLQ** $m_{b'} = 800$ GeV	**VLQ** $m_{b'} = 1200$ GeV	**SM**	**VLQ** $m_{b'} = 800$ GeV	**VLQ** $m_{b'} = 1200$ GeV
Bare	2.73×10^{-7}	2.49×10^{-5}	2.35×10^{-5}	2.04×10^{-17}	1.70×10^{-13}	1.51×10^{-13}
LO	5.89×10^{-6}	4.32×10^{-5}	4.25×10^{-5}	9.48×10^{-15}	5.11×10^{-13}	4.94×10^{-13}
NLO	2.61×10^{-3}	4.46×10^{-2}	4.37×10^{-2}	1.86×10^{-9}	5.46×10^{-7}	5.23×10^{-7}

At the LO, contributions from the intermediate s and d quarks differ only in the CKM factors, their sum, using unitarity is $-V^*_{cb}V_{ub}$ leading to a large suppression in the amplitude.

At NLO, the functional dependence of the amplitudes on s and d quark masses becomes substantial, the amplitude is $\propto V^*_{cs}V_{us}$ and is enhanced.

Left-Right Symmetric Model

The minimal left right symmetric model is based on the gauge group $SU(3)_c \times SU(2)_L \times \mathrm{SU}(2)_\mathrm{R}$.

The electric charge $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$.

To ensure perturbative interactions between right-handed gauge boson and fermions, $\zeta_g = g_R/g_L$, (where g_R and g_L are the right and left handed couplings) Should not be too large. Direct search impose the bound $\zeta_g M_{W_2} > 2.5\, TeV$.

Also, v_R should be in the TeV range. These constraints imply that $0 < \zeta_g < 2$.

- ✓ Charged gauge bosons, $\boldsymbol{W_L, W_R}$ are mixtures of the mass eigenstates $\boldsymbol{W_1, W_2}$ with a mixing angle $\boldsymbol{\zeta}$, which is restricted to lie in the range $\boldsymbol{(0 - 10^{-3})}$.

- ✓ Since minimal LRSM models are becoming harder to realize, we use a RH mixing matrix which is distinct from the LH CKM matrix. To decrease the no. of parameters, we take the RH CKM to be

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{12} = cos\phi_{12}, s_{12} = sin\phi_{12}$$

Left Right Contribution

$$\mathcal{L}_{eff} = -\frac{eG_F}{4\sqrt{2}\pi^2}\left[\mathcal{A}\bar{u}\sigma^{\mu\nu}RcF_{\mu\nu} + \mathcal{B}\bar{u}\sigma^{\mu\nu}LcF_{\mu\nu}\right]$$

where $\mathcal{A}$ and $\mathcal{B}$ are the bare SD contributions to c_L and c_R respectively given by

$$\mathcal{A}= \sum_{\ell}\Big\{Q_1\big(M\cos^2\zeta\lambda_\ell^{LL}G_1^{LL} + m\zeta_g^2\sin^2\zeta\lambda_\ell^{RR}G_1^{RR} + m_\ell\zeta_g\sin\zeta\cos\zeta e^{i\phi}\lambda_\ell^{LR}G_1^{LR}$$

$$+m_\ell\zeta_g\sin\zeta\cos\zeta e^{-i\phi}\lambda_\ell^{RL}G_1^{RL}\big) + Q_2\big(M\cos^2\zeta\lambda_\ell^{LL}G_2^{LL} + m\zeta_g^2\sin^2\zeta\lambda_\ell^{RR}G_2^{RR}$$

$$+m_\ell\zeta_g\sin\zeta\cos\zeta e^{i\phi}\lambda_\ell^{LR}G_2^{LR} + m_\ell\zeta_g\sin\zeta\cos\zeta e^{-i\phi}\lambda_\ell^{RL}G_2^{RL}\big)\Big\}$$

$$\mathcal{B}= \sum_{\ell}\Big\{Q_1\big(m\cos^2\zeta\lambda_\ell^{LL}H_1^{LL} + M\zeta_g^2\sin^2\zeta\lambda_\ell^{RR}H_1^{RR} + m_\ell\zeta_g\sin\zeta\cos\zeta e^{i\phi}\lambda_\ell^{LR}H_1^{LR}$$

$$+m_\ell\zeta_g\sin\zeta\cos\zeta e^{-i\phi}\lambda_\ell^{RL}H_1^{RL}\big) + Q_2\big(m\cos^2\zeta\lambda_\ell^{LL}H_2^{LL} + M\zeta_g^2\sin^2\zeta\lambda_\ell^{RR}H_2^{RR}$$

$$+m_\ell\zeta_g\sin\zeta\cos\zeta e^{i\phi}\lambda_\ell^{LR}H_2^{LR} + m_\ell\zeta_g\sin\zeta\cos\zeta e^{-i\phi}\lambda_\ell^{RL}H_2^{RL}\big)\Big\}.$$

Additional parameters of left-right symmetry with vector-like quark and the Enhanced **BR**

Parameters	LRSM
ζ	$0 - 10^{-3}$
ζ_g	$0 - 2$
ϕ_{12}	$0 - 2\pi$

LRSM+VLQ	
Parameter	Range
$m_{b'}$	$800, 1200\text{GeV}$
$\phi_{i4}(i = 1, 2, 3)$	$0 - 2\pi$
$\theta_{ij}(i = 1, 2, 3; j = 2, 3, 4)$	listed in Table I

Model		BR
LRSM	Max	1.96×10^{-11}
	Min	0.67×10^{-15}
LRSM+VLQ (800 GeV)	Max	4.65×10^{-8}
	Min	1.69×10^{-13}
LRSM+VLQ (1200 GeV)	Max	0.96×10^{-7}
	Min	1.42×10^{-13}

BR's can be Enhanced

Long Distance Contributions

These being non-perturbative are hard to estimate.
Separated into two classes.

First one corresponds to the annihilation or exchange diagrams
$c\overline{q_1} \rightarrow q_2\overline{q_3}$ with a photon attached to any of the four quark lines.
At hadronic level these diagrams manifest as long distance pole diagrams.

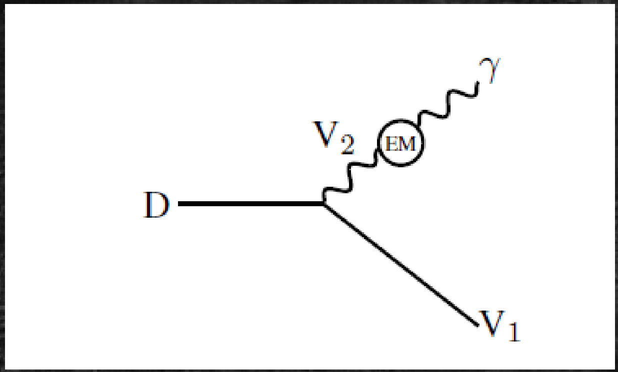
The second corresponds to the process $c \rightarrow q_1\overline{q_2}\mathbf{q}$, followed by
$\overline{q_2}\mathbf{q} \rightarrow \gamma$ .At hadronic level this is the vector dominance mechanism (VMD).

Pole Contributions

$$\mathcal{A}_I^{PC}(D \to V\gamma) = \sum_n h_{V\gamma P_n} \frac{1}{m_D^2 - m_{P_n}^2} \langle P_n | \mathcal{H}_W^{(\text{eff})} | D \rangle$$

$$\mathcal{A}_{II}^{PC}(D \to V\gamma) = \sum_n \langle V | \mathcal{H}_w | D_n^* \rangle \frac{1}{m_D^2 - m_{D_n^*}} h_{D_n^* \gamma D}.$$

Vector Meson Dominance



$D \to V_1 V_2,\ V_2 \to \gamma$

Using the factorization assumption, the squared VMD amplitude is:

$$|\mathcal{A}_{VMD}|^2 = \frac{G_F^2 \left|V_{cq}^* V_{uq'}\right|^2}{2 m_D^2 \mathrm{k}^2} a_i^2(m_c^2) f_X^2 I \times \left[(m_D + m_Y)^2 A_1^2(q_0^2) + \frac{4\mathrm{k}^2 m_D^2 V^2(q_0^2)}{(m_D+m_Y)^2} \right] \times \frac{4\pi\alpha}{f_{V_2}^2}$$

Correspond to Color favoured/ suppressed operators

X, is the final meson which couples to vacuum

Y, appears from the $D \to Y$ transition

$$\langle Y(p_Y)|J^\mu|D(P)\rangle = \frac{2V(q^2)}{m_D+m_Y}\epsilon^{\mu\nu\rho\sigma}\epsilon_\nu^* P_\rho p_{Y_\sigma} + 2m_Y i A_0(q^2)\frac{(\epsilon^* . q)}{q^2}q^\mu + i\left[(m_D+m_Y)A_1(q^2)\epsilon^{*\mu} - \frac{(\epsilon^* . q)A_2(q^2)}{m_D+m_Y}(P+p_Y)^\mu - 2m_Y A_3(q^2)\frac{(\epsilon^* . q)}{q^2}q^\mu\right]$$

To calculate the form factors, we use the form,

$$A_1(q_0^2) = \frac{A_1(0)}{1 - b'x} \, , \; V(q_0^2) = \frac{V(0)}{(1-x)(1-ax)}$$

…. Fajfer, Kamenik PRD **72,** 034029 (2005)

The decay constants are determined in terms of $\boldsymbol{V \to e^+e^-}$ data.

Photon Polarization as a probe of New Physics

Within SM, in the penguin diagram for $c \rightarrow u\gamma$, only LH components of the external fermions couple to the W .

A helicity flip on the c quark leg $\propto m_c$, contributes to amp. for emission of left polarized photons, while that on the u quark leg, $\propto m_u$, results in right polarized photons.

In the LRSM, since the physical W_1 couples to both left and right handed quarks, a helicity flip is also possible on the internal (d,s,b) quark lines, $\propto m_b\zeta$.

With the additional vector like quark, $\propto m_{b'}\zeta$

Photon polarization for the process, $c \to u\gamma$

We define the photon polarization for the $c \to u\gamma$ process as,

$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

where c_R, c_L denote the amplitudes for the right and left polarized photons in the process.

For SM, since SD contributions to c_R are negligible, with only SD contributions, $\lambda_\gamma = -1$.

However, the exclusive decay modes corresponding to $c \to u\gamma$ are dominated by LD contributions. To account for these, we add all the pole type and VMD amplitudes of all the exclusive charmed meson processes. Due to the uncertainty in the sign of the VMD, the LD amplitude lies in the range $(2.08 \times 10^{-9} - 8.78 \times 10^{-7}) 1/GeV$

Polarization Values

SM case: The LD amplitudes do not have any preferred polarization, they contribute equally to both $\boldsymbol{c_R}$ **and** $\boldsymbol{c_L}$. This results in an almost vanishing value of polarization, $\boldsymbol{\lambda_\gamma \sim \mathcal{O}(10^{-8} - 10^{-5})}$.

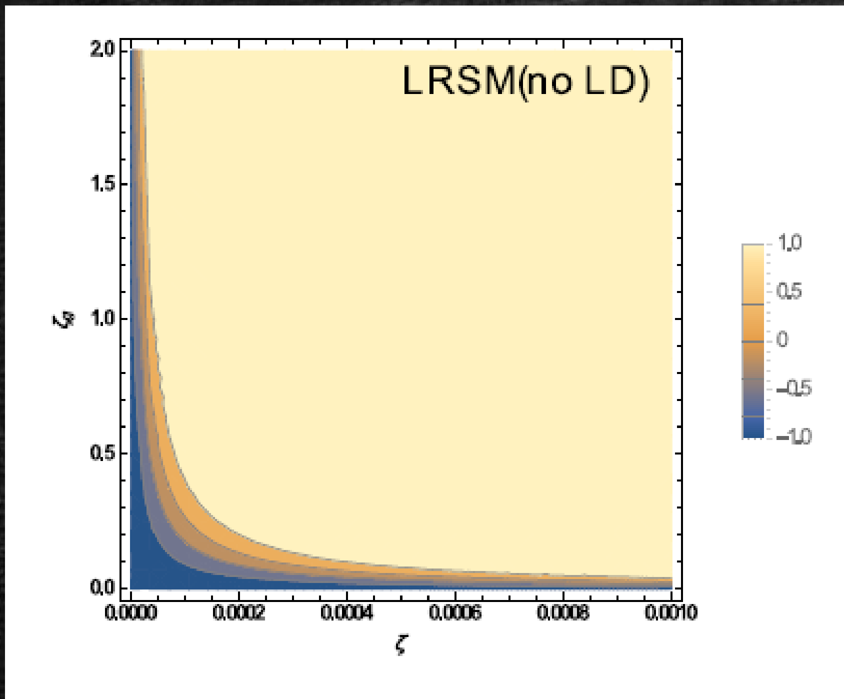
VLQ Without LR symmetry, isosinglet VLQ can only couple to $\boldsymbol{W_L}$, and hence its addition will only enhance the left Polarized amplitude. For this case, in presence of LD contribution, $\boldsymbol{\lambda_\gamma}$ lies in the range $\boldsymbol{(-6.1 \times 10^{-6}\ to\ -2.6 \times 10^{-3})}$

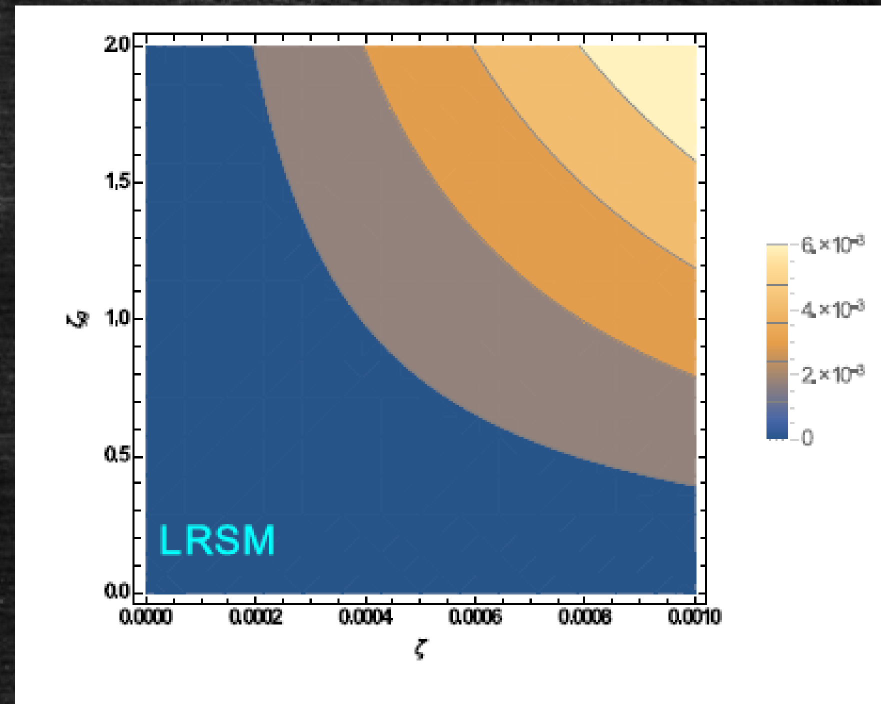
The Interesting Scenario

The photon polarization can be expressed as a function of $\zeta, \zeta_g, \phi_{12}$ for the case of LRSM and of $\zeta, \zeta_g, \phi_{12}, \phi_{14}, \phi_{24}, \phi_{34}$ for LRSM+VLQ

These parameters are varied within their allowed ranges and one looks for the maximum deviation of the polarization from its SM value.

LRSM, without and with LD

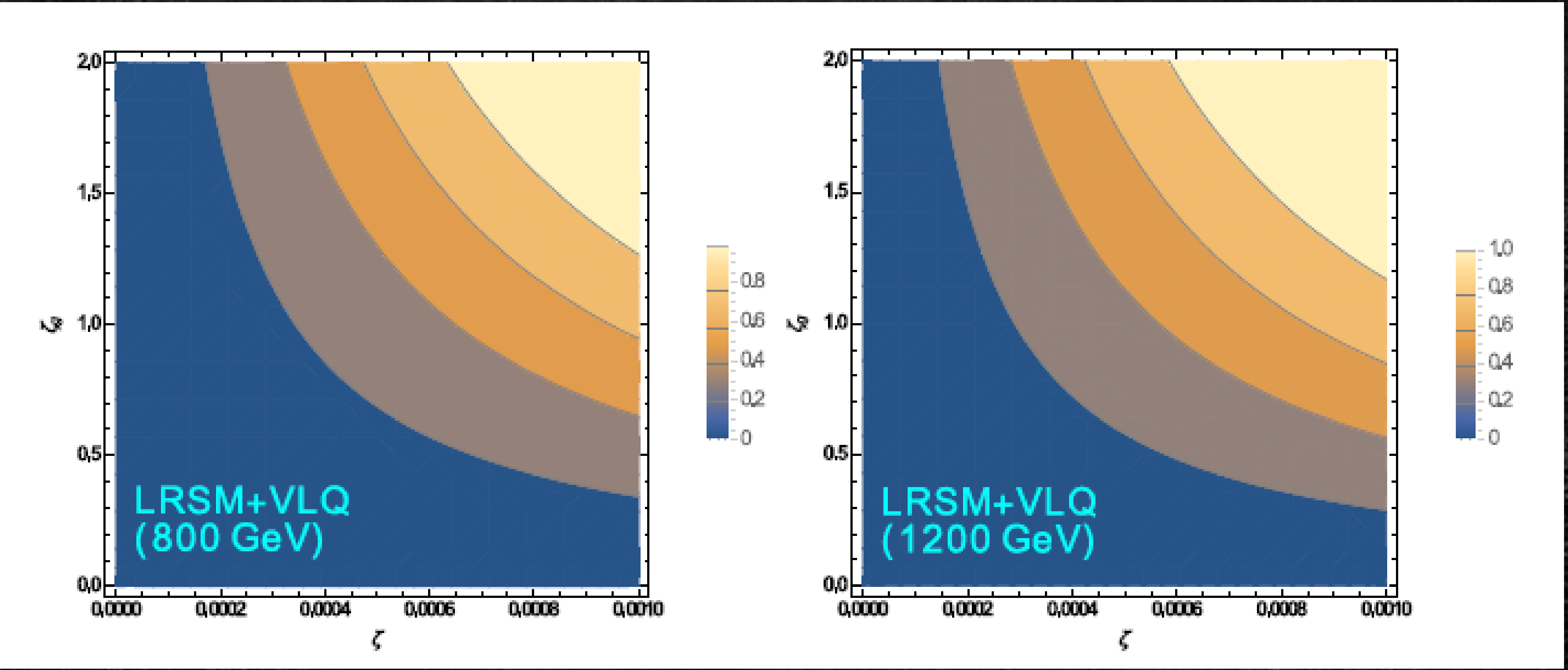




For very small values of ζ, ζ_g LRSM approaches the SM, hence in absence of long distance contribution, the polarization is left handed ($\lambda_\gamma = -1$).

However, as the parameters, ζ, ζ_g increase, the polarization changes from -1 to $+1$

LRSM with a vector-like quark

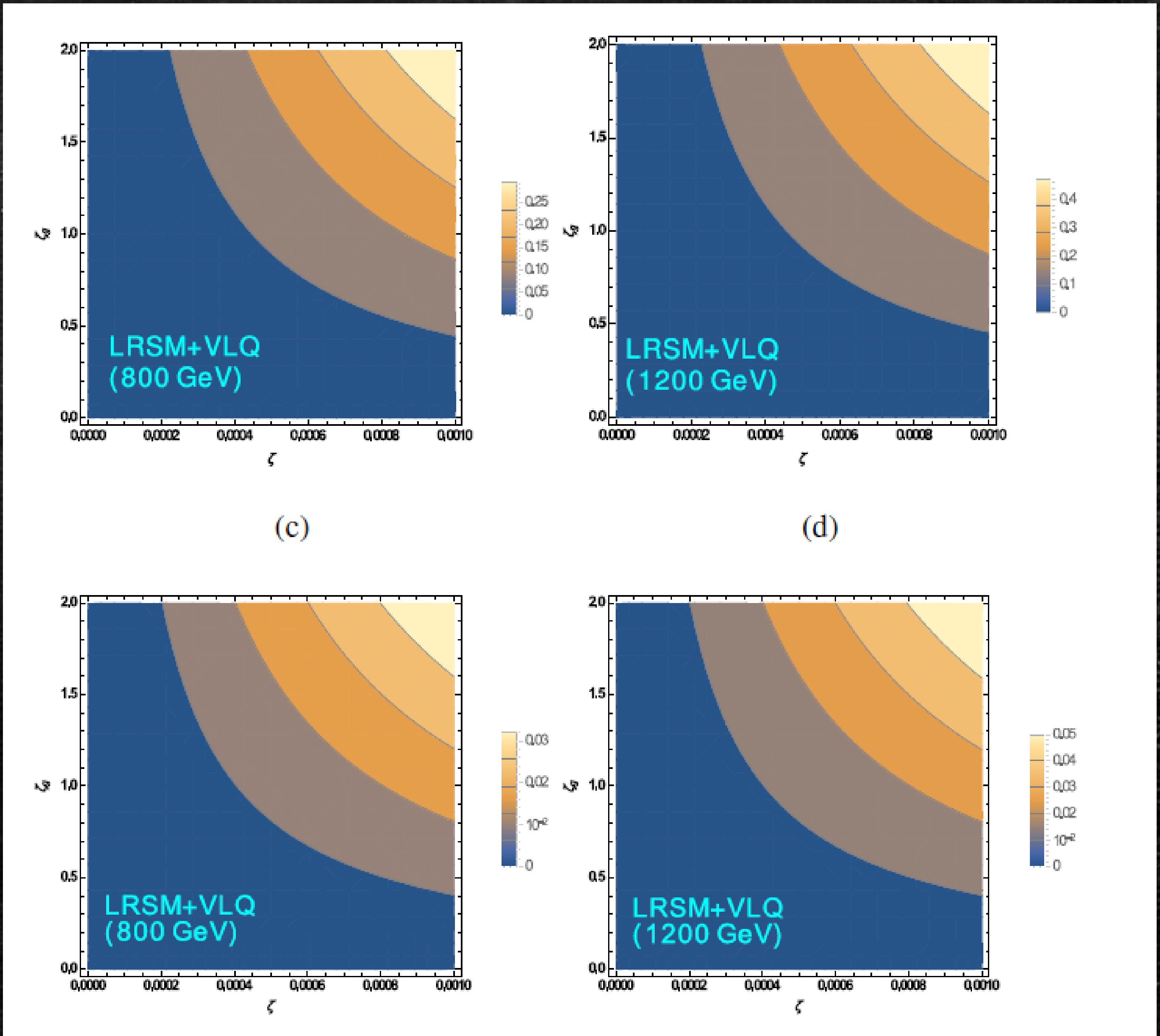


LD amplitude taken to be 2×10^{-9}

With larger LD

LD amplitude of 1×10^{-8}

LD amplitude of 8×10^{-8}



Even with the max. LD amplitude, the polarization can be 10^{-3}

(Differing from the SM value by five orders of magnitude).

On the Experimental side….. Polarization

Recently an observation of photon polarization in the $b \to s\gamma$ transition reported by LHCb.

Photon polarization is obtained by the angular distribution of the photon direction with respect to the plane defined by the momenta of the three final state hadrons in their center of mass frame.

A similar technique could be used to measure the photon polarization for the case of $D \to \omega\gamma$, since the decay of ω into three pions will permit the measurement of an up-down asymmetry between the number of events with photons on either side of the plane.

On the Experimental side….. Branching Ratios

Belle

$$\mathrm{BR}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.3 \pm 0.07) \times 10^{-5},$$

$$\mathrm{BR}(D^0 \to \phi\gamma) = (2.76 \pm 0.19 \pm 0.10) \times 10^{-5},$$

$$\mathrm{BR}(D^0 \to \overline{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.21) \times 10^{-4}.$$

Depending on the LD amplitude, NP SD contribution may/may not be allowed.

For $\rho\gamma, K^*\gamma$,Photon polarization could be obtained from photon conversion to e^+e^-.

Conclusions

Charmed decay modes including radiative ones are expected to be plagued by long distance contributions.

For certain values of the parameter space of the model with LRSM and a down type isosinglet vector-like quark, SD $\boldsymbol{BR}$s could be enhanced by even $\boldsymbol{O(10^{10})}$ wrt SM SD $\boldsymbol{BR}$. They could hence be above the long distance contribution.

Such an enhancement could signal the presence of NP. However, the uncertainty in the size of the long distance contributions may not allow this to be easily feasible.

However, the photon polarization continues to be different from the SM value, over the entire range of the estimated long distance contributions and hence can in principle be a robust signature of the presence of NP.

Back Up

The operators Q_1^q and Q_2^q are the only ones that contribute at $m_b < \mu < M_W$. Within SM, these are the only operators that contribute for $c \to u\gamma$. This is in contrast with radiative bottom decays.

$$Q_1^q = (\bar{u}_L \gamma_\mu T^a q_L)(\bar{q}_L \gamma^\mu T^a c_L), \qquad Q_2^q = (\bar{u}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu c_L).$$

Operators Q_3 to Q_8 are generated at $m_c < \mu < m_b$ due to the matching at scale m_b.

$$\begin{aligned}
Q_3 &= \bar{u}_L \gamma_\mu c_L \sum_q \bar{q} \gamma^\mu q, \qquad Q_4 = \bar{u}_L \gamma_\mu T^a c_L \sum_q \bar{q} \gamma^\mu T^a q, \\
Q_5 &= \bar{u}_L \gamma_\mu \gamma_\nu \gamma_\rho c_L \sum_q \bar{q} \gamma^\mu \gamma^\nu \gamma^\rho q, \qquad Q_6 = \bar{u}_L \gamma_\mu \gamma_\nu \gamma_\rho T^a c_L \sum_q \bar{q} \gamma^\mu \gamma^\nu \gamma^\rho T^a q, \\
Q_7 &= -\frac{g_{em}}{16\pi^2} m_c \bar{u}_L \sigma^{\mu\nu} c_R F_{\mu\nu}, \qquad Q_8 = -\frac{g_s}{16\pi^2} m_c \bar{u}_L \sigma^{\mu\nu} T^a c_R G^a_{\mu\nu}.
\end{aligned}$$

The evolution can be schematically expressed as

$$C^{(O)}(\mu = m_c) = U^{(O)}_{(f=4)}(\mu = m_c, m_b) R^{(O)}_{match} U^{(O)}_{(f=5)}(m_b, M_W) C^{(O)}(M_W)$$

with O ={LO, NLO} specifying the order in QCD corrections.

$U^{(O)}_{(f=5)}(m_b, M_W)$ is 2×2 and $U^{(O)}_{(f=4)}$ is 8×8 matrix.

At LO, $U^{(LO)}_{(f=5)}(m_b, M_W)$ and $U^{(LO)}_{(f=4)}$ are dependent on LO anomalous dimensio matrix. For NLO, they dependent on NLO anomalous dimension matrix. Both taken from 10.1007/JHEP08(2016)091(Boaer, Muller, Seidel).

$R^{(LO)}_{match}$ is Identity matrix. $R^{(NLO)}_{match}$ taken from 10.1007/JHEP08(2016)091(Boaer Muller, Seidel).

LO initial conditions

$$C_1(M_W) = 0, \qquad C_2(M_W) = 1.$$

NLO initial conditions

$$C_1(M_W) = \frac{15\alpha_s(M_W)}{4\pi}, \qquad C_2(M_W) = 1.$$