Search for new physics in rare charm processes

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Outline

- Rare charm decays → experimental results

f_{D_s} puzzle: lattice – experiment in $D_s \to l\nu_l$

Are there any correlations between NP in $D_s \to l\nu_l$ and $D \to \mu^+\mu^-$?

- Leptoquarks mediated tree level processes
  - general approach , GUT SU(5) and proton decay
  - SM allowed (charged current)
  - SM forbidden at tree level → FCNCs
  - LFV
- Summary

Rare charm decays: experimental results

$$D \to X\gamma$$

Belle and In 2008

BABAR $D \to \phi\gamma$ $(2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$

BABAR $D \to K^*\gamma$ $(3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$

can be understood within SM -long distance contributions

Dilepton rare charm decays

D0 $D \to \pi\mu\mu < 3.9 \times 10^{-6}$

CLEO-c $D \to \pi ee < 4.7 \times 10^{-6}$

CDF result (2008)

$$BR(D \to \mu^+\mu^-) < 4.3 \times 10^{-7}$$

EPS (2009), Belle col. improvement!

$$BR(D \to \mu^+\mu^-) < 1.4 \times 10^{-7}$$

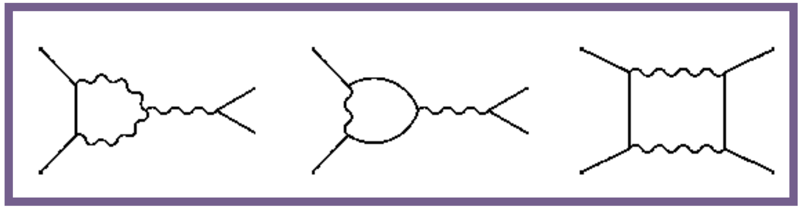
Lepton flavor violating processes

$D \to e^+\mu^- < 8.1 \times 10^{-7}$ $D^+ \to K^+e^-\mu^+ < 3.7 \times 10^{-6}$

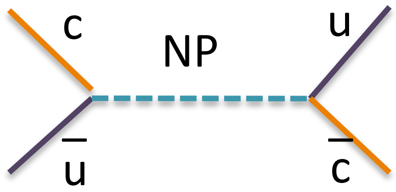
$D_s^+ \to K^+e^-\mu^+ < 3.6 \times 10^{-6}$ $\Lambda_c^+ \to pe^-\mu^+ < 7.5 \times 10^{-6}$

$D \to \mu^+ \mu^-$ ↔ possibility for new physics

SM

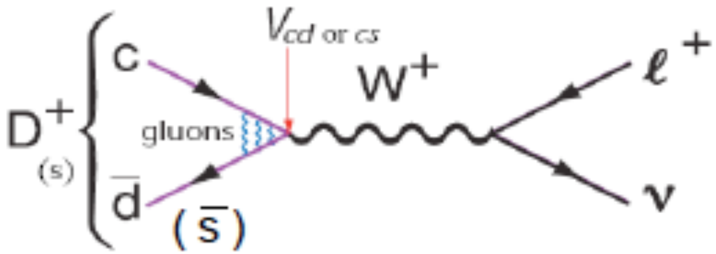


Model	$\mathcal{B}_{D^0 \to \mu^+ \mu^-}$
Standard Model (SD)	$\sim 10^{-18}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q = +2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q = -1/3$ Vectorlike Singlet	$1 \times 10^{-11} \ (m_S/500 \text{ GeV})^2$
$Q = -1/3$ Fourth Family	$1 \times 10^{-11} \ (m_S/500 \text{ GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$
Family Symmetry	$0.7 \ 10^{-18}$ (Case A)
RPV-SUSY	$1.7 \times 10^{-9} \ (500 \text{ GeV}/m_{\tilde{d}_k})^2$



Petrov ,
CHARM 2009

Puzzle $D_s \to l\nu_l$



disagreement between experimental and lattice result

$D \to l\nu_l$ lattice and experiment are in agreement

Are there any correlations between NP in $D \to l\nu_l$ and $D \to \mu^+\mu^-$?

$D_s^+ \to \mu^+\nu$ and two $D_s^+ \to \tau^+\nu$ measurements statistically independent: combine

Average:

$f_{D_s} = 259.5 \pm 6.6 \pm 3.1$ MeV
Lattice: 241 ± 3 MeV

Puzzle!

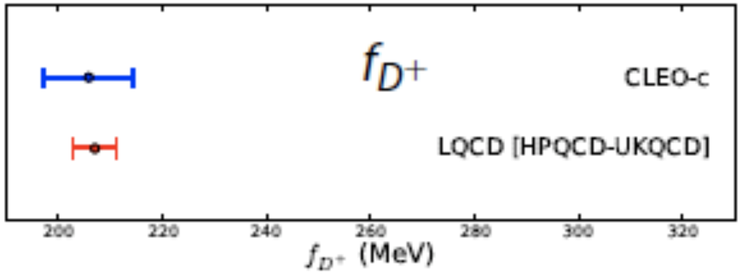
Recall

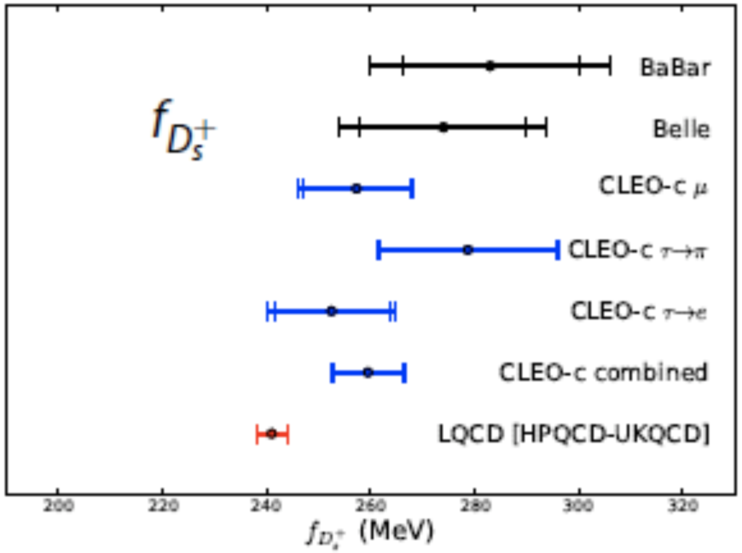
$f_D = 205.8 \pm 8.5 \pm 2.5$ MeV
Lattice: 207 ± 4 MeV

So

$f_{D_s}/f_D = 1.26 \pm 0.06 \pm 0.02$
Lattice: 1.162 ± 0.009

PRD 79, 052001 (2009)

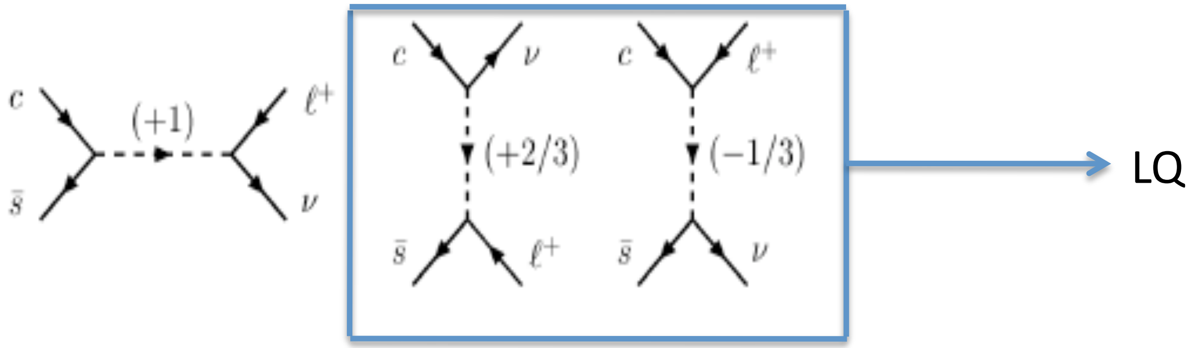




from P. Onysi, CHARM (2009)

The f_{D_s} puzzle introduced new possibility: NP effects in charged charm meson leptonic decays.

Dobrescu and Kronfeld (2008) have suggested that charged Higgs or scalar leptoquarks can explain the lattice-experiment discrepancy.



(I. Doršner , S.F., J. F. Kamenik and N. Košnik ; **0906.5585**)

We consider all possible renormalizable leptoquark interactions with SM matter fields.

Leptoquarks

- Singlets
- Doublets
- Triplets

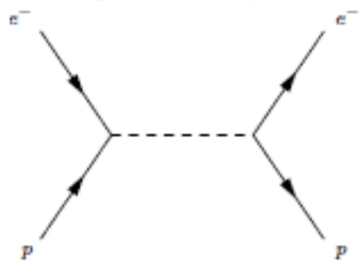
$\mathbf{SU(2)_L}$

Leptoquarks

- arise naturally in unification theories, Pati-Salam, *R*-parity violating SUSY (squarks), extended technicolor, compositeness models

- Experimentally they have been searched directly:

  Single production at $e^{\pm}p \to e^{\pm}p$ experiments (HERA, ZEUS)
  $\Rightarrow$ Constraints in the coupling-mass plane



- Pair production in hadron colliders

S. Abdullin, F. Charles / Physics Letters B 464 (1999) 223–231

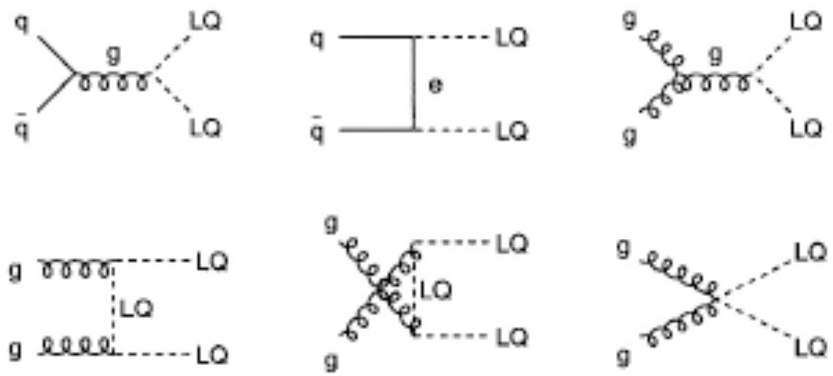
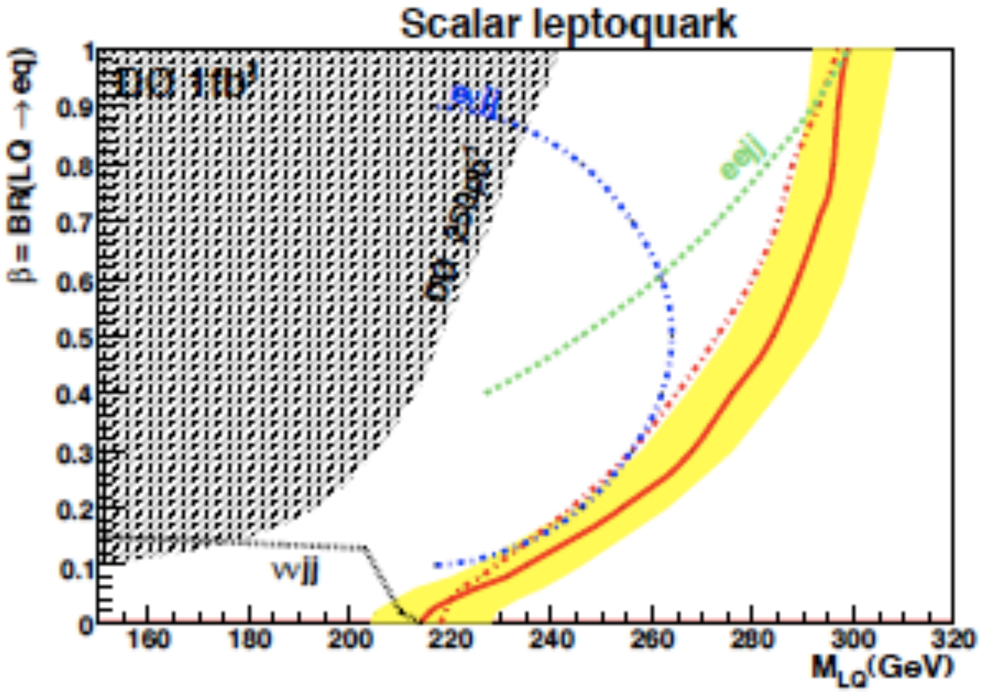


Fig. 1. Leptoquark pair production diagrams.

- False indication for on-shell production in HERA *ep* scattering (1997)

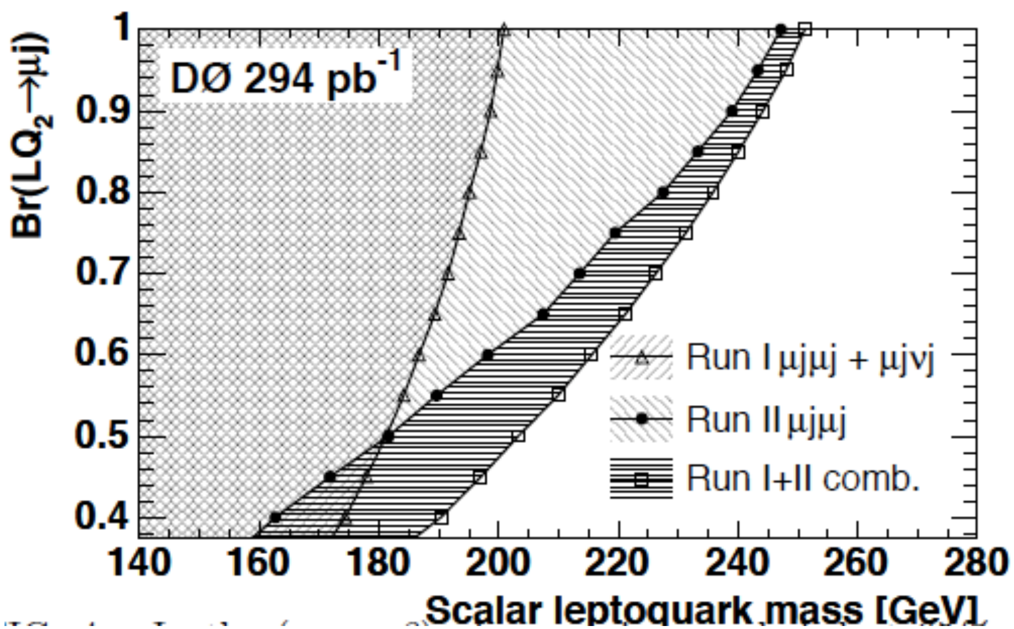
- Lower bound on mass from D0,CDF $\sim 230 - 250$ GeV for leptoquarks coupled to 1st or 2nd generation



DØ Collaboration

arXiv: 0907.1048

(first generation)



hep-ex/0601047

(second generation)

➢ leptoquarks and proton decay

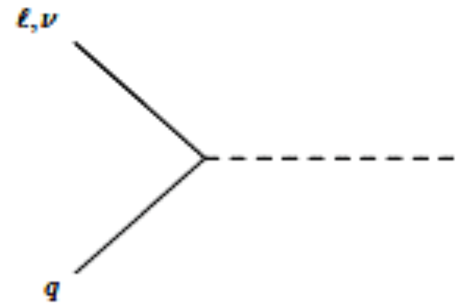
?

➢leptoquarks in low energy physics

leptoquarks ⟷ diquarks

dangerous for proton decay should be much above electroweak scale.

"genuine " leptoquark: couples to quark and lepton



If one requires that leptoquarks contribute only at tree level , then one can talk about:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \text{ gauge groups:}$$
$$(\mathbf{3},\mathbf{3},-1/3),\ (\bar{\mathbf{3}},\mathbf{2},-7/6) \text{ and } (\mathbf{3},\mathbf{1},-1/3)$$

only doublet is "genuine" leptoquark

SU(5) embedding

Matter fields :

$$\mathbf{10_i}(=(\mathbf{1},\mathbf{1},\mathbf{1})_\mathbf{i}\oplus(\overline{\mathbf{3}},\mathbf{1},-\mathbf{2}/\mathbf{3})_\mathbf{i}\oplus(\mathbf{3},\mathbf{2},\mathbf{1}/\mathbf{6})_\mathbf{i}=(\mathbf{e_i^C},\mathbf{u_i^C},\mathbf{Q_i}))$$
$$\overline{\mathbf{5}}_i(=(\mathbf{1},\mathbf{2},-\mathbf{1}/\mathbf{2})_\mathbf{i}\oplus(\overline{\mathbf{3}},\mathbf{1},\mathbf{1}/\mathbf{3})_\mathbf{i}=(\mathbf{L_i},\mathbf{d_i^C}))$$
where $Q_i = (u_i \quad d_i)^T$ and $L_i = (\nu_i \quad e_i)^T$.

up quark (down quark and charged lepton) masses originate from the contraction of

$\mathbf{10_i}$ and $\mathbf{10_j}$ ($\overline{\mathbf{5}}_j$) with 5- and/or 45-dimensional Higgs representation.
$\mathbf{10}\times\mathbf{10}=\overline{\mathbf{5}}\oplus\overline{\mathbf{45}}\oplus\overline{\mathbf{50}}$ and $\mathbf{10}\times\overline{\mathbf{5}}=\mathbf{5}\oplus\mathbf{45}$.

Most general renormalizable set of Yukawa coupling contractions with $\mathbf{5_H}$ and $\mathbf{45_H}$ is

$$\begin{aligned} V &= Y_{5^*}^{ij}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\alpha j}\mathbf{5}^*_{H\beta} + Y_5^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\gamma\delta}\mathbf{5}_H^{\epsilon} \\ &+ Y_{45^*}^{ij}\mathbf{10}_i^{\alpha\beta}\overline{\mathbf{5}}_{\delta j}\mathbf{45}^{*\,\delta}_{H\alpha\beta} + Y_{45}^{ij}\epsilon_{\alpha\beta\gamma\delta\epsilon}\mathbf{10}_i^{\alpha\beta}\mathbf{10}_j^{\zeta\gamma}\mathbf{45}_{H\zeta}^{\delta\epsilon}, \end{aligned}$$

mass matrices

$$M_D = \left(Y_{5*}^T v_5^* + 2Y_{45*}^T v_{45}^*\right)/\sqrt{2},$$
$$M_E = \left(Y_{5*} v_5^* - 6Y_{45*} v_{45}^*\right)/\sqrt{2},$$
$$M_U = \left[4(Y_5^T + Y_5)v_5 - 8(Y_{45}^T - Y_{45})v_{45}\right]/\sqrt{2},$$

where $\langle 5_H^5 \rangle = v_5/\sqrt{2}$, $\langle 45_{H1}^{15} \rangle = \langle 45_{H2}^{25} \rangle = \langle 45_{H3}^{35} \rangle = v_{45}/\sqrt{2}$ and $|v_5|^2 + |v_{45}|^2 = v^2$ ($v = 247\,\mathrm{GeV}$). Y_{5*}, Y_{45*}, Y_5 and Y_{45} are arbitrary 3×3 Yukawa matrices.

Higgs in 5 $M_E^T = M_D$

one Higgs (only) in 5, at GUT scale

$m_\tau/m_b = m_\mu/m_s = m_e/m_d$

Higgs in 45 $M_E^T = -3M_D$

In this approach both are needed 5_H and 45_H

Leptoquarks

$$\mathbf{45_H} = (\boldsymbol{\Delta_1}, \boldsymbol{\Delta_2}, \boldsymbol{\Delta_3}, \boldsymbol{\Delta_4}, \boldsymbol{\Delta_5}, \boldsymbol{\Delta_6}, \boldsymbol{\Delta_7}) = (\mathbf{8}, \mathbf{2}, \mathbf{1/2}) \oplus (\overline{\mathbf{6}}, \mathbf{1}, \mathbf{-1/3}) \oplus (\mathbf{3}, \mathbf{3}, \mathbf{-1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{2}, \mathbf{-7/6}) \oplus (\mathbf{3}, \mathbf{1}, \mathbf{-1/3}) \oplus (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{4/3}) \oplus (\mathbf{1}, \mathbf{2}, \mathbf{1/2})$$

Proton decay and triplet, doublet and singlet of LQ

triplet $\Delta_3 = (3, 3, -1/3)$

$\mathbf{10\text{-}\bar{5}\text{-}45^*_H}$ → lepton-quark pair coupling with the LQ triplet

$\mathbf{10\text{-}10\text{-}45_H}$ → quark-quark coupling with the LQ triplet

} no proton decay

doublet $\Delta_4 = (3, 2, -7/6)$

It cannot couple to quark – quark pair even via mixing with Higgs doublet and other Higgs states.

singlet $\Delta_5 = (\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$

$\mathbf{10\text{-}10\text{-}45_H}$ → lepton-quark pair coupling with the LQ triplet, if only this term is present no proton instability

$\mathbf{10\text{-}\bar{5}\text{-}45^*_H}$ → quark-quark –LQ , absence of this contraction, proton stable

Contraction of 10, 10 and 45 can lead to proton decay, but SUSY SU(5) GUT sufficiently suppresses proton decay.

Fermion weak doublets

weak ⟷ mass – eigen basis

$$\begin{bmatrix} f_1 \\ f_2 \end{bmatrix}$$

(Blum, Grossman, Nir and Perez 0903.2118)

CKM and PMNS matrix $K - \bar{K},\ D - \bar{D}$

$$\overline{Q^w_q} X^{q\ell} = (\overline{u^w_q} \quad \overline{d^w_q}) X^{q\ell} = (\overline{u_q} \quad \overline{d'_q})(U^\dagger X)^{q\ell},$$

$$X'^{q\ell} L^w_\ell = X'^{q\ell} (\nu^w_\ell \quad e^w_\ell)^T = (X'E)^{q\ell} (\nu'_\ell \quad e_\ell)^T,$$

3 x 3 Yukawa matrix in the weak basis

rotations are assigned to down-type quarks and neutrions

$$Y_{LQ} \equiv U^\dagger X \qquad (V_{CKM} = U^\dagger D)$$

$$d' = V_{CKM} d \qquad \nu' = V_{PMNS} \nu$$

$$Y'_{LQ} \equiv X'E \qquad (V_{PMNS} = E^\dagger N)$$

quark-mass eigen states:

$$(Q_1, Q_2, Q_3) = \begin{pmatrix} u & c & t \\ d' & s' & b' \end{pmatrix}, \quad (d' \quad s' \quad b') = (d \quad s \quad b) V^T_{\rm CKM}$$

We use parameterization $$Y^{q\ell}_{LQ} = y^{\ell}_{LQ}(\sin\phi, \cos\phi)$$

$$d' = \cos\theta_c d + \sin\theta_c s,\; s' = -\sin\theta_c d + \cos\theta_c s$$
$$V_{us} = -V_{cd} = \sin\theta_c = 0.225$$

(good approximation – to neglect effects of the third generation)

If the Y_{LQ} matrix had all rows, except for the q-th one, set to zero, which would correspond to leptoquark coupling *only* to u_q, one would still get non-zero couplings to all three left-handed down-quarks.

antinuetrino in a process the factor $\sum_j Y'^{qj}_{LQ} V^{ji}_{PMNS}$

(neutrino) → V^{li}_{PMNS}

Neutrinos are not tagged in present experiment

The sum over all neutrino species gives

$$\sum_{i=1,2,3} |\mathcal{A}_i|^2 \sim \sum_{i=1,2,3} V^{ji}_{PMNS} V^{li*}_{PMNS} = \delta^{jl}$$

(equivalent to the absence of neutrino mixing!)

Triplet leptoquarks

$$\mathcal{L}_3 = Y_3^{ij}\, \overline{Q_i^c} i\tau_2\, \boldsymbol{\tau} \cdot \boldsymbol{\Delta}_3^*\, L_j + \text{h.c.}$$

arbitrary 3x3 matrix

Leptoquark triplet $\left\{ \begin{matrix} \Delta_3^{-4/3} \\ \Delta_3^{-1/3} \\ \Delta_3^{2/3} \end{matrix} \right\}$

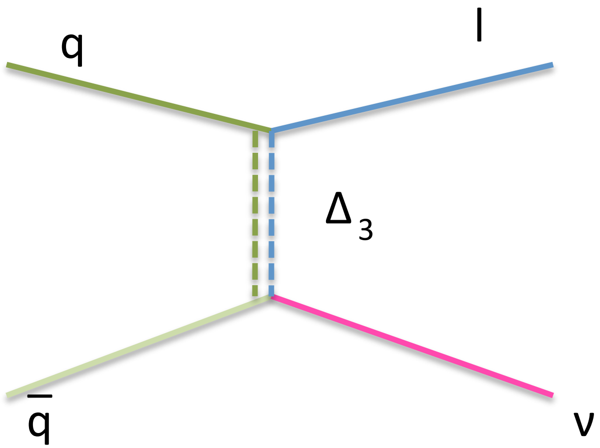
$$\tilde{Y}_3^{q\ell} \equiv \begin{cases} Y_3^{q\ell} & ;\ q = u, c, t, \\ (V_{CKM}^T Y_3)^{q\ell} & ;\ q = d, s, b. \end{cases}$$

$\tilde{Y}_3^{s\tau} \tilde{Y}_3^{s\mu *}$, $\tilde{Y}_3^{d\tau} \tilde{Y}_3^{d\mu *}$ **and**

$Y_3^{u\tau} Y_3^{u\mu *} = (\cos\theta_c \tilde{Y}_3^{d\tau} + \sin\theta_c \tilde{Y}_3^{s\tau})(\cos\theta_c \tilde{Y}_3^{d\mu *} + \sin\theta_c \tilde{Y}_3^{s\mu *})$

these couplings are not independent

We consider contributions to following processes:



$$D_s \to \mu\nu_\mu$$
$$D_s \to \tau\nu_\tau$$
$$\tau \to \eta\mu$$
$$\tau \to \pi\mu$$
$$\tau \to K\mu$$
$$K \to \mu\nu_\mu$$
$$K^+ \to \pi^+\nu\bar{\nu}$$
$$K_L \to \mu^+\mu^-$$

$$\pi_{\mu/\tau} \equiv Br(\tau \to \pi\nu)/Br(\pi \to \mu\nu)$$

(also for K)

$\tau \rightarrow \eta\mu$

constraints

$$\tilde{Y}_3^{s\tau}\tilde{Y}_3^{s\mu*}, \quad \tilde{Y}_3^{d\tau}\tilde{Y}_3^{d\mu*}$$

$$Y_3^{u\tau}Y_3^{u\mu*} = (\cos\theta_c \tilde{Y}_3^{d\tau} + \sin\theta_c \tilde{Y}_3^{s\tau})(\cos\theta_c \tilde{Y}_3^{d\mu*} + \sin\theta_c \tilde{Y}_3^{s\mu*})$$

$\pi_{\mu/\tau}$

In triplet LQ scenario one needs one of the measured decay widths $D_s \rightarrow \ell\nu$

to reproduce $Br(D_s \rightarrow \tau\nu) = 0.0561(44)$

and using lattice result $f_{D_s} = 241(3)\ \mathrm{MeV}$

$$\sqrt{\delta_3^\tau} \approx 0.002\ \mathrm{GeV}^{-1}$$

$$\delta_3^\tau \equiv \frac{Y_3^{c\tau*}\tilde{Y}_3^{s\tau}}{V_{cs} m_{\Delta_3}^2}$$

$$(y_3^\tau)^2 \sin\phi \cos\phi(-\tan\theta_c + \tan\phi)/m_{\Delta_3}^2$$

SM correction

two solutions

to satisfy $D \to \tau\nu_\tau$ and $\pi_{\mu,\tau}$ one needs either:

1. leptoquarks couple only to s but not to d quark $\tan\phi \approx \tan\theta_c \quad (\tilde{Y}_3^{d\tau} \approx 0)$

   and sizable $Y_3^{u\tau} \to K_{\mu,\tau}$

2. leptoquarks couple only to c but not to u quark $\sin\phi \approx 0 \quad (Y_3^{u\tau} = 0)$

   sizable $\tilde{Y}_3^{d\tau}$

$$\left\{\begin{matrix} K^+ \to \pi^+ \nu\bar{\nu} \\ Br(\tau \to K\nu)/Br(K \to \mu\nu) \end{matrix}\right\}$$

$$Br(D \to \mu\nu) = 3.8(4) \times 10^{-4}$$ agrees with SM

If $\tilde{Y}_3^{s\tau}$ sizable, then $\tilde{Y}_3^{s\mu} \sim 0$ from $\tau \to \eta\mu$ decay width

additional constraint comes from $K_L \to \mu^+\mu^-$

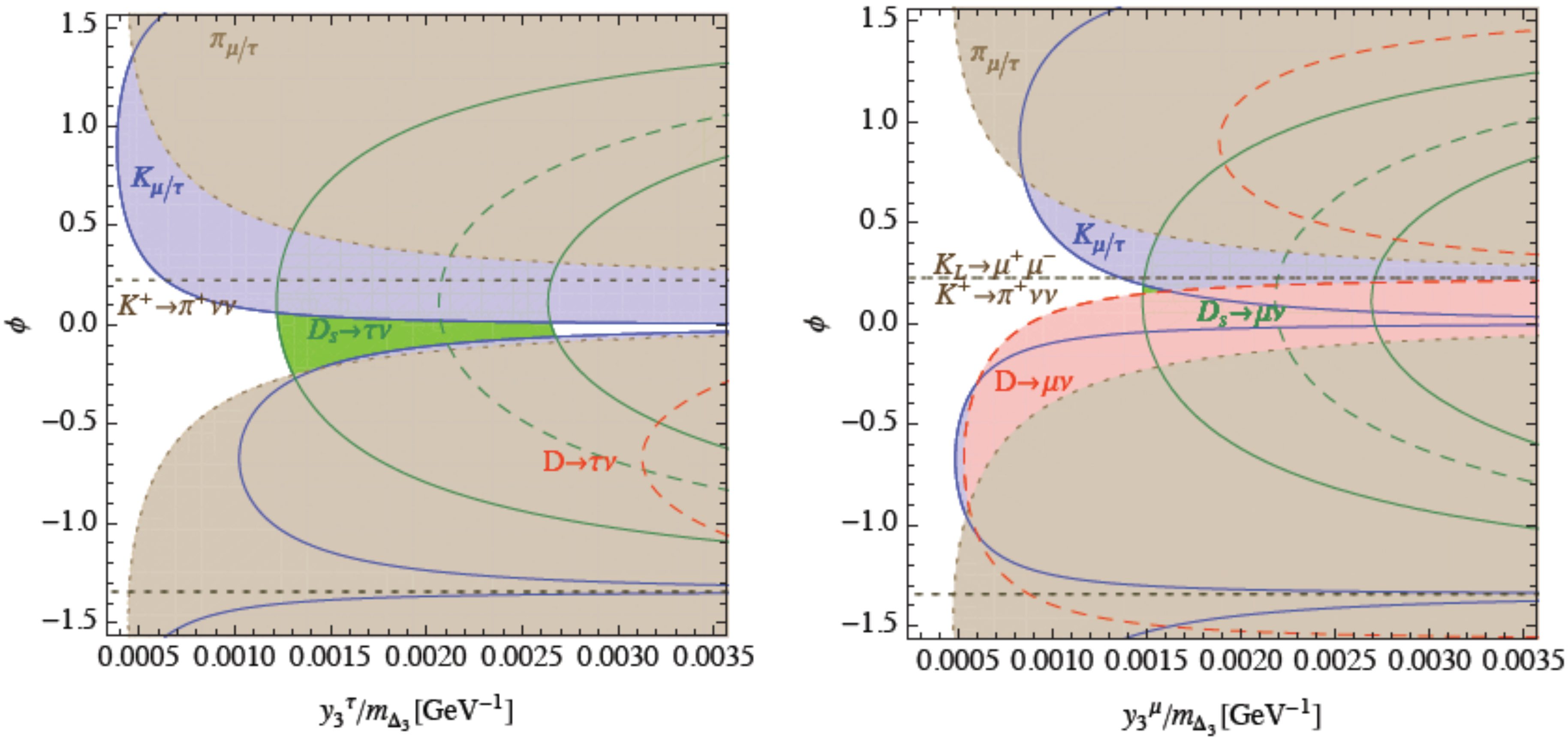
Combining these two constraints a triplet explanation is completely excluded!

Our assumption:

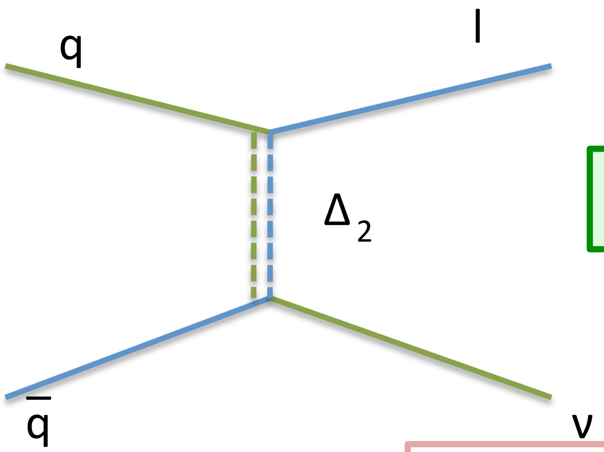
Leptoquark multiplet are nearly degenerate

We require :

- all the measured constraints to be satisfied within one standard deviation (at 68 %C.L.)
- for the upper we use 90% C.L. limit



Combined bounds on triplet LQ parameters in two-generation case.



Doublet Leptoquarks

$$(\bar{\mathbf{3}}, \mathbf{2}, -7/6) \rightarrow \left\{ \begin{array}{l} \Delta_2^{-2/3} \\ \Delta_2^{-5/3} \end{array} \right\}$$

$$\mathcal{L}_2 = Y_{2L}^{ij}\,\overline{Q}_i\, i\tau_2 \Delta_2^* \, e_j + Y_{2R}^{ij}\,\overline{u}_i \Delta_2^\dagger L_j + \text{h.c.}$$

In SU(5) $\quad$ $\mathbf{10}$ and $\overline{\mathbf{5}}$ with $\mathbf{45}_{\mathbf{H}}^*$ $\quad$ $\mathbf{10}$ and $\mathbf{10}$ being contracted with $\mathbf{45}_{\mathbf{H}}$.

We consider constraints coming from

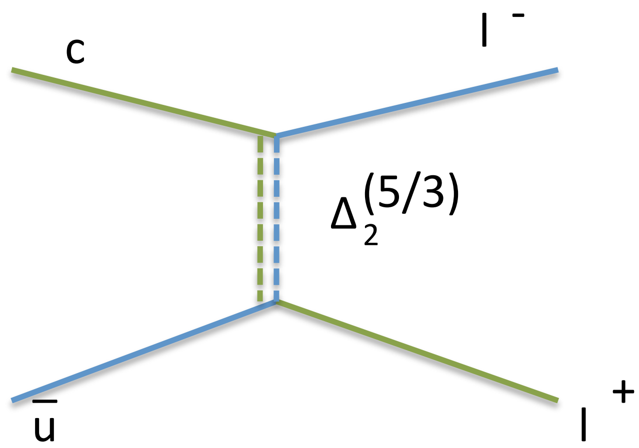
$$D_s \longrightarrow l\nu_l$$
$$D^0 \longrightarrow \mu^+\mu^-$$
$$K_L \longrightarrow \mu^+\mu^-$$

and LFV $\quad$ $\tau \longrightarrow \eta\mu$

the couplings of left-handed down and up type quarks are misaligned

$$\tilde{Y}_{2L}^{q\ell} \equiv (V_{CKM}^{\dagger} Y_{2L})^{q\ell} \text{ for } q = d, s, b$$

$$D^0 \to \mu^+\mu^-$$



$$Y_{2R}^{c\mu} Y_{2L}^{u\mu*} = Y_{2R}^{c\mu}(\cos\theta_c \tilde{Y}_{2L}^{d\mu*} + \sin\theta_c \tilde{Y}_{2L}^{s\mu*})$$

$$Y_{2L}^{c\mu} Y_{2L}^{u\mu*} = (\cos\theta_c \tilde{Y}_{2L}^{s\mu} - \sin\theta_c \tilde{Y}_{2L}^{d\mu})(\cos\theta_c \tilde{Y}_{2L}^{d\mu*} + \sin\theta_c \tilde{Y}_{2L}^{s\mu*})$$

The measurement of $D \to \mu\nu$ directly constraints $\tilde{Y}_{2L}^{d\mu}$

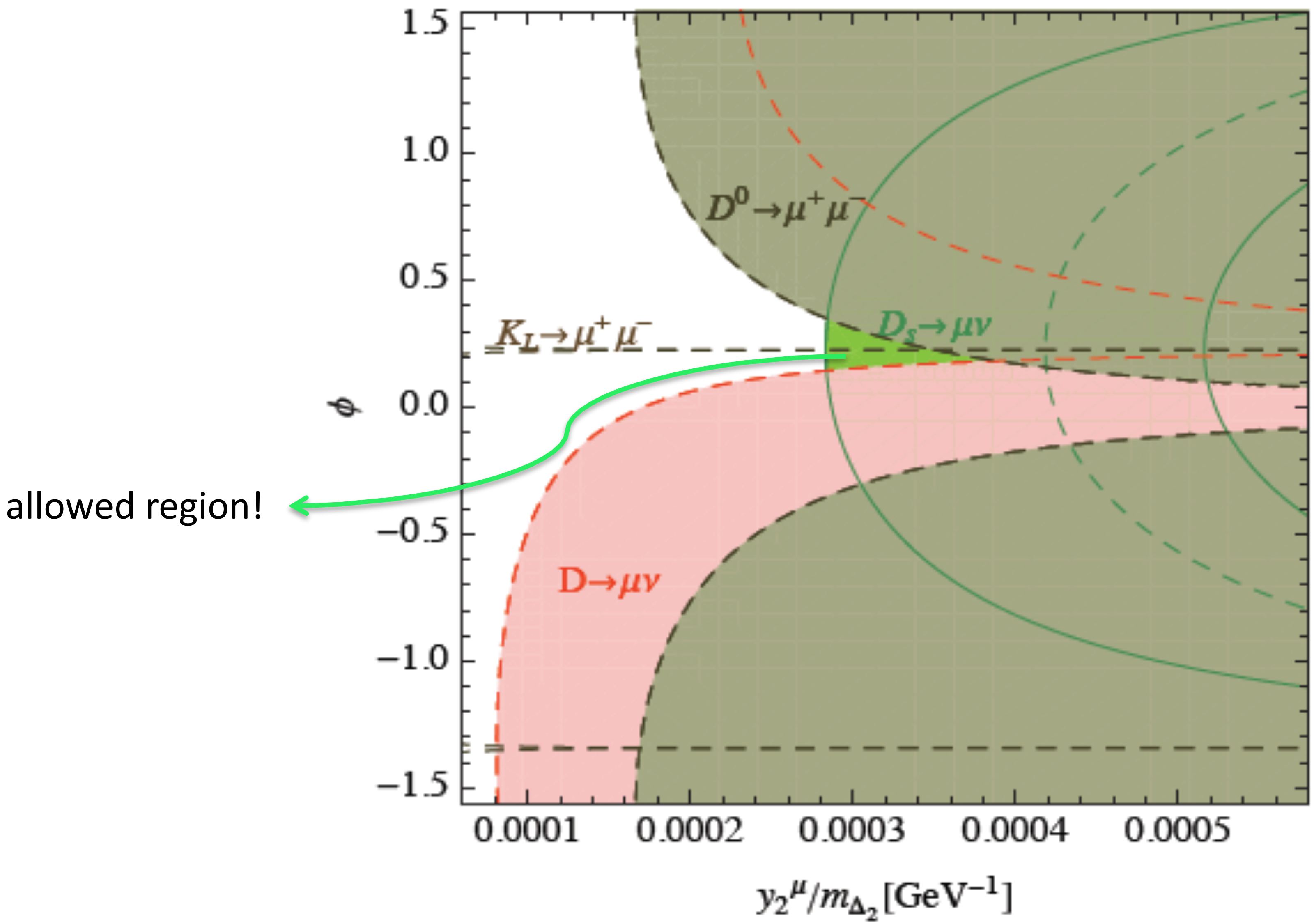
For the numerical analysis we use parameterization:

$$\tilde{Y}_{2L}^{s\mu} = y_{2L}^{\mu} \cos\phi \qquad \tilde{Y}_{2L}^{d\mu} = y_{2L}^{\mu} \sin\phi$$

chosen $Y_{2R}^{u\mu} = 0 \qquad Y_{2R}^{c\mu} = y_{2R}$

we vary y_{2L}^{μ} and y_{2R}^{μ} keeping fixed $y_2^{\mu} = \sqrt{y_{2L}^{\mu} y_{2R}^{\mu}}$

(keep in mind that first generation ($\pi_{\mu/\tau}$) is strongly constrained)



Combined bounds on the doublet LQ.

$D_s \rightarrow \tau\nu$

- far from being conclusive in doublet case (D decay mode is not measured)

-no strong experimental bound on FCNC in up sector involving tau (doublet leptoquarks do not contribute to $s \rightarrow d\nu\bar{\nu}$)

$$\delta_2^\ell \equiv \frac{m_{D_s}^2}{m_\ell(m_c + m_s)} \frac{Y_{2R}^{c\ell *} \tilde{Y}_{2L}^{s\ell}}{V_{cs}^* m_{\Delta_2}^2}$$

$$\tau \rightarrow \eta^{(\prime)}\mu \ \sim \ \left| \tilde{Y}_{2L}^{s\tau} \tilde{Y}_{2L}^{s\mu *} \right|^2$$

$$\delta_2^{LFV} = |Y_{2L}^{s\tau} Y_{2L}^{*s\mu}| / m_{\Delta_2}^2$$

perturbative treatment for couplings

$$|Y_{2L,R}^{ij}| < \sqrt{4\pi}$$

$$m_{\Delta_2} < \sqrt{4\pi\, \delta_2^{LFV} / |\delta_2^\mu \delta_2^\tau|}$$

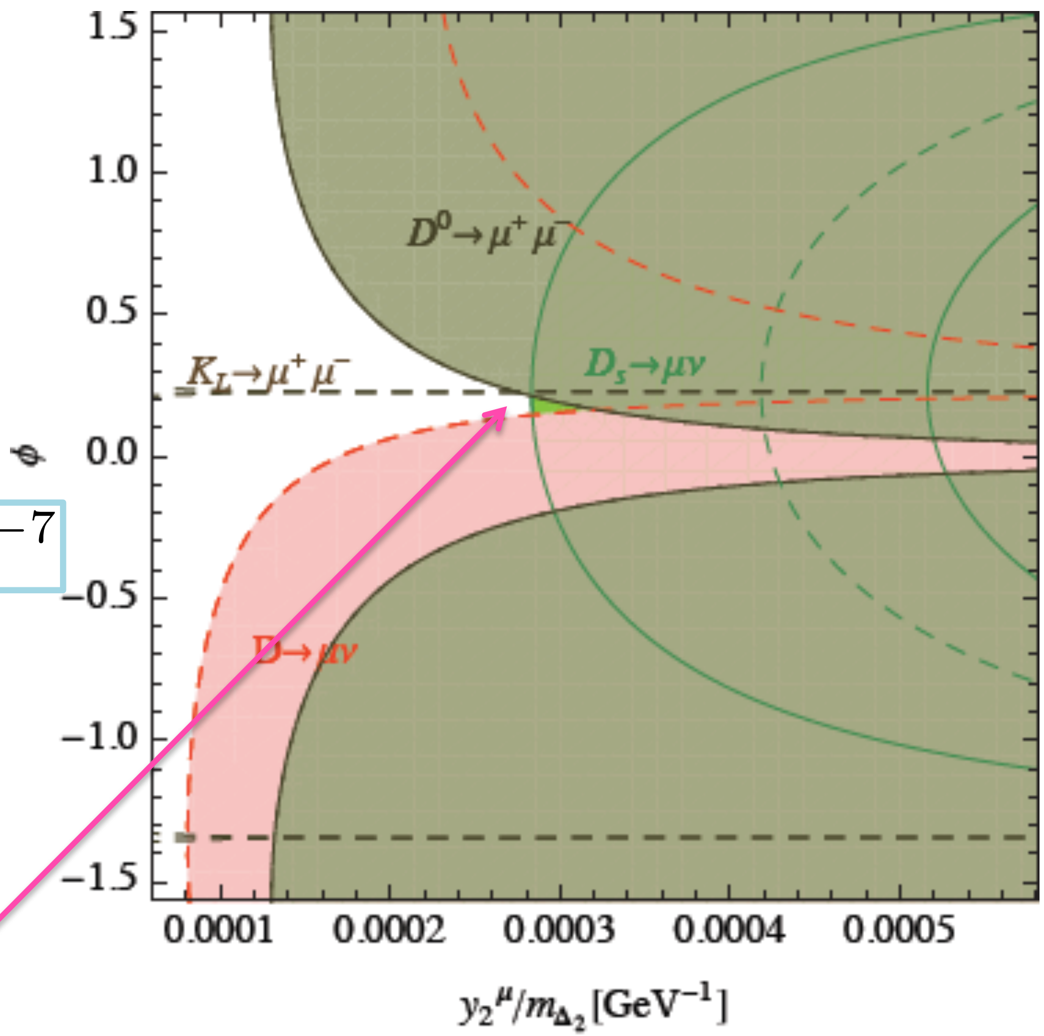
with present bound

$Br(\tau \rightarrow \eta\mu) < 6.5 \times 10^{-8}$ at 90 % C.L.

$$m_{\Delta_2} \sim 1.4 \ \ \mathrm{TeV}$$

with new improved bound
(Belle EPS, 2009)

$$BR(D \to \mu^+ \mu^-) < 1.4 \times 10^{-7}$$



Doublet leptoquarks excluded!

SINGLET LEPTOQUARK $(3,1,-1/3)$

$$\Delta_1^{-1/3}$$

$$\mathcal{L}_1 = Y_{1L}^{ij}\overline{Q_i^c} i\tau_2 \Delta_1^* L_j + Y_{1R}^{ij}\overline{u_i^c}\Delta_1^* e_j + \text{h.c.}$$

the same term as in MSSM R parity violating

this terms gives modification in

$$D_s \longrightarrow \tau\nu_\tau$$

we use

$$K^+ \to \pi^+ \nu\bar{\nu} \quad \tilde{Y}_{1L}^{d\ell} \approx 0$$

$$\frac{\Gamma^{(1)}_{D_s\to\tau\nu}}{\Gamma^{SM}_{D_s\to\tau\nu}} \qquad \frac{\Gamma^{(1)}_{\tau\to K\nu}}{\Gamma^{SM}_{\tau\to K\nu}}$$

$$D^0 \to \mu^+\mu^-$$

free parameters can be chosen as an overall amplitude δ and two angles: (ϕ, ω)

$$\tilde{Y}^{s\mu}_{1L} = y^{\mu}_1 \sin\omega,\; Y^{c\mu}_{1R} = y^{\mu}_1 \cos\omega \cos\phi \text{ and } Y^{u\mu}_{1R} = y^{\mu}_1 \cos\omega \sin\phi$$

bound from perturbation approach: $y^{\mu}_1 < \sqrt{4\pi}$

numerical fit $(y^{\mu}_1, \omega, \phi)$ to above constraints constraints leads to

- exp. result for $Br(D_s \to \mu\nu)$ cannot be reproduced within one standard deviation without violating any other constraints.

- but, due to the lack of exp. information on FCNC in up sector, leaves the verdict on singlet leptoquark in $D_s \to \tau\nu$ open .

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

Experimentally: $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$

this includes contributions of ρ, ω, ϕ resonances

SM long distance contributions almost saturate this result.

$$\mathcal{A}_V^{\rm LD} = \frac{a_V}{q^2 - m_V^2 + i m_V \Gamma_V} \bar{u}(k_-) \not{p}\, v(k_+)$$

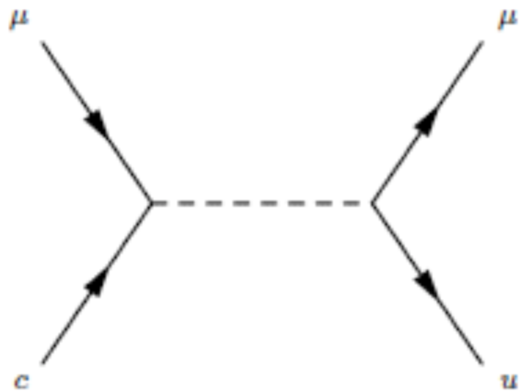
Parameters a_V fitted to $\mathcal{B}$ of resonant mode $D^+ \to \pi^+ V \to \pi^+\mu^+\mu^-$

Result: resonant branching fraction

$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)_{\rm res} = (1.8 \pm 0.2) \times 10^{-6}$$

S.F. and N. Kosnik (2009), S.F., N.K. and S. Prelovsek (2007)

$$\mathcal{L}_{LQ} = \tilde{d}\,\kappa_\ell(\bar{\nu}_\ell P_R s^c - \bar{\ell} P_R c^c) + \tilde{d}\,\kappa'_\ell \bar{\ell} P_L c^c + \text{H.c.},$$



$$\mathcal{L}_{\text{eff}}(c \to u\ell^+\ell^-) = \frac{1}{8M_{\tilde{d}^2}}\,[C^{L*}_{\ell c} C^{L}_{\ell u}\,(\bar{u}c)_{V-A}(\bar{\ell}\ell)_{V-A} + C^{R*}_{\ell c} C^{R}_{\ell u}\,(\bar{u}c)_{V+A}(\bar{\ell}\ell)_{V+A}$$
$$+C^{L*}_{\ell c} C^{R}_{\ell u}\left(\frac{1}{2}\,(\bar{u}\sigma^{\mu\nu}c)(\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\ell) - (\bar{u}c)_{S-P}(\bar{\ell}\ell)_{S-P}\right)$$
$$+\,C^{R*}_{\ell c} C^{L}_{\ell u}\,\left(\frac{1}{2}(\bar{u}\sigma^{\mu\nu}c)(\bar{\ell}\sigma_{\mu\nu}(1+\gamma_5)\ell) - (\bar{u}c)_{S+P}(\bar{\ell}\ell)_{S+P}\right)\Big]$$

From $D^+ \to \pi^+\mu^+\mu^-$ we find constraints on the two combinations

$$\frac{|C_{\mu c}^{L(R)} C_{\mu u}^{L(R)}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.19, \qquad \frac{|C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.16,$$

one of which is also present in $D^0 \to \mu^+\mu^-$ (helicity-lifted):

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \tau_{D_0} \frac{f_D^2 m_{D_0}^5}{256\pi m_c^2} \frac{|C_{\mu c}^L C_{\mu u}^R|^2 + |C_{\mu c}^R C_{\mu u}^L|^2}{M_{\tilde{d}}^4}$$

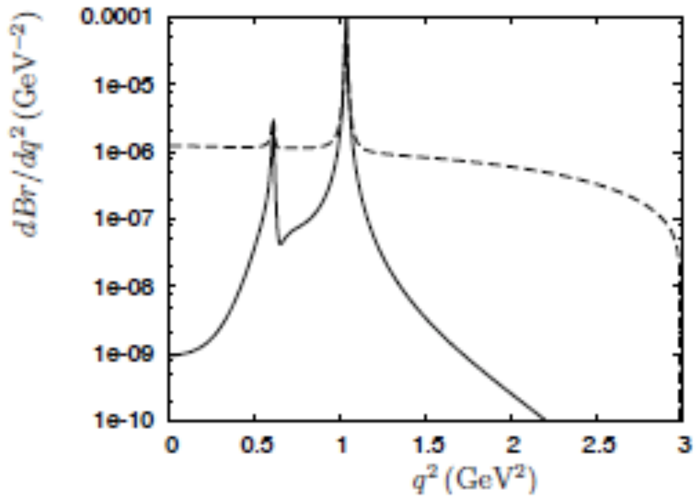
and from $\mathcal{B}(D^0 \to \mu^+\mu^-)$ there is much stronger bound

$$\boxed{\frac{|C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}|}{(M_{\tilde{d}}/\mathrm{TeV})^2} < 0.032}$$

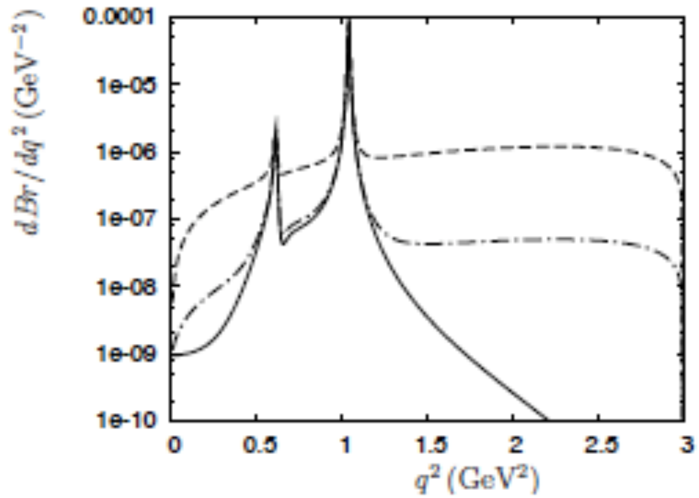
This bound, applied to $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$ results in $9.4 \times 10^{-8} \to$
$C_{\mu c}^{L(R)} C_{\mu u}^{R(L)}$ cannot be observed in $D^+ \to \pi^+\mu^+\mu^-$

Present experimental bound on the $D^0 \to \mu^+\mu^-$ rate leads to the rate $D^+ \to \pi^+\mu^+\mu^-$ two order of magnitude smaller than the SM result.

$C^{L(R)}_{\mu c} C^{L(R)}_{\mu u}$



$C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}$



ruled out

- inclusion of $Q = -1/3$ weak-isosinglet scalar leptoquark leads to tree-level $c \to u\mu\mu$
- $D^+ \to \pi^+\mu^+\mu^-$ sensitive to both $C^{L(R)}_{\mu c} C^{L(R)}_{\mu u}$, $C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}$
- $D^0 \to \mu^+\mu^-$ only to helicity-unsuppressed $C^{L(R)}_{\mu c} C^{R(L)}_{\mu u}$
- Bound from $\mathcal{B}(D^0 \to \mu^+\mu^-)$ renders $D^+ \to \pi^+\mu^+\mu^-$ only sensitive to $C^{L(R)}_{\mu c} C^{L(R)}_{\mu u}$

Summary:

- Scalar leptoquarks cannot explain both $D_s \to l\nu$ decay widths, due to constraints coming from precision kaon, tau and D mesons.

- The triplet leptoquark is excluded from contributing to any of the widths.

- Sizable contributions due to single right-handed down squark exchange in RPV supersymmetric models are also excluded.

- Leptoquark singlet is definitely excluded only from explaining the $D_s \to \mu\nu$ width.

- The doublet contribution in $D^0 \to \mu^+\mu^-$ is excluded with the new Belle bound.

Future perspective

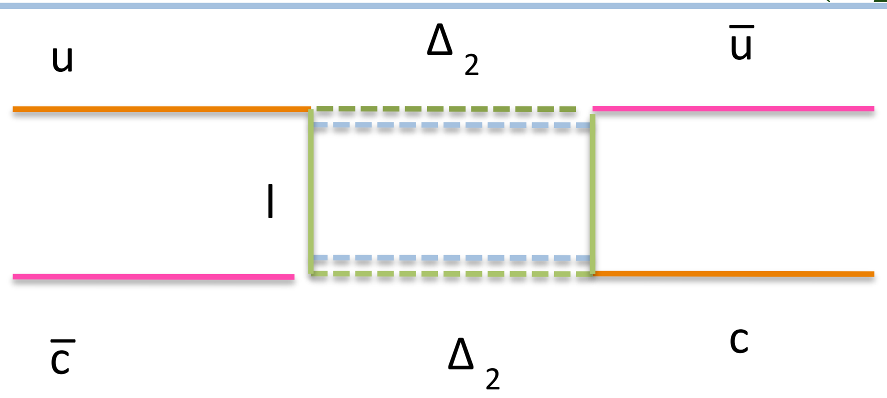
Possible signatures of LQ in $D_s \to \tau\nu$

- $Br(J/\psi \to \tau^+\tau^-)$ at the level of 10^{-11} (probably beyond the reach of BESIII)
- $Br(t \to c\tau^+\tau^-)$ at the level of 10^{-5} (close to the limiting sensitivity of the LHC)

$D^0 - \bar{D}^0$ and $K^0 - \bar{K}^0$ oscillations

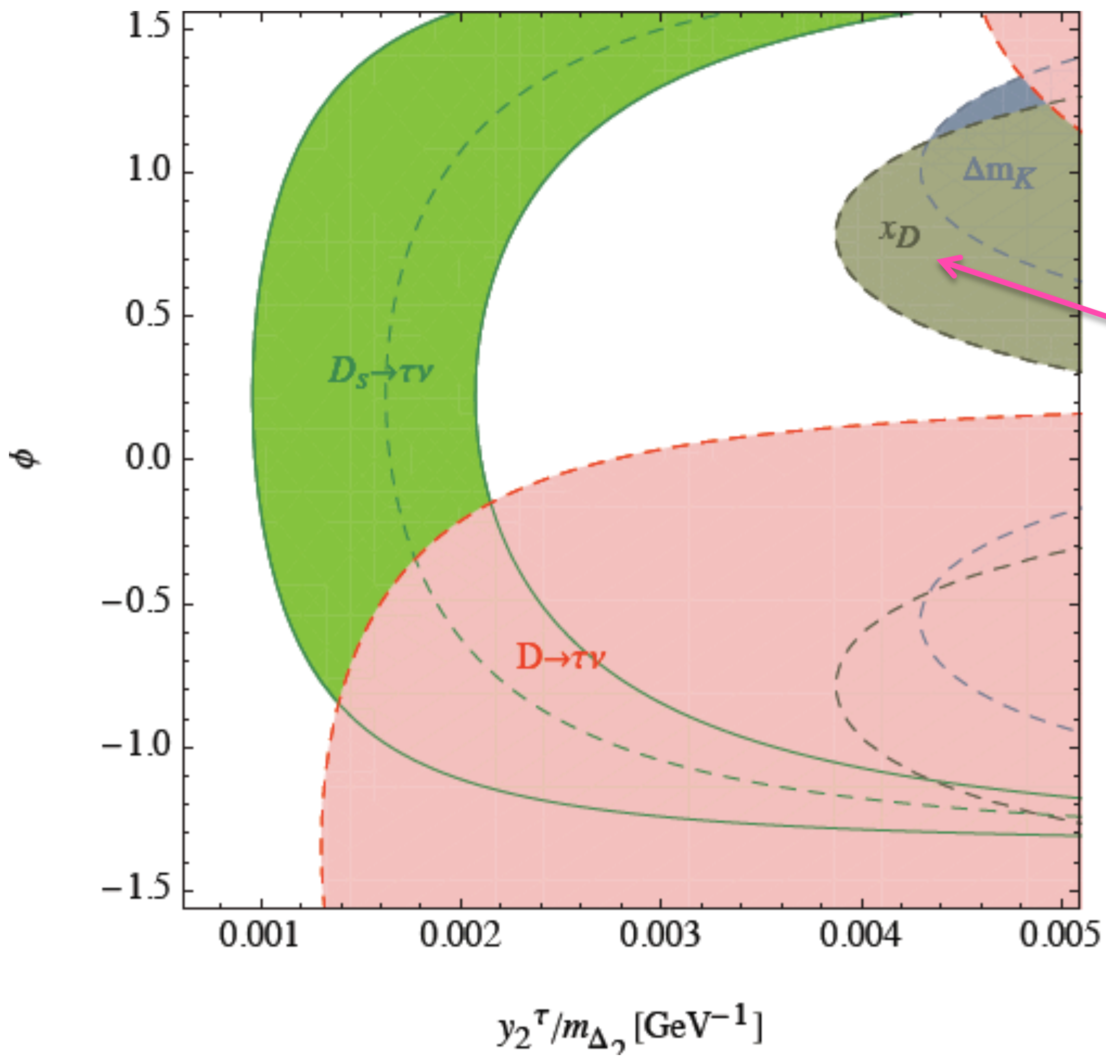
Doublet leptoquarks

$$\mathcal{M}(D^0 \leftrightarrow \bar{D}^0) = \frac{1}{8\pi^2 m_{\Delta_2}^2}\{\Sigma_{l=\mu,\tau}(Y_{2L}^{cl}Y_{2L}^{ul*})^2(\bar{c}u)_{V-A}(\bar{c}u)_{V-A} + (Y_{2R}^{cl}Y_{2R}^{ul*})^2(\bar{c}u)_{V+A}(\bar{c}u)_{V+A})\}$$



$$\mathcal{M}(K^0 \leftrightarrow \bar{K}^0) = \frac{1}{8\pi^2 m_{\Delta_2}^2}\{\Sigma_{l=\mu,\tau}(\tilde{Y}_{2L}^{dl}\tilde{Y}_{2L}^{sl*})^2(\bar{s}d)_{V-A}(\bar{s}d)_{V-A}\}$$

$$Y_{2L}^{cl}Y_{2L}^{ul*} = (cos\theta_c\tilde{Y}_{2L}^{sl} - sin\theta_c\tilde{Y}_{2L}^{dl})(cos\theta_c\tilde{Y}_{2L}^{dl*} + sin\theta_c\tilde{Y}_{2L}^{sl*}).$$



Loop processes are not relevant for the bounds coming from the tree level diagrams!