# Low energy phenomenology and search for leptoquarks at LHC

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QCD@work 2014, 16-19 June 2014, Giovinazzo (Bari –Italy)

# Outline

- Motivation;
- Colored scalar leptoquarks (3,2,7/6);
- Low-energy constraints "minimal model" and its extension for $b \to s\gamma$ ;
- Leptoquarks and GUT;
- Colored scalars at LHC;
- Summary.

Based on I.Doršner, S.F., N.Košnik, I. Nisandžić, JHEP 1311 (2013) 084
S.F. J.F. Kamenik and Nisandžić Phys.Rev. D85 (2012) 094025
I.Doršner, S.F., N.Košnik, Phys.Rev. D86 (2012) 015013;
I.Doršner, S.F and A. Greljo, 1406.xxxx;
I.Doršner, S. F., N.Košnik, in preparation.

# Motivation

- Scalar LQ might explain small deviation: experiment $\leftrightarrow$ SM prediction;

$$\left\{\begin{array}{l} B \to D^{(*)}\tau\nu_\tau \\ B \to K^* l^+ l^- \\ Z \to b\bar{b} \\ (g-2)_\mu \end{array}\right.$$

- LQ's are present in GUT theories;
- Scalar LQ might modify mass matrices;
- LQ intensive searches at LHC.

LHC assumption: one LQ decays into one quark and one lepton of the same generations:

# ATLAS Exotics Searches* - 95% CL Exclusion

Status: April 2014

**ATLAS** Preliminary

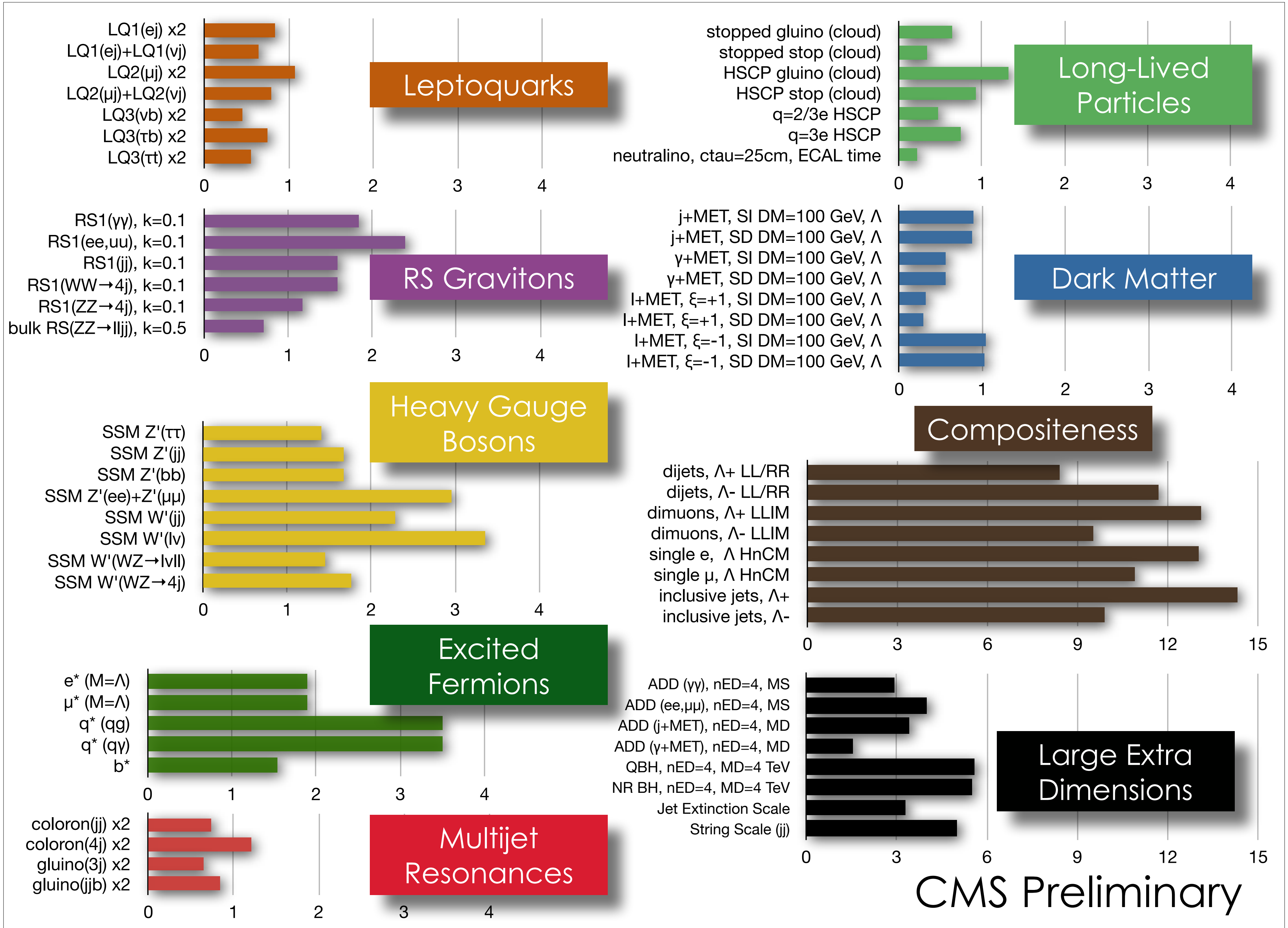
$\int \mathcal{L}\,dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

| | Model | $\ell, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Extra dimensions | ADD $G_{KK} + g/q$ | – | 1-2 j | Yes | 4.7 | $M_D$ 4.37 TeV | $n = 2$ | 1210.4491 |
| | ADD non-resonant $\ell\ell/\gamma\gamma$ | $2\gamma$ or $2e, \mu$ | – | – | 4.7 | $M_S$ 4.18 TeV | $n = 3$ HLZ NLO | 1211.1150 |
| | ADD QBH $\to \ell q$ | $1\ e, \mu$ | 1 j | – | 20.3 | $M_{th}$ 5.2 TeV | $n = 6$ | 1311.2006 |
| | ADD BH high $N_{trk}$ | $2\ \mu$ (SS) | – | – | 20.3 | $M_{th}$ 5.7 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | 1308.4075 |
| | ADD BH high $\sum p_T$ | $\geq 1\ e, \mu$ | $\geq 2$ j | – | 20.3 | $M_{th}$ 6.2 TeV | $n = 6$, $M_D = 1.5$ TeV, non-rot BH | ATLAS-CONF-2014-016 |
| | RS1 $G_{KK} \to \ell\ell$ | $2\ e, \mu$ | – | – | 20.3 | $G_{KK}$ mass 2.47 TeV | $k/\overline{M}_{Pl} = 0.1$ | ATLAS-CONF-2013-017 |
| | RS1 $G_{KK} \to ZZ \to \ell\ell qq/\ell\ell\ell\ell$ | 2 or 4 $e, \mu$ | 2 j or – | – | 1.0 | $G_{KK}$ mass 845 GeV | $k/\overline{M}_{Pl} = 0.1$ | 1203.0718 |
| | RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$ | $2\ e, \mu$ | – | Yes | 4.7 | $G_{KK}$ mass 1.23 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1208.2880 |
| | Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$ | – | 4 b | – | 19.5 | $G_{KK}$ mass 590-710 GeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2014-005 |
| | Bulk RS $g_{KK} \to t\bar{t}$ | $1\ e, \mu$ | $\geq 1$ b, $\geq 1$J/2j | Yes | 14.3 | $g_{KK}$ mass 0.5-2.0 TeV | BR = 0.925 | ATLAS-CONF-2013-052 |
| | $S^1/Z_2$ ED | $2\ e, \mu$ | – | – | 5.0 | $M_{KK} \approx R^{-1}$ 4.71 TeV | | 1209.2535 |
| | UED | $2\ \gamma$ | – | Yes | 4.8 | Compact. scale $R^{-1}$ 1.41 TeV | | ATLAS-CONF-2012-072 |
| Gauge bosons | SSM $Z' \to \ell\ell$ | $2\ e, \mu$ | – | – | 20.3 | $Z'$ mass 2.86 TeV | | ATLAS-CONF-2013-017 |
| | SSM $Z' \to \tau\tau$ | $2\ \tau$ | – | – | 19.5 | $Z'$ mass 1.9 TeV | | ATLAS-CONF-2013-066 |
| | SSM $W' \to \ell\nu$ | $1\ e, \mu$ | – | Yes | 20.3 | $W'$ mass 3.28 TeV | | ATLAS-CONF-2014-017 |
| | EGM $W' \to WZ \to \ell\nu\,\ell'\ell'$ | $3\ e, \mu$ | – | Yes | 20.3 | $W'$ mass 1.52 TeV | | ATLAS-CONF-2014-015 |
| | LRSM $W'_R \to t\bar{b}$ | $1\ e, \mu$ | 2 b, 0-1 j | Yes | 14.3 | $W'$ mass 1.84 TeV | | ATLAS-CONF-2013-050 |
| CI | CI $qqqq$ | – | 2 j | – | 4.8 | $\Lambda$ 7.6 TeV | $\eta = +1$ | 1210.1718 |
| | CI $qq\ell\ell$ | $2\ e, \mu$ | – | – | 5.0 | $\Lambda$ 13.9 TeV | $\eta_{LL} = -1$ | 1211.1150 |
| | CI $uutt$ | $2\ e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | $\Lambda$ 3.3 TeV | $\lvert C\rvert = 1$ | ATLAS-CONF-2013-051 |
| DM | EFT D5 operator | – | 1-2 j | Yes | 10.5 | $M_*$ 731 GeV | at 90% CL for $m(\chi) < 80$ GeV | ATLAS-CONF-2012-147 |
| | EFT D9 operator | – | 1 J, $\leq 1$ j | Yes | 20.3 | $M_*$ 2.4 TeV | at 90% CL for $m(\chi) < 100$ GeV | 1309.4017 |
| LQ | Scalar LQ $1^{st}$ gen | $2\ e$ | $\geq 2$ j | – | 1.0 | LQ mass 660 GeV | $\beta = 1$ | 1112.4828 |
| | Scalar LQ $2^{nd}$ gen | $2\ \mu$ | $\geq 2$ j | – | 1.0 | LQ mass 685 GeV | $\beta = 1$ | 1203.3172 |
| | Scalar LQ $3^{rd}$ gen | $1\ e, \mu, 1\ \tau$ | 1 b, 1 j | – | 4.7 | LQ mass 534 GeV | $\beta = 1$ | 1303.0526 |
| Heavy quarks | Vector-like quark $TT \to Ht + X$ | $1\ e, \mu$ | $\geq 2$ b, $\geq 4$ j | Yes | 14.3 | T mass 790 GeV | T in (T,B) doublet | ATLAS-CONF-2013-018 |
| | Vector-like quark $TT \to Wb + X$ | $1\ e, \mu$ | $\geq 1$ b, $\geq 3$ j | Yes | 14.3 | T mass 670 GeV | isospin singlet | ATLAS-CONF-2013-060 |
| | Vector-like quark $BB \to Zb + X$ | $2\ e, \mu$ | $\geq 2$ b | – | 14.3 | B mass 725 GeV | B in (B,Y) doublet | ATLAS-CONF-2013-056 |
| | Vector-like quark $BB \to Wt + X$ | $2\ e, \mu$ (SS) | $\geq 1$ b, $\geq 1$ j | Yes | 14.3 | B mass 720 GeV | B in (T,B) doublet | ATLAS-CONF-2013-051 |
| Excited fermions | Excited quark $q^* \to q\gamma$ | $1\ \gamma$ | 1 j | – | 20.3 | $q^*$ mass 3.5 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | 1309.3230 |
| | Excited quark $q^* \to qg$ | – | 2 j | – | 13.0 | $q^*$ mass 3.84 TeV | only $u^*$ and $d^*$, $\Lambda = m(q^*)$ | ATLAS-CONF-2012-148 |
| | Excited quark $b^* \to Wt$ | 1 or 2 $e, \mu$ | 1 b, 2 j or 1 j | Yes | 4.7 | $b^*$ mass 870 GeV | left-handed coupling | 1301.1583 |
| | Excited lepton $\ell^* \to \ell\gamma$ | $2\ e, \mu, 1\ \gamma$ | – | – | 13.0 | $\ell^*$ mass 2.2 TeV | $\Lambda = 2.2$ TeV | 1308.1364 |
| Other | LRSM Majorana $\nu$ | $2\ e, \mu$ | 2 j | – | 2.1 | $N^0$ mass 1.5 TeV | $m(W_R) = 2$ TeV, no mixing | 1203.5420 |
| | Type III Seesaw | $2\ e, \mu$ | – | – | 5.8 | $N^{\pm}$ mass 245 GeV | $\lvert V_e\rvert$=0.055, $\lvert V_\mu\rvert$=0.063, $\lvert V_\tau\rvert$=0 | ATLAS-CONF-2013-019 |
| | Higgs triplet $H^{\pm\pm} \to \ell\ell$ | $2\ e, \mu$ (SS) | – | – | 4.7 | $H^{\pm\pm}$ mass 409 GeV | DY production, BR($H^{\pm\pm} \to \ell\ell$)=1 | 1210.5070 |
| | Multi-charged particles | – | – | – | 4.4 | multi-charged particle mass 490 GeV | DY production, $\lvert q\rvert = 4e$ | 1301.5272 |
| | Magnetic monopoles | – | – | – | 2.0 | monopole mass 862 GeV | DY production, $\lvert g\rvert = 1g_D$ | 1207.6411 |

$\sqrt{s} = 7$ TeV  $\sqrt{s} = 8$ TeV

Mass scale [TeV] ($10^{-1}$, 1, 10)

*Only a selection of the available mass limits on new states or phenomena is shown.




CMS Exotica Physics Group Summary – March, 2014

## Color triplet candidates

| $(SU(3), SU(2))_Y$ | spin | LQ couplings | $3B$ | $L$ | |
|---|---|---|---|---|---|
| $(3,2)_{1/6}$ | 0 | $\overline{Q}\nu_R,\ \overline{d}_R L$ | $+1$ | $-1$ | ✓ |
| $(3,2)_{7/6}$ | 0 | $\overline{Q}\ell_R,\ \overline{u}_R L$ | $+1$ | $-1$ | ✓ |
| $(3,1)_{-1/3}$ | 0 | $\overline{Q}i\tau^2 L^C,\ \overline{d}_R\nu_R^C,\ \overline{u}_R\ell_R^C$ | | | might destabilize proton ID, SF, NK 1204.0674 |
| $(3,3)_{-1/3}$ | 0 | $\overline{Q}\tau^i i\tau^2 L^C$ | | | |
| $(3,1)_{2/3}$ | 1 | $\overline{u}_R\gamma_\mu\nu_R,\ \overline{Q}\gamma^\mu L$ | $+1$ | $-1$ | we do not consider these states |
| $(3,3)_{2/3}$ | 1 | $\overline{Q}\tau^i\gamma^\mu L$ | $+1$ | $-1$ | |
| $(3,2)_{1/6}$ | 1 | $\overline{u}_R\gamma_\mu i\tau^2 L^C,\ \overline{Q}\gamma_\mu\nu_R^C$ | $+1$ | $-1$ | |
| $(\overline{3},2)_{5/6}$ | 1 | $\overline{Q}\gamma^\mu\ell_R^C,\ \overline{d}_R i\tau^2\gamma_\mu L^C$ | $+1$ | $-1$ | |

$Q = I_3 + Y$

$(3,2)_{7/6}$ and $(3,2)_{1/6}$ proper candidates among scalar LQ

# Experiment – Theory in B → D(D*) $\tau\nu_\tau$

In ratios there is no dependence on CKM matrix elements:

$$\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\ell\nu)} = 0.332 \pm 0.030$$

$$\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D\tau\nu)}{\mathcal{B}(B\to D\ell\nu)} = 0.440 \pm 0.072$$

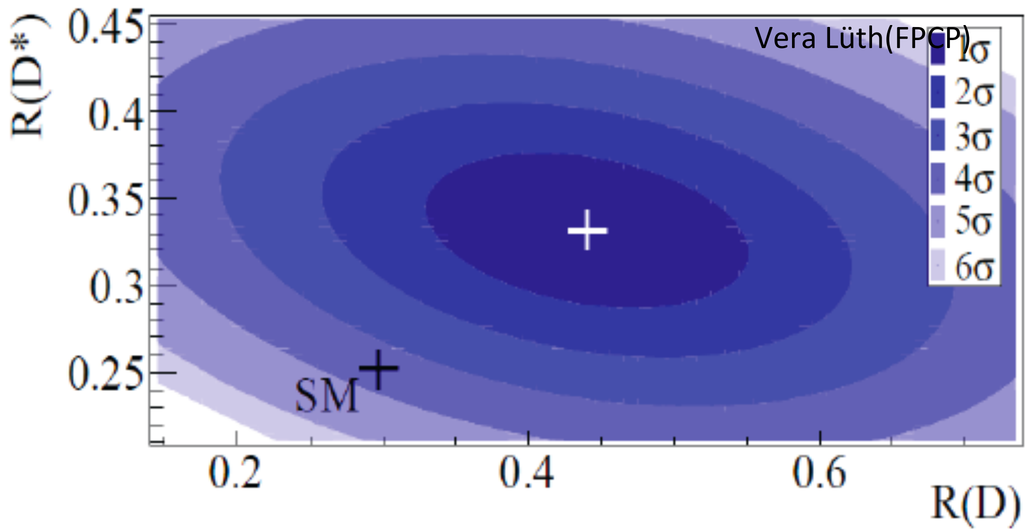
BaBar: 1205.5442
Belle: 0706.4429

combined 3.4σ
larger than SM

Standard Model

$$\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 0.252(3)$$

$$\mathcal{R}^{\mathrm{SM}}_{\tau/\ell} = 0.296(16)$$



## Standard Model or New Physics?

Can observed effects be explained within SM?

New form-factors show up in $B \to D^{(*)} \tau \nu_\tau$

How well do we know all form-factors?

Lattice improvements?

Lepton flavor universality violation in B semileptonic decays?

S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872

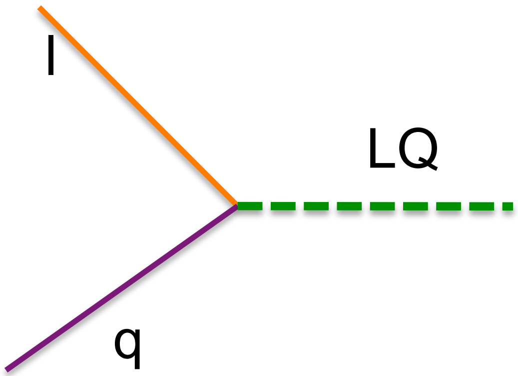
Many proposals of NP:

P. Ko et al.,1212.4607;
A.Celis et al, 1210.8443;
D. Becirevic et al. 1206.4977;
A. Crivelin et al., 1206.2634;
P. Biancofiore et al.,1302.1042,
…

P. Ko et al.,1212.4607;
A.Celis et al, 1210.8443;
D. Becirevic et al. 1206.4977;
A. Crivelin et al., 1206.2634;
P. Biancofiore et al.,1302.1042,
…

One more proposal of NP:

**Leptoquark contribution in $b \to c\tau\nu_\tau$**




Scalar and vector leptoquark that trigger b-> c l υ,
I. Dorsner, S.F., N. Kosnik, 1306.6493

Color triplet bosons (scalars or vectors) with renormalizable couplings to the SM fermions

Charge $\begin{cases} |Q| = 2/3 \\ |Q| = 1/3 \end{cases}$

If LQ is a weak doublet then left down-quark fields "communicate" with up-quark fields through the CKM matrix (the same for leptons – PMNS matrix)

Interactions of Δ = (3,2,7/6) state

$$\boxed{\mathcal{L} = \bar{\ell}_R\, Y\, \Delta^\dagger Q + \bar{u}_R\, Z\, \tilde{\Delta}^\dagger L + \text{H.c.}}$$

$$\Delta = \begin{cases} \Delta^{(2/3)} \\ \Delta^{(5/3)} \end{cases}$$

$$\tilde{\Delta} = i\tau_2 \Delta^*$$

Fields are in the weak base. We use a basis in which all rotations are assigned to neutrinos and up-like quarks.
Transition to a mass base:

$$\mathcal{L}^{(2/3)} = (\bar{\ell}_R Y d_L)\, \Delta^{(2/3)*} + (\bar{u}_R [Z V_{\text{PMNS}}] \nu_L)\, \Delta^{(2/3)} + \text{H.c.}$$
$$\mathcal{L}^{(5/3)} = (\bar{\ell}_R [Y V^\dagger_{\text{CKM}}] u_L)\, \Delta^{(5/3)*} - (\bar{u}_R Z \ell_L)\, \Delta^{(5/3)} + \text{H.c.}\,.$$

Requirements:

- to explain deviation of SM prediction in $b \to c\tau\nu_\tau$,
- no contributions in $b \to cl\nu_l,\ \ l = e,\ \ \mu$

We impose: b couples to τ only and c quark to neutrinos

$\Delta^{(2/3)}$ couplings

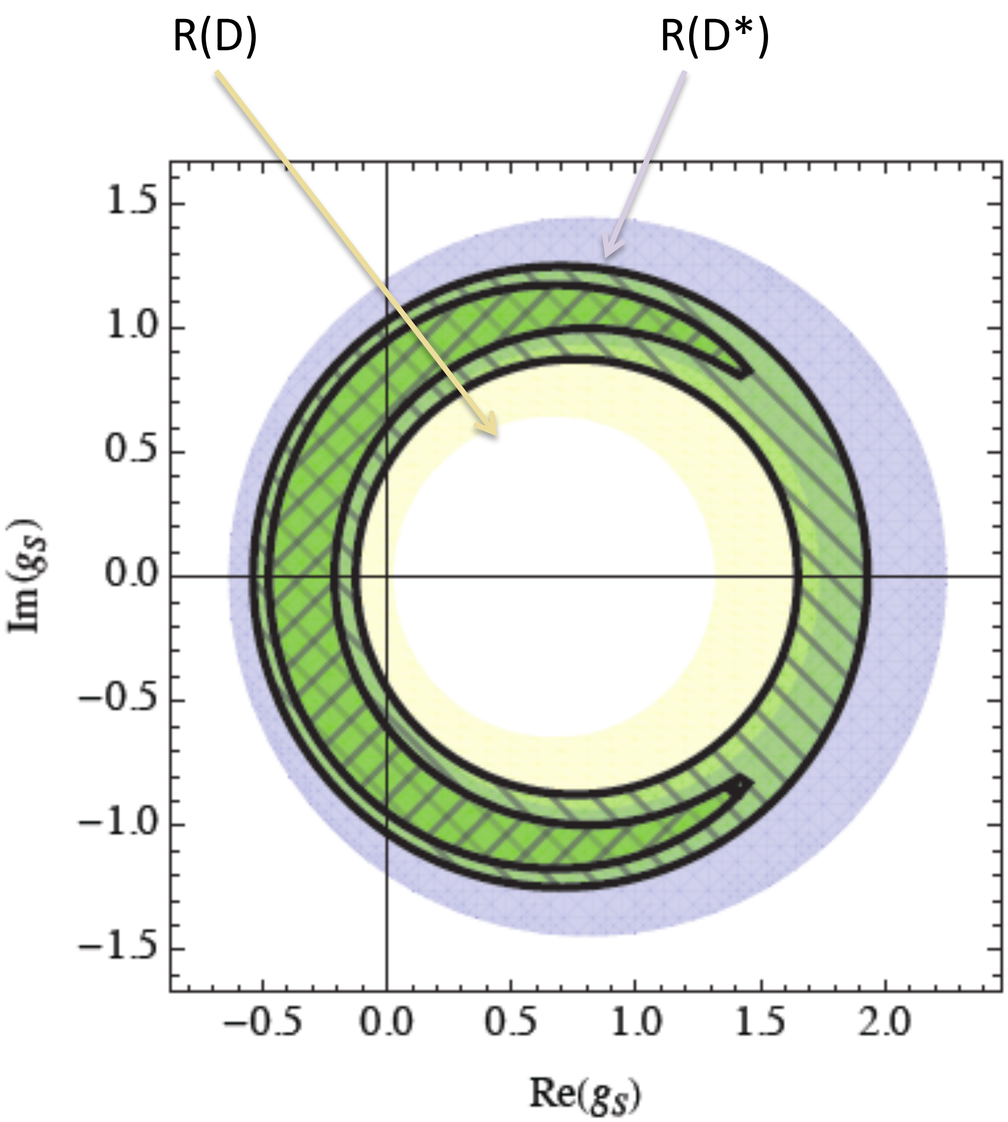
$$\mathcal{L}^{(2/3)} = (\bar{\ell}_R Y d_L)\,\Delta^{(2/3)*} + (\bar{u}_R [Z V_{\rm PMNS}] \nu_L)\,\Delta^{(2/3)} + \text{H.c.}$$

$$Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{33} \end{pmatrix}, \qquad Z V_{\rm PMNS} = \begin{pmatrix} 0 & 0 & 0 \\ z_{21} & z_{22} & z_{23} \\ 0 & 0 & 0 \end{pmatrix}$$

$\Delta^{(5/3)}$ couplings

$$\mathcal{L}^{(5/3)} = (\bar{\ell}_R [Y V_{\rm CKM}^\dagger] u_L)\,\Delta^{(5/3)*} - (\bar{u}_R Z \ell_L)\,\Delta^{(5/3)} + \text{H.c.}$$

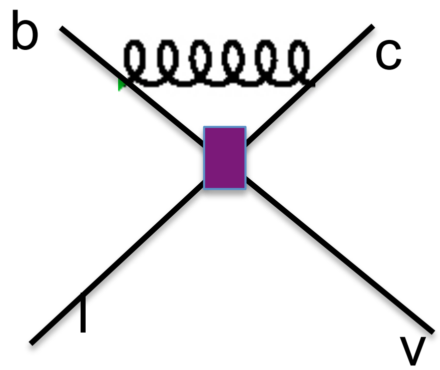
$$Y V_{\rm CKM}^\dagger = y_{33} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix}, \qquad Z = \begin{pmatrix} 0 & 0 & 0 \\ \tilde{z}_{21} & \tilde{z}_{22} & \tilde{z}_{23} \\ 0 & 0 & 0 \end{pmatrix}$$




1σ range

$$g_S(m_b) = -0.37^{+0.10}_{-0.07}$$

$$m_b, m_c << v$$




scalar and tensor  operators have anomalous dimension contrary to  V and A  currents

$$g_T(m_b) \simeq 0.14\, g_S(m_b)$$

Effective hamiltonian for $b \to c\tau\nu_\tau$ transition induced by LQ transition

$$\boxed{\mathcal{H}^{(2/3)} = \frac{y_{33} z_{2i}}{2m_\Delta^2}\left[(\bar{\tau}_R \nu_{iL})(\bar{c}_R b_L) + \frac{1}{4}(\bar{\tau}_R \sigma^{\mu\nu} \nu_{iL})(\bar{c}_R \sigma_{\mu\nu} b_L)\right]}$$

(Fierz's transformation are used)

SM + NP operators

$$\boxed{\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(\bar{\tau}_L \gamma^\mu \nu_L)(\bar{c}_L \gamma_\mu b_L) + g_S(\bar{\tau}_R \nu_L)(\bar{c}_R b_L) + g_T(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)(\bar{c}_R \sigma_{\mu\nu} b_L)\right]}$$

$$g_S(m_\Delta) = 4g_T(m_\Delta) \equiv \frac{1}{4}\frac{y_{33} z_{23}}{2m_\Delta^2}\frac{\sqrt{2}}{G_F V_{cb}}$$

this relation holds on the mass scale of Δ

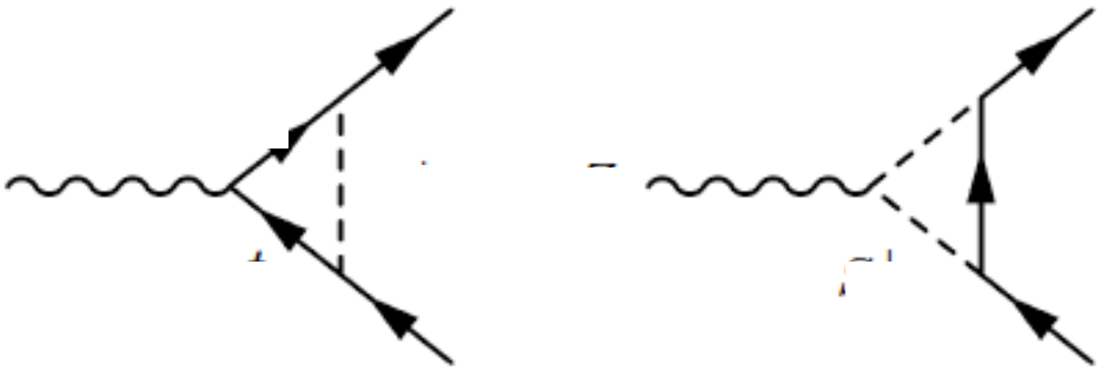
The model is constrained by:

$Z \to b\bar{b}$ ( $\tau$ in the loop)

$(g-2)_\mu$ (c –quark in the loop)

$\tau \to \mu\gamma$

$\mu \to e\gamma$



$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$

$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$

$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-9}$

MEG experiment result on muon BR for LFV decay is much strongert hen for bound on tau LFV decay rate . The μ liftime and the strong bound on LFV $\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ compensate for a helicity suppression.

## Lepton electromagnetic current

$$-\,ie\,\bar{u}_\ell(p+q)\gamma^\mu u_\ell(p)$$

$$\boxed{-ie\,\bar{u}_\ell(p+q)\left[F_E(q^2)\gamma^\mu + \frac{F_M^\ell(q^2)}{2m_\ell} i\sigma^{\mu\nu}q_\nu + F_d^\ell(q^2)\,\sigma^{\mu\nu}q_\nu\gamma_5\right]u_\ell(p)}$$

## Muon anomalous magnetic moment

$\Delta^{(5/3)}$ enters loop functions
charm quark in the loop

$$\delta a_\mu \equiv F_M^\mu(q^2=0) = -\frac{N_c|\tilde{z}_{22}|^2 m_\mu^2}{16\pi^2 m_\Delta^2}\left[Q_c F_q(x) + Q_\Delta F_\Delta(x)\right]$$

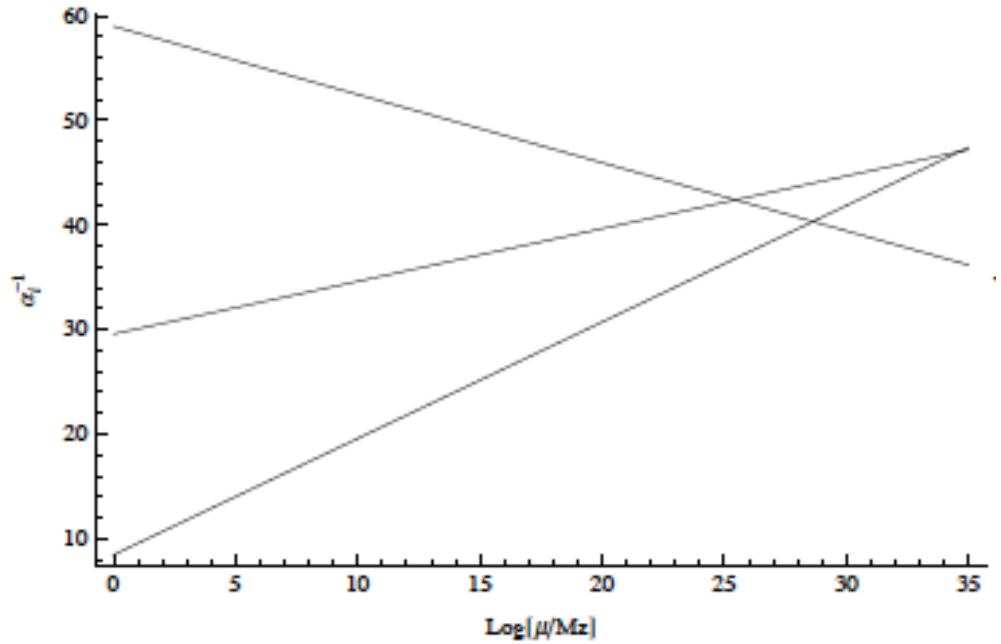
Is our low-energy Yukawa ansatz compatible with the idea of GUT?

GUT models contain such a state in  an extended SU(5), SO(10).

Georgi-Glashow (1974) proposed $SU(5) \longrightarrow SU(3) \times SU(2) \times U(1)$

Two problems:

- Minimal SU(5) GUT fails!
- $M_E \approx M_D$ at GUT scale



Our assumption: $(3,2)_{7/6}$ in 45 of SU(5)

- without 45: $M_E \approx M_D$ at GUT scale
- with 45 : $M_E = \approx -3\, M_D$ at GUT scale

Representation 45 with its vev modifies mass relation for down-like quarks and charged leptons

$$2M_D^{\rm diag} D_R^T = -2Y_1 v_{45} - Y_3 v_5$$

$$2E_R M_E^{\rm diag} = 6Y_1 v_{45} - Y_3 v_5$$

We assume that $D_R$, $U_R$, $E_R$ are real!

$$\boxed{M_D^{\rm diag} D_R^T - E_R M_E^{\rm diag} = 4U_R Z v_{45}}$$

this equation should be satisfied at GUT scale!

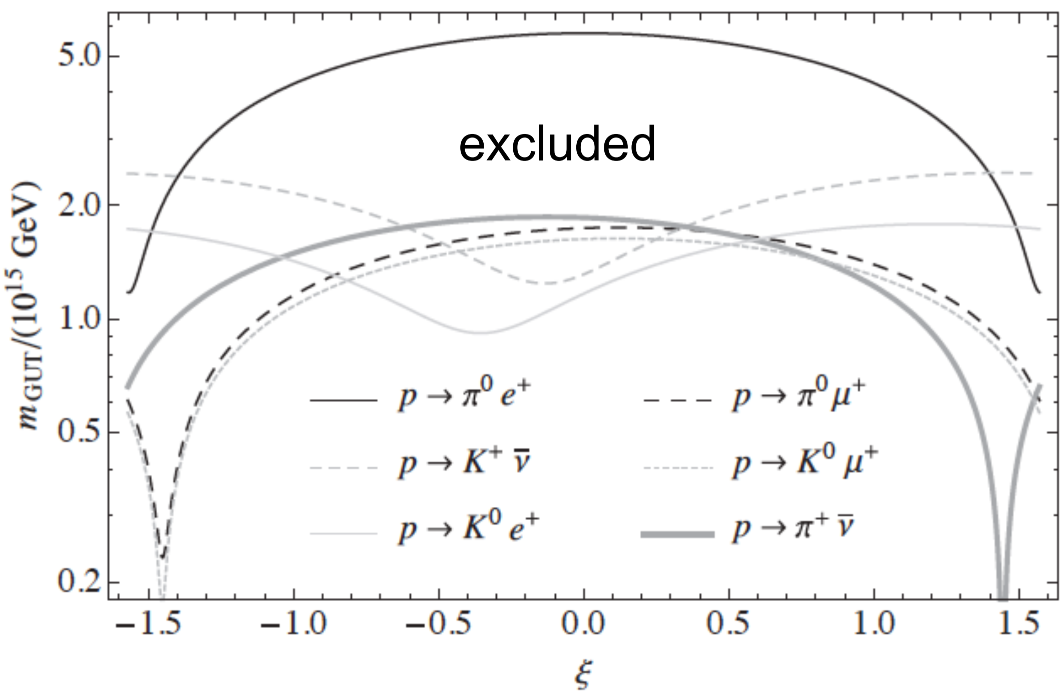
11 parameters and 9 equations  only parameter ξ can not be fixed!

$$\boxed{\tilde{z}_{21} : \tilde{z}_{22} : \tilde{z}_{23} = 0.024 : 0.32 : 1}$$

Proton decay amplitude depends on one parameter!

necessary to know:

- all unitary transformations in the charged fermion sector;
- masses of all proton mediated gauge bosons and
- a gauge coupling constant;



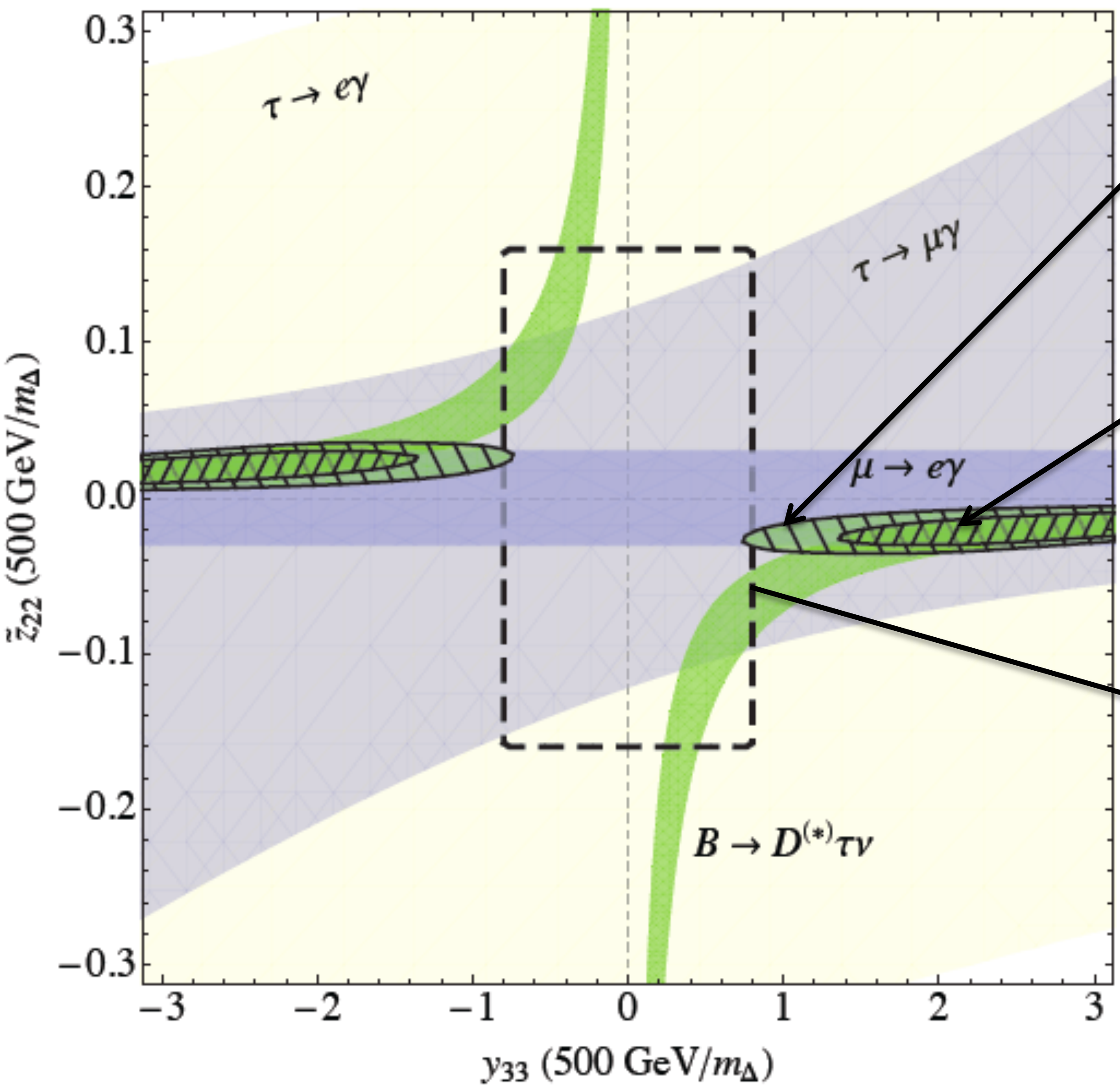

input

$$\tau_{p\to\pi^0 e^+} > 1.3 \times 10^{34}$$
$$\tau_{p\to K^+ \bar{\nu}^+} > 4.0 \times 10^{33}$$
$$\tau_{p\to K^0 e^+} > 1.0 \times 10^{33}$$
$$\tau_{p\to\pi^0 \mu^+} > 1.1 \times 10^{34}$$
$$\tau_{p\to K^0 \mu^+} > 1.6 \times 10^{33}$$
$$\tau_{p\to\pi^+ \bar{\nu}} > 1.1 \times 10^{34}$$

In our approach proton decay prediction depend on:

$$m_{GUT}, \ \alpha_{GUT}, \ \xi$$

In some part of parameter space $p \to \pi^0 e^+$ is suppressed in comparison with $p \to K^+ \bar{\nu}$, $p \to K^0 e^+$




2σ region allowed by existing data

1σ region allowed by existing data

couplings remain perturbative all the way to the GUT scale

2σ allowed region:

$$0.74 < |y_{33}| < 0.80$$

$$0.021 < |\tilde{z}_{22}| < 0.032$$

$$f_{\rm RGE}\, 5.0\, {\rm GeV} < v_{45} < f_{\rm RGE}\, 7.6\, {\rm GeV} \quad ( f_{\rm RGE} \in [1.1, 3.7] )$$

## Predictions

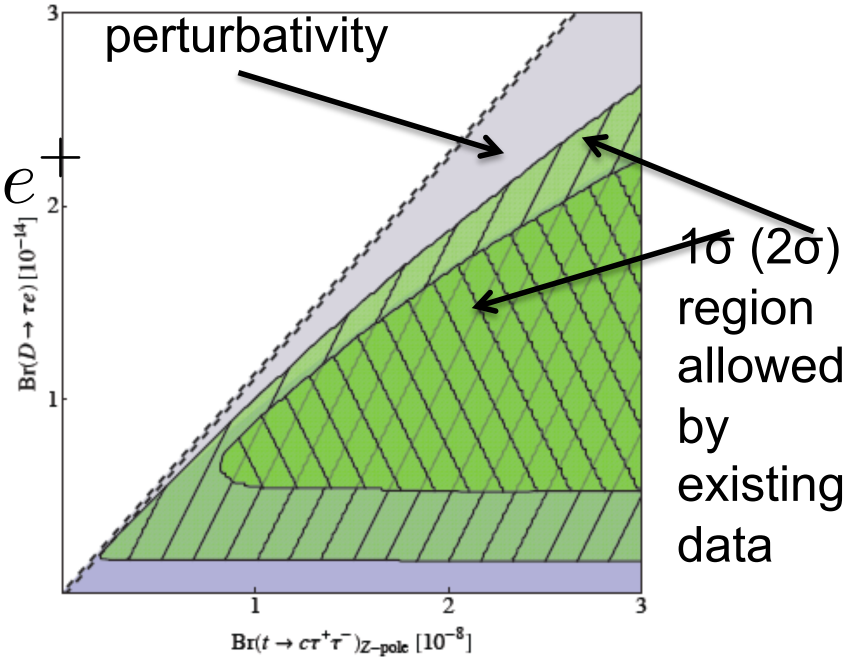
$$BR_{SM+LQ}(B_c \to \tau\nu_\tau) \simeq \begin{cases} 0.36 BR_{SM}(B_c \to \tau\nu_\tau) & g_S = -0.37 \\ 84 BR_{SM}(B_c \to \tau\nu_\tau) & g_s \simeq 1.8 \pm 0.4i \end{cases}$$

SM: $\mathcal{B}(B_c \to \tau\nu) = 0.0194(18)$

generate $t \to c\tau^+\tau^-$ & $\bar{D}^0 \to \tau^- e^+$

$$BR_{LQ}(t \to c\tau^+\tau^-) \sim 10^{-8}$$

$$BR_{LQ}(\bar{D}^0 \to \tau^- e^+) \sim 10^{-14}$$



Can this model be used to induce $b \to s\, l^+ l^-$ ?

$$\mathcal{L}^{(2/3)} = (\bar{\ell}_R Y d_L)\,\Delta^{(2/3)*} + (\bar{u}_R[Z V_{\mathrm{PMNS}}]\nu_L)\,\Delta^{(2/3)} + \mathrm{H.c.}\,,$$
$$\mathcal{L}^{(5/3)} = (\bar{\ell}_R[Y V_{\mathrm{CKM}}^\dagger]u_L)\,\Delta^{(5/3)*} - (\bar{u}_R Z \ell_L)\,\Delta^{(5/3)} + \mathrm{H.c.}\,.$$

N. Košnik, 1206.2970;
R. Mohanta 1310.0713

The presented model should be adjusted by introducing new couplings

New Y:

$$Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \boxed{\epsilon_{22} \quad \epsilon_{23}} \\ 0 & 0 & y_{33} \end{pmatrix} \qquad Y V_{\mathrm{CKM}}^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ V_{us}^* \epsilon_{22} & V_{cs}^* \epsilon_{22} & V_{tb}^* \epsilon_{23} \\ V_{ub}^* y_{33} & V_{cb}^* y_{33} & V_{tb}^* y_{33} \end{pmatrix}$$

Dominant contributions; others are suppressed by CKM

## SM and NP in $b \to s\mu^+\mu^-$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t\Big[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S}(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)) + C_T\mathcal{O}_T + C_{T5}\mathcal{O}_{T5}\Big],$$

$$\lambda_t = V_{tb}V_{ts}^*$$

$$\mathcal{O}_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell), \quad \mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\ell),$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell), \quad \mathcal{O}_T = \frac{e^2}{16\pi^2}(\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}\sigma_{\mu\nu}\ell),$$

$$\mathcal{O}_{T5} = \frac{e^2}{16\pi^2}(\bar{s}\sigma^{\mu\nu} b)(\bar{\ell}\sigma_{\mu\nu}\gamma_5\ell).$$

The (3,2,7/6) LQ contributes to effective hamiltonian for $b \to s\mu^+\mu^-$

$$\mathcal{H}_{\rm LQ} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^*(C_9^{\rm NP}O_9 + C_{10}^{\rm NP}O_{10})$$

$$C_9^{NP} = C_{10}^{NP} = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{\epsilon_{22}\epsilon_{23}^*}{m_\Delta^2}$$

can be constrained by

$$\left\{\begin{array}{l} B \to K^* l^+ l^- \\ B \to K\, l^+ l^- \\ B \to X_s l^+ l^- \\ B_s \to l^+ l^- \end{array}\right.$$

$$B_s \to \mu^+\mu^- \longrightarrow C_9^{NP}$$

$$B_s \to K\mu^+\mu^- \longrightarrow C_{10}^{NP}$$

$$B_s \to K^*\mu^+\mu^- \longrightarrow C_9^{NP} \quad C_{10}^{NP}$$

$$B_s \to X_s\mu^+\mu^- \longrightarrow C_9^{NP} \quad C_{10}^{NP}$$


N. Košnik, 1206.2970;
R. Mohanta 1310.0713;
I. Doršner, S.F. N. Košnik. in preparation.

Global fit of NP contributions (S. Decotes-Genot et al.,1307.5683)

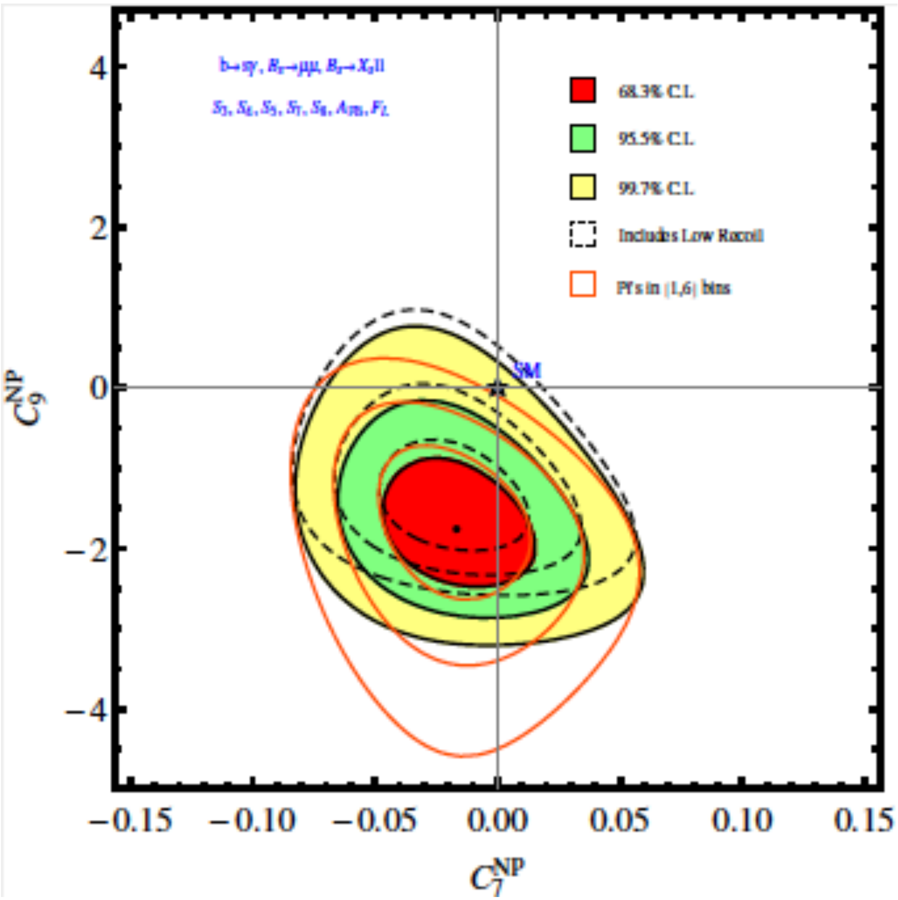
47 observables

$$BR(B \to X_s\gamma), \quad BR(B \to X_s\mu^+\mu^-)_{Low\ q^2}$$

$$BR(B_s \to \mu^+\mu^-), \quad A_I(B \to K^*\gamma), \quad S(B \to K^*\gamma)$$

$$B \to K^*\mu^+\mu^- :\ \langle P_1\rangle, \langle P_2\rangle, \langle P_4'\rangle, \langle P_5'\rangle, \langle P_6'\rangle, \langle P_8'\rangle, \langle A_{\rm FB}\rangle$$

| Coefficient | $1\,\sigma$ | $2\,\sigma$ | $3\,\sigma$ |
|---|---|---|---|
| $\mathcal{C}_7^{\rm NP}$ | $[-0.05, -0.01]$ | $[-0.06, 0.01]$ | $[-0.08, 0.03]$ |
| $\mathcal{C}_9^{\rm NP}$ | $[-1.6, -0.9]$ | $[-1.8, -0.6]$ | $[-2.1, -0.2]$ |
| $\mathcal{C}_{10}^{\rm NP}$ | $[-0.4, 1.0]$ | $[-1.2, 2.0]$ | $[-2.0, 3.0]$ |
| $\mathcal{C}_{7'}^{\rm NP}$ | $[-0.04, 0.02]$ | $[-0.09, 0.06]$ | $[-0.14, 0.10]$ |
| $\mathcal{C}_{9'}^{\rm NP}$ | $[-0.2, 0.8]$ | $[-0.8, 1.4]$ | $[-1.2, 1.8]$ |
| $\mathcal{C}_{10'}^{\rm NP}$ | $[-0.4, 0.4]$ | $[-1.0, 0.8]$ | $[-1.4, 1.2]$ |




Most likely modifications of SM Wilson coefficients;
confirmed also by Altmannshofer and Straub 1308.1501,
Beujean, Bobeth, van Dyk 1310.2478,
Horgan et al., 1310.3887

$$\boxed{B_s \to \mu^+\mu^-}$$

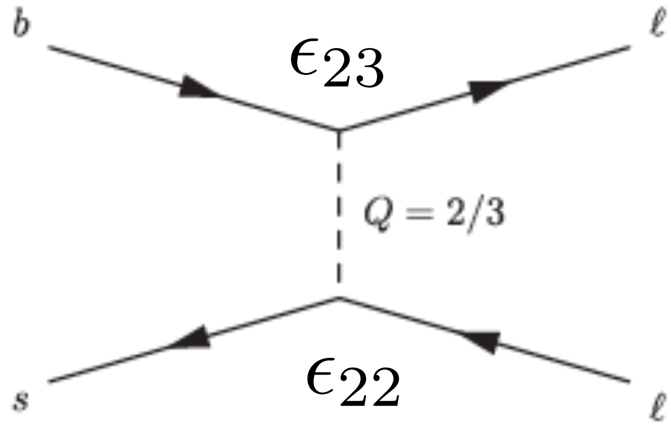
$$BR(B_s \to \mu^+\mu^-)_{LHCb} = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$
$$BR(B_s \to \mu^+\mu^-)_{CMS} = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

Experimental results 2013

$$BR(B_s \to \mu^+\mu^-)_{SM} = (3.23 \pm 0.23) \times 10^{-9}$$

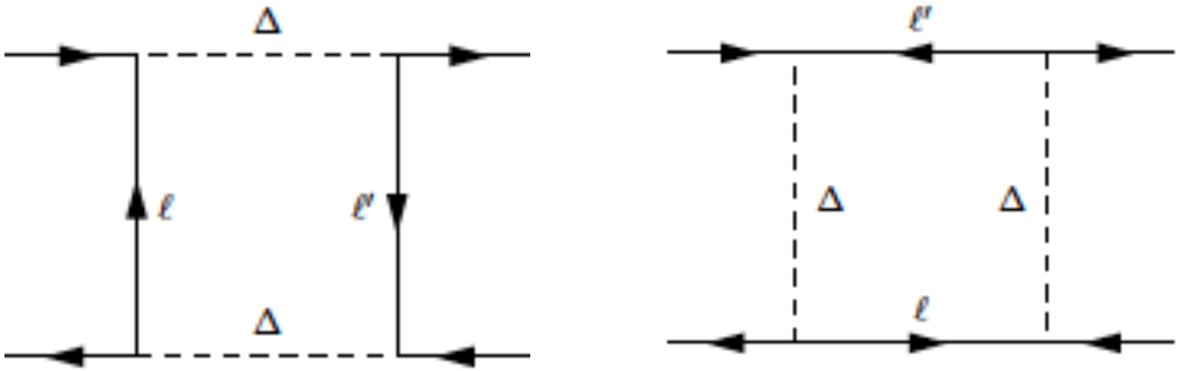
Buras et al, 1208.0934

$$\boxed{C_{10}^{SM} \to C_{10}^{SM} + C_{10}^{NP}}$$



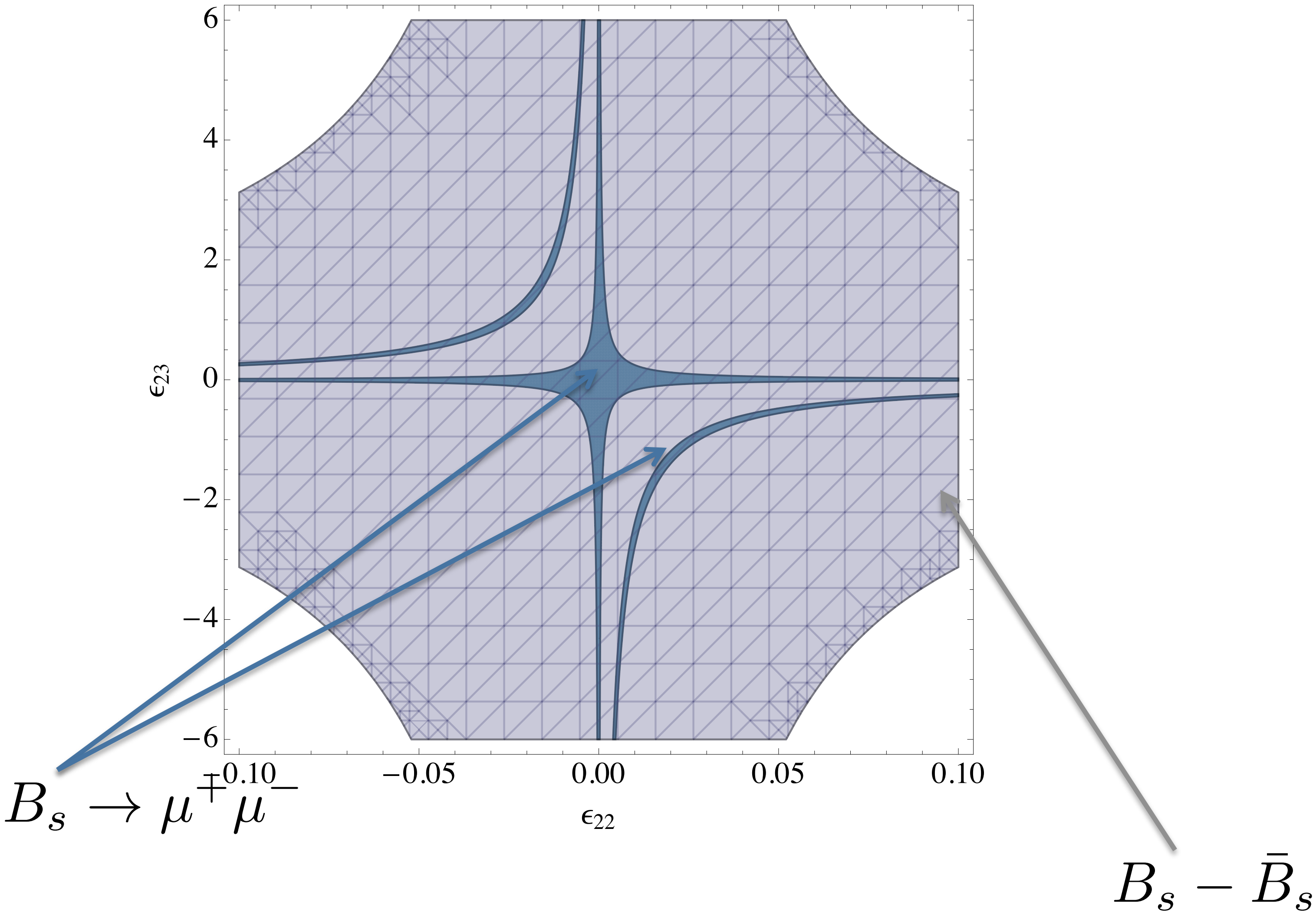

$$\boxed{C_{10}^{NP} \sim \frac{\epsilon_{22}\epsilon_{23}^*}{m_\Delta^2}}$$

The same coupling contribute at loop level to $\boxed{B_s - \bar{B}_s}$




$$\boxed{C_{box}^{SM} \to C_{box}^{SM} + C_{box}^{NP}}$$

$$\boxed{C_{box}^{NP} \sim \frac{\epsilon_{22}^{2}\epsilon_{23}^{*2}}{m_{\Delta}^{2}}}$$




BR($B_s \to \mu^+\mu^-$) most constraining!

## Constraints from charm physics: $D^0 \to \mu^+\mu^-$ and $D^0 - \bar{D}^0$

LHCb 2013: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$

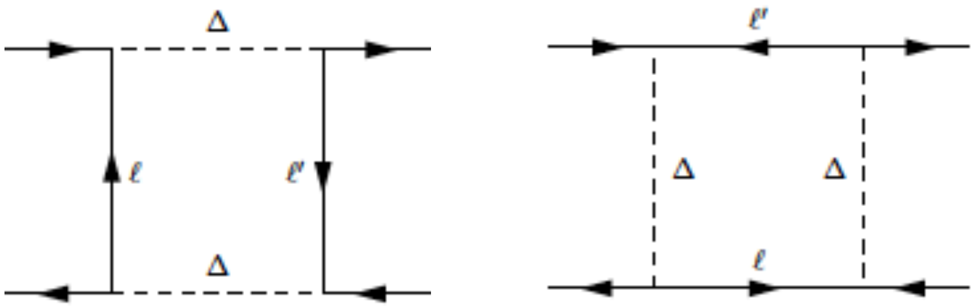
$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \tau_D \frac{f_D^2 m_D^5}{256\pi m_c^2} |V_{us}|^2 \left| \frac{\epsilon_{22}\tilde{z}_{22}}{m_\Delta^2} \right|^2$$

$$|\epsilon_{22}\tilde{z}_{22}| < 0.016 \frac{m_\Delta^2}{1\ \mathrm{TeV}^2}$$

Stronger constraints from LFV process $\mu \to e\gamma$

$\epsilon_{22}^2$ contributes too, but helicity suppressed contribution!

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




Couplings with $\Delta^{5/3}$

$$\bar{\tau} c \;:\; i(V_{cb}^* y_{33} P_L - \tilde{z}_{23}^* P_R)$$

$$\bar{\mu} c \;:\; i(V_{cs}^* \epsilon_{22} P_L - \tilde{z}_{22}^* P_R)$$

$$\bar{u} \tau \;:\; i V_{ub} y_{33}^* P_R$$

$$\bar{u} \mu \;:\; i V_{us} \epsilon_{22}^* P_R$$

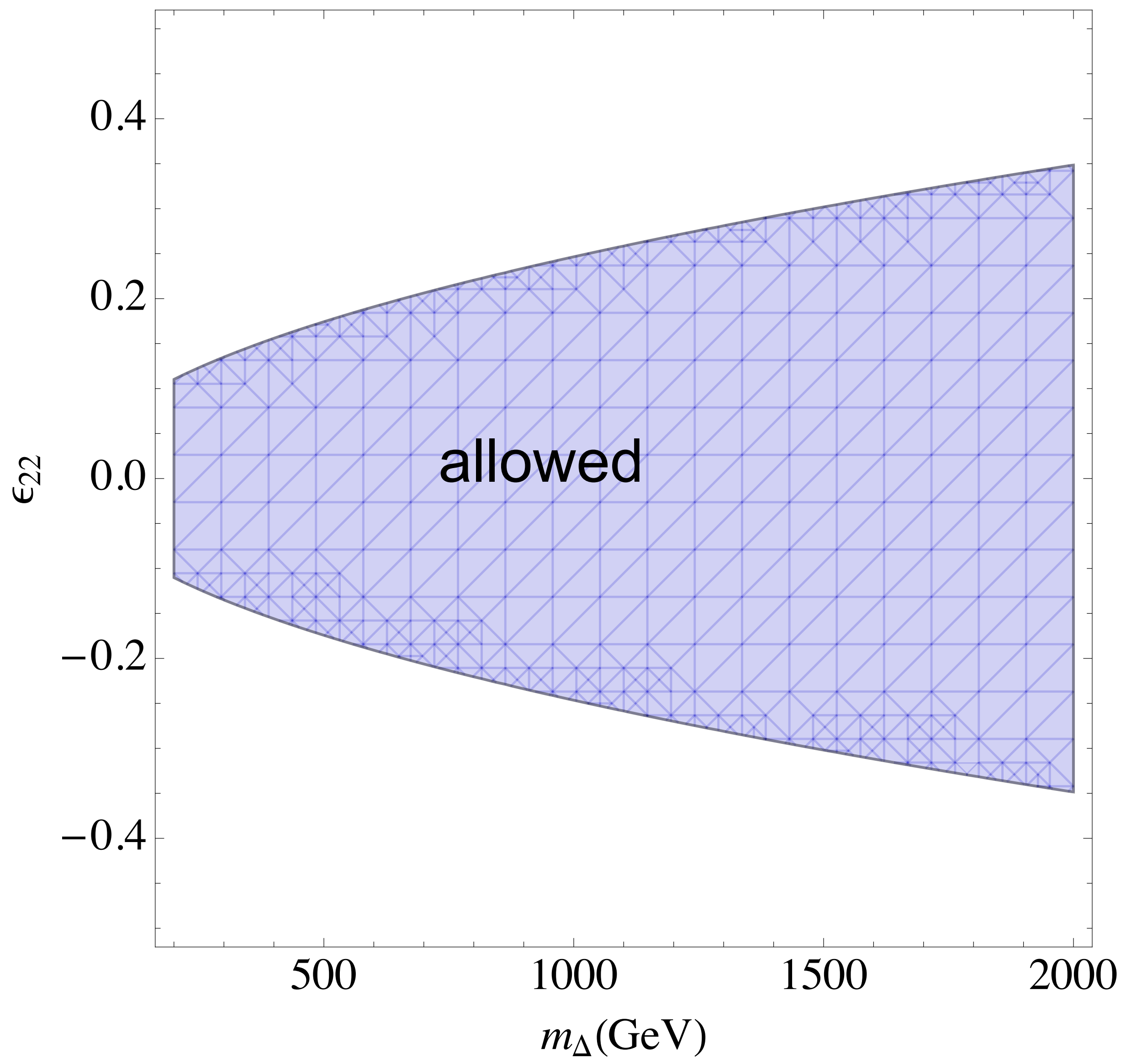
$$\mathcal{H}_{\Delta C=2} = (\bar{u}_\alpha \gamma^\mu P_L c_\alpha)(\bar{u}_\beta \gamma_\mu P_L c_\beta) \; [C_{\mu\mu} + C_{\tau\tau} + C_{\tau\mu}]$$

$$C_{\tau\tau} = \frac{(V_{ub} V_{cb}^*)^2 |y_{33}|^4}{128\pi^2 m_\Delta^2} \sim \lambda^{10} y_{33}^4 \,,$$

$$C_{\mu\mu} = \frac{(V_{us} V_{cs}^*)^2 |\epsilon_{22}|^4}{128\pi^2 m_\Delta^2} \sim \lambda^2 \epsilon_{22}^4 \,,$$

$$C_{\mu\tau} = \frac{V_{us} V_{ub} V_{cs}^* V_{cb}^* |\epsilon_{22}|^2 |y_{33}|^2}{64\pi^2 m_\Delta^2} \sim \lambda^6 \epsilon_{22}^2 y_{33}^2$$

Wolfenstein's parameter
λ =0.225




Based on UTFit 1402.1664

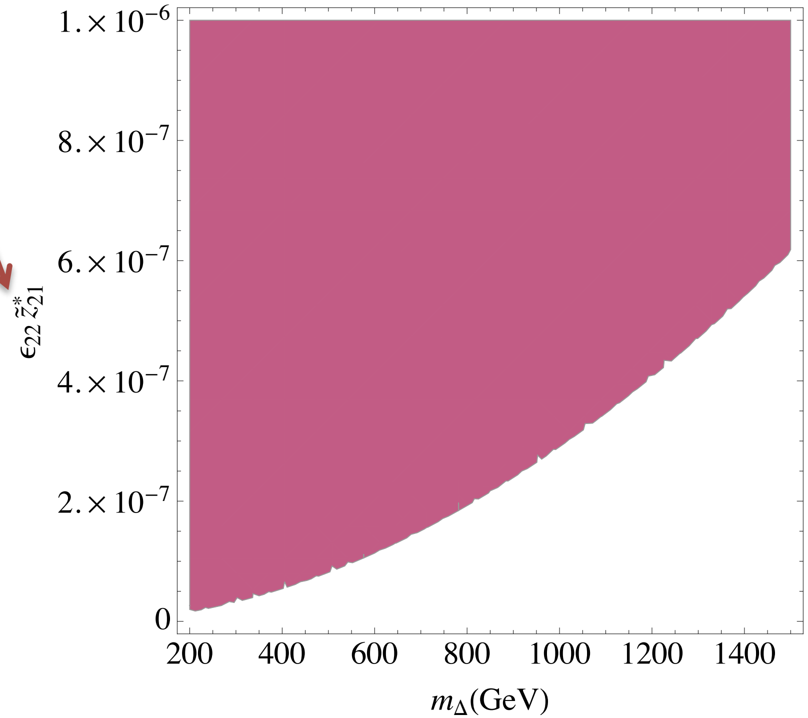
$$\mu \to e\gamma$$

$$\mathcal{A}_{\mu\to\ell\gamma} = \bar{e}(p')\sigma^{\mu\nu}\,\epsilon^*_\mu(q)q_\nu\,(AP_R + BP_L)\,\mu(p)$$

$$A = \frac{-N_c e}{48\pi^2 m_\Delta^2}\left[\boxed{m_c V_{cs}\epsilon_{22}\tilde{z}^*_{21}(1+4\log x_c)} + \frac{m_\mu}{2}\tilde{z}_{22}\tilde{z}^*_{21}(3+4x_c\log x_c)\right]$$

$$B \sim \mathcal{O}(m_e)\,.$$

If $\epsilon_{22}$ is constrained by charm data, then $\tilde{z}^*_{21}$ has to be very small!



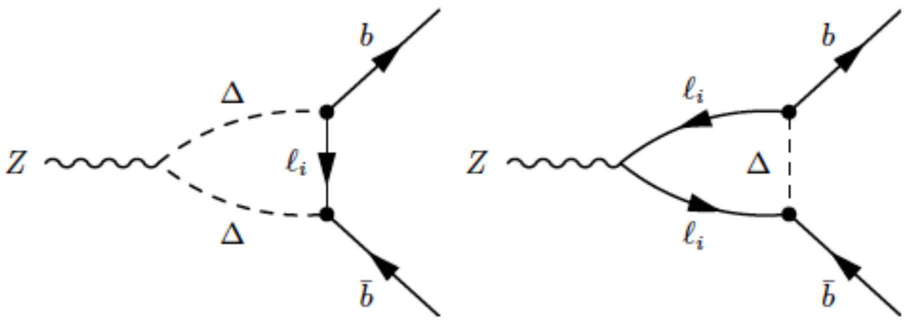
## Additional constraints

$Z \to b\bar{b}$

• is not affected due to -1/3 charge of quarks and 2/3 charge of the LQ;

$(g-2)_\mu$

• muon and tau in the loop –negligible modification of the $g_L$ coupling




**Is GUT possible with such extension?**

The small $\tilde{z}_{12} \sim 10^{-5}$ coupling implies vev of representation 45 $v_{45}$ to be large!

## Low energy constraints and searches for LQ at LHC

What do we achieve obtaining bounds from low energy phenomenology?

-If leptoquarks are relatively light (mass ~ 1 TeV) one might check if unification is possible within SU(5) and SO(10)!

- ATLAS and CMS search for LQ. Are these bounds relevant for their searches?

# Experimental searches for LQ

Tevatron (CDF, D0)

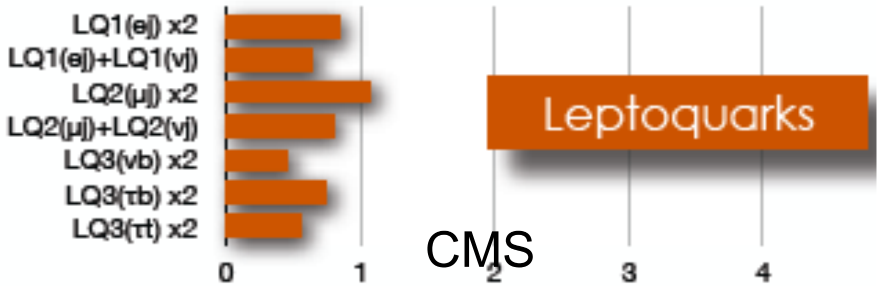
ATLAS

CMS

Search for LQ of only one generation (in majority of models LQ couples to all three generations of quarks and leptons)

ATLAS

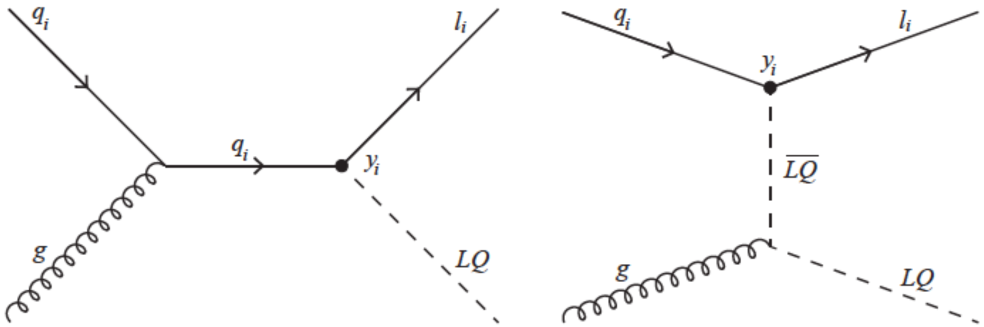
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LQ | Scalar LQ 1$^{st}$ gen | $2\,e$ | $\geq 2$ j | – | 1.0 | LQ mass | 660 GeV |
| | Scalar LQ 2$^{nd}$ gen | $2\,\mu$ | $\geq 2$ j | – | 1.0 | LQ mass | 685 GeV |
| | Scalar LQ 3$^{rd}$ gen | $1\ e, \mu, 1\ \tau$ | 1 b, 1 j | – | 4.7 | LQ mass | 534 GeV |



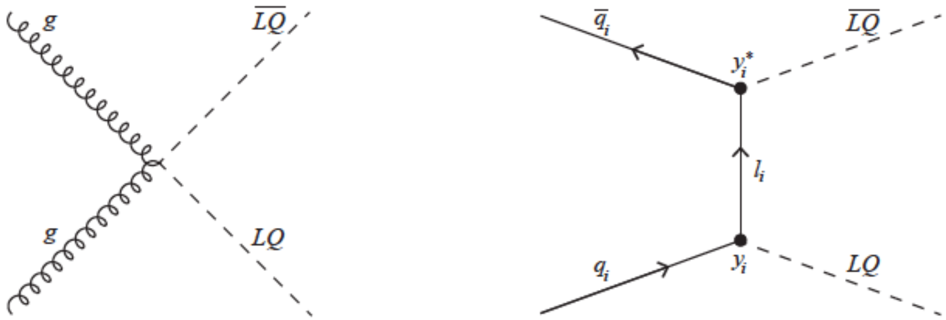

CMS

## Single LQ production

$$\sigma_{\text{single}}(y_i, m_{\text{LQ}}) = a(m_{\text{LQ}})|y_i|^2$$




## Double LQ production




$$\sigma_{\text{pair}}(y_i, m_{\text{LQ}}) = a_0(m_{\text{LQ}}) + a_2(m_{\text{LQ}})|y_i|^2 + a_4(m_{\text{LQ}})|y_i|^4$$

- Sizable Yukawa couplings of LQ with SM fermions could influence pair production at LHC;
- For small Yukawas LQ production is the same as within QCD.

For simplicity we assume only diagonal couplings in the search for LQ at LHC!

I generation couplings: best constraints come from atomic parity violation

$$\mathcal{L}_{\rm PV} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} (C_{1q}\bar{e}\gamma^{\mu}\gamma_5 e\bar{q}\gamma_{\mu}q + C_{2q}\bar{e}\gamma^{\mu}e\bar{q}\gamma_{\mu}\gamma_5 q)$$

$$C_{1d} = C_{1d}^{\rm SM} + \delta C_{1d}$$

$$\delta C_{1u(d)} = \frac{\sqrt{2}}{G_F}\frac{|y_{u(d)e}|^2}{8m_{\rm LQ}^2} \begin{cases} |y_{de}| \leq 0.34 \left(\frac{m_{\rm LQ}}{1\,\rm TeV}\right) \\ |y_{ue}| \leq 0.36 \left(\frac{m_{\rm LQ}}{1\,\rm TeV}\right) \end{cases}$$

$\boxed{K_L \to \mu^- e^+}$

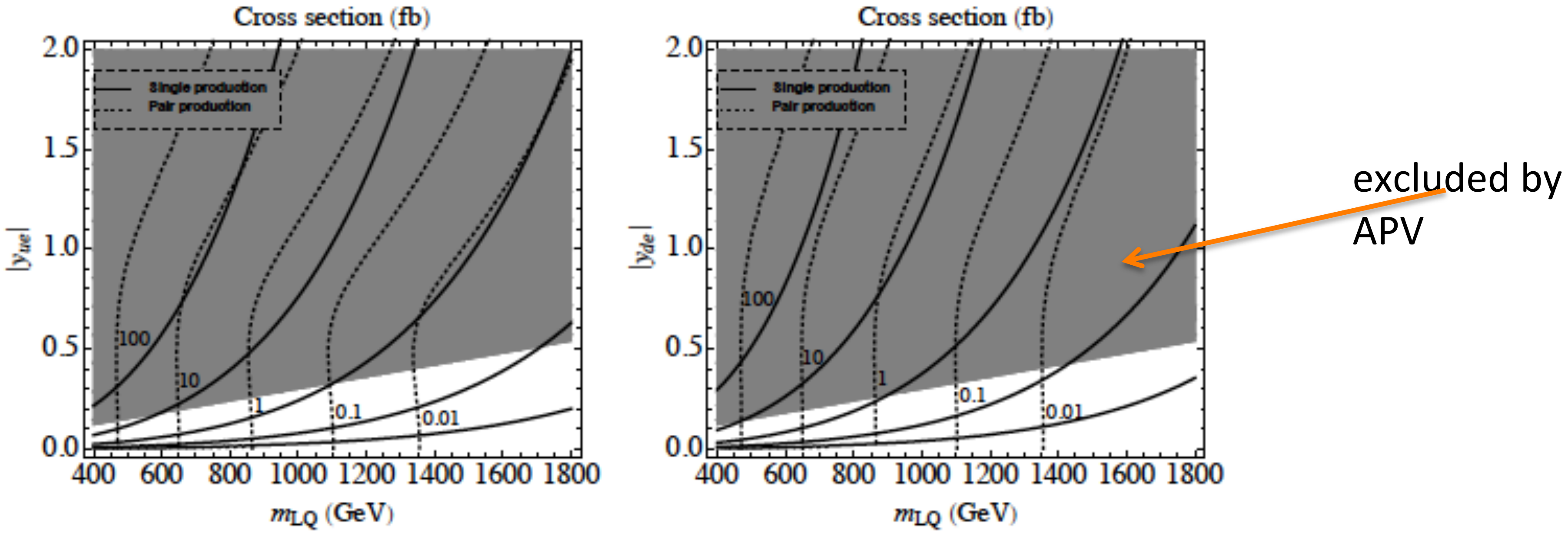
Bounds on II generation LQ

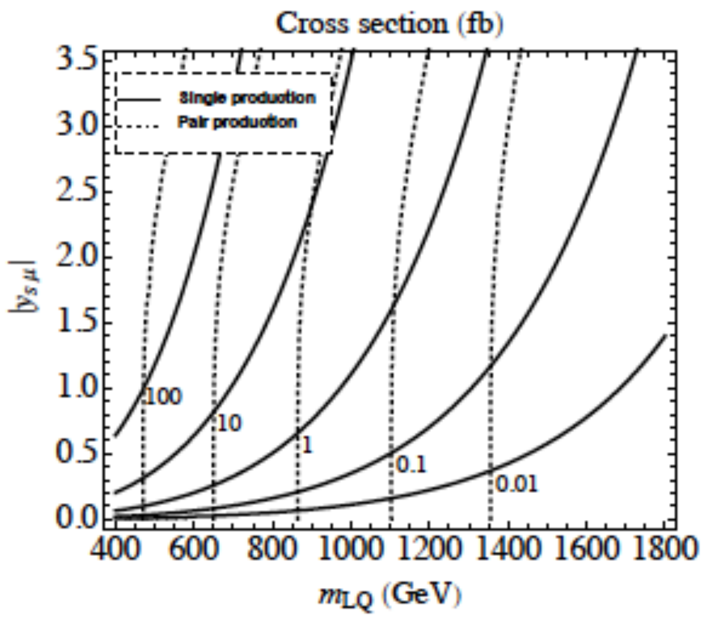
$$BR(K_L \to \mu^{\pm}e^{\mp}) < 4.7 \times 10^{-12}$$

Experimental bound:

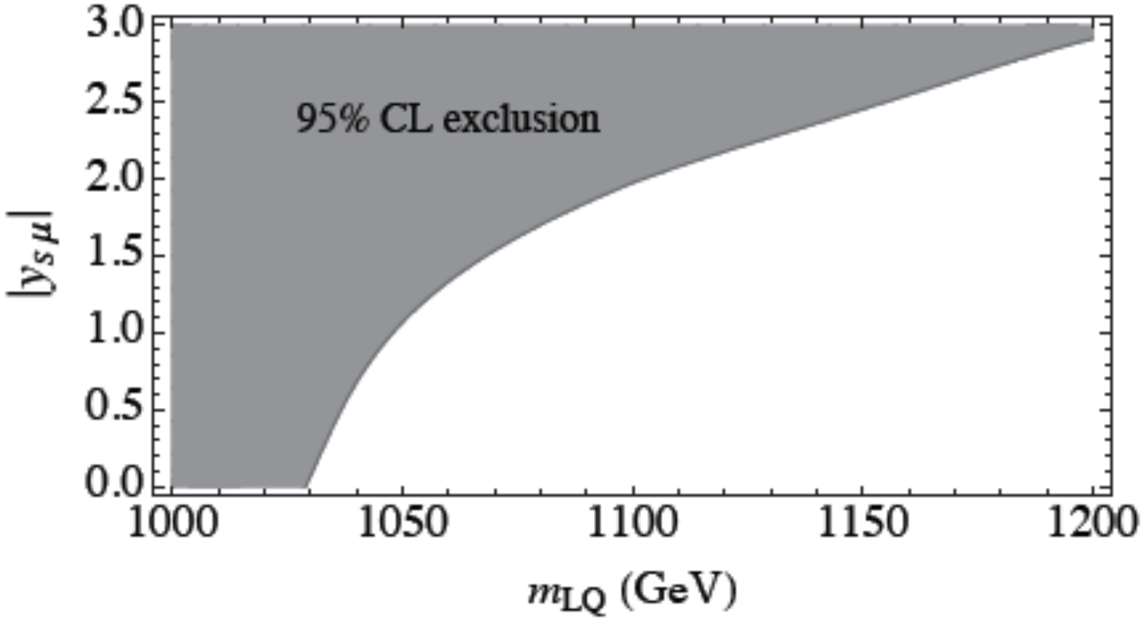
$$|y_{s\mu}y_{de}^*| < 2.1 \times 10^{-5}\left(\frac{m_{\rm LQ}}{1\rm TeV}\right)^2$$

The LQ of the first generation is fully constrained by APV, hence couplings of $R_2$ to a down quark and an electron is very small.
We assume in the further analysis that coupling of s and μ to $R_2$ is of the order 1.




If Yukawa couplings are large, one also needs to take into consideration a single leptoquark production and t-channel leptoquark pair production.




This study shows importance of the t-channel pair production and the single LQ production through the recast of an existing CMS search at LHC for the LQ coupling to s and μ.

# Summary

• (3,2,7/6) state introduced to explain R(D) and R(D*);

• scalar with charge 2/3 introduces scalar and tensor operator into effective Lagrangian;

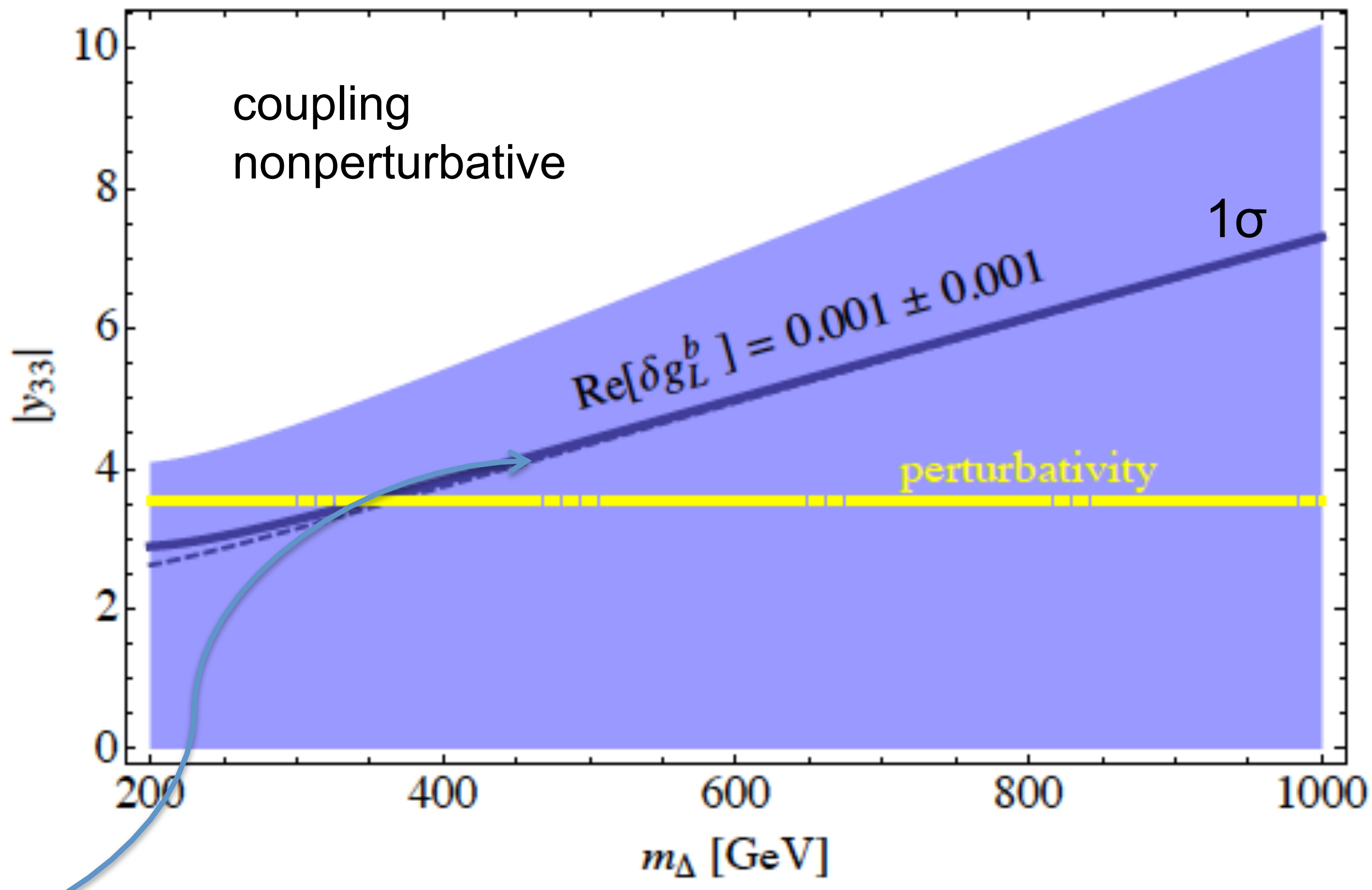
• charge 5/3 state induces quark and lepton flavor changing processes;

• constraints from $Z \to \bar{b}b,\ \ ,(g-2)_\mu,\ \ d_\tau,\ \ \tau \to \mu\gamma\,,\, \mu \to e\gamma;$

• (3,2,7/6) can adjust b-> s data;

• Model with (3,2,7/6) LQ state can be accommodated with SU(5) GUT by adding 45 scalar representation.

• Searches of LQ at LHC do depend on LQ couplings to quark and lepton, for large Yukawa couplings a single leptoquark production and t-channel leptoquark pair production are important - IMPORTANCE OF FLAVOUR PHYSICS FOR LHC!




$$|y_{33}|_{\mathrm{central}} = 1.57 + 2.86\frac{m_\Delta}{500\ \mathrm{GeV}}\,.$$ accurate within 5%

(3,2,1/6) LQ

$$\mathcal{L}_{\mathrm{Y}} = -y_{ij}\bar{d}_R^i \tilde{R}_2^a \epsilon^{ab} L_L^{j,b} + \mathrm{h.c.},$$

$$\mathcal{L}_{\mathrm{Y}} = -y_{ij}\bar{d}_R^i e_L^j \tilde{R}_2^{2/3} + (yV_{\mathrm{PMNS}})_{ij}\bar{d}_R^i \nu_L^j \tilde{R}_2^{-1/3} + \mathrm{h.c.}$$

N. Košnik, 1206.2970;
R. Mohanta 1310.0713

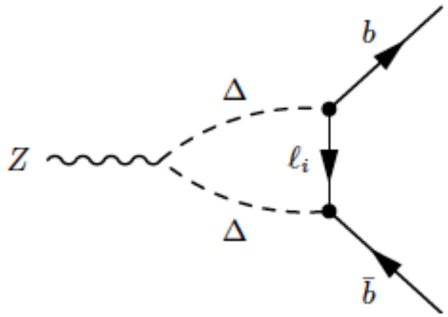
$$\mathcal{H}_{LQ} = \frac{y_{22}y_{23}^*}{8M_{LQ}}\bar{s}\gamma^\mu(1+\gamma_5)b\mu\gamma_\mu(1-\gamma_5)\mu \qquad C_9'^{\mathrm{NP}} = -C_{10}'^{\mathrm{NP}}$$

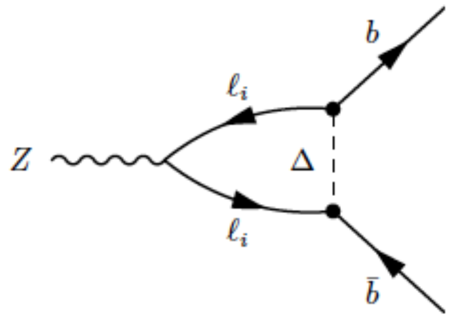
(3,2,1/6) LQ can influence $\left\{\begin{array}{l} Z \to b\bar{b} \\ (g-2)_\mu \end{array}\right.$

$Z \to b\bar{b}$

$$\delta g_L^b = 0.001 \pm 0.001\,, \qquad \delta g_R^b = (0.016 \pm 0.005) \cup (-0.17 \pm 0.005)$$

(3,2,1/6) can accommodate this value




$(g-2)_\mu$ down quarks and 2/3 charged LQ give vanishing contribution!

# Constraints from charm physics: $D^0 \to \mu^+\mu^-$ and $D^0 - \bar{D}^0$

LHCb 2013: $$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$$

New physics contribution:

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \tau_D \frac{f_D^2 m_D^3}{32\pi} \beta(m_\mu) \left[ |S|^2 \beta(m_\mu)^2 + |P|^2 \right]$$

$$S = \frac{m_D}{m_c}(C_S - C'_S), \qquad P = \frac{m_D}{m_c}(C_P - C'_P) + \frac{2m_\mu}{m_D}(C_{10} - C'_{10})$$

$$\mathcal{O}_S = (\bar{u}P_R c)(\bar{\mu}\mu), \qquad \mathcal{O}_P = (\bar{u}P_R c)(\bar{\mu}\gamma_5\mu),$$
$$\mathcal{O}_{10} = (\bar{u}\gamma_\mu P_L c)(\bar{\mu}\gamma^\mu\gamma_5\mu).$$

$$C_S = C_P = -\frac{V_{us}\epsilon_{22}^* \tilde{z}_{22}^*}{4m_\Delta^2} \qquad C_9 = C_{10} = \frac{|\epsilon_{22}|^2 V_{us} V_{cs}^*}{8m_\Delta^2}$$

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \tau_D \frac{f_D^2 m_D^5}{256\pi m_c^2} |V_{us}|^2 \left|\frac{\epsilon_{22}\tilde{z}_{22}}{m_\Delta^2}\right|$$

$$|\epsilon_{22}\tilde{z}_{22}| < 0.016 \frac{m_\Delta^2}{1\ \mathrm{TeV}^2}$$

## Scalar in SU(5) with SU(3)xSU(2)xU(1) quantum numbers

Inclusion of 45 Higgs representation SU(5) GUT

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

Both are needed:
Higgses in 5 and 45!

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

$\Delta_3$, $\Delta_{4,}$ $\Delta_5$ studied by I. Doršner, S.F, N. Košnik, J.F. Kamenik, 0906.5585 for the first two generations, based on the experimental results from K and D

## Is unification possible with some of light scalars in 45?

Yes!

I.Doršner, S.F. J.F. Kamenik and N. Košnik, 0906.5585; 1007.2604 ;

Unification possible with 2 light scalars!

## Up-quarks

5

45

$$(Y_2')_{ij} 10_i 10_j 5$$

$$(Y_2)_{ij} 10_i 10_j 45$$

$$M_U = [4({Y_2'}^T + Y_2')v_5 - 8(Y_2^T - Y_2)v_{45}]/\sqrt{2}$$

$$\langle \mathbf{5} \rangle^5 = \sqrt{2} v_5$$

$$\langle \mathbf{45} \rangle_1^{51} = \langle \mathbf{45} \rangle_2^{52} = \langle \mathbf{45} \rangle_3^{53} = \sqrt{2} v_{45}$$

$$2|v_5|^2 + 48|v_{45}|^2 = v^2$$

$$v = 246\,\mathrm{GeV}$$

Down-quarks and charged lepton

$(Y_1)_{ij} 10_i \bar{5}_j 45*$

$(Y_3)_{ij} 10_i \bar{5}_j 5*$

$$M_E = 3Y_1^T v_{45}^* - \frac{1}{2} Y_3^T v_5^*$$

$$M_D = -Y_1 v_{45}^* - \frac{1}{2} Y_3 v_5^*$$

without 45: $M_E \approx M_D$ at GUT scale

with 45 : $M_E = \approx -3\, M_D$ at GUT scale

$$B \to X_s l^+ l^-$$

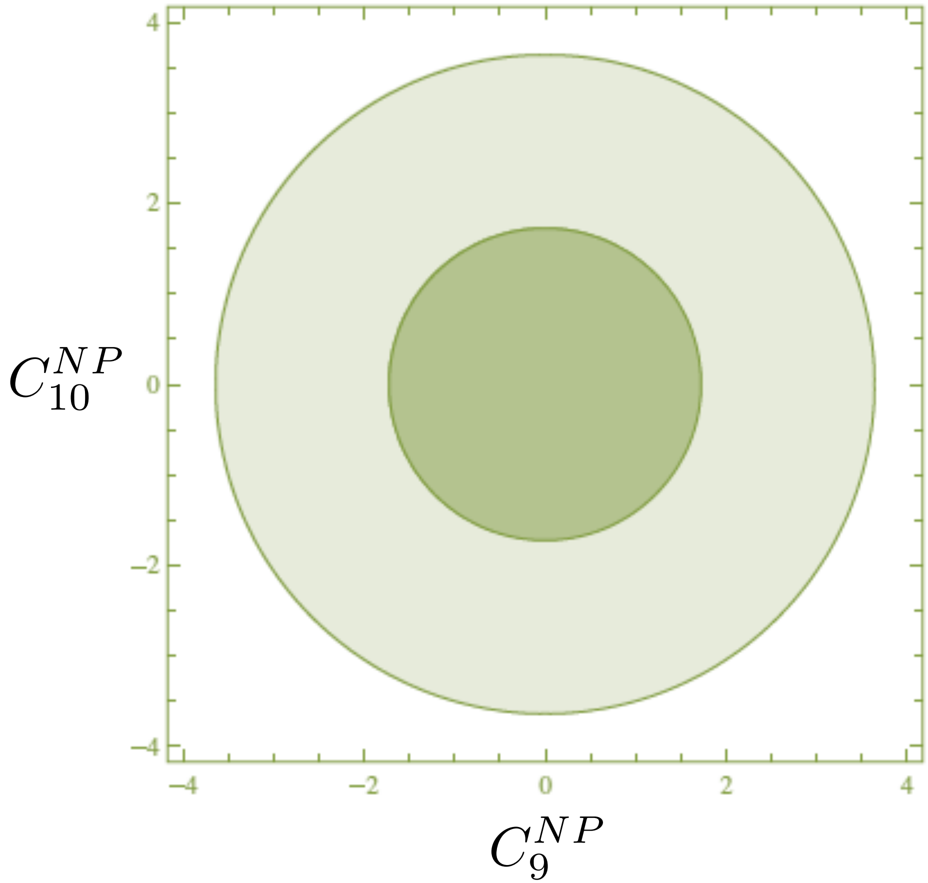
$$\mathrm{BR}(B_d^0 \to X_s \mu^+ \mu^-) = (1.60 \pm 0.50) \times 10^{-6} \quad \text{low } q^2$$
$$= (0.44 \pm 0.12) \times 10^{-6} \quad \text{high } q^2,$$

Bounds from $B \to X_s l^+ l^-$

N. Košnik, 1206.2970;

R. Mohanta 1310.0713

$$C_9^{NP} = C_9^{NP}$$



## $(3,2)_{7/6}$ in GUT

$(3,2)_{7/6}$ can be found in representations 45 and 50 of SU(5)

has both couplings Z and Y

has only Y couplings

In SO(10) scenario: 120 and 126

anti-symmetric couplings to matter

symmetric couplings to matter fields

## Is our low-energy Yukawa ansatz compatible with the idea of GUT?

Scalar in 120 and 126 of SO(10) can realize the same coupling as scalar in 45 of SU(5);

Scalar in 50 of SU(5) can be only in 126 of SO(10).

**Our assumption: $(3,2)_{7/6}$ in 45 of SU(5)**

Higgs doublet is in 5 and in 45

Couplings to matter fields

$$(Y_1)_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\mathbf{45} \qquad (Y_3)_{ij}\mathbf{10}_i\overline{\mathbf{5}}_j\mathbf{5}$$

arbitrary matrices

Transition from weak to mass basis for down-like quarks (up-like, charged lepton);
Unitary transformations $D_L$ and $D_R$, $U_L$ and $U_R$, $E_R$ and $E_L$;
(assumption: neutrinos are Majorana fermions)

$\nu_L \to V_{\mathrm{PMNS}} \nu_L \qquad u_L \to V^\dagger_{\mathrm{CKM}} u_L$. ( $D_L$, $E_L$ are diagonal)

$D_R$, $U_R$, $E_R$ are unknown

$$\left.\begin{aligned} 2M_D^{\mathrm{diag}} D_R^T &= -2Y_1 v_{45} - Y_3 v_5 \\ 2E_R M_E^{\mathrm{diag}} &= 6Y_1 v_{45} - Y_3 v_5 \end{aligned}\right\} \qquad Y_1 = -U_R Z.$$

We assume that $D_R$, $U_R$, $E_R$ are real!

All angles in $D_R$, $U_R$, $E_R$ are specified with our ansatz, except one in $U_R$ within proposed framework (restrictive nature of our Z!)

$$\boxed{M_D^{\text{diag}} D_R^T - E_R M_E^{\text{diag}} = 4 U_R Z v_{45}}$$

this equation should be satisfied at GUT scale!

11 parameters and 9 equations

$$U_R = (O_2(\xi)\, O_3(\phi)\, O_1(\theta))^T$$

$$O_3(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}$$

only parameter ξ can not be fixed!

Input: masses of down-like quarks and charged leptons at GUT Scale.
Satisfactory solution (up to $v_{45}$ VEV) leads to:

$$\boxed{\tilde{z}_{21} : \tilde{z}_{22} : \tilde{z}_{23} = 0.024 : 0.32 : 1}$$