Scalar Leptoquarks at Low and High Energies

Svjetlana Fajfer

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

Institute Rudjer Bošković, Zagreb, 22nd September 2015

Outline

- Motivation;
- Low-energy constraints
- LQ at high energies;
- Leptoquarks and GUT;
- Leptoquarks at LHC;
- Summary.

Based on

D. Bečirević, SF, N. Košnik, Phys.Rev D 92 (2015) 014016;
I.Doršner, S.F.,J.F.Kamenik, N.Košnik, I. Nisandžić, JHEP 1506 (2015) 108;
I.Doršner, S.F and A. Greljo, JHEP 1410 (2014) 154;
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;

Motivation

- We need Beyond Standard Model Physics;
- Many proposals and searches of new non-SM particles at LHC;
- Leptoquarks are present in GUT theories;
- Scalar LQ might modify mass matrices;

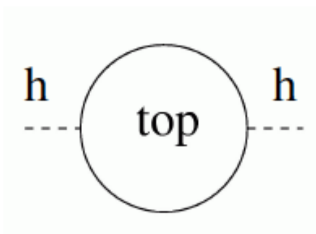
} Theory arguments

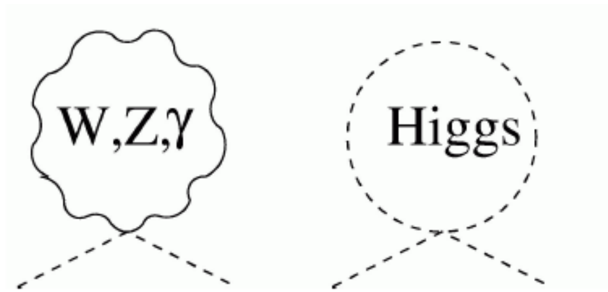
- Intensive searches of LQ at LHC → Experimental bounds
- Explanation of anomalous events at low energies by LQ

Why Beyond SM Physics?

1) Naturalness

quadratic divergences





$$\delta M_h^2 = -\frac{\lambda_F^2}{8\pi^2}\Lambda^2 + \ldots$$

Comment: all others SM particles get logarithmic corrections!

2) Neutrinos have masses: does it come from BSM?

3) What is the nature of dark matter?

4) We need more CP violation to understand baryon – antibaryon asymmetry in the universe!

ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

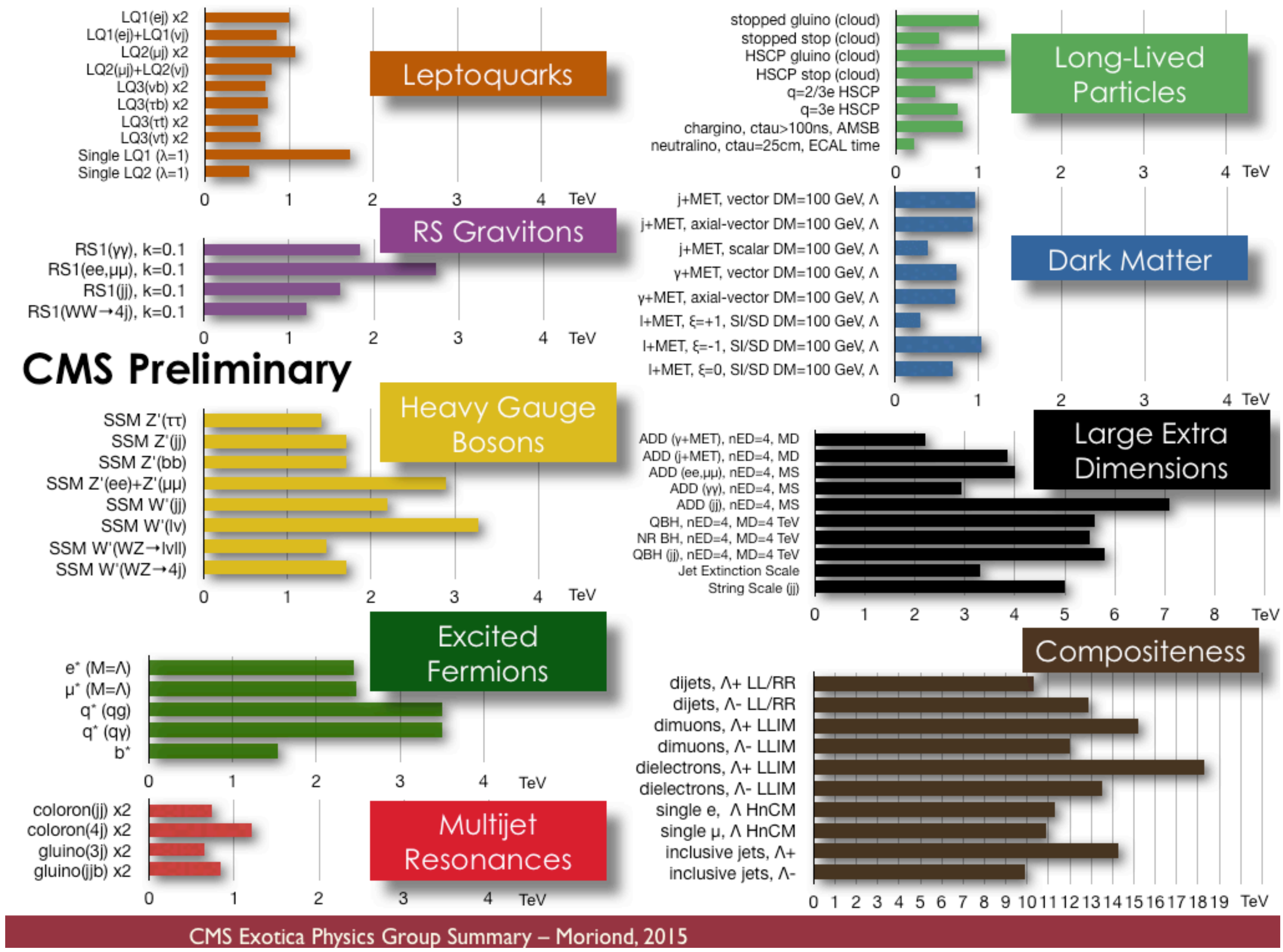
$\int \mathcal{L}\, dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W′ mass 760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \rightarrow t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	20.3	Z′ mass 2.9 TeV		1405.4123
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z′ mass 2.02 TeV		1502.07177
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	20.3	W′ mass 3.24 TeV		1407.7494
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	3 e, μ	–	Yes	20.3	W′ mass 1.52 TeV		1406.4456
	EGM $W' \rightarrow WZ \rightarrow qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W′ mass 1.59 TeV		1409.6190
	EGM $W' \rightarrow WZ \rightarrow qqqq$	–	2 J	–	20.3	W′ mass 1.3-1.5 TeV		1506.00962
	HVT $W' \rightarrow WH \rightarrow \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W′ mass 1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \rightarrow t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W′ mass 1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W′ mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL} \rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \rightarrow Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	20.3	q* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \rightarrow \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \rightarrow \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	Preliminary

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

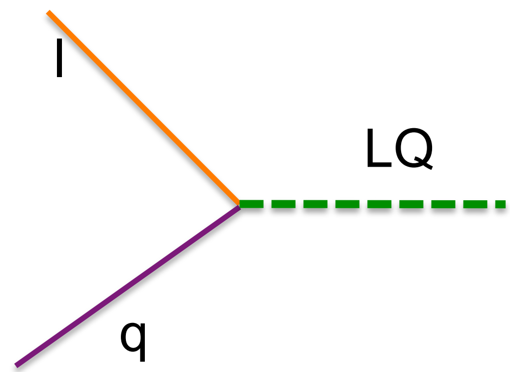
Mass scale [TeV]: 10^{-1}, 1, 10

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


Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
CMS Preliminary
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – Moriond, 2015

Leptoquarks

Some of proposals of Physics beyond Standard Model contain



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)

Leptoquark 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	$\overline{Q}i\tau^2 L^C$, $\overline{d}_R \nu_R^C$, $\overline{u}_R \ell_R^C$		
$(3,3)_{-1/3}$	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
$(3,3)_{2/3}$	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
$(\bar{3},2)_{5/6}$	1	$\overline{Q}\gamma^\mu\ell_R^C$, $\overline{d}_R i\tau^2\gamma_\mu L^C$	$+1$	-1

✓ ✓

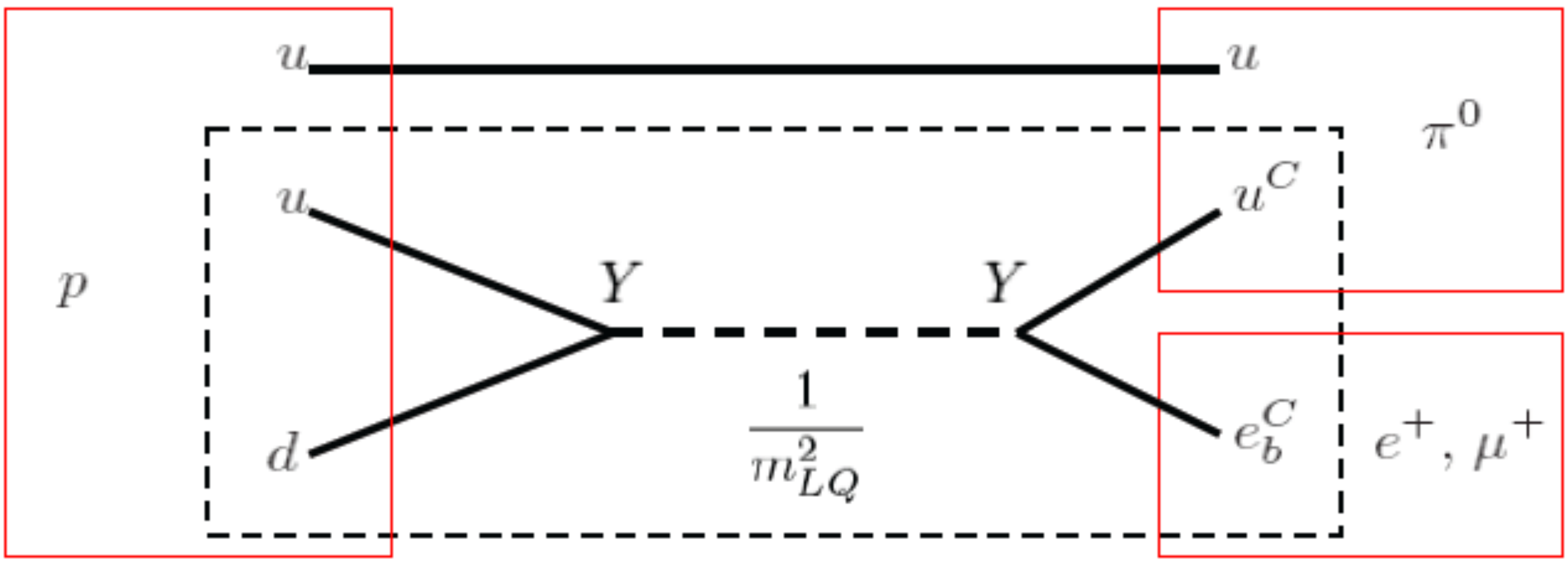
might destabilize proton
ID, SF, NK
1204.0674

we do not consider these states

$Q = I_3 + Y$

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

Most famous role of leptoquarks: proton destabilization



Experimental bound

$$\tau(p \to e^+\pi^0) > 1.3 \times 10^{34} \;\; years$$

Low energy constraints on leptoquark couplings

Scalar LQ might explain small deviation:

Experimental result

↕ ~ 2-3 σ

SM prediction

$$B \to D^{(*)} \tau \nu_\tau$$

$$B \to K^* l^+ l^-$$

$$Z \to b\bar{b}$$

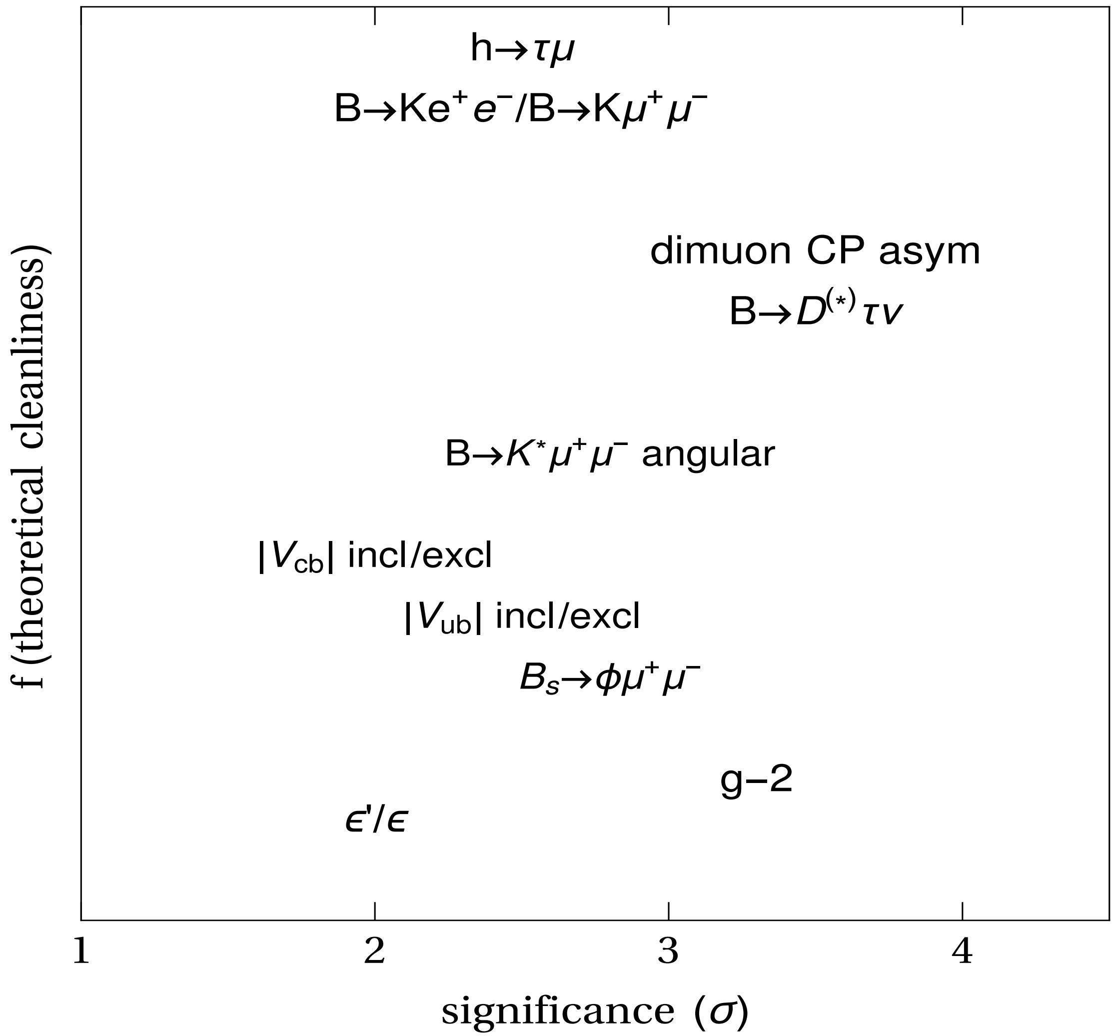
$$(g-2)_\mu$$

$$\mu \to e\gamma$$

$$\tau \to \mu\gamma$$

$$R_K$$

$$h \to \tau\mu$$ (?)



From Z. Ligeti, LP 2015, Ljubljana

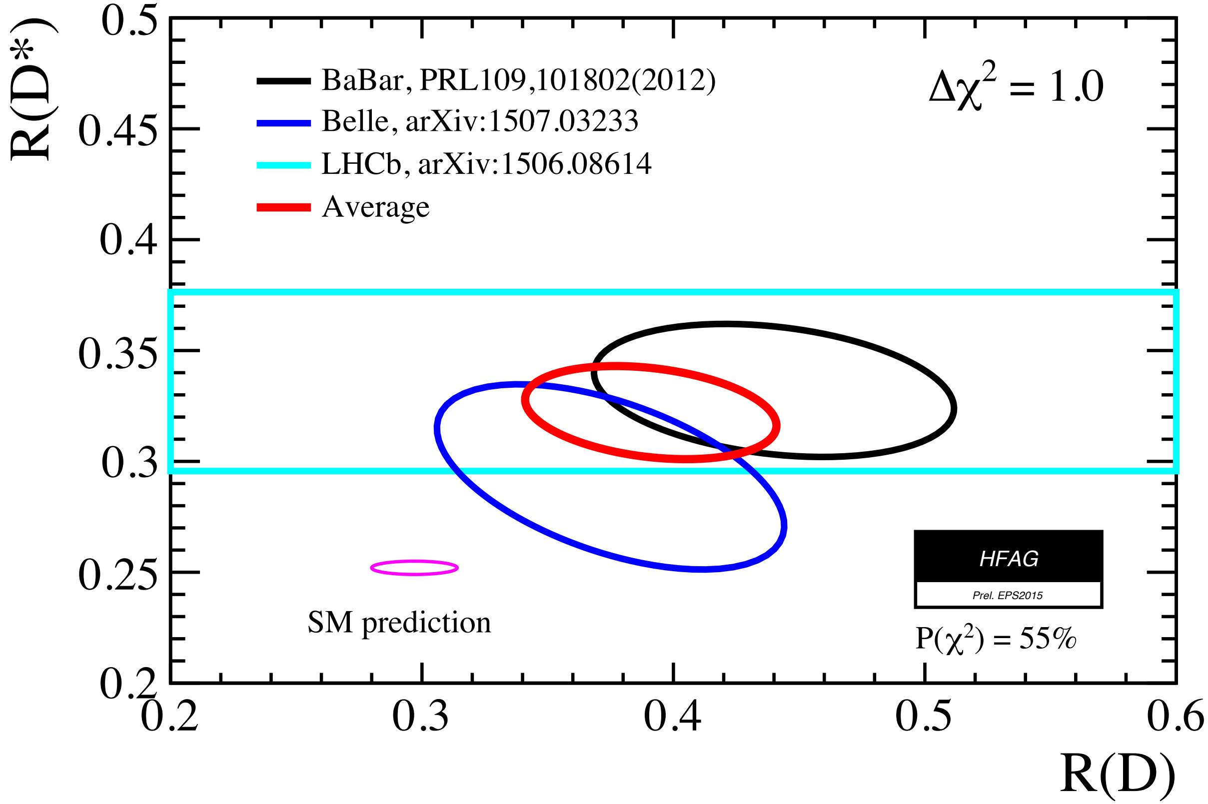
Experiment – Theory in $B \to D(D^*)\,\tau\nu_\tau$

In ratios there is no dependence on CKM matrix elements:

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

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

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.391 ± 0.050	0.322 ± 0.022
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005

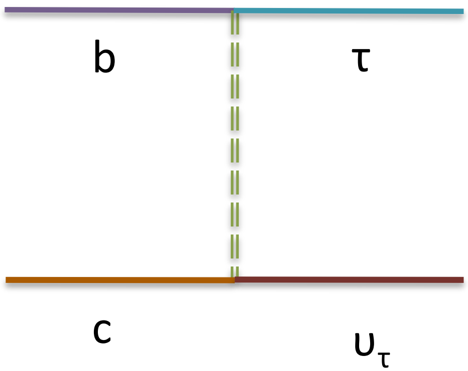


combined 3.4σ larger than SM

Standard Model

$$\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 0.252(3)$$
$$\mathcal{R}^{\mathrm{SM}}_{\tau/\ell} = 0.296(16)$$

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



Scalar and vector
leptoquark that trigger
b$\longrightarrow$c l υ,
I.Doršner, S.F., N. Košnik, (2013)

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)

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. Bečirević 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. Bečirević et al. 1206.4977;
A. Crivelin et al., 1206.2634;
P. Biancofiore et al.,1302.1042,
…

Interactions of Δ = (3,2,7/6) state

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

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

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

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:

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

Requirements:

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

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

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

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

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

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

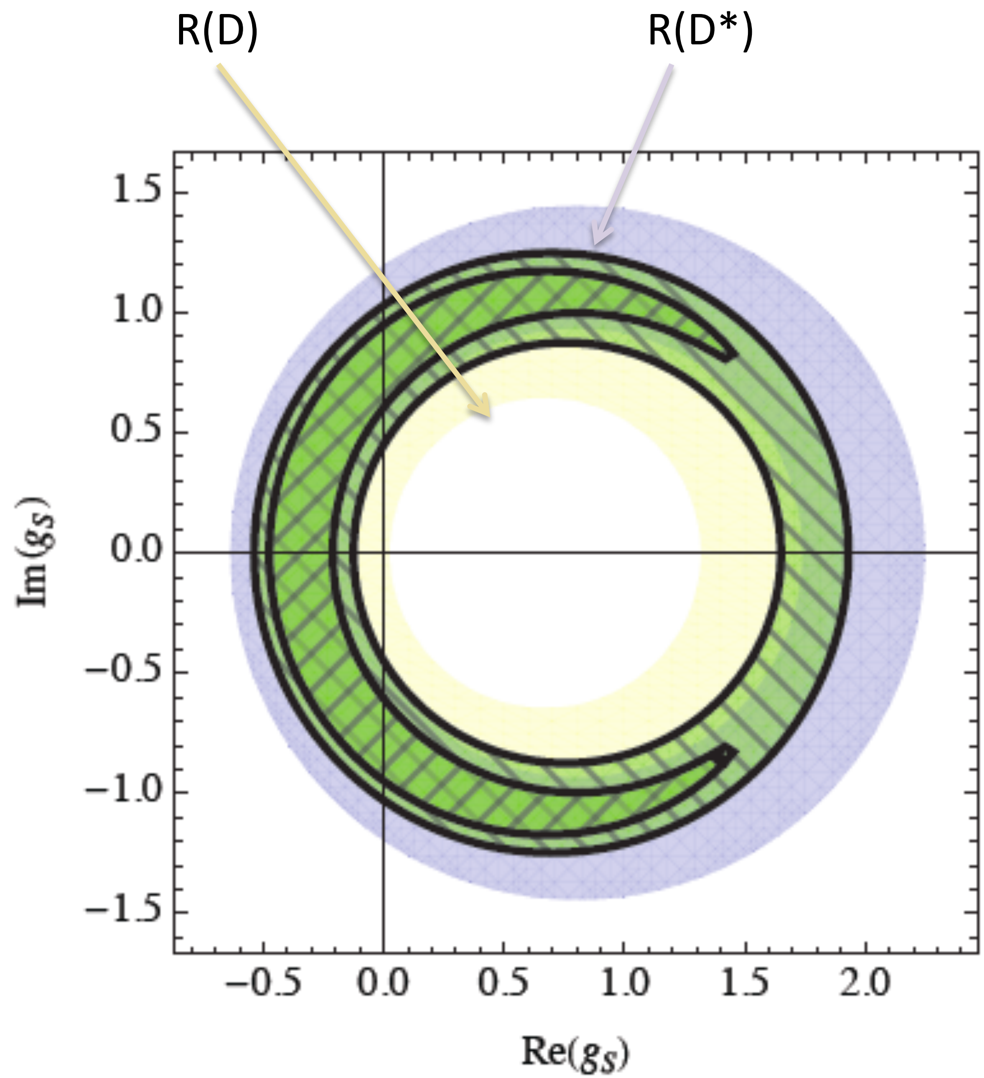
(Fierz's transformation are used)

SM + NP operators

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

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

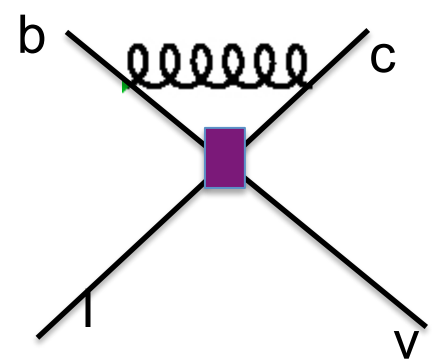
this relation holds on the mass scale of Δ



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

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

Lepton electromagnetic current

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

↓

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

Muon anomalous magnetic moment

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

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

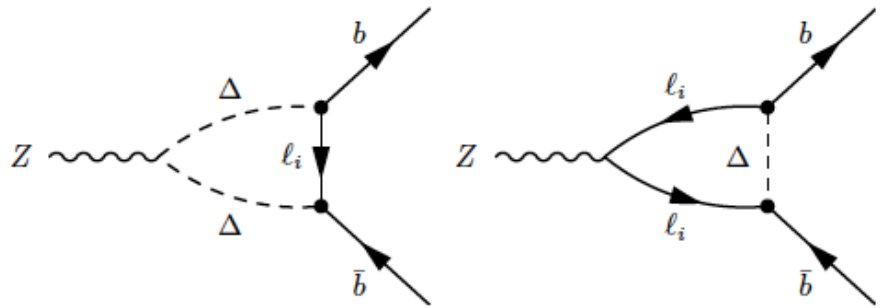
Additional constraints

$Z \to b\bar{b}$

- 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!

$$a_\mu^{\exp} = 1.16592080(63) \times 10^{-3}$$
$$a_\mu^{\rm SM} = 1.16591793(68) \times 10^{-3}$$

$$\delta a_\mu = a_\mu^{\exp} - a_\mu^{\rm SM} = (2.87 \pm 0.93) \times 10^{-9}$$

$$\mathcal{B}(\mu \to e\gamma) < 5.7 \times 10^{-13}$$
$$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8}$$
$$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-9}$$

MEG experiment result on muon BR for LFV decay is much stronger then for bound on tau LFV decay rate. The μ liftime and the strong bound on LFV compensate for a helicity suppression.

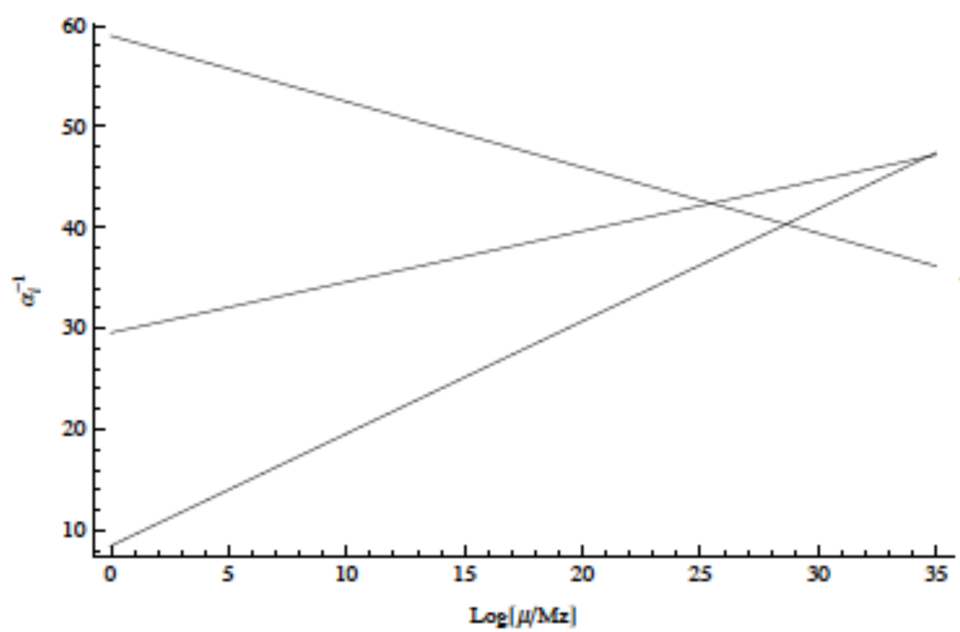
Is our low-energy Yukawa ansatz compatible with the idea of GUT?

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



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

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

has both couplings Z and Y

In SO(10) scenario: 120 and 126

anti-symmetric couplings to matter

symmetric couplings to matter fields

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

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

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

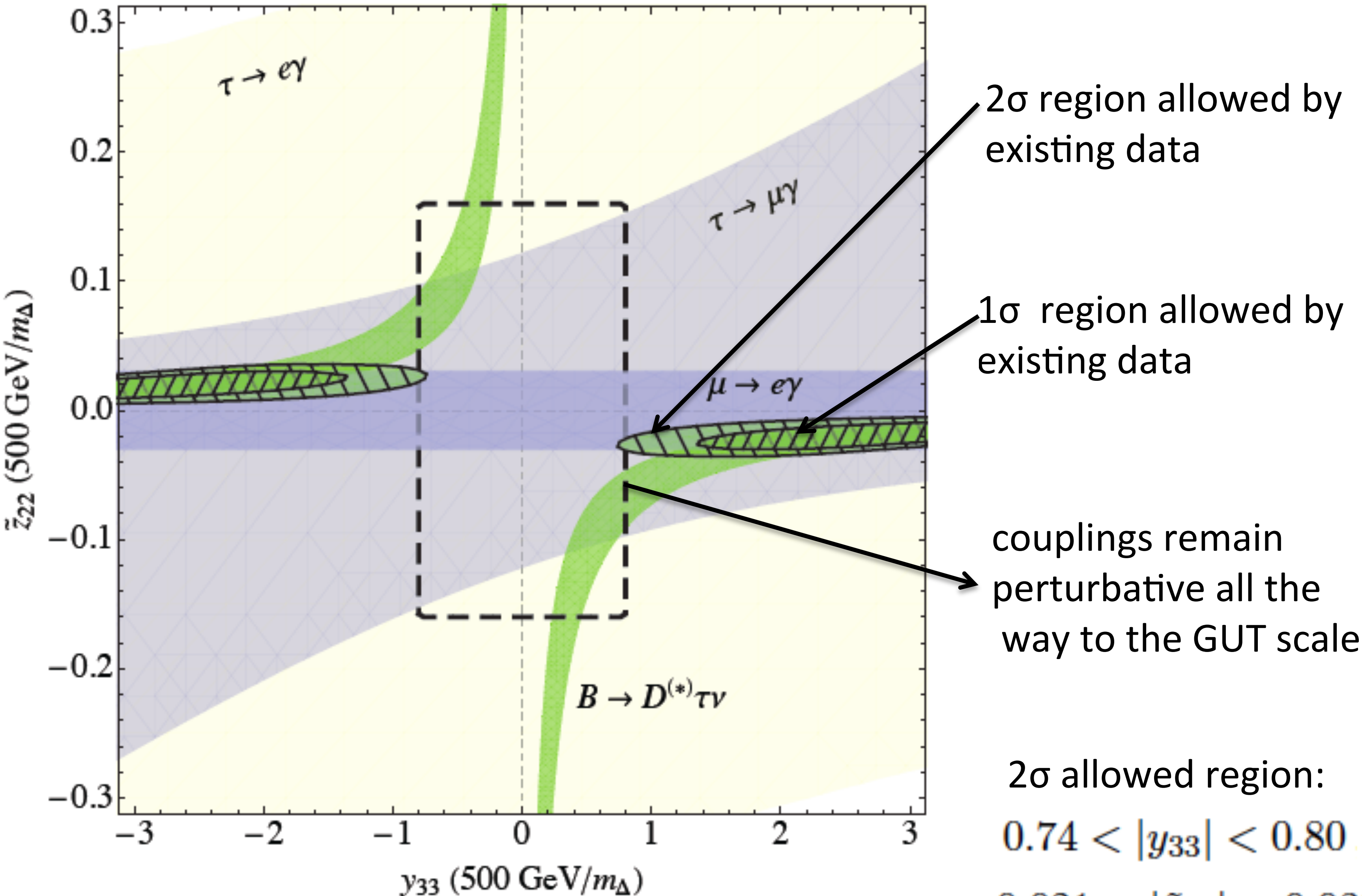
We assume that D_R, U_R, E_R are real!

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

this equation should be satisfied at GUT scale!

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

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



2σ allowed region:

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

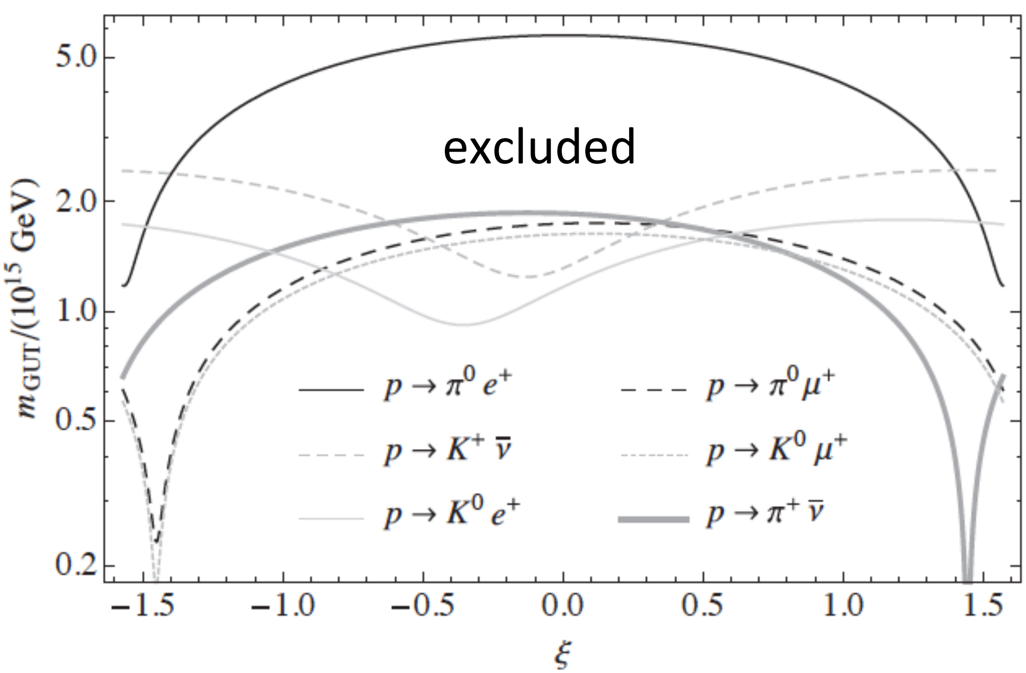
$$0.021 < |\tilde{z}_{22}| < 0.032$$

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

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 $p \to K^+\bar{\nu}$, $p \to K^0 e^+$

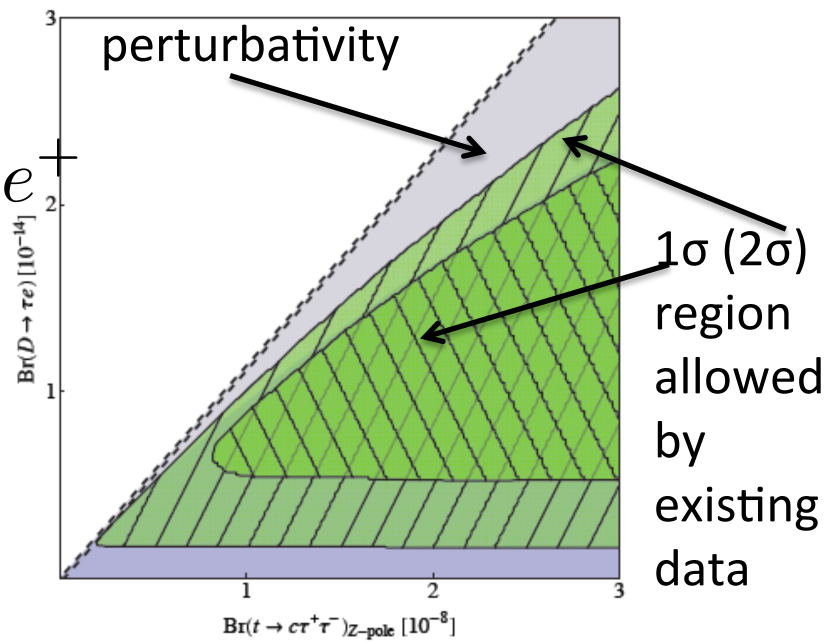
Predictions

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

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

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

$$BR_{LQ}(t \to c\tau^+\tau^-) \sim 10^{-8}$$
$$BR_{LQ}(\bar{D}^0 \to \tau^- e^+) \sim 10^{-14}$$

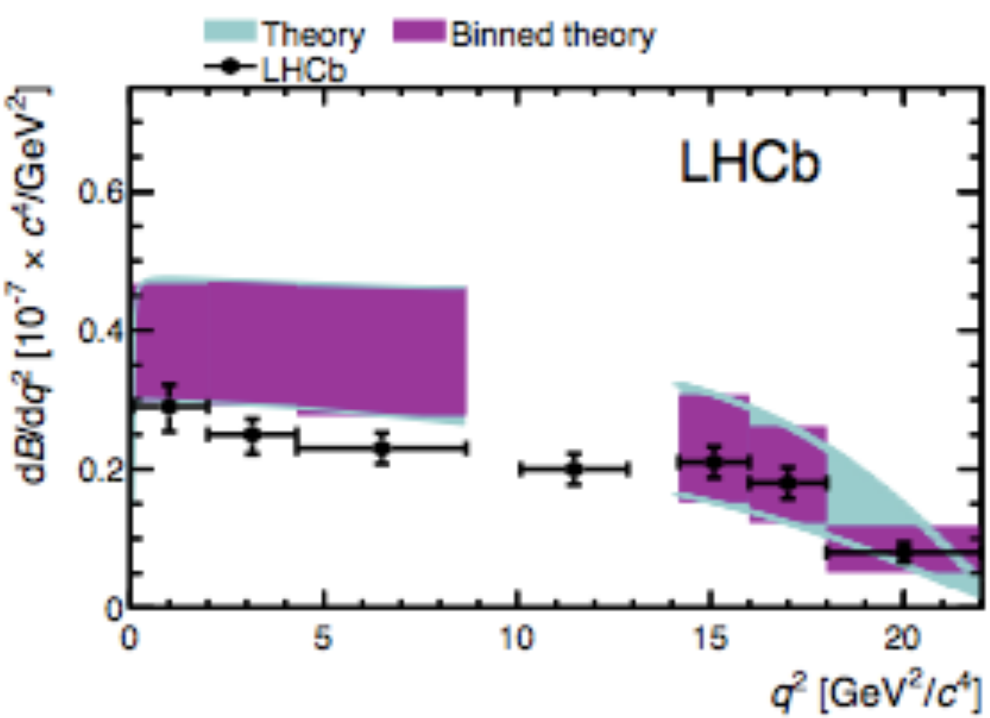


Lepton flavor universality violation: R_K

G. Hiller and F. Kruger, hep-ph/0310219 suggested to measure

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}{\mathcal{B}(B \to Ke^+e^-)_{q^2\in[1,6]\ \mathrm{GeV}^2}}$$

$$R_K^{\mathrm{LHCb}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036 \qquad R_K^{SM} = 1.0003 \pm 0.0001$$



This decay modes give useful constraints on NP!

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

In our study we use:

Experimental results 2013

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

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

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

Buras et al, 1208.0934

Effective Hamiltonian for $b \to s\mu^+\mu^-$

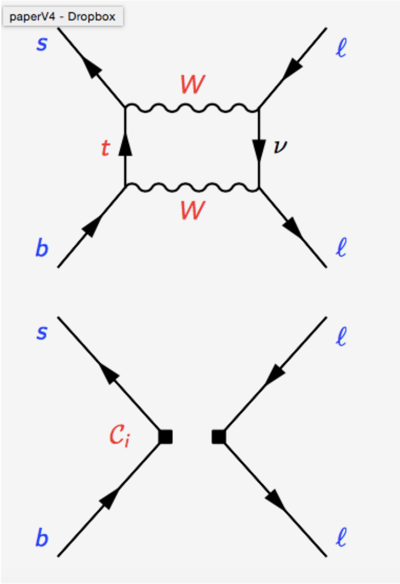
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu)\right) \right]$$

opposite chirality

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} , \qquad \mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} G^{\mu\nu} P_R b) ,$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) , \qquad \mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) .$$

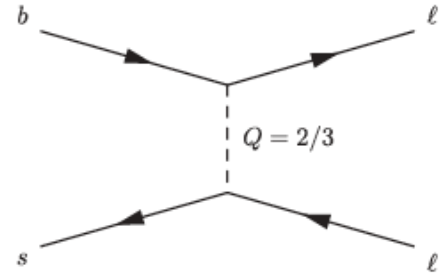
$$P_{L/R} = (1 \mp \gamma_5)/2$$



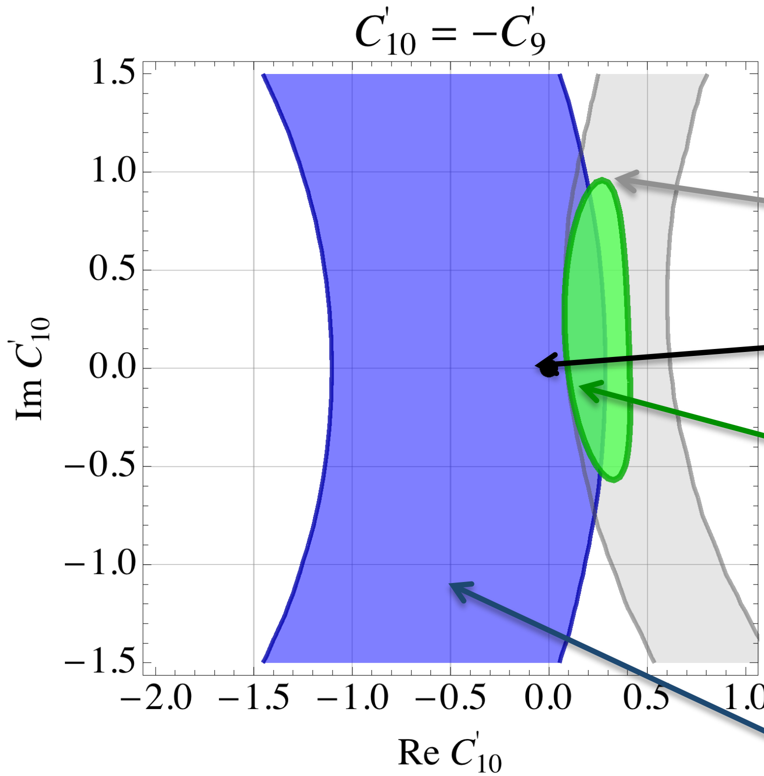
Wilson coefficients mix under QCD renormalisation- effective Wilson coefficients are used!

Our explanation of R_K anomaly (D. Bečirević, SF, N. Košnik, 1503.09024)

NP in $C'_9 = -C'_{10}$



$$R_K(C'_{10}) = 1.001(1) - 0.46\ \mathrm{Re}[C'_{10}] - 0.094(3)\ \mathrm{Im}[C'_{10}] + 0.057(1)|C'_{10}|^2 .$$



in agreement with exp. results for at 1 σ

$$R_K^{\mathrm{pred.}} = 0.88 \pm 0.08 ,$$

G. Hiller & M. Schmaltz : observed R_K can be explained by LQ which fulfill

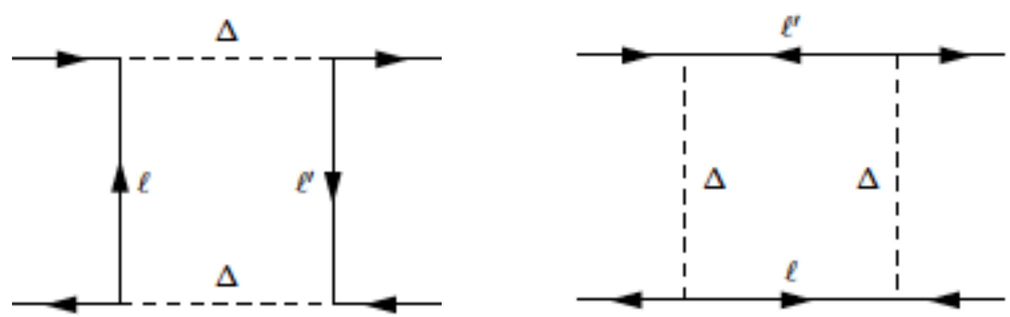
$$C_9' = -C_{10}'$$

$$\mathcal{L} = Y_{ij}\overline{L}_i\, i\tau^2\Delta^* d_{Rj} + \text{h.c.}$$
$$= Y_{ij}\left(-\bar{\ell}_{Li} d_{Rj}\Delta^{(2/3)*} + \bar{\nu}_{Lk}(V^{\text{PMNS}})^\dagger_{ki} d_{Rj}\Delta^{(-1/3)*}\right) + \text{h.c.}$$

$$C_{10}' = -C_9' = \frac{-\pi}{2\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\,\frac{Y_{\mu b}Y_{\mu s}^*}{m_\Delta^2}$$

However, it can contribute to

$$B_s - \bar{B}_s$$



$$C_6^{\text{LQ}}(m_\Delta) = -\frac{Y_{\mu b}^{*2}Y_{\mu s}^2}{64\pi^2 m_\Delta^2}$$

With value C_{10}' one can get very loose bound on m_Δ ~ 100 TeV.

Our suggestion: new observables

$$R_{K^*} = \frac{\Gamma(B \to K^* \mu^+ \mu^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}{\Gamma(B \to K^* e^+ e^-)_{q^2 \in [1,6]\ \mathrm{GeV}^2}}$$

$$X_K = \frac{R_{K^*}}{R_K} - 1$$

$$A^{\ell}_{\mathrm{fb}[4-6]} = \frac{3}{4} \frac{\int_{4\ \mathrm{GeV}^2}^{6\ \mathrm{GeV}^2} I_6^s(q^2)\ dq^2}{\Gamma(B \to K^* \ell^+ \ell^-)_{q^2 \in [4,6]\ \mathrm{GeV}^2}}$$

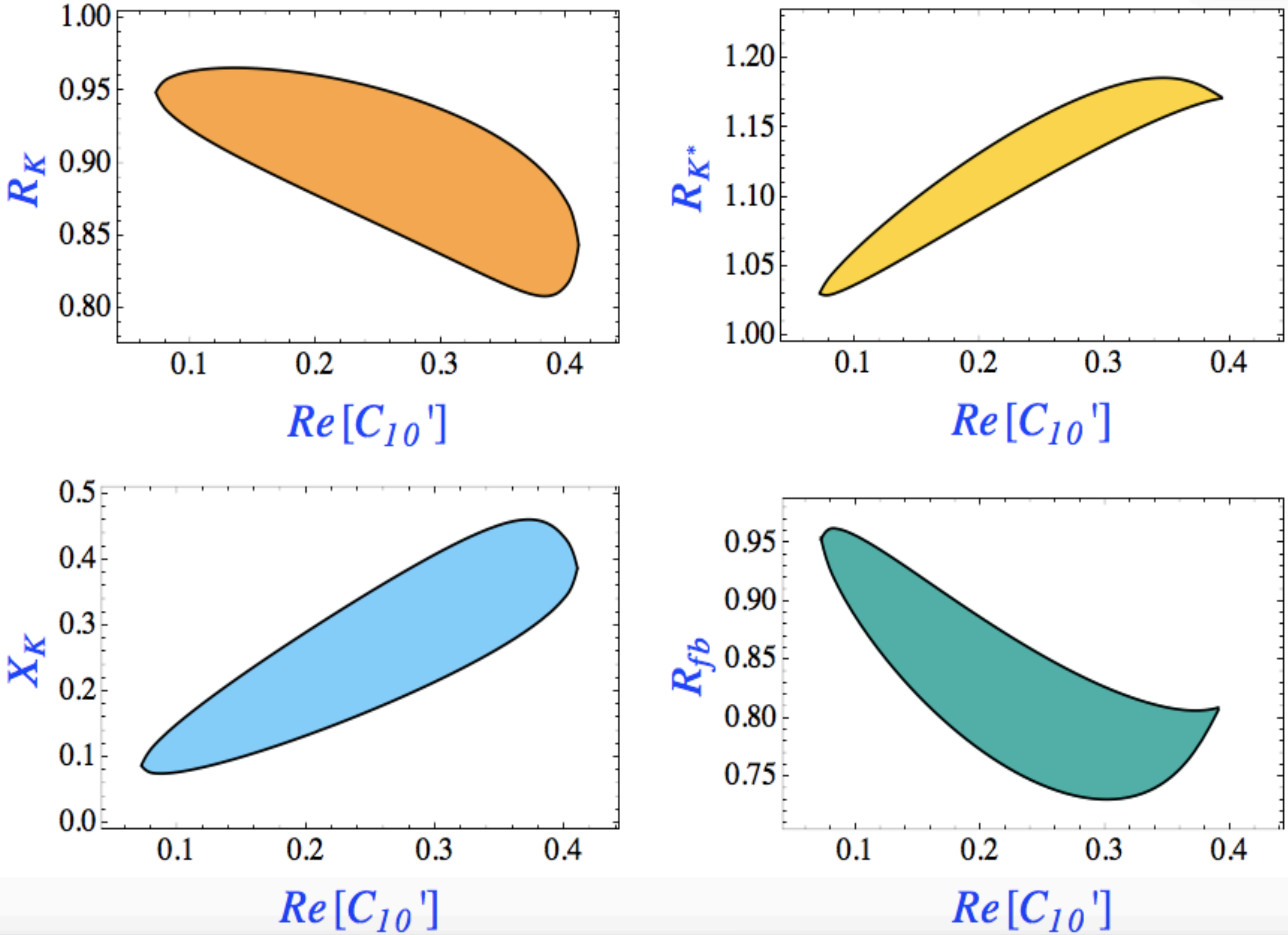
$$R_{\mathrm{fb}} = \frac{A^{\mu}_{\mathrm{fb}[4-6]}}{A^{e}_{\mathrm{fb}[4-6]}}$$

LQ (3,2,1/6) in suggested observables leads to :

$$R_K = 0.88 \pm 0.08\,, \qquad R_{K^*} = 1.11 \pm 0.08\,,$$

$$X_K = 0.27 \pm 0.19\,, \qquad R_{\mathrm{fb}} = 0.84 \pm 0.12\,,$$

It can give increase of the rate for $B \to K \nu \bar{\nu}$ at the order of 5%



R_K
1.00
0.95
0.90
0.85
0.80
0.1
0.2
0.3
0.4
Re[C_10']
R_K*
1.20
1.15
1.10
1.05
1.00
0.1
0.2
0.3
0.4
Re[C_10']
X_K
0.5
0.4
0.3
0.2
0.1
0.0
0.1
0.2
0.3
0.4
Re[C_10']
R_fb
0.95
0.90
0.85
0.80
0.75
0.1
0.2
0.3
0.4
Re[C_10']

Lepton flavor violating decay $h \to \tau\mu$

CMS result
(assuming SM
Higgs production)

$$\mathcal{B}(h \to \tau\mu) = \left(0.84^{+0.39}_{-0.37}\right)\%$$

After EWSB

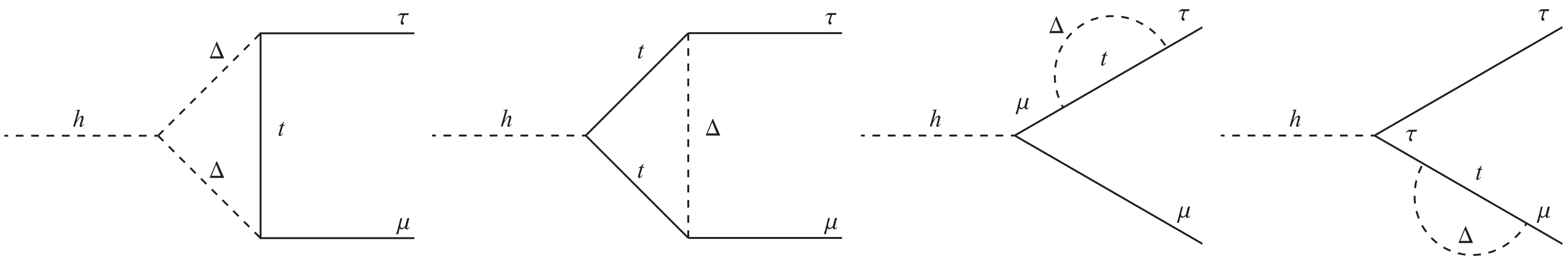
$$\mathcal{L}_{Y_\ell}^{\text{eff.}} = -m_i \delta_{ij} \bar{\ell}_L^i \ell_R^j - y_{ij} \left(\bar{\ell}_L^i \ell_R^j\right) h + \ldots + \text{h.c.}$$

$$\mathcal{B}(h \to \tau\mu) = \frac{m_h}{8\pi\Gamma_h} \left(|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2\right)$$

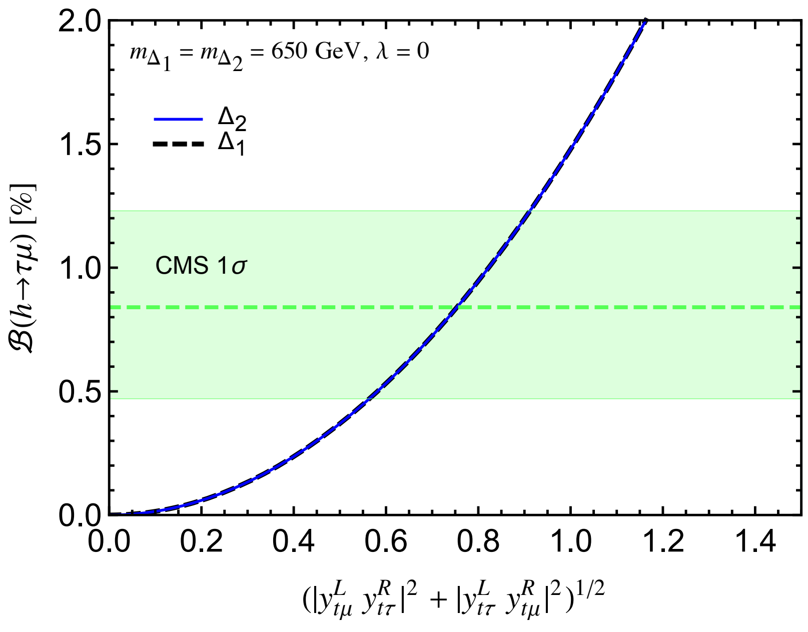
$$0.0019(0.0008) < \sqrt{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2} < 0.0032(0.0036) \text{ at } 68\% \ (95\%) \text{ C.L.}$$

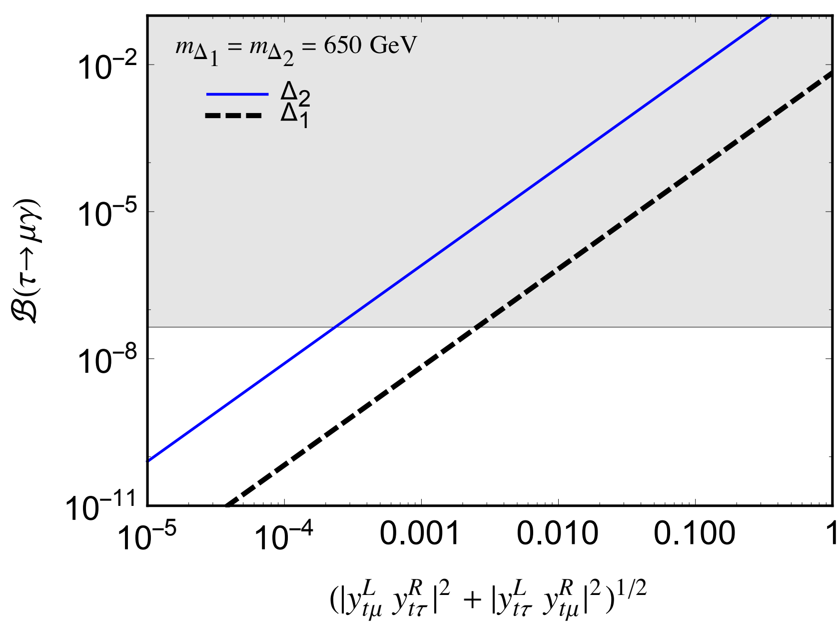
We considered low energy bounds and found that if CMS result holds the at Belle II $\tau \to \mu\gamma$ should be observed!

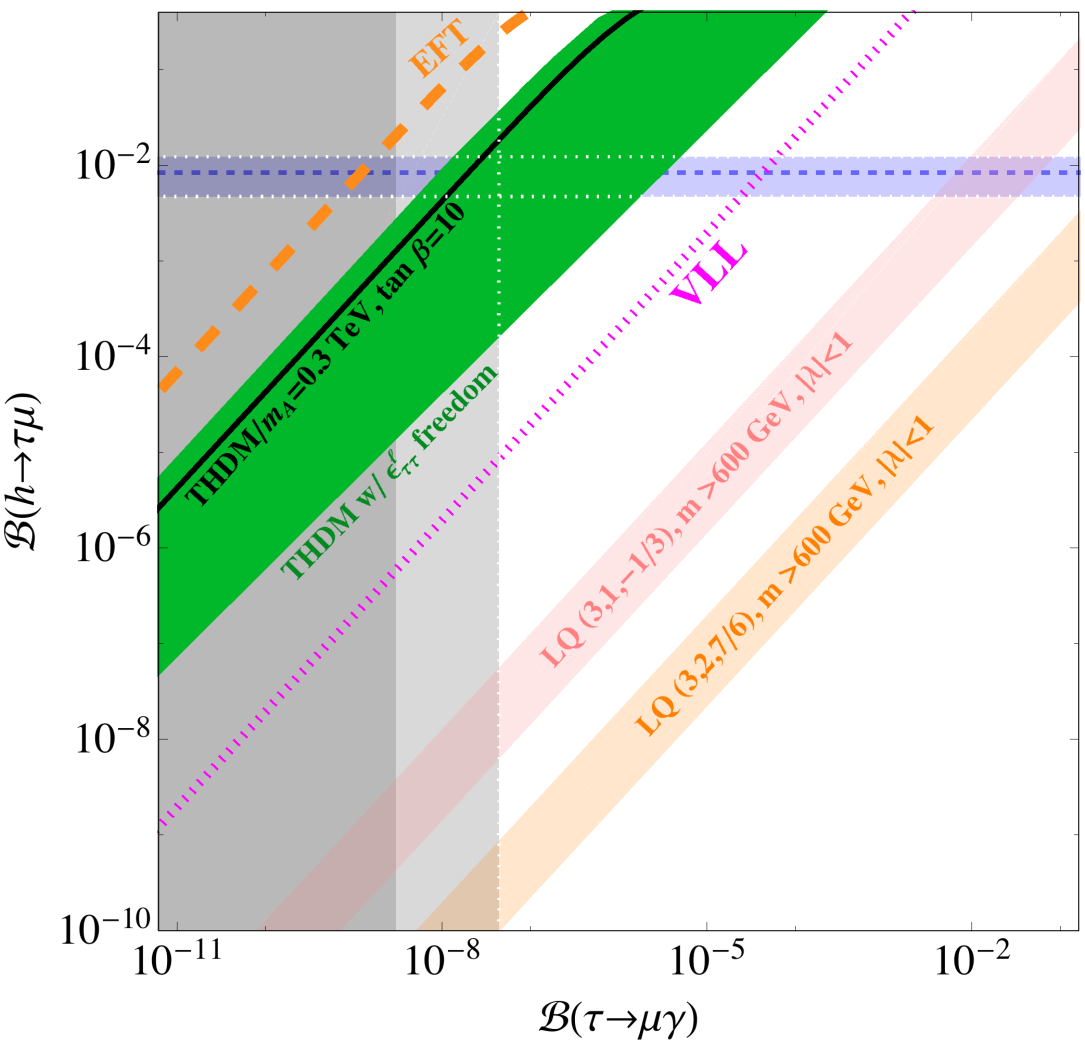
LQ candidates: Δ_1 =(3,1,-1/3)
Δ_2=(3,2,7/6)



$$\mathcal{L}_{\Delta_1} = y^L_{ij} \bar{Q}^{i,a} \Delta_1 \epsilon^{ab} L^{C\,j,b} + y^R_{ij} \bar{U}^i \Delta_1 E^{C\,j} + \text{h.c.}\,,$$







LQ alone cannot explain LFV rate of Higgs and make sensible prediction for $\tau \to \mu\gamma$ rate. We suggested LQ+ vector-like T quark (I.Doršner, S.F.,J.F.Kamenik, N.Košnik, I. Nisandžić, 1502.07784)

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 whether 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

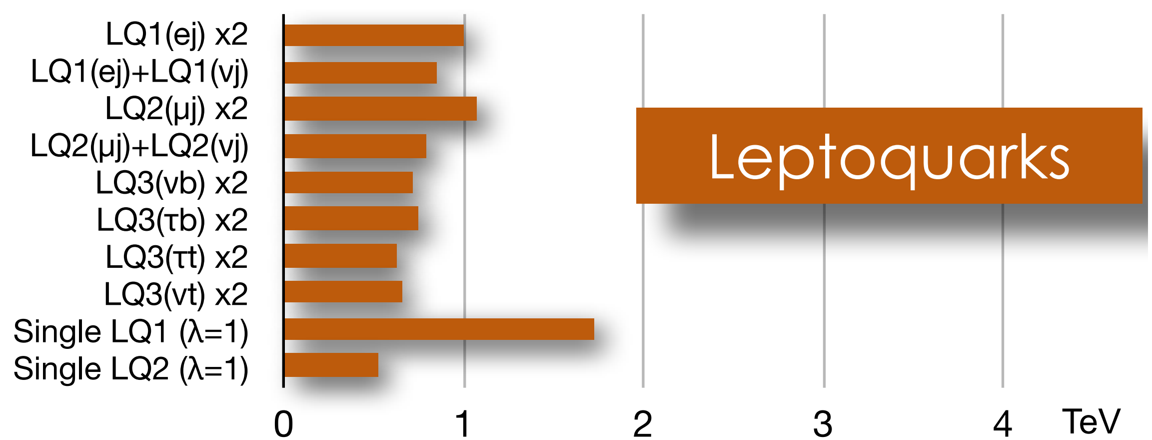
Tevatron (CDF, D0)

ATLAS

CMS

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

CMS

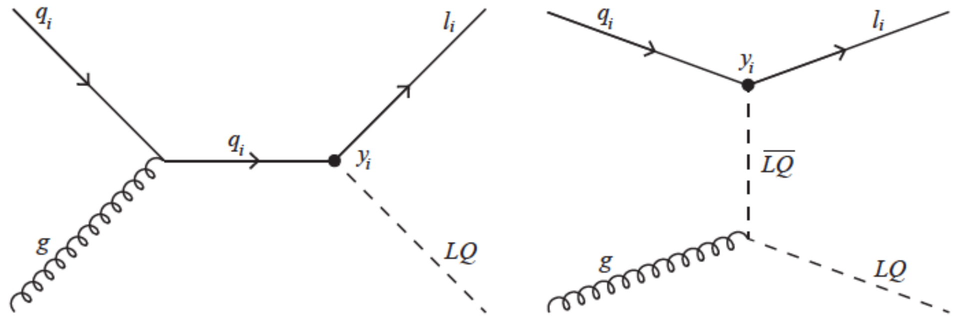


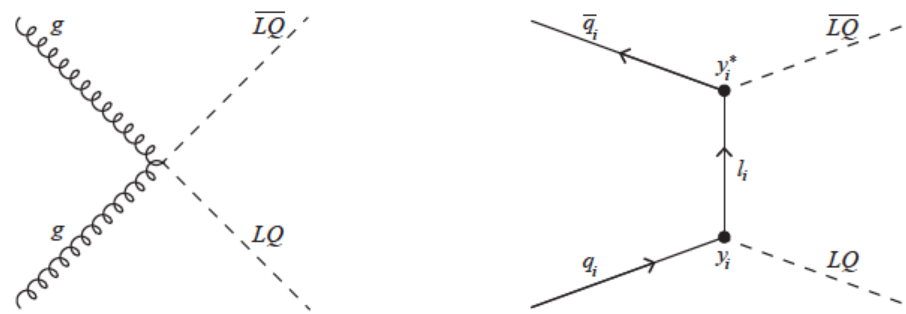
ATLAS

LQ	Scalar LQ 1st gen	2 e	$\geq$ 2 j	–	20.3	LQ mass 1.05 TeV
	Scalar LQ 2nd gen	2 μ	$\geq$ 2 j	–	20.3	LQ mass 1.0 TeV
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	LQ mass 640 GeV

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.

Search of LQ(3,2,1/6) at LHC

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

I generation couplings: best constraints come from atomic parity violation

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

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

$$\delta C_{1u(d)} = \frac{\sqrt{2}}{G_F}\frac{|y_{u(d)e}|^2}{8m_{\rm LQ}^2}$$

$$|y_{de}| \leq 0.34\left(\frac{m_{\rm LQ}}{1\,{\rm TeV}}\right)$$

$$|y_{ue}| \leq 0.36\left(\frac{m_{\rm LQ}}{1\,{\rm TeV}}\right)$$

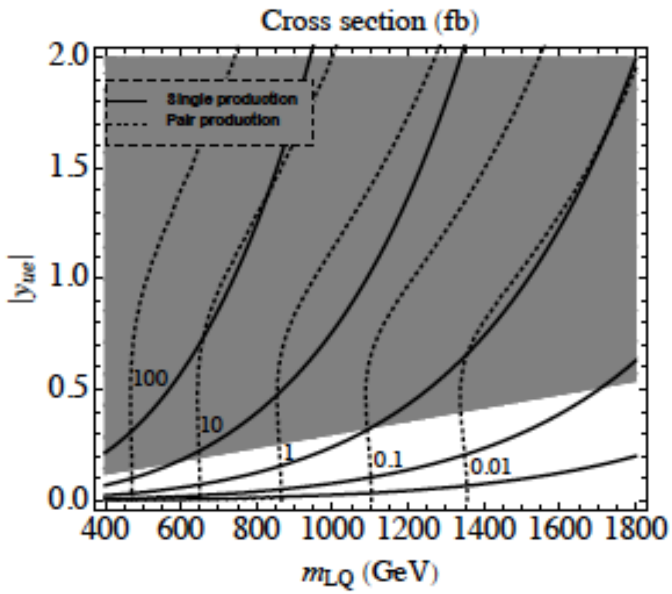
Bounds on II generation LQ

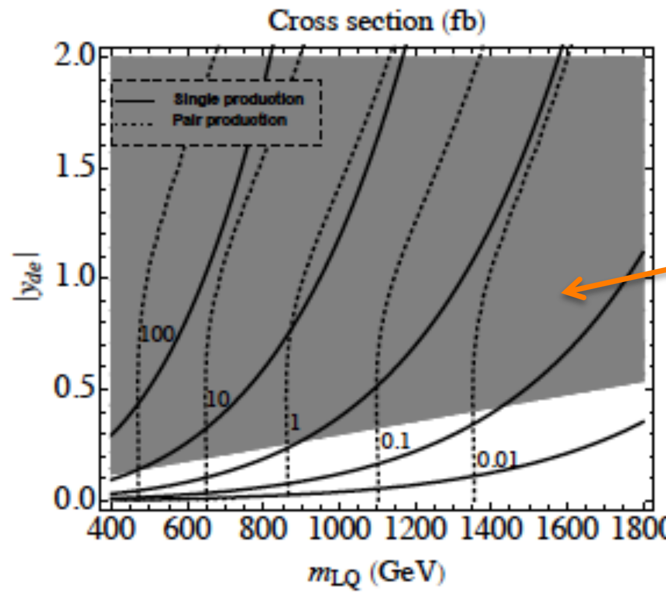
$$BR(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$$

Experimental bound:

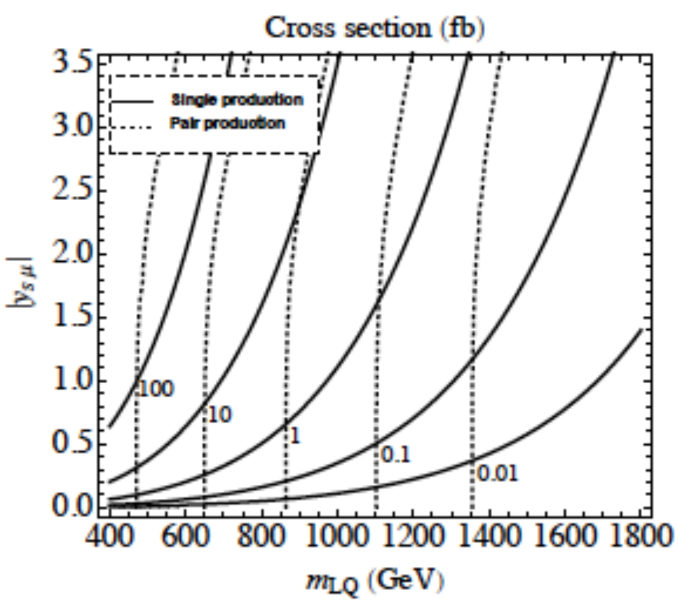
$$|y_{s\mu}y_{de}^*| < 2.1 \times 10^{-5}\left(\frac{m_{\rm LQ}}{1{\rm TeV}}\right)^2$$

The LQ of the first generation is fully constrained by APV, hence couplings of LQ to a down quark and an electron is very small.





excluded by APV



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

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 $Z \to \bar{b}b, \;, (g-2)_\mu, \; d_\tau, \; \tau \to \mu\gamma$, $\mu \to e\gamma$;
- Model with (3,2,7/6) LQ state can be accommodated with SU(5) GUT by adding 45 scalar representation.
- (3,2,1/6) can explain R_K anomaly.
- LQ alone cannot explain LFV rate of Higgs and make sensible prediction for $\tau \to \mu\gamma$ rate .
- 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!

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

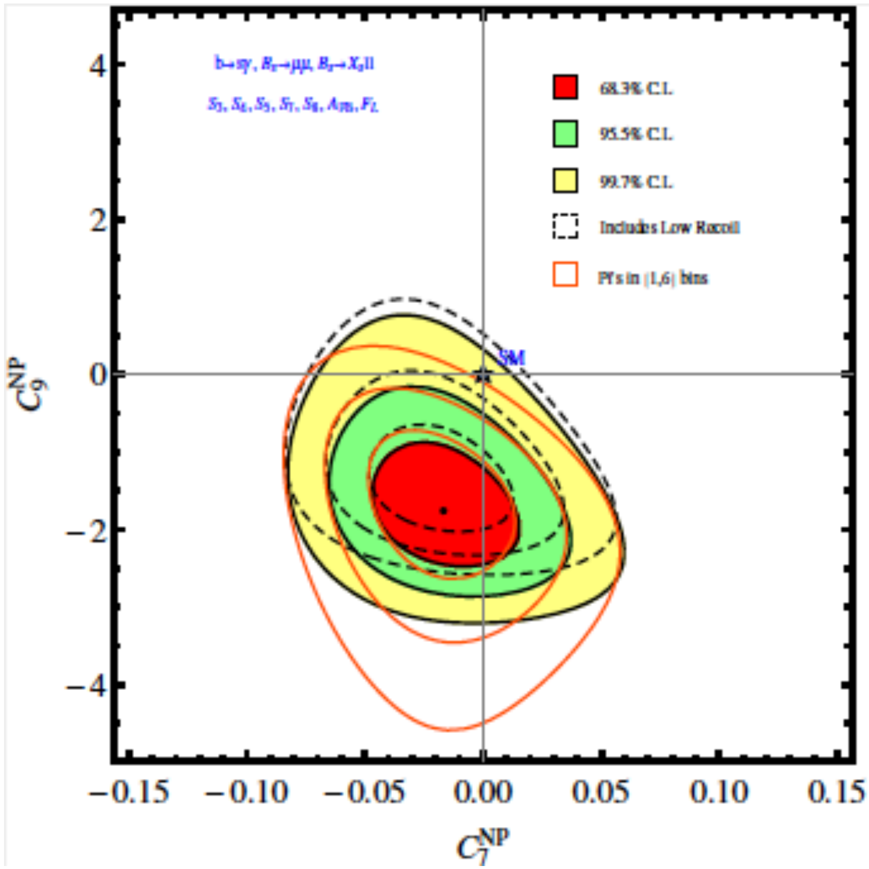
47 observables

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

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

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

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



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