# Low energy phenomenology and search for leptoquarks at LHC


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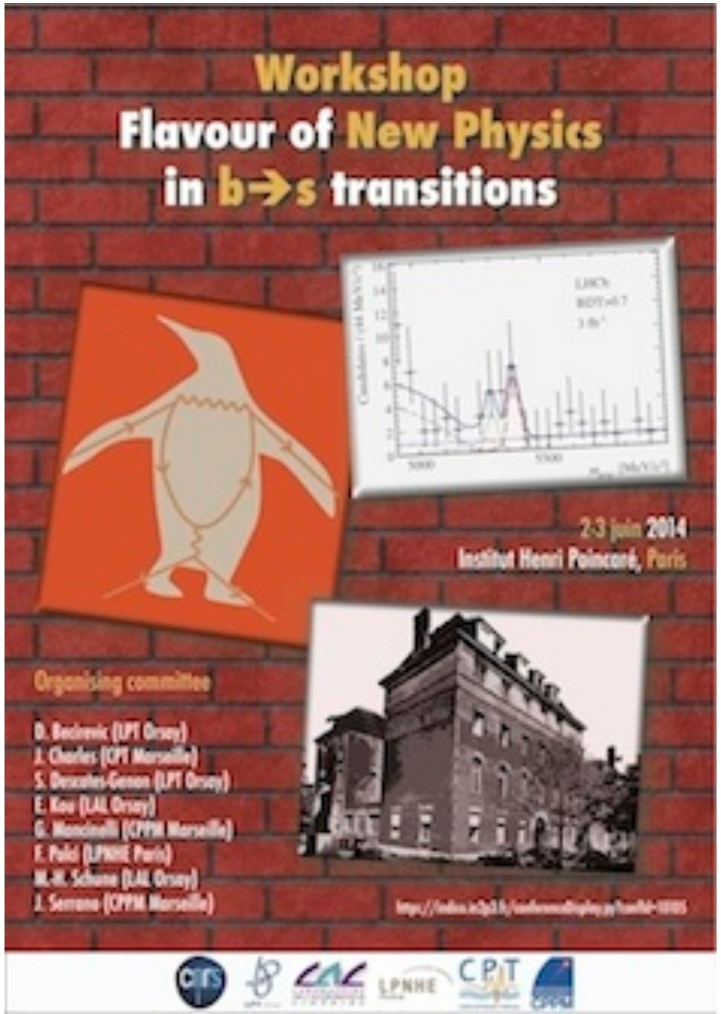


# Outline

- Motivation
- Colored scalar leptoquarks (3,2,7/6) and (3,2,1/6);
- Low-energy constraints;
- Colored scalars at LHC;
- Leptoquarks and GUT;
- Summary.

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

# Motivation

- Scalar LQ might explain small deviation: experiment $\leftrightarrow$ SM prediction; $\longrightarrow$ $\left\{ \begin{array}{l} B \to D^{(*)}\tau\nu_\tau \\ B \to K^* l^+ l^- \\ Z \to b\bar{b} \\ (g-2)_\mu \end{array} \right.$
- 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

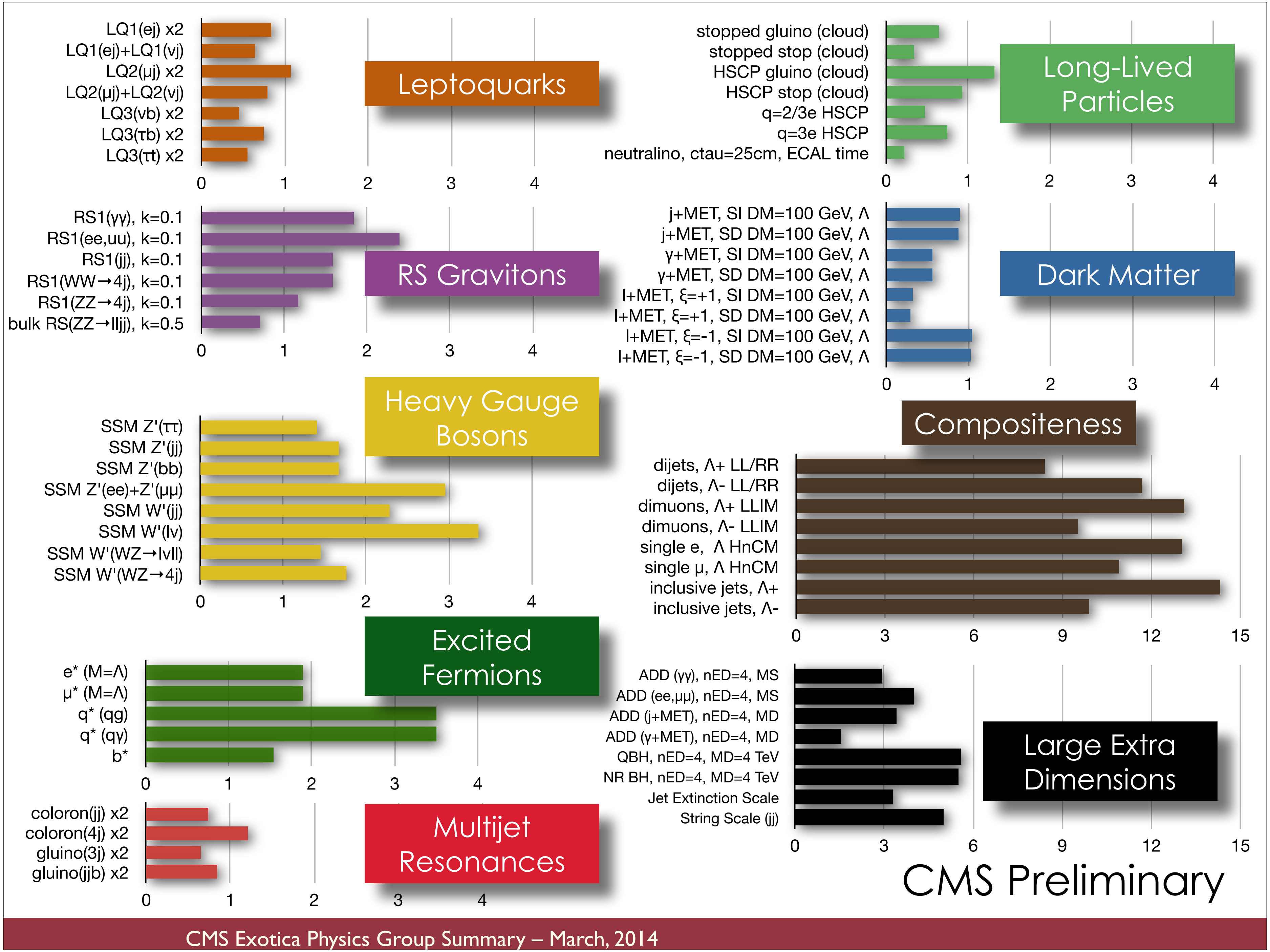
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

| | 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, $\lvert g \rvert = 1 g_D$ | 1207.6411 |

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

$10^{-1}$ 1 10 **Mass scale [TeV]**

*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(ττ) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,uu), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
RS1(ZZ→4j), k=0.1
bulk RS(ZZ→lljj), k=0.5
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
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)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0
1
2
3
4
6
9
12
15
CMS Preliminary
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 | $\overline{Q}i\tau^2 L^C,\ \overline{d}_R\nu_R^C,\ \overline{u}_R\ell_R^C$ | | |
| $(3,3)_{-1/3}$ | 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 | $\overline{u}_R\gamma_\mu i\tau^2 L^C,\ \overline{Q}\gamma_\mu\nu_R^C$ | $+1$ | $-1$ |
| $(\overline{3},2)_{5/6}$ | 1 | $\overline{Q}\gamma^\mu\ell_R^C,\ \overline{d}_R i\tau^2\gamma_\mu L^C$ | $+1$ | $-1$ |

✓ ✓

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

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

In  ratios there is no dependence on CKM matrix elements:

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

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

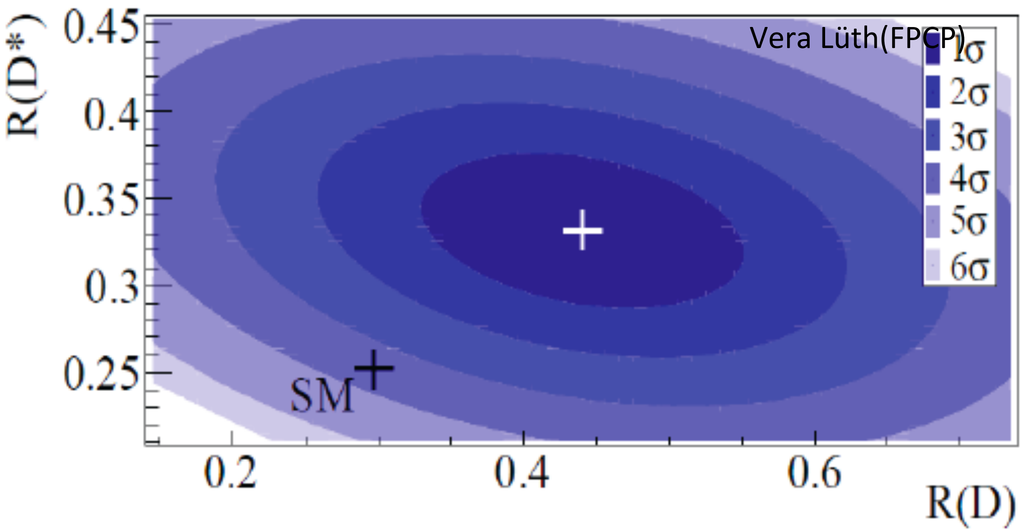
BaBar: 1205.5442
Belle: 0706.4429

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

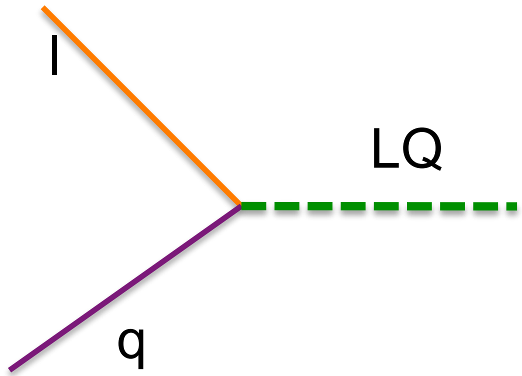
Many proposals of NP:

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 $b \to c l \bar{\nu}_l$




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

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

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

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 $b \to c l \nu_l, \quad l = e, \quad \mu$

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

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

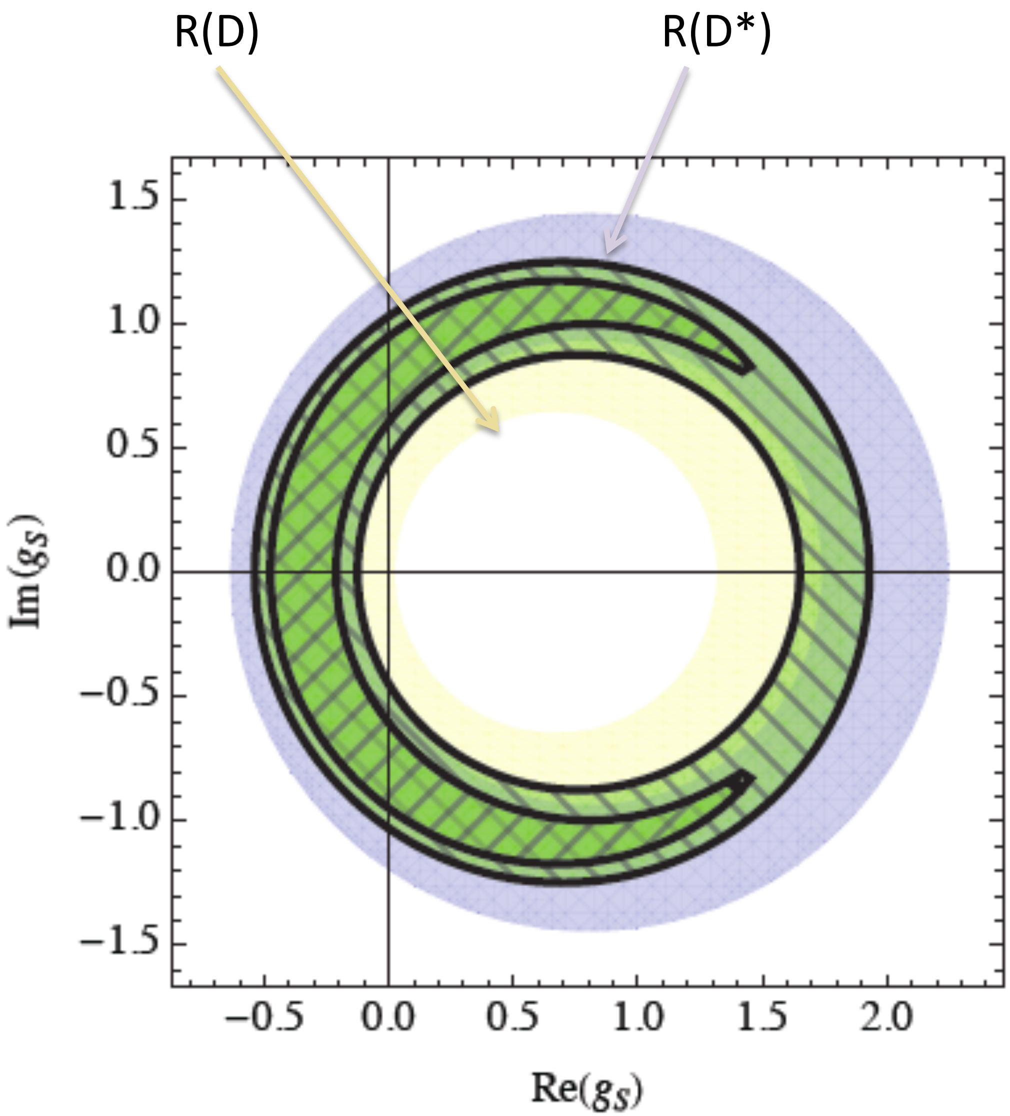
(Fierz's transformation are used)

SM + NP operators

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

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

this relation holds on the mass scale of Δ



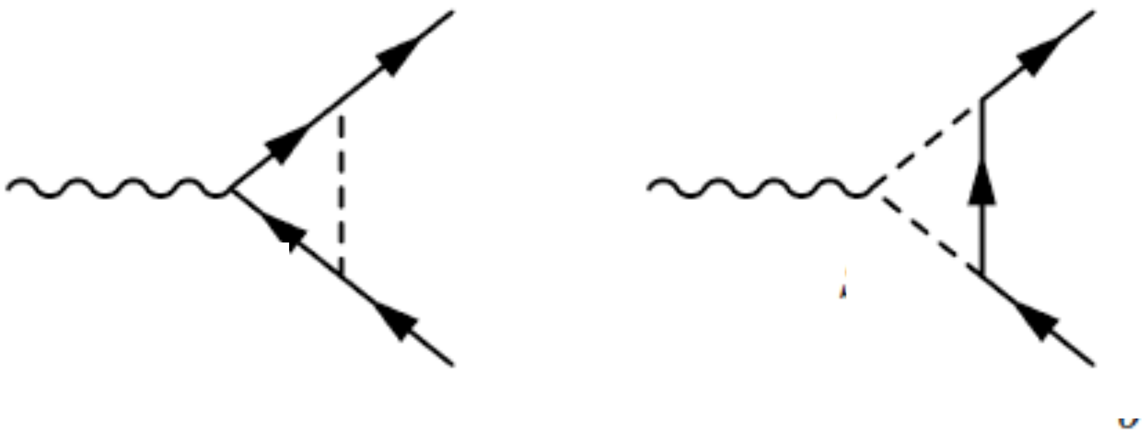

1σ range

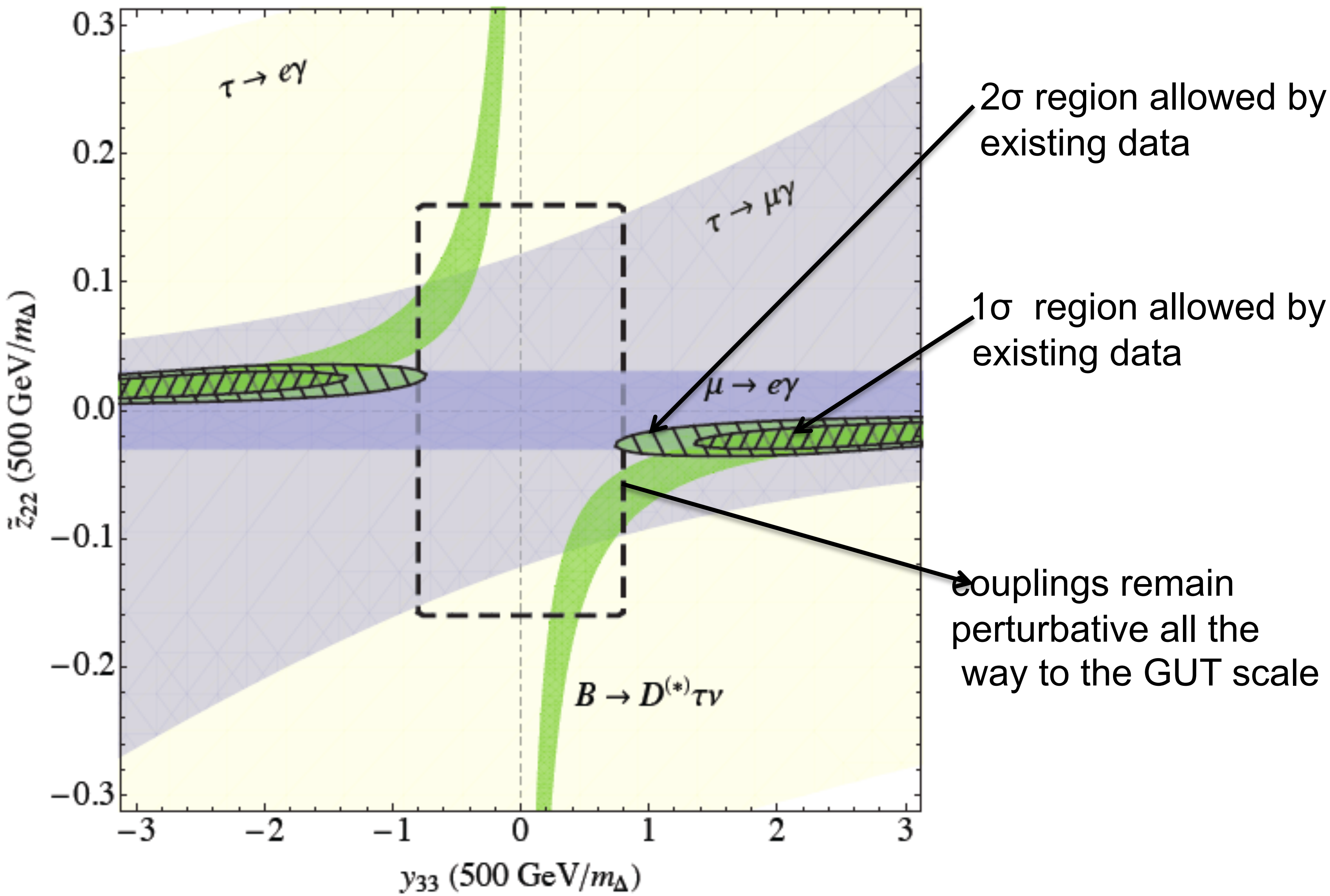
$$g_S(m_b) = -0.37^{+0.10}_{-0.07}$$

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

The model is constrained by:

- $Z \to b\bar{b}$ ( $\tau$ in the loop)
- $(g-2)_\mu$ (c –quark in the loop)
- τ electric dipole moment
- $\tau \to \mu\gamma$





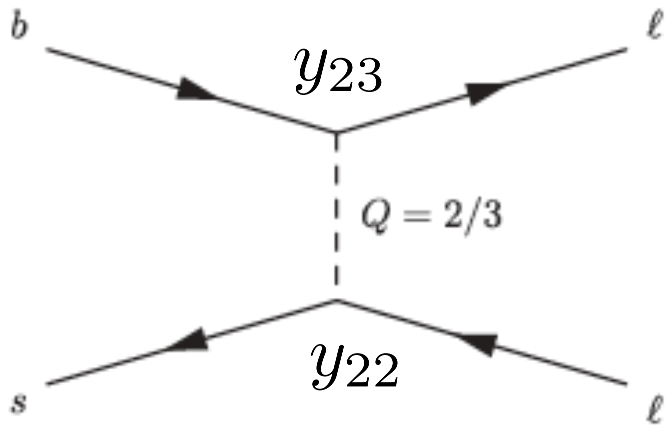
$\tau \to e\gamma$
$\tau \to \mu\gamma$
$\mu \to e\gamma$
$B \to D^{(*)}\tau\nu$
$\tilde{z}_{22}$ (500 GeV/$m_\Delta$)
$y_{33}$ (500 GeV/$m_\Delta$)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−3
−2
−1
0
1
2
3
2σ region allowed by existing data
1σ region allowed by existing data
couplings remain perturbative all the way to the GUT scale

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

N. Košnik, 1206.2970;
R. Mohanta 1310.0713

The presented model should be adjusted by introducing new couplings

$$Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & 0 & y_{33} \end{pmatrix}$$



The effective hamiltonian is:

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

$$\frac{y_{22} y_{23}^{*}}{8 {m_\Delta}^2}$$

Consequences:

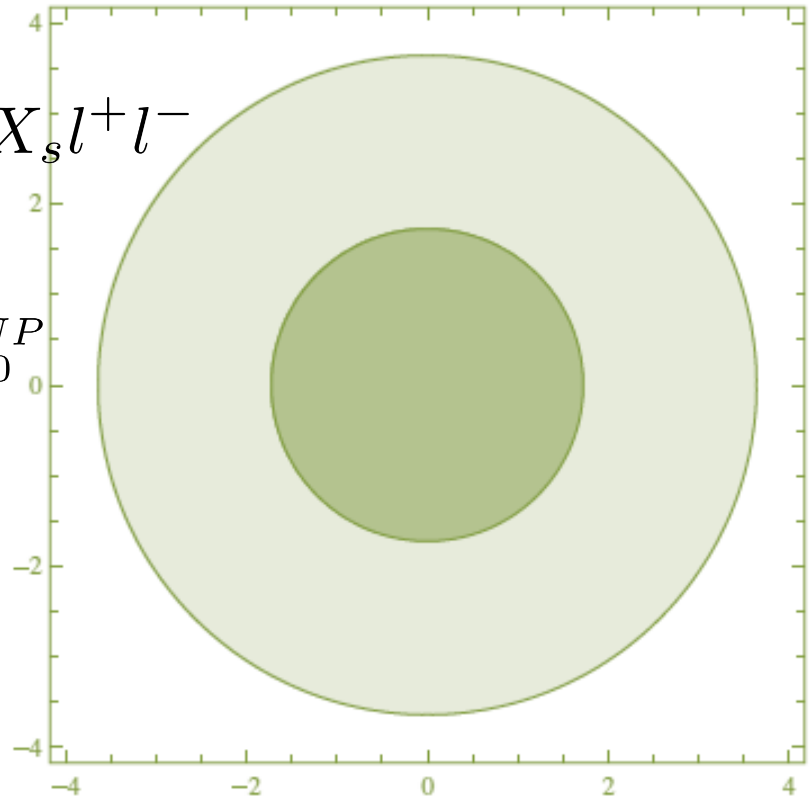
$(g-2)_\mu$ is not affected due to -1/3 charge of quarks and 2/3 charge of the LQ;

$Z \to b\bar{b}$ muon and tau in the loop –negligible modification of the $g_L$ coupling

$C_{9,10}^{NP}$ can be constrained by

$$B \to K^* l^+ l^-$$
$$B \to K\, l^+ l^-$$
$$B \to X_s l^+ l^-$$
$$B_s \to l^+ l^-$$

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




$C_{10}^{NP}$

$C_9^{NP}$

N. Košnik, 1206.2970;

R. Mohanta 1310.0713

The LQ parameter space constrained using $BR(B_S \to \mu^+ \mu^-)$ at LHCb and CMS

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

$$\boxed{\left|\frac{y_{23} y_{23}^*}{m_\Delta^2}\right| \leq 4.8 \cdot 10^{-9} \mathrm{GeV}^{-2}}$$

(3,2,1/6) LQ

$$\mathcal{L}_{\rm Y} = -y_{ij}\bar{d}^i_R \tilde{R}^a_2 \epsilon^{ab} L^{j,b}_L + \text{h.c.},$$

$$\mathcal{L}_{\rm Y} = -y_{ij}\bar{d}^i_R e^j_L \tilde{R}^{2/3}_2 + (yV_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + \text{h.c.}$$

N. Košnik, 1206.2970;
R. Mohanta 1310.0713

Košnik's for talk for $b \to s l^+ l^-$

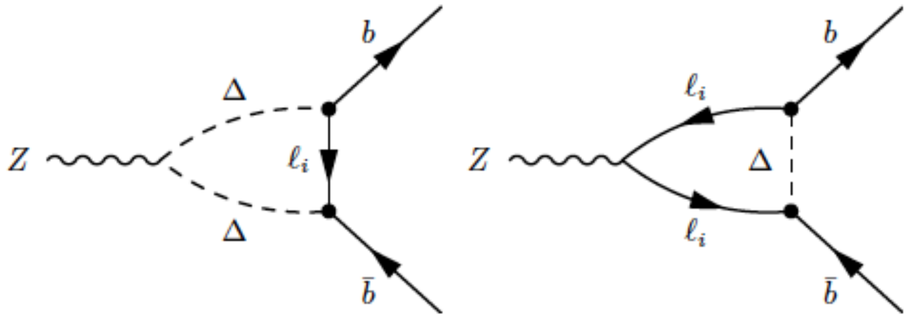
$$\mathcal{H}_{LQ} = \frac{y_{22}y^*_{23}}{8M_{LQ}}\bar{s}\gamma^\mu(1+\gamma_5)b\mu\gamma_\mu(1-\gamma_5)\mu \qquad C'^{\rm NP}_9 = -C'^{\rm NP}_{10}$$

(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!

# Experimental searches for LQ

Tevatron (CDF, D0)

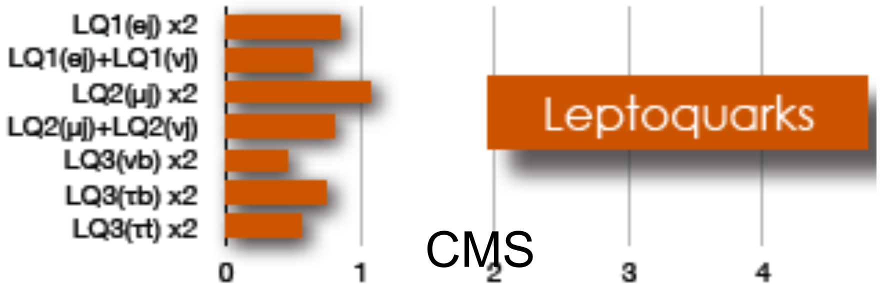
ATLAS

CMS

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

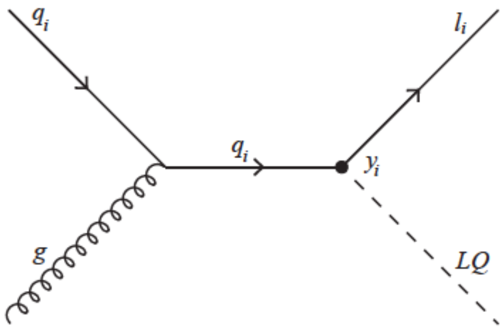
ATLAS

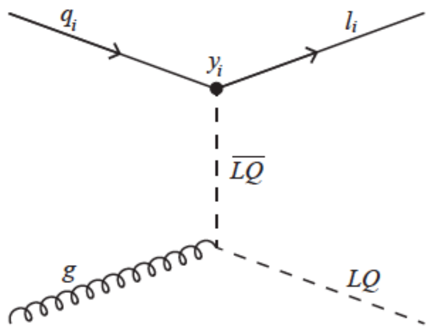
| | | | | | | |
|---|---|---|---|---|---|---|
| LQ | Scalar LQ 1st gen | 2 $e$ | $\geq 2$ j | – | 1.0 | LQ mass 660 GeV |
| | Scalar LQ 2nd gen | 2 $\mu$ | $\geq 2$ j | – | 1.0 | LQ mass 685 GeV |
| | Scalar LQ 3rd gen | 1 $e, \mu$, 1 $\tau$ | 1 b, 1 j | – | 4.7 | LQ mass 534 GeV |




CMS

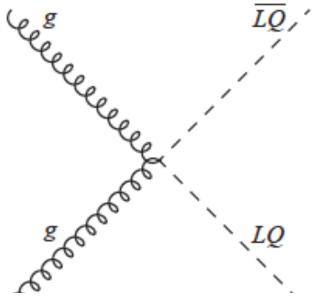
## Single LQ production

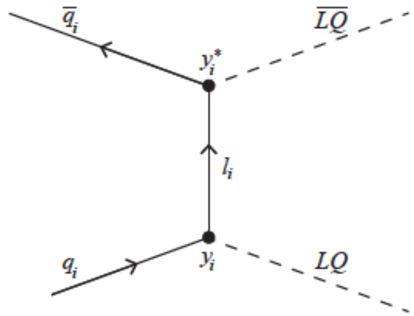



$$\sigma_{\text{single}}(y_i, m_{\text{LQ}}) = a(m_{\text{LQ}})|y_i|^2$$

## 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

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

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

$$\begin{cases} |y_{de}| \leq 0.34 \left(\frac{m_{\rm LQ}}{1\,\rm TeV}\right) \\ |y_{ue}| \leq 0.36 \left(\frac{m_{\rm LQ}}{1\,\rm TeV}\right) \end{cases}$$

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

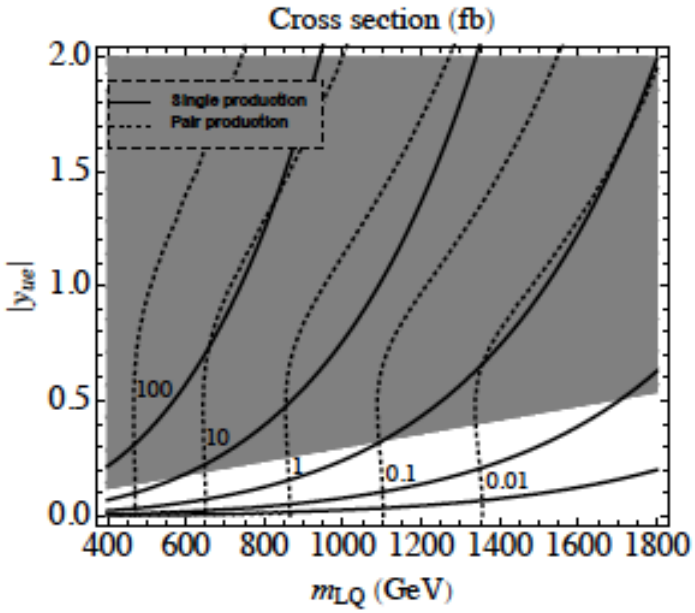
Bounds on II generation LQ

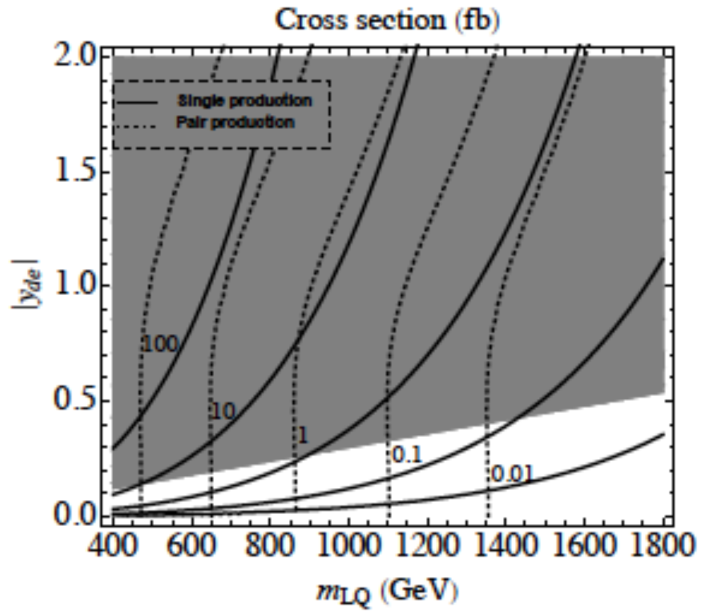
$$BR(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$$

Experimental bound:

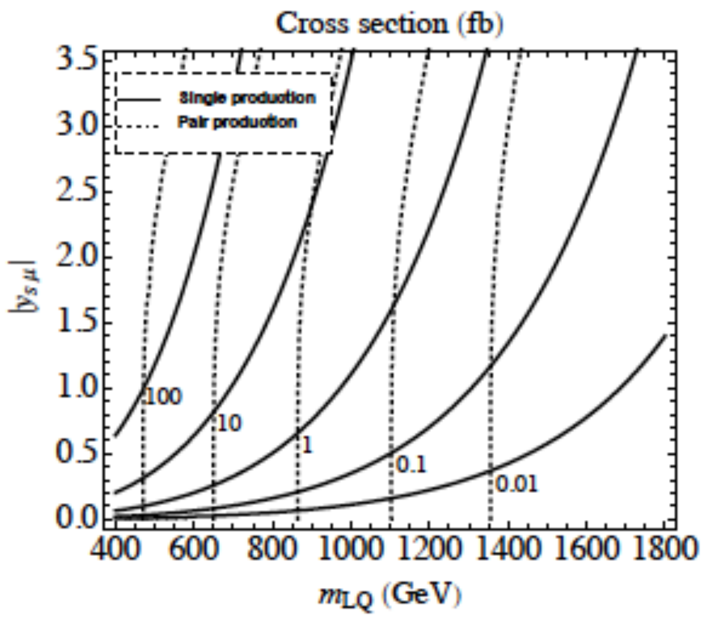
$$|y_{s\mu}y_{de}^*| < 2.1 \times 10^{-5} \left(\frac{m_{\rm LQ}}{1\rm TeV}\right)^2$$

The LQ of the first generation 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.

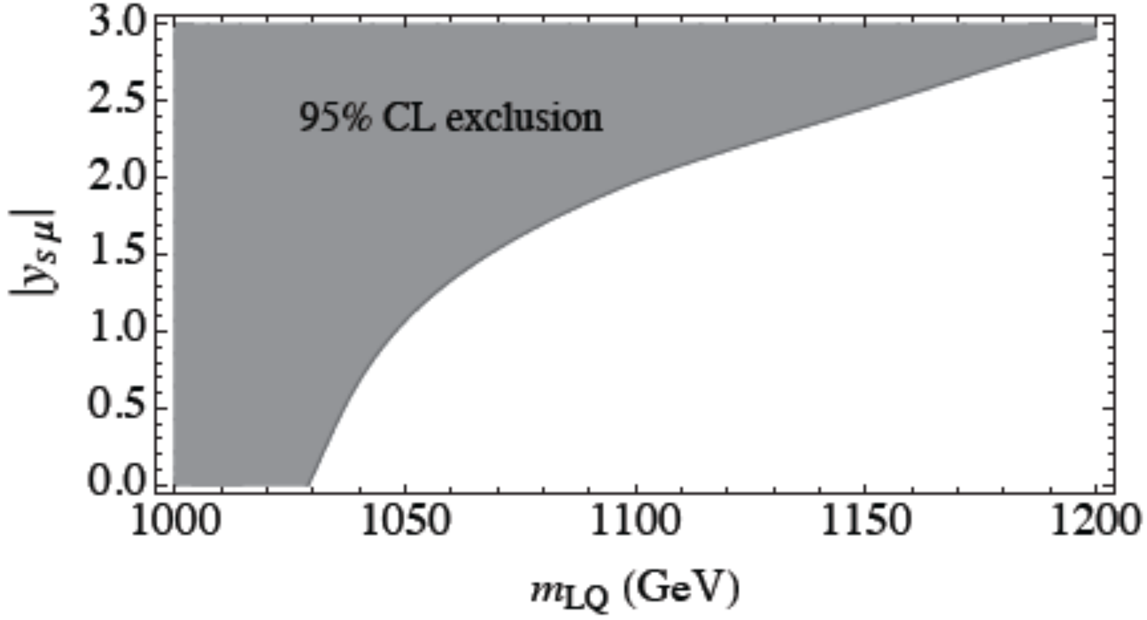



excluded by APV




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




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.

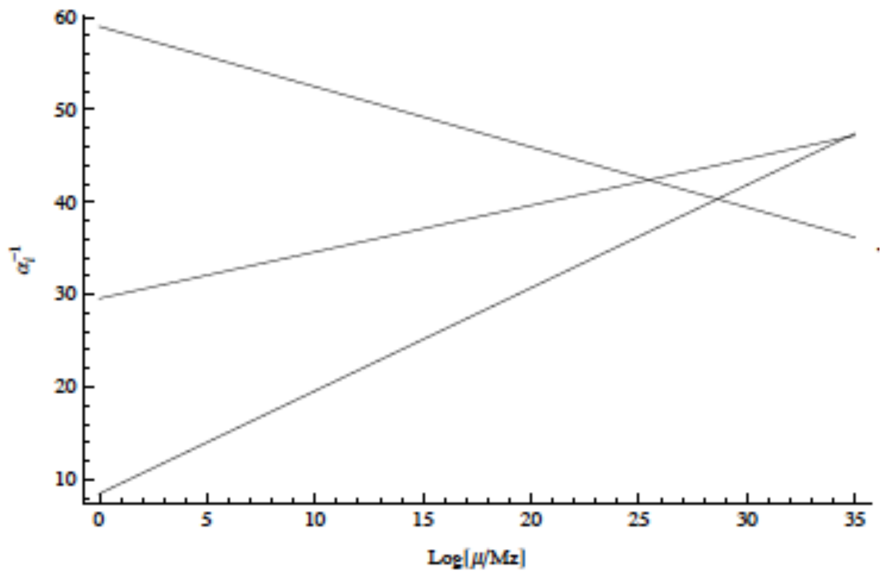
Is our low-energy Yukawa ansatz compatible with the idea of GUT?

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

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

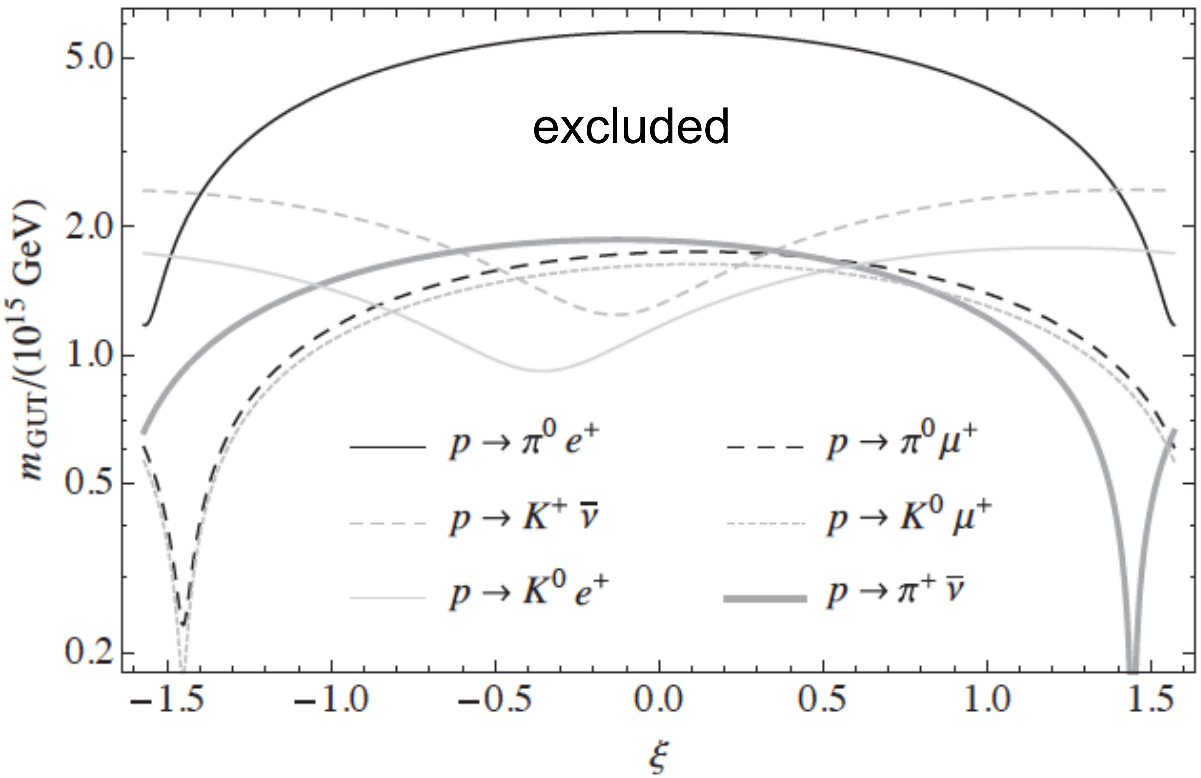
$$\boxed{M_D^{\rm diag} D_R^T - E_R M_E^{\rm diag} = 4 U_R Z v_{45}}$$

this equation should be satisfied at GUT scale!

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

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

Proton decay amplitude depends on one parameter!




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

# 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 $\boxed{Z \to \bar{b}b, \quad , (g-2)_\mu, \quad d_\tau, \quad \tau \to \mu\gamma}$;

• (3,2,7/6) and (3,2,1/6) can adjust b-> s data;

• 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;

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

## Predictions

$$B_c \to \tau \nu_\tau$$

$$\mathcal{B}(B_c \to \ell\nu) = \frac{m_{B_c}}{8\pi}\tau_{B_c} f_{B_c}^2 |G_F V_{cb} m_\ell|^2 \left(1 - \frac{m_\ell^2}{m_{B_c}^2}\right)^2 r^2$$

correction due to NP

$$f_{B_c} = 0.427(6)(2)\ \mathrm{GeV} \quad \mathrm{HPQCD}$$

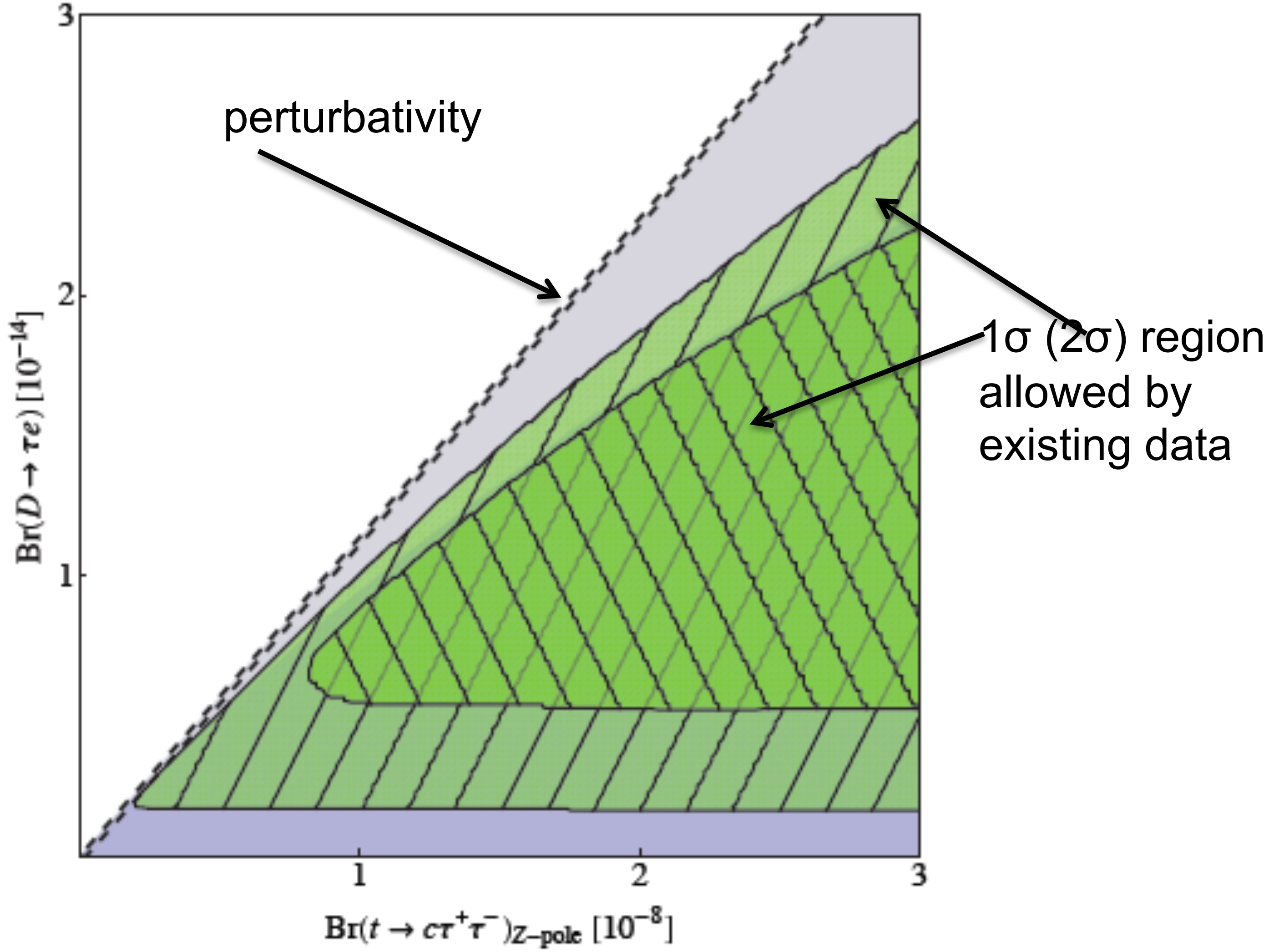
$$r = \left| 1 + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} g_S \right|$$

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

decrease $r^2 \simeq 0.36 \qquad g_S = -0.37$

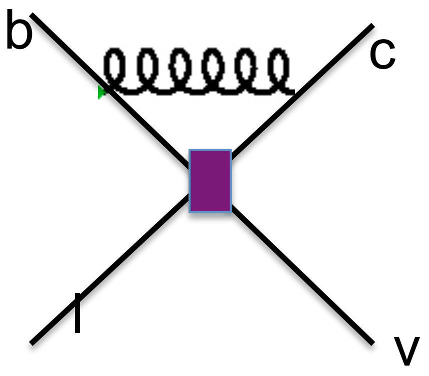
or increase of SM prediction $(r^2 \simeq 84)$ $\quad g_s \simeq 1.8 \pm 0.4i$

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



scalar and tensor operators have anomalous dimension

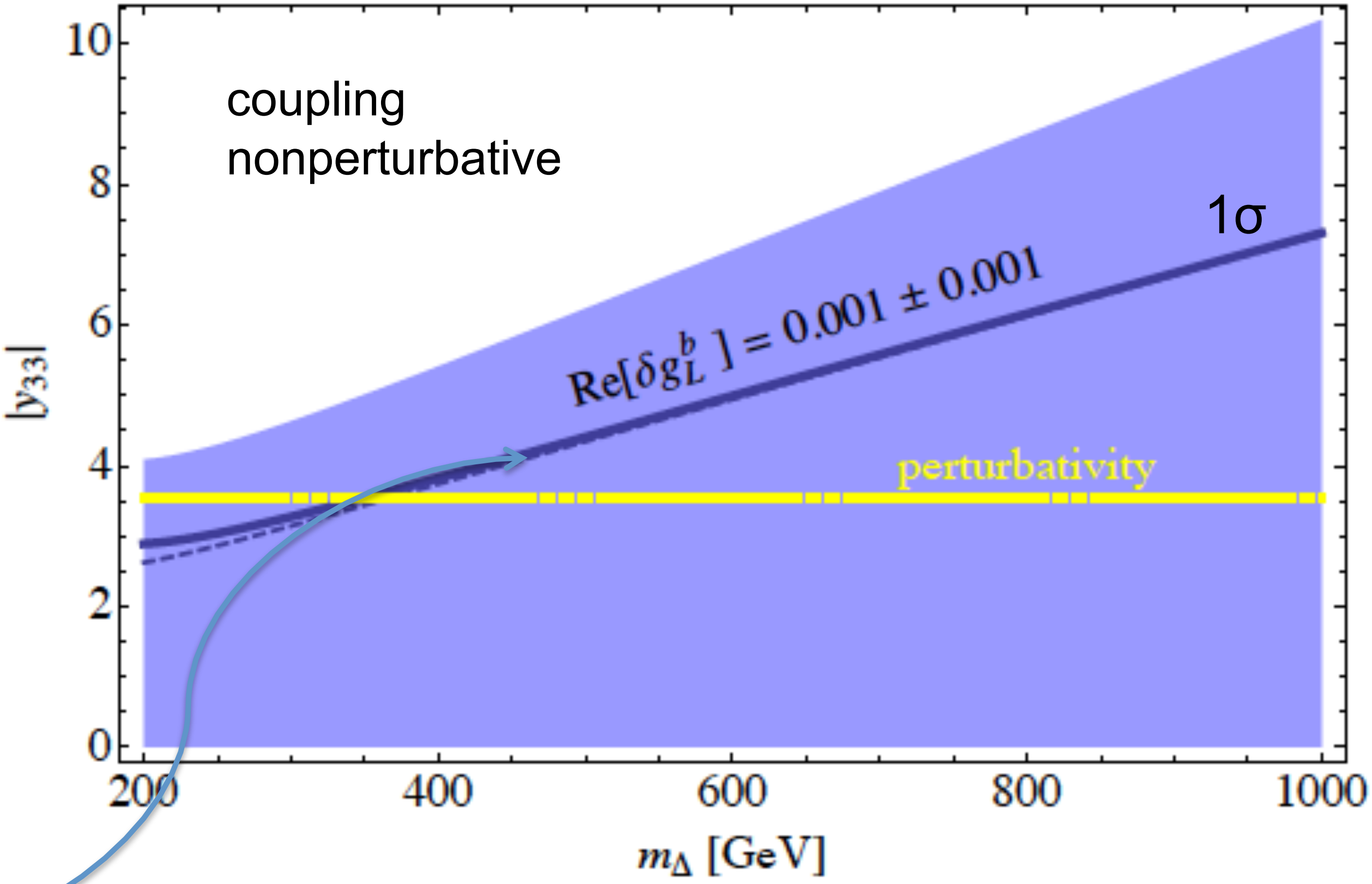
contrary to V and A currents




$$m_b, m_c << v$$

$$\boxed{g_T(m_b) \simeq 0.14\, g_S(m_b)}$$

$$m_\Delta = 500 \text{ GeV}$$




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

## Lepton electromagnetic current

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

$$\downarrow$$

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

## Muon anomalous magnetic moment

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

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