Lecture II

$B \to D^{(*)} \tau \nu_\tau$ decay and New Physics

Svjetlana Fajfer

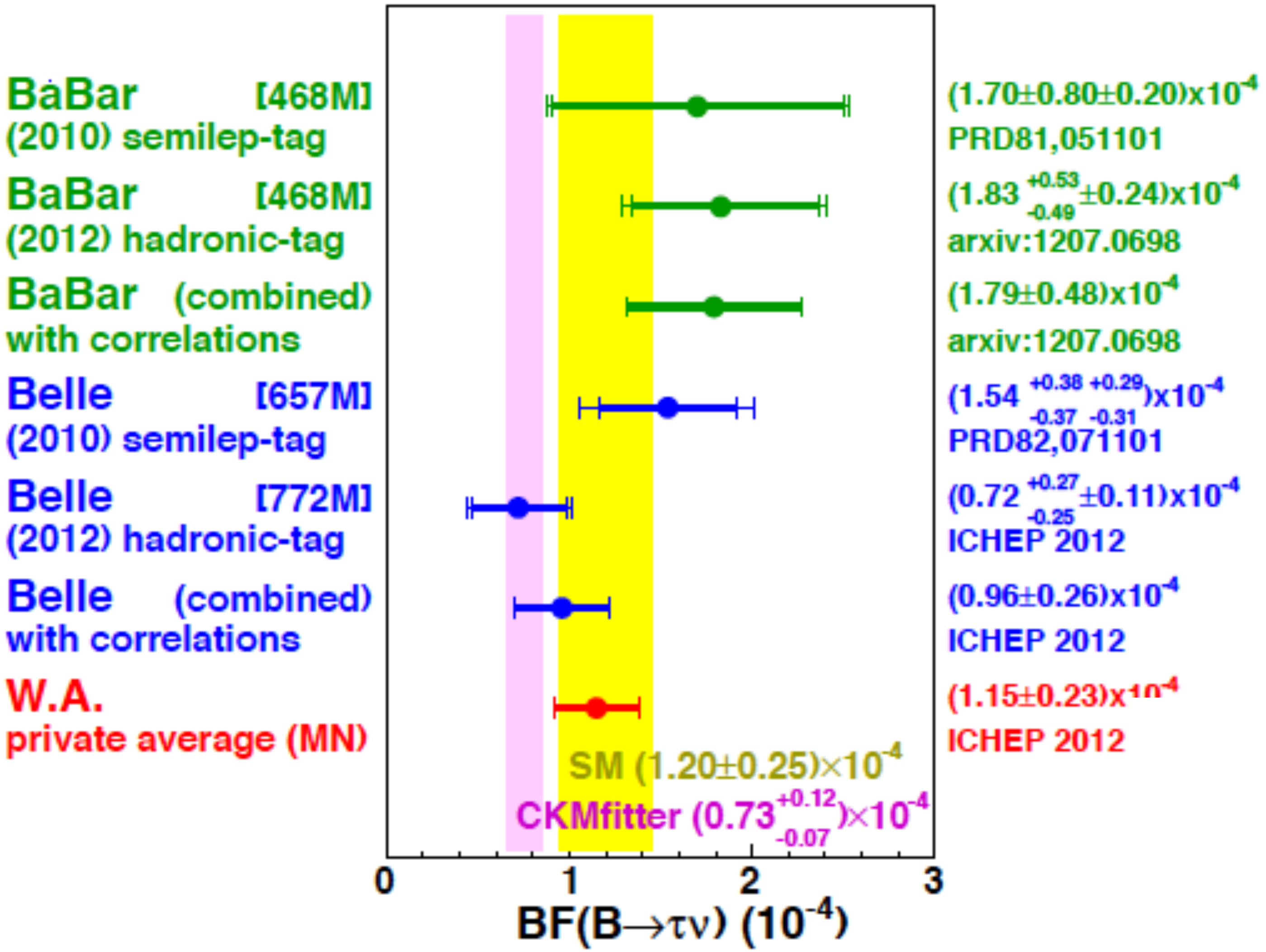
Physics Department, University of Ljubljana and
Institute J. Stefan, Ljubljana
Slovenia

Helmholtz International School "Physics of Heavy Quarks"
July 15-28, 2013, JINR, Dubna, Russia

Outline

1. Why B decay modes with $\tau\ \nu_\tau$ in the final state are interesting?
2. Theory SM + NP(?): $B \longrightarrow \tau\nu_\tau$;
3. SM + NP(?) in $B \rightarrow D(D^*) * \tau\nu_{\tau;}$
4. New variables in $B \rightarrow D(D^*) * \tau\nu_{\tau;;}$
5. Lepton flavor universality?
6. Summary and outlook.

Experimental results on BR($B \rightarrow \tau \upsilon_\tau$)



Babar - arXiv:1207.0698
Belle - arXive1208.4678

from Nakao, ICHEP 2012

Before ICHEP 2012 $BR(B \to \tau\nu_\tau) = (16.8 \pm 3.1) \times 10^{-5}$

2.9 σ disagreement with SM prediction (global fit CKM fitter)

$$\mathcal{B}(B \to \tau\nu) = (0.72^{+0.27}_{-0.25}(\text{stat.}) \pm 0.11(\text{syst.})) \times 10^{-4}$$

Yook, ICHEP 2012, new Belle result arXive:1208.4678

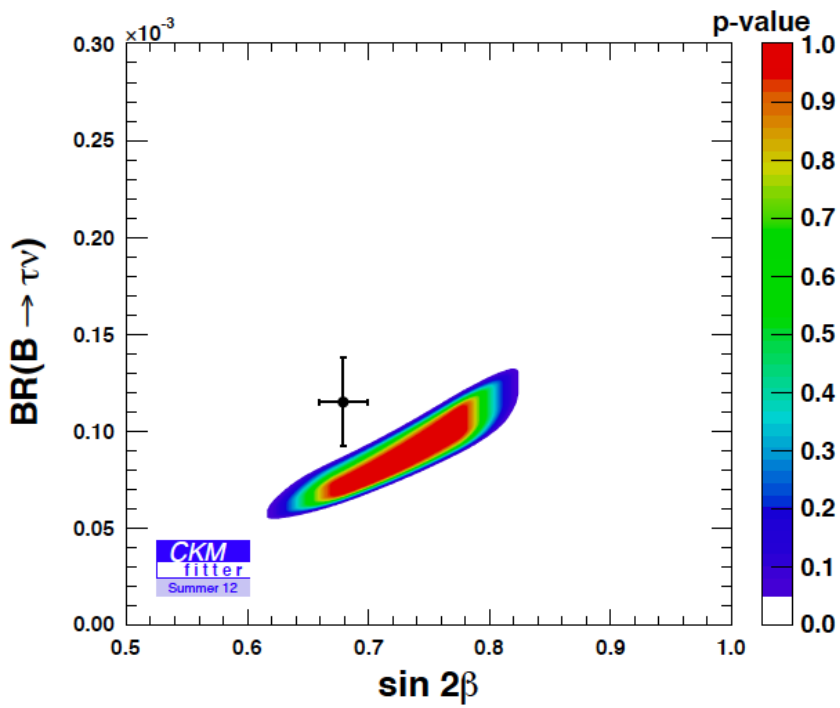
new world average

$$\mathcal{B}(B^- \to \tau^-\bar{\nu}) = (11.4 \pm 2.3) \times 10^{-5}$$

2.4σ disagreement

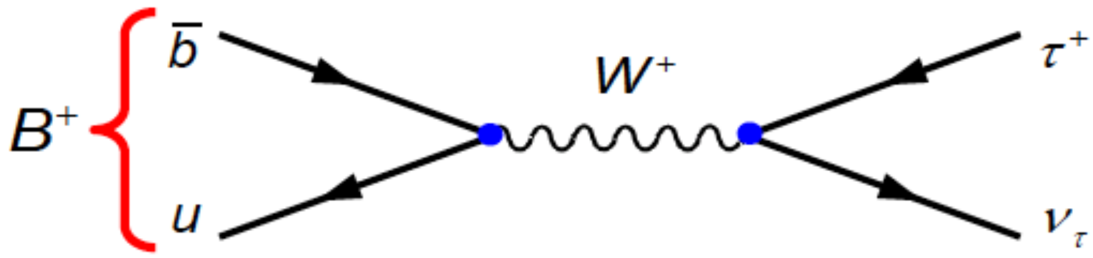
Impact on UT angle fits:

$\beta(\phi_1)$



SM in B⟶τυτ

f_B Lattice QCD



MILC Collaboration, 112.3051

$$f_{B^+} = 196.9(8.9)\ \text{MeV}$$
$$f_{B_s} = 242.0(9.5)\ \text{MeV}$$

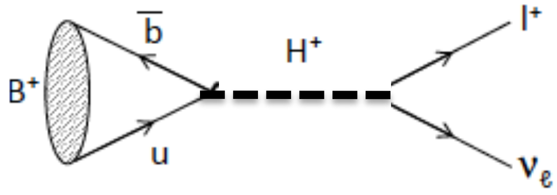
$$f_{B_s}/f_{B^+} = 1.229(0.026)$$

HPQCD Collaboration, 1202.4914

$$f_B = 0.191(9)\ \ \text{GeV}$$
$$f_{B_s} = 0.228(10)\ \ \text{GeV}$$

$$\frac{f_B}{f_{B_s}} = 1.188(18)$$

NP in $B \to \tau\nu_\tau$



$$\frac{BR(B \to \tau\nu_\tau)_{SM+NP}}{BR(B \to \tau\nu_\tau)_{SM}} = R_{NP}$$

$$R_{2HDM} = [1 - \tan^2\beta \frac{\mathrm{M_B^2}}{\mathrm{M_H^2}}]^2$$

0306037 (Akeroyd & Recksiegel)
W.-S. Hou, Phys. Rev. D 48, 2342 (1993). $\tan\beta = v_2/v_1$

Blankenburg & Isidori:1107.1216
(2HDM +MFV)

$R_{2HDM,MFV} > 1.2$

2HDM

One more Higgs doublet added to SM
Scalar spectrum {h, H, A, $H^{\pm}$}

$$\mathcal{L}_Y \sim \frac{\sqrt{2}}{c} H^+ \{\bar{u}[\xi_d V M_d P_R - \xi_u M^\dagger V P_L] d + \xi_l \bar{\nu} M_l P_R l\}$$

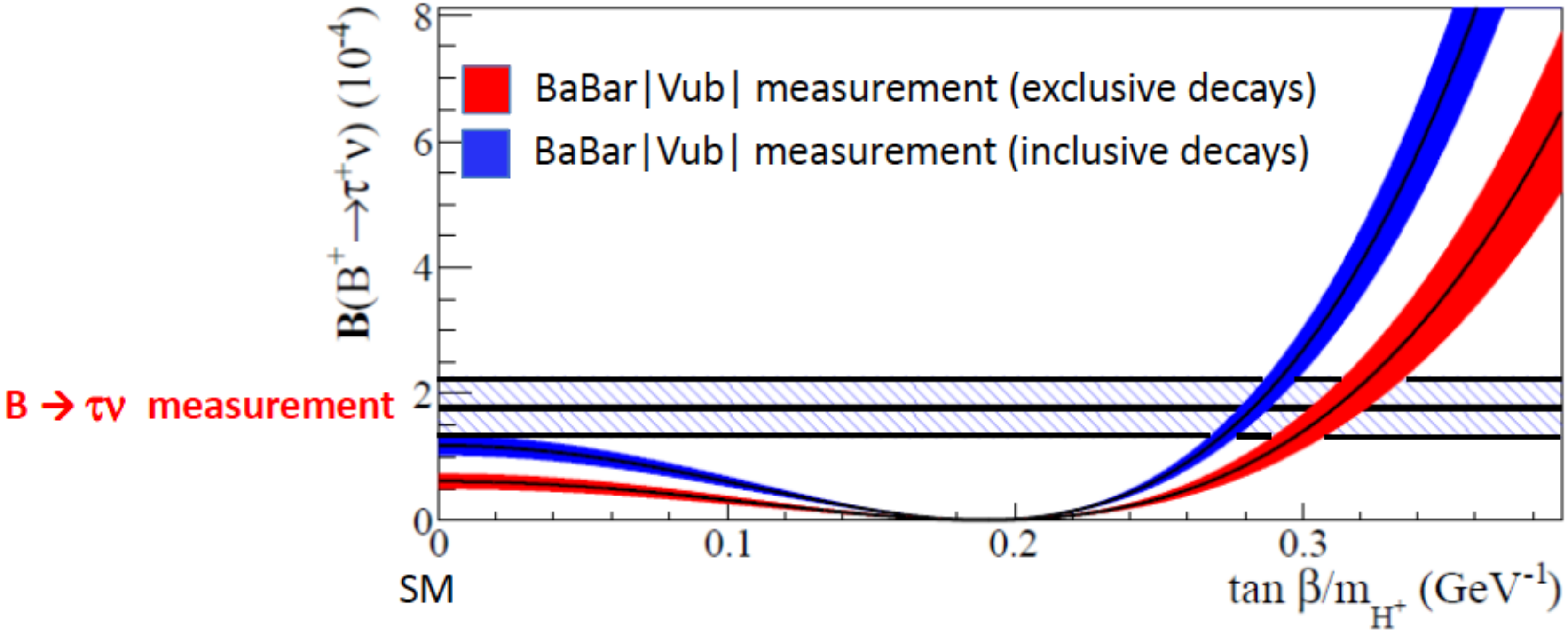
Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

ξ_f flavor universal

2HDM with natural flavor Conservation

A. Celis et al, 1210.8443

$$R_{2HDM} = [1 - \tan^2\beta \frac{\mathrm{M_B^2}}{\mathrm{M_H^2}}]$$



from Denardo, ICHEP 2012

$$\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}) = (14.6 \pm 0.7) \times 10^{-5}$$

Consistent with CKM unitarity prediction (UTfit; 0908.3470 and 1106.4041).

$$\mathcal{R}^{\pi}_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu})}{\mathcal{B}(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu})} = 0.73 \pm 0.15$$

$$\mathcal{R}^{\pi,\mathrm{SM}}_{\tau/\ell} = 0.31(6)$$

no sensitivity on V_{ub}

2.6σ discrepancy

Experimental results

In ratios there is no dependence on CKM matrix elements:

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

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

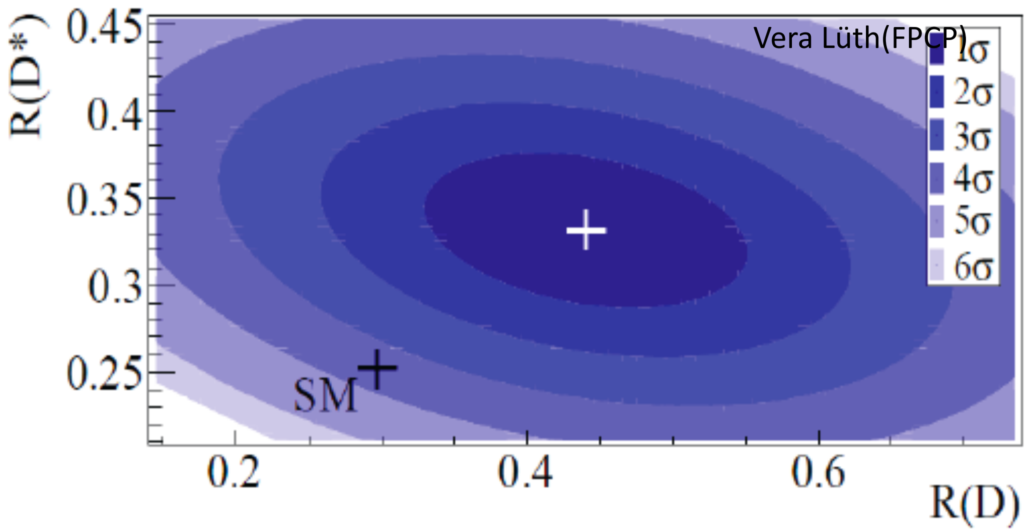
BaBar: 1205.5442
Belle: 0706.4429

combined 3.4σ larger than SM

Standard Model

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

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

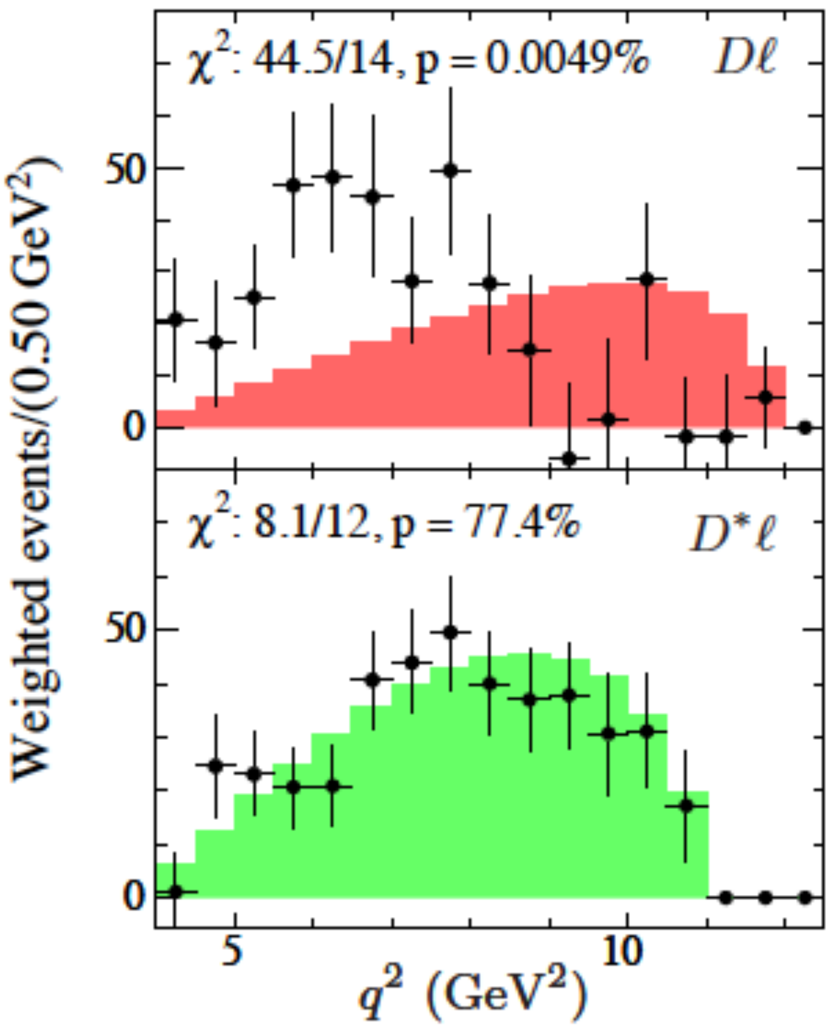


$$\mathcal{R}^-(D) = \frac{\mathcal{B}(B^- \to D^0\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}_\ell)} = 0.429 \pm 0.082 \pm 0.052,$$

$$\mathcal{R}^-(D^*) = \frac{\mathcal{B}(B^- \to D^{*0}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^{*0}\ell^-\bar{\nu}_\ell)} = 0.322 \pm 0.032 \pm 0.022,$$

$$\mathcal{R}^0(D) = \frac{\mathcal{B}(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell)} = 0.469 \pm 0.084 \pm 0.053,$$

$$\mathcal{R}^0(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell)} = 0.355 \pm 0.039 \pm 0.021.$$



BaBar , 1303.0571

Momentum transfer distributions

Standard Model or New Physics?

Can observed effects be explained within SM?

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

How well do we know all new/old form-factors?

Lattice improvements?

Lepton flavor universality violation in B semileptonic decays?

Comment on π and K physics: Tests of LFU conservation holds up to 1 percent level for all three lepton generations. Experiment and SM expectations – excellent agreement!

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

NP signatures in $B \to D\tau\nu_\tau$

effective hamiltonian

$B \to D\tau\nu_\tau$

$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}} J_{bc,\mu} \sum_{\ell=e,\mu,\tau} (\bar{\ell}\gamma^\mu P_L \nu_\ell) + \text{h.c.}$$

$$J^\mu_{bc} = \underbrace{\bar{c}\gamma^\mu P_L b}_{\text{SM}} + \underbrace{g_{SL} i\partial^\mu(\bar{c}P_L b) + g_{SR} i\partial^\mu(\bar{c}P_R b)}_{\text{NP}}$$

only scalar (pseudoscular) currents!

$$R \equiv \frac{Br(B \to D\tau\bar{\nu}_\tau)}{Br(B \to De\bar{\nu}_e)}$$

modification of new physics

$$R/R_{\rm SM} = 1 + 1.5{\rm Re}[m_\tau(g_{SR}+g_{SL})] + 1.0|m_\tau(g_{SR}+g_{SL})|^2$$

using form-factor shapes
from HFAG and PDG parameters

Mescia& Kamenik : 0802.3790
Tanaka & Watanabe, 1006.4306;
Faller, Mannel&Tyrczyk 1105.3679.,
S.F., J.F.Kamenik, Nisanndzic, 1203.2654.

New NP tests in $B \to D \tau \nu_\tau$

Lepton helicity are defined in the rest frame of W

$$\frac{d\Gamma_-}{dq^2} = \frac{1}{24\pi^3}(1-\frac{m_l^2}{q^2})|\vec{p}_D|^3|G_V F_+(q^2) - \frac{m_l}{M_B}G_T F_2(q^2)|^2$$

$$\frac{d\Gamma_+}{dq^2} = \frac{1}{16\pi^3}(1-\frac{m_l^2}{q^2})\frac{|\vec{p}_D|}{q^2}\{|\frac{1}{3}|\vec{p}_D|^2 m_l G_V F_+(q^2) - \frac{q^2}{M_B}G_T F_2(q^2)|^2 + \frac{M_B^2-M_D^2}{4M_B^2}|(m_l G_V - \frac{q^2}{M_B^2-M_D^2}F_0(q^2)\}$$

allowing new vector, scalar and tensor currents

$$G_S = \tfrac{1}{2}(g_{SL}+g_{SR})$$
$$G_P = \tfrac{1}{2}(g_{SR}-g_{SL})$$

Helicity asymmetry

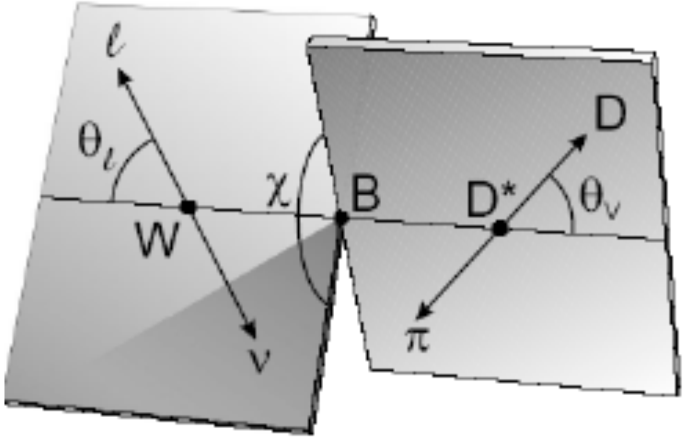
SM: $\begin{cases} G_V \to G_F V_{ij} \\ G_S = G_T = 0 \end{cases}$

$$P_L = \frac{\Gamma_+(B\to D\tau\nu_\tau) - \Gamma_-(B\to D\tau\nu_\tau)}{\Gamma(B\to D\tau\nu_\tau)}$$

Baily et al., 1206.4992 (MILC col.)
Tanaka&Watanabe, 1005.4306

$$P_L(D) = 0.325(4)(3)$$

SM in $B \to D^* \tau \nu_\tau$



helicity amplitudes

$$\frac{d^2\Gamma_\tau}{dq^2 d\cos\theta} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}| q^2}{256\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times$$

$$\Bigg[(1-\cos\theta)^2 |H_{++}|^2 + (1+\cos\theta)^2 |H_{--}|^2 + 2\sin^2\theta |H_{00}|^2 +$$

$$\frac{m_\tau^2}{q^2} \left((\sin^2\theta (|H_{++}|^2 + |H_{--}|^2) + 2|H_{0t} - H_{00}\cos\theta|^2 \right) \Bigg],$$

S.F. , J.F.Kamenik, Nisanndzic, 1203.2654,
Körner& Schuller, ZPC 38 (1988) 511,
S. Faller et al., 1105.3679,
Sakaki&Tanaka, 1205.4908.

$$H_{\pm\pm}^{\rm SM}(q^2) = (m_B + m_{D^*})A_1(q^2) \mp \frac{2m_B}{m_B + m_{D^*}}|\mathbf{p}|V(q^2)\,,$$

$$H_{00}^{\rm SM}(q^2) = \frac{1}{2m_{D^*}\sqrt{q^2}}\left[(m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2) - \frac{4m_B^2|\mathbf{p}|^2}{m_B + m_{D^*}}A_2(q^2)\right]$$

$$H_{0t}^{\rm SM}(q^2) = \frac{2m_B|\mathbf{p}|}{\sqrt{q^2}}A_0(q^2)\,.$$

Heavy Quark limit for b and c quarks ⟶ only one form-factor!
Lattice form factors are not yet available.

$$A_0(q^2) = \frac{R_0(w)}{R_{D^*}}h_{A_1}(w)$$

$$A_2(q^2) = \frac{R_2(w)}{R_{D^*}}h_{A_1}(w)$$

$$V(q^2) = \frac{R_1(w)}{R_{D^*}}h_{A_1}(w)$$

$$h_{A_1}(w) = A_1(q^2)\frac{1}{R_{D^*}}\frac{2}{w+1}$$

$$w \equiv v_B \cdot v_{D^*} = \frac{m_B^2 + m_{D*}^2 - q^2}{2m_B m_{D*}}$$

Caprini et al., hep-ph/9712417

recent work form-factors: Gambino et a.l, 1206.2296

NP in $R_{\tau/l}$ and $R_{\tau/l}{}^*$

$$\mathcal{R}^{*,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 1.32 \pm 0.12$$

$$\mathcal{R}^{\pi,\mathrm{exp}}_{\tau/\ell}/\mathcal{R}^{\pi,\mathrm{SM}}_{\tau/\ell} = 2.38 \pm 0.66$$

combined excess 3.9σ

NP generated at a scale Λ higher than the electroweak scale

Effective Lagrangian approach (1206.1872)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_a \frac{z_a}{\Lambda^{d_a-4}} \mathcal{Q}_i + \mathrm{h.c.}$$

NP contribution

$$c_a = z_a(\Lambda/v)^{d_a-4}$$

$$v = (\sqrt{2}/4G_F)^{1/2} \simeq 174 \text{ GeV}$$

(see A. Crivellin et al., 1206.2634)

assumptions: a) no down – type FCNCs;
b) no LFU in pion and kaon sector

the lowest dimensional operators $d_i \leq 8$ are:

i,j are generational indices

$$\mathcal{Q}_L = (\bar{q}_3 \gamma_\mu \tau^a q_3) \mathcal{J}^\mu_{3,a} \,,$$

$$\mathcal{Q}^i_R = (\bar{u}_{R,i} \gamma_\mu b_R)(H^\dagger \tau^a \tilde{H}) \mathcal{J}^\mu_{3,a}$$

$$\mathcal{Q}_{LR} = i\partial_\mu (\bar{q}_3 \tau^a H b_R) \textstyle\sum_j \mathcal{J}^\mu_{j,a} \,,$$

$$\mathcal{Q}^i_{RL} = i\partial_\mu (\bar{u}_{R,i} \tilde{H}^\dagger \tau^a q_3) \textstyle\sum_j \mathcal{J}^\mu_{j,a} \,,$$

down quark basis

$$q_i = (V^{ji*}_{CKM} u_{L,j}, d_{L,i})^T$$

and charged lepton basis

$$l_i = (V^{ji*}_{PMNS} \nu_{L,j}, e_{L,i})^T$$

$$\tau_a = \sigma_a/2, \; \mathcal{J}^\mu_{j,a} = (\bar{l}_j \gamma^\mu \tau_a l_j), \; \tilde{H} \equiv i\sigma_2 H^*$$

a new light invisible fermion ψ could mimic the missing energy of SM neutrinos

$$\mathcal{Q}^i_{\psi S} = (\bar{q}_i b_R)(\bar{l}_3 \psi_R) \,, \; \mathcal{Q}^i_{\psi V} = (\bar{u}_i \gamma_\mu b_R)(\bar{\tau}_R \gamma^\mu \psi_R)$$

Minimal Flavor Violation

- requirement no tree-level FCNC in down sector
- charged currents are proportional to the same CKM elements

MFV implies for the right handed operators
$\mathcal{Q}^i_R, \mathcal{Q}^i_{RL}$ or $\mathcal{Q}^i_\psi \longrightarrow z^i_{R,RL} \propto m_{u_i}$ } not good candidate

a) $\mathcal{Q}_L$ contributions are rescaled by $|1+c_L/2|^2$ $\quad c_L = z_L(v/\Lambda)^2$

✓ $$|1+c_L/2| \simeq 1.18 \qquad (\chi^2 \simeq 4)$$

new physics scale: $\Lambda|z_L|^{-1/2} = v|c_L|^{-1/2} \simeq 0.29$ TeV

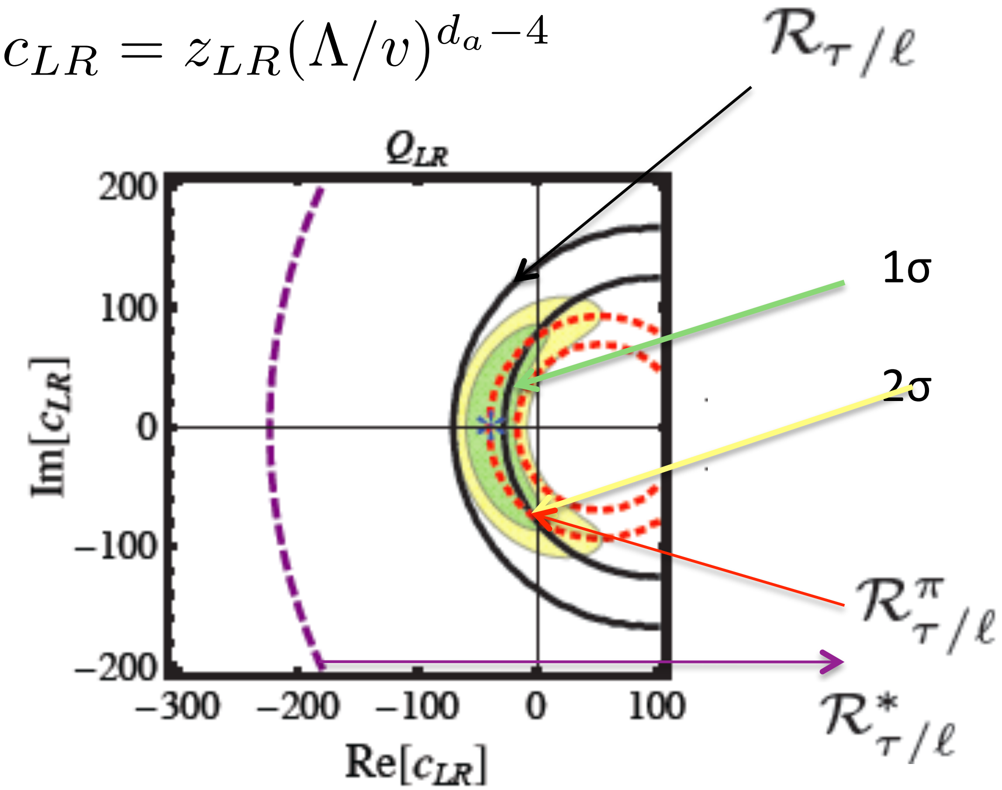
$\mathcal{R}_{\tau/\ell}$ and $\mathcal{R}^*_{\tau/\ell}$ well accommodated

$\mathcal{R}^\pi_{\tau/\ell}$ tension 1.5σ level

$B \rightarrow \pi$ form-factors from recent lattice QCD (Laiho, 0910.2928)

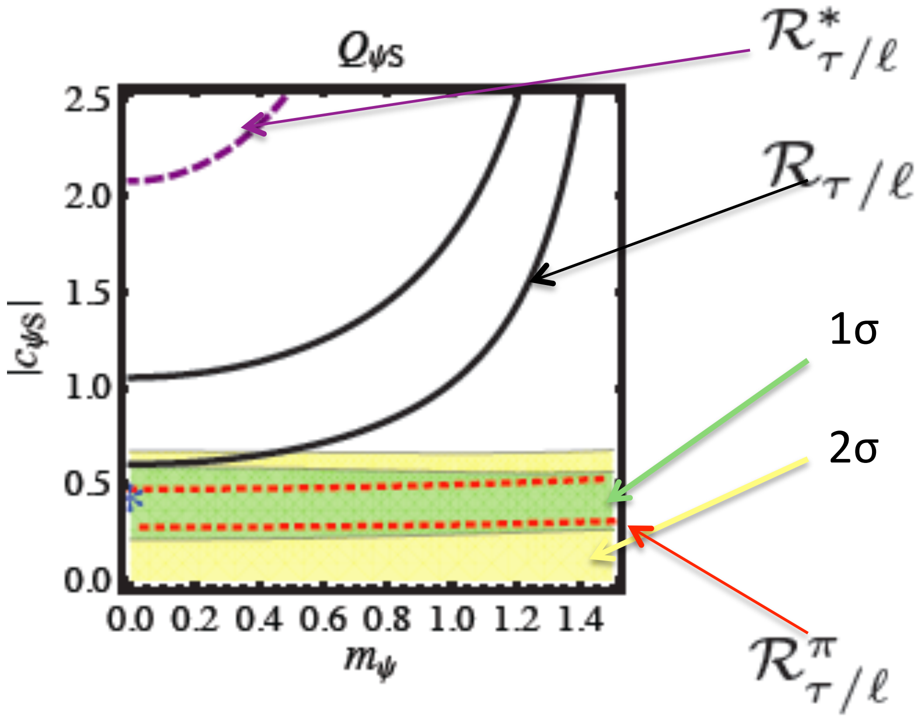
b) LR operator

$$c_{LR} = z_{LR}(\Lambda/v)^{d_a - 4}$$



Tension between observables for LR operator!
LR operator cannot be responsible for the observed deviation from SM.

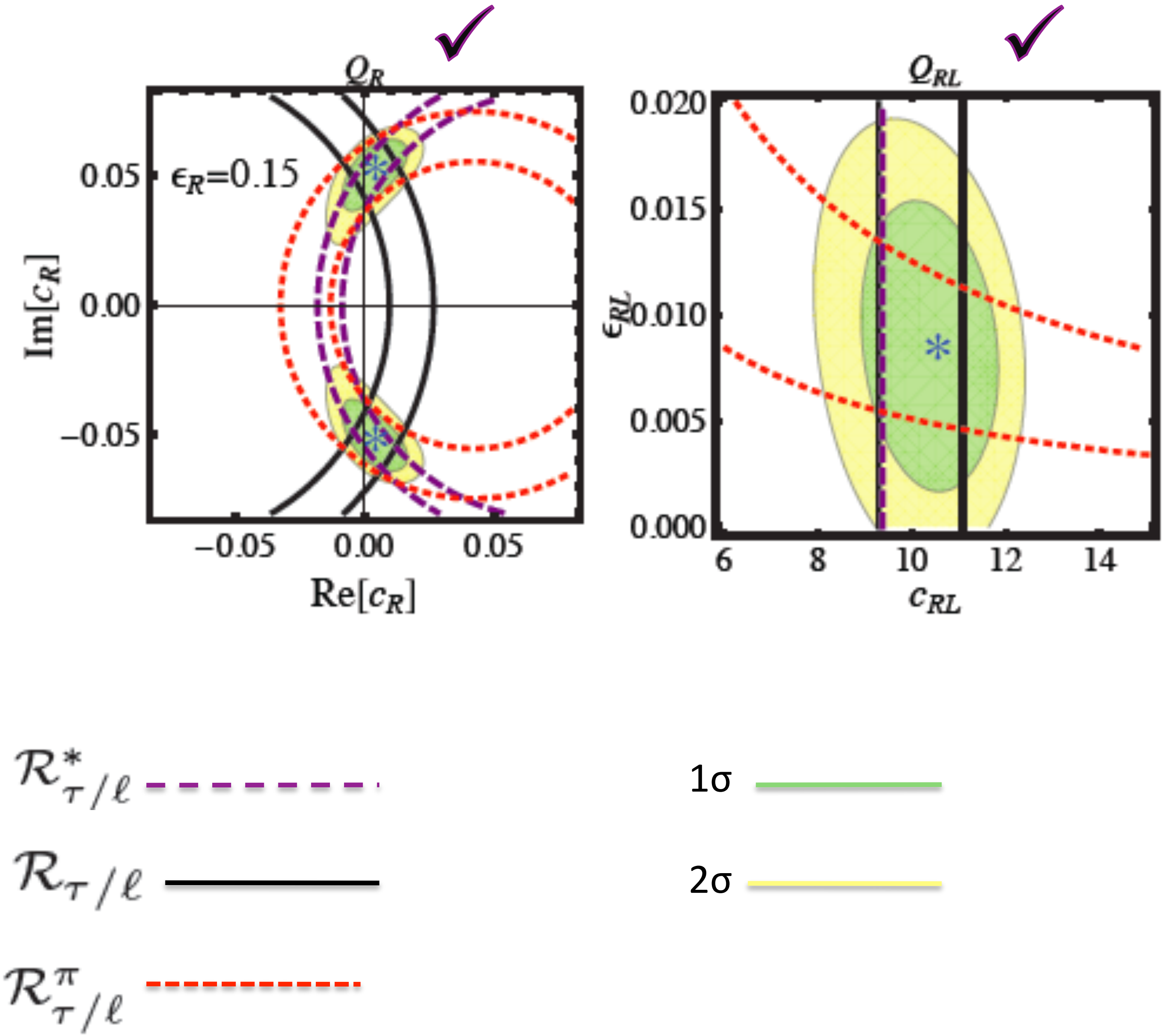
b) $\mathcal{Q}_{\Psi S}$



best fit value
tension remains

$$c_\psi \simeq 0.54 \text{ and } m_\psi = 0$$

Operators which can satisfy all requests:



Explicit models

2HDM

There are varieties of 2HDM: Type I, Type II, "lepton specific", and "flipped" (see e.g. Branco et al. 1106.0034)

$$c_{LR} = (2m_b v/m_{H+}^2)\{\mathrm{ctg}^2\beta, \mathrm{tg}^2\beta, -1, -1\}$$
$$c_{RL}^i = (2m_u^i v/m_{H+}^2)\{\mathrm{ctg}^2\beta, -1, -1, \mathrm{ctg}^2\beta\}$$

for $m_{H+} \gtrsim 80\ \mathrm{GeV}$ LEP constraints

$\mathcal{O}(1) \leq tg\beta \leq \mathcal{O}(100)$ (Yukawas are perturbative)

None of the natural flavor conservation 2HDMs can simultaneously account for the three LFU ratios!

In 1206.2634 (Crivellin, Greub and Kokulu): 2HDM III with MSSM-like Higgs potential and flavor violation in the up-sector with masses of A, H^0, $H^\pm$ around 500 GeV (A.Celis, M.Jung, A. Pich, 1210. 8443)

2HDM II

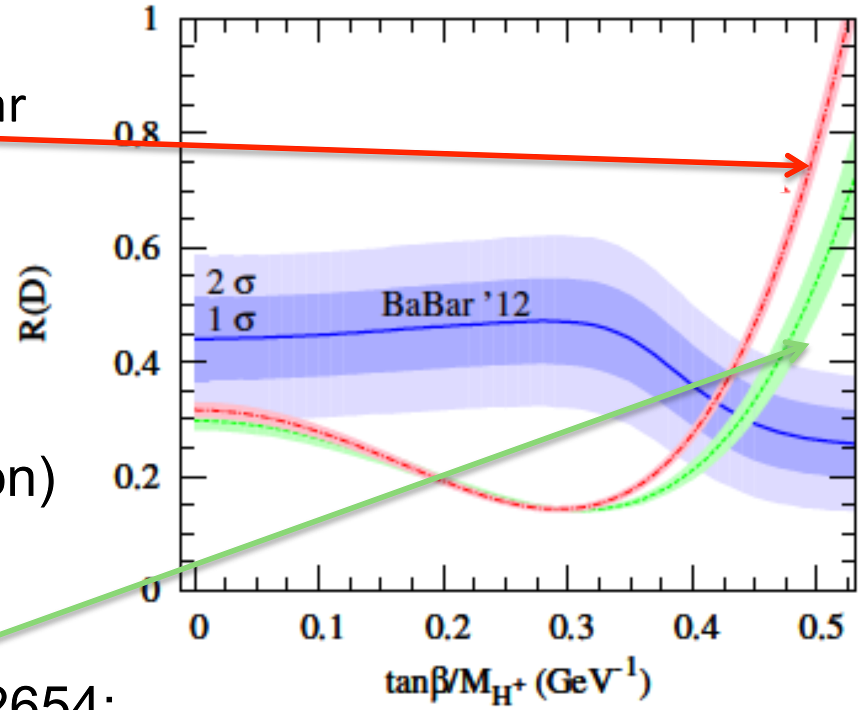
$$R(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to Dl\nu_l)} \qquad G_S \to G_F V_{ij} \frac{m_l(m_c + m_b \tan^2\beta)}{M_H^2}$$

$$R(D)_{BaBar} = 0.440 \pm 0.058 \pm 0.042 \quad R(D)_{lat} = 0.316(12)(7)$$

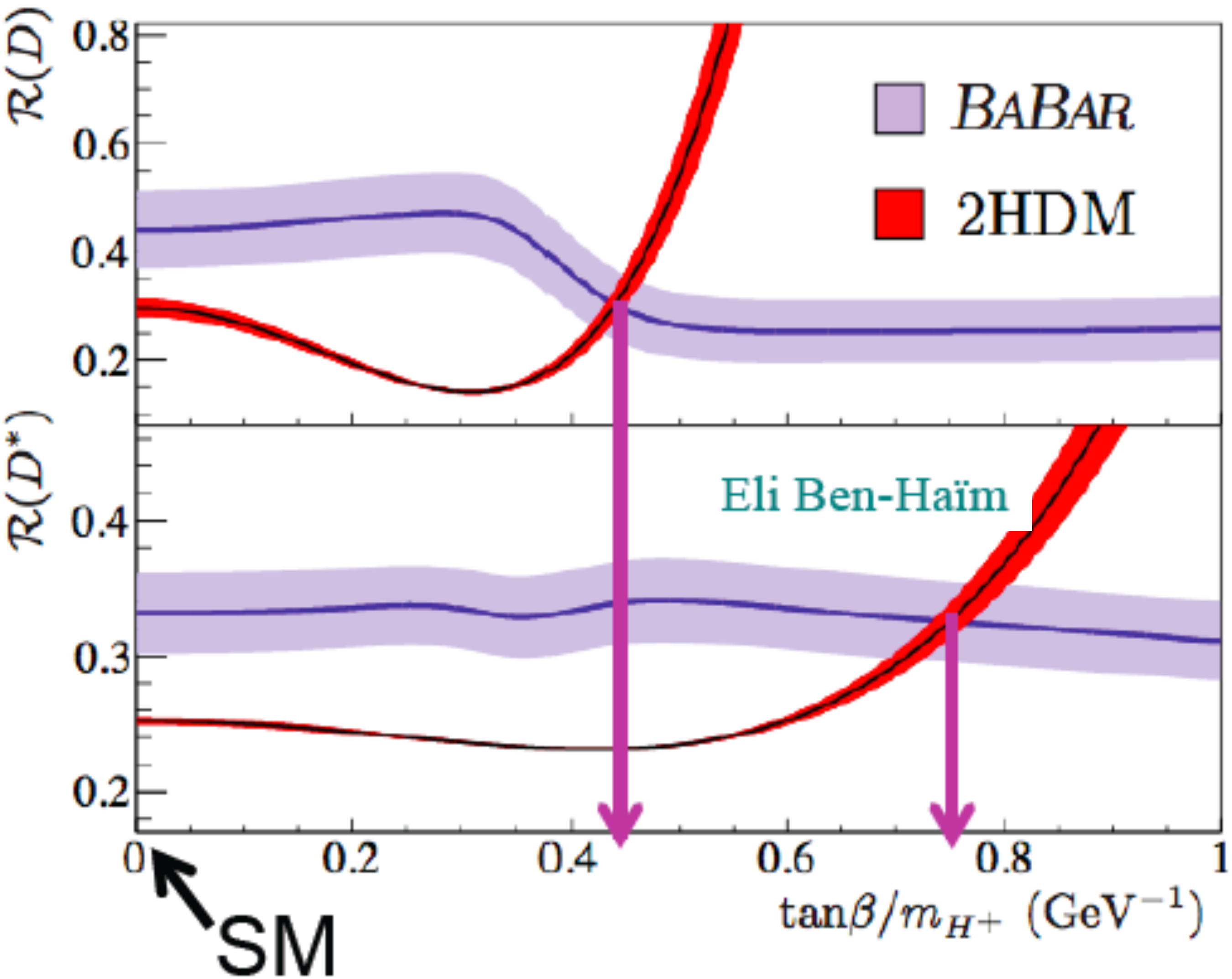
Tension SM – experiment decreases!

In 1206.4992 authors reexamined BaBar constraints on 2HDMII and found that ratio R(D) is highly sensitive on $f_0(q^2)$

(Fermilab lattice and MILC collaboration)

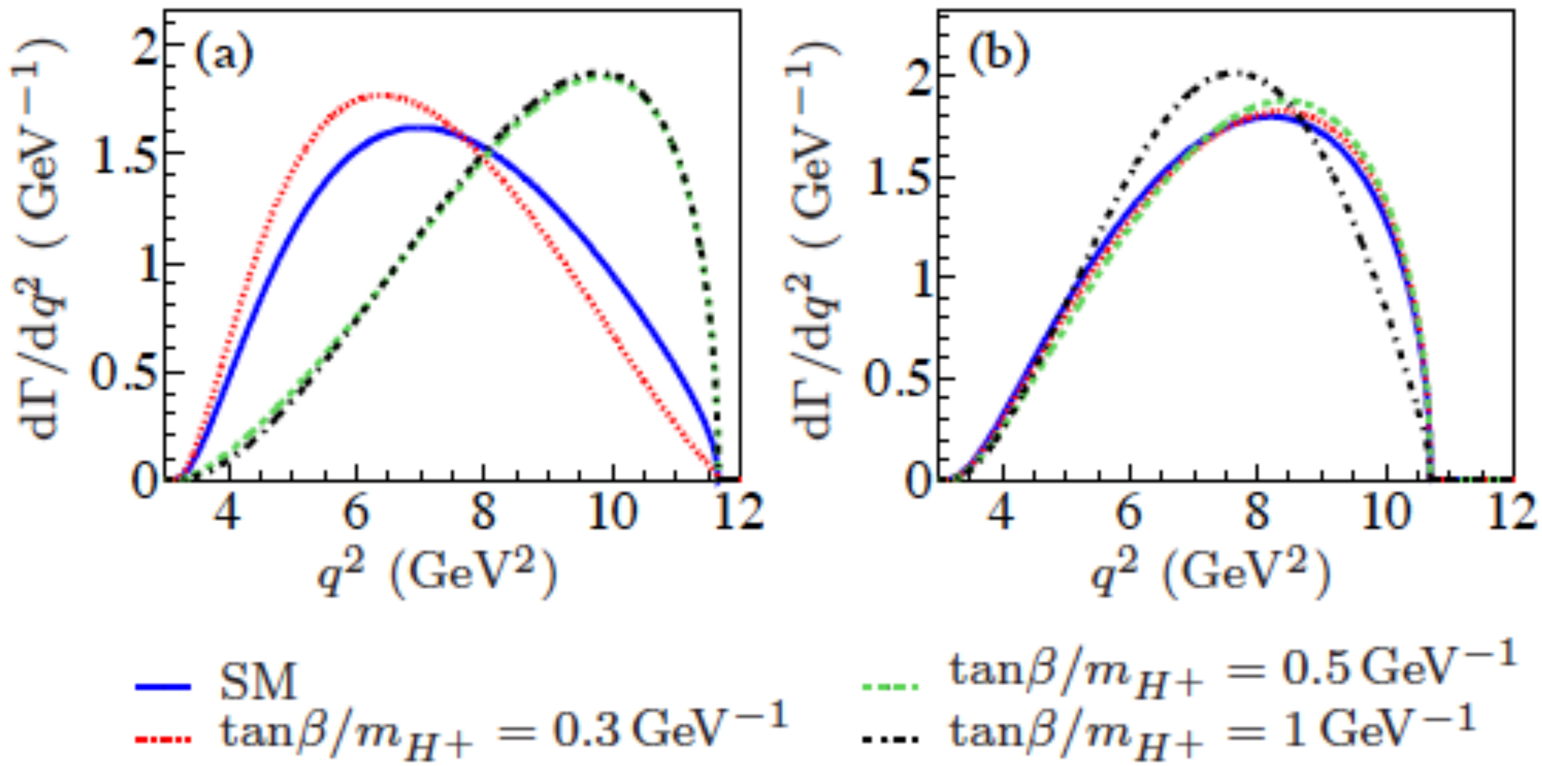


Kamenik & Mescia, 0802.3790;
S.F., Kamenik& Nisandzic, 1203.2654;



Eli Ben-Haim@ EPS2013
BaBar, 1303.0571

R(D) → $\tan\beta/m_H = 0.44 \pm 0.02$
R(D*) → $\tan\beta/m_H = 0.75 \pm 0.04$



A.Celis, M.Jung, A. Pich, 1210. 8443

2HDM with the more general flavor structure

Limit: only one Higgs doublet obtains vev

$$\mathcal{L} \supset \kappa^i_{RL}\bar{q}_3 u^i_R \bar{H} + \kappa^i_{LR}\bar{b}_R \bar{H}^\dagger q_i + \kappa^\tau \bar{\tau}_R l_3 \bar{H} + \mathrm{h.c}$$

Wilson coefficients

$$c^{i\tau}_{RL} = -\kappa^{i*}_{RL}(\kappa^\tau v/m_\tau)(v/m_{H^+})^2$$
$$c^{i\tau}_{LR} = -\kappa^{i*}_{LR}(\kappa^\tau v/m_\tau)(v/m_{H^+})^2$$

the best fit regions $(\kappa^u_{LR} - \kappa^u_{RL})\kappa^\tau \simeq \{0.9, -4\}\cdot 10^{-3}(m_{H^+}/v)^2$

$$(\kappa^c_{RL}\kappa^\tau, \kappa^c_{LR}\kappa^\tau) \simeq \{(-6, 8), (-12, 1)\} \cdot 10^{-2}(m_{H^+}/v)^2$$

too large- severe flavor building problem!

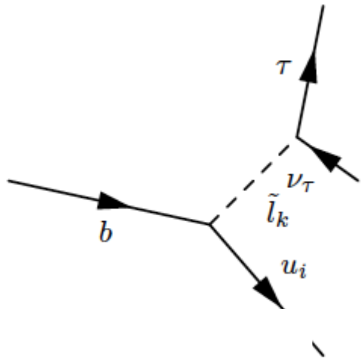
$\kappa^{c(u)}_{RL}\kappa^\tau$ is about 2-3 times larger than Yukawas $(m_{c(u)}/v)(m_\tau/v)$

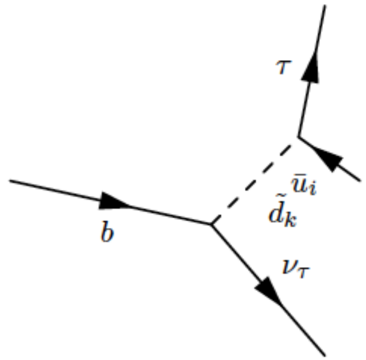
FCNC bounds from D, B, B_s require an order of magnitude cancellation

$\kappa^\tau = 1$ ($\kappa^i_{LR} = 0$, to suppress $\Delta B = 2$)

$\not{R}$ MSSM

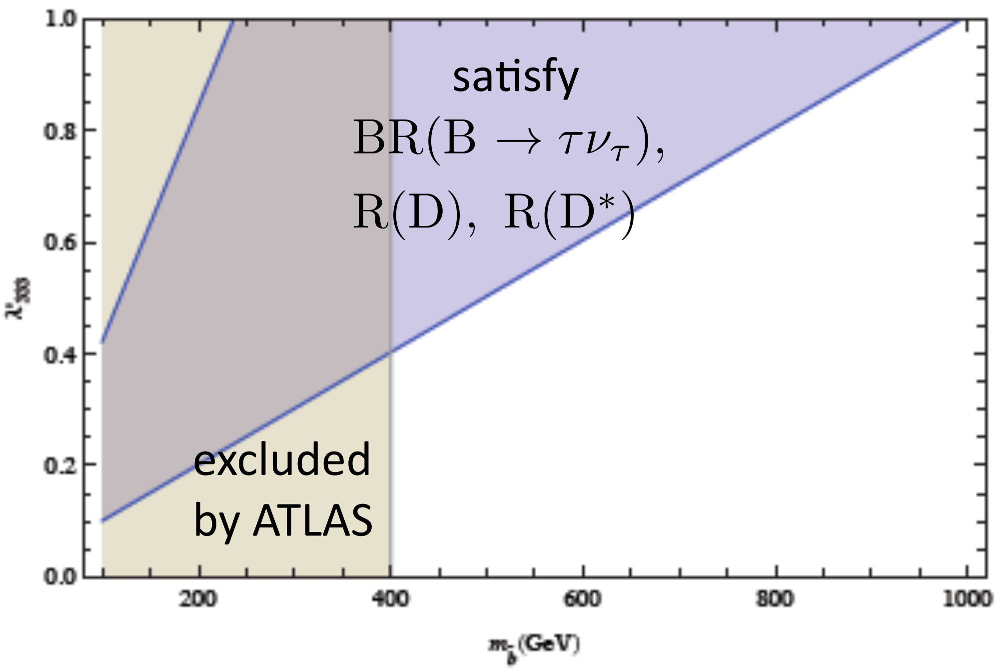
Deshpande & Menon 1208.4134





$$L_{\mathrm{EFF}} = -V_{3m}^{\mathrm{CKM}} \frac{4G_f}{\sqrt{2}} [1 + \Delta] (\bar{u}_m \gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

$0.12 \lesssim \Delta \lesssim 0.52$ can explain all $\mathrm{BR}(\mathrm{B} \to \tau\nu_\tau),\ R(D),\ R(D^*)$



Composite III generation of fermions

$$\mathcal{L} \sim y_i^{Q_d} \bar{Q} H d_R^i + y_i^{Q_u} \bar{Q} \tilde{H} u_R^i + h.c. \qquad f_i^{q,l} \in [0,1]$$

$$\mathcal{Q}_{L,R} \longrightarrow \frac{z_L}{\Lambda^2} \sim \frac{g_\rho^2}{m_\rho^2}[f_3^q]^2[f_3^l]^2 , \quad \frac{z_R^{u(c)}}{\Lambda^4} \sim \frac{g_\rho^2}{m_\rho^2}\frac{y_3^{Qd} y_{1(2)}^{Qu}}{m_Q^2}[f_3^l]^2$$

$g_\rho \lesssim \sqrt{4\pi} \quad m_\rho \sim \mathcal{O}(\text{TeV})$

vector resonance

$m_Q \lesssim \mathcal{O}(\text{TeV})$

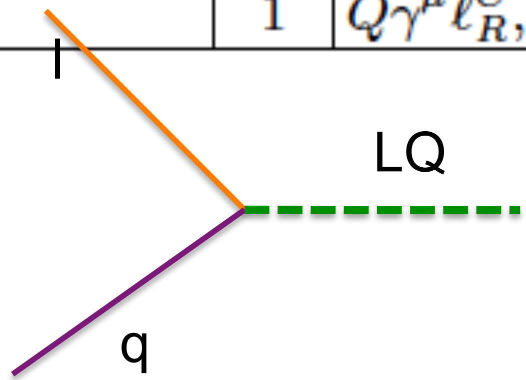
strong sector fermion resonance

$$\epsilon_{32} \equiv y_3^{Qd} y_2^{Qu} v^2/m_Q^2 \simeq 0(0.01)$$
$$\epsilon_{31} \equiv y_3^{Qd} y_1^{Qu} v^2/m_Q^2 \simeq -0.01(0.05)$$

two solutions

Leptoquark contribution

$(SU(3), SU(2))_Y$	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



Scalar and vector leptoquark that trigger b-> c l u,

I. Dorsner, S.F., N. Kosnik, 1306.6493

(3,2,7/6) state

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

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

Fields are in the weak base. Transition to a mass base

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

We require minimal set of couplings needed to explain deviation of SM prediction in $b \to c\tau\nu_\tau$ while in $b \to cl\nu_l,\ l = e,\ \mu$ the experimental result agrees with the SM theoretical prediction.

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

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

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

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

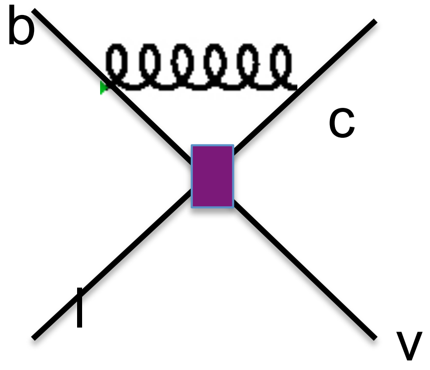
(Fierz's transformation are used)

SM +NP operators

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

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

on the scale of mass of Δ this relation hold



Contrary to axial and vector current operators, scalar and tensor operators have anomalous dimension. Namely due to smallness of b and c quark masses in comparison with electroweak symmetry breaking scale, both currents V and A are conserved.

$$m_b, m_c << v$$

$$g_S(m_b) = \left(\frac{\alpha_S(m_b)}{\alpha_S(m_t)}\right)^{-\frac{\gamma_S}{2\beta_0^{(5)}}} \left(\frac{\alpha_S(m_t)}{\alpha_S(m_\Delta)}\right)^{-\frac{\gamma_S}{2\beta_0^{(6)}}} g_S(m_\Delta)$$

$$\gamma_S = -8,\ \gamma_T = 8/3$$

$$g_T(m_b) = \left(\frac{\alpha_S(m_b)}{\alpha_S(m_t)}\right)^{-\frac{\gamma_T}{2\beta_0^{(5)}}} \left(\frac{\alpha_S(m_t)}{\alpha_S(m_\Delta)}\right)^{-\frac{\gamma_S}{2\beta_0^{(6)}}} g_T(m_\Delta)$$

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

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

$$B \to D\tau\nu_\tau$$

Matrix elements of currents are

$$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = \left(p_B^\mu + p_D^\mu - \frac{m_B^2 - m_D^2}{q^2} q^\mu\right) f_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q^\mu f_0(q^2)$$

$$\langle D(p_D)|\bar{c}\sigma^{\mu\nu} b|\bar{B}(p_B)\rangle = -i(p_B^\mu p_D^\nu - p_D^\mu p_B^\nu)\frac{2 f_T(q^2)}{m_B + m_D}$$

New form factor

Differential branching ratio

$$\frac{d\mathcal{B}}{dq^2}(B \to D\ell\bar{\nu}_\ell) = \frac{\tau_B G_F^2 |V_{cb}|^2}{192\pi^3 m_B^3} f_+(q^2)^2 \left(1 - \frac{m_l^2}{q^2}\right)^2 \lambda^{1/2} \Bigg[\lambda^2 \left(1 + \frac{m_l^2}{2q^2}\right)$$

$$+ |g_T|^2 \lambda^2 \frac{2q^2}{(m_B + m_D)^2}\left(1 + \frac{2m_l^2}{q^2}\right)\left(\frac{f_T(q^2)}{f_+(q^2)}\right)^2$$

$$- \lambda^2 \frac{6 m_l}{m_B + m_D} \Re(g_T) \frac{f_T(q^2)}{f_+(q^2)}$$

$$+ \left|1 - \frac{q^2}{m_l(m_b - m_c)} g_S\right|^2 \frac{3}{2}\frac{m_l^2}{q^2}(m_B^2 - m_D^2)^2 \left(\frac{f_0(q^2)}{f_+(q^2)}\right)^2\Bigg],$$

Tensor form factor estimation based on hep-ph/001113

$$f_T(q^2)/f_+(q^2) = 1.03(1)$$

$$f_+(q^2) = \frac{G_1(w)}{R_D}\Big|_{w(q^2)},$$

$$f_0(q^2) = R_D \frac{1+w}{2} G_1(w) \frac{1+r_D}{1-r_D} \Delta(w)\Big|_{w(q^2)}$$

$$G_1(w) = G_1(1)[1 - 8\rho_D^2 z(w) + (51\rho_D^2 - 10)z(w)^2 - (252\rho_D^2 - 84)z(w)^3]$$

$$\Delta(w) = 0.46 \pm 0.02$$

constant - consistent with lattice study

$B \to D^* \tau \nu_\tau$

In addition to matrix elements of vector/axial-vector current, there are tensor currents!

$$\langle D^*(p_{D^*}, \epsilon)|\bar{c}\sigma_{\mu\nu}(1-\gamma_5)b|\bar{B}(p_B)\rangle = T_0(q^2)\frac{\epsilon^* \cdot q}{(m_B + m_{D^*})^2}\epsilon_{\mu\nu\alpha\beta}\, p_B^\alpha\, p_{D^*}^\beta$$

$$+ T_1(q^2)\epsilon_{\mu\nu\alpha\beta}p_B^\alpha \epsilon^{*\beta} + i\Big[T_3(q^2)(\epsilon^*_\mu p_{B,\nu} - \epsilon^*_\nu p_{B,\mu})$$

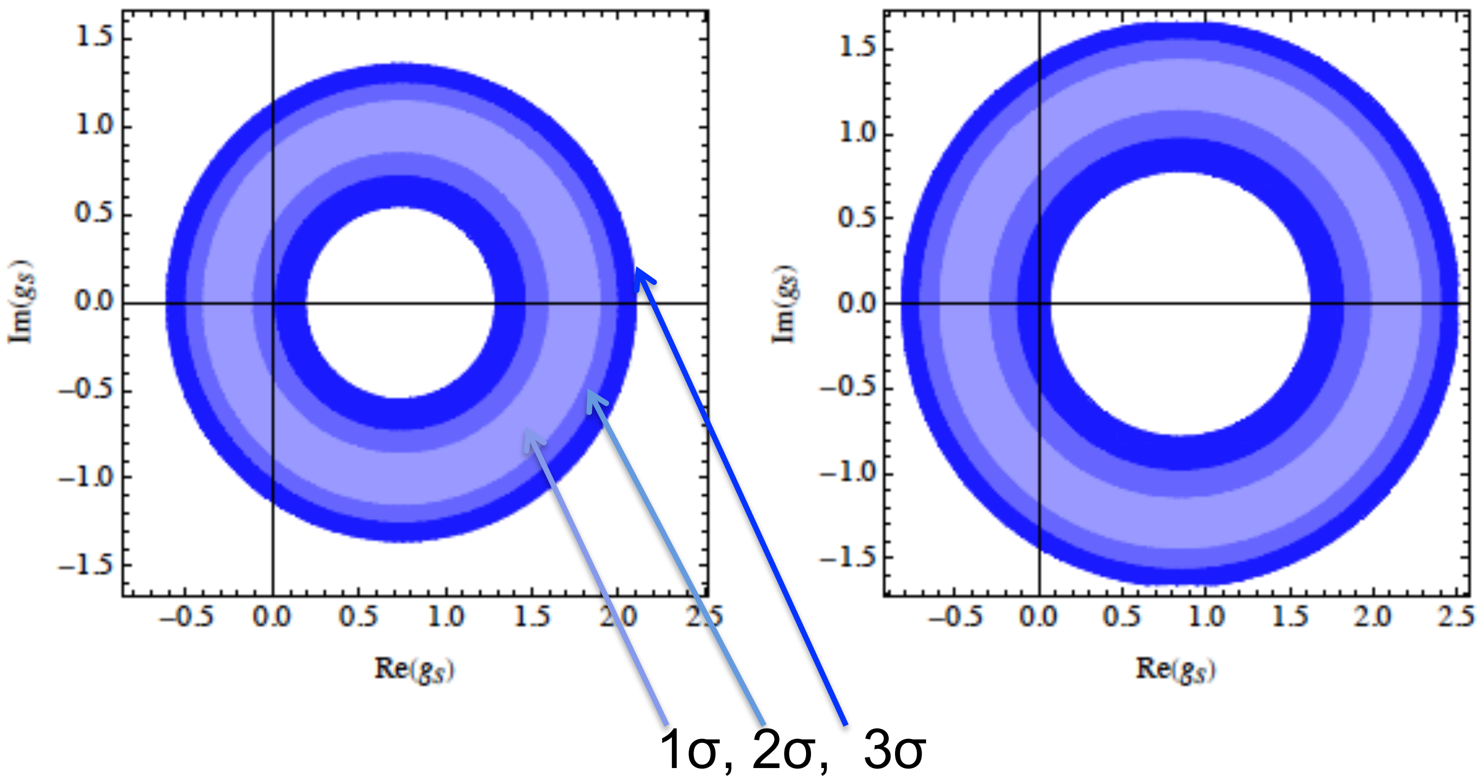
$$+ T_4(q^2)(\epsilon^*_\mu p_{D^*,\nu} - \epsilon^*_\nu p_{D^*,\mu}) + T_5(q^2)\frac{\epsilon^* \cdot q}{(m_B + m_{D^*})^2}(p_{B,\mu}p_{D^*,\nu} - p_{B,\nu}p_{D^*,\mu})\Big].$$

$$T_0(q^2) = T_5(q^2) = 0,$$

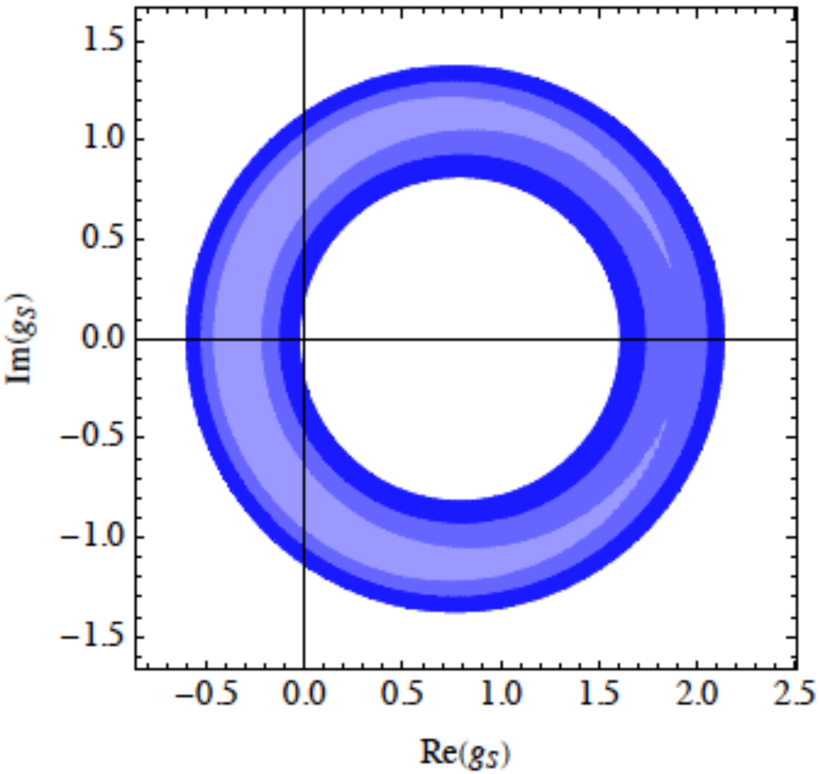
$$T_1(q^2) = T_3(q^2) = \sqrt{\frac{m_{D^*}}{m_B}}\xi(w)|_{w(q^2)}$$

$$T_2(q^2) = T_4(q^2) = \sqrt{\frac{m_B}{m_{D^*}}}\xi(w)|_{w(q^2)}$$

$R(D)$ $\qquad\qquad$ $R(D^*)$



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



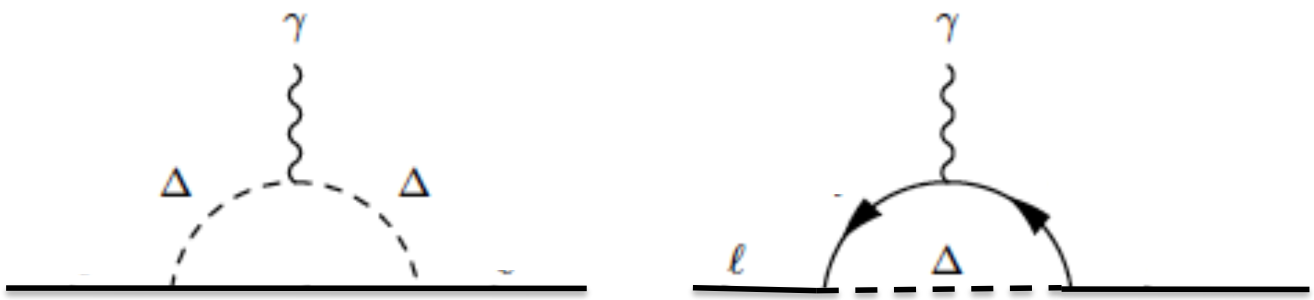
$$g_S(m_b) = -0.37^{+0.10}_{-0.07}$$

1σ range

The model is constrained by:

- $Z \to b\bar{b}$
- $(g-2)_\mu$
- τ electric dipole moment

$\tau \to \mu\gamma$



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

LEP experiment measured

$$\mathcal{L}_{Zb\bar{b}} = \frac{g}{c_W} Z^\mu \bar{b} \gamma_\mu \left[(g_L^b + \delta g_L^b) P_L + (g_R^b + \delta g_R^b) P_R \right] b$$

SM tree level

$$g_L^{b0} = -1/2 + s_W^2/3$$

$$g_R^{b0} = s_W^2/3$$

Corrections: within SM the largest contribution comes from top quark in the loop!

The shift from SM value

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

$$\delta g_L^b(y_{33}) = \frac{|y_{33}|^2}{384\pi^2}\left[g_0(x) + s_W^2 g_2(x)\right]$$

$$x = m_\Delta^2/m_Z^2$$

$$g_0(x) \simeq -\frac{2}{3x},$$

$$g_2(x) \simeq \frac{8}{x}(\log x + 2/9 + i\pi)$$

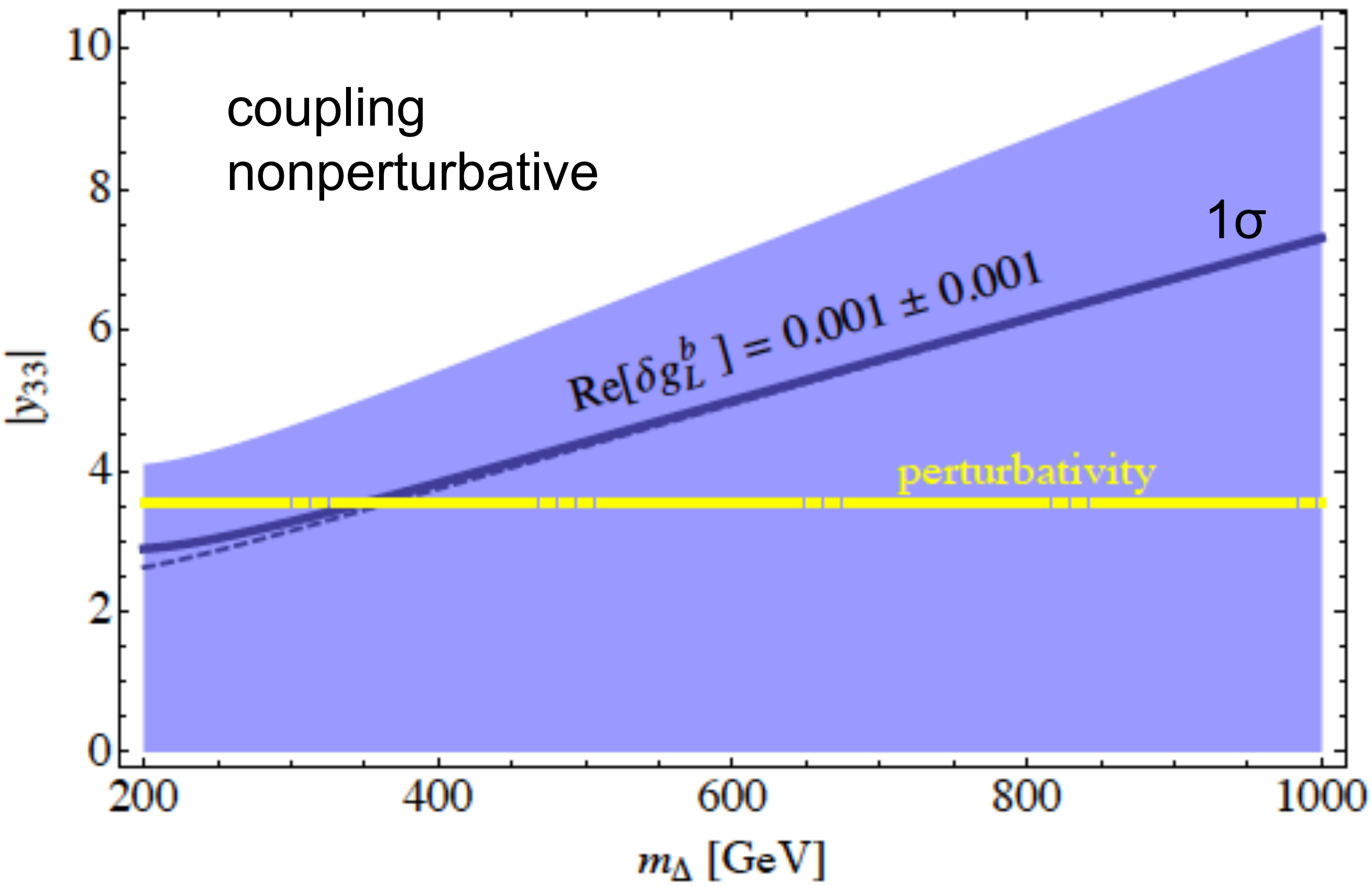
Loop functions

T on mass-shell in the loop

LQ modifies the left handed couplings. In order to explain LEP anomaly one needs change in both, left and right coupling.

$$\mathrm{Re}[\delta g_L^b(y_{33})] = 0.001 \pm 0.001$$

$$|y_{33}|_{\mathrm{central}} = 1.57 + 2.86\frac{m_\Delta}{500\ \mathrm{GeV}}$$



coupling
nonperturbative
1σ
Re[δg_L^b] = 0.001 ± 0.001
perturbativity
|y33|
m_Δ [GeV]
0
2
4
6
8
10
200
400
600
800
1000

Lepton electromagnetic current

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

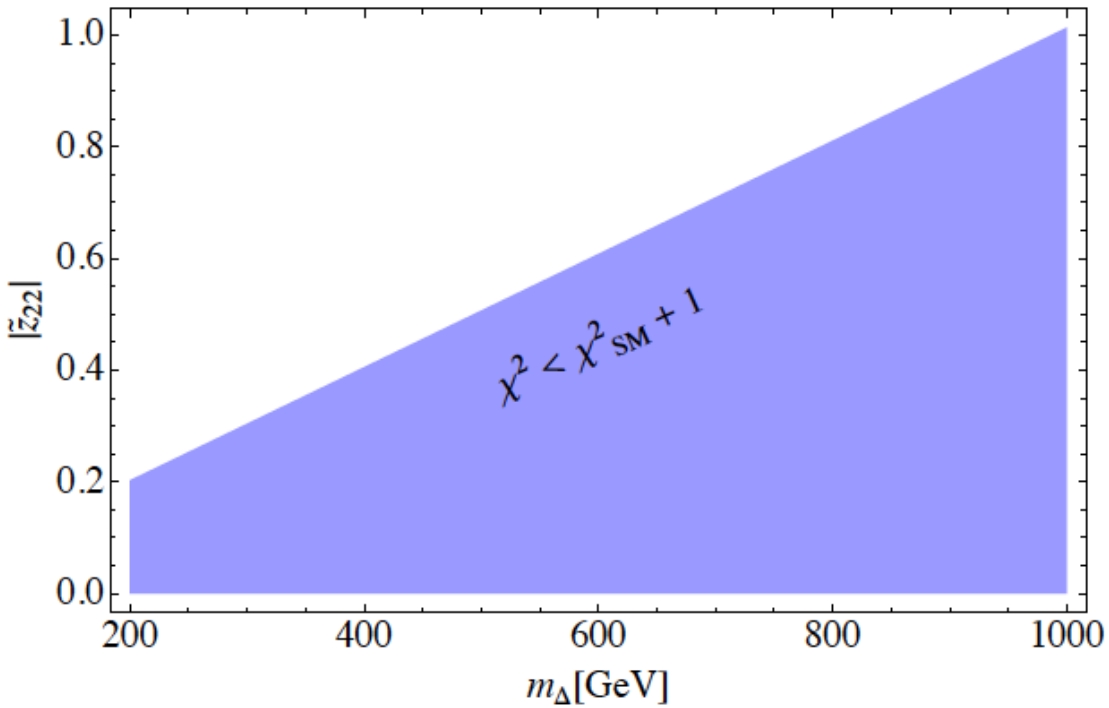
$$-ie\,\bar{u}_\ell(p+q)\left[F_E(q^2)\gamma^\mu + \frac{F^\ell_M(q^2)}{2m_\ell} i\sigma^{\mu\nu}q_\nu + F^\ell_d(q^2)\,\sigma^{\mu\nu}q_\nu\gamma_5\right]u_\ell(p)$$

Muon anomalous magnetic moment

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

enters loop functions $\Delta^{(5/3)}$

$$\delta a_\mu^{\mathrm{exp-SM}} = (287 \pm 80) \times 10^{-11}$$



region allowed by muon g-2

T dipole electric moment

appears due to two different couplings at one loop level!

$$d_\tau \equiv eF_d^\tau(q^2 = 0) = e\,\frac{m_c \mathrm{Im}\,[V_{cb} y_{33}^* \tilde{z}_{23}|}{32\pi^2 m_\Delta^2}\left[1 + 4\log\frac{m_c^2}{m_\Delta^2}\right]$$

$$-2.2\times 10^{-17} e\ \mathrm{cm} < d_\tau < 4.5\times 10^{-17} e\ \mathrm{cm}$$

Belle bounds

$\tau \to \mu\gamma$

$$\mathcal{A}_{\tau\to\ell\gamma} = \bar{\ell}(p')\sigma^{\mu\nu}\,\epsilon^*_\mu(q)q_\nu\,(A_\ell P_R + B_\ell P_L)\,\tau(p)$$

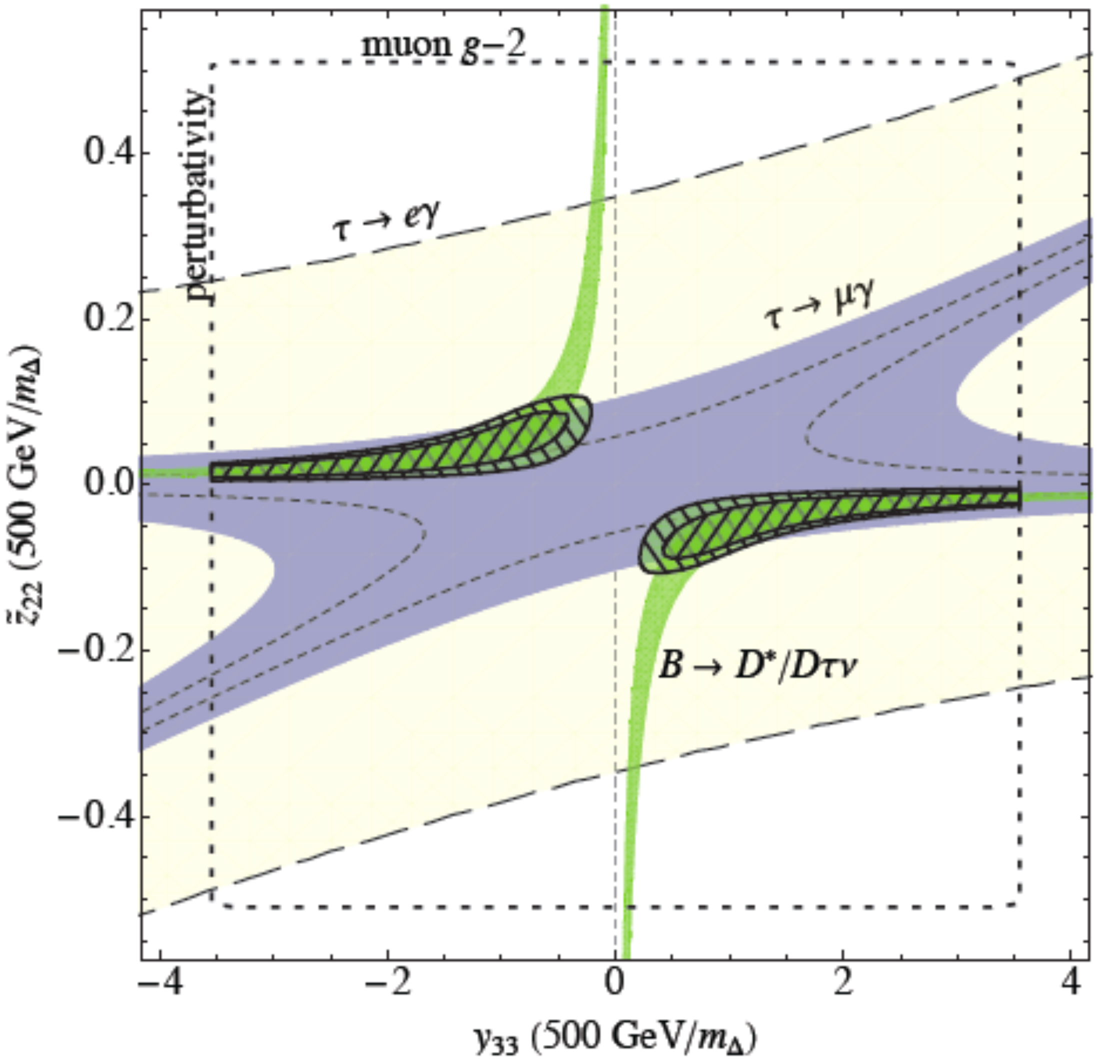
$$\mathcal{B}(\tau \to \ell\gamma) = \frac{\tau_\tau}{8\pi}\frac{(m_\tau^2 - m_\ell^2)^3}{m_\tau^3}\left(|A|^2 + |B|^2\right)$$

$$A_\ell = \frac{-N_c e}{48\pi^2 m_\Delta^2}\left[m_c V_{cb} y^*_{33}\tilde{z}^*_{2\ell}(1 + 4\log x_c) + \frac{m_\tau}{2}\tilde{z}_{23}\tilde{z}^*_{2\ell}(3 + 4x_c\log x_c)\right]$$

$$B_\ell = 0\,,$$

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

BaBar bounds



1σ region allowed by existing data

Predictions

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

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

$$f_{B_c} = 0.427(6)(2)\ \text{GeV} \qquad \text{HPQCD}$$

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

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

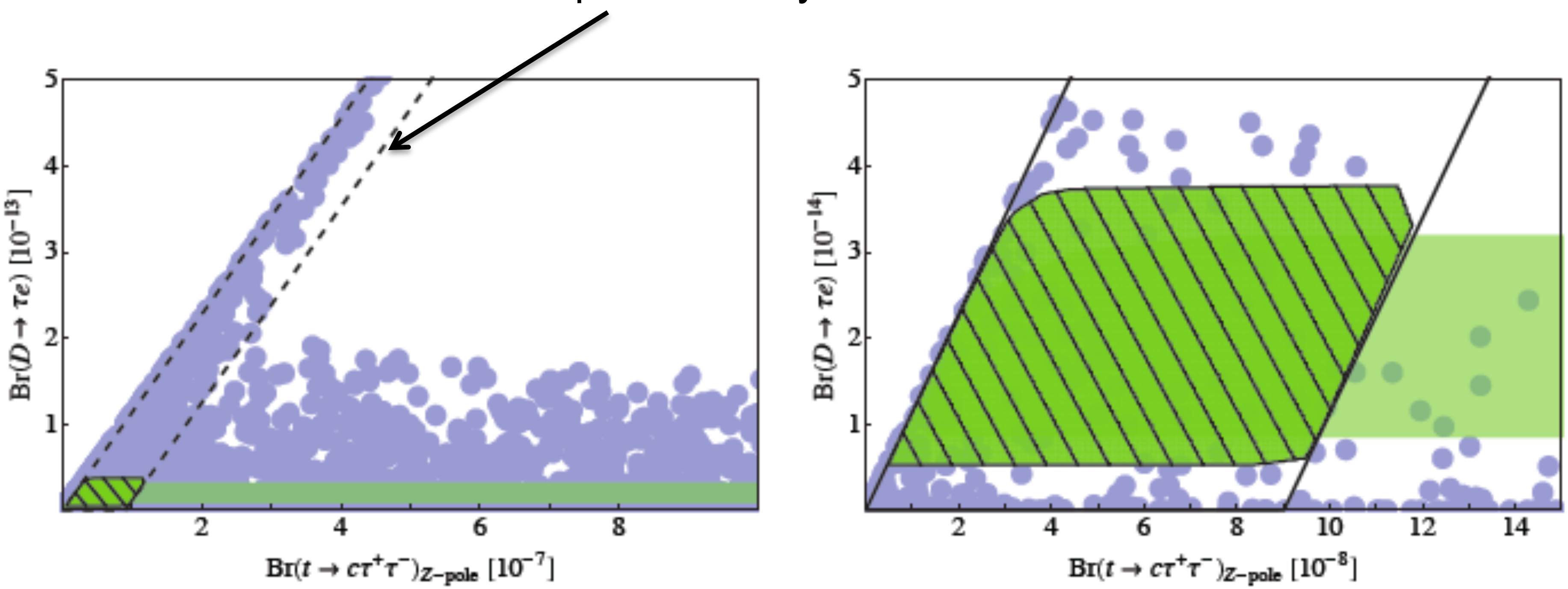
decrease $r^2 \simeq 0.36 \quad g_S = -0.37$

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

$$t \to c\tau^+\tau^-$$

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

perturbativity



allowed by $\tau \to \mu\gamma$

Possibility for a GUT

This LQ state can be accommodated in representation of 45 of SU(5) GUT theory!

One more vev! $$|v_5|^2/2 + 12|v_{45}|^2 = v^2$$

SM vev

With 45 in the game one can modify GUT relation for down quarks and lepton appearing minimal SU(5) GUT, with Higgses in 5

$$M_D = -M_L^T$$

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

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

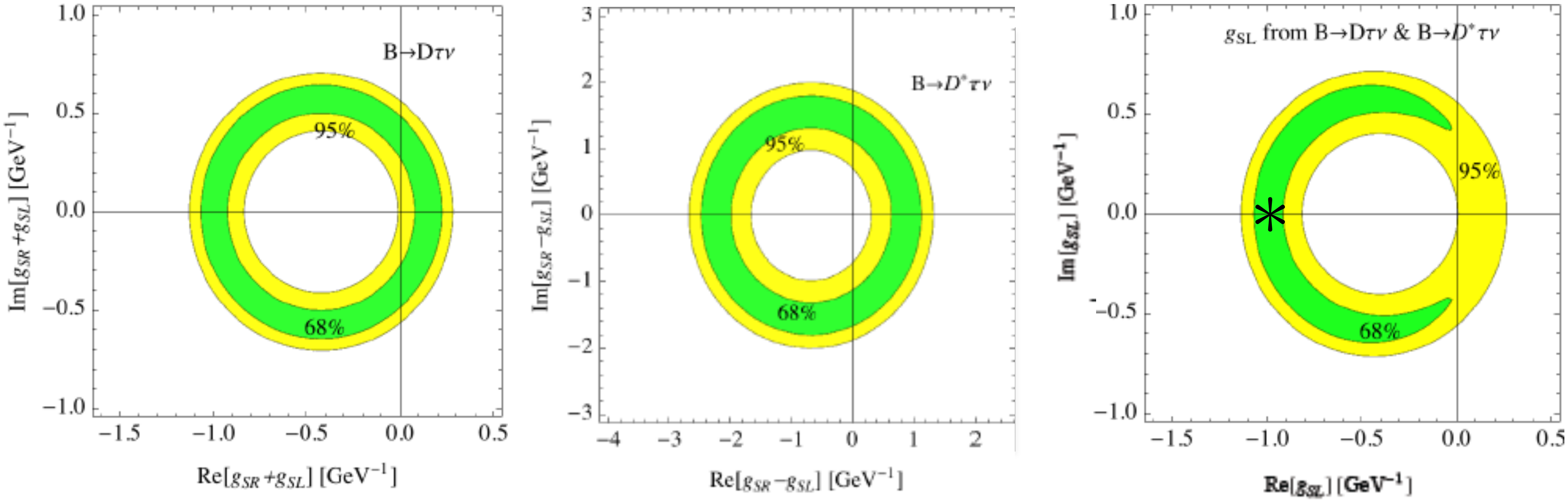
$$Y_1 = -U_R Z.$$

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

SU(5) GUT with 5+ 45 is compatible with all constraints coming from low-energy phenomenology

NP observables in $B \to D^* \tau \nu_\tau$

NP modifies $$H_{0t} = H_{0t}^{\rm SM} \left[1 + (g_{SR} - g_{SL}) \frac{q^2}{m_b + m_c} \right]$$



$$R^* = R^*_{\rm SM} \left\{ 1 + 0.12 {\rm Re}[m_\tau (g_{SR} - g_{SL})] + 0.05 |m_\tau (g_{SR} - g_{SL})|^2 \right\}$$

$\ast$ $g_{SL} \simeq -0.9\,{\rm GeV}^{-1}$

S.F., J.F.Kamenik, Nisanndzic, 1203.2654, S. Faller et al., 1105.3679, Sakaki&Tanaka, 1205.4908

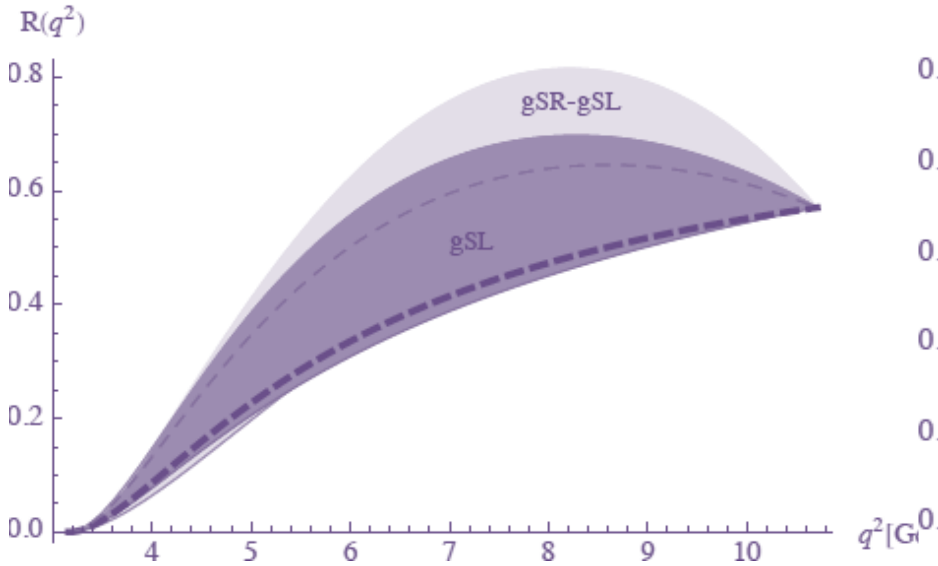
Possible variables:

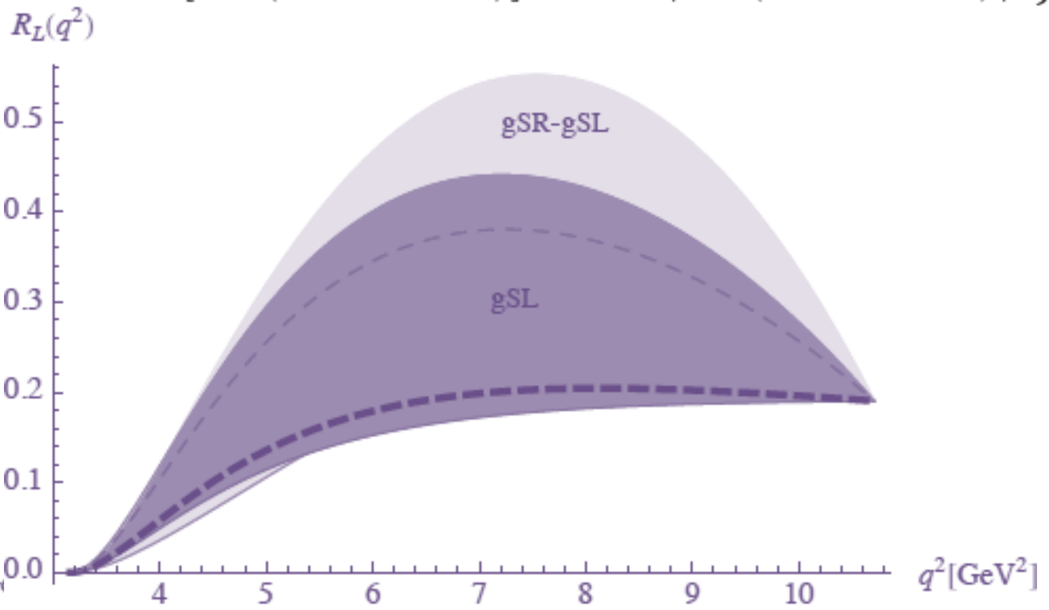
$$R^*(q^2) = \frac{d\Gamma_\tau/dq^2}{d\Gamma_\ell/dq^2} = \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2}\frac{|H_{0t}|^2}{|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2}\right]$$

sensitivity on H_{0t}

NP contributes only to longitudinally polarized D* (information comes from the study of angular distribution of D π)

$$R_L^* \equiv \frac{Br(B \to D_L^* \tau \bar{\nu}_\tau)}{Br(B \to D^* e \bar{\nu}_\tau)} = 0.115(2)\left\{1 + 0.27\mathrm{Re}[m_\tau(g_{SR} - g_{SL})] + 0.10|m_\tau(g_{SR} - g_{SL})|^2\right\}$$





Opening angle asymmetry

$$A_\theta(q^2) \equiv \frac{\int_{-1}^{0} d\cos\theta (d^2\Gamma_\tau/dq^2 d\cos\theta) - \int_0^1 d\cos\theta (d^2\Gamma_\tau/dq^2 d\cos\theta)}{d\Gamma_\tau/dq^2}$$

$$= \frac{3}{4}\frac{|H_{++}|^2 - |H_{--}|^2 + 2\frac{m_\tau^2}{q^2}\mathrm{Re}(H_{00}H_{0t})}{\left[(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2)\left(1+\frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]}.$$

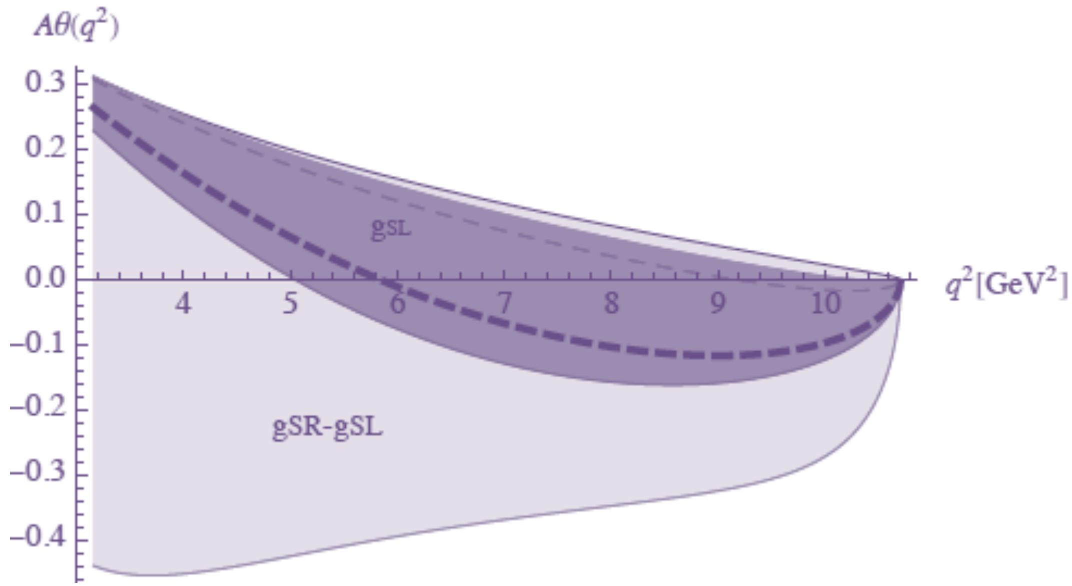
SM: $A_\theta = 0$ for $q_0^2 \simeq 5.6\ \mathrm{GeV}^2$

integrated

$$A_{\theta,SM} = -6.0(8)\%$$

SM + NP: $A_{\theta,NP}$

for benchmark points 3.4%, being even -30%



using τ helicity

$$A_\lambda(q^2) = \frac{d\Gamma_\tau/dq^2(\lambda_\tau = -1/2) - d\Gamma_\tau/dq^2(\lambda_\tau = 1/2)}{d\Gamma_\tau/dq^2}$$

Helicity asymmetry

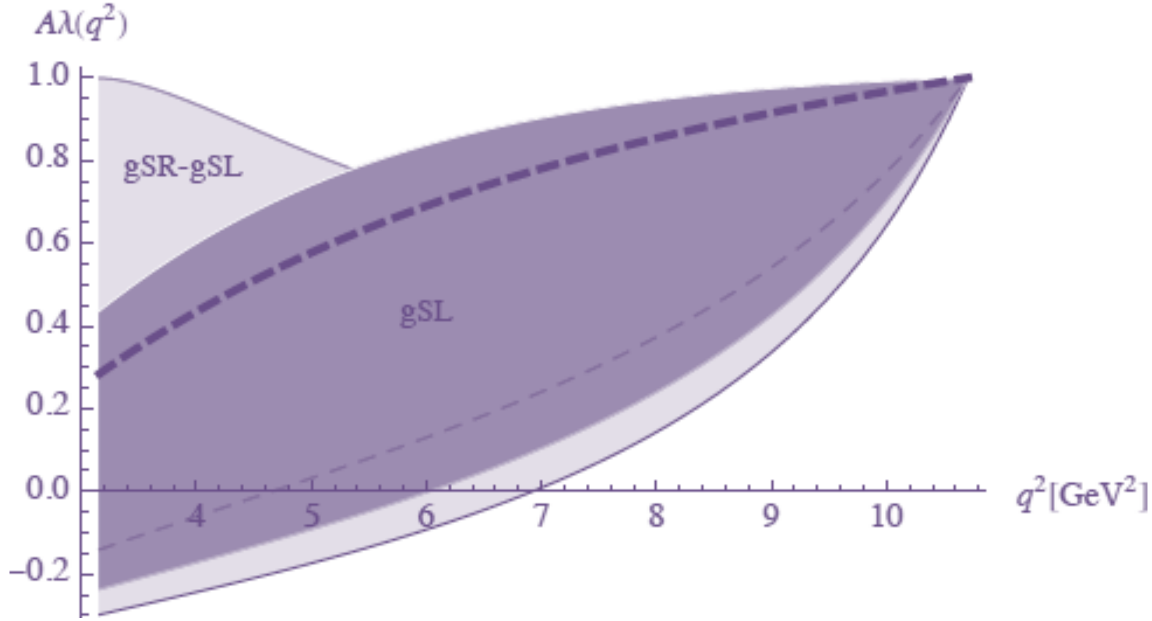
$$A_\lambda(q^2) = 1 - \frac{6|H_{0t}|^2 m_\tau^2}{(2q^2 + m_\tau^2)(|H_{--}|^2 + |H_{00}|^2 + |H_{++}|^2) + 3|H_{0t}|^2 m_\tau^2}$$

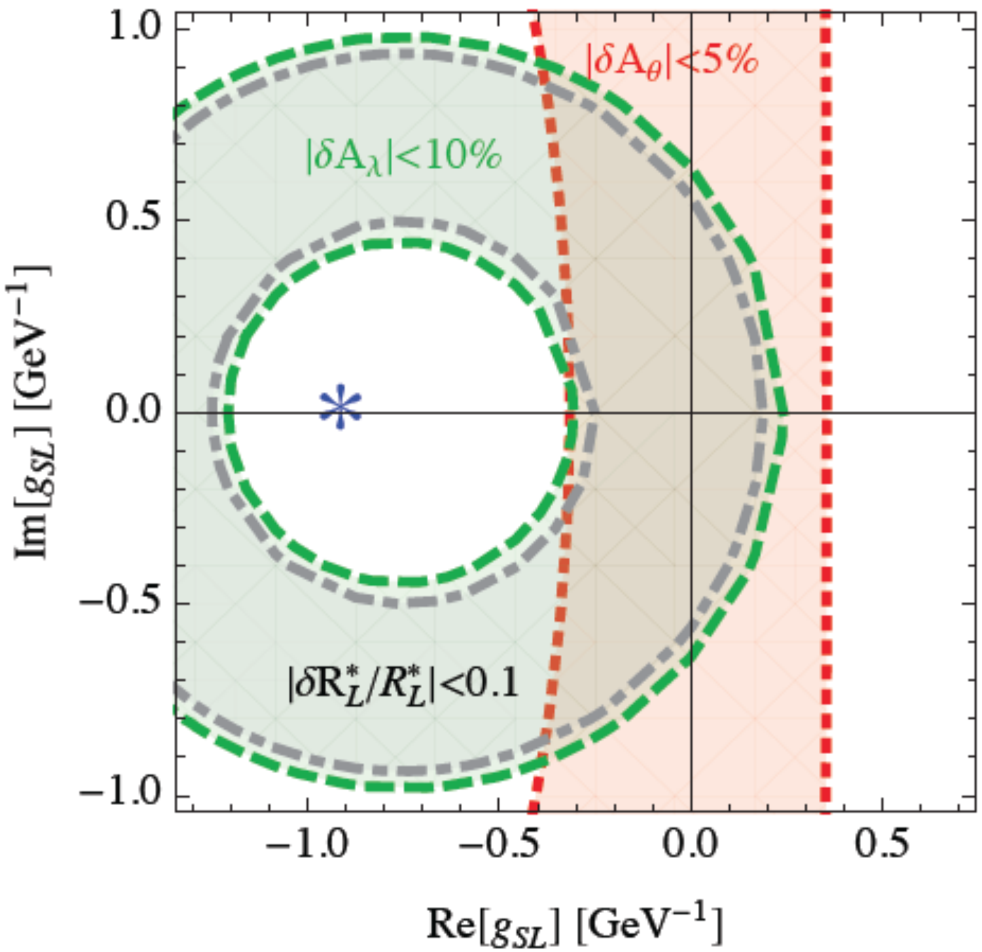
SM only:

$$A_{\lambda,SM} = 0.829(15)$$

SM+NP (benchmark point):

$$A_{\lambda,NP} = 0.36$$

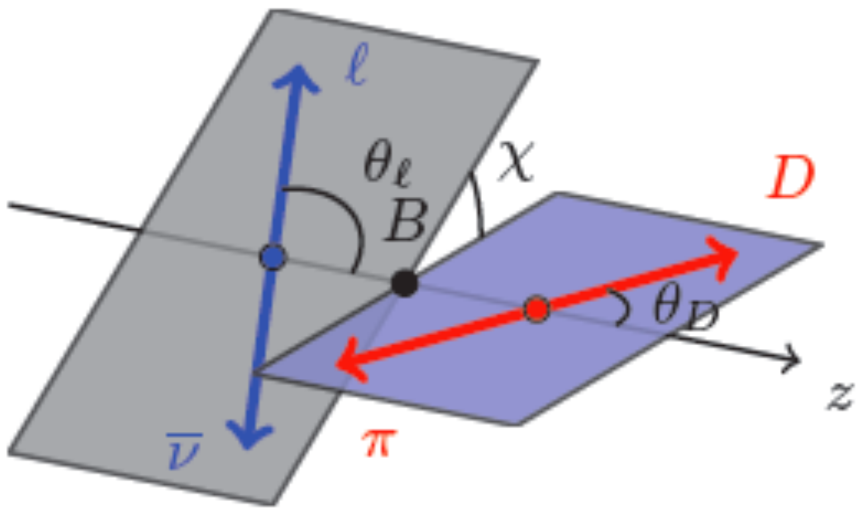




Regions allowed by future 10% (5%) precision measurement

NP observables in $B \to D\tau\nu_\tau$ and $B \to D^*\tau\nu_\tau$

Belle and BaBar studied $q^2, cos\theta_l, cos\theta_D, \chi$



Note: BaBar and Belle assume only SM contribution in their studies!

The goal: to redo the analysis by not assuming validity of SM

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb} \big[(1 + g_V) \bar{c} \gamma_\mu b + (-1 + g_A) \bar{c} \gamma_\mu \gamma_5 b + g_S \, i\partial_\mu (\bar{c} b) + g_P \, i\partial_\mu (\bar{c} \gamma_5 b)$$

$$+ g_T \, i\partial_\nu (\bar{c} i \sigma_{\mu\nu} b) + g_{T5} \, i\partial_\nu (\bar{c} i \sigma_{\mu\nu} \gamma_5 b) \big] \times L^\mu = \frac{G_F}{\sqrt{2}} V_{cb} \, H_\mu L^\mu$$

Assumption lepton current known $L^\mu = \bar{\ell} \gamma^\mu (1 - \gamma_5) \nu_\ell$

$$g_{V,A} \sim \mathcal{O}\left(\frac{v^2}{\Lambda_{\rm NP}^2} \right) , \quad g_{S,P,T,T5} \sim \frac{1}{v} \mathcal{O}\left(\frac{v^2}{\Lambda_{\rm NP}^2} \right)$$

$$\bar{c} \sigma_{\mu\nu} \gamma_5 b = -\tfrac{i}{2} \epsilon_{\mu\nu\alpha\beta} \bar{c} \sigma^{\alpha\beta} b$$

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell$$

$$a_{\theta_\ell}(q^2) = \frac{G_F^2|V_{cb}|^2}{256\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_D(q^2)} \left[|h_0(q^2)|^2 + \frac{m_\ell^2}{q^2}|h_t(q^2)|^2\right]$$

$$b_{\theta_\ell}(q^2) = -\frac{G_F^2|V_{cb}|^2}{128\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_D(q^2)} \frac{m_\ell^2}{q^2}\mathcal{R}e[h_0(q^2)h_t^*(q^2)]$$

$$c_{\theta_\ell}(q^2) = -\frac{G_F^2|V_{cb}|^2}{256\pi^3 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_D(q^2)}\,|h_0(q^2)|^2$$

$$h_0(q^2) = \tilde{\varepsilon}_0^{\mu *}\langle D|J_\mu|\overline{B}\rangle$$

$$h_t(q^2) = \tilde{\varepsilon}_t^{\mu *}\langle D|J_\mu|\overline{B}\rangle$$

$$\mathcal{A}_{FB}^{(\ell)}(q^2) = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2}$$

$$\frac{d^2\Gamma}{dq^2 d\chi} = a_\chi(q^2) + b^c_\chi(q^2)\cos\chi + b^s_\chi(q^2)\sin\chi + c^c_\chi(q^2)\cos 2\chi + c^s_\chi(q^2)\sin 2\chi$$

CP violating

$$a_\chi(q^2) = \frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \sqrt{\lambda_{D^*}(q^2)} \times \left\{ [|H_+|^2 + |H_-|^2 + |H_0|^2] \left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2 \right\}$$

$$c^c_\chi(q^2) = -\frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{R}e\,[H_+ H_-^*]$$

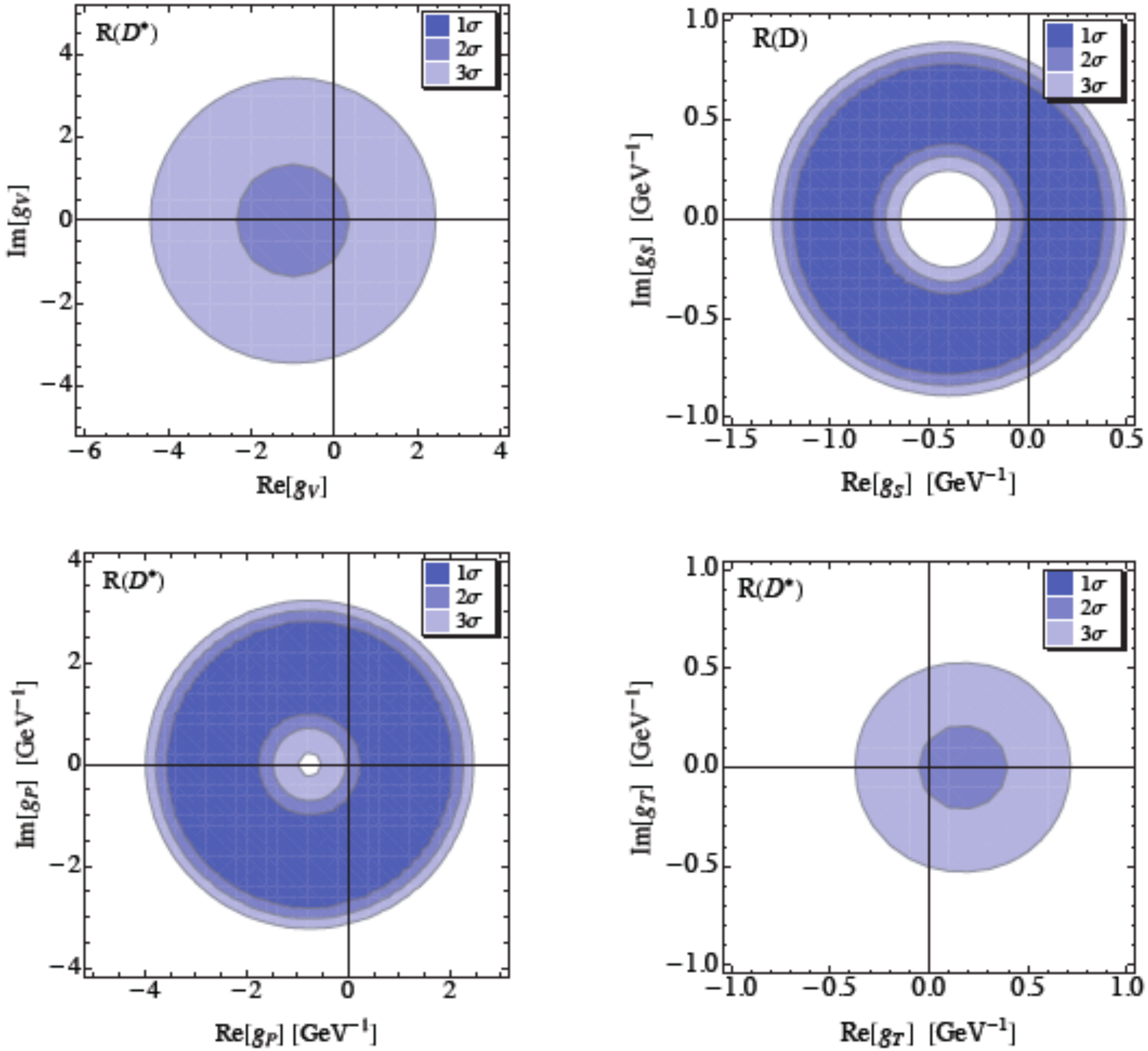
$$c^s_\chi(q^2) = -\frac{G_F^2|V_{cb}|^2}{384\pi^4 m_B^3} q^2 \left(1 - \frac{m_\ell^2}{q^2}\right)^3 \sqrt{\lambda_{D^*}(q^2)} \times \mathcal{I}m\,[H_+ H_-^*]$$

$c^s_\chi(q^2) = 0$ in SM $\Rightarrow$ $c^s_\chi(q^2) \neq 0$ would be a clear signal of NP!

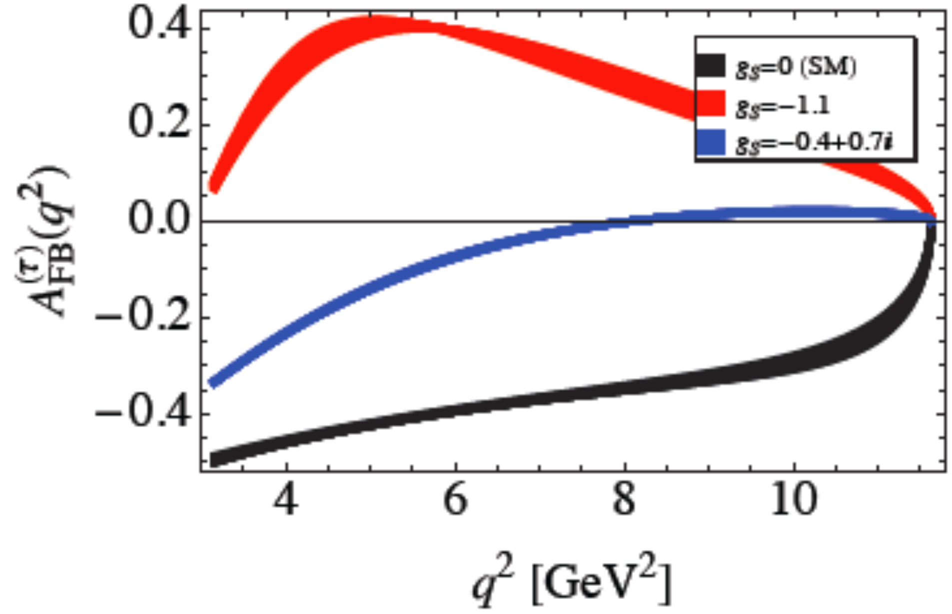
Proposal: new variables

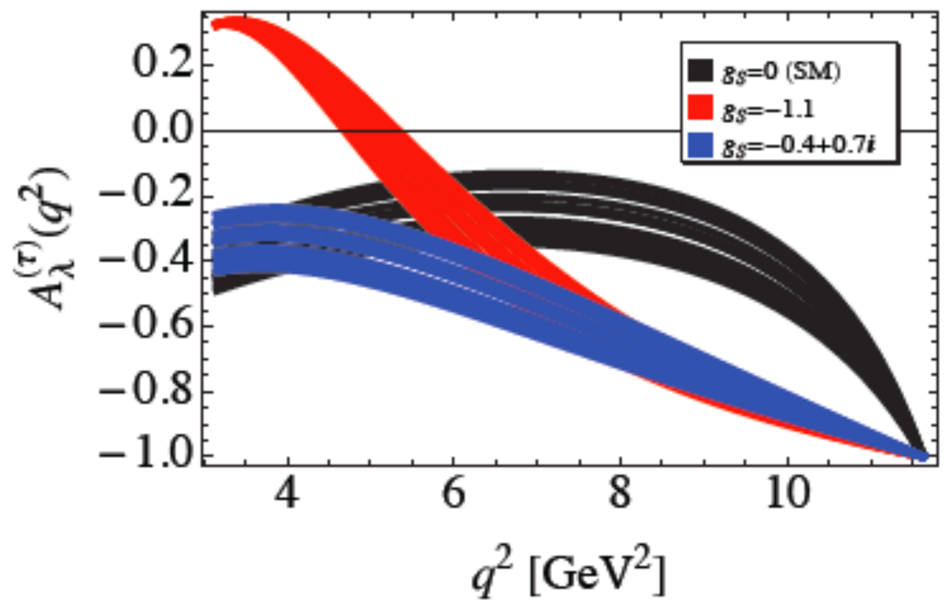
$$C_\chi^{(\ell)}(q^2) = \frac{c_\chi^c(q^2)}{a_\chi(q^2)}, \qquad S_\chi^{(\ell)}(q^2) = \frac{c_\chi^s(q^2)}{a_\chi(q^2)}$$

Ratios R(D) and R(D*) are insensitive to g_V (g_A)

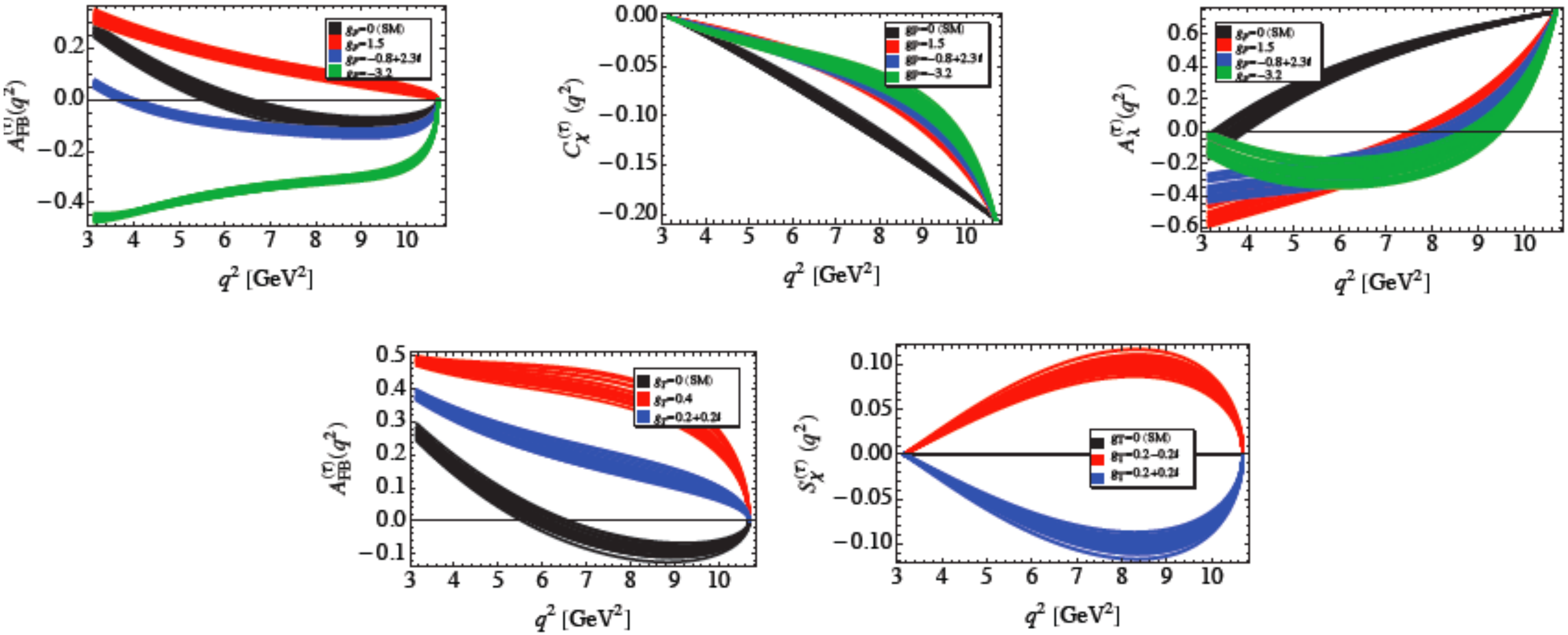

R(D^*)
1σ
2σ
3σ
Re[g_V]
Im[g_V]
R(D)
1σ
2σ
3σ
Re[g_S] [GeV^{-1}]
Im[g_S] [GeV^{-1}]
R(D^*)
1σ
2σ
3σ
Re[g_P] [GeV^{-1}]
Im[g_P] [GeV^{-1}]
R(D^*)
1σ
2σ
3σ
Re[g_T] [GeV^{-1}]
Im[g_T] [GeV^{-1}]

$\mathrm{B}\to D\tau\nu_\tau$





B→ $D^{*}\tau\nu_{\tau}$



$A_{FB}^{(\tau)}(q^2)$
g_P=0 (SM)
g_P=1.5
g_P=−0.8+2.3i
g_P=−3.2
q^2 [GeV^2]
$C_{\chi}^{(\tau)}(q^2)$
g_P=0 (SM)
g_P=1.5
g_P=−0.8+2.3i
g_P=−3.2
q^2 [GeV^2]
$A_{\lambda}^{(\tau)}(q^2)$
g_P=0 (SM)
g_P=1.5
g_P=−0.8+2.3i
g_P=−3.2
q^2 [GeV^2]
$A_{FB}^{(\tau)}(q^2)$
g_T=0 (SM)
g_T=0.4
g_T=0.2+0.2i
q^2 [GeV^2]
$S_{\chi}^{(\tau)}(q^2)$
g_T=0 (SM)
g_T=0.2−0.2i
g_T=0.2+0.2i
q^2 [GeV^2]

Anatomy of NP searches $\mathrm{B}\rightarrow D\tau\nu_\tau$

$B \rightarrow D\ell\overline{\nu}_\ell$

observable	g_V	g_S	g_T
$\mathcal{B}^{(\mu)}$	$\star\star$	—	$\star\star$
$\mathcal{B}^{(\tau)}$	$\star$	$\star\star\star$	$\star$
$R(D)$	—	$\star\star\star$	—
$\mathcal{A}_{FB}^{(\mu)}$	—	$\star$	—
$\mathcal{A}_{FB}^{(\tau)}$	—	$\star\star\star$	—
$\mathcal{A}_{\lambda}^{(\tau)}$	—	$\star\star$	—

Anatomy of NP searches $\mathrm{B} \to D^* \tau \nu_\tau$

$B \to D^* \ell \overline{\nu}_\ell$

observable	g_V	g_A	g_P	g_T
$\mathcal{B}^{(\mu)}$	⋆	⋆⋆	–	⋆⋆⋆⋆
$\mathcal{B}^{(\tau)}$	–	⋆	⋆	⋆⋆⋆
$R(D^*)$	⋆	–	⋆	⋆⋆
$\mathcal{A}_{FB}^{(\mu)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆
$\mathcal{A}_{FB}^{(\tau)}$	⋆⋆⋆	⋆⋆⋆	⋆⋆	⋆⋆⋆
$\mathcal{A}_{\lambda}^{(\tau)}$	–	–	⋆⋆⋆	–
$C_{\chi}^{(\mu)}$	–	–	–	⋆
$C_{\chi}^{(\tau)}$	–	–	⋆⋆	⋆
$S_{\chi}^{(\mu)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆
$S_{\chi}^{(\tau)}$	⋆⋆⋆	⋆⋆⋆	–	⋆⋆⋆⋆

Prospect to check LFU in B physics

$$[\mathcal{B}(B \to \pi\tau\nu)/\mathcal{B}(B \to \pi\ell\nu)]^{\rm SM} = 0.68 \pm 0.03$$

- measurements of $BR(B \to \pi\tau\nu_\tau)$ and $BR(B_c \to \tau\nu_\tau)$

- lattice improvements of the scalar form-factor

Impact on LHC

- search for charged Higgs, LQ

- all models predict $h + \tau + \not{E}_T$ → missing transverse energy

- models with $\mathcal{Q}_R^i$, $\mathcal{Q}_{LR}$ and $\mathcal{Q}_{RL}^i$ $t + \not{E}_T$

$(t+)\tau + \not{E}_T$

LHC signatures

1) Higgs lighter than top the signal $t \to bH^+$

existing searches at ATLAS and CMS

$|\kappa^t_{RL,LR}| \lesssim \mathcal{O}(0.2 - 0.4)$ for 80 GeV < m_{H-} < 160 GeV

2) Heavier Higgs $m_{H^-} = 200 \text{ GeV}$

dominant signal $gb \to H^- t$

LHC: at 8 TeV $\sigma_{pp} = 1.4 \; pb(|\kappa^t_{RL}|^2 + |\kappa^t_{LR}|^2)$

Summary and outlook

- exp. and SM disagree in exclusive $b \to c\tau\nu_\tau$;

- knowledge of SM form factor can be improved;

- NP models can be constraint:

- MFV disfavored; 2HDM Type I, Type II, “lepton specific”, and “flipped” can not account new $\tau\upsilon_\tau$ final states observables;
- right and right-left scalar currents are viable candidates
- 2HDM with general FV LQ, composite fermions, …
are able to account τυ observables;

- NP possible to constrain better in a number of new observables in $B \to D^*\tau\nu_\tau$

- measurements of $BR(B \to \pi\tau\nu_\tau)$ $BR(B_c \to \tau\nu_\tau)$
would give additional check of possible LFU ;

- possible LHC signatures!

$$\mathrm{F}_+(q^2) = \frac{1}{2\sqrt{m_B m_D}}[(m_B + m_D)h_+(w) - (m_B + m_D)h_-(w)]$$

$$\begin{aligned} h_+(w) &= \left[C_1 + \frac{w+1}{2}(C_2 + C_3) + (\epsilon_b + \epsilon_c)L_1\right]\xi(w) \\ &= \tilde{h}_+(w)\xi(w), \end{aligned}$$

$$\begin{aligned} h_-(w) &= \left[\frac{w+1}{2}(C_2 - C_3) + (\epsilon_c - \epsilon_b)L_4\right]\xi(w) \\ &= \tilde{h}_-(w)\xi(w), \end{aligned}$$

$$L_1 \simeq 0.72(w-1)\bar{\Lambda}, \qquad L_2 \simeq -0.16(w-1)\bar{\Lambda},$$

$$L_3 \simeq -0.24\bar{\Lambda}, \qquad L_4 \simeq 0.24\bar{\Lambda},$$

$$L_5 \simeq -\bar{\Lambda}, \qquad L_6 \simeq -\frac{3.24}{w+1}\bar{\Lambda}.$$

$$\frac{C_1^5}{C_1} = 1 - \frac{4\alpha_s}{3\pi} r_f(w), \qquad \frac{C_2^{(5)}}{C_1} = -\tfrac{2\alpha_s}{3\pi} H_{(5)}\left(w, \tfrac{1}{z_m}\right)$$

$$\frac{C_3^{(5)}}{C_1} = \mp \frac{2\alpha_s}{3\pi} H_{(5)}(w, z_m),$$

$z_m = \frac{m_c}{m_b}$

$$r_f(w) = \frac{1}{\sqrt{w^2-1}} \log\left[w + \sqrt{w^2-1}\right],$$

$$
\begin{aligned}
H_{(5)}(w, z_m) = {} & \frac{z_m(1 - \log z_m \mp z_m)}{1 - 2wz_m + z_m^2} + \frac{z_m}{(1 - 2wz_m + z_m^2)^2} \\
& \times [2(w \mp 1)z_m(1 \pm z_m) \log z_m \\
& - [(w \pm 1) - 2w(2w \pm 1)z_m \\
& + (5w \pm 2w^2 \mp 1)z_m^2 - 2z_m^3] r_f(w)].
\end{aligned}
$$

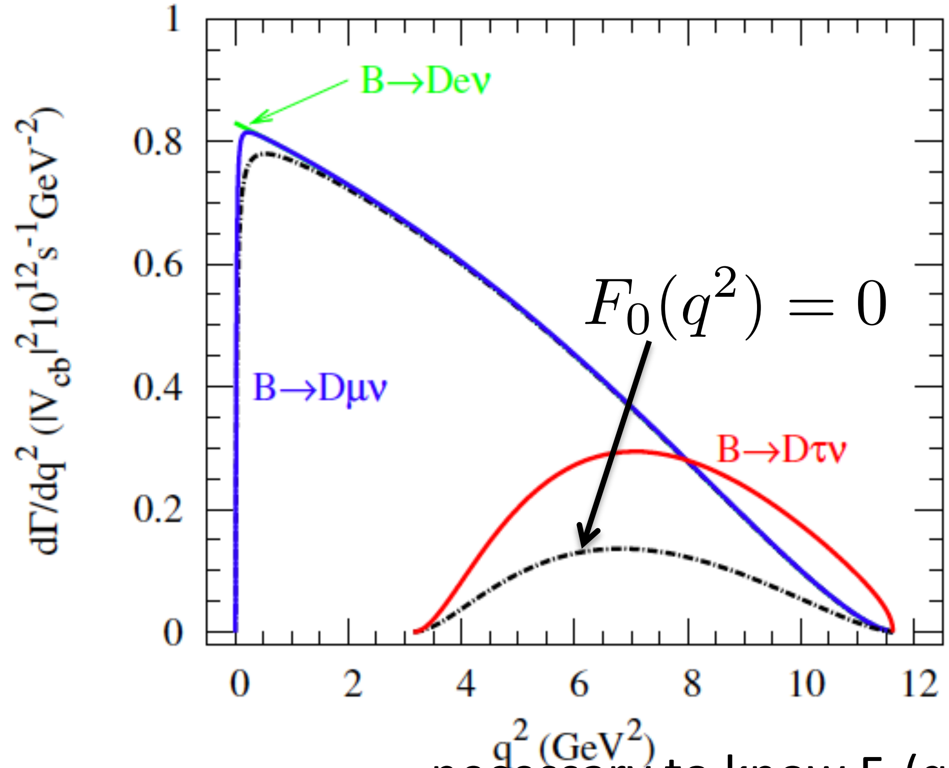
Exclusive semileptonic $B \longrightarrow D\, l\nu_l$ decays

$$\langle D(p')|\bar{c}\gamma_\mu b|\bar{B}(p)\rangle = \left(p_\mu + p'_\mu - \frac{m_B^2 - m_D^2}{q^2} q_\mu\right) F_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q_\mu F_0(q^2)$$

$B \longrightarrow D\, \tau\nu_\tau$: scalar form factor contributes!
massless lepton: only vector form factor contributes.

comparison: $B \longrightarrow D\tau\upsilon_\tau$ and
$B \longrightarrow D\, \mu\nu_\mu$

Kronfeld@ Lattice 2012



necessary to know $F_0(q^2)$!

SM in $B \longrightarrow D\, l\nu_l$

• mostly HQ approach useful;

• perturbative correction + HQE (Nierste et al, 0801.4938, Tanaka & Watanabe, 1006.4306);

• complete information comes from – lattice QCD;

MILC collaboration: 1206.4992, first SM lattice calculation (unquenched);

• In ratio uncertainties cancel:

$$R \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

Mescia& Kamenik, 0802.3790
Tanaka & Watanabe,1006.430
Faller, Mannel &Tyrczyk 1105.36796
Nierste, Trine & Westhoff, 0801.4938
S.F., J.F.Kamenik, Nisanndzic, 1203.2654

Generic flavor structure; b $\longrightarrow$ u and b $\longrightarrow$ c transitions are not correlated

1) $\mathcal{Q}_R^i$

NP in $\mathcal{R}^{\pi}_{\tau/\ell}$ is not related to $\mathcal{R}^{(*)}_{\tau/\ell}$

SM values for $\mathcal{R}_{\tau/\ell}$ modified by $|1 - c_R/2V_{cb}|^2$

$\mathcal{R}^{\pi}_{\tau/\ell}$ by $|1 + \epsilon_R c_R/2V_{ub}|^2$

$$\mathcal{R}^{*,R(\mathrm{MFV})}_{\tau/\ell}/\mathcal{R}^{*,\mathrm{SM}}_{\tau/\ell} = 1 - 0.88\,\mathrm{Re}(c_R/V_{cb}) + 0.25|c_R/V_{cb}|^2.$$

$c_R \simeq -0.0039 \pm 0.053i$

$\epsilon_R \simeq 0.15$

presence of large ~~CP~~

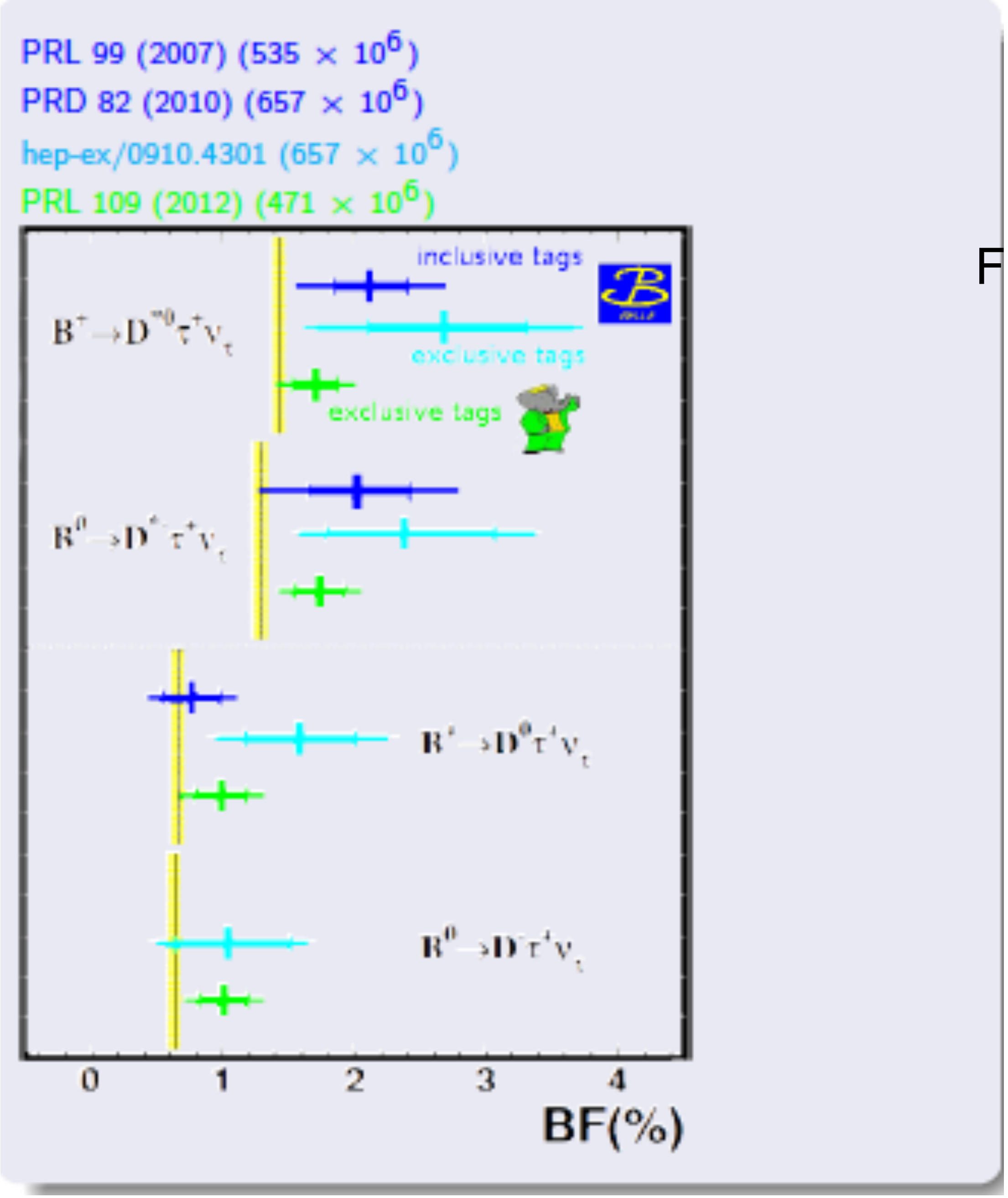
$v|\mathrm{Im}(c_R)|^{-1/4} \simeq 0.36\ \mathrm{TeV}$

2) $\mathcal{Q}_{RL}^i$

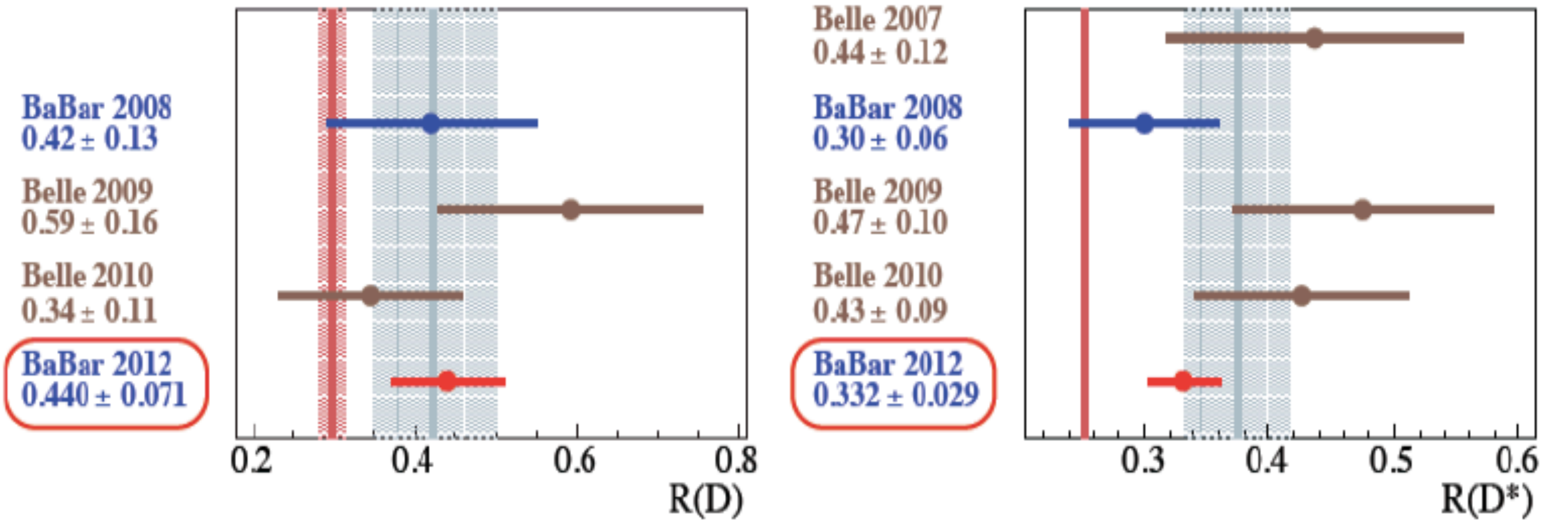
low NP scale!

$c_{RL} \simeq 11$ and $\epsilon_{RL} \simeq 0.0084$ $\quad v|c_{RL}|^{-1/4} \simeq 97\ \mathrm{GeV}$

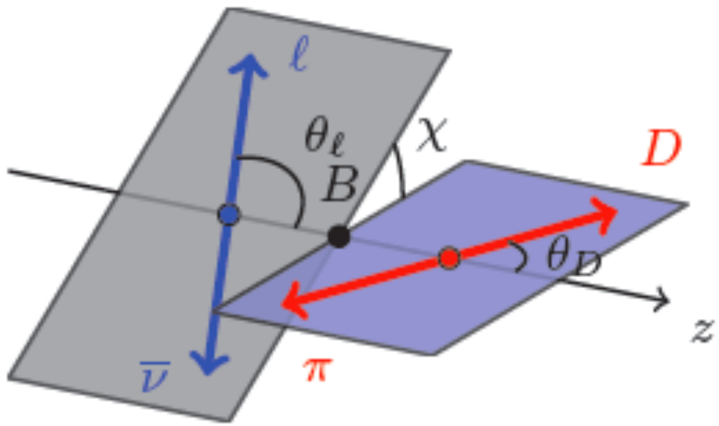
Experimental results $B \longrightarrow D^{(*)} \tau \nu_\tau$



From Bozek FPCP 2013



Belle 2007
0.44 ± 0.12
BaBar 2008
0.42 ± 0.13
0.30 ± 0.06
Belle 2009
0.59 ± 0.16
0.47 ± 0.10
Belle 2010
0.34 ± 0.11
0.43 ± 0.09
BaBar 2012
0.440 ± 0.071
0.332 ± 0.029
0.2
0.4
0.6
0.8
R(D)
0.3
0.4
0.5
0.6
R(D*)



ℓ
θ_ℓ
χ
D
B
θ_D
z
$\overline{\nu}$
π