New Physics in $\bar{B} \to D^{(*)} \tau \bar{\nu}$

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Based on works with Y.Sakaki, A. Tayduganov and R. Watanabe

WRU Symposium 2016
"Interplay between LHC and Flavor Physics"
Nagoya, Mar. 15 2016

Introduction

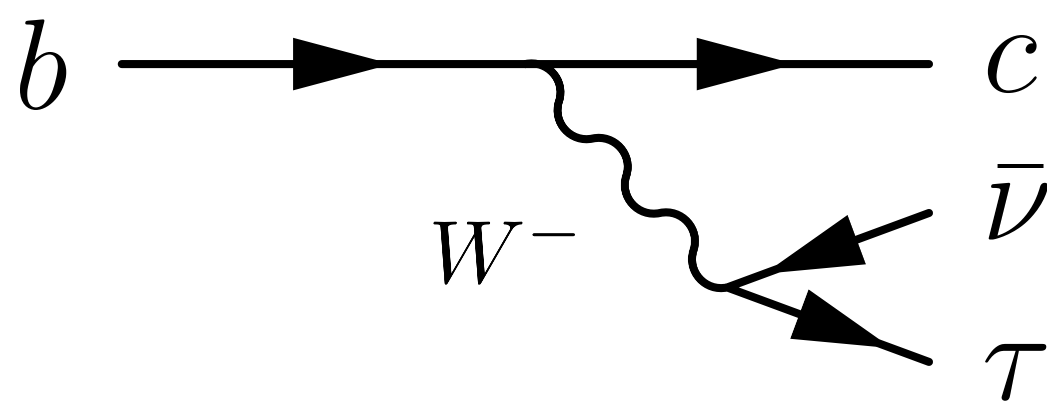
$\bar{B} \to D^{(*)} \tau \bar{\nu}$ Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

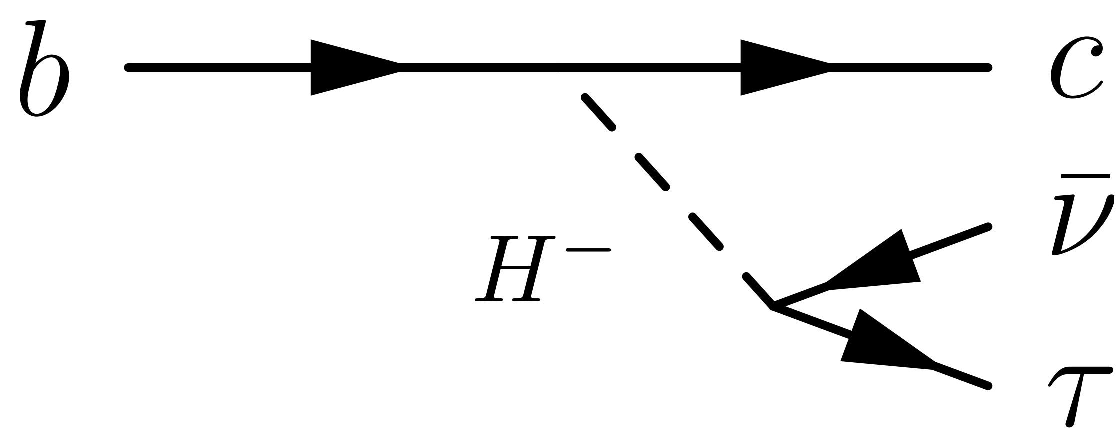
Theoretical motivation

W.S. Hou and B. Grzadkowski (1992)



SM: gauge coupling

lepton universality



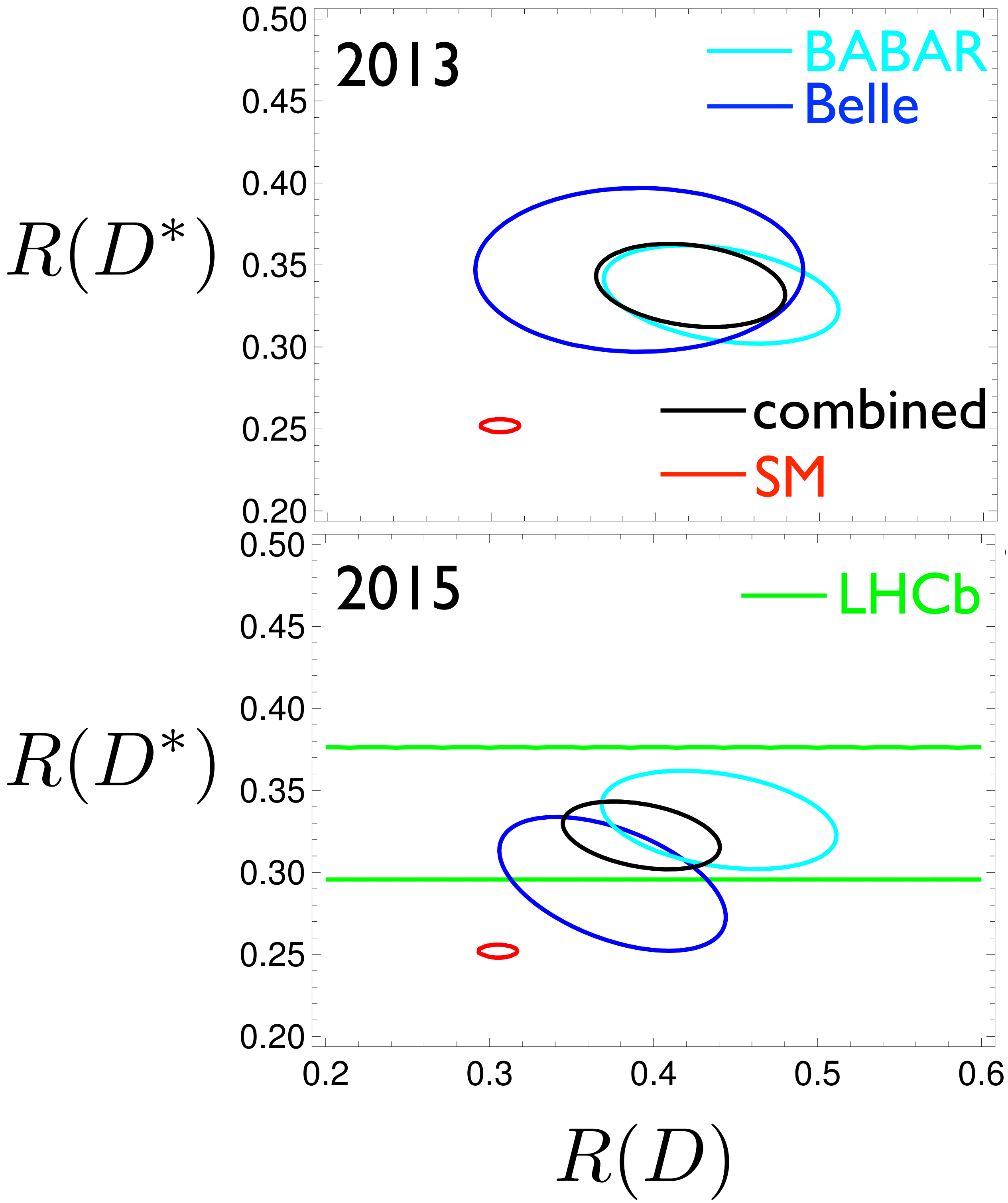
Type-II 2HDM (SUSY)

Yukawa coupling

$\propto m_b m_\tau \tan^2 \beta$

Experiments

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



$$R(D) = 0.421 \pm 0.058$$
$$R(D^*) = 0.337 \pm 0.025$$

~3.5σ

Y. Sakaki, MT, A. Tayduganov, R. Watanabe

$$R(D) = 0.391 \pm 0.041 \pm 0.028$$
$$R(D^*) = 0.322 \pm 0.018 \pm 0.012$$

~3.9σ **HFAG**

Belle, Moriond 2016

$$R(D^*) = 0.302 \pm 0.030 \pm 0.011$$

Standard model predictions

Theoretical uncertainty: form factors

data from $\bar{B} \to D^{(*)}\ell\bar{\nu}$ $(\ell = e, \mu)$

+ HQET or pQCD

+ lattice QCD

$R(D) = 0.296 \pm 0.016$ (Fajfer, Kamenik, Nisandzic)

0.302 ± 0.015 (Sakaki, MT, Tayduganov, Watanabe)

0.299 ± 0.011 (Bailey et al.)

$0.337^{+0.038}_{-0.037}$ (Fan, Xiao, Wang, Li)

$0.391 \pm 0.041 \pm 0.028$ (Exp. HFAG)

$R(D^*) = 0.252 \pm 0.003$ (Fajfer, Kamenik, Nisandzic)

0.252 ± 0.004 (Sakaki, MT, Tayduganov, Watanabe)

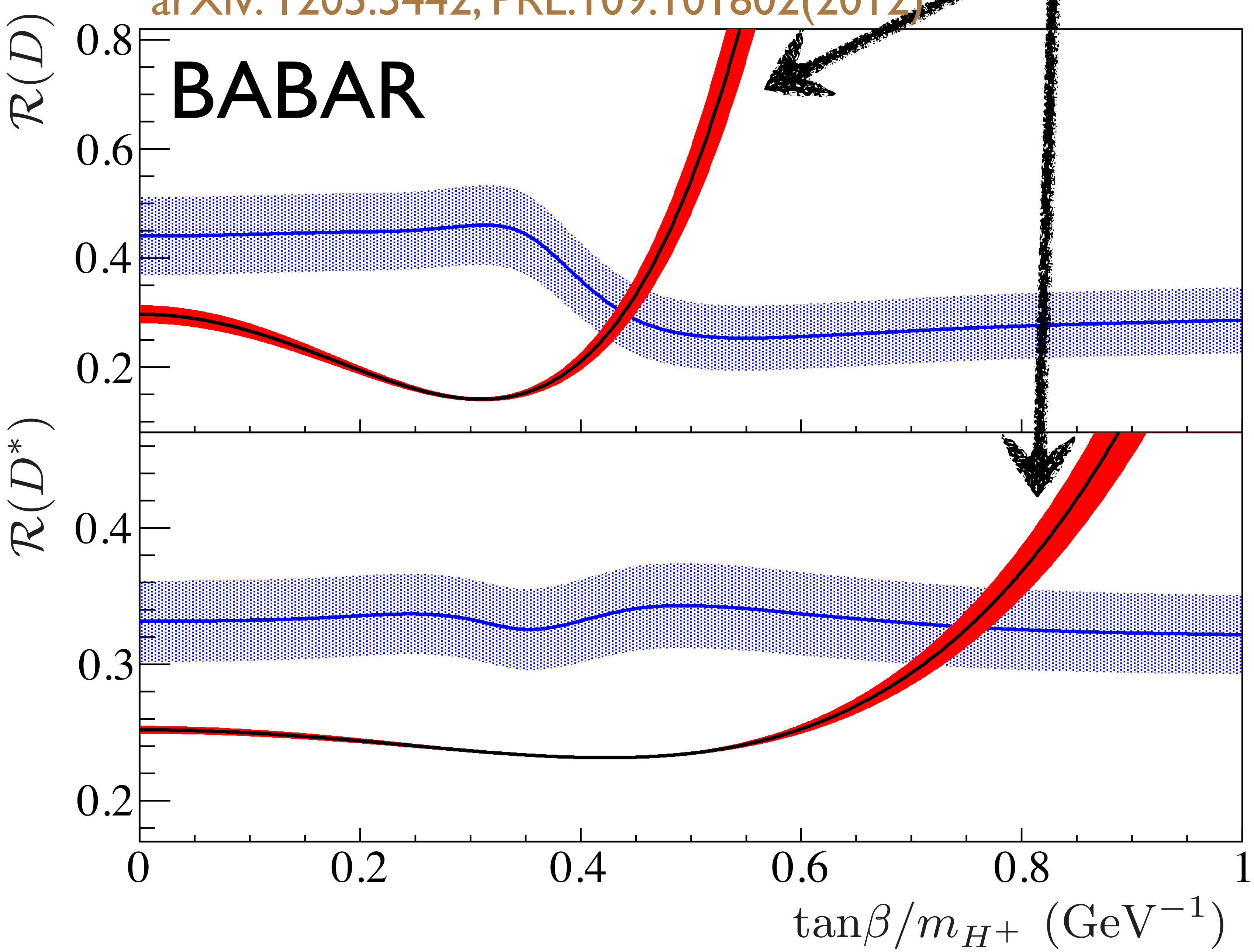
$0.269^{+0.021}_{-0.020}$ (Fan, Xiao, Wang, Li)

$0.322 \pm 0.018 \pm 0.012$ (Exp. HFAG)

Charged Higgs boson

predictions of 2HDM II

arXiv: 1205.5442, PRL.109.101802(2012)



Charged Higgs *excluded* at 99.8% CL

Model-independent approach

MT, R.Watanabe,arXiv1212.1878, PRD87.034028(2013).

Effective Lagrangian for $b \longrightarrow c\tau\bar{\nu}$

all possible 4f operators with LH neutrinos

$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb} \sum_{l=e,\mu,\tau} \left[(\delta_{l\tau} + C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T \right]$$

SM

$$\mathcal{O}^l_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$$ SM-like, RPV, LQ,W'

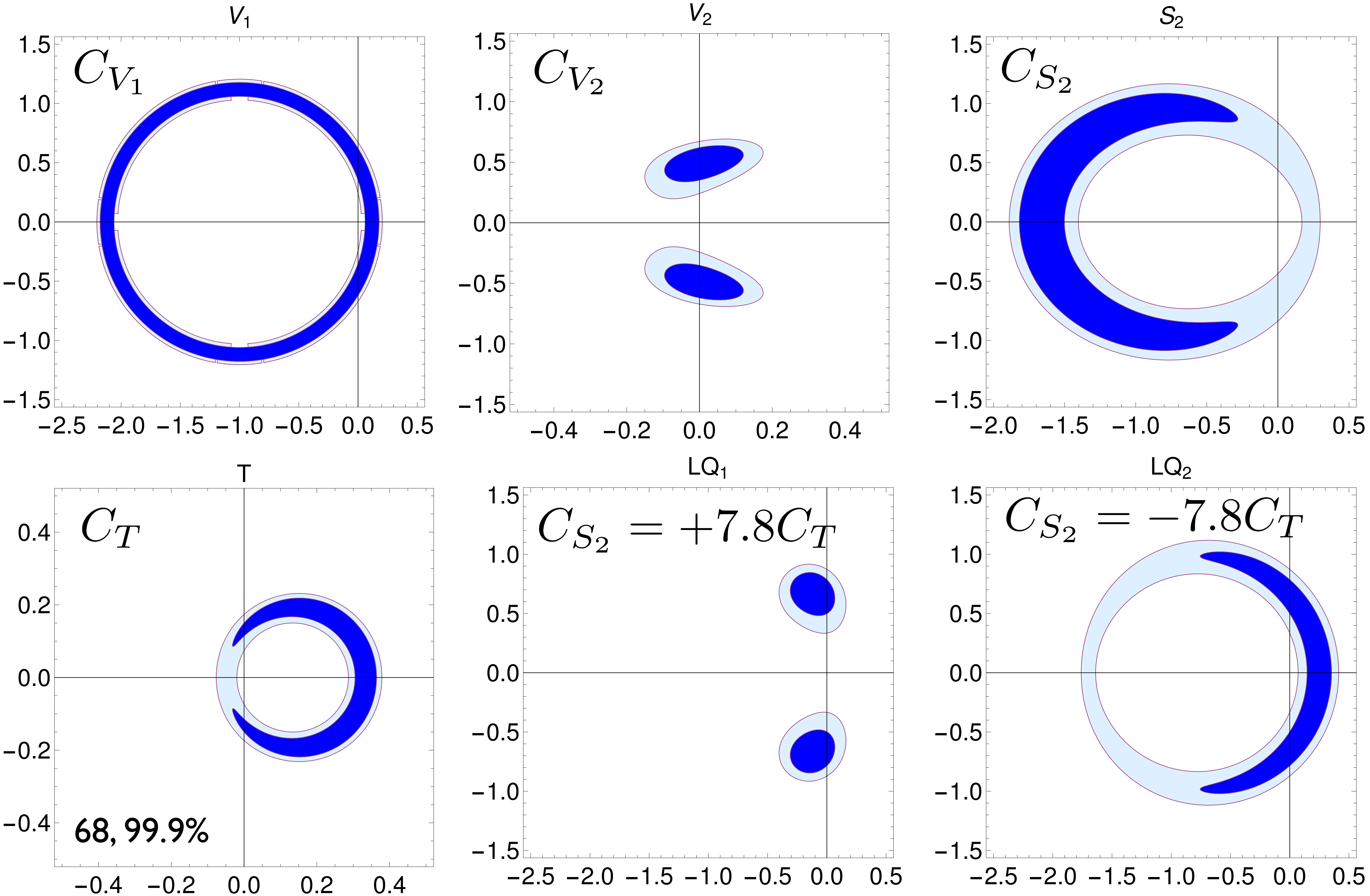
$$\mathcal{O}^l_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,,$$ RH current

$$\mathcal{O}^l_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_{Ll}\,,$$ charged Higgs II, RPV, LQ

$$\mathcal{O}^l_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_{Ll}\,,$$ charged Higgs III, LQ

$$\mathcal{O}^l_T = \bar{c}_R\sigma^{\mu\nu} b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_{Ll}$$ LQ

Allowed regions



Y. Sakaki, MT, A. Tayduganov, R. Watanabe
arXiv:1309.0301; PRD88, 094012(2013)

Leptoquark models

Six types of LQ possible

Buchmueller, Ruckl, Wyler (1987)

	S_1	S_3	V_2	R_2	U_1	U_3
spin	0	0	1	0	1	1
$F = 3B + L$	-2	-2	-2	0	0	0
$SU(3)_c$	3^*	3^*	3^*	3	3	3
$SU(2)_L$	1	3	2	2	1	3
$U(1)_{Y=Q-T_3}$	$1/3$	$1/3$	$5/6$	$7/6$	$2/3$	$2/3$

$$C^l_{V_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[\frac{g^{kl}_{1L} g^{23*}_{1L}}{2M^2_{S_1^{1/3}}} - \frac{g^{kl}_{3L} g^{23*}_{3L}}{2M^2_{S_3^{1/3}}} + \frac{h^{2l}_{1L} h^{k3*}_{1L}}{M^2_{U_1^{2/3}}} - \frac{h^{2l}_{3L} h^{k3*}_{3L}}{M^2_{U_3^{2/3}}}\right],$$

constrained by $\bar{B} \to X_s \nu \bar{\nu}$

$$C^l_{V_2} = 0,$$

$$C^l_{S_1} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[-\frac{2g^{kl}_{2L} g^{23*}_{2R}}{M^2_{V_2^{1/3}}} - \frac{2h^{2l}_{1L} h^{k3*}_{1R}}{M^2_{U_1^{2/3}}}\right],$$

disfavored

$$C^l_{S_2} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[-\frac{g^{kl}_{1L} g^{23*}_{1R}}{2M^2_{S_1^{1/3}}} - \frac{h^{2l}_{2L} h^{k3*}_{2R}}{2M^2_{R_2^{2/3}}}\right],$$

$$C^l_{T} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3}\left[\frac{g^{kl}_{1L} g^{23*}_{1R}}{8M^2_{S_1^{1/3}}} - \frac{h^{2l}_{2L} h^{k3*}_{2R}}{8M^2_{R_2^{2/3}}}\right],$$

$$C_{S_2}(m_{\mathrm{LQ}}) = \pm 4 C_T(m_{\mathrm{LQ}})$$

$$\Big\downarrow \text{RG}$$

$$C_{S_2}(m_b) = \pm 7.8 C_T(m_b)$$

q2 distribution

Y. Sakaki, MT, A. Tayduganov, R. Watanabe
arXiv:1412.3761; PRD91, 14028 (2015)

Several possible NP scenarios

$(\dots)$ current best fits

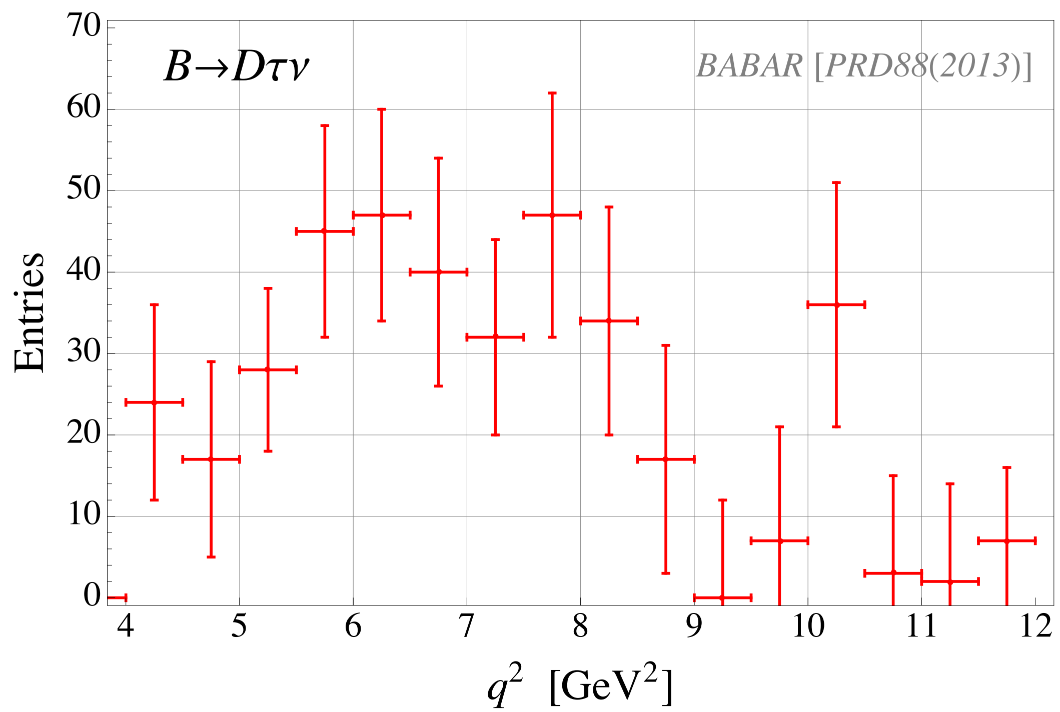
$$V_1 : C_{V_1} = 0.16\ (0.12)$$
$$V_2 : C_{V_2} = 0.01 \pm 0.60i\ (0.01 \pm 0.51i)$$
$$S_2 : C_{S_2} = -1.75\ (-1.67)$$
$$T : C_T = 0.33\ (0.34)$$
$$\mathrm{LQ}_1 : C_{S_2} = 7.8 C_T = -0.17 \pm 0.80i\ (-0.12 \pm 0.69i)$$
$$\mathrm{LQ}_2 : C_{S_2} = -7.8 C_T = 0.34\ (0.25)$$

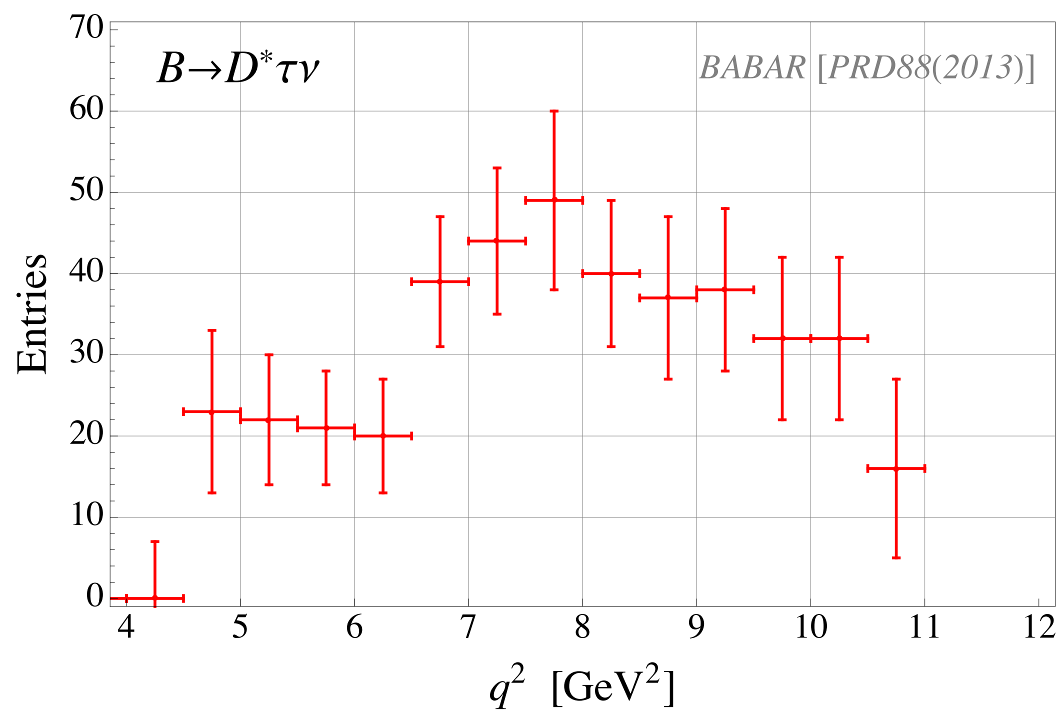
How to discriminate: other observables

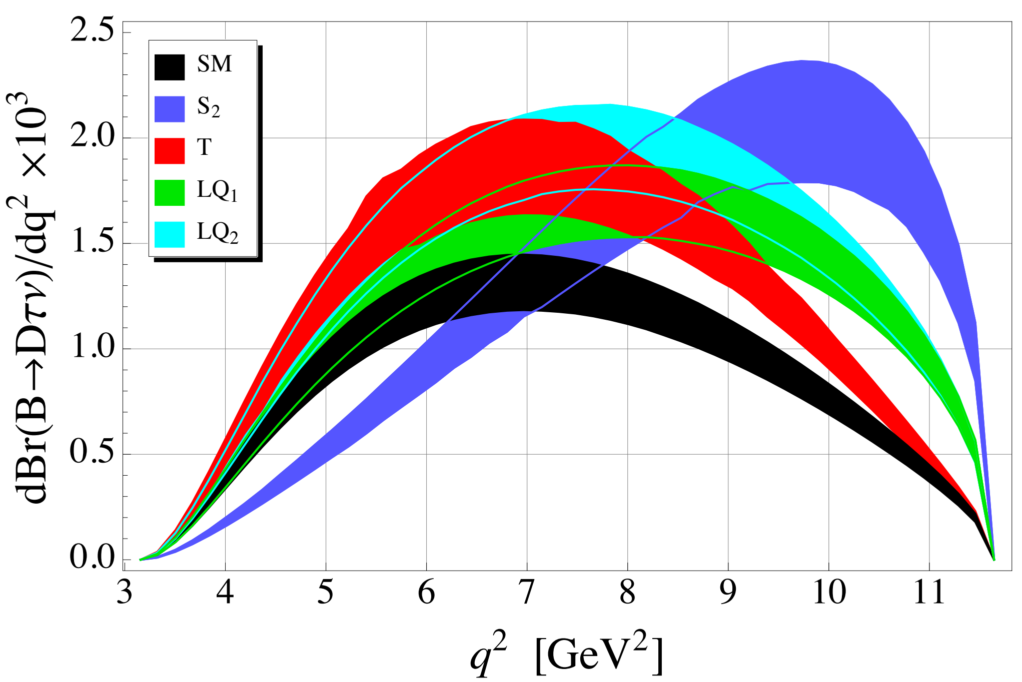
$A_{FB},\ P_\tau,\ P_{D^*}$ rather hard to measure

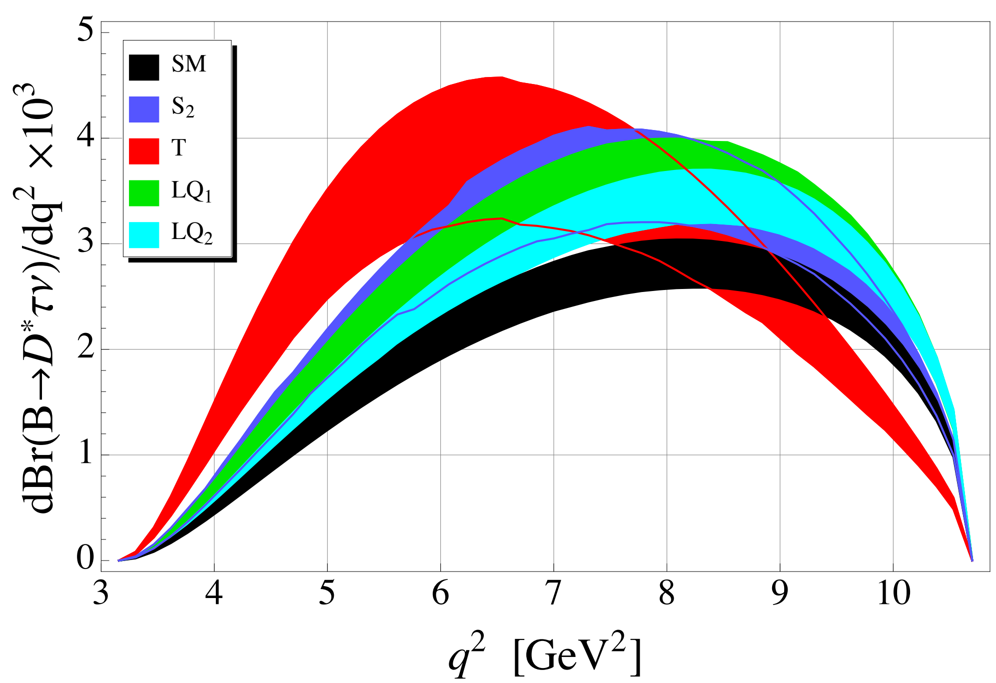
$q^2 = (p_B - p_{D^{(*)}})^2$ easier

Implication of the BABAR q2 data









p value

model	$\overline{B} \to D\tau\overline{\nu}$	$\overline{B} \to D^*\tau\overline{\nu}$	$\overline{B} \to (D + D^*)\tau\overline{\nu}$
SM	54%	65%	67%
V_1	54%	65%	67%
V_2	54%	65%	67%
S_2	0.02%	37%	0.1%
T	58%	0.1%	1.0%
LQ_1	13%	58%	25%
LQ_2	21%	72%	42%

$S_2, \ T$ disfavored

$\mathrm{LQ}_{1,2}$ (combinations of $S_2, \ T$) allowed

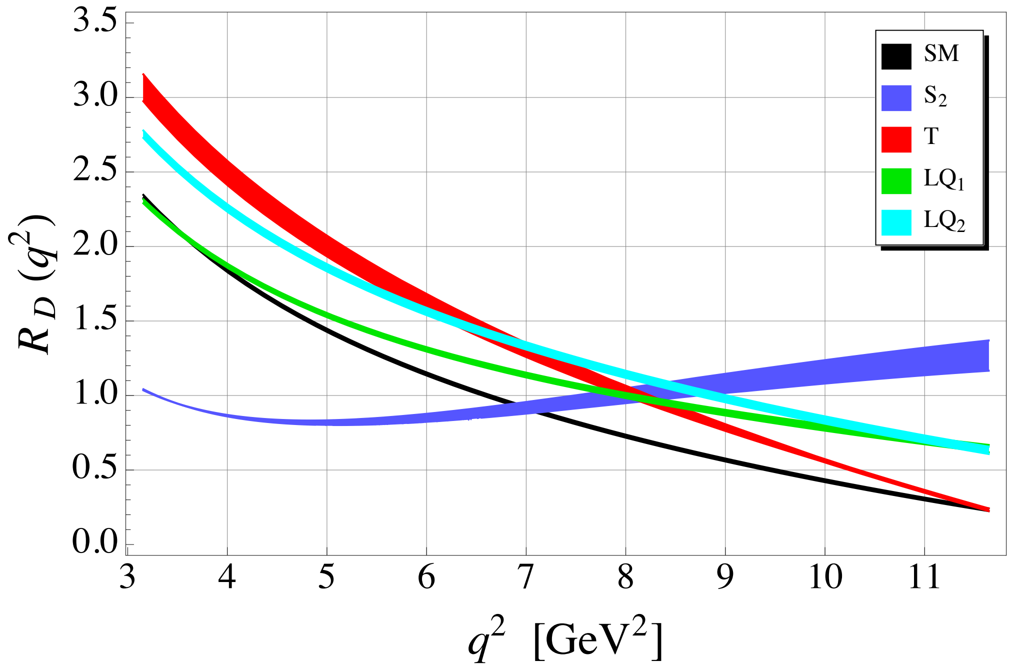
Ratio of the q2 distributions

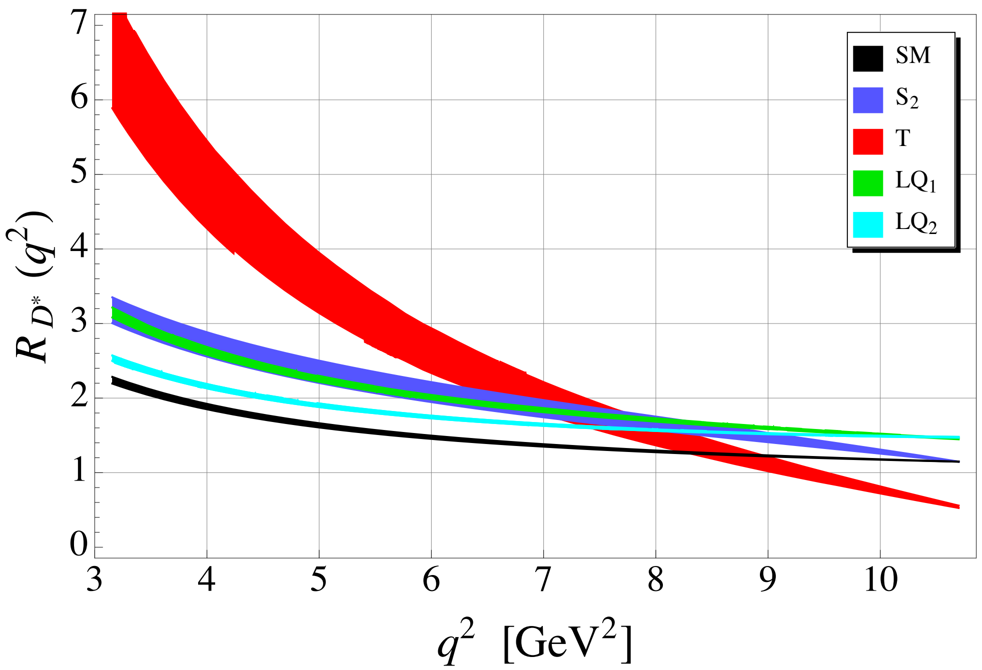
$$R_D(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D\ell\overline{\nu})/dq^2} \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

$$R_{D^*}(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D^*\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D^*\ell\overline{\nu})/dq^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2} .$$

$$\lambda_{D^{(*)}}(q^2) = ((m_B - m_{D^{(*)}})^2 - q^2)((m_B + m_{D^{(*)}})^2 - q^2)$$

No Vcb dependence, less form factor uncertainties





Simulated data vs tested models

χ^2 of the binned $R_{D^{(*)}}(q^2)$

Required luminosity to exclude the tested model

$\mathcal{L}$ [fb^{-1}]		model						
		SM	V_1	V_2	S_2	T	LQ$_1$	LQ$_2$
"data"	V_1	1170 (270)		10^6 (×)	500 (×)	900 (×)	4140 (×)	2860 (1390)
	V_2	1140 (270)	10^6 (×)		510 (×)	910 (×)	4210 (×)	3370 (1960)
	S_2	560 (290)	560 (13750)	540 (36450)		380 (×)	1310 (35720)	730 (4720)
	T	600 (270)	680 (×)	700 (×)	320 (×)		620 (×)	550 (1980)
	LQ$_1$	1010 (270)	4820 (×)	4650 (×)	1510 (×)	800 (×)		5920 (1940)
	LQ$_2$	1020 (250)	3420 (1320)	3990 (1820)	1040 (20560)	650 (4110)	5930 (1860)	

(...): integrated quantities

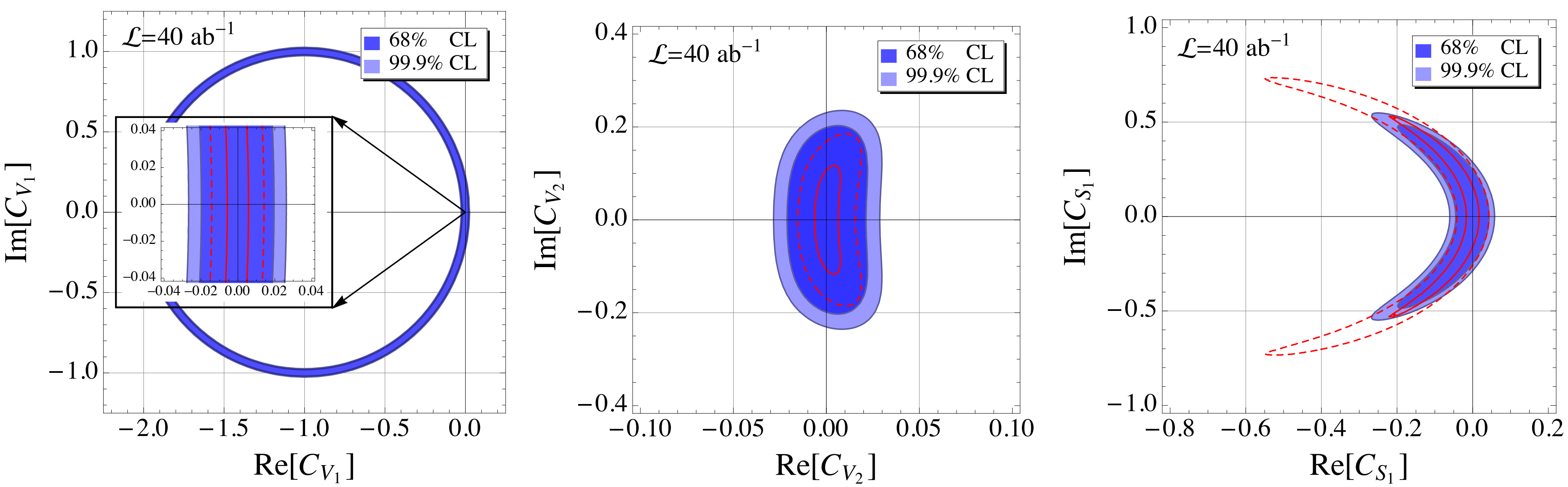
99.9 % CL

$L \lesssim 6\ \mathrm{ab}^{-1}$ in most cases

→ A good target at an earlier stage of Belle II

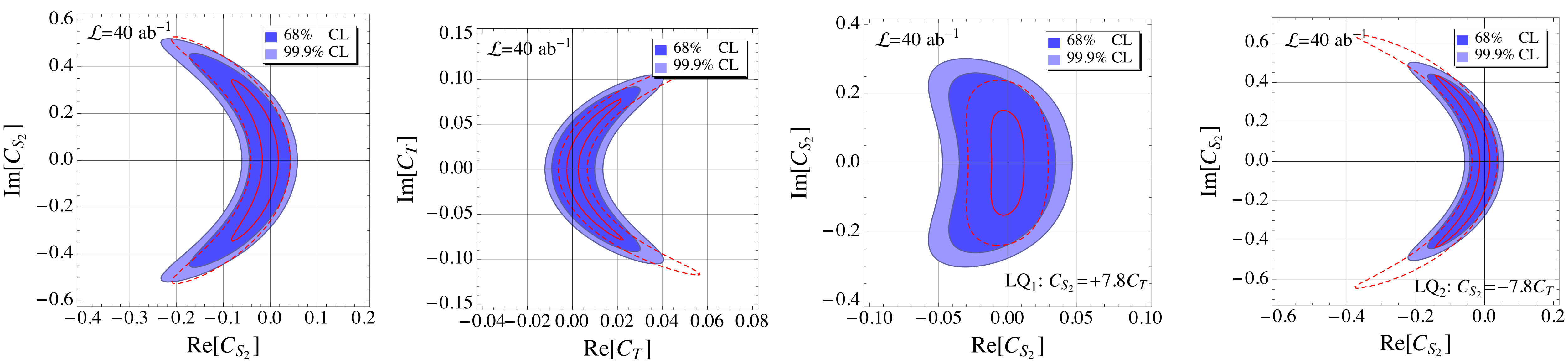
Belle II sensitivity at 40/ab

Assuming exp. = SM for $R(D),\ R(D^*)$



blue $R_{D^{(*)}}(q^2)$

red $R(D^{(*)})$



$$M_{\rm NP} \gtrsim 5(7),\ 5(6),\ 7(10),\ 5(7),\ 5(6)\ \text{TeV}$$

$V_{1,2}$ $\quad S_{1,2}$ $\quad T$ $\quad \mathrm{LQ}_1$ $\quad \mathrm{LQ}_2$

Other flavor signals of LQ

Scalar LQ S_1 $(\mathbf{3}^*, \mathbf{1}, 1/3)$ Bauer, Neubert 1511.01900

Tree: $B \to X_s \nu\bar{\nu},\ K^{(*)}\nu\bar{\nu}$

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

Loop: $b \to s\ell\bar{\ell}$

$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

2.6σ LHCb (2014)

$(g-2)_\mu,\ \tau \to \mu\gamma$

Vector LQ U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$ Fajfer, Kosnik 1511.06024

Tree: $B \to X_s \nu\bar{\nu},\ K^{(*)}\nu\bar{\nu}$

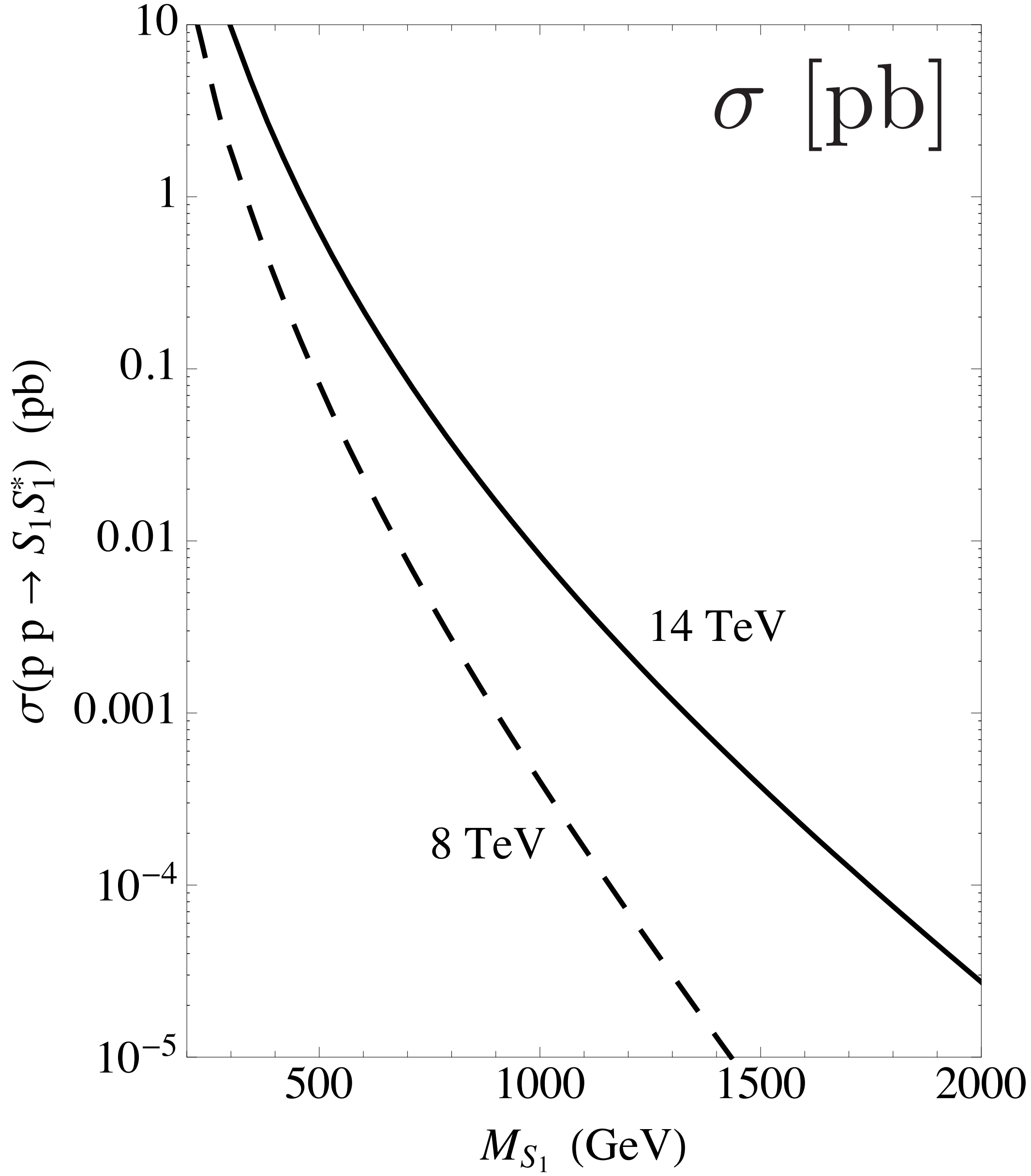
$b \to s\ell\bar{\ell},\ P_5',\ R_K$

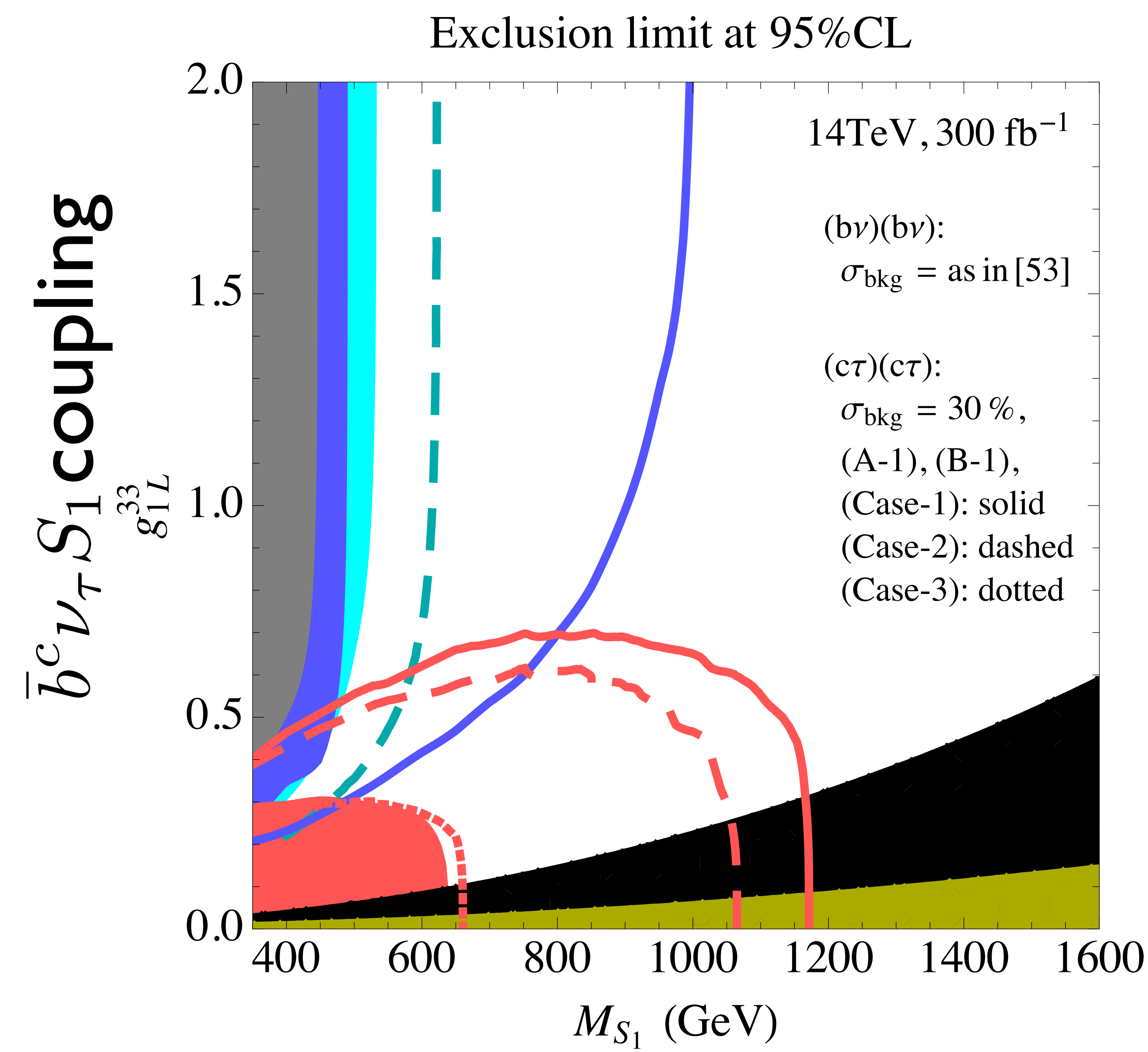
$t \to b\tau^+\nu$

Search for a scalar LQ at LHC

$S_1 \ (\mathbf{3}^*, \mathbf{1}, 1/3)$

Dumont, Nishiwaki, Watanabe, to appear





Outlook

- Excess of semitauonic B decays
  $R(D), R(D^*)$ ~ 4σ
- Testing NP with the q2 distribution
  The earlier stage of Belle II ~ 5-10 /ab
- Other observables $A_{FB},\ P_\tau,\ P_{D^*},\ R(X_c)$
  Belle II, LHCb prospect?
- Flavor structure of possible NP
  $(\bar{u}b)(\bar{\tau}\nu)$? $B^- \to \tau\bar{\nu}\,,\ B \to \pi\tau\bar{\nu}$ Belle, 150906521
  Bernlochner, 150906938
  MFV Freytsis, Ligeti, Ruderman 150608896
  U(2) Barbieri et al. 151201560