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

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Introduction

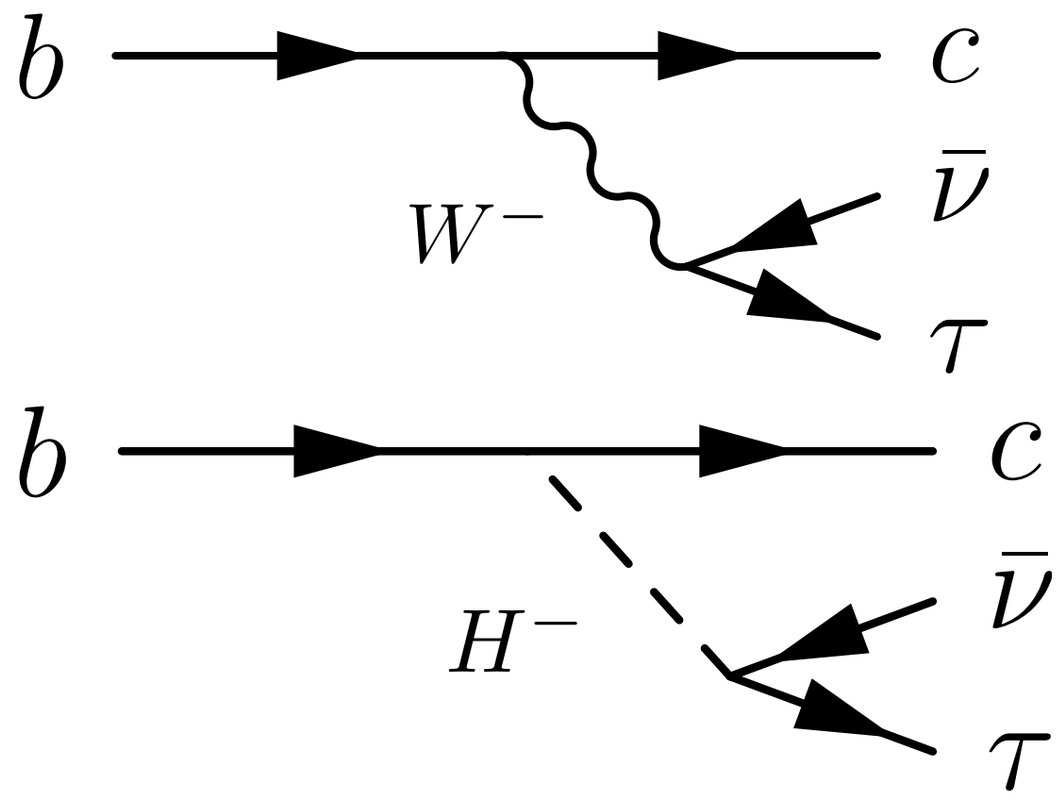
$\bar{B} \to D^{(*)}\tau\bar{\nu}$ Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

Theoretical motivation

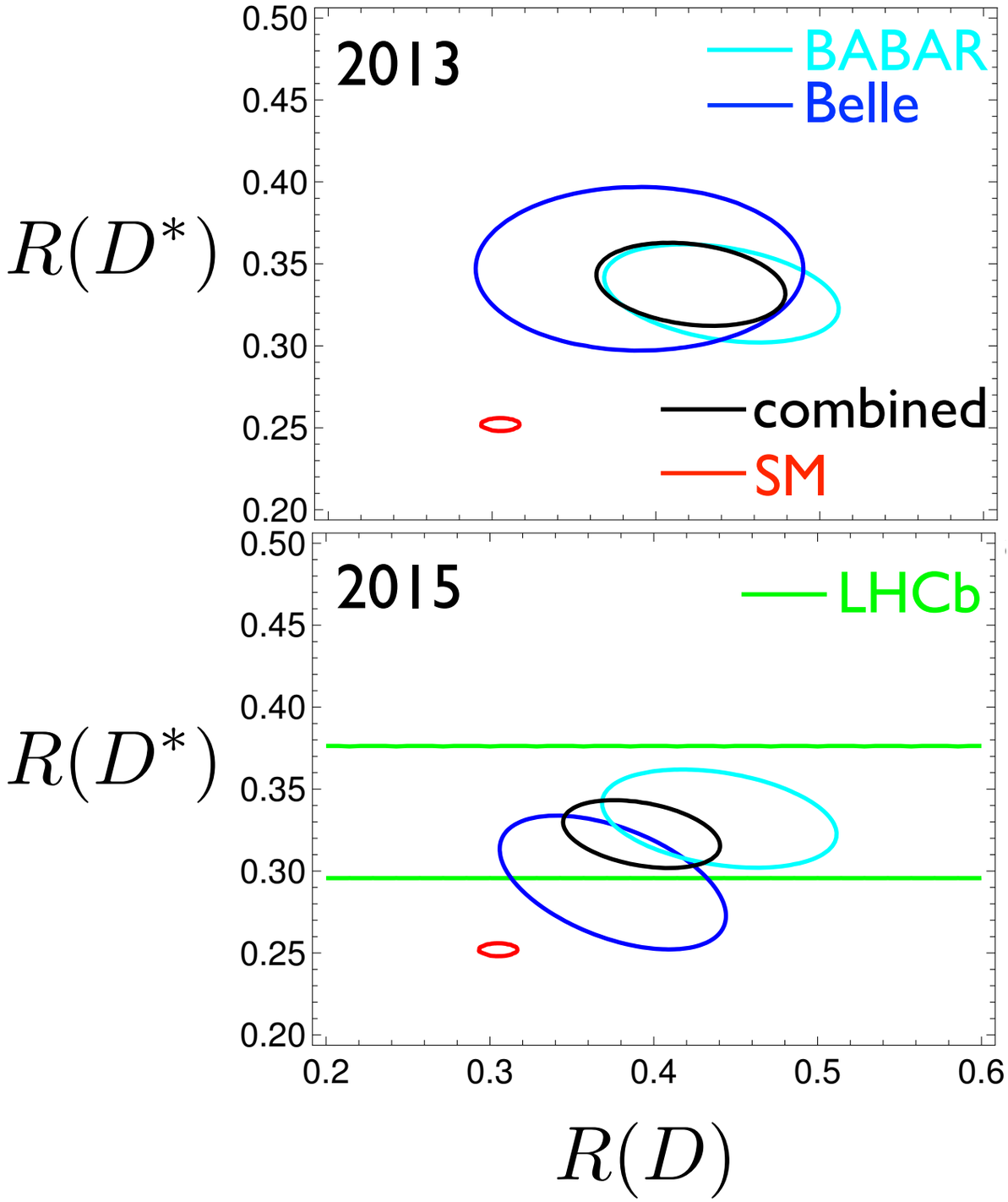
W.S. Hou and B. Grzadkowski (1992)



SM: gauge coupling
lepton universality

Type-II 2HDM (SUSY)
Yukawa coupling
$\propto m_b m_\tau \tan^2\beta$

Experiments



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

~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

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)

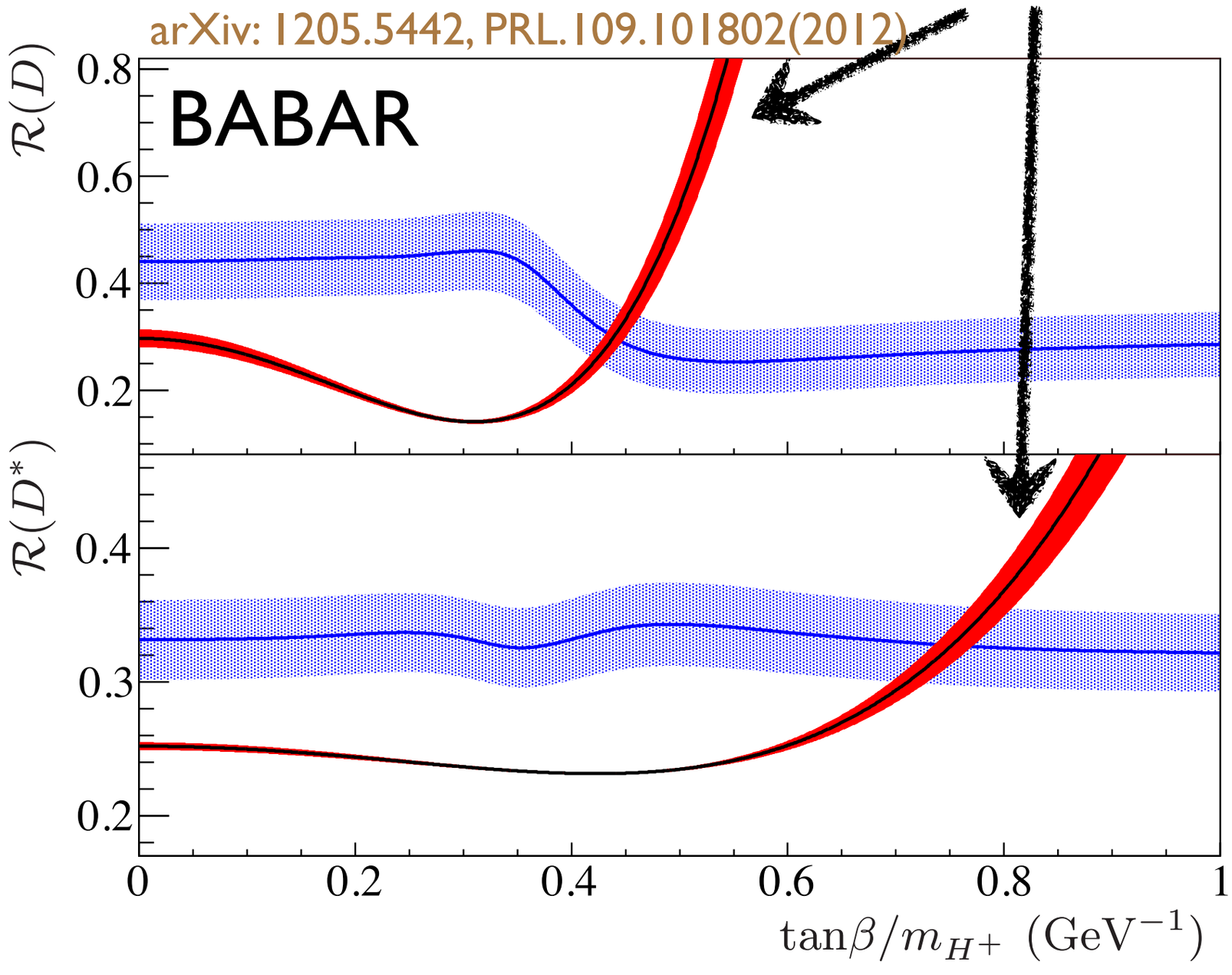
0.252 ± 0.004 (Sakaki, MT, Tayduganov, Watanabe)

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

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

Charged Higgs boson

predictions of 2HDM II



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

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

SM

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

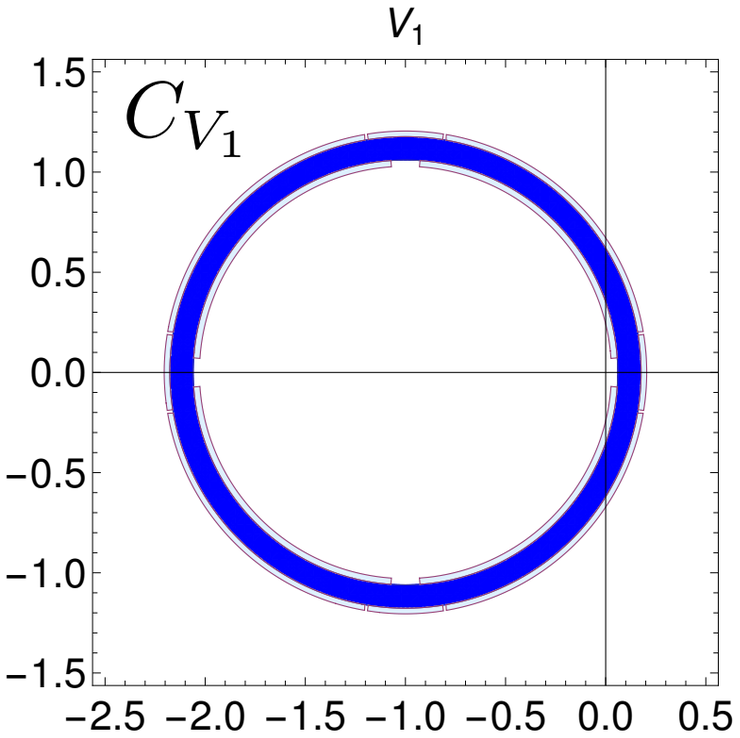
$$\mathcal{O}_{V_2}^l = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_{Ll}\,, \quad \text{RH current}$$

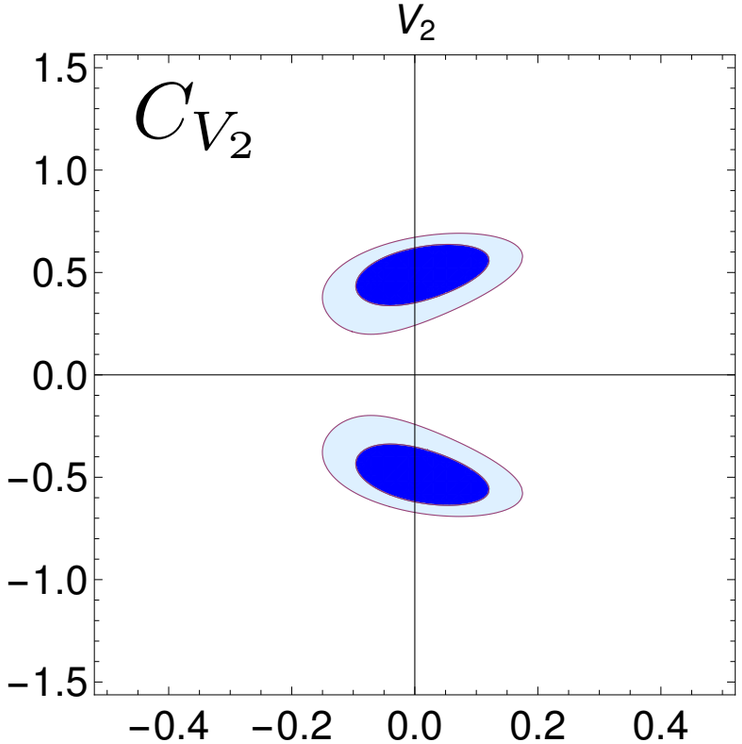
$$\mathcal{O}_{S_1}^l = \bar{c}_L b_R\,\bar{\tau}_R\nu_{Ll}\,, \quad \text{charged Higgs II, RPV, LQ}$$

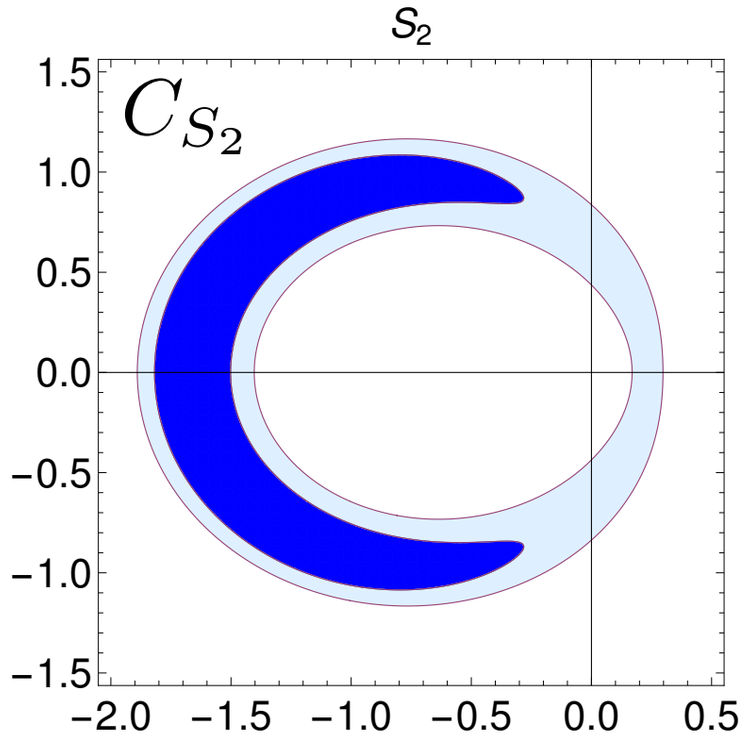
$$\mathcal{O}_{S_2}^l = \bar{c}_R b_L\,\bar{\tau}_R\nu_{Ll}\,, \quad \text{charged Higgs III, LQ}$$

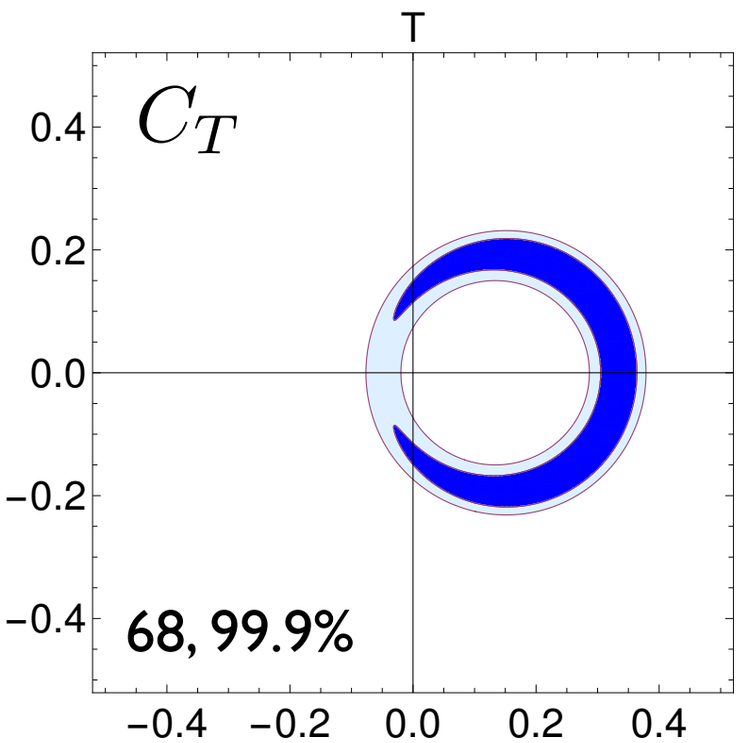
$$\mathcal{O}_T^l = \bar{c}_R\sigma^{\mu\nu} b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_{Ll} \quad \text{LQ}$$

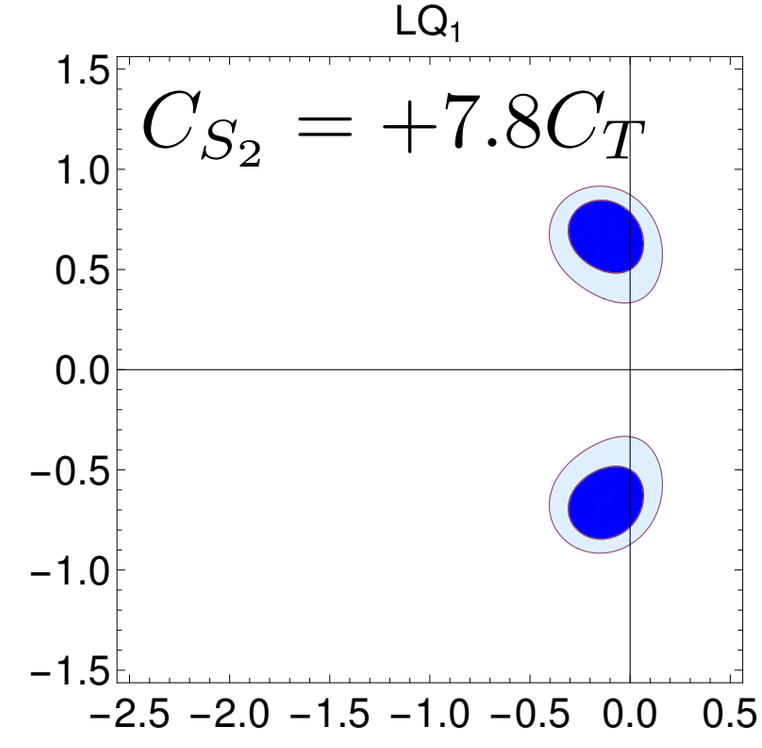
Allowed regions

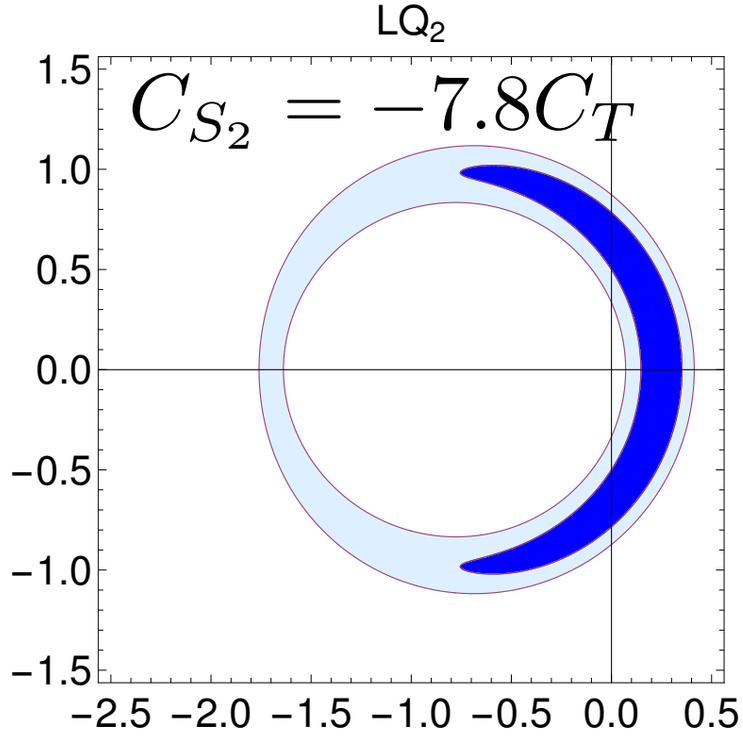












Leptoquark models

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

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

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

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

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

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

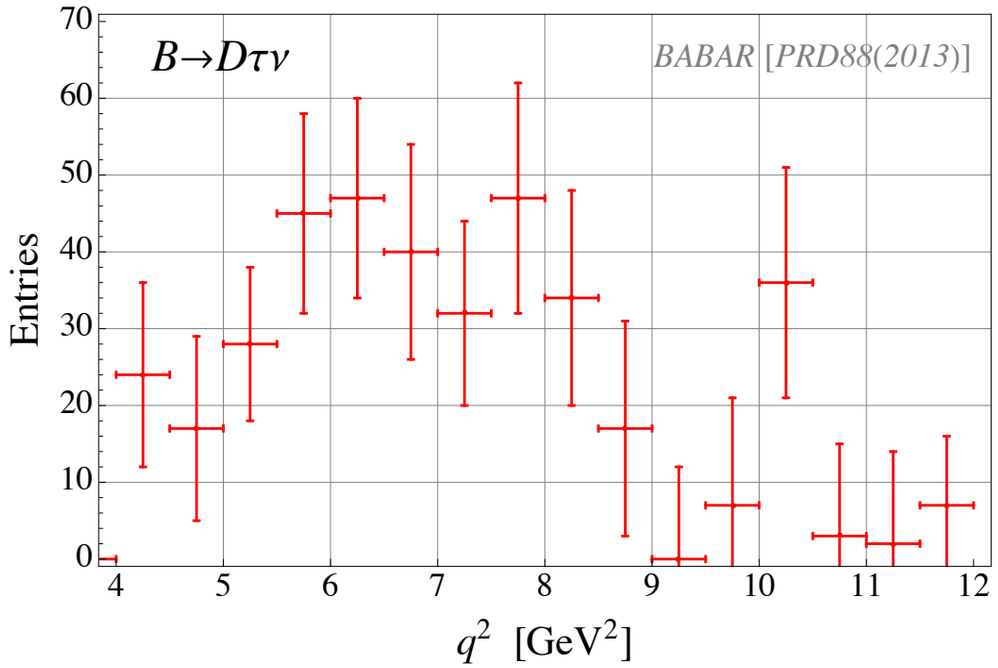
$$V_1 : C_{V_1} = 0.16\ (0.12)$$
$$V_2 : C_{V_2} = 0.01 \pm 0.60i\ (0.01 \pm 0.51i)$$
$$S_2 : C_{S_2} = -1.75\ (-1.67)$$
$$T : C_T = 0.33\ (0.34)$$
$$\mathrm{LQ}_1 : C_{S_2} = 7.8 C_T = -0.17 \pm 0.80i\ (-0.12 \pm 0.69i)$$
$$\mathrm{LQ}_2 : C_{S_2} = -7.8 C_T = 0.34\ (0.25)$$

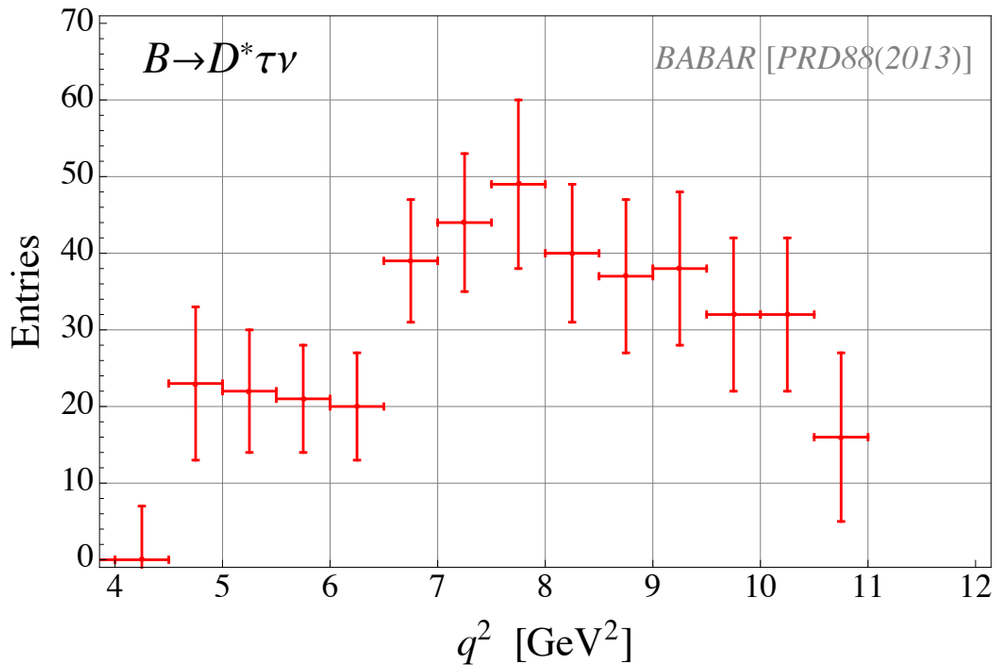
How to discriminate: other observables

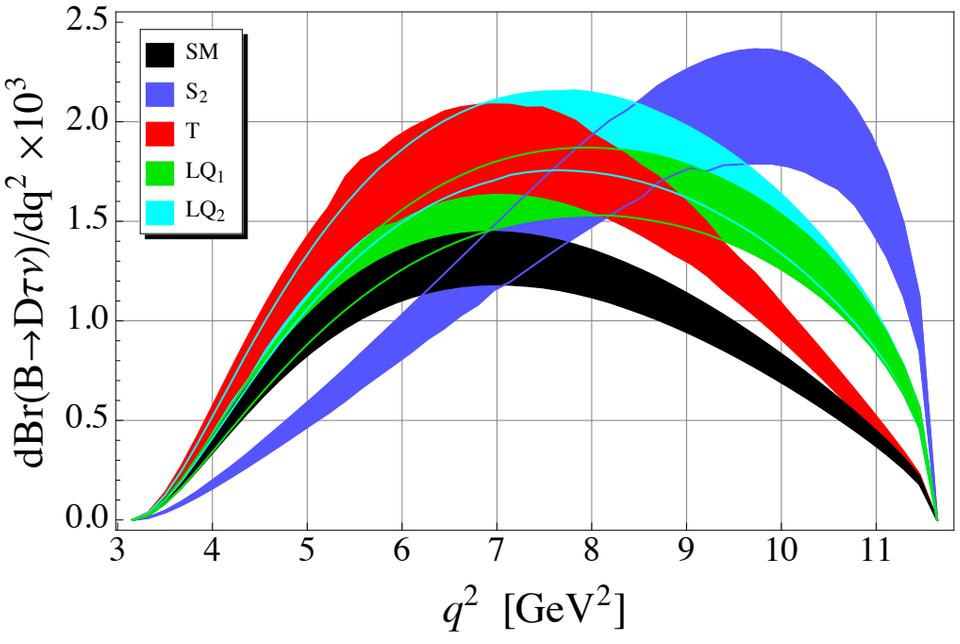
$A_{FB},\ P_\tau,\ P_{D^*}$ rather hard to measure

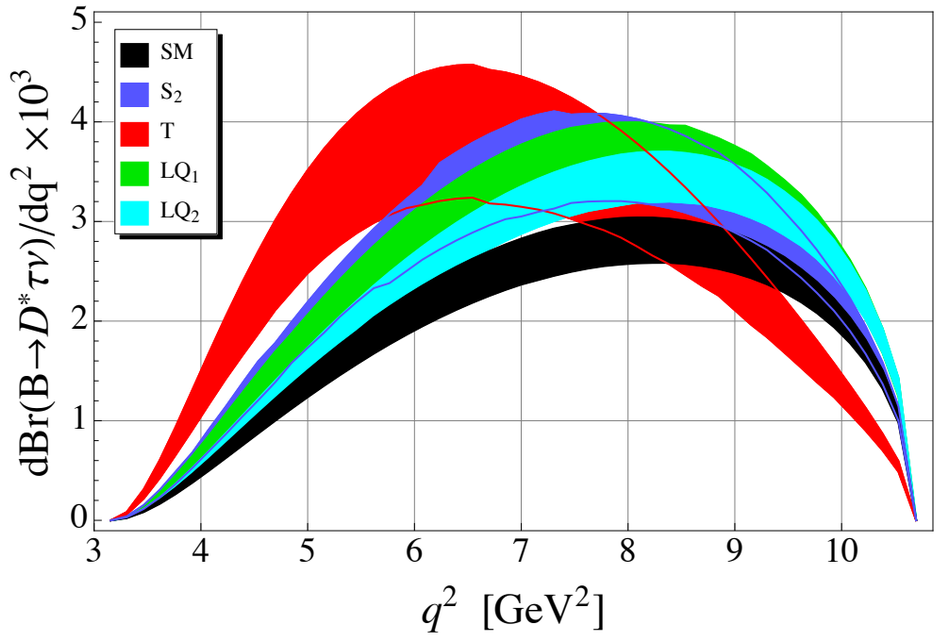
$q^2 = (p_B - p_{D^{(*)}})^2$ easier

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

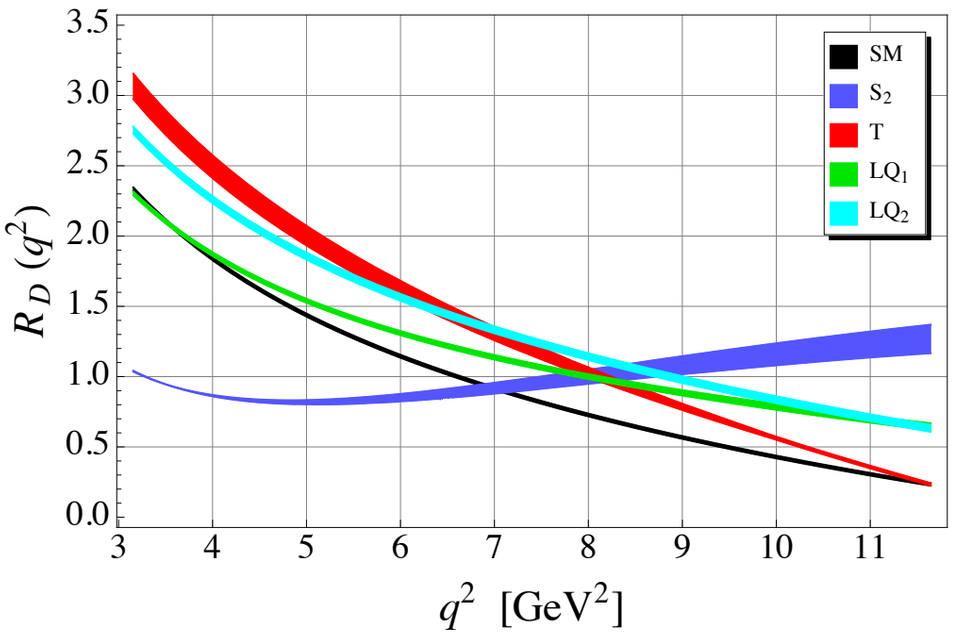
Ratio of the q2 distributions

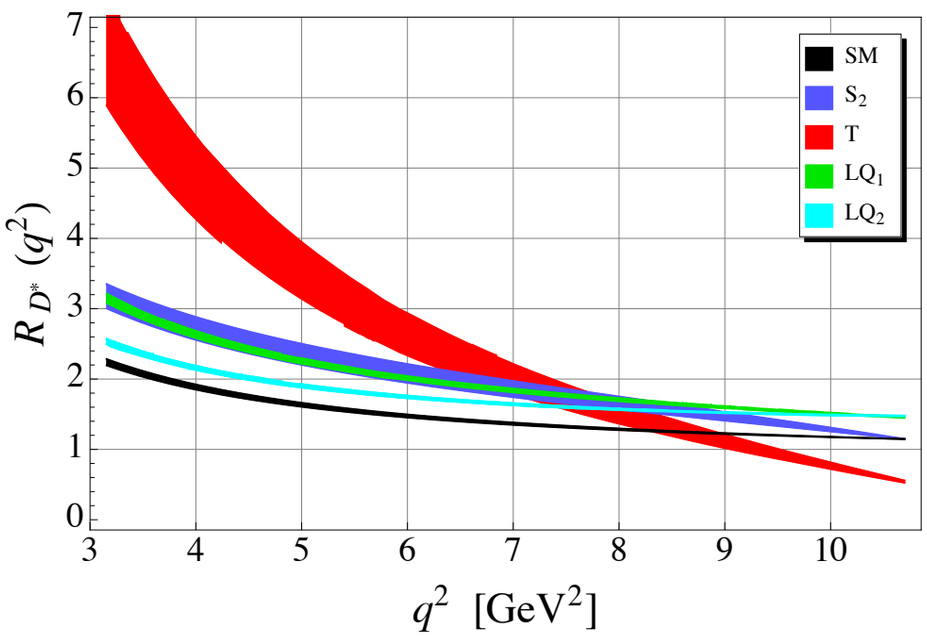
$$R_D(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D\ell\overline{\nu})/dq^2} \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

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

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

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)	

99.9 % CL

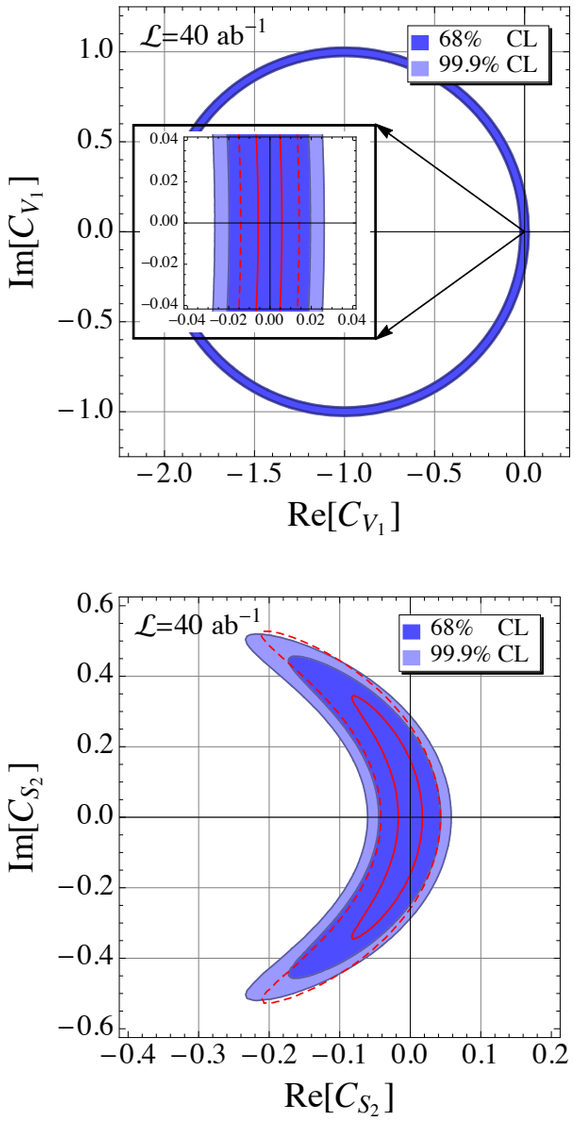
(...): integrated quantities

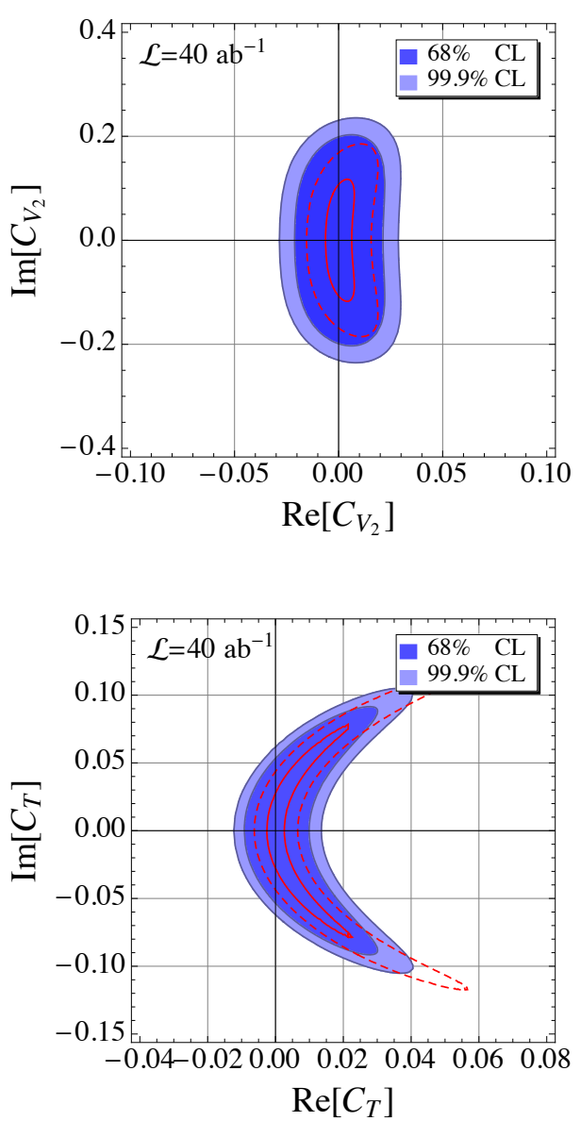
$L \lesssim 6$ ab^{-1} in most cases

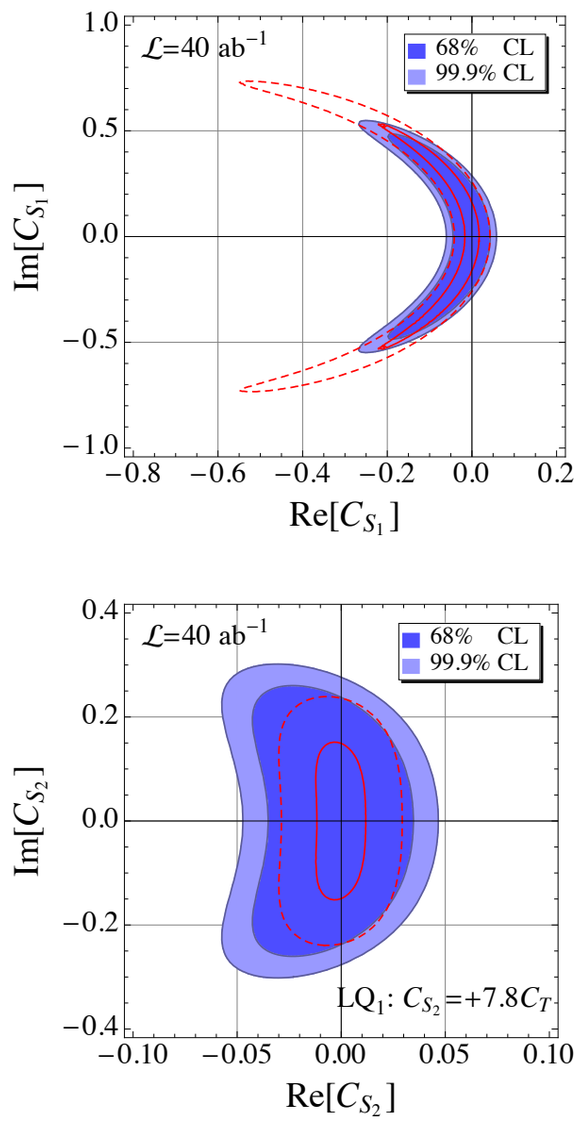
→ A good target at an earlier stage of Belle II

Belle II sensitivity at 40/ab

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

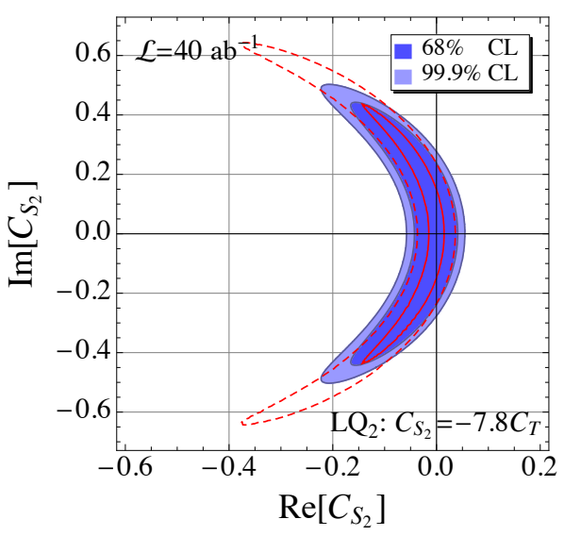






blue $R_{D^{(*)}}(q^2)$

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



$$M_{\rm NP} \gtrsim \underset{V_{1,2}}{5(7)},\ \underset{S_{1,2}}{5(6)},\ \underset{T}{7(10)},\ \underset{\rm LQ_1}{5(7)},\ \underset{\rm LQ_2}{5(6)}\ \text{TeV}$$

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

  MFV? $(\bar{u}b)(\bar{\tau}\nu)$?

Related talks and a session

M. Rotondo, Mon.

R. Watanabe, Mon.

Z. Ligeti, WG1, Wed.

K. Adamczyk, WG1, Wed.

J. Hansenbusch, WG1, Wed.

F. Bernlochner, WG1, Wed.

Y. Sato, WG9, Thu.

Discussion on R(D) and R(D*), WG1, Wed.