Physics
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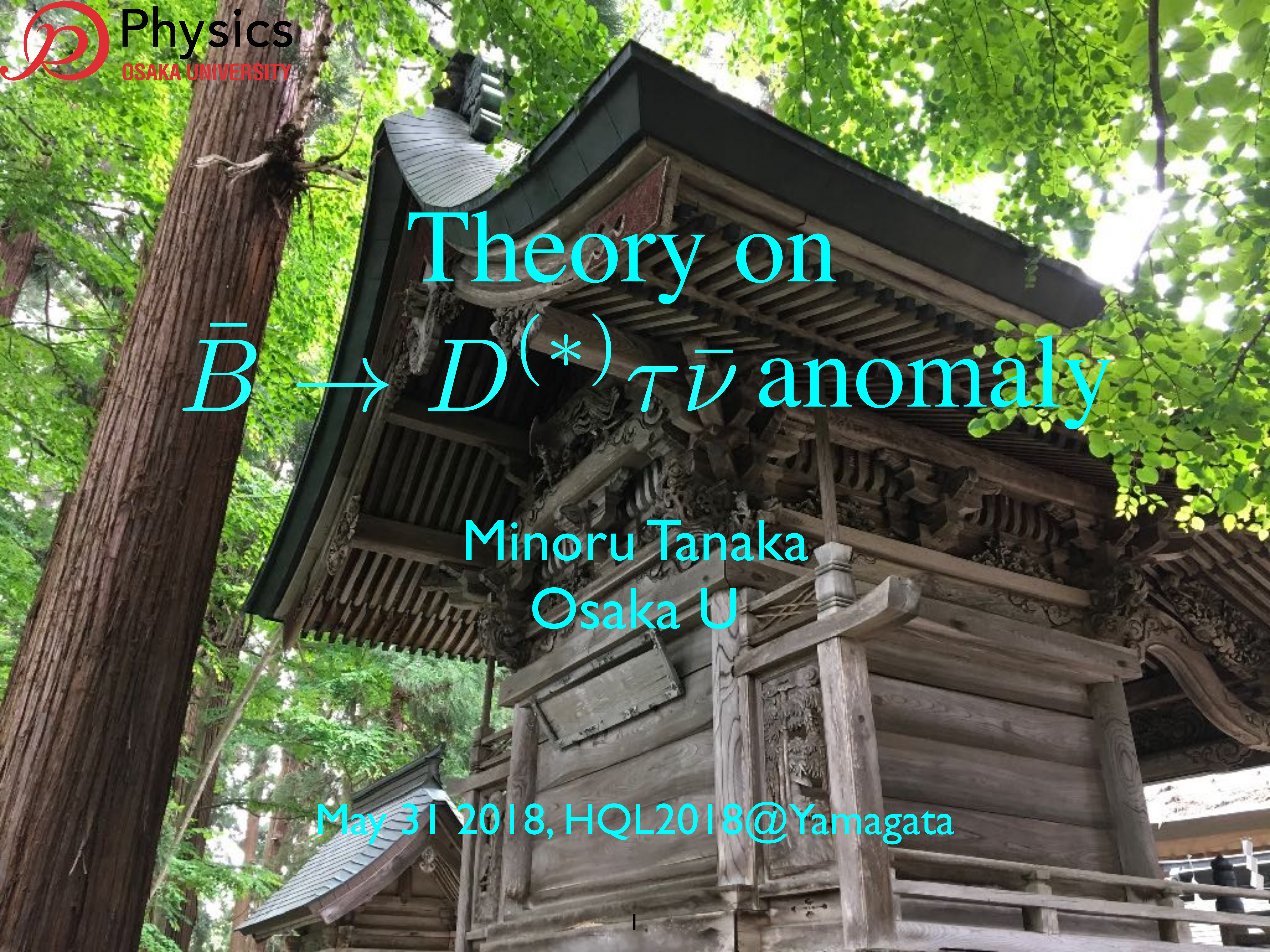

Theory on $\bar{B} \to D^{(*)} \tau \bar{\nu}$ anomaly

Minoru Tanaka
Osaka U

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

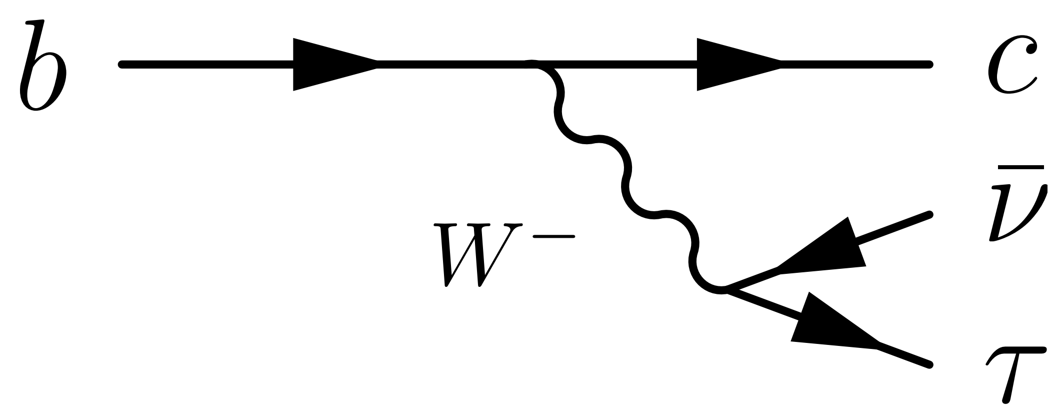
Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

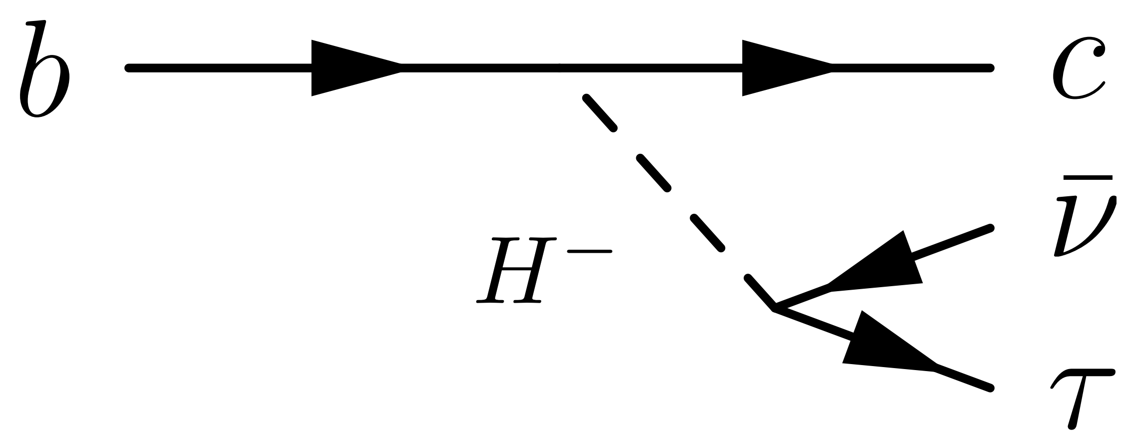
Archetypal theoretical motivation

B. Grzadkowski, W.S. Hou, PLB283, 427 (1992)



SM: gauge coupling

lepton universality



Type-II 2HDM (SUSY)

Yukawa coupling

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

Lepton Flavor (Non-)Universality

Ratio of branching fractions

$$R(D^{(*)}) := \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)} \qquad \ell = e, \mu$$

Predictable in the SM: Source of LFNU = mass

Smaller theoretical errors in the SM (and beyond)

No Vcb in the ratio

MT, Z. Phys. C67, 321 (1995)

Form factor uncertainty tends to cancel.

Controlled by

$\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$ experimental data, lattice QCD,

Heavy Quark Effective Theory, QCD sum rule

Standard model predictions

$$R(D) = 0.302 \pm 0.015$$ (MT, Watanabe, 2010,HQET)

$$0.296 \pm 0.016$$ (Fajfer, Kamenik, Nisandzic, 2012, HQET)

$$0.299 \pm 0.011$$ (Bailey et al., 2015, lattice)

$$0.300 \pm 0.008$$ (Na et al., 2015, lattice)

$$0.299 \pm 0.003$$ (Bigi, Gambino, 2016, combined)

$$0.299 \pm 0.003$$ (Bernlochner et al., 2017, combined)

$$0.407 \pm 0.039 \pm 0.024$$ (Exp. HFLAV, 2017) $2.3\ \sigma$

$$R(D^*) = 0.252 \pm 0.003$$ (Fajfer, Kamenik, Nisandzic, 2012, HQET)

$$0.252 \pm 0.004$$ (MT, Watanabe, 2013,HQET)

$$0.257 \pm 0.003$$ (Bernlochner et al., 2017, combined)

$$0.260 \pm 0.008$$ (Bigi, Gambino, Schacht, 2017, combined)

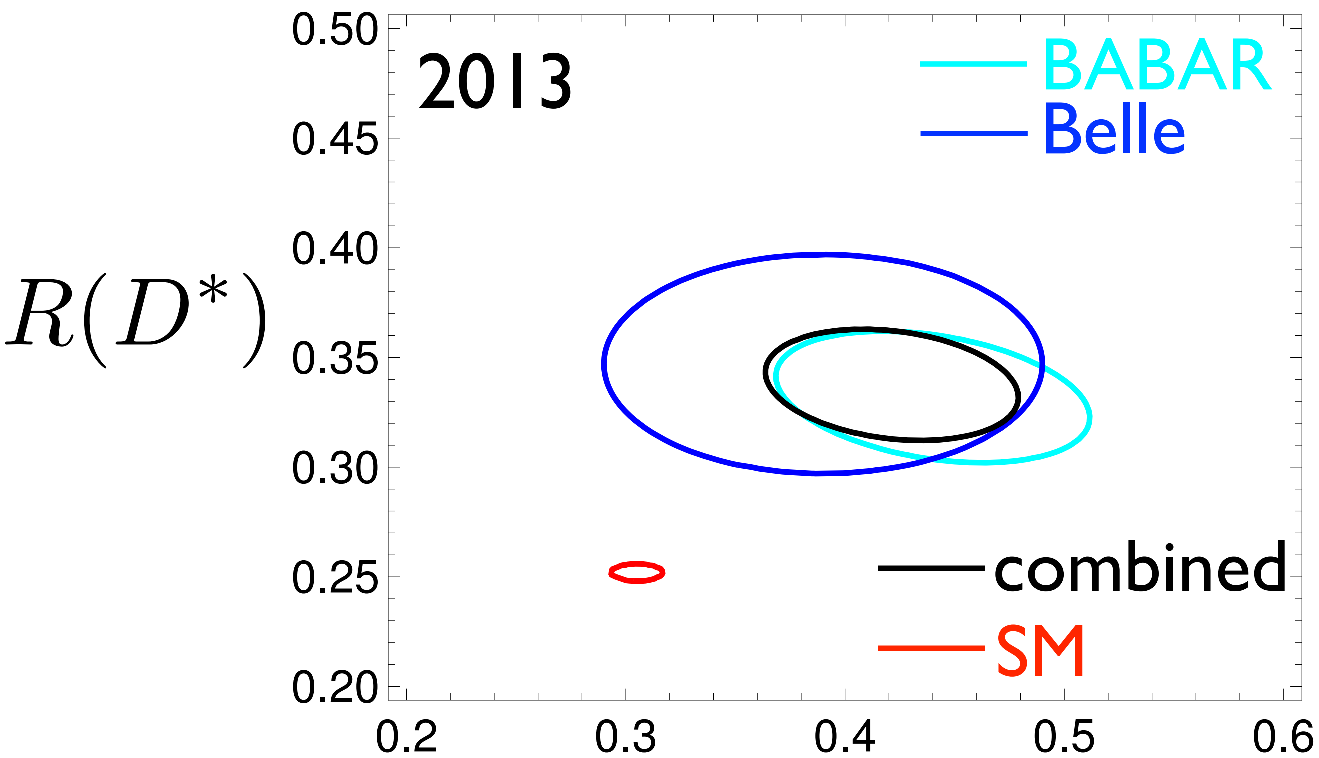
$$0.259 \pm 0.006$$ (Jaiswal, Nandi, Patra, 2017, CLN)

$$0.257 \pm 0.005$$ (Jaiswal, Nandi, Patra, 2017, BGL)

$$0.304 \pm 0.013 \pm 0.007$$ (Exp. HFLAV, 2017) $3.4\ \sigma$

Experiments and status of the SM

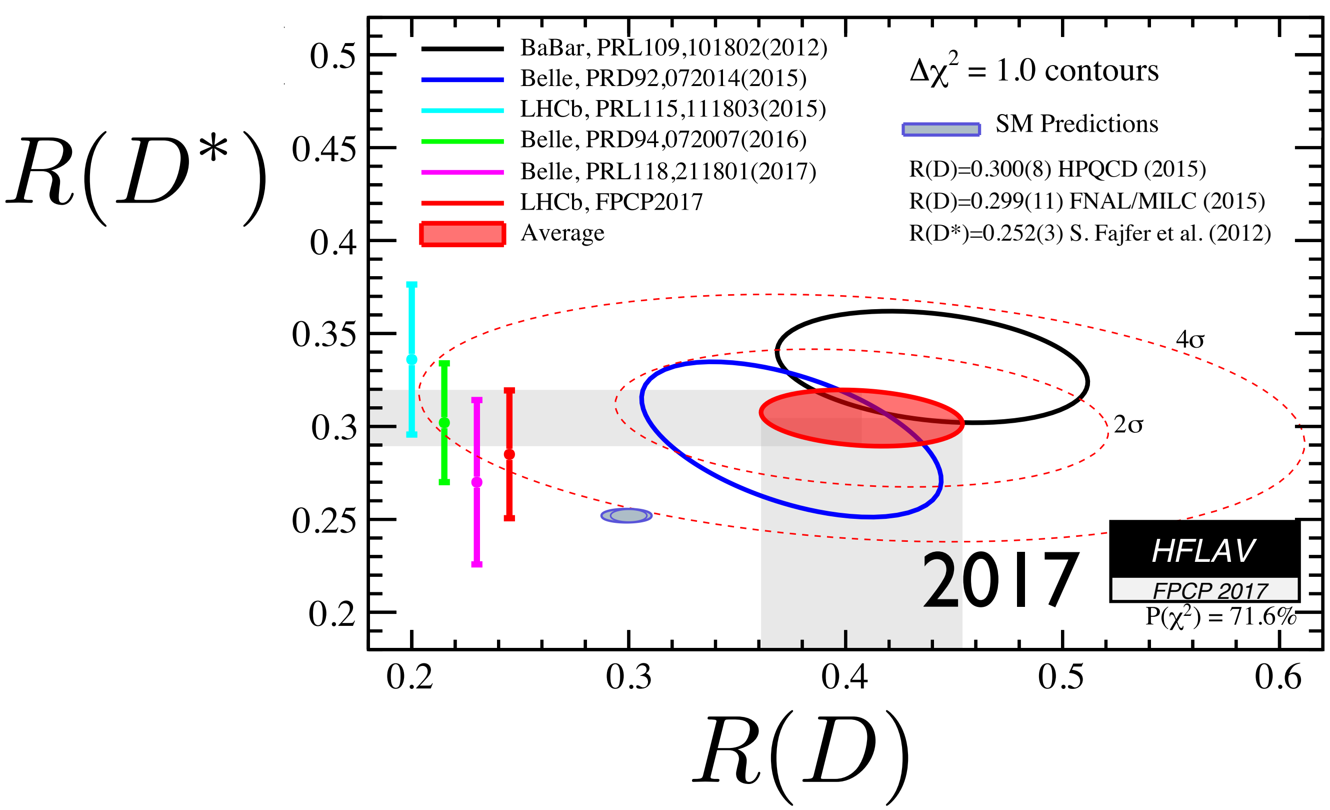
$$R(D^{(*)}) := \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)}$$



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

~3.5 σ

Y. Sakaki, MT, A. Tayduganov, R. Watanabe, PRD88, 094012 (2013)



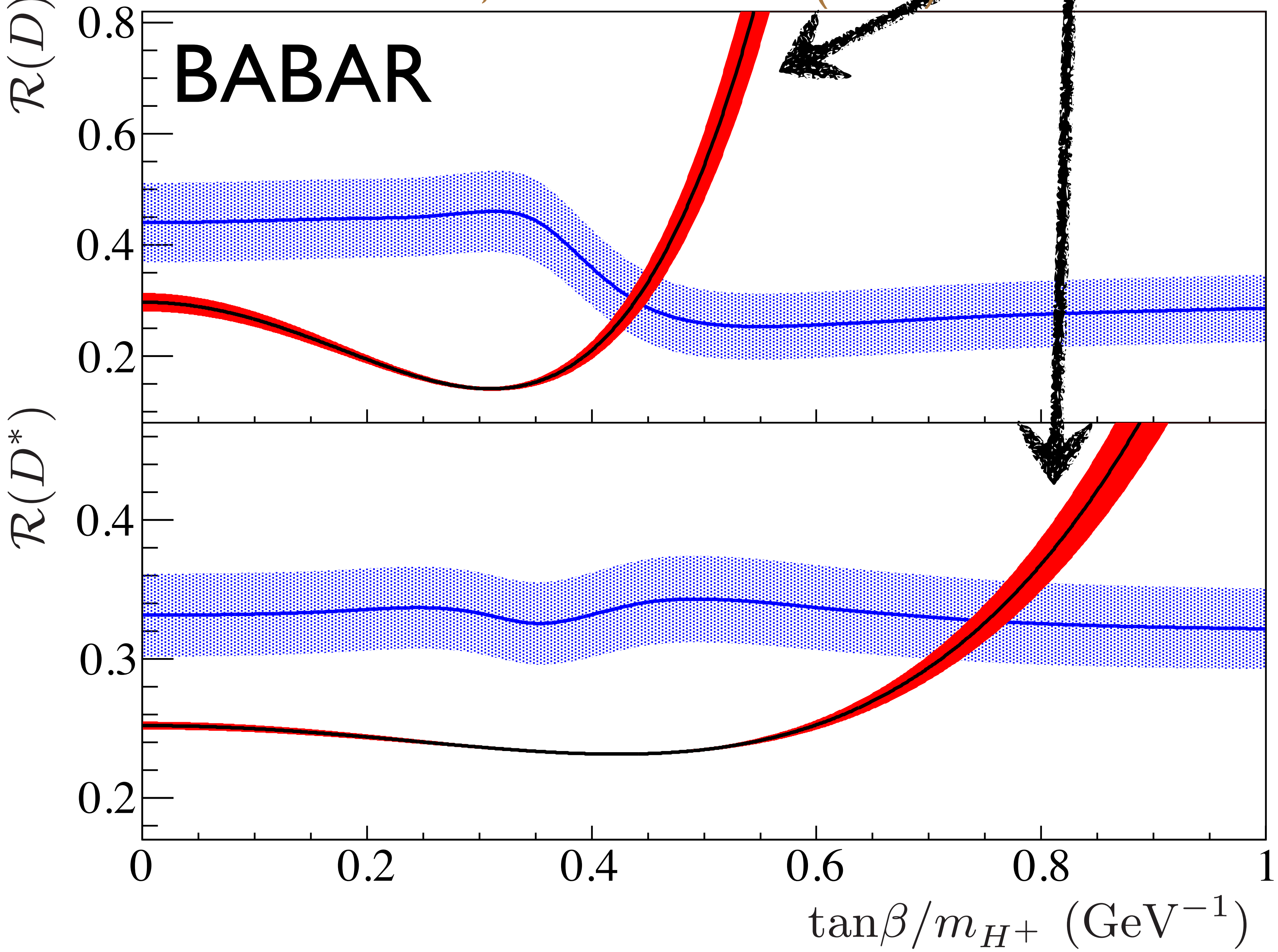
$$R(D) = 0.407 \pm 0.039 \pm 0.024$$
$$R(D^*) = 0.304 \pm 0.013 \pm 0.007$$

~4.1 σ HFLAV

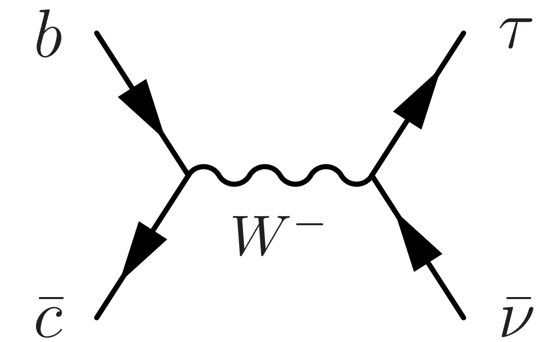
Charged Higgs boson

predictions of 2HDM II

arXiv: 1205.5442, PRL.109.101802(2012)



Charged Higgs (type II) *excluded* at 99.8% CL



$B_c^- \to \tau\bar{\nu}_\tau$

The same field content at the quark-level

$\tau_{B_c} = 0.507(9)\ \mathrm{ps}$ PDG (CDF, D0, LHCb)

$\tau_{B_c}^{\mathrm{OPE}} = 0.52^{+0.18}_{-0.12}\ \mathrm{ps}$ M. Beneke, G. Buchalla, PRD53, 4991 (1996)

$\Rightarrow$ $\mathcal{B}(B_c^- \to \tau\bar{\nu}_\tau) \lesssim 0.3$ R. Alonso, B. Grinstein, J. M. Camalich, PRL118, 081802 (2017)

$B_{u,c} \to \tau\bar{\nu}$ search@LEP

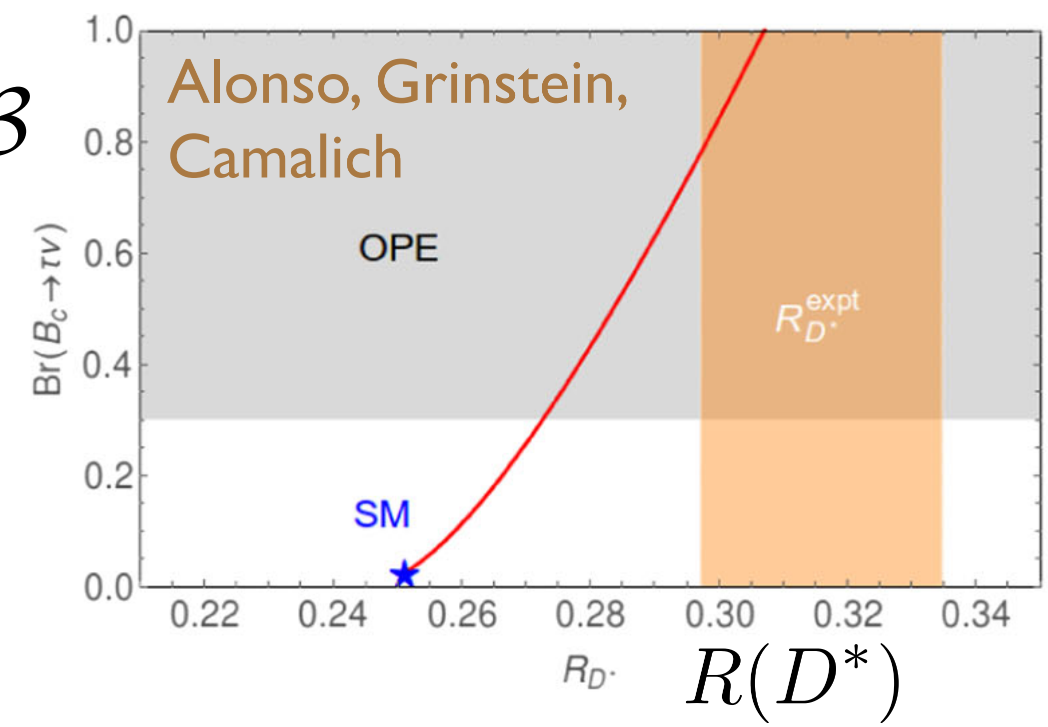
$\Rightarrow$ $\mathcal{B}(B_c^- \to \tau\bar{\nu}_\tau) \lesssim 0.1$ A.G. Akeroyd, Chuan-Hung Chen, PRD96, 075011 (2017)

Theory

$$\propto \left| 1 + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} (C_{S_1} - C_{S_2}) \right|^2$$

pseudoscalar enhancement

$\mathcal{B}$



$B_c \to J/\psi\,\tau\bar{\nu}_\tau$

The same quark-level process

$$R(J/\psi) := \frac{\mathcal{B}(B_c \to J/\psi\,\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\,\ell\bar{\nu}_\ell)}$$

Experiment: $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$ LHCb

PRL120, 121801 (2018)

SM prediction

Form factors similar to $\bar{B} \to D^*$, but less accurate

$$R(J/\psi)_{\mathrm{SM}} = [0.279,\ 0.301]$$ R. Dutta, A. Bhol PRD96, 076001 (2017)

$$= 0.283 \pm 0.048$$ R. Watanabe, PLB776 (2018) 5

~1.7 σ

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

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

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

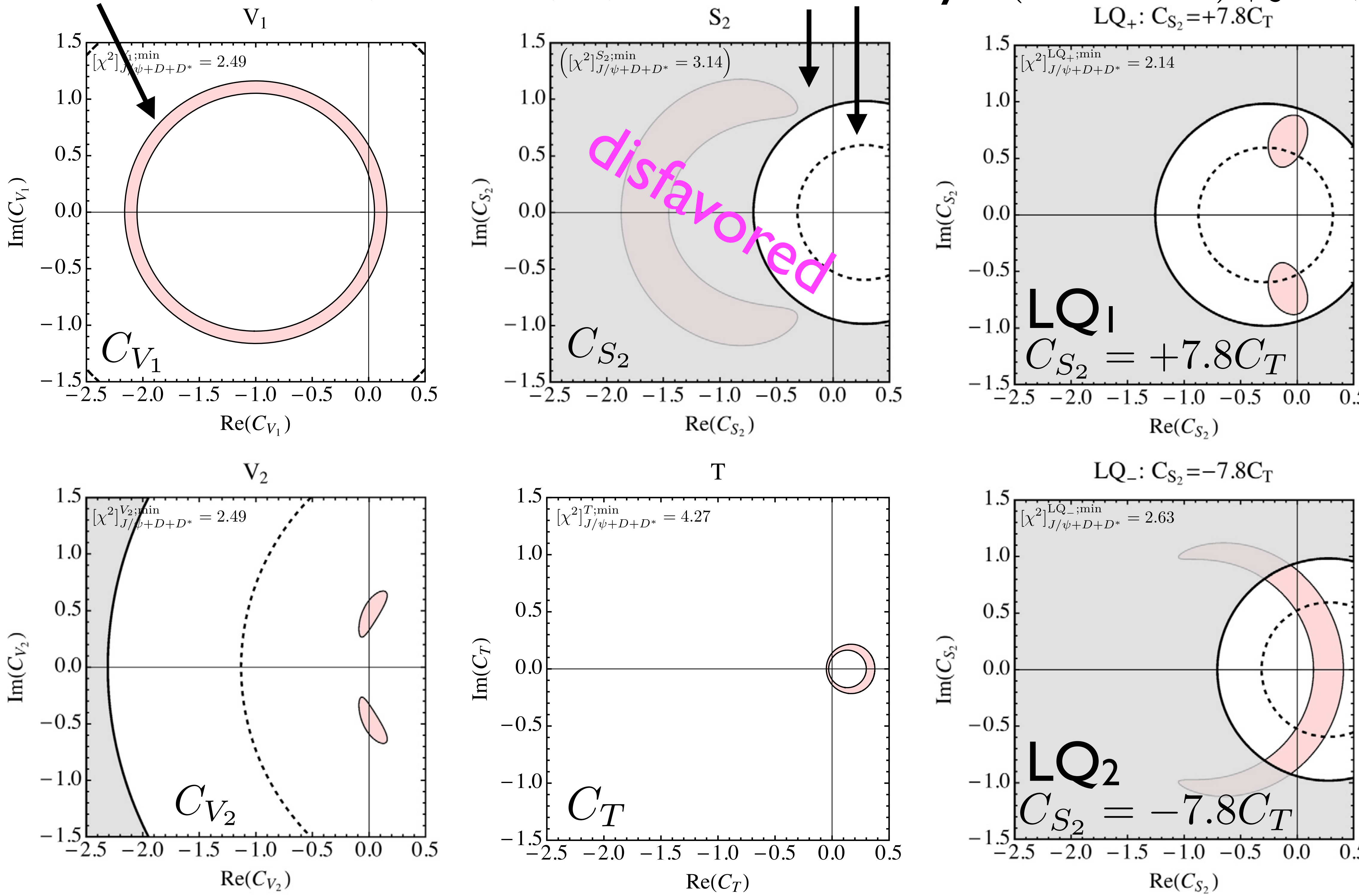
$$\mathcal{O}^l_{S_1} = \bar{c}_L b_R\, \bar{\tau}_R\nu_{Ll}\,,$$ charged Higgs II, RPV, LQ

$$\mathcal{O}^l_{S_2} = \bar{c}_R b_L\, \bar{\tau}_R\nu_{Ll}\,,$$ 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 in complex Cx plane

Allowed at 95% CL $(D, D^*, J/\psi)$ **Excluded by** $\mathcal{B}(B_c \to \tau\bar{\nu}) \lesssim 30, 10~\%$



R. Watanabe, PLB776 (2018) 5

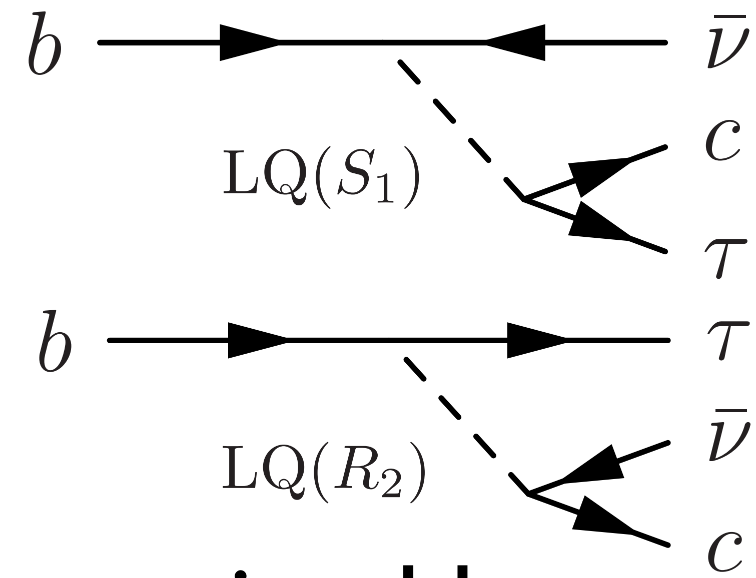
Leptoquark models

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

Six of ten types of LQ contribute.

Buchmüller, Rückl, Wyler
PLB191 (1987) 442

	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

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

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

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

RG

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

Tau longitudinal polarization

MT, Z. Phys. C67, 321 (1995)

$$P_\tau := \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\lambda_\tau = \pm$

τ helicity defined in the $\tau\nu$ rest frame

Experiment

$$P_\tau(D^*) = -0.44 \pm 0.47^{+0.20}_{-0.17}$$ Belle arXiv:1608.06391

SM prediction

$$P_\tau(D^*) = -0.497 \pm 0.013$$ MT, R. Watanabe 2013

$$P_\tau(D^*) = -0.47 \pm 0.04$$ D. Bigi, P. Gambino, S. Schacht JHEP11(2017)061

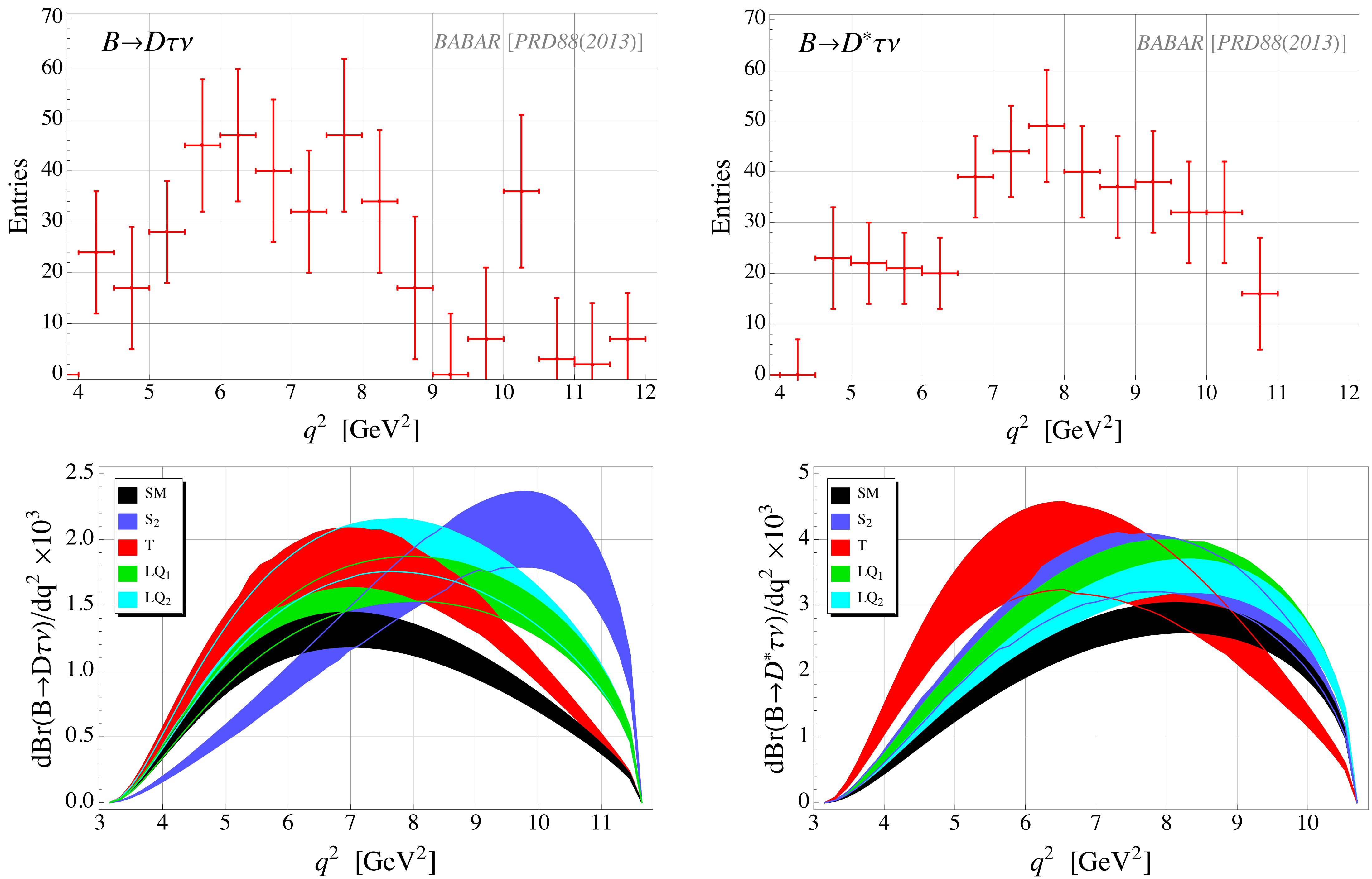
NP predictions

R. Watanabe, PLB776 (2018) 5

	V_1	V_2	T	LQ_1	LQ_2
$P_\tau(D^*)$	-0.50	-0.50	$+0.14$	-0.41	-0.50

Implication of the BABAR q^2 data

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



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

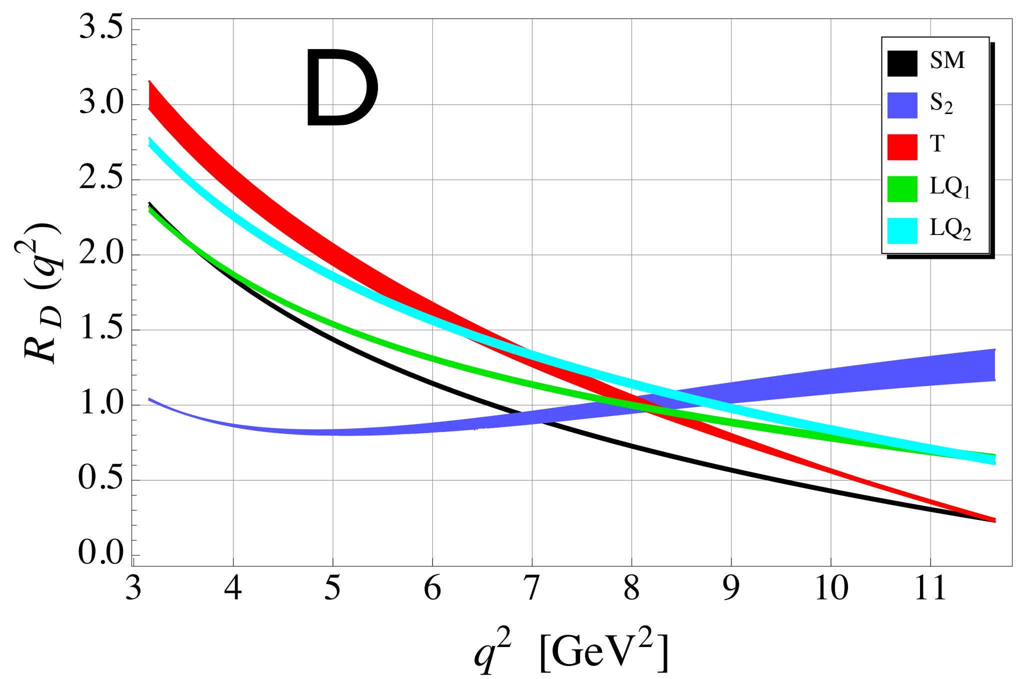
Ratio of the q^2 distributions

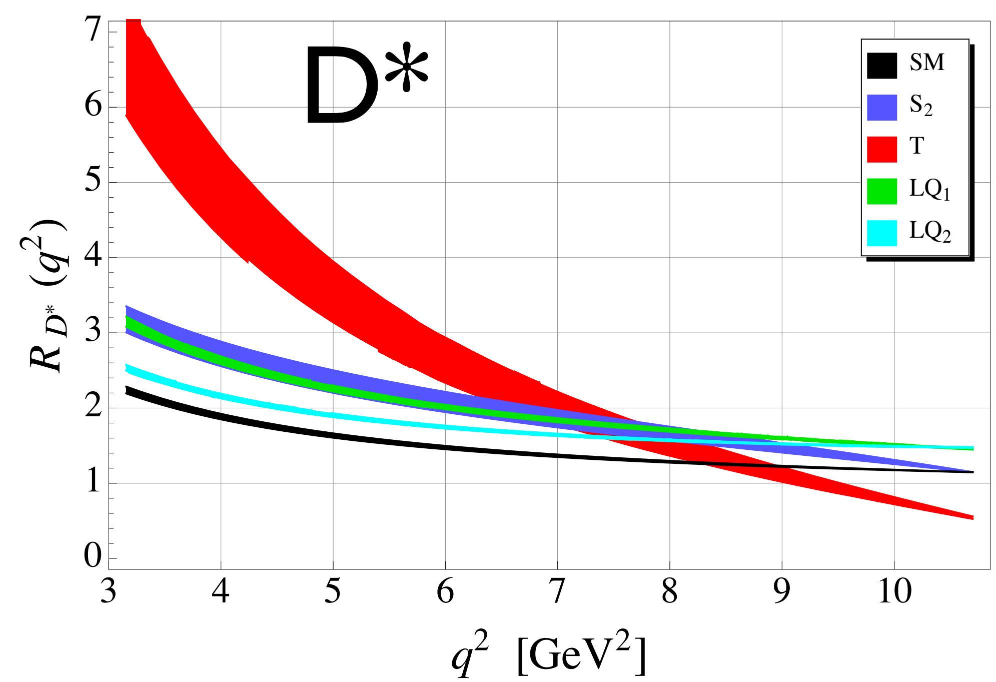
$$R_D(q^2) \equiv \frac{d\mathcal{B}(\overline{B} \to D\tau\overline{\nu})/dq^2}{d\mathcal{B}(\overline{B} \to D\ell\overline{\nu})/dq^2} \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}$$

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

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

No Vcb dependence, less form factor uncertainties





Simulated data vs benchmark models

χ^2 of the binned $R_{D^{(*)}}(q^2)$

Required luminosity to exclude the 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

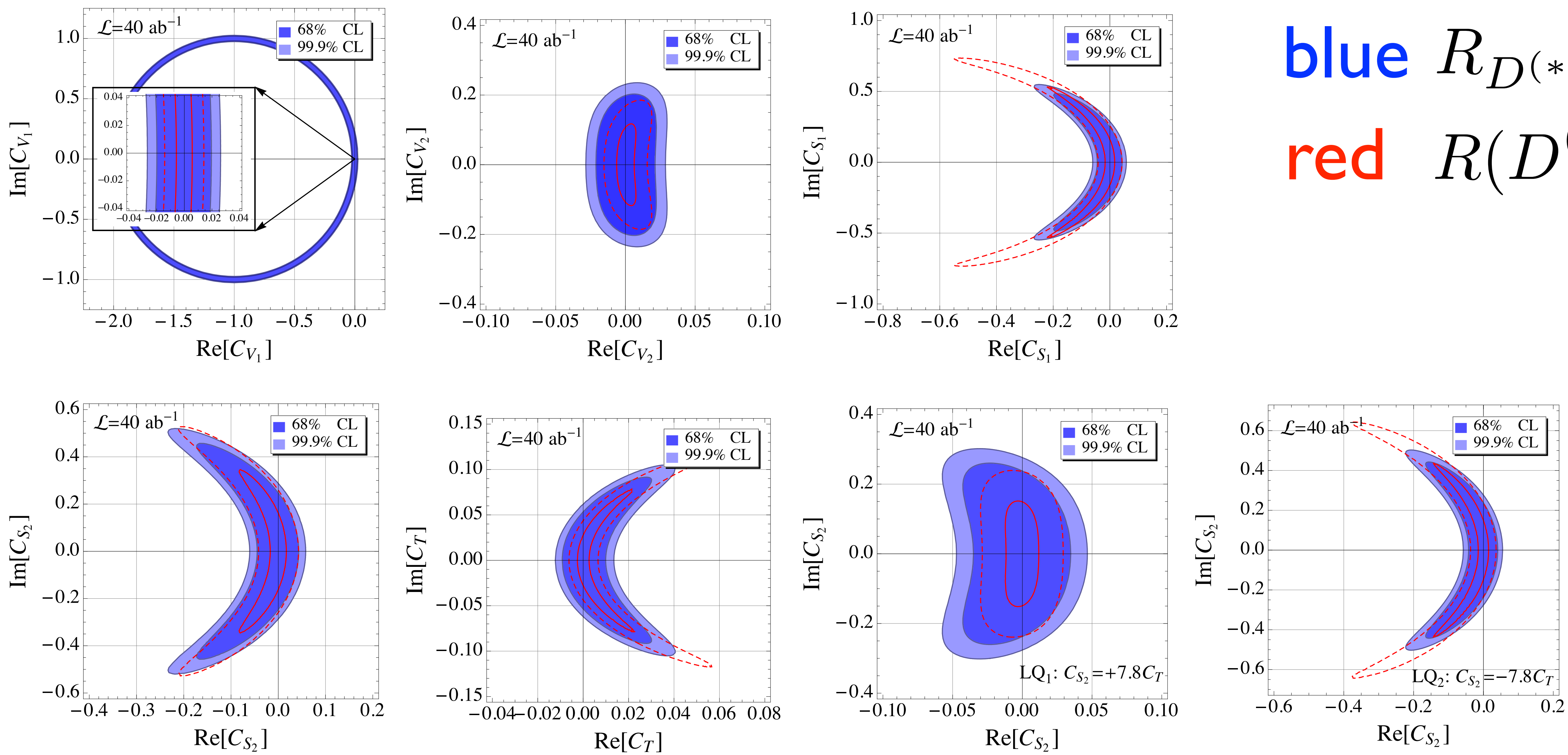
99.9 % CL

$L \lesssim 6\ \mathrm{ab}^{-1}$ 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 $R(D^{(*)})$

$$M_{\rm NP} \equiv (2\sqrt{2}G_F V_{cb} C_X)^{-1/2}$$

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

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

Summary

- Excess of $\bar{B} \to D^{(*)}\tau\bar{\nu}$: $R(D), R(D^*)$ ~ 4.1 σ
- Favored NP scenarios

  V_1 (left-handed), V_2 (right-handed), T, LQ's
- Other modes and observables

  $R(J/\psi),\ R(\eta_c),\ R(D_s),\ R(\Lambda_c),\ R(X_c)$

  $q^2,\ P_\tau,\ P_{D^*},\ A_{\rm FB}$
- Belle II: Factor 2(5) improvement with 5(50) /ab
- Flavor structure of possible NP

  $(\bar{u}b)(\bar{\tau}\nu)$ $B^- \to \tau\bar{\nu}\,,\ B \to \pi\tau\bar{\nu}$ MT, R.Watanabe, PTEP 013B05 (2017)

  Other flavor anomalies, NP search at LHC

  Freytsis, Ligeti, Ruderman PRD92, 054018 (2015); Fajfer, Kosnik PLB755, 270 (2016)
  Bauer, Neubert PRL116,141802 (2016); Dumont, Nishiwaki, Watanabe PRD94, 034001(2016)