Theory Status of Leptonic and Semileptonic b-decays: Window to New Physics

Alejandro Celis

Ludwig-Maximilians-Universität München

LMU Ludwig-Maximilians-Universität München

Arnold Sommerfeld Center for Theoretical Physics

Unterstützt von / Supported by Alexander von Humboldt Stiftung/Foundation

March 30, 2017

Contents

Motivation

Tree level charged current mediated decays in the SM

New Physics (NP) expected subdominant compared to SM

Allows extraction of CKM matrix elements with expected small or negligible NP contamination

Laboratory for non-perturbative QCD studies

Motivation

Leptonic and Semileptonic B meson decays
as a Window to New Physics

But what New Physics?

I will focus on possible violations
of Lepton Flavour Universality (LFU)

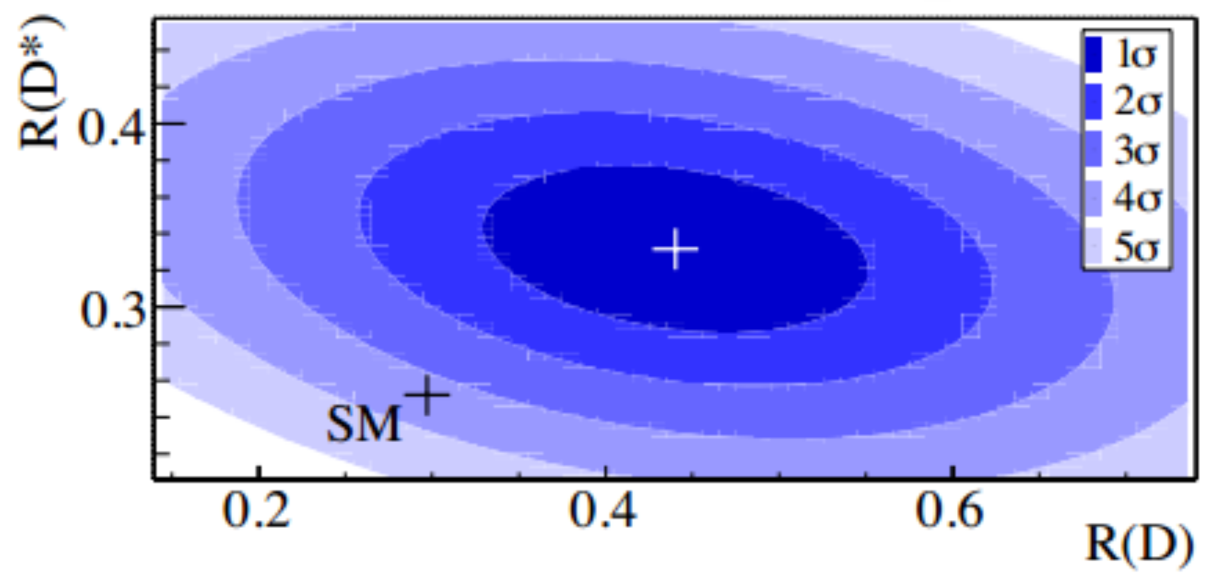
Motivation

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}l\nu)}$$

Why?

back in 2012…

$\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$



$$R(D) = \begin{cases} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{cases} \quad \mathbf{2.0\sigma}$$

$$R(D^*) = \begin{cases} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{cases} \quad \mathbf{2.7\sigma}$$

Combined: $\mathbf{3.4\sigma}$

SM predictions

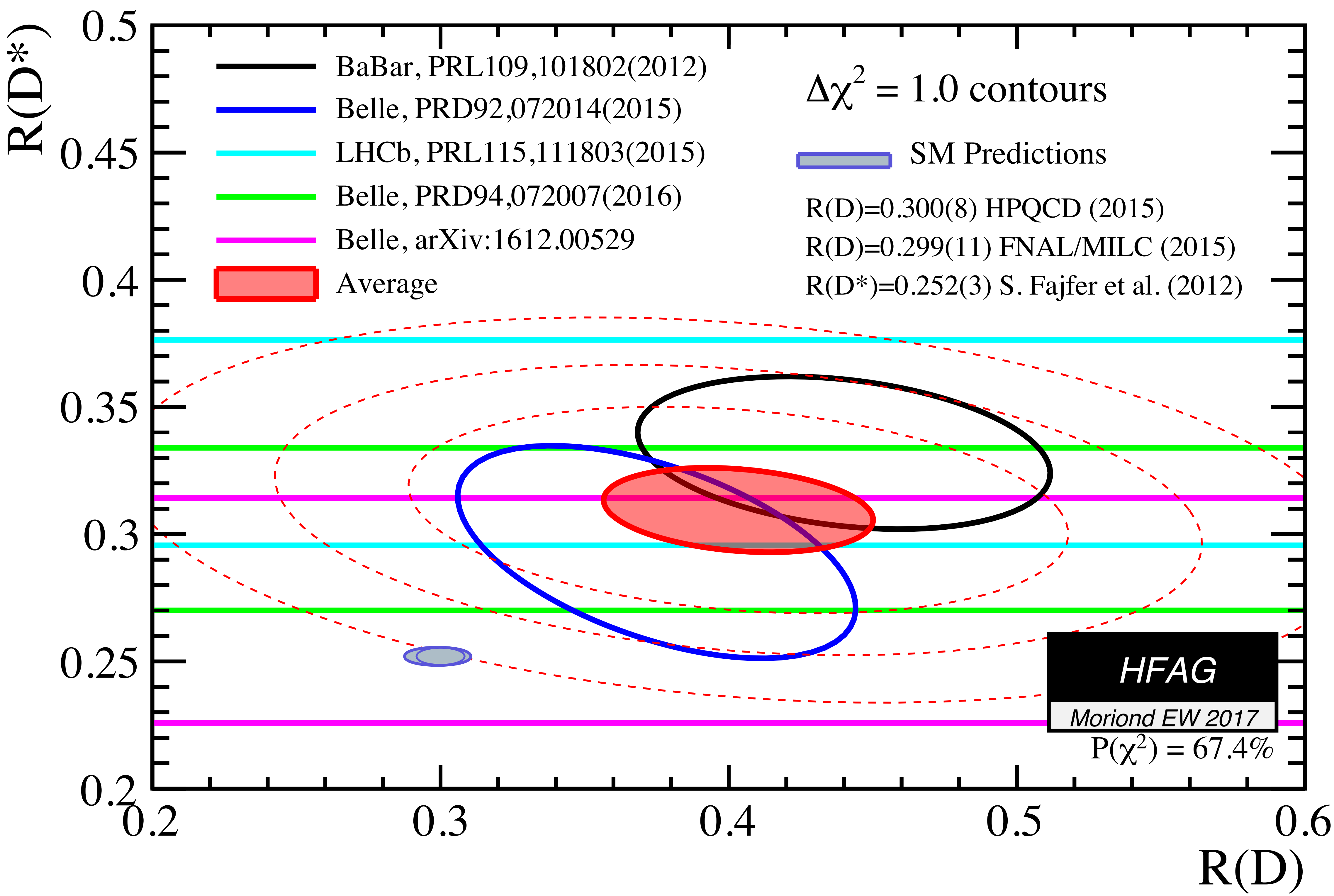
Kamenik, Mescia [Phys.Rev. D78 (2008) 014003]

Fajfer, Kamenik, Nisandzic [Phys.Rev. D85 (2012) 094025]

BaBar [Phys. Rev. D86 (2012) 032001]

Motivation

HFAG average today



Motivation

Considering both observables, **the difference with the SM predictions is at about 3.9 sigma**

Taken at face value, hints to **violation of LFU** at the **30% level**

This would be surprising, given that

	$\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar{\nu}_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar{\nu}_\mu}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to\mu\bar{\nu}_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012
	$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}$	$\Gamma_{\pi\to\mu\bar{\nu}_\mu}/\Gamma_{\pi\to e\bar{\nu}_e}$	$\Gamma_{K\to\mu\bar{\nu}_\mu}/\Gamma_{K\to e\bar{\nu}_e}$	$\Gamma_{K\to\pi\mu\bar{\nu}_\mu}/\Gamma_{K\to\pi e\bar{\nu}_e}$
$\lvert g_\mu/g_e\rvert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002
	$\Gamma_{W\to\mu\bar{\nu}_\mu}/\Gamma_{W\to e\bar{\nu}_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to e\bar{\nu}_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

taken from A. Pich lectures (arXiv:1201.0537)

Observables

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}l\nu)}$$

$B \to D^{(*)}\tau\nu$ $\quad q^2 = (p_B - p_{D^{(*)}})^2$ differential distribution

$B \to D^{(*)}\tau\nu$ $\quad$ tau polarization asymmetry

experimental error still very large

Standard Model predictions

$$B \to D \ell \nu$$

Parametrization of the hadronic amplitude

$f_+(0) = f_0(0)$

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

$q^2 = (p_B - p_D)^2$

vector form factor **scalar form factor**

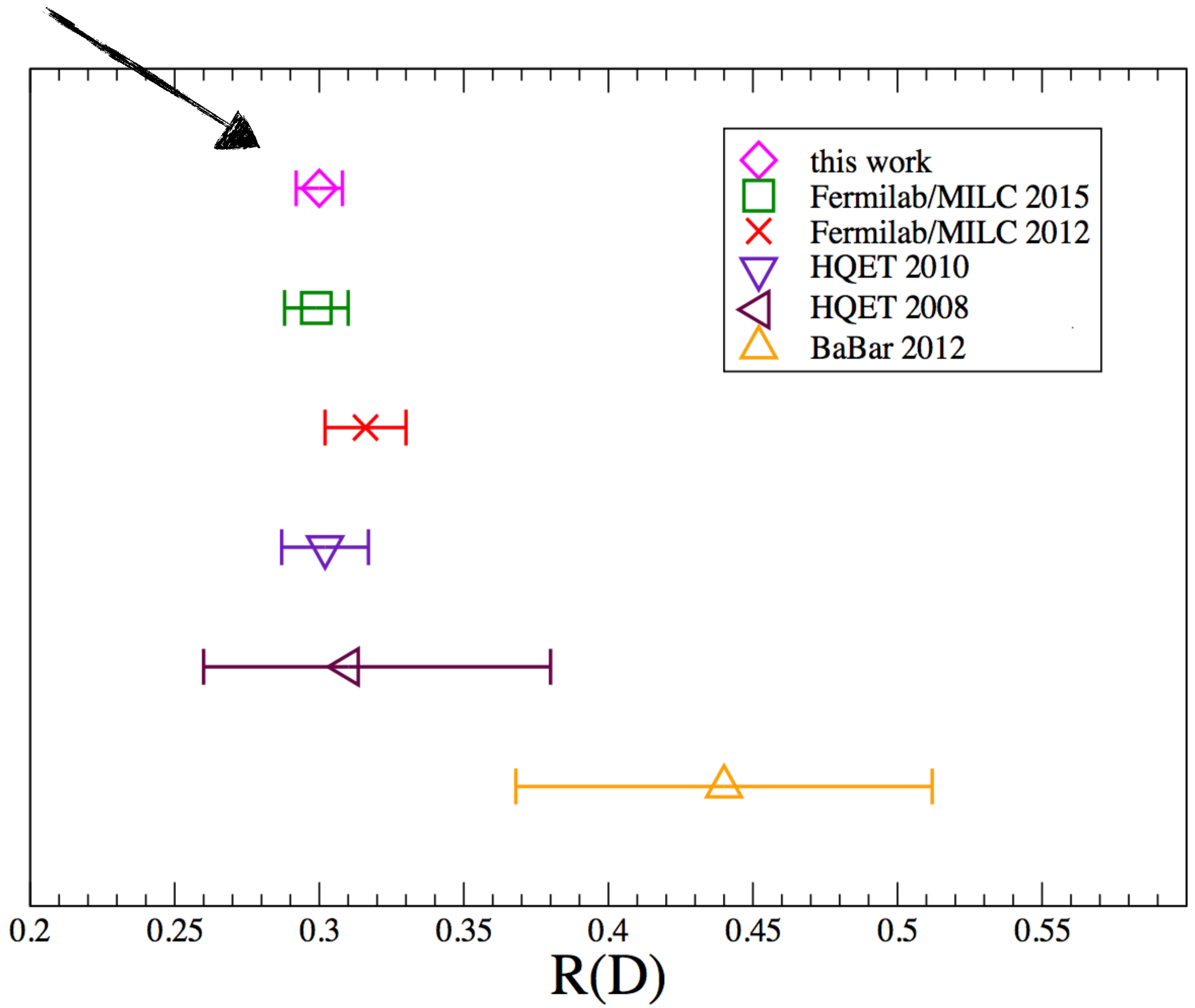
Fermilab Lattice and MILC Collaborations (2015)	$R(D) = 0.299(11)$
HPQCD Collaboration (2015)	$R(D) = 0.300(8)$
P. Gambino and D. Bigi (2016)	$R(D) = 0.299(3)$

Current experimental data

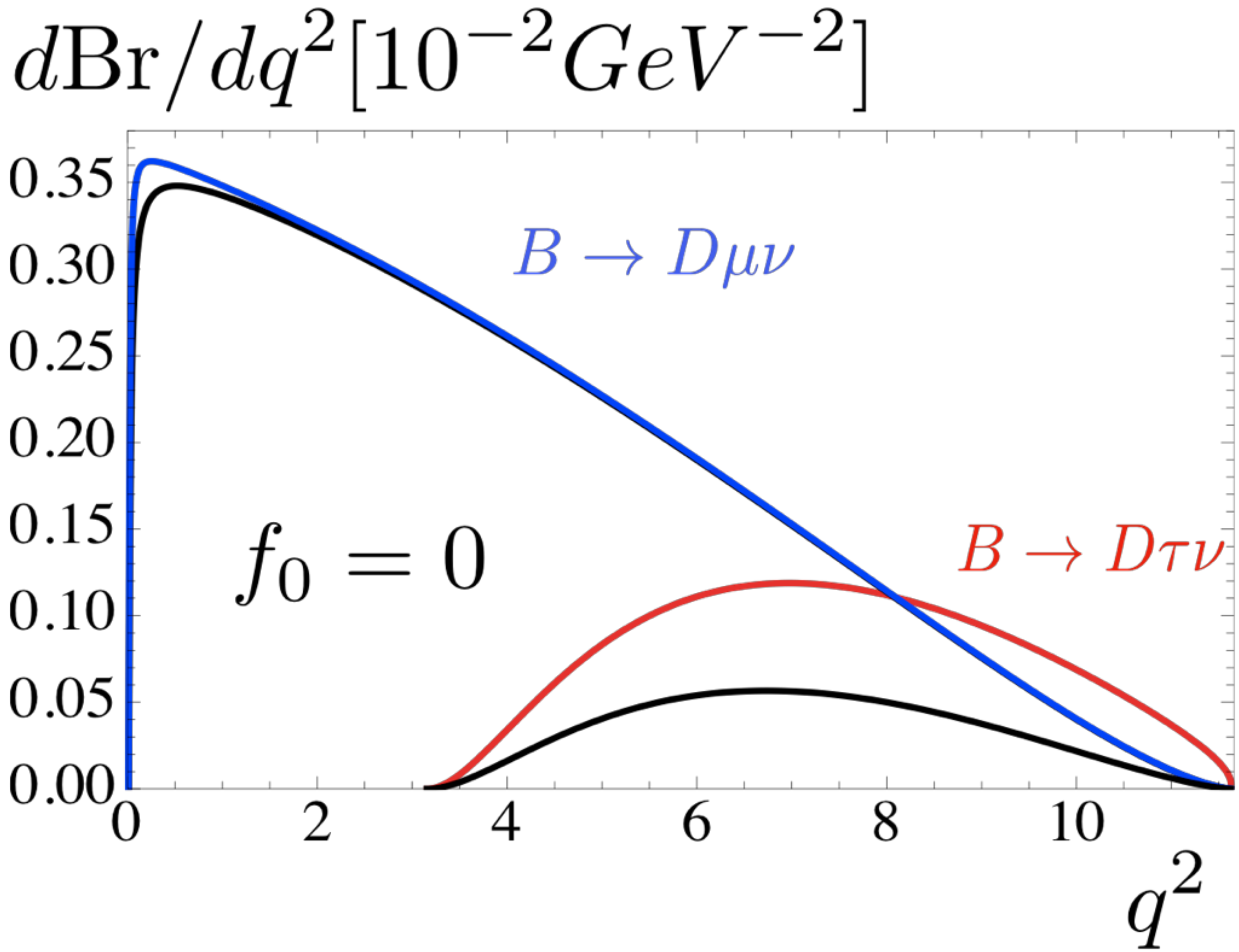
HFAG average today $R(D)_{\text{exp}} = 0.403 \pm 0.040 \pm 0.024$

Standard Model predictions

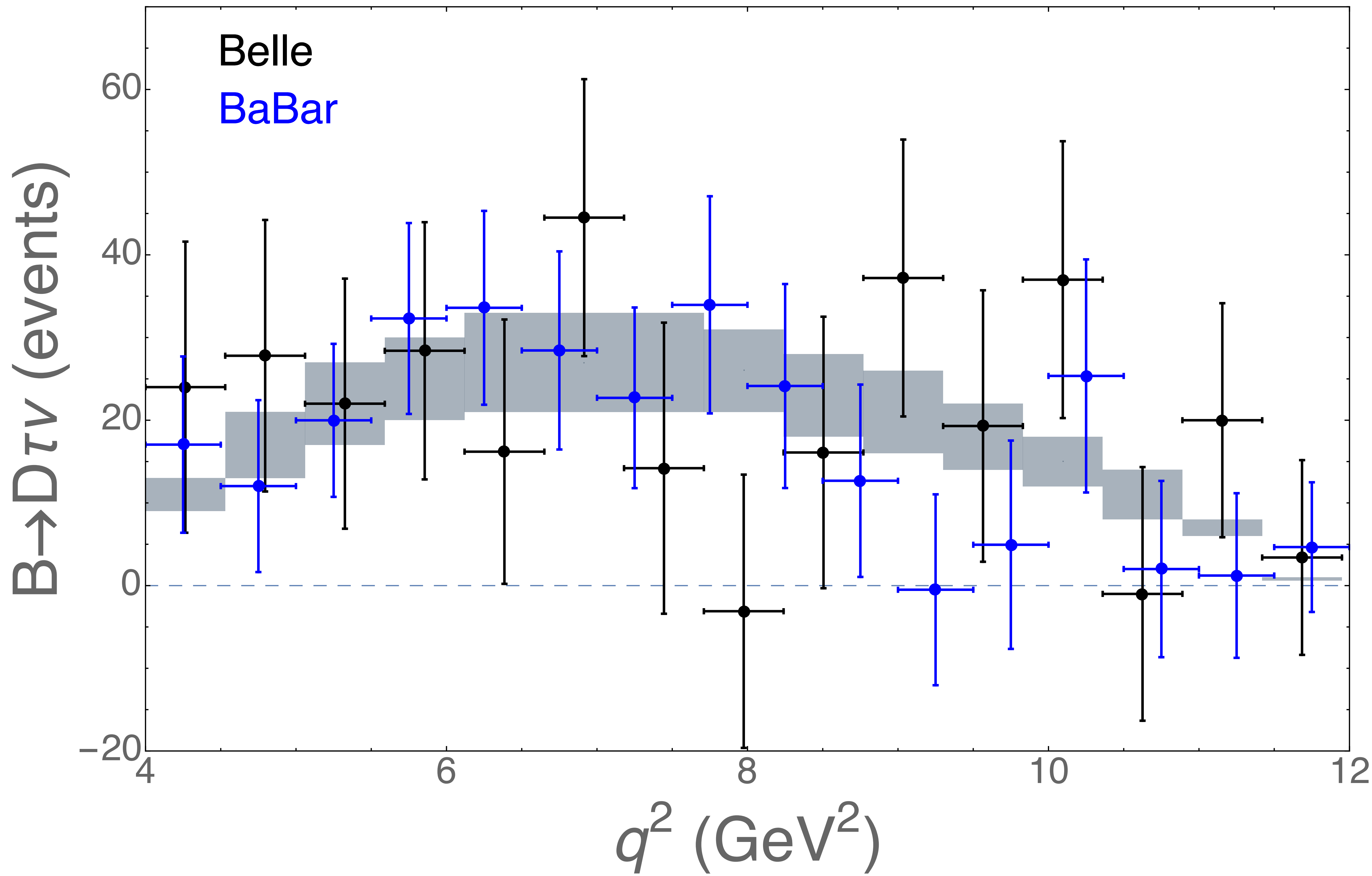
HPQCD Collaboration (2015)



Standard Model predictions



Standard Model predictions | **Current experimental data**



adapted from AC, Jung, Xin-Qiang, Pich [1612.07757]

Standard Model predictions

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

$$V(q^2) = \frac{R_1(w)}{R_{D^*}} h_{A_1}(w) \qquad A_0(q^2) = \frac{R_0(w)}{R_{D^*}} h_{A_1}(w)$$

$$A_1(q^2) = R_{D^*} \frac{w+1}{2} h_{A_1}(w) \qquad A_2(q^2) = \frac{R_2(w)}{R_{D^*}} h_{A_1}(w)$$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z(w) + (53\rho^2 - 15)\, z(w)^2 - (231\rho^2 - 91)\, z(w)^3\right]$$

$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

Caprini, Lellouch, Neubert [9712417]

$h_{A_1}(1)$, ρ^2, $R_1(1)$ and $R_2(1)$ values from $\bar{B} \to D^* \ell \bar{\nu}$ $(\ell = e, \mu)$ ‣ HFAG

$R_0(1)$ extracted from Heavy Quark Effective Theory [Falk, Neubert (1992)]

$$R_3(1) = \frac{R_2(1)(1-r) + r\,[R_0(1)(1+r) - 2]}{(1-r)^2} = 0.97 \pm 0.10$$

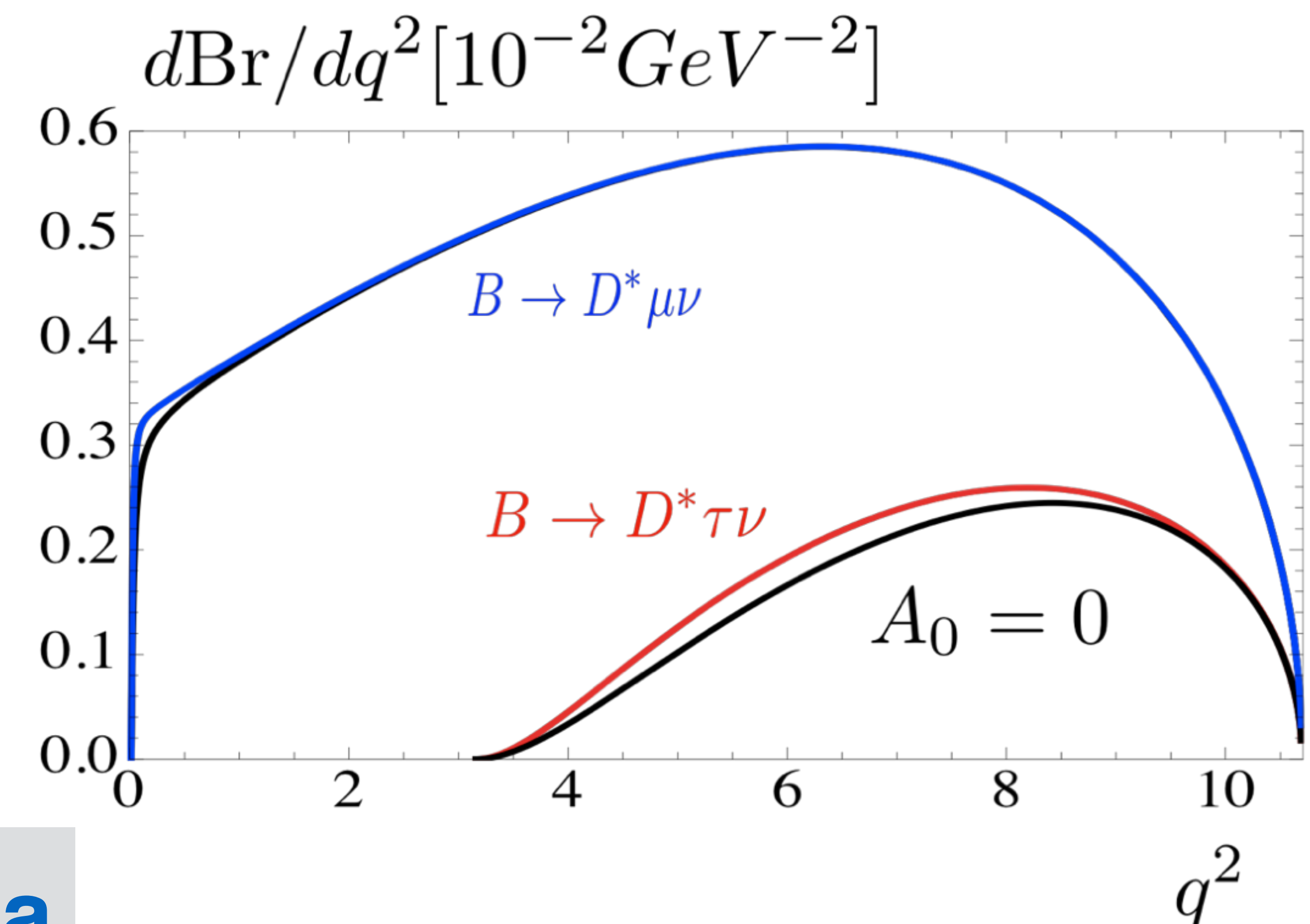
includes leading-order perturbative (in α_s) and power $(1/m_{b,c})$ corrections to the heavy-quark limit, plus 10% uncertainty to account for higher-order contributions.

Standard Model predictions

$$R(D^*) = 0.252 \pm 0.003$$

Fajfer, Kamenik, Nisandzic (2012)

scalar form factor has a small impact

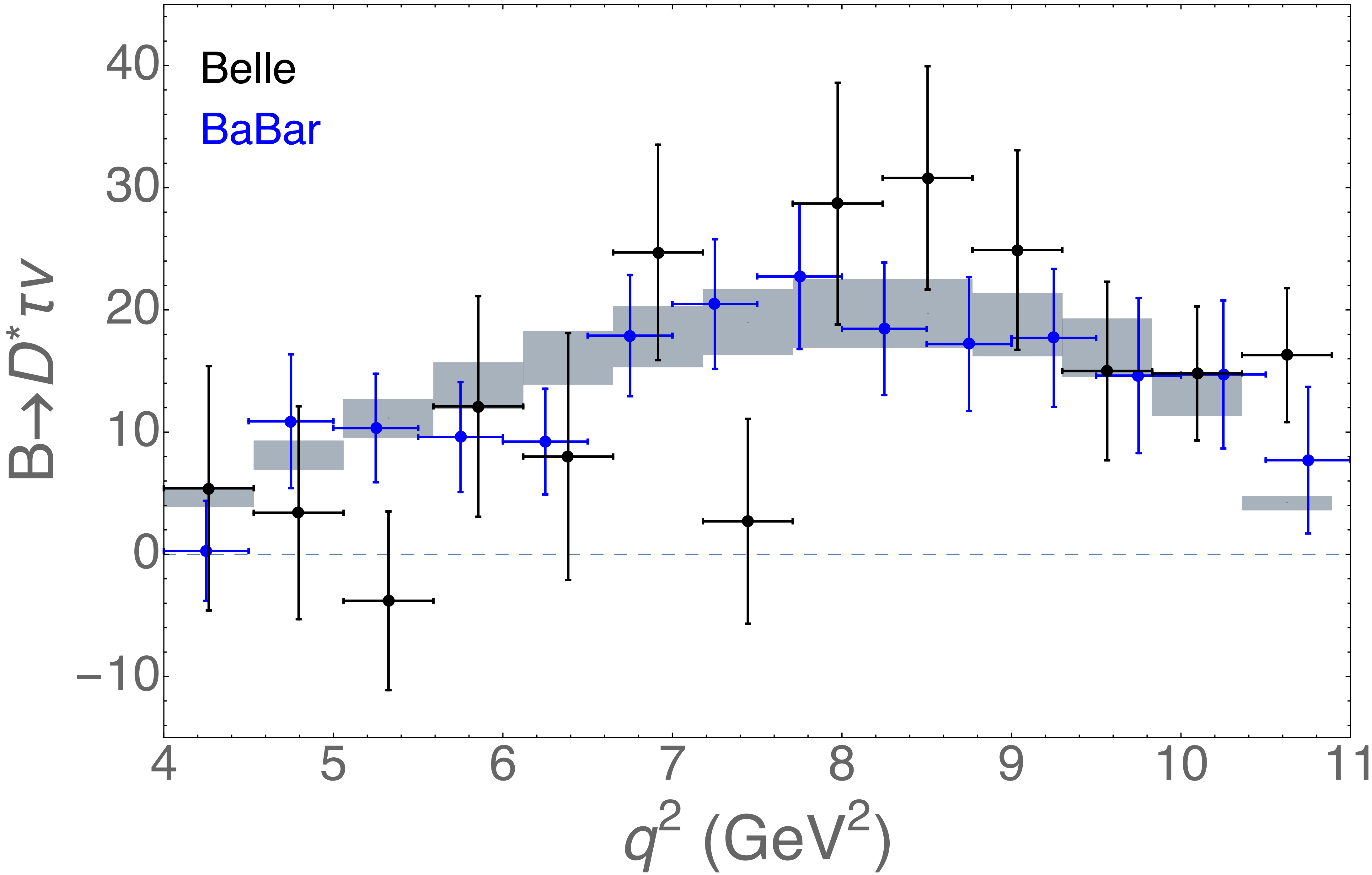


Current experimental data

HFAG average today $R(D^*)_{\rm exp} = 0.310 \pm 0.015 \pm 0.008$

Standard Model predictions

Current experimental data

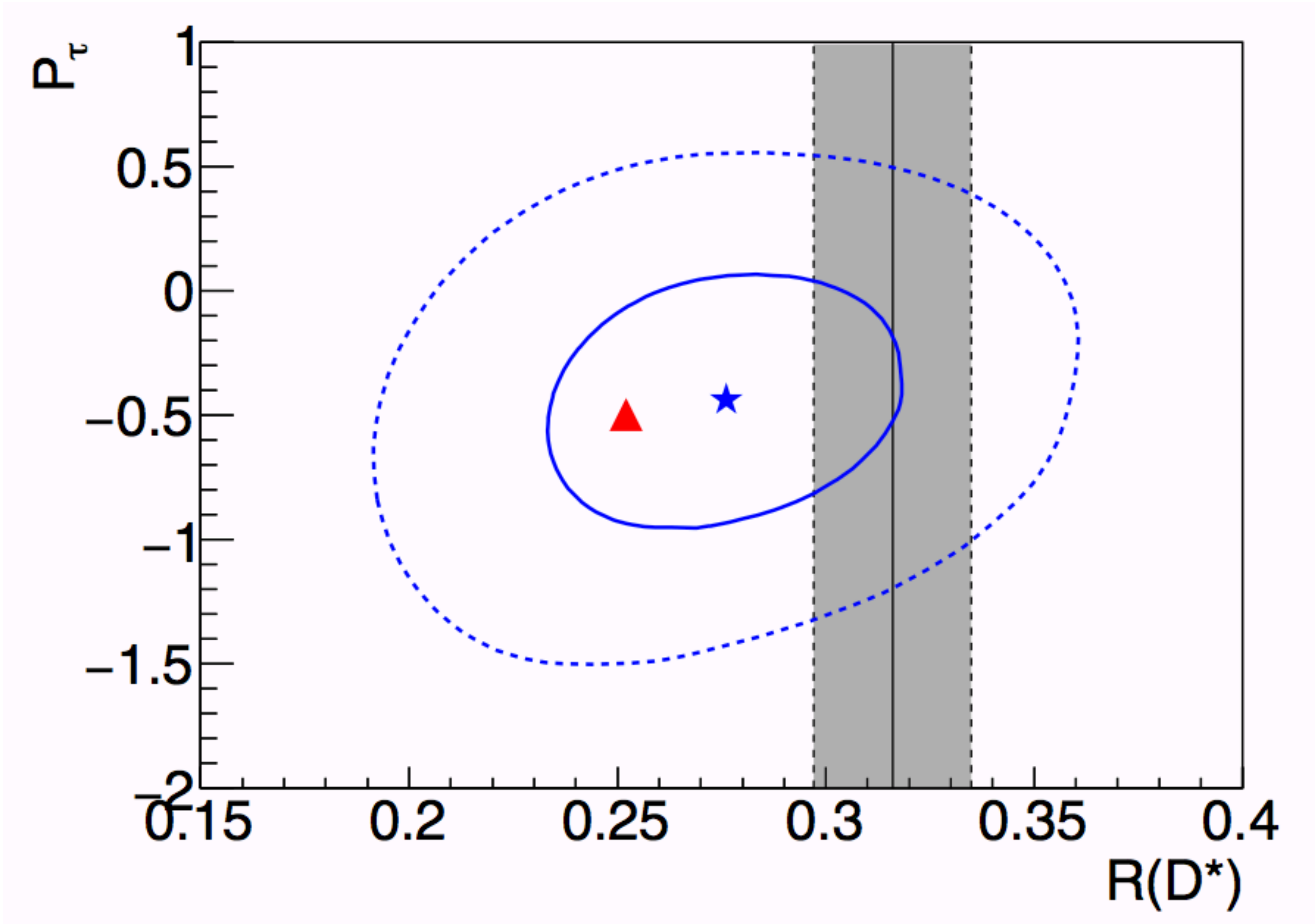


adapted from AC, Jung, Xin-Qiang, Pich [1612.07757]

Standard Model predictions | **Current experimental data**

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

$$\tau^- \to \pi^- \nu \,, \rho^- \nu$$

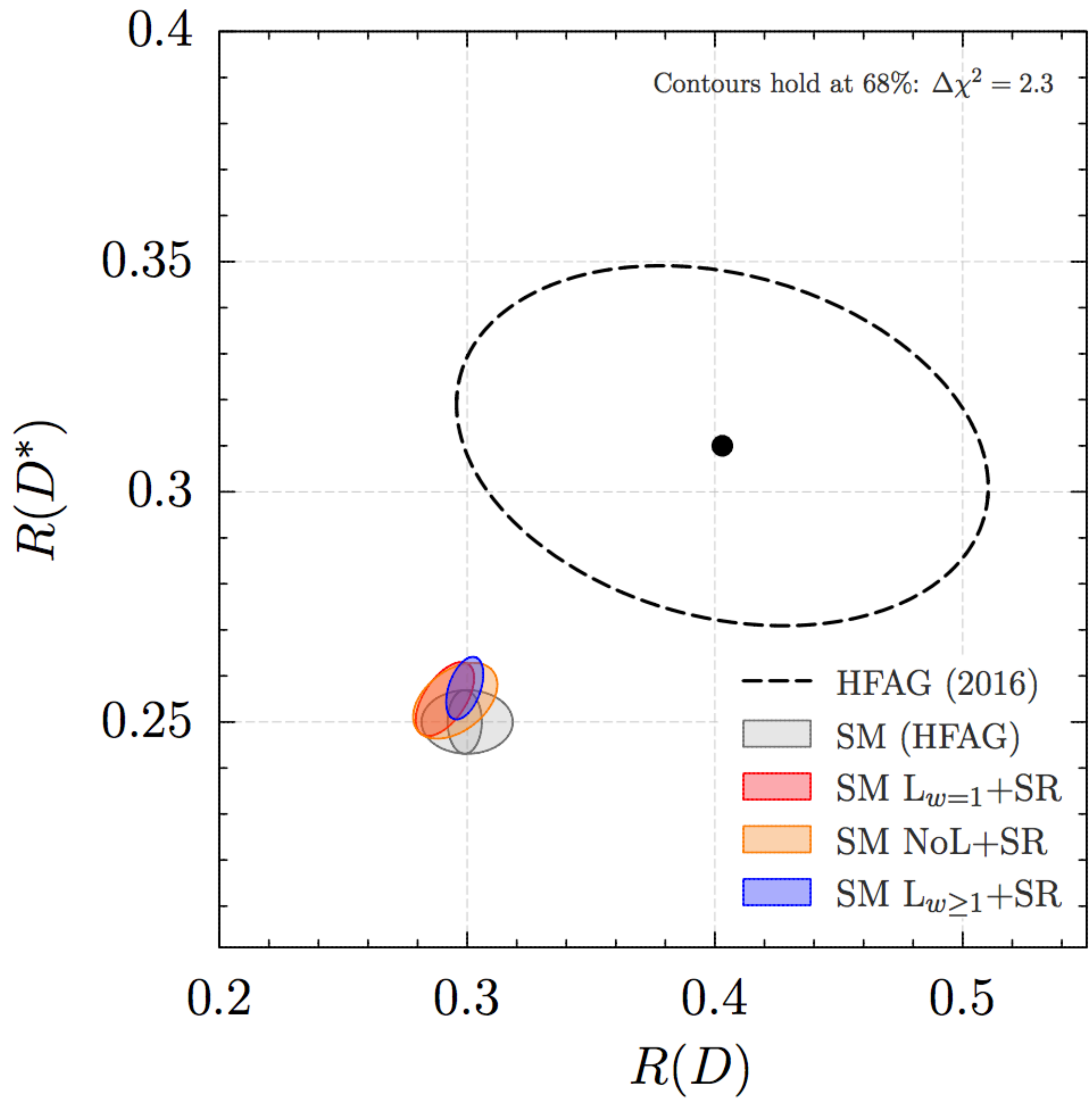


Belle (2016)

With Belle II in mind, considerable recent progress on the description of the full angular distributions in the presence of generic NP

Becirevic´, Tayduganov, Fajfer, Nisandzic, Alonso, Camalich, Westhoff, Datta, Duraisamy, Ghosh

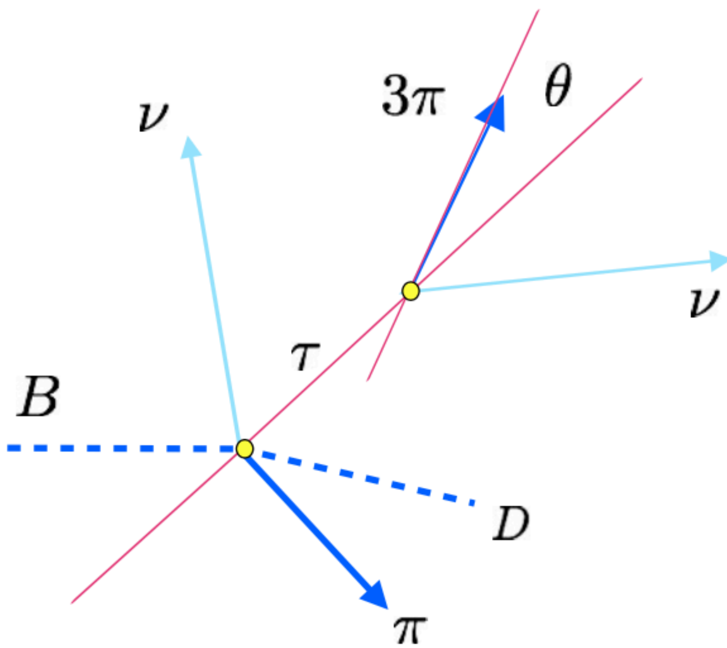
Standard Model predictions | **Current experimental data**



Bernlochner, Ligeti, Papucci, Robinson (2017)

Current experimental data

Reconstruction of $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ from a known vertex



Tau decay	BR
$e^-\bar{\nu}_e\nu_\tau, \mu^-\bar{\nu}_\mu\nu_\tau$	~ 18%
$\pi^-\nu$	~ 11%
$\pi^-\pi^0\nu$	~ 25%
$\pi^-\pi^0\pi^0\nu$	~ 9%
$\pi^-\pi^+\pi^-\nu$	~ 9%
$\pi^-\pi^+\pi^-\pi^0\nu$	~ 3%

Expected LHCb measurement Federico Betti talk in Moriond 2017

Estimated statistical precision is competitive with previous LHCb measurement in the muonic mode

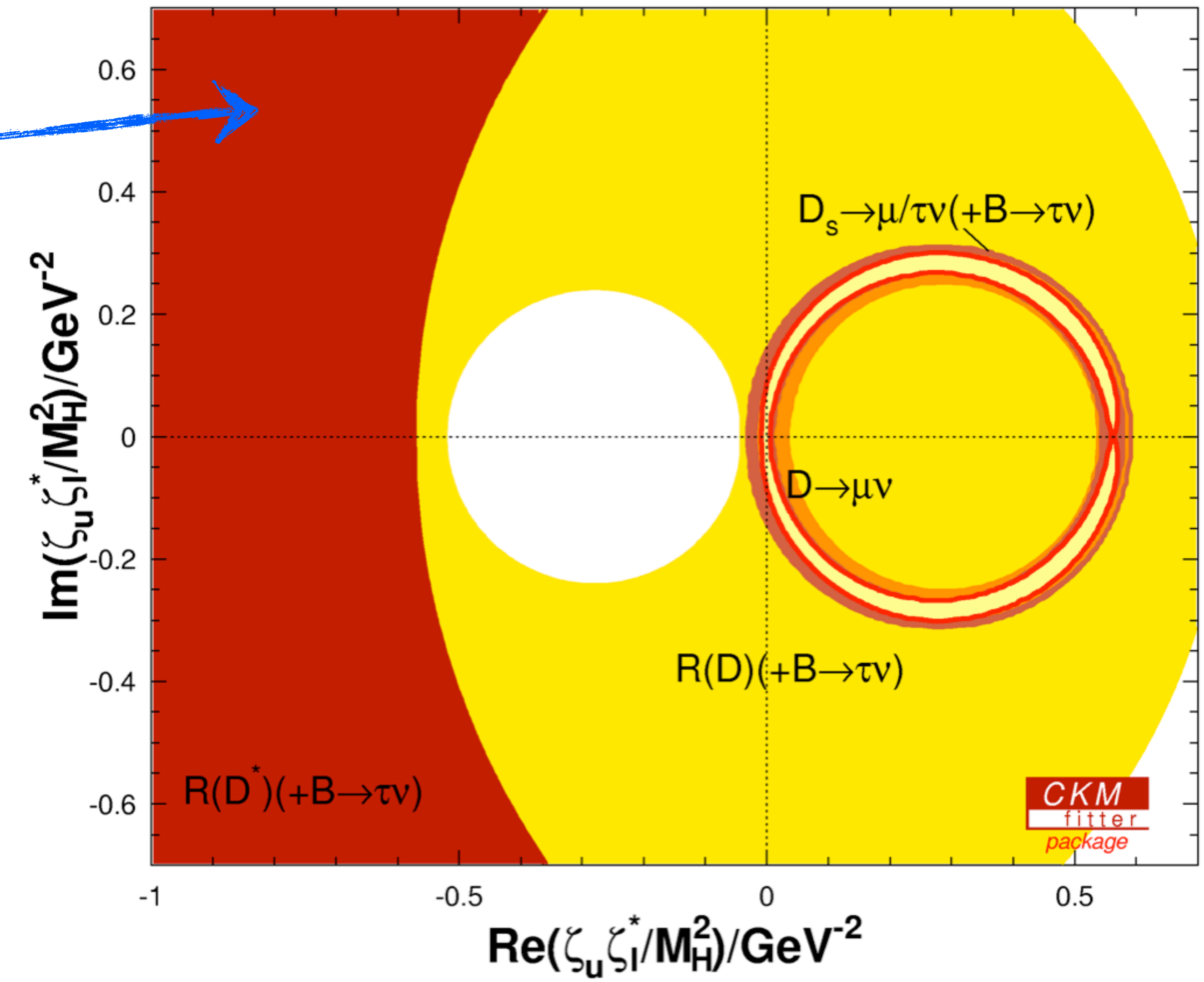
New Physics scenarios   Problems with a charged scalar

$$\mathcal{L}_Y \supset -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V M_d \mathcal{P}_R - \varsigma_u\, M_u^\dagger V \mathcal{P}_L \right] d \,+\, \varsigma_l\, \bar{\nu} M_l \mathcal{P}_R l \right\}$$

at 95 % CL   AC, Jung, X-Q. Li , Pich (2012)

$$\mathbf{R(D^*)(+B \to \tau\nu)}$$

→ $|\varsigma_u \varsigma_l| / M_{H^\pm}^2 \sim \mathcal{O}(1)\ \mathrm{GeV}^{-2}$



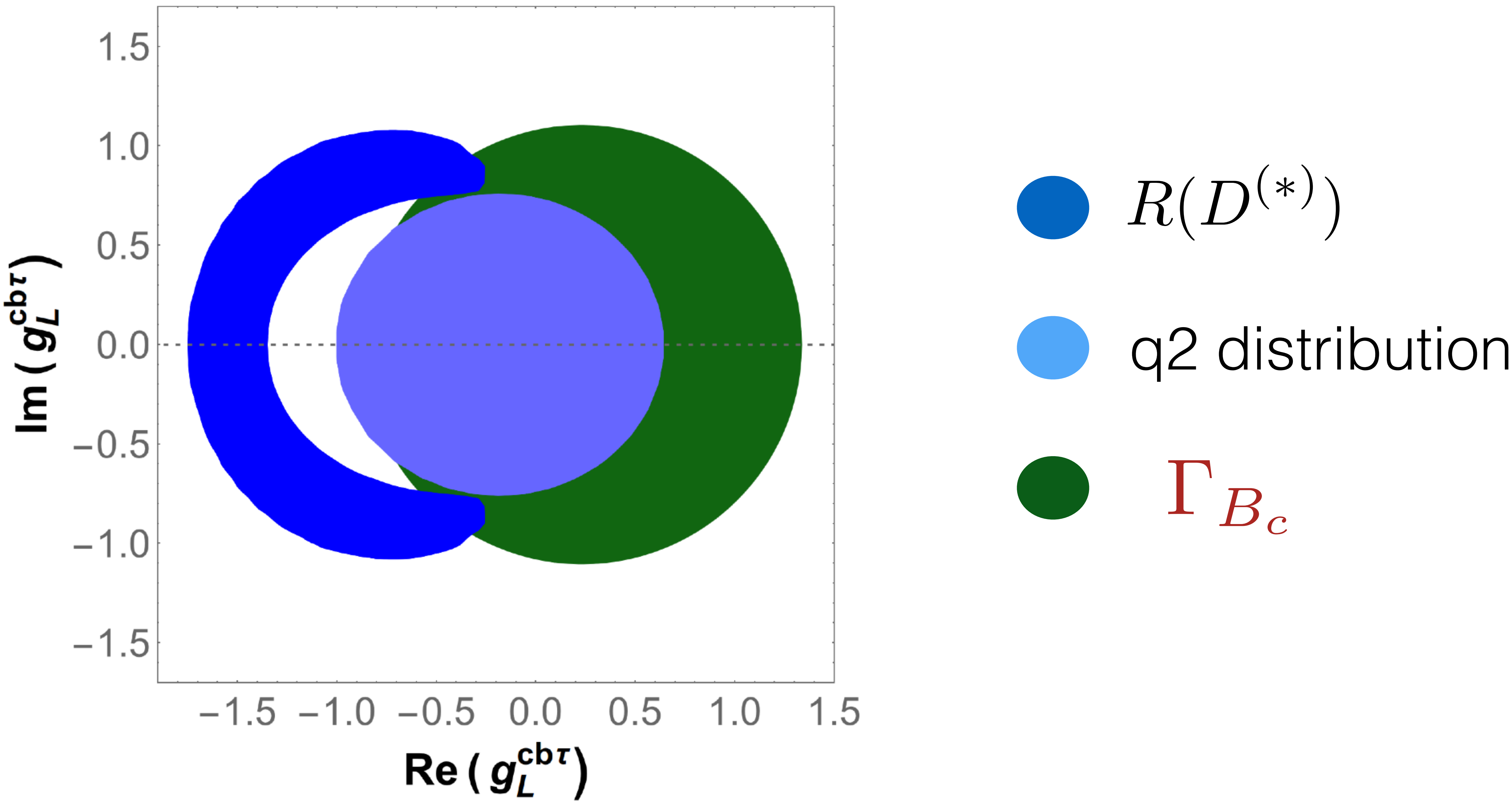
big tension between $D_{(s)}$ leptonic decays, R(D*) and B -> Tau Nu

None of the 2HDM with NFC can accommodate the excess in R(D*)

but possible with Type III 2HDM (with tree-level FCNCs) Crivellin et al.

New Physics scenarios

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{q_u q_d}}{\sqrt{2}} \left[\bar{q}_u (g_L^{q_u q_d \ell}\mathcal{P}_L + g_R^{q_u q_d \ell}\mathcal{P}_R) q_d\right] [\bar{\ell}\mathcal{P}_L \nu_\ell]$$



[1612.07757]

New Physics scenarios

Γ_{B_c}

Xin-Qiang Li, Y.-D. Yang, and X. Zhang (2016)

Alonso, B. Grinstein, and J. Martin Camalich (2016)

$$\Gamma(B_c \to \tau\nu_\tau) = G_F^2 m_\tau^2 f_{B_c}^2 |V_{cb}|^2 \frac{m_{B_c}}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 |1 - \Delta_{cb}^\tau|^2$$

$$\Delta_{qb}^l = \frac{(g_L^{qbl} - g_R^{qbl}) m_B^2}{m_l(\overline{m}_b + \overline{m}_q)}$$

PDG

Beneke, Buchalla (1996)

$$\tau_{B_c} = 0.507(8) \text{ ps}$$

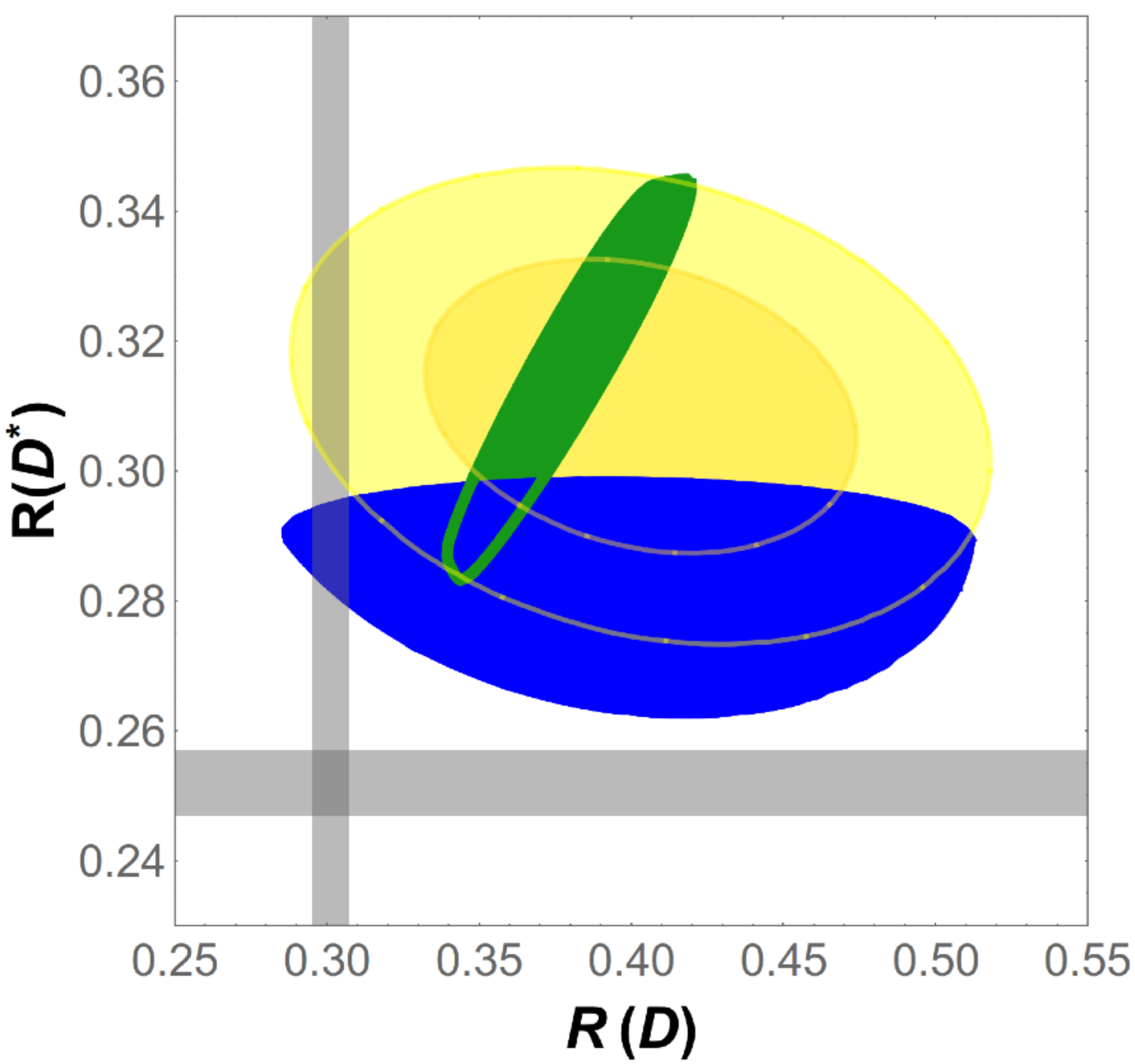
$$\tau_{B_c}^{\mathrm{OPE}} = 0.52^{+0.18}_{-0.12} \text{ ps}$$

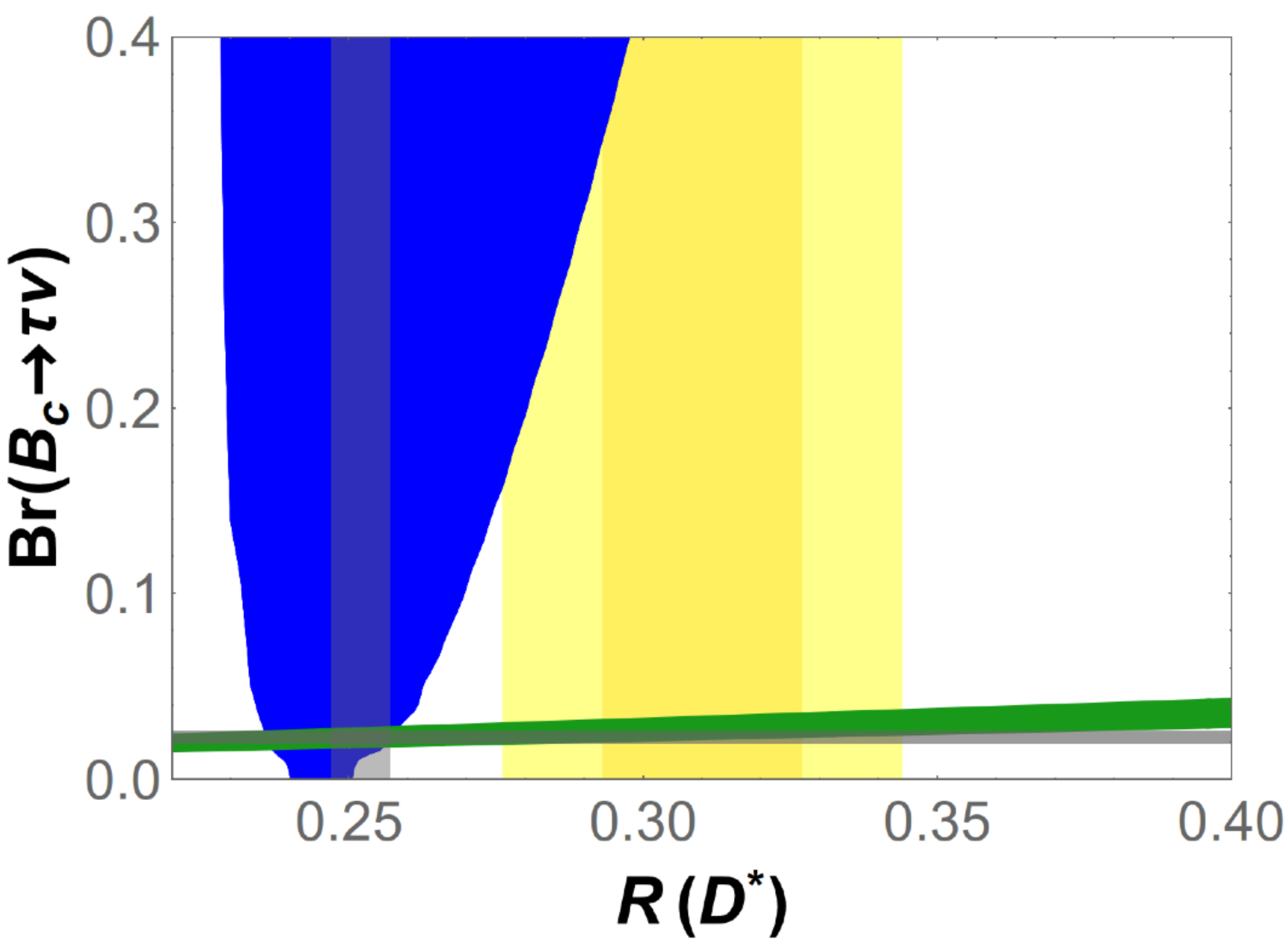
$$\mathrm{Br}(B_c \to \tau\nu) \leq 30 - 40\%$$

New Physics scenarios

- Vector scenario
- Scalar scenario

$$\mathcal{L}_{\rm eff} = -\frac{4G_F V_{cb}}{\sqrt{2}} g_{V_L} (\bar{c}\gamma_\mu \mathcal{P}_L b)(\bar{\tau}\gamma^\mu \mathcal{P}_L \nu) + \text{h.c.}$$



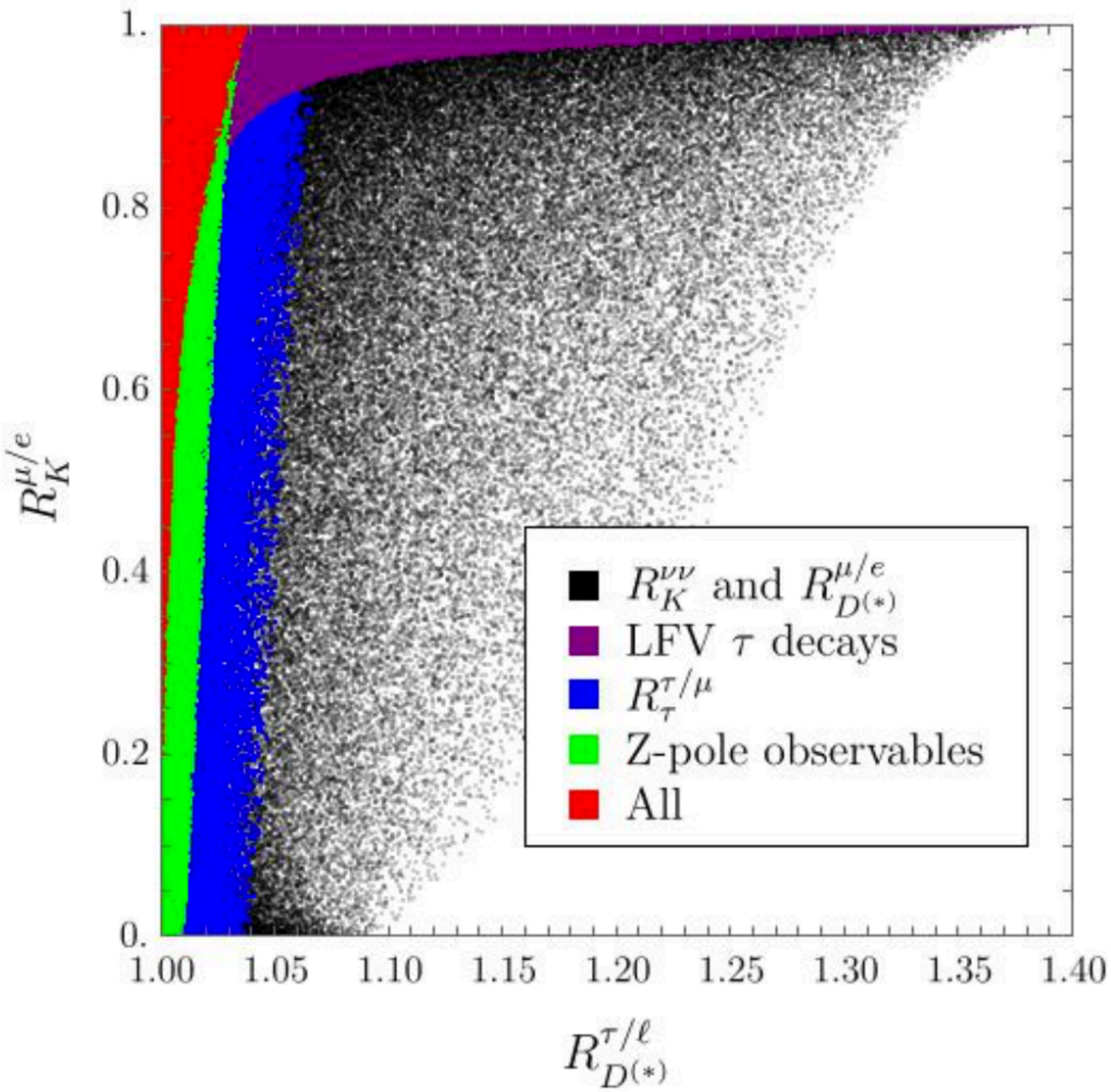


[1612.07757]

New Physics scenarios

$$\mathcal{L}_{\rm NP} = \frac{C_1}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \ell_{3L}\right) + \frac{C_3}{\Lambda^2}\left(\bar{q}_{3L}\gamma^\mu \tau^a q_{3L}\right)\left(\bar{\ell}_{3L}\gamma_\mu \tau^a \ell_{3L}\right)$$

Feruglio, Pattori, Paradisi (2016)



NP models expected to generate a richer spectrum of operators

↓

DsixTools

AC, J. Fuentes-Martin, A. Vicente, J. Virto

2499 ADM of D=6 SMEFT op.

M. Trott et al.

among other things,
expected to be public in April

more details in Avelino talk in Portoroz

Summary

Hints for violation of LFU in semileptonic B decays

SM predictions for R(D) and R(D*) from latest analyses find good agreement with previous estimates. The theory uncertainty has been reduced.

Model building associated to these hints is very challenging. Large NP effects required usually cause problems in other observables.