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# RD and RD*
# Theoretical Developments

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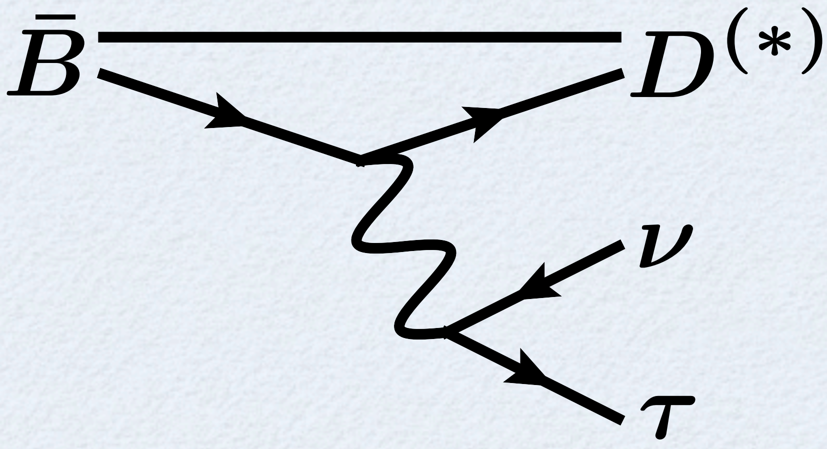



**are tree level processes**

- **Precise prediction on the Ratio has been done**

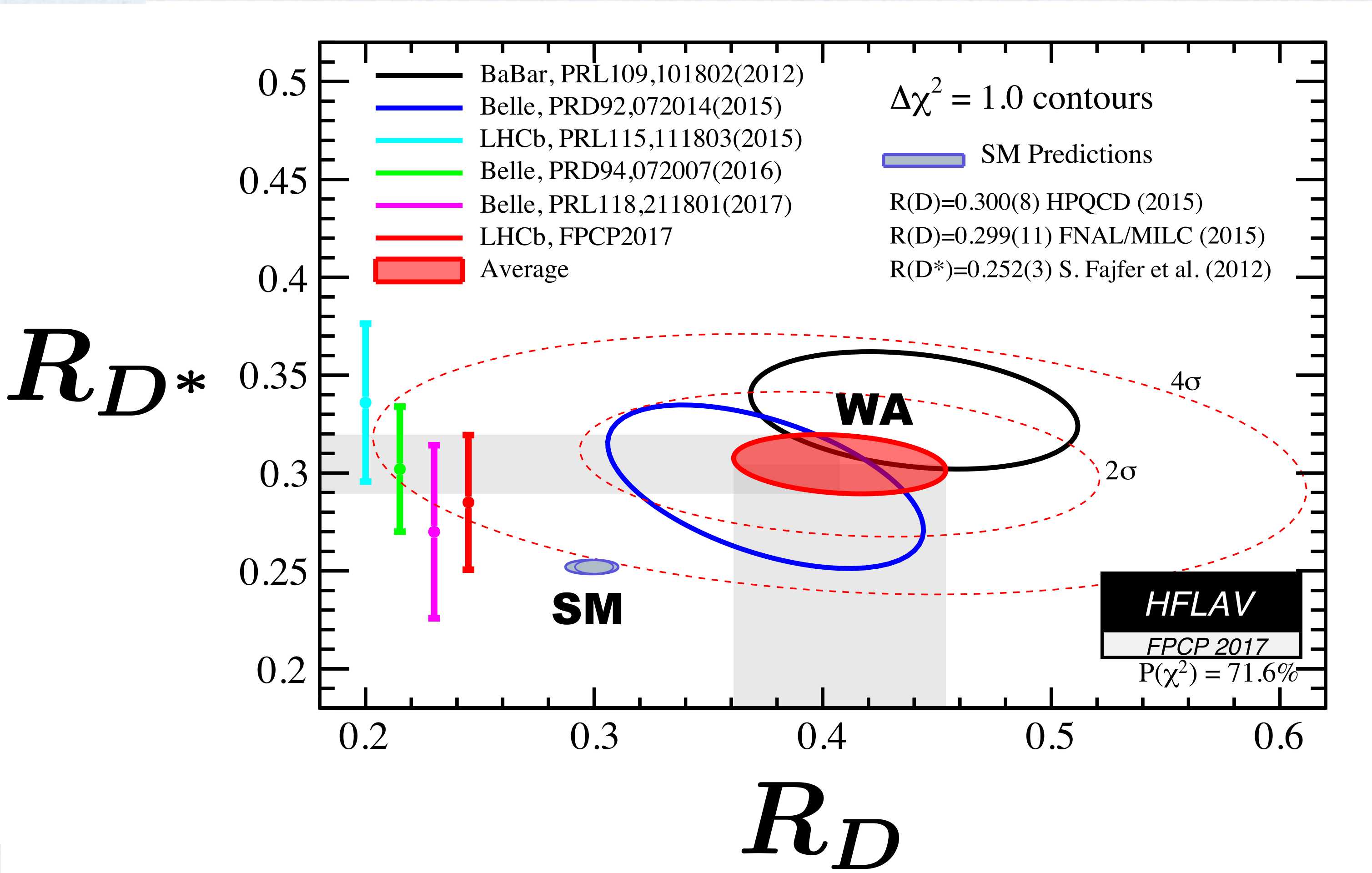
$$R_D = \frac{\Gamma(\bar{B} \to D\tau\bar{\nu})}{\Gamma(\bar{B} \to D\ell\bar{\nu})} = 0.299 \pm 0.003$$

$$\sim 1\%$$

$$R_{D^*} = \frac{\Gamma(\bar{B} \to D^*\tau\bar{\nu})}{\Gamma(\bar{B} \to D^*\ell\bar{\nu})} = 0.257 \pm 0.003$$

**Nevertheless,**

- **the SM values are NOT in agreement with data**




$\sim 4.1\,\sigma$

**BaBar : PRL 109, 101802 (2012), PRD 88, 072012 (2013)**
**Belle : PRD 92, 072014 (2015), PRD 94, 072007 (2016), arXiv 1608.06391**
**LHCb : PRL 115, 111803 (2015), arXiv 1708.08856**

# Topics

- **SM predictions**
- **NP explanations**
- **Relevant observables**

# SM predictions

## [1] Form Factor

**Main uncertainty in RD(*) comes from Form Factors**

$$\langle D(v')|\bar{c}\gamma_\mu b|B(v)\rangle = \sqrt{m_B m_D}\left[h_+(q^2)(v+v')_\mu + h_-(q^2)(v-v')_\mu\right]$$

$$\frac{d\Gamma(B\to D\ell\nu)}{dw} = \frac{G_F^2|V_{cb}|^2\,\eta^2\,m_B^5}{48\pi^3}\,(w(q^2)^2-1)^{3/2}\,r_D^3\,(1+r_D)^2\,\mathcal{G}(q^2)^2$$

**Using Heavy Quark Effective Theory, q^2 dependence can be described**

$$\mathcal{G} = h_+ - \frac{1-r_D}{1+r_D}h_- = \xi_{IW}(q^2) + \frac{\alpha_s}{\pi}\chi_1(q^2) + \frac{\Lambda_{\rm QCD}}{m_{c,b}}\chi_2(q^2) + \cdots$$

**The functions are then determined with QCD sum-rule / lattice**

**+ fit to data of the light lepton mode.**

**QCDSR + lattice QCD + Fit to Belle data of** $B \to D(*)\ell\nu \;\; (\ell = e, \mu)$

**up to the NLO, i.e.** $O(\alpha_s), O(1/m_Q)$

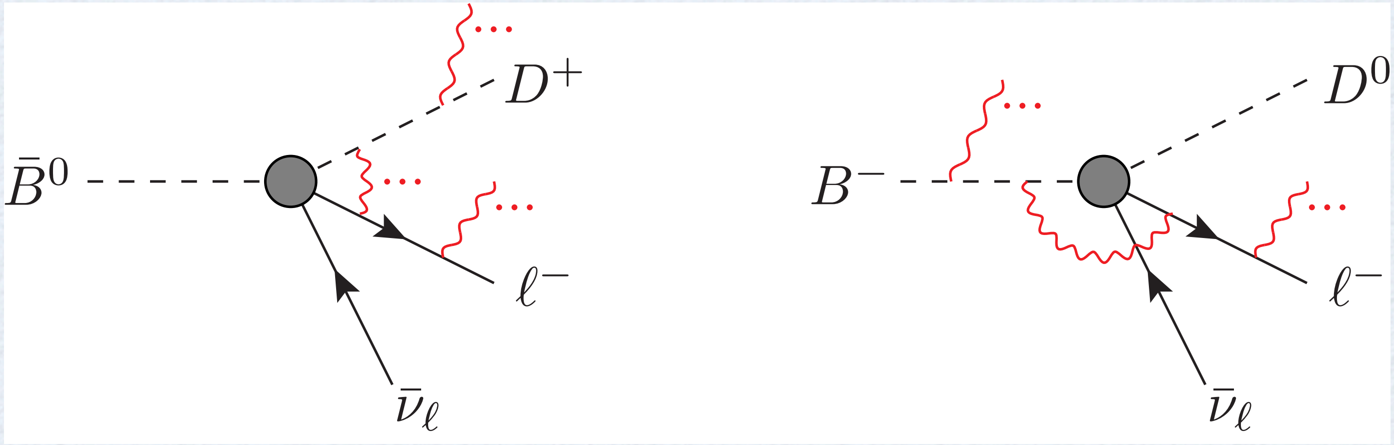
**Ligeti et al., 1703.05330**

| Scenario | $R(D)$ | $R(D^*)$ | Correlation | |
|---|---|---|---|---|
| $L_{w=1}$ | $0.292 \pm 0.005$ | $0.255 \pm 0.005$ | 41% | |
| $L_{w=1}$+SR | $0.291 \pm 0.005$ | $0.255 \pm 0.003$ | 57% | |
| NoL | $0.273 \pm 0.016$ | $0.250 \pm 0.006$ | 49% | |
| NoL+SR | $0.295 \pm 0.007$ | $0.255 \pm 0.004$ | 43% | **This study** |
| $L_{w\geq 1}$ | $0.298 \pm 0.003$ | $0.261 \pm 0.004$ | 19% | |
| $L_{w\geq 1}$+SR | $\mathbf{0.299 \pm 0.003}$ | $\mathbf{0.257 \pm 0.003}$ | **44%** | |
| th:$L_{w\geq 1}$+SR | $0.306 \pm 0.005$ | $0.256 \pm 0.004$ | 33% | |
| Data [9] | $0.403 \pm 0.047$ | $0.310 \pm 0.017$ | −23% | **Measurements** |
| Refs. [53, 57, 59] | $0.300 \pm 0.008$ | — | — | |
| Ref. [58] | $0.299 \pm 0.003$ | — | — | **Previous studies** |
| Ref. [34] | — | $0.252 \pm 0.003$ | — | |

## [2] Radiative correction

Kitahara et al., 1803.05881

**Another development. Soft-photon effects depend on lepton mass, which leads to corrections even in RD(*)**




**Soft-photon corrections to RD result in**

**(1) leading to RD^+ ≠ RD^0**

**(2) depending on photon energy cut**

**(3) non-negligible constructive contribution to RD, at most 4〜6%**

**Kitahara et al., 1803.05881**

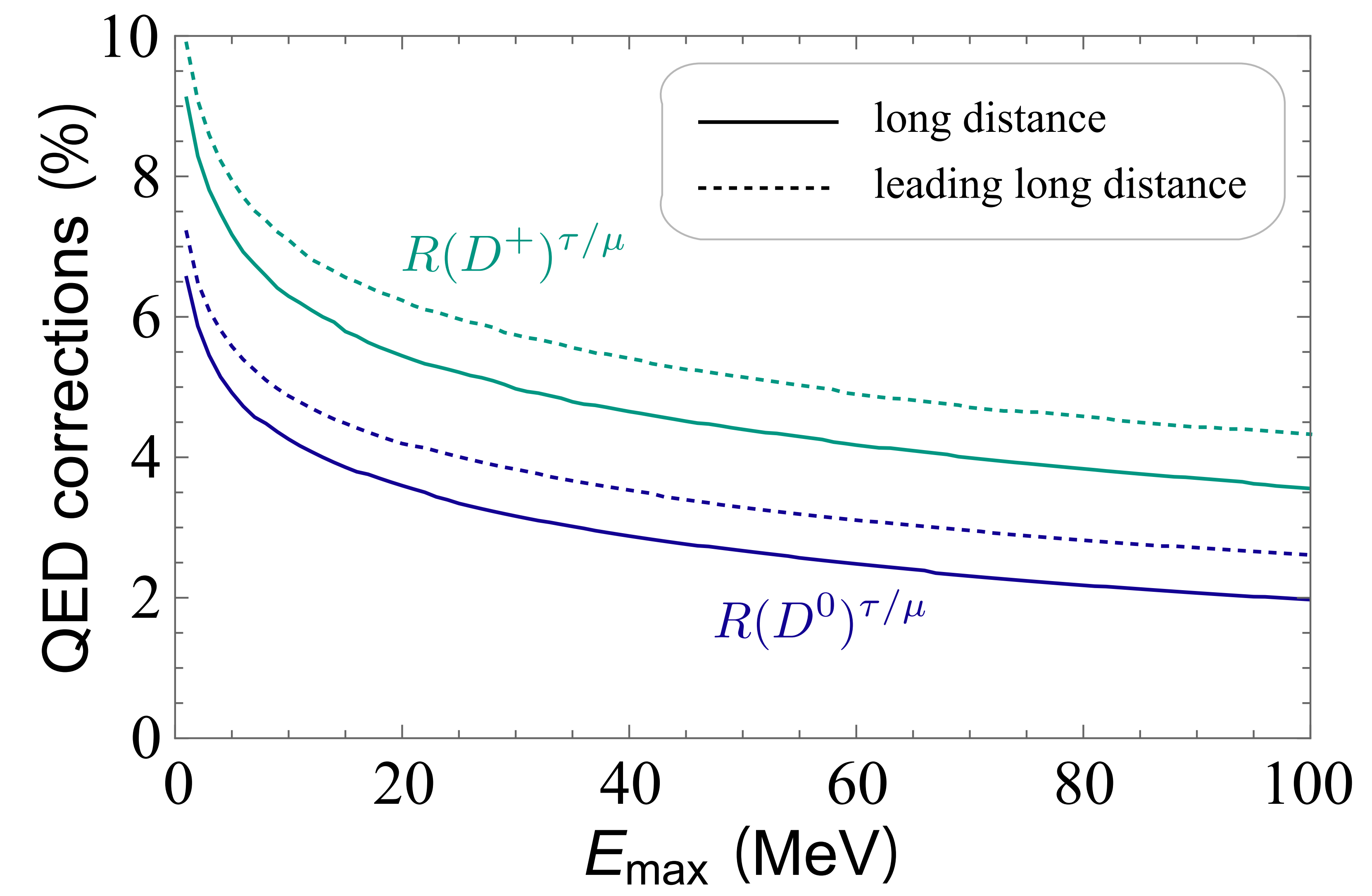
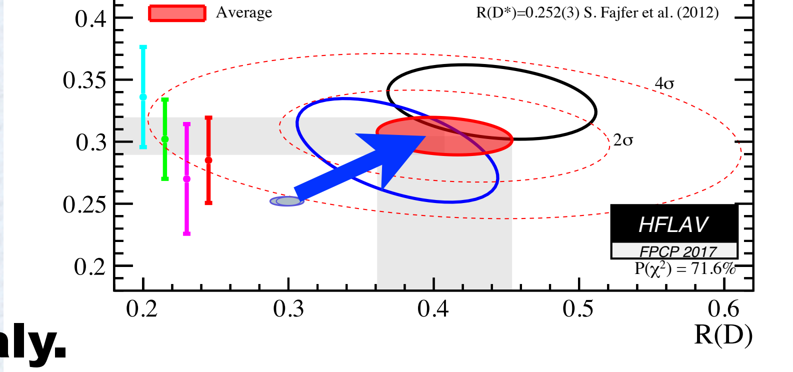



FIG. 3. The (leading) long-distance QED corrections to $R(D^+)^{\tau/\mu}$ and $R(D^0)^{\tau/\mu}$ as a function of $E_{\rm max}$.




# NP explanations

**There exist several solutions to the RD(*) anomaly.**

**In terms of effective operators, possible NPs are given as follows**

$$\mathcal{L}_{\text{eff}}^{\text{NP}} \equiv -2\sqrt{2}G_F V_{cb}\, C_{\text{NP}} \mathcal{O}_{\text{NP}}$$

**V−A :** $\mathcal{O}_{V_1} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$

**Models :** **(SM), W' boson, Vector Leptoquark, ...**

**Fit to data :** $C_{V_1} \sim +0.17$

- **NP with 17% contribution of the SM value is required**
- **Assuming NP coupling =1, it implies ∼2TeV NP scale**

**V+A (quark sector) :** $\mathcal{O}_{V_2} = (\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu)$

**Models :** W' boson, ...?

**Fit to data :** $C_{V_2} \sim 0.01 + 0.6i$

- Complex coupling is necessary

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**Scalar types :** $\mathcal{O}_{S_{1(2)}} = (\bar{c}\, P_{R(L)} b)(\bar{\tau} P_L \nu)$

**Models :** Charged Higgs, Scalar Leptoquark, ...

**Fit to data :** $C_{S_1} = \text{no solution}$, $C_{S_2} \sim -1.5$

- 2HDM of typeII is disfavored
- Large scalar contribution is needed

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**Tensor type :** $\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$

**Models :** Doublet vector/scalar Leptoquark (in part)

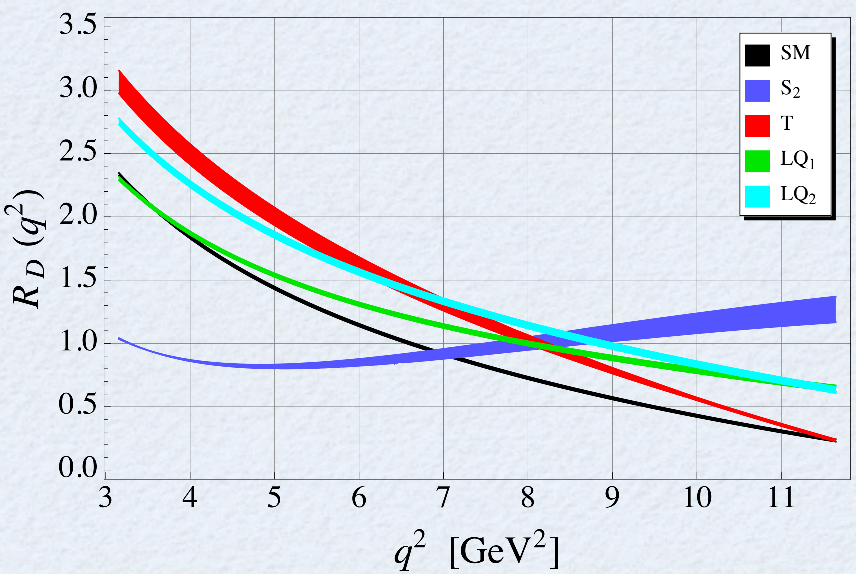
**Fit to data :** $C_T \sim 0.3$

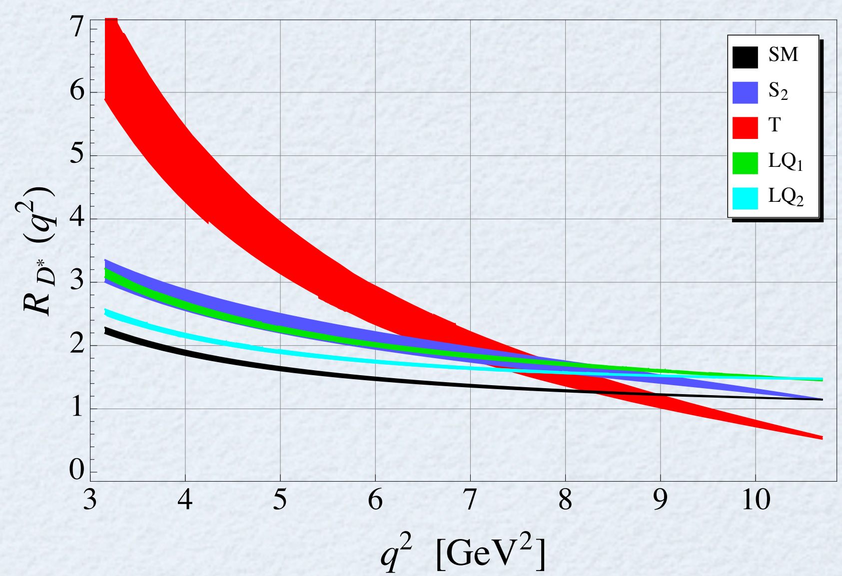
# Relevant observables

## [1] q^2 distribution

**RW et al. 1412.3761, B2TiP report**

**Distributions for the case that $C_{\mathrm{NP}}$ = best fit to the current results of $R_{D^{(*)}}$**

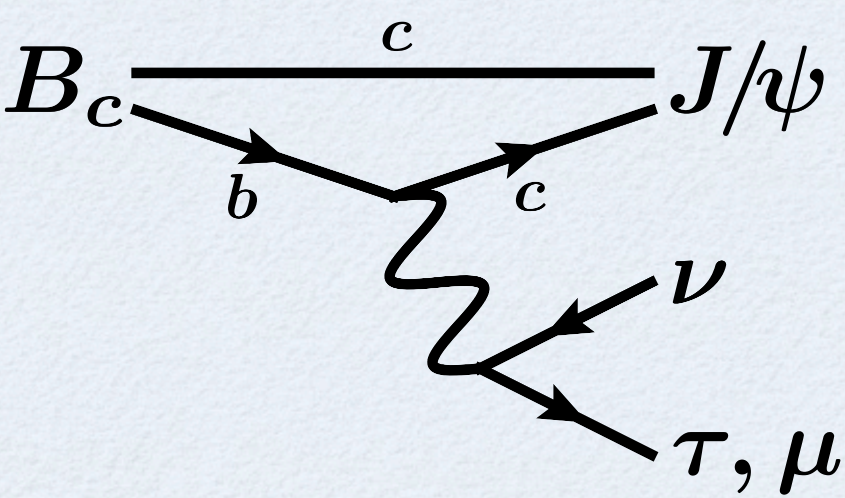



**Some simple test with statistics was done and it turns out that**

**"5ab^-1 data for q^2 distributions enable us to distinguish the NP scenarios in case that the present anomalies still remain in the future"**

[2] $B_c \to J/\psi\, \tau\nu$ **RW, 1709.08644**




**has been observed at LHCb**

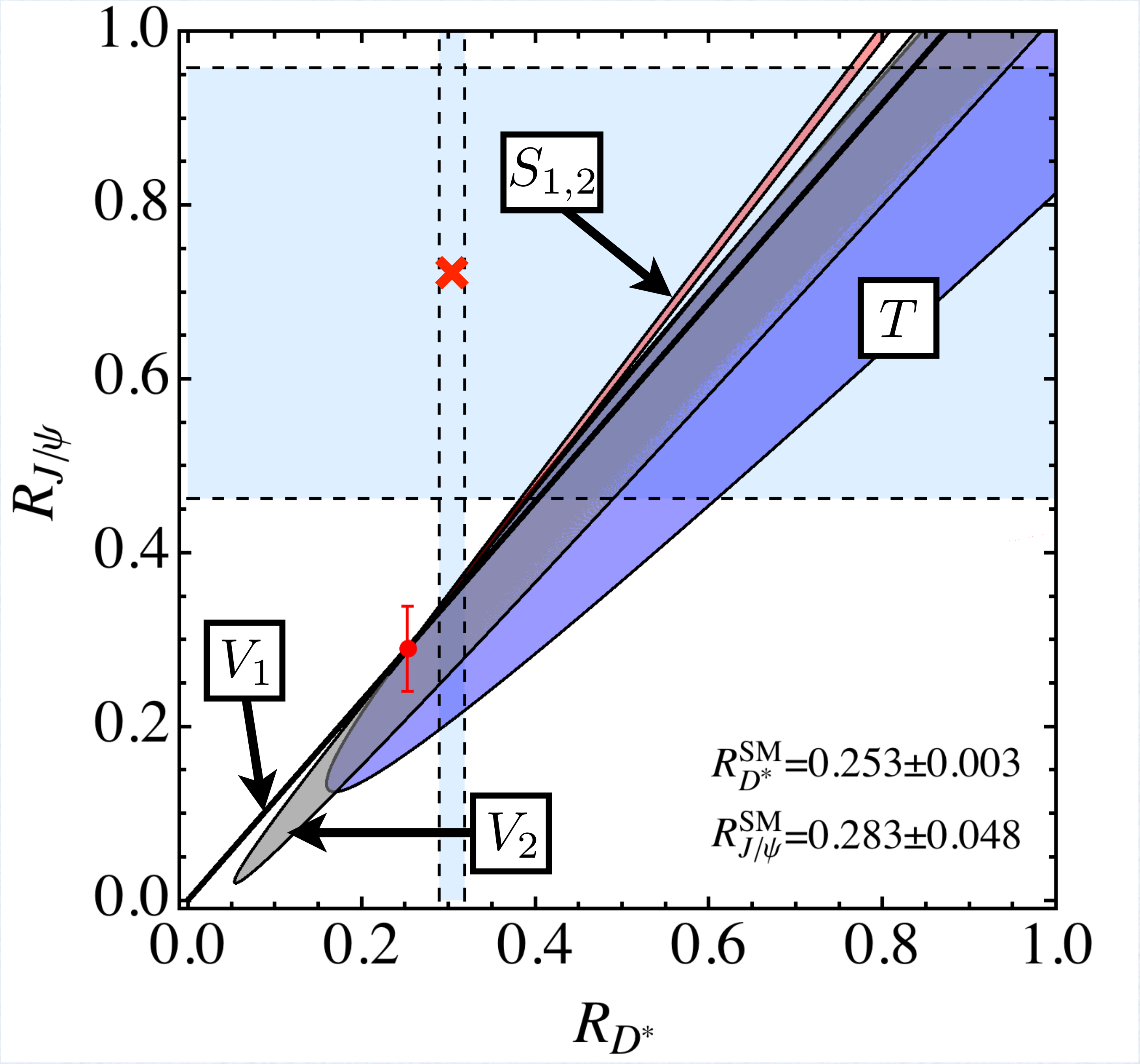
$$R_{J/\psi} = \frac{\Gamma(B_c \to J/\psi \tau \bar{\nu})}{\Gamma(B_c \to J/\psi \mu \bar{\nu})}$$

**data :** $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ **LHCb, 1711.05623**

**SM :** $R_{J/\psi} = 0.283 \pm 0.048$ **RW, 1709.08644**

- **Perturbative QCD analysis provides the form factor.**
- **Still large errors both in data (35%) and SM (17%)**
- **Deviation ~1.7σ**

**NP :** **Central value of the data cannot be reproduced**



$S_{1,2}$
$T$
$V_1$
$V_2$
$R_{D^*}^{\mathrm{SM}}$=0.253±0.003
$R_{J/\psi}^{\mathrm{SM}}$=0.283±0.048
$R_{J/\psi}$
$R_{D^*}$
0.0
0.2
0.4
0.6
0.8
1.0

[3] $B_c \to \tau\nu$

Grinstein et al, 1611.06676
Akeroyd, 1708.04072

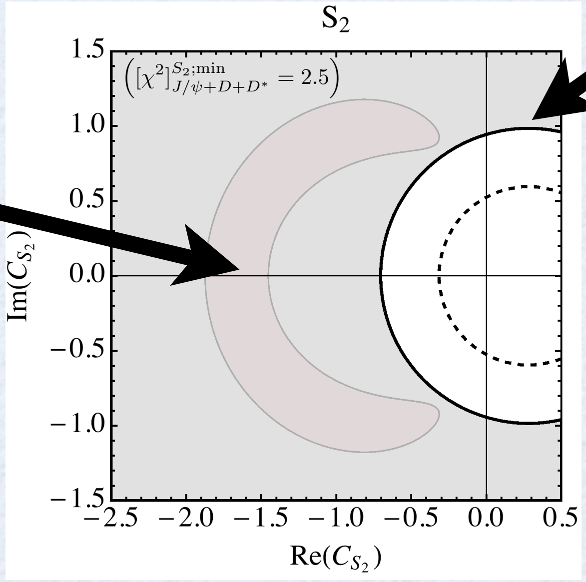
**Not directly measured,**
**but some limits have been estimated from Bc decay**

**From Bc life time : uncertainty of theoretical evaluation implies**
**From LEP data : extracted from data at the Z boson peak**

- **Indirect bound is then given as** $\mathcal{B}(B_c \to \tau\nu) < 10 - 30\%$
- **This kills the Scalar NP explanation**

**[Best fit point]**

$C_{S_2} \sim -1.5$



# Thank you!

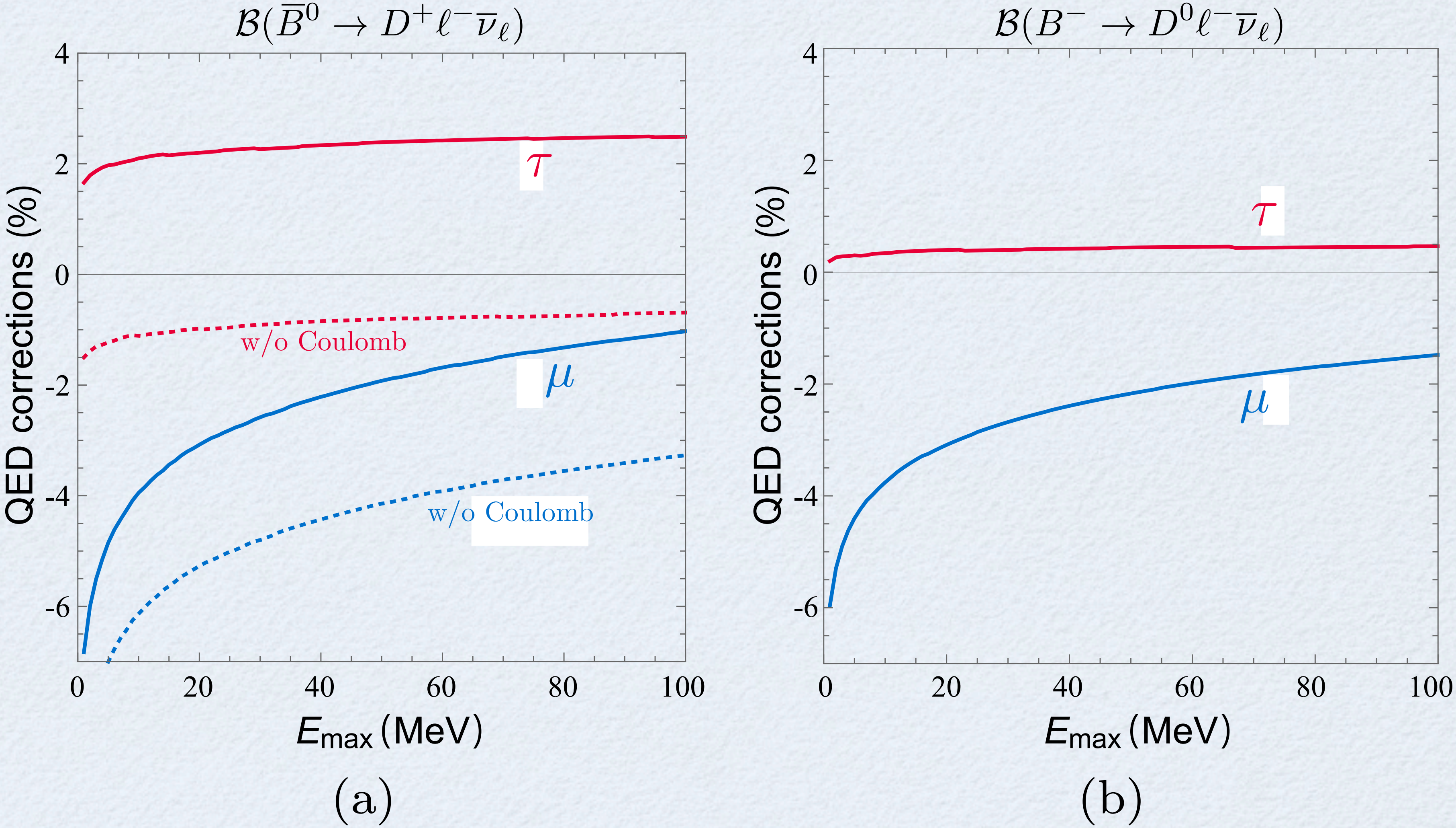



FIG. 2. (a) The long-distance QED corrections to the branching ratios of $\overline{B}^0 \to D^+\ell^-\overline{\nu}_\ell$ and (b) $B^- \to D^0\ell^-\overline{\nu}_\ell$, where $\ell = \mu$, $\tau$, as a function of $E_{\max}$. The dotted lines show the corrections to $\overline{B}^0 \to D^+\ell^-\overline{\nu}_\ell$ without the Coulomb contributions, for the purpose of illustration.