Theory status and implications of $R(D^{(*)})$ and polarization observables

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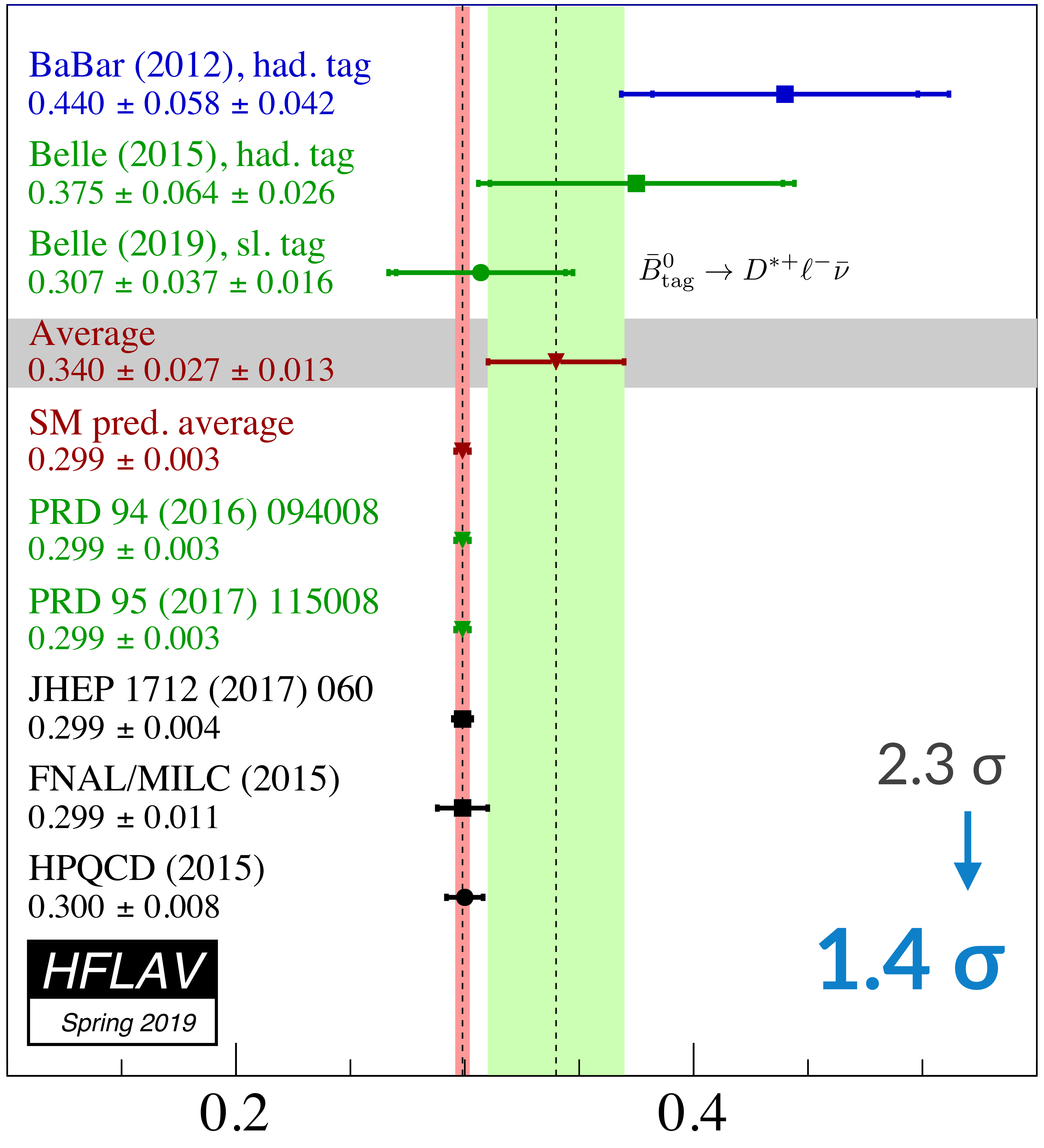
NAGOYA UNIVERSITY

$b \to c\tau\bar{\nu}$ in Standard Model

Current status of $R(D)$ and $R(D^*)$

[HFLAV averages Spring 2019]



$D^{0,+}$ ↔ $D^{*0,+}$

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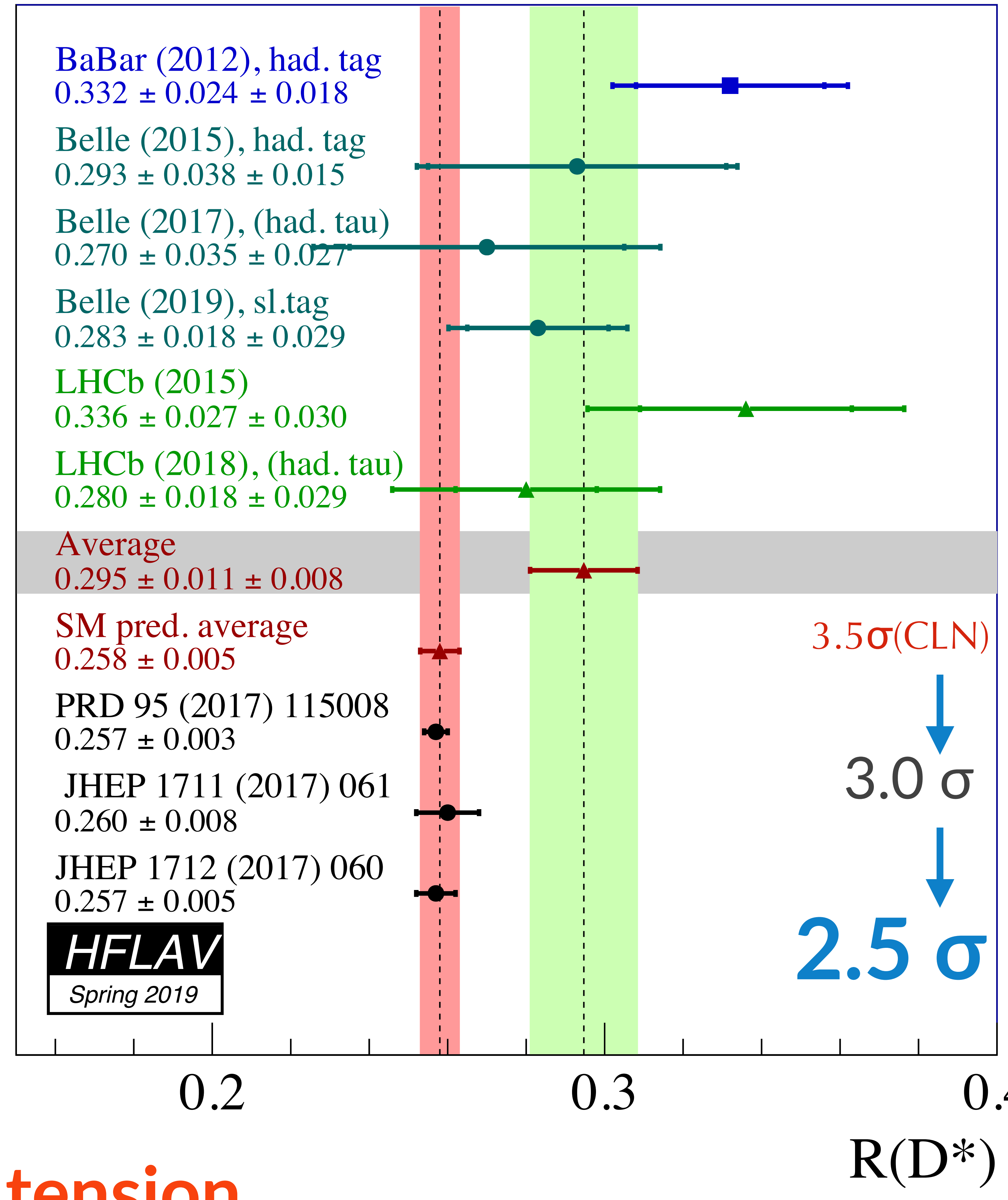
Belle New result
1904.08794

After Belle 2019



$D^{*0,+}$
$D^{*0,+}$
D^{*+}
$D^{*0,+}$
D^{*+}
D^{*+}

3.5σ(CLN)

S.Fajfer et al. (2012)
0.252 ± 0.003

BGL parametrization

After Belle 2019

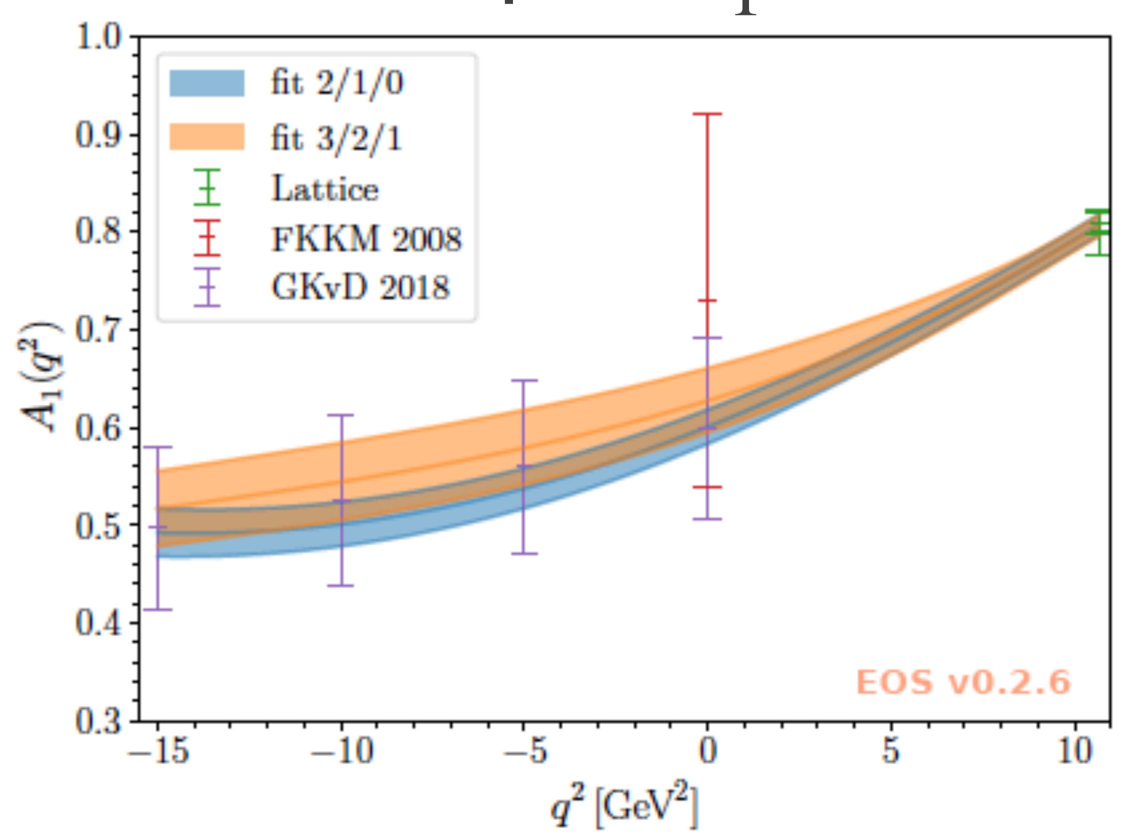
3.8 σ

combine: 3.1 σ tension

Latest SM predictions

- *All* $\mathcal{O}(1/m_c^2)$ corrections in the heavy quark expansion are included and fit all form factors (previous works are $\mathcal{O}(1/m_c)$, $\mathcal{O}(\alpha_s)$, $\mathcal{O}(1/m_b)$ + part of $\mathcal{O}(1/m_c^2)$) [Bordone, Jung, van Dyk 1908.09398]

example: A_1 FF



2/1/0: $\mathcal{O}(1/m_c^2)$ corrections are just constants
3/2/1: ω dependence in $\mathcal{O}(1/m_c^2)$ is included

$$w = (m_B^2 + m_D^{(*)2} - q^2)/2m_B m_D^{(*)}$$

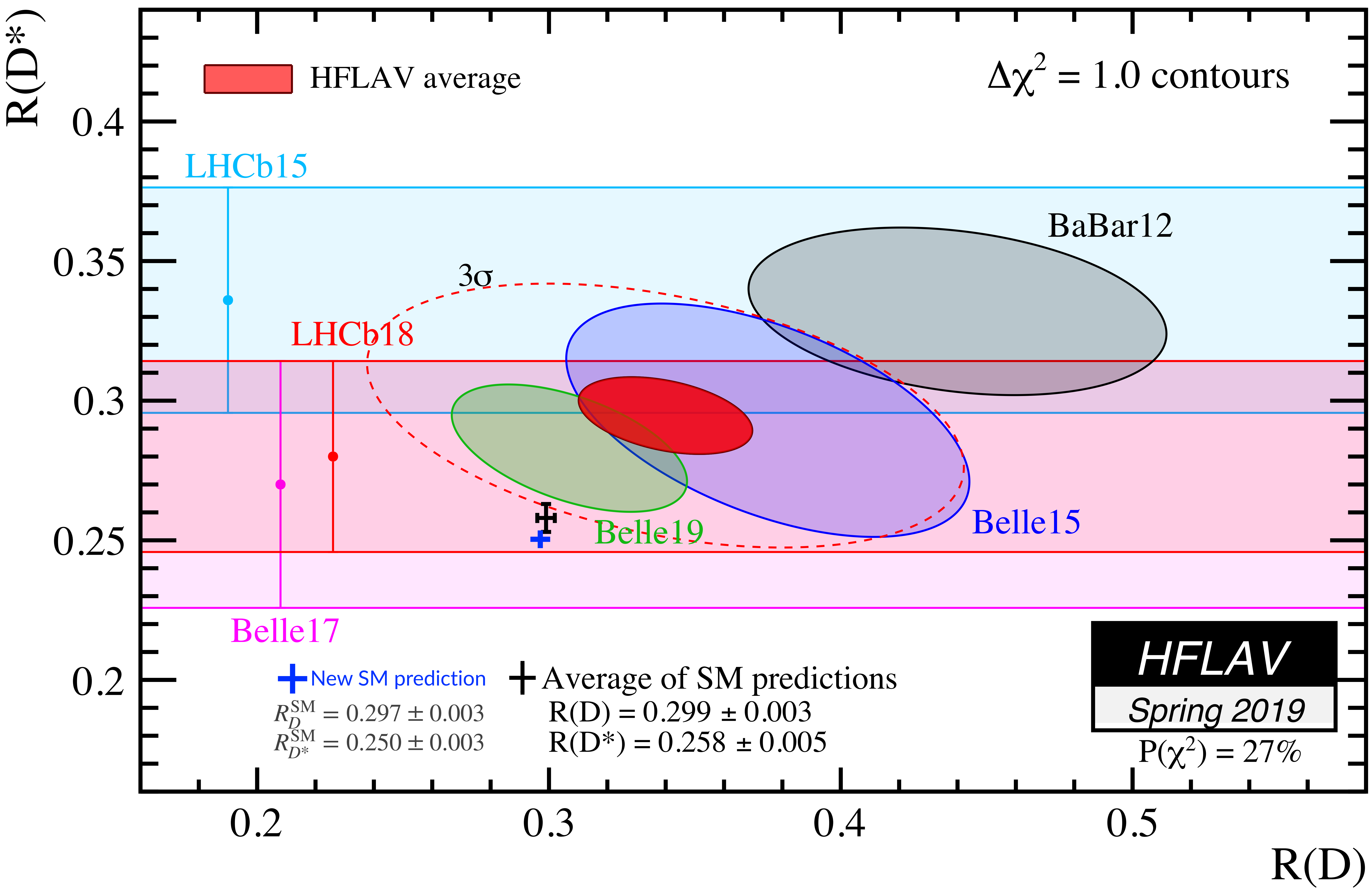
- All lattice data, QCDSR, and the latest LCSR result [Gubernari, Kokulu, van Dyk '19]

$$R(D)_{\rm SM} = 0.298 \pm 0.003 \qquad R(D^*)_{\rm SM} = 0.247 \pm 0.006$$

- + Angular distributions from Belle data [Belle, 1510.03657, 1702.01521, 1809.03290]

$$R(D)_{\rm SM} = 0.297 \pm 0.003 \qquad R(D^*)_{\rm SM} = 0.250 \pm 0.003$$

$R(D)$: 1.4 → 1.4 σ
$R(D^*)$: 2.5 → 3.4 σ
combine: 3.1 → 3.9 σ (my personal analysis)



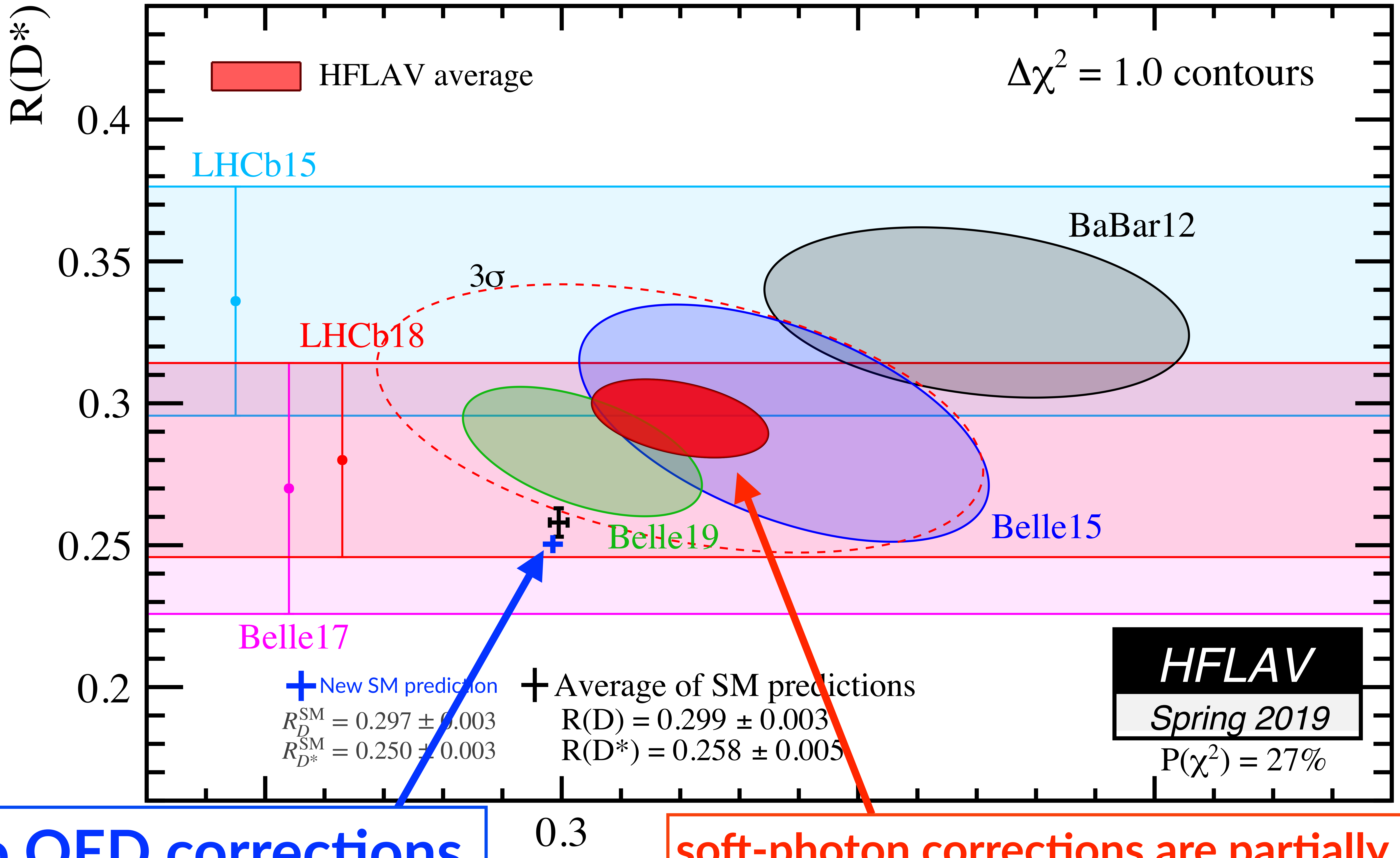
[HFLAV averages Spring 2019]

$$R(J/\Psi) = \frac{\mathrm{BR}(B_c \to J/\Psi\tau\nu)}{\mathrm{BR}(B_c \to J/\Psi\ell\nu)}$$ @LHCb

same-direction tension ~2σ.

But form factors are poorly known because heavy quark expansion is broken by m_c

e.g., [Watanabe, '18]



[HFLAV averages Spring 2019]

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No QED corrections

Error = QCD

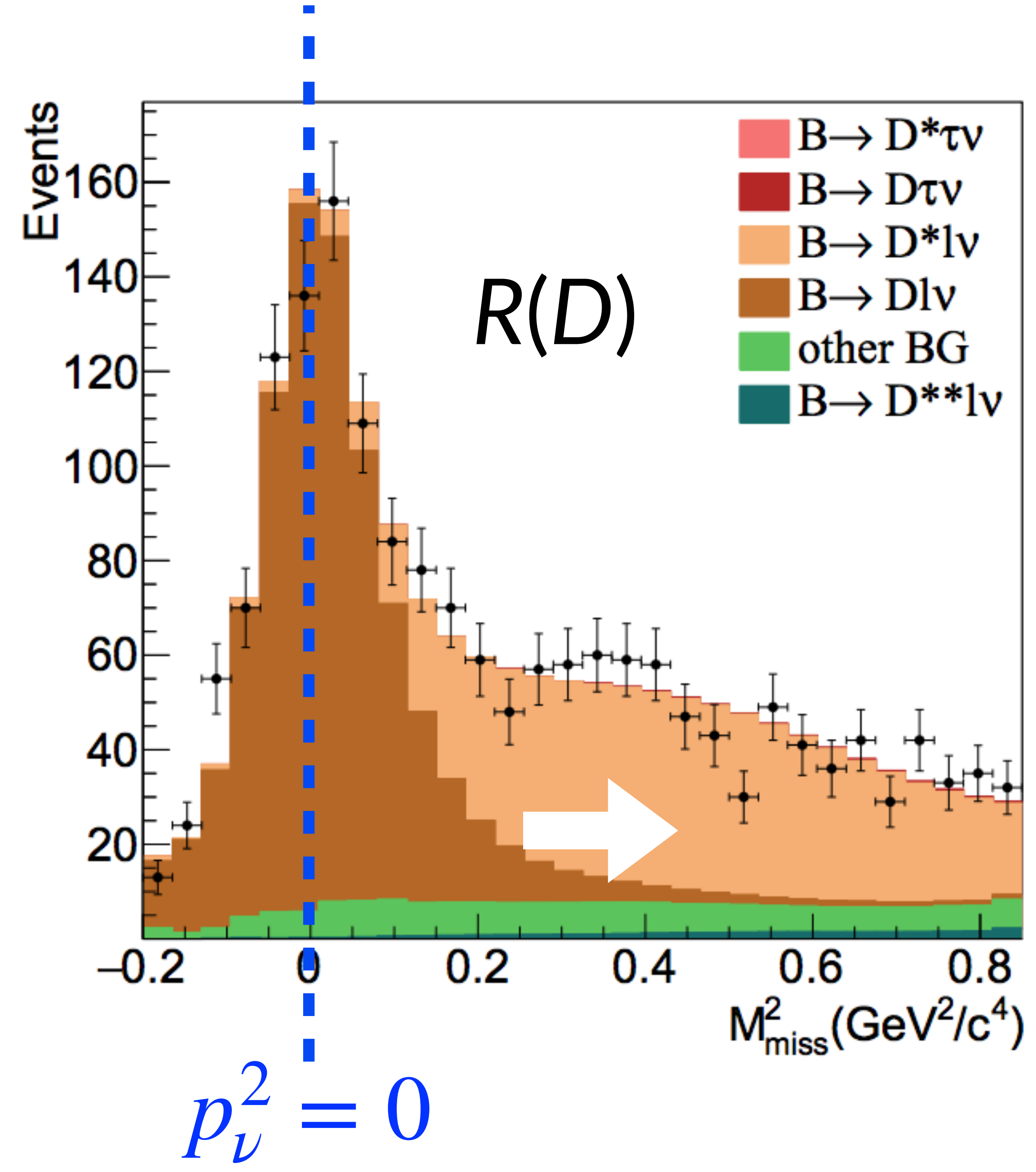
soft-photon corrections are partially subtracted by PHOTOS Monte-Carlo simulation

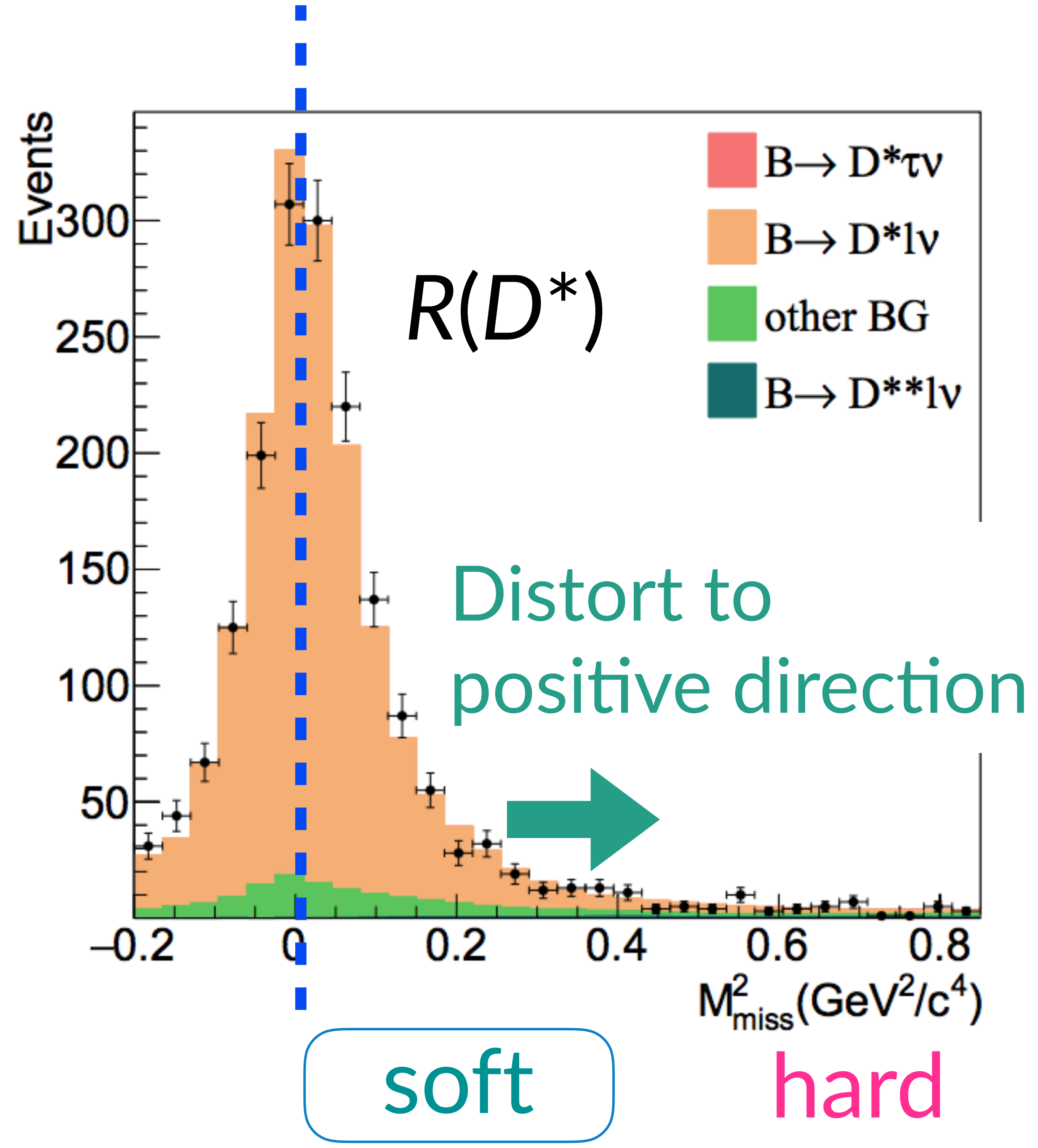
Photon emissions in data

- **The experiments have not explicitly utilized the photon cut** for event selections for B semileptonic decay
- The photon emission **distorts** the missing mass squared distribution **to the positive direction**

$$M^2_{\rm miss} \equiv \left(p_{e^+e^-} - p_{B_{\rm tag}} - p_D - p_\ell\right)^2 = (p_\nu + p_\gamma)^2 = 2E_\nu E_\gamma\,(1-\cos\theta_{\nu\gamma}) > 0 \qquad E_{\nu_\ell} = 0.5 - 2\,{\rm GeV}$$

Missing mass squared distributions of selected events@ Belle





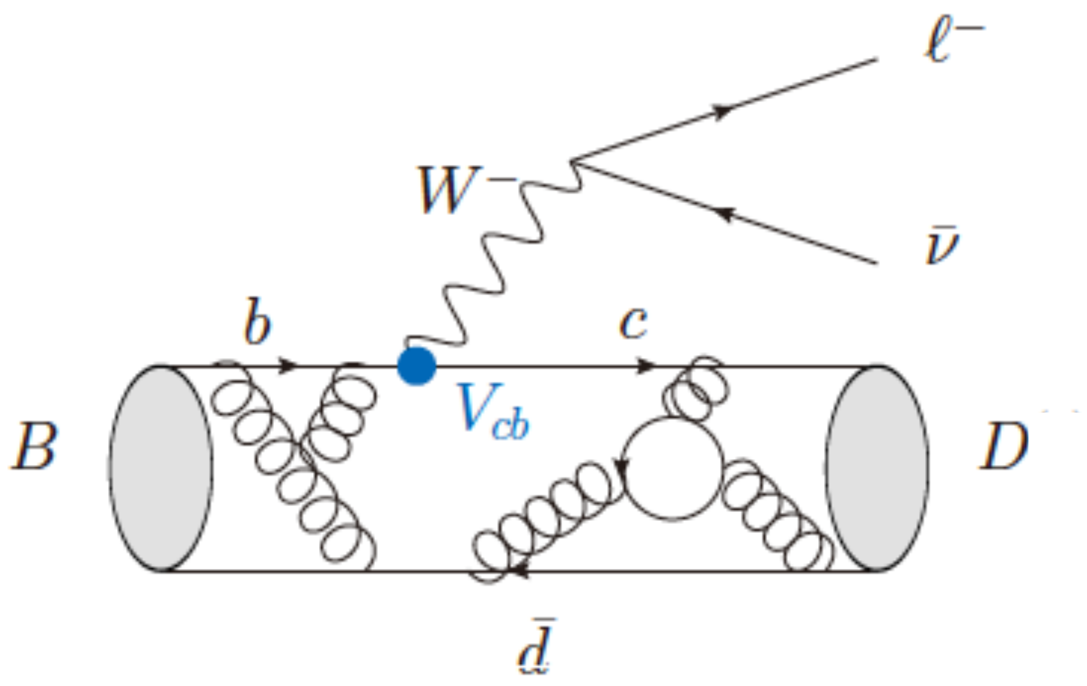
Soft emission distorts around the center of the missing mass dist.

Hard emission distorts only the tail

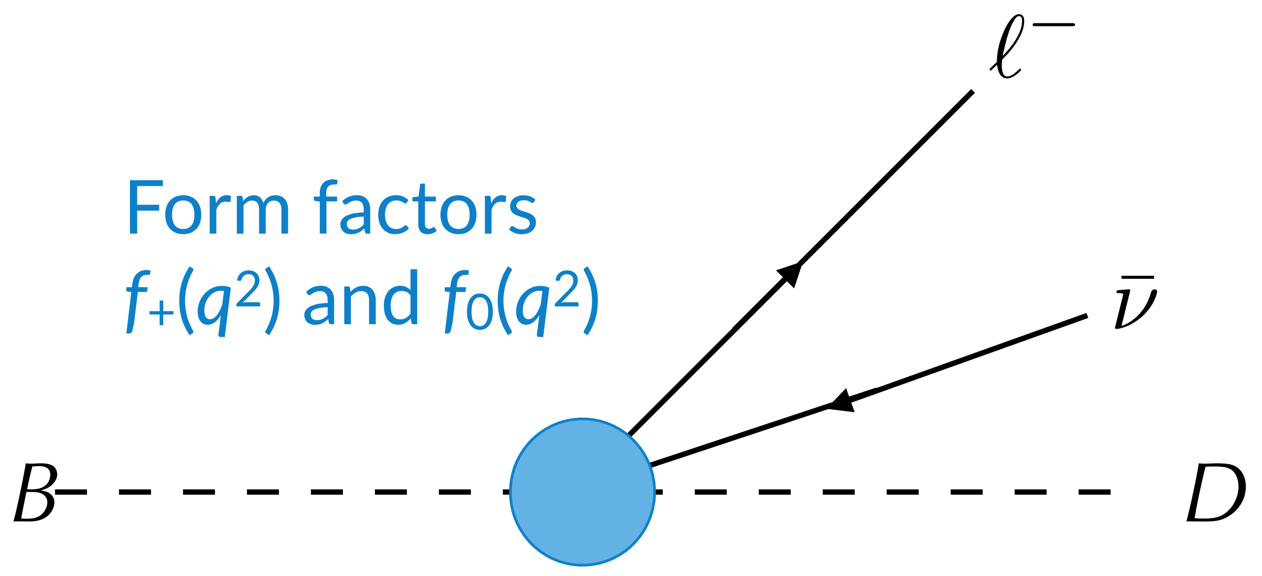
[Belle, PRD92 (2015) no.7, 072014]

Soft-photon corrections

- At large distance ($\mu < \Lambda_{\rm QCD}$), the QED interactions of the charged mesons are well described by **the scalar QED (point-like particle approximation)**

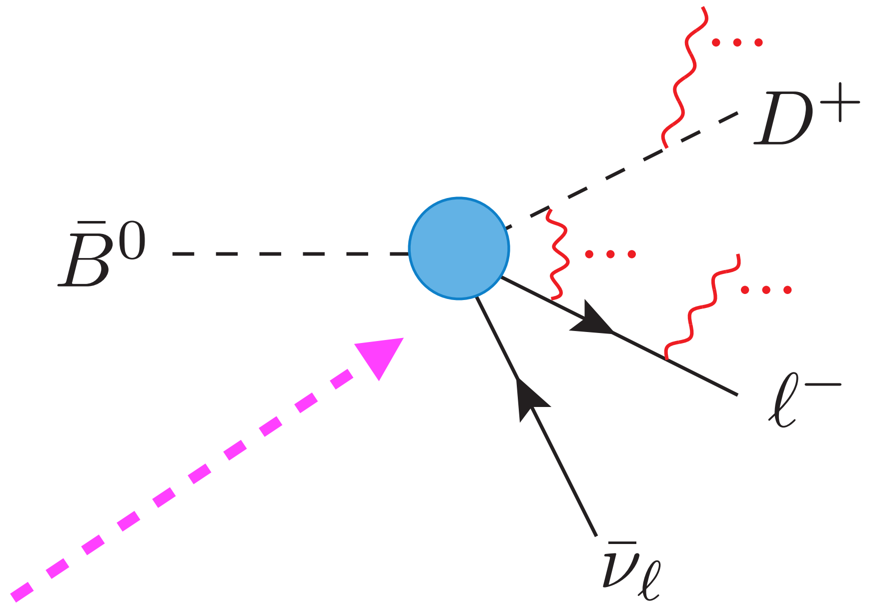


$\mu \lesssim \Lambda_{\rm QCD}$

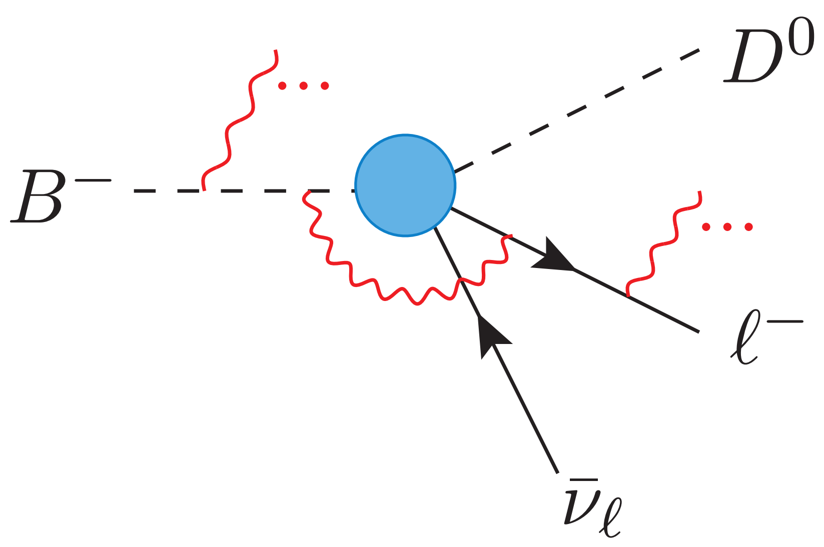


- One must distinguish neutral and charged *B* modes

Coulomb pole $\dfrac{\pi\alpha}{v_{\rm rel}}$

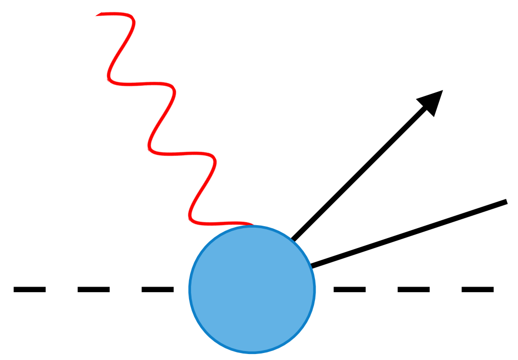


$\bar{B}^0 \to D^+ \ell \bar{\nu}$ $[R(D^+)]$



$B^- \to D^0 \ell \bar{\nu}$ $[R(D^0)]$

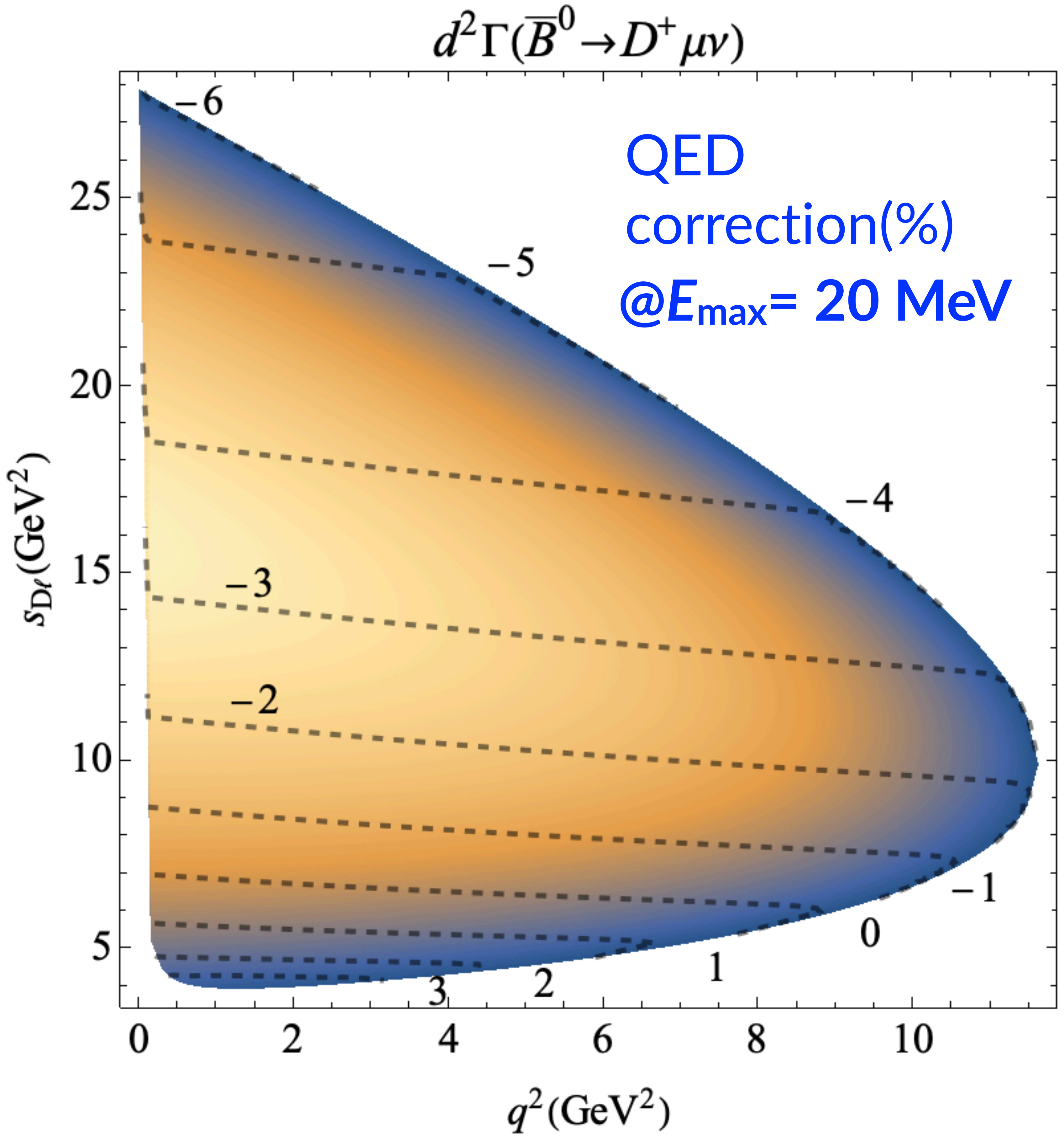
- ***BDℓνγ* vertex** (Inner-Bremsstrahlung)

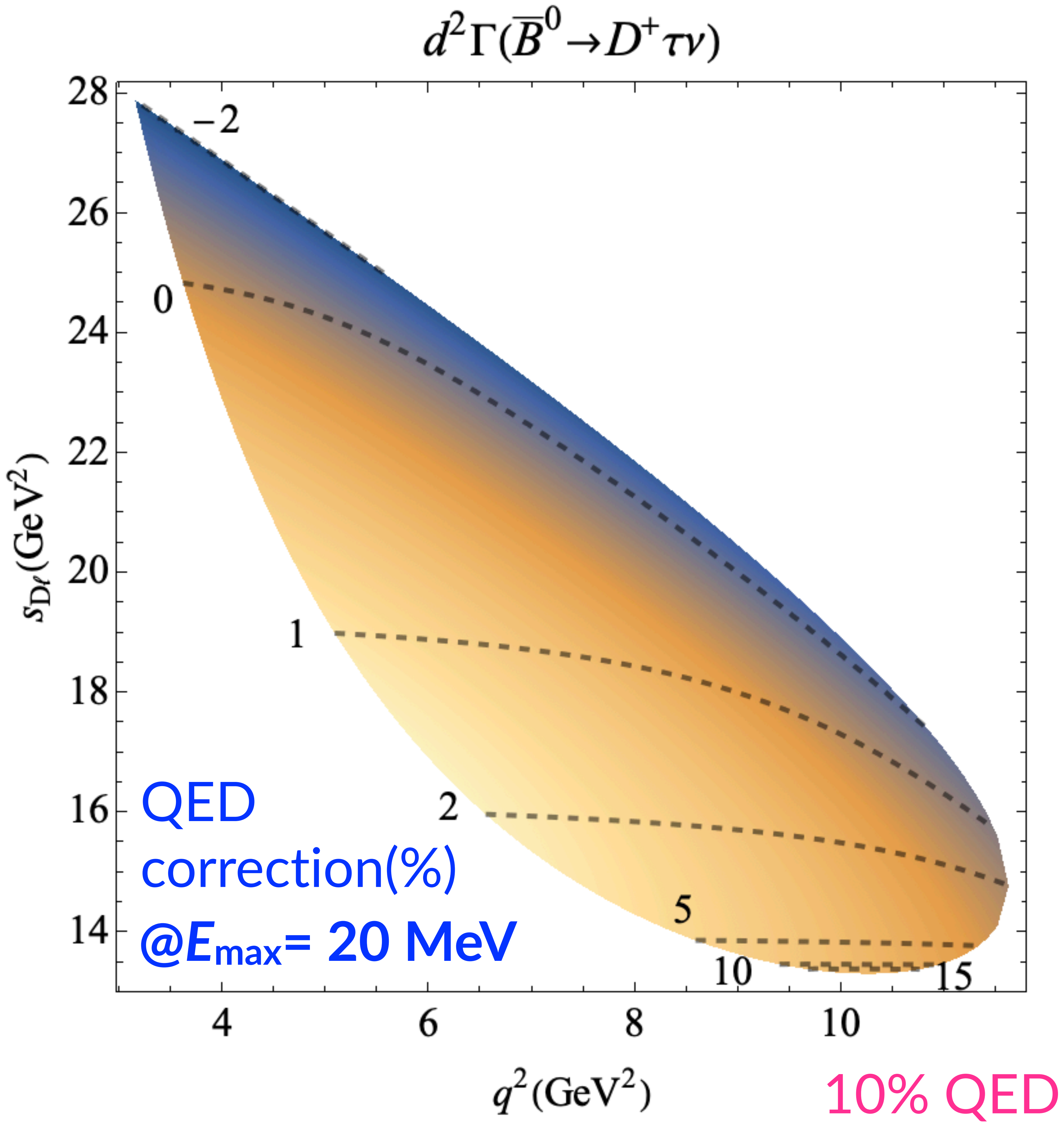


required for $U(1)_{\rm EM}$ symmetry

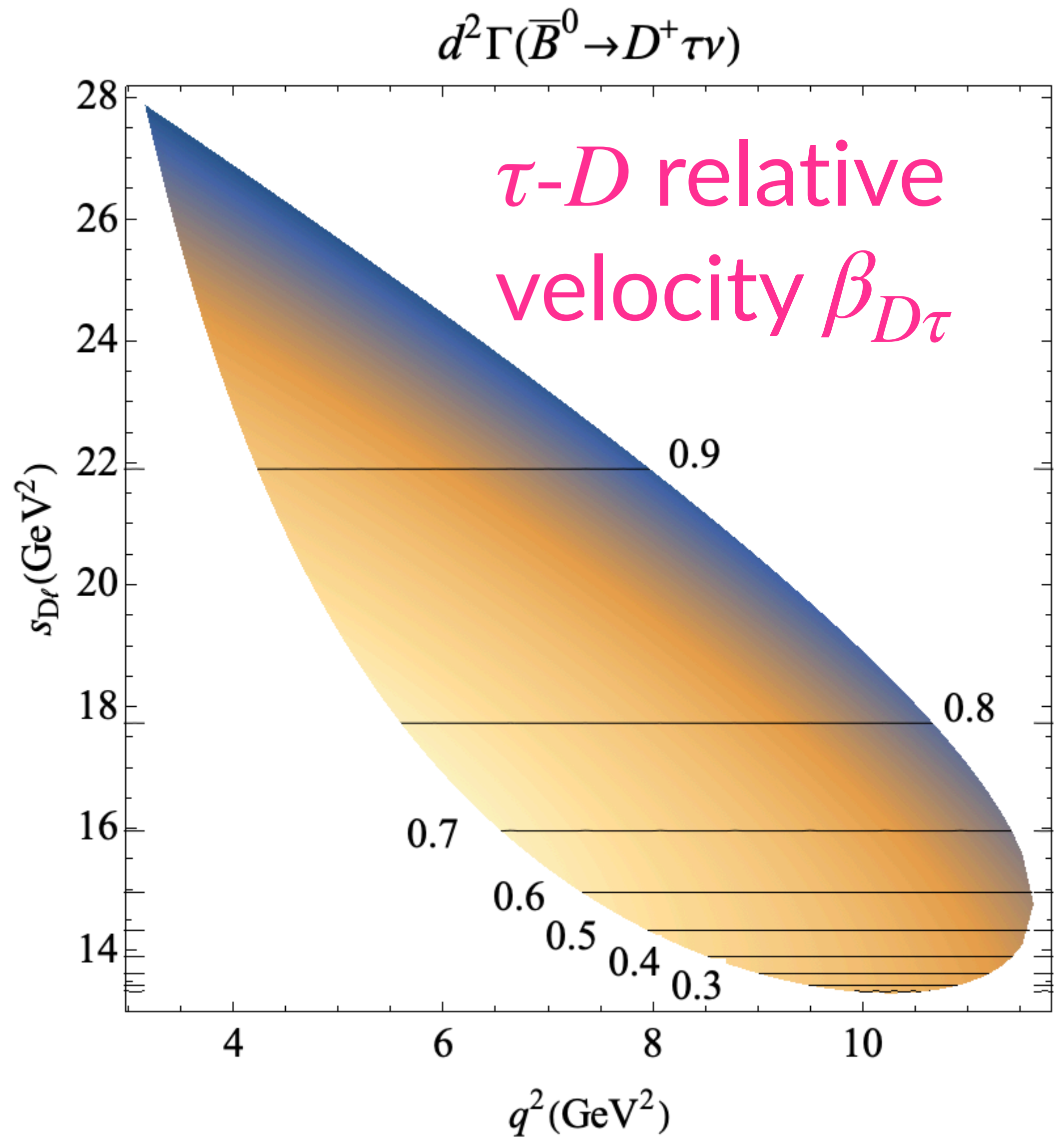
QED corrections on Dalitz plane

- **Three independent parameters: E_{max} and 2 Dalitz variables:** $q^2 = (p_B - p_D)^2,\ s_{D\ell} = (p_D + p_\ell)^2$



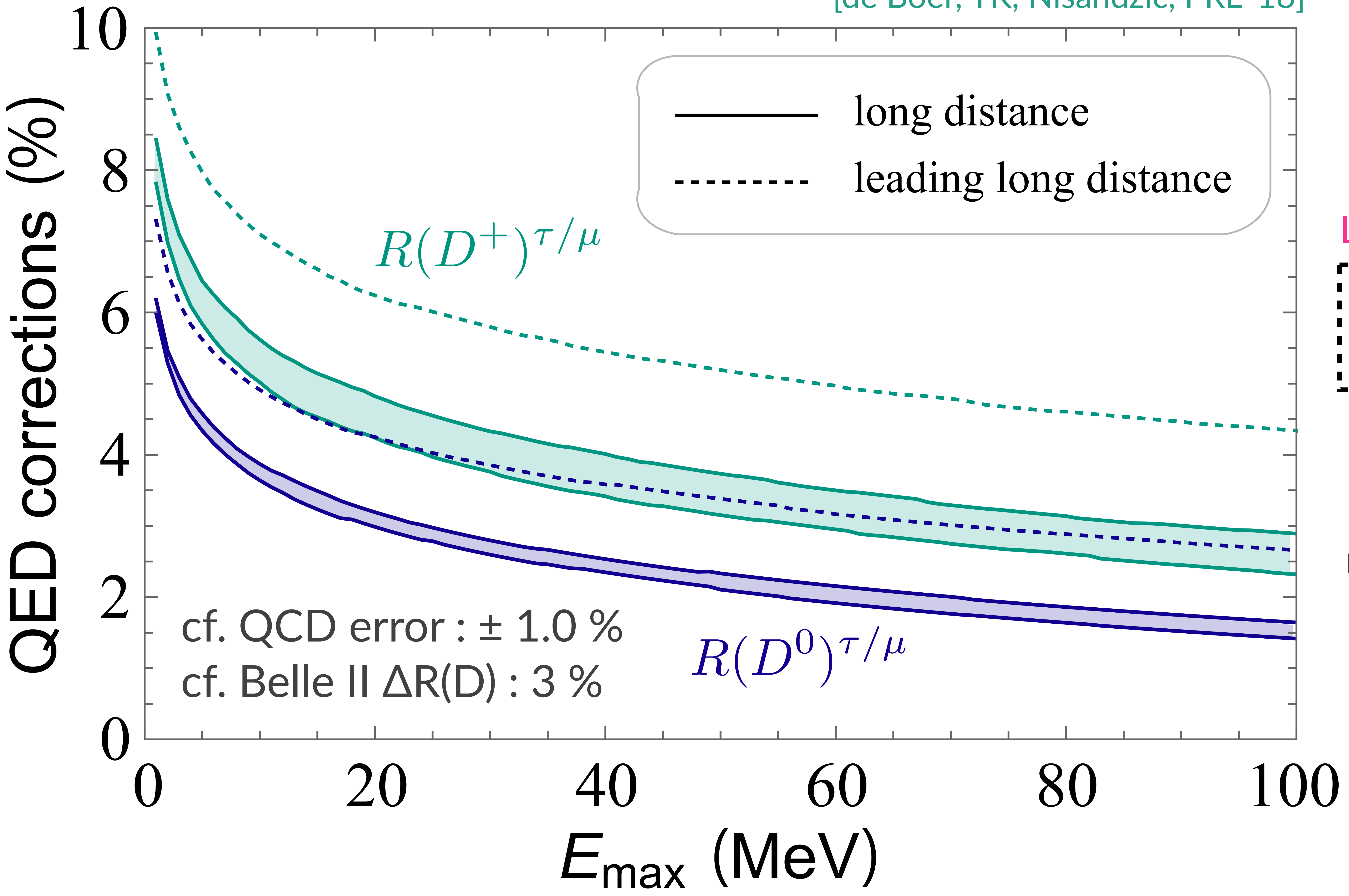


τ is non-relativistic



10% QED corrections by α/β

[de Boer, TK, Nisandzic, PRL ’18]



Leading long distance

Real emissions
+ I_{lowk_l} + self energy

= μ(UV)-independent, spin-independent

renormalization scale

100MeV < μ < 1GeV

We conclude that the QED corrections to $R(D^+)$ and $R(D^0)$ are different at 1-1.5%

PHOTOS MC simulation

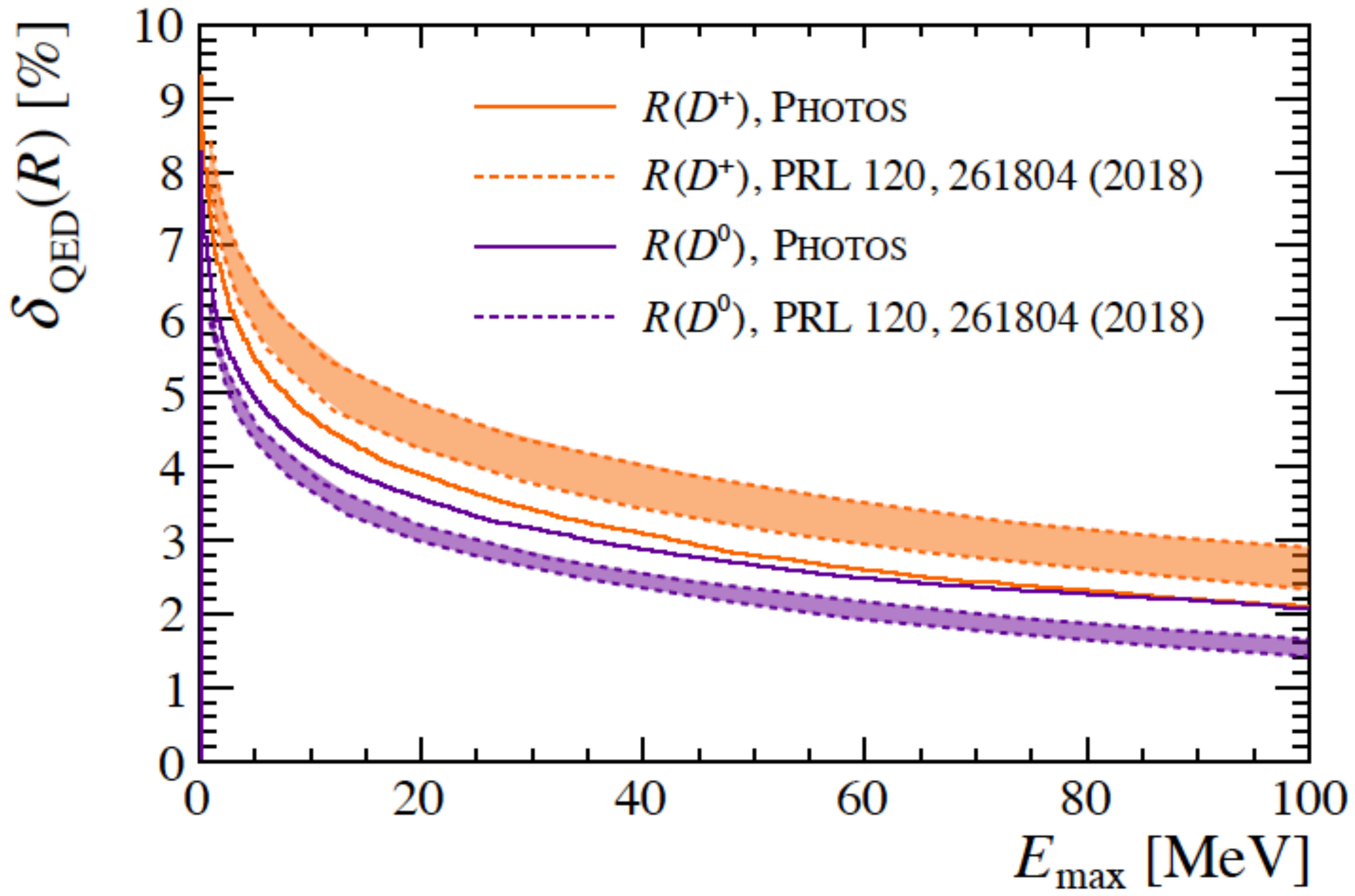
[Barberio, Eijk, Was, ’91; Barberio, Was, ‘94; Davidson, Przedzinski, Was ’16]

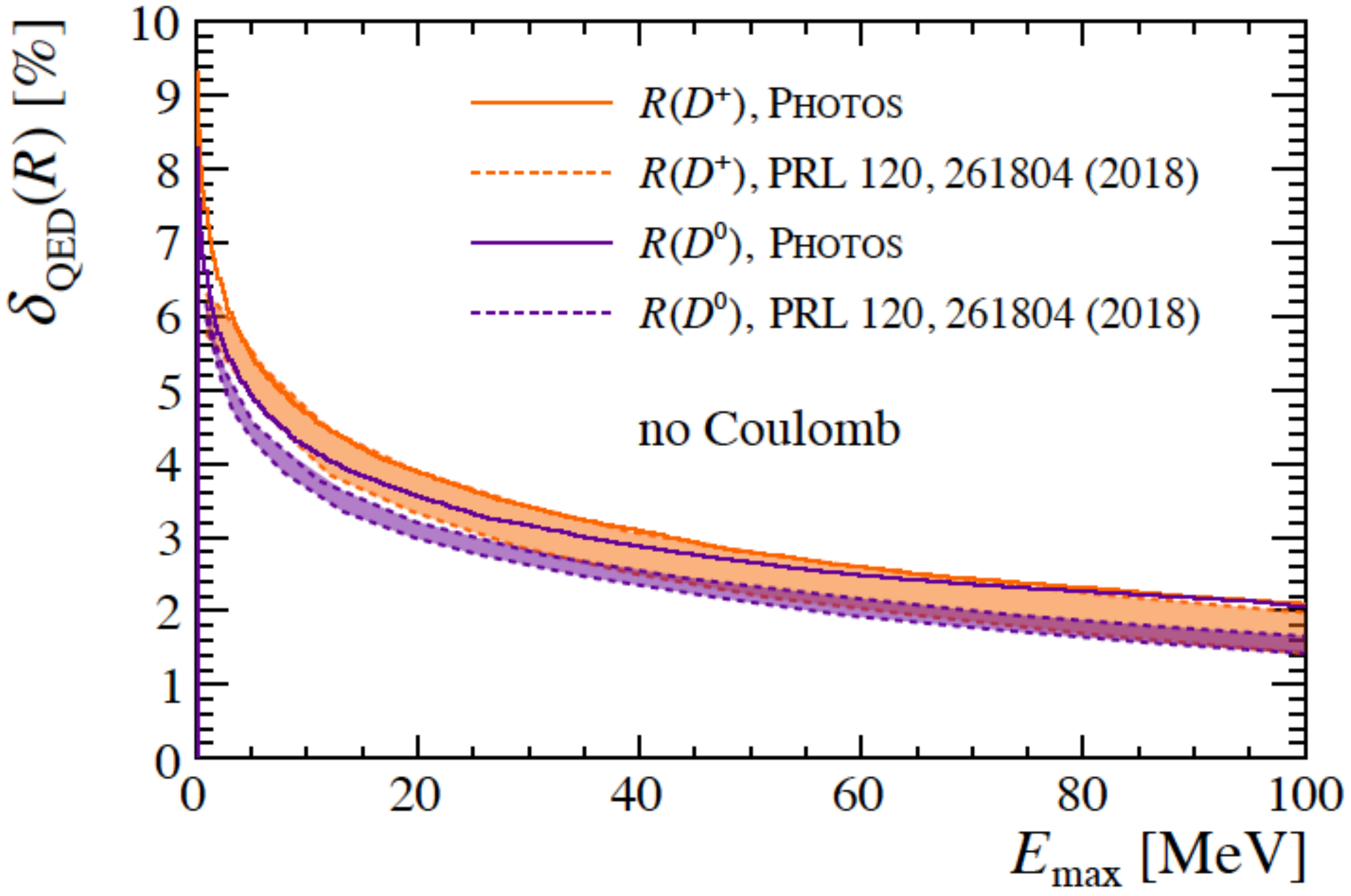
- PHOTOS Monte-Carlo generator can simulate modifications of the kinematic variables **induced by final-state photon radiations (NO initial state)** in the leading-logarithmic collinear approximation
- PHOTOS has been utilized in Belle **(v2.02)** /BaBar **(v2.13)**/LHCb **(v3.56)** for B semileptonic decay searches
- **All virtual corrections (Coulomb pole also)** are **not covered** in PHOTOS
  - **Quantum interference of** $O(E^0_{max})$ **in emissions** are **not covered** in PHOTOS (**< v2.07(single), v2.13 (multiple)**)
  - LHCb analysis *does* **include the interference of the final-state emissions**
- $O(\ln E_{max})$ contributions to $B^- \to D^0 e\bar{\nu}$ have been checked (soft E_γ and hard E_γ) by PHOTOS **v1.06** compared to analytic formula assuming constant FFs [E. Richter-Was ’93]

Crosscheck by PHOTOS

- Part of LHCb colleagues have checked the soft-photon correction by PHOTOS v.3.56

[Calí, Klaver, Rotondo, Sciascia '19]

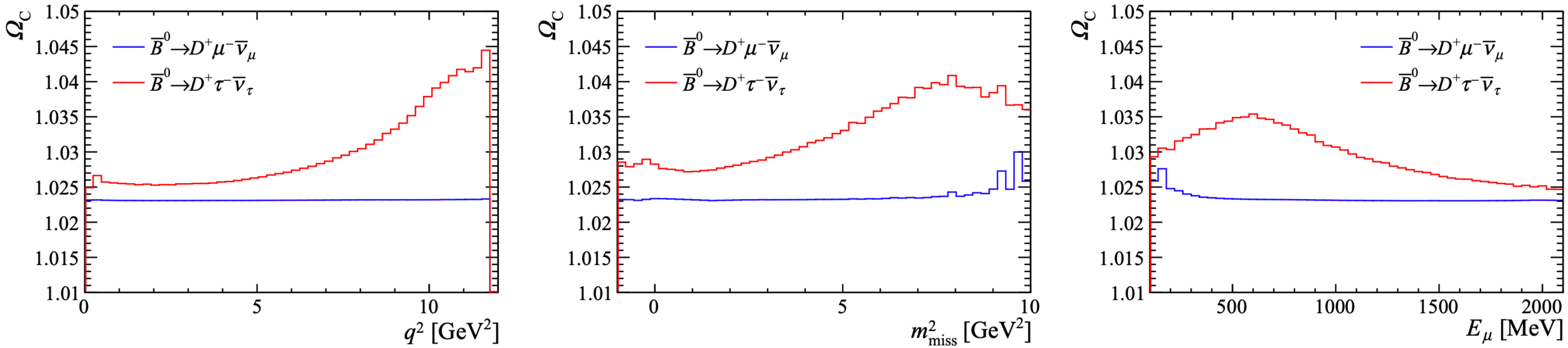




- Leading LFU-violating contribution is reproduced by PHOTOS **v.3.56 with interference switch=on**
- The small gap comes from **virtual (Coulomb) correction** which is absent in PHOTOS

Coulomb contribution

- Coulomb contribution depends on kinematics: $q^2, m^2_{\text{miss}}, E_\mu$
- Coulomb correction would give impacts on the experimental results through a change of the fit template shape [Calí, Klaver, Rotondo, Sciascia '19]



- Impacts of these modifications have not been studied yet

Polarization observables in D^* decay (into $D\pi$)

- Longitudinal D^* polarization

$$F_L\left(D^*\right) = \frac{\Gamma\left(B \to D_L^* \tau\nu\right)}{\Gamma\left(B \to D^* \tau\nu\right)}$$

- Data vs. SM

[Belle, 1903.03102]

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

$$F_L(B^0 \to D^{*-} e^+ \nu) = 0.56 \pm 0.02$$

[Alok, Kumar, Kumbhakar, Sankar '17]

$$F_L(D^*)_{\rm SM} = 0.46 \pm 0.04$$

(1.4σ)

[Bordone, Jung, van Dyk 1908.09398]

$$F_L(D^*)_{\rm SM} = 0.470 \pm 0.012$$

(1.4σ)

$$F_L(D^* e\nu)_{\rm SM} = 0.54 \pm 0.01$$

(<1σ)

- Belle II sensitivity

$$\Delta F_L(D^*) = \pm 0.01 \pm 0.04$$ (can exclude SM at >3σ level) [Adamczyk, 1901.06380]

50 ab^{-1}

Polarization observables in τ decays (into $\pi\nu$, $\rho\nu$)

- τ polarization asymmetry along the longitudinal directions of τ [Alonso, Camalich, Westhoff '17]

$$P_\tau(D^{(*)}) = \frac{\Gamma\left(B \to D^{(*)}\tau^{\lambda=+1/2}\nu\right) - \Gamma\left(B \to D^{(*)}\tau^{\lambda=-1/2}\nu\right)}{\Gamma\left(B \to D^{(*)}\tau\nu\right)}$$

- Data vs. SM

[Belle, 1612.00529, 1709.00129]	[Belle estimation, 1612.00529]	[Bordone, Jung, van Dyk 1908.09398]
$P_\tau(D)$: no reuslt	$P_\tau(D)_{\rm SM} = 0.325 \pm 0.009$	$P_\tau(D)_{\rm SM} = 0.321 \pm 0.003$
$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$	$P_\tau(D^*)_{\rm SM} = -0.497 \pm 0.013$ (<1σ)	$P_\tau(D^*)_{\rm SM} = -0.488 \pm 0.018$ (<1σ)

- Belle II sensitivity

50 ab^{-1}

$\Delta P_\tau(D) = 3\,\%$ (stat. uncertainty only) [Alonso, Camalich, Westhoff '17]

$\Delta P_\tau(D^*) = \pm 0.07$ [Belle II Physics Book, 1808.10567]

New Physics Interpretation

New physics interpretations

- New Physics above B meson scale is described model-independently by

$$H_{\rm eff}^{\rm NP} = 2\sqrt{2}G_F V_{cb}\left[\left(1 + C_V^L\right) O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\right]$$

$$\begin{aligned} O_V^L &= (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \\ O_S^R &= (\bar{c} P_R b)\,(\bar{\tau} P_L \nu_\tau) \\ O_S^L &= (\bar{c} P_L b)\,(\bar{\tau} P_L \nu_\tau) \\ O_T &= (\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau) \end{aligned}$$

- $O_V^R = (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$ is lepton flavour universal in dimension-six level
- Light right-handed neutrinos can also be included but are constrained by the collider bound

Constraint from $\mathrm{BR}(B_c \to \tau\nu)$

- Searches for $B^+_{u,c} \to \tau^+\nu$ at LEP1 set $\mathrm{BR}(B_c \to \tau\nu) < 10\,\%$ (at Z peak)
  - Scalar OPs C_S^R, C_S^L are strongly constrained via $\mathrm{BR}\,(B_c \to \tau\nu) \simeq 0.02\left|1 + C_V^L + 4.3\,(C_S^R - C_S^L)\right|^2$
- It has become clear that the original estimation misses the p_T dependence of f_c/f_u

[Blanke, Crivellin, de Boer, TK, Moscati, Nierste, Nisandzic, ’19]

From CMS and LHCb [Akeroyd, Chen ’17]

$$2.1 \times 10^{-3} \lesssim f_c \lesssim 4.4 \times 10^{-3}$$

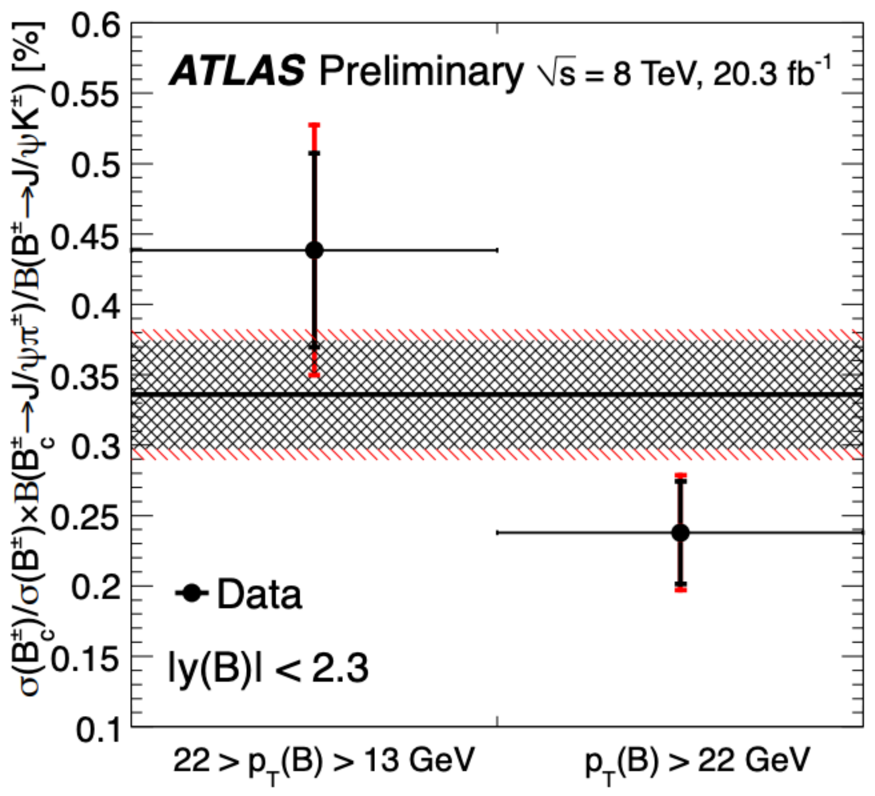
$$\longleftrightarrow \quad \frac{f_c}{f_u}\frac{\mathrm{BR}\,(B_c^- \to J/\psi\pi^-)}{\mathrm{BR}\,(B^- \to J/\psi K^-)} = (6.72 \pm 0.19) \times 10^{-3}$$

NRQCD next-to-leading order at Z peak

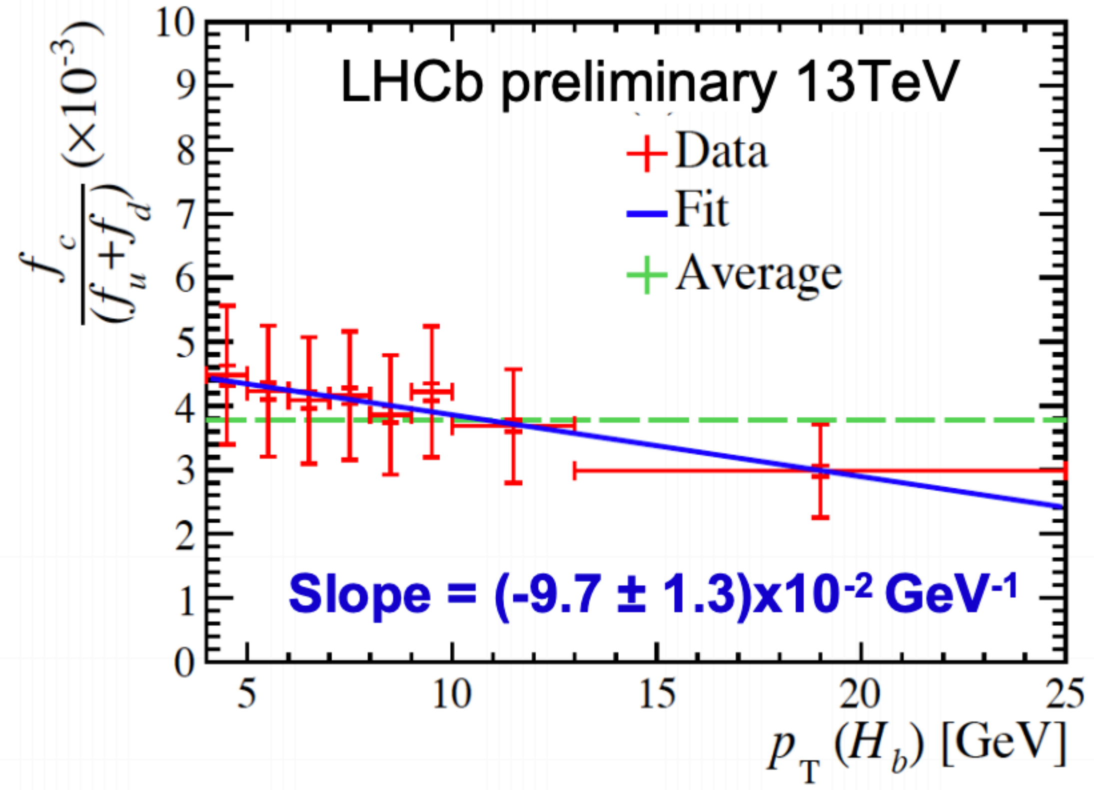
[Zheng, Chang, Feng, Pan '18, Zheng, Chang, Feng, Wu '19]

$$f_c \sim 6 \times 10^{-4}$$

p_T dependence of f_c/f_u from ATLAS and LHCb



[See Konstantin Toms talk]



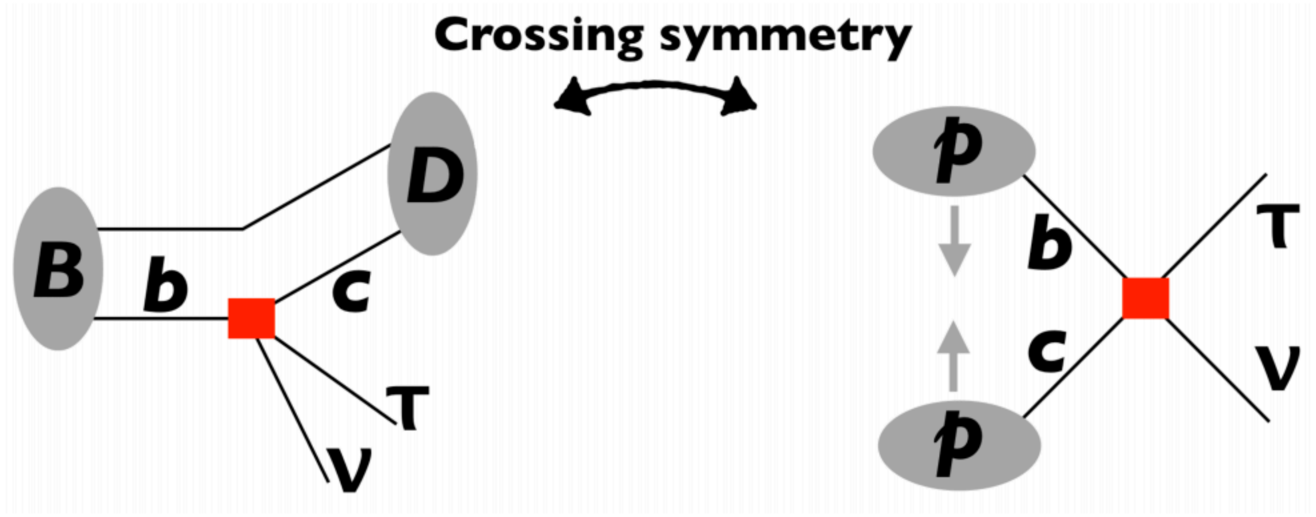
[See Marcello Rotondo talk]

Constraint from $pp \to \tau\nu$

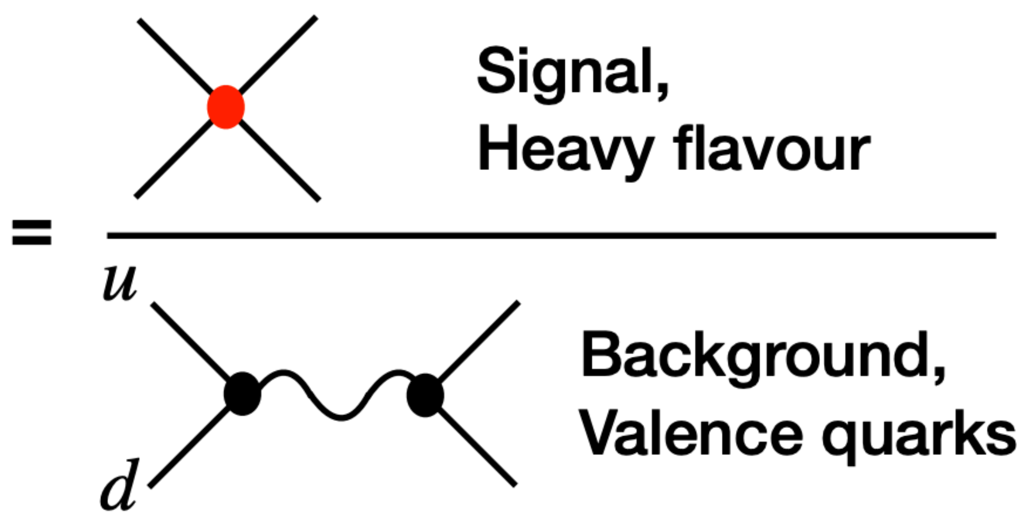
- The constraint $\mathrm{BR}(B_c \to \tau\nu) < 10\,\%$ seems to be overestimated by a factor AT LEAST 3. Now, the constraint from $\mathrm{BR}(B_c \to \tau\nu)$ is no longer the strongest one

- The strongest constraint comes from collider search: high-p_T tails in mono-τ searches

[Greljo, Camalich, Ruiz-Alvarez '19]



$$\frac{\Delta\sigma}{\sigma} \sim \frac{\mathrm{L}_{ij} \times |V_{ij}|^2 \times \left(\frac{m_W^2}{\hat{s}} - C_S^L\right)^2}{\mathrm{L}_{ud+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{m_W^2}{\hat{s}}\right)^2}$$



2σ upper bound at $\mu = m_b$

$$|C_V^L| < 0.32, \quad \left|C_S^{L(R)}\right| < 0.57, \quad |C_T| < 0.16$$

Tensor operator vs. $F_L(D^*)$

- Tensor operator in new physics scenario is significantly constrained by $F_L(D^*)$

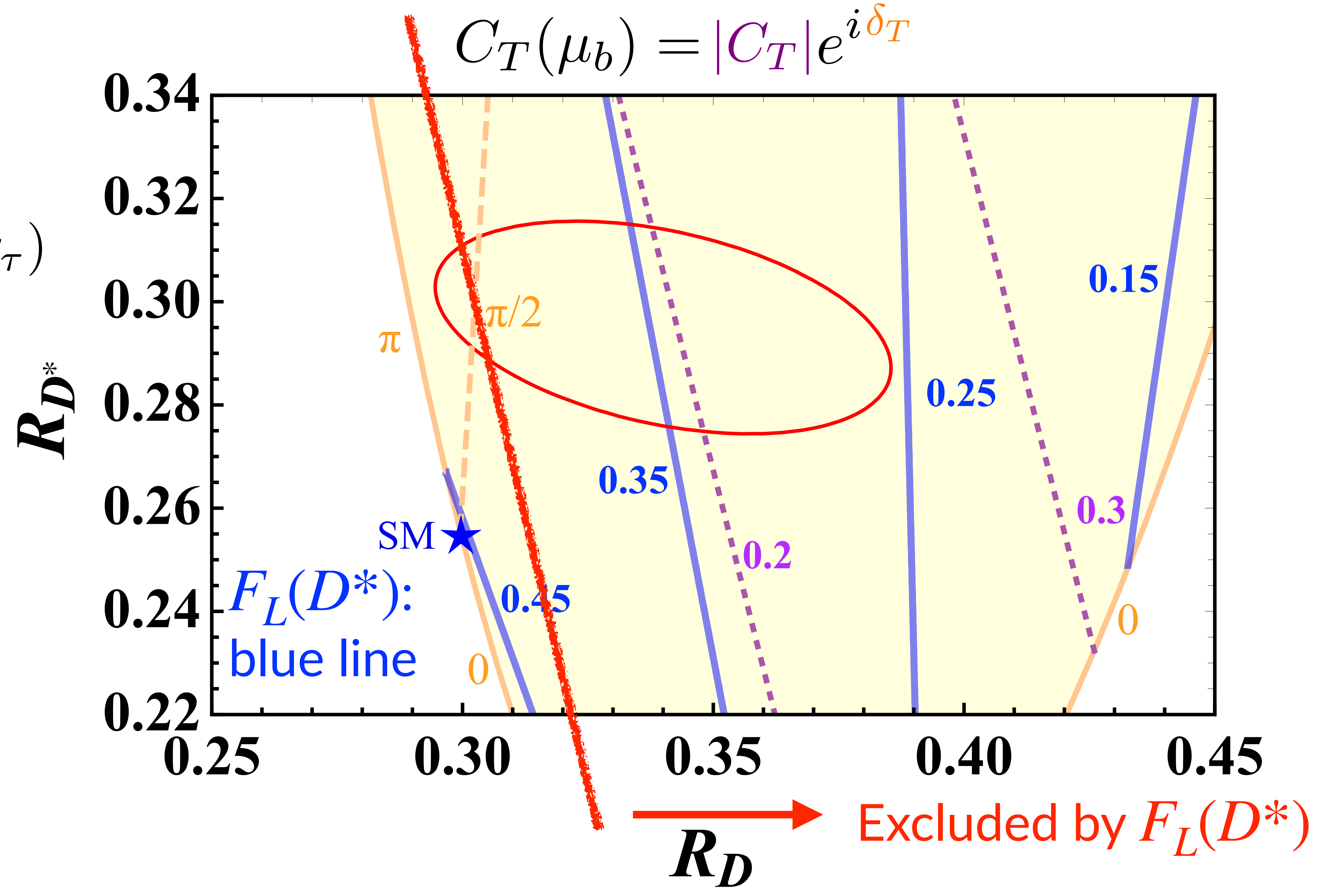
$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V_{cb} C_T(\mu) \, (\bar{c}\sigma^{\mu\nu} P_L b) \, (\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau)$$

$$C_{T,\,\rm SM} = 0$$

$$F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

[Belle, 1903.03102]

[Iguro, TK, Omura, Watanabe, Yamamoto, '19, UPDATED]



"Single particle" scenarios

- One WC scenarios

C_V^L	W', left-handed SU(2)$_L$-singlet vector LQ, SU(2)$_L$-triplet and/or -singlet scalar LQ
C_S^R	Charged Higgs, SU(2)$_L$-doublet vector LQ (V_2)
C_S^L	Charged Higgs with generic flavour structure
$C_S^L = 4C_T$	scalar SU(2)$_L$-doublet LQ (R_2) ("4" is modified by RG evolution)

- Two WCs scenarios

$(C_V^L, C_S^L = -4C_T)$	SU(2)$_L$-singlet scalar LQ (S_1)
(C_V^L, C_S^R)	SU(2)$_L$-singlet vector LQ (U_1)
(C_S^R, C_S^L)	Charged Higgs with generic flavour structure
(Re($C_S^L = 4C_T$), Im($C_S^L = 4C_T$))	scalar SU(2)$_L$-doublet LQ (R_2)

- There are so many detailed studies for **each** single particle scenarios
- There are also "two particle" scenarios [See Nejc Košnik talk]

[Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic ’19]

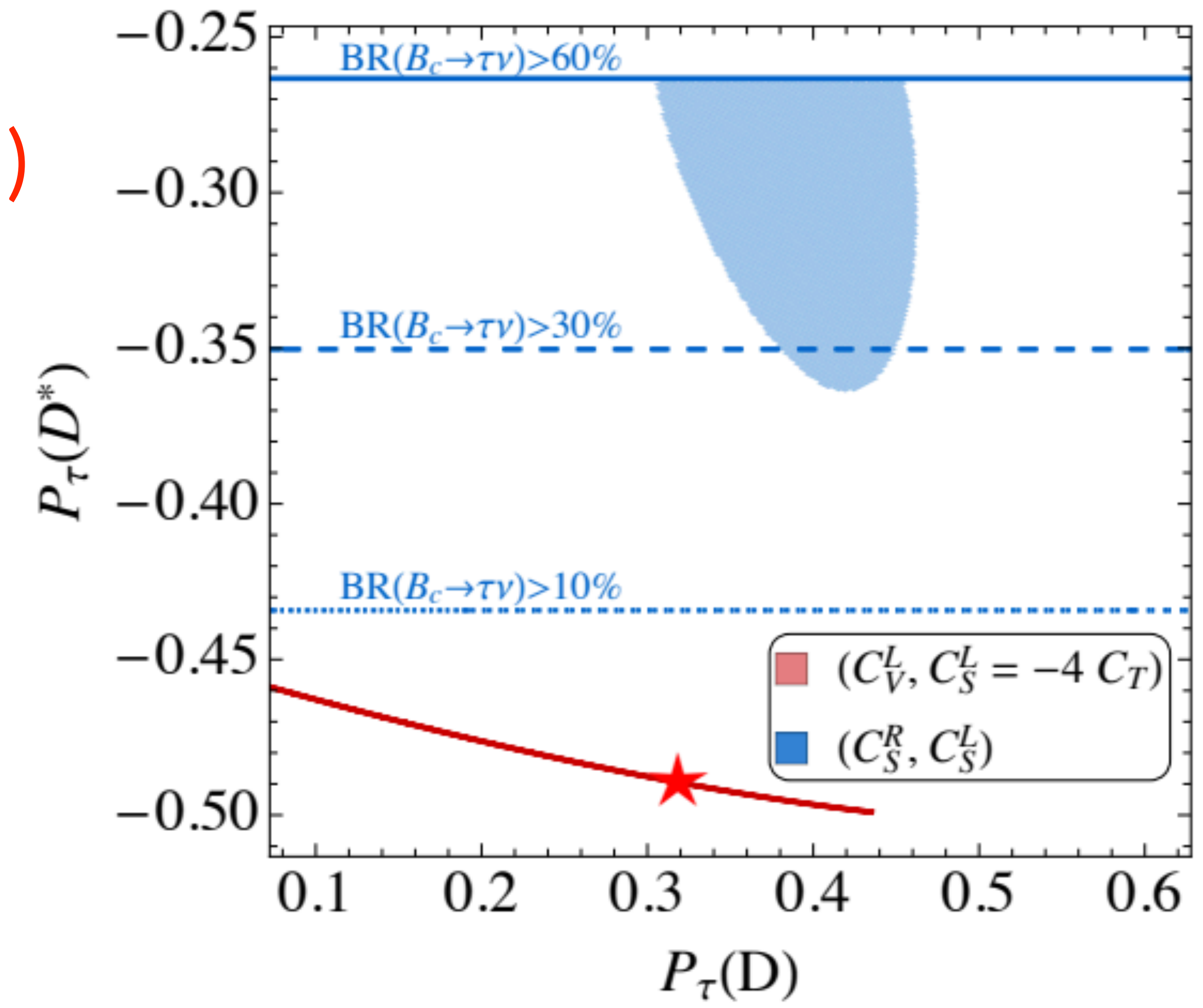
SU(2)L-singlet scalar LQ (S_1)

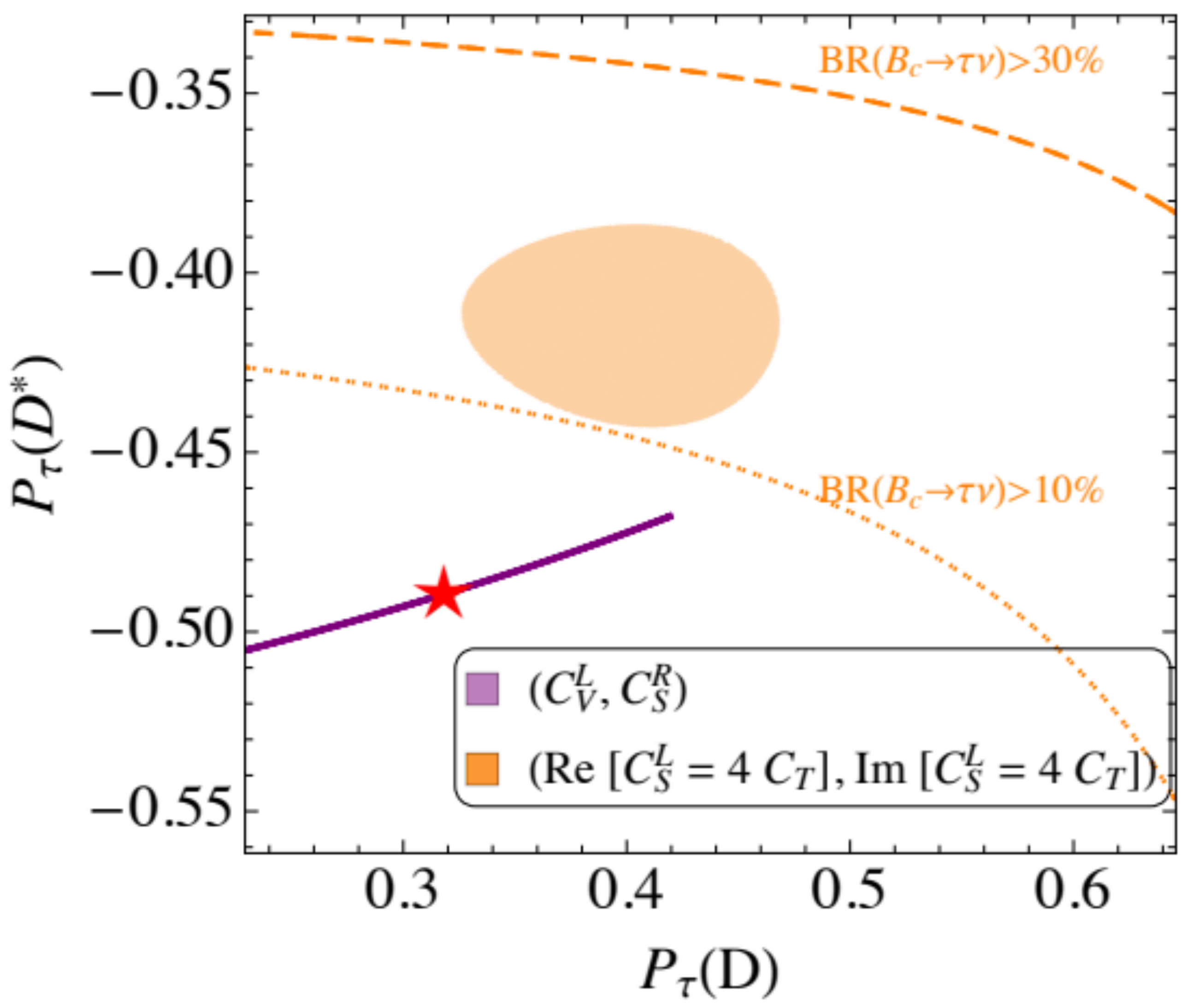
Charged Higgs

SU(2)L-singlet vector LQ (U_1)

SU(2)L-doublet scalar LQ (R_2)

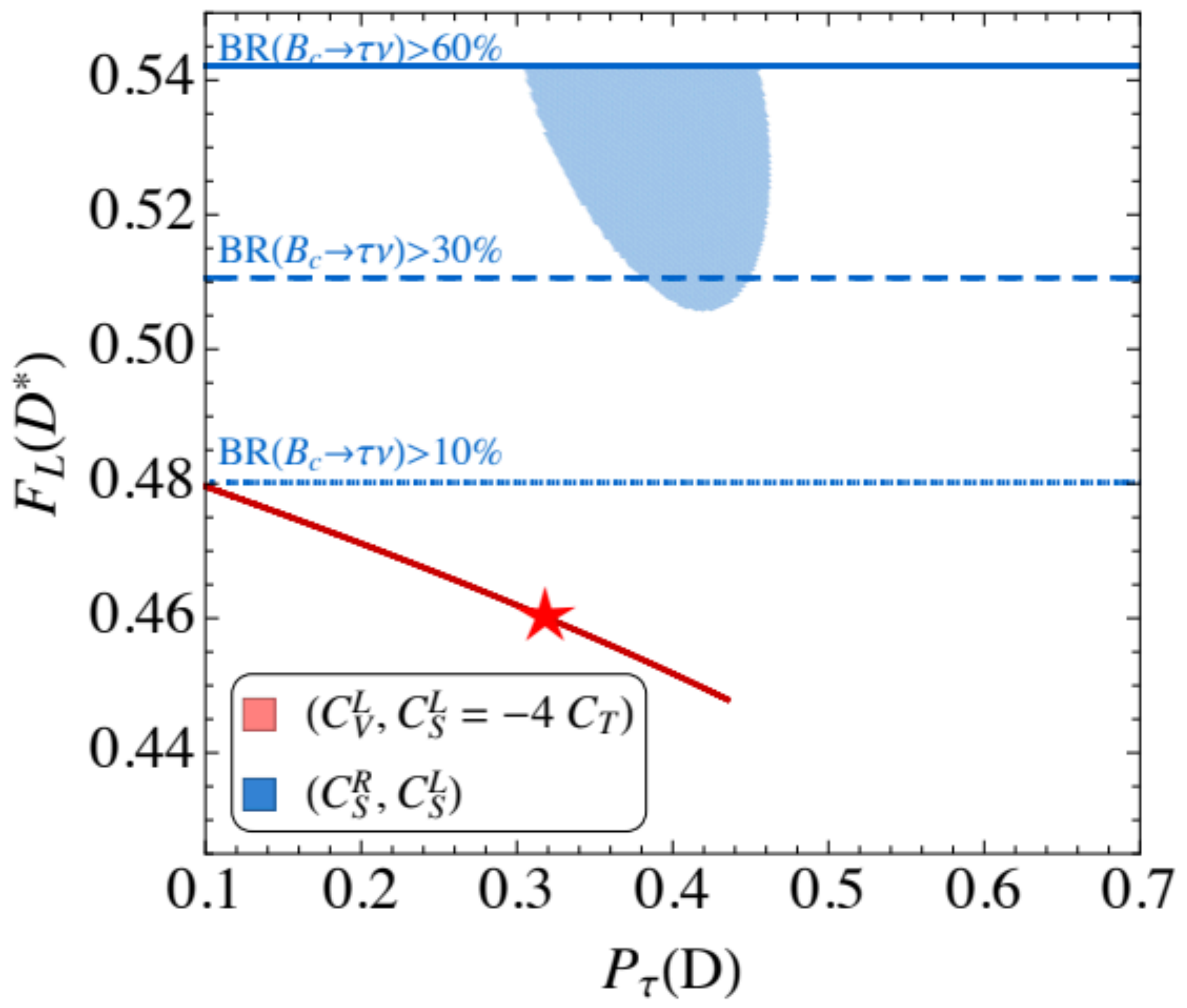
$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{P_\tau(D^*)}$

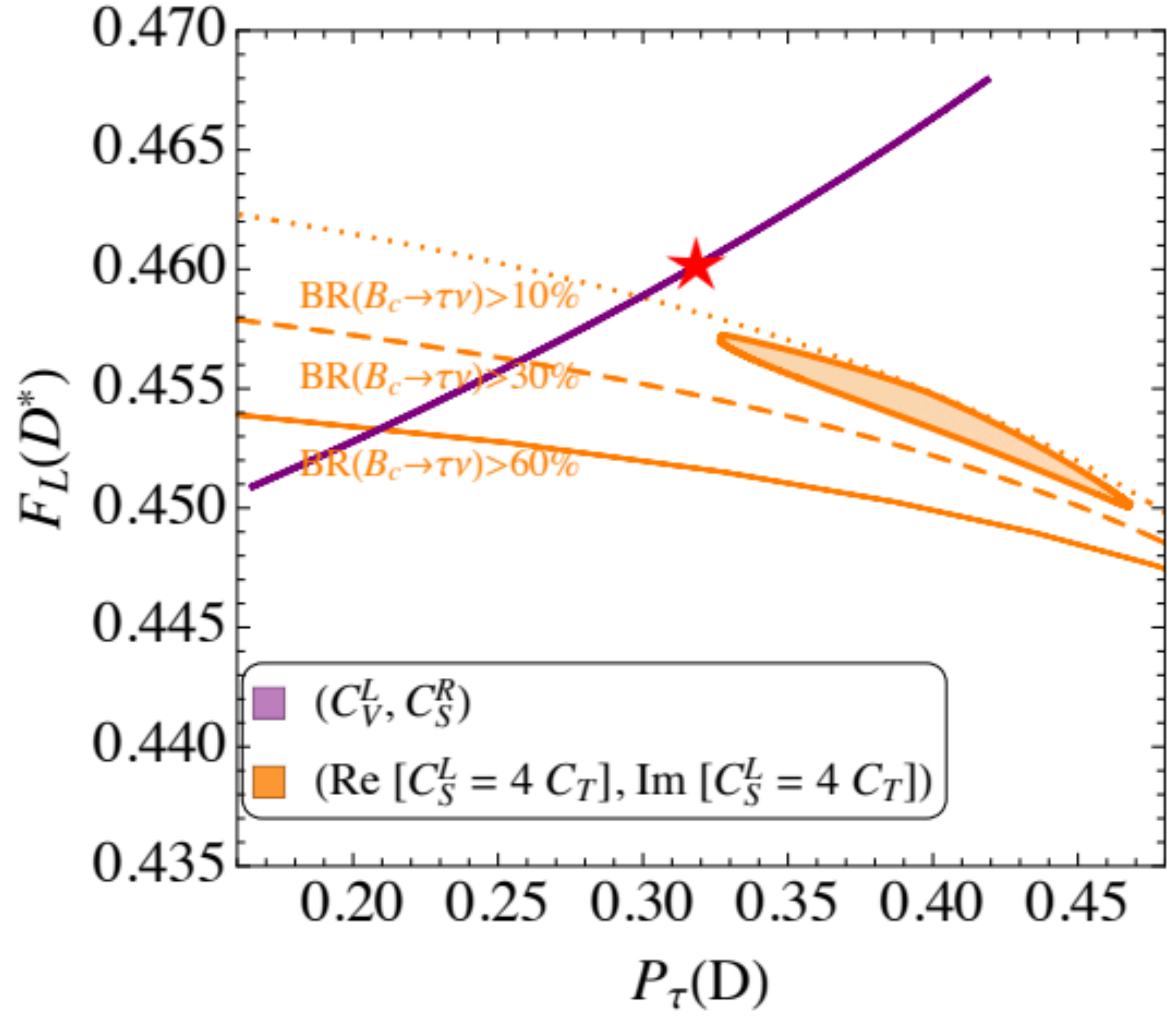




$P_\tau(D)$ can discriminate the new physics

$\boldsymbol{P_\tau(D)}$ vs. $\boldsymbol{F_L(D^*)}$





$P_\tau(D^*)$ could discriminate the new physics

$F_L(D^*)$ is difficult to discriminate them

Predicted ranges of polarization observables

- Full parameter searches of each LQ model. LHC mono-τ search [Greljo, Martin Camalich, Ruiz-Alvarez '19] and $\mathrm{BR}(B_c^+ \to \tau^+\nu) < 30\,\%$ [Alonso, Grinstein, Martin Camalich '17] are included

[Iguro, TK, Omura, Watanabe, Yamamoto '19, UPDATED]

[Predicted ranges]

	$F_L^{D^*}$	P_τ^D	$P_\tau^{D^*}$	R_D	R_{D^*}
R_2 LQ	[0.442, 0.447]	[0.336, 0.456]	[−0.464, −0.424]	$1\,\sigma$ data	$1\,\sigma$ data
S_1 LQ	[0.436, 0.481]	[−0.006, 0.489]	[−0.512, −0.450]	$1\,\sigma$ data	$1\,\sigma$ data
U_1 LQ	[0.440, 0.459]	[0.156, 0.422]	[−0.542, −0.488]	$1\,\sigma$ data	$1\,\sigma$ data
SM	0.46(4)	0.325(9)	−0.497(13)	0.299(3)	0.258(5)
data	0.60(9)	-	−0.38(55)	**0.340(30)**	**0.295(14)**
Belle II [50 ab^{-1}]	0.04	3%	0.07	3%	2%

- $P_\tau(D)$ can discriminate the new physics

- LHC mono-τ search gives more severe bound than $\mathrm{BR}(B_c^+ \to \tau^+\nu) < 30\,\%$

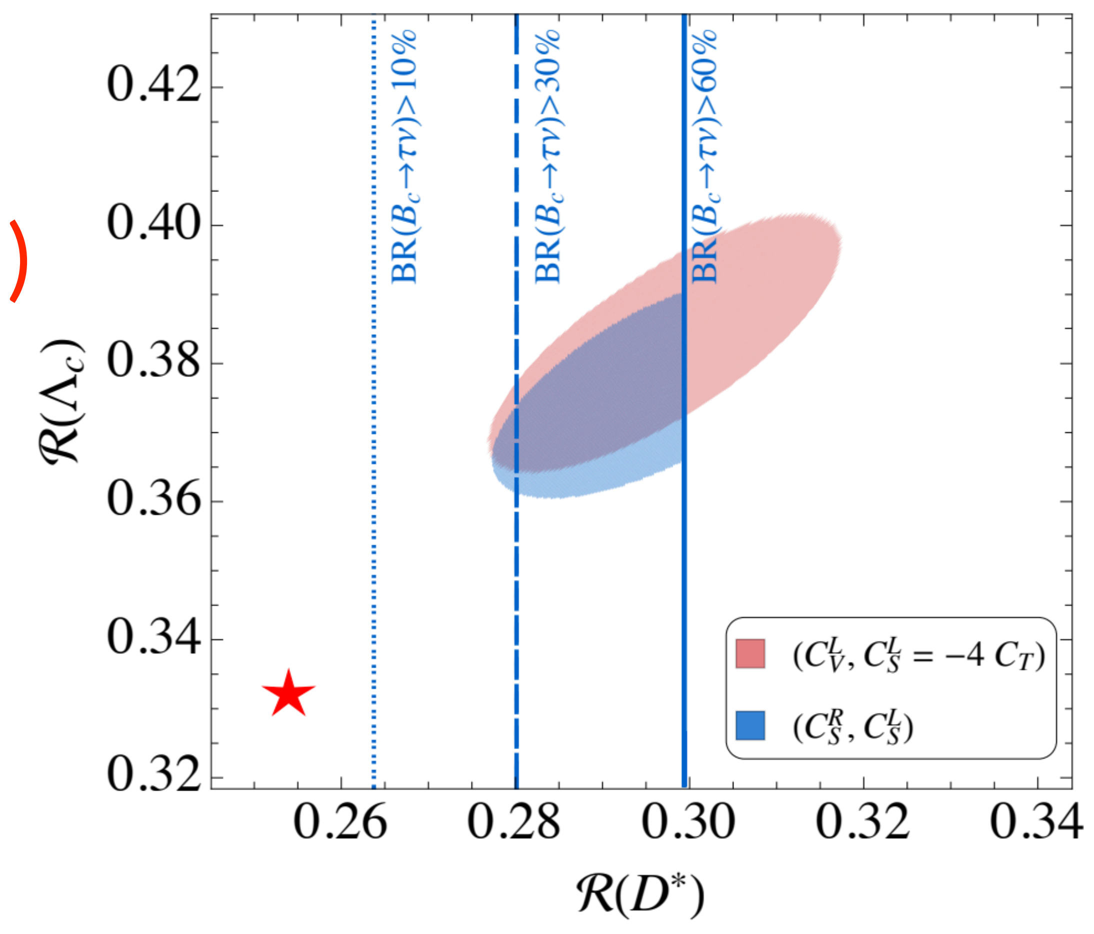
Model-independent prediction: $R(\Lambda_c)$

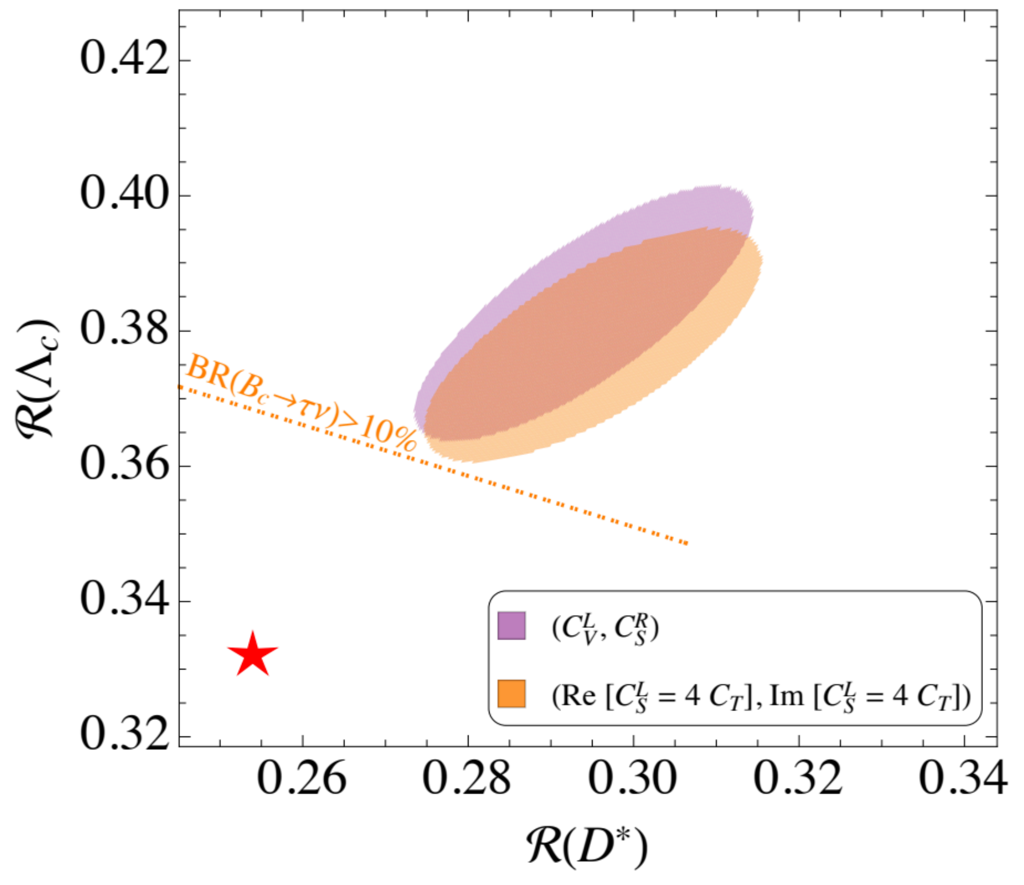
- $R(\Lambda_c) = \mathrm{BR}(\Lambda_b \to \Lambda_c \tau\nu)/\mathrm{BR}(\Lambda_b \to \Lambda_c \ell\nu)$ @ LHCb [Blanke, Crivellin, TK, Moscati, Nierste, Nisandzic '19]

Motivated two WCs scenarios

SU(2)$_L$-singlet scalar LQ (S_1)

Charged Higgs





SU(2)$_L$-singlet vector LQ (U_1)

SU(2)$_L$-doublet scalar LQ (R_2)

Similar ellipses!

- Sum rule for $R(\Lambda_c)$ prediction [Blanke, Crivellin, de Boer, TK, Moscati, Nierste, Nisandzic, '19]

Model-independent sum rule
(also valid for RH neutrino)

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.26\frac{R(D)}{R(D)_{\rm SM}} + 0.74\frac{R(D^*)}{R(D^*)_{\rm SM}}$$

$$R(\Lambda_c) = 0.38 \pm 0.01_{R(D^{(*)})} \pm 0.01_{\rm FF}$$

[Detmold, Lehner, Meinel '15] $R(\Lambda_c)_{\rm SM} = 0.33 \pm 0.01$

Crosscheck of $R(D^{(*)})$ anomaly is possible by $R(\Lambda_c)$

There is no data yet, but soon?

Conclusions

- SM expected values for $B \to D^{(*)}$ transitions are improved: $\mathcal{O}(1/m_c^2)$
- Soft-photon corrections depend on lepton's **mass** and **velocity** and hence **can violate lepton flavor universality**, which is also reproduced by PHOTOS v.3.56 with interference switch=on up to Coulomb contributions
- Polarisation observables, especially $P_\tau(D)$, are well suited to distinguish among different EFT scenarios
- $\Lambda_b \to \Lambda_c \tau \nu$ provides experimental cross-check of $R(D^{(*)})$ anomaly