Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle

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Mini-workshop on D(*)τν and related topics, Nagoya University

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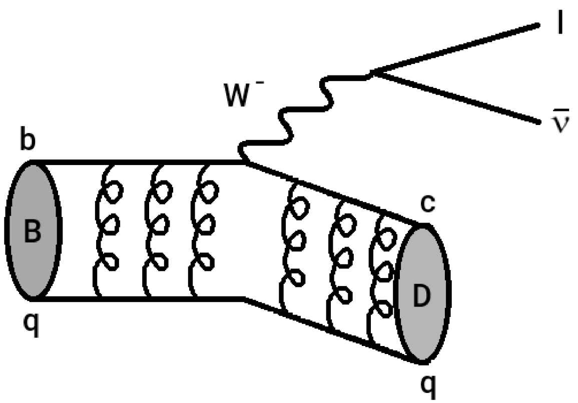

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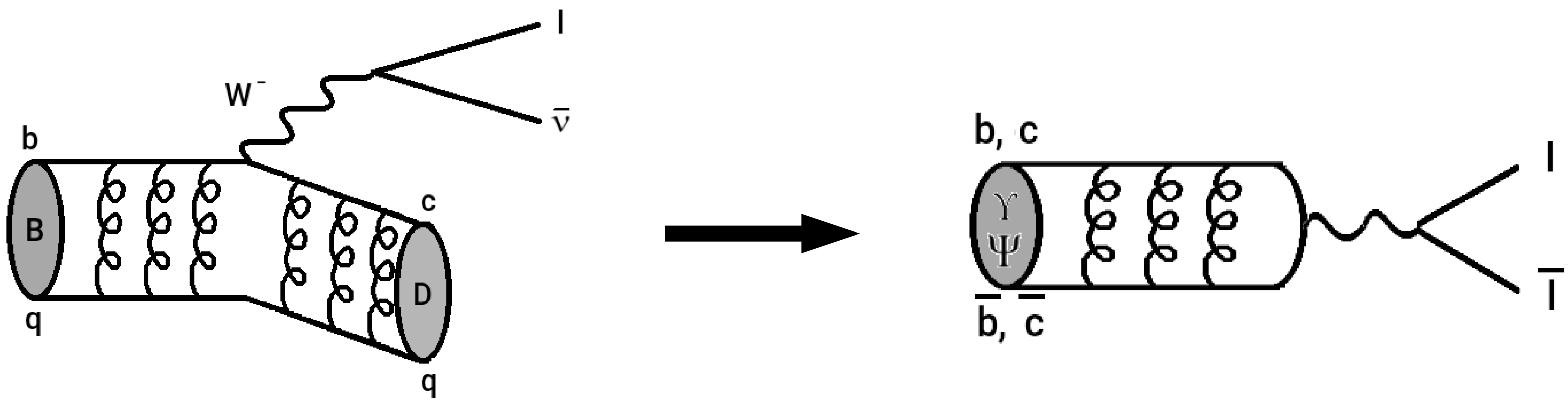

Outline

- Introduction – The $R(D^{(*)})$ puzzle
- The EFT and emergence of neutral currents
- Vector meson decays
- Implications of EFT on LFU violation in Υ and ψ decays
- Future prospects
- Summary

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The effective field theory

EFT – complete basis

- Demand $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance
- Assume no RH neutrinos, *i.e.* $B \to D\tau\bar{\nu}_L$
- A complete set for $b \to c\tau\bar{\nu}$ transitions contains only four operators
  - $(\bar{e}L)(\bar{u}Q)$
  - $(\bar{e}\sigma^{\mu\nu}L)(\bar{u}\sigma_{\mu\nu}Q)$
  - $(\bar{L}\gamma^{\mu}\tau_a L)(\bar{Q}\gamma^{\mu}\tau_a Q)$
  - $(\bar{Q}d)(\bar{e}L)$

EFT – unavoidable NC

- All four operators contain also neutral currents (NC)
  - ➔ For instance

$$(\bar{e}L)(\bar{u}Q) = \overbrace{(\bar{e}_R \nu_L)(\bar{u}_R d_L)}^{CC} - \overbrace{(\bar{e}_R e_L)(\bar{u}_R u_L)}^{NC}$$

- We looked for observables sensitive to those NC

- Neutral currents unavoidably modify $b\bar{b}, c\bar{c} \to \tau\bar{\tau}$

EFT – NC observables

- *D. A. Faroughy, A. Greljo, J. F. Kamenik* * – High P_T distribution of $\tau\bar{\tau}$ signature at the LHC (tomorrow)

- We looked on lepton non universality of Υ and ψ decays

$$R^V_{\tau/\ell} \equiv \frac{\Gamma(V \to \tau^+\tau^-)}{\Gamma(V \to \ell^+\ell^-)}, \quad (V = \Upsilon, \psi(2s);\ \ell = e, \mu)$$

- Wilson coefficients are evaluated at the same scale

* *D. A. Fraoughy, A. Greljo, J. F. Kamenik*, ***Phys. Lett. B764 (2017) 126-134***

Vector meson decay

Vector meson decay - SM

- Within the SM

$$R^V_{\tau/\ell} \simeq (1 + 2x_\tau^2)(1 - 4x_\tau^2)^{1/2}$$

where $x_\tau = m_\tau / m_V$.

- Dominantly QED – 1 photon exchange

- For $\ell = e, \mu$ we take $x_\ell = 0$

Vector meson decay – SM corrections

- Within the SM

$$R^V_{\tau/\ell} \simeq (1+2x_\tau^2)(1-4x_\tau^2)^{1/2}$$

where $x_\tau = m_\tau/m_V$.

- Leading corrections:
  - Corrections due to m_μ are $\delta R^V_{\tau/\ell} \lesssim \mathcal{O}(10^{-7})$
  - Corrections due to Z exchange are $\delta R^V_{\tau/\ell} \lesssim \mathcal{O}(10^{-5})$
  - QED at 1-loop $\delta R^V_{\tau/\ell} \simeq 6 \cdot 10^{-3}\, x_\tau^2 \sim \mathcal{O}(10^{-4})$ (inclusive)

$R^{V}_{\tau/\ell}$ - Prediction vs. measurement

$V(nS)$	SM prediction	Exp. value $\pm\sigma_{\rm stat} \pm \sigma_{\rm syst}$
$\Upsilon(1S)$	$0.9924 \pm \mathcal{O}(10^{-5})$	$1.005 \pm 0.013 \pm 0.022$
$\Upsilon(2S)$	$0.9940 \pm \mathcal{O}(10^{-5})$	$1.04 \pm 0.04 \pm 0.05$
$\Upsilon(3S)$	$0.9948 \pm \mathcal{O}(10^{-5})$	$1.05 \pm 0.08 \pm 0.05$
$\psi(2S)$	$0.390 \pm \mathcal{O}(10^{-4})$	0.39 ± 0.05

Vector meson decay – dim(6) operators

- Nine independent dim.(6) operators contribute to leptonic meson decays

$$\mathcal{L}_{\ell q} = C^{q\ell}_{VRR}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_R\gamma_\mu q_R) + C^{q\ell}_{VRL}(\bar{e}_R\gamma^\mu e_R)(\bar{q}_L\gamma_\mu q_L)$$
$$+ C^{q\ell}_{VLR}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_R\gamma_\mu q_R) + C^{q\ell}_{VLL}(\bar{e}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu q_L)$$
$$+ C^{q\ell}_{T}(\bar{e}_L\sigma^{\mu\nu} e_R)(\bar{q}\sigma_{\mu\nu} q) + \text{h.c. } (+\text{scalar operators})$$

- A straightforward calculation relates the 9 Wilson coefficient $C^{q\ell}_A$ to 4 form factors appearing in the ratio

$$R^V_{\tau/\ell} \simeq \frac{\sqrt{1-4x_\tau^2}}{(4\pi\alpha Q_q)^2}\left[|\tilde{A}^{q\tau}_V|^2\left(1+2x_\tau^2\right) + |\tilde{B}^{q\tau}_V|^2\left(1-4x_\tau^2\right) + \frac{|\tilde{C}^{q\tau}_V|^2}{2}\left(1-4x_\tau^2\right)^2 + \frac{|\tilde{D}^{q\tau}_V|^2}{2}\left(1-4x_\tau^2\right) + 2\mathrm{Re}\left[\tilde{A}^{q\tau}_V\tilde{C}^{*q\tau}_V\right]x_\tau\left(1-4x_\tau^2\right)\right]$$

Daniel Aloni, Arxiv: **1702.07356**

Connecting charge currents to neutral currents

The need for assumptions

- There are four independent CC operators
- There are nine independent NC operators
- CC + Gauge invariance $\longrightarrow$ NC
  - ➔ Not enough measurements to fix the values of the Wilson coefficients of the four CC operators *
  - ➔ No information on the other five NC operators

** D. Bardhan, P. Byakti, D. Ghosh,* ***JHEP 1701****, 125 (2017)*

EFT from simplified models

- Recall that
  - ➔ Within the SM $b \to c\tau\bar{\nu}$ is a tree-level process
  - ➔ Central value is ~ 30% enhanced compared to prediction
- Huge enhancement of tree-level suggests new bosons which also modify $b \to c\tau\bar{\nu}$ at tree-level
- There are eight different possible mediators

$$W'_\mu \sim (1,3)_0, U_\mu \sim (3,1)_{2/3}, X_\mu \sim (3,3)_{2/3}, S \sim (3,1)_{-1/3},$$
$$T \sim (3,3)_{-1/3}, \phi \sim (1,2)_{1,2}, D \sim (3,2)_{7/6}, V_\mu \sim (3,2)_{-5/6}$$

EFT – fixing all NC

- Motivated by FCNC and LHC constraints
  - ➔ We impose $U(2)_Q$ symmetry of the light left-handed quarks
  - ➔ We assume flavor alignment to the down mass basis

- Choosing a simplified model
  - ➔ Fixes the 4 CC Wilson coefficients (up to overall normalization)
  - ➔ Fixes the 4 corresponding NC, as well as the 5 other NC. For instance a mediator which generates $(\bar{u}L)(\bar{e}Q)$ will also generate $(\bar{u}L)(\bar{L}u), (\bar{e}Q)(\bar{Q}e)$

Numerical results

Numerical results – analysis

- Complete list of simplified models -

  $W'_\mu \sim (1,3)_0, U_\mu \sim (3,1)_{2/3}, X_\mu \sim (3,3)_{2/3}, S \sim (3,1)_{-1/3},$
  $T \sim (3,3)_{-1/3}, \phi \sim (1,2)_{1,2}, D \sim (3,2)_{7/6}, V_\mu \sim (3,2)_{-5/6}$

- Normalize the Wilson coefficients by Integrating out the heavy mediator

- Find best-fit values of new couplings to minimize the $R(D^{(*)})$ anomaly (χ^2)

- Calculate the *p-value* for each model

- Find the 95% C.L. interval of the new couplings

- Calculate $R^{\Upsilon}_{\tau/\ell}$ and $R^{\psi}_{\tau/\ell}$ within the allowed region

Numerical results – example $U_\mu \sim (3,1)_{2/3}$

- UV

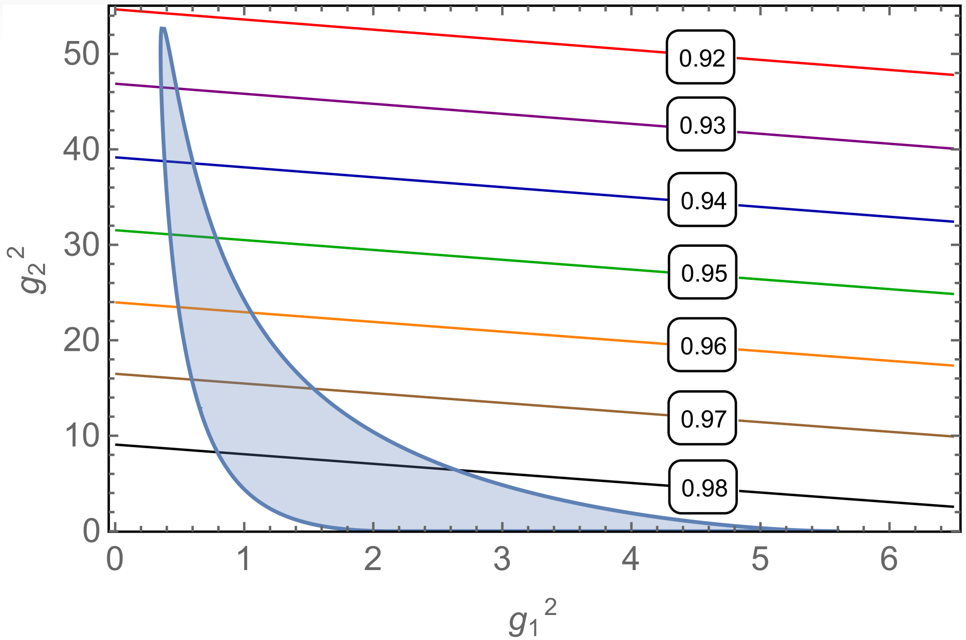
$$\mathcal{L}_U = g_1 \bar{Q}_3 \not{U} L_3 + g_2 \bar{d}_3 \not{U} e_3 + h.c.$$

- EFT

$$\mathcal{L}_U^{EFT} = -\frac{|g_1|^2}{2M_U^2}\overbrace{(\bar{L}\gamma^\mu L)(\bar{Q}\gamma_\mu Q)}^{N.C.} - \frac{2|g_1|^2}{M_U^2}\overbrace{(\bar{L}\gamma^\mu \tau_a L)(\bar{Q}\gamma_\mu \tau_a Q)}^{N.C.+C.C.}$$
$$-\frac{|g_2|^2}{M_U^2}\overbrace{(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)}^{N.C.} + \left[\frac{g_1 g_2^*}{M_U^2}\overbrace{(\bar{Q}d)(\bar{e}L)}^{N.C.+C.C.} + h.c.\right]$$

Numerical results – example $U_\mu \sim (3,1)_{2/3}$

- Results: $(g_1^{2\ bfp}, g_2^{2\ bfp}) = (3.3, 0.4)\left(\frac{M_U}{TeV}\right)^2,\ p = 100\%$



$$R_{\tau/\ell}^{\Upsilon(1S)} = 0.922 - 0.990$$
$$R_{\tau/\ell}^{\Upsilon(2S)} = 0.915 - 0.991$$
$$R_{\tau/\ell}^{\Upsilon(3S)} = 0.911 - 0.992$$

- $R_{\tau\ell}^{\psi(2S)}$ is not modified

Numerical results

UV field content	$R_{\tau/\ell}^{\Upsilon(1S)}$	$R_{\tau/\ell}^{\psi(2S)}$	Predicted modification to $R_{\tau/\ell}^{\Upsilon(1S)}$
$W'_\mu \sim (1,3)_0$	0.989-0.991	0.390	Decrease by $0.2\% - 0.4\%$
$U_\mu \sim (3,1)_{+2/3}$	0.922-0.990	SM	Decrease by $0.3\% - 7.1\%$
$S \sim (3,1)_{-1/3}$	SM	0.389-0.390	–
$V_\mu \sim (3,2)_{-5/6}$	0.975-0.985	SM	Decrease by $0.7\% - 1.7\%$
SM	0.992	0.390	
Current measurement	1.005 ± 0.025	0.39 ± 0.05	
Achievable uncertainty (with current data)	± 0.01	± 0.02	
Projected uncertainty ($\mathcal{L}^{\Upsilon(3S)} = 1/\text{ab}$ in Belle II)	± 0.004	–	

- $R_{\tau\ell}^{\Upsilon(1S)}$ is starting to probe relevant models

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Future prospects

Future prospects - $\psi(2S)$

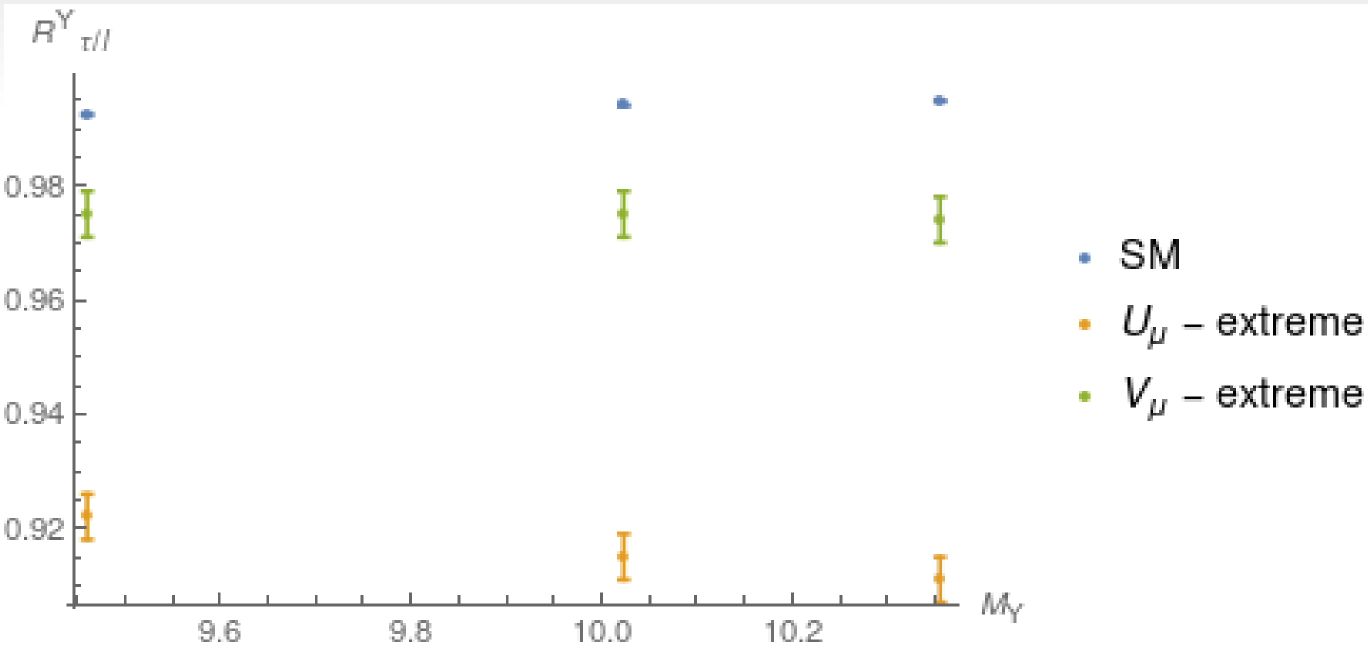
- Current error is $\sigma \sim 13\%$
- Bess II already has 10 times larger data sample than what was analyzed, giving $\sigma \sim 4\%$
- We predict that $R^{\psi}_{\tau/\ell}$ is modified by at most few per-mil
- Removing the imposed $U(2)_Q$ symmetry might lead to a much larger modification (work in progress)
- An order of magnitude improvement is needed to be achieved in Bess III

Future prospects - $\Upsilon(nS)$

- Current error is ~ $\sigma_{1S}^{BaBar} \sim 2\%, \ \sigma_{2S}^{CLEO} \sim 5\%, \ \sigma_{3S}^{CLEO} \sim 8\%$
- Babar and Belle have 16-20 times larger data samples than what was analyzed, giving $\sigma \sim 1\%$
- Running at $\Upsilon(3S)$ with $\mathcal{L} \sim 1/ab$ Belle II might reach $\sigma_{1S} \simeq 0.4\%$
- LFU in Υ decays provide additional motivation to study $\Upsilon(3S)$ at early physics program of Belle II (w/o full vertex detector)

Future prospects - $\Upsilon(nS)$

- We suggest a SM test:



$$R_{\tau/\ell}(m_{\Upsilon(nS)}) = \left[1 + 2x^2_{\tau,1S}\left(\frac{m_{\Upsilon(1S)}}{m_{\Upsilon(nS)}}\right)^2\right]\left[1 - 4x^2_{\tau,1S}\left(\frac{m_{\Upsilon(1S)}}{m_{\Upsilon(nS)}}\right)^2\right]^{1/2}$$

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Summary

- $R(D^{(*)})$ is enhanced compared to the SM at 3.9σ
- Explaining this enhancement suggests new bosons which mediate the $b \to c\tau\nu$ transition at tree-level
- Such bosons can generate observable LFU violation in vector meson decay
- Current measurements of ψ decays do not have the required accuracy
- Current (not analyzed) data of $\Upsilon(1S)$ can already disfavor some of the parameter space
- Belle II can contribute significantly if operates below the $\Upsilon(4S)$ resonance

Thank you!

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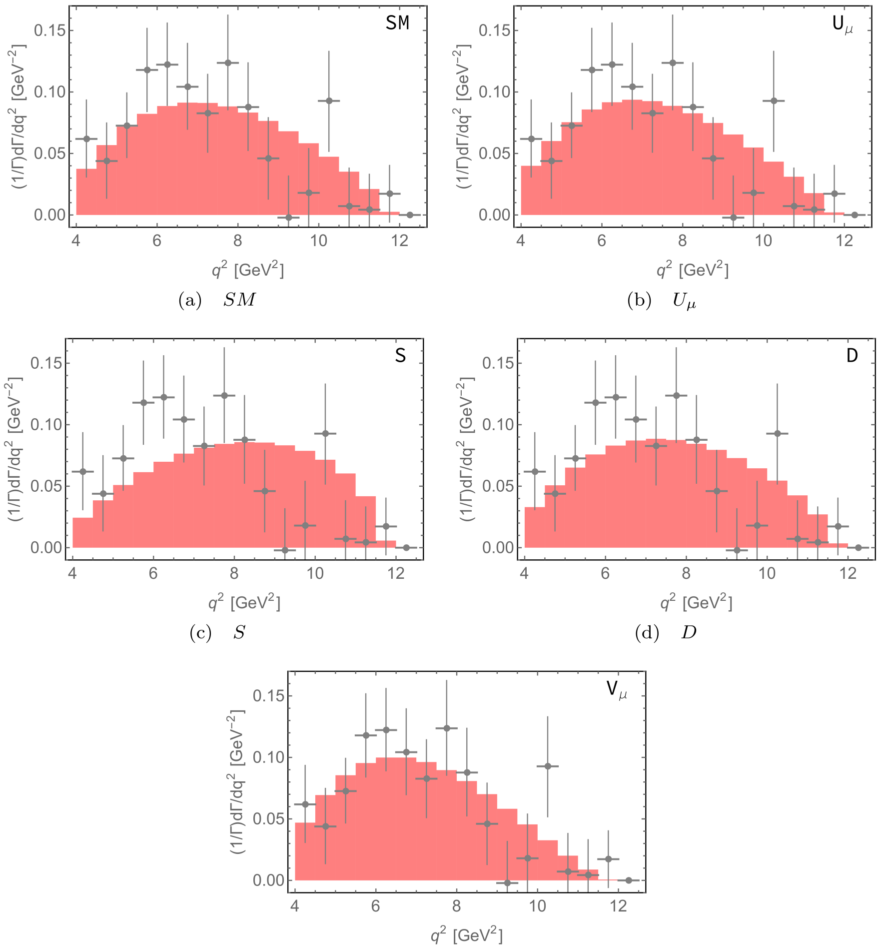
Backup

q^2 distributions



(a) SM (b) U_μ (c) S (d) D (e) V_μ

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Corrections – Z exchange

$$\delta R_V^Z = \left(\frac{\epsilon}{\epsilon - 1}\right)^2 \left(\frac{g_V^q}{8Q_q c_W^2 s_W^2}\right)^2 \left(\frac{64x_\ell^2}{1 + 2x_\ell^2}\right)$$

Where $\epsilon = m_V^2/m_Z^2$ and $g_V^q = T_3^q - 2Q_q s_W^2$

Corrections – QED 1-loop

$$R^V_{\tau/\ell} = (1 - 4x_\tau^2)^{1/2}\left(1 + 2x_\tau^2\right)$$
$$\cdot\left[1 + \frac{4\alpha x_\tau^2}{\pi}(2 - \log[4])\right]$$

Vector meson decay – Dim(6) operators

Relation between Wilson coefficient and Form-factors:

$$A_V^{q\ell} = -4\pi\alpha Q_q + \frac{m_V^2}{4}\left[\left(C_{VLL}^{q\ell} + C_{VRR}^{q\ell} + C_{VLR}^{q\ell} + C_{VRL}^{q\ell}\right) + 16 x_\ell \frac{f_V^T}{f_V}\mathrm{Re}\left[C_T^{q\ell}\right]\right] ,$$

$$B_V^{q\ell} = \frac{m_V^2}{4}\left(C_{VRR}^{q\ell} + C_{VRL}^{q\ell} - C_{VLR}^{q\ell} - C_{VLL}^{q\ell}\right) ,$$

$$C_V^{q\ell} = 2 m_V^2 \frac{f_V^T}{f_V}\mathrm{Re}\left[C_T^{q\ell}\right] ,$$

$$D_V^{q\ell} = 2 m_V^2 \frac{f_V^T}{f_V}\mathrm{Im}\left[C_T^{q\ell}\right] .$$

where

$$\langle 0|\bar{q}\gamma^\mu|V(p)\rangle = f_V m_V \epsilon^\mu(p) \ , \ \ \langle 0|\bar{q}\sigma^{\mu\nu}|V(p)\rangle = f_V^T[\epsilon^\mu(p)p^\nu - \epsilon^\nu(p)p^\mu]$$