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

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QWG 2019 - Torino

In collaboration with

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Motivation

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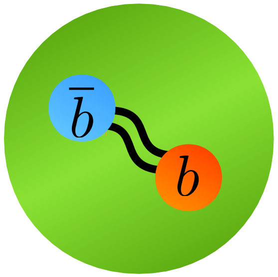
QWG 2019 - The 13th International Workshop on Heavy Quarkonium



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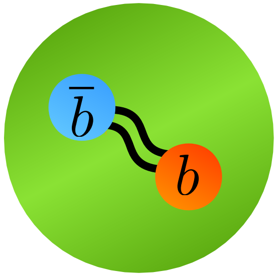

Torino derives its name from a Celtic word tau,meaning mountain…..

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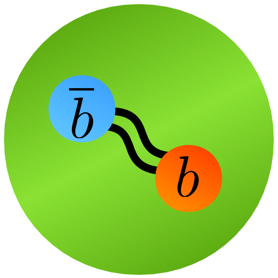

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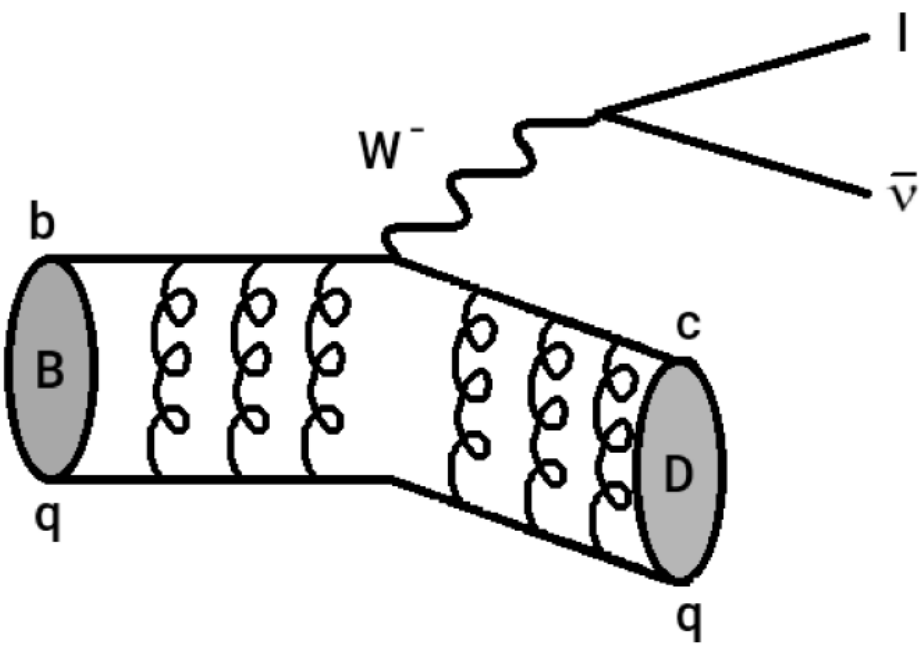
Today: Υ to tau tau!

Motivation

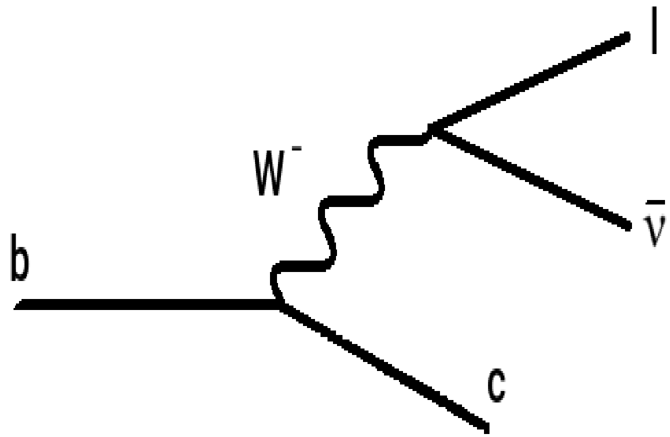
- $\mathrm{R(D^{(*)})} \equiv \dfrac{BR(B \to D^{(*)}\,\tau\,\bar{\nu})}{BR(B \to D^{(*)}\,\ell\,\bar{\nu})}$, $\ell = \mu, e$



Motivation

- $\mathrm{R(D^{(*)})} \equiv \frac{BR(B \to D^{(*)}\,\tau\,\bar{\nu})}{BR(B \to D^{(*)}\,\ell\,\bar{\nu})} \quad , \quad \ell = \mu, e$

- At the quark level: $b \to c\tau(\ell)\bar{\nu}$



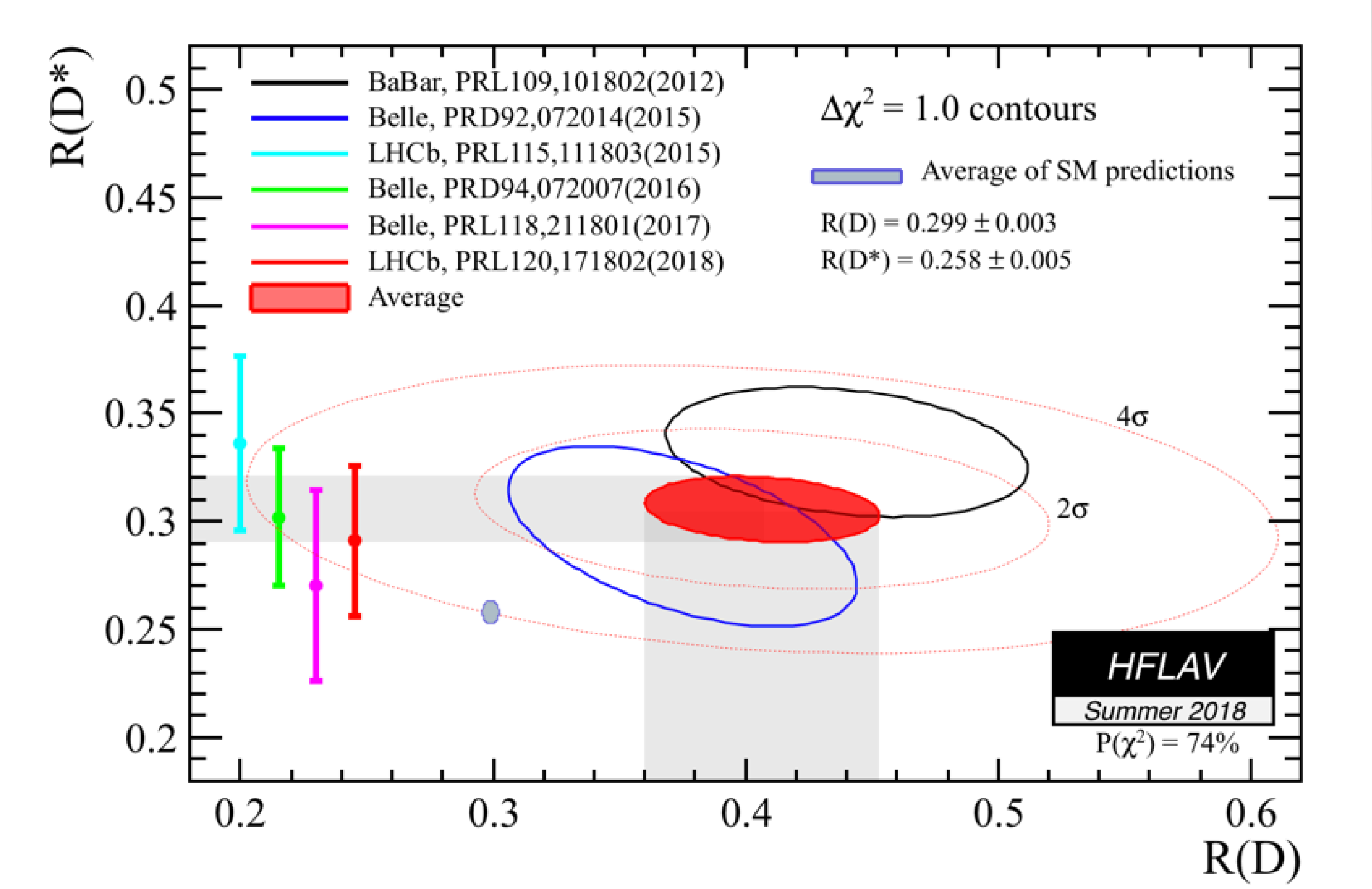
- SM: $b \to c\tau(\ell)\bar{\nu}$ transition is mediated by the W boson

The SM prediction

- $R^{SM}(D) = 0.299 \pm 0.003\ ,\ \ R^{SM}(D^*) = 0.258 \pm 0.005$ *
- How do we know that so well?
  - ➔ Semileptonic
  - ➔ Unknown parameters cancel in the ratio
  - ➔ In the heavy quark limit $m_b,\, m_c \to \infty$, we have only phase space suppression
  - ➔ In the degenerate lepton masses limit $m_\tau \to m_\ell$, R(D)=R(D*)=1
- We know to expand systematically around this small parameters

* HFLAV Average

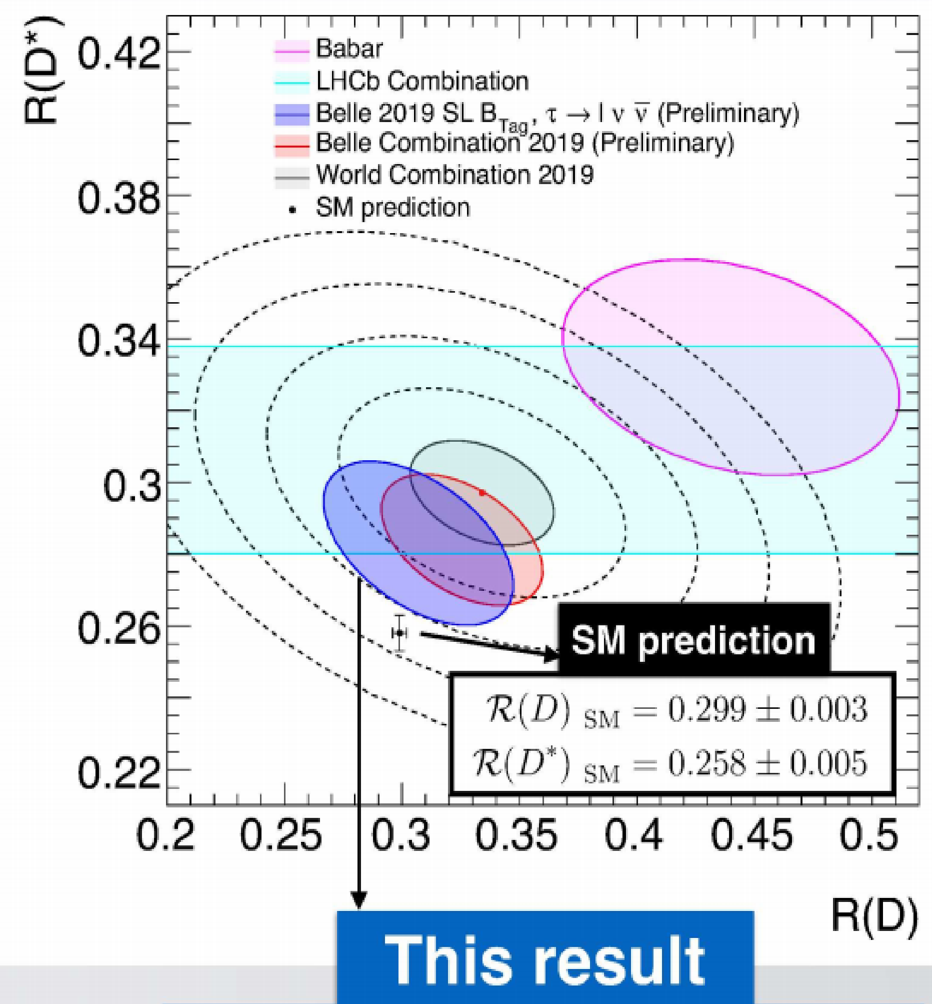
Measurement



- $\sim 4\sigma$ deviation from SM prediction

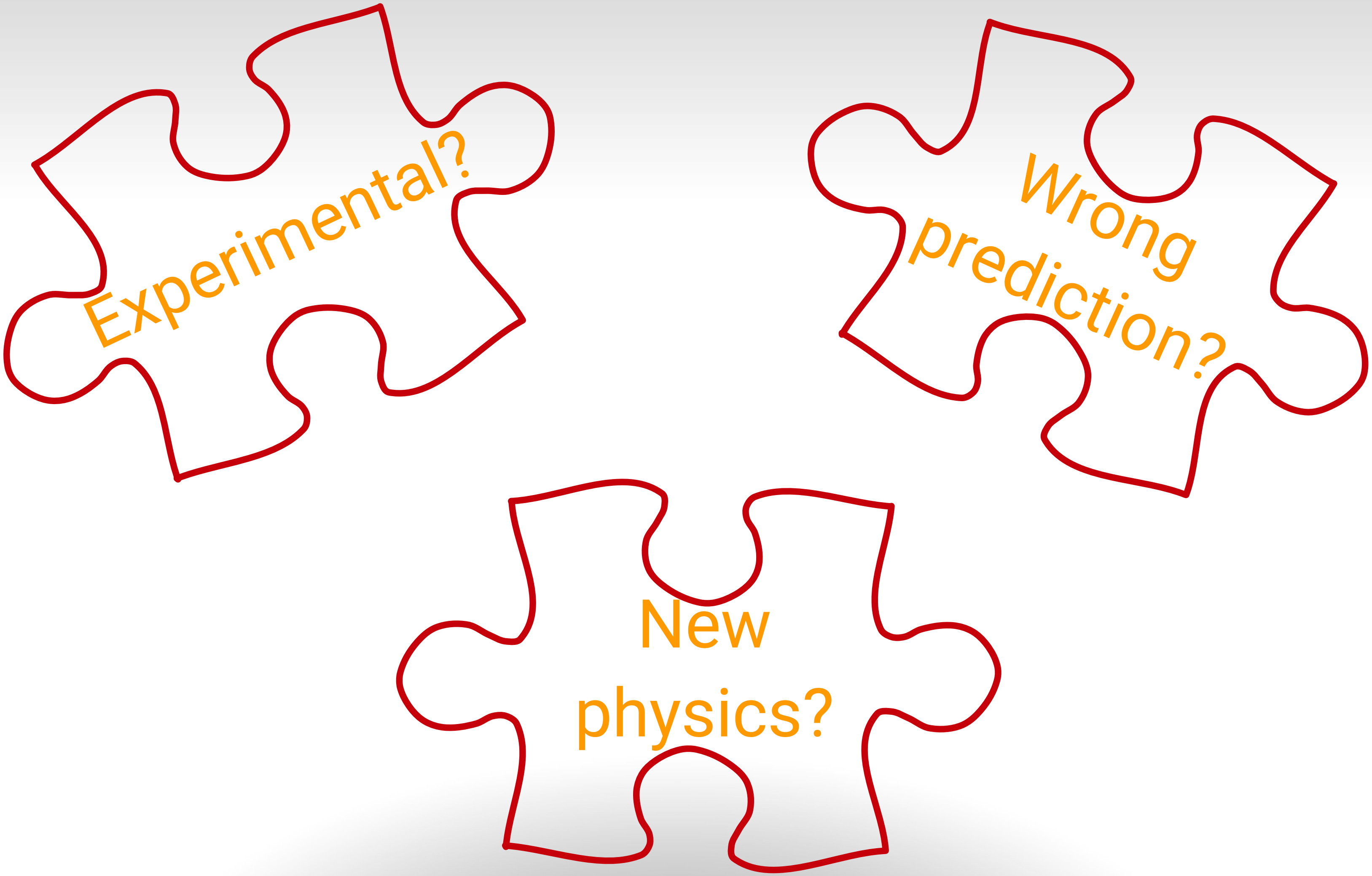
Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

This is puzzling



If new physics

- Central values are enhanced by 30% compared to SM → NP amplitude 15%-30% compared to SM

- New physics is non-universal and breaks lepton flavor symmetry

- New physics is probably heavy → Can work with an effective 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
  - $(\bar{e}L)(\bar{u}Q)$
  - $(\bar{e}\sigma^{\mu\nu}L)(\bar{u}\sigma_{\mu\nu}Q)$
  - $(\bar{L}\gamma^{\mu}\tau_a L)(\bar{Q}\gamma^{\mu}\tau_a Q)$
  - $(\bar{Q}d)(\bar{e}L)$

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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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 $b\bar{b}$ and/or $c\bar{c} \to \tau\bar{\tau}$

EFT – NC observables

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

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

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

  - $\Upsilon = b\bar{b}$ bound state
  - $\psi = c\bar{c}$ bound state

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

Vector meson decay - SM

- Within the SM

$$R^{V}_{\tau/\ell} \simeq \left[1 + \frac{2m_\tau^2}{m_V^2}\right]\left[1 - \frac{4m_\tau^2}{m_V^2}\right]^{1/2} = 1 - \mathcal{O}\left(\frac{m_\tau^4}{m_V^4}\right)$$

where $V = \Upsilon,\ \psi$

- Dominantly QED – 1 photon mediated

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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

$R^V_{\tau/\ell}$:

$V(nS)$	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

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$m_{\Upsilon(4S)} > 2m_B \quad \Rightarrow \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S)$

$m_{\psi(1S)} < 2m_\tau$

$\Rightarrow \psi(2S)$

$m_{\psi(3S)} > 2m_D$

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The need for assumptions

- There are four independent CC operators
- There are eight independent NC operators
- CC + Gauge invariance → NC

  → Not enough measurements to fix the values of the Wilson coefficients of the four CC operators

  → No information on the other four NC operators

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

- Each boson breaks LFU in Υ and/or ψ decays in a different way

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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 $0.2\% - 0.4\%$
$U_\mu \sim (3,1)_{+2/3}$	0.952-0.990	SM	Decrease by $0.3\% - 4.0\%$
$S \sim (3,1)_{-1/3}$	SM	0.389-0.390	–
$V_\mu \sim (3,2)_{-5/6}$	0.976-0.987	SM	Decrease by $0.5\% - 1.6\%$
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 - $\Upsilon(nS)$

- 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 $\sigma_{1S} \simeq 0.4\%$

Summary

- Current error is $\sigma_{1S}^{BaBar} \sim 2\%$

- Running at $\Upsilon(3S)$ with $\mathcal{L} \sim 1/ab$ Belle II might covers most region of parameter space related to $R(D^{(*)})$

- LFU in Υ decays provide additional motivation to study $\Upsilon(3S)$ at Belle II

- Test the SM and Probe NP even if $R(D^{(*)})$ disappears

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

Thank you!

Backup

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)

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 4 other NC. For instance a mediator which generates $(\bar{u}L)(\bar{e}Q)$ will also generate $(\bar{u}L)(\bar{L}u), (\bar{e}Q)(\bar{Q}e)$

Vector meson decay – dim(6) operators

- Eight 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 8 Wilson coefficient $C^{q\ell}_A$ to 4 form factors appearing in the ratio

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

Vector meson decay – Dim(6) operators

Relation between Wilson coefficient and Form-factors:

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

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

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

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

where

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

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

- UV

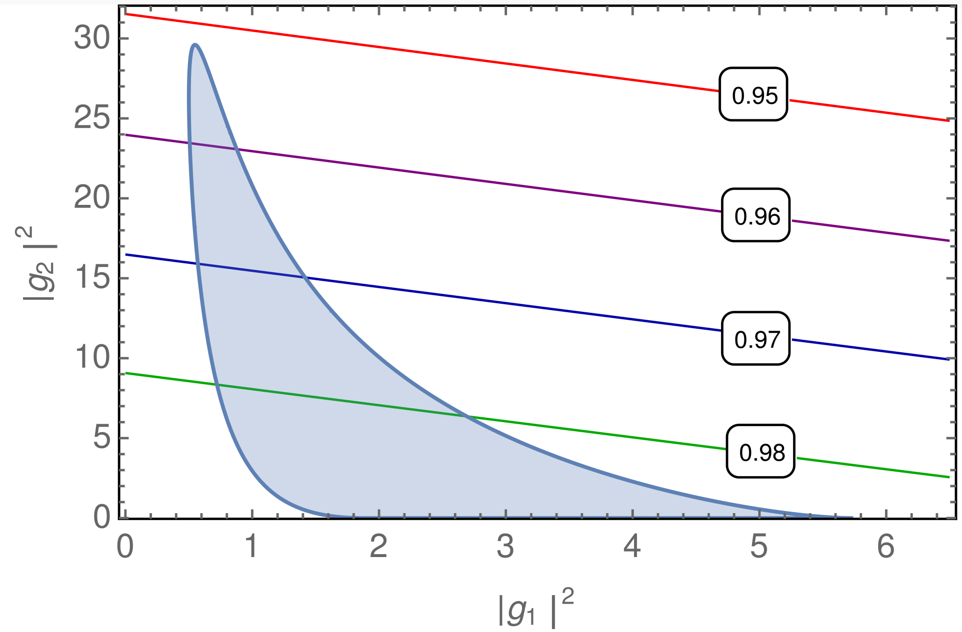
$$\mathcal{L}_U = g_1 \bar{Q}_3 \not{U} L_3 + g_2 \bar{d}_3 \not{U} e_3 + h.c.$$

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



$$R_{\tau/\ell}^{\Upsilon(1S)} = 0.952 - 0.990$$
$$R_{\tau/\ell}^{\Upsilon(2S)} = 0.949 - 0.991$$
$$R_{\tau/\ell}^{\Upsilon(3S)} = 0.946 - 0.992$$

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

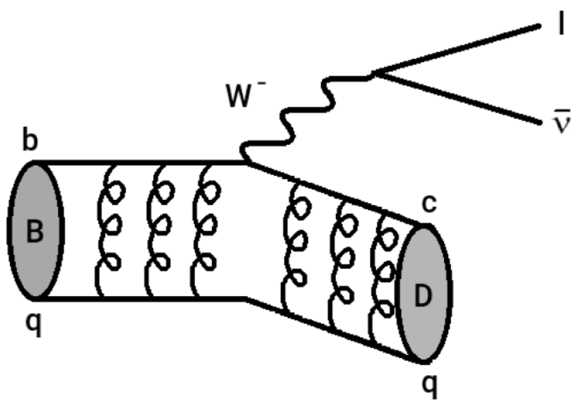
Future prospects - $\psi(2S)$

- 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

In a cartoon

In a cartoon

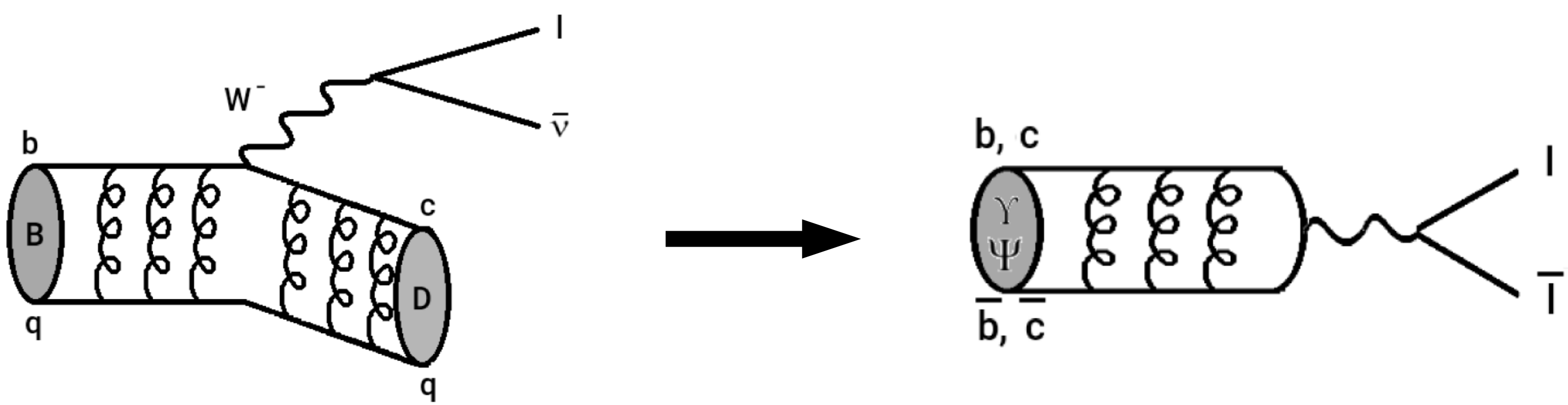
Charge current (CC)



In a cartoon

Charge current (CC)

Neutral current (NC)



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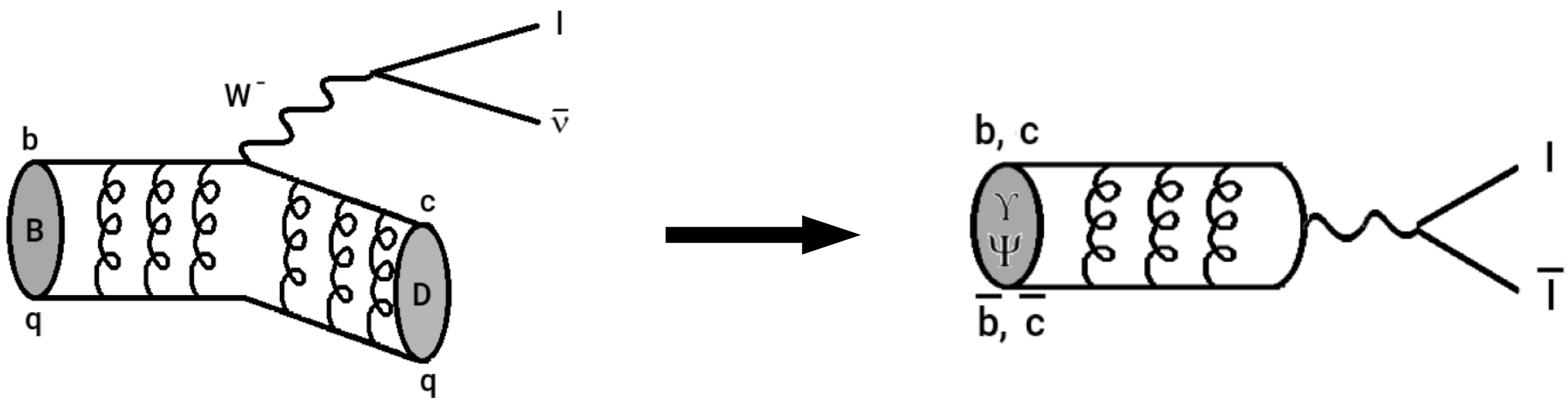

ν is part of a doublet → if we have ν we have τ

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