Flavour anomalies at the HL/HE LHC

Martin Jung

“Workshop on the physics of HL-LHC, and perspectives at HE-LHC”

CERN, 19th of June 2018
Anomalies and projections 2018

$b \rightarrow c\tau\nu$

- Presently $\sim 4\sigma$ from SM
- Relative to tree-level
- Low NP scale?

$b \rightarrow s\ell^+\ell^-$ [Albrecht+’17]

- $\sim 5\sigma$ from SM
- Relative to EW penguin loop
- Consistent BR, angular + LFU data

If anomalies are real, they will be established before 2nd upgrade
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Consequently the objectives change:

- Differentiation between NP structures
  - Distributions in $q^2 + \text{angles, polarization...}$
  - Require analyses beyond 1/2 operators
- Flavour structure on the lepton side ($\tau \leftrightarrow \mu \leftrightarrow e$)
  - Hardware improvements for electrons? Ideas for $\tau$s?
- Flavour structure on the quark side (e.g. $b \rightarrow u \leftrightarrow b \rightarrow c$)
  - Possibilities in charm and top decays (not part of this talk)

A lot of this is not yet done, insufficient data
  
  Close collaboration of experiment and theory necessary

Objectives of this talk:

- Examples of challenging systematics (th + exp)
- Going beyond $R(D^{(*)})$ in charged-current modes
- Identification of “clean” observables with differentiating power
What if the anomalies go away?

Think long & hard about systematic + theory uncertainties...

 располагаем панелью рисования

All these observable remain valuable! Strategies:

- Semi-true statement: “The smaller the SM rate, the larger the potential relative NP contribution”
- Strong motivation for (very) rare decays
- Large “Background” doesn’t matter if you understand it well
- Motivation for tree-level modes

Theoretically, high precision can be achieved by that time:

- Basically all CC sl decays (LQCD), challenges at ~ 1%-level
- Golden rare modes: $B_{d,s} \rightarrow \mu^+ \mu^-$
- High-precision predictions for LFU ratios
- Very precise, but also very specific
- Generally $b \rightarrow s(d)\ell^+\ell^-$, limits from charm-(charm+up-) quark loops, but recent proposals for control via data [Bobeth+, Blake+'18]
A couple of systematic issues

Form factors:
- $V_{cb} +$ WCs only in combination w/ FFs
  - SM: shape from exp., normalization from non-perturbative methods
  - NP: FFs needed from theory, only!
- Reanalyses cannot resolve $R(D^{(*)})$
  [Bigi+, Grinstein+, Bernlochner+]

Branching ratio measurements: [MJ’15]
- Implicit isospin assumption in extraction of BRs at $B$ factories
  - Affects BRs @ LHC, improvable with Belle (II) data
  - Address isospin for high-precision measurements (e.g. $f_u/f_d$)

Implicit SM assumptions:
- Signal shape assumptions in CC sl decays
  - Has to be avoided for high precision NP analyses
  - Not trivial! How to present data model-independently?

Spectroscopic Information:
$B \rightarrow D^{**}$ badly understood $\rightarrow$ measurements with $D^{**}$, $B_c \rightarrow J/\psi\tau\nu$
Higgs EFT(s)

Apparent gap between EW and NP scales:
- EFT approach at the electroweak scale:
  - SM particle content
  - SM gauge group
  - Embedding of $h$
  - Power-counting
  - Formulate NLO

Linear embedding of $h$:
- $h$ part of doublet $H$
- Appropriate for weakly-coupled NP
- Power-counting: dimensions
  - Finite powers of fields
- LO: SM

Non-linear embedding of $h$:
- $h$ singlet, $U$ Goldstones
- Appropriate for strongly-coupled NP
- Power-counting: loops ($\sim \chi$PT)
  - Arbitrary powers of $h/\nu, \phi$
- LO: SM + modified Higgs-sector

Scale:
- NP (>few TeV)
- EW ($h, t, Z, W$)
- B (~5 GeV)
- QCD (<1 GeV)
Implications of the Higgs EFT for flavour [Cata/MJ’15]

\( q \rightarrow q'\ell\ell : \)

- Tensor operators absent in linear EFT for \( d \rightarrow d'\ell\ell \) [Alonso+’14]
  - Present in general! (already in linear EFT for \( u \rightarrow u'\ell\ell \))
- Scalar operators: linear EFT \( C_S^{(d)} = -C_P^{(d)}, \ C_S''^{(d)} = C_P'^{(d)} \) [Alonso+’14]
  - Analogous for \( u \rightarrow u'\ell\ell \), but no relations in general!

\( q \rightarrow q'\ell\nu : \)

- Relations between different transitions: weak doublets \( C_{VR} \) is lepton-flavour universal [see also Cirigliano+’09]
  Relations between charged- and neutral-current processes, e.g.
  \[
  \sum_{U=u,c,t} \lambda_{Us} C_{SR}^{(U)} = -\frac{e^2}{8\pi^2} \lambda_{ts} C_S^{(d)} \] [see also Cirigliano+’12, Alonso+’15]
- These relations are again absent in the non-linear EFT

\[ \text{Flavour physics sensitive to Higgs embedding!} \]
  - Surprising, since no Higgs is involved
  - Difficult differently [e.g. Barr+, Azatov+’15]

For NP below 1 TeV, SMEFT not really the best framework
Differentiating models with $b \to c \tau \nu$ observables

Large $R(D^*)$ possible with NP in $V_L$ ($\hat{R}(X) = R(X)/R(X)_{SM} \sim 1.25$):

- can be related to anomaly in $B \to K^{(*)}\ell^+\ell^-$ modes
- $\hat{R}(X_c) = 0.99 \pm 0.10$ measured by LEP, oversaturation
- issues with $\tau \to \mu \nu \nu$ [Feruglio+'16] and $b\bar{b} \to X \to \tau^+\tau^-$ [Faroughy+'16]

Scalar NP: $R(D^*)$ limited by $\Gamma(B_c)$, worse issue w/ $b\bar{b} \to X \to \tau^+\tau^-$
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Fit results for the two scenarios for $B \rightarrow D^{(*)}\tau\nu$: 

![Graph showing fit results for the two scenarios for $B \rightarrow D^{(*)}\tau\nu$.]
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Scalar NP: $R(D^*)$ limited by $\Gamma(B_c)$, worse issue w/ $b\bar{b} \rightarrow X \rightarrow \tau^+\tau^-$

Fit predictions for polarization-dependent $B \rightarrow D^{*}\tau\nu$ observables:

Combination independent of scalar NP: [Celis/MJ/Li/Pich’13]

$$X^{D(*)}_{2}(q^2) \equiv R_{D(*)}(q^2) \left[ A^{D(*)}_{\lambda}(q^2) + 1 \right] = X^{D(*)}_{2,SM}(q^2)$$
Differentiating models with $b \rightarrow c\tau\nu$ observables

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Scalar NP: $R(D^*)$ limited by $\Gamma(B_c)$, worse issue w/ $b\bar{b} \rightarrow X \rightarrow \tau^+\tau^-$

Fit predictions for $B \rightarrow X_c\tau\nu$ and $\Lambda_b \rightarrow \Lambda_c\tau\nu$: 
Quark flavour structure: NP in $b \rightarrow u\tau\nu$ transitions

$b \rightarrow u\tau\nu$ less explored experimentally, $|V_{ub}/V_{cb}|^2 \lesssim 1\%$:

- $R(\tau) \equiv BR(B \rightarrow \tau\nu)/BR(B \rightarrow \pi\ell\nu)$ about $1.8\sigma$ from SM
- $R(\pi)$ not significantly measured yet

Data consistent with SM as well as sizable NP
Quark flavour structure: NP in $b \to u\tau\nu$ transitions

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- Data consistent with SM as well as sizable NP

Analyse $b \to u\tau\nu$ individually:

- $R(\tau)$ yields correlation between $R(\pi)$ and $R(p)$

More observables needed!
Λ$_b$ provides uncommon parameter combinations

$B_s \to K^{(*)}\tau\nu$ decays competitive?
Detector requirements?
Pionic final states possible?
Lepton flavour structure: $b \to c \ell \nu$ decays [MJ/Straub’18]

Left-handed vector currents: $\tilde{V}^e_{cb}/\tilde{V}^\mu_{cb} = 1.011 \pm 0.012$

Right-handed vector currents: Affect $V^{incl.}_{cb}$ vs. $V^{excl.}_{cb}$ [e.g. Voloshin’97]

Scalar currents: $q^2_{\text{max}} (B \to D)$ highly sensitive to NP [see also Nierste+’08]

Tensor currents: $q^2_{\text{min}} (B \to D^*)$ highly sensitive to NP

Similar to what we want to do for $b \to c \tau \nu$.

Large impact of differential distributions
Prospects $b \rightarrow (u, c)(e, \mu)\nu$ @ LHCb

Potential unambiguous $|V_{xb}|$ determination before phase-II upgrade

- Measuring $b \rightarrow u, c\ell\nu$ not about this

Instead, model-independent determinations of NP contributions

- If FNU in $b \rightarrow c$ is confirmed, expect “something” in $b \rightarrow u$
- Also, with $b \rightarrow c\tau\nu$ affected, $\mu$ vs. $e$ important to check
- Universality checks of right-handed currents interesting

$|V_{ub}/V_{cb}|$ from $\Lambda_b$ important ingredient right now...

- Tests different NP combinations than mesonic modes
- Which observables are measurable?
- How much can we reduce the systematics?
- FFs need improvement, but not the main issue

$B_s \rightarrow K\ell\nu$ essentially probes the same physics as $B \rightarrow \pi\ell\nu$

- Direct competition with Belle II

$B \rightarrow p p\ell\nu$ interesting new idea

- Challenging, qualititative theory progress required!
Prospects $b \to (s, d)\ell\ell'$ @ LHC

Again, model-independent determinations of NP contributions

- If NP in $b \to s$ is confirmed, expect “something” in $b \to d$
  
  - $|V_{td}/V_{ts}|^2 \sim 1/34 \to$ high luminosity important

- With $b \to s\mu\mu$ affected, $\mu$ vs. $\tau$, $e$ important to check
  
  - Angular analysis in $b \to$ see
  
  - Golden Channel $b \to s\tau\tau$: improvements possible?

- Also $b \to (d, s)\nu\nu$ important $\to$ Belle II

- Other FCNCs partly related, $s \to d$, $t \to c$, $u$, $c \to u$

LFV: “generic” implication of NP in $\ell\ell$ [Glashow+'15]

- Not always true, see e.g. [Celis/Fuentes-Martín/MJ/Serôdio, Alonso+'15]

- In any case worth looking for
Conclusions

Excellent physics potential for LHCb beyond Run 4

- $b \rightarrow c \ell \nu + b \rightarrow s \ell \ell$: indications of lepton-non-universal NP
  - New measurements/observables constrain NP more severely
- Unprecedented control over uncertainties necessary
- Should tensions be real, they’re established by LS 3
  - Expect smaller deviations anyway (smaller $R(D^*)$ would improve most NP interpretations)
  - Need to pin down precise structure of NP (Dirac, flavour)
  - Need for distributions + polarization measurements
  - $b \rightarrow c \ell \nu$ shows potential
- Clean observables available to differentiate between different NP
- We start to constrain $b \rightarrow u + b \rightarrow d$ transitions now
  - Experimentally challenging, HL indispensable
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Excellent physics potential for LHCb beyond Run 4

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Thank you for your attention!
Importance of (semi-)leptonic hadron decays

In the Standard Model:

• Determination of $|V_{ij}|$ (7/9)

Beyond the Standard Model:

• Leptonic decays $\sim m_i^2$
  - Large relative NP influence possible (e.g. $H^{\pm}$)
• NP in semi-leptonic decays moderate
  - Need to understand the SM very precisely!
• NP: Relative to tree, $\tau$ least constrained

Key advantages:

• Large rates
• Minimal hadronic input
  - This input is systematically improvable

Additionally: (almost) all flavour anomalies involve leptons
\( |V_{xb}|: \) inclusive versus exclusive

Long-standing problem:

- Very hard to explain by NP [Crivellin/Pokorski’15]
  (but see [Colangelo/de Fazio’15])
- Likely experimental/theoretical systematics
$V_{cb}$: Recent developments

Recent Belle $B \rightarrow D, D^* \ell \nu$ analyses
Recent lattice results for $B \rightarrow D$
[FNAL/MILC, HPQCD, RBC/UKQCD (ongoing)]

$B \rightarrow D$ between incl. + $B \rightarrow D^*$
New lattice result for $B \rightarrow D^*$ [HPQCD]

$V_{cb}^{incl}$ cv, compatible with old result
$B \rightarrow D^* \ell \nu$ re-analyses with CLN,

$|V_{cb}| = 39.3(1.0)10^{-2}$ [Bernlochner+'17]
$+ BGL$ [Bigi+,Grinstein+'17] (Belle only),

$|V_{cb}| = 40.4(1.7)10^{-2}$
New BaBar analysis of $V_{ub}$ incl.:
Dependence on theory treatment!

GGOU $2\sigma$ lower than WA
Compatible w/ PDG exclusive avg

Hints towards resolution, not yet conclusive
New systematics: BR measurements and isospin violation

Branching ratio measurements require normalization...

- $B$ factories: depends on $\Upsilon \rightarrow B^+ B^-$ vs. $B^0 \bar{B}^0$
- LHCb: normalization mode, usually obtained from $B$ factories
New systematics: BR measurements and isospin violation
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Assumptions entering this normalization:
- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+ B^-) / \Gamma(\Upsilon \to B^0 \bar{B}^0) \equiv 1$
- LHCb: (mostly) assumes $f_u \equiv f_d$, uses $r_{+0}^{HFAG} = 1.058 \pm 0.024$
New systematics: BR measurements and isospin violation

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Both approaches problematic: [MJ’16 [1510.03423]]

- Potential large isospin violation in $\Upsilon \rightarrow BB$ [Atwood/Marciano’90]
- Measurements in $r_{+0}^{HFAG}$ assume isospin in exclusive decays
  - This is one thing we want to test!
- Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$

- Isospin asymmetries test NP with $\Delta I = 1, 3/2$ (e.g. $b \rightarrow s\bar{u}u$)
  - Isospin asymmetry $B \rightarrow J/\psi K$: $A_I = -0.009 \pm 0.024$

**Affects every percent-level BR measurement $B \rightarrow J/\Psi K$ can be used to determine $f_u/f_d$!**
SM predictions

Sl amplitude: kinematics $\times$ FC coupling (SM: CKM) $\times$ form factor

Strategy SM predictions: $V_{cb} +$ leading FF cancels
data + theoretical input from LQCD/HQET for FF ratios

$B \to D$: 2 form factors $f_{+,0}$
- Data determines shape of $f_+(q^2)$
- LQCD required for $f_0$: fit HPQCD + FNAL/MILC, use $f_+(0) = f_0(0)$

$$R(D) = 0.301 \pm 0.003 \ [\text{Bigi/Gambino’16}]$$

$B \to D^*$: 4 form factors $V, A_{0,1,2}$
- $3/4 \to$ data (+HQET, unitarity $\to$ CLN)
- HQET for $A_0$ [Falk/Neubert], enhance uncertainty [Fajfer/Kamenik]

$$R(D^*) = 0.252 \pm 0.003, \ (0.257 \text{ from re-analysis } [\text{Bernlochner+’17}])$$

- LQCD for non-maximal recoil underway

(Very) good control, effect too large to be in CLN relations
NP in (semi-)leptonic decays

EFT for $b \to c\tau\nu$ transitions (no light $\nu_R$, SM: $C_{V_L} = 1$, $C_i \neq V_L = 0$):

$$\mathcal{L}_{\text{eff}}^{b \to c\tau\nu} = - \frac{4 G_F}{\sqrt{2}} V_{cb} \sum_{j} C_j \mathcal{O}_j,$$

with

$$\mathcal{O}_{V_{L,R}} = (\bar{c} \gamma^\mu P_{L,R} b) \bar{\tau} \gamma_\mu \nu, \quad \mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b) \bar{\tau} \nu, \quad \mathcal{O}_T = (\bar{c} \sigma^{\mu\nu} P_L b) \bar{\tau} \sigma_{\mu\nu} \nu.$$

NP models typically generate subsets; for a charged scalar:

NP couplings $C_{S_{L,R}}$ (complex), $C_{V_L} = C_{V_L}^{\text{SM}} = 1$, $C_{V_R} = C_T = 0$

- Model-independent subclass as long as $C_{S_{L,R}}$ general
- Phenomenologically $C_{S_{L,R}}^{quqd} \sim m_{qu} m_l$ (e.g. Type III)

Used to illustrate here, appearing combinations:

$$R(D) : \delta_{cbl} \equiv \frac{(C_{S_L} + C_{S_R})(m_B - m_D)^2}{m_l(\bar{m}_b - \bar{m}_c)} \quad R(D^*) : \Delta_{cbl} \equiv \frac{(C_{S_L} - C_{S_R})m_B^2}{m_l(\bar{m}_b + \bar{m}_c)}$$

Can trivially explain $R(D^{(*)})$! Exclusion possible with specific flavour structure or more $b \to c\tau\nu$ observables!
$b \rightarrow c\tau\nu$ data and scalar NP [Celis/MJ/Li/Pich’17]

$R(D)$, $R(D^*)$:

- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge ($|C_{SL} - C_{SR}| \sim 1 - 5$)
- Can’t go beyond circles with just $R(D, D^*)$!
$b \rightarrow c \tau \nu$ data and scalar NP [Celis/MJ/Li/Pich’17]

Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \rightarrow D \tau \nu$
- “theory-dependence” of data needs addressing [Bernlochner+’17]
$b \rightarrow c\tau\nu$ data and scalar NP \cite{Celis/MJ/Li/Pich'17}

Total width of $B_c$:

- $B_c \rightarrow \tau\nu$ is an obvious $b \rightarrow c\tau\nu$ transition
  - not measurable in foreseeable future
  - can oversaturate total width of $B_c$! \cite{X.Li+'16}

- Excludes second real solution in $\Delta^\tau_{cb}$ plane
  (even scalar NP for $R(D^*)$? \cite{Alonso+'16})
\( b \to c\tau\nu \) data and scalar NP \[\text{[Celis/MJ/Li/Pich'17]}\]

\( \tau \) polarization:

- So far not constraining \( (\text{shown: } \Delta \chi^2 = 1) \)
- Differentiate NP models: with scalar NP \[\text{[Celis/MJ/Li/Pich'13]}\]

\[
\chi_2^{D(*)}(q^2) \equiv R_{D(*)}(q^2) \left[ A_\lambda^{D(*)}(q^2) + 1 \right] = \chi_{2,SM}(q^2)
\]

Consistent explanation in 2HDMs possible, flavour structure?
Generic features and issues in 2HDMs

Charged Higgs possible as explanation of $b \rightarrow c \tau \nu$ data...

However, typically expect $\Delta R(D^*) < \Delta R(D)$

Generic feature: Relative influence larger in leptonic decays!

- No problem in $b \rightarrow c \tau \nu$ since $B_c \rightarrow \tau \nu$ won’t be measured
- Large charm coupling required for $R(D^*)$
- Embedding $b \rightarrow c \tau \nu$ into a viable model complicated!
- $D_{d,s} \rightarrow \tau, \mu \nu$ kill typical flavour structures with $C_{S_{L,R}} \sim m$
- Only fine-tuned models survive all (semi-)leptonic constraints

$b \rightarrow s \ell \ell$ very complicated to explain with scalar NP

- 2HDM alone tends to predict $b \rightarrow s \ell \ell$ to be QCD-related

$b\bar{b} \rightarrow (H, A) \rightarrow \tau^+ \tau^-$ poses a severe constraint [Faroughy+’16]

2HDMs strongly prefer a smaller value for $R(D^*)$!
The differential distributions $d\Gamma(B \to D^{(*)} \tau \nu)/dq^2$

- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D)$, excluded by distribution
- Need better experimental precision, ideally $dR(D)/dq^2$
- Parts of NP parameter space clearly excluded
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  - Red: SM fit (distributions only)
  - Green: Allowed by $R(D^*)$, excluded by distribution
- Need better experimental precision, ideally $dR(D^*)/dq^2$
- Not very restrictive at the moment
Implications of the Higgs EFT for Flavour: $q \rightarrow q' \ell \nu$

$b \rightarrow c \tau \nu$ transitions (SM: $C_{V_L} = 1$, $C_{i \neq V_L} = 0$):

$$L_{\text{eff}}^{b \rightarrow c \tau \nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 C_j O_j ,$$

with

$$O_{V_{L,R}} = (\bar{c} \gamma^\mu P_{L,R} b) \bar{\tau} \gamma_\mu \nu , \quad O_{S_{L,R}} = (\bar{c} P_{L,R} b) \bar{\tau} \nu ,$$

$$O_T = (\bar{c} \sigma^{\mu \nu} P_L b) \bar{\tau} \sigma_{\mu \nu} \nu .$$

- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  - $C_{V_R}$ is lepton-flavour universal [see also Cirigliano+'09]
  - Relations between charged- and neutral-current processes, e.g.
    $$\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2} \lambda_{ts} C_{S}^{(d)}$$ [see also Cirigliano+'12, Alonso+'15]
- These relations are again absent in the non-linear EFT
Matching for $b \rightarrow c \ell \nu$ transitions

\[ C_{V_L} = -N_{CC} \left[ C_L + \frac{2}{v^2} c_{V5} + \frac{2V_{cb}}{v^2} c_{V7} \right], \]
\[ C_{V_R} = -N_{CC} \left[ \hat{C}_R + \frac{2}{v^2} c_{V6} \right], \]
\[ C_{S_L} = -N_{CC} \left( c_{S1} + \hat{c}_{S5} \right), \]
\[ C_{S_R} = 2N_{CC} \left( c_{LR4} + \hat{c}_{LR8} \right), \]
\[ C_T = -N_{CC} \left( c_{S2} + \hat{c}_{S6} \right), \]

where $N_{CC} = \frac{1}{2V_{cb} \Lambda^2}$, $C_L = 2c_{LL2} - \hat{c}_{LL6} + \hat{c}_{LL7}$ and $\hat{C}_R = -\frac{1}{2} \hat{c}_{Y4}$. 
List of minimal $\chi^2$ values

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\chi^2_{\text{min}}$</th>
<th># obs.</th>
<th># pars.</th>
<th>central values ($\delta^\tau_{cb}$, $\Delta^\tau_{cb}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$R(D^{(\ast)})$ only</td>
</tr>
<tr>
<td>SM</td>
<td>23.1</td>
<td>2</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>S1</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>$(0.2 + 0.7i, 10.0 - 6.3i)$</td>
</tr>
<tr>
<td>S1 real</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>$(0.4, -3.6)$</td>
</tr>
<tr>
<td>$g^c_{\text{b}^{\tau}}^L$</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>$g^c_{\text{b}^{\tau}}^L = -1.3 - 0.6i$</td>
</tr>
<tr>
<td>$g^c_{\text{b}^{\tau}}^R$</td>
<td>9.1</td>
<td>2</td>
<td>2</td>
<td>$g^c_{\text{b}^{\tau}}^R = 0.3 + 0.1i$</td>
</tr>
<tr>
<td>$g_{V_L}$</td>
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<tr>
<td>SM</td>
<td>65.9</td>
<td>61</td>
<td>4</td>
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<tr>
<td>S1</td>
<td>49.2</td>
<td>61</td>
<td>8</td>
<td>$(0.4 + 0.1i, -2.4 + 0.1i)$</td>
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<tr>
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<td>61</td>
<td>6</td>
<td>$(0.4, -2.4)$</td>
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<td>61</td>
<td>6</td>
<td>$g^c_{\text{b}^{\tau}}^L = -0.4 + 0.8i$</td>
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<td>$g^c_{\text{b}^{\tau}}^R = 0.3 + 0.1i$</td>
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<tr>
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<td>62</td>
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</tr>
<tr>
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