Flavor Physics - A Theory Review

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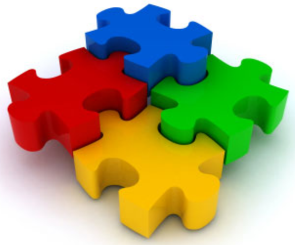
Flavor Introduction

Flavor Is Still a Mystery

Why are there three flavors of quarks and leptons?



What is the origin of the hierarchies in the fermion spectrum?

What is the origin of the hierarchies in the quark mixing?

Is lepton mixing anarchic?

The connection of flavor and new physics is two-fold

(1) The flavor puzzle motivates models of new physics that address some of the mysteries (e.g. fermion mass hierarchies from flavor symmetries, from extra-dimensions, from loops, ...)

(2) Flavor and CP violating processes are highly sensitive probes of new physics (e.g. meson oscillations, $\mu \to e\gamma$, EDMs, rare B decays, ...)

$$\mathcal{L}_{\rm SM} \sim \quad \Lambda^4 + \Lambda^2 H^2 + \lambda H^4$$

$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi$$

CC problem

Hierarchy problem

Vacuum stability?

Strong CP problem

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SM flavor puzzle

Flavor and New Physics

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Hierarchy problem

Vacuum stability?

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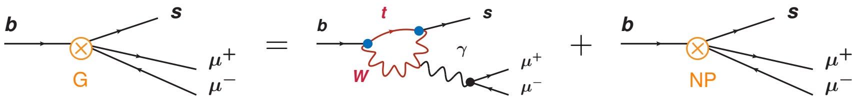
$$+ \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 + F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \frac{1}{\Lambda^2} \sum_i \mathcal{O}_i^{\rm dim6} + \ldots$$

SM flavor puzzle

Neutrino masses

Flavorful new physics?

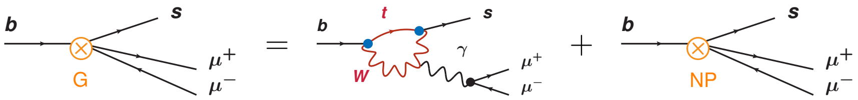


$$G \sim \frac{e^2}{16\pi^2} G_F \frac{m_t^2}{m_W^2} V_{tb} V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

measure precisely

calculate precisely the SM contribution

get information on NP coupling and scale



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"Anomalies" in flavor observables could establish
a new scale in particle physics

Flavor at Circular e^+e^- Colliders

Circular e^+e^- Colliders are Flavor Factories

Running on the Z pole allows one to probe the flavor structure of Z couplings with extreme precision.

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In addition one gets very large samples of all b hadrons, c hadrons, τ's with large boost in a clean environment.

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Running in Higgs factory mode can probe FCNC single top production

$\Rightarrow$ unique sensitivity to a large number of flavor processes that are not accessible at LHC(b) or Belle II

Flavor Violating Z Decays

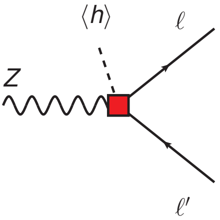
- SM (with neutrino masses) predicts vanishingly small rates. Any observation in the foreseeable future would be a clear sign of new physics.

- Existing Bounds from LEP and LHC around 10^{-6}. Expect sensitivities to improve by $\sim$ 1 order of magnitude at the HL-LHC.

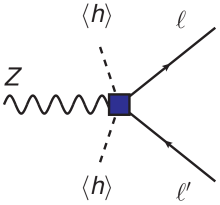
- Expected Sensitivity with 10^{12} Z bosons: preliminary study in the context of FCC-ee (Mogens Dam 1811.09408)
$\mathrm{BR}(Z \to \mu e) \sim 10^{-10}$ and $\mathrm{BR}(Z \to \tau \ell) \sim 10^{-9}$

- Parameterize New Physics in a systematic and controlled way in terms of dim-6 operators of the SMEFT

dipoles



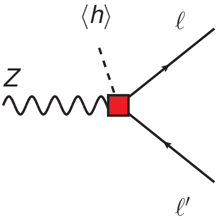
Higgs currents



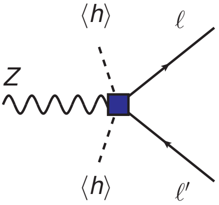
Complementarity with Low Energy Probes

- Parameterize New Physics in a systematic and controlled way in terms of dim-6 operators of the SMEFT

dipoles



Higgs currents



- Many flavor violating low energy processes will be affected as well.
- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).
- Complementary sensitivity in the case of taus.

  (see talk by Lorenzo Calibbi)

b Hadrons from 10^{12} Z bosons

Particle	@ Tera-Z	@ Belle II		@ LHCb
b hadrons				
B^+	6×10^{10}	3×10^{10}	$(50\,\text{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\text{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\text{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}

- CEPC vs. Belle II:
  - similar numbers of B^+ and B^0, but not much B_s and no Λ_b at Belle II.
  - $b\bar{b}$ from Z decays are boosted; efficient b tag from vertexing.
- CEPC vs. LHCb:
  - lower yields at CEPC, but cleaner environment (e^+e^- vs. pp).
  - much better access to final states with neutrals (π^0, γ, ...).

- Rare b decays with taus in the final state are very weakly constrained at the moment.
- Expected sensitivities at LHCb and Belle II still far from the SM predictions.

$$\text{BR}(B_s \to \tau\tau)_{\text{SM}} = (7.7 \pm 0.5) \times 10^{-7}$$ (Bobeth et al. 1311.0903)

$$\text{BR}(B \to K\tau\tau)_{\text{SM}} = (1.2 \pm 0.1) \times 10^{-7}$$ (Du et al. 1510.02349)

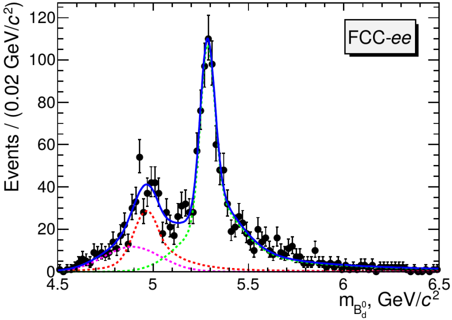
Observables	Belle $0.71\,\text{ab}^{-1}$ $(0.12\,\text{ab}^{-1})$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\text{Br}(B^+ \to K^+\tau^+\tau^-)\cdot 10^5$	< 32	< 6.5	< 2.0
$\text{Br}(B^0 \to \tau^+\tau^-)\cdot 10^5$	< 140	< 30	< 9.6
$\text{Br}(B_s^0 \to \tau^+\tau^-)\cdot 10^4$	< 70	< 8.1	–

(Belle II Physics Book 1808.10567)

$B \to K^* \tau\tau$ at the Z Pole

- Z vertex from primary tracks
- B vertex from $K\pi$
- tau vertices from 3 prong tau decays

$\Rightarrow$ decay can be fully reconstructed



(Kamenik, Monteil, Semkiv, Silva 1705.11106)

- with 10^{12} Z bosons expect O(50) reconstructed $B \to K^* \tau\tau$ events
- backgrounds? (see talk by Lingfeng Li in the BSM session)

The Decays $B_c \to \ell\nu$

- Measuring $B_c \to \ell\nu$ branching ratios offers determinations of V_{cb} without form-factor uncertainties.

- Ratios of branching ratios are a probe of lepton universality of the weak interactions

$$\text{BR}(B_c \to \tau\nu) : \text{BR}(B_c \to \mu\nu) : \text{BR}(B_c \to e\nu) = m_\tau^2 : m_\mu^2 : m_e^2$$

- Signature of $B_c \to \ell\nu$:
  on signal side single charged track + missing energy
  Precision measurements of $B_c \to \tau\nu$ should be possible.
  (see talk by Taifan Zheng)

Taus at the Z pole

Particle	@ Tera-Z	@ Belle II	
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$

- Similar statistics w.r.t. Belle II, but larger boost at Z pole
- Lepton universality tests in tau decays

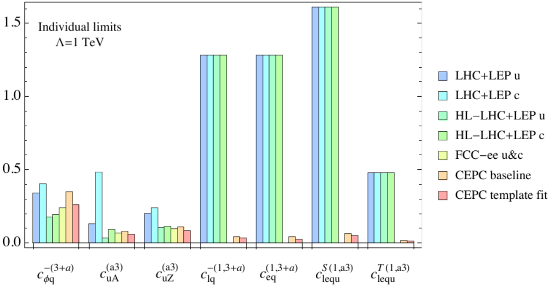
$$\frac{\mathrm{BR}(\tau \to \mu\nu\nu)}{\mathrm{BR}(\tau \to e\nu\nu)} = 0.9796 \pm 0.0016 \pm 0.0036$$ (BaBar 0912.0242)

  enormous statistics should help with the systematics (10^{-3}? 10^{-4}?).

- Flavor violating tau decays ($\tau \to \ell\gamma$, $\tau \to 3\ell$, $\tau \to \ell$ hadrons, ...)

  Current limits (mainly) from B factories at the level of 10^{-7} to 10^{-8}.
  Sensitivity improves by 1-2 orders of magnitude at Belle II.
  Should be comparable at CEPC/FCC-ee.

- Running in Higgs factory mode (240 GeV) is not sufficient for $t\bar{t}$ production. But, single top production possible in the presence of non-standard flavor violating interactions $(\bar{t}q)(\bar{e}e)$ (negligible in the SM)

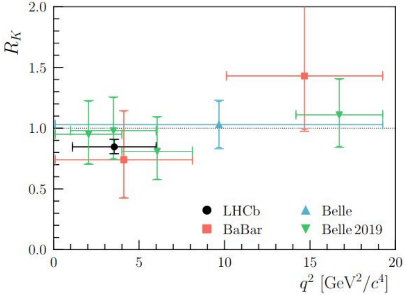


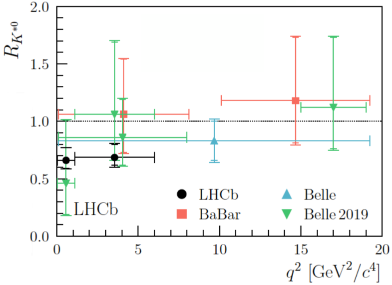
- Four fermion operators $(\bar{t}q)(\bar{e}e)$ can be probed up to several TeV

(Shi, Zhang 1906.04573)

Anomalies in Neutral Current B Decays

R_K and R_{K^*}: Experimental Situation





$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

$$R_K^{[1,6]} = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$$

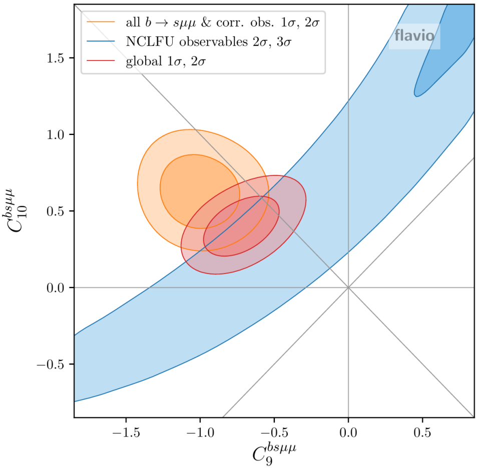
$$R_{K^*}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

3 observables
deviating by $\sim 2\sigma - 2.5\sigma$
from the SM predictions $R \simeq 1$

also: $R_{pK}^{[0.1,6]} = 0.86^{+0.14}_{-0.11} \pm 0.05$

Compatibility with Other $b \to s\mu\mu$ Anomalies



(Peter Stangl @ Beyond the Flavour Anomalies workshop April 1, 2020; update of 1903.10434)

the LFU observables are fully compatible with other anomalies that are seen in $b \to s\mu\mu$ transitions ("P_5' and friends")

Sufficient to describe all $b \to s\ell\ell$ anomalies:

new physics in final states with muons

$$C_9^\mu (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

+SM-like final states with electrons

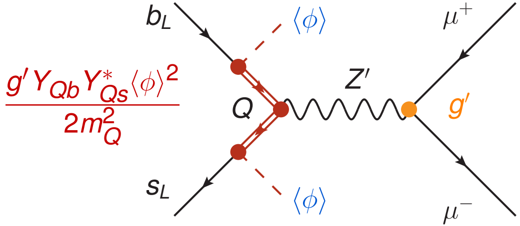
Implications for the New Physics Scale

unitarity bound	$\frac{4\pi}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 120~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb} V_{ts}^* \,(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb} V_{ts}^* \,(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6~\text{TeV} \times (C_9^{\rm NP})^{-1/2}$

(MFV = Minimal Flavor Violation)

Z' based on gauging $L_\mu - L_\tau$
with effective flavor violating couplings to quarks

WA, Gori, Pospelov, Yavin 1403.1269; WA, Yavin 1508.07009



Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

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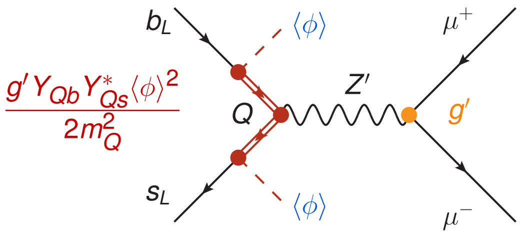


predicted Lepton Universality Violation!

predicts absence of Lepton Flavor Violation

Q: heavy vectorlike fermions with mass $\sim 1 - 10$ TeV
ϕ: scalar that breaks $L_\mu - L_\tau$

see also recent extension of the model that includes flavor universal axial vector currents

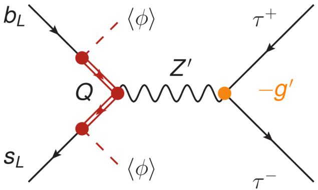
WA, Davighi, Nardecchia 1909.02021

- Many models that address the anomalies in $R_{K^{(*)}}$ predict characteristic effects in $b \to s\tau\tau$

- Model with gauged $L_\mu - L_\tau$ predicts
  (WA, Gori, Pospelov, Yavin 1403.1269)

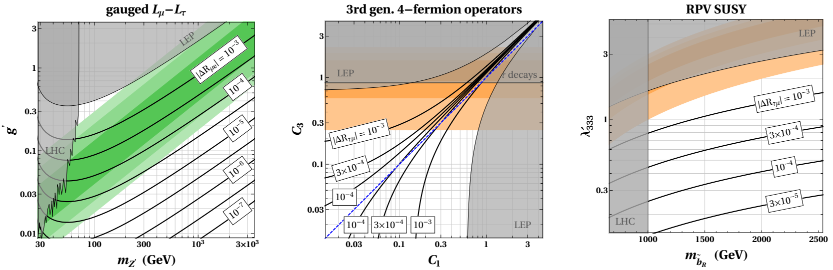
  BR($B_s \to \tau\tau$) is SM-like

  BR($B \to K^{(*)}\tau\tau$) is enhaced by $\sim$ 25% with respect to SM



- Some leptoquark models predict order of magnitude enhanced $b \to s\tau\tau$ transitions. (see talk by Andreas Crivellin)

- Most models that address the anomalies in $R_{K^{(*)}}$ (and $R_{D^{(*)}}$) predict lepton flavor universality violation in Z decays
- With 10^{12} Z bosons, statistics is not an issue.
- Key is the control of systematic uncertainties ($e/\mu/\tau$ efficiencies).
- relative BR measurements with 10^{-4} could probe essentially all parameter space of many models that explain R_K, R_{K^*}, R_D, R_{D^*}.

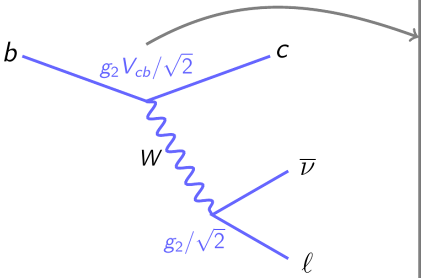


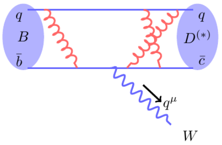
(WA, unpublished)

Anomalies in Charged Current B Decays

(slides prepared by Dean Robinson)

Semileptonic Decays: $b \to c\ell\nu$





NB: Hadronic decays:

$B \to D^{(*)}$ (spin 0, 1)

$\Lambda_b \to \Lambda_c$ (spin 1/2)

...

- Tree-level W exchange (in the SM)
- Approx. 25% of all B decays: huge statistics!
- Theoretically clean:

Probe of lepton flavor universality ($\ell = e, \mu, \tau$) up to masses: PS and FF effects

Measurement of $|V_{cb}|$ inclusively (OPE)

Hadronic matrix elements $\Longrightarrow$ measure $|V_{cb}|$ in exclusive modes

$|V_{cb}|$ anomaly

Inclusive $B \to X_c l \nu$ versus exclusive $B \to D^* l \nu$ $(l = e,\ \mu)$

$$|V_{cb}|_{X_c} \simeq (42.2 \pm 0.8) \times 10^{-3}$$
$$|V_{cb}|_{D^*} \simeq (38.7 \pm 0.7) \times 10^{-3}$$

A 3σ tension?!?

$R(D^{(*)})$ anomaly

Can factor out $|V_{cb}|$, and measure the ratios

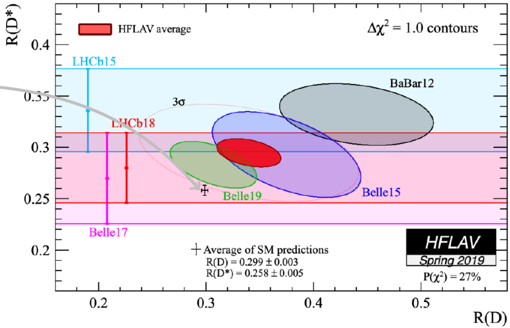
$$R(D^{(*)}) \equiv \frac{\Gamma[B \to D^{(*)}\tau\nu]}{\Gamma[B \to D^{(*)}l\nu]}, \qquad l = e, \mu\,.$$

Persistent signals lepton flavor universality violation for 8+ years

SM prediction

$\sim$ 20-30% tension at $\sim 3.1\sigma$ level with SM predictions

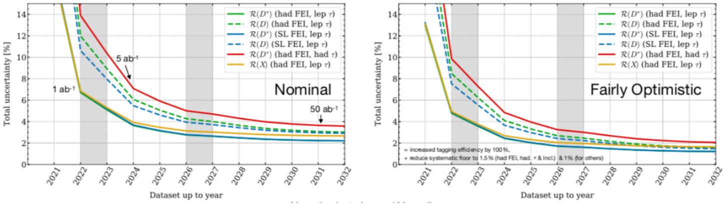
(was 4σ < March 2019)



Also mild anomaly in $B_c \to J/\psi\tau\nu$, and (possibly) in $B \to X_c\tau\nu$.

Future precision/measurements

- Belle II will likely achieve percent level precision in measurements of $R(D^{(*)})$.



Rough estimates of stat+sys uncertainties folded with lumi profile.

[Courtesy F Bernlochner]

- Can a future Tera-Z machine do better? Unclear....
  - Belle II: Will produce 10^{11} $B\overline{B}$ pairs; similar precision to LHCb including efficiencies etc
  - Tera-Z: Roughly few $\times\ 10^{10}$ $B\overline{B}$ pairs
- But....

"Golden"(?) Alternatives

Two important processes for $|V_{cb}|$ and LFUV ratios; neither will likely be measured at Belle II

1. $B_c \to \tau\nu$
   - Approx few $\times 10^9$ B_c produced at a Tera-Z machine (approximately 10^{12} at LHCb, but much less clean!)
   - $B_c \to J/\psi\ell\nu$ will be well-measured by LHCb, but $B_c \to \tau\nu$ is hard (2+ missing neutrinos)
   - Theoretically extremely clean for $|V_{cb}|$ (only uncertainty from f_{B_c})
   - Chiral suppression makes μ, e modes hard measure, but will set strong contraints on (pseudo)scalar NP operators

$$\Gamma[B_c \to \tau\nu] = \Gamma_{\rm SM}\left[1 + C_{RL}^V + \frac{m_{B_c}^2}{m_\tau(m_b - m_c)}(C_{LL}^S - C_{RL}^S)\right]^2$$

"Golden"(?) Alternatives

2. $\Lambda_b \to \Lambda_c \ell \nu$
   - Approx 10^{11} Λ_b produced at a Tera-Z machine (approximately 10^{14} at LHCb)
   - Some HQET:
     - The brown muck is in spin-0 state: $\frac{1}{2}^+_c \otimes 0^+ = \frac{1}{2}^+$. The $\Lambda_{c,b}$ have the simplest HQET!
     - Corrections to HQ limit enter at $1/m_c^2$. HQ expansion has only 2 unknown hadronic (Isgur Wise) functions at NNLO!
     - Size of one term already measured non-zero at 3σ
   - $\Lambda_b \to \Lambda_c \ell \nu$ might be the theoretically cleanest SL laboratory for precision exclusive $|V_{cb}|$ measurements at a Tera Z facillity. SM prediction $R(\Lambda_c) = 0.3237 \pm 0.0036$ already known to percent level

$b \to u$ Transitions

3. $b \to u\ell\nu$
   - There is a similar inclusive/exclusive tension for $|V_{ub}|$
   - The DCS mode $\Lambda_b \to p\ell\nu$ might be similarly powerful for measuring $|V_{ub}|$ at a Tera Z facillity.
   - Belle II will measure $B \to \pi/\rho\ell\nu$, including LFUV ratios for the τ mode
   - Can one contemplate measuring $B_c \to D^{(*)}\tau\nu$ at a Tera Z facility?

- CEPC has unique sensitivity to a large number of flavor processes that are not accessible at LHC(b) or Belle II.
- Examples: Flavor violating Z decays, Lepton Universality in Z decays, rare $b \to s\tau\tau$ decays, rare $b \to s\nu\nu$ decays, B_c decays, $\Lambda_b \to \Lambda_c \ell\nu$ and $\Lambda_b \to p\ell\nu$ decays, flavor violating tau decays, lepton universality in tau decays, FCNC single top production, ...
- Dream scenario: (1) LHCb/Belle II conclusively establish new physics in $R_{K^{(*)}}$ and/or $R_{D^{(*)}}$; (2) CEPC observes predicted effects in $b \to s\tau\tau$ and $Z \to \mu\mu/Z \to ee$; (3) 100 TeV collider directly discovers the new physics.