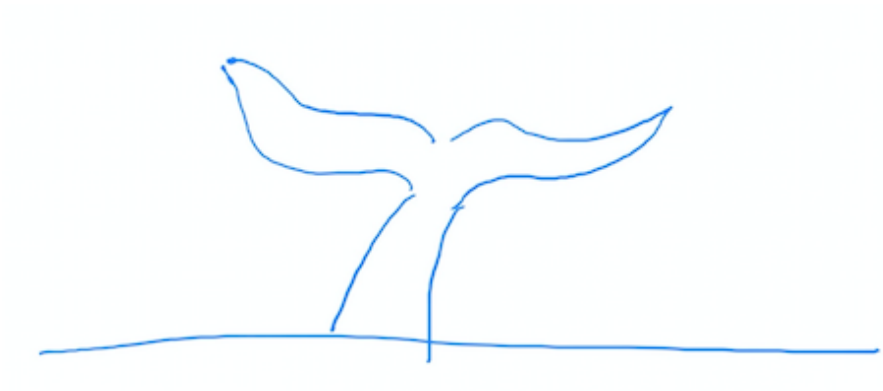
B-Anomalies overview and TH/PH/EX directions



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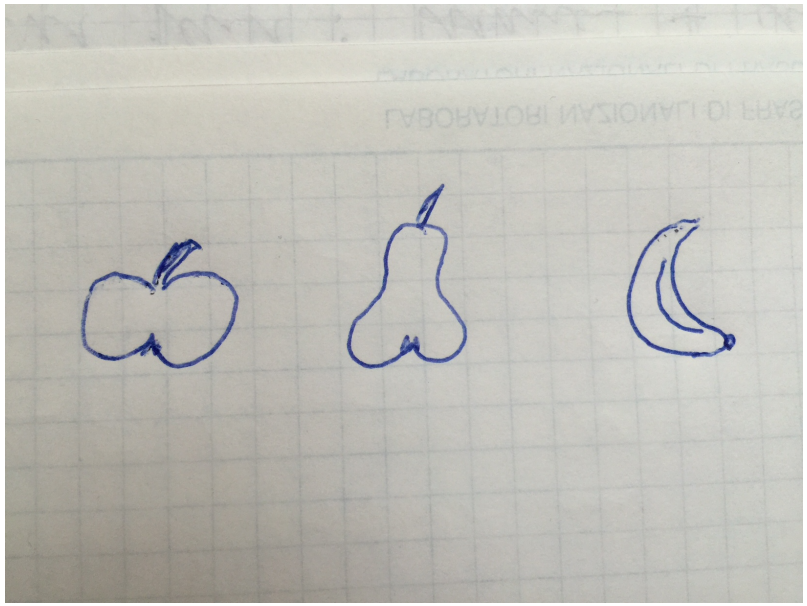
Supported by excellent collaborateurs and the Federal Ministry for Education and Research (BMBF)

about



the same yet not the same

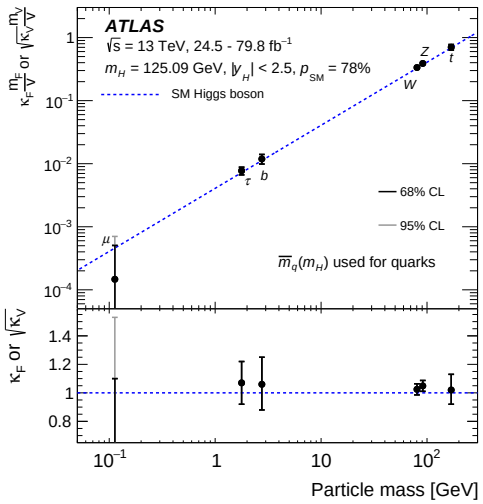
Flavor puzzle

Yukawa coupling Y to Higgs in $\mathcal{L}_{SM} = -\bar{\psi} Y \psi H + ...$ is a 3×3 matrix.

$$Y_u \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix}$$

$$Y_d \sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad Y_e \sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right)$$

very peculiar structure versus universality in gauge interactions $\psi \to \psi_i$, $i = 1, 2, 3$ yukawa plot from 1909.02845



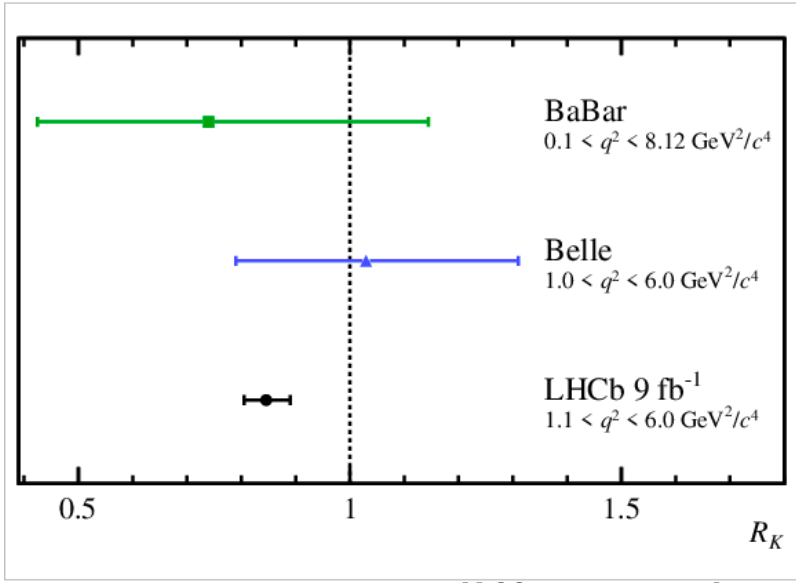
..... the flavor puzzle "origin of flavor" starts into yet another season

flavor is a window to BSM physics

Rare and suppressed processes are great places to look for new physics; Null tests specifically probe SM features. Lepton-universal models (incl. SM): $R_H = 1+$tiny GH, Krüger, hep-ph/0310219

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \text{ same cuts for } e \text{ and } \mu, \quad H = K, K^*, X_s, \ldots$$

3.1σ evidence of new physics in $b \to sll$, non-universality between e's and μ's in $R_K(1.1 < q^2 < 6\,\text{GeV}^2) = 0.846^{+0.044}_{-0.041}$ LHCb 2103.11769



Electrons and muons appear more different than thought.

Flavor anomalies

2 anomalies strengthened in past few months: R_K: 3.1σ new LHCb result 2103.11769 $(g-2)$ of muon 4.2σ– new FNAL result

– rates and angular distributions $b \to s\mu\mu$, $b \to s\gamma$ aka "the global fit"

– R_{K,K^*}: ratio of branching fractions $b \to s\mu\mu$ vs $b \to see$ hep-ph/0310219

– R_{D,D^*}: $b \to c\tau\nu$ vs $b \to c(e,\mu)\nu$

– Cabibbo-angle anomaly V_{us} from $s \to u\mu\nu$ vs $d \to ue\nu$

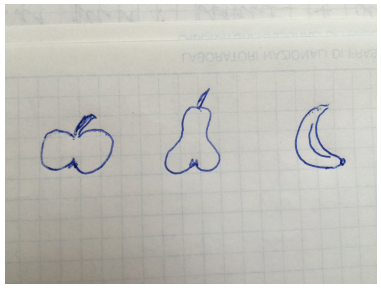
– $(g-2)$ of muon and electron

common denominator: "something with leptons (in low energy data) "

the anomalies require flavor BSM model building and flavorful fits.

Lepton Non-Universality?

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$



Anomalies in semileptonic B-meson decays:

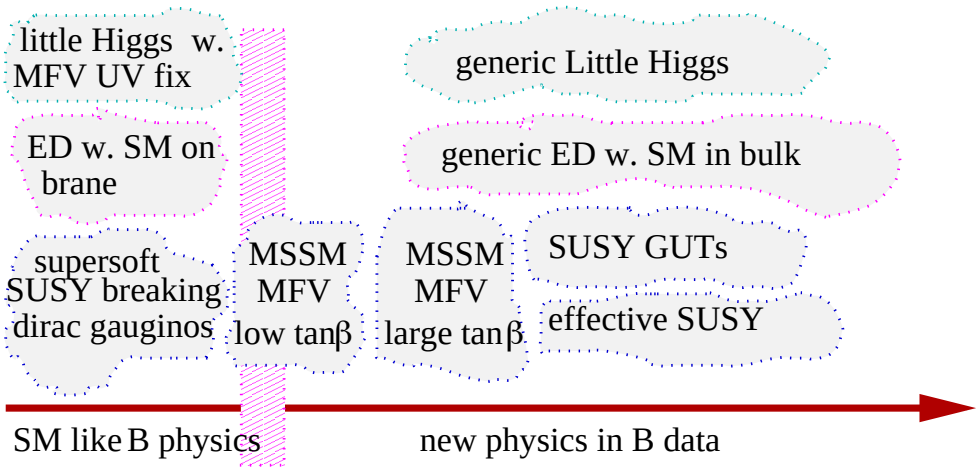
$R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$ 3.1σ (LHCb'14,19,21)

$R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu\mu)}{\mathcal{B}(B \to K^*ee)}$ 2.6σ (LHCb'17)

$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$ $\sim 2.7\sigma$ (D^*), $\sim 2\sigma$ (D)
(LHCb'15,B-factories)

R_K: Impact on model building

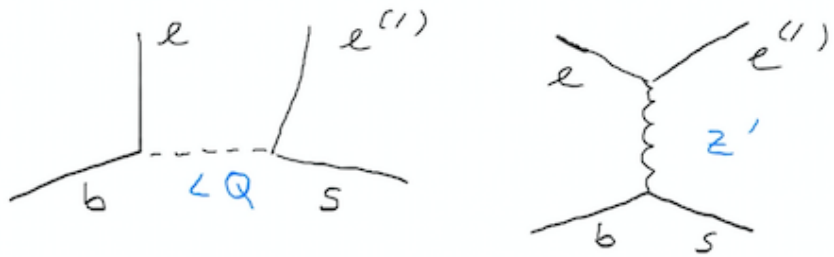
ψ_i may be more different than we thought



model space 2002

2002: top-down models plot from hep-ph/0207121

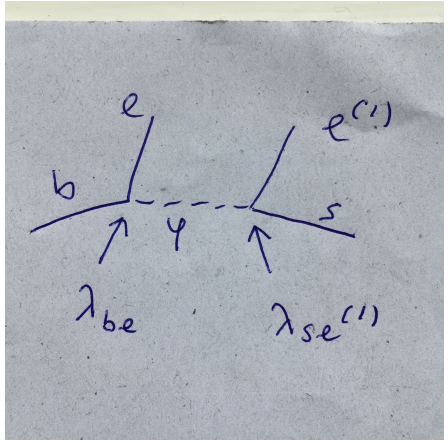
since ∼2014:



theory activities how to get these from UV-models 1708.06450, 1708.06350, 1706.05033, 1808.00942 ..

LFV and other flavor effects

From a flavor perspective, LNU quite generically implies LFV 1411.0565



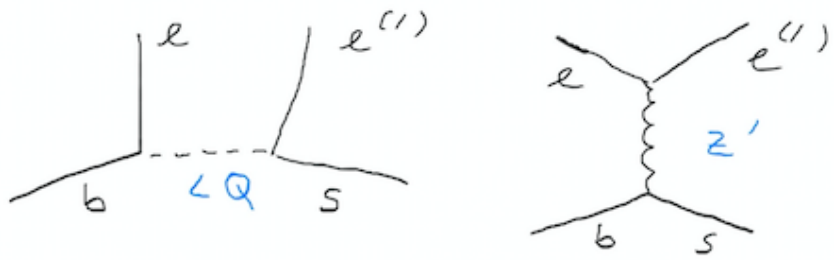
Leptoquark coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$

rows=quarks, columns =leptons

(different from SM-Yukawas; with opportunities for flavor 1503.01084)

Flavor anomalies implications

If lepton flavor universality violation indeed exists as a phenomenon it should show up in other places, too!

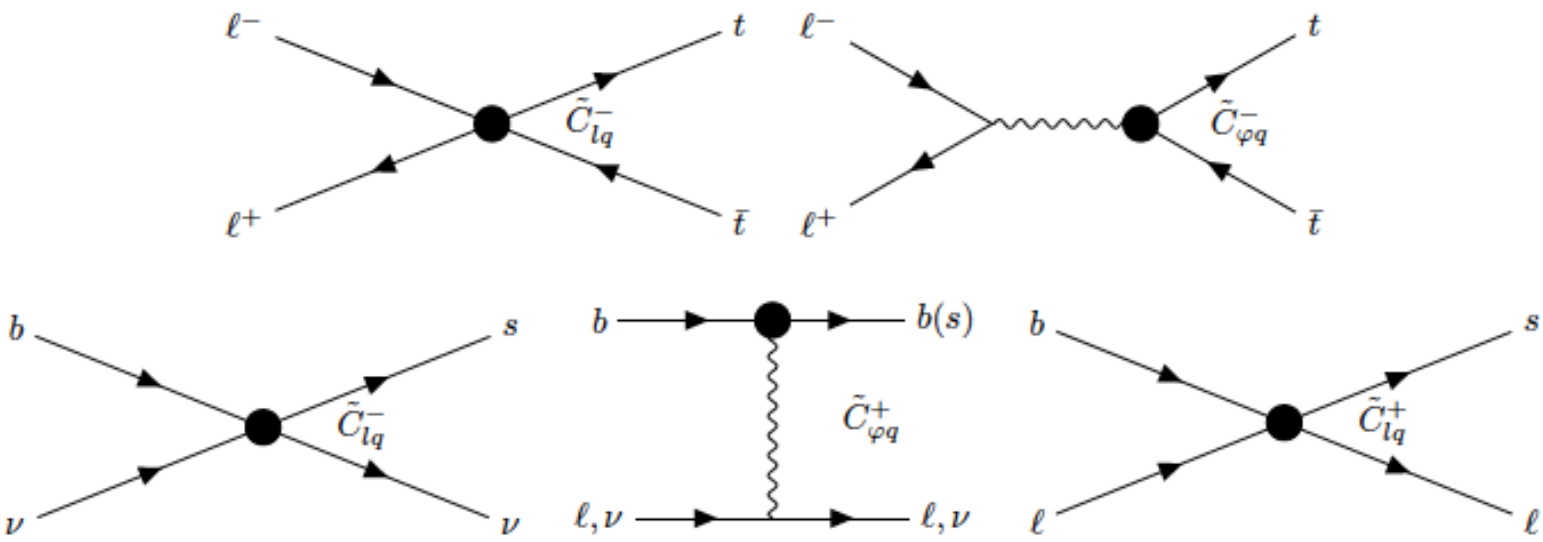


require sizable $O(10-20\%)$ modification of SM amplitudes in $B \to K^{(*)}\ell^+\ell^-$

From a low/weak scale perspective, with NP at TeV or higher, semileptonic 4-fermion operators are switched on; preference to $SU(2)_L$-doublet quarks and supporting doublet leptons:

$\bar{L}L\bar{Q}Q$, $Q = (u_L, d_L)$, $L = (\nu, \ell_L)$
links with dineutrinos and the up-quark sector (all generations).

top and beauty synergies



SMEFT coefficients $C^{\pm} = C^{(1)} \pm C^{(3)}$ top and beauty, leptons and neutrinos, linked and complementary; flat directions are removed

$b \to s\mu\mu$ (LHC), probes C^+

$b \to s\nu\nu$ (BelleII), probes C^- (not observed yet)

$e^+e^- \to t\bar{t}$ (CLIC-like), probes C^- — quark flavor link implied $C_{23} = V_{tb}V^*_{ts}C_{33}$, lepton universality,....

flavor consideration

11 dim 6 operators in fit 2012.10456 . Penguins, dipole operators

$$O_{\varphi q}^{(1)} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}_L \gamma^\mu q_L\right) , \quad O_{\varphi q}^{(3)} = \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{q}_L \tau^I \gamma^\mu q_L\right) ,$$

$$O_{\varphi u} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}_R \gamma^\mu u_R\right) , O_{uG} = \left(\bar{q}_L \sigma^{\mu\nu} T^A u_R\right) \tilde{\varphi} G^A_{\mu\nu} ,$$

$$O_{uB} = \left(\bar{q}_L \sigma^{\mu\nu} u_R\right) \tilde{\varphi} B_{\mu\nu}, O_{uW} = \left(\bar{q}_L \sigma^{\mu\nu} \tau^I u_R\right) \tilde{\varphi} W^I_{\mu\nu},$$

and semileptonic four-fermion operators

$$O_{lq}^{(1)} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{q}_L \gamma^\mu q_L\right) , O_{lq}^{(3)} = \left(\bar{l}_L \gamma_\mu \tau^I l_L\right)\left(\bar{q}_L \gamma^\mu \tau^I q_L\right) , O_{qe} = \left(\bar{q}_L \gamma_\mu q_L\right)\left(\bar{e}_R\right.$$

$$O_{eu} = \left(\bar{e}_R \gamma_\mu e_R\right)\left(\bar{u}_R \gamma^\mu u_R\right) , \quad O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{u}_R \gamma^\mu u_R\right) .$$

Corresponding Wilson coefficients have up to four flavor indices,
for instance $C_{lq}^{(1)klij} \cdot \left(\bar{l}_{Lk} \gamma_\mu l_{Ll}\right)\left(\bar{q}_{Li} \gamma^\mu q_{Lj}\right), \quad i, j, k, l = 1, 2, 3.$

quark flavor considerations

Quark flavor patterns in operators: $\bar{q}_{Li}(..)q_{Lj}$, $\bar{q}_{Li}(..)u_{Rj}$ and $\bar{u}_{Ri}(..)u_{Rj}$.

Top-(beauty)-philic flavor pattern: only $C^{i=3,j=3}$ switched on.

Consider second-third generation only

Top-(beauty)-philic: $C_x^{ij} = C_x^{33} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$ for all 11 ops O_x.

Flavor mixing for doublets q_L: $V_{\rm CKM} = V_u V_d^\dagger$. In up-mass basis $V_u = 1$. $\quad d_L^{\rm mass} = V_{\rm CKM} d_L^{\rm flavor}$

all $\bar{q}_{Li}(..)q_{Lj}$ ops:

$$C_{lq}^{(1,3)}, C_{\varphi q}^{(1,3)}, C_{qe} \propto \begin{pmatrix} |V_{ts}|^2 & V_{tb}V_{ts}^* \\ h.c. & |V_{tb}|^2 \end{pmatrix} \sim \begin{pmatrix} 0 & -0.04 \\ -0.04 & 1 \end{pmatrix}$$

tree level FCNCs; synergies between top and $b \to s$ anomalies

lepton flavor considerations

1. most of todays data, e.g., $b \to s\ell^+\ell^-$, is for $\ell = \mu$. Therefore, most of the results are "lepton-specific" $k = l = 2$.

2. notable exceptions are bounds on dineutrino modes $B(B \to K^{(*)}\nu\bar{\nu}) = \sum_{k,l} B(B \to K^{(*)}\nu_k\bar{\nu}_l)$, which are flavor-summed.

3. To include 2., we assume lepton universality. So, in the semileptonic 4-fermion operators, we assume for the lepton flavor $C^{kl} \propto \delta_{kl}$.

(in view of 1., this is only a mild assumption, however, turns out that $B(B \to K^{(*)}\nu\bar{\nu})$ in particular when observed, is an important constraint)

4. In view of current tensions with R_K etc, it is desirable to perform lepton-specific fits for $ee, \mu\mu$ $(\tau\tau)$ operators as well as LFV ones.

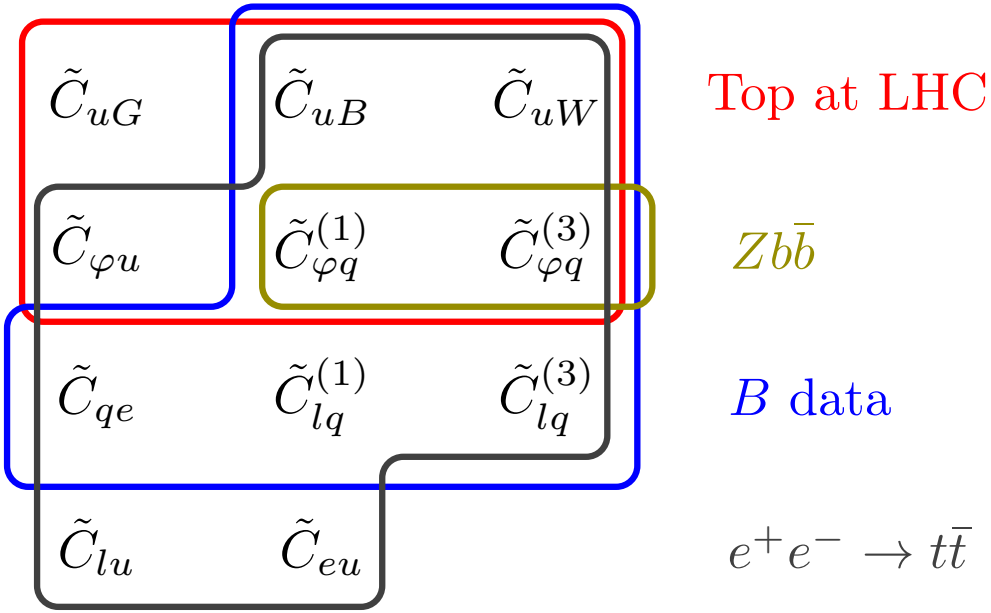
choose your initial state: e^+e^--collider, muon collider are complementary

top and beauty synergies – a global fit

procedure:

scan 11 C_i at $\Lambda = 1$ TeV. 1-loop RGE to m_t, m_W. Matching onto WET, computation of b-observables, flavio, wilson tools

confronting to data; EFT-fitter



Global top-b fit

Process	Observable	Two-fermion operators	sl. four-fermion operators
$pp \to t\bar{t}$	σ^{inc}	$\tilde{C}_{uG}$	-
$pp \to t\bar{t}\gamma$	σ^{fid}	$\tilde{C}_{uB}$, $\tilde{C}_{uW}$, $\tilde{C}_{uG}$	-
$pp \to t\bar{t}Z$	σ^{inc}	$\tilde{C}_{uB}$, $\tilde{C}_{uW}$, $\tilde{C}_{uG}$, $\tilde{C}^{-}_{\varphi q}$, $\tilde{C}_{\varphi u}$	-
$t \to bW$	$F_{0,L}$	$\tilde{C}_{uW}$	-
Top decay	Γ_t	$\tilde{C}^{(3)}_{\varphi q}$, $\tilde{C}_{uW}$	-
$Z \to b\bar{b}$	A^b_{FB}, R_b, σ_{had}	$\tilde{C}^{+}_{\varphi q}$	-
$b \to s\gamma$	BR	$\left[\tilde{C}_{uB}\right]$, $\left[\tilde{C}_{uW}\right]$, $\left\{\tilde{C}_{uG}\right\}$, $\left[\tilde{C}^{(3)}_{\varphi q}\right]$	-
$b \to s\ell^+\ell^-$	BR, A_{FB}, $P_i^{(\prime)}$, ..	$\left[\tilde{C}_{uB}\right]$, $\left[\tilde{C}_{uW}\right]$, $\left\{\tilde{C}_{uG}\right\}$, $\tilde{C}^{+(*)}_{\varphi q}$, $\left[\tilde{C}^{(3)}_{\varphi q}\right]$	$\tilde{C}^{+(*)}_{lq}$, $\tilde{C}^{(*)}_{qe}$
$b \to s\nu\bar{\nu}$	BR	$\tilde{C}^{+(**)}_{\varphi q}$	$\tilde{C}^{-(*)}_{lq}$
Mixing	ΔM_s	$\left[\tilde{C}_{uW}\right]$, $\left\{\tilde{C}_{uG}\right\}$, $\left[\tilde{C}^{(1,3)}_{\varphi q}\right]$	-
$e^+e^- \to t\bar{t}$	σ, A_{FB}	$\tilde{C}_{uB}$, $\tilde{C}_{uW}$, $\left\{\tilde{C}_{uG}\right\}$, $\tilde{C}^{-}_{\varphi q}$, $\tilde{C}_{\varphi u}$	$\tilde{C}_{eu}$, $\tilde{C}_{qe}$, $\tilde{C}_{lu}$, $\tilde{C}^{-}_{lq}$

$b \to s$ and $Zb\bar{b}$-output: now, WET

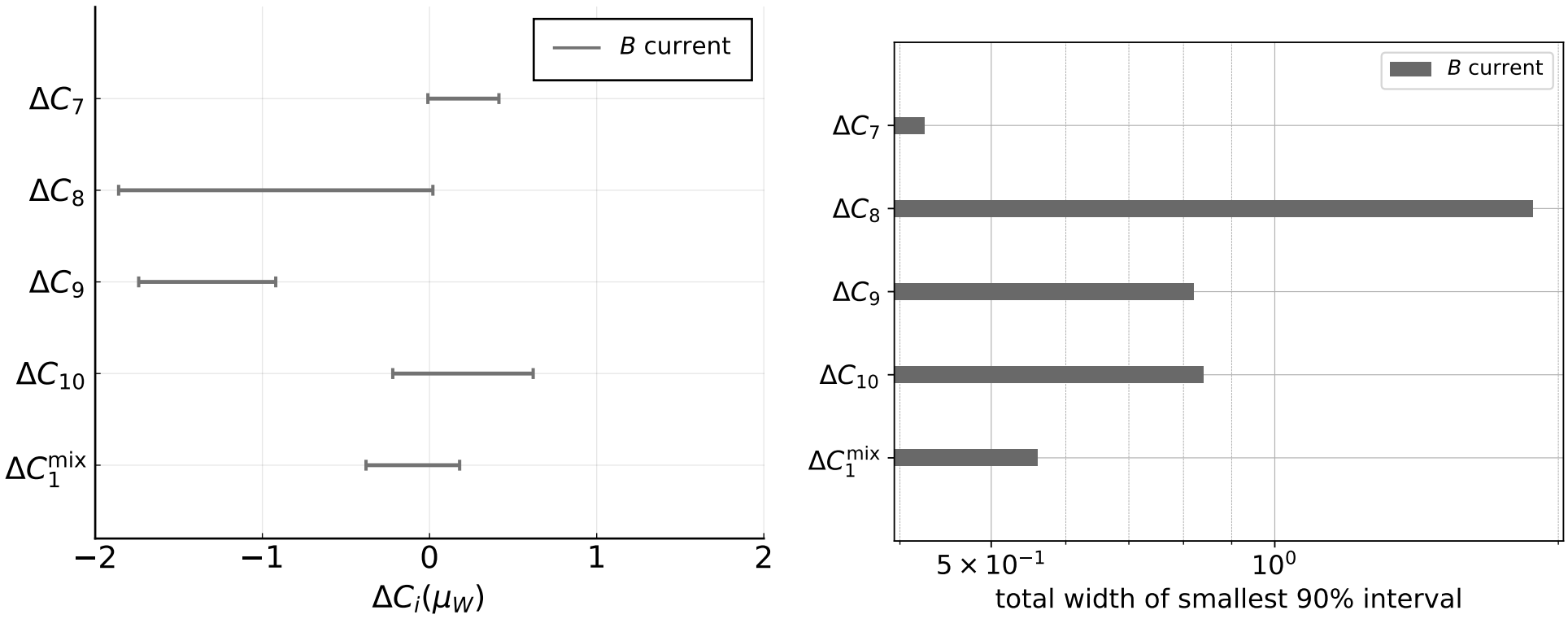


Figure 1: Constraints on WET coefficients ΔC_i at the scale $\mu = \mu_W$. 5 WET-WCs constrained, new physics hint in C_9

$b \to s$ and $Zb\bar{b}$-output: now, SMEFT

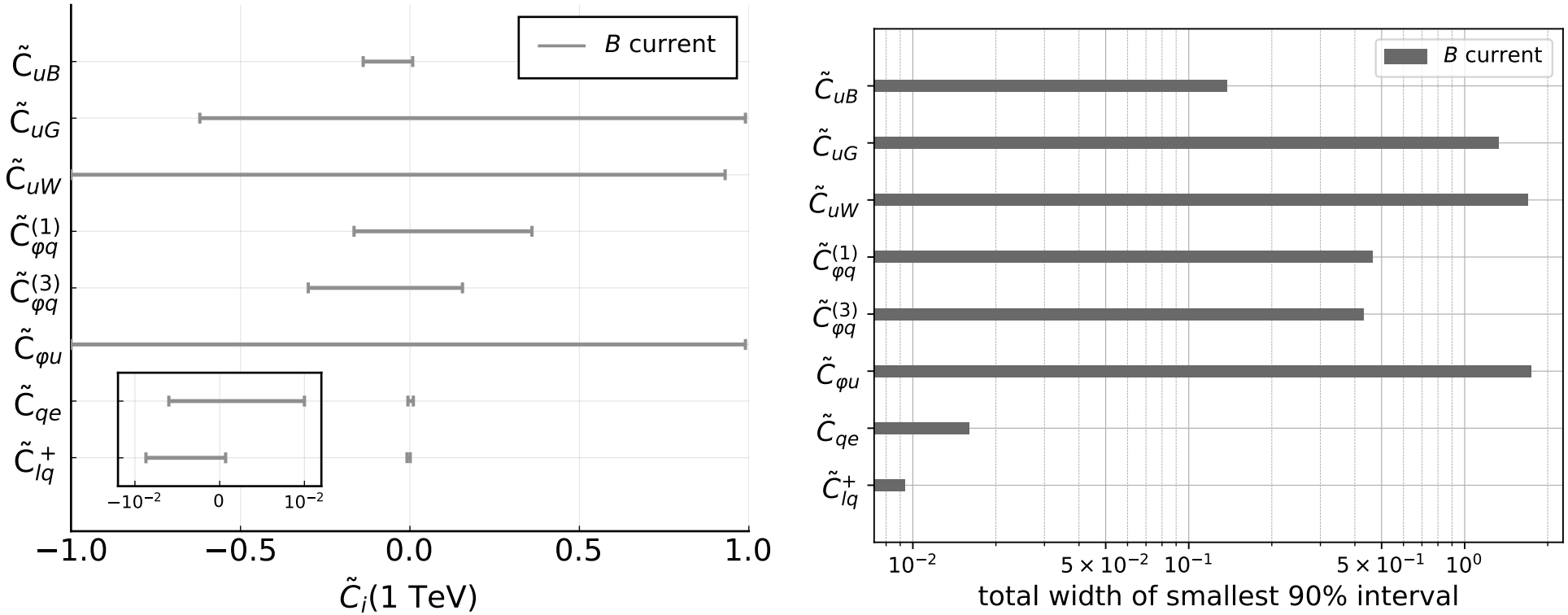


Figure 2: Constraints on SMEFT coefficients (lower plots) from measurements of B observables in Tab. **??**. Shown are the marginalized smallest intervals containing 90 % of the posterior probability (left) and the total width of these intervals (right) obtained in a fit of five WET (upper plots) and eight SMEFT coefficients (lower plots) to the data. 8 SMEFT WCs constrained, incl 2 sl 4-fermis with tight constraints, others (penguins, dipoles) except C_{uB} not too great

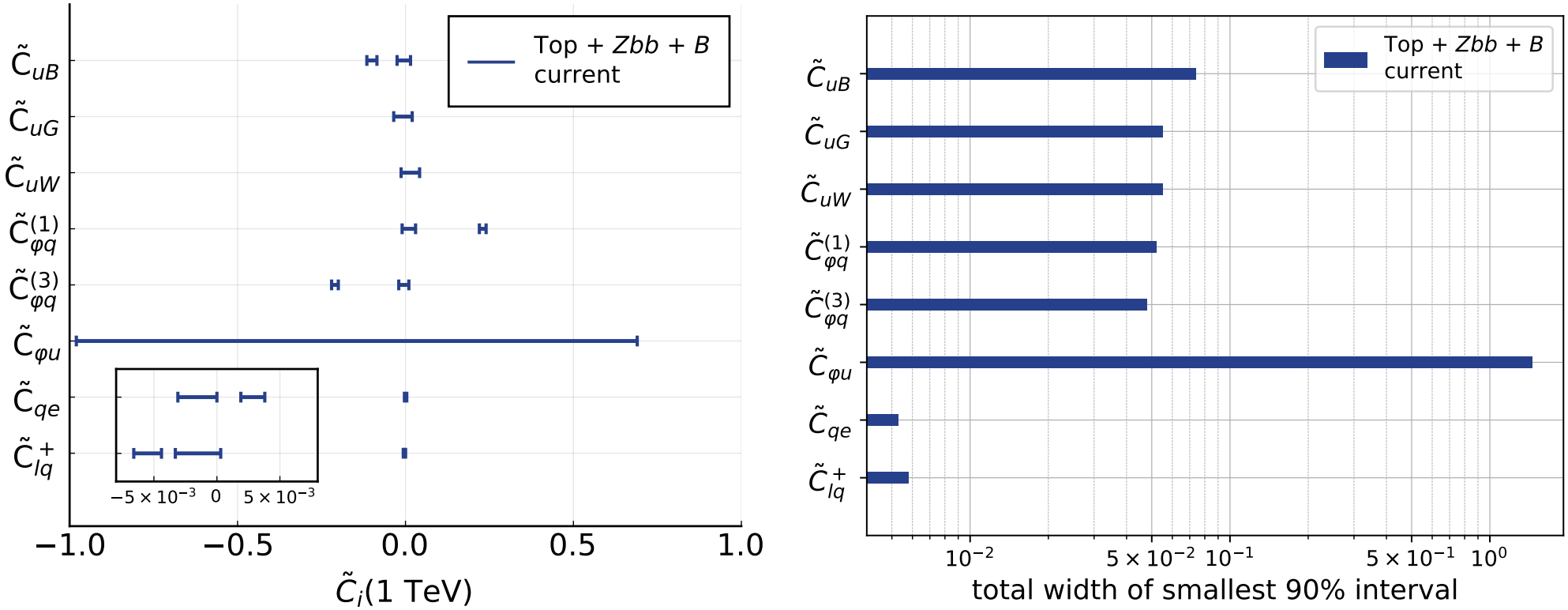


Figure 3: Constraints on SMEFT coefficients $\tilde{C}_i$ in Eq. (**??**) obtained in a fit to top-quark data in Tab. **??**, Zbb data, and B physics data in Tab. **??**. Shown are smallest intervals containing 90 % posterior probability (left) and total width of these intervals (right). For the prior we assume a uniform distribution over the interval $-1 \leq \tilde{C}_i \leq 1$. 8 WCs constrained, including 2 sl 4-fermis, $C^{+}_{lq} \lesssim 10^{-2}$, C_{uB} and penguins improved, $C_{\varphi u}$ still a mess

beauty and top; now

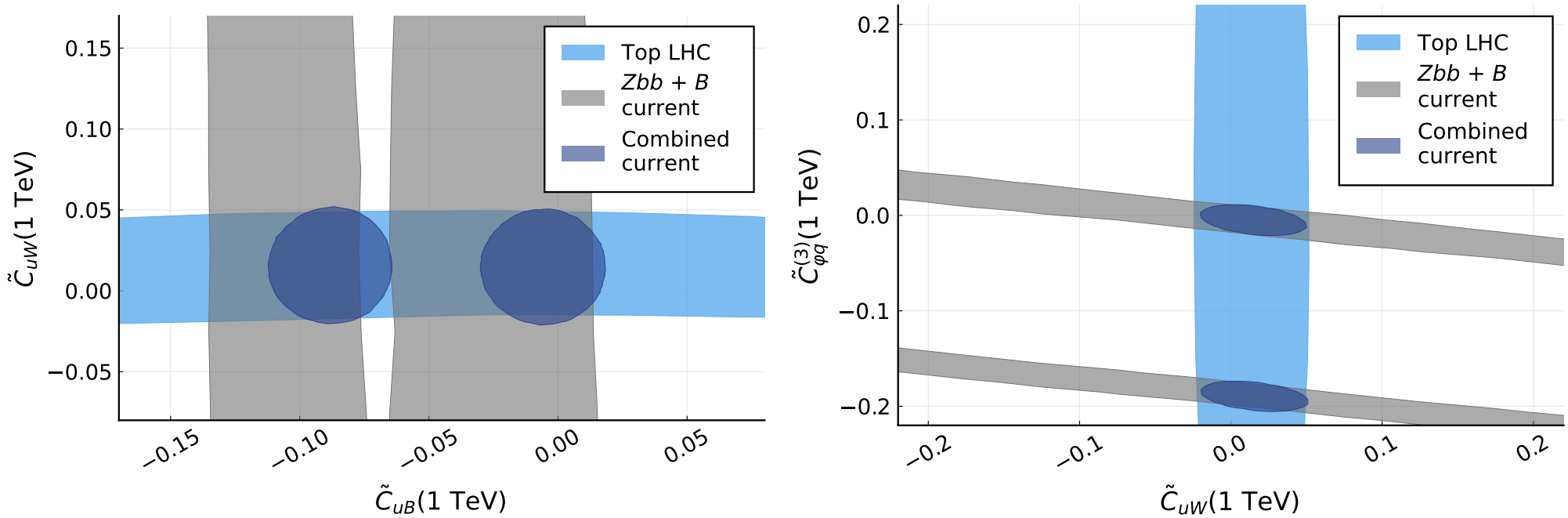


Figure 4: Examples for two-dimensional posterior distributions of SMEFT coefficients $\tilde{C}_i$ in Eq. (**??**) obtained in a fit to top-quark data (light blue), B physics data (grey) and the combined dataset including Zbb data (blue). Shown are the smallest intervals containing 90 % of the posterior distribution. For the prior we assume a uniform distribution over the interval $-1 \leq \tilde{C}_i \leq 1$. synergies at work, see also 1909.13632 for C_{uB}

top-b synergies near: w Belle II+HL-LHC

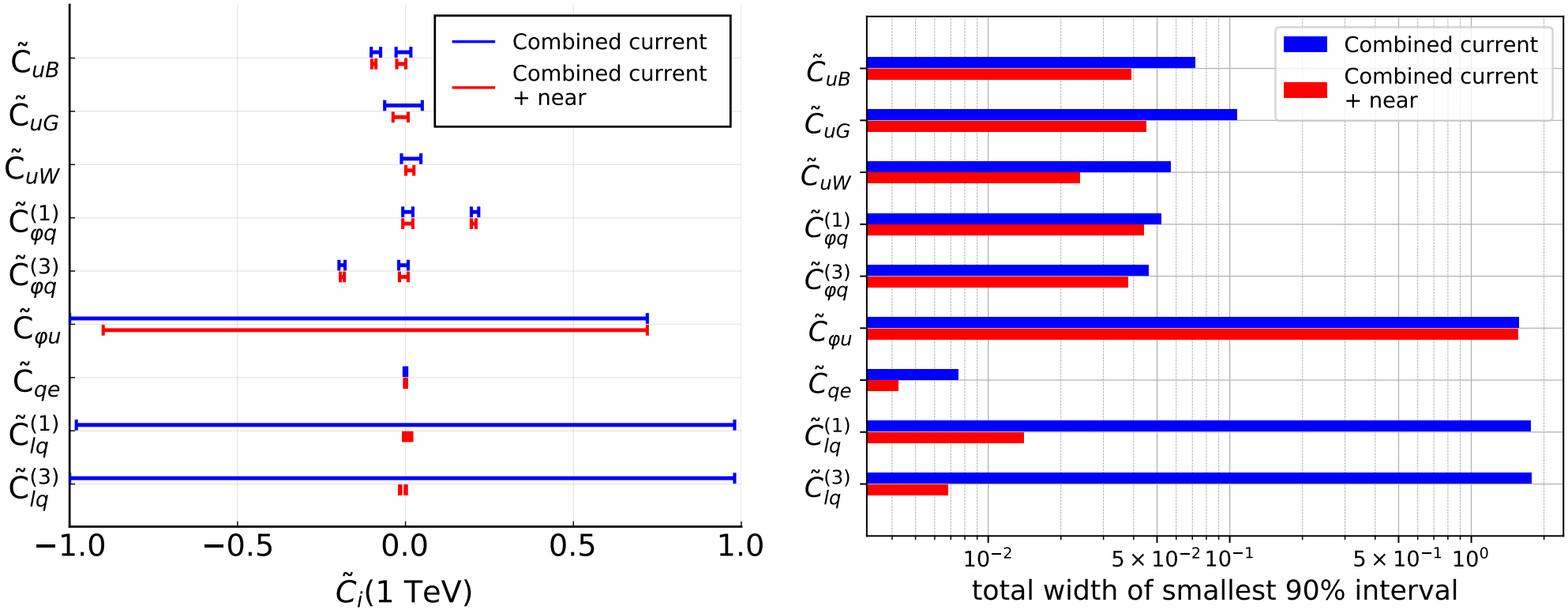
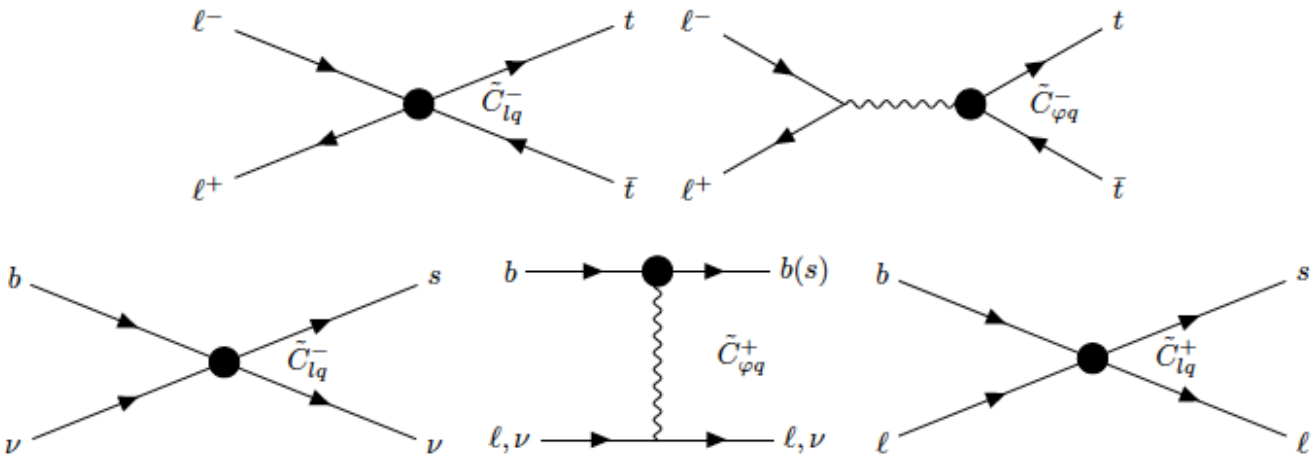


Figure 5: Constraints on coefficients $\tilde{C}_i$ from fits to current top-quark and B measurements in Tabs. **??** and **??** (blue) and to current measurments and projections of top-quark and B observables in Tabs. **??**-**??** (red). Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). 9 WCs constrained; both $C^{\pm}_{lq}$ resolved; BSM solution due to b-anomalies visible in $C^{(1)}_{lq}$ and $C^{(3)}_{lq}$.

top-b synergies future (w CLIC)

Observable	$\sqrt{s}$	Polarization (e^-, e^+)	Ref. experiment
$\sigma_{t\bar{t}}$, A_{FB}	380 GeV	$(80\%, 0)$	Abramowicz:2018
$\sigma_{t\bar{t}}$, A_{FB}	1.4 TeV	$(80\%, 0)$	Abramowicz:2018
$\sigma_{t\bar{t}}$, A_{FB}	3 TeV	$(80\%, 0)$	Abramowicz:2018

Table 1: Observables at different energies and polarizations for $t\bar{t}$ production at CLIC Abramowicz:2018. SM predictions are taken from Durieux:2018tev.



top-b synergies future (Belle II+HL-LHC+CLIC)

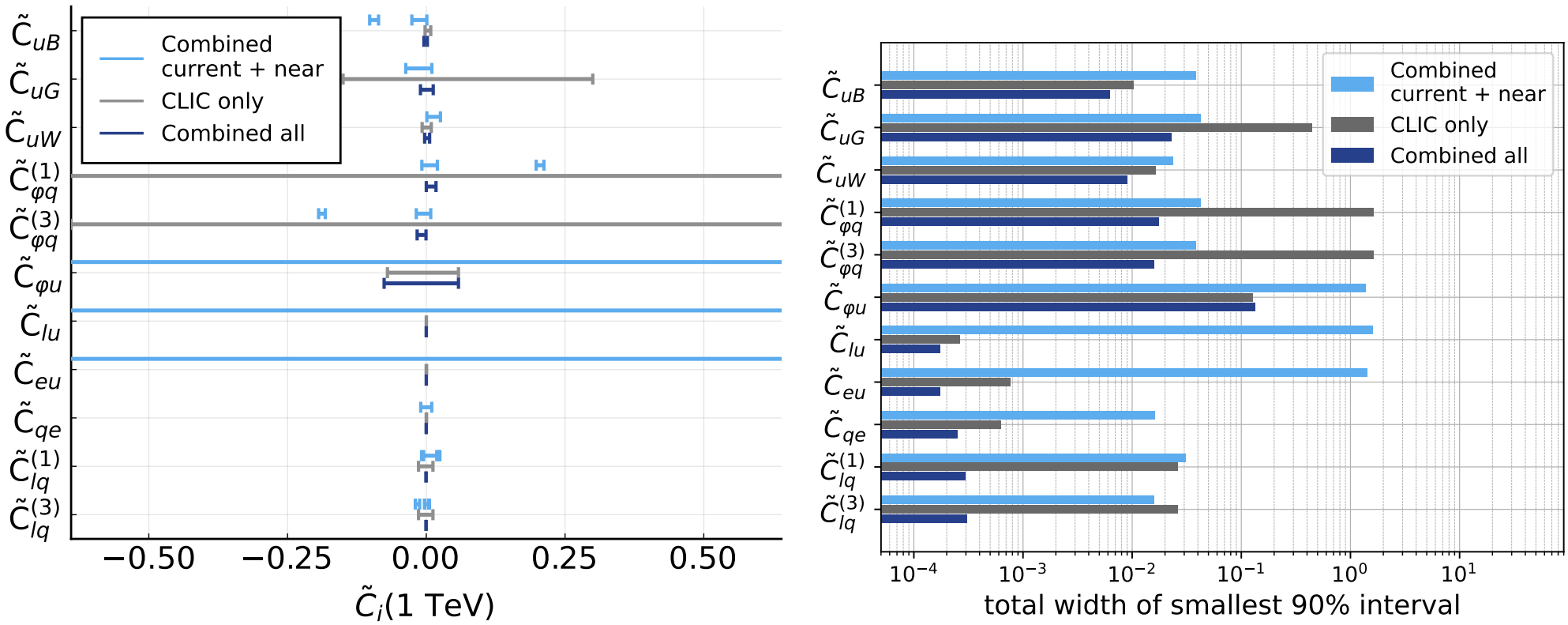
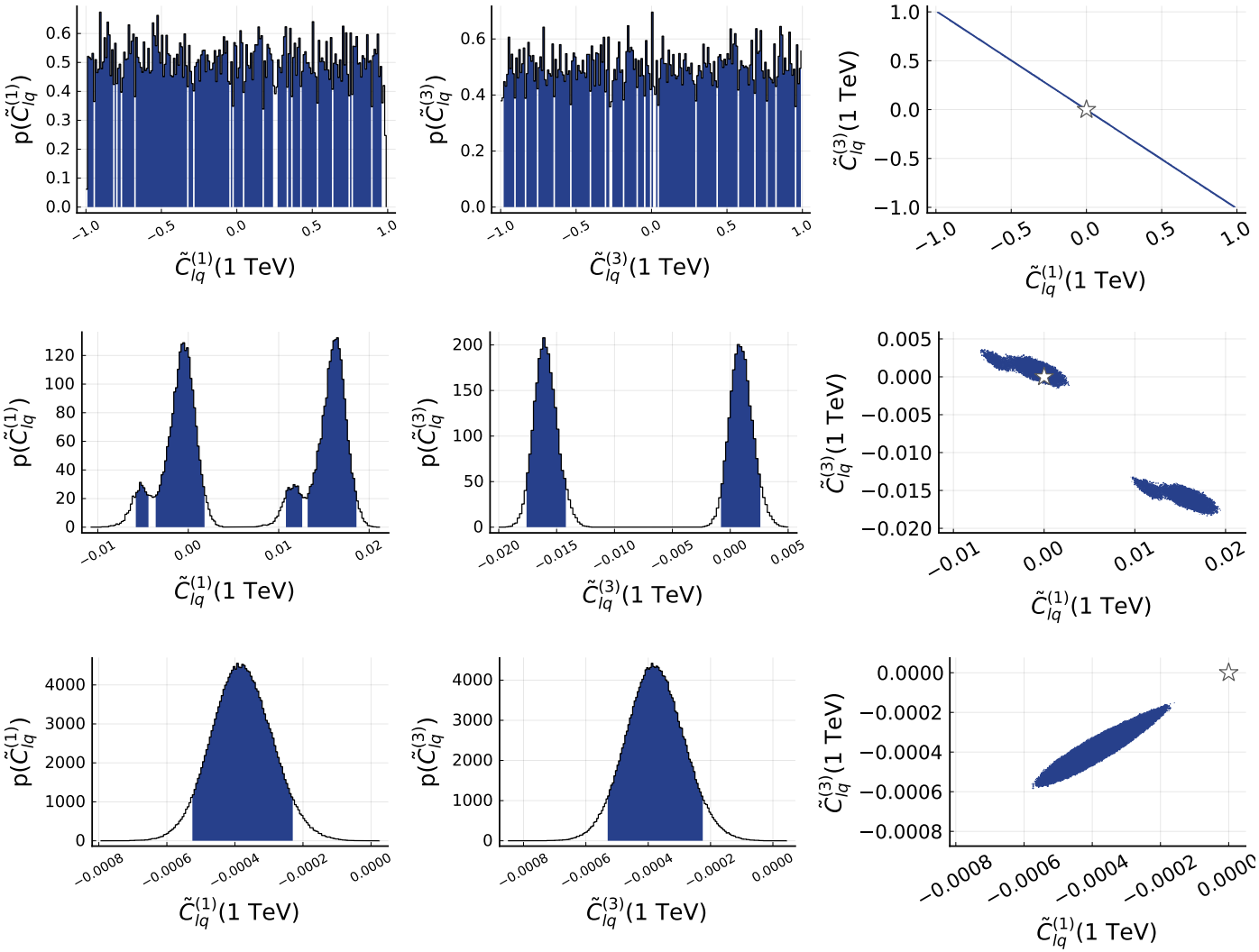


Figure 6: Constraints on coefficients $\tilde{C}_i$ from fits to top-quark and B data and near-future projections at HL-LHC and Belle II in Tabs. **??**-**??** and CLIC future projections in Tab. 1. Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). synergies for semileptonic 4-fermi operators

b-anomalies today, near, far (Belle II+HL-LHC+CLIC)



1D and 2D (right) projections of the posterior distribution for $\tilde{C}_{lq}^{(1)}$ and $\tilde{C}_{lq}^{(3)}$; star denotes SM. b-anomalies become visible in future fit

Testing lepton universality and charged lepton flavor conservation with dineutrino* modes

concrete model-independent proposal 2007.05001 [hep-ph]

application to charm 2010.02225 [hep-ph]

Idea: Use $SU(2)_L$-link for left-handed SM leptons $L = (\nu, \ell)$; assume only SM-like light neutrinos

*neutrino flavors untagged!

PS: there is presently no search for any semileptonic $c \to u\nu\bar{\nu}$ transition, eg $D \to \pi\nu\bar{\nu}$ reported; due to GIM, all of them are nulltests of the SM, and an observation a signal of BSM physics.

Since the neutrino flavors are not tagged, the branching ratio is obtained by an incoherent sum

$$\mathcal{B}\left(c \to u\,\nu\bar{\nu}\right) = \sum_{i,j} \mathcal{B}\left(c \to u\,\nu_i\bar{\nu}_j\right)$$

in terms of Wilson coefficients

$$\mathcal{B}\left(c \to u\,\nu\bar{\nu}\right) = \sum_{i,j} \mathcal{B}\left(c \to u\,\nu_i\bar{\nu}_j\right) \propto \sum_{i,j} |\mathcal{C}_L^{Uij}|^2 + |\mathcal{C}_R^{Uij}|^2$$

with $SU(2)$-links to Wilson coefficients of charged leptons!

$$\mathcal{B}\left(c \to u\,\nu\bar{\nu}\right) \propto \sum_{\nu=i,j} \left(\left|\mathcal{C}_L^{Uij}\right|^2 + \left|\mathcal{C}_R^{Uij}\right|^2\right) = tr\left[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger}\right]$$

$$= tr\left[\mathcal{K}_L^D\mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U\mathcal{K}_R^{U\dagger}\right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j}\left(\left|\mathcal{K}_L^{Dij}\right|^2 + \left|\mathcal{K}_R^{Uij}\right|^2\right) + \mathcal{O}(\lambda)\ ,$$

$\mathcal{K}_L^{Dij}$: coeffs for mass eigenstate charged leptons in $s \to d\ell^{i+}\ell^{j-}$
$\mathcal{K}_R^{Uij}$: coeffs mass eigenstates charged leptons in $c \to u\ell^{i+}\ell^{j-}$

lhs: observable dineutrino branching ratio

rhs: couplings to charged leptons/Wilson coefficients

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto \sum_{\nu=i,j} \left(|\mathcal{C}_L^{U\,ij}|^2 + |\mathcal{C}_R^{U\,ij}|^2 \right) = tr\left[\mathcal{C}_L^U\,\mathcal{C}_L^{U\dagger} + \mathcal{C}_R^U\,\mathcal{C}_R^{U\dagger} \right]$$

$$= tr\left[\mathcal{K}_L^D \mathcal{K}_L^{D\dagger} + \mathcal{K}_R^U \mathcal{K}_R^{U\dagger} \right] + \mathcal{O}(\lambda) = \sum_{\ell=i,j} \left(|\mathcal{K}_L^{D\,ij}|^2 + |\mathcal{K}_R^{U\,ij}|^2 \right) + \mathcal{O}(\lambda)\,,$$

We obtain upper limits on dineutrino branching ratios from upper limits of charged dilepton modes 2007.05001 depending on scenarios

i) $\mathcal{K}_{L,R}^{ij} \propto \delta_{ij}$, that is, *lepton-universality* (LU).

ii) $\mathcal{K}_{L,R}^{ij}$ are diagonal, that is, *charged lepton flavor conservation* (cLFC)

iii) $\mathcal{K}_{L,R}^{ij}$ arbitrary, that is, with charged lepton flavor violation

universality tests with $q \to q' \nu \bar{\nu}$, quantitatively

		ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
sd	$\lvert\bar{\mathcal{K}}^{D\ell\ell'}_{L,R}\rvert$	3.5	1.9	6.7	2.0	6.1	6.6
cu	$\lvert\bar{\mathcal{K}}^{U\ell\ell'}_{L,R}\rvert$	2.9	1.6	5.6	1.6	4.7	5.1
dd	$\lvert\mathcal{K}^{D_{11}\ell\ell'}_{L,R}\rvert$	2.8	1.5	5.5	1.1	3.3	3.6
ss	$\lvert\mathcal{K}^{D_{22}\ell\ell'}_{L,R}\rvert$	9.0	4.9	17	5.2	17	18
bd	$\lvert\bar{\mathcal{K}}^{D_{13}\ell\ell'}_{L,R}\rvert$	4.9	2.7	9.5	3.1	9.7	10
bs	$\lvert\bar{\mathcal{K}}^{D_{23}\ell\ell'}_{L,R}\rvert$	13	7.0	25	8.0	27	30

Upper limits on leptonic couplings $\bar{\mathcal{K}}_{L,R}$ from high–p_T Fuentes-Martin et al 2020 ,Angelescu et al 2020. The last two rows show limits on down sector couplings involving b-quarks. LFV-bounds are quoted as charge-averaged, $\sqrt{|\bar{\mathcal{K}}^{\ell^+\ell'^-}|^2 + |\bar{\mathcal{K}}^{\ell^-\ell'^+}|^2}$.

muon bounds are the best

universality tests with $c \to u\nu\bar{\nu}$, quantitatively

including CKM-corrections $\mathcal{C}_L^U = W^\dagger \mathcal{K}_L^D W + \mathcal{O}(\lambda), \;\; \lambda \simeq V_{us} \sim 0.2$

$$R^{\ell\ell'} = |\mathcal{K}_L^{D12\ell\ell'}|^2 + |\mathcal{K}_R^{U12\ell\ell'}|^2 , \qquad R_\pm^{\ell\ell'} = |\mathcal{K}_L^{D12\ell\ell'} \pm \mathcal{K}_R^{U12\ell\ell'}|^2 , \qquad R_\pm^{\ell\ell'} \leq 2\, R^{\ell\ell'}$$

$$\delta R^{\ell\ell'} = 2\,\lambda\, \Re(\mathcal{K}_L^{D12\ell\ell'}\, \mathcal{K}_L^{D22\ell\ell'*} - \mathcal{K}_L^{D12\ell\ell'} \mathcal{K}_L^{D11\ell\ell'*}) < 2\,\lambda\, |\mathcal{K}_L^{D12\ell\ell'}| \left(|\mathcal{K}_L^{D22\ell\ell'}| + |\mathcal{K}_L^{D11\ell\ell'}| \right)$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto 3\, R^{\mu\mu} \lesssim 34\,, \quad \text{(LU)} \tag{1}$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} \lesssim 196\,, \quad \text{(cLFC)} \tag{2}$$

$$\mathcal{B}\,(c \to u\,\nu\bar{\nu}) \propto R^{ee} + R^{\mu\mu} + R^{\tau\tau} + 2(R^{e\mu} + R^{e\tau} + R^{\mu\tau}) \lesssim 716. \tag{3}$$

dimuons have the most stringent bounds and provide the LU-limit.
Lepton flavor limit is violated if measured branching ratio is too large!
Upper limits data-driven, and evolve with charged lepton data.

charm rates at e^+e^- machines

h_c	$f(c \to h_c)$	$N(h_c)$ (a)	$N(h_c)$ (b)
D^0	0.59	$6 \cdot 10^{11}$	$8 \cdot 10^{10}$
D^+	0.24	$3 \cdot 10^{11}$	$3 \cdot 10^{10}$
D_s^+	0.10	$1 \cdot 10^{11}$	$1 \cdot 10^{10}$
Λ_c^+	0.06	$7 \cdot 10^{10}$	$8 \cdot 10^{9}$

Table 2: Charm fragmentation fractions $f(c \to h_c)$ and the number of charmed hadrons h_c, $N(h_c)$, expected at benchmarks with $N(c\bar{c}) = 550 \cdot 10^9$ (a, FCC-ee) and $N(c\bar{c}) = 65 \cdot 10^9$ (b, Belle II with $50\,\text{ab}^{-1}$). In absence of further information for the Ξ_c^+ we use $f(c \to \Xi_c^+) \simeq f(c \to \Lambda_c^+)$.

charm rates at e^+e^- machines

$h_c \to F$	$\mathcal{B}^{\text{max}}_{\text{LU}}$ $[10^{-7}]$	$\mathcal{B}^{\text{max}}_{\text{cLFC}}$ $[10^{-6}]$	$\mathcal{B}^{\text{max}}$ $[10^{-6}]$	$N^{\text{max}}_{\text{LU}}/\eta_{\text{eff}}$	$N^{\text{max}}_{\text{cLFC}}/\eta_{\text{eff}}$	$N^{\text{max}}/\eta_{\text{eff}}$
$D^0 \to \pi^0$	6.1	3.5	13	47 k (395 k)	270 k (2.3 M)	980 k (8.3 M)
$D^+ \to \pi^+$	25	14	52	77 k (650 k)	440 k (3.7 M)	1.6 M (14 M)
$D_s^+ \to K^+$	4.6	2.6	9.6	6 k (50 k)	34 k (290 k)	120 k (1.1 M)
$D^0 \to \pi^0\pi^0$	1.5	0.8	3.1	11 k (95 k)	64 k (540 k)	230 k (2.0 M)
$D^0 \to \pi^+\pi^-$	2.8	1.6	5.9	22 k (180 k)	120 k (1.0 M)	450 k (3.8 M)
$D^0 \to K^+K^-$	0.03	0.02	0.06	0.2 k (1.9 k)	1.3 k (11 k)	4.8 k (40 k)
$\Lambda_c^+ \to p^+$	18	11	39	14 k (120 k)	82 k (700 k)	300 k (2.6 M)
$\Xi_c^+ \to \Sigma^+$	36	21	76	28 k (240 k)	160 k (1.4 M)	590 k (5.0 M)
$D^0 \to X$	15	8.7	32	120 k (980 k)	660 k (5.6 M)	2.4 M (21 M)
$D^+ \to X$	38	22	80	120 k (1.0 M)	680 k (5.8 M)	2.5 M (21 M)
$D_s^+ \to X$	18	10	38	24 k (200 k)	140 k (1.1 M)	500 k (4.2 M)

Table 3: Upper limits on branching ratios $\mathcal{B}^{\text{max}}_{\text{LU}}$, $\mathcal{B}^{\text{max}}_{\text{cLFC}}$ and $\mathcal{B}^{\text{max}}$ corresponding to Eqs. (1), (2) and (3), respectively; expected number of events $N_F^{\text{exp}} = \eta_{\text{eff}}\, N(h_c)\, \mathcal{B}(h_c \to F\,\nu\,\bar{\nu})$ per reconstruction efficiency η_{eff} for Belle II with $50\,\text{ab}^{-1}$ (FCC-ee in parentheses) corresponding to LU, cLFC, and general.

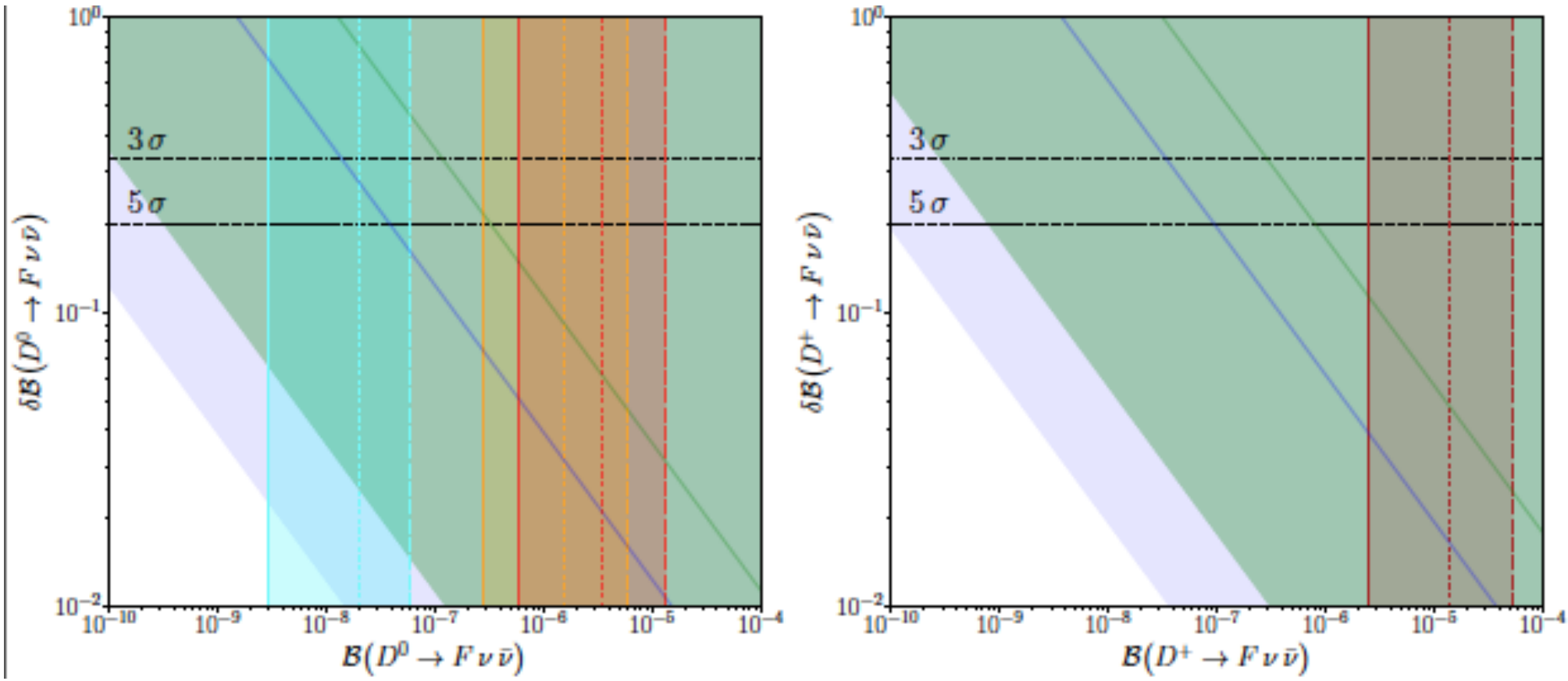


Figure 7: Relative statistical uncertainty $\delta\mathcal{B}$ versus branching ratio $\mathcal{B}$ for decays of the D^0 (upper left), the D^+ (upper right) and the Λ_c^+ (lower plot). Shaded areas correspond to $\eta_{\text{eff}} = 1$, whereas the solid tilted lines illustrate the impact of reconstruction efficiencies $\eta_{\text{eff}} = 10^{-3}$ for the FCC-ee (lilac) and Belle II (green). Horizontal lines indicate $3\,\sigma$ (dotted) and $5\,\sigma$ (dashed) black. Vertical lines represent upper limits assuming LU (solid), cLFC (dotted) and generic lepton flavor (dashed) for different decays. red: $D \to \pi\nu\bar{\nu}$, yellow $D \to \pi\pi\nu\bar{\nu}$, blue: $D \to KK\nu\bar{\nu}$

Summary

- Current anomalies $R_K, R_{K^*}, R_D, R_{D^*}$ in semileptonic B-meson decays hint at violation of lepton-universality – and therefore breakdown of standard model.
  Huge impact on model-building and searches (leptoquarks, Z')
- Future data – LNU updates and others $R_\Phi, R_{Xs}..., B \to K^* ee$ – from LHCb and from Belle II are eagerly awaited.
- New ideas for LNU and cLFC tests with dineutrino modes suitable for Belle II, BES III and Z-factory; Any observation of $c \to u\nu\bar{\nu}$ is new physics.
- Semileptonic 4-fermion operators connect top to b-anomalies; synergies at work Fox et al 2007, Bissmann '21, Brugisser '21

  CMS reports constraints on semileptonic four-fermion operators from tops with leptons 2012.04120; weaker than our bounds for C_{qe}, C_{lq}^-, but CMS also probes C_{eu}, C_{lu} which are presently unconstrained.
- Lepton specific fits (all flavors, including neutrinos) are desirable
- Global fits have sensitivity to flavor —- exploit more flavor links
- Flavor broader and more exciting and fun than ever –stay tuned