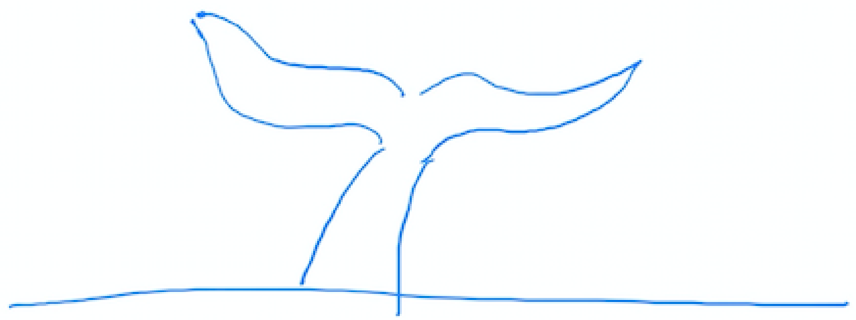
EFT synergies between Top and Beauty



based on works with Stefan Bissmann, Cornelius Grunwald and Kevin Kröninger, 2012.10456 [hep-ph], JHEP 06 (2021) 010, and Rigo Bause, Hector Gisbert and Marcel Golz 2109.01675 [hep-ph].

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Flavor 2021plus

DPG spring meeting March 2021: 6 sessions on flavor physics

NA 62	s
Belle, BaBar	c, b
BES III	c
Belle II	c, b
LHCb	$c, b, (s)$
ATLAS, CMS	b, t (c, s)
Z-factory (CLIC-like)	c, b (t)

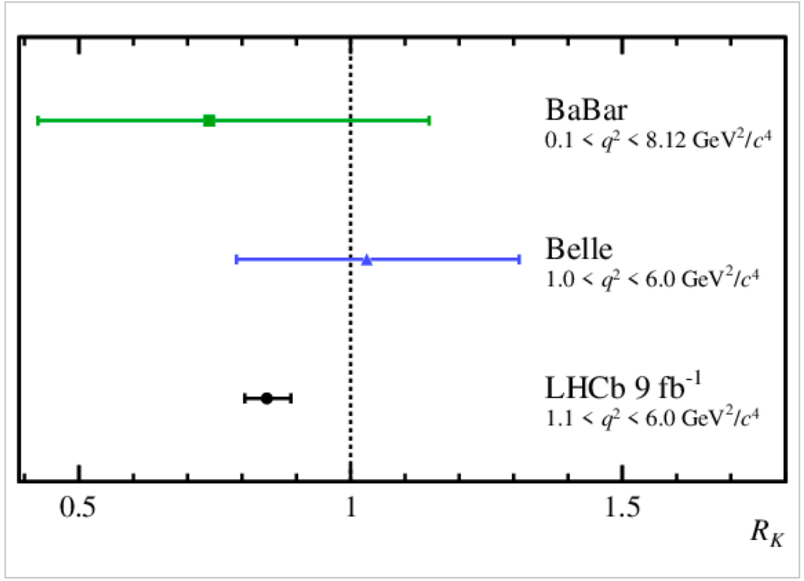
Dream time to be in flavor physics

Flavor is a window to BSM physics

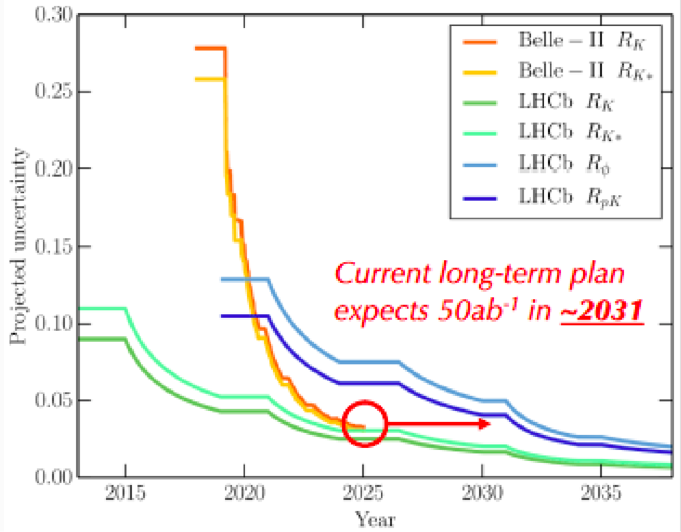
Rare and suppressed processes are great places to look for new physics; Null tests specifically probe SM features. Lepton-universal models (incl. SM): $R_H = 1+$tiny GH, Krüger, hep-ph/0310219

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

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



Nucl. Part. Phys. 46 023001



Current long-term plan expects $50\,\text{ab}^{-1}$ in ~2031

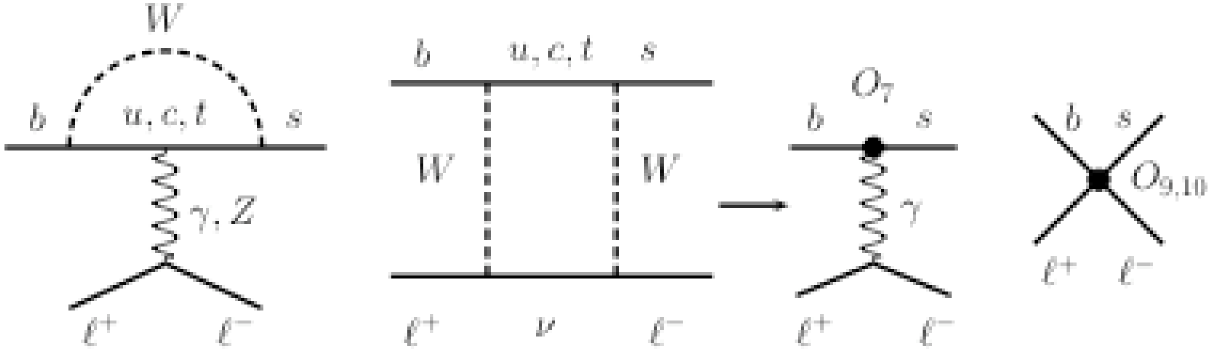
Electrons and muons appear more different than thought.

Flavor anomalies

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

by M.Rama and T.Dong

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



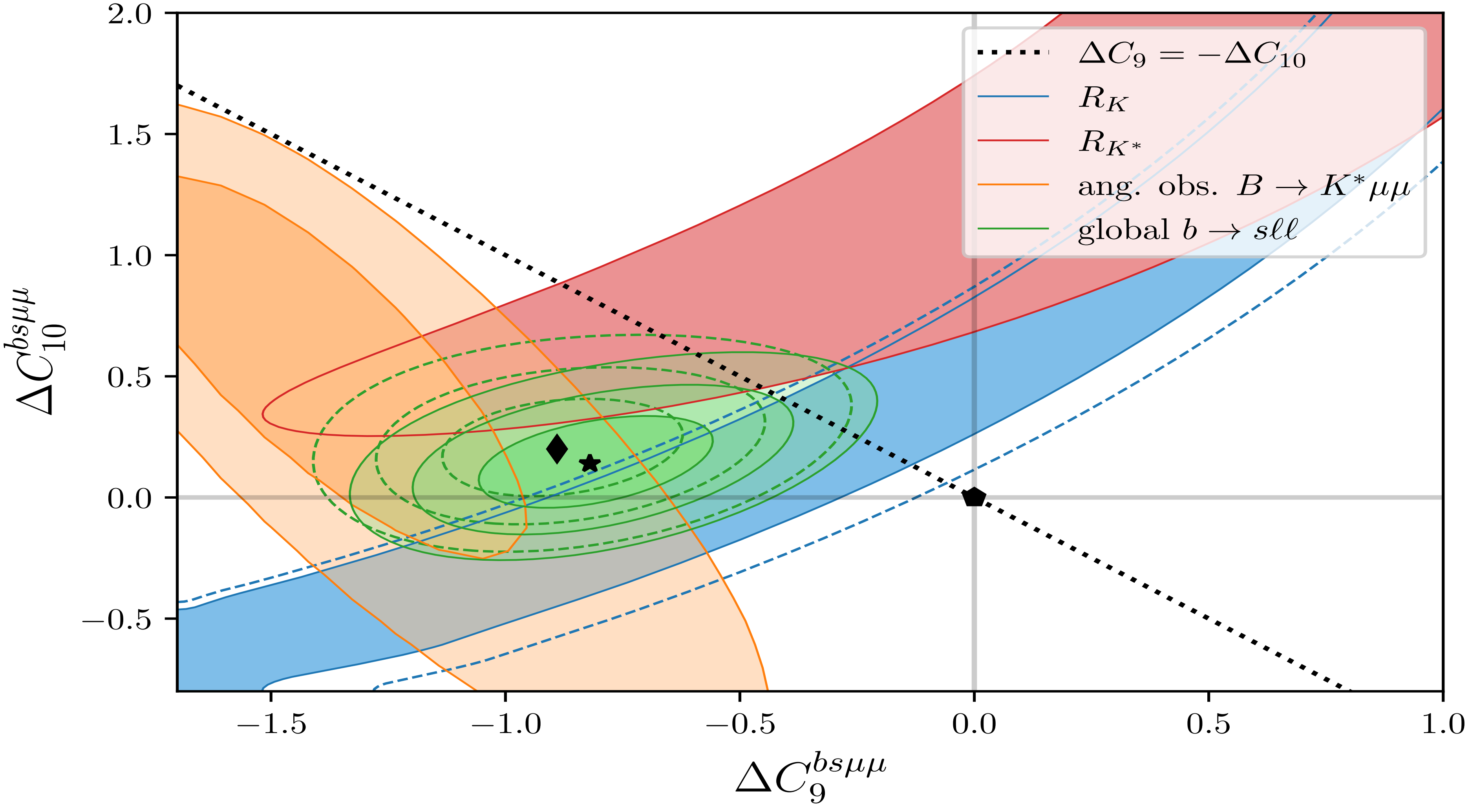
$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu), \qquad G_F/\sqrt{2} = g^2/(8m_W^2) \qquad \text{(”WET”)}$$

$$\mathcal{O}_9^\ell = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10}^\ell = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu\gamma_5 \ell]\,, \qquad \ell = e, \mu, \tau$$

$C_{9\,\text{SM}} \simeq 4.1, C_{10\,\text{SM}} \simeq -4.2$ (lepton universal) $\qquad C_i^\ell = C_{i\,\text{SM}} + \Delta C_i^\ell$

see talks by M.Bordone and M.Kreps at this meeting

2021 global $b \to s$ fit (2104.00015)



$\sim 6\sigma$ pull! (solid green lines, incl R_K from LHCb-March '21)

Moving ahead .... getting more global

towards more global approach across the flavors s, c, b, t...

NA 62	s
Belle, BaBar	c, b
BES III	c
Belle II	c, b
LHCb	c, b, (s)
ATLAS, CMS	b, t

The tool to achieve a cross community global anaysis are effective field theories: Study correlations among multi-observables from different experiments ($B \to K^{(*)}\mu\mu, B_s \to \mu\mu, B \to X_s\gamma$) in WET (the global $b \to s$-fit aka C_7, C_9, C_{10}-fits). ongoing precision program
Use SMEFT to include tops, and exploit unbroken SM symmetries $SU(2)_L \times U(1)_Y$ as a lab for flavor links.

$\mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{v^2} \mathcal{O}_i$ SMEFT operators include tops

joint top and beauty fits: why they work

1. The B-anomalies require NP in semileptonic 4-fermion operators

$$\bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

2. In SMEFT, these are of type[a]

$$\bar{Q}\gamma_\mu Q \bar{L}\gamma^\mu L, \qquad \bar{Q}\gamma_\mu \tau^I Q \bar{L}\gamma^\mu \tau^I L$$

with, by $SU(2)$, $Q_3 = (t_L, b_L)$ and $L = (\nu, \ell_L)$ and so on. That is, a single coupling for different left-handed fermions.

$$C_{lq}^{(1)} \cdot \bar{Q}Q\bar{L}L = C_{lq}^{(1)} \cdot (\bar{t}t\nu\nu + \bar{b}b\ell\ell + \bar{b}b\nu\nu + \bar{t}t\ell\ell)$$
$$C_{lq}^{(3)} \cdot \bar{Q}\tau^3 Q\bar{L}\tau^3 L = C_{lq}^{(3)} \cdot (\bar{t}t\nu\nu + \bar{b}b\ell\ell - \bar{b}b\nu\nu - \bar{t}t\ell\ell)$$

3. It follows a link* between up-type and down-type quarks, as well as charged leptons and neutrinos.

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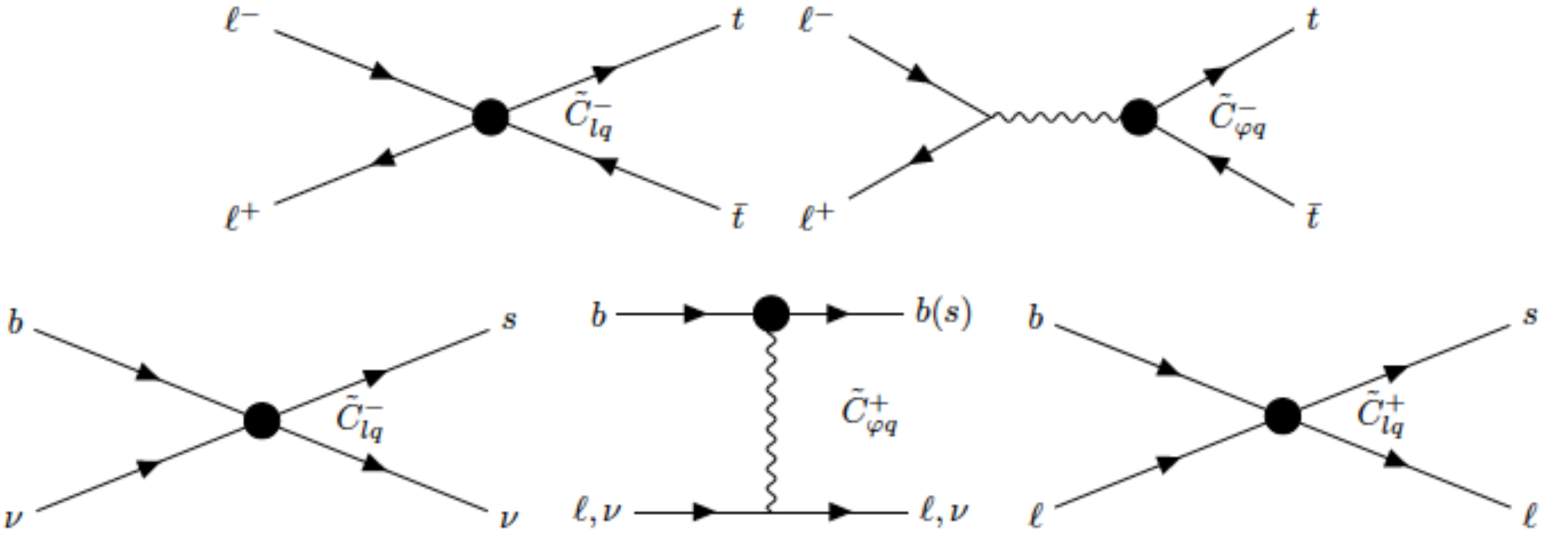
* This link provides test of lepton universality with $B \to K^{(*)}\nu\bar{\nu}$, or $c \to u\nu\bar{\nu}$, 2010.02225, 2109.01675. [a] NP heavier than EWK

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^-

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

preparing the fit: SMEFT operators

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

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

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

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: $V_{\mathrm{CKM}} = V_u V_d^\dagger$. In up-mass basis $V_u = 1$. $d_L^{\mathrm{mass}} = V_{\mathrm{CKM}} d_L^{\mathrm{flavor}}$

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.

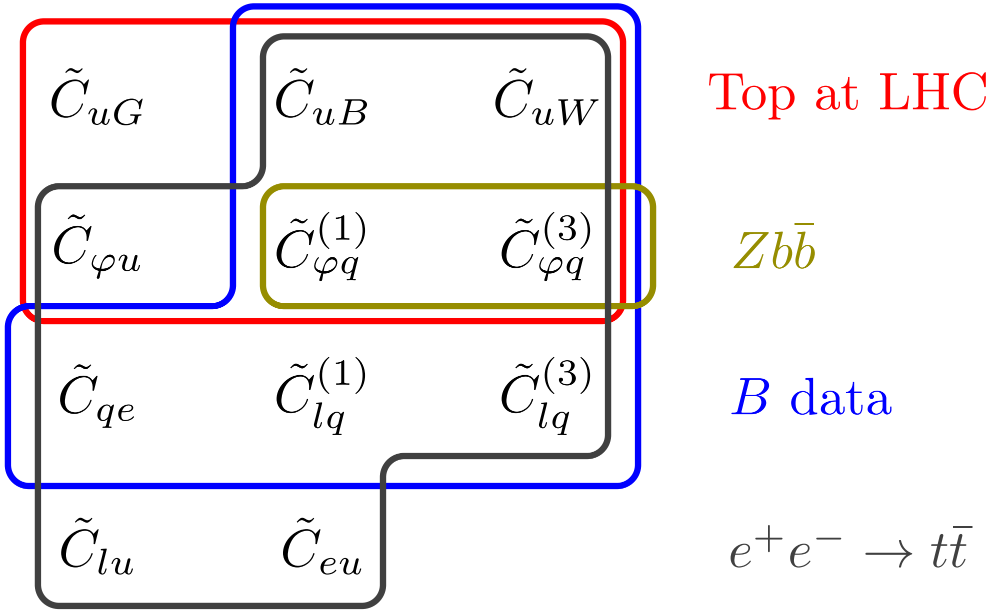
choose your initial state: e^+e^--collider, muon collider are complementary

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



$\tilde{C}_{uG}$ $\tilde{C}_{uB}$ $\tilde{C}_{uW}$

$\tilde{C}_{\varphi u}$ $\tilde{C}^{(1)}_{\varphi q}$ $\tilde{C}^{(3)}_{\varphi q}$

$\tilde{C}_{qe}$ $\tilde{C}^{(1)}_{lq}$ $\tilde{C}^{(3)}_{lq}$

$\tilde{C}_{lu}$ $\tilde{C}_{eu}$

Top at LHC

$Zb\bar{b}$

B data

$e^+e^- \to t\bar{t}$

Global top-b fit: Input and sensitivities

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}	$\tilde{C}_{uB}, \tilde{C}_{uW}, \left\{\tilde{C}_{uG}\right\}, \tilde{C}^{-}_{\varphi q}, \tilde{C}_{\varphi u}$	$\tilde{C}_{eu}, \tilde{C}_{qe}, \tilde{C}_{lu}, \tilde{C}^{-}_{lq}$

top-output: now

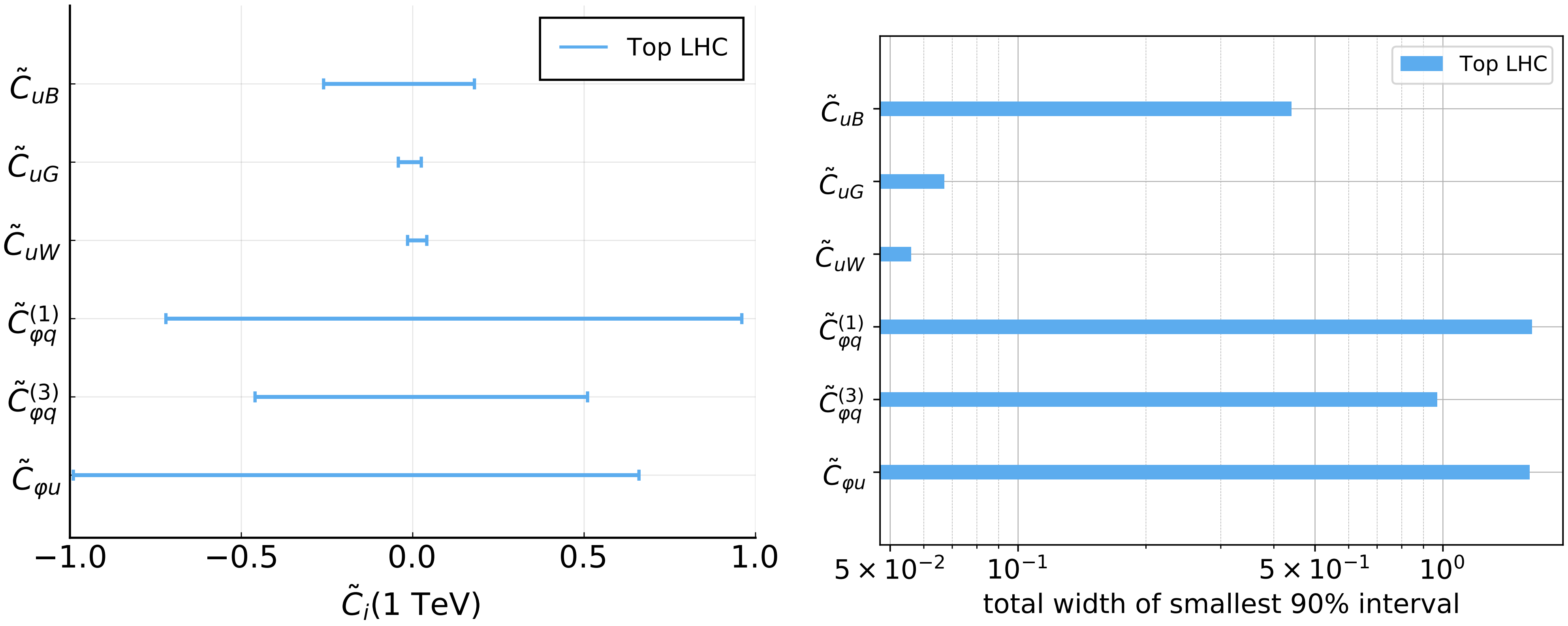


Figure 1: Constraints on SMEFT $\tilde{C}_i$ at $\Lambda = 1$ TeV from top measurements ; marginalized smallest intervals containing 90 % posterior probability (left) and the total width of these intervals (right). For all coefficients we choose a uniform distribution in $-1 \leq \tilde{C}_i \leq 1$ as the prior. 6 WCs constrained, all penguins $C_{\varphi x}$ poorly

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

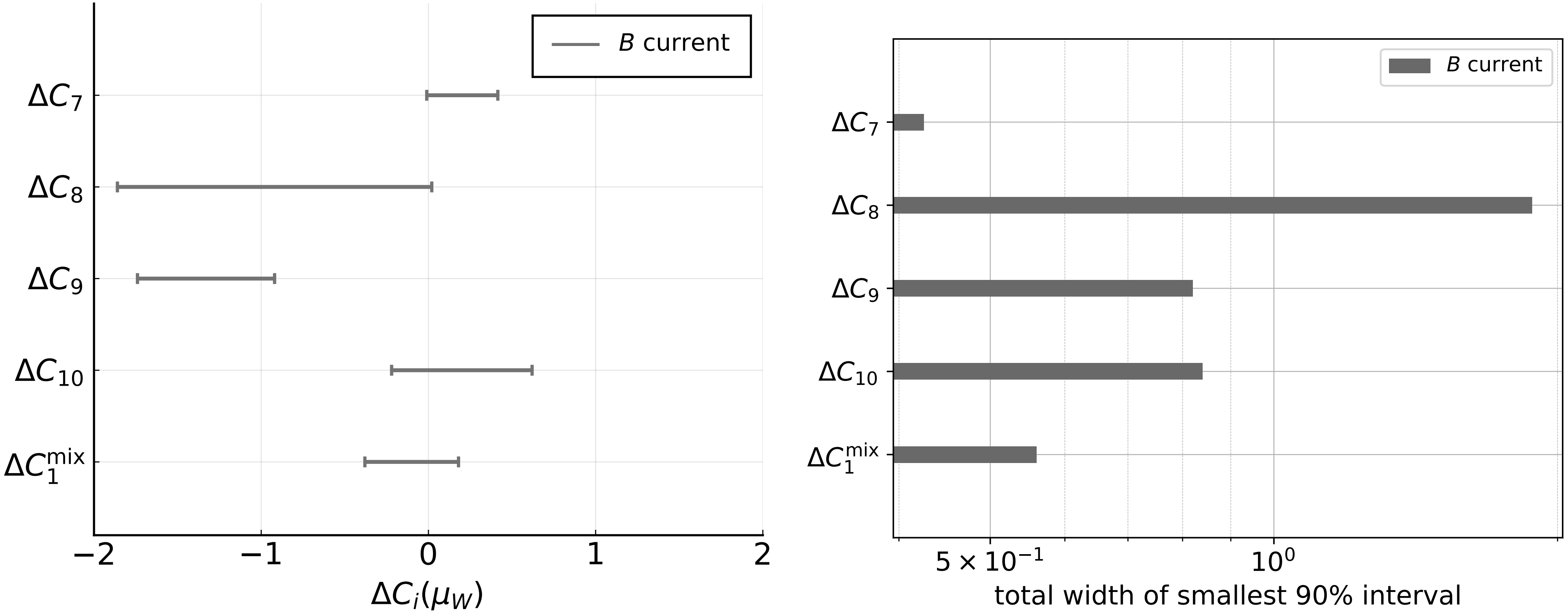


Figure 2: Constraints on WET coefficients ΔC_i at the scale $\mu = \mu_W$. 5 WET-WCs constrained, new physics hint in C_9

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

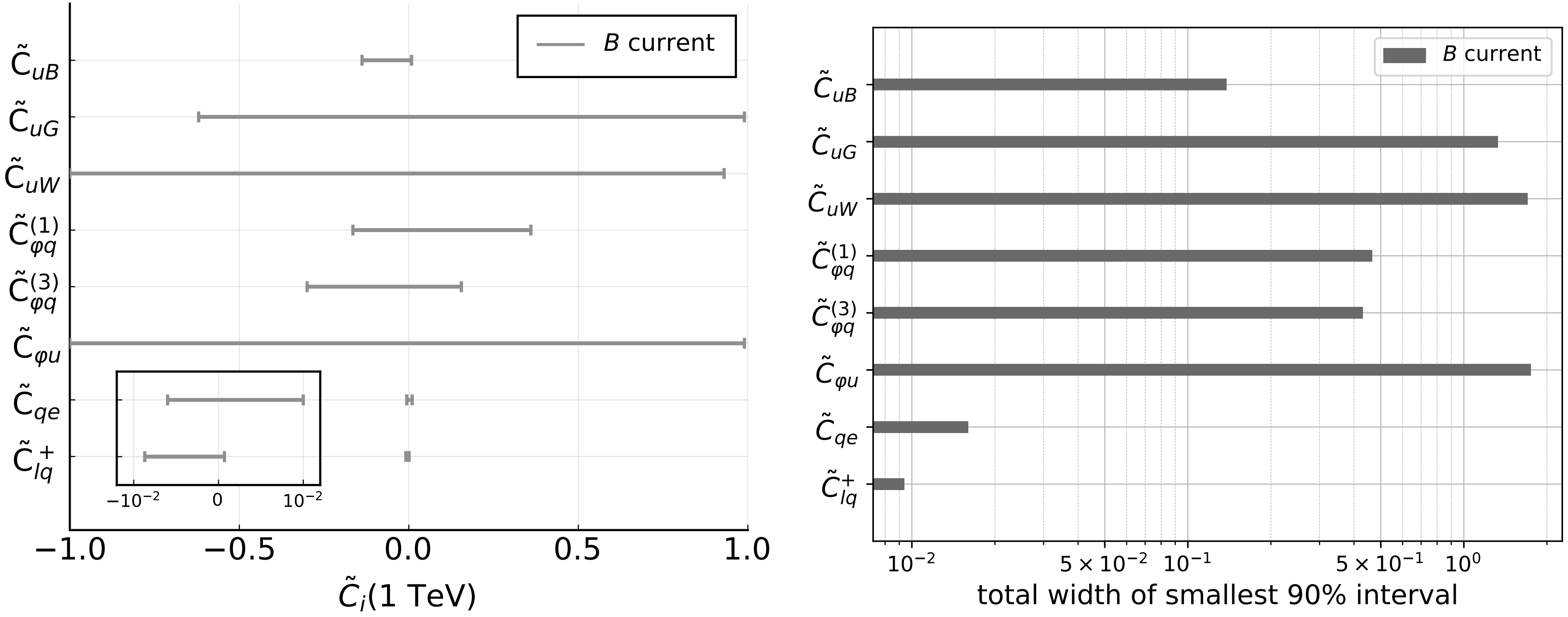


Figure 3: Constraints on SMEFT coefficients (lower plots) from measurements of B observables. Shown are the marginalized smallest intervals containing 90 % of the posterior probability (left) and the total width of these intervals (right) obtained in a fit of five WET (upper plots) and eight SMEFT coefficients (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

beauty and top; now

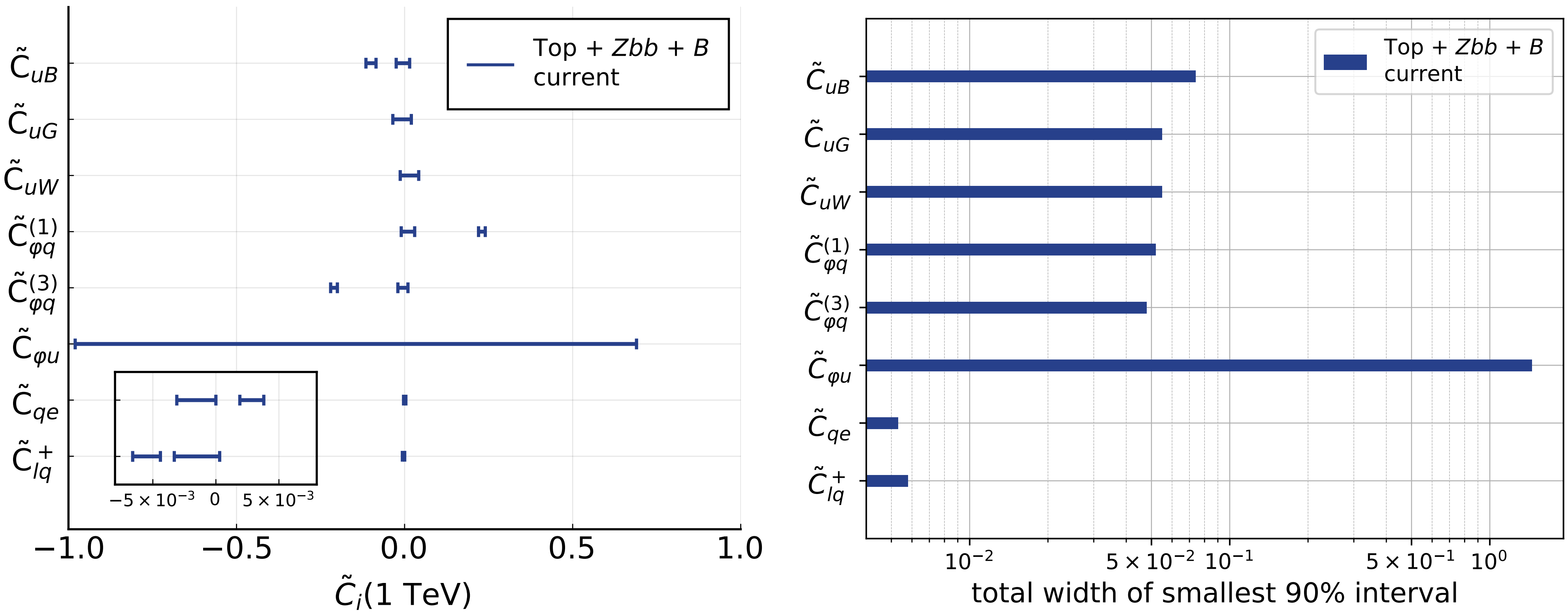


Figure 4: Constraints on SMEFT coefficients $\tilde{C}_i$ obtained in a fit to top-quark data, Zbb data, and B physics data. Shown are smallest intervals containing 90 % posterior probability (left) and total width of these intervals (right). For the prior we assume a uniform distribution over the interval $-1 \leq \tilde{C}_i \leq 1$. 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

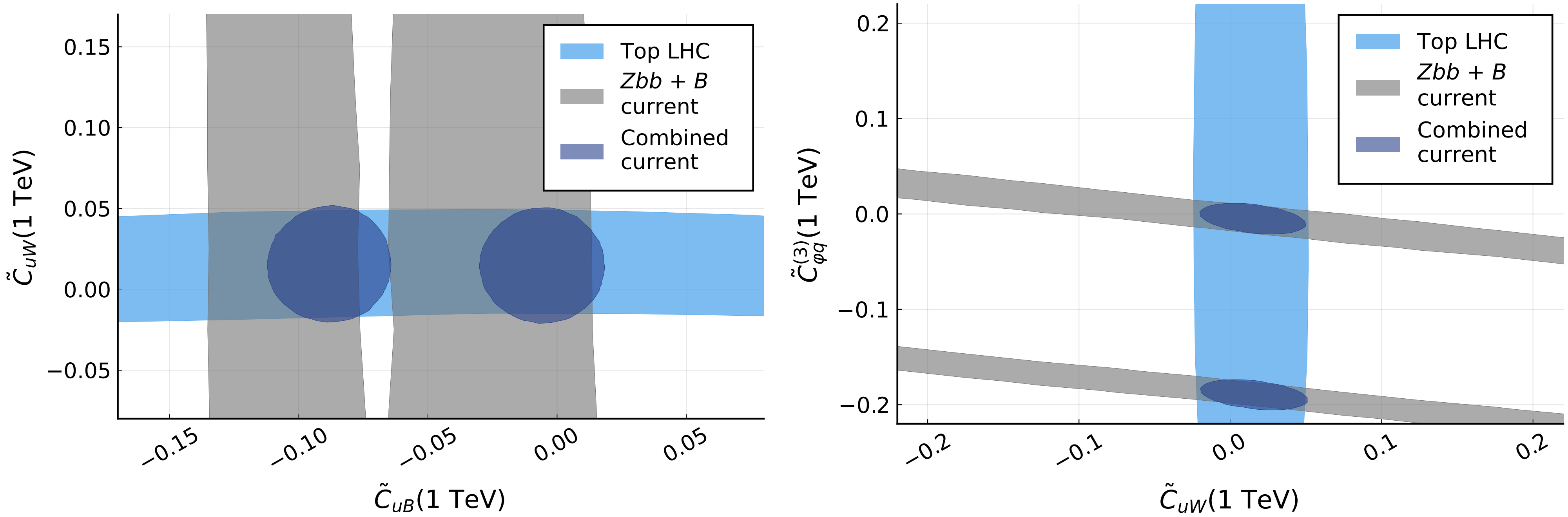


Figure 5: Examples for two-dimensional posterior distributions of SMEFT coefficients $\tilde{C}_i$ obtained in a fit to top-quark data (light blue), B physics data (grey) and the combined dataset including Zbb data (blue). Shown are the smallest intervals containing 90 % of the posterior distribution. 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

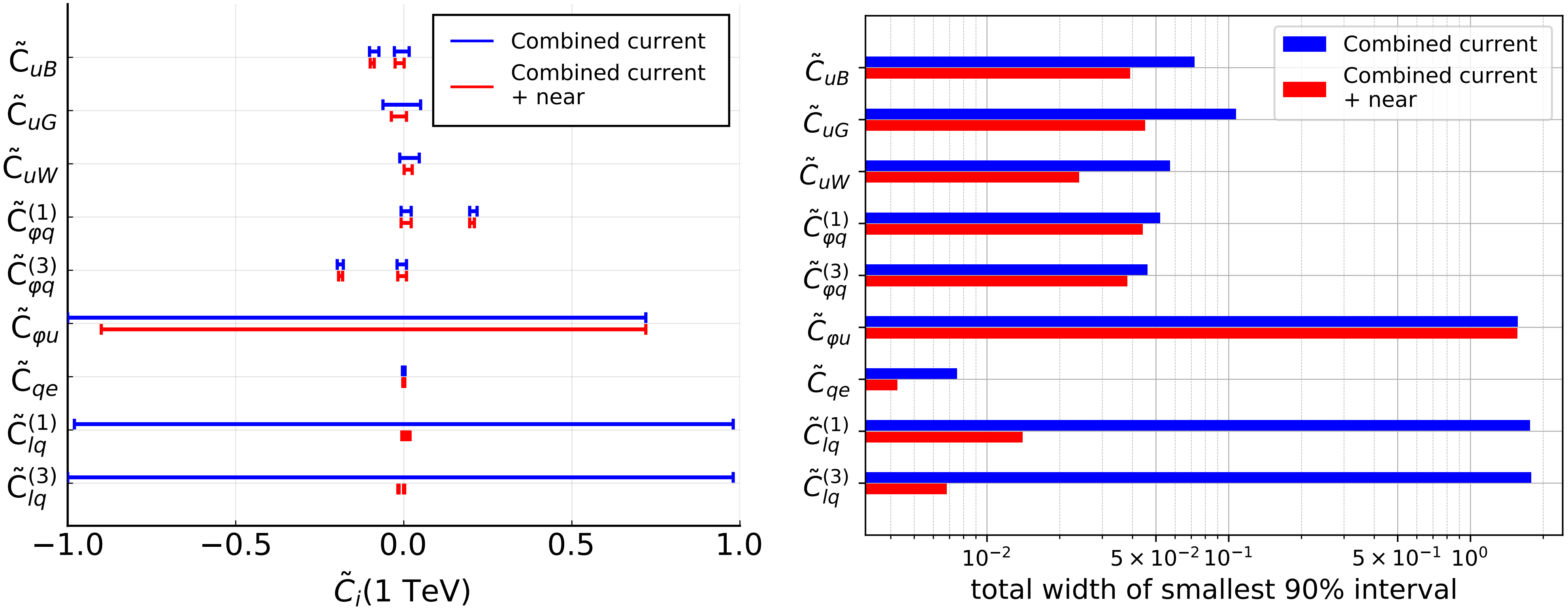
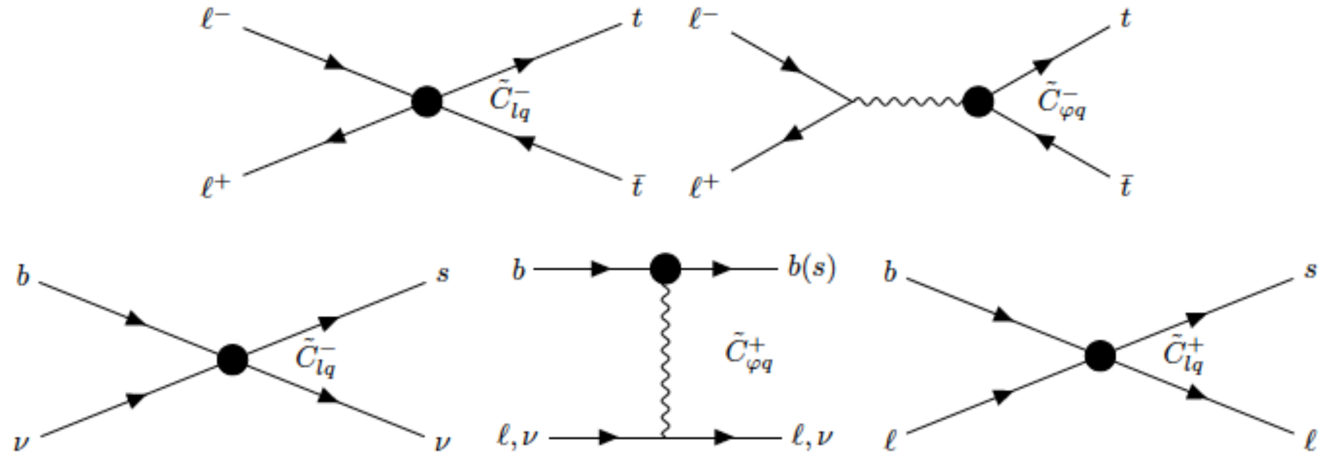


Figure 6: Constraints on coefficients $\tilde{C}_i$ from fits to current top-quark and B measurements.(blue) and projections of top-quark and B observables. (red). Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). 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 CLIC only

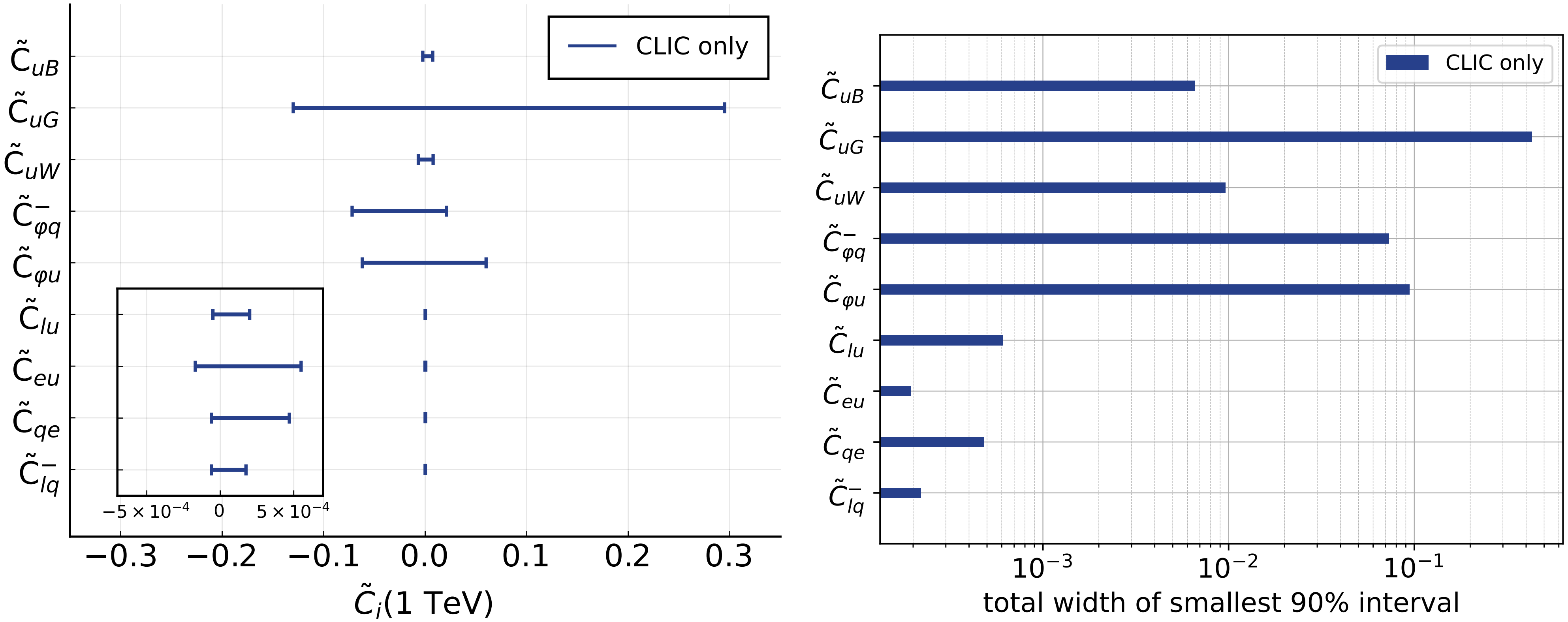


Figure 7: Constraints on coefficients $\tilde{C}_i$ from fits to CLIC observables in Tab. 1. Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). 4 sl 4-fermis; electron-specific; only C^{-}_{lq} and $C^{-}_{\varphi q}$

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

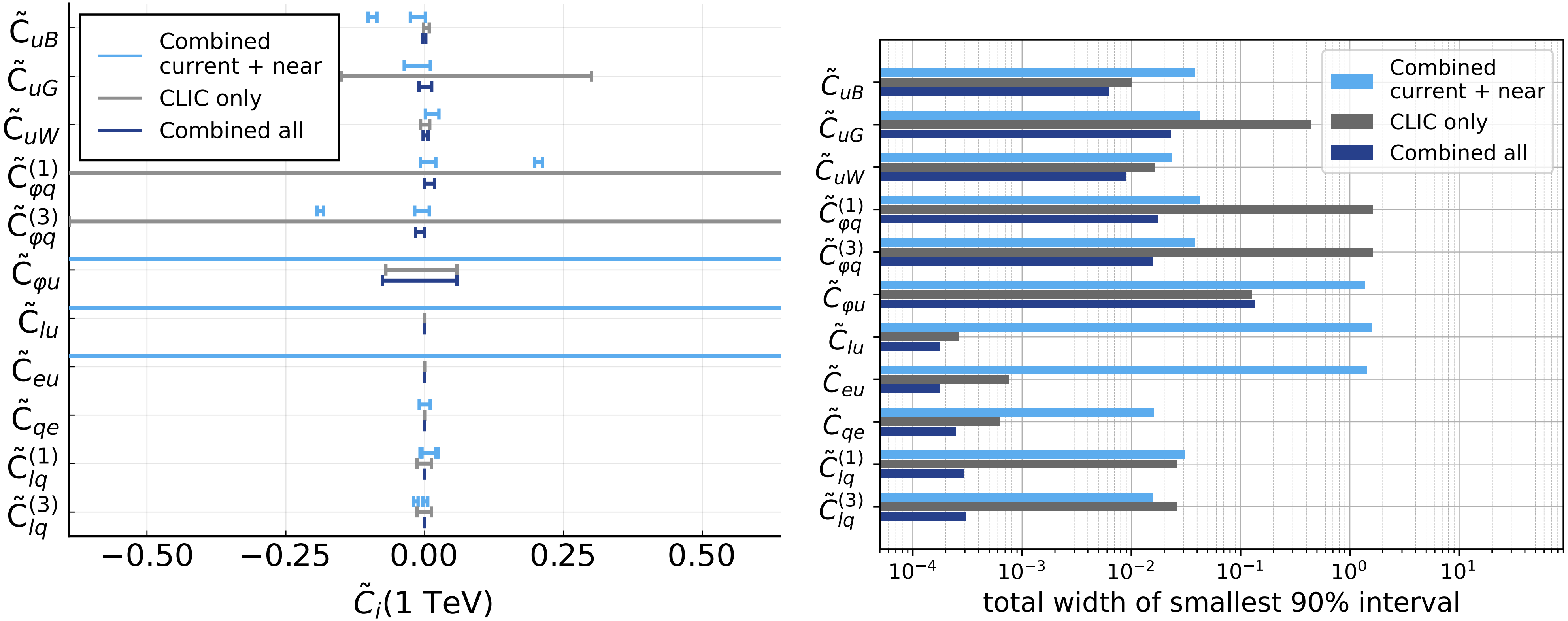
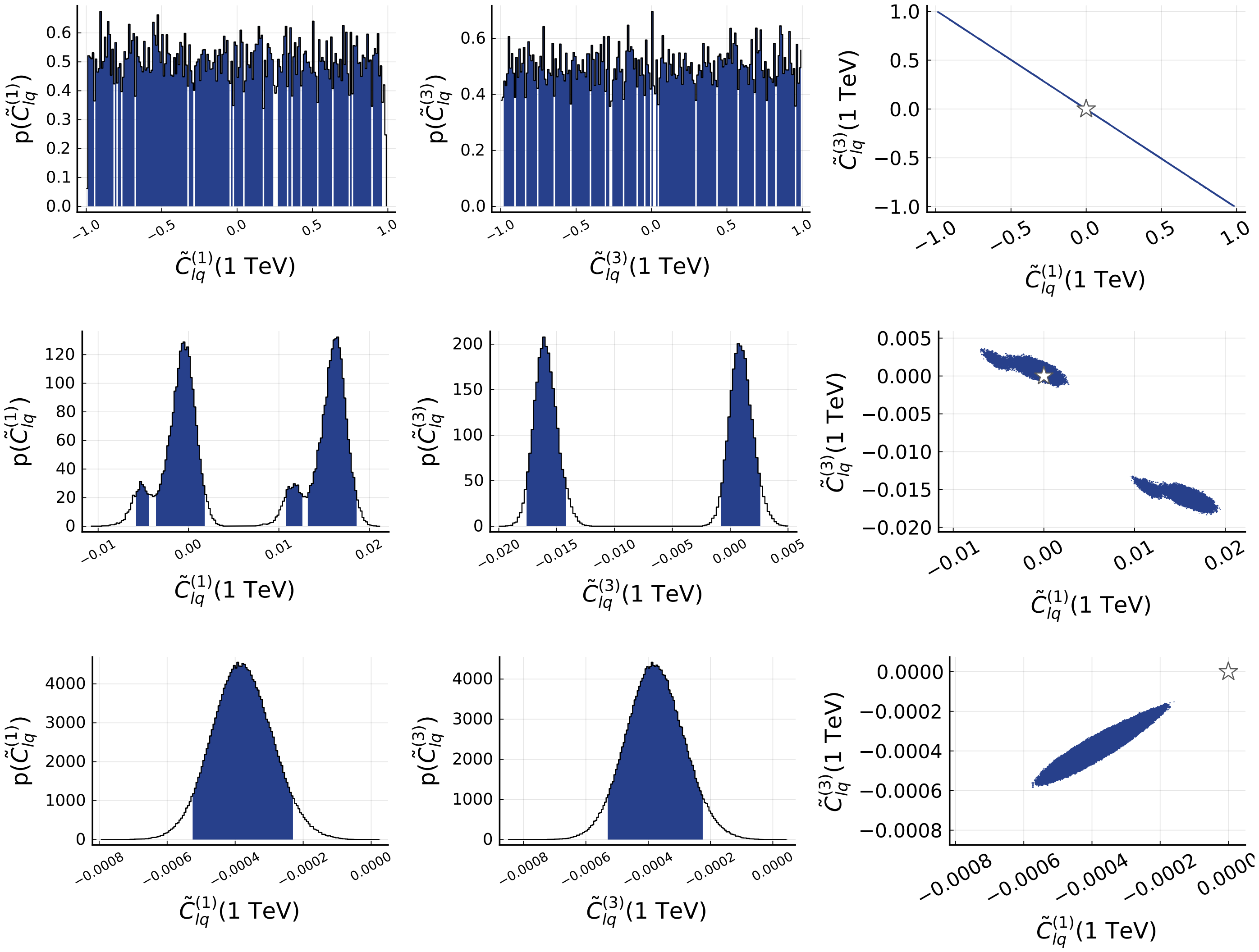


Figure 8: Constraints on coefficients $\tilde{C}_i$ from fits to top-quark and B data and near-future projections at HL-LHC and Belle II and CLIC future projections.Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). 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

Summary

- Synergies between beauty and top are happening Fox et al 2007, Bissmann '21, Brugisser '21 and do work!
- More top-observables could have been considered in fit, however, here bin-to-bin correlations for distributions are not publicly available, and those matter in SMEFT fits 1912.06090
- Semileptonic 4-fermion operators connect top to b-anomalies

  comment 1: 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.

  comment 2: Top-FCNC couplings $ct\ell\ell'$ and $ut\ell\ell'$ for all $\ell\ell' = ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$ are constrained by $B \to K^{(*)}\nu\bar{\nu}$ and $B^+ \to (\pi^+, \rho^+)\nu\bar{\nu}$ limits due to $SU(2)_L$ 2109.01675. Constraints are stronger than those availabe for $ttee, tt\mu\mu$ from CMS.

Summary

Data source	$\lvert\kappa_A^{q_1q_2\ell\ell'}\rvert$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
Rare B decays to Dineutrinos	$\lvert\kappa_R^{bd\ell\ell'}\rvert$	210	210	210	210	210	210
	$\kappa_L^{tu\ell\ell'}$	$[-197, 223]$	$[-197, 223]$	$[-197, 223]$	210	210	210
	$\lvert\kappa_R^{bs\ell\ell'}\rvert$	35	35	35	32	32	32
	$\kappa_L^{tc\ell\ell'}$	$[-22, 47]$	$[-22, 47]$	$[-22, 47]$	32	32	32
Rare B decays to Charged dileptons	$\kappa_R^{bd\ell\ell'}$	~ 10	$[-4, 4]$	~ 2500	~ 20	~ 280	~ 200
	$\kappa_L^{bd\ell\ell'}$	~ 10	$[-8, 2]$	~ 2500	~ 20	~ 280	~ 200
	$\kappa_R^{bs\ell\ell'}$	$\mathcal{O}(1)$	$[0.2, 0.8]$	~ 800	~ 2	~ 50	~ 60
	$\kappa_L^{bs\ell\ell'}$	$\mathcal{O}(1)$	$[-1.6, -1.1]$	~ 800	~ 2	~ 50	~ 60
Drell-Yan	$\lvert\kappa_{L,R}^{bd\ell\ell'}\rvert$	578	311	1112	260	800	866
	$\lvert\kappa_{L,R}^{bs\ell\ell'}\rvert$	328	177	631	142	486	529
$t+\ell$	$\kappa_L^{tt\ell\ell'}$	$[-196, 243]$	$[-196, 243]$	–	–	–	–

Table 2: Upper limits on bd, bs, tu, tc charged lepton couplings $\kappa_A^{q_1q_2\ell\ell'}$, from 2109.01675. $t+\ell$ bounds adapted from CMS 2012.04120

Summary

- In view of b-anomalies hinting at universality violation lepton specific fits/analyses desirable; all of them – e, μ, τ, ν, also LFV