Top and Beauty synergies in SMEFT fits

based on works with Stefan Bissmann, Cornelius Grunwald and Kevin Kröninger, 2012.10456 [hep-ph], to appear in JHEP

Gudrun Hiller, TU Dortmund

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

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

2 anomalies strengthened in past few weeks: 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) "

Flavor continues to be interesting and inspiring; the anomalies require flavor BSM model building and flavorful fits.

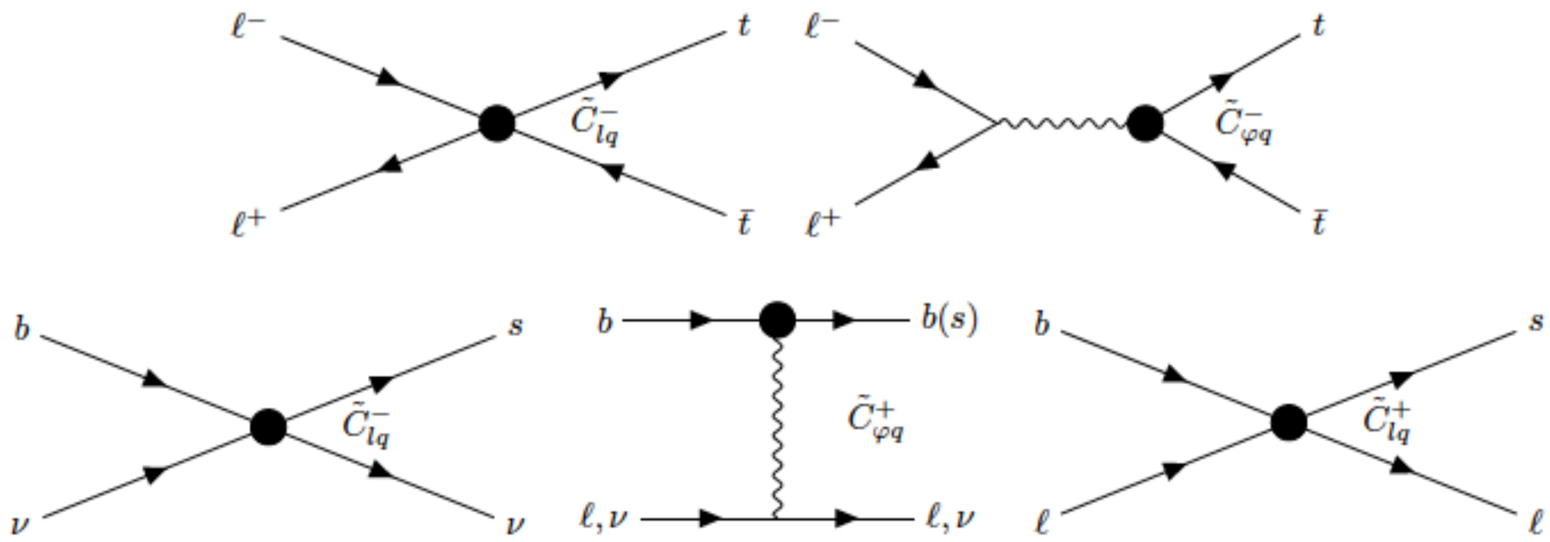
Moving ahead .... getting more global

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.



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,....

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

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

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

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

and semileptonic four-fermion operators

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

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

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

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 $V_u = 1$. $d_L^{\rm mass} = V_{\rm CKM} d_L^{\rm flavor}$

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 $C^{kl} \propto \delta_{kl}$.

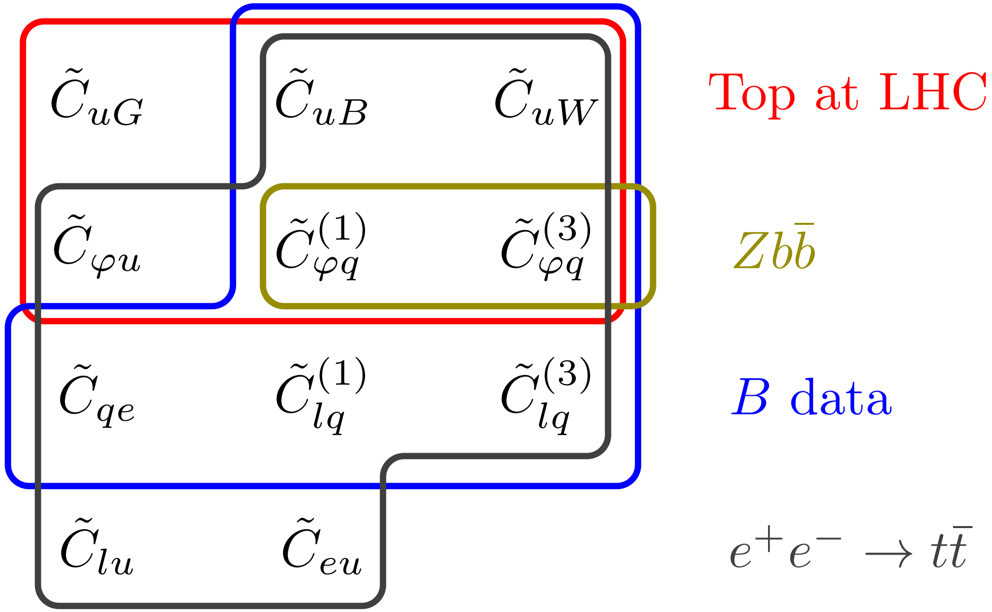
(in view of 1., this is only a mild assumption, however, turns out that $B(B \to K^{(*)}\nu\bar{\nu})$ in particular when observed, is an important constraint)

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 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



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	$\tilde{C}^{(3)}_{\varphi q}, \tilde{C}_{uW}$	-
$Z \to b\bar{b}$	$A^b_{FB}, R_b, \sigma_{\text{had}}$	$\tilde{C}^{+}_{\varphi q}$	-
$b \to s\gamma$	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}	$\tilde{C}_{uB}, \tilde{C}_{uW}, \left\{\tilde{C}_{uG}\right\}, \tilde{C}^{-}_{\varphi q}, \tilde{C}_{\varphi u}$	$\tilde{C}_{eu}, \tilde{C}_{qe}, \tilde{C}_{lu}, \tilde{C}^{-}_{lq}$

Process	Observable	$\sqrt{s}$	Int. luminosity	Experimen
$t\bar{t}\gamma$	$\sigma^{\rm fid}(t\bar{t}\gamma, 1\ell)$, $\sigma^{\rm fid}(t\bar{t}\gamma, 2\ell)$	13 TeV	36.1 fb^{-1}	ATLAS
$t\bar{t}Z$	$\sigma^{\rm inc}(t\bar{t}Z)$	13 TeV	77.5 fb^{-1}	CMS
$t\bar{t}$	$\sigma^{\text{inc}}(t\bar{t})$	13 TeV	36.1 fb^{-1}	ATLAS
	F_0 , F_L	8 TeV	20.2 fb^{-1}	ATLAS
	Γ_t	8 TeV	20.2 fb^{-1}	ATLAS

Table 1: Considered bservables for top- quark processes at the LHC 2012.10456 [hep-ph] .

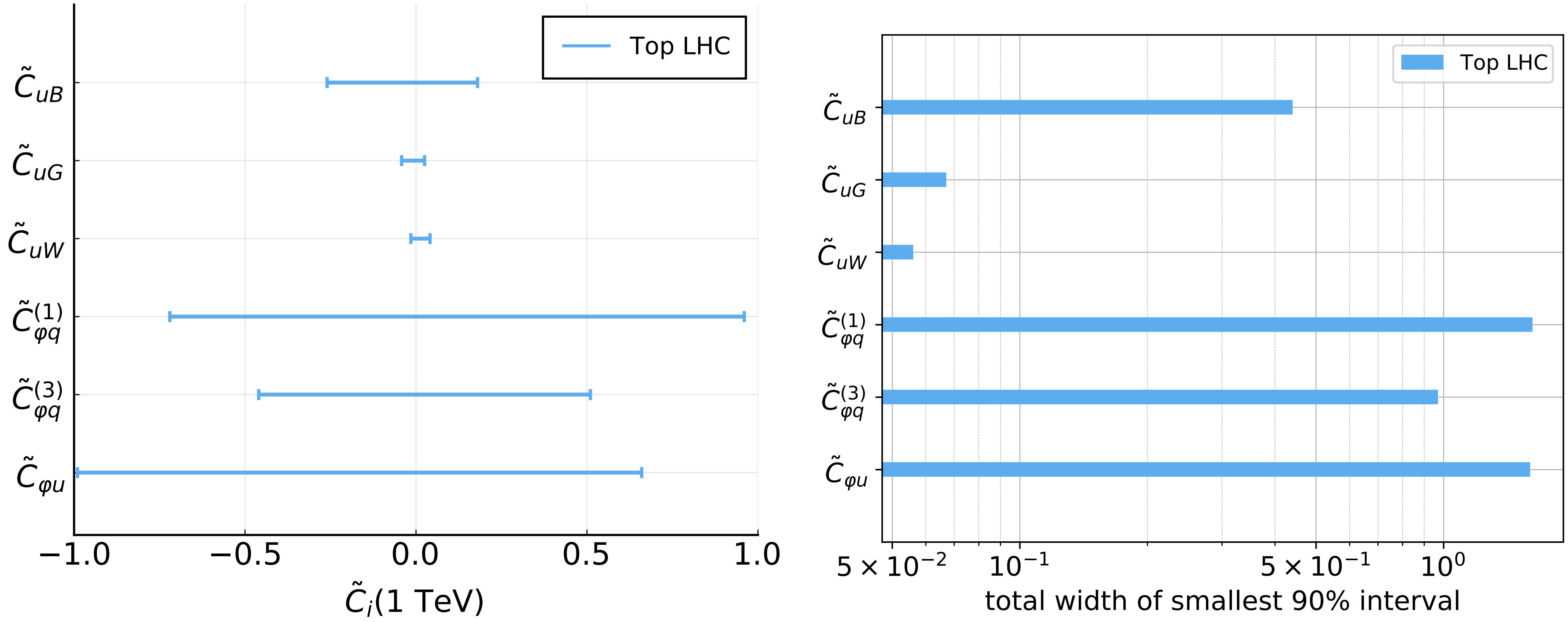


Figure 1: Constraints on SMEFT $\tilde{C}_i$ at $\Lambda = 1$ TeV from top measurements in Tab. 1; marginalized smallest intervals containing 90 % posterior probability (left) and the total width of these intervals (right). For all coefficients we choose a uniform distribution in $-1 \leq \tilde{C}_i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

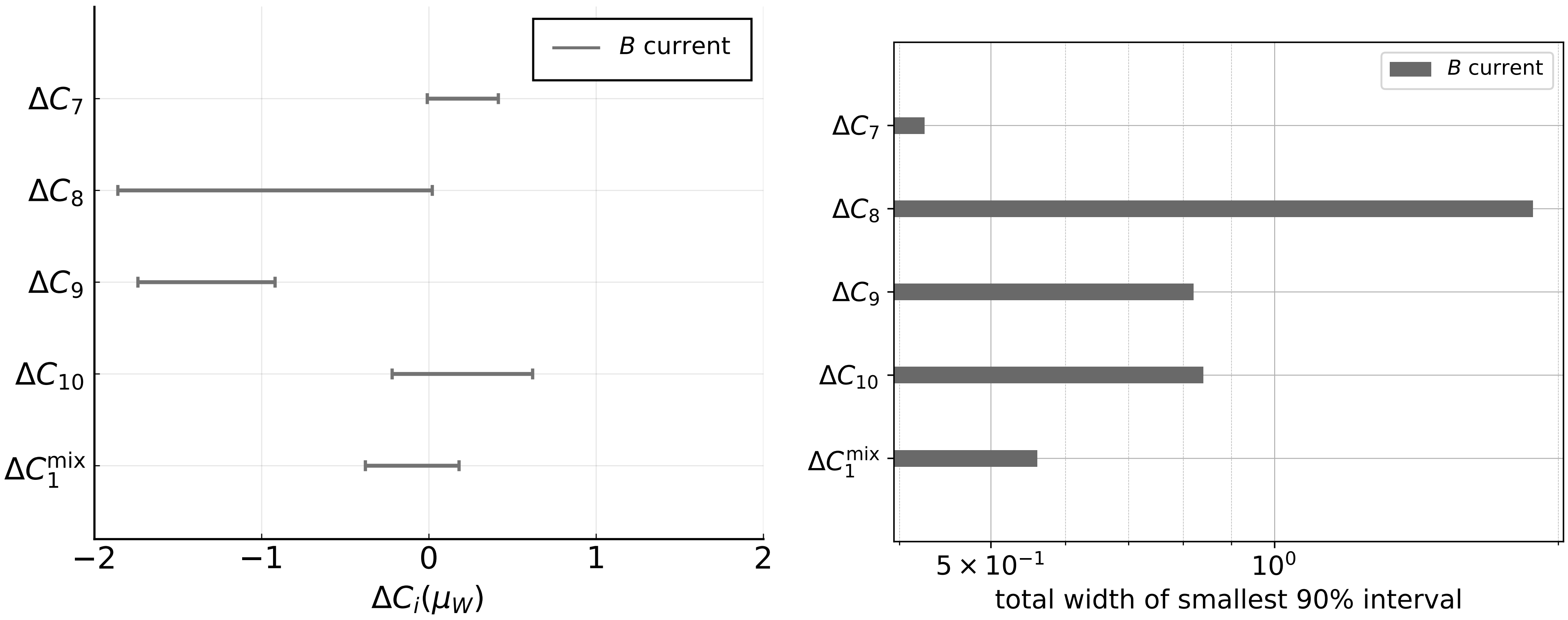


Figure 2: Constraints on WET coefficients ΔC_i at the scale $\mu = \mu_W$. 5 WET-WCs constrained, new physics hint in C_9

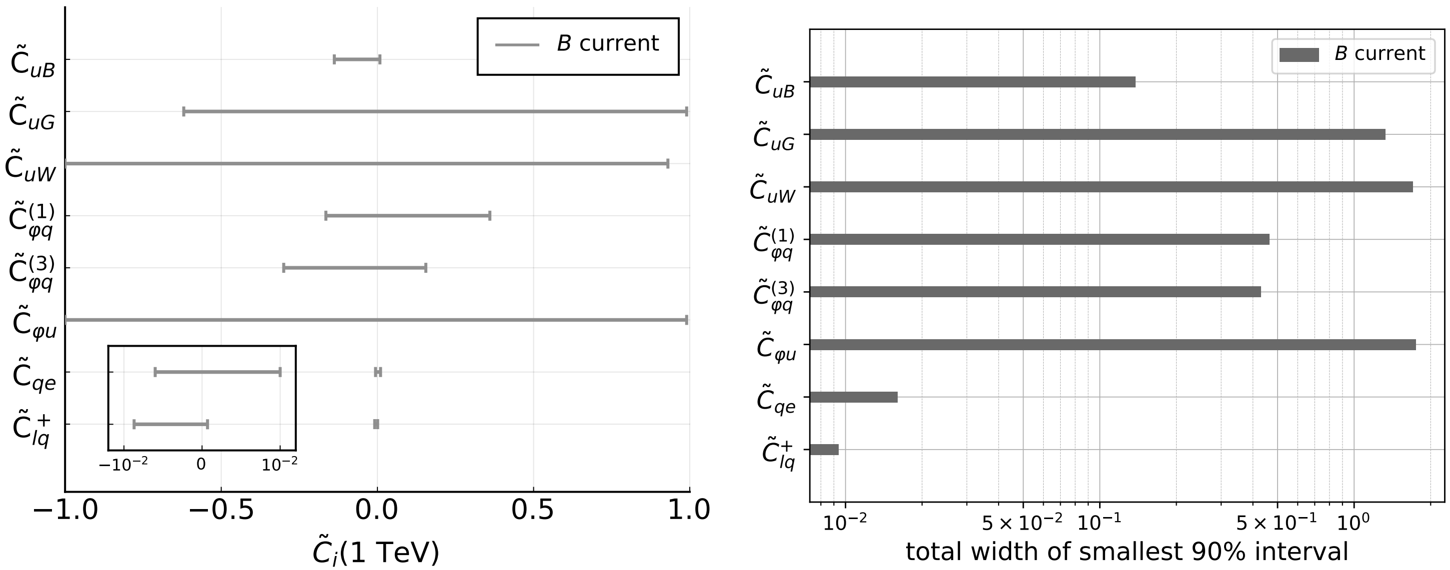


Figure 3: Constraints on SMEFT coefficients (lower plots) from measurements of B observables in Tab. **??**. Shown are the marginalized smallest intervals containing 90 % of the posterior probability (left) and the total width of these intervals (right) obtained in a fit of five WET (upper plots) and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

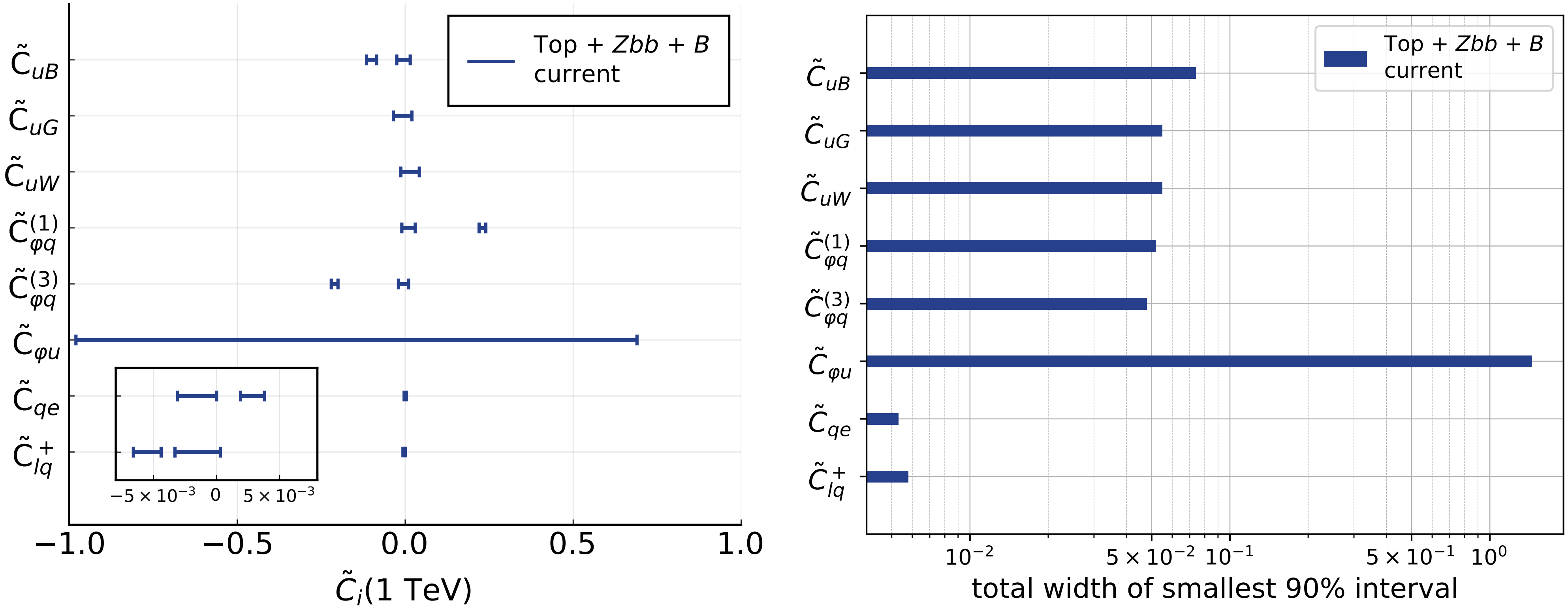


Figure 4: Constraints on SMEFT coefficients $\tilde{C}_i$ in Eq. (**??**) obtained in a fit to top-quark data in Tab. 1, Zbb data, and B physics data in Tab. **??**. Shown are smallest intervals containing 90 % posterior probability (left) and total width of these intervals (right). For the prior we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

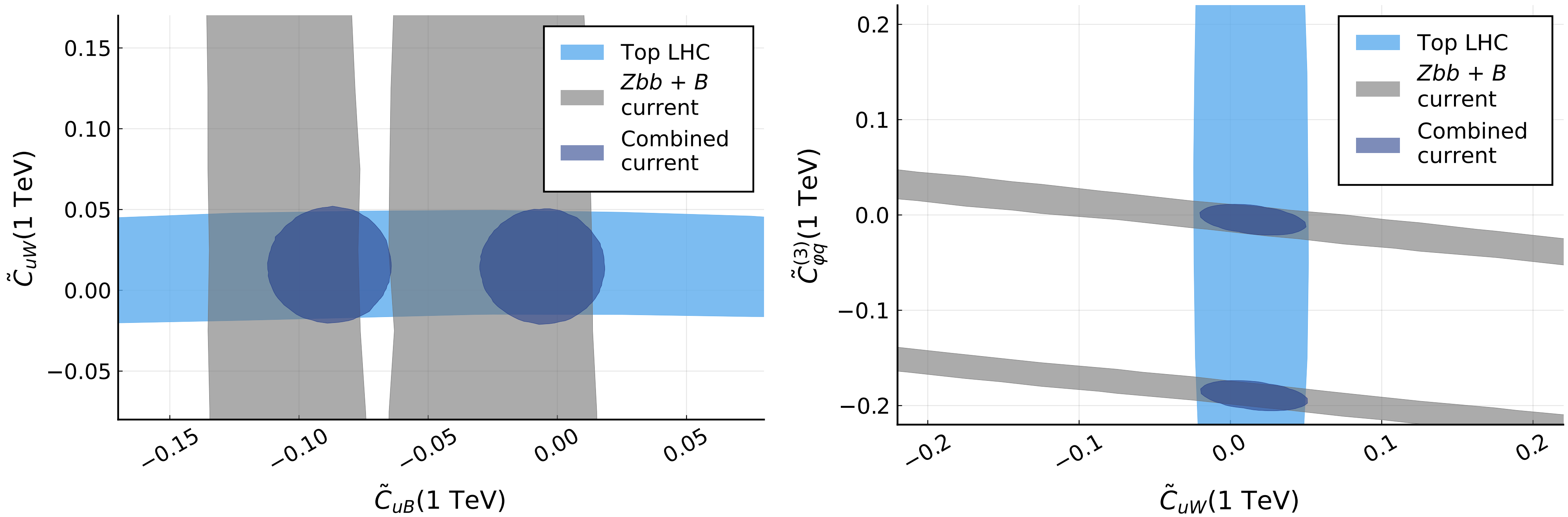


Figure 5: Examples for two-dimensional posterior distributions of SMEFT coefficients $\tilde{C}_i$ in Eq. (**??**) obtained in a fit to top-quark data (light blue), B physics data (grey) and the combined dataset including Zbb data (blue). Shown are the smallest intervals containing 90 % of the posterior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

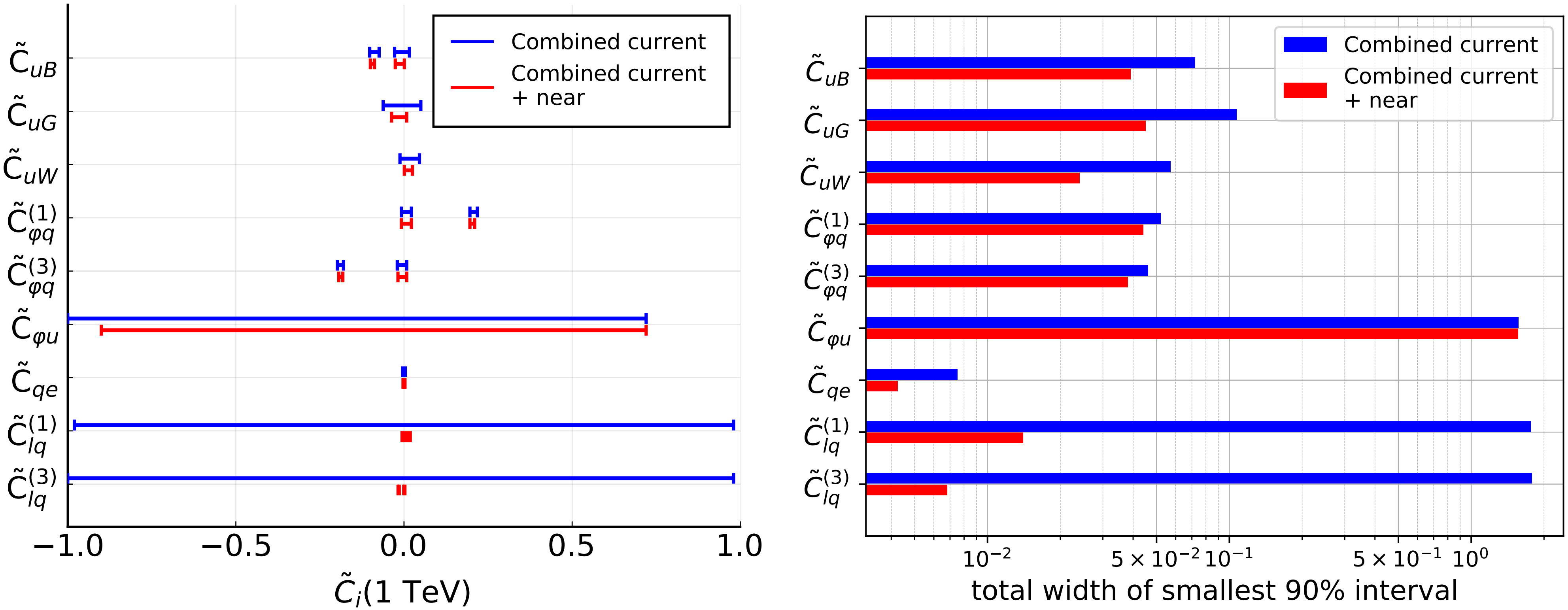
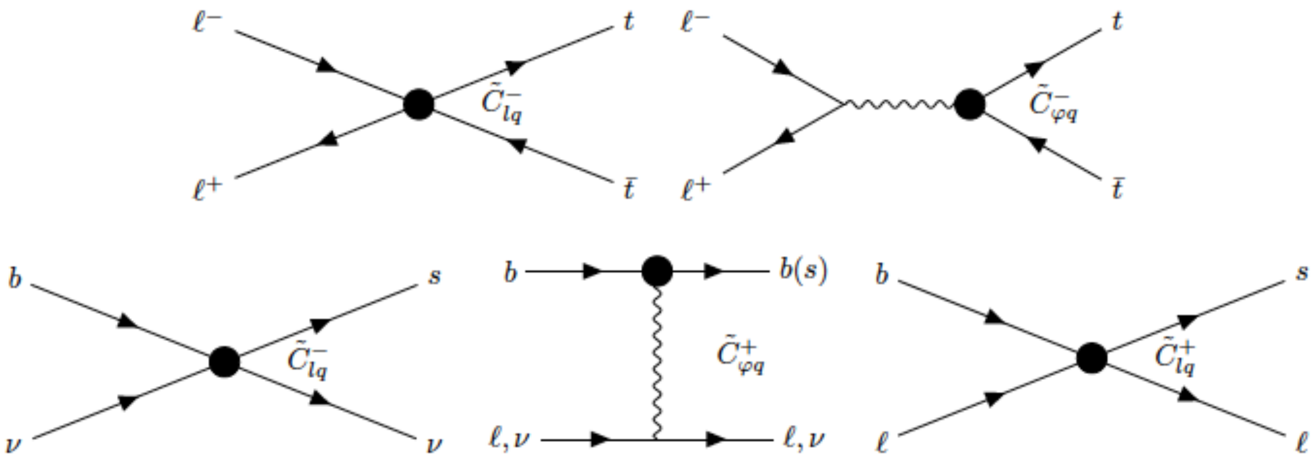


Figure 6: Constraints on coefficients $\tilde{C}_i$ from fits to current top-quark and B measurements in Tabs. 1 and **??** (blue) and to current measurments and projections of top-quark and B observables in Tabs. 1-**??** (red). Shown are the marginalized smallest intervals containing 90 % posterior 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 $C^{(3)}_{lq}$.

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



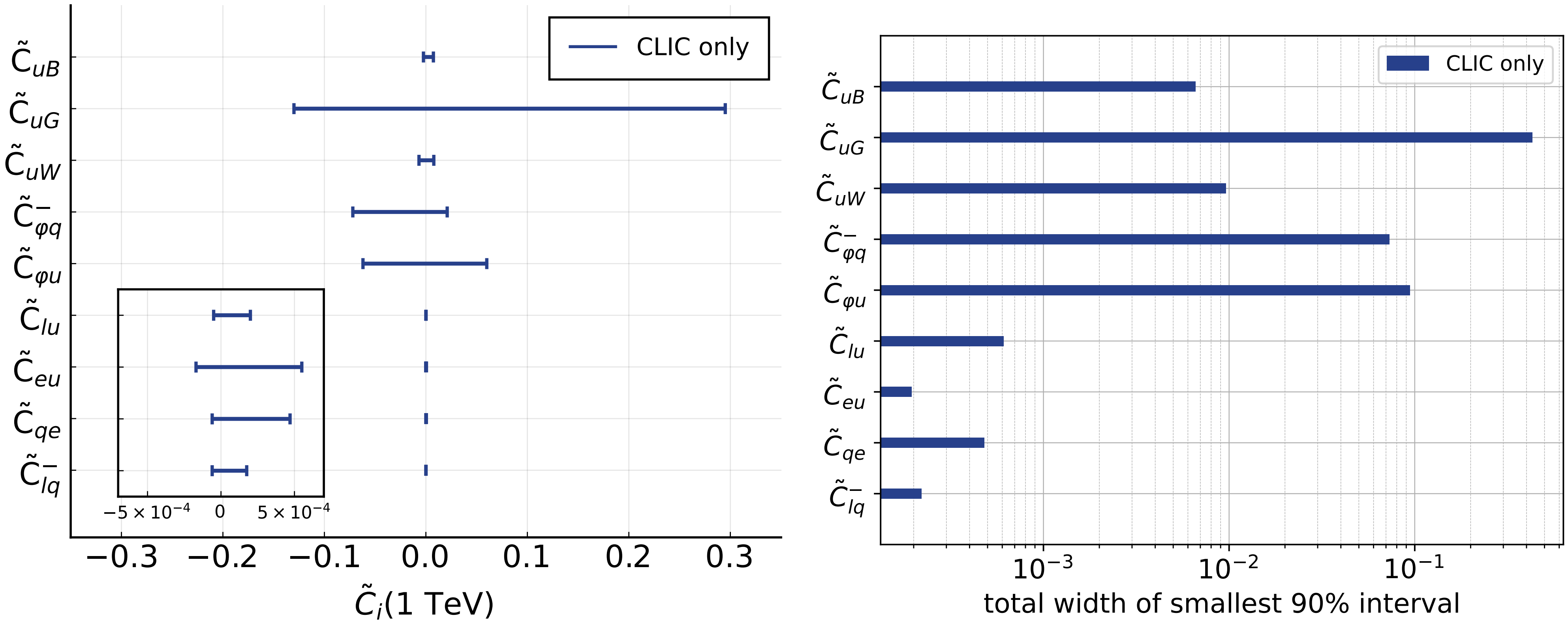


Figure 7: Constraints on coefficients $\tilde{C}_i$ from fits to CLIC observables in Tab. 2. Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths of these intervals (right). 4 sl 4-fermis; electron-specific; only C^{-}_{lq} and $C^{-}_{\varphi q}$

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

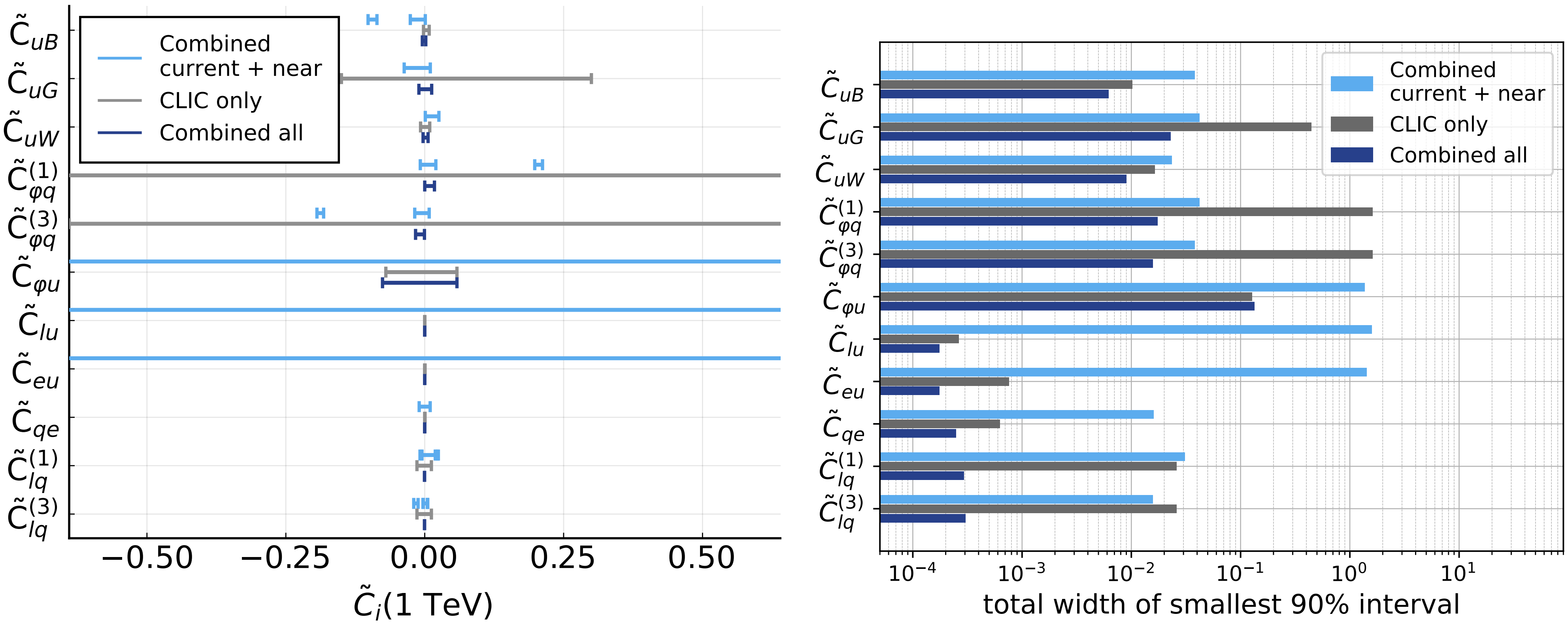
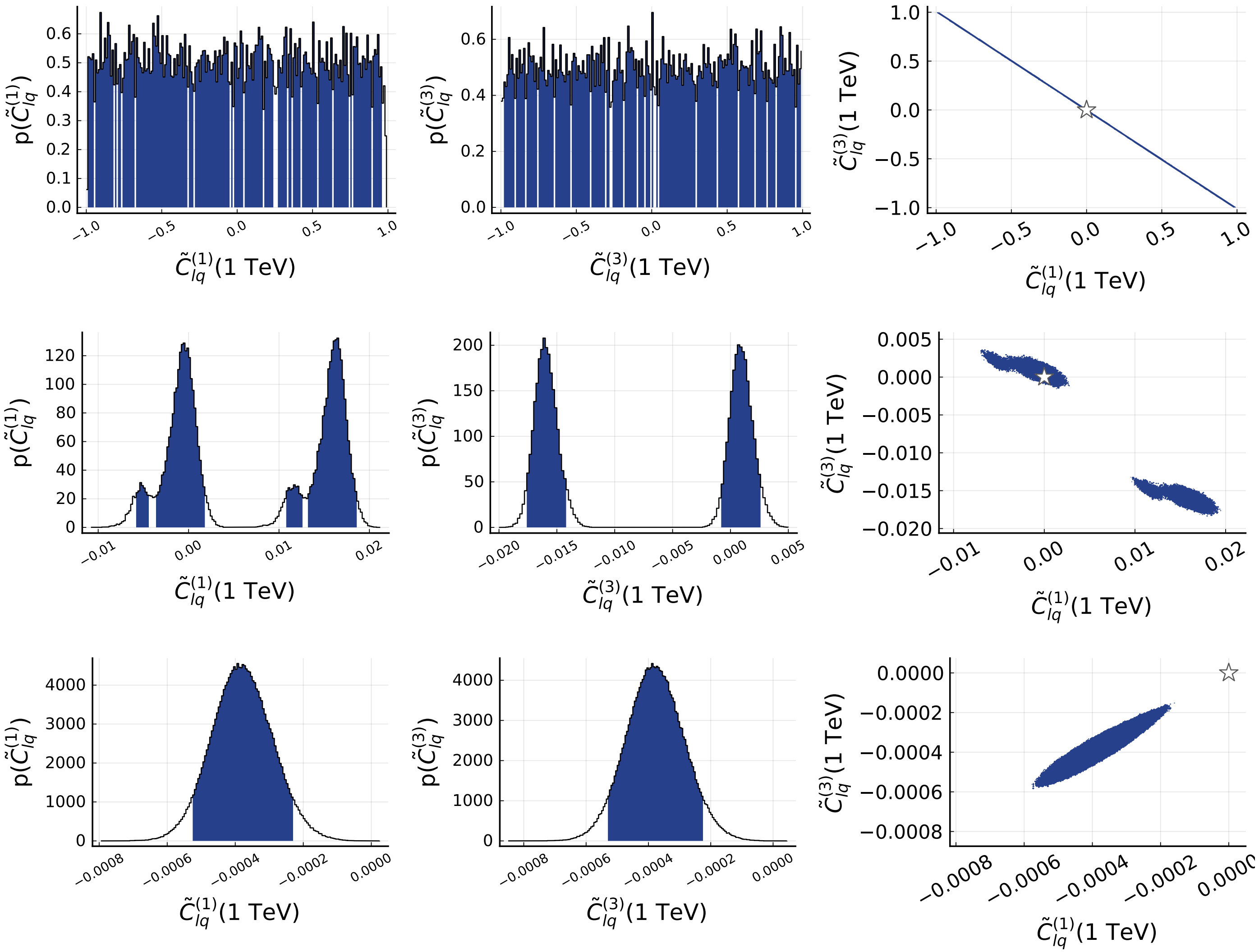


Figure 8: Constraints on coefficients $\tilde{C}_i$ from fits to top-quark and B data and near-future projections at HL-LHC and Belle II in Tabs. 1-**??** and CLIC future projections in Tab. 2. Shown are the marginalized smallest intervals containing 90 % posterior probability (left) and the total widths 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

- Synergies between beauty and top are reality Fox et al 2007, Bissmann '21, Brugisser '21 and do work!

- Semileptonic 4-fermion operators connect top to b-anomalies

  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 NOW unconstrained.

- In view of b-anomalies hinting at universality violation lepton specific fits become desirable

- Global fits have sensitivity to flavor —- exploit more flavor links

- Merge with other sectors (EWK, Higgs,..)