PANE 2026

The Top Quark Under SMEFT Precision Lens

Subhajit Kala

Based on: JHEP 11 (2025) 071 [arXiv:2505.07926] & JHEP 11 (2026) 106 [arXiv:2602.10201]

In collaboration with: Dr Lipika Kolay, Dr Lopamudra Mukherjee, Prof Soumitra Nandi

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Status after LHC Run 2

- Higgs discovered (2012): SM spectrum complete, couplings agree with the SM
- $\sqrt{s} = 13$ TeV, ~ 140 fb^{-1}: no new resonance
- Direct searches: new states excluded up to a few TeV

$\Rightarrow$ NP, if present, is heavy: $\Lambda \gg v,\, E$

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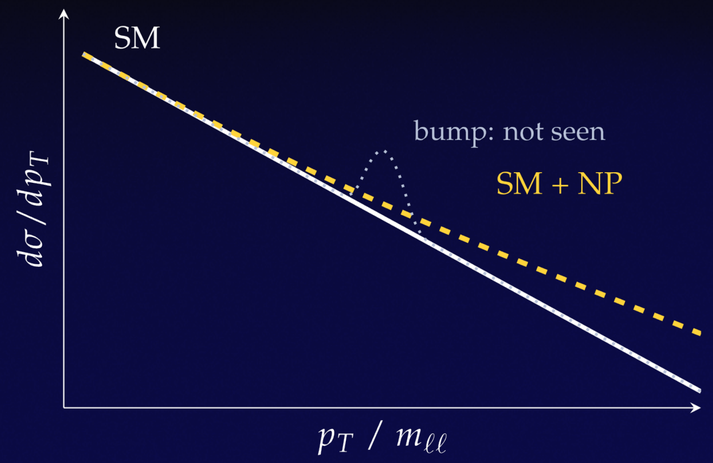
Change of strategy: from bumps to tails

- $\Lambda \gg E$: no on-shell new state to produce
- Instead: small deviations from the SM that grow with energy, $\delta\sigma/\sigma_{\rm SM} \sim E^2/\Lambda^2$
- Largest in high-p_T / high-mass tails: $pp \to \ell\ell,\ t\bar{t},\ tj,\ tW$



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EFT: a model-independent language

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- SM fields + SM gauge symmetry
- Any UV model $\rightarrow$ a pattern of $C_i^{(d)}$
- Tails parametrised by the Wilson coefficients; at $d = 6$:

$$\frac{\sigma}{\sigma_{\text{SM}}} \simeq 1 + C\,\frac{E^2}{\Lambda^2} + C^2\,\frac{E^4}{\Lambda^4}$$

- Measurements $\rightarrow$ bounds on $C_i^{(d)}/\Lambda^{d-4}$, not on one model

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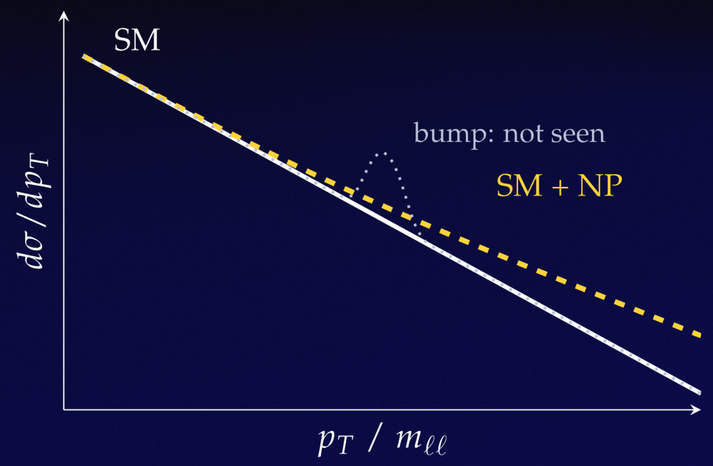

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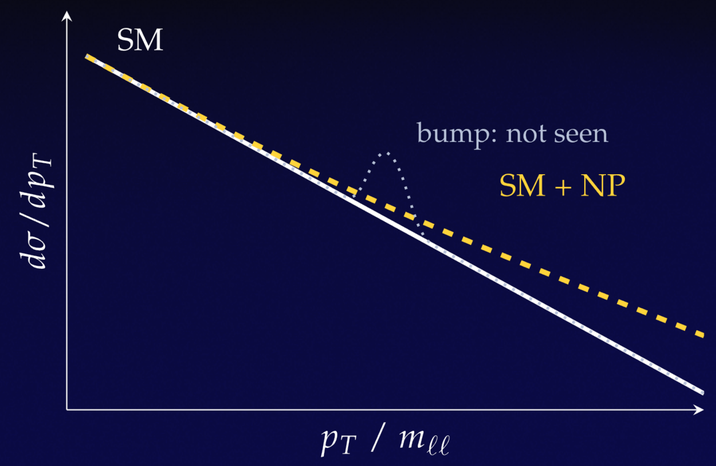
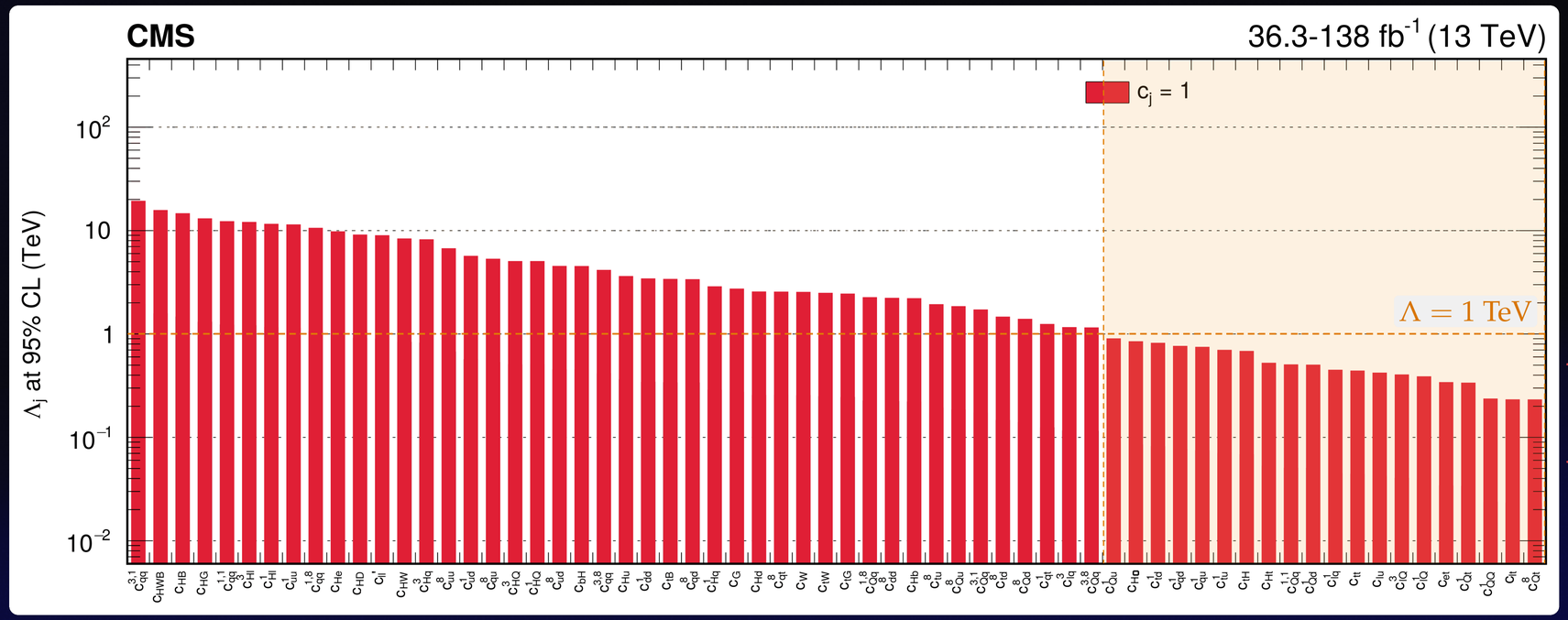


How far can we probe Λ?

Why a **Global** Study ??

Source: arXiv-2504.02958



What the **collider** says

- CMS SMEFT fit, $c_j = 1$: 20 operators with $\Lambda_j < 1$ TeV
- Mostly third-generation quark & semileptonic four-fermion
- But the LHC probes $E \gtrsim \Lambda$, i.e. $E/\Lambda \gtrsim 1$:

$$\frac{\sigma}{\sigma_{\rm SM}} = 1 + C^{(6)}(E/\Lambda)^2 + \left[(C^{(6)})^2 + C^{(8)}\right](E/\Lambda)^4 + \dots$$

higher orders not suppressed: EFT expansion fails

$\Rightarrow$ A collider-only bound is not the full story

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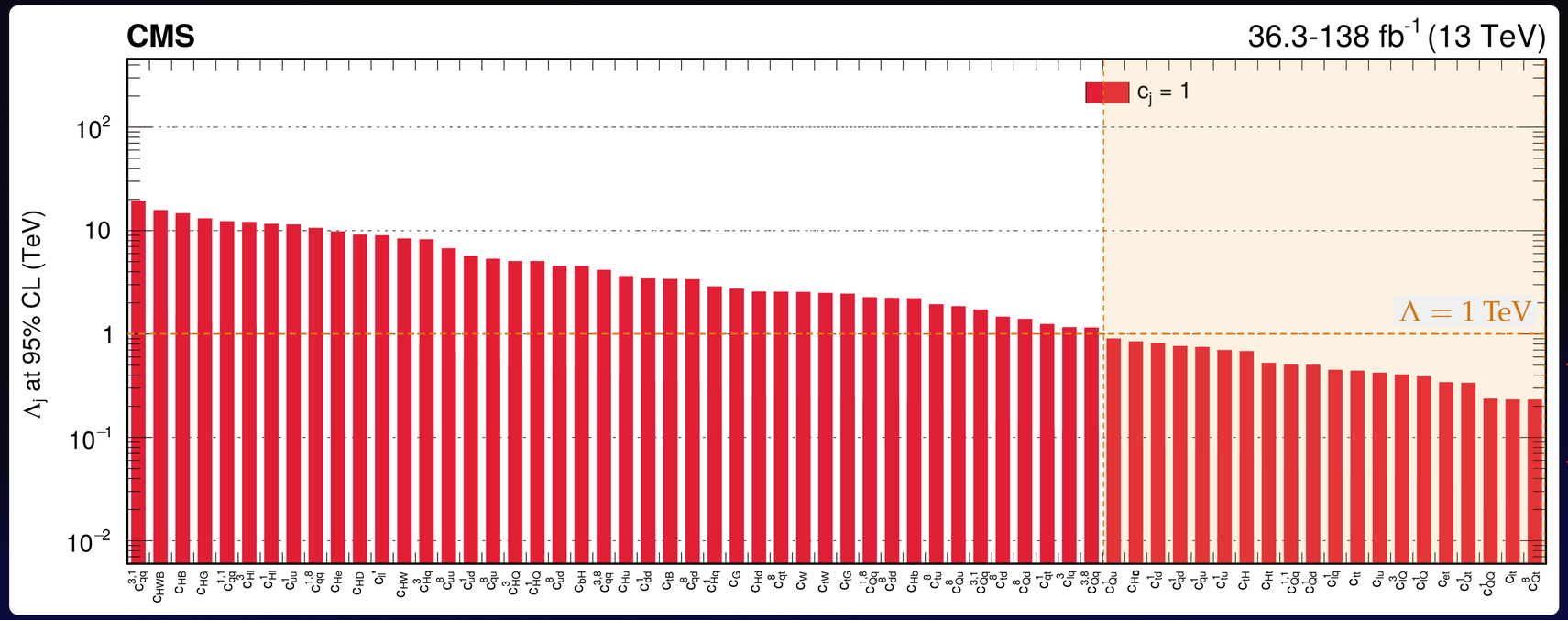

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The **same** C_i enters elsewhere

- Gauge invariance: $Q_3 = (t_L, b_L) \Rightarrow$ top operators shift b-quark physics
- Top loops + RG running: $b \to s\gamma$, B_s–$\bar{B}_s$ mixing, $b \to s\ell\ell$
- $Z \to b\bar{b}$, EWPO, Higgs; EDMs for Im C_i

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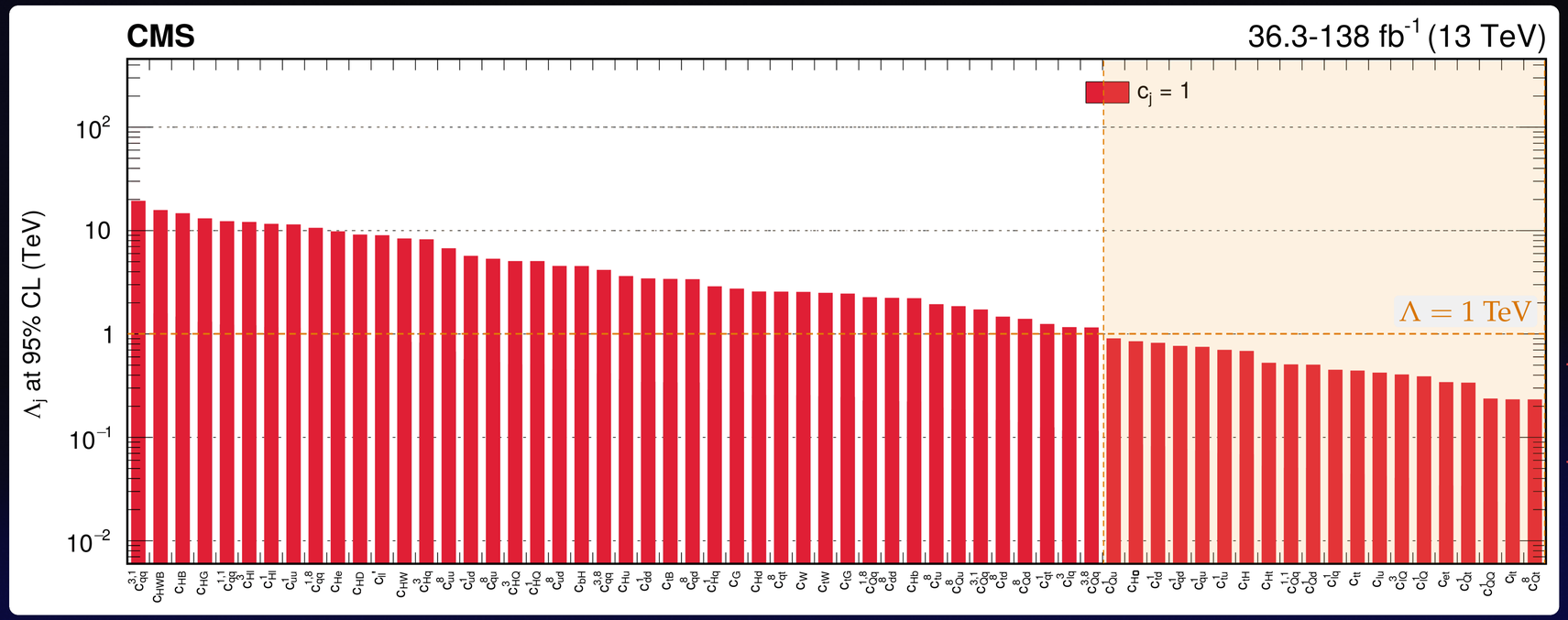

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Global study

A deviation (or a bound) is physical only if all observables tell the same story for the same C_i

$\Rightarrow$ Combine LHC + low-energy + EW precision + top + Higgs observables

The idea: why the top quark?

- **SM probe:** $\mathcal{B}(t \to bW) \simeq 100\% \Rightarrow$ tests V_{tb} & the left-handed structure
- **NP window:** FCNC absent at tree level, $\mathcal{B}(t \to qX) \sim 10^{-12}$–$10^{-17} \Rightarrow$ clean null test
- **Complementarity:** LHC: direct bounds; low energy: top in loops $\Rightarrow$ global fit

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Anomalous couplings in each sector

- **Charged current (Wtb):**

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\,\bar{b}\,\gamma^{\mu}\Big(V_L P_L + V_R P_R\Big)t\,W^{-}_{\mu} - \frac{g}{\sqrt{2}}\,\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\Big(g_L P_L + g_R P_R\Big)t\,W^{-}_{\mu} + \text{h.c.}$$

SM: $V_L = V_{tb}$, $V_R = g_L = g_R = 0$

- **Top FCNC (tqX, $q = u, c$):**

tqZ	vector $\gamma^{\mu}P_{L,R}$ + tensor $\sigma^{\mu\nu}q_{\nu}P_{L,R}$
$tq\gamma$, tqg	tensor (dipole) $\sigma^{\mu\nu}q_{\nu}P_{L,R}$
tqh	scalar $P_{L,R}$

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Objectives of the study

To establish the most rigorous, model-independent constraints on anomalous top-quark couplings by leveraging the precision of low-energy observables

1. Exploit indirect probes

2. Ensure theoretical rigour

$$\Big[C_i(\Lambda) \xrightarrow{\text{RGE}} C_i(\mu_{\text{EW}}) = L_i(\mu_{\text{EW}}) \xrightarrow{\text{RGE}} L_i(\mu_{\text{low}})\Big]$$

3. Perform global analysis

4. Predict future signatures

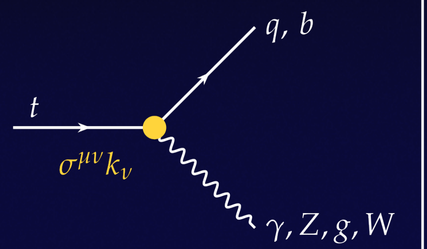
Operator basis of **anomalous top couplings**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i \left(C_i\,\mathcal{O}_i + \text{h.c.}\right) \qquad C_i \in \mathbb{C} \;\Rightarrow \text{CP violation}$$

flavour indices implicit; h.c. omitted for Hermitian O_i

Dipole

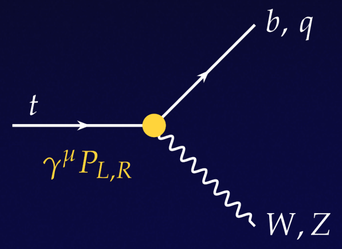
$\mathcal{O}_{uW}$: $(\bar{q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W^I_{\mu\nu}$
$\mathcal{O}_{uB}$: $(\bar{q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$
$\mathcal{O}_{uG}$: $(\bar{q}\sigma^{\mu\nu}T^A u)\tilde{H}G^A_{\mu\nu}$
$\mathcal{O}_{dW}$: $(\bar{q}\sigma^{\mu\nu}d)\tau^I H W^I_{\mu\nu}$



CC C^{33}_{uW}, $C^{33}_{dW} \to tbW$
FCNC $C^{i3,3i}_{uW,uB} \to tq\gamma,\ tqZ$
$C^{i3,3i}_{uG} \to tqg$

Current

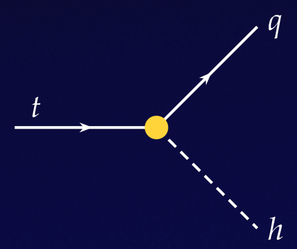
$\mathcal{O}^{(1)}_{Hq}$: $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{Hq}$: $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
$\mathcal{O}_{Hu}$: $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{Hud}$: $(\tilde{H}^\dagger iD_\mu H)(\bar{u}\gamma^\mu d)$



CC $C^{(3)33}_{Hq}$, $C^{33}_{Hud} \to tbW$
FCNC $C^{(1,3)i3}_{Hq}$, $C^{i3}_{Hu} \to tqZ$
($C^{(1,3)}_{Hq}$: also $d_i d_j Z$ via $SU(2)_L$)

Yukawa-type

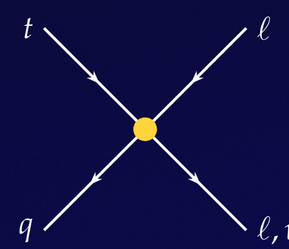
$\mathcal{O}_{uH}$: $(H^\dagger H)(\bar{q}\,u\,\tilde{H})$



FCNC $C^{i3,3i}_{uH} \to tqh$

Semileptonic

$\mathcal{O}^{(1)}_{lq}$: $(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$
$\mathcal{O}^{(3)}_{lq}$: $(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$
$\mathcal{O}_{eu}$: $(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$
$\mathcal{O}^{(1)}_{lequ}$: $(\bar{l}^j e)\,\epsilon_{jk}(\bar{q}^k u)$
…



NC $C^{\alpha\beta 33} \to tt\ell\ell$ $(2t2\ell)$
CC $C^{\alpha\beta i3} \to t\,d_i\,\ell\nu$

This talk

S. Kala, L. Kolay, L. Mukherjee, S. Nandi, JHEP **11** (2025) 071 [Wtb]
S. Kala, S. Nandi, JHEP **11** (2026) 106 [top FCNC]

See Sonakshi's talk
$2t2\ell$ & $t\,d_i\,\ell\nu$

Complete sets of **Observables**

$\Lambda = 1$ **TeV**
SMEFT C_i (complex)
LHC: $t \to u_j X$

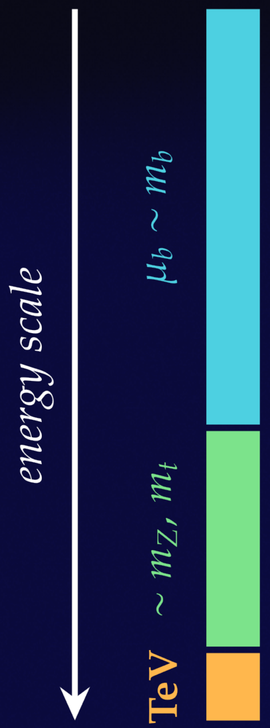
SMEFT RGE

$\mu_{\rm EW} = m_Z$
tree: $t \to u_j X$ couplings
1-loop: EWPO, Higgs, TGC, tWb

match + LEFT RGE

$\mu_b = m_b$
LEFT: $b \to s\ell\ell$, $B \to X_s\gamma$, $\nu\bar{\nu}$, $b \to c\ell\nu$, d_n

Observables in the global fit



class	category	observables
Low-energy FCNC	$b \to s\ell\ell$ ($\ell = \mu, e$)	angular obs., $d\mathcal{B}/dq^2$, R_K, R_{K^*}, CP asymmetries
	radiative	$\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B_{s,d} \to V\gamma)$, CP asym., $S_{K^*\gamma}$
	rare / invisible	$\mathcal{B}(B_{s,d} \to \mu\mu)$, $\mathcal{B}(K_L \to \mu\mu)$, $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$
	meson mixing	$\Delta M_{d,s}$
Low-energy FCCC	$b \to c(u)\ell\nu$	$\mathcal{B}(P \to M\ell\nu)$, $\mathcal{B}(P \to \ell\nu)$, $R(D)$, $R(D^*)$
EDM	nucleon	neutron EDM d_n
EW precision	W, Z pole	S, T, U, W- and Z-pole observables
Higgs	decays / production	$\Gamma(H \to b\bar{b}, WW^*, \gamma\gamma, Z\gamma)$, κ_g, κ_γ, $\kappa_{Z\gamma}$
Gauge & top	TGC, dipoles, tWb	triple gauge couplings, top CMDM, CEDM; $\lvert f_L V_{tb}\rvert$, V_R, $g_{L,R}$
LHC	top FCNC	$\mathcal{B}(t \to u_j X)$, $X = g, \gamma, Z, H$

Why $b \to s\ell\ell$?

Rare in the SM: FCNC, loop + GIM + CKM suppressed

↓

Top-loop dominated in the SM

↓

Precisely measured: B factories **Belle, Belle II** + **LHCb**, CMS, ATLAS

↓

Theoretically clean

Why $b \to s\ell\ell$?

Rare in the SM: FCNC, loop + GIM + CKM suppressed

- $\mathcal{B}(B^+ \to K^+\mu^+\mu^-) \approx 4.5 \times 10^{-7}$
- $\mathcal{B}(B_s \to \mu^+\mu^-) \approx 3.4 \times 10^{-9}$ (SM: 3.66×10^{-9})

↓

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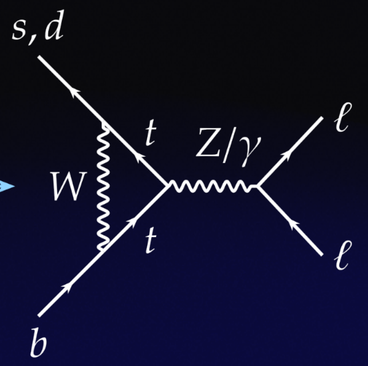
Top-loop dominated in the SM → $\mathcal{A}_{\rm SM} \propto V_{tb}V_{ts}^*$



top-sector C_i enter at the same order

↓

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- $\mathcal{B}$, $d\mathcal{B}/dq^2$
- angular: P_5', F_L, A_{FB}
- R_K, $R_{K^*} \approx 1$ (LHCb 2022, SM-like)
- A_{CP}

↓

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Theoretically clean

- form factors: lattice QCD, LCSR
- $B_s \to \mu\mu$: only f_{B_s}; $R_{K^{(*)}}$: uncertainties cancel

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Theoretically clean

Low-energy EFT

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i'\right)$$

Dipole: $\mathcal{O}_7$ (γ), $\mathcal{O}_8$ (g) **Vector:** $\mathcal{O}_9$, $\mathcal{O}_{10}$ **Scalar:** $\mathcal{O}_S$, $\mathcal{O}_P$ **Tensor:** $\mathcal{O}_T$, $\mathcal{O}_{T5}$ $\nu\bar{\nu}$: $\mathcal{O}_{L,R}^{\nu}$

primed: opposite chirality. G. Buchalla, A. J. Buras, M. E. Lautenbacher, Rev. Mod. Phys. **68** (1996) 1125 [hep-ph/9512380]

$$\mathcal{H}_{\text{eff}}^{b\to d_j\ell\ell} \supset -\frac{4G_F}{\sqrt{2}} V_{tb}V_{td_j}^*\Big(C_9\,\mathcal{O}_9 + C_{10}\,\mathcal{O}_{10} + C_S\,\mathcal{O}_S\Big)$$

Top-sector SMEFT operators modify (C_9, C_{10}, C_S)

CC tbW: $C_{Hq}^{(3)33}$, C_{Hud}^{33}, C_{uW}^{33}, C_{dW}^{33}

FCNC tqX: $C_{uB,uW}^{i3}$, $C_{Hq}^{(1,3)i3}$, C_{Hu}^{i3}, C_{uH}^{i3}

$$C_i(\mu) = C_i^{\text{SM}}(\mu) + \Delta C_i(\mu)$$

Meson-level processes

$b \to s\mu\mu$: $B \to K^{(*)}\mu\mu$, $B_s \to \phi\mu\mu$, $R_{K^{(*)}}$

leptonic: $B_s \to \mu\mu$, $B^0 \to \mu\mu$, $K_{L,S} \to \mu\mu$

Case study: rare FCNC $(b \to s(d)\ell\ell)$

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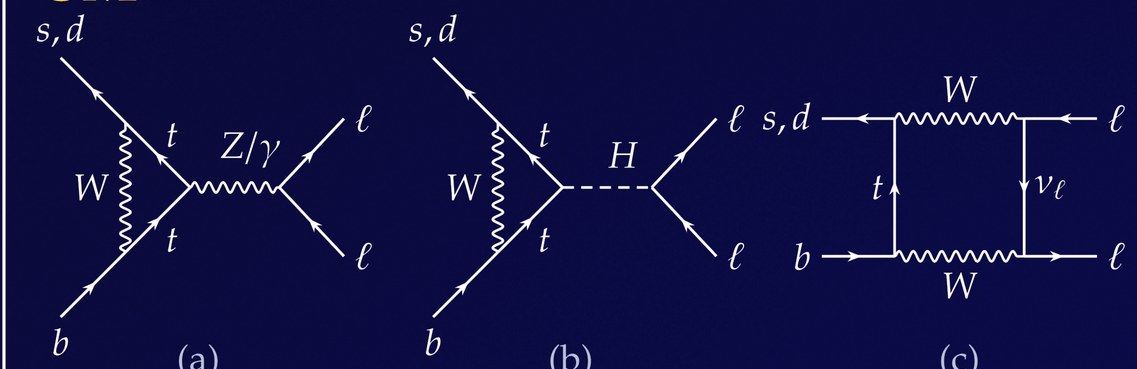
SM



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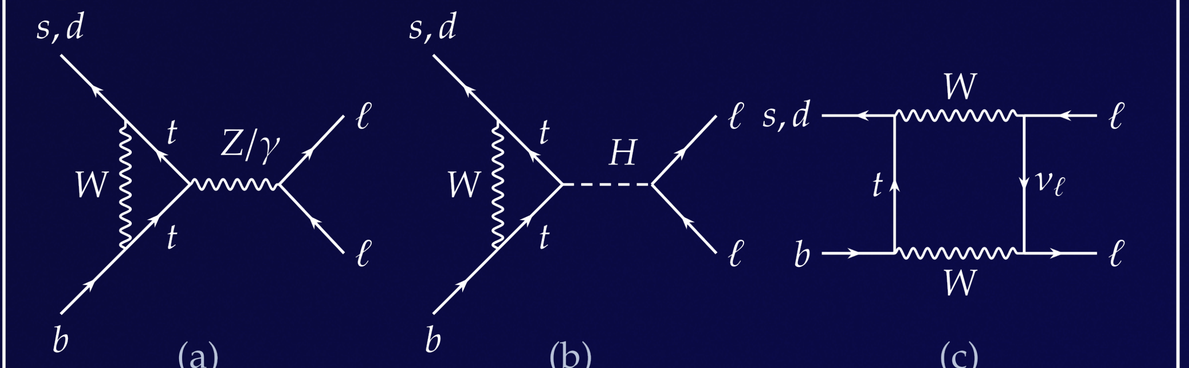
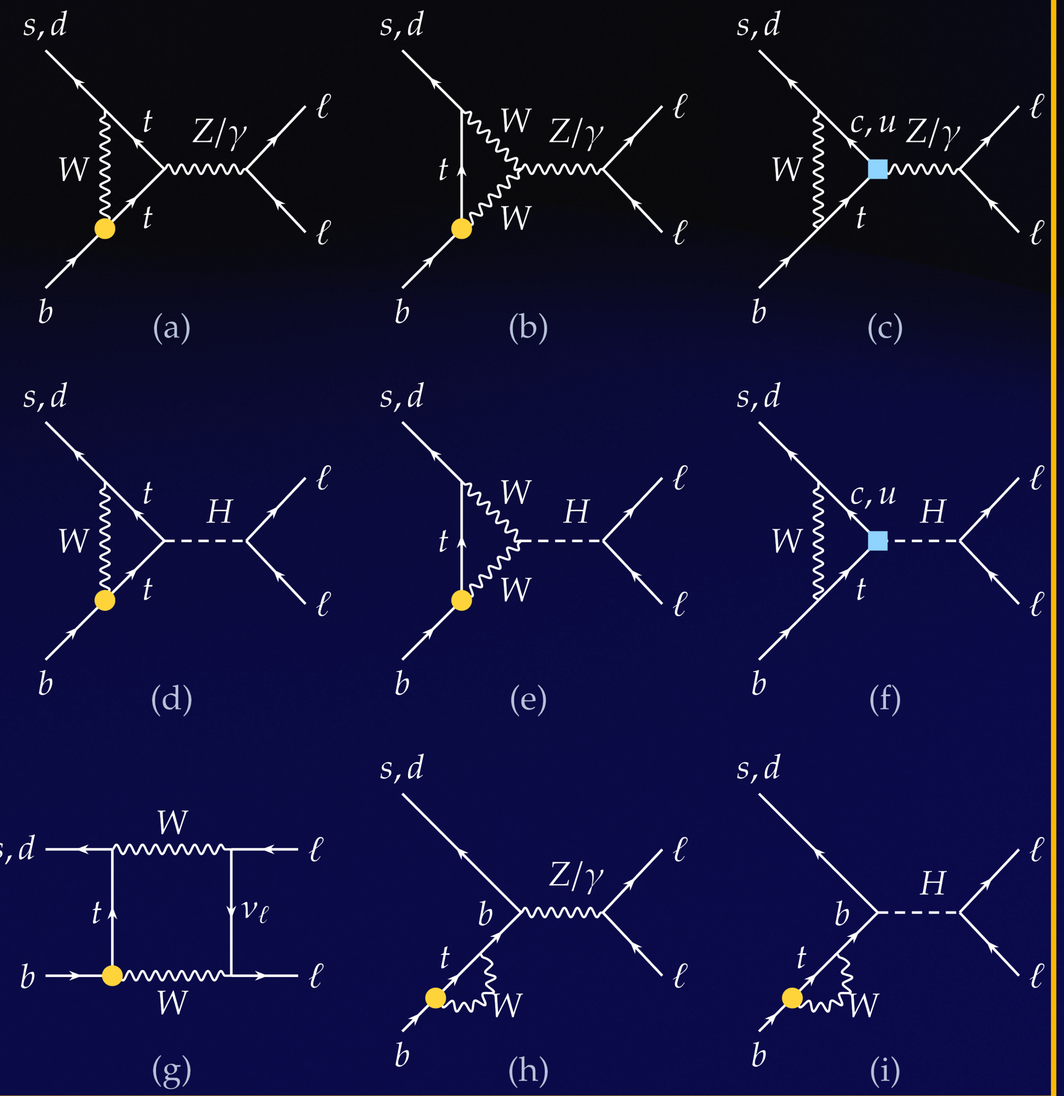


Top-sector SMEFT insertions

● tbW (CC) ■ $tqZ/tq\gamma/tqh$ (FCNC)



$\Lambda = 1$ **TeV**

$$C^i_{\text{SMEFT}}(\Lambda) \in \mathbb{C}$$

SMEFT

Target

$$C_i(\mu_b) = C_i^{\text{SM}}(\mu_b) + \Delta C_i(\mu_b \leftarrow \Lambda)$$

SMEFT RGE

μ_{EW}

$$\Delta C_i(\mu_{\text{EW}}) = g\left(C^i_{\text{SMEFT}}\right)$$

one-loop matching

WET RGE

$$C_i(\mu_b) = U_{ij}(\mu_b, \mu_{\text{EW}})\, C_j(\mu_{\text{EW}})$$

RGE

$$16\pi^2\, \mu \frac{dC_i}{d\mu} = \gamma_{ij}\, C_j$$

$$\Rightarrow\ C_i(\mu) = U_{ij}(\mu, \mu_0)\, C_j(\mu_0), \qquad U \simeq \exp\left[\frac{\gamma}{16\pi^2} \ln \frac{\mu}{\mu_0}\right]$$

γ_{ij}: anomalous-dimension matrix; U shown at leading log (constant γ)

μ_b

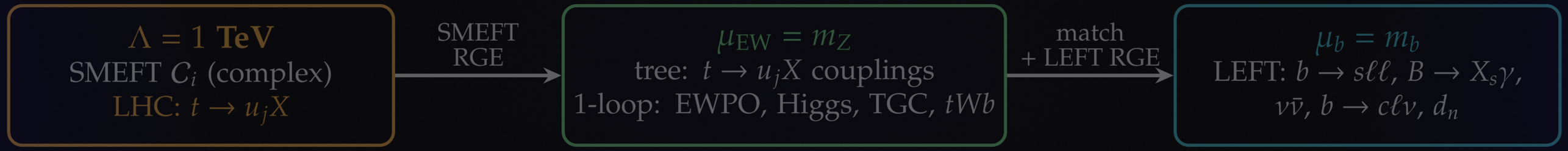
$$C_i(\mu_b) = C_i^{\text{SM}} + U_{ij}\, g\left(C^j_{\text{SMEFT}}\right)$$

low-energy observables

$C_i^{\text{SM}}(\mu_b)$: Mahmoudi et al., Symmetry **16** (2024) 1006

$$\mathcal{B}(B_q \to \mu^+\mu^-) = \tau_{B_q} f_{B_q}^2 m_{B_q}^3 \frac{G_F^2 \alpha^2}{64\pi^3} |V_{tq}^* V_{tb}|^2 \beta_\mu(m_{B_q}^2) \left[\frac{m_{B_q}^2}{m_b^2} \left|C_S - C_S'\right|^2 \left(1 - \frac{4m_\mu^2}{m_{B_q}^2}\right) + \left|\frac{m_{B_q}}{m_b}(C_P - C_P') + 2\frac{m_\mu}{m_{B_q}}(C_{10} - C_{10}')\right|^2\right]$$

Complete sets of **Observables**



Observables in the global fit

[JHEP 11 (2025) 071 | JHEP 11 (2026) 106]



class	category	observables
Low-energy FCNC	**$b \to s\ell\ell$ ($\ell = \mu, e$)**	**angular obs., $d\mathcal{B}/dq^2$, R_K, R_{K^*}, CP asymmetries**
	radiative	$\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B_{s,d} \to V\gamma)$, CP asym., $S_{K^*\gamma}$
	rare / invisible	**$\mathcal{B}(B_{s,d} \to \mu\mu)$**, $\mathcal{B}(K_L \to \mu\mu)$, $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$, $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$
	meson mixing	$\Delta M_{d,s}$
Low-energy FCCC	$b \to c(u)\ell\nu$	$\mathcal{B}(P \to M\ell\nu)$, $\mathcal{B}(P \to \ell\nu)$, $R(D)$, $R(D^*)$
EDM	nucleon	neutron EDM d_n
EW precision	W, Z pole	S, T, U, W- and Z-pole observables
Higgs	decays / production	$\Gamma(H \to b\bar{b}, WW^*, \gamma\gamma, Z\gamma)$, κ_g, κ_γ, $\kappa_{Z\gamma}$
Gauge & top	TGC, dipoles, tWb	triple gauge couplings, top CMDM, CEDM; $\lvert f_L V_{tb}\rvert$, V_R, $g_{L,R}$
LHC	top FCNC	$\mathcal{B}(t \to u_j X)$, $X = g, \gamma, Z, H$

$$\chi^2_{\text{Global}} = \chi^2_{\text{Flavour}} + \chi^2_{\text{EDM}} + \chi^2_{\text{EWPO}} + \chi^2_{\text{Higgs, top}} + \chi^2_{\text{Collider}}$$

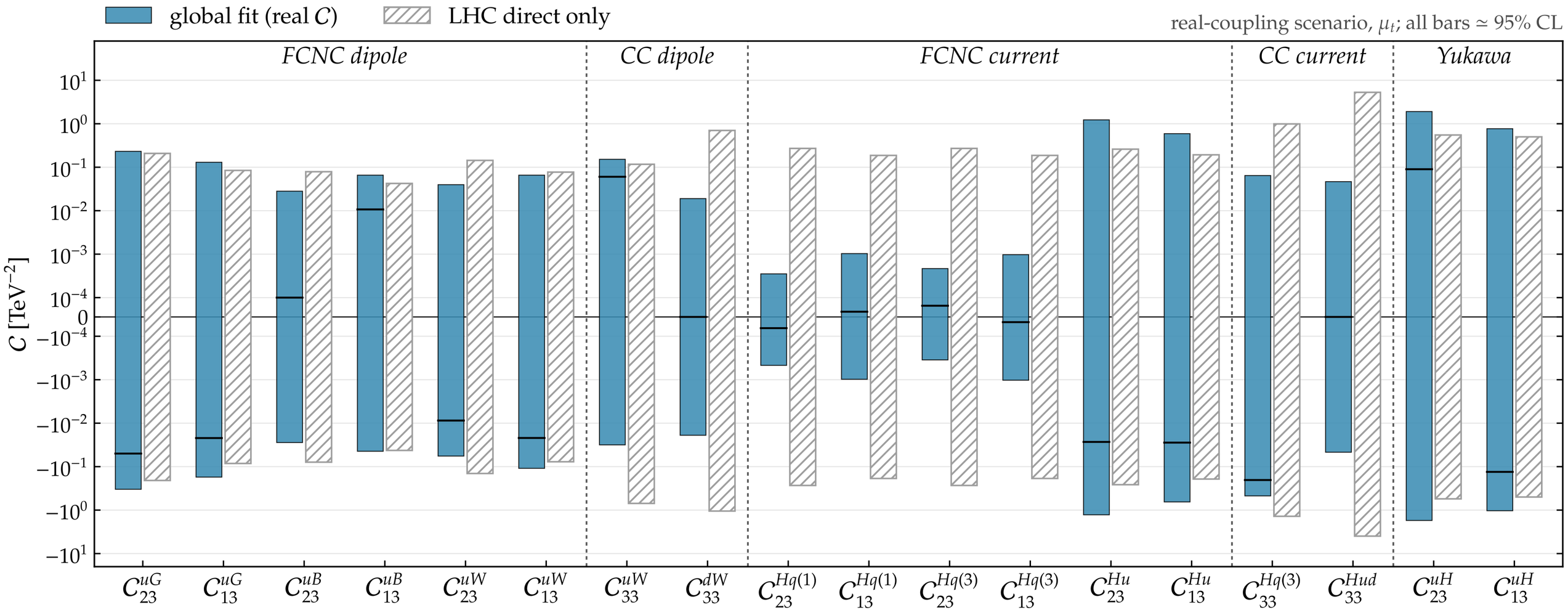
$$\chi^2(C) = \sum_{ij} \Delta\mathcal{O}_i \, (V^{-1})_{ij} \, \Delta\mathcal{O}_j, \qquad \Delta\mathcal{O} = \mathcal{O}^{\text{th}}(C) - \mathcal{O}^{\text{exp}}$$

V: covariance matrix (experimental + theory uncertainties, incl. correlations)

Fits performed: one-at-a-time (1D) | multi-parameter | real C_i | complex C_i (Re + Im)

Shown here: **real C_i, one at a time** *others in backup*

Results: Real SMEFT WCs at $\mu_{\rm EW}$



Key takeaways

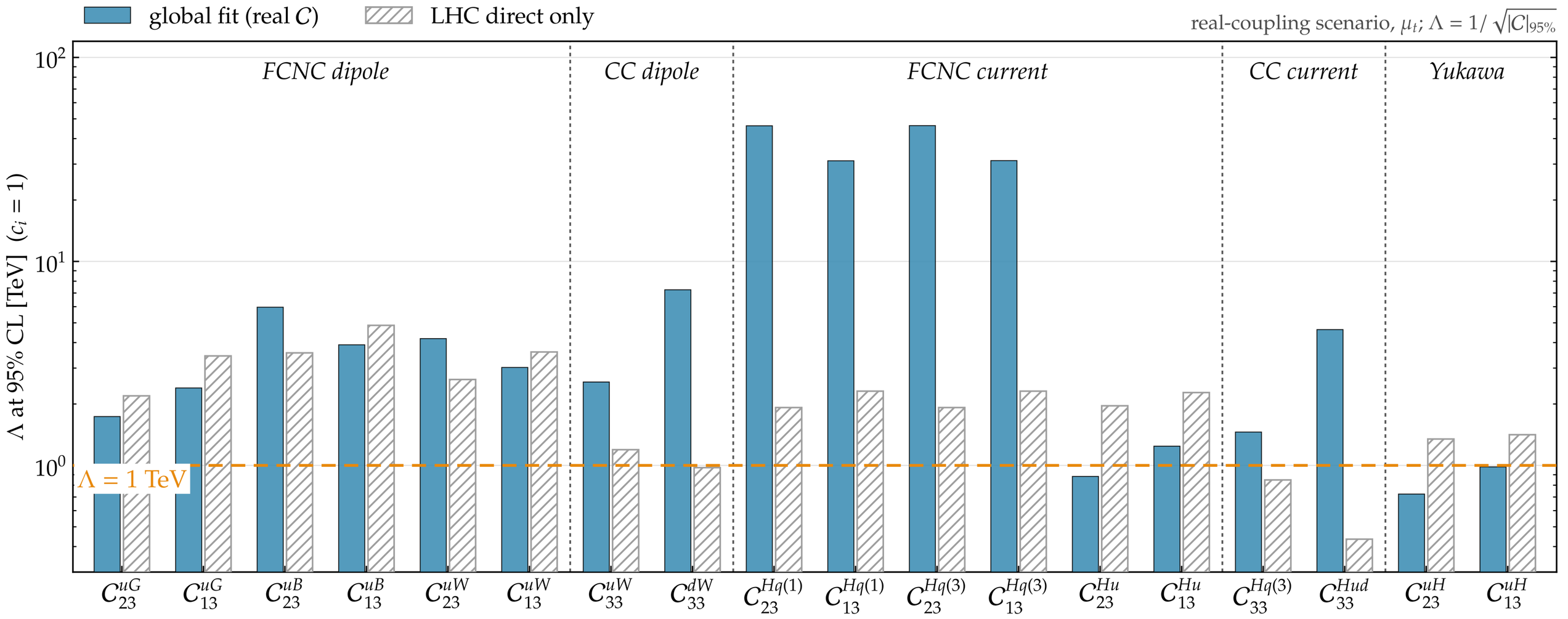
FCNC current: $\sim 10^{-4}\,\text{TeV}^{-2}$, $10^3\times$ LHC (tree-level $b \to s\ell\ell$)

CC sector: low-energy fit beats CMS by $\sim 10\times$

FCNC dipoles: global ≃ LHC: complementary

C^{Hu}, C^{uH}: still LHC-dominated

Results: Real SMEFT WCs at $\mu_{\rm EW}$



Key takeaways

FCNC current: $\Lambda \gtrsim$ 30–45 TeV vs ~ 2 TeV (LHC)

CC sector: Λ ~ 2.5–7.5 TeV vs $\lesssim$ 1 TeV (CMS)

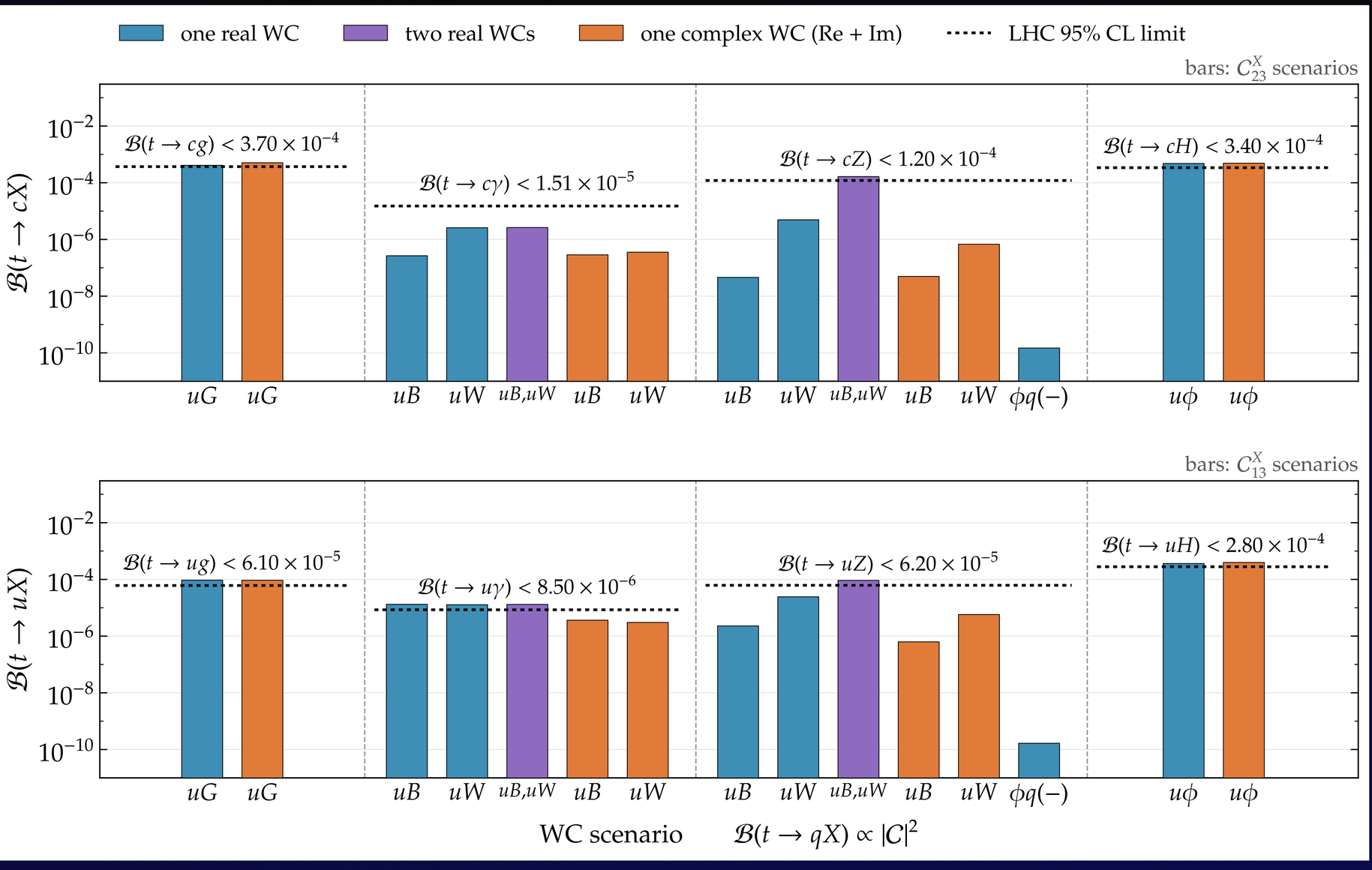
FCNC dipoles: Λ ~ 2–6 TeV, global $\simeq$ LHC

C^{Hu}, C^{uH}: Λ ~ 1 TeV, EFT validity marginal

Predictions: Top FCNC decays vs LHC

$\mathcal{B}(t \to qX) \propto |C|^2 \quad \Rightarrow \quad$ global-fit bound on $C \to$ upper limit on $\mathcal{B}$

bars: different WC scenarios dotted line: LHC limit, same for all scenarios of a process



Key takeaways

$C^{\phi q(-)}$: $\mathcal{B}(t \to qZ) \sim 10^{-10}$, $10^6\times$ below LHC (tree-level $b \to s\ell\ell$)

Dipoles uB, uW: $t \to c\gamma,\ cZ$ 10^1–$10^3\times$ below LHC

Complex WCs: EDM fixes the phase $\Rightarrow$ lower $\mathcal{B}(t \to u\gamma,\ uZ)$

$uG,\ u\phi$: LHC-limited

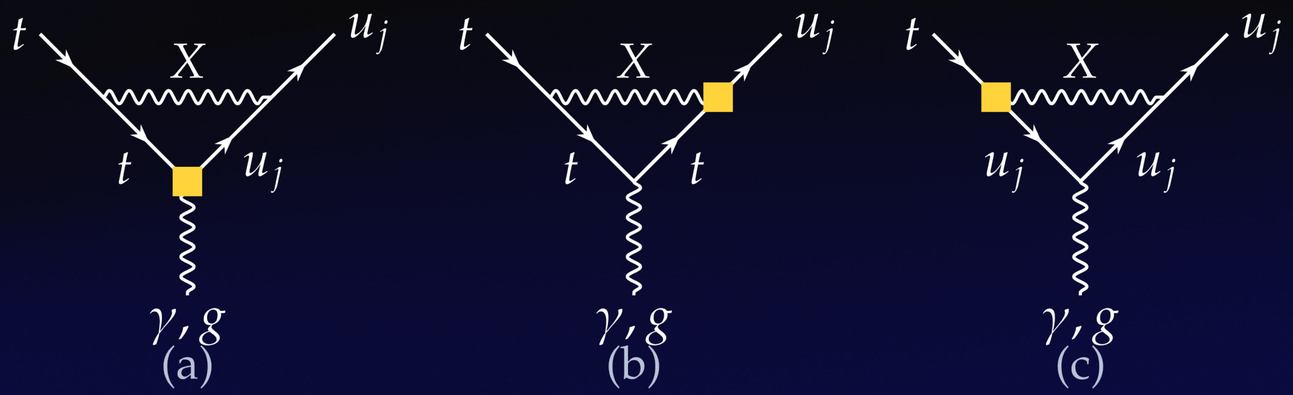
Predictions: CP asymmetries in $(t \to qg, t \to q\gamma)$

The idea

$\Delta_{CP} \neq 0$ needs **two interfering amplitudes** with different weak *and* strong phases

Weak phase: complex SMEFT WCs C_i

Strong phase: absorptive part of one-loop diagrams (on-shell states)



$$\Delta_{CP,\pm} = \frac{\Gamma(t \to u_j\gamma_\pm) - \Gamma(\bar{t} \to \bar{u}_j\gamma_\mp)}{\Gamma(t \to u_j\gamma) + \Gamma(\bar{t} \to \bar{u}_j\gamma)}$$

$$\Delta_{CP,+} \propto m_{u_j}, \quad \Delta_{CP,-} \propto m_t \quad \Rightarrow \quad |\Delta_{CP,+}| \ll |\Delta_{CP,-}|$$

- FCNC vertex C_i $\quad X = W, Z, h, \gamma, g$

Predictions: CP asymmetries in $(t \to qg, t \to q\gamma)$

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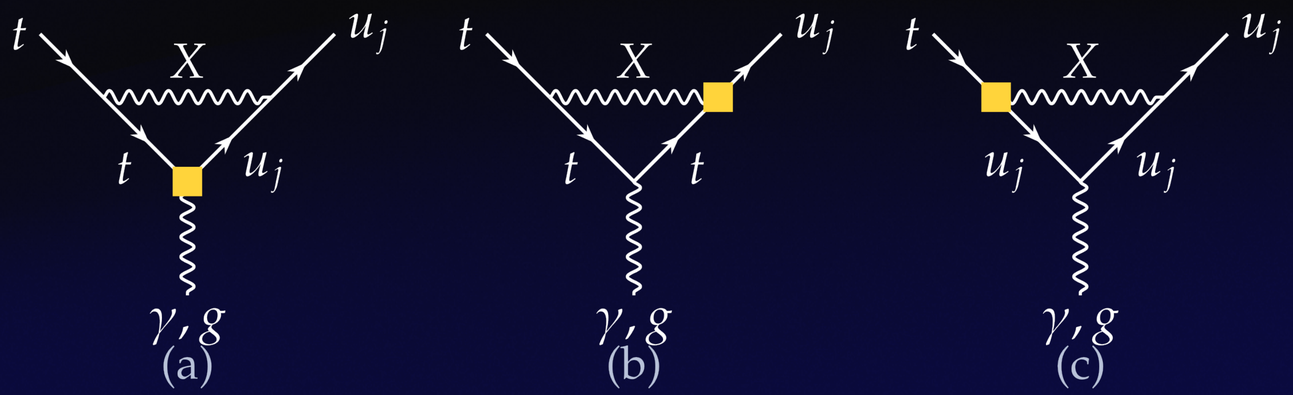


■ FCNC vertex C_i $\quad X = W, Z, h, \gamma, g$

$$\Delta_{CP,\pm} = \frac{\Gamma(t \to u_j\gamma_\pm) - \Gamma(\bar{t} \to \bar{u}_j\gamma_\mp)}{\Gamma(t \to u_j\gamma) + \Gamma(\bar{t} \to \bar{u}_j\gamma)}$$

$$\Delta_{CP,+} \propto m_{u_j}, \quad \Delta_{CP,-} \propto m_t \quad \Rightarrow \quad |\Delta_{CP,+}| \ll |\Delta_{CP,-}|$$

Decay	$\Delta_{CP,+}$	$\Delta_{CP,-}$
$t \to c\gamma$	$(1.05 \pm 4.93) \times 10^{-4}$	$(-0.11 \pm 6.06) \times 10^{-3}$
$t \to u\gamma$	$(-2.31 \pm 6.56) \times 10^{-9}$	$(-0.26 \pm 2.24) \times 10^{-4}$
$t \to cg$	$(-0.05 \pm 1.81) \times 10^{-4}$	$(-0.95 \pm 6.30) \times 10^{-3}$
$t \to ug$	$(-1.18 \pm 3.52) \times 10^{-8}$	$(-0.32 \pm 1.19) \times 10^{-4}$

$(V-A)$ weak interaction $\Rightarrow$ emitted γ, g mainly left-handed

all channels: $\Delta_{CP,-}$ up to $\mathcal{O}(10^{-4}$–$10^{-3})$: a clean probe of $\mathrm{Im}\, C_i$, complementary to EDMs

Key takeaways

- Collider data alone are not enough: a global SMEFT fit is needed
- Low-energy data probe top couplings up to $\Lambda \sim 30$–45 TeV
- Top-FCNC rates predicted far below current LHC limits
- EDMs & A_{CP} pin down the CP phases

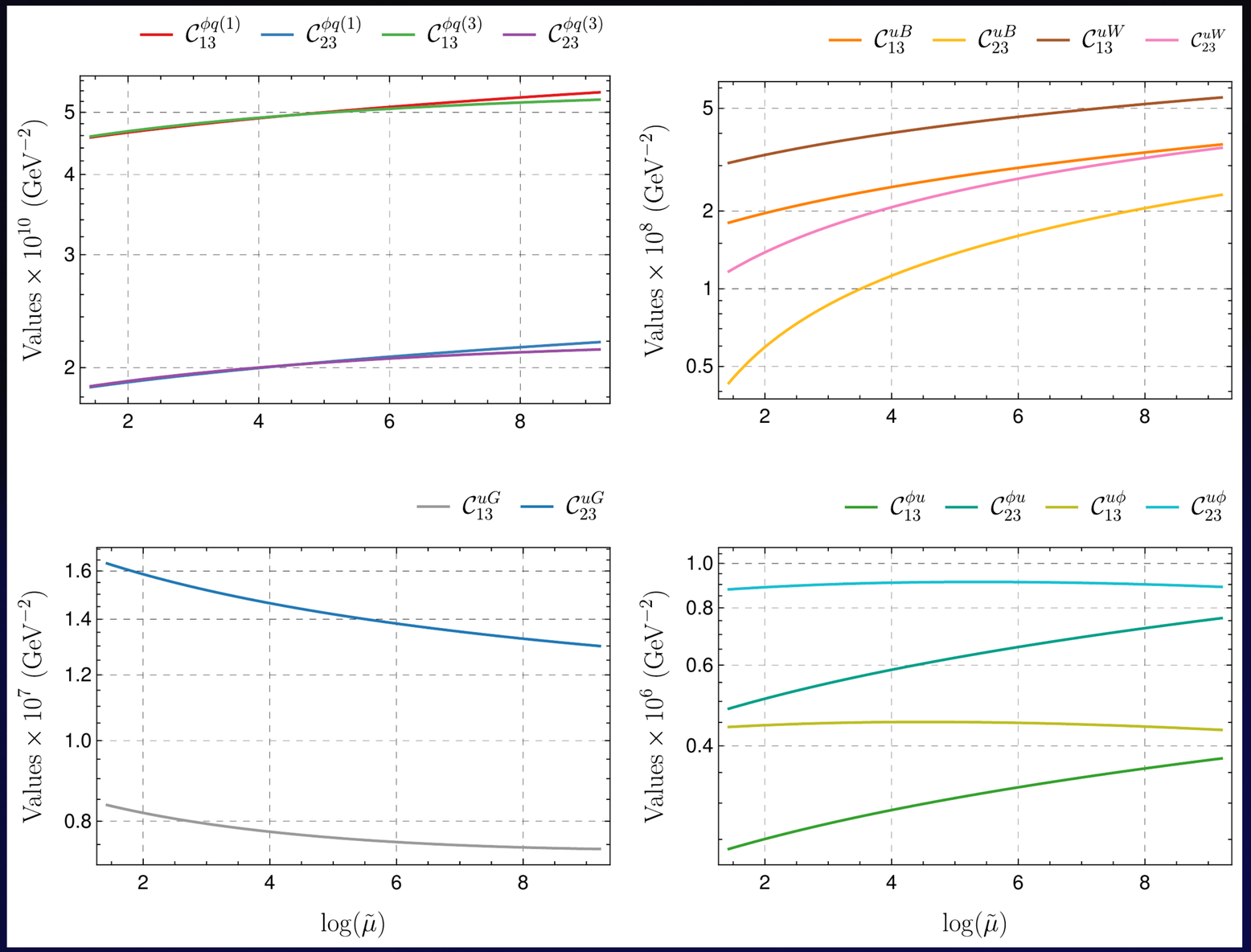
Thank You

for your kind attention

For any questions or discussion in future, feel free to contact me: s.kala@iitg.ac.in

Back Up Slides

Impact of Running



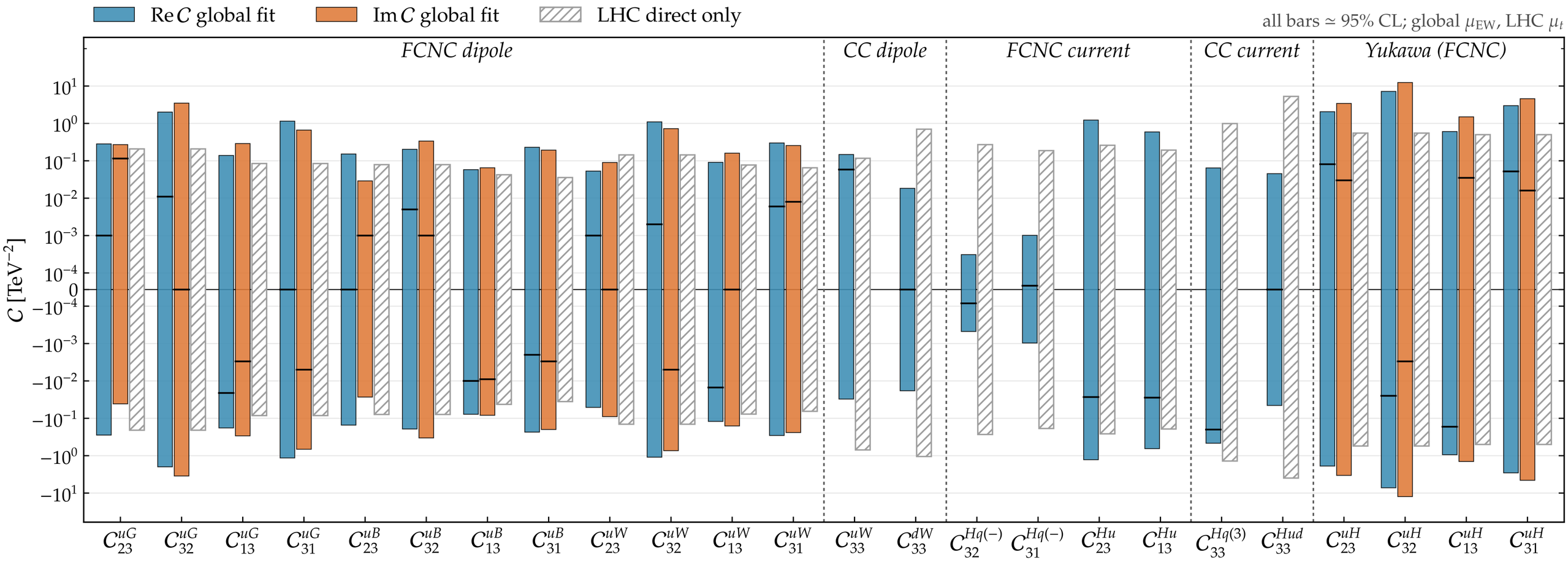
Takeaway

- **QCD-driven ↓:**
  C^{uG} decreases, $C^{u\phi}$ nearly flat
  C^{uG}: ~15–20% from $\mu_b \to 10$ TeV
- **EW-driven ↑:**
  $C^{uB}, C^{uW}, C^{\phi q}, C^{\phi u}$ grow with μ
- **Largest effect:**
  EW dipoles, C_{23}^{uB} changes by ×5

⇒ bounds must be quoted with their scale

$C_i \equiv c_i/\Lambda^2$, $\tilde{\mu} = \mu/1\,\text{GeV}$ | *real couplings,* C_{i3} | $\mu_b \to \Lambda = 10\,\text{TeV}$

Results: Complex SMEFT WCs at $\mu_{\rm EW}$



Key takeaways

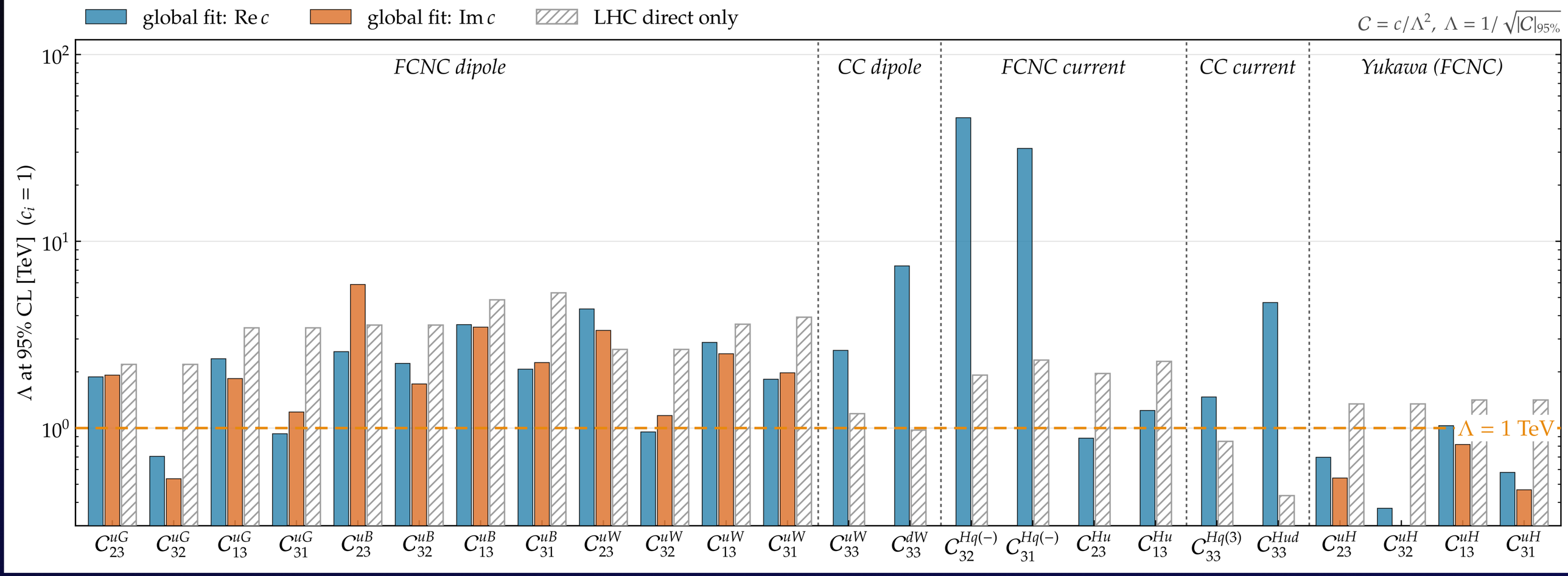
*i*3 **dipoles:** Re & Im both $\mathcal{O}(10^{-2}$–$10^{-1})$ TeV^{-2}, ≃ LHC

Im C**:** fixed by EDM + $A_{CP}(b \to s\gamma)$, not by LHC rates

Currents: $C^{Hq(-)} \sim 10^{-4}$, CC sector ~ 10× beyond CMS

3*i* **dipoles,** C^{uH}**:** still LHC-dominated

Results: Complex SMEFT WCs at $\mu_{\rm EW}$



Key takeaways

FCNC current: $\Lambda \simeq$ 30–45 TeV vs $\sim$ 2 TeV (LHC)

CC sector: $\Lambda \sim$ 1.5–7.5 TeV vs $\lesssim$ 1 TeV (CMS)

$i3$ **dipoles:** $\Lambda \sim$ 2–6 TeV for both Re and Im

$3i$**, Yukawa:** $\Lambda \lesssim$ 1 TeV, LHC-limited