Probing Top Quark Anomalous Effective Couplings Through Precision Studies in the SMEFT Framework.

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Outline of the talk

- Framework of Effective Field Theory (EFT)
- Framework of SMEFT & LEFT
- Phenomenological Implications [Top quark effective couplings]
- Future Predictions

The Quest for New Physics (NP)

- **The Standard Model is successful but incomplete !!**

  Explain the Electroweak precision test, the Higgs discovery, the success of flavour physics,…..

  But can not explain,

  Dark Matter, Neutrino mass & oscillation, Baryon asymmetry, Hierarchy problem, Flavour anomaly,….

- **Direct searches at LHC**

  No new heavy resonance up to **multi-TeV scales.**

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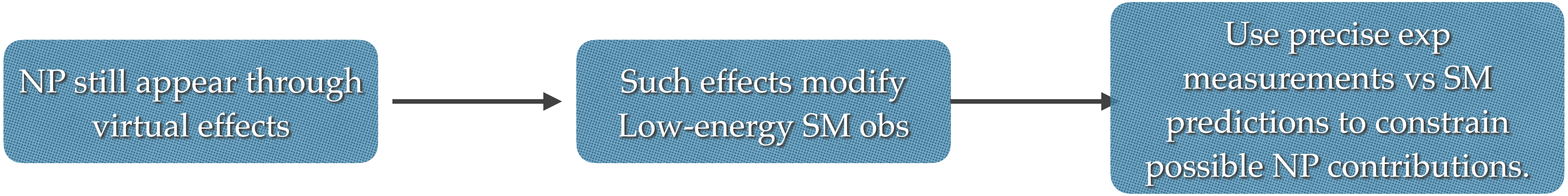
However, that does mean NP is absent!!

- **Indirect searches of NP** (The Shift to the Precision Frontier)



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Such effects modify Low-energy SM obs

Use precise exp measurements vs SM predictions to constrain possible NP contributions.

The Shift to the Precision Frontier

- **Indirect searches of NP**

NP still appear through virtual effects → Such effects modify Low-energy SM obs → Use precise exp measurements vs SM predictions to constrain possible NP contributions.

- Why use low-energy physics to constrain the Heavy Physics??

Direct Collider (ATLAS/CMS)

- Top pair / Single top production, W helicity fractions
- Limited by hadronic uncertainties, experimental systematics etc.
- Sometimes current bounds are loose [More detail in future slides]

Indirect Bounds (Quantum Loops)

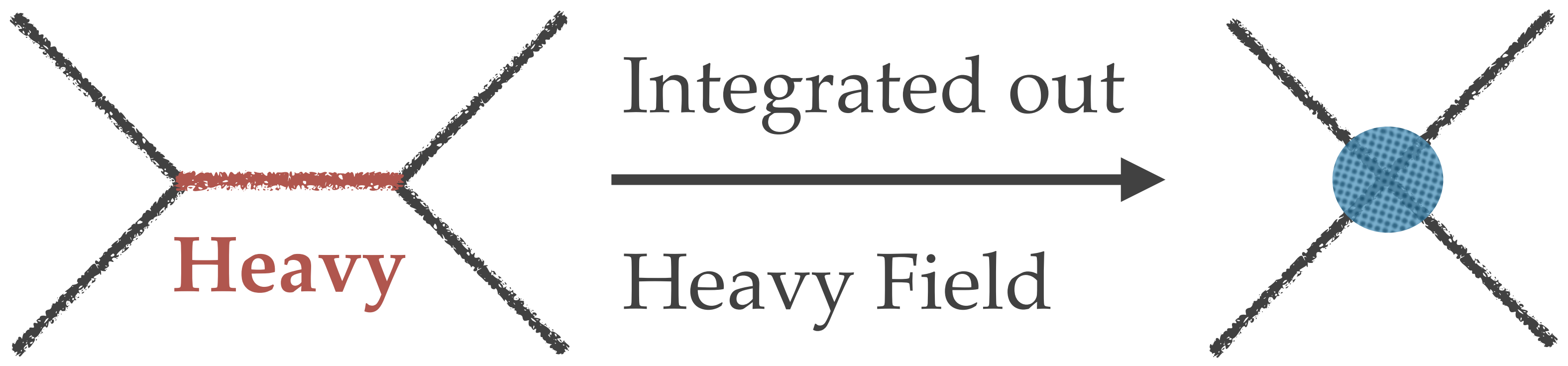
- Loop-induced low-energy processes (*B* meson decays, Meson mixings,...)
- Low-energy observables are measured with extreme precision at LHCb and Belle II.

Effective Field Theory (EFT)

- **Key Idea**

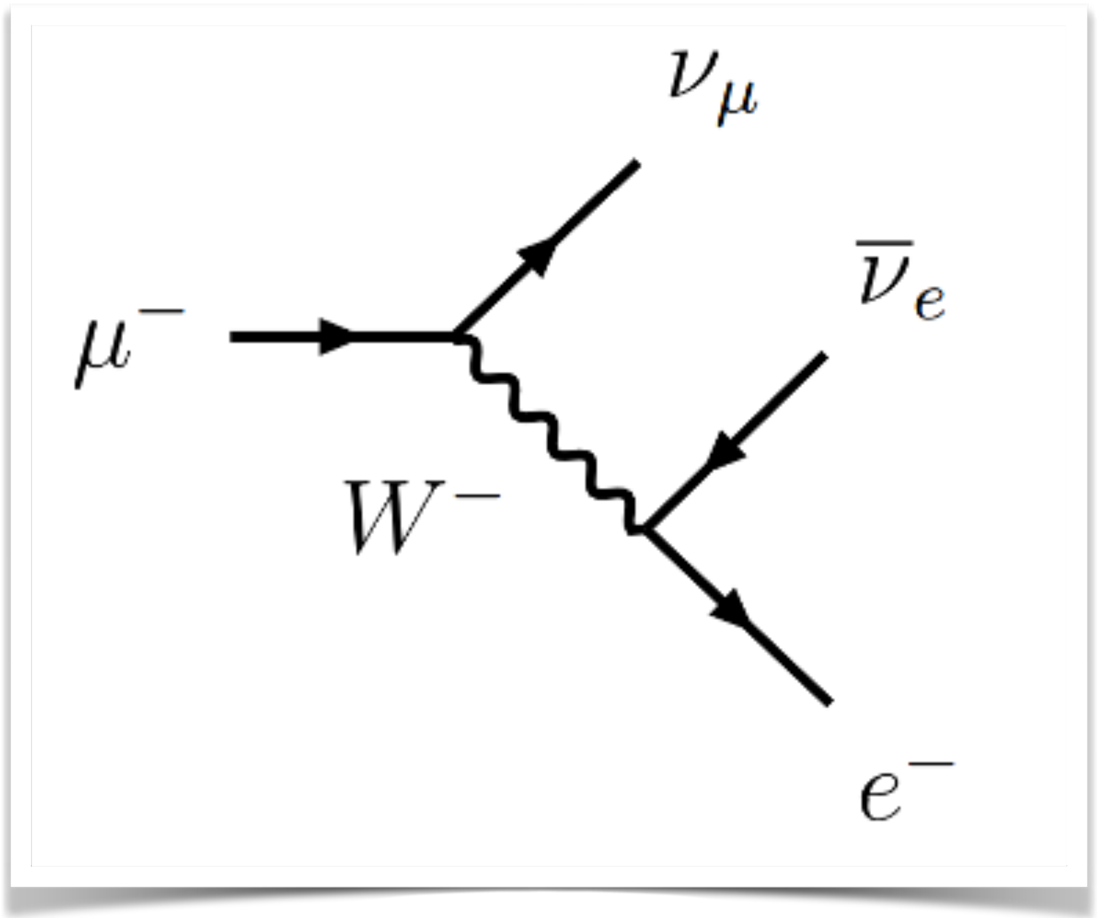
Integrate out heavy states → get effective operators

Top-down approach

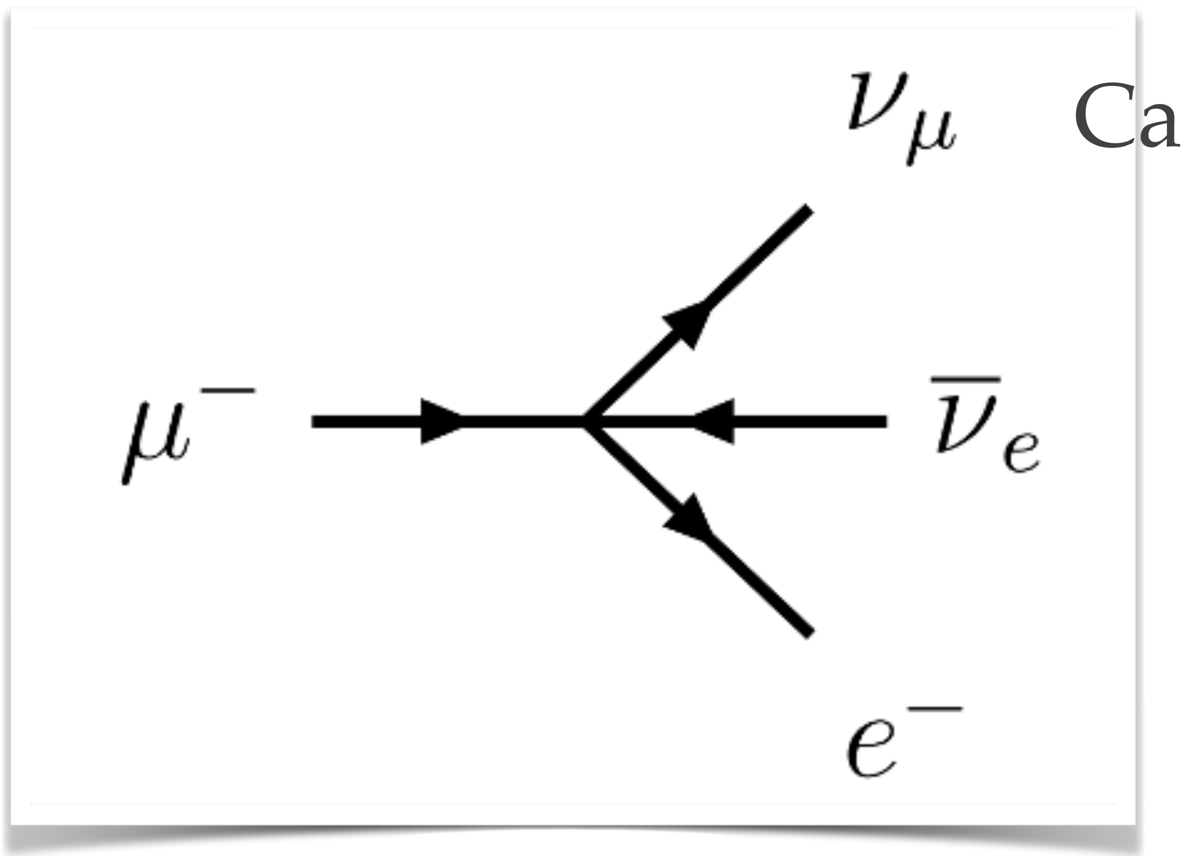


Coefficient of the effective operator incorporates the essence of NP!!

Example: Effective four-Fermi theory $(\mu^- \to e^- \bar{\nu}_e \nu_\mu)$



Integrated out →



Calculate the same process from both the theories

$$\frac{g^2}{q^2 - M_W^2} \xrightarrow{q^2 \ll M_W^2} \frac{g^2}{M_W^2}$$

Matching Eq. $$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8M_W^2}$$

G_F : Fermi Constant

Effective Field Theory (EFT)

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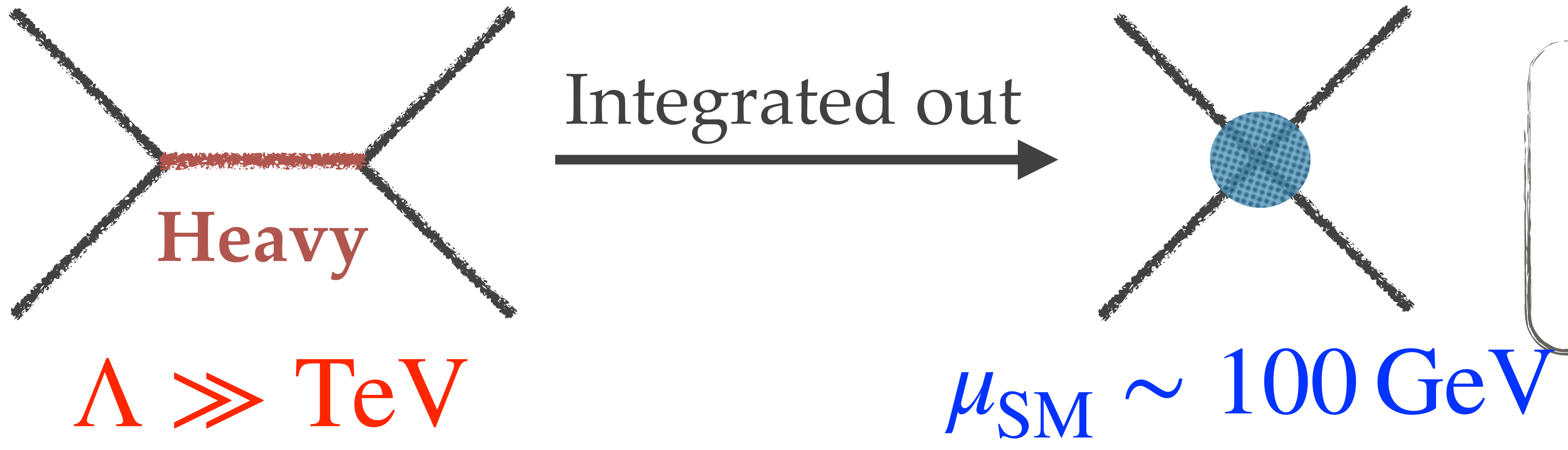

Coefficient of the effective operator incorporates the essence of NP!!

Λ represents the heavy scale where NP interaction or particle live

$$\left[\mathscr{L}^{(d)} = \sum_{i}^{n_d} \frac{\mathscr{C}_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)} \right]$$

A systematic expansion of new physics in powers of $(1/\Lambda)$.

Here $\mathscr{C}_i$ are the **dimensionless** couplings (**Wilson Coefficient**), but depend on the **renormalisation scale** (μ).

The scale dependency enters through the renormalisation of effective operators

Operator Renormalisation

Effective operators are not renormalised!!

$$\mathcal{O}_i^{\text{bare}} = \sum_j Z_{ij}^{\mathcal{O}} \mathcal{O}_j^{\text{ren}}$$

Just like couplings, EFT operators must be renormalised —loops make them mix…..

Renormalisation Matrix $Z_{ij}^{\mathcal{O}} = \left(\delta_{ij} + \frac{A_{ij}}{\epsilon} + \mathcal{O}\left(\frac{1}{\epsilon}\right)^n\right)$

In a renormalised theory, this UV divergence can be absorbed within WCs.

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Example

Consider a matrix element of four quark operator: $\langle \mathcal{O}^i \rangle$

$$\langle \mathcal{O}_i(\psi_i) \rangle \xrightarrow{\text{Renormalisation}} \langle \mathcal{O}_i \rangle^b = Z_\psi^{-2} Z_{ij} \langle \mathcal{O}_j \rangle^r$$

Higher-order corrections give divergence!!

Quark fields RG

Operator RG

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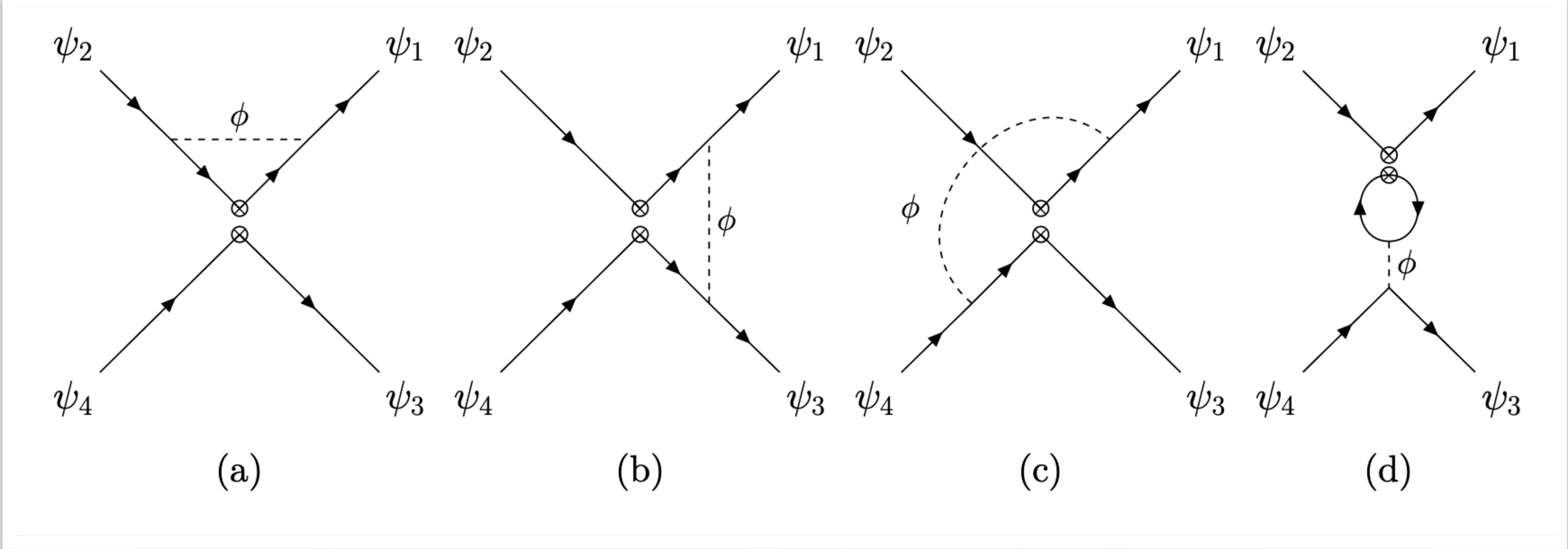

(a) (b) (c) (d)

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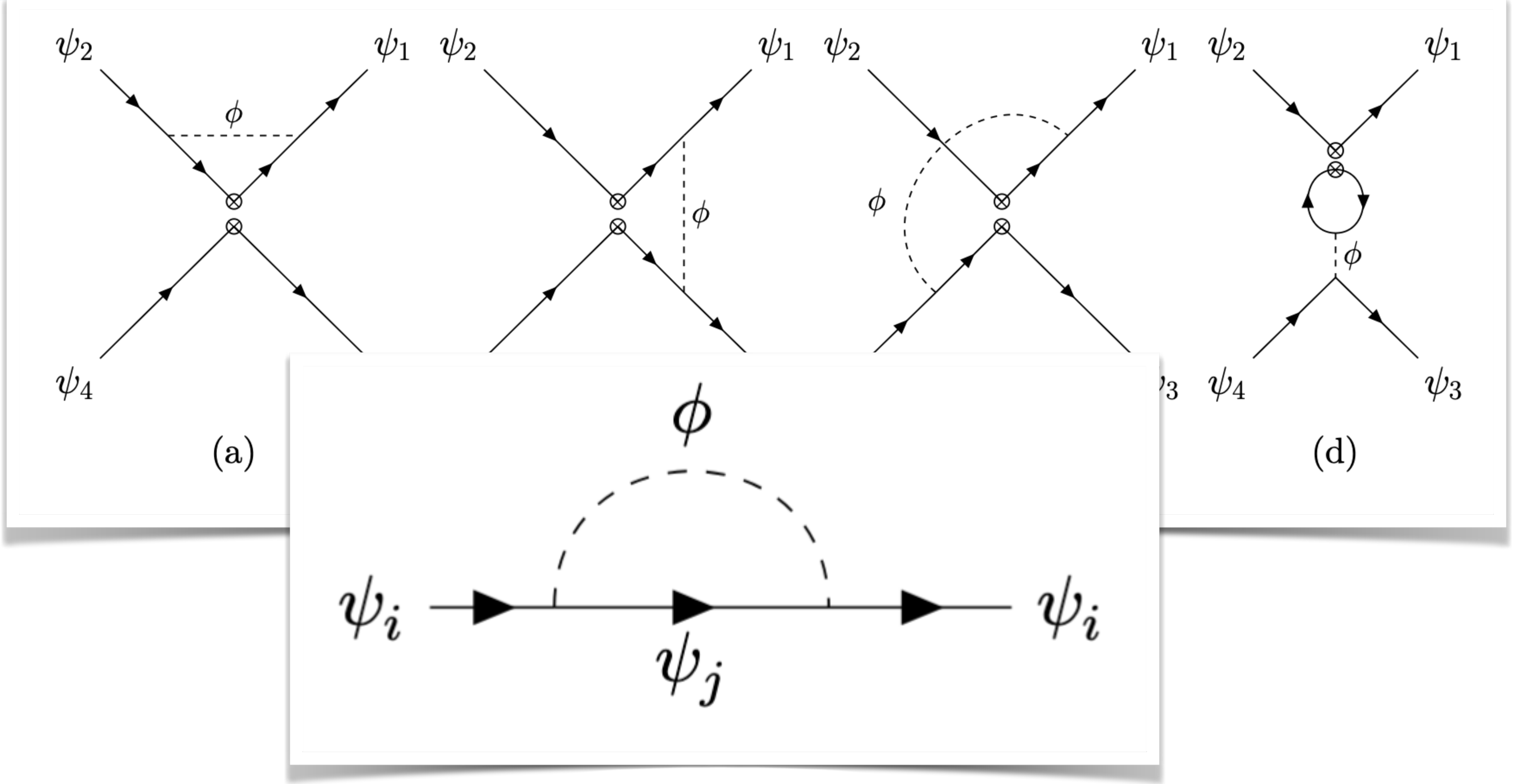

Running & Anomalous Dimension Matrix (ADM)

To maintain renormalizability across the scale, information of the running of WCs is crucial

$$\mu\frac{d}{d\mu}\mathcal{O}_i^{\text{bare}} = \mu\frac{d}{d\mu}\left(Z_{ij}^{\mathcal{O}}\mathcal{O}_j^{\text{ren}}\right) = 0$$

$$\downarrow$$

$$\mu\frac{d}{d\mu}\mathcal{O}_i^{\text{ren}} = -\underbrace{\left(Z^{-1}\mu\frac{d}{d\mu}Z\right)_{ij}}_{\gamma_{ij}}\mathcal{O}_j^{\text{ren}}$$

Anomalous Dimension Matrix (ADM)

In a Complementary Approach

$$\mu\frac{d}{d\mu}\mathscr{C}_i^{\text{ren}}(\mu) = -(\gamma^T)_{ij}\mathscr{C}_j^{\text{ren}}(\mu)$$

γ_{ij}

The ADM is the DNA of an EFT.

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ADM carries the information

- **Running of couplings.**
- **Mixing of operators.**
- **This helps to connect your theory to collider observables.**

Standard Model Effective Field Theory (SMEFT)

- With no new particles up to a few TeV, allows one to parametrise NP with higher-dimensional, gauge-invariant operators built from SM fields….

- Follow the SM gauge symmetry. $\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y}$
- **Valid above the EW scale.**
- Degrees of freedom: SM fields including $(t, H, W, Z, \cdots)$
- Operator bases are constructed obeying E.O.M., Fiertz Identity, and IBP.
- Dim 5 SM Lagrangian has a single op.
- Dim 6 SM Lagrangian has 59 independent op.

SMEFT

NP is integrated out

$\Lambda \gg \text{Vev}$

$$\mathscr{L}^{(d)}_{\text{SMEFT}} = \mathscr{L}^{(4)}_{\text{SM}} + \sum_{d\geq5}\sum_{i} \frac{\mathscr{C}_i^{(d)}}{\Lambda^{(d-4)}}\mathscr{O}_i^{(d)}$$

- **Operator Basis**: **Warsaw**, SILH, JMT, HISZ, EGGM, …
- **ADM are known** (Up to dim 8) Jenkins, Manohar, Trott

(arXiv: 1308.2627)
(arXiv: 1310.4838)
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But what about the physics below the EWSB scale??

Low Energy Effective Field Theory (LEFT)

An alternative, complementary way to search NP below the **EW scale!!**

- Respect the gauge symmetry $(\mathrm{SU}(3) \times U(1)_Q)$
- **Valid below the EW scale and basis is constructed after EWSB.**
- **Degrees of freedom: light quark (u,d,s,c,b), leptons, photon and gluon.**
- **Used for the process at the hadronic scale or low-energy processes.**
- Larger operators set due to lesser gauge restrictions

(Dim 6, $70(B = L = 0)$, $123(B \neq L \neq 0)$)

LEFT

NP along with SM heavy d.o.f (t, H, Z, W) are integrated out

$$\mathscr{L}_{\mathrm{LEFT}} = \mathscr{L}_{\mathrm{QCD+QED}} + \sum_{d \geq 5} \sum_i L_i^{(d)} O_i^{(d)}$$

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SMEFT is the right tool above the EW scale; LEFT takes over below it. Matching at the μ_{EW} ensures a consistent description of NP effects across all energy regimes.

Matching between SMEFT & LEFT

We can match both the theories at μ_{EW} scale

$$\mathscr{L}_{\text{LEFT}}\Big|_{\mu_W} = \mathscr{L}_{\text{SMEFT}}\Big|_{\mu_W}$$

$$\mathscr{L}^{\text{ren ,Tree}}_{\text{LEFT}} + \mathscr{L}^{\text{Loop}}_{\text{LEFT}} + \mathscr{L}^{\text{C.T.}}_{\text{LEFT}}\Big|_{\mu_W} = \mathscr{L}^{\text{ren ,Tree}}_{\text{SMEFT}} + \mathscr{L}^{\text{Loop}}_{\text{SMEFT}} + \mathscr{L}^{\text{C.T.}}_{\text{SMEFT}}\Big|_{\mu_W}$$

Expand the integrands of the loop integrals in the low-energy scales

$$\mathscr{L}^{\text{Loop}}_{\text{LEFT}} = 0$$

In the Dimensional Regularisation

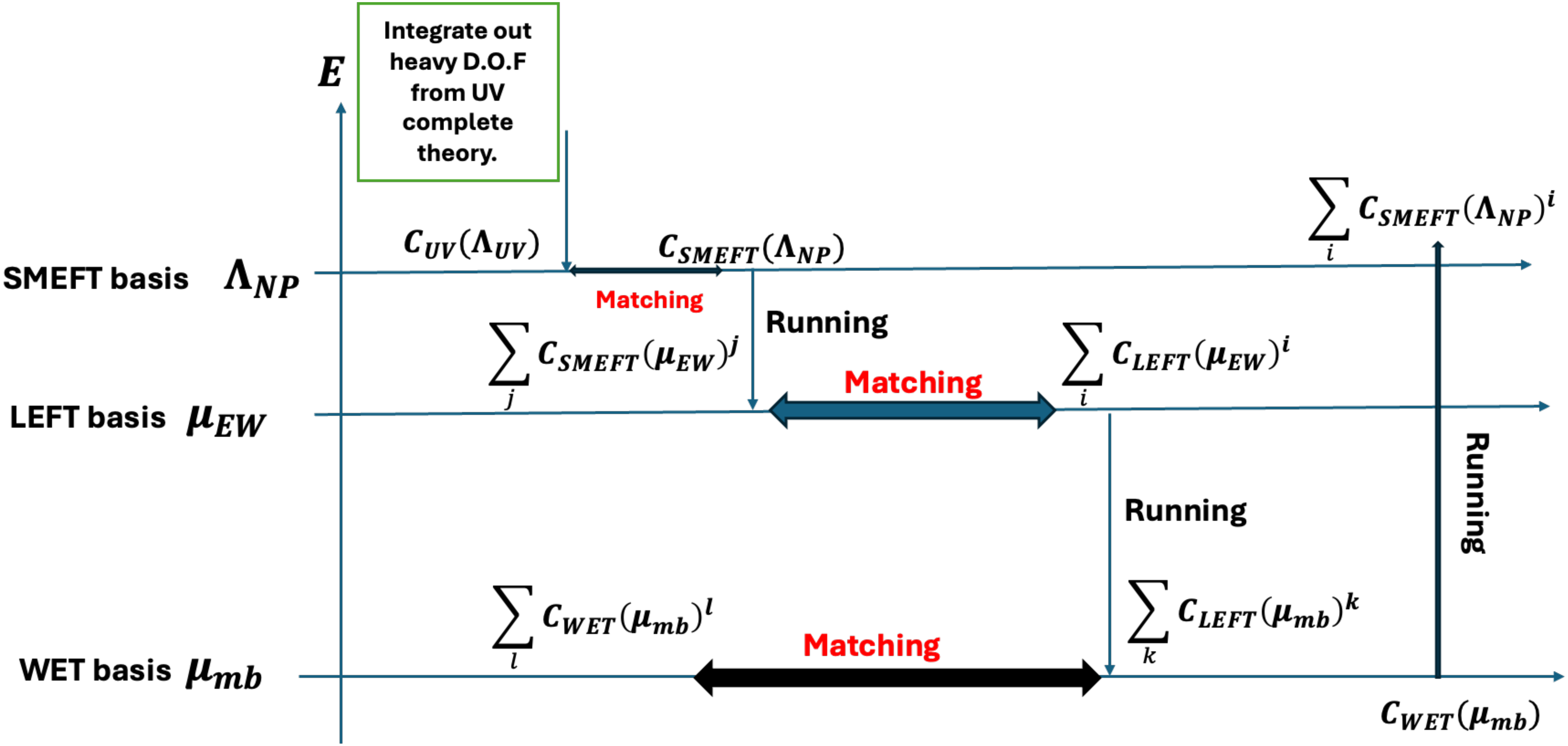
$$\mu^{2\epsilon}\int\frac{\mathrm{d}^{\mathsf{d}}k}{(2\pi)^{\mathsf{d}}}\frac{\left(k^2\right)^a}{\left(k^2-M^2\right)^b} = \frac{i\mu^{2\epsilon}}{(4\pi)^{\mathsf{d}/2}}\frac{(-1)^{a-b}\Gamma(\mathsf{d}/2+a)\Gamma(b-a-\mathsf{d}/2)}{\Gamma(\mathsf{d}/2)\Gamma(b)}\left(M^2\right)^{\mathsf{d}/2+a-b}$$

$$\boxed{\mathscr{L}^{\text{ren ,Tree}}_{\text{LEFT}}\Big|_{\mu_W} = \mathscr{L}^{\text{ren ,Tree}}_{\text{SMEFT}} + \mathscr{L}^{\text{Loop}}_{\text{SMEFT}} + \left(\mathscr{L}^{\text{C.T.}}_{\text{SMEFT}} - \mathscr{L}^{\text{C.T.}}_{\text{LEFT}}\right)\Big|_{\mu_W}}$$

$\Bigg\{$

Tree-level matching:
Jenkins, Manohar, Stoffer
JHEP03(2018)016
One-Loop matching:
Dekens, Stoffer
JHEP 10(2019)197

Summary of Toolkit



Some Phenomenological studies on top decays

- Constraining **anomalous** *Wtb* and related SMEFT couplings using low-energy and electroweak precision observables. [JHEP 11(2025)071]

- A Comprehensive Study on **Top Quark FCNC** Interaction in SMEFT Framework. [arXiv: 2602.10201]

Why Top quark decays??

- **Top as a SM probe:** The dominant decay ($t \to bW$) tests the charged current structure (CKM element V_{tb}) with high precision.
- **Top as a NP window:** Rare FCNC decays are forbidden at tree level and highly suppressed in the SM $\mathscr{B}(t \to qX) \sim (10^{-15} - 10^{-17})$.
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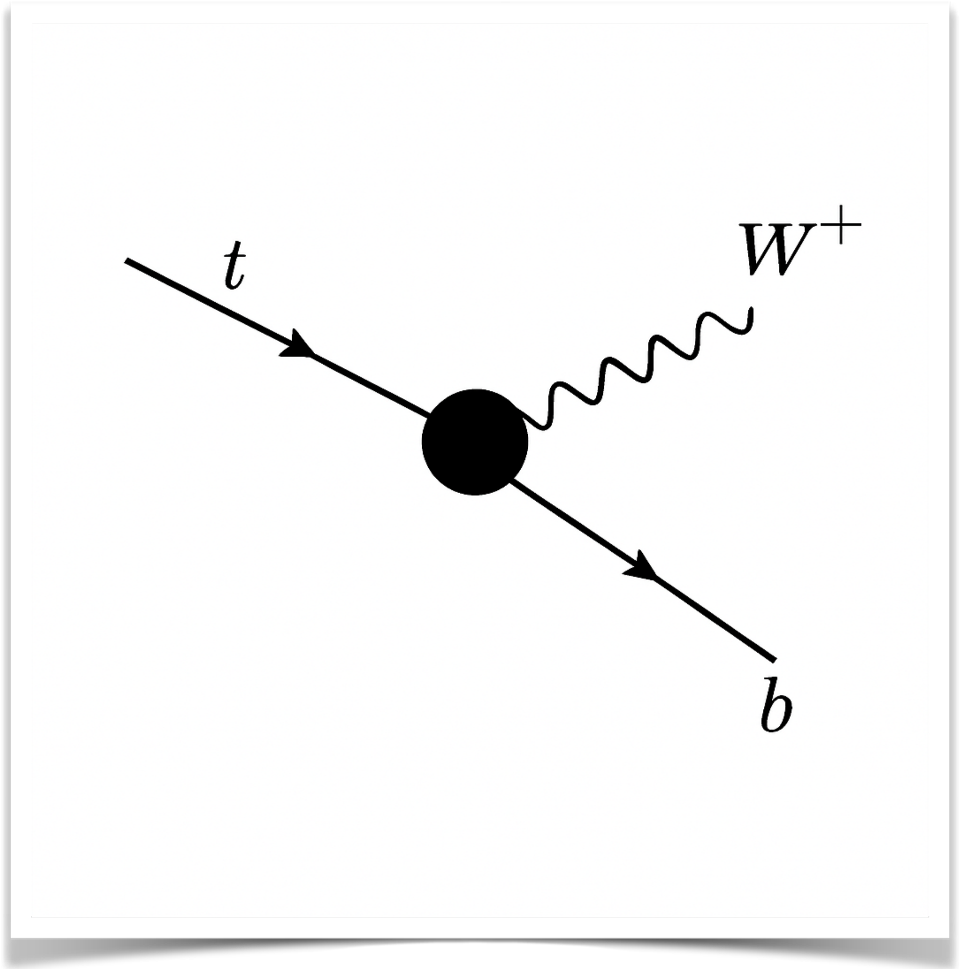
Objectives of the Study

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

1. Exploit Indirect Probes
2. Ensure Theoretical Rigor [Matching + RGE]
3. Perform Global Analysis
4. Predict Future Signatures

Top quark effective interactions [Charged Current]



$$\mathscr{L}_{Wtb} = -\frac{g}{\sqrt{2}}\left(\bar{b}\gamma_\mu(V_L' P_L + V_R P_R)tW^{\mu-} + \bar{b}\frac{i\sigma_{\mu\nu}q^\nu}{m_W}(g_L P_L + g_R P_R)tW^{\mu-}\right) + \mathrm{h.c.}$$

$$V_L' = V_{tb}(1 + V_L)$$

In SM Tree level, $V_L' = V_{tb}\ , V_R = 0\ , g_L = 0\ , g_R = 0\ .$

Matching with SMEFT basis

$$\left.\begin{array}{l} \mathscr{L}_{\text{SMEFT}} = \sum_i \mathscr{C}_i \mathscr{O}_i + \mathrm{h.c.} \\ \mathscr{O}_{pr}^{\phi q(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi)\,(\bar{q}_p \tau^I \gamma^\mu q_r) \\ \mathscr{O}_{pr}^{\phi ud} = i(\tilde{\phi}^\dagger D_\mu \phi)\,(\bar{u}_p \gamma_\mu d_r) \\ \mathscr{O}_{pr}^{dW} = (\bar{q}_p \sigma_{\mu\nu} d_r)\tau^I \phi\ W_{\mu\nu}^I \\ \mathscr{O}_{pr}^{uW} = (\bar{q}_p \sigma_{\mu\nu} u_r)\tau^I \tilde{\phi}\ W_{\mu\nu}^I \end{array}\right\} \xrightarrow{\mathscr{L}_{\text{SMEFT}}(\mu_t) = \mathscr{L}_{Wtb}(\mu_t)} \left\{\begin{array}{l} V_L(\mu_t) = \frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{\phi q(3)}(\mu_t) \\ V_R(\mu_t) = \frac{1}{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{\phi ud}(\mu_t) \\ g_L(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{*\,dW}(\mu_t) \\ g_R(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{uW}(\mu_t) \end{array}\right.$$

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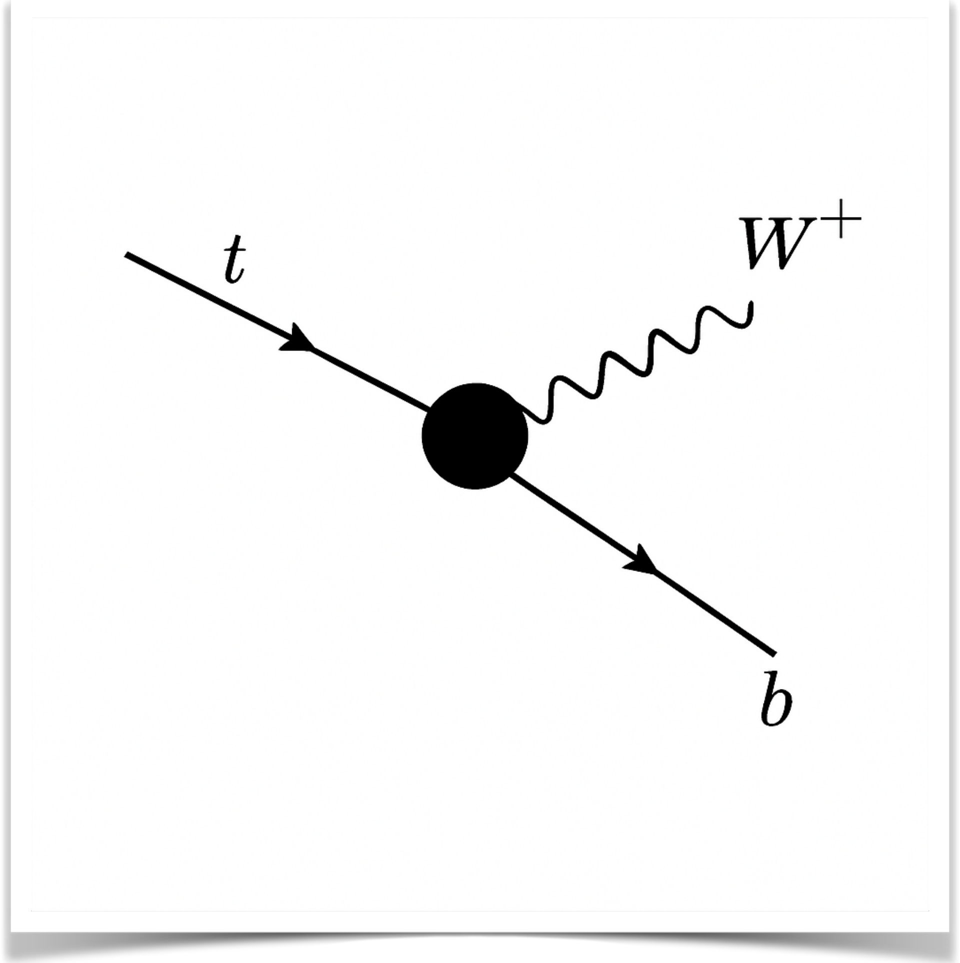

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In SM Tree level, $\boxed{V_L' = V_{tb}\ ,\ V_R = 0\ ,\ g_L = 0\ ,\ g_R = 0\ .}$

Effective Parameterisation is important

Matching with SMEFT basis

Couple to both charged and neutral gauge bosons under the same WCs.

$$\mathscr{L}_{\mathrm{SMEFT}} = \sum_i \mathscr{C}_i\mathcal{O}_i + \mathrm{h.c.}$$

$$\mathcal{O}_{pr}^{\phi q(3)} = (\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)\,(\bar{q}_p\tau^I\gamma^\mu q_r)$$

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$$\mathcal{O}_{pr}^{dW} = (\bar{q}_p\sigma_{\mu\nu}d_r)\tau^I\phi\;W^I_{\mu\nu}$$

$$\mathcal{O}_{pr}^{uW} = (\bar{q}_p\sigma_{\mu\nu}u_r)\tau^I\tilde{\phi}\;W^I_{\mu\nu}$$

$$\mathscr{L}_{\mathrm{SMEFT}}(\mu_t) = \mathscr{L}_{Wtb}(\mu_t) \longrightarrow$$

$$V_L(\mu_t) = \frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{\phi q(3)}(\mu_t)$$

$$V_R(\mu_t) = \frac{1}{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{\phi ud}(\mu_t)$$

$$g_L(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{*\,dW}(\mu_t)$$

$$g_R(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}_{33}^{uW}(\mu_t)$$

Top quark effective interactions [Flavor Changing Neutral Current]

$$-\mathcal{L}_{\text{eff}} = \sum_{u_j=u,c} \bar{u}_j \left[\frac{g_s}{2m_t} T^A \sigma^{\mu\nu} \left(\xi_L^{u_j t} P_L + \xi_R^{u_j t} P_R \right) G^A_{\mu\nu} \right.$$

$$+ \frac{e}{2m_t} \sigma^{\mu\nu} \left(\lambda_L^{u_j t} P_L + \lambda_R^{u_j t} P_R \right) F_{\mu\nu}$$

$$+ \frac{g_W}{2c_W m_t} \sigma^{\mu\nu} \left(\kappa_L^{u_j t} P_L + \kappa_R^{u_j t} P_R \right) Z_{\mu\nu} - \frac{g_W}{2c_W} \gamma^\mu \left(X_L^{u_j t} P_L + X_R^{u_j t} P_R \right) Z_\mu$$

$$\left. - \frac{1}{\sqrt{2}} \left(\eta_L^{u_j t} P_L + \eta_R^{u_j t} P_R \right) H \right] t + \text{H.C.}$$

At the SM Tree level

$$\xi_{l,R} \, , \lambda_{L,R} \, , \kappa_{L,R} \, , X_{L,R} \, , \eta_{L,R} = 0$$

Top quark effective interactions [Flavor Changing Neutral Current]

$$
\begin{aligned}
-\mathscr{L}_{\text{eff}} = \sum_{u_j=u,c} \bar{u}_j \Bigg[& \frac{g_s}{2m_t} T^A \sigma^{\mu\nu} \left(\xi_L^{u_j t} P_L + \xi_R^{u_j t} P_R \right) G^A_{\mu\nu} \\
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\end{aligned}
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$t \to u_j \, g$

At the SM Tree level

$$\xi_{l,R}\,,\lambda_{L,R}\,,\kappa_{L,R}\,,X_{L,R}\,,\eta_{L,R} = 0$$

Top quark effective interactions [Flavor Changing Neutral Current]

$$-\mathscr{L}_{\rm eff} = \sum_{u_j=u,c} \bar{u}_j \left[\frac{g_s}{2m_t} T^A \sigma^{\mu\nu} \left(\xi_L^{u_jt} P_L + \xi_R^{u_jt} P_R \right) G^A_{\mu\nu} \right.$$

$t \to u_j g$

$$+ \frac{e}{2m_t} \sigma^{\mu\nu} \left(\lambda_L^{u_jt} P_L + \lambda_R^{u_jt} P_R \right) F_{\mu\nu}$$

$t \to u_j \gamma$

$$+ \frac{g_W}{2c_W m_t} \sigma^{\mu\nu} \left(\kappa_L^{u_jt} P_L + \kappa_R^{u_jt} P_R \right) Z_{\mu\nu} - \frac{g_W}{2c_W} \gamma^\mu \left(X_L^{u_jt} P_L + X_R^{u_jt} P_R \right) Z_\mu$$

$$\left. - \frac{1}{\sqrt{2}} \left(\eta_L^{u_jt} P_L + \eta_R^{u_jt} P_R \right) H \right] t + \text{H.C.}$$

At the SM Tree level

$$\xi_{l,R} \,, \lambda_{L,R} \,, \kappa_{L,R} \,, X_{L,R} \,, \eta_{L,R} = 0$$

Top quark effective interactions [Flavor Changing Neutral Current]

$$
\begin{aligned}
-\mathscr{L}_{\text{eff}} = \sum_{u_j=u,c} \bar{u}_j \Bigg[& \frac{g_s}{2m_t} T^A \sigma^{\mu\nu} \left(\xi_L^{u_j t} P_L + \xi_R^{u_j t} P_R \right) G^A_{\mu\nu} \\
& + \frac{e}{2m_t} \sigma^{\mu\nu} \left(\lambda_L^{u_j t} P_L + \lambda_R^{u_j t} P_R \right) F_{\mu\nu} \\
& + \frac{g_W}{2c_W m_t} \sigma^{\mu\nu} \left(\kappa_L^{u_j t} P_L + \kappa_R^{u_j t} P_R \right) Z_{\mu\nu} - \frac{g_W}{2c_W} \gamma^\mu \left(X_L^{u_j t} P_L + X_R^{u_j t} P_R \right) Z_\mu \\
& - \frac{1}{\sqrt{2}} \left(\eta_L^{u_j t} P_L + \eta_R^{u_j t} P_R \right) H \Bigg] t + \text{H.C.}
\end{aligned}
$$

$t \to u_j\, g$

$t \to u_j\, \gamma$

$t \to u_j\, Z$

At the SM Tree level

$$\xi_{l,R}\,,\, \lambda_{L,R}\,,\, \kappa_{L,R}\,,\, X_{L,R}\,,\, \eta_{L,R} = 0$$

Top quark effective interactions [Flavor Changing Neutral Current]

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& + \frac{e}{2m_t} \sigma^{\mu\nu} \left(\lambda_L^{u_j t} P_L + \lambda_R^{u_j t} P_R \right) F_{\mu\nu} \\
& + \frac{g_W}{2c_W m_t} \sigma^{\mu\nu} \left(\kappa_L^{u_j t} P_L + \kappa_R^{u_j t} P_R \right) Z_{\mu\nu} - \frac{g_W}{2c_W} \gamma^\mu \left(X_L^{u_j t} P_L + X_R^{u_j t} P_R \right) Z_\mu \\
& - \frac{1}{\sqrt{2}} \left(\eta_L^{u_j t} P_L + \eta_R^{u_j t} P_R \right) H \Bigg] t + \text{H.C.}
\end{aligned}
$$

$t \to u_j\, g$

$t \to u_j\, \gamma$

$t \to u_j\, Z$

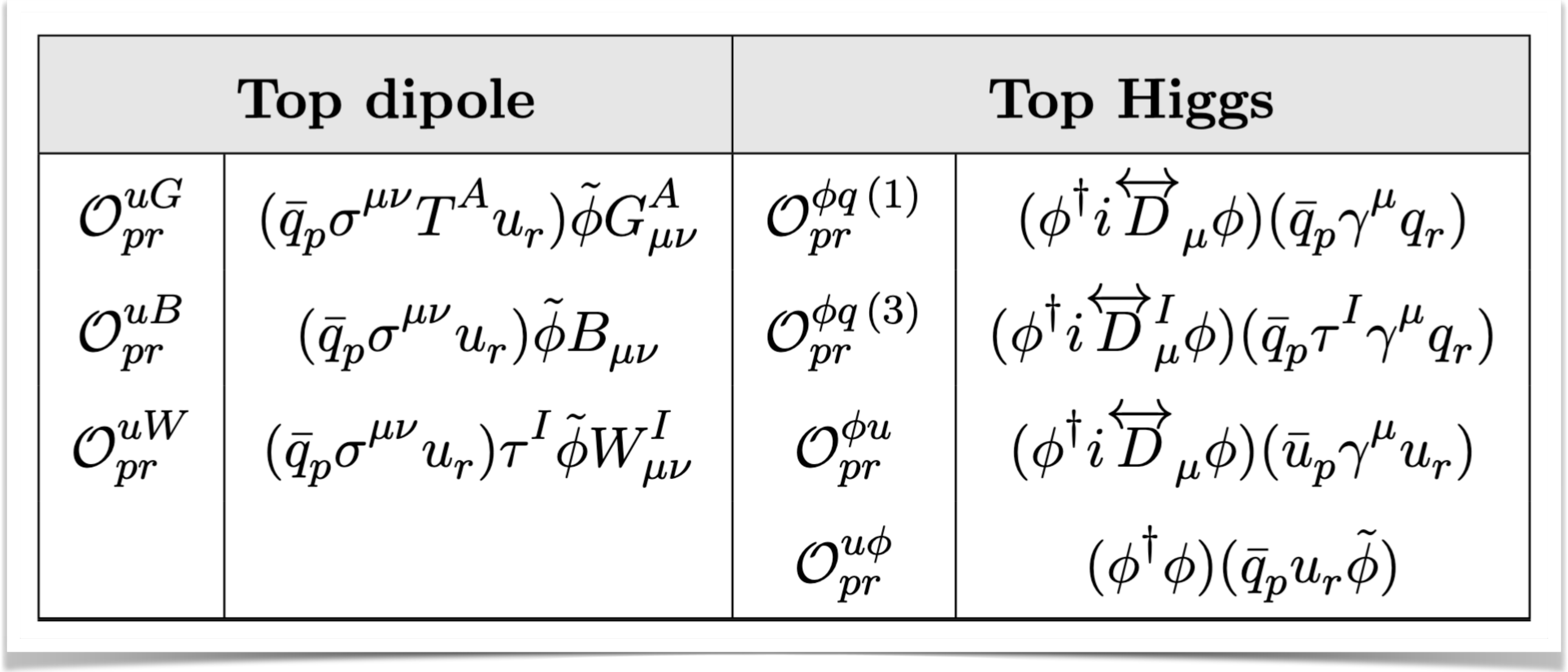
$t \to u_j\, H$

At the SM Tree level

$$\xi_{l,R}\,,\lambda_{L,R}\,,\kappa_{L,R}\,,X_{L,R}\,,\eta_{L,R} = 0$$

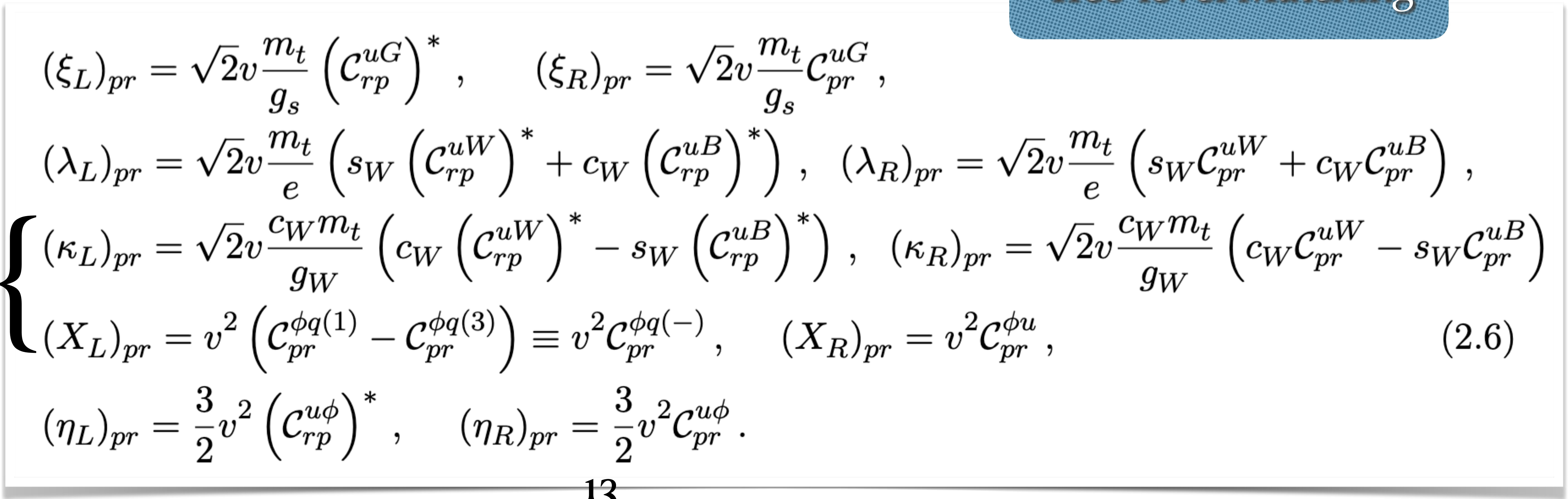
Matching with SMEFT Framework

SMEFT



Top dipole		Top Higgs	
$\mathcal{O}^{uG}_{pr}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{\phi}G^A_{\mu\nu}$	$\mathcal{O}^{\phi q\,(1)}_{pr}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}^{uB}_{pr}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{\phi}B_{\mu\nu}$	$\mathcal{O}^{\phi q\,(3)}_{pr}$	$(\phi^\dagger i\overleftrightarrow{D}^I_\mu\phi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}^{uW}_{pr}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{\phi}W^I_{\mu\nu}$	$\mathcal{O}^{\phi u}_{pr}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_p\gamma^\mu u_r)$
		$\mathcal{O}^{u\phi}_{pr}$	$(\phi^\dagger\phi)(\bar{q}_p u_r\tilde{\phi})$

Tree-level Matching



$t \to u_j g$

$$(\xi_L)_{pr} = \sqrt{2}v\frac{m_t}{g_s}\left(C^{uG}_{rp}\right)^* , \qquad (\xi_R)_{pr} = \sqrt{2}v\frac{m_t}{g_s}C^{uG}_{pr} ,$$

$t \to u_j \gamma$

$$(\lambda_L)_{pr} = \sqrt{2}v\frac{m_t}{e}\left(s_W\left(C^{uW}_{rp}\right)^* + c_W\left(C^{uB}_{rp}\right)^*\right) , \quad (\lambda_R)_{pr} = \sqrt{2}v\frac{m_t}{e}\left(s_W C^{uW}_{pr} + c_W C^{uB}_{pr}\right) ,$$

$t \to u_j Z$

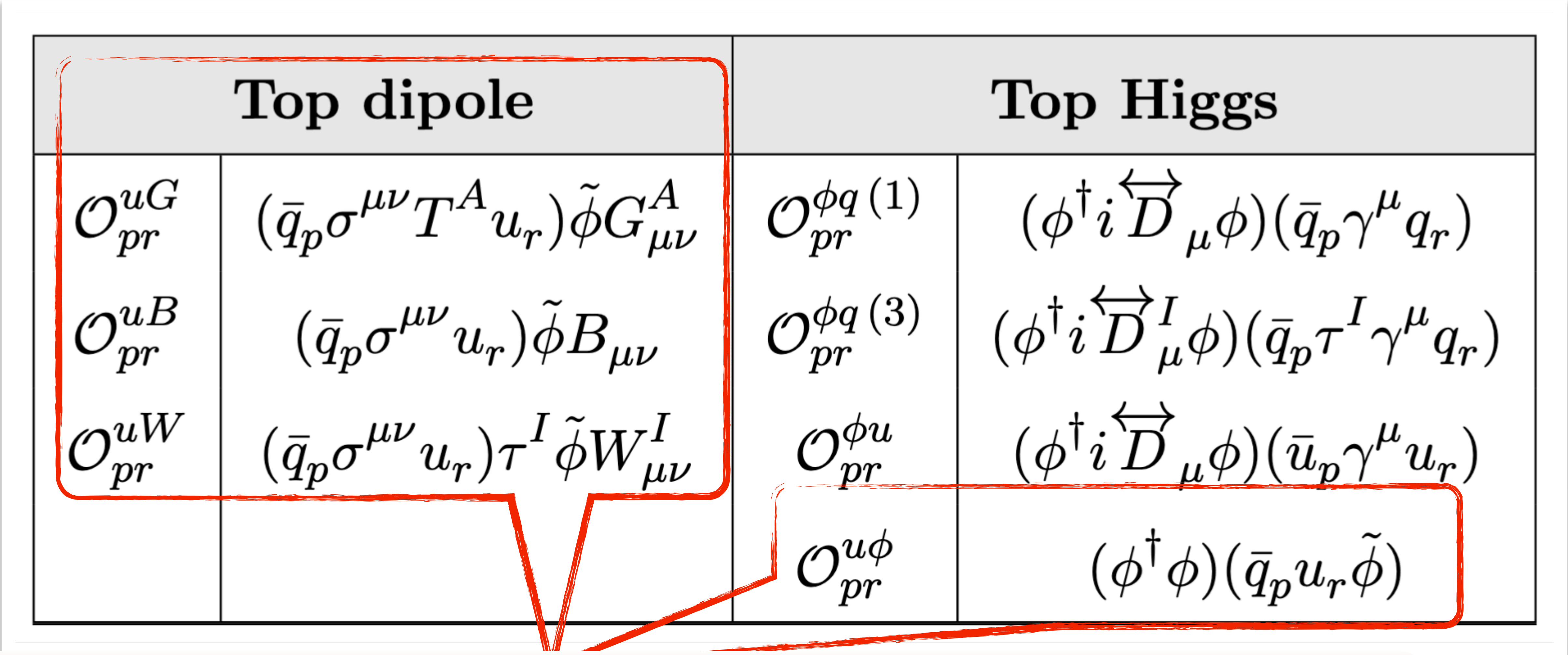
$$\begin{cases}(\kappa_L)_{pr} = \sqrt{2}v\frac{c_W m_t}{g_W}\left(c_W\left(C^{uW}_{rp}\right)^* - s_W\left(C^{uB}_{rp}\right)^*\right) , \quad (\kappa_R)_{pr} = \sqrt{2}v\frac{c_W m_t}{g_W}\left(c_W C^{uW}_{pr} - s_W C^{uB}_{pr}\right) \\ (X_L)_{pr} = v^2\left(C^{\phi q(1)}_{pr} - C^{\phi q(3)}_{pr}\right) \equiv v^2 C^{\phi q(-)}_{pr} , \qquad (X_R)_{pr} = v^2 C^{\phi u}_{pr} , \end{cases} \tag{2.6}$$

$t \to u_j H$

$$(\eta_L)_{pr} = \frac{3}{2}v^2\left(C^{u\phi}_{rp}\right)^* , \qquad (\eta_R)_{pr} = \frac{3}{2}v^2 C^{u\phi}_{pr} .$$

Matching with SMEFT Framework

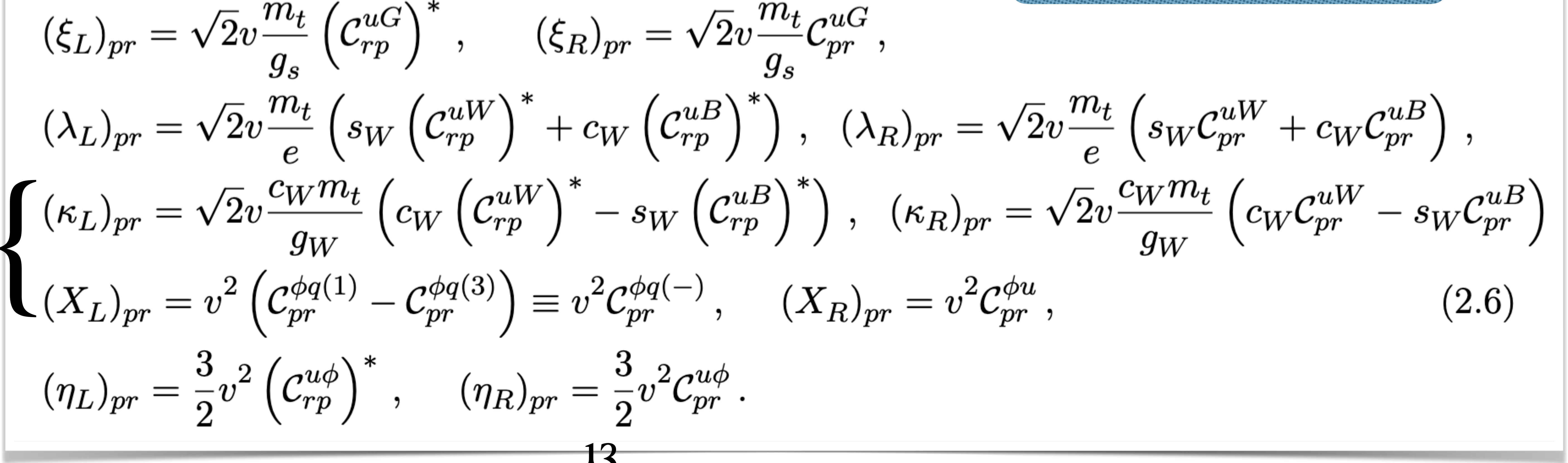
SMEFT



Top dipole		**Top Higgs**	
$\mathcal{O}^{uG}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{\phi} G^A_{\mu\nu}$	$\mathcal{O}^{\phi q\,(1)}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}^{uB}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\phi} B_{\mu\nu}$	$\mathcal{O}^{\phi q\,(3)}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}^{uW}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\phi} W^I_{\mu\nu}$	$\mathcal{O}^{\phi u}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}^{u\phi}_{pr}$	$(\phi^\dagger \phi)(\bar{q}_p u_r \tilde{\phi})$

Complex operator, induces CP violation through imaginary parts

Tree-level Matching



$t \to u_j\, g$

$$(\xi_L)_{pr} = \sqrt{2} v \frac{m_t}{g_s} \left(\mathcal{C}^{uG}_{rp} \right)^* , \qquad (\xi_R)_{pr} = \sqrt{2} v \frac{m_t}{g_s} \mathcal{C}^{uG}_{pr} ,$$

$t \to u_j\, \gamma$

$$(\lambda_L)_{pr} = \sqrt{2} v \frac{m_t}{e} \left(s_W \left(\mathcal{C}^{uW}_{rp} \right)^* + c_W \left(\mathcal{C}^{uB}_{rp} \right)^* \right) , \quad (\lambda_R)_{pr} = \sqrt{2} v \frac{m_t}{e} \left(s_W \mathcal{C}^{uW}_{pr} + c_W \mathcal{C}^{uB}_{pr} \right) ,$$

$t \to u_j\, Z$

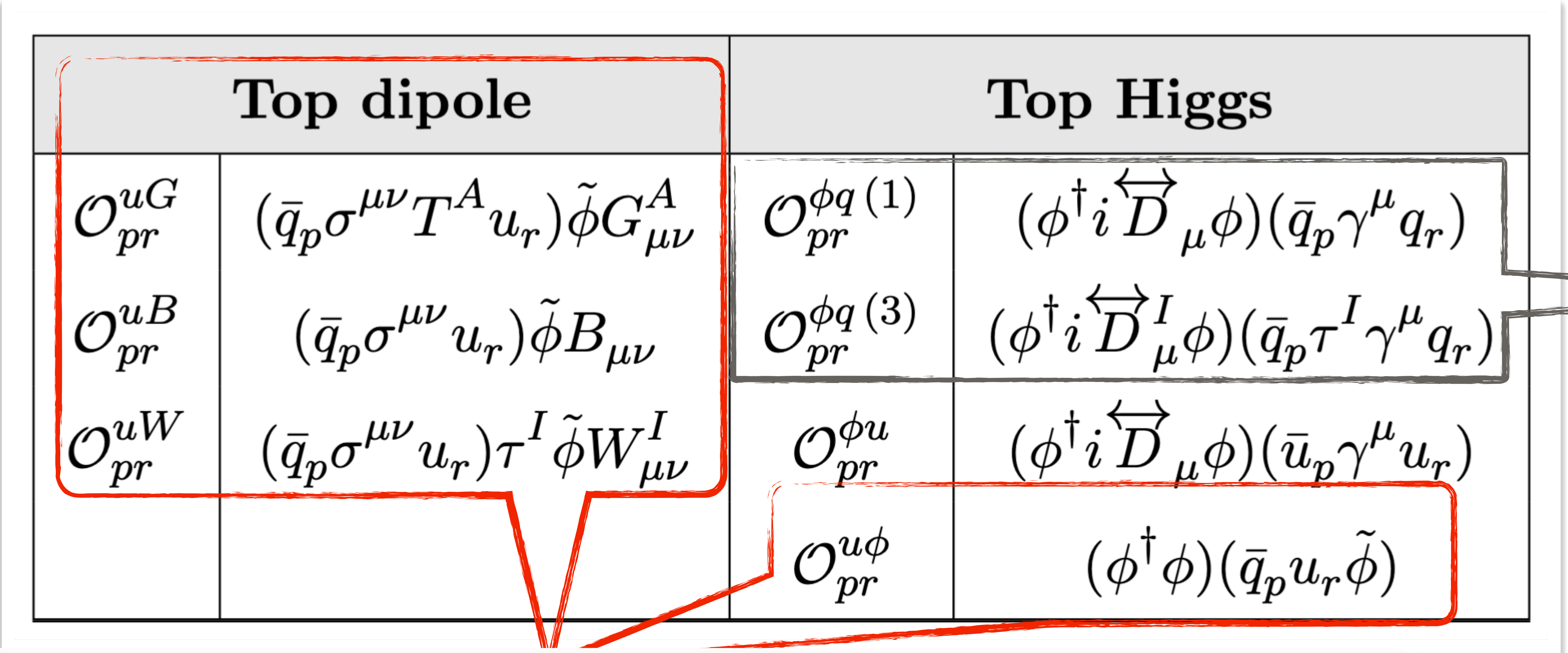
$$\left\{ \begin{aligned} &(\kappa_L)_{pr} = \sqrt{2} v \frac{c_W m_t}{g_W} \left(c_W \left(\mathcal{C}^{uW}_{rp} \right)^* - s_W \left(\mathcal{C}^{uB}_{rp} \right)^* \right) , \quad (\kappa_R)_{pr} = \sqrt{2} v \frac{c_W m_t}{g_W} \left(c_W \mathcal{C}^{uW}_{pr} - s_W \mathcal{C}^{uB}_{pr} \right) \\ &(X_L)_{pr} = v^2 \left(\mathcal{C}^{\phi q(1)}_{pr} - \mathcal{C}^{\phi q(3)}_{pr} \right) \equiv v^2 \mathcal{C}^{\phi q(-)}_{pr} , \qquad (X_R)_{pr} = v^2 \mathcal{C}^{\phi u}_{pr} , \end{aligned} \right. \tag{2.6}$$

$t \to u_j\, H$

$$(\eta_L)_{pr} = \frac{3}{2} v^2 \left(\mathcal{C}^{u\phi}_{rp} \right)^* , \qquad (\eta_R)_{pr} = \frac{3}{2} v^2 \mathcal{C}^{u\phi}_{pr} .$$

Matching with SMEFT Framework

SMEFT

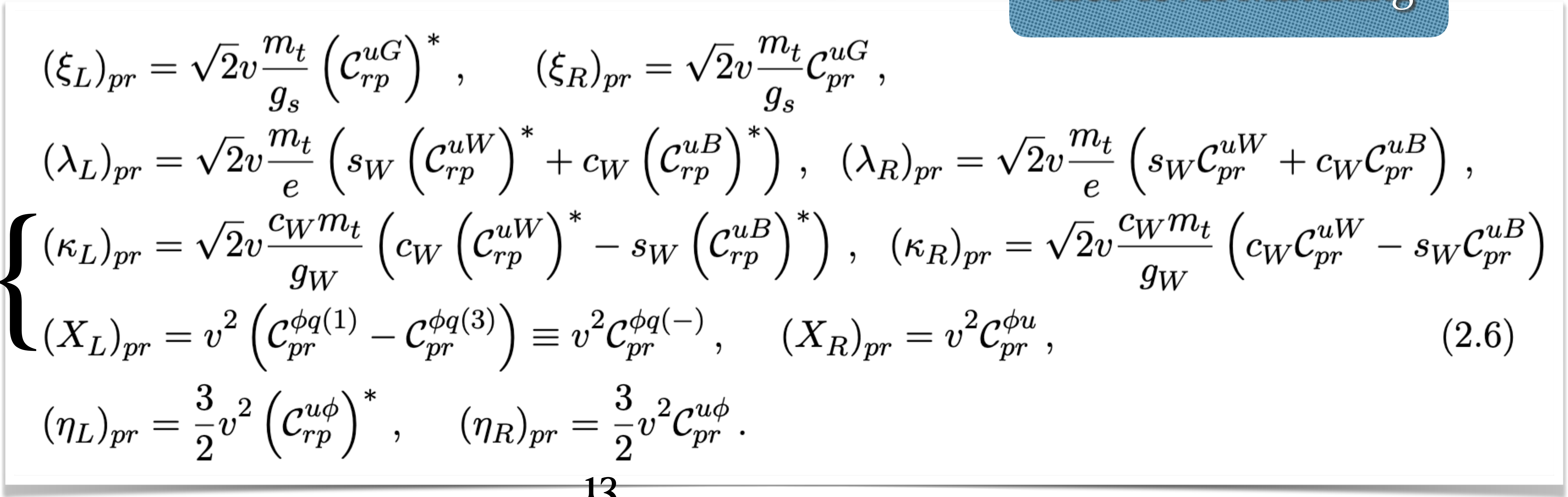


Top dipole		Top Higgs	
$\mathcal{O}^{uG}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{\phi} G^A_{\mu\nu}$	$\mathcal{O}^{\phi q\,(1)}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}^{uB}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\phi} B_{\mu\nu}$	$\mathcal{O}^{\phi q\,(3)}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}^{uW}_{pr}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\phi} W^I_{\mu\nu}$	$\mathcal{O}^{\phi u}_{pr}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}^{u\phi}_{pr}$	$(\phi^\dagger \phi)(\bar{q}_p u_r \tilde{\phi})$

Due to $SU(2)$ conjugate str, these operator can generate both types FCNC (up & down) Under the same WCs.

Complex operator, induces CP violation through imaginary parts

Tree-level Matching



$t \to u_j g$

$$(\xi_L)_{pr} = \sqrt{2} v \frac{m_t}{g_s} \left(C^{uG}_{rp}\right)^* , \qquad (\xi_R)_{pr} = \sqrt{2} v \frac{m_t}{g_s} C^{uG}_{pr} ,$$

$t \to u_j \gamma$

$$(\lambda_L)_{pr} = \sqrt{2} v \frac{m_t}{e} \left(s_W \left(C^{uW}_{rp}\right)^* + c_W \left(C^{uB}_{rp}\right)^* \right) , \quad (\lambda_R)_{pr} = \sqrt{2} v \frac{m_t}{e} \left(s_W C^{uW}_{pr} + c_W C^{uB}_{pr} \right) ,$$

$t \to u_j Z$

$$\left\{ \begin{array}{l} (\kappa_L)_{pr} = \sqrt{2} v \frac{c_W m_t}{g_W} \left(c_W \left(C^{uW}_{rp}\right)^* - s_W \left(C^{uB}_{rp}\right)^* \right) , \quad (\kappa_R)_{pr} = \sqrt{2} v \frac{c_W m_t}{g_W} \left(c_W C^{uW}_{pr} - s_W C^{uB}_{pr} \right) \\ (X_L)_{pr} = v^2 \left(C^{\phi q(1)}_{pr} - C^{\phi q(3)}_{pr} \right) \equiv v^2 C^{\phi q(-)}_{pr} , \qquad (X_R)_{pr} = v^2 C^{\phi u}_{pr} , \end{array} \right. \tag{2.6}$$

$t \to u_j H$

$$(\eta_L)_{pr} = \frac{3}{2} v^2 \left(C^{u\phi}_{rp}\right)^* , \qquad (\eta_R)_{pr} = \frac{3}{2} v^2 C^{u\phi}_{pr} .$$

Complete List of Observables: Low Energy Observables

Rare FCNC Processes

- **Semileptonic decay** $\left(b \to s(d)\ell\ell\right)$
- **Radiative decay** $\left(b \to s(d)\gamma\right)$
- **Invisible decay** $\left(b \to s(d)\nu\nu\right)$

[(Differential) Branching Fraction, CP Asymmetries, Various Angular & Ratio Observables (updated R_K & R_K^*)]

Neutral Meson Mixing

- $\left(B_s^0 - \bar{B}_s^0,\ B^0 - \bar{B}^0\right)$ Meson mixing

[Mass difference $(\Delta M = 2|M_{12}| = \frac{|\mathscr{M}^{\text{Tot}}|}{m_B})$]

FCCC Processes

- **Leptonic decay** $\left(P \to \ell\nu\right)$
- **Semileptonic decay** $\left(P \to M\ell\nu\right)$

[(Differential) Branching Fraction, CKM elements]

Electroweak & other relevant Observables

Electroweak Precision Observables

- **Oblique Parameters (S,T,U)**
- Z **Pole Observables**
- W **Pole Observables**

[$\delta M_W(\Delta\rho, \Delta r)$, Ratio observables, Asymmetric observables.]

Other relevant Observables

- **Higgs decays**
- **Triple Gauge Couplings** $(WWV(\gamma, Z))$
- **Electric and Magnetic Dipole moments of quarks.** [CP Violating Obs]

[Branching ratios, couplings in the kappa framework, TCG couplings, ….]

Case Study: Low Energy Observables

Rare FCNC Processes

Semileptonic decay $\left(b \to s(d)\ell\ell\right)$

Radiative decay $\left(b \to s\,\gamma\,(g)\right)$

Invisible decay $\left(b \to s(d)\,\nu\nu\right)$

$$\mathcal{H}^{b\to d_j}_{\mathrm{LEFT}} = -\frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[\sum_{i=1}^{6} C_i(\mu)O_i(\mu) + \sum_{i=7,8,9,10,P,S,T,T5}\left(C_i(\mu)O_i + C'_i(\mu)O'_i\right)\right] - \frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[C^\nu_L O^\nu_L + C^\nu_R O^\nu_R\right]$$

$$O_9 = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \qquad O'_9 = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\ell),$$

$$O_{10} = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \qquad O'_{10} = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell),$$

$$O_S = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\ell), \qquad O'_S = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_L b)(\bar{\ell}\ell),$$

$$O_P = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\gamma_5\ell), \qquad O'_P = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_L b)(\bar{\ell}\gamma_5\ell),$$

$$\mathcal{O}_T = \frac{e^2}{16\pi^2}m_b(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma^{\mu\nu}\ell), \qquad \mathcal{O}_{T5} = \frac{e^2}{16\pi^2}m_b(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell),$$

$$O_7 = \frac{e}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O'_7 = \frac{e}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}P_L b)F^{\mu\nu},$$

$$O_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}, \qquad O'_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a}.$$

$$\mathcal{O}^\nu_L = \frac{e^2}{16\pi^2}\left(\bar{d}_j\gamma_\mu P_L b\right)(\bar{\nu}\gamma^\mu P_L\nu), \qquad \mathcal{O}^\nu_R = \frac{e^2}{16\pi^2}\left(\bar{d}_j\gamma_\mu P_R b\right)(\bar{\nu}\gamma^\mu P_L\nu)\ ,$$

Case Study: Low Energy Observables

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$$\mathscr{H}^{b\to d_j}_{\rm LEFT} = -\frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[\sum_{i=1}^{6} C_i(\mu)O_i(\mu) + \sum_{i=7,8,9,10,P,S,T,T5}\left(C_i(\mu)O_i + C'_i(\mu)O'_i\right)\right] - \frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[C^\nu_L O^\nu_L + C^\nu_R O^\nu_R\right]$$

$$\boxed{\begin{aligned} O_9 &= \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \\ O_{10} &= \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \\ O_S &= \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\ell), \end{aligned}}$$

$$O_P = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\gamma_5\ell),$$

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$$O_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}, \qquad O'_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a}.$$

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$$\mathcal{H}^{b\to d_j}_{\text{LEFT}} = -\frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[\sum_{i=1}^{6} C_i(\mu)O_i(\mu) + \sum_{i=7,8,9,10,P,S,T,T5}\left(C_i(\mu)O_i + C'_i(\mu)O'_i\right)\right] - \frac{4\,G_F}{\sqrt{2}}V_{tb}V^*_{td_j}\left[C^\nu_L O^\nu_L + C^\nu_R O^\nu_R\right]$$

$$O_9 = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell), \qquad O'_9 = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\ell),$$

$$O_{10} = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \qquad O'_{10} = \frac{e^2}{16\pi^2}(\bar{d}_j\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell),$$

$$O_S = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\ell), \qquad O'_S = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_L b)(\bar{\ell}\ell),$$

$$O_P = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_R b)(\bar{\ell}\gamma_5\ell), \qquad O'_P = \frac{e^2}{16\pi^2}m_b(\bar{d}_j P_L b)(\bar{\ell}\gamma_5\ell),$$

$$\mathcal{O}_T = \frac{e^2}{16\pi^2}m_b(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma^{\mu\nu}\ell), \qquad \mathcal{O}_{T5} = \frac{e^2}{16\pi^2}m_b(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma^{\mu\nu}\gamma_5\ell),$$

$$O_7 = \frac{e}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad O'_7 = \frac{e}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}P_L b)F^{\mu\nu},$$

$$O_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}, \qquad O'_8 = \frac{g_s}{16\pi^2}m_b(\bar{d}_j\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a}\,.$$

$$\mathcal{O}^\nu_L = \frac{e^2}{16\pi^2}\left(\bar{d}_j\gamma_\mu P_L b\right)(\bar{\nu}\gamma^\mu P_L\nu), \qquad \mathcal{O}^\nu_R = \frac{e^2}{16\pi^2}\left(\bar{d}_j\gamma_\mu P_R b\right)(\bar{\nu}\gamma^\mu P_L\nu)\ ,$$

Rare FCNC Processes ($b \to s(d)\ell\ell$)

$$\mathcal{H}_{\text{eff}}^{b\to d_j\ell\ell} \supset -\frac{4\,G_F}{\sqrt{2}}V_{tb}V_{td_j}^{*}\left(C_9(\mu)O_9(\mu) + C_{10}(\mu)O_{10}(\mu) + C_S(\mu)O_S(\mu)\right).$$

Due to Anomalous *Wtb* couplings
(O_9, O_{10}, O_S) are getting modified.

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

Rare FCNC Processes ($b \to s(d)\ell\ell$)

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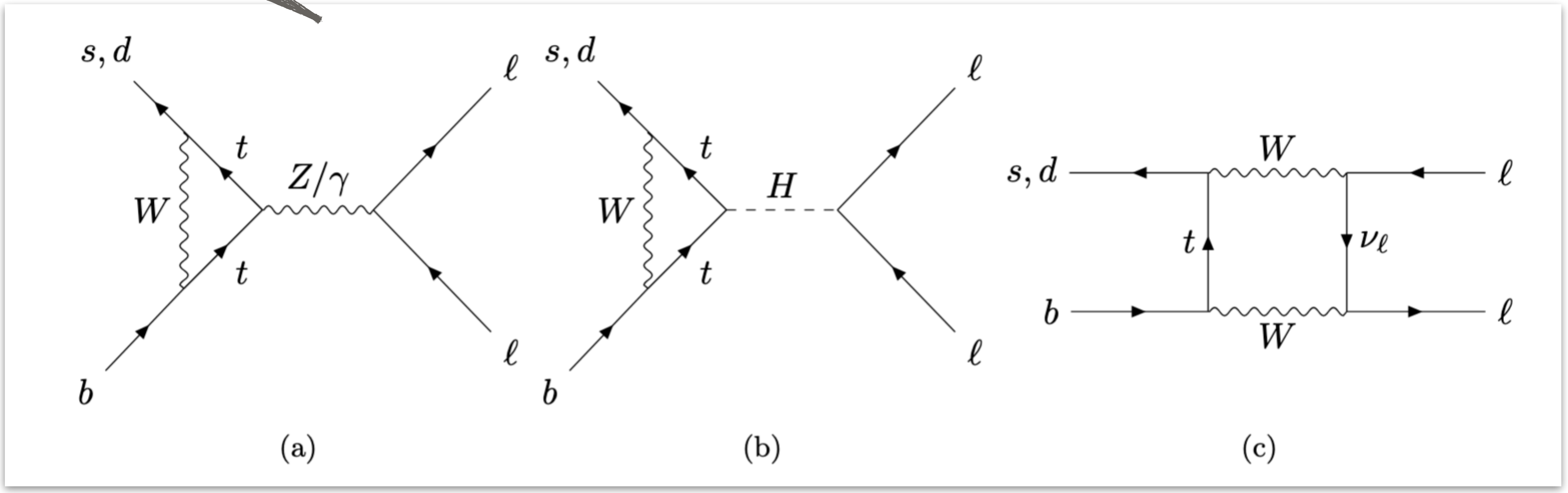
SM



(a) (b) (c)

Rare FCNC Processes ($b \to s(d)\ell\ell$)

Presence of Wtb couplings

$$\mathscr{H}_{\rm eff}^{b\to d_j\ell\ell} \supset -\frac{4\,G_F}{\sqrt{2}} V_{tb}V^*_{td_j}\Big(C_9(\mu)O_9(\mu) + C_{10}(\mu)O_{10}(\mu) + C_S(\mu)O_S(\mu)\Big)\,.$$

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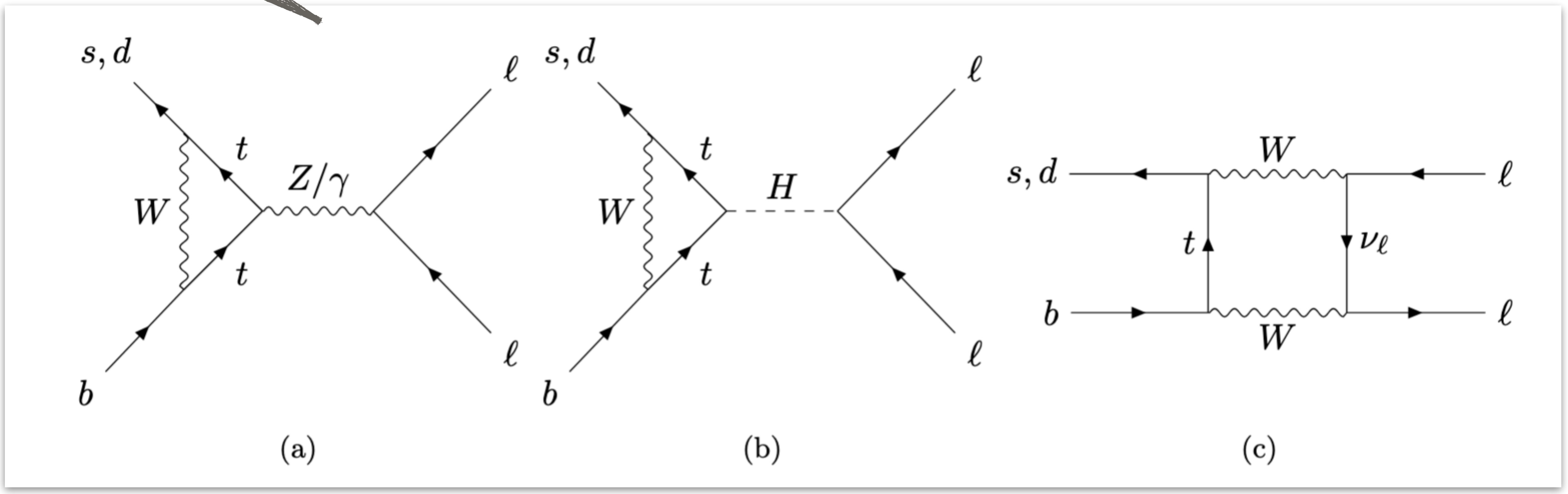
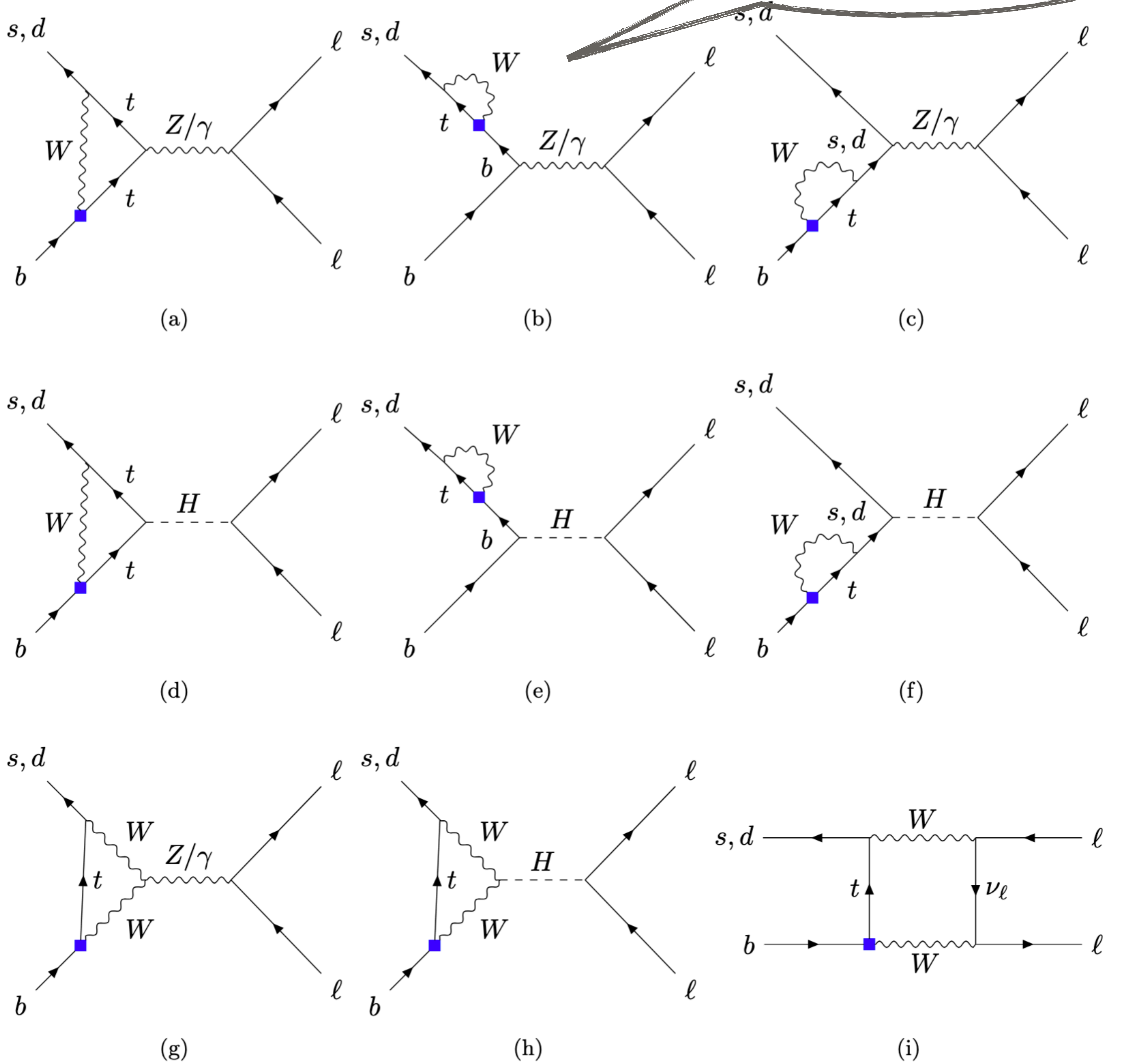
SM



(a) (b) (c)



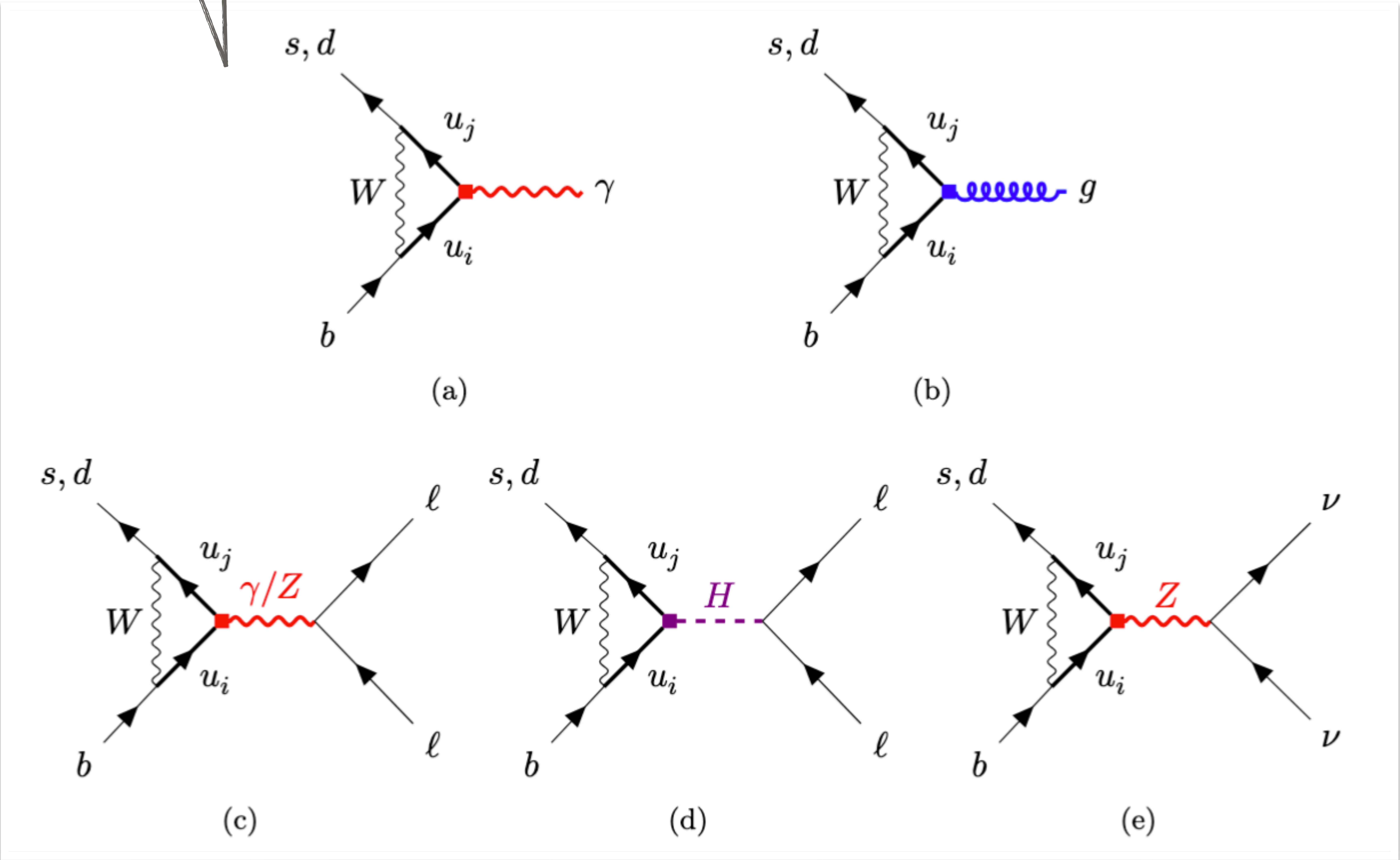
(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Rare FCNC Processes

Presence of top FCNC couplings



Rare FCNC Processes

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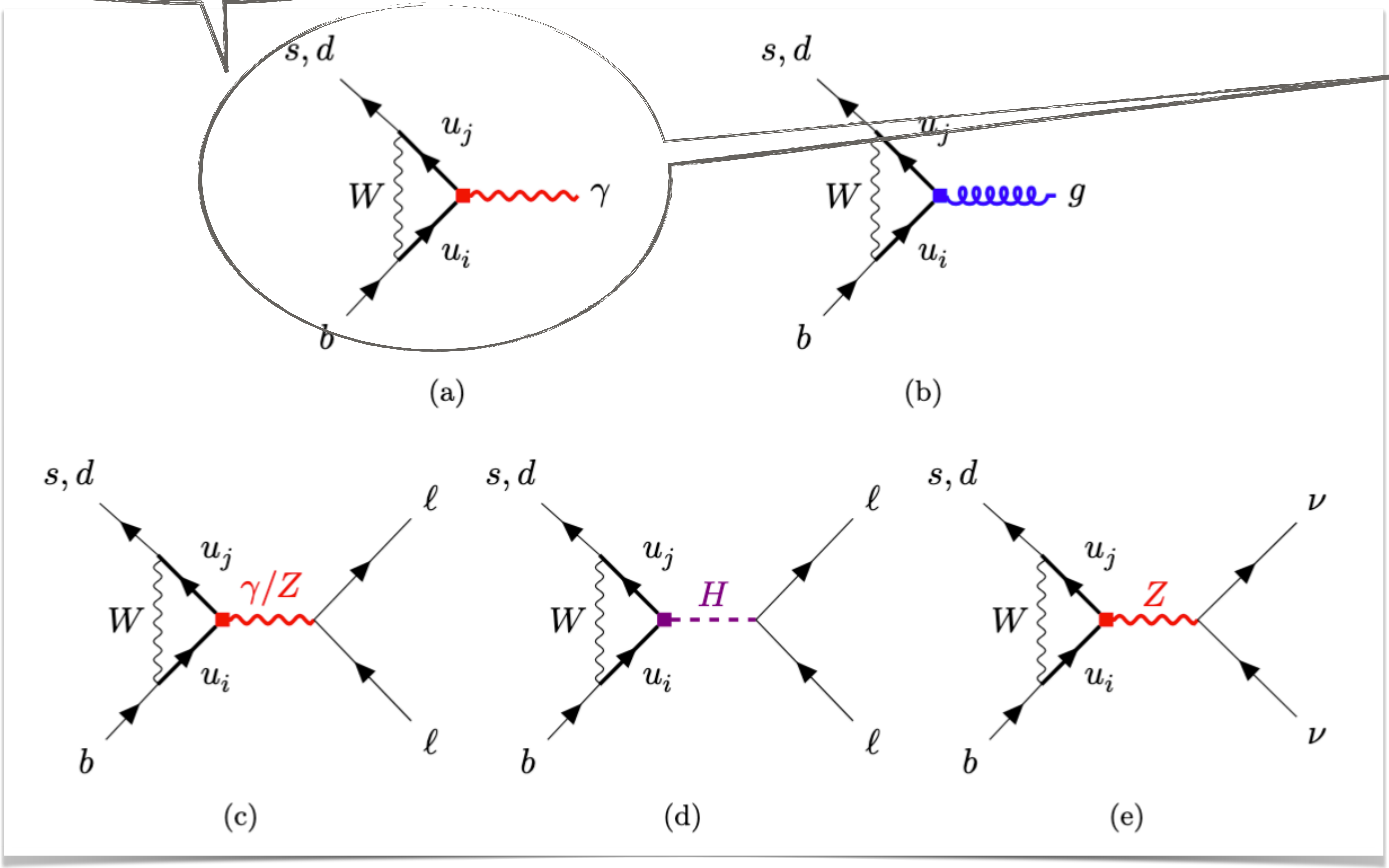

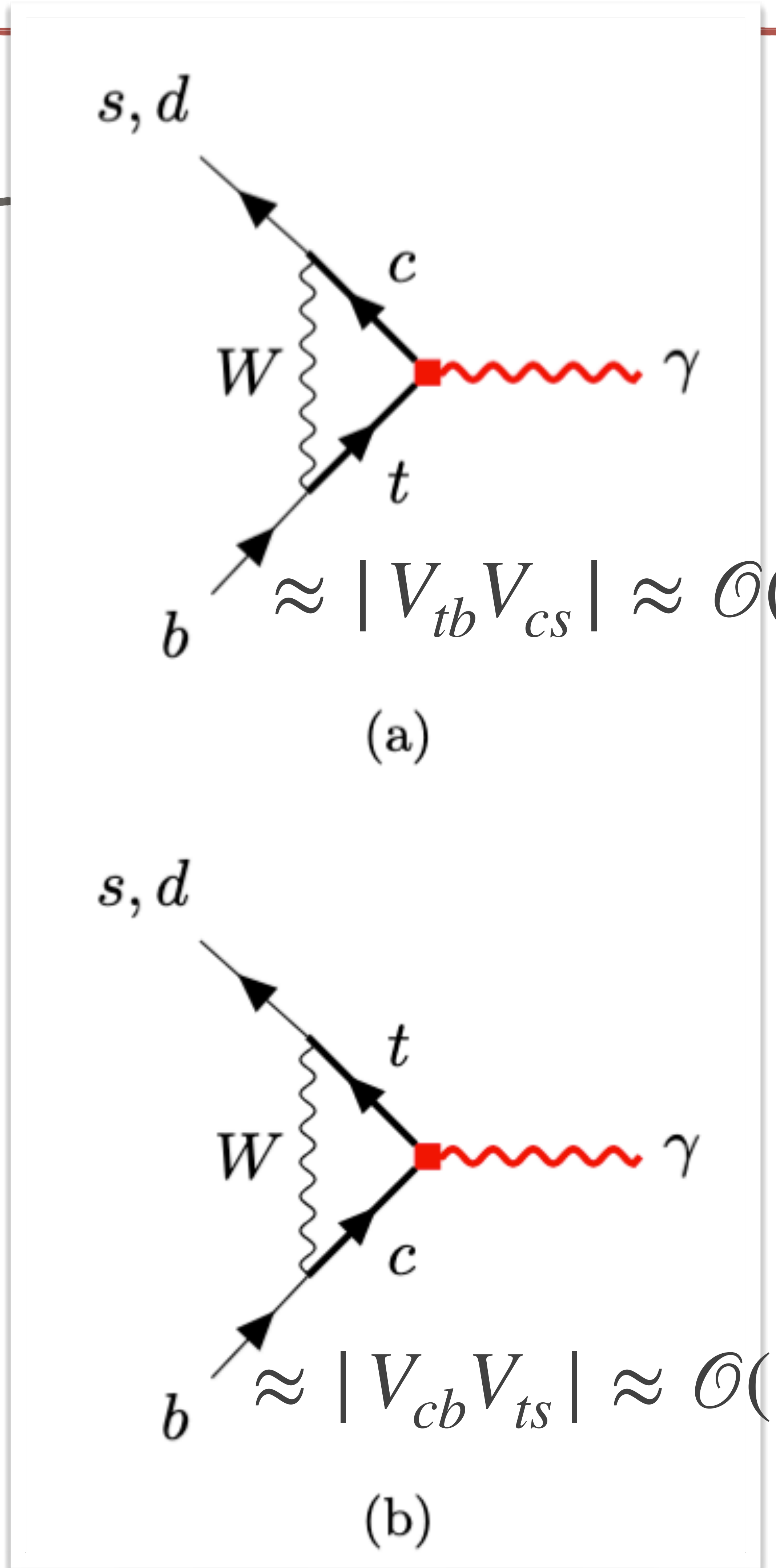

$\approx |V_{tb}V_{cs}| \approx \mathcal{O}(1)$

$\approx |V_{cb}V_{ts}| \approx \mathcal{O}(10^{-3})$

Rare FCNC Processes ($b \to s(d)\ell\ell$)

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

Matching at EW Scale $$\Delta\, C_i(\mu_{\rm EW}) = g(\mathscr{C}^i_{\rm SMEFT})\,(\mu_{\rm EW})$$

Loop Factor containing NP

$g(\mathscr{C}^i_{\rm SMEFT})$

WET RGEs

$$\begin{pmatrix} C_9 \\ C_{10} \\ C_S \end{pmatrix}_{\mu_b} = \begin{pmatrix} 0.99522 & 0.00716 & 0 \\ 0.00716 & 1.0 & 0 \\ 0 & 0 & 1.37433 \end{pmatrix} \begin{pmatrix} C_9 \\ C_{10} \\ C_S \end{pmatrix}_{\mu_{\rm EW}}$$

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

Observables at μ_bScale $$C_i(\mu_b) = C_i^{\rm SM}(\mu_b) + U_{ij}(\mu_b, \mu_{\rm EW})g(\mathscr{C}^i_{\rm SMEFT})(\mu_{\rm EW})$$

F Mahmoudi, et al.
[Symmetry 16(2024)8,1006]

$$C_7(\mu_b) = -0.3143$$
$$C_8(\mu_b) = -0.1710$$
$$C_9(\mu_b) = 4.0459$$
$$C_{10}(\mu_b) = -4.2939$$

$$\mathscr{B}(B_q \to \mu^+\mu^-) = \tau_{B_q} f^2_{B_q} m^3_{B_q} \frac{G_F^2\alpha^2}{64\pi^3} |V^*_{tq}V_{tb}|^2 \beta_\mu(m^2_{B_q}) \left[\frac{m^2_{B_q}}{m_b^2} |C_s(\mu_b) - C'_s(\mu_b)|^2 \left(1 - \frac{4m_\mu^2}{m^2_{B_q}}\right) + \left| \frac{m_{B_q}}{m_b}(C_p(\mu_b) - C'_p(\mu_b)) + 2\frac{m_\mu}{m_{B_q}}(C_{10}(\mu_b) - C'_{10}(\mu_b)) \right|^2 \right],$$

FCCC (Charge Current Process)

SM baseline: tree-level, clean, very small theory uncertainty.
High Event rates: Precision measurements are possible.
Direct probe of CKM elements: V_{cb}, V_{ub} from semileptonic B decays, V_{tb} from top decay/single top prod.

$$\mathscr{H}_{eff}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb}\left[(1+C_{V_1}^{\ell})\mathscr{O}_{V_1}^{\ell} + C_{V_2}^{\ell}\mathscr{O}_{V_2}^{\ell}\right]$$

$$\mathscr{O}_{V_1}^{\ell} = (\bar{c}_L\gamma^{\mu}b_L)(\bar{\ell}_L\gamma_{\mu}\nu_{\ell L}) \qquad \mathscr{O}_{V_2}^{\ell} = (\bar{c}_R\gamma^{\mu}b_R)(\bar{\ell}_L\gamma_{\mu}\nu_{\ell L}),$$

$$\left|V_{ij}\right| \to \left|V_{ij}\left(1 + C_{V_1}^{\ell}(\mu_b) \pm C_{V_2}^{\ell}(\mu_b)\right)\right|$$

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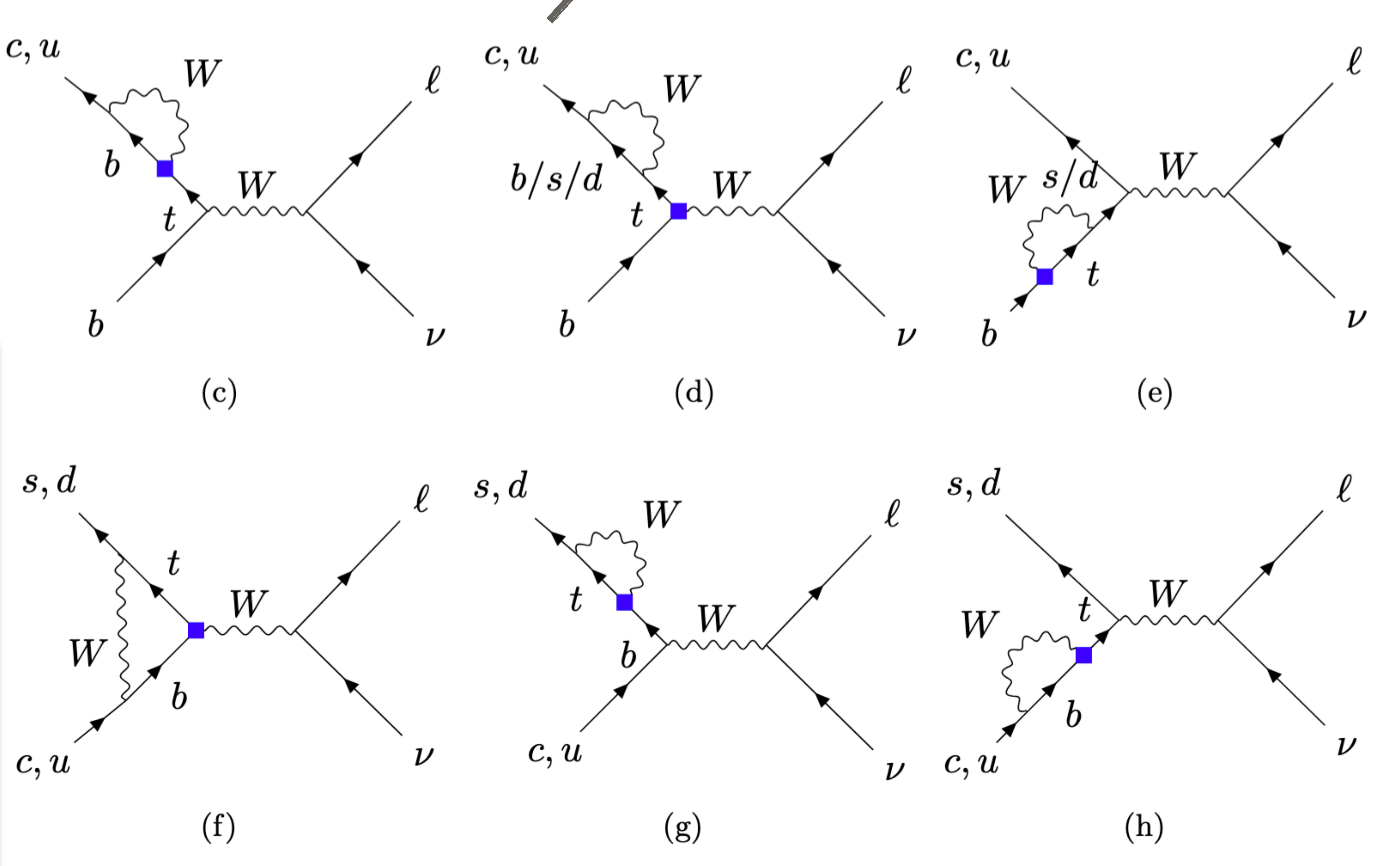
$$\mathcal{O}^{\ell}_{V_1} = (\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_{\ell L}) \qquad \mathcal{O}^{\ell}_{V_2} = (\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_{\ell L})\,,$$

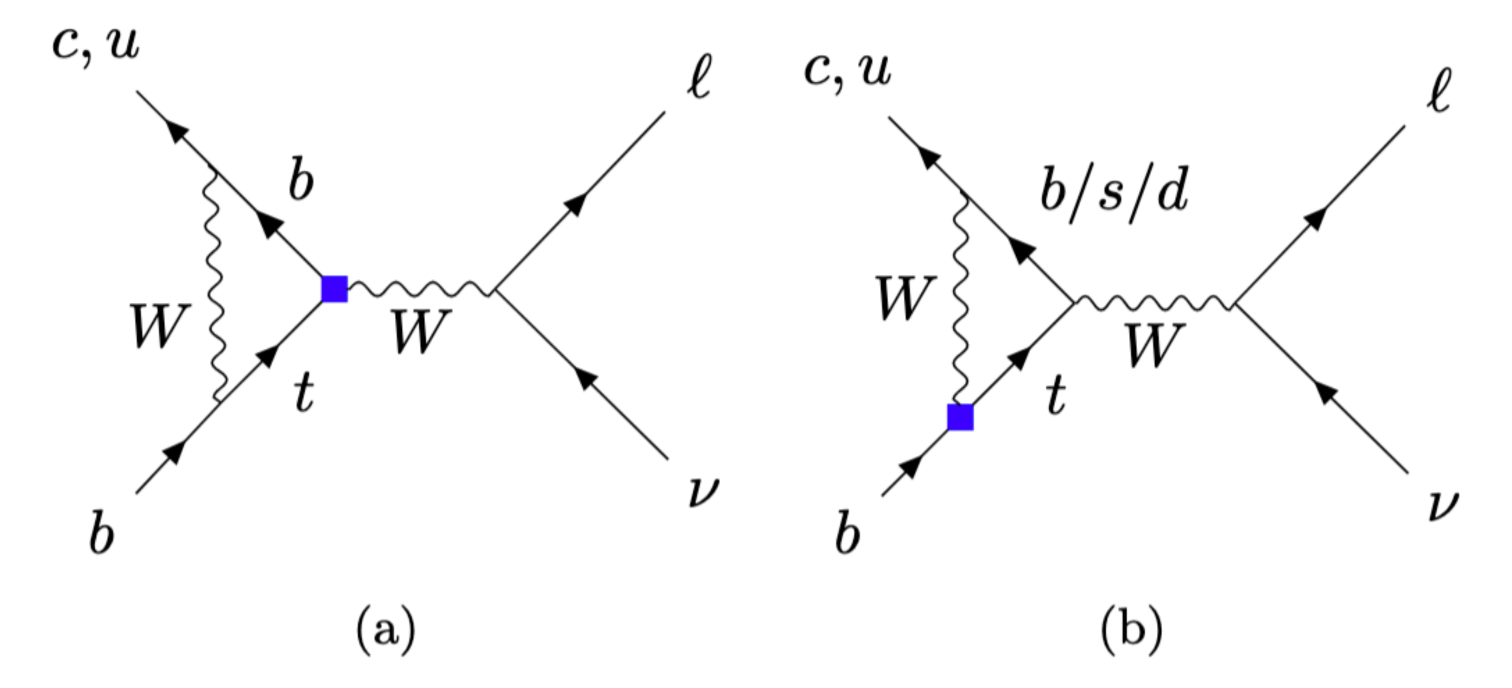
$$\left|V_{ij}\right| \to \left|V_{ij}\left(1 + C^{\ell}_{V_1}(\mu_b) \pm C^{\ell}_{V_2}(\mu_b)\right)\right|$$

Presence of *Wtb* couplings



(c) (d) (e)

(f) (g) (h)



(a) (b)

FCCC (Charge Current Process)

Differential decay rates ($P \to M\ell\nu$)

Helicity amplitudes

$$\frac{d\Gamma(P \to M\ell\nu_\ell)}{dq^2} = \frac{G_F^2}{192\pi^3 m_P^3} q^2 \sqrt{\underset{\big\downarrow}{\lambda_M(q^2)}} \left(1 - \frac{m_\ell^2}{q^2}\right) \left| \underbrace{V_{ij}(1 + C_{V_1}^\ell + C_{V_2}^\ell)} \right|^2 \left\{ \left(1 + \frac{m_\ell^2}{2q^2}\right) {H_{V,0}^s}^2 + \frac{3}{2}\frac{m_\ell^2}{q^2} {H_{V,t}^s}^2 \right\}.$$

Kallen Function

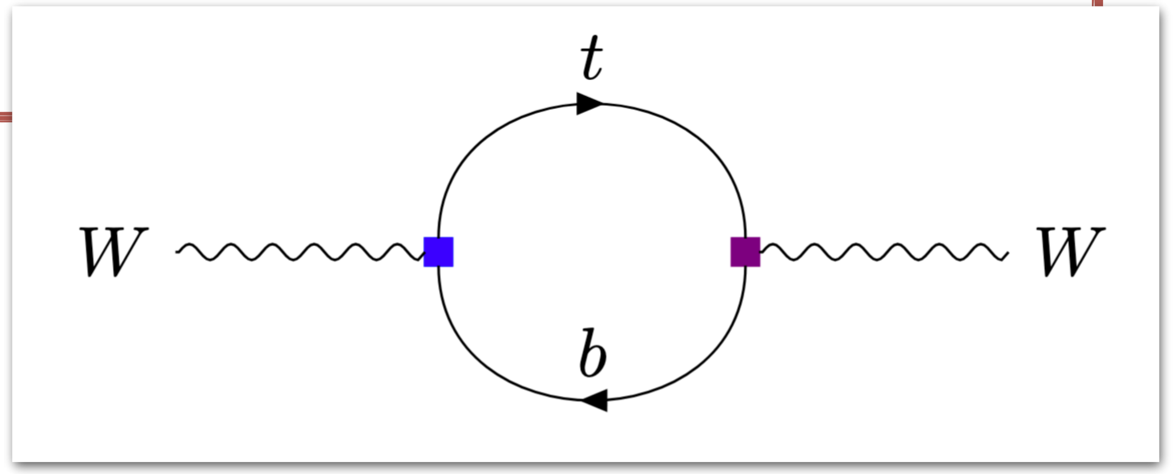
Semi-leptonic decay ($B \to D\ell\nu$) ⟶ $\left|V_{cb}\right| \to \left|V_{cb}\left(1 + C_{V_1}^\ell(\mu_b) + C_{V_2}^\ell(\mu_b)\right)\right|$

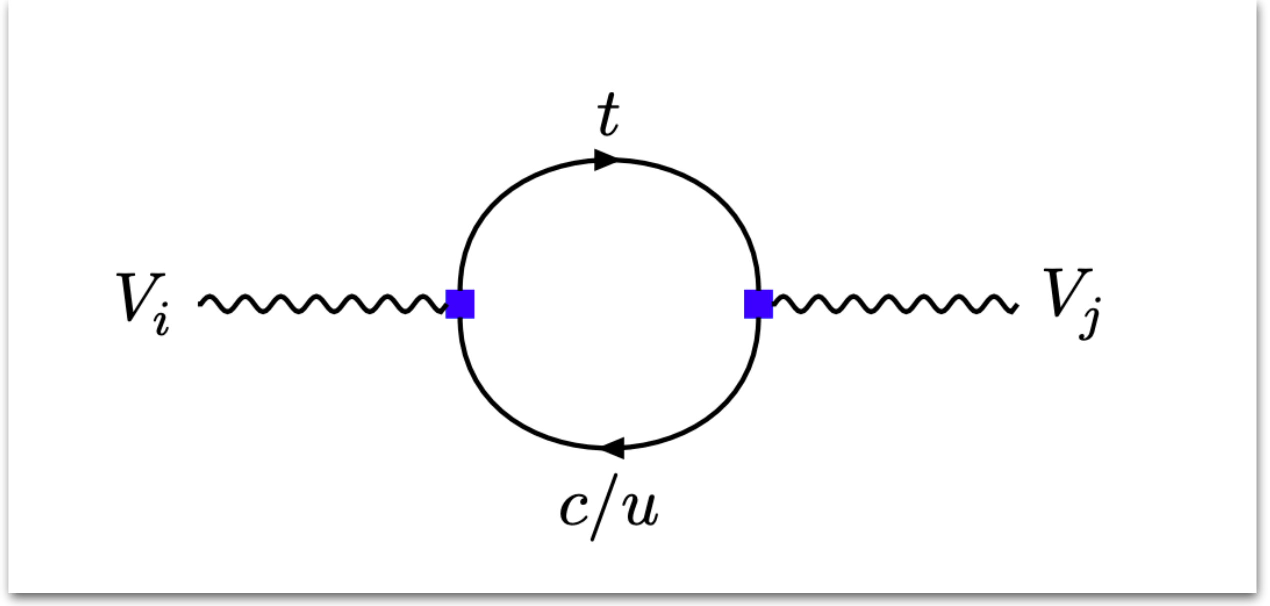
$$\begin{pmatrix} C_{V_L} \\ C_{V_R} \end{pmatrix}_{\mu_b} = \begin{pmatrix} 1.00716 & 0 \\ 0 & 1.00358 \end{pmatrix} \begin{pmatrix} C_{V_L} \\ C_{V_R} \end{pmatrix}_{\mu_{\rm EW}}$$

Leptonic decay rates ($P \to \ell\nu$)

$$\mathscr{B}(P \to \ell\nu_\ell) = \frac{\tau_P}{8\pi} m_P m_\ell^2 f_P^2 G_F^2 \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 \left| V_{u_j d_i}(1 + C_{V_1}^\ell - C_{V_2}^\ell) \right|^2 .$$

EW Precision Observables





Oblique Parameters (S, T, U)

$$S = \left(\frac{4s_W^2c_W^2}{\alpha_e}\right)\left(\left[\frac{\delta\Sigma^T_{ZZ}(m_Z^2)-\delta\Sigma^T_{ZZ}(0)}{m_Z^2}\right]-\frac{c_W^2-s_W^2}{c_Ws_W}\frac{\delta\Sigma^T_{\gamma Z}(m_Z^2)}{m_Z^2}-\frac{\delta\Sigma^T_{\gamma\gamma}(m_Z^2)}{m_Z^2}\right)$$

$$U = \frac{4s_W^2}{\alpha_e}\left(\left[\frac{\delta\Sigma^T_{WW}(m_W^2)-\delta\Sigma^T_{WW}(0)}{m_W^2}\right]-\frac{c_W}{s_W}\frac{\delta\Sigma^T_{Z\gamma}(m_Z^2)}{m_Z^2}-\frac{\delta\Sigma^T_{\gamma\gamma}(m_Z^2)}{m_Z^2}\right)-S$$

$$T = \frac{1}{\alpha_e}\left(\frac{\delta\Sigma^T_{WW}(0)}{m_W^2}-\frac{\delta\Sigma^T_{ZZ}(0)}{m_Z^2}\right)$$

In the SM reference point,
$S, T, U = 0$

GFitter Collaboration
$$S = 0.05 \pm 0.11\,,$$
$$T = 0.09 \pm 0.13\,,$$
$$U = 0.01 \pm 0.11\,.$$

Here Σ_{ij} is the self-energy of the gauge boson

Based on these parameters, many more observables can be constructed

In SM, $\rho = \frac{G_{NC}}{G_{CC}} = \frac{M_W^2}{c_W^2M_Z^2} = 1\,.$

BSM , $\rho = \frac{1}{1-\Delta\rho}, \quad \Delta\rho = (\Delta\rho)^{(1)} + (\Delta\rho)^{(2)} + \cdots$

$$(\Delta\rho)^{(1)} = -\,\alpha_{em}\Delta T$$

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha_{em}}{\sqrt{2}G_F}\frac{1}{1-\Delta r}\,.$$

$$\Delta r = \frac{\alpha_{em}}{s_W^2}\left(-\frac{1}{2}\Delta S + c_W^2\Delta T + \frac{c_W^2-s_W^2}{4s_W^2}\Delta U\right)$$

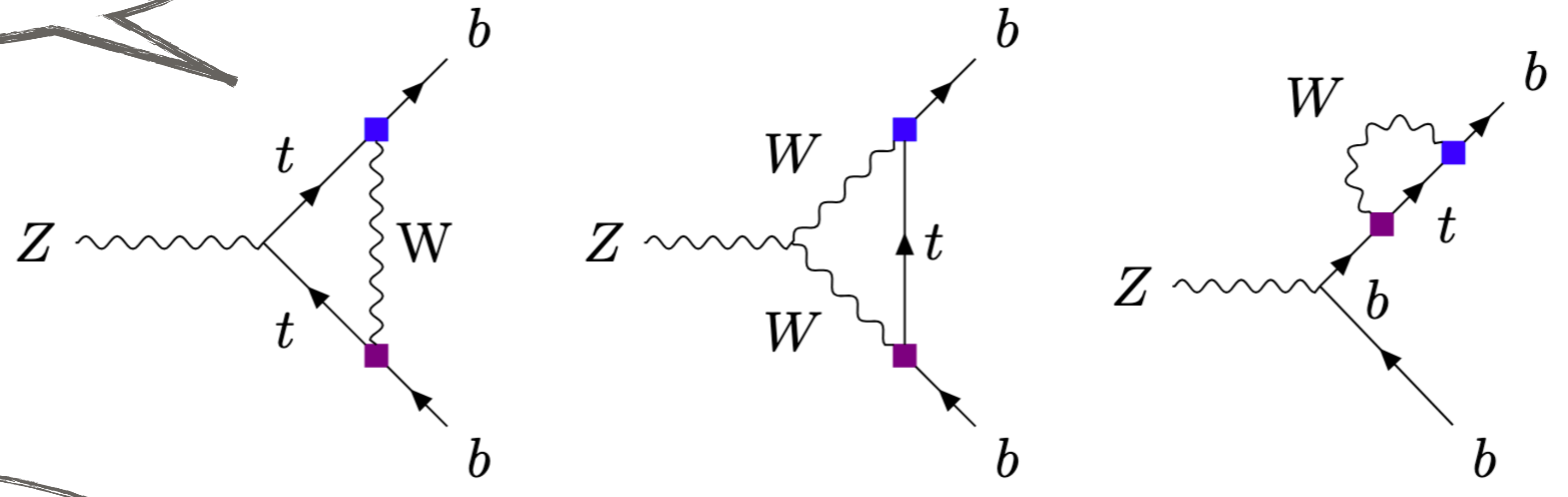
Key observables for the precision measurement of M_W

LHCb, ATLAS,
D0, CDF

Z & W pole Observables

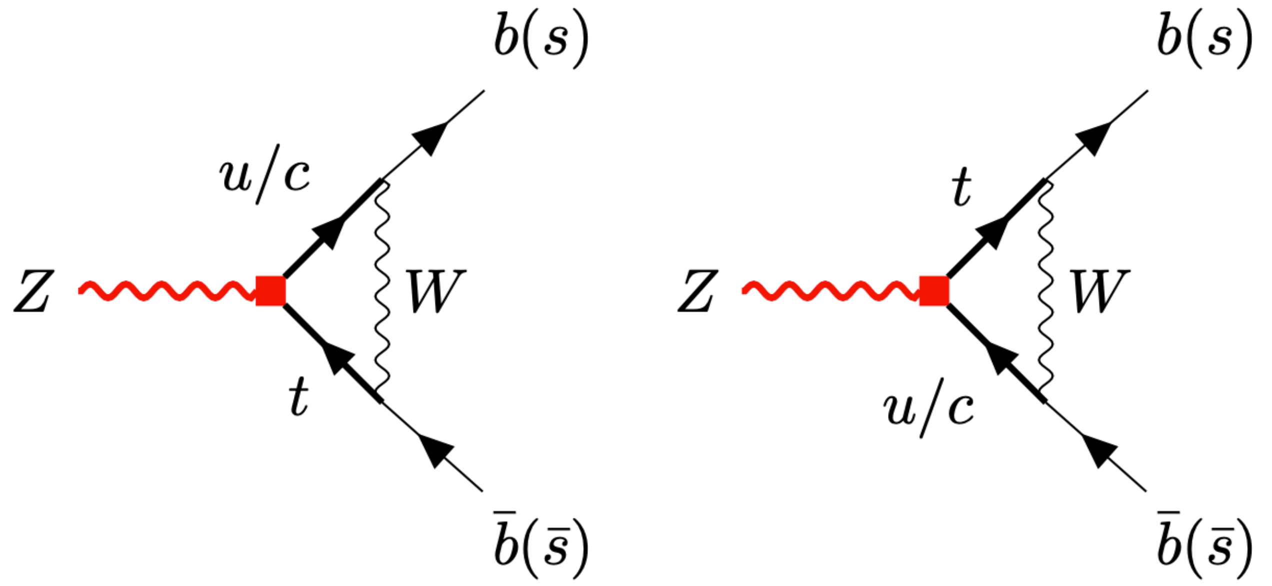
Z Pole Obs.

Presence of *Wtb* couplings



(a)

Presence of top FCNC



(a) (b)

Affected obs.

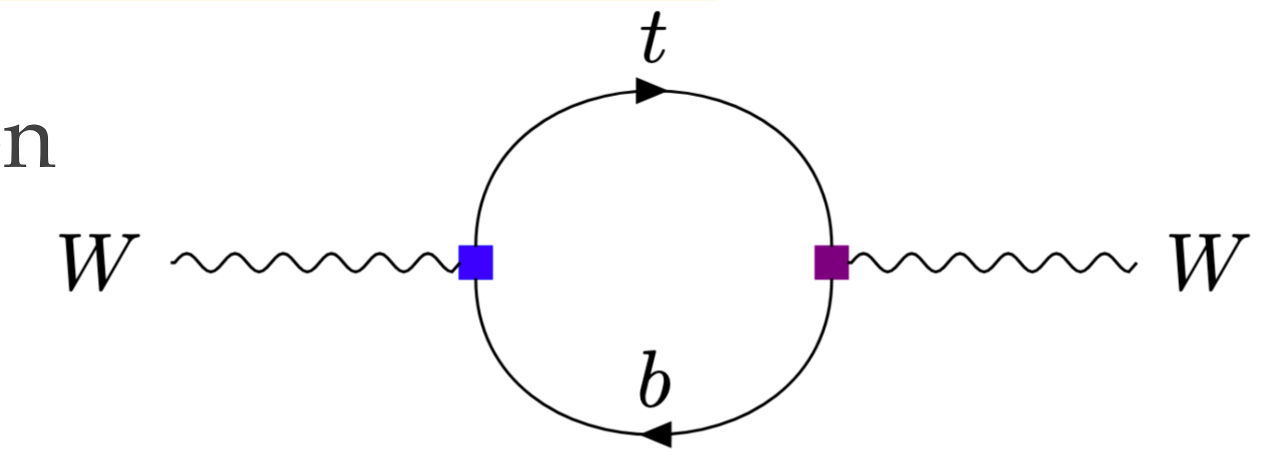
$$g_{Vb}^{\text{tot}} = g_{Vb}^{\text{SM}} + \delta g_{Vb}\,,$$

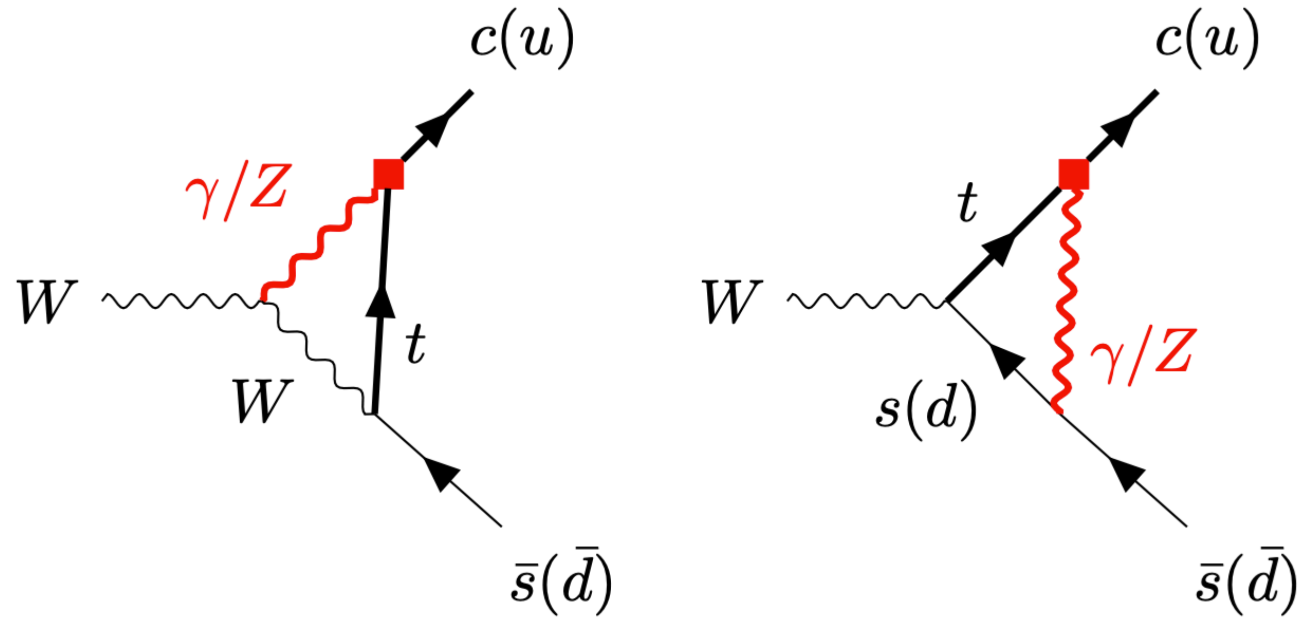
$$g_{Ab}^{\text{tot}} = g_{Ab}^{\text{SM}} + \delta g_{Ab}\,.$$

$$R_b = \frac{\Gamma_b}{\Gamma_{\text{had}}} \qquad A_b = \frac{\Gamma(Z \to b_L\bar{b}_L) - \Gamma(Z \to b_R\bar{b}_R)}{\Gamma(Z \to b\bar{b})} \qquad A_b^{\text{FB}} = \frac{3}{4}A_eA_b$$

W Pole Obs.

W boson mass correction





(a) (b)

+ Many more

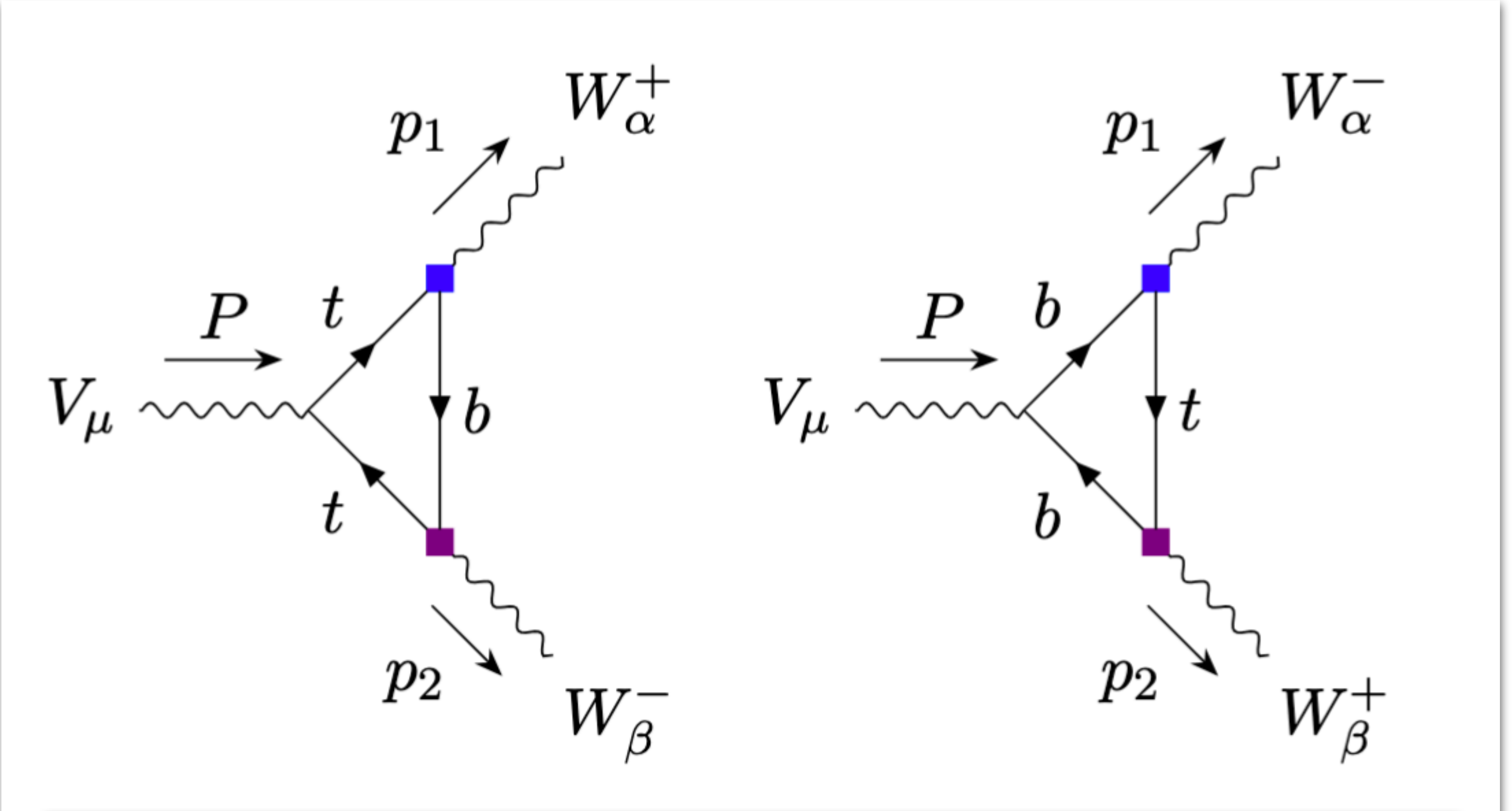
Affected obs.

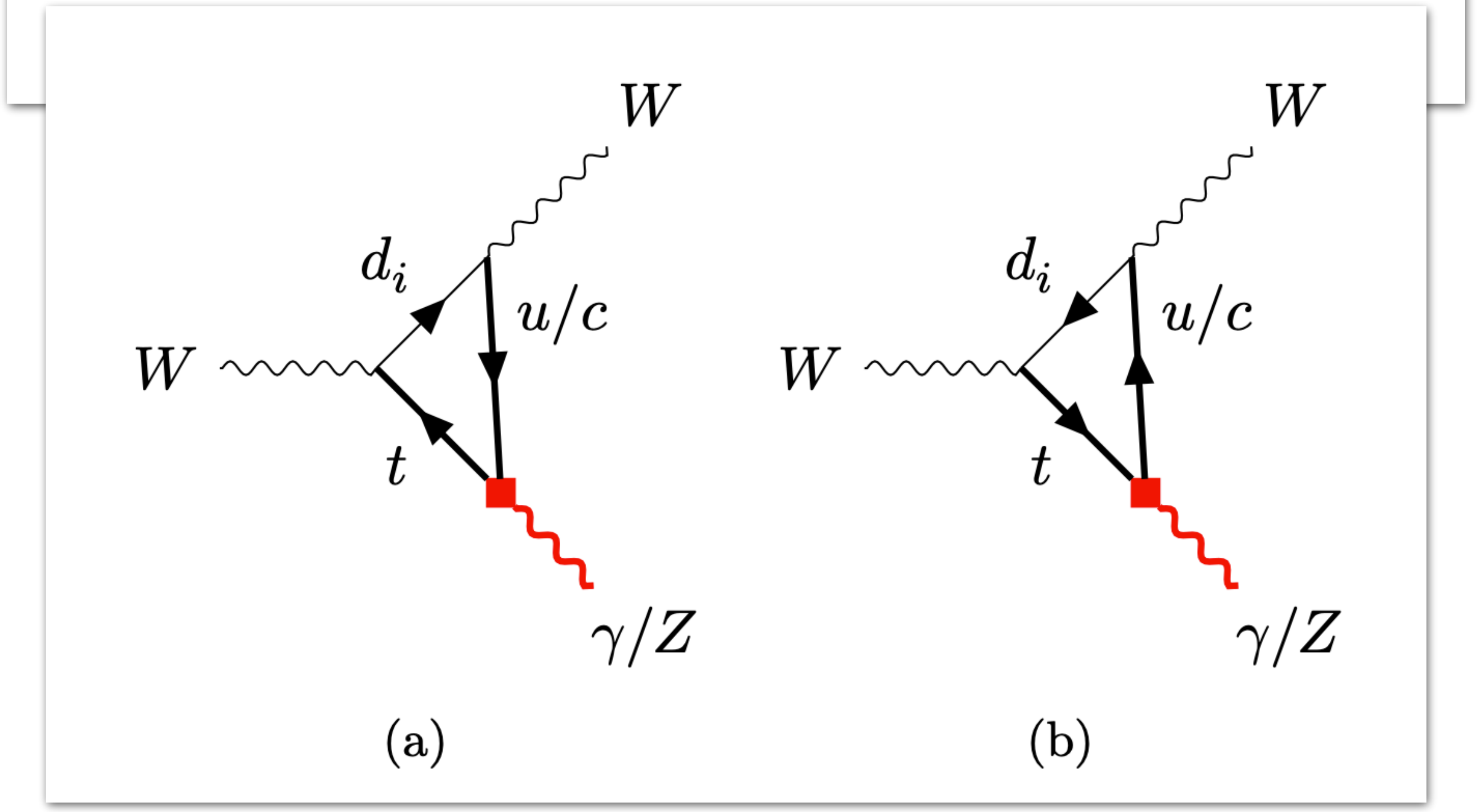
$$\mathscr{B}(W \to \ell\nu), R_{\ell_1/\ell_2}$$

$$R_{Wc} = \frac{\Gamma(W \to cs)}{\Gamma(W \to ud) + \Gamma(W \to cs)}$$

Trilinear Gauge Couplings

Direct test of **Non-Abelian gauge symmetry SM**.
Extensively studied at **LEP & LHC**





(a)

(b)

$$\mathcal{L}_{WWV} = ig_{WWV}\Big(g_1^V (W^+_{\mu\nu}W^{-\mu}W^{+\nu} - W^+_\mu W^-_\nu W^{\mu\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\lambda\mu}W^{-\mu}_\nu V^{\nu\lambda} + i g_4^V W^+_\mu W^-_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma}(W^+_\mu \overset{\leftrightarrow}{\partial}_\rho W^-_\nu)V_\rho + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{M_W^2} W^+_{\lambda\mu}W^{-\mu}\tilde{V}^{\nu\lambda}\Big). \qquad (4.42)$$

Here, $V = (\gamma/Z)$

Among the 7 couplings
$$\begin{cases} g_1^V, \kappa^V, \lambda^V, g_5^V & \text{(CP conserving)} \\ g_4^V, \tilde{\kappa}_V, \tilde{\lambda}_V & \text{(CP violating)} \end{cases}$$

We are also getting contributions in these couplings

At SM, tree level $\left(g_1^Z, g_1^\gamma, \kappa_Z, \kappa_\gamma = 1\right)$

Global Analysis

We have performed sector-wise and Global (Combined) fits in order to put constraints on these couplings.

Global χ^2 analysis

$$\chi^2_{\text{Global}}(\mathscr{C}_i(\mu_{\text{EW}})) = \chi^2_{\text{Flavour}}(\mathscr{C}_i(\mu_{\text{EW}})) + \chi^2_{\text{EWPOs}}(\mathscr{C}_i(\mu_{\text{EW}})) + \chi^2_{\text{others}}(\mathscr{C}_i(\mu_{\text{EW}}))$$

$$\chi^2(\mathscr{C}) = \sum_{ij} \left(\mathcal{O}_i^{\text{Exp}}(\mathscr{C}_i) - \mathcal{O}_i^{\text{EFT}}\right) (V)^{-1}_{ij} \left(\mathcal{O}_j^{\text{Exp}}(\mathscr{C}_j) - \mathcal{O}_j^{\text{EFT}}\right)$$

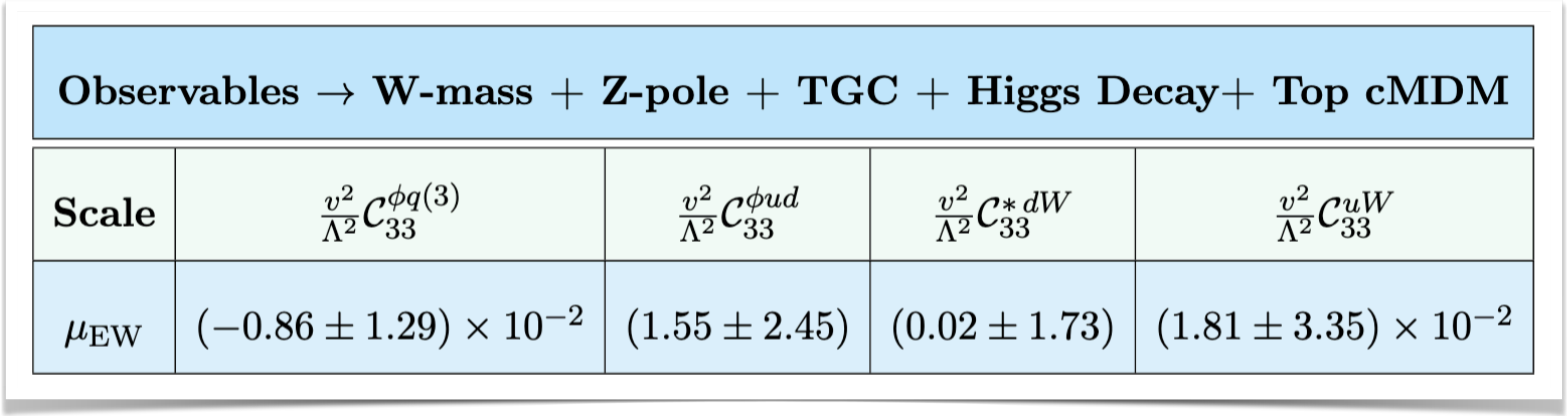
V_{ij} is the covariance matrix of Exp measurements.

Fitting is performed for one-parameter scenarios as well as multi-parameter scenarios.

Results I (Charged Current Couplings)

Results I (Charged Current Couplings)

$$\chi^2_{\text{EWPO+others}}(\mathscr{C}_i(\mu_{\text{EW}}))$$

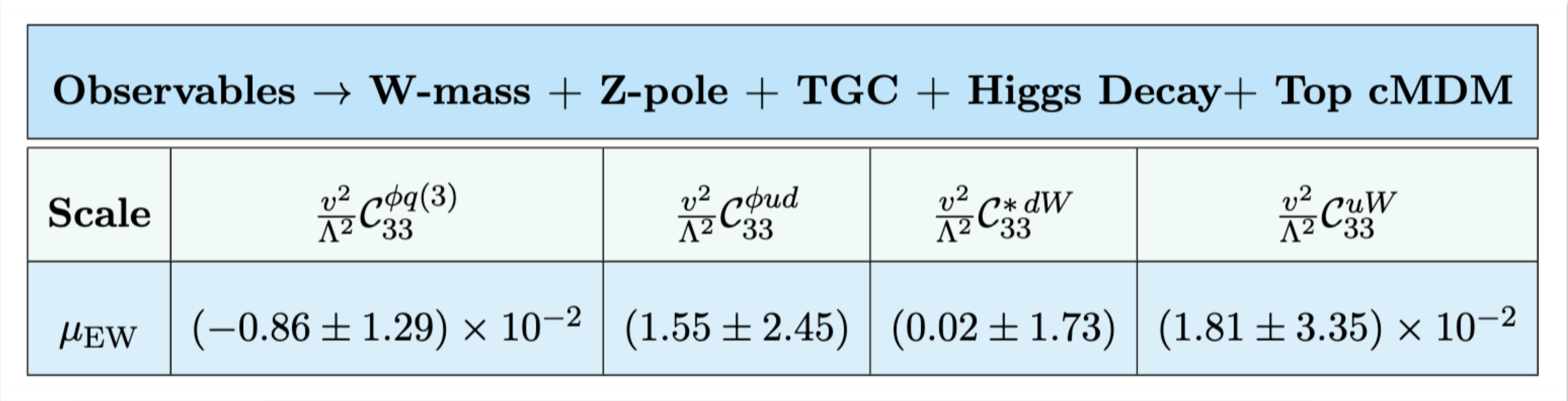


Observables → W-mass + Z-pole + TGC + Higgs Decay+ Top cMDM

Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}$
μ_{EW}	$(-0.86 \pm 1.29) \times 10^{-2}$	(1.55 ± 2.45)	(0.02 ± 1.73)	$(1.81 \pm 3.35) \times 10^{-2}$

Results I (Charged Current Couplings)

$\chi^2_{\text{EWPO+others}}(\mathscr{C}_i(\mu_{\text{EW}}))$



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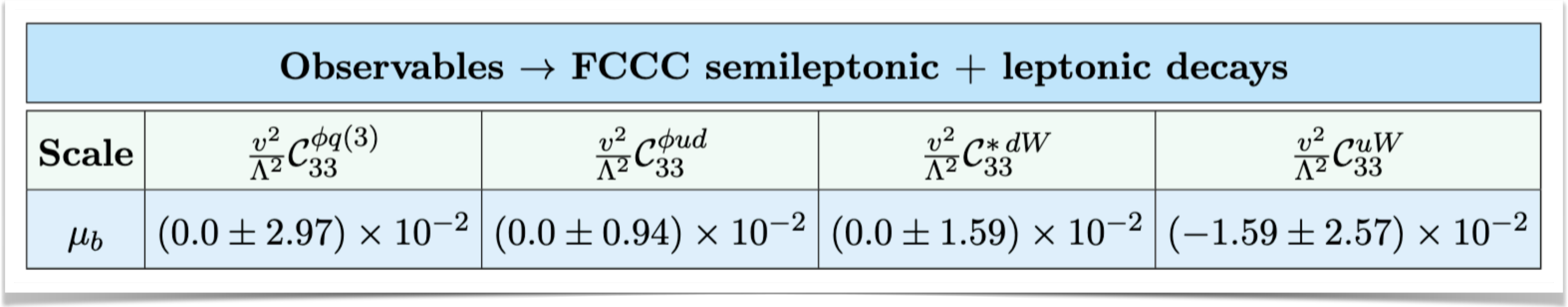
Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}$
μ_{EW}	$(-0.86 \pm 1.29) \times 10^{-2}$	(1.55 ± 2.45)	(0.02 ± 1.73)	$(1.81 \pm 3.35) \times 10^{-2}$

$\chi^2_{\text{FCCC}}(\mathscr{C}_i(\mu_b))$

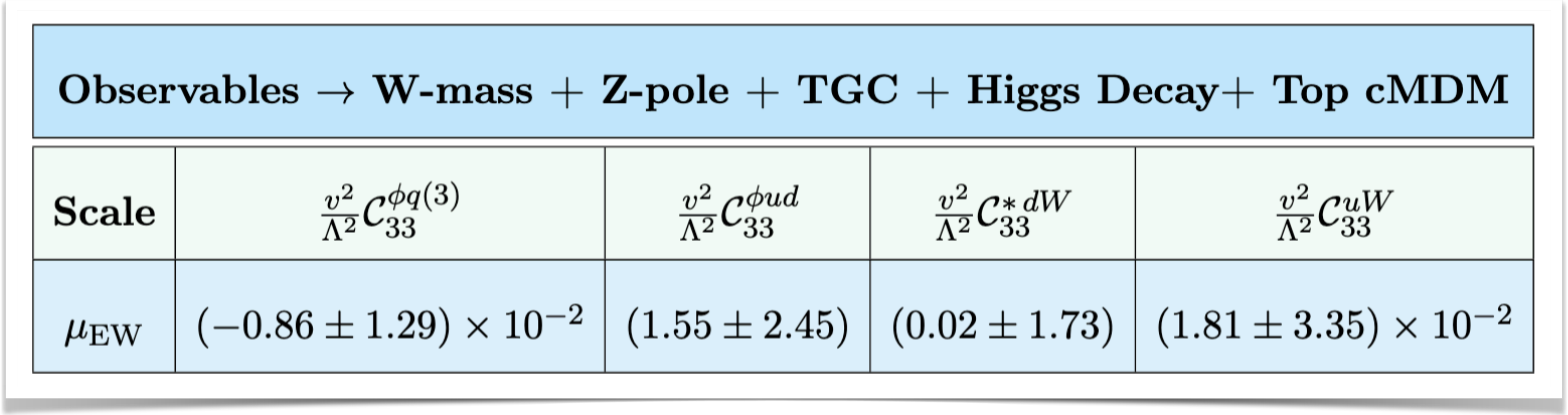


Observables → FCCC semileptonic + leptonic decays

Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}$	$\frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}$
μ_b	$(0.0 \pm 2.97) \times 10^{-2}$	$(0.0 \pm 0.94) \times 10^{-2}$	$(0.0 \pm 1.59) \times 10^{-2}$	$(-1.59 \pm 2.57) \times 10^{-2}$

Results I (Charged Current Couplings)

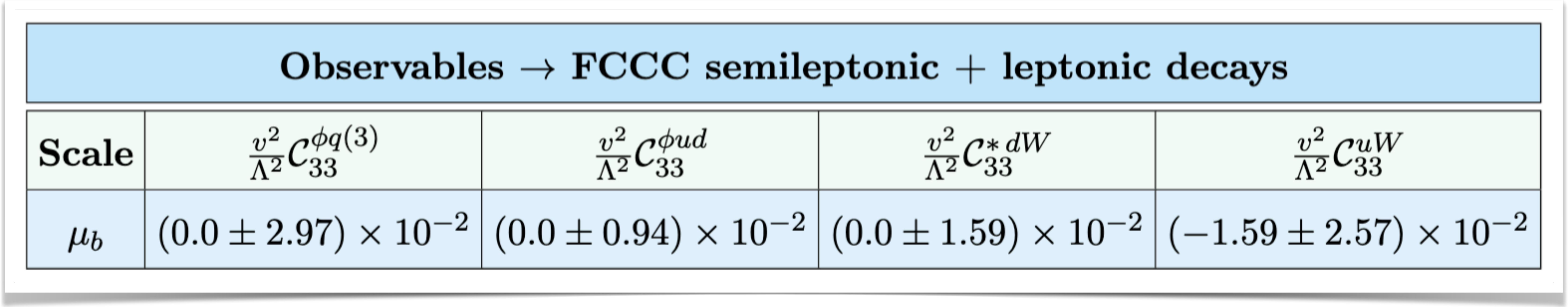
$\chi^2_{\text{EWPO+others}}(\mathscr{C}_i(\mu_{\text{EW}}))$



Observables → W-mass + Z-pole + TGC + Higgs Decay+ Top cMDM

Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}$
μ_{EW}	$(-0.86 \pm 1.29) \times 10^{-2}$	(1.55 ± 2.45)	(0.02 ± 1.73)	$(1.81 \pm 3.35) \times 10^{-2}$

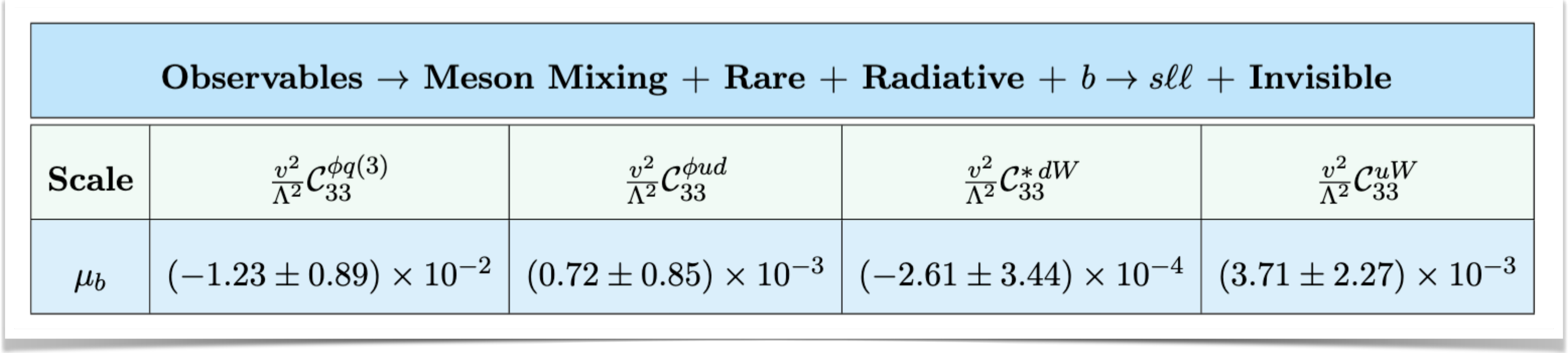
$\chi^2_{\text{FCCC}}(\mathscr{C}_i(\mu_b))$



Observables → FCCC semileptonic + leptonic decays

Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}$
μ_b	$(0.0 \pm 2.97) \times 10^{-2}$	$(0.0 \pm 0.94) \times 10^{-2}$	$(0.0 \pm 1.59) \times 10^{-2}$	$(-1.59 \pm 2.57) \times 10^{-2}$

$\chi^2_{\text{FCNC}}(\mathscr{C}_i(\mu_b))$



Observables → Meson Mixing + Rare + Radiative + $b \to s\ell\ell$ + Invisible

Scale	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}$	$\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}$
μ_b	$(-1.23 \pm 0.89) \times 10^{-2}$	$(0.72 \pm 0.85) \times 10^{-3}$	$(-2.61 \pm 3.44) \times 10^{-4}$	$(3.71 \pm 2.27) \times 10^{-3}$

Remember,
Matching Relation

Results I (Charged Current Couplings)

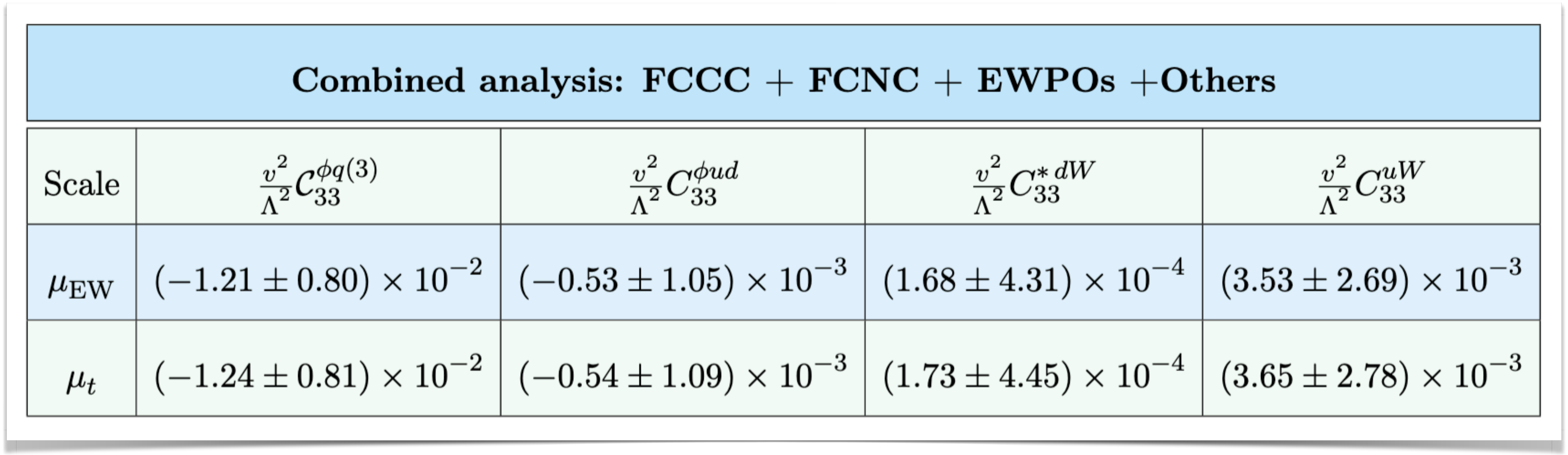
$\chi^2_{\text{Global}}(\mathscr{C}_i(\mu_{\text{EW}}))$

$$V_L(\mu_t) = \frac{v^2}{\Lambda^2}\mathscr{C}^{\phi q(3)}_{33}(\mu_t)$$

$$V_R(\mu_t) = \frac{1}{2}\frac{v^2}{\Lambda^2}\mathscr{C}^{\phi ud}_{33}(\mu_t)$$

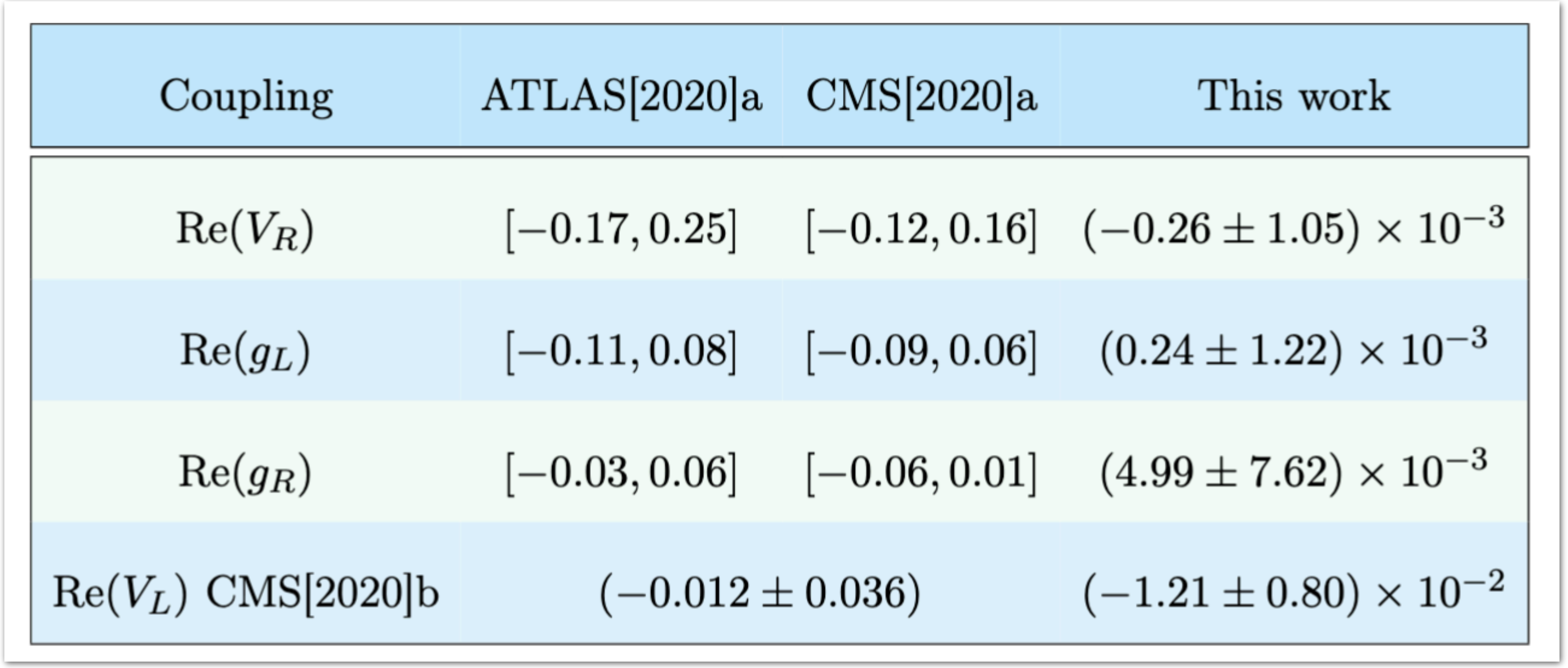
$$g_L(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}^{*\,dW}_{33}(\mu_t)$$

$$g_R(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}^{uW}_{33}(\mu_t)$$



Combined analysis: FCCC + FCNC + EWPOs +Others

Scale	$\frac{v^2}{\Lambda^2}C^{\phi q(3)}_{33}$	$\frac{v^2}{\Lambda^2}C^{\phi ud}_{33}$	$\frac{v^2}{\Lambda^2}C^{*\,dW}_{33}$	$\frac{v^2}{\Lambda^2}C^{uW}_{33}$
μ_{EW}	$(-1.21 \pm 0.80) \times 10^{-2}$	$(-0.53 \pm 1.05) \times 10^{-3}$	$(1.68 \pm 4.31) \times 10^{-4}$	$(3.53 \pm 2.69) \times 10^{-3}$
μ_t	$(-1.24 \pm 0.81) \times 10^{-2}$	$(-0.54 \pm 1.09) \times 10^{-3}$	$(1.73 \pm 4.45) \times 10^{-4}$	$(3.65 \pm 2.78) \times 10^{-3}$



Coupling	ATLAS[2020]a	CMS[2020]a	This work
$\text{Re}(V_R)$	$[-0.17, 0.25]$	$[-0.12, 0.16]$	$(-0.26 \pm 1.05) \times 10^{-3}$
$\text{Re}(g_L)$	$[-0.11, 0.08]$	$[-0.09, 0.06]$	$(0.24 \pm 1.22) \times 10^{-3}$
$\text{Re}(g_R)$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$(4.99 \pm 7.62) \times 10^{-3}$
$\text{Re}(V_L)$ CMS[2020]b	(-0.012 ± 0.036)		$(-1.21 \pm 0.80) \times 10^{-2}$

- Exp Inputs: ATLAS[2020]a, CMS[2020]a, CMS[2020]b

All the bounds are given at 95% CL

Remember,
Matching Relation

Results I (Charged Current Couplings)

$\chi^2_{\text{Global}}(\mathscr{C}_i(\mu_{\text{EW}}))$

$$V_L(\mu_t) = \frac{v^2}{\Lambda^2}\mathscr{C}^{\phi q(3)}_{33}(\mu_t)$$

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$$g_L(\mu_t) = \sqrt{2}\frac{v^2}{\Lambda^2}\mathscr{C}^{*\,dW}_{33}(\mu_t)$$

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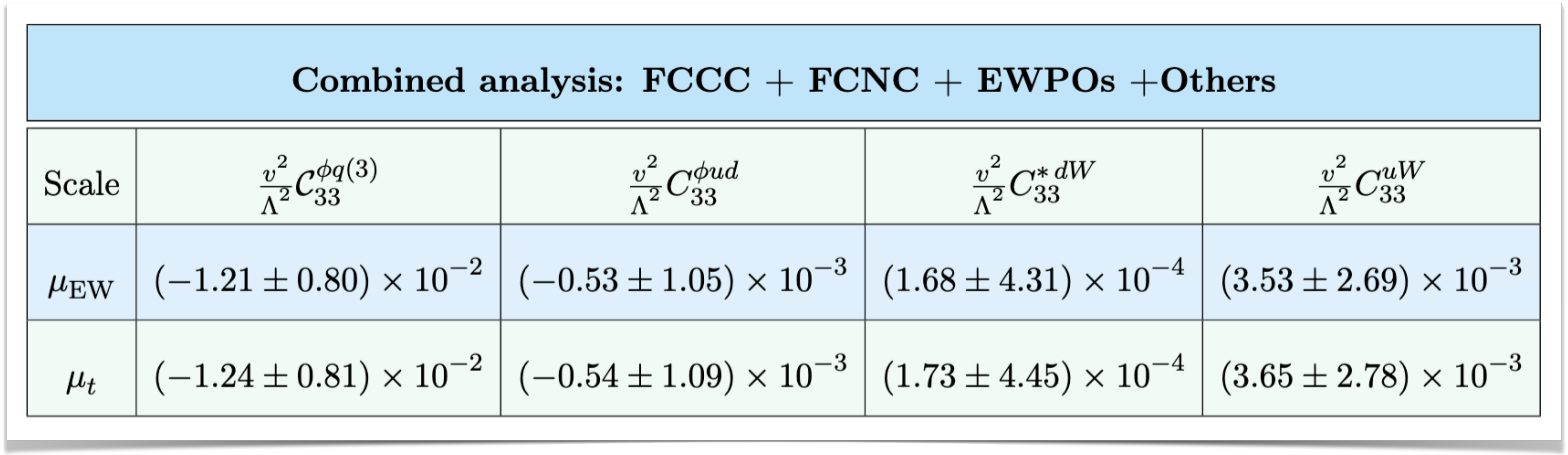
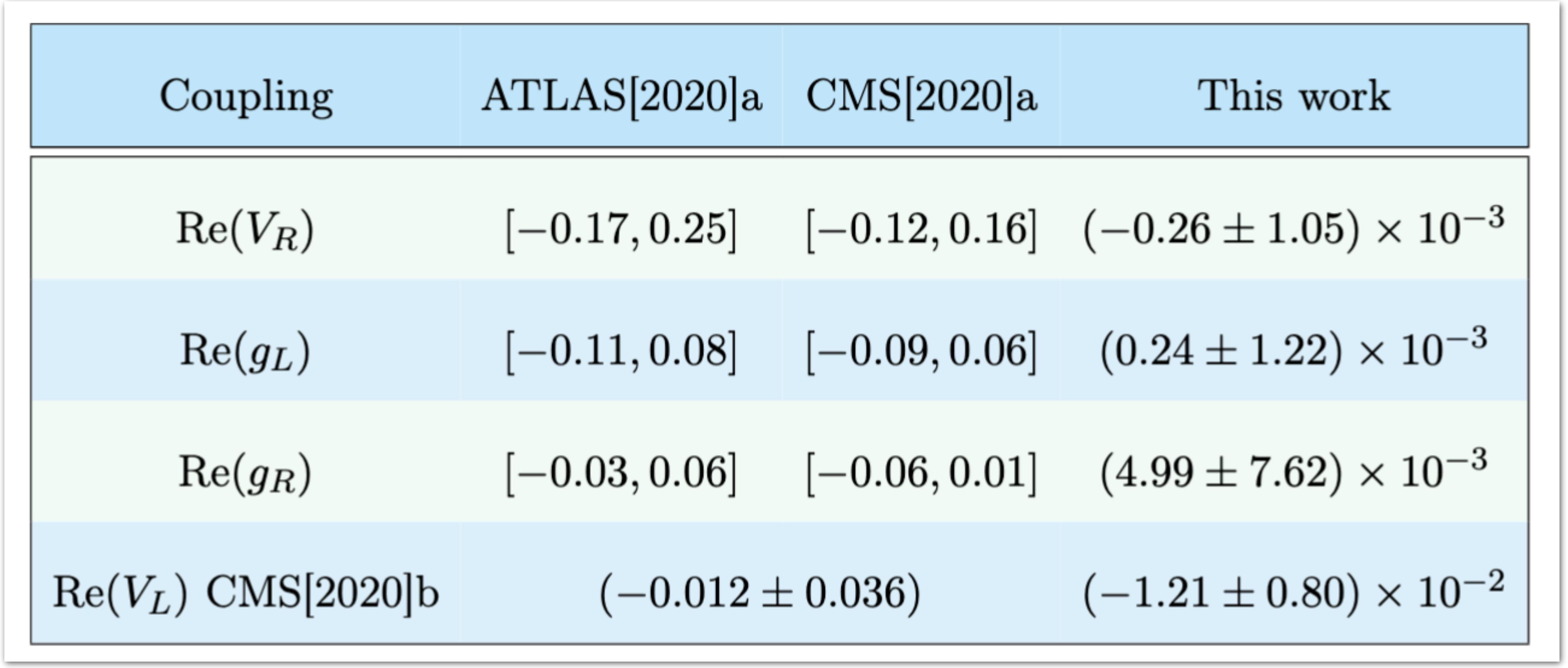


Combined analysis: FCCC + FCNC + EWPOs +Others

Scale	$\frac{v^2}{\Lambda^2}C^{\phi q(3)}_{33}$	$\frac{v^2}{\Lambda^2}C^{\phi ud}_{33}$	$\frac{v^2}{\Lambda^2}C^{*\,dW}_{33}$	$\frac{v^2}{\Lambda^2}C^{uW}_{33}$
μ_{EW}	$(-1.21 \pm 0.80) \times 10^{-2}$	$(-0.53 \pm 1.05) \times 10^{-3}$	$(1.68 \pm 4.31) \times 10^{-4}$	$(3.53 \pm 2.69) \times 10^{-3}$
μ_t	$(-1.24 \pm 0.81) \times 10^{-2}$	$(-0.54 \pm 1.09) \times 10^{-3}$	$(1.73 \pm 4.45) \times 10^{-4}$	$(3.65 \pm 2.78) \times 10^{-3}$

- Low-energy obs provides constraints up to **two orders of magnitude** stronger than direct collider bounds.
- Radiative decays heavily constrain V_R & $g_L \rightarrow \mathcal{O}(10^{-3})$
- Neutral meson mixing tightly constrains V_L & g_R
- Slight tension in (Δ_d) pull V_L slightly away from zero, though consistent within 2σ



Coupling	ATLAS[2020]a	CMS[2020]a	This work
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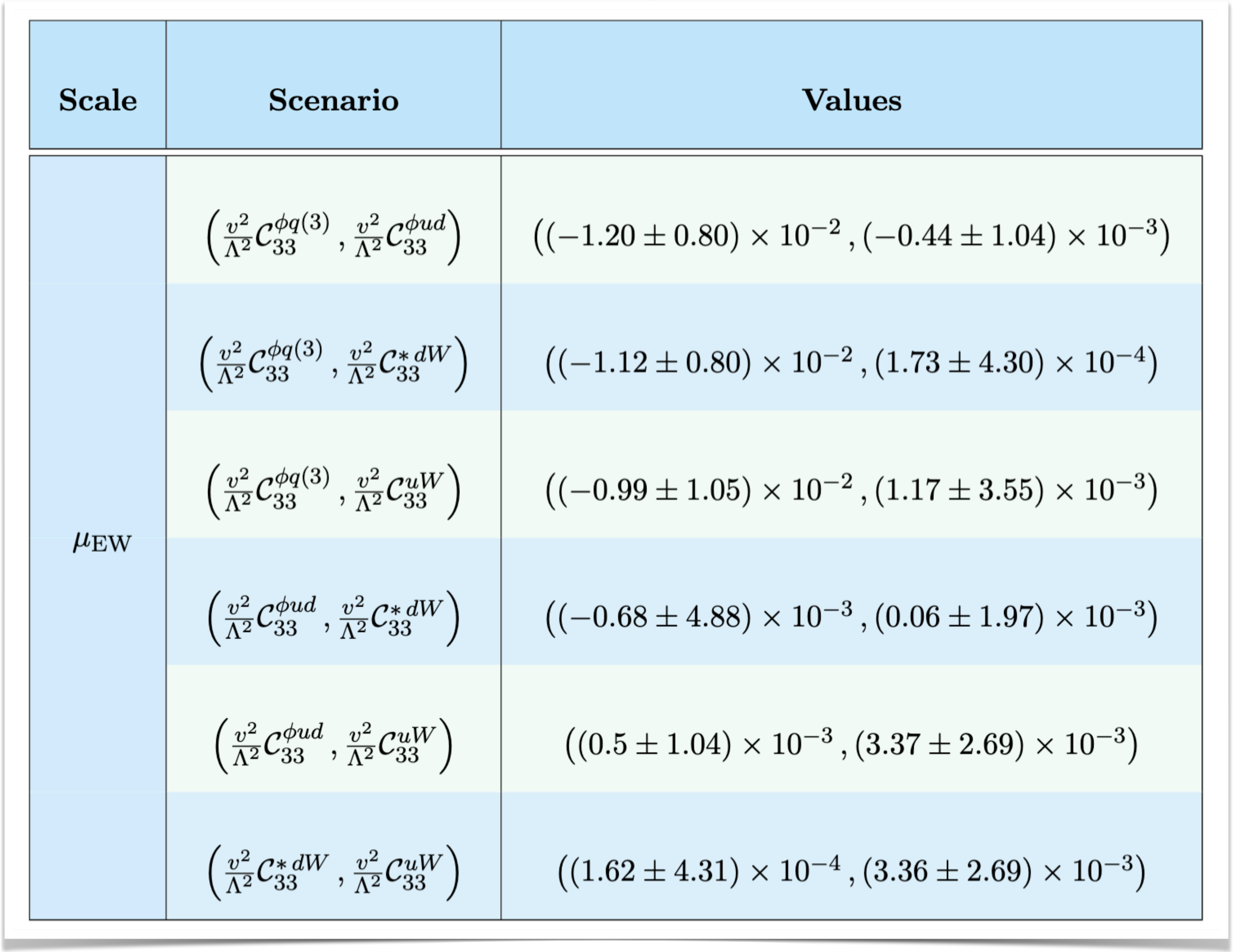
$\text{Re}(g_R)$	$[-0.03, 0.06]$	$[-0.06, 0.01]$	$(4.99 \pm 7.62) \times 10^{-3}$
$\text{Re}(V_L)$ CMS[2020]b	(-0.012 ± 0.036)		$(-1.21 \pm 0.80) \times 10^{-2}$

All the bounds are given at 95% CL

Results I (Charged Current Couplings)

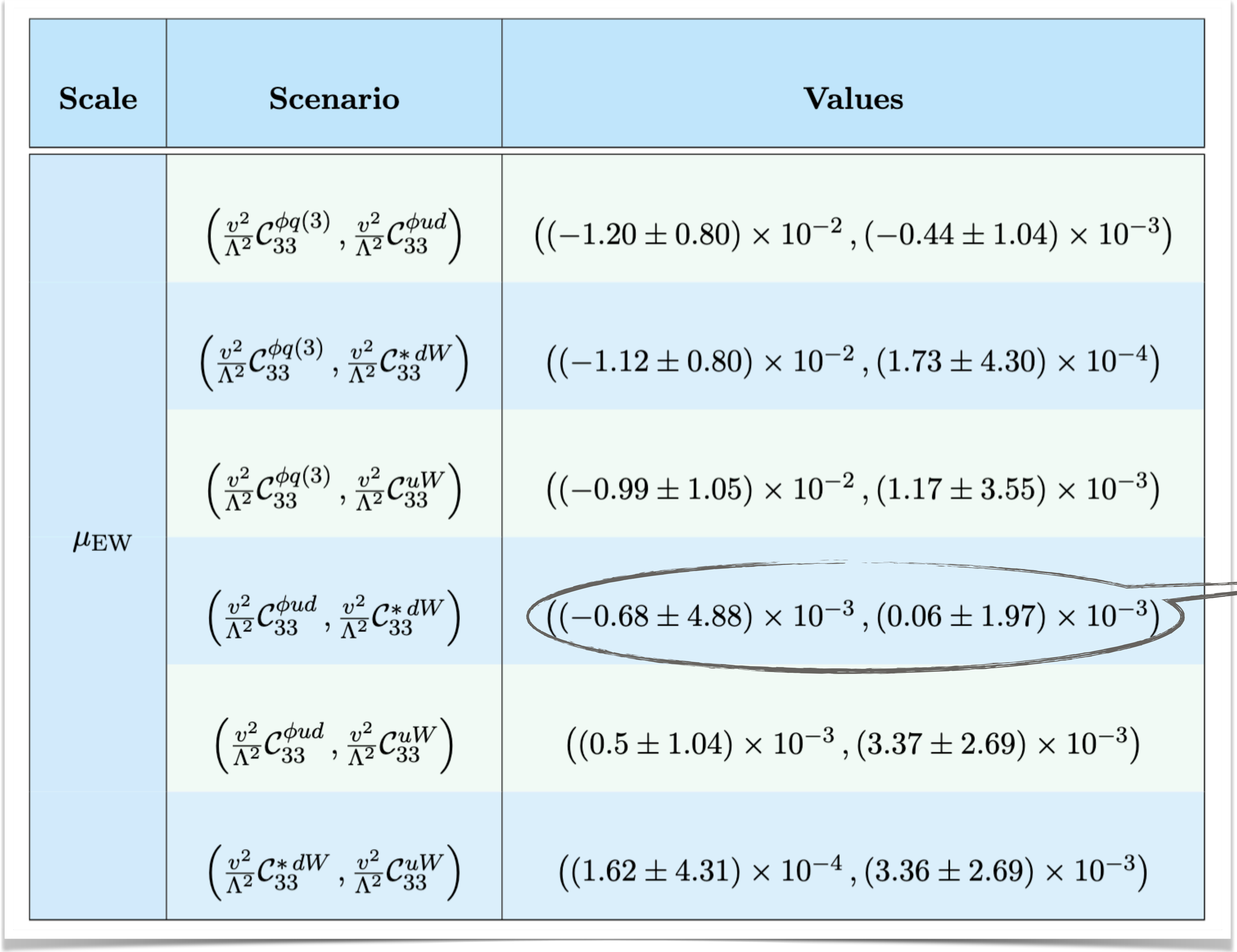


Scale	Scenario	Values
μ_{EW}	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}\right)$	$\left((-1.20\pm 0.80)\times 10^{-2}\,,(-0.44\pm 1.04)\times 10^{-3}\right)$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}\right)$	$\left((-1.12\pm 0.80)\times 10^{-2}\,,(1.73\pm 4.30)\times 10^{-4}\right)$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$\left((-0.99\pm 1.05)\times 10^{-2}\,,(1.17\pm 3.55)\times 10^{-3}\right)$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}\right)$	$\left((-0.68\pm 4.88)\times 10^{-3}\,,(0.06\pm 1.97)\times 10^{-3}\right)$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$\left((0.5\pm 1.04)\times 10^{-3}\,,(3.37\pm 2.69)\times 10^{-3}\right)$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}\,,\,\frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$\left((1.62\pm 4.31)\times 10^{-4}\,,(3.36\pm 2.69)\times 10^{-3}\right)$

Multiparameter Scenario

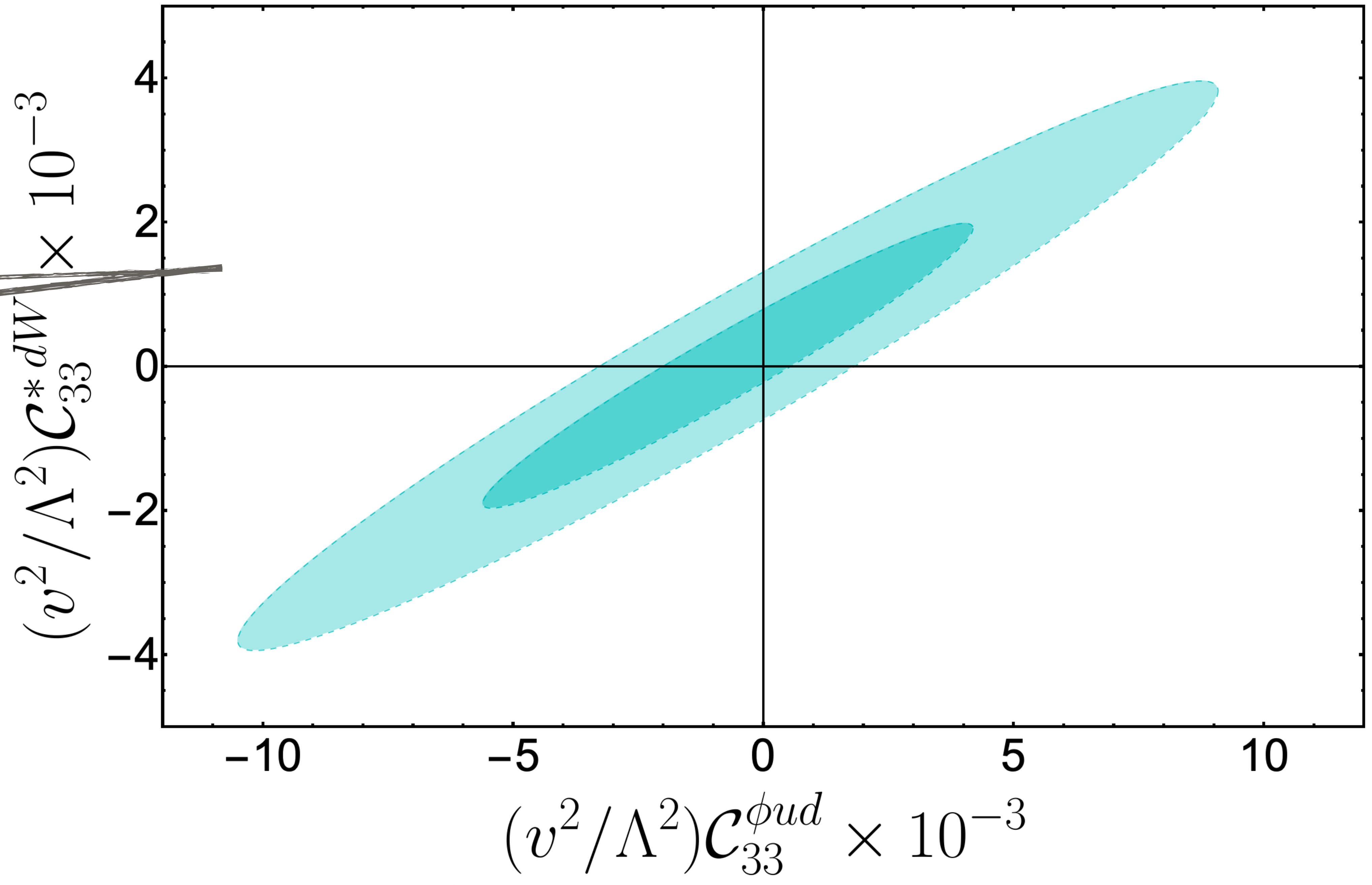
Strong positive correlations

Results I (Charged Current Couplings)



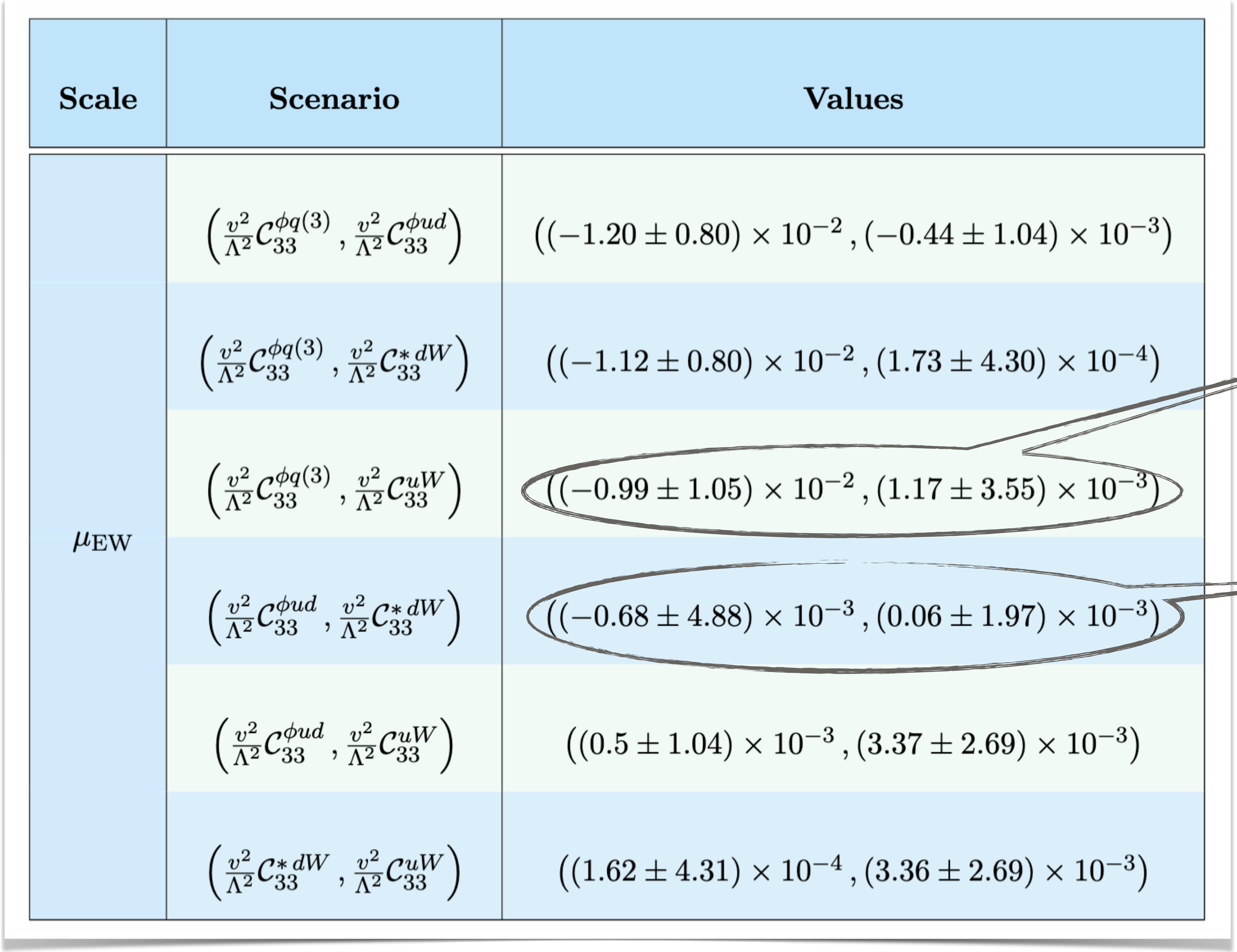
Scale	Scenario	Values
μ_{EW}	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}\right)$	$((-1.20 \pm 0.80) \times 10^{-2}, (-0.44 \pm 1.04) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}\right)$	$((-1.12 \pm 0.80) \times 10^{-2}, (1.73 \pm 4.30) \times 10^{-4})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi q(3)}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}\right)$	$((-0.99 \pm 1.05) \times 10^{-2}, (1.17 \pm 3.55) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}\right)$	$((-0.68 \pm 4.88) \times 10^{-3}, (0.06 \pm 1.97) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{\phi ud}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}\right)$	$((0.5 \pm 1.04) \times 10^{-3}, (3.37 \pm 2.69) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{*\,dW}, \frac{v^2}{\Lambda^2}\mathcal{C}_{33}^{uW}\right)$	$((1.62 \pm 4.31) \times 10^{-4}, (3.36 \pm 2.69) \times 10^{-3})$

Multiparameter Scenario



Strong positive correlations

Results I (Charged Current Couplings)



Scale	Scenario	Values
$\mu_{\rm EW}$	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}, \frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}\right)$	$((-1.20 \pm 0.80) \times 10^{-2}, (-0.44 \pm 1.04) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}, \frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}\right)$	$((-1.12 \pm 0.80) \times 10^{-2}, (1.73 \pm 4.30) \times 10^{-4})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi q(3)}_{33}, \frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$((-0.99 \pm 1.05) \times 10^{-2}, (1.17 \pm 3.55) \times 10^{-3})$
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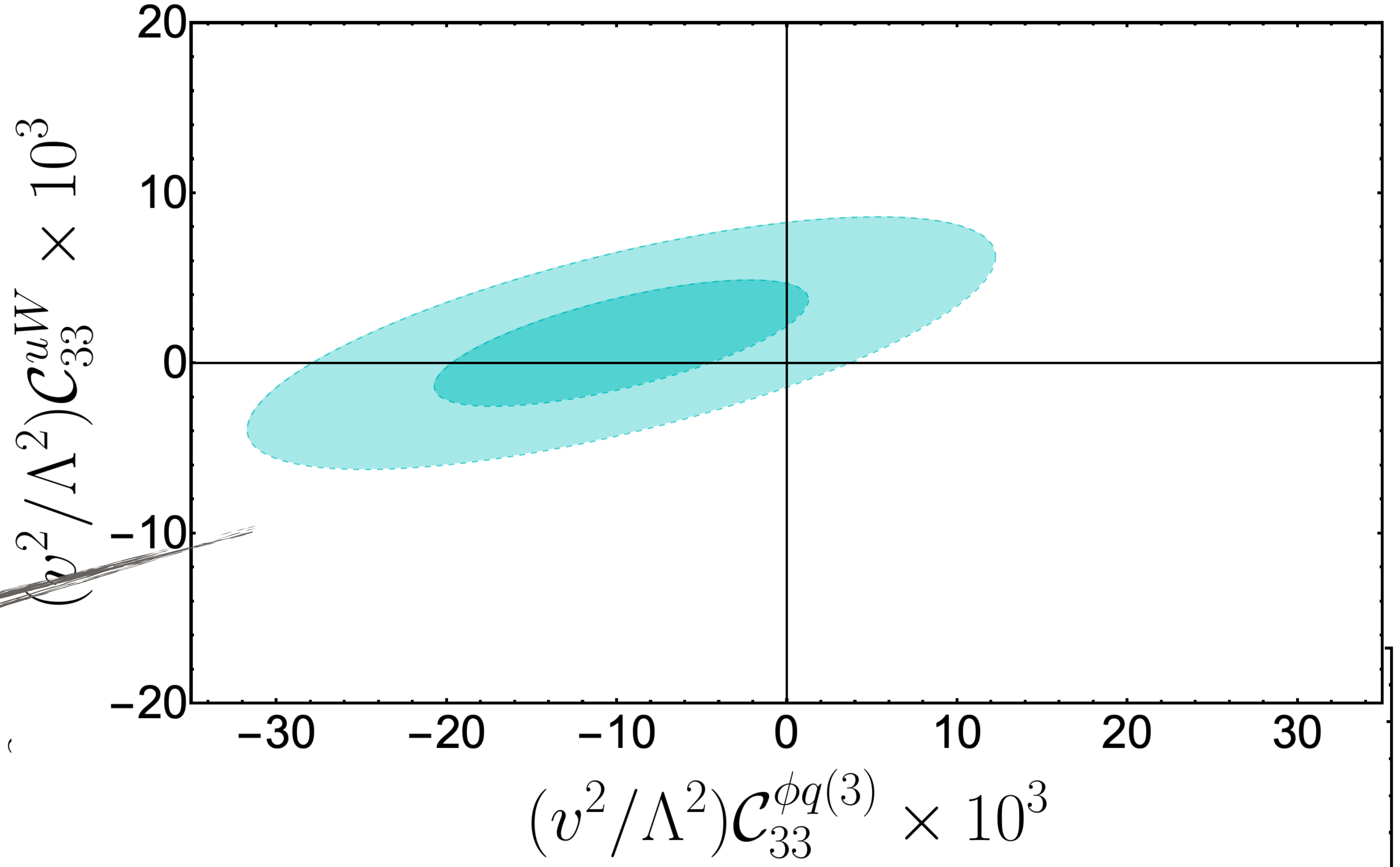
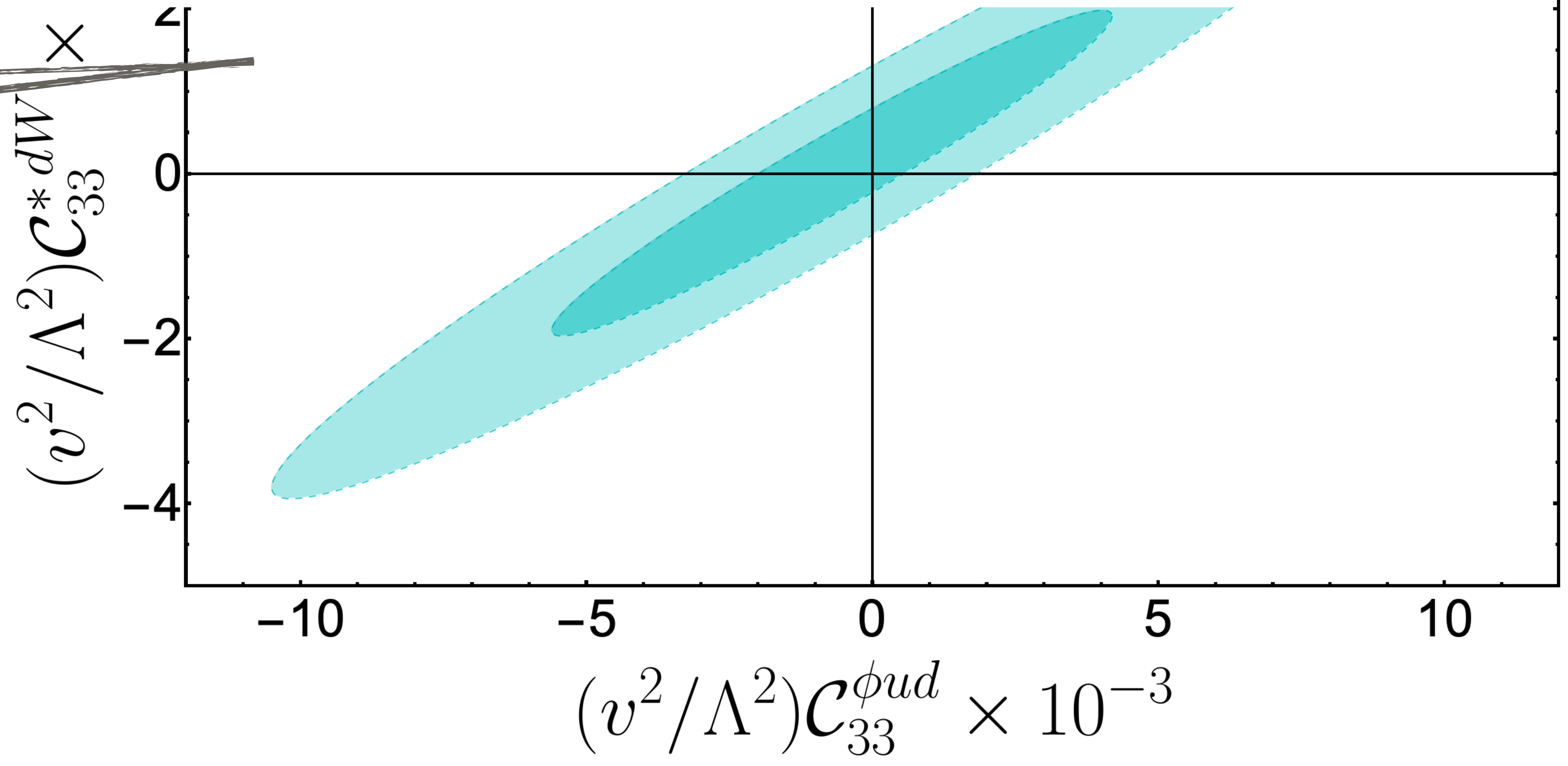
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{\phi ud}_{33}, \frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$((0.5 \pm 1.04) \times 10^{-3}, (3.37 \pm 2.69) \times 10^{-3})$
	$\left(\frac{v^2}{\Lambda^2}\mathcal{C}^{*\,dW}_{33}, \frac{v^2}{\Lambda^2}\mathcal{C}^{uW}_{33}\right)$	$((1.62 \pm 4.31) \times 10^{-4}, (3.36 \pm 2.69) \times 10^{-3})$

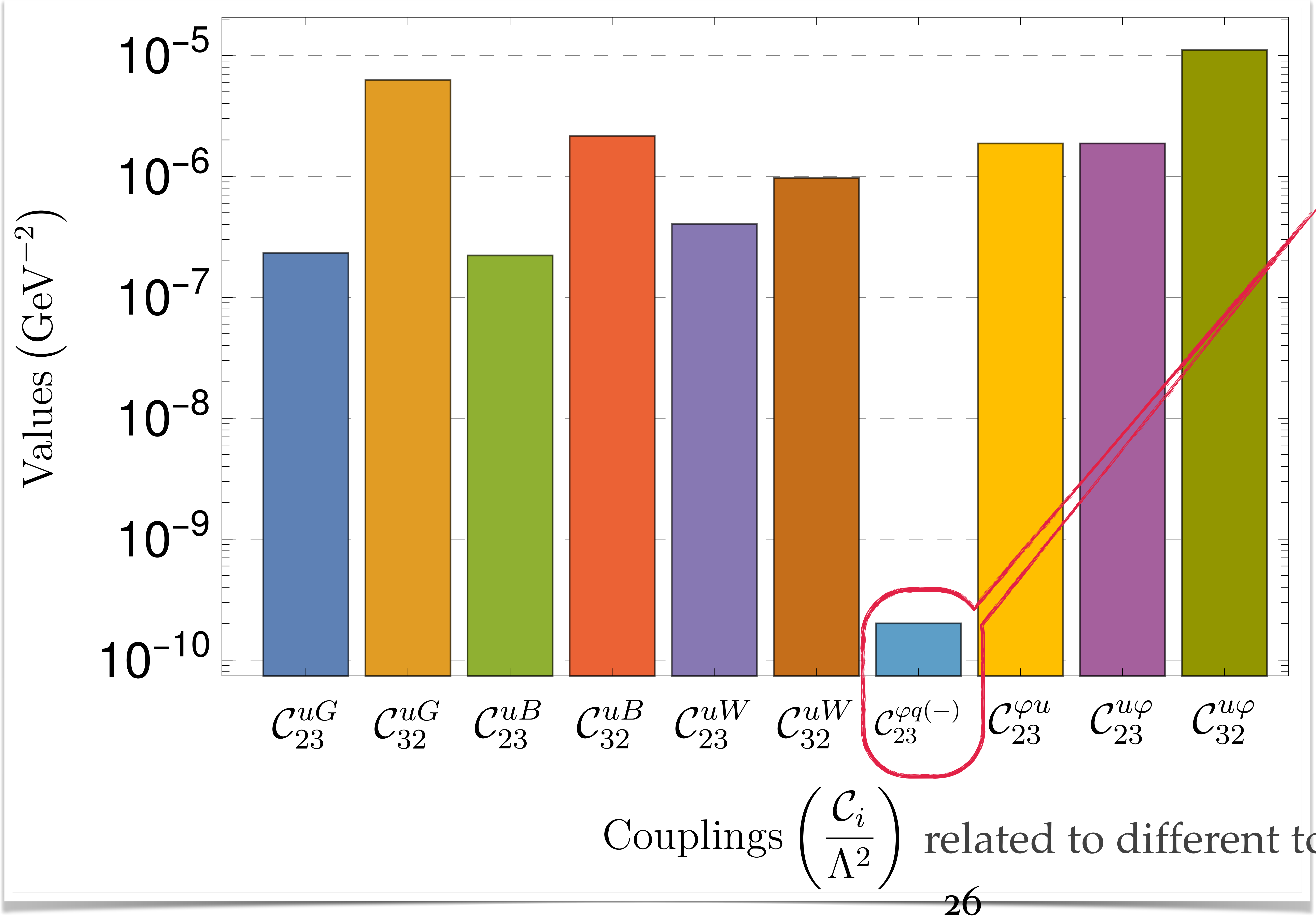




Multiparameter Scenario

Strong positive correlations

Result II (Real Top FCNC Couplings)



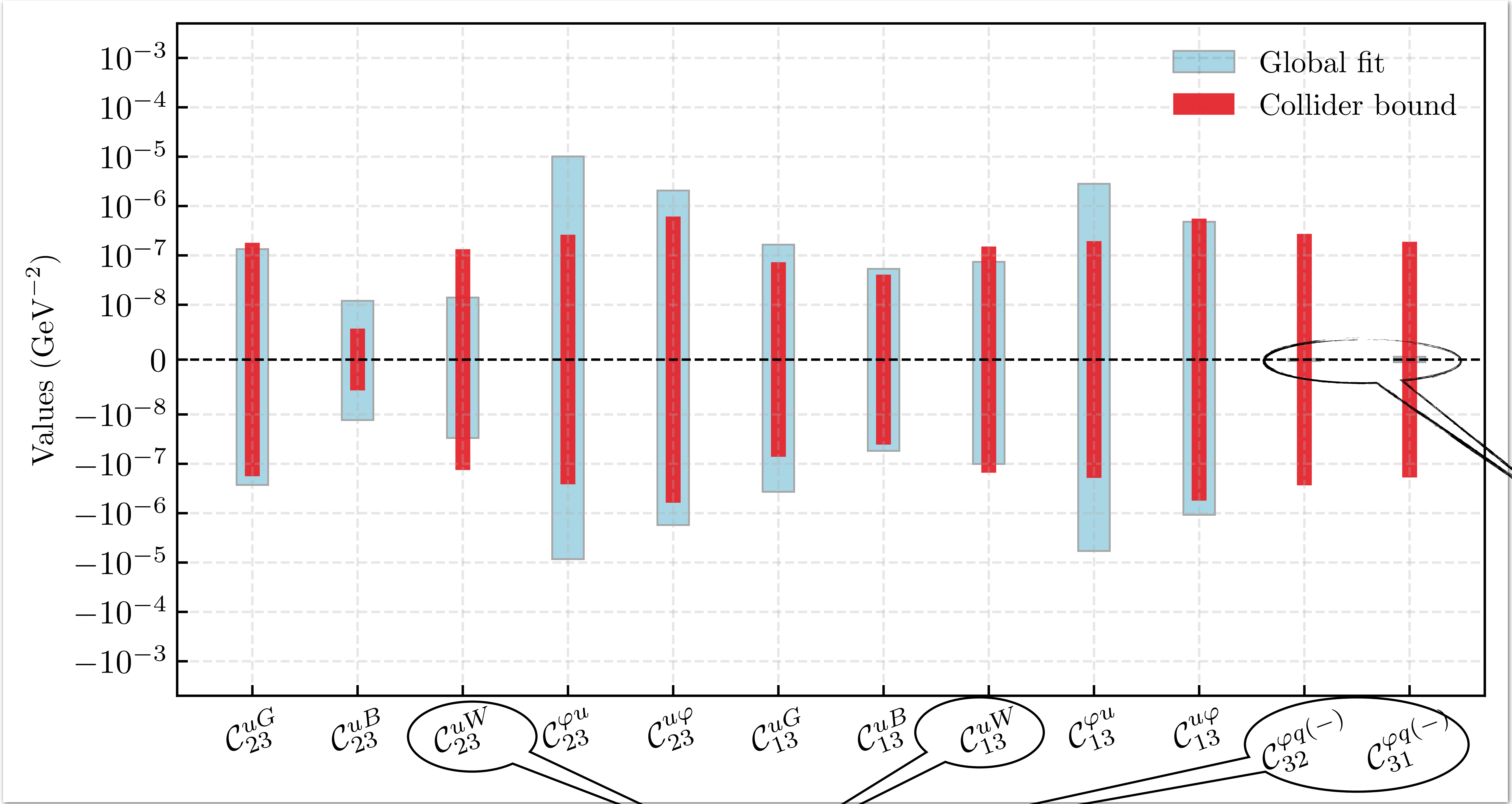
Couplings $\left(\frac{\mathcal{C}_i}{\Lambda^2}\right)$ related to different tcX processes

Key Observation

- The vector-type coupling $\mathscr{C}_{32}^{\varphi q(-)}$ is tightly constrained from the tree-level flavour data (rare FCNC).
- $\mathscr{C}_{32}^{uG}, \mathscr{C}_{32}^{u\varphi}$ are not constrained well by the current experimental data.
- The remaining couplings are well constrained from the experimental data, ranging between $(10^{-6} - 10^{-7})$.
- The order of the couplings is almost the same for $(t \to u\,X)$ processes.

Comparison with Collider bound (Top FCNC couplings)

Indirect bounds are important!!



Experimental Inputs:
ATLAS[2023],
ATLAS[2022],
ATLAS[2024],
ATLAS[2022],
ATLAS[2023],
CMS[2023],
CMS[2017]

Tightly constrained !!

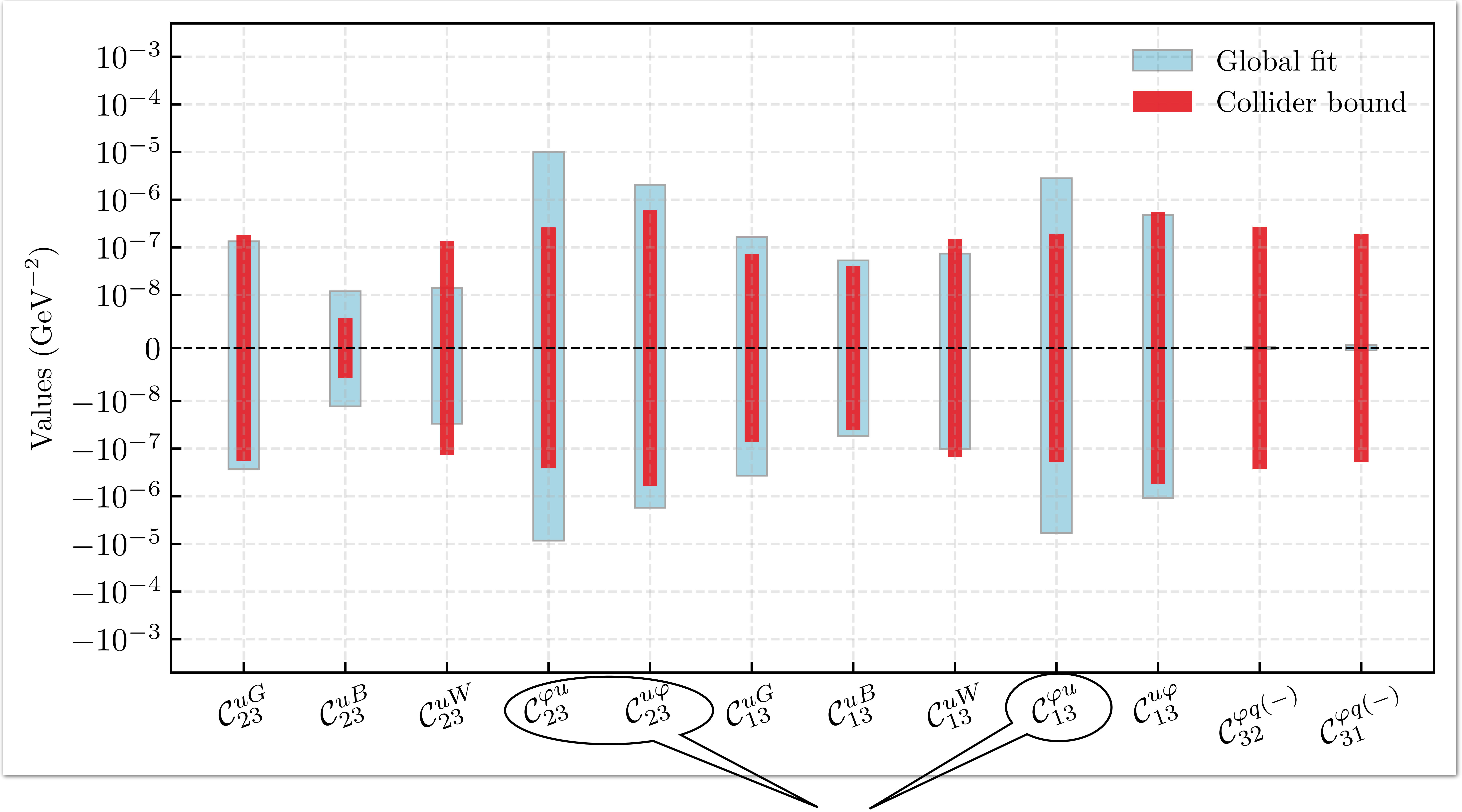
$$\mathcal{C}_{32}^{\phi q\,(-)}(\mu_{\rm EW}) = (-0.58 \pm 2.02) \times 10^{-10},$$

$$\mathcal{C}_{31}^{\phi q\,(-)}(\mu_{\rm EW}) = (0.27 \pm 4.95) \times 10^{-10}.$$

Better than collider bounds

Comparison with Collider bound (Top FCNC couplings)

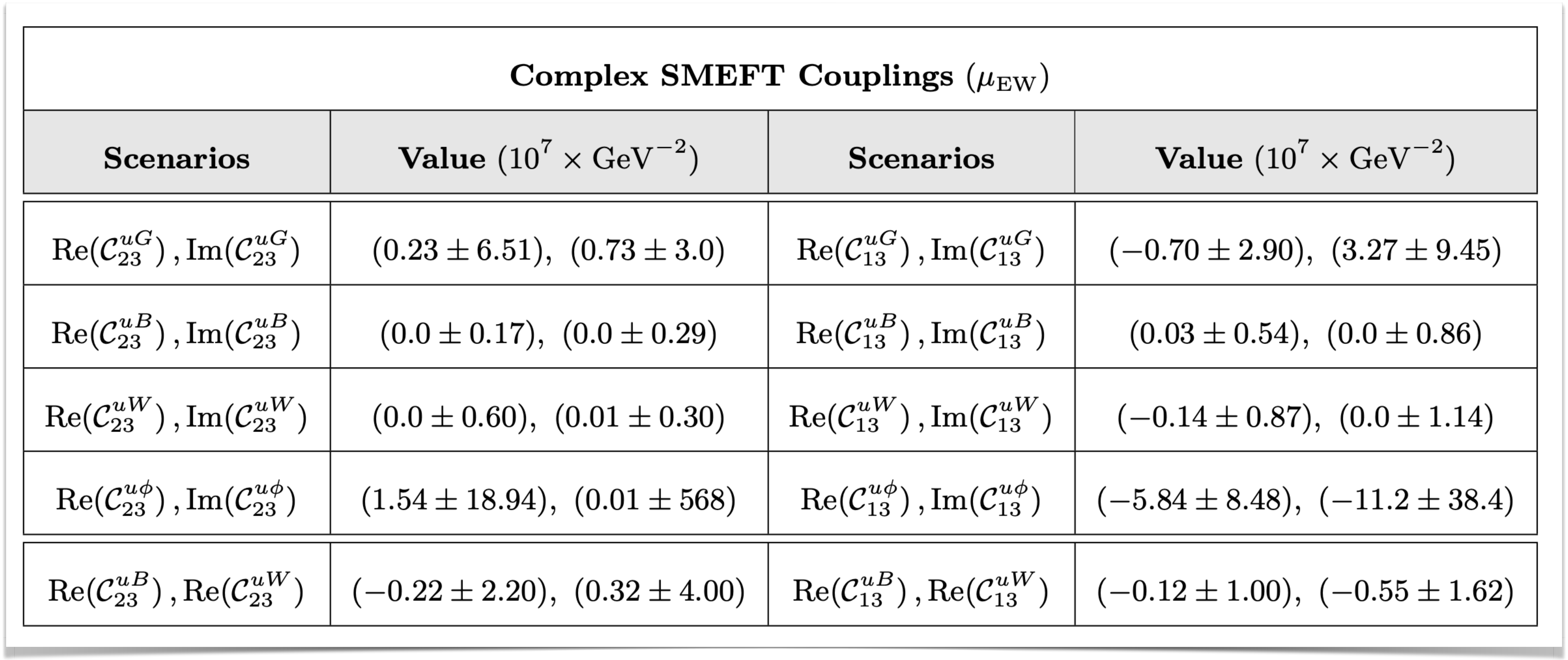
Indirect bounds are important!!



Experimental Inputs:
ATLAS[2023],
ATLAS[2022],
ATLAS[2024],
ATLAS[2022],
ATLAS[2023],
CMS[2023],
CMS[2017]

Top Higgs couplings are loosely constrained from indirect searches!!

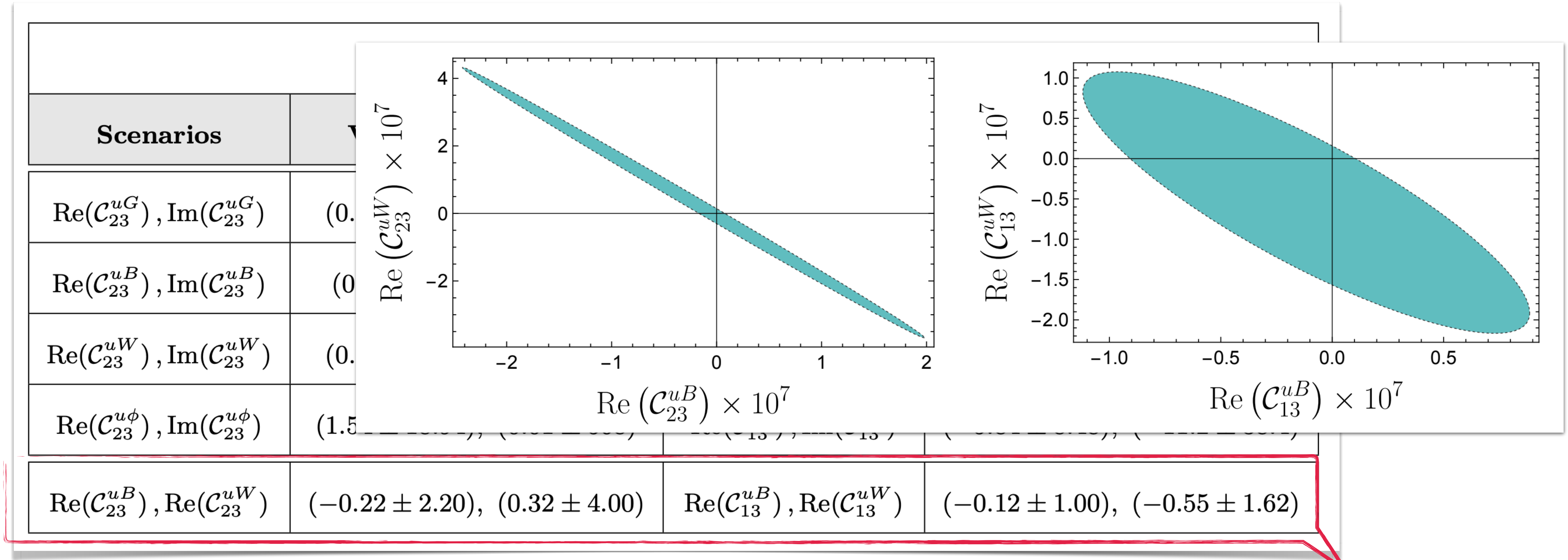
Result II (Complex Top FCNC Couplings)



Complex SMEFT Couplings ($\mu_{\rm EW}$)			
Scenarios	**Value** ($10^7 \times \mathrm{GeV}^{-2}$)	**Scenarios**	**Value** ($10^7 \times \mathrm{GeV}^{-2}$)
$\mathrm{Re}(\mathcal{C}_{23}^{uG})\,,\mathrm{Im}(\mathcal{C}_{23}^{uG})$	$(0.23 \pm 6.51),\ (0.73 \pm 3.0)$	$\mathrm{Re}(\mathcal{C}_{13}^{uG})\,,\mathrm{Im}(\mathcal{C}_{13}^{uG})$	$(-0.70 \pm 2.90),\ (3.27 \pm 9.45)$
$\mathrm{Re}(\mathcal{C}_{23}^{uB})\,,\mathrm{Im}(\mathcal{C}_{23}^{uB})$	$(0.0 \pm 0.17),\ (0.0 \pm 0.29)$	$\mathrm{Re}(\mathcal{C}_{13}^{uB})\,,\mathrm{Im}(\mathcal{C}_{13}^{uB})$	$(0.03 \pm 0.54),\ (0.0 \pm 0.86)$
$\mathrm{Re}(\mathcal{C}_{23}^{uW})\,,\mathrm{Im}(\mathcal{C}_{23}^{uW})$	$(0.0 \pm 0.60),\ (0.01 \pm 0.30)$	$\mathrm{Re}(\mathcal{C}_{13}^{uW})\,,\mathrm{Im}(\mathcal{C}_{13}^{uW})$	$(-0.14 \pm 0.87),\ (0.0 \pm 1.14)$
$\mathrm{Re}(\mathcal{C}_{23}^{u\phi})\,,\mathrm{Im}(\mathcal{C}_{23}^{u\phi})$	$(1.54 \pm 18.94),\ (0.01 \pm 568)$	$\mathrm{Re}(\mathcal{C}_{13}^{u\phi})\,,\mathrm{Im}(\mathcal{C}_{13}^{u\phi})$	$(-5.84 \pm 8.48),\ (-11.2 \pm 38.4)$
$\mathrm{Re}(\mathcal{C}_{23}^{uB})\,,\mathrm{Re}(\mathcal{C}_{23}^{uW})$	$(-0.22 \pm 2.20),\ (0.32 \pm 4.00)$	$\mathrm{Re}(\mathcal{C}_{13}^{uB})\,,\mathrm{Re}(\mathcal{C}_{13}^{uW})$	$(-0.12 \pm 1.00),\ (-0.55 \pm 1.62)$

- The bounds on the imaginary parts of the couplings are more relaxed than those of the real parts.
- The complex phase provides a crucial probe for studying the CP-violating nature of the top quark.

Result II (Complex Top FCNC Couplings)



Scenarios	V		
$\mathrm{Re}(\mathcal{C}^{uG}_{23})\,,\mathrm{Im}(\mathcal{C}^{uG}_{23})$	(0.		
$\mathrm{Re}(\mathcal{C}^{uB}_{23})\,,\mathrm{Im}(\mathcal{C}^{uB}_{23})$	(0		
$\mathrm{Re}(\mathcal{C}^{uW}_{23})\,,\mathrm{Im}(\mathcal{C}^{uW}_{23})$	(0.		
$\mathrm{Re}(\mathcal{C}^{u\phi}_{23})\,,\mathrm{Im}(\mathcal{C}^{u\phi}_{23})$	(1.5		
$\mathrm{Re}(\mathcal{C}^{uB}_{23})\,,\mathrm{Re}(\mathcal{C}^{uW}_{23})$	$(-0.22 \pm 2.20),\ (0.32 \pm 4.00)$	$\mathrm{Re}(\mathcal{C}^{uB}_{13})\,,\mathrm{Re}(\mathcal{C}^{uW}_{13})$	$(-0.12 \pm 1.00),\ (-0.55 \pm 1.62)$

More multi-parameter scenario: **arXiv 2602.10201**

Multi-parameter scenario

Both $\mathscr{C}_{uB}$ & $\mathscr{C}_{uW}$ couplings contribute to the $t \to q\gamma(Z)$ interactions, making them strongly correlated.

$$(\lambda_L)_{pr} = \sqrt{2}v\frac{m_t}{e}\left(s_W\left(\mathcal{C}^{uW}_{rp}\right)^* + c_W\left(\mathcal{C}^{uB}_{rp}\right)^*\right), \quad (\lambda_R)_{pr} = \sqrt{2}v\frac{m_t}{e}\left(s_W\mathcal{C}^{uW}_{pr} + c_W\mathcal{C}^{uB}_{pr}\right),$$

$$(\kappa_L)_{pr} = \sqrt{2}v\frac{c_W m_t}{g_W}\left(c_W\left(\mathcal{C}^{uW}_{rp}\right)^* - s_W\left(\mathcal{C}^{uB}_{rp}\right)^*\right), \quad (\kappa_R)_{pr} = \sqrt{2}v\frac{c_W m_t}{g_W}\left(c_W\mathcal{C}^{uW}_{pr} - s_W\mathcal{C}^{uB}_{pr}\right);$$

Imprint of CP violation on WCs

$$\mathscr{L}_{\rm eff} \supset + d_q(\mu)\frac{i}{2}\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} + \tilde{d}_q(\mu)\frac{i}{2}g_s(\mu)\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu}$$

d_q EDM
$\tilde{d}_q$ chromo EDM

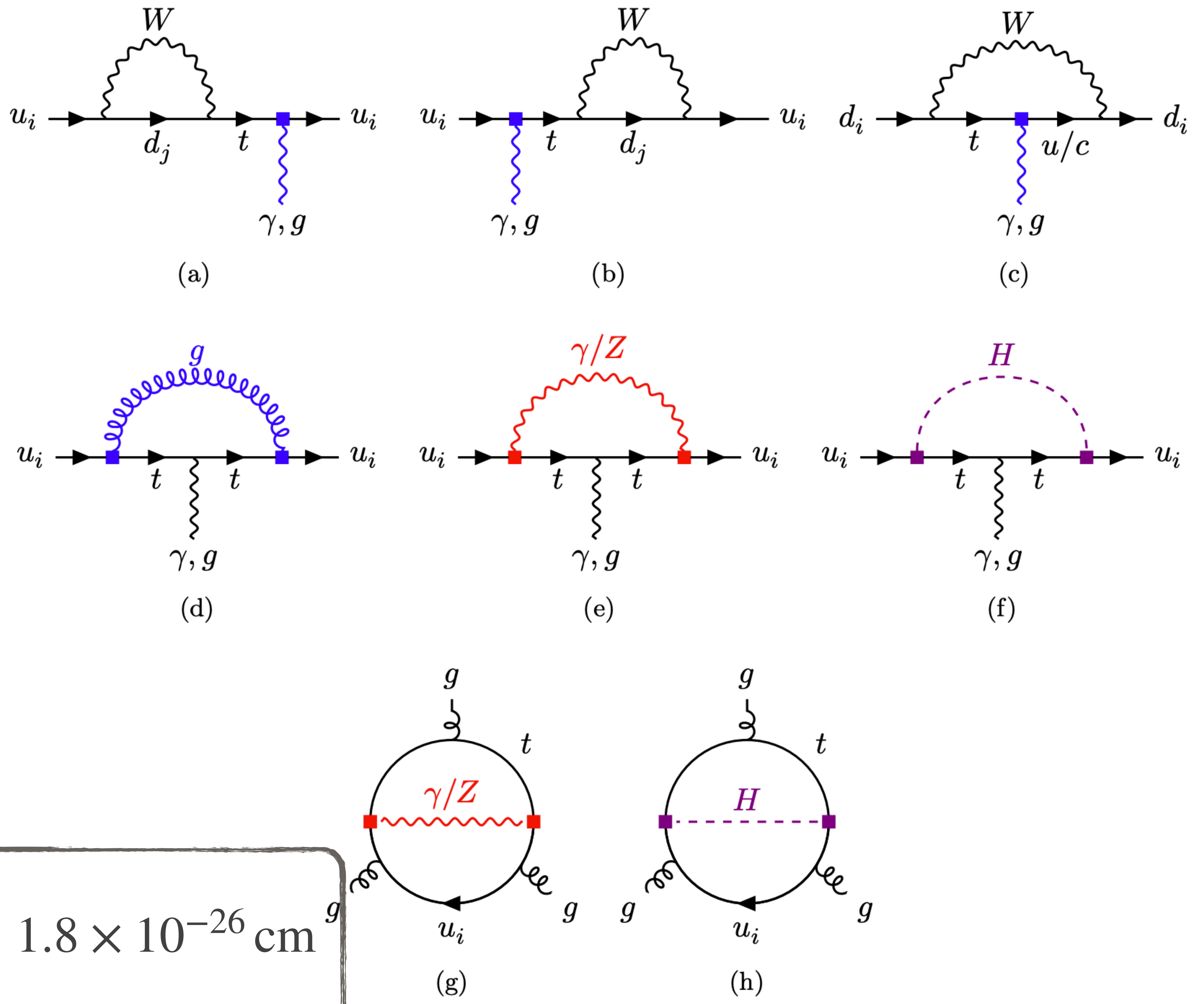
A non-zero EDM of a fundamental particle violates both parity and time reversal symmetry.

SM prediction is tiny, $d_q^{\rm SM} \approx 10^{-31} e\,.\,\mathrm{cm}$, (very much loop suppressed)

Light quark EDMs can be probed via nucleon EDMs (d_n, d_p).

$$\frac{d_n}{e} = -\,1.97\times 10^{-14}\left(g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s\right) -2.15\times 10^{-14}(1\pm 0.5)\left\{\left(\tilde{d}_d + 0.5\,\tilde{d}_u\right)\right\}\ \mathrm{cm}$$

$$\left|\frac{d_n}{e}\right| < 1.8\times 10^{-26}\,\mathrm{cm}$$



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Result III (EDM Constraints)

$$\left|\frac{d_n}{e}\right| < 1.8 \times 10^{-26}\,\mathrm{cm}$$

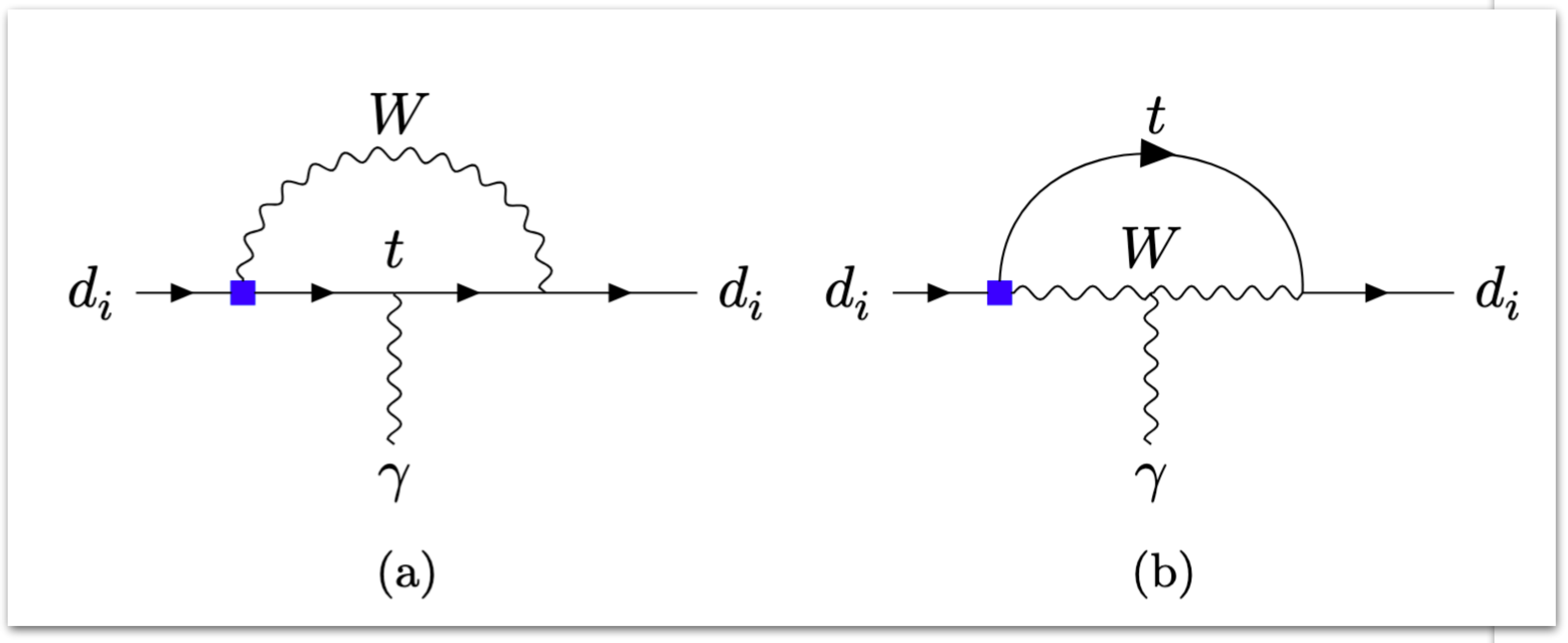
Top FCNC SMEFT Couplings

$$\left|\mathrm{Im}\left(\mathcal{C}^{uG}_{31}\mathcal{C}^{uG}_{13}\right)\right| < 0.91 \times 10^{-17}$$
$$\left|\mathrm{Im}\left(\mathcal{C}^{uG}_{32}\mathcal{C}^{uG}_{23}\right)\right| < 3.68 \times 10^{-14}$$

$$\left|\mathrm{Im}\left(\mathcal{C}^{uW}_{31}\mathcal{C}^{uW}_{13} + \mathcal{C}^{uB}_{31}\mathcal{C}^{uB}_{13}\right)\right| < 1.15 \times 10^{-17}$$

$$\left|\mathrm{Im}\left(\mathcal{C}^{uW}_{32}\mathcal{C}^{uW}_{23} + \mathcal{C}^{uB}_{32}\mathcal{C}^{uB}_{23}\right)\right| < 1.26 \times 10^{-14}$$

$$\left|\mathrm{Im}\left(\mathcal{C}^{u\phi}_{31}\mathcal{C}^{u\phi}_{13}\right)\right| < 1.95 \times 10^{-17}$$
$$\left|\mathrm{Im}\left(\mathcal{C}^{u\phi}_{32}\mathcal{C}^{u\phi}_{23}\right)\right| < 2.14 \times 10^{-14}$$

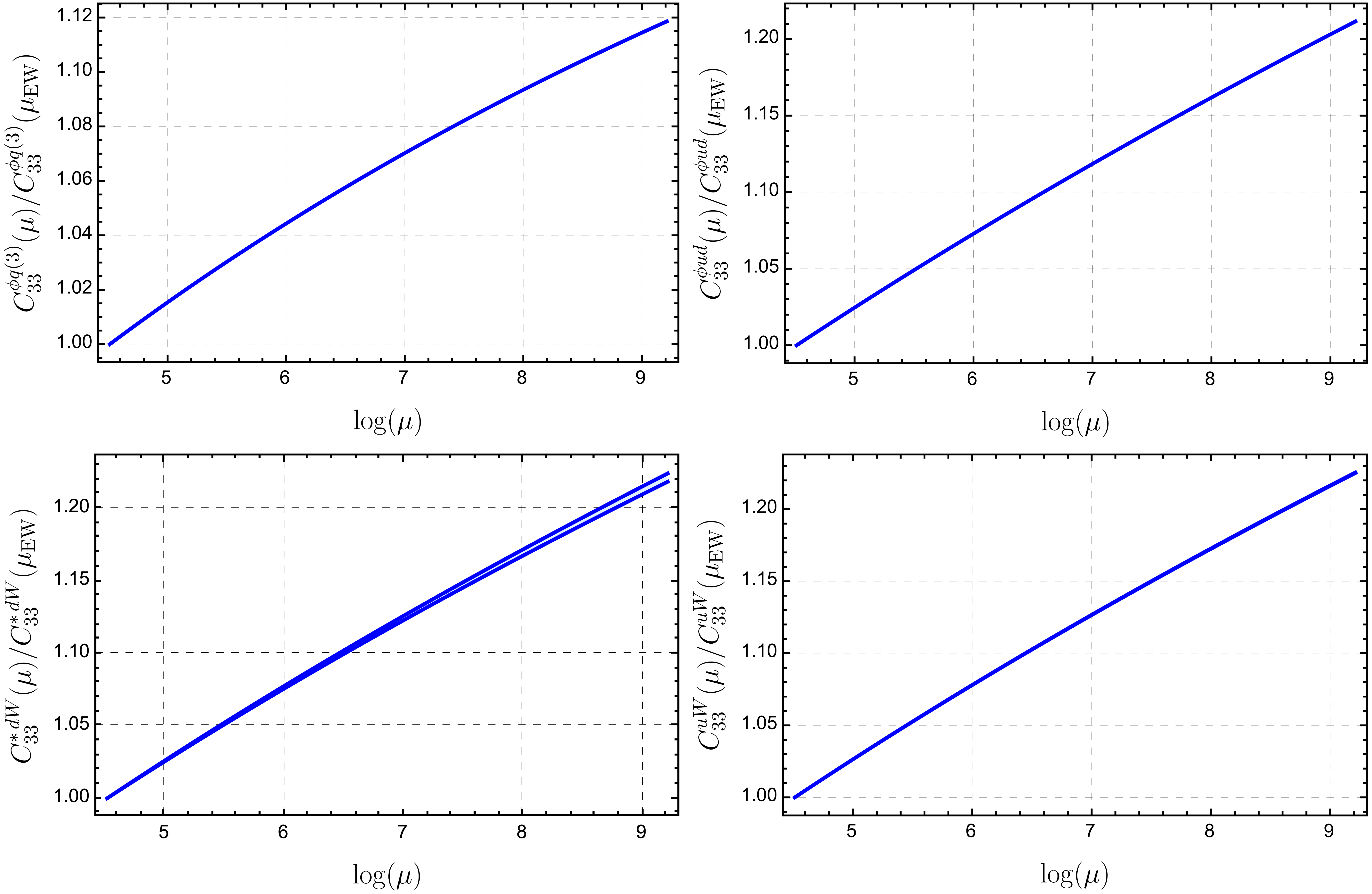


Wtd_j charged current SMEFT Couplings

$$\left|\mathrm{Im}\left(\mathcal{C}^{dW}_{31}\right)\right| < 2.95 \times 10^{-11}$$
$$\left|\mathrm{Im}\left(\mathcal{C}^{dW}_{32}\right)\right| < 4.62 \times 10^{-10}$$
$$\left|\mathrm{Im}\left(\mathcal{C}^{\phi ud}_{31}\right)\right| < 7.86 \times 10^{-10}$$
$$\left|\mathrm{Im}\left(\mathcal{C}^{\phi ud}_{32}\right)\right| < 1.23 \times 10^{-8}$$

- Tightly constrained imaginary part of the couplings !!

Impact of RGE



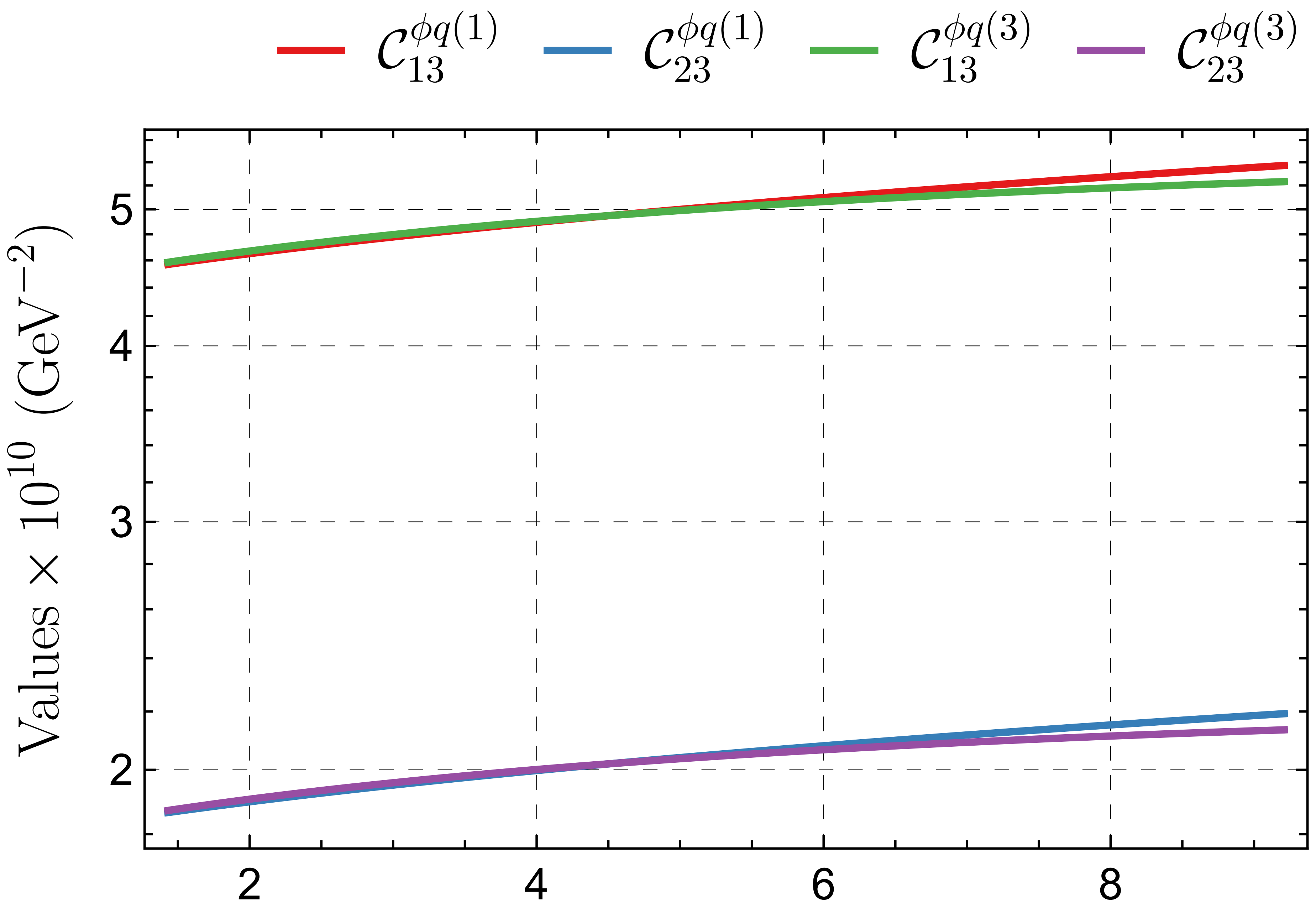
Variation of couplings with the scale

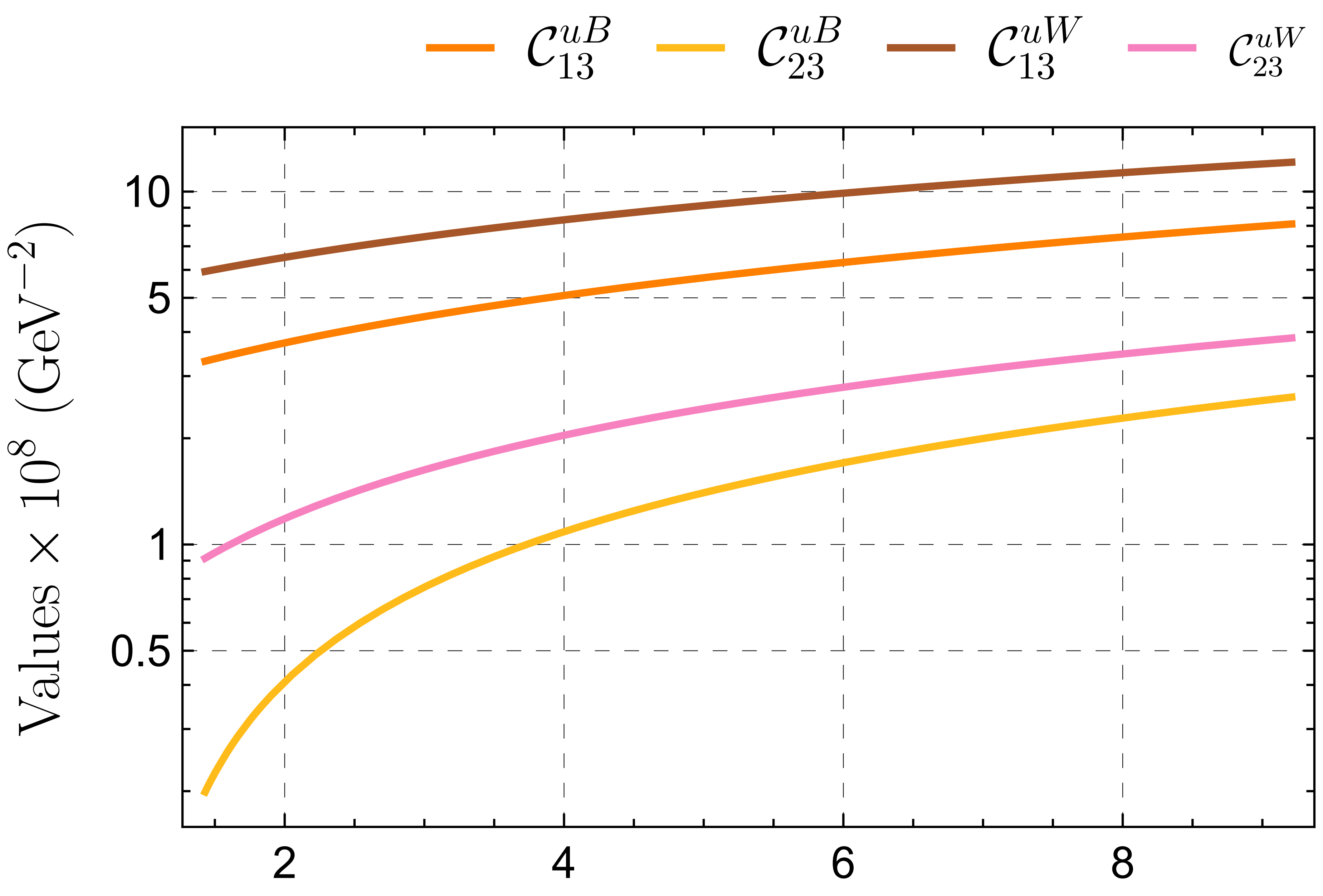
$(\mu_{\rm EW} \to \mu_{\Lambda=10{\rm TeV}})$

$\mathscr{C}_{33}^{\phi q(3)} \approx 12\,\%$

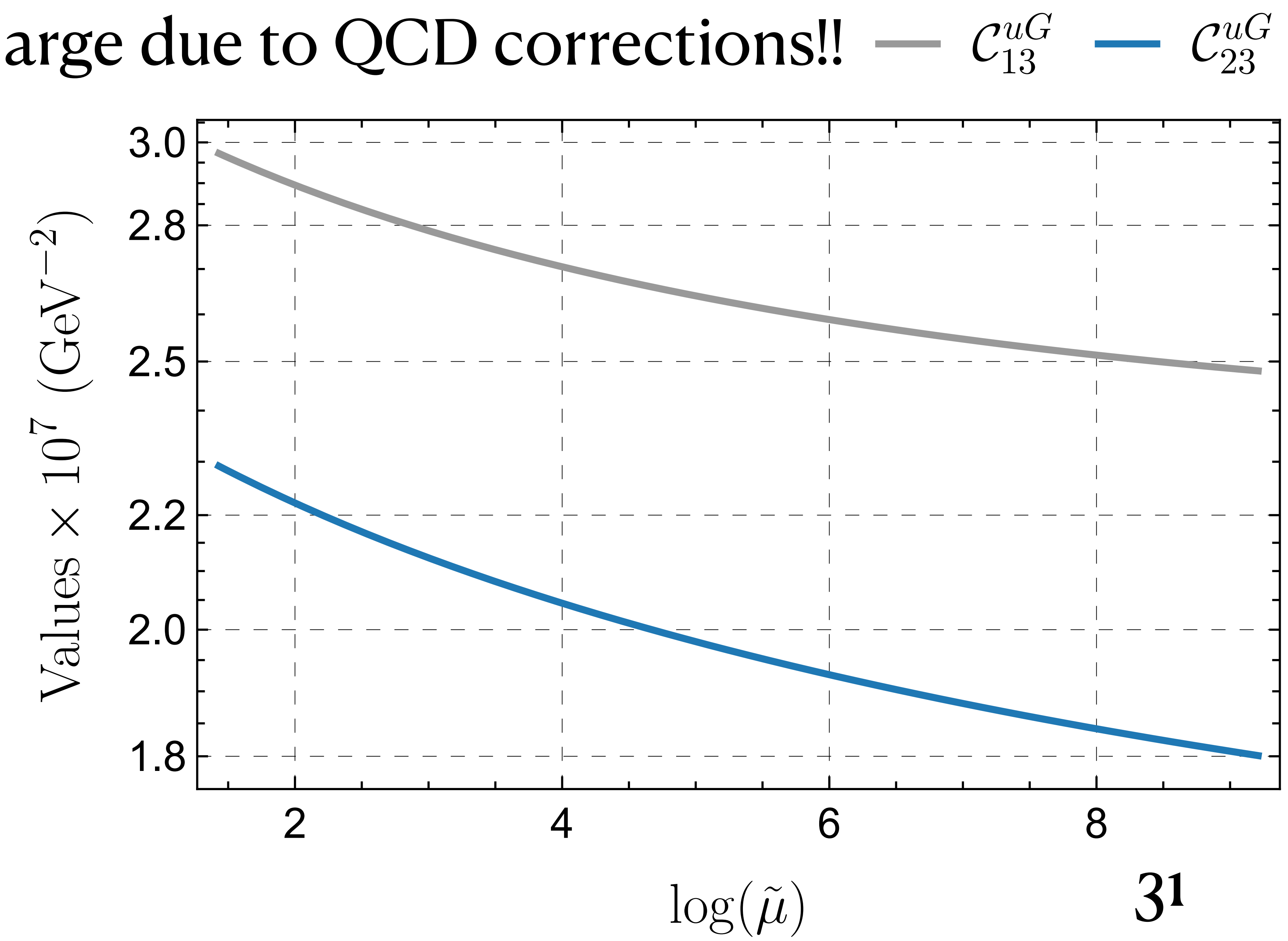
For other couplings

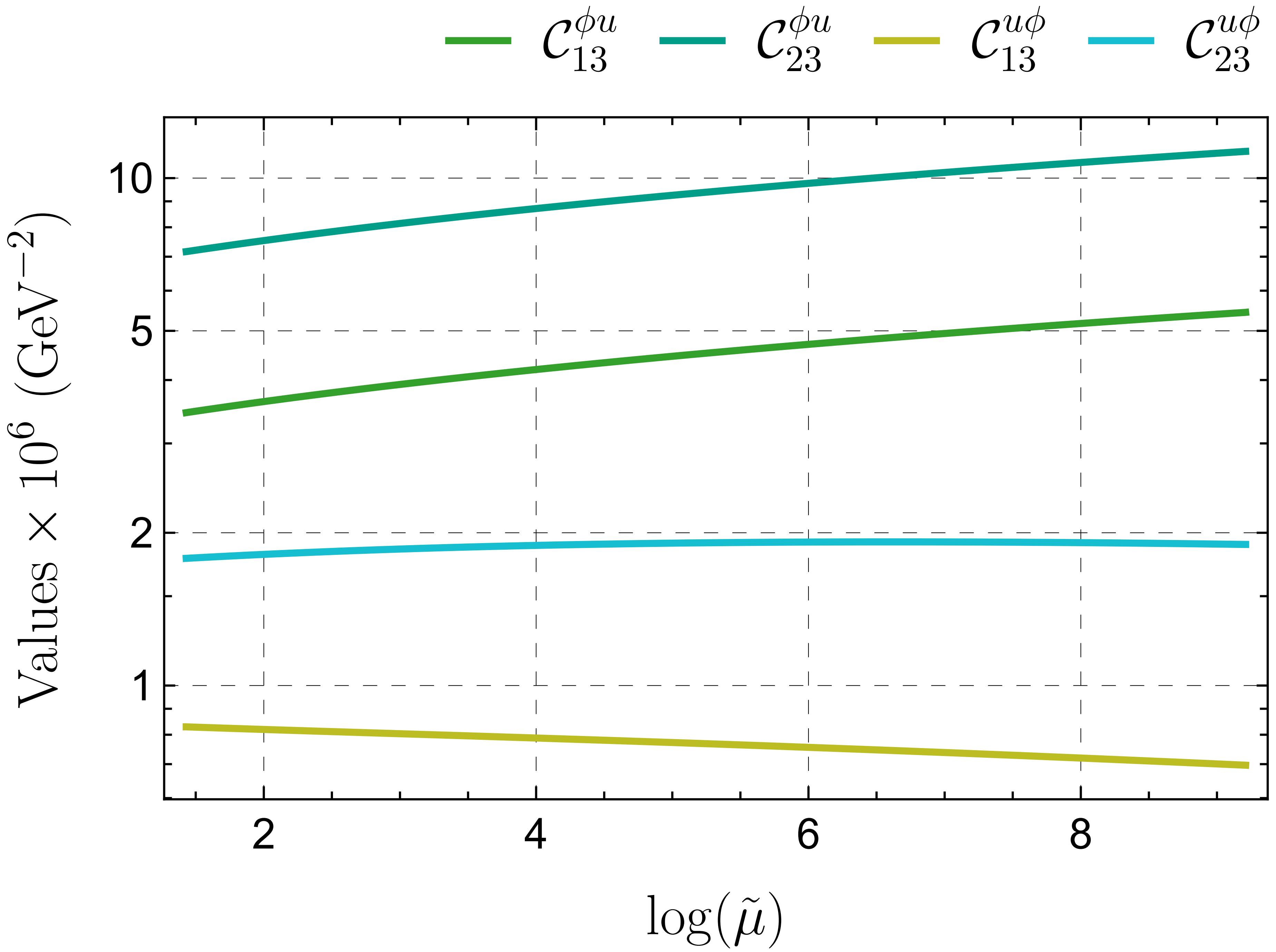
$\approx (20-25)\,\%$





Impact is quite large due to QCD corrections!!

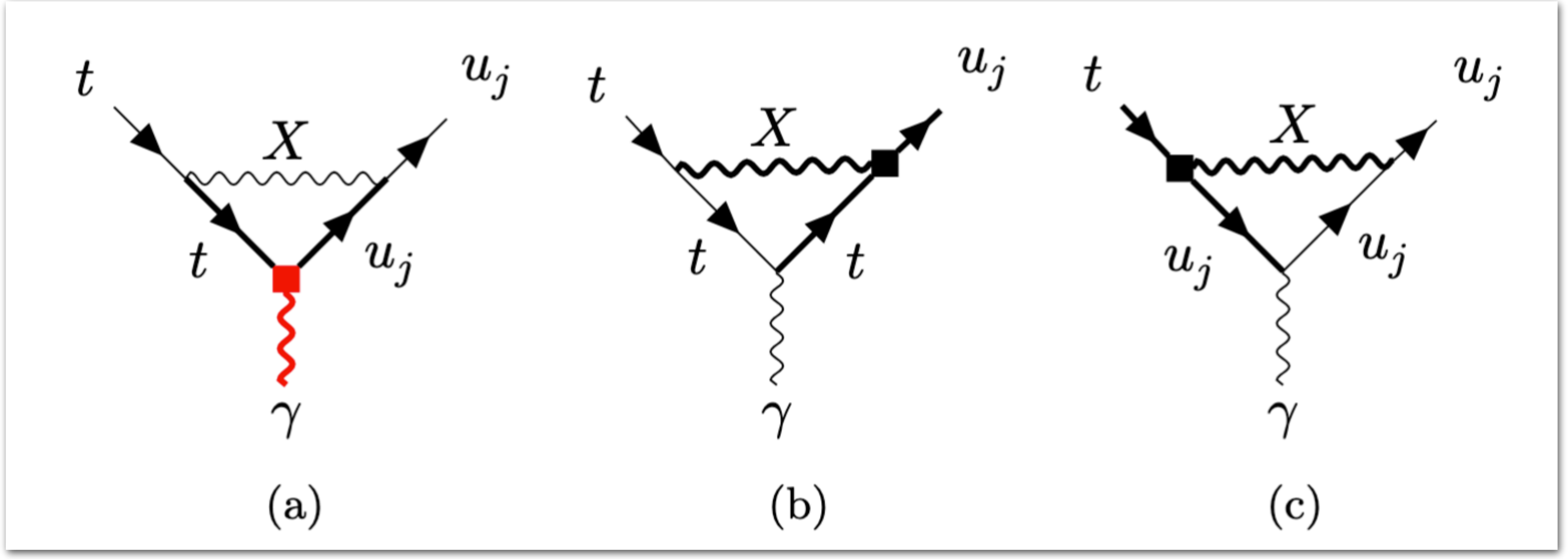




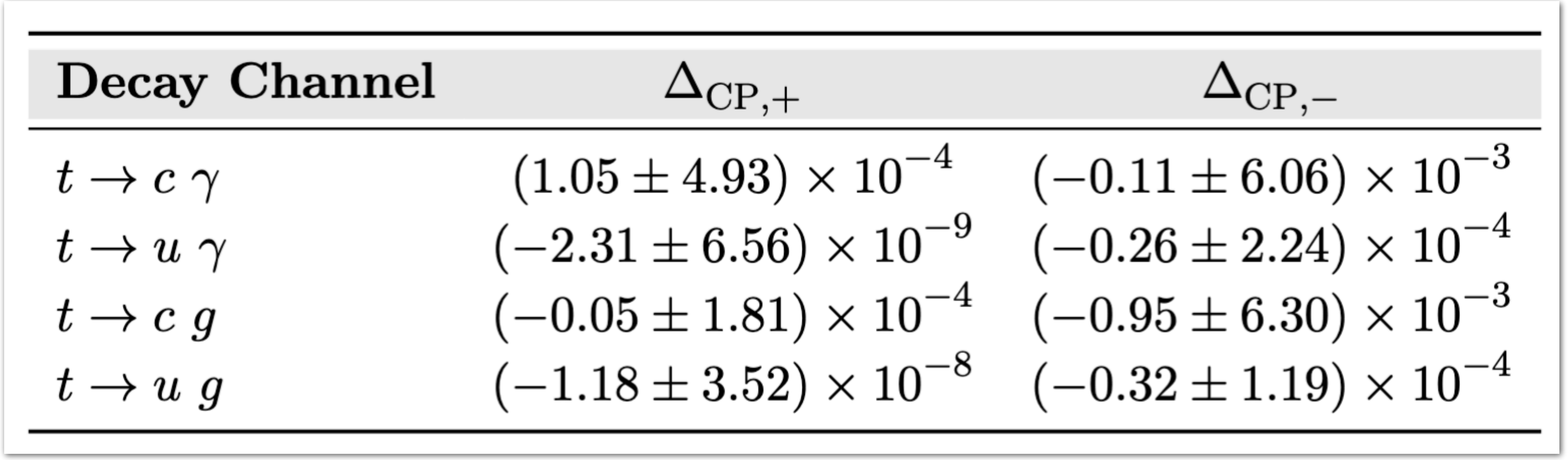
Prediction for CP Asymmetry

Origin of CP Violation in Top FCNCs:

- A non-vanishing asymmetry Δ_{CP} requires the interference of at least two amplitudes with different Weak phases and different strong phases.
- **Weak Phase:** Provided by the complex SMEFT Wilson Coefficients (C_i)
- **Strong Phase:** Generated by the absorptive parts of the one-loop diagrams, where intermediate states go on-shell ($t \rightarrow u_j \gamma(g)$ loops) .



(a) (b) (c)



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

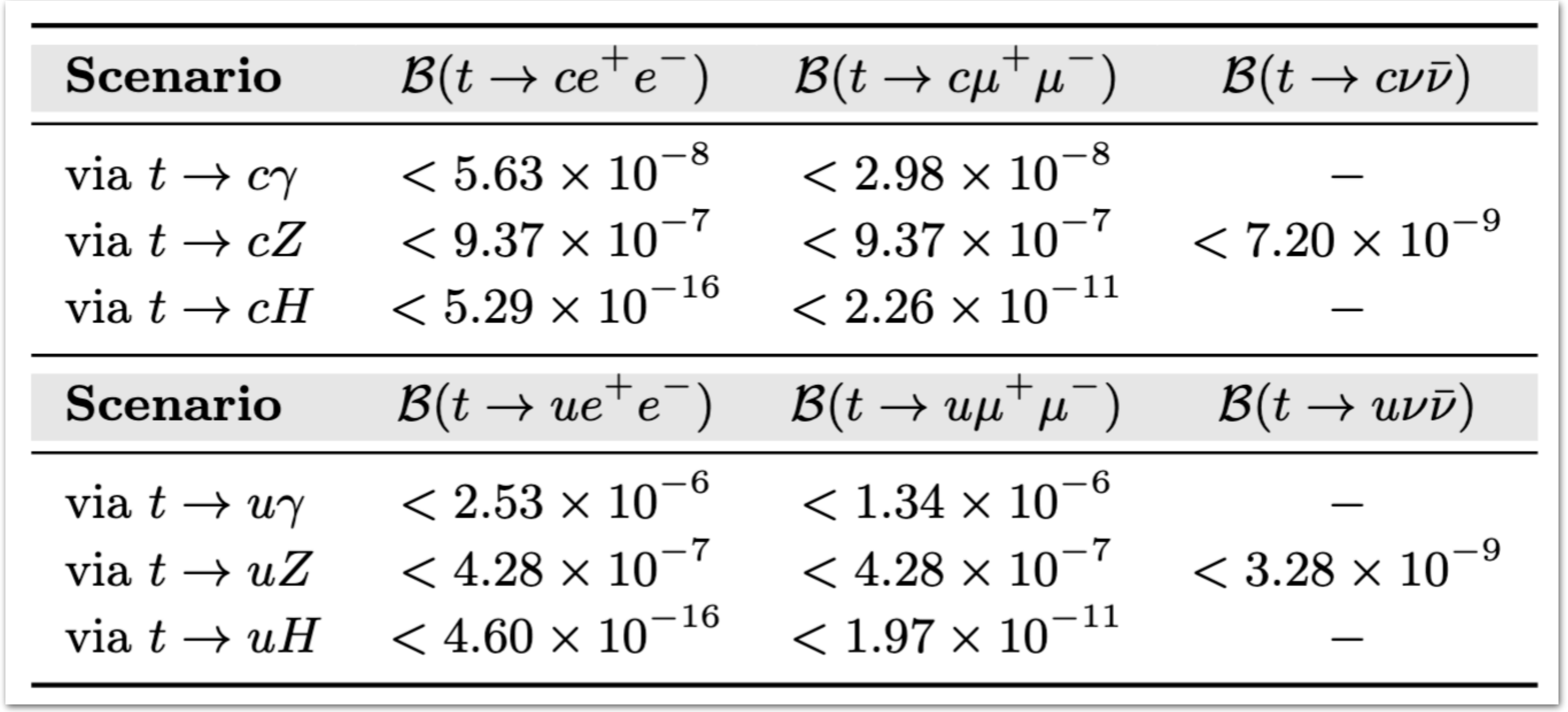
The strict hierarchy $\Delta_{\text{CP},+} < \Delta_{\text{CP},-}$ is a direct consequence of angular mom conservation and $(V-A)$ structure of the weak interaction, demonstrating that photons and gluons emitted in the top FCNC radiative decays are **left-handed**.

Prediction for Three-Body Top FCNC decays

Connecting Two-Body Bounds to Three-Body Signatures:

- Instead of relying on four-fermion contact interactions, we model the three-body decays ($t \to q_i \ell^+ \ell^-$ and $t \to q_i \nu \bar{\nu}$) as cascade processes mediated by SM gauge bosons (Z, H, γ)

Our Predictions

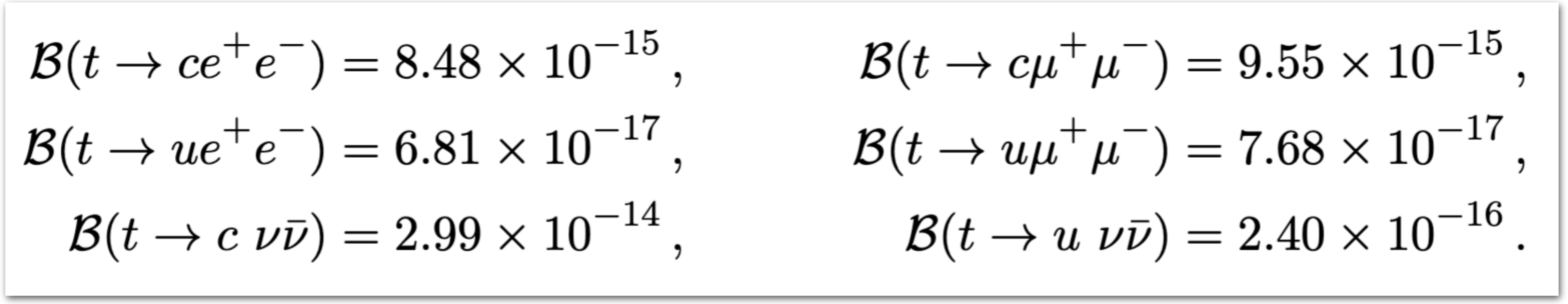


Scenario	$\mathcal{B}(t \to c e^+ e^-)$	$\mathcal{B}(t \to c \mu^+ \mu^-)$	$\mathcal{B}(t \to c \nu \bar{\nu})$
via $t \to c\gamma$	$< 5.63 \times 10^{-8}$	$< 2.98 \times 10^{-8}$	–
via $t \to cZ$	$< 9.37 \times 10^{-7}$	$< 9.37 \times 10^{-7}$	$< 7.20 \times 10^{-9}$
via $t \to cH$	$< 5.29 \times 10^{-16}$	$< 2.26 \times 10^{-11}$	–
Scenario	$\mathcal{B}(t \to u e^+ e^-)$	$\mathcal{B}(t \to u \mu^+ \mu^-)$	$\mathcal{B}(t \to u \nu \bar{\nu})$
via $t \to u\gamma$	$< 2.53 \times 10^{-6}$	$< 1.34 \times 10^{-6}$	–
via $t \to uZ$	$< 4.28 \times 10^{-7}$	$< 4.28 \times 10^{-7}$	$< 3.28 \times 10^{-9}$
via $t \to uH$	$< 4.60 \times 10^{-16}$	$< 1.97 \times 10^{-11}$	–

All the bounds are given at 95% CL

SM Predictions

[JHEP 11(2025) 071, PRD 74 (2006) 073014]



$$\mathcal{B}(t \to c e^+ e^-) = 8.48 \times 10^{-15}\,, \qquad \mathcal{B}(t \to c \mu^+ \mu^-) = 9.55 \times 10^{-15}\,,$$

$$\mathcal{B}(t \to u e^+ e^-) = 6.81 \times 10^{-17}\,, \qquad \mathcal{B}(t \to u \mu^+ \mu^-) = 7.68 \times 10^{-17}\,,$$

$$\mathcal{B}(t \to c\ \nu \bar{\nu}) = 2.99 \times 10^{-14}\,, \qquad \mathcal{B}(t \to u\ \nu \bar{\nu}) = 2.40 \times 10^{-16}\,.$$

Summary and Outlook

1. A unified SMEFT Framework: bridging high P_T top physics with low-energy precision observables via rigorous matching and scale evolution (RGE).

2. **Key Findings:** Low-energy data restricts anomalous *Wtb* couplings up to two orders of magnitude stringently constrained than direct collider bounds. Top photon couplings are tightly constrained from Low-energy observables, and other FCNC couplings are at ballpark of collider limit.

   EDM limits exceptionally tight constraints on the imaginary parts of complex SMEFT WCs.

Future Prospects

Limitations

1. The SMEFT/LEFT framework captures NP effects only as **contact interactions among SM fields** and is valid **below some cut-off or renormalisation scale**.

2. They can not directly tell us the **particle content of NP** or its cosmological implications (e.g. **Dark Matter**).

Complete Basis

Operator Renormalisation (Anomalous dim Matrix)

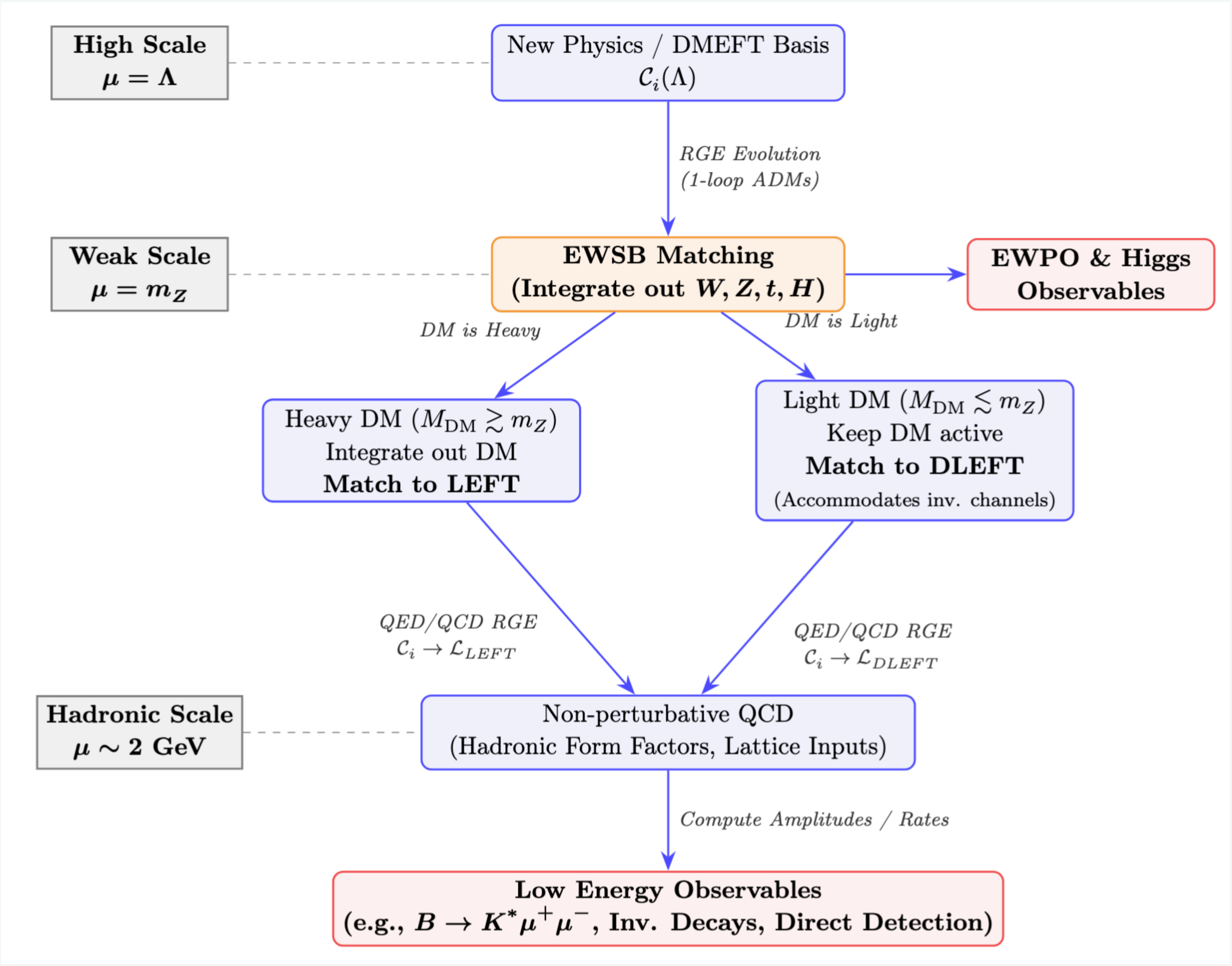
Matching with LEFT basis

BSM Phenomenology & (Flavour+EW precision inputs)

SM + DM
DM: **spin 0(φ), spin 1/2 (χ), Spin 1(X_μ)**
Aebischer, Altmanshofer, Manohar
(JHEP06(2022)086)

Thank You!!

BACK UP



High Scale
$\mu = \Lambda$

New Physics / DMEFT Basis
$\mathcal{C}_i(\Lambda)$

RGE Evolution
(1-loop ADMs)

Weak Scale
$\mu = m_Z$

EWSB Matching
(Integrate out W, Z, t, H)

EWPO & Higgs
Observables

DM is Heavy

DM is Light

Heavy DM ($M_{\mathrm{DM}} \gtrsim m_Z$)
Integrate out DM
Match to LEFT

Light DM ($M_{\mathrm{DM}} \lesssim m_Z$)
Keep DM active
Match to DLEFT
(Accommodates inv. channels)

QED/QCD RGE
$\mathcal{C}_i \to \mathcal{L}_{LEFT}$

QED/QCD RGE
$\mathcal{C}_i \to \mathcal{L}_{DLEFT}$

Hadronic Scale
$\mu \sim 2$ **GeV**

Non-perturbative QCD
(Hadronic Form Factors, Lattice Inputs)

Compute Amplitudes / Rates

Low Energy Observables
(e.g., $B \to K^* \mu^+ \mu^-$, Inv. Decays, Direct Detection)

DMEFT basis can directly accommodate Invisible Channels (**light DM particles**)

$B \to K^{(*)}$ + invisible, $K \to \pi$ + invisible ,
$\tau \to \mu$ + invisible, $\mu \to e$ + invisible ,
$H \to$ invisible, $Z \to$ invisible,
etc..

Other low-energy flavour processes are **loop-induced**

Rare FCNC decays, Meson Mixings and decays, Electron EDM, neutron EDM, LFV decays,
Electroweak Precision Observables, etc…

Neutral Meson Mixings

$B_s^0 - \bar{B}_s^0, B^0 - \bar{B}^0$ Meson mixing process

$$\mathscr{L}^{\bar{b}d_j \leftrightarrow \bar{d}_j b} = C_{V_L}(\bar{d}_j \gamma_\mu P_L b)(\bar{d}_j \gamma_\mu P_L b) + C_{V_R}(\bar{d}_j \gamma_\mu P_R b)(\bar{d}_j \gamma_\mu P_R b)\,.$$

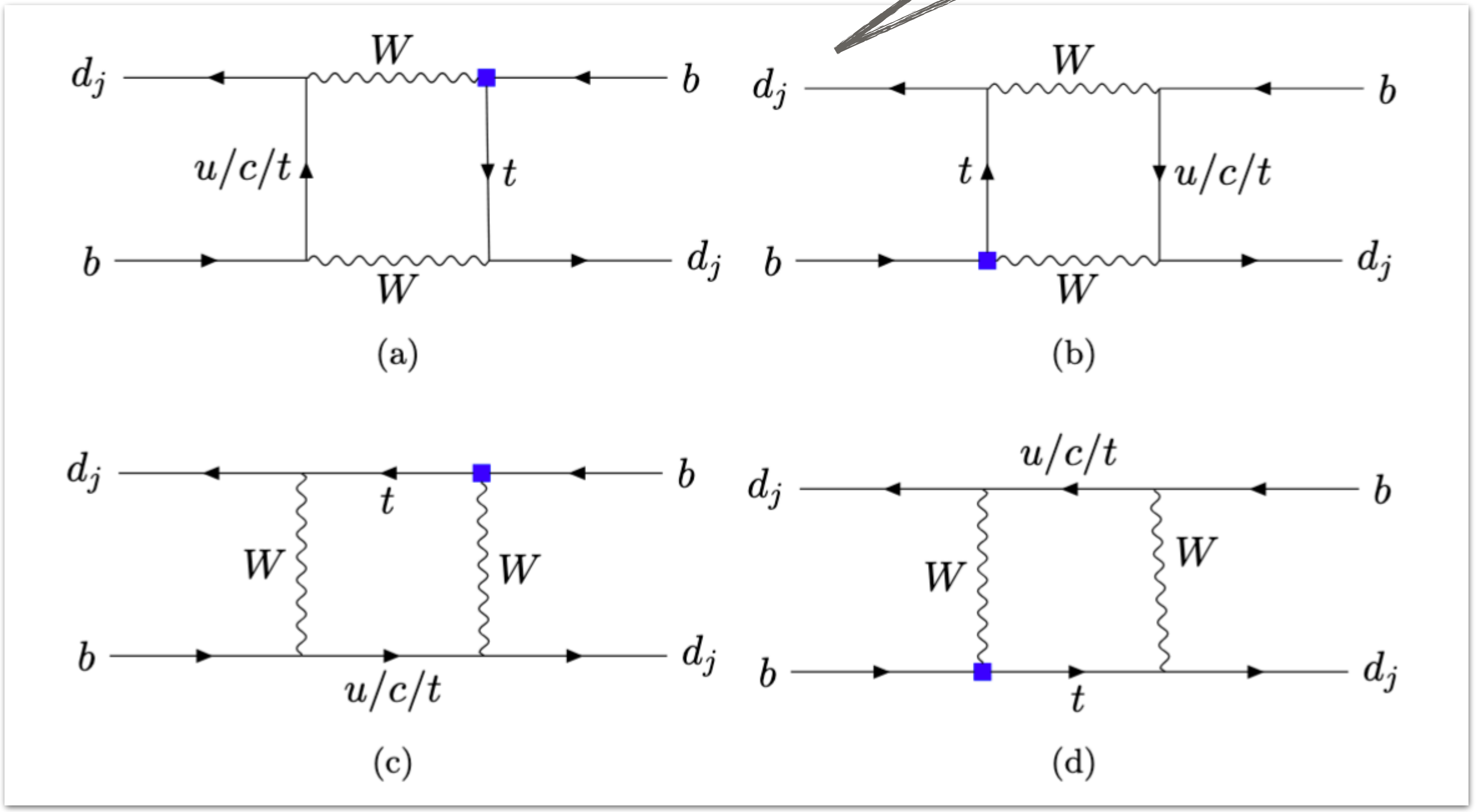
Observables: Mass difference $[\Delta M = \Delta M_{\mathrm{SM}}(1 + \Delta q)]$

$$\begin{aligned} \Delta_d &= -0.05327 \pm 0.03733\,, \\ \Delta_s &= -0.02551 \pm 0.03368\,. \end{aligned}$$

Based on inputs from

SM: J Albrecht et al. (2402.04224)

Exp: LHCb [2024], Belle II [2023]



Presence of *Wtb* couplings

Operator Renormalisation & Running

Effective operators are not renormalised!!

$$\mathcal{O}_i^{\text{bare}} = \sum_j Z_{ij}^{\mathcal{O}} \mathcal{O}_j^{\text{ren}}$$

$$\downarrow$$

Just like couplings, EFT operators must be renormalised —loops make them mix…..

Renormalisation Matrix $Z_{ij}^{\mathcal{O}} = \left(\delta_{ij} + \frac{A_{ij}}{\epsilon} + \mathcal{O}\left(\frac{1}{\epsilon}\right)^n\right)$

$$\downarrow$$

To maintain renormalizability across the scale, information of the running of WCs is crucial

$$\mu\frac{d}{d\mu}\mathcal{O}_i^{\text{bare}} = \mu\frac{d}{d\mu}\left(Z_{ij}^{\mathcal{O}}\mathcal{O}_j^{\text{ren}}\right) = 0$$

$$\downarrow$$

$$\mu\frac{d}{d\mu}\mathcal{O}_i^{\text{ren}} = -\underbrace{\left(Z^{-1}\mu\frac{d}{d\mu}Z\right)_{ij}}_{\gamma_{ij}}\mathcal{O}_j^{\text{ren}}$$

Anomalous Dimension Matrix (ADM)

In a Complementary Approach

$$\mu\frac{d}{d\mu}\mathcal{C}_i^{\text{ren}}(\mu) = -(\gamma^T)_{ij}\mathcal{C}_j^{\text{ren}}(\mu)$$

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Example

Consider a matrix element of four quark operator: $\langle \mathcal{O}^i \rangle$

$$\langle \mathcal{O}_i(\psi_i) \rangle \xrightarrow{\text{Renormalisation}} \langle \mathcal{O}_i \rangle^b = Z_\psi^{-2} Z_{ij} \langle \mathcal{O}_j \rangle^r$$

Higher-order corrections give divergence!!

Quark fields RG

Operator RG

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↓

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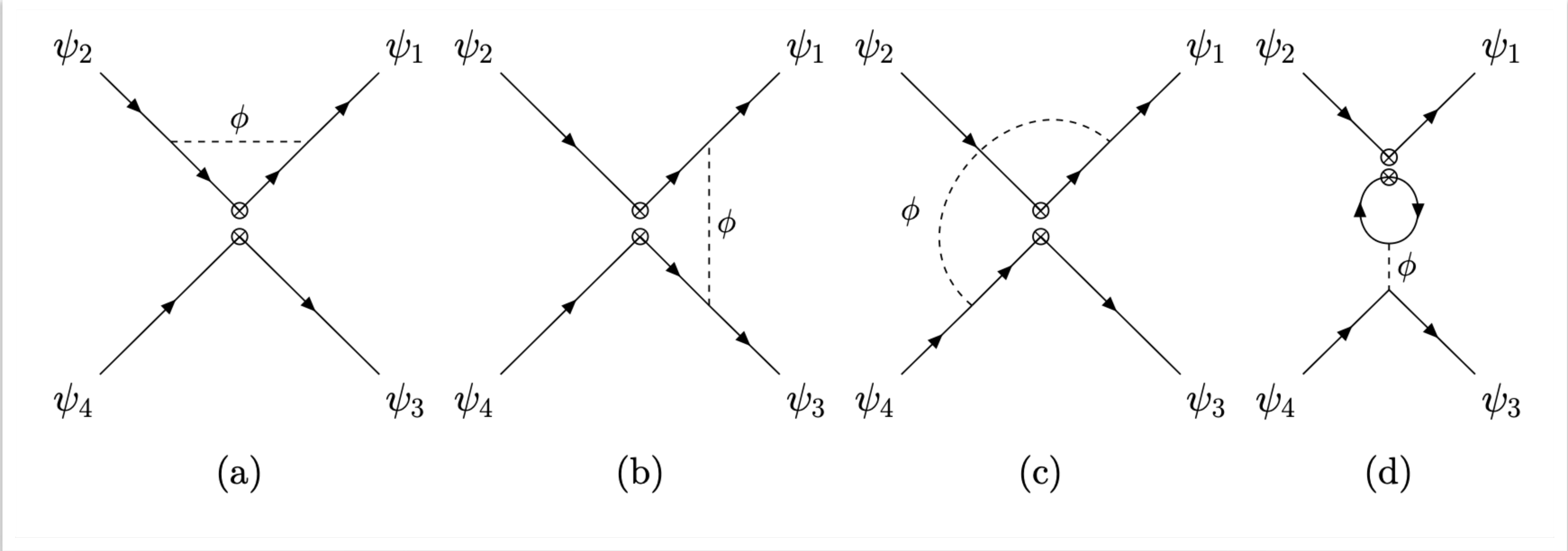

(a) (b) (c) (d)

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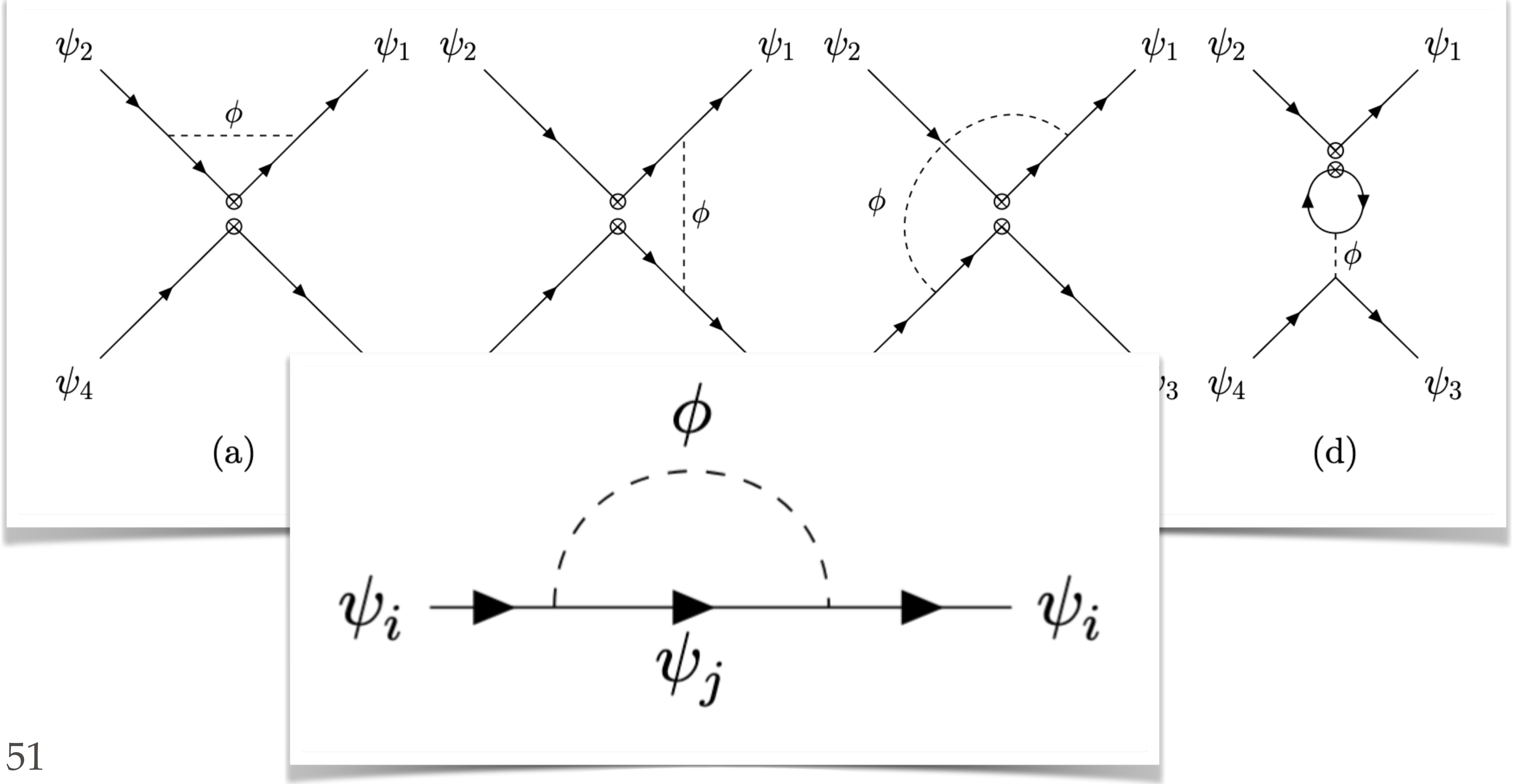

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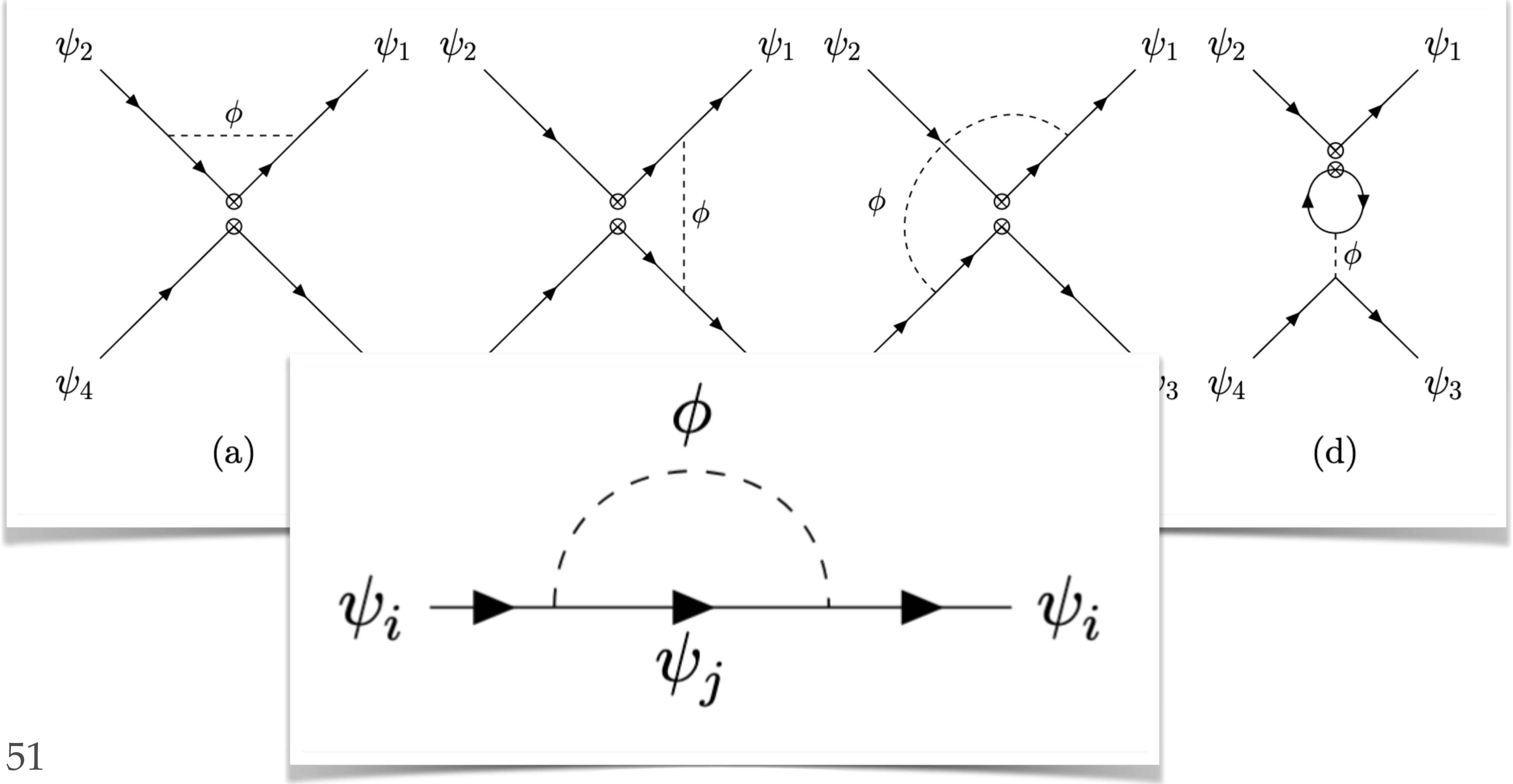
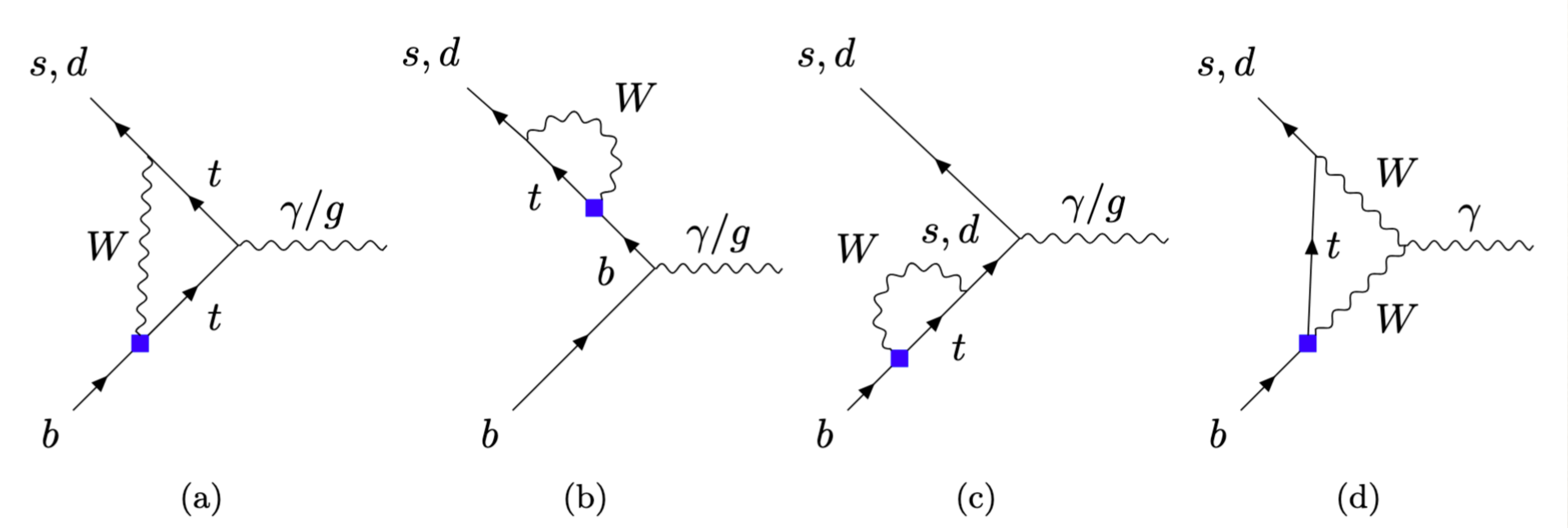


Rare FCNC Processes (Radiative decay)



(a) (b) (c) (d)

$$\mathscr{H}_{eff}^{b\to d_j\gamma} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{td_j}^{*}\Big(C_7(\mu)O_7(\mu) + C_8(\mu)O_8(\mu)\Big)\,.$$

LEFT RGEs

$$\begin{pmatrix} C_7 \\ C_8 \end{pmatrix}_{\mu_b} = \begin{pmatrix} 0.66301 & 0.09259 \\ 0.00326 & 0.69877 \end{pmatrix} \begin{pmatrix} C_7 \\ C_8 \end{pmatrix}_{\mu_{\mathrm{EW}}}$$

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

- Inclusive Radiative decay

$$\mathscr{B}(B \to X_s\gamma) \times 10^4 = (3.40 \pm 0.17) - 8.25\Delta C_7\,(\mu_b) - 2.10\Delta C_8\,(\mu_b)\,.$$

- Exclusive Radiative decay

$$\mathscr{B}(B_q \to V\gamma) = \tau_{B_q}\frac{G_F^2\alpha_{\mathrm{em}}m_{B_q}^3 m_b^2}{32\pi^3}\left(1 - \frac{m_V^2}{m_{B_q}^2}\right)^3 |\lambda_t|^2\Big(\,|\,C_7(\mu_b)\,|^2 + |\,C_7'(\mu_b)\,|^2\,\Big)\,T_1(0)$$

Rare FCNC Processes (Semileptonic decay)

$$\mathscr{H}_{\rm eff}^{b\to d_j\ell\ell} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{td_j}^* \left(C_9(\mu) O_9(\mu) + C_{10}(\mu) O_{10}(\mu) + C_S(\mu) O_S(\mu) \right).$$

Branching Ratio (Rare decay)

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

$$\mathscr{B}(B^0 \to \mu^+\mu^-)^{\rm exp} = \left(1.2^{+0.8}_{-0.7} \ \pm 0.1\right) \times 10^{-10},$$
$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)^{\rm exp} = \left(3.83^{+0.38\ +0.24}_{-0.36\ -0.21}\right) \times 10^{-9}.$$

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-)^{\rm SM} = (3.66 \pm 0.14) \times 10^{-9},$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-)^{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}.$$

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

Branching Ratio (Rare decay)

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

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

$$\boxed{\Delta\, C_i(\mu_{\text{EW}}) \to f(V_L, V_R, g_L, g_R)\,(\mu_{\text{EW}})}$$

$f(V_L, V_R, g_L, g_R)/g(\mathscr{C}^i_{\text{SMEFT}})$ **Loop Factor**

WET RGEs

$$\xrightarrow{\hspace{4cm}}$$

$$\begin{pmatrix} C_9 \\ C_{10} \\ C_S \end{pmatrix}_{\mu_b} = \begin{pmatrix} 0.99522 & 0.00716 & 0 \\ 0.00716 & 1.0 & 0 \\ 0 & 0 & 1.37433 \end{pmatrix}\begin{pmatrix} C_9 \\ C_{10} \\ C_S \end{pmatrix}_{\mu_{\text{EW}}}$$

$$\begin{cases} C_i(\mu_b) = U_{ij}(\mu_b, \mu_{\text{EW}})C_j(\mu_{\text{EW}}) \\ C_i(\mu_b) = C_i^{\text{SM}}(\mu_b) + U_{ij}(\mu_b, \mu_{\text{EW}})f(V_L, V_R, g_L, g_R)(\mu_{\text{EW}}) \end{cases}$$

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$$\left. + \left|\frac{m_{B_q}}{m_b}(C_p(\mu_b) - C_p'(\mu_b)) + 2\frac{m_\mu}{m_{B_q}}(C_{10}(\mu_b) - C_{10}'(\mu_b))\right|^2\right]\,,$$

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