Testing the Flavour Structure of the SMEFT

Based on: 1910.03606 and 2101.07273

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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Sebastian Bruggisser

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High-Low connection

Gauge Structure

$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i) \qquad O_{Qq}^{3,8} = C_{Qq}^{3,8}(\bar{q}_3\gamma^\mu T^A \tau^I q_3)(\bar{q}_i\gamma_\mu T^A \tau^I q_i)$$

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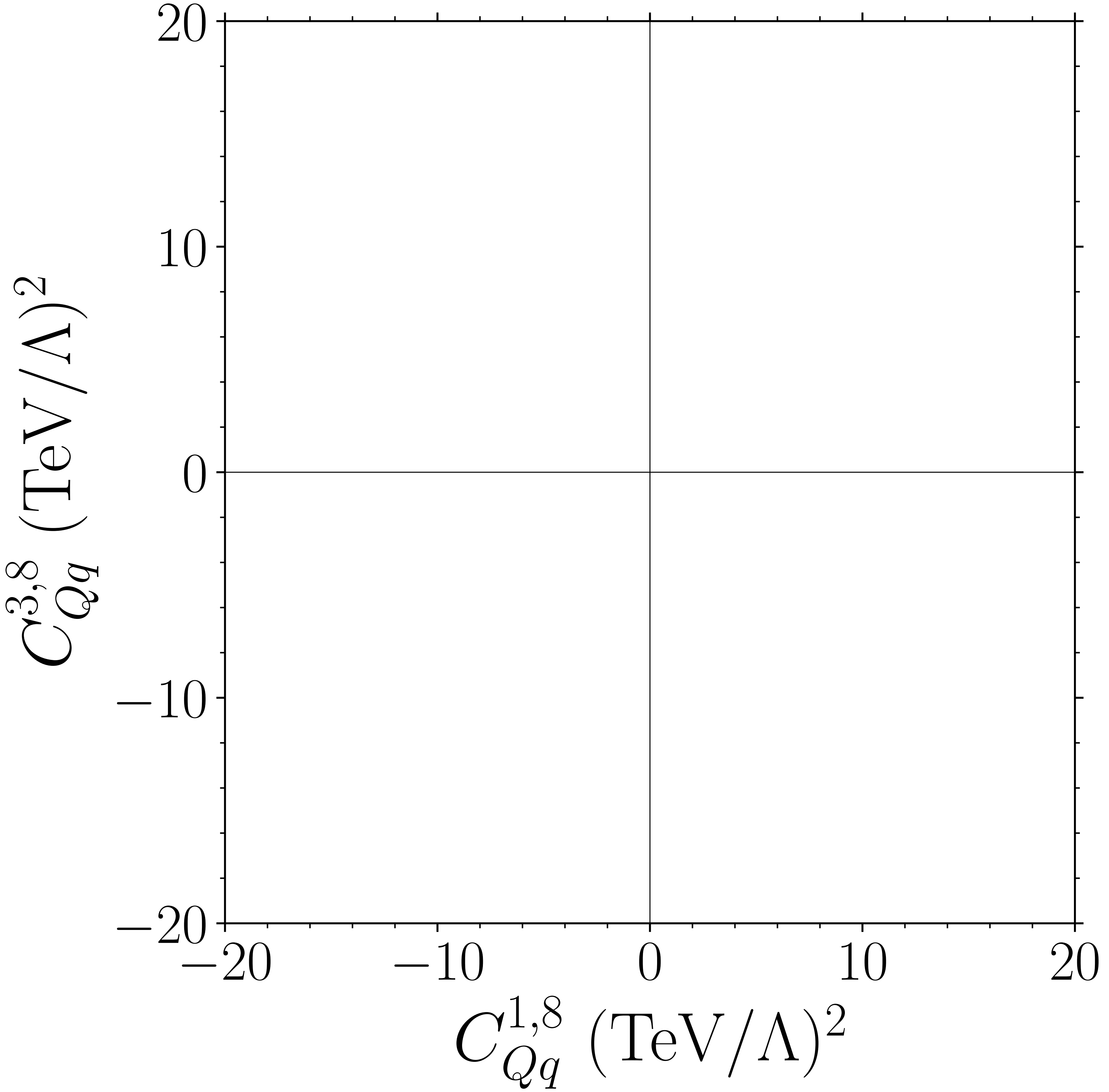

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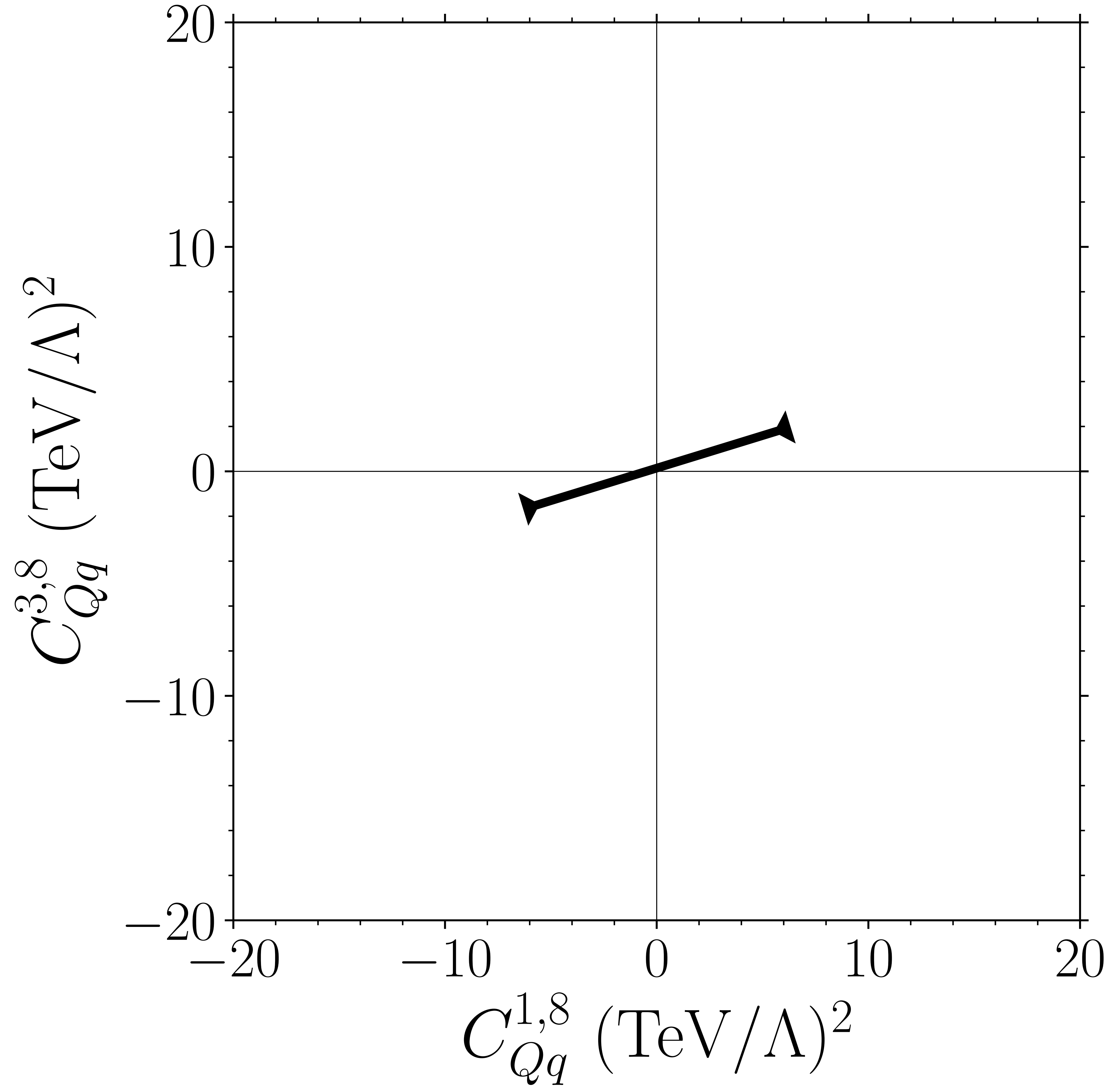

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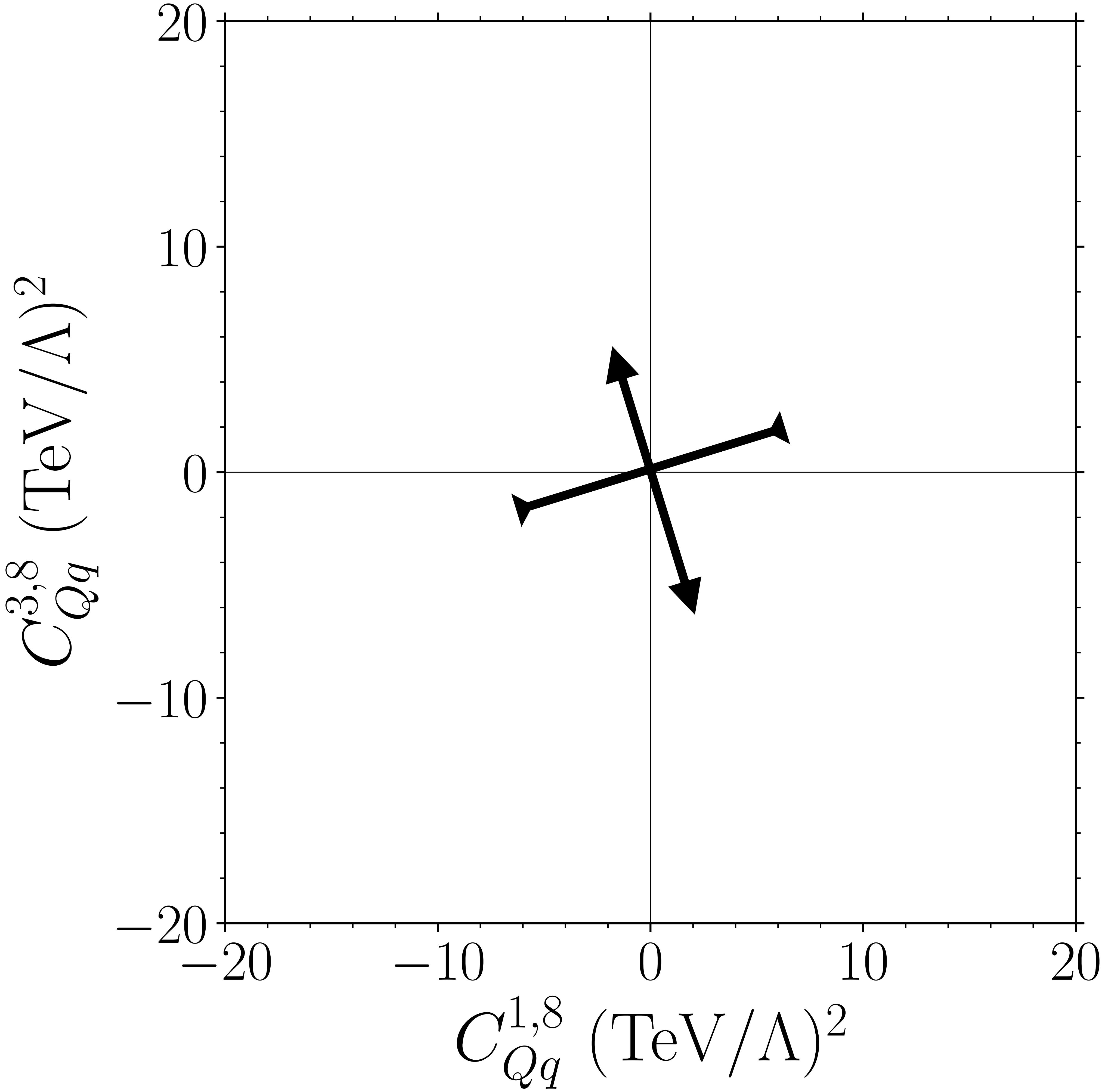

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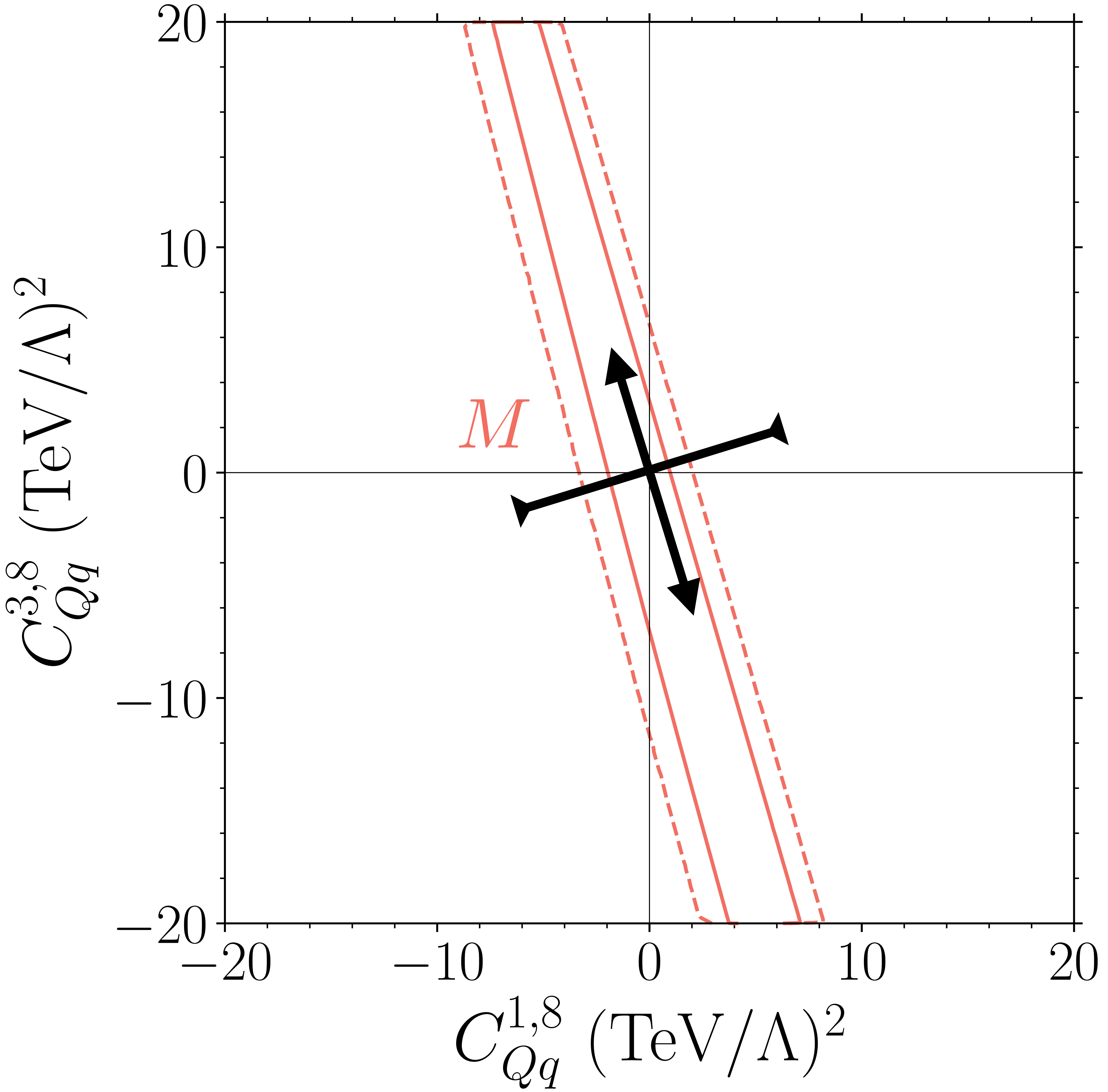

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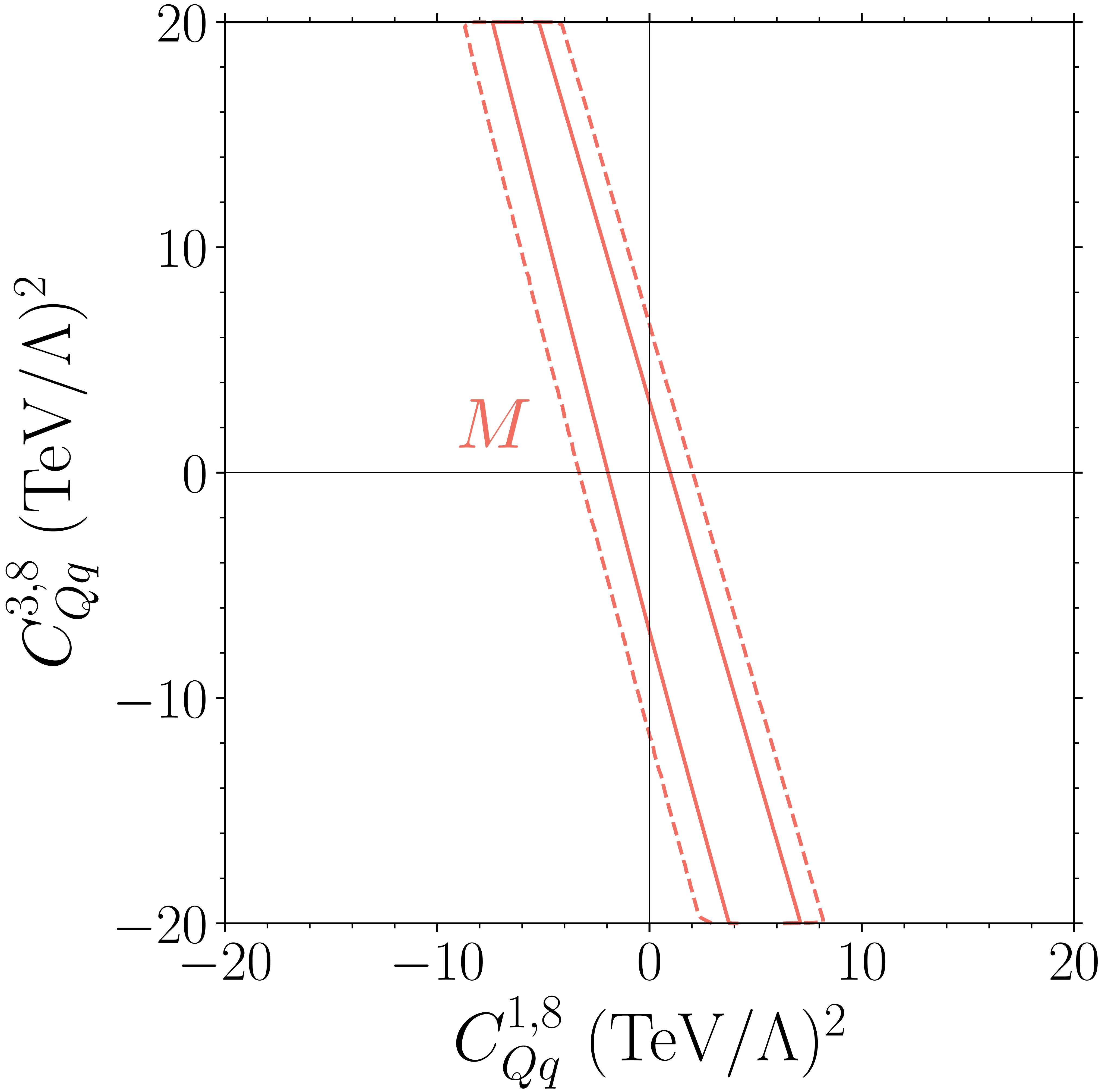

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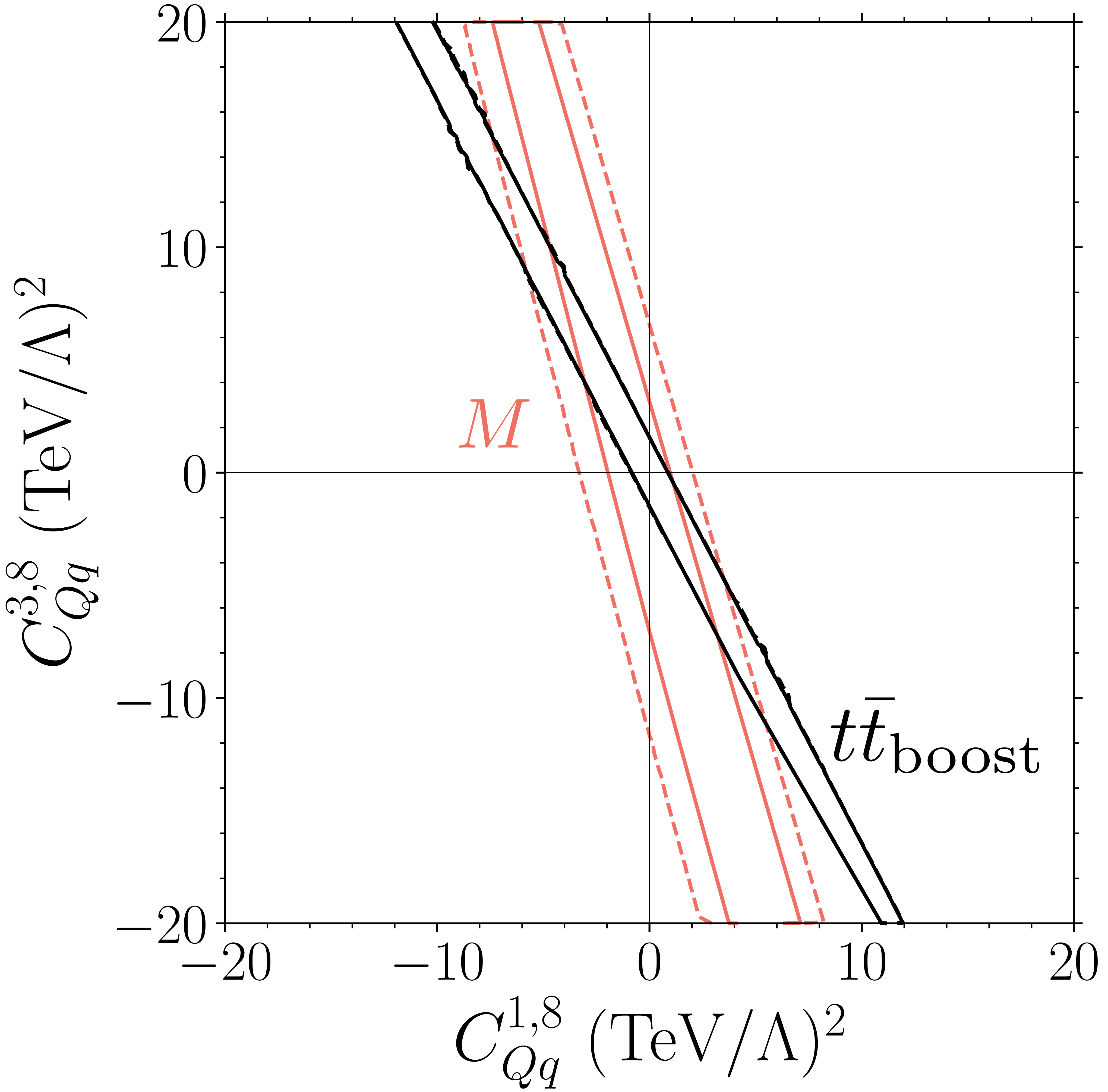

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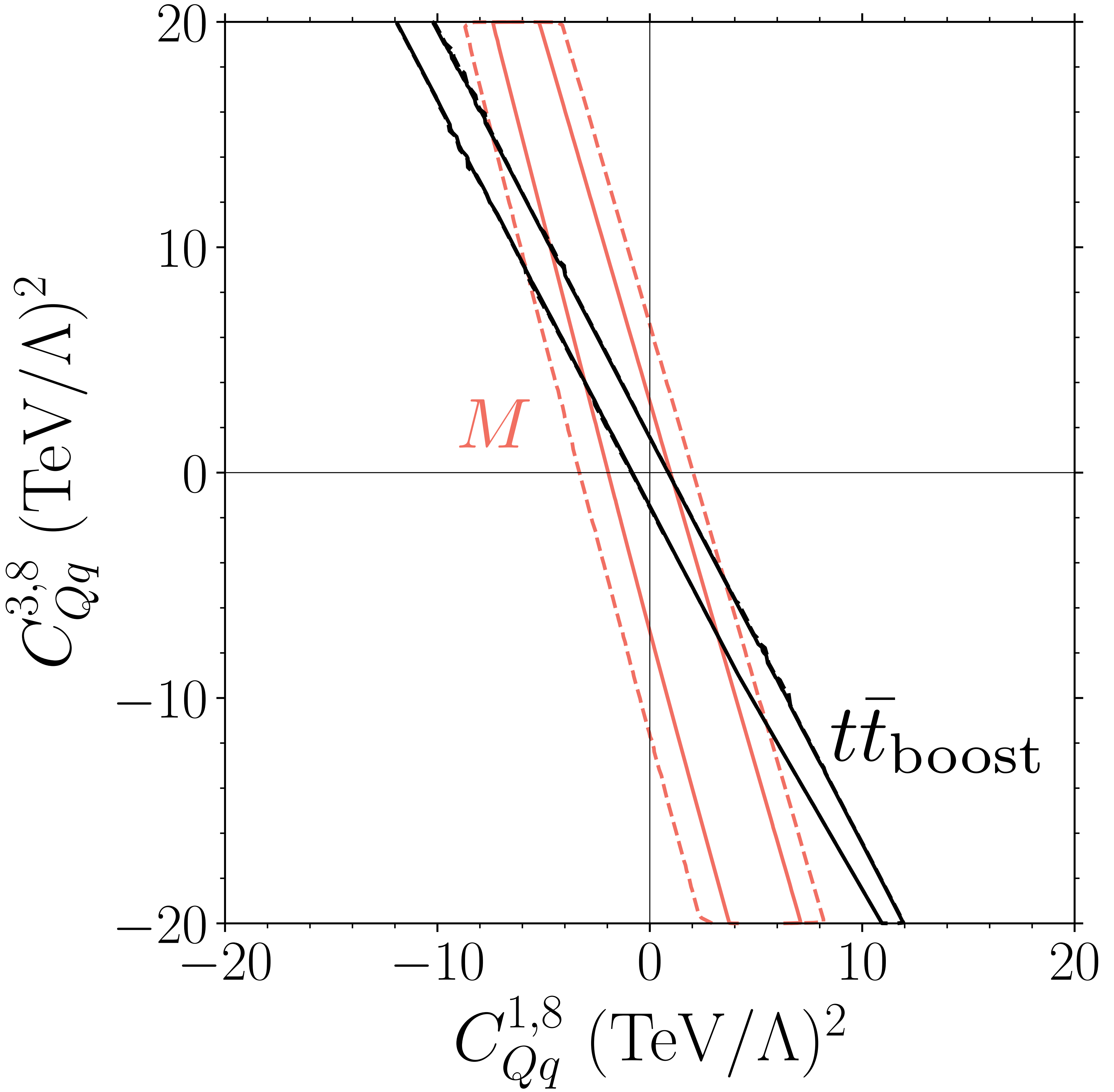

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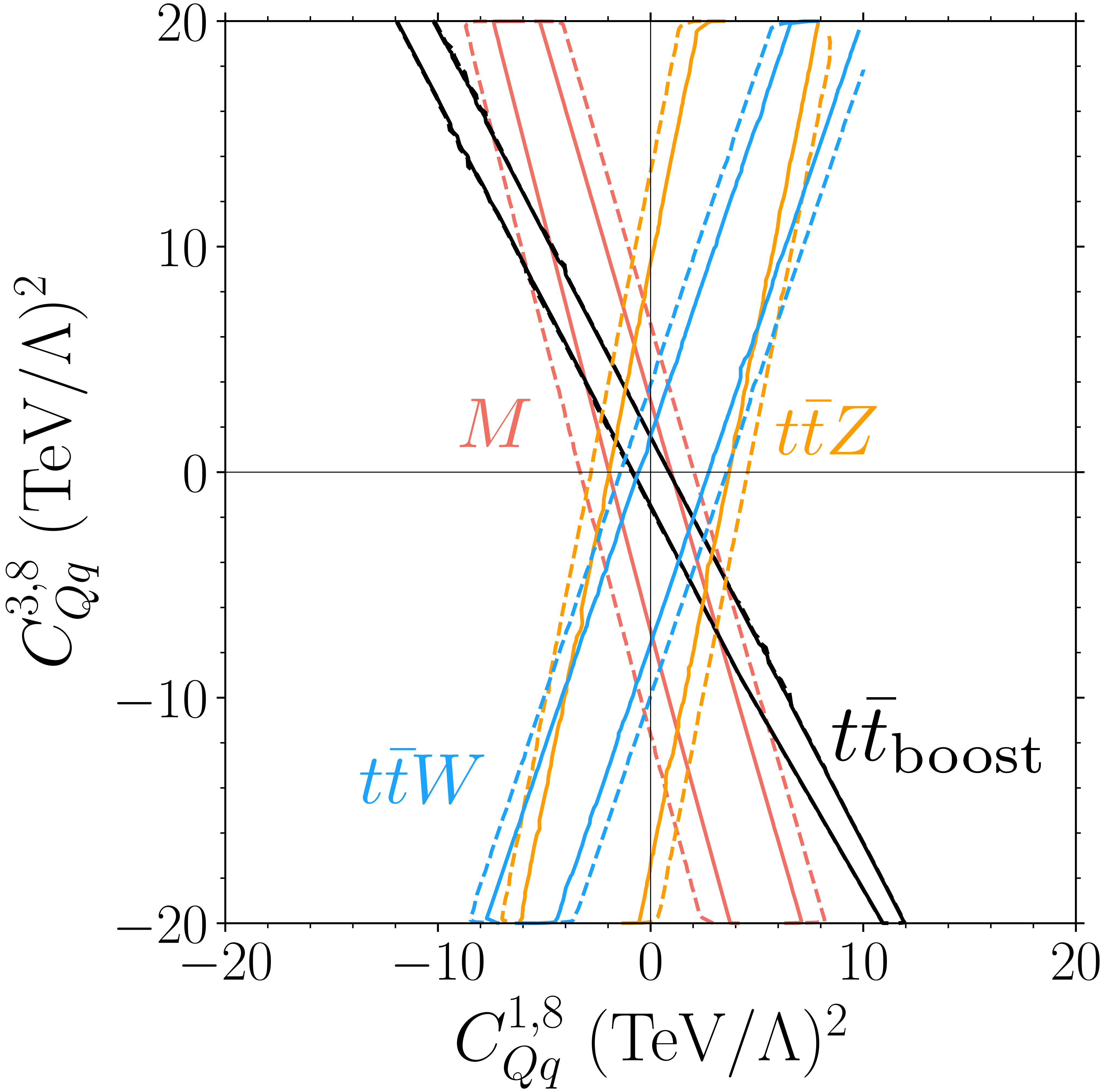

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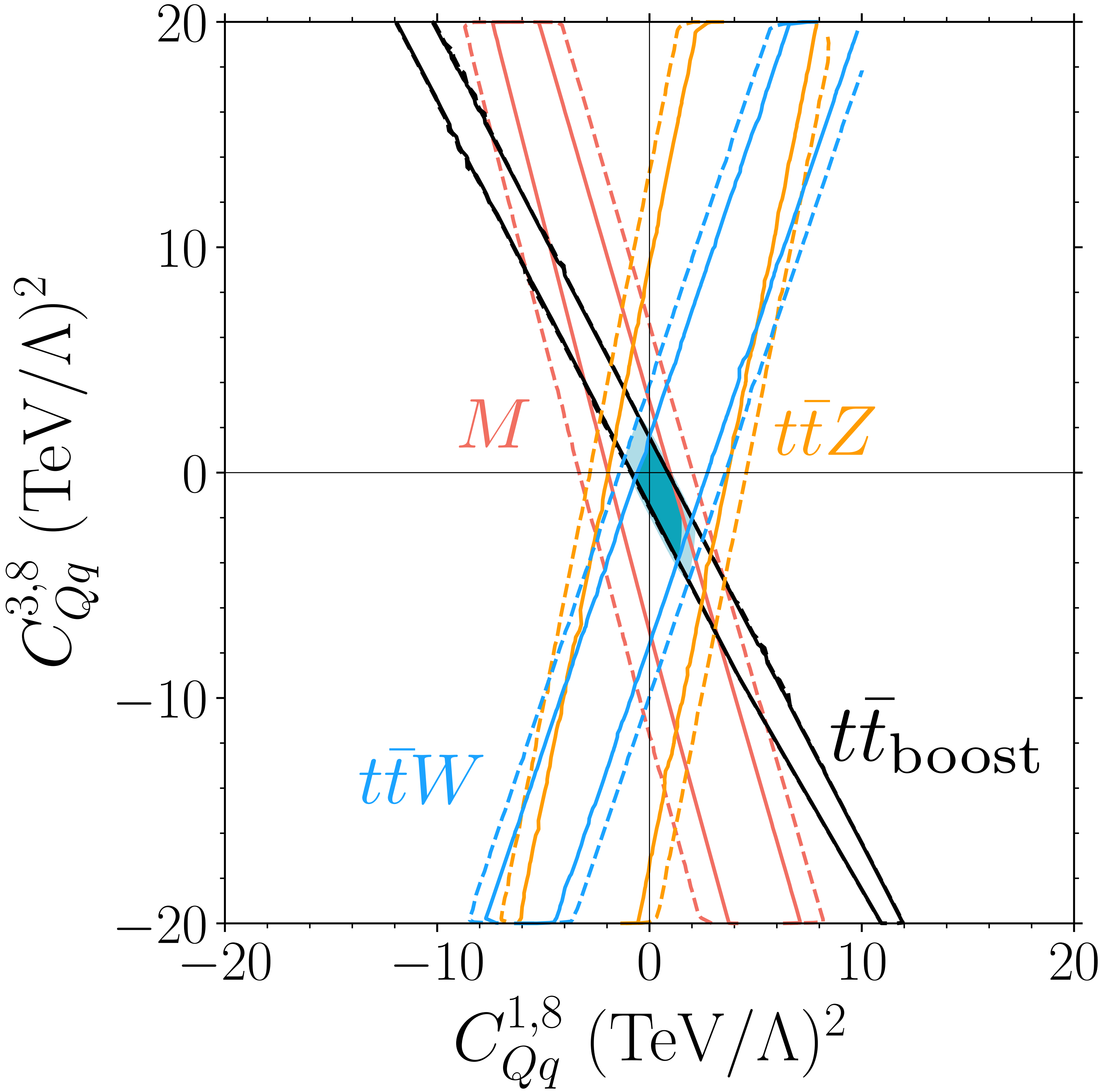

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a long story

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- Here: Subset of operators in MFV as a proof of principle

MFV

$$U(3)_Q \times U(3)_u \times U(3)_d$$

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$$Y_d \sim (3, 1, \bar{3})$$

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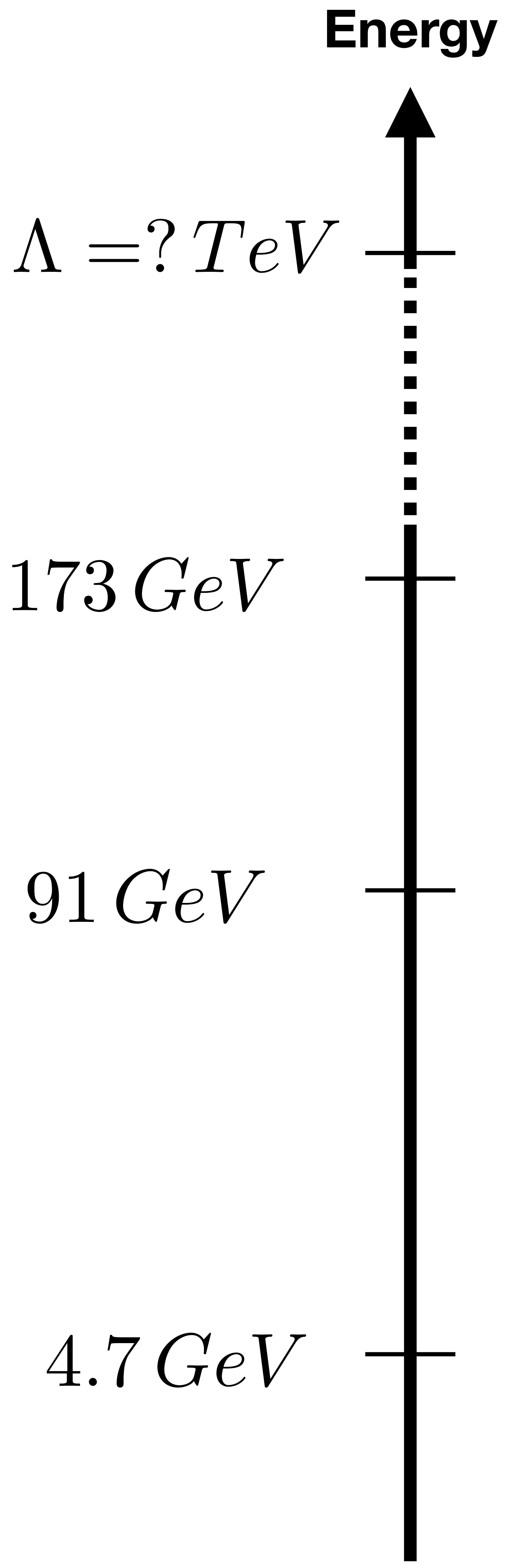
	$C_{\phi q}^{(1)}$	$C_{\phi q}^{(3)}$	$C_{\phi u}$	$C_{\phi d}$	$C_{\phi ud}$	C_{uX}	C_{dX}
ii	a	a	a	a	0	0	0
33	$a + by_t^2$	$a + by_t^2$	$a + by_t^2$	a	$(a + by_t^2)y_b y_t V_{tb}$	$(a + by_t^2)y_t$	$(a + by_t^2)y_b V_{tb}$
ki	$cy_b^2 V_{kb} V_{ib}^*$	$cy_b^2 V_{kb} V_{ib}^*$	0	0	0	0	0
$i3$	$cy_b^2 V_{ib} V_{tb}^*$	$cy_b^2 V_{ib} V_{tb}^*$	0	0	0	$cy_b^2 y_t V_{ib} V_{tb}^*$	$ay_b V_{ib}$
#	3	3	2	1	1	2	2

MFV

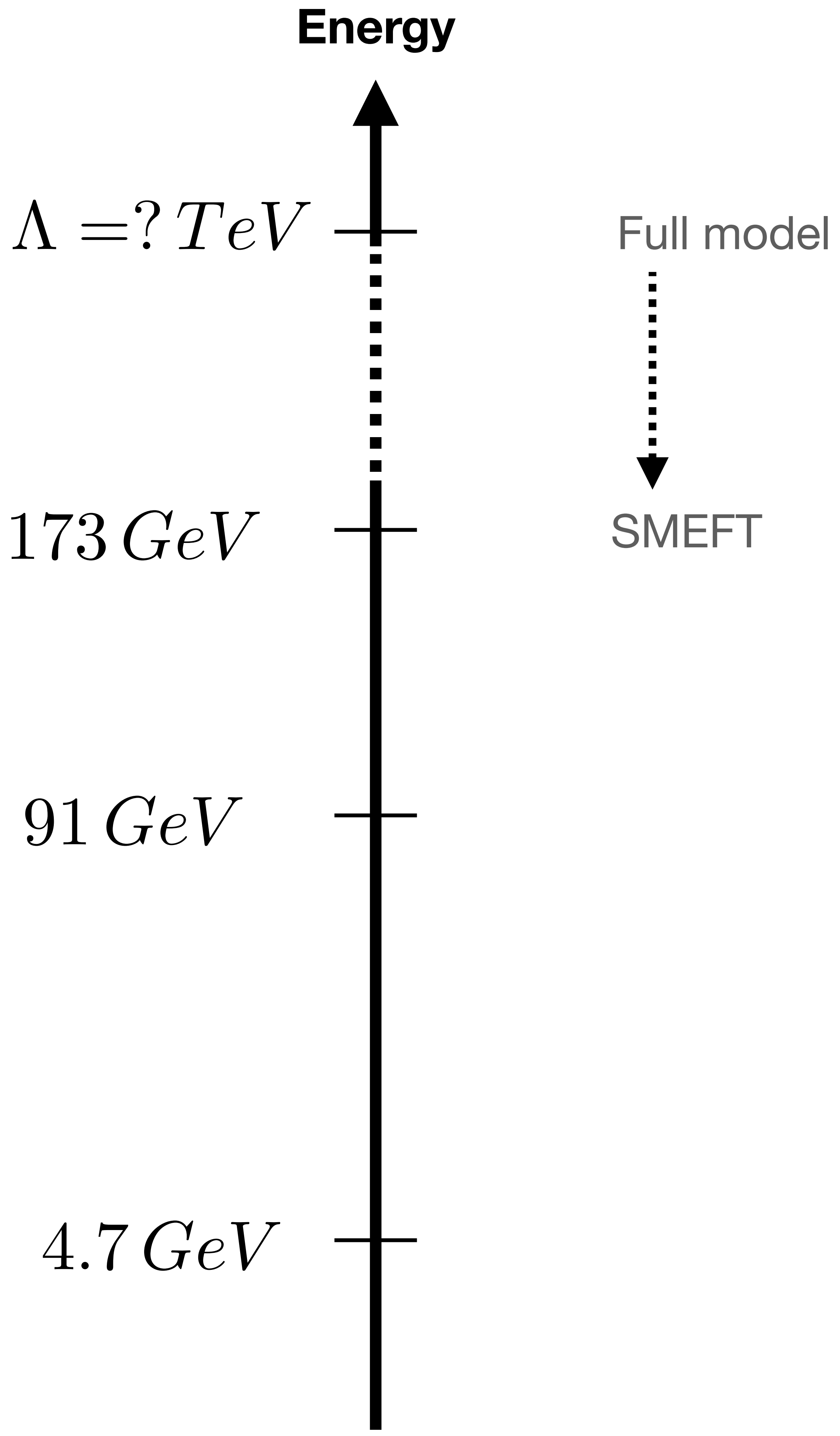
	$C_{qq}^{(1)},\, C_{qq}^{(3)}$	C_{uu}	C_{dd}
$iiii$	$(aa)+(\widetilde{aa})$	$(aa)+(\widetilde{aa})$	$(aa)+(\widetilde{aa})$
$iijj$	(aa)	(aa)	(aa)
$ijji$	$(\widetilde{aa})$	$(\widetilde{aa})$	$(\widetilde{aa})$
$33ii$	$(aa)+(ba)y_t^2$	$(aa)+(ba)y_t^2$	(aa)
$3ii3$	$(\widetilde{aa})+(\widetilde{ba})y_t^2$	$(\widetilde{aa})+(\widetilde{ba})y_t^2$	$(\widetilde{aa})$
3333	$(aa)+(\widetilde{aa})+2((ba)+(\widetilde{ba}))y_t^2+\mathcal{O}(y_t^4)$	$(aa)+(\widetilde{aa})+2((ba)+(\widetilde{ba}))y_t^2+\mathcal{O}(y_t^4)$	$(aa)+(\widetilde{aa})$
$iikl$	$(ac)y_b^2 V_{kb}V_{lb}^*$	0	0
$ilki$	$(\widetilde{ac})y_b^2 V_{kb}V_{lb}^*$	0	0
$33kl$	$((ac)+(bc)y_t^2)y_b^2 V_{kb}V_{lb}^*$	0	0
$3lk3$	$((\widetilde{ac})+(\widetilde{bc})y_t^2)y_b^2 V_{kb}V_{lb}^*$	0	0
#	9	5	2

Top-Down



Full model

Top-Down



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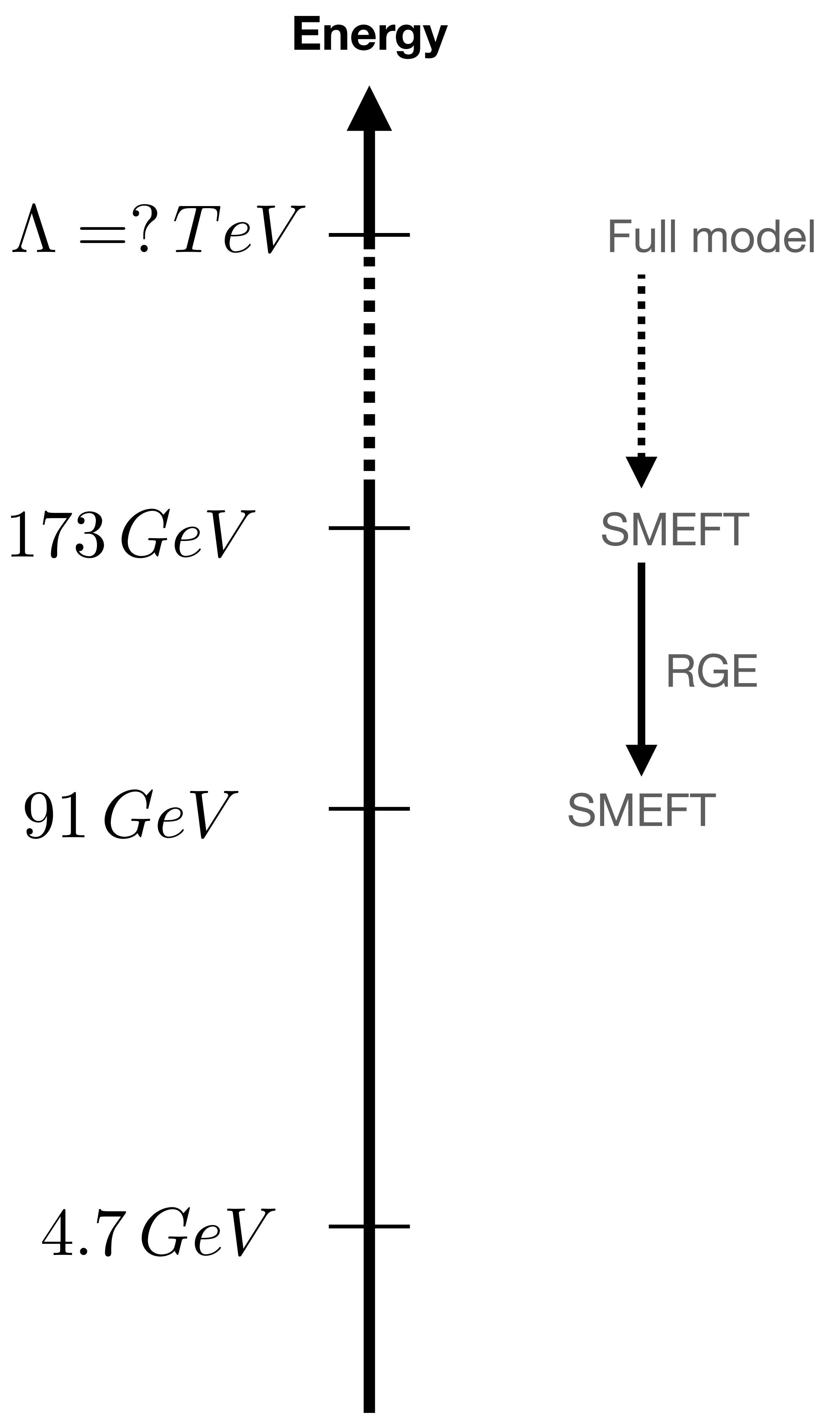

Energy
$\Lambda = ?\, TeV$
Full model
$173\, GeV$
SMEFT
RGE
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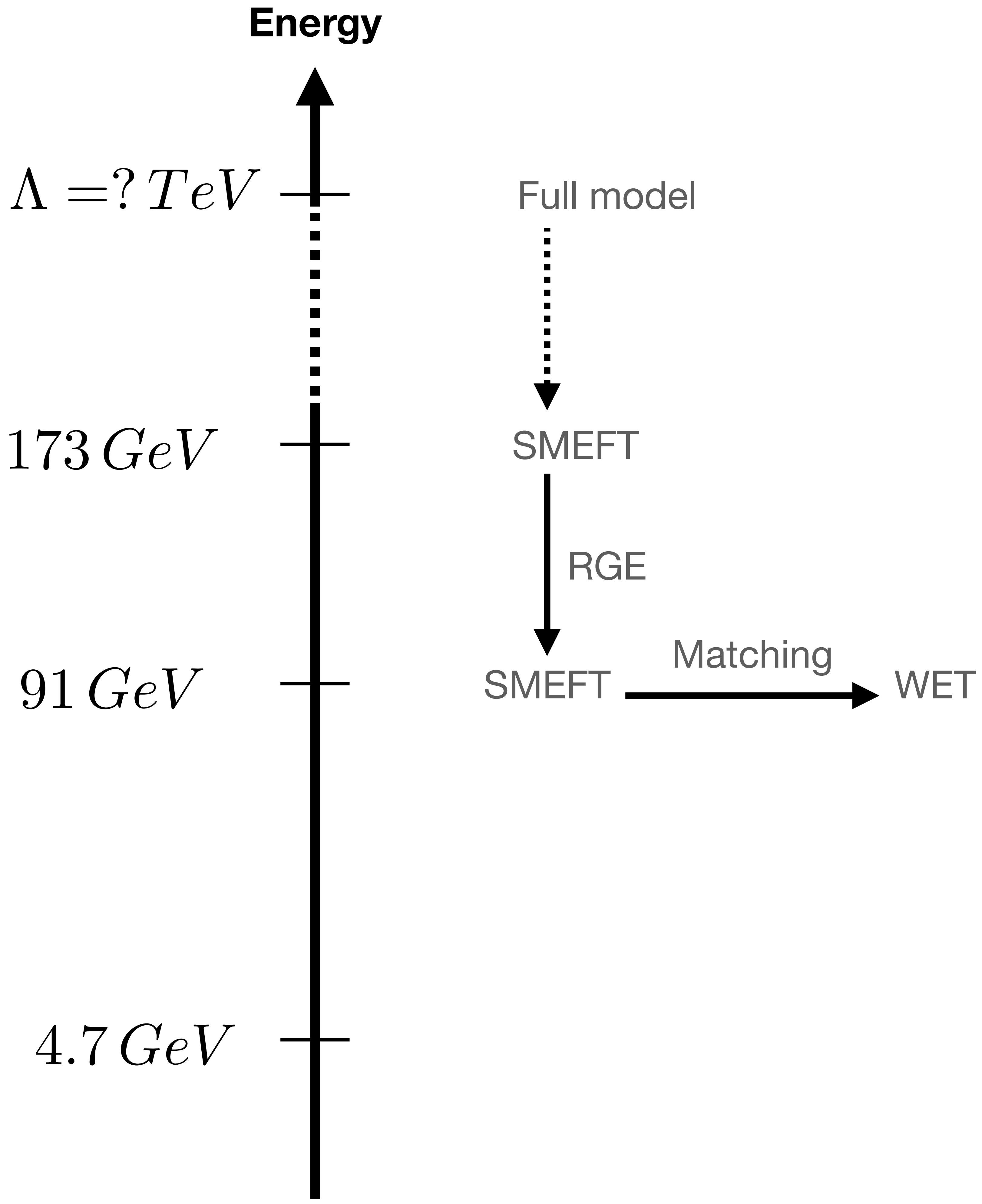

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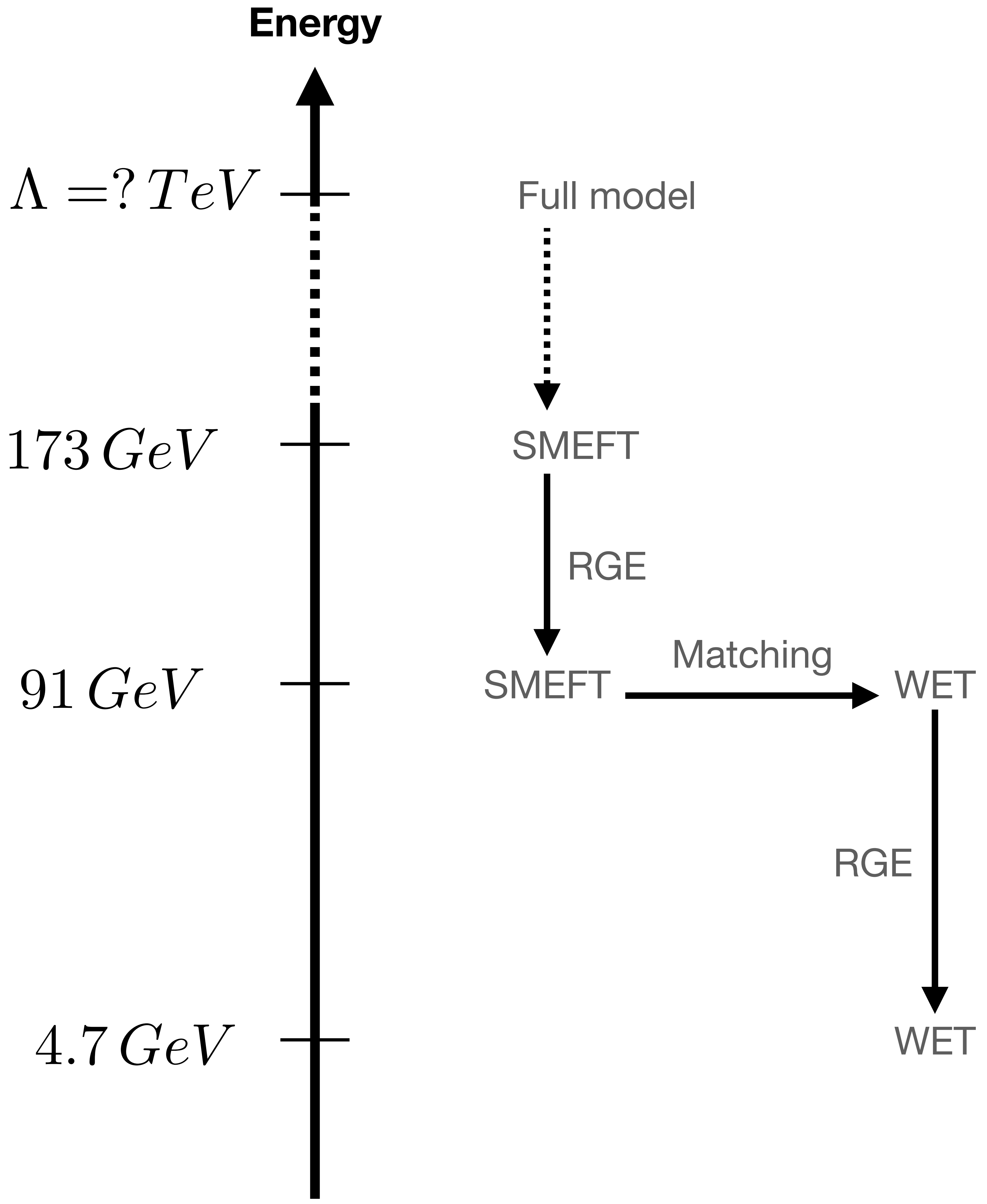
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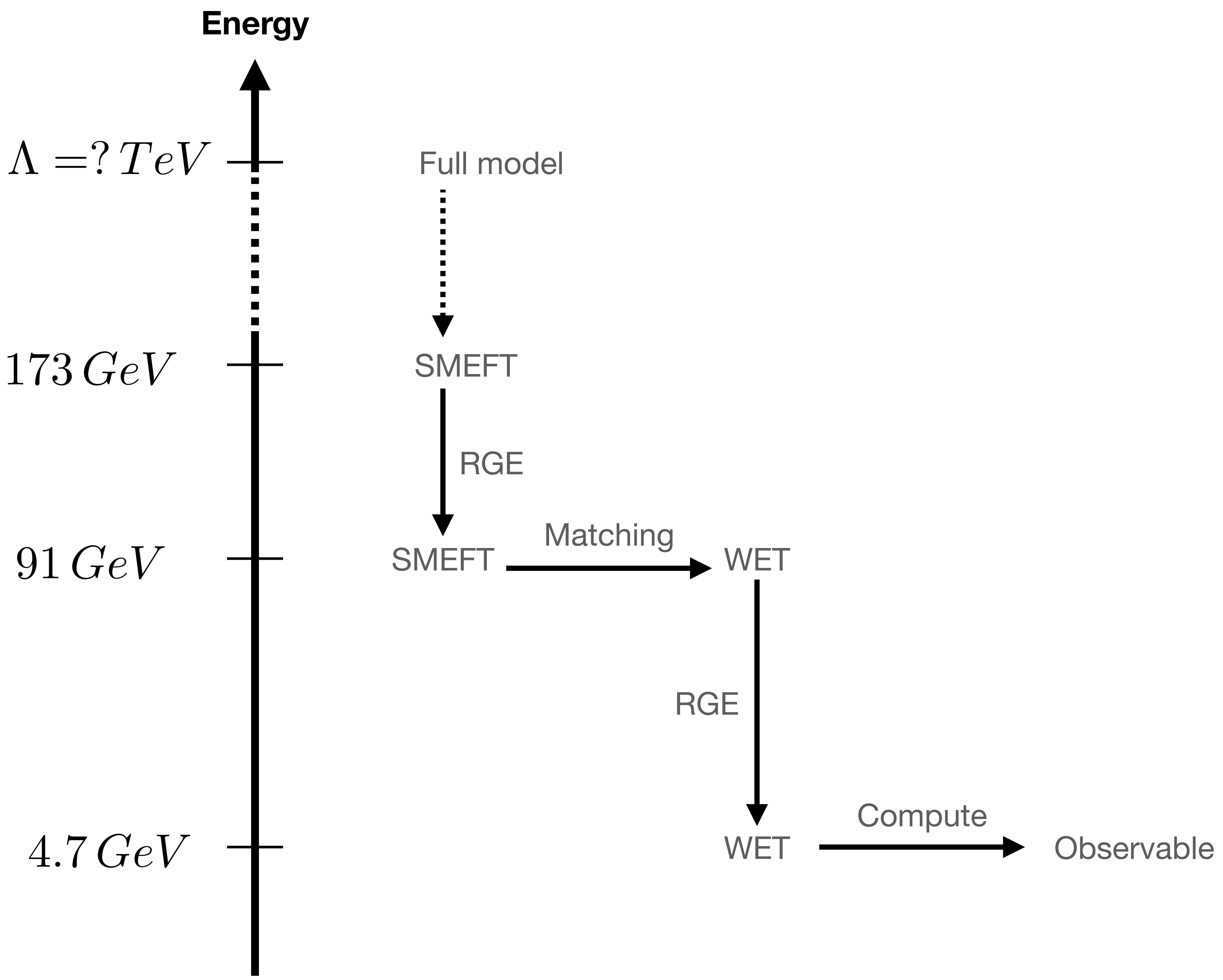
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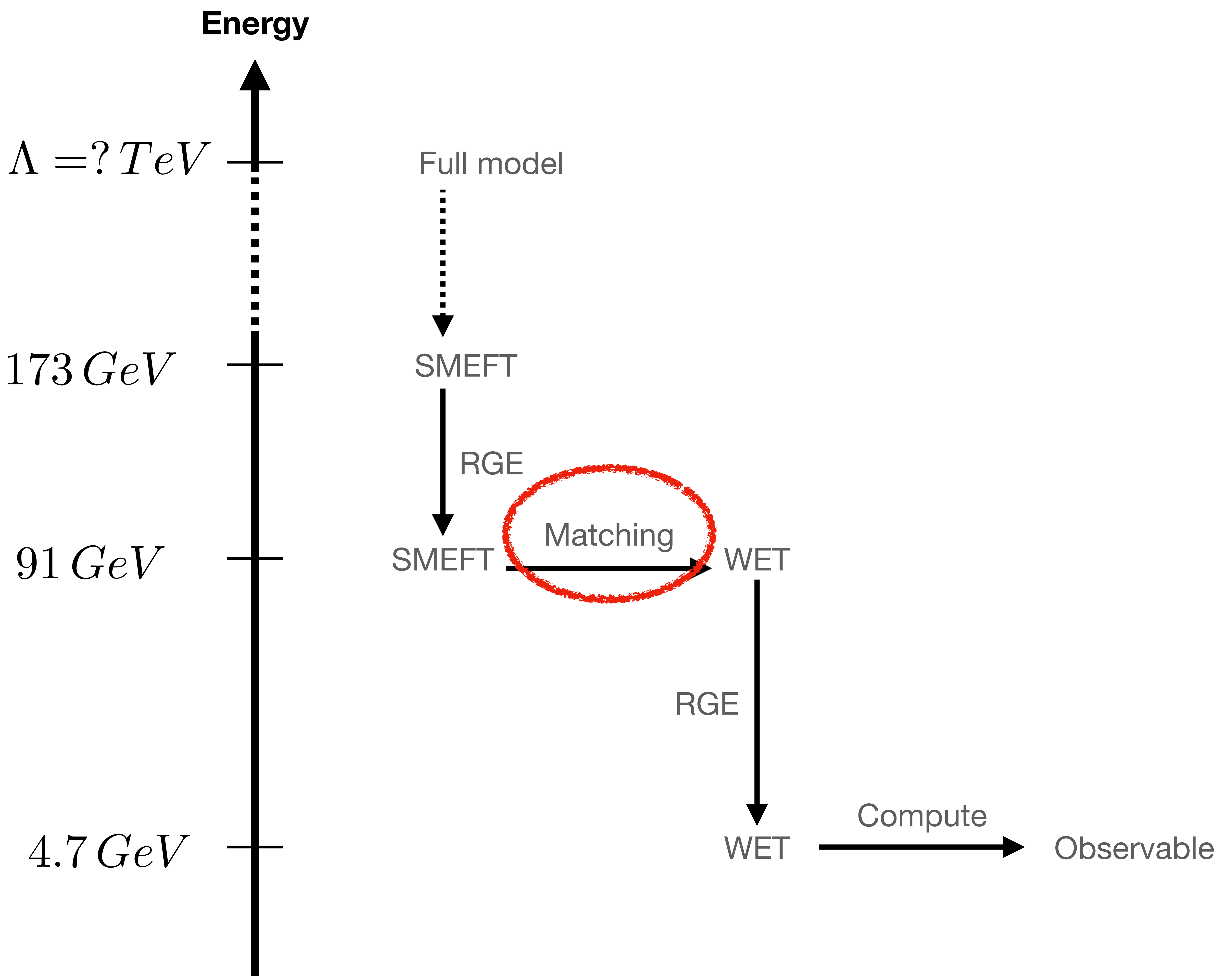

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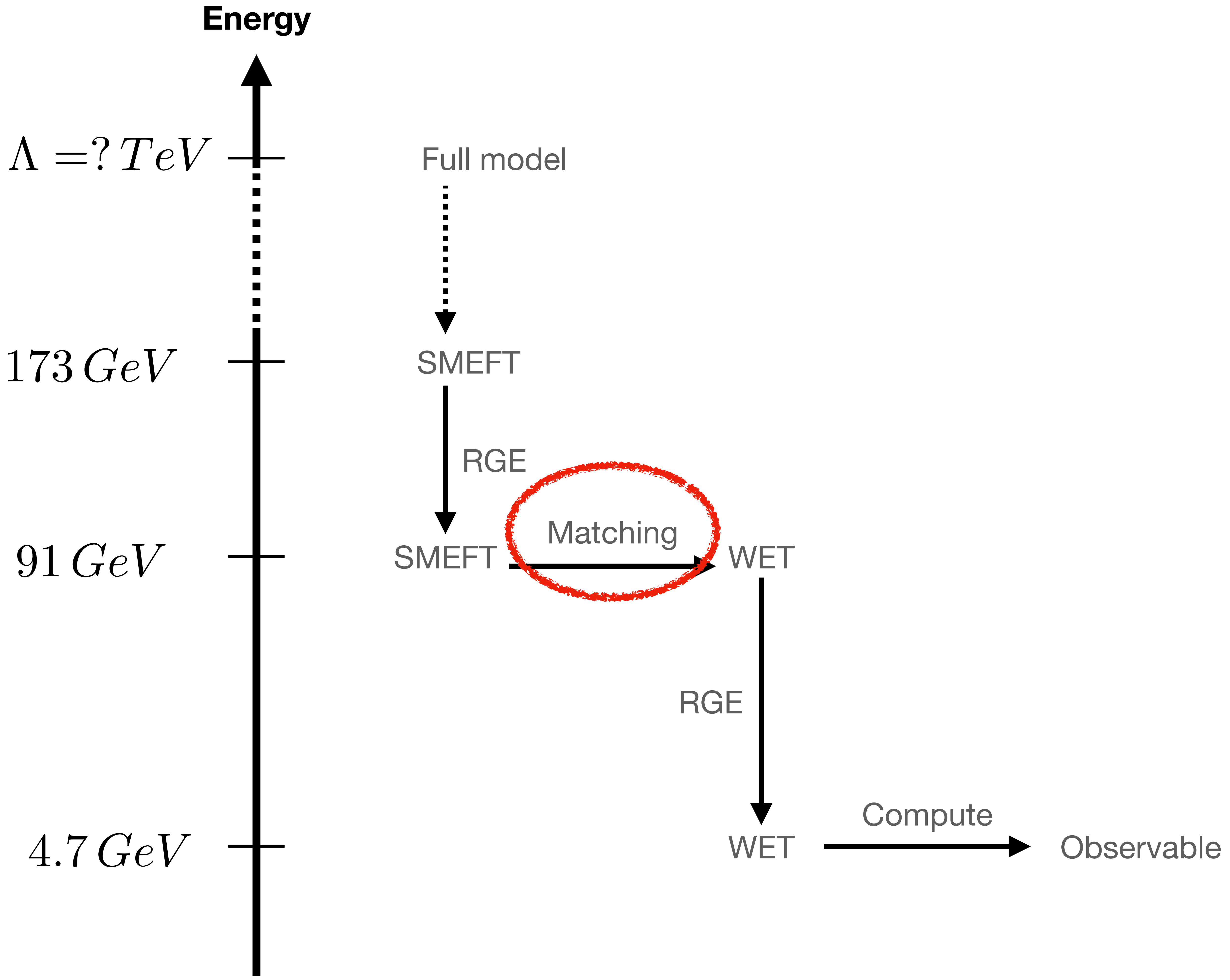

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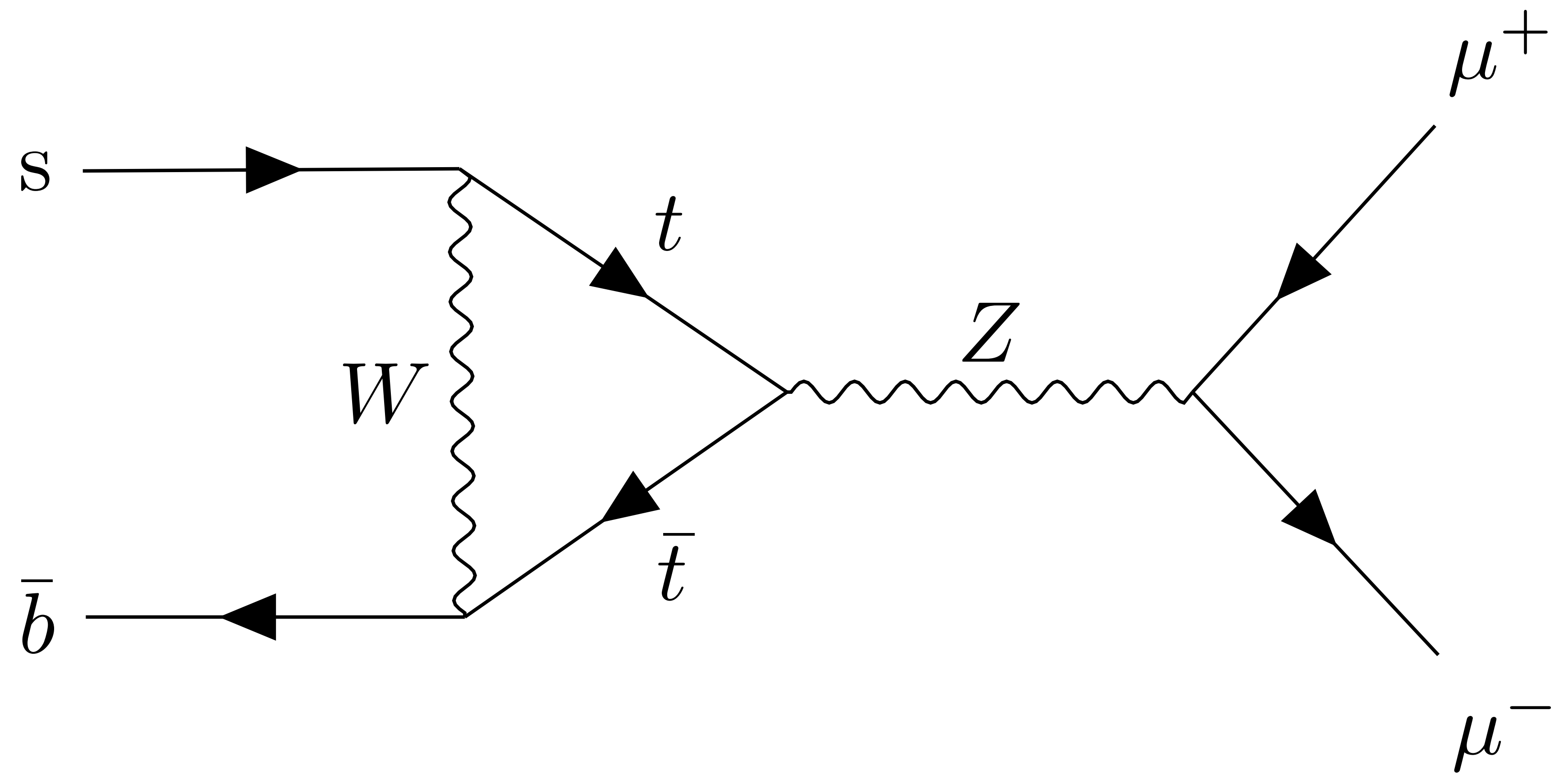
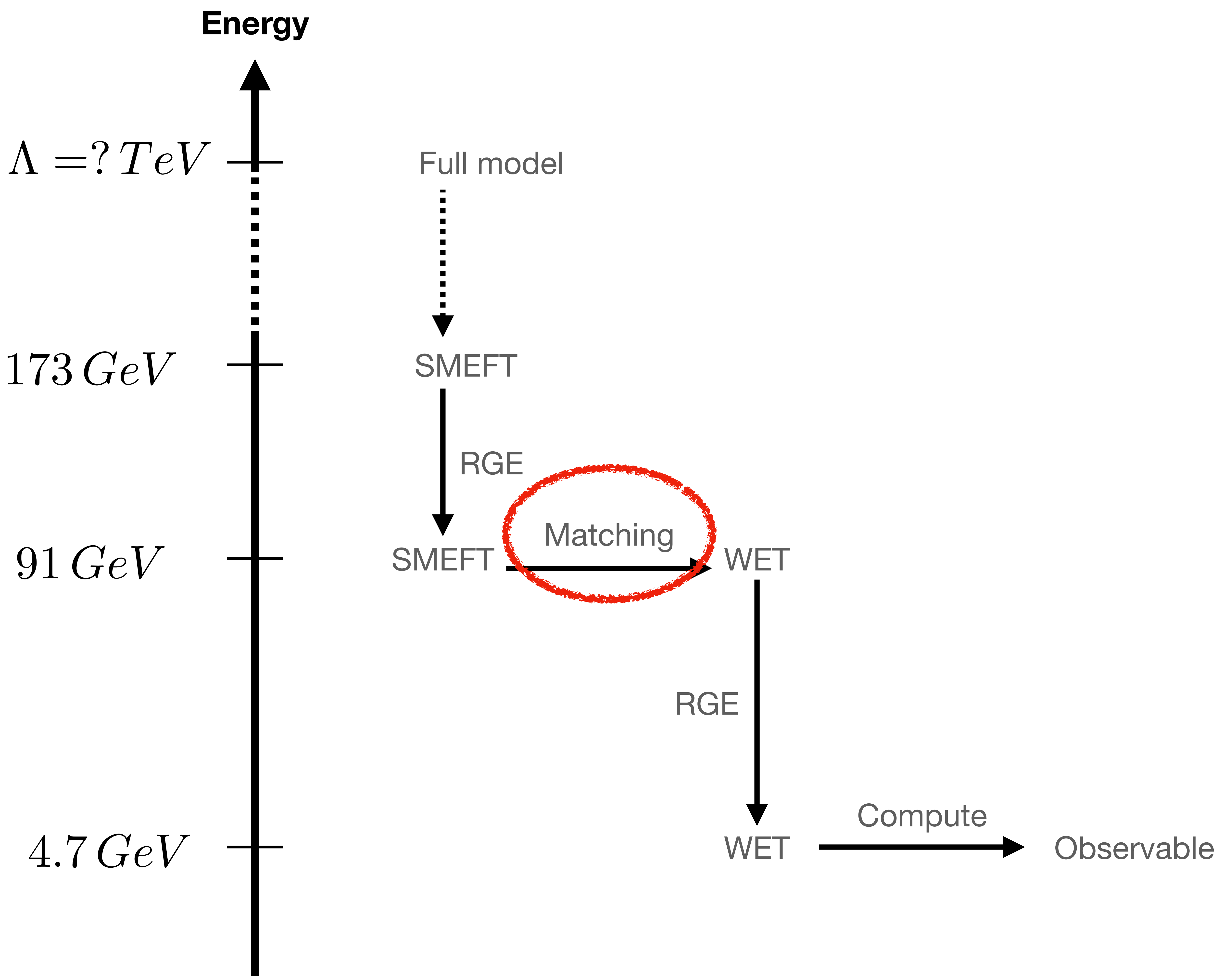
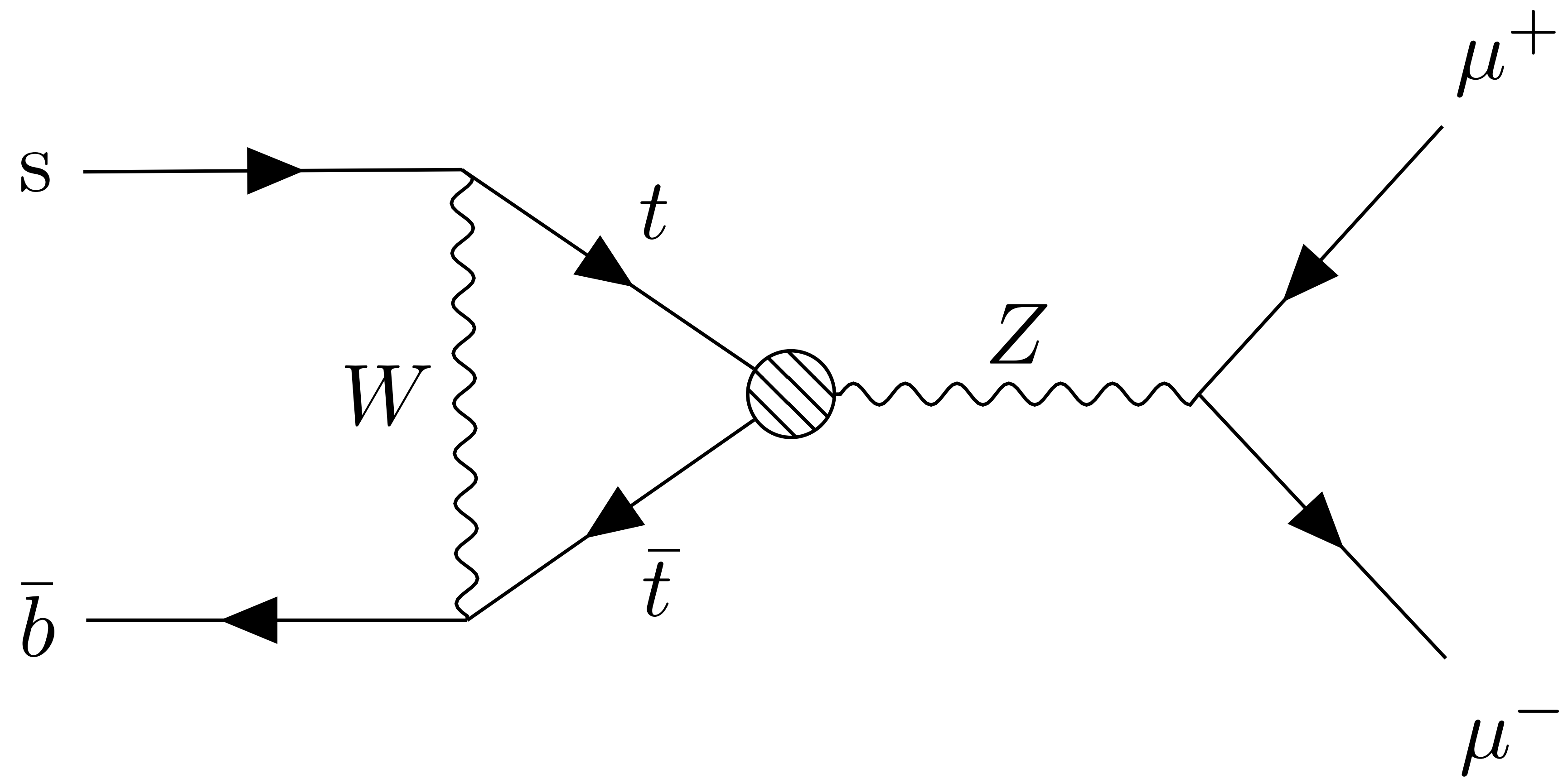
Compute
Observable



s
$\bar{b}$
W
t
$\bar{t}$
Z
μ^+
μ^-

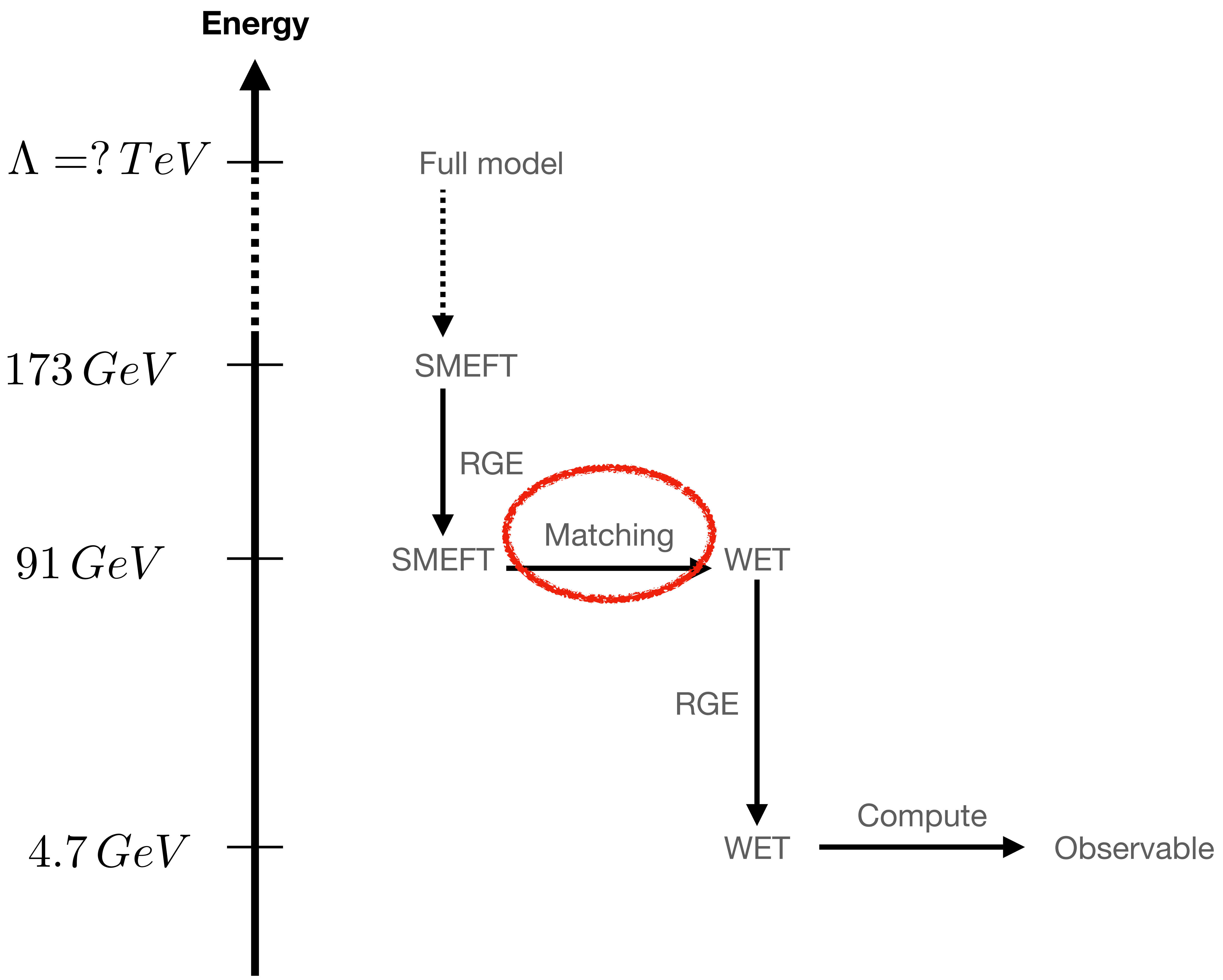
Top-Down

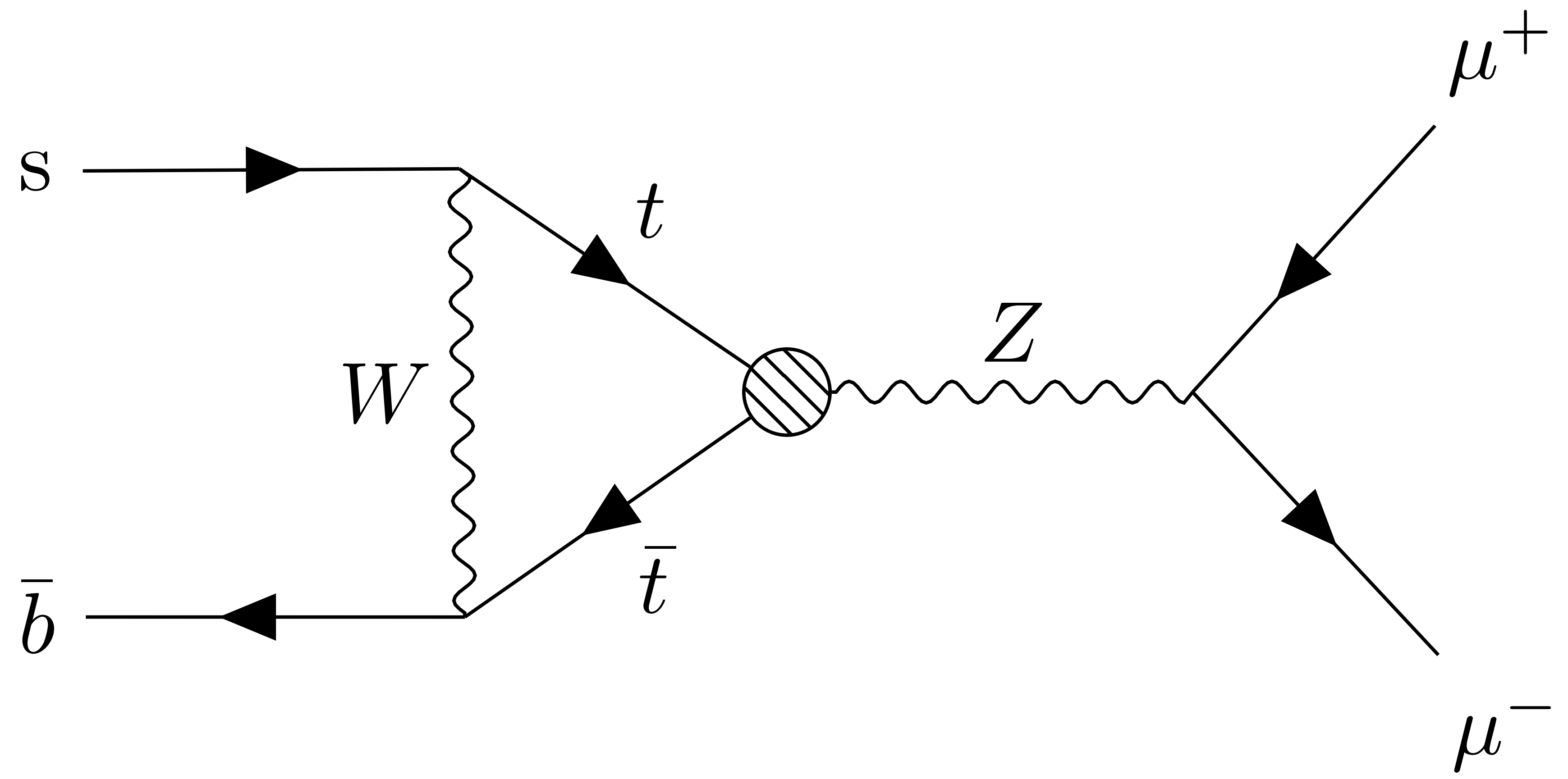




$$[\mathcal{O}^1_{\phi q}]_{ij} = \left(\phi^\dagger \, i \, \overleftrightarrow{D}_\mu \, \phi\right) (\bar{q}_i \gamma^\mu q_j)$$

Top-Down



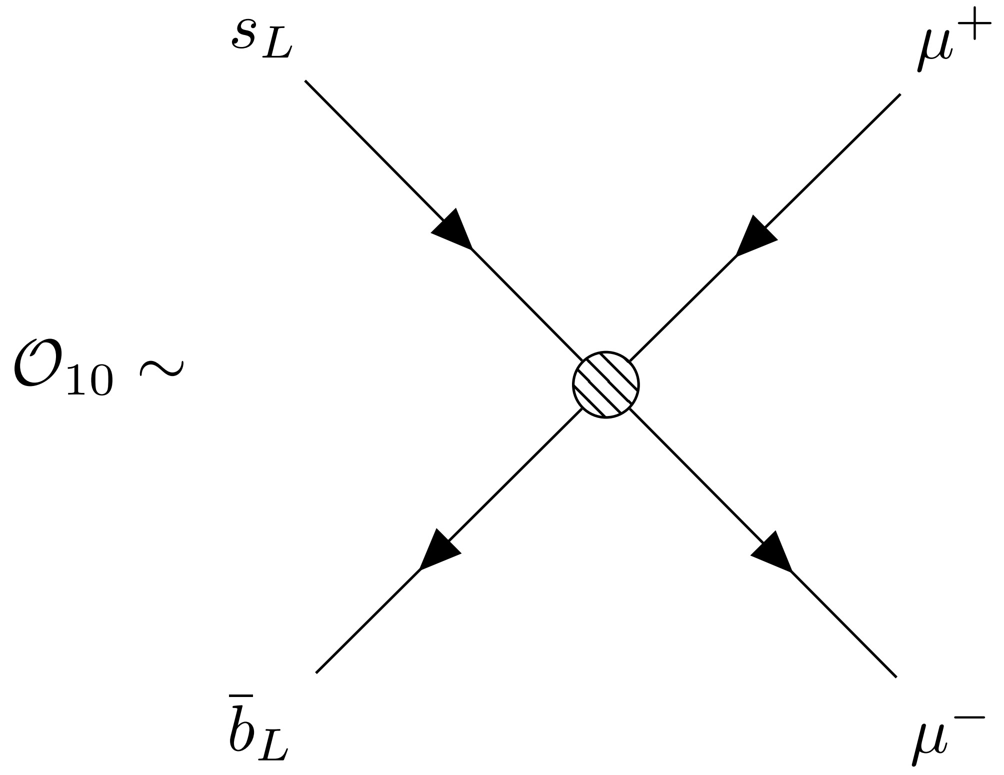


$$\left[\mathcal{O}^1_{\phi q}\right]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)(\bar{q}_i \gamma^\mu q_j)$$

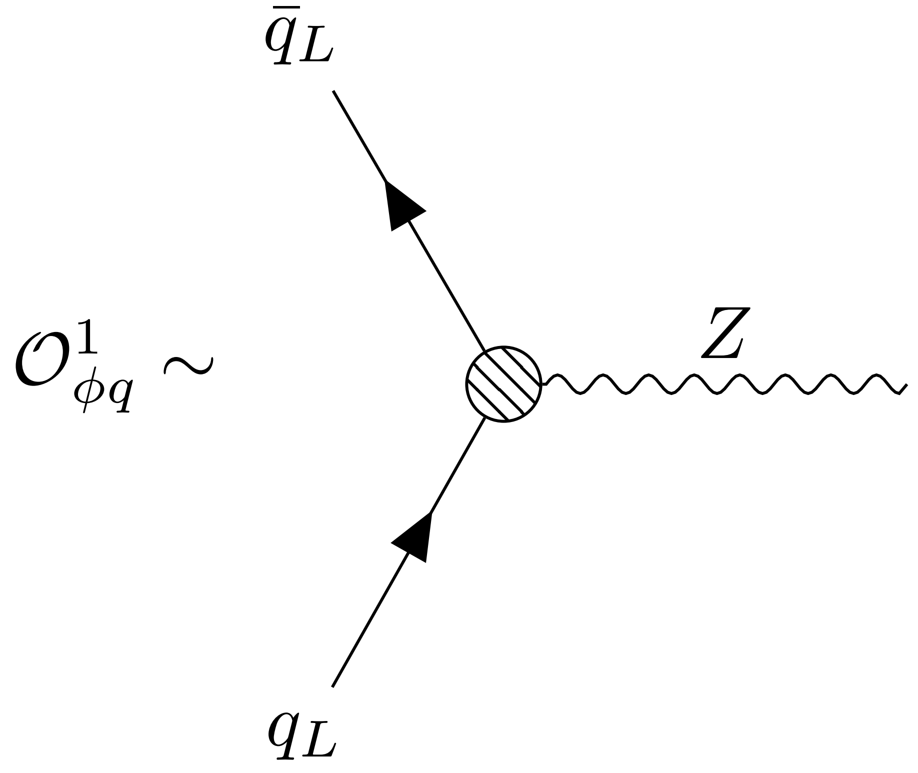
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

WET

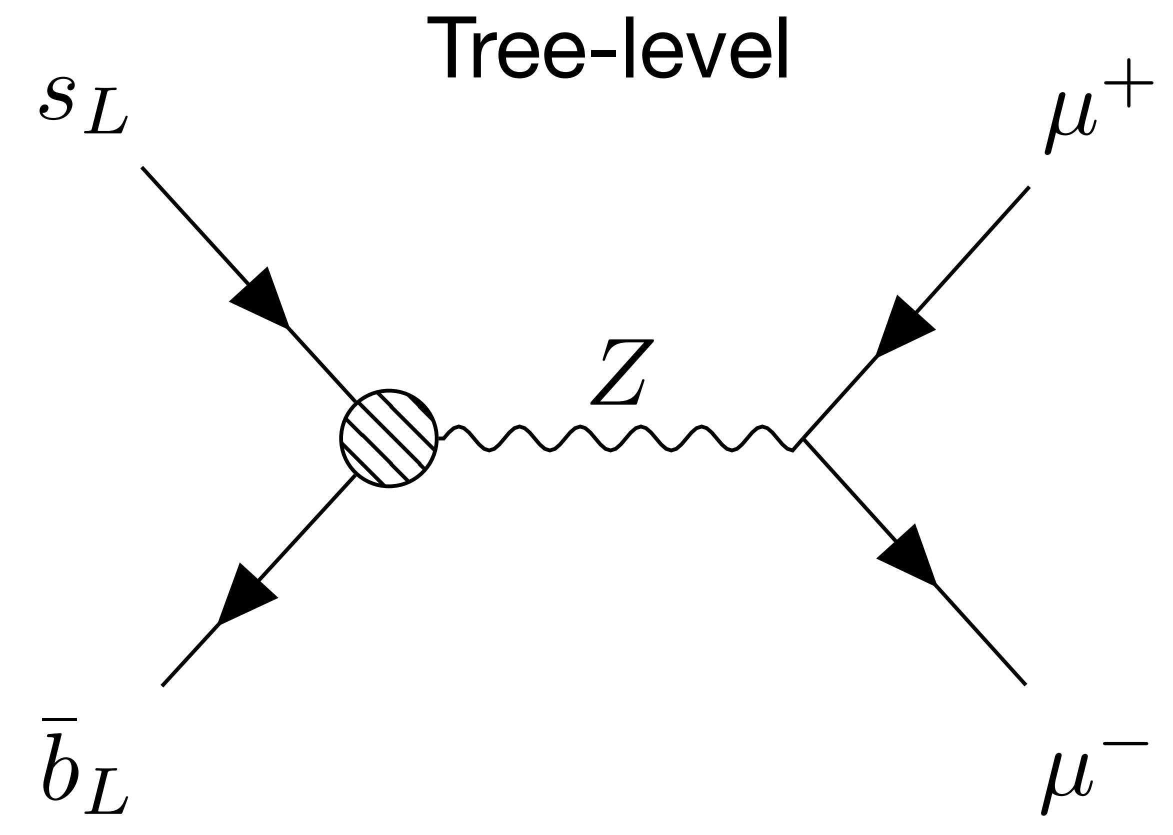


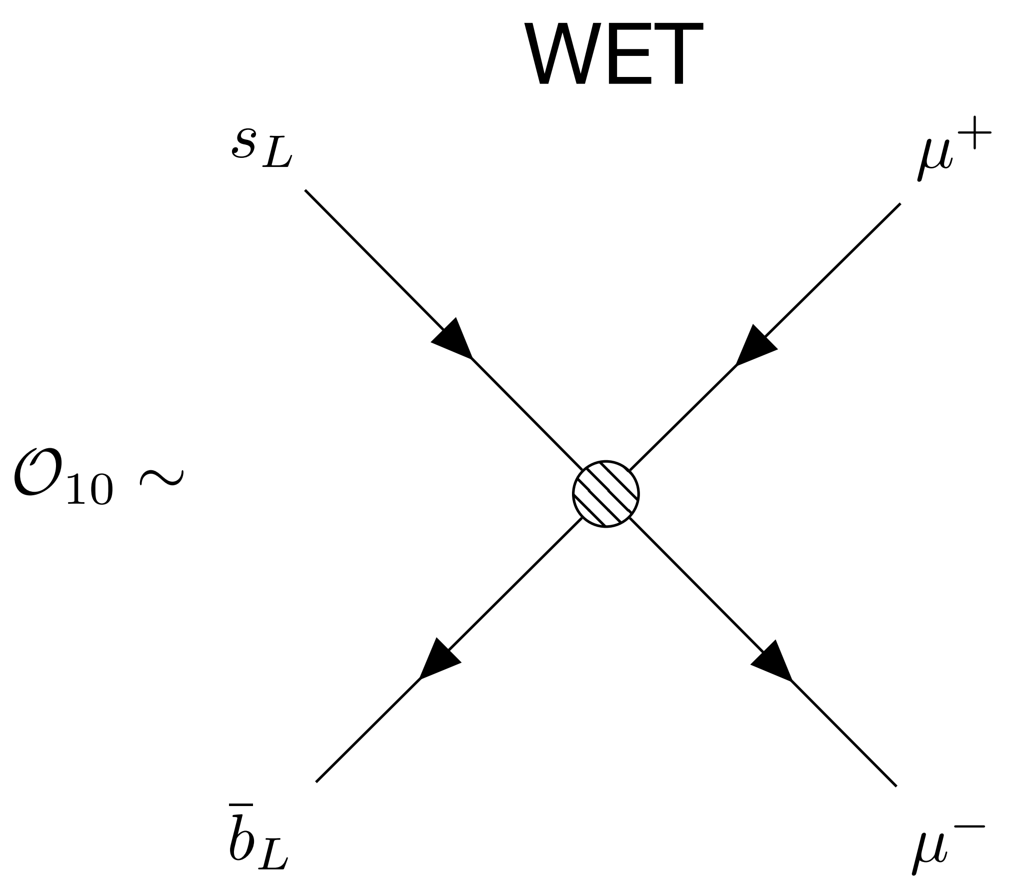
SMEFT

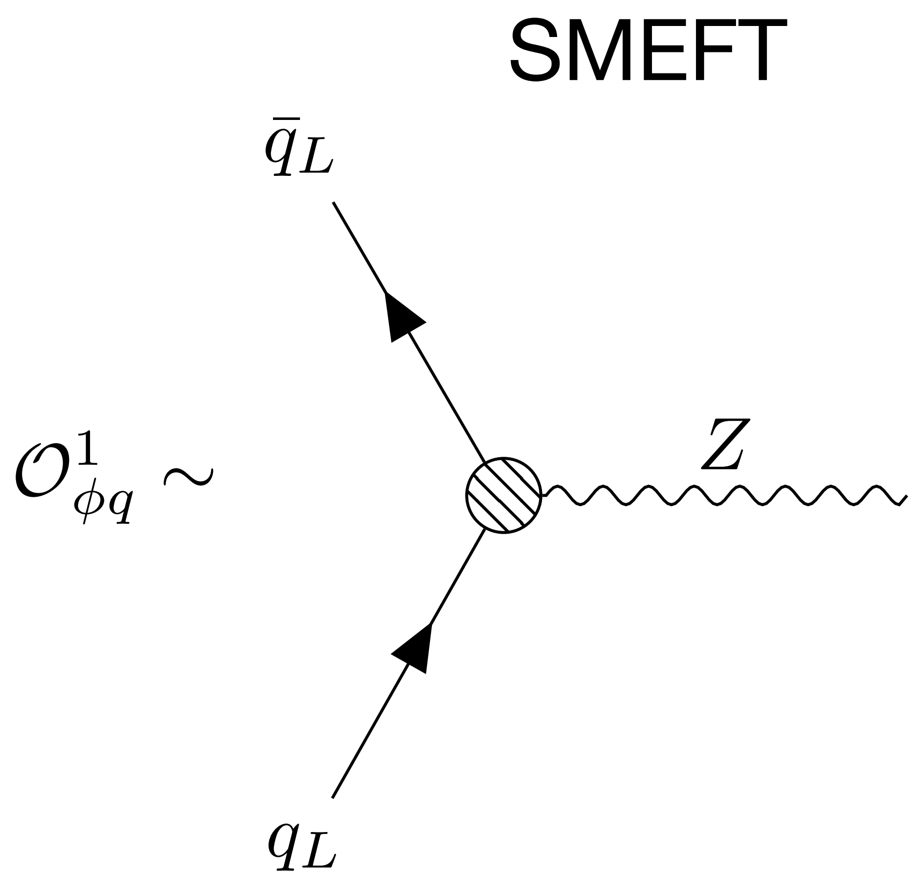


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

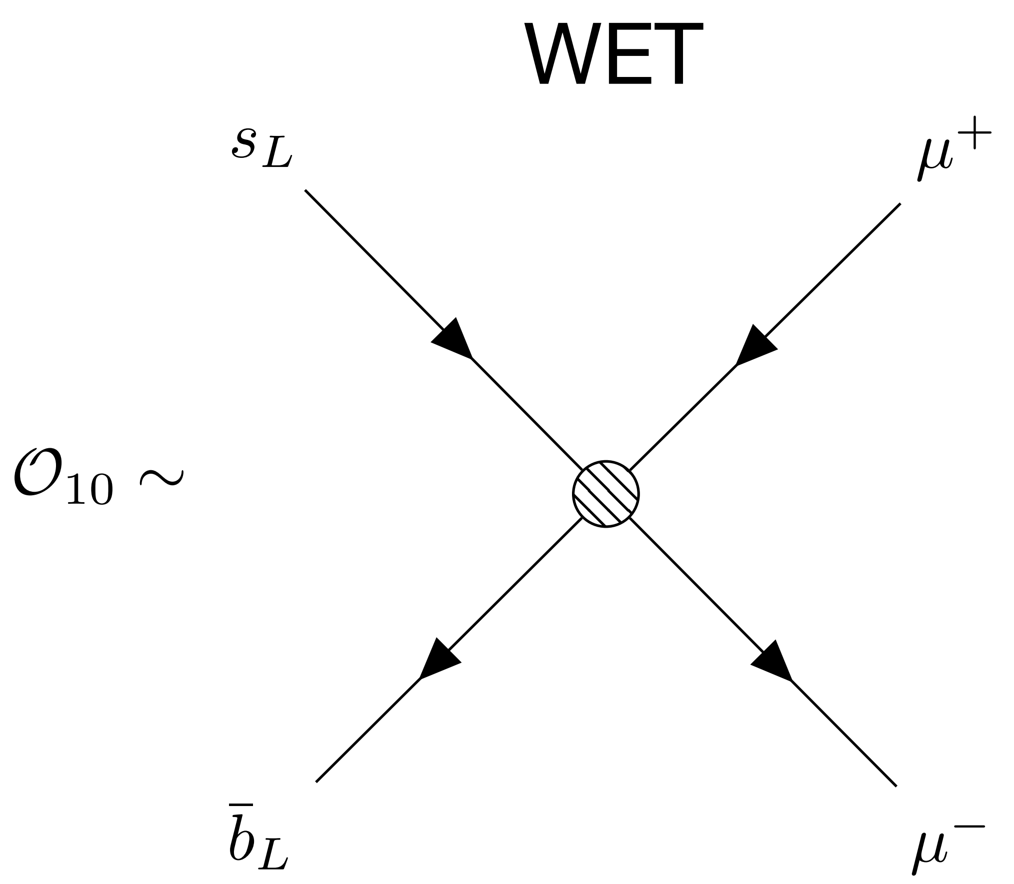


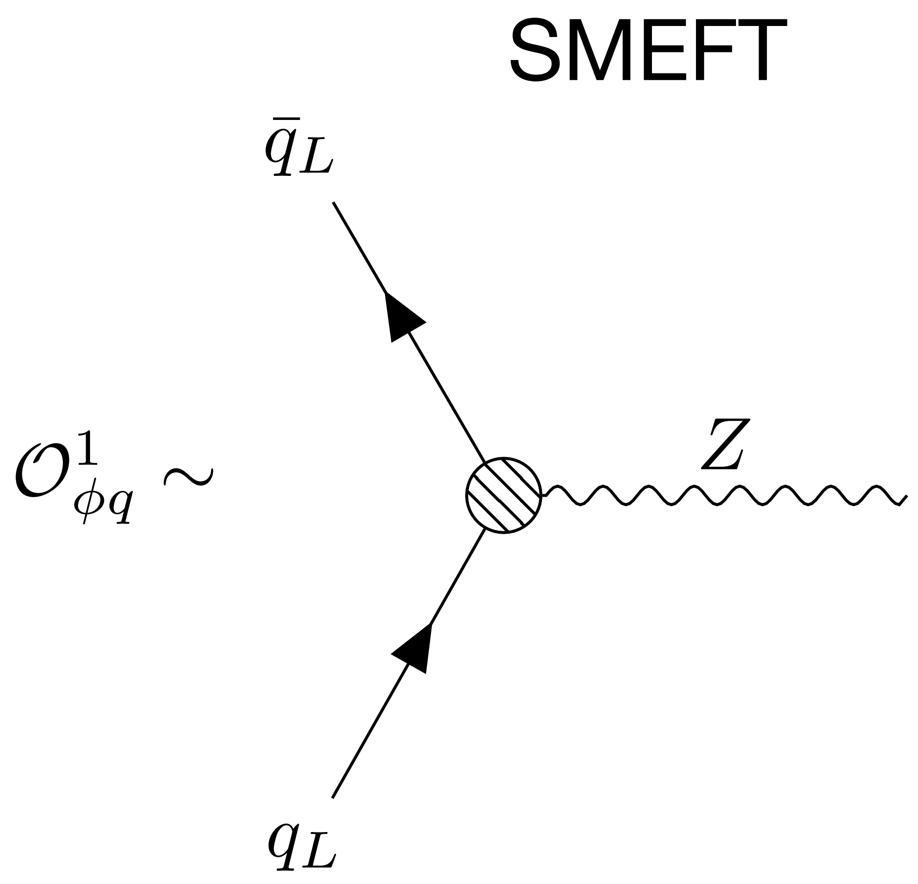


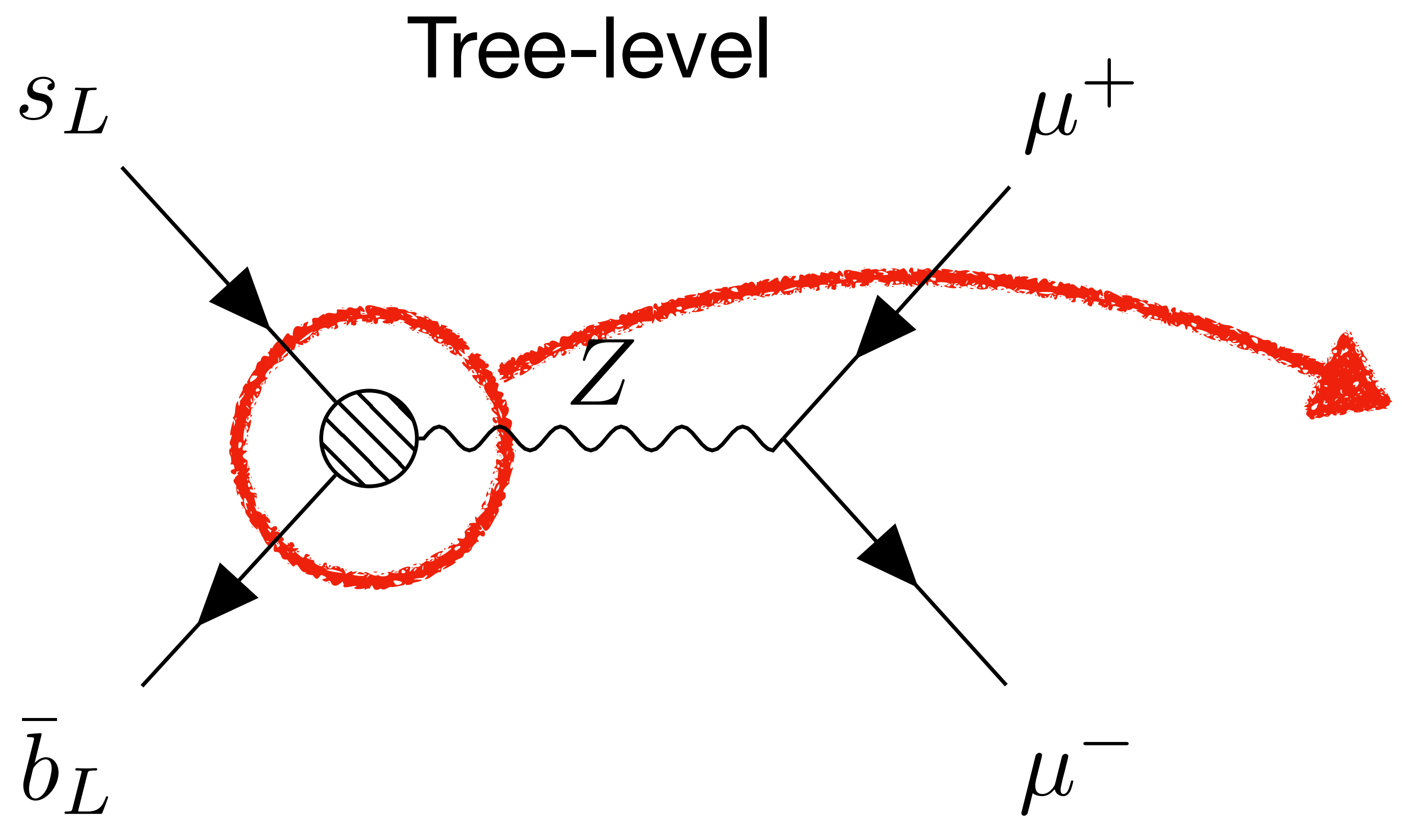


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down







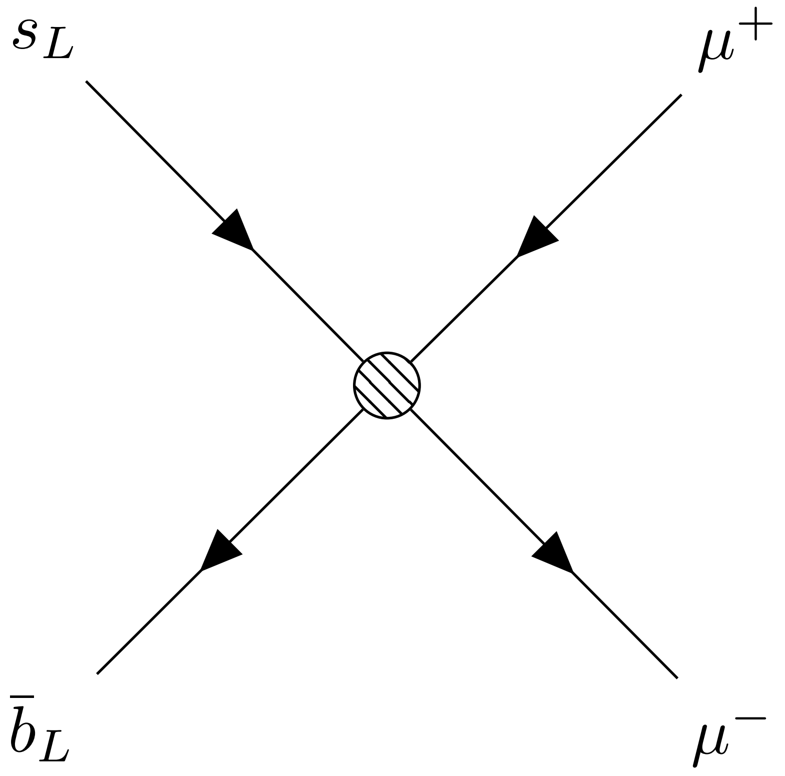
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

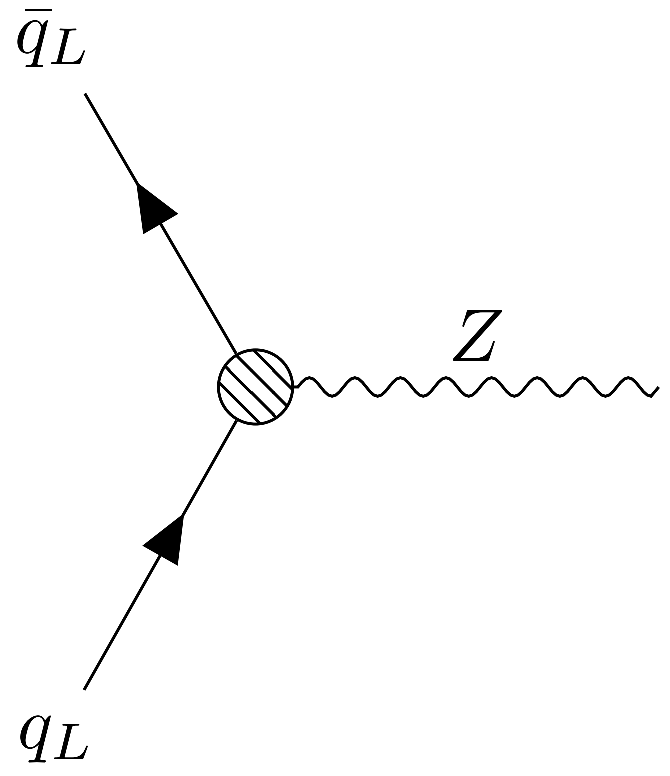
WET

$\mathcal{O}_{10} \sim$

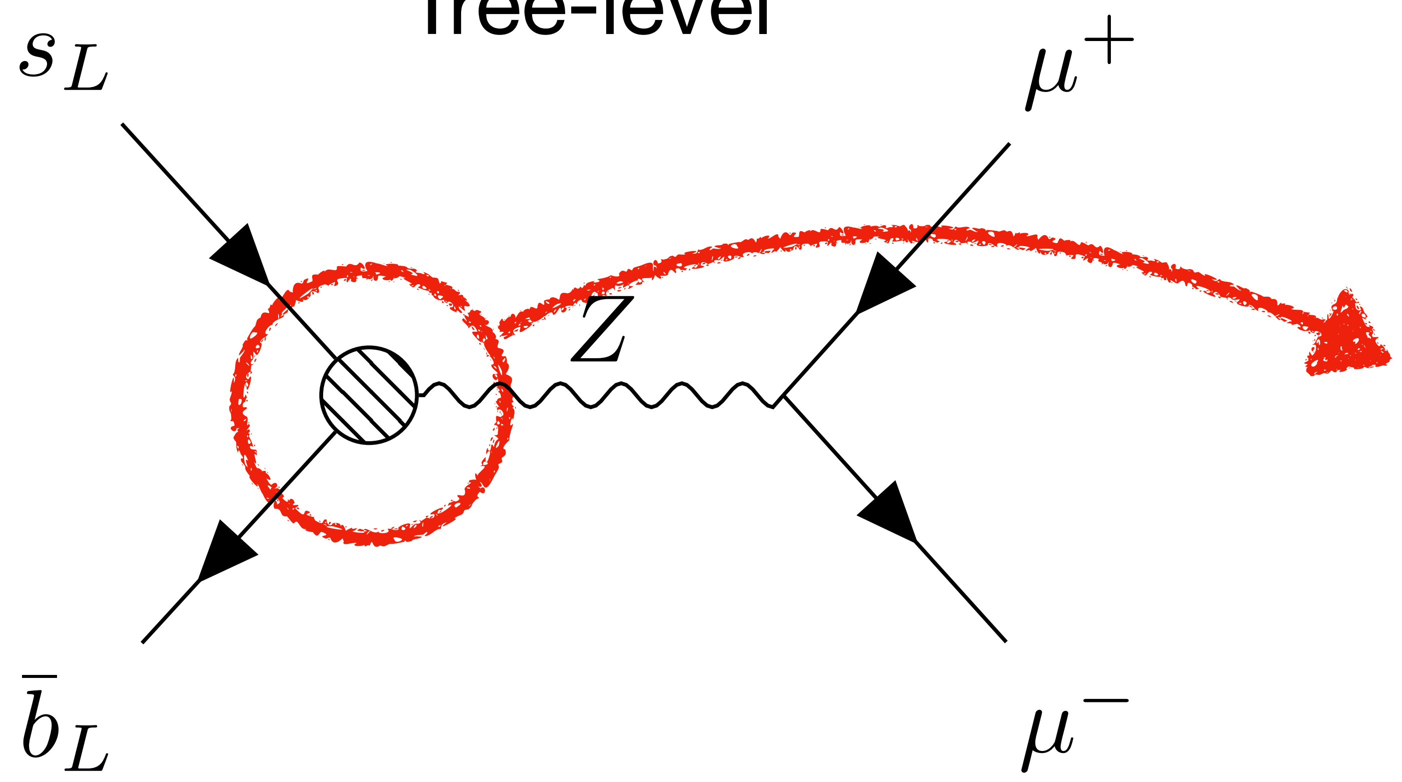


SMEFT

$\mathcal{O}^1_{\phi q} \sim$



Tree-level



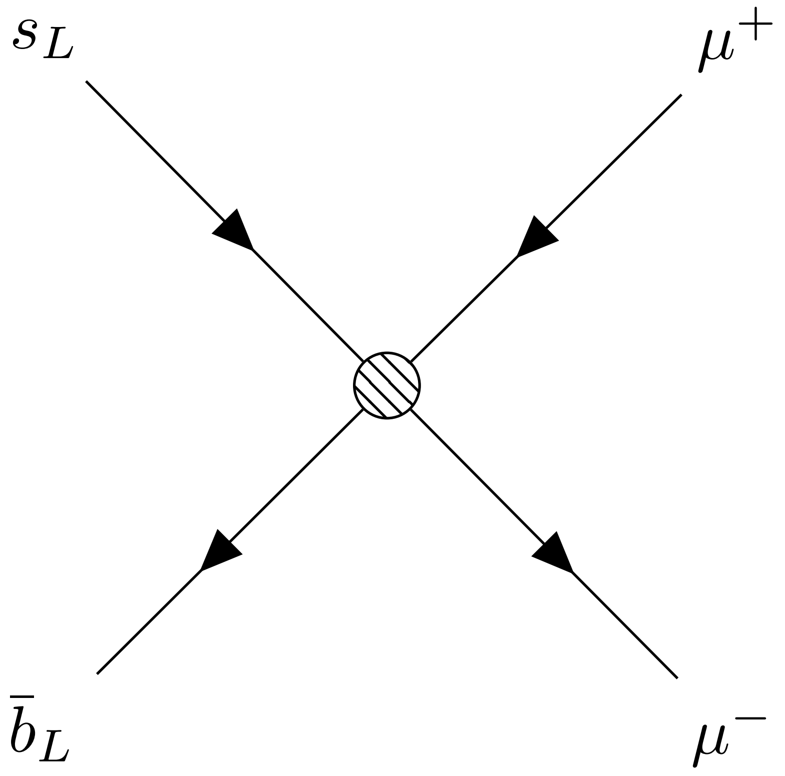
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

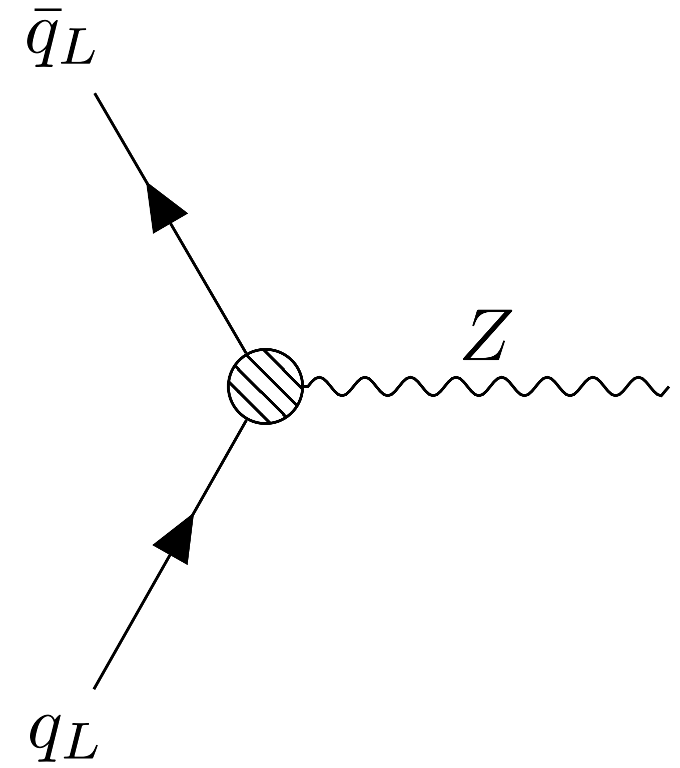
WET

$\mathcal{O}_{10} \sim$

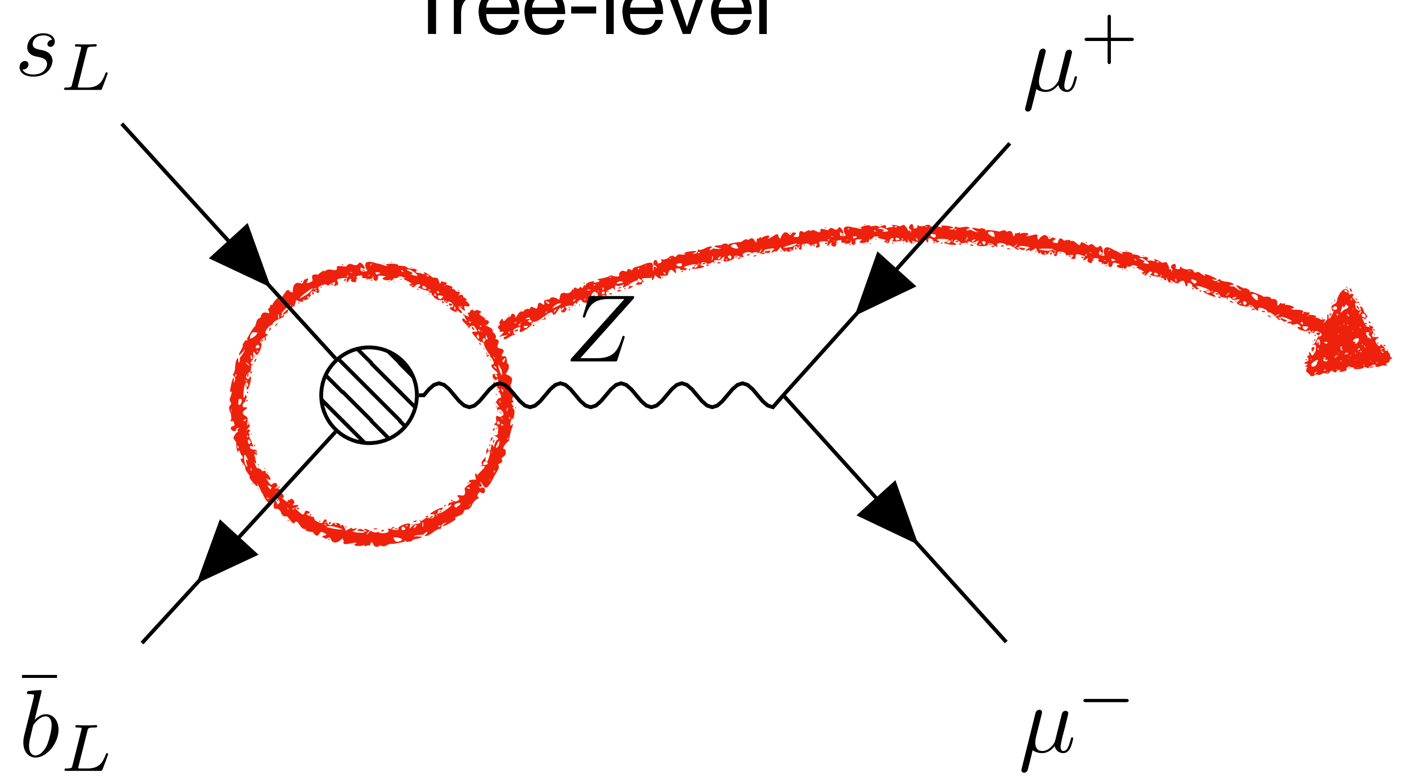


SMEFT

$\mathcal{O}^1_{\phi q} \sim$



Tree-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

$$\mathcal{C}_{10}$$

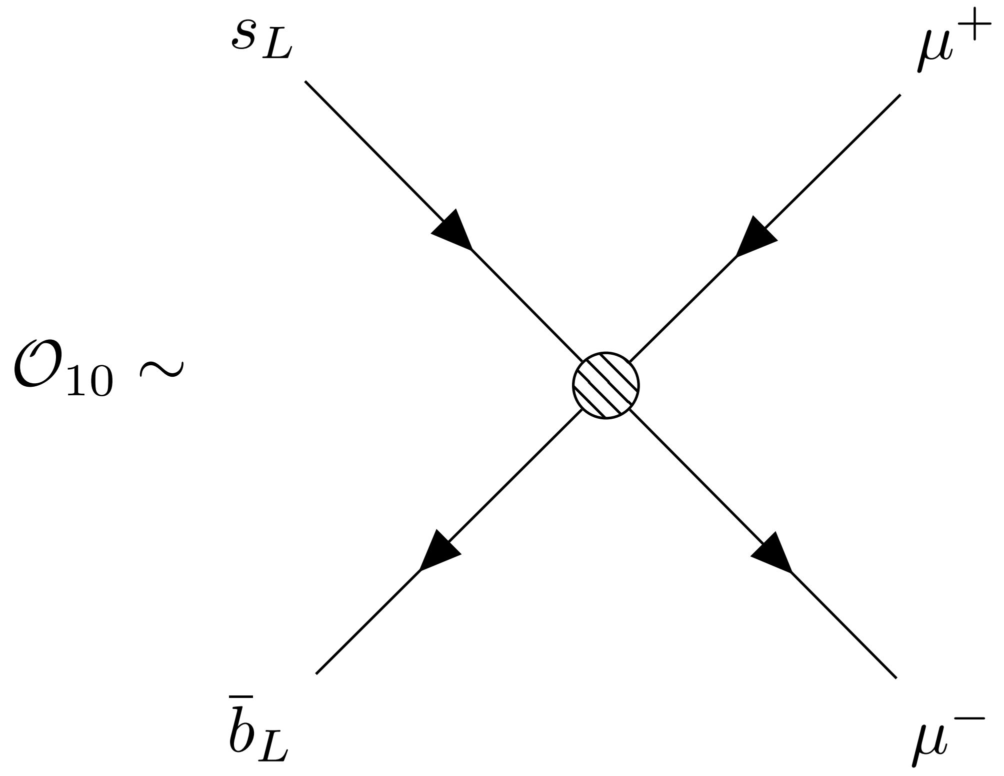
$$b$$

$\mathcal{C}^1_{\phi q}$ { Tree-level / Loop-level

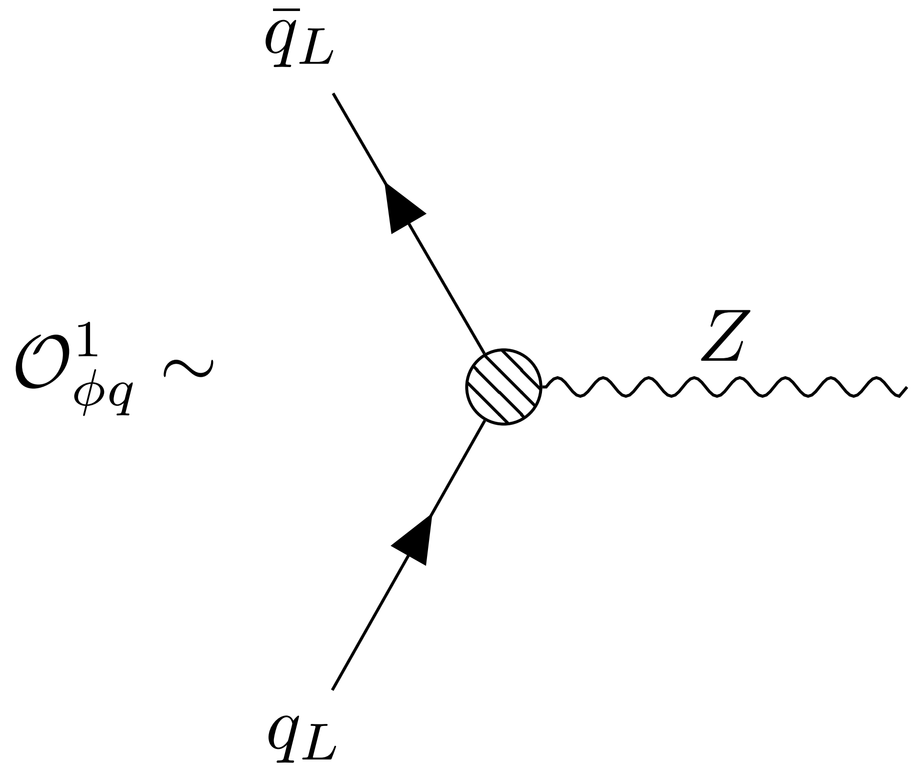
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

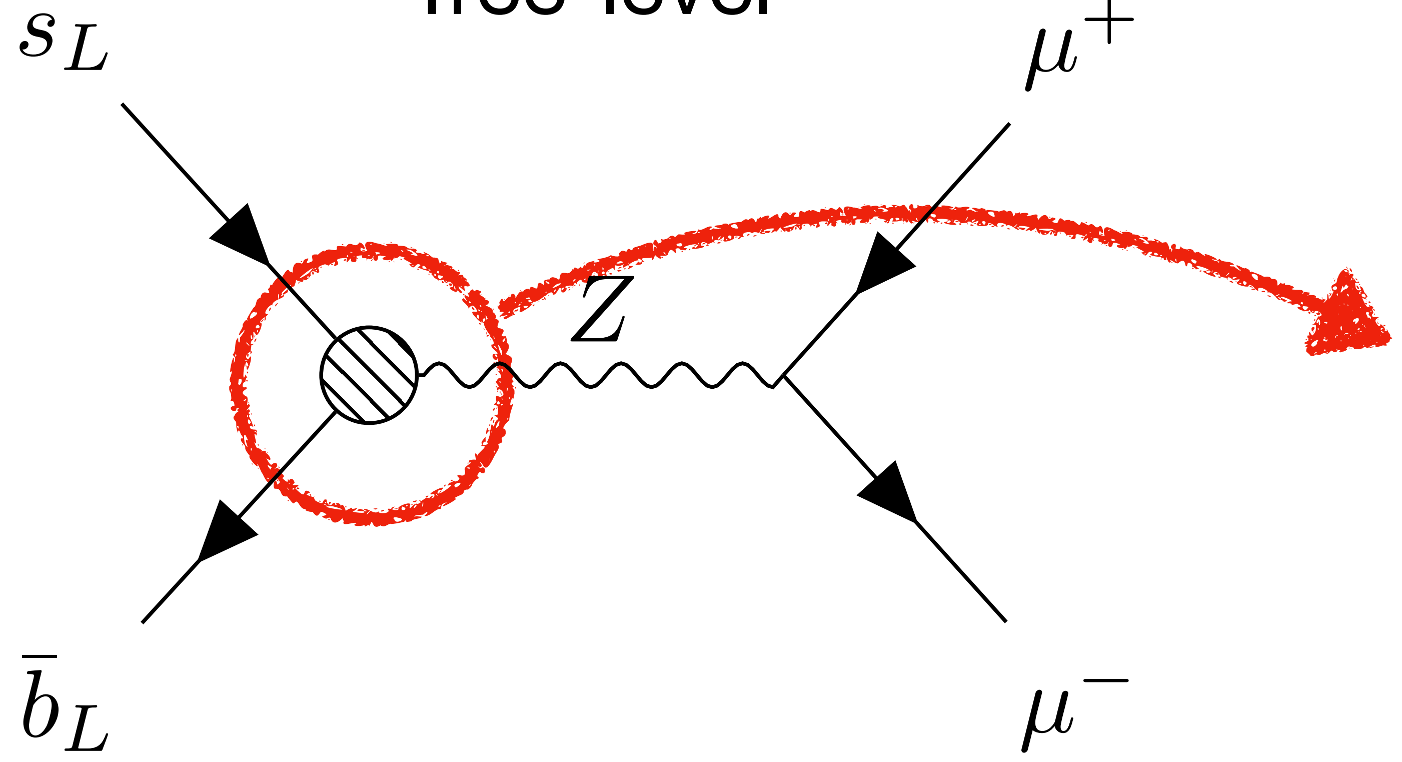
WET



SMEFT



Tree-level



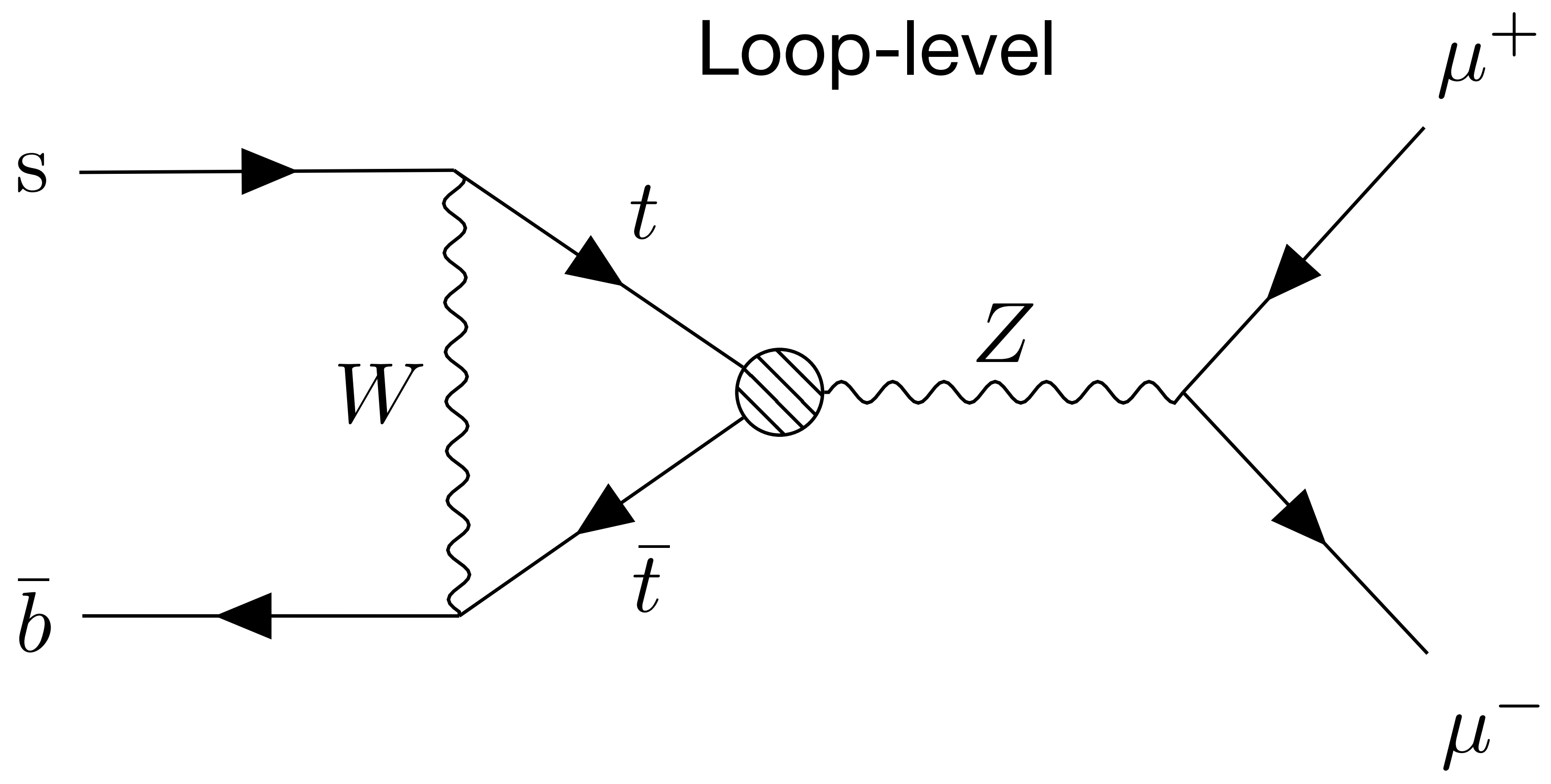
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

$$\mathcal{C}_{10}$$

$$b$$

$\mathcal{C}^1_{\phi q}$ { Tree-level / Loop-level

Loop-level

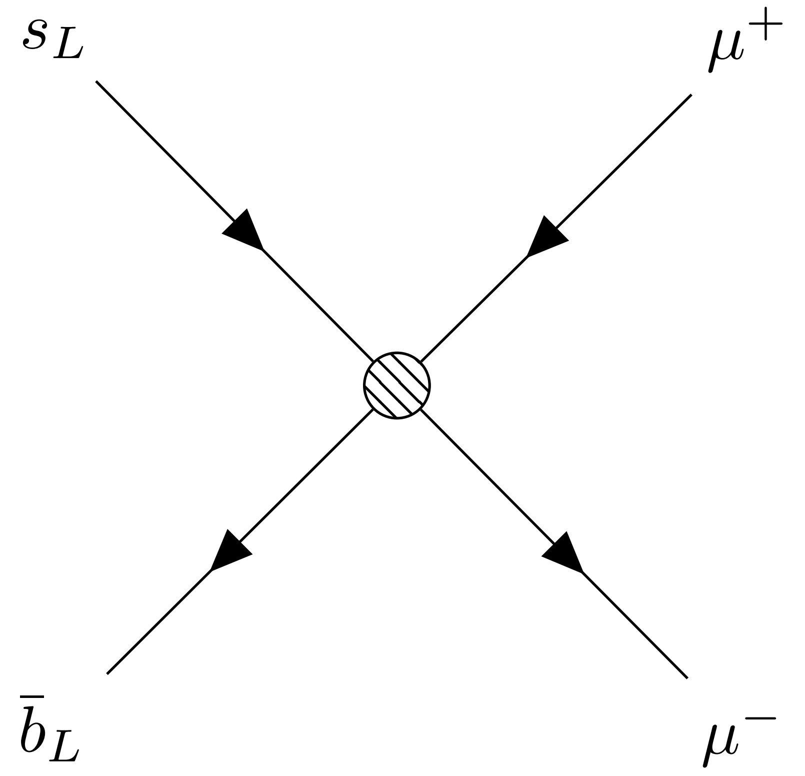


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

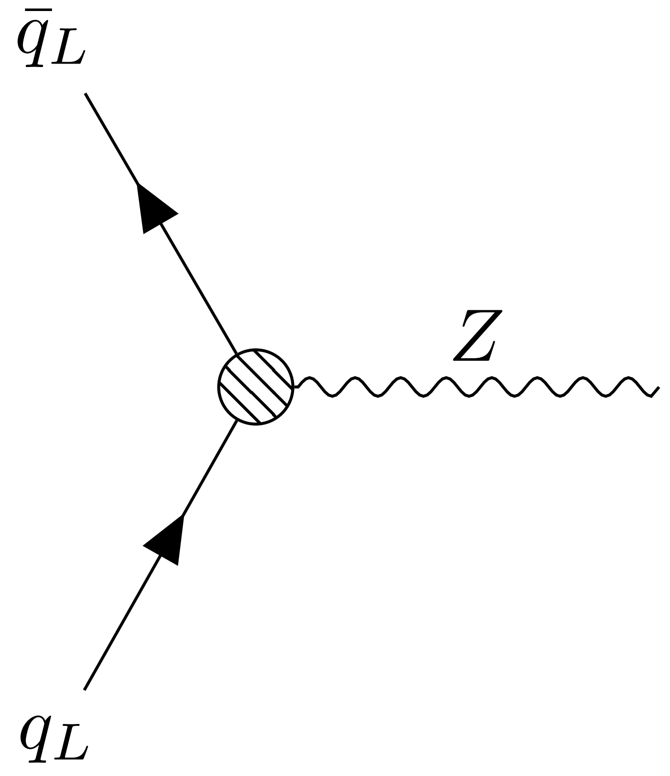
WET

$\mathcal{O}_{10} \sim$

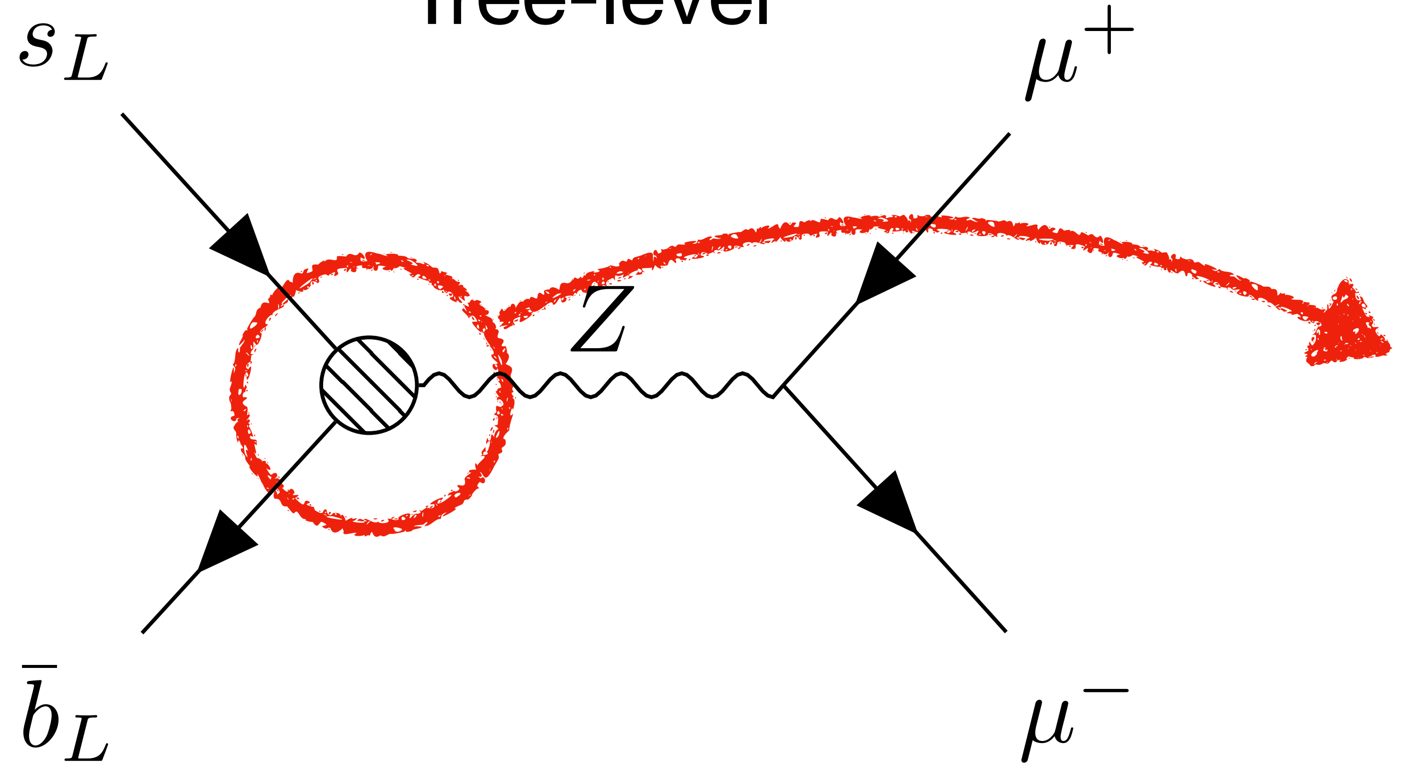


SMEFT

$\mathcal{O}^1_{\phi q} \sim$

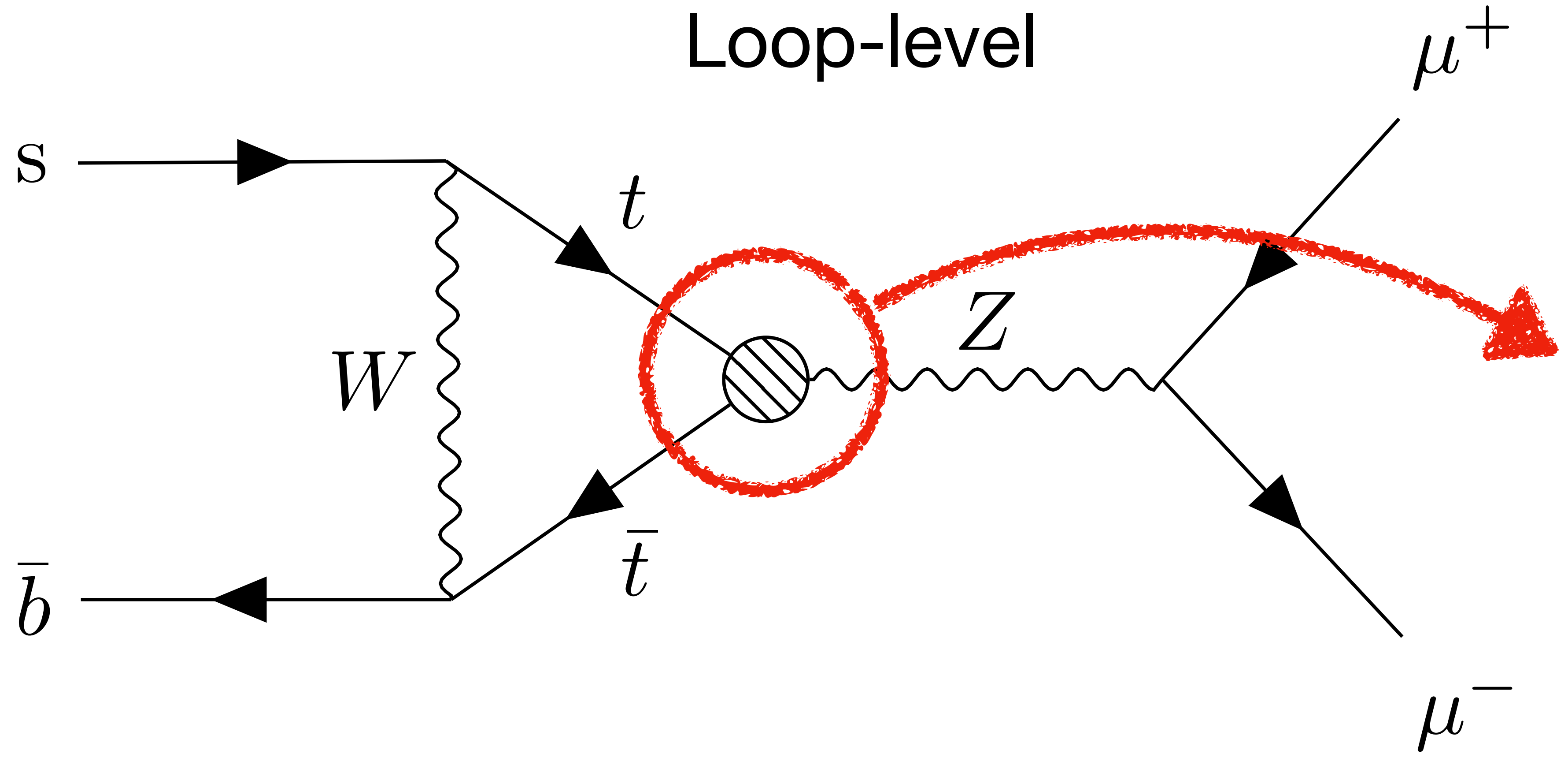


Tree-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

Loop-level



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

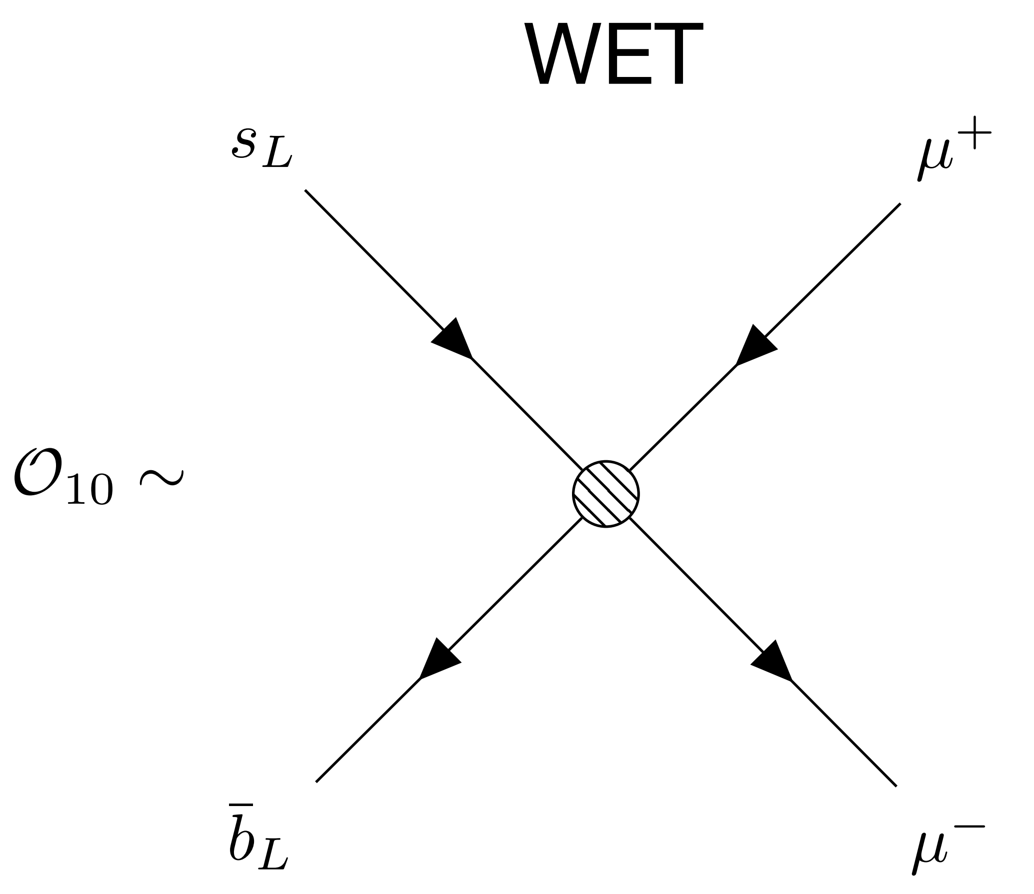
$$\mathcal{C}_{10}$$

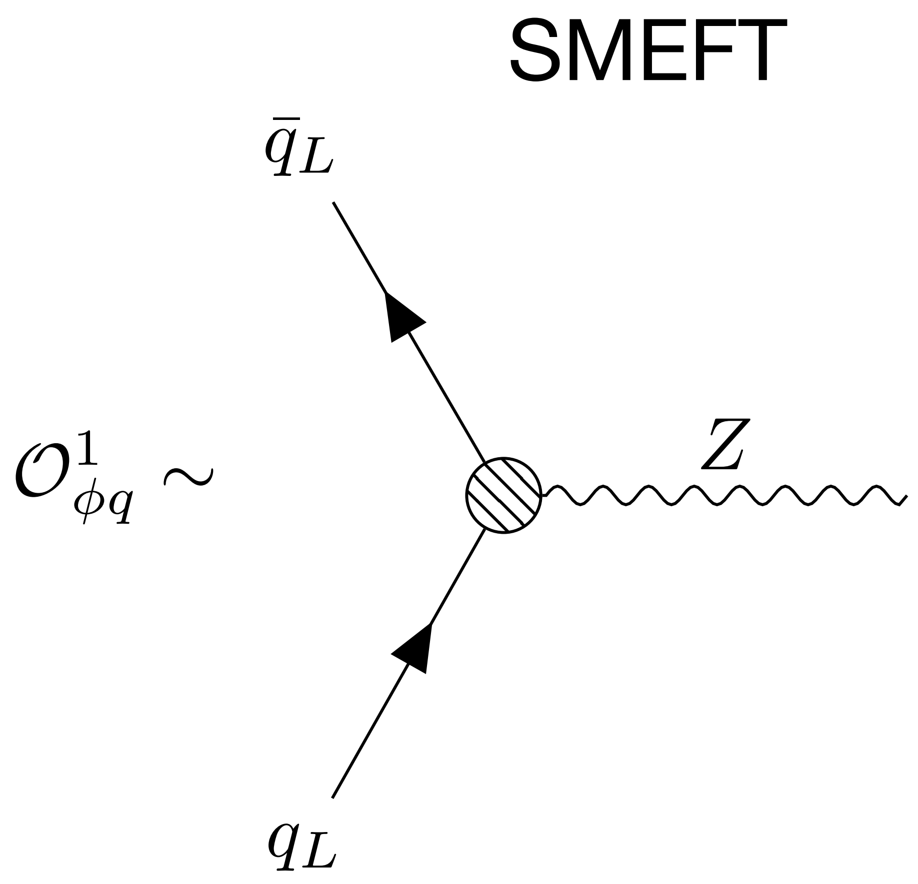
$$b$$

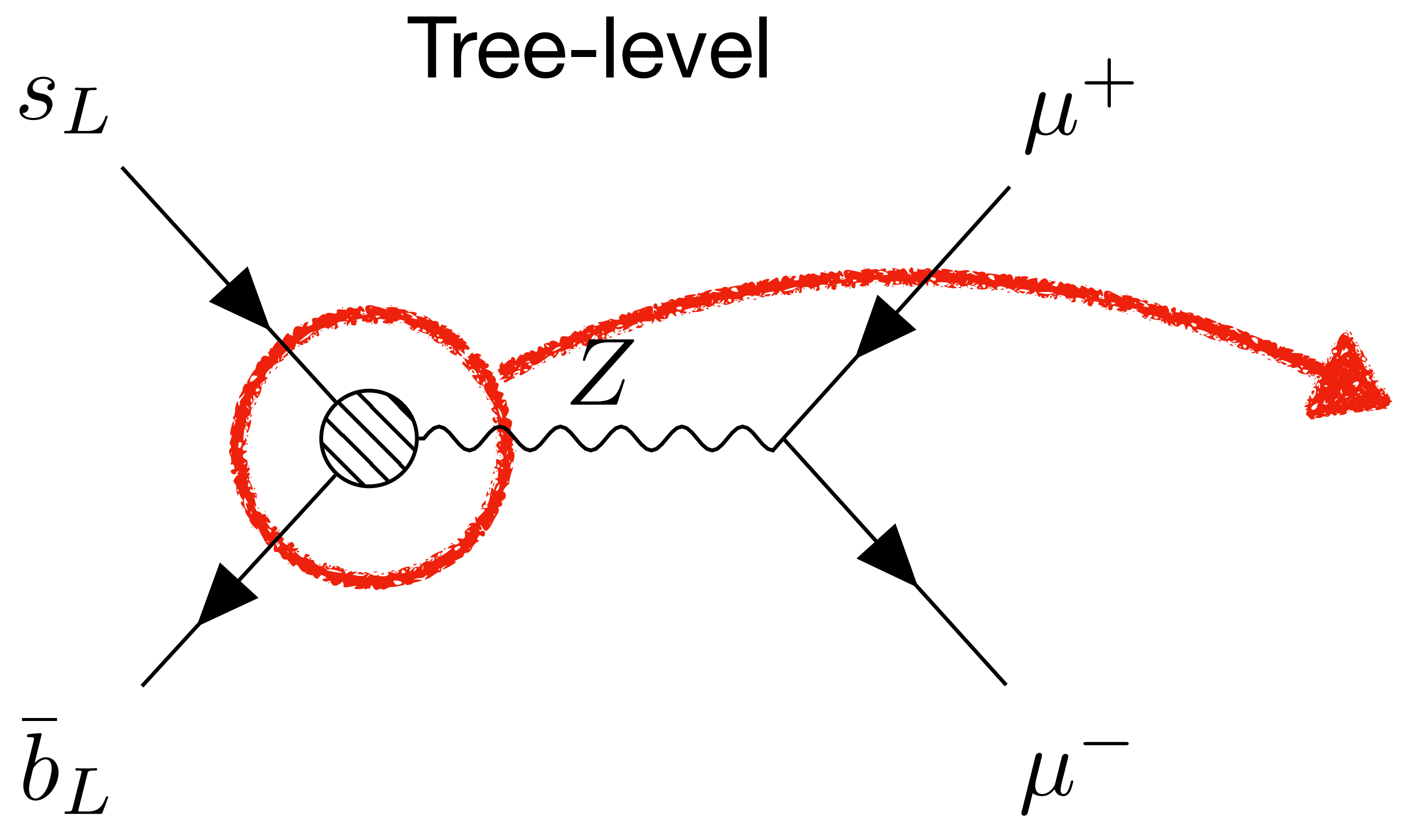
$\mathcal{C}^1_{\phi q}$ { Tree-level / Loop-level

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

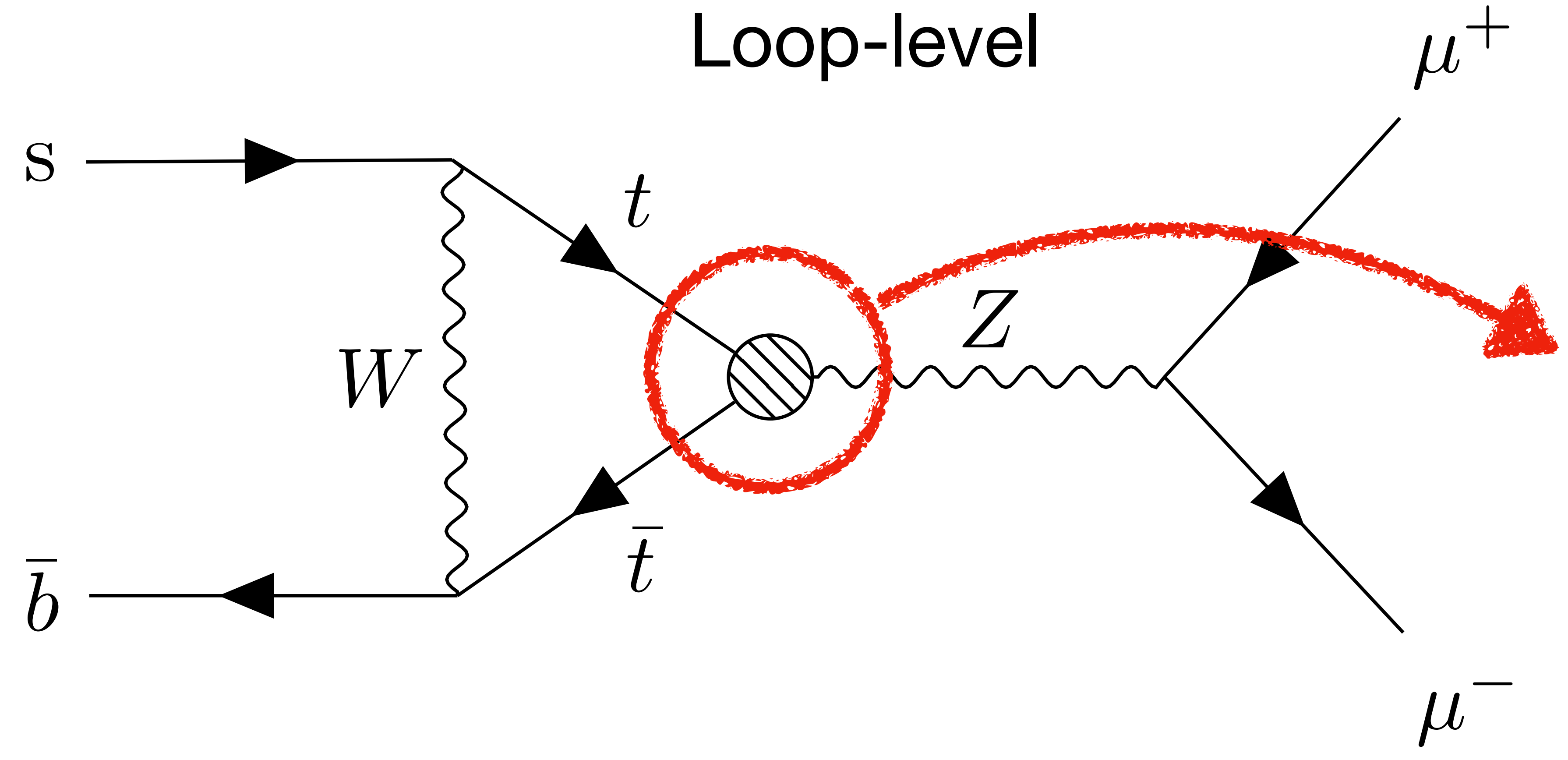
Top-Down







$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

$$\mathcal{C}_{10}$$

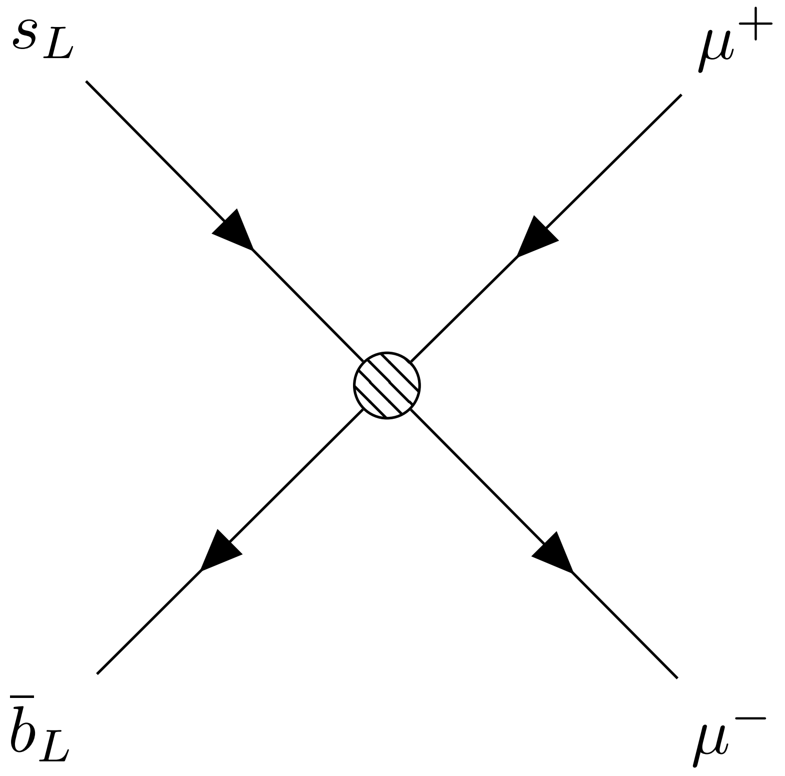
$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} & b \\ \text{Loop-level} & a + y_t^2 b \end{cases}$$

MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

Top-Down

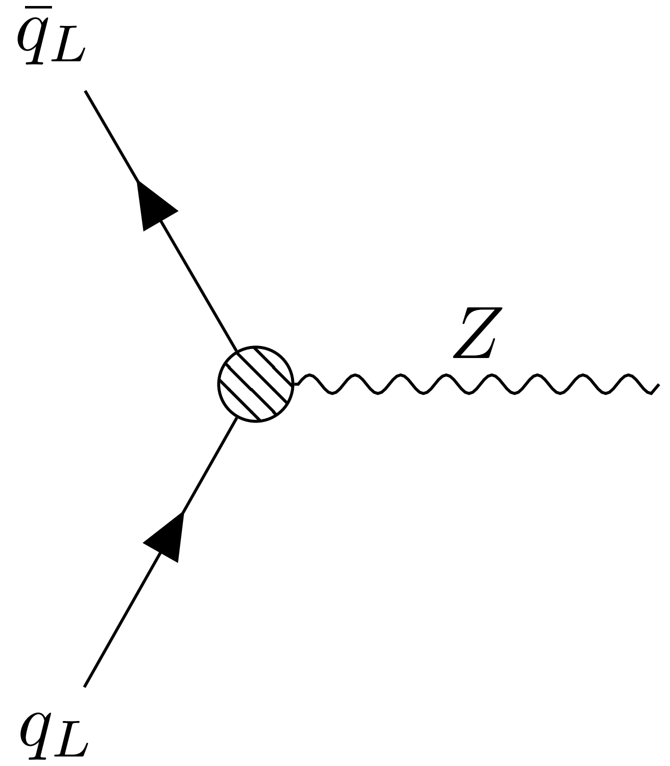
WET

$\mathcal{O}_{10} \sim$

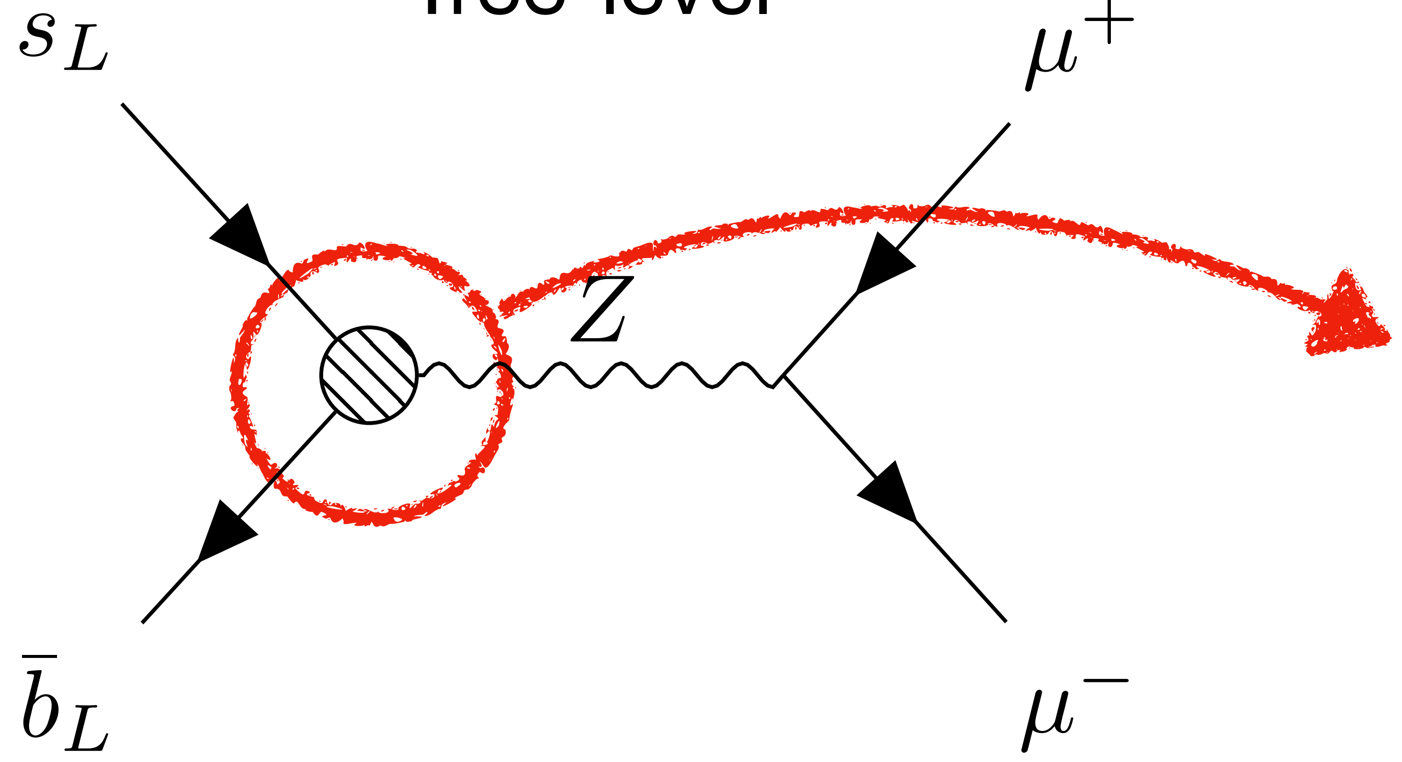


SMEFT

$\mathcal{O}^1_{\phi q} \sim$

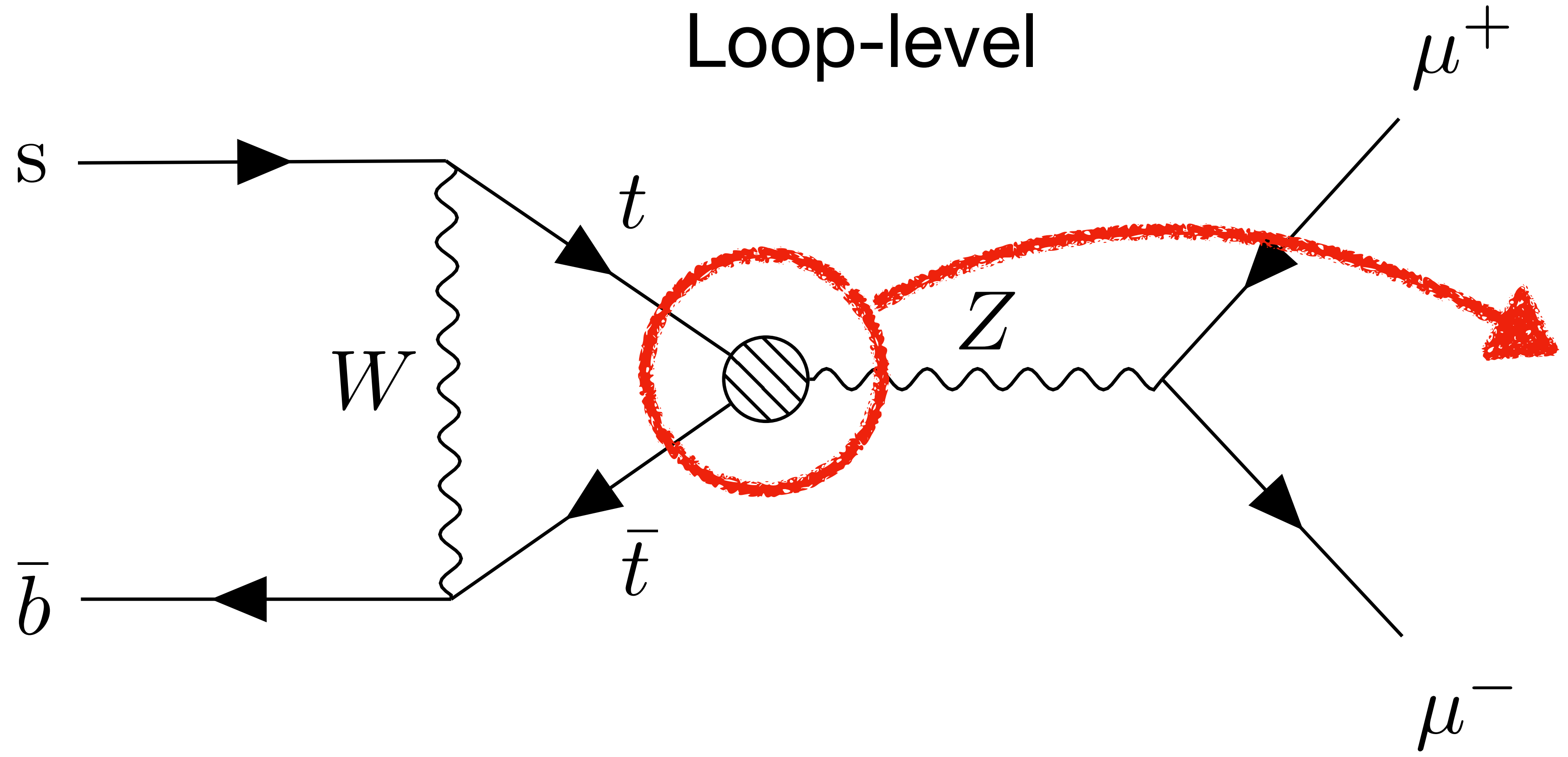


Tree-level



$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$

Loop-level



$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$

Matching & Running	$\mathcal{C}_{10}$
$a^1_{\phi q}$	0.1
$b^1_{\phi q}$	24.73

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$$\left[\mathcal{O}^1_{\phi q}\right]_{ij} = \left(\phi^\dagger \, i \, \overleftrightarrow{D}_\mu \, \phi\right)\left(\bar{q}_i \gamma^\mu q_j\right)$$

$$\left[\mathcal{O}^3_{\phi q}\right]_{ij} = \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$$

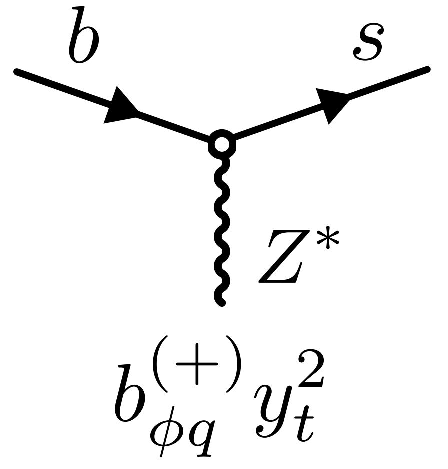
An Example: $C^{1}_{\phi Q}$ & $C^{3}_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^{1}_{\phi Q} - C^{3}_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^{1}_{\phi Q} + C^{3}_{\phi Q}$$

$$\left[\mathcal{O}^{1}_{\phi q}\right]_{ij} = \left(\phi^\dagger \, i \overleftrightarrow{D}_{\mu} \, \phi\right)\left(\bar{q}_i \gamma^\mu q_j\right)$$

$$\left[\mathcal{O}^{3}_{\phi q}\right]_{ij} = \left(\phi^\dagger i \overleftrightarrow{D}^{I}_{\mu} \phi\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$$



$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2$$

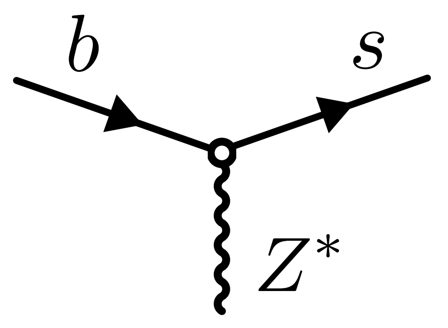
An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

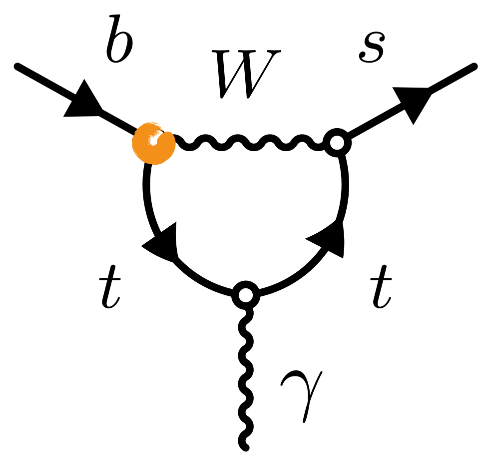
$$\left[\mathcal{O}^1_{\phi q}\right]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)\left(\bar{q}_i \gamma^\mu q_j\right)$$

$$\left[\mathcal{O}^3_{\phi q}\right]_{ij} = \left(\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$$

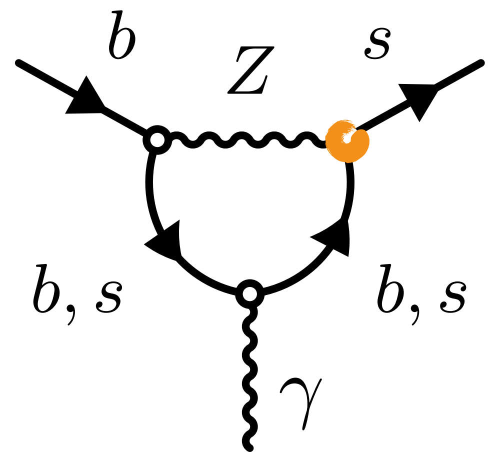


$b^{(+)}_{\phi q} y_t^2$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9 = 3.57 - 41.0\, b^{(+)}_{\phi q} + 117.8 (b^{(+)}_{\phi q})^2$$



$a^{(3)}_{\phi q} + b^{(3)}_{\phi q} y_t^2$



$b^{(3)}_{\phi q}$

$$\mathcal{B}(B \to X_s \gamma) \times 10^4 = 3.26 + 0.36\, a^{(3)}_{\phi q} - 0.76\, b^{(3)}_{\phi q}$$

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$$

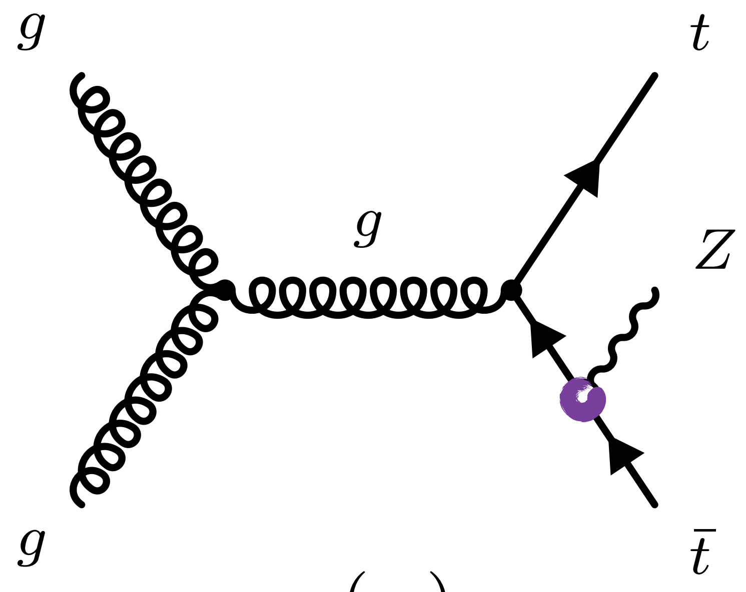
An Example: $C^{1}_{\phi Q}$ & $C^{3}_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^{1}_{\phi Q} - C^{3}_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^{1}_{\phi Q} + C^{3}_{\phi Q}$$

$$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$$



$A^{(-)}_{\phi q}$

$$A = a + y_t^2 b$$

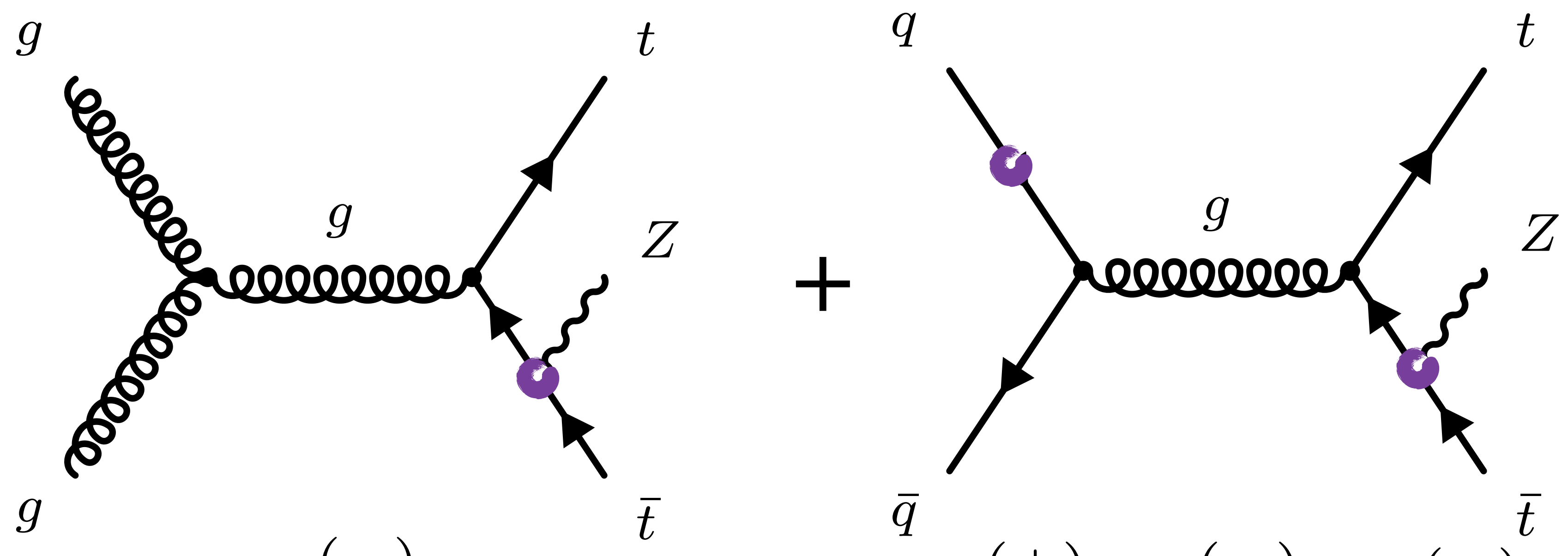
An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$

$$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$$



$A^{(-)}_{\phi q}$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$

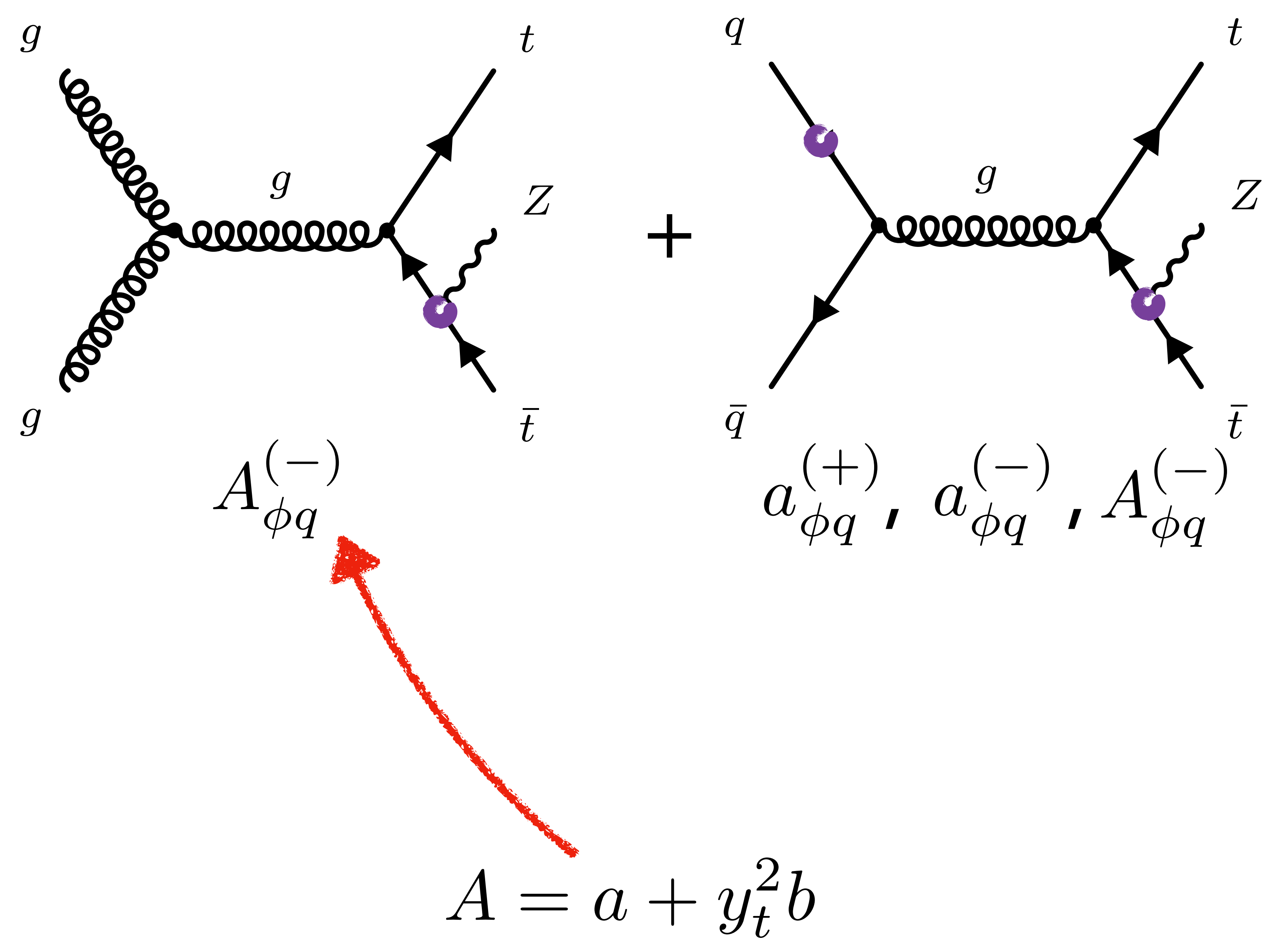
$$A = a + y_t^2 b$$

An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

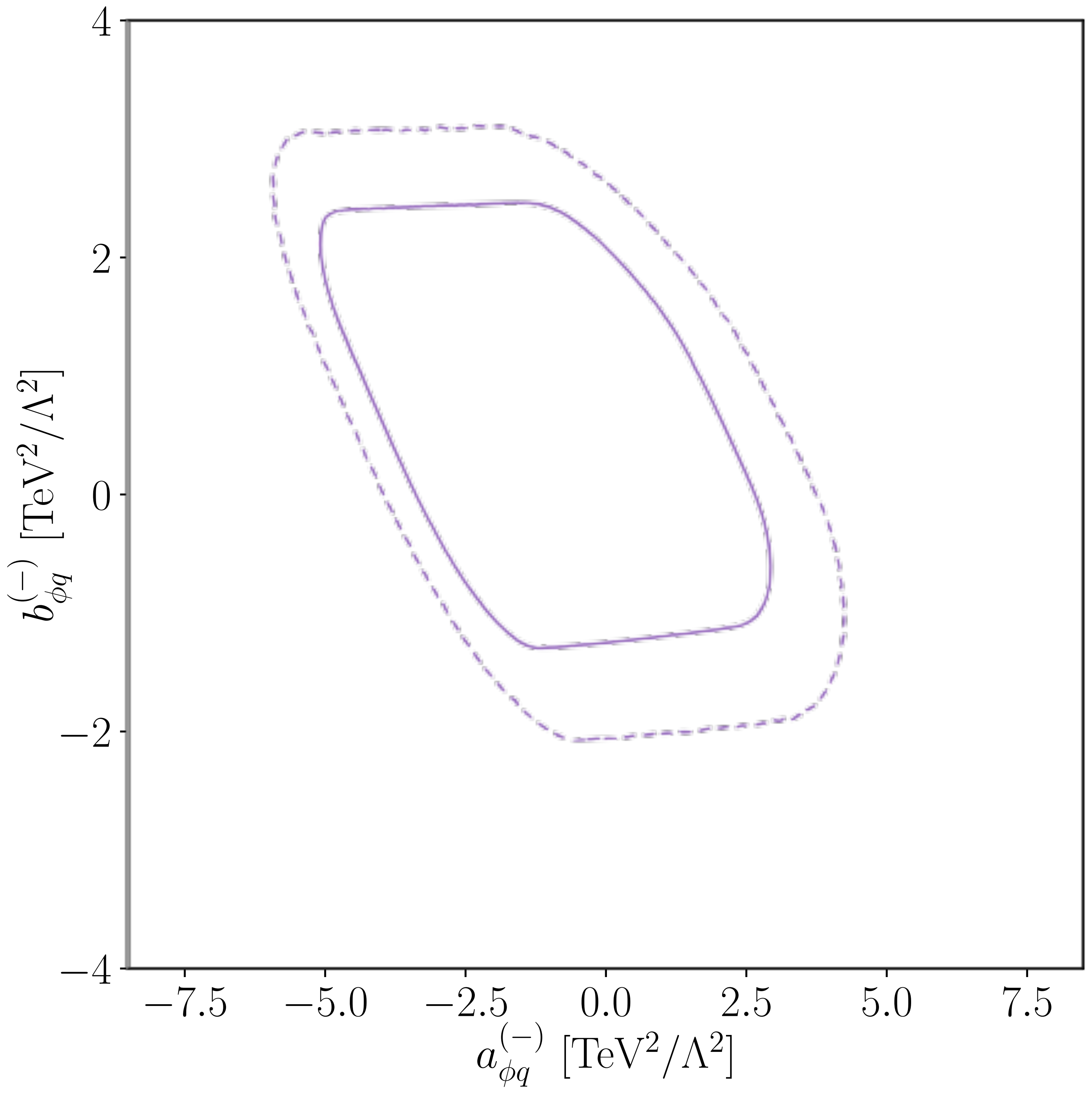
TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$



$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$

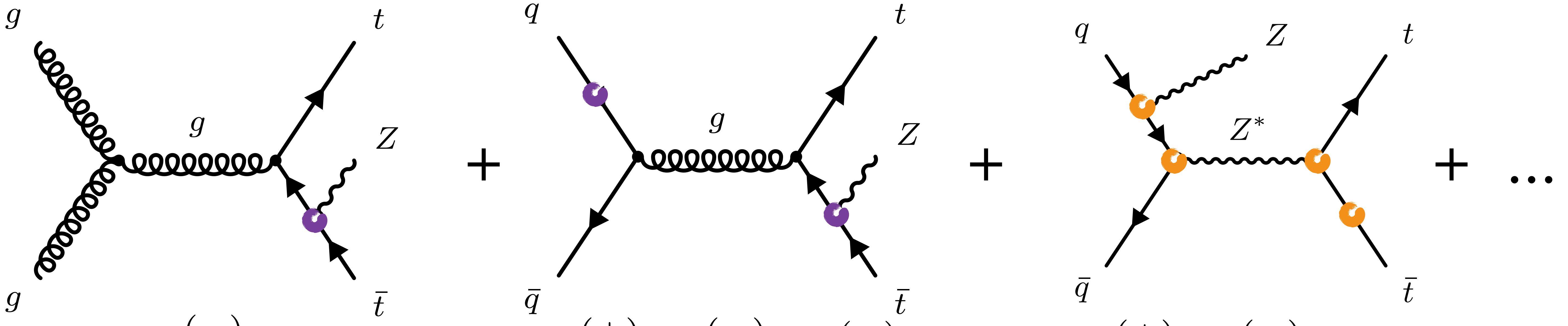


An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

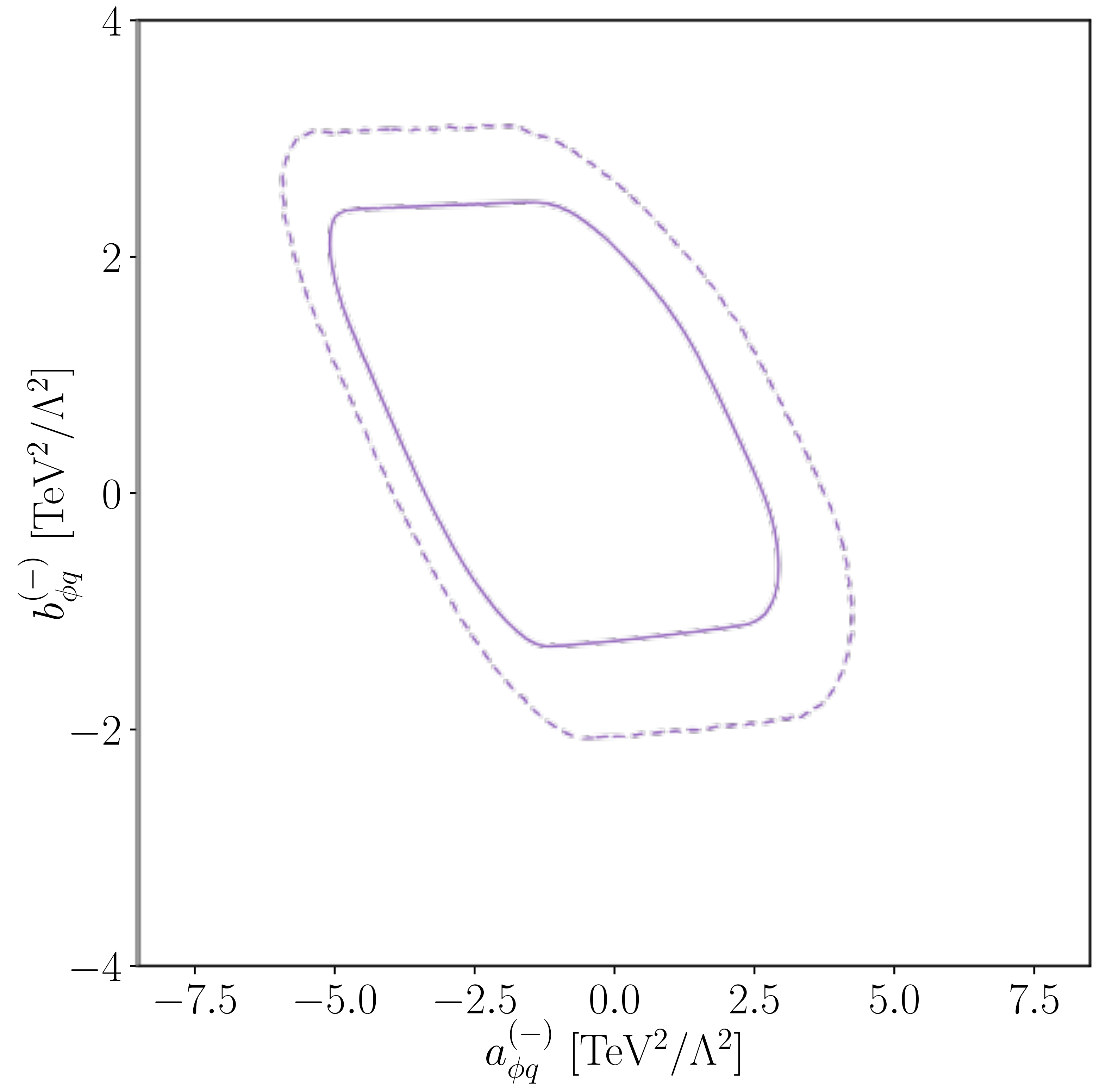
$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$



$A^{(-)}_{\phi q}$ $\qquad$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$ $\qquad$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$

$$A = a + y_t^2 b$$

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$

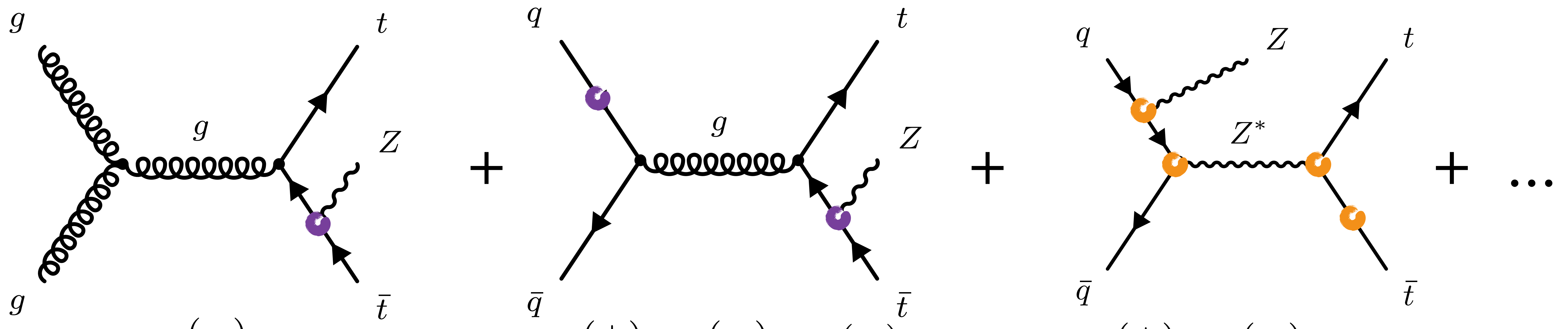


An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

TTZ Production and EW effects

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

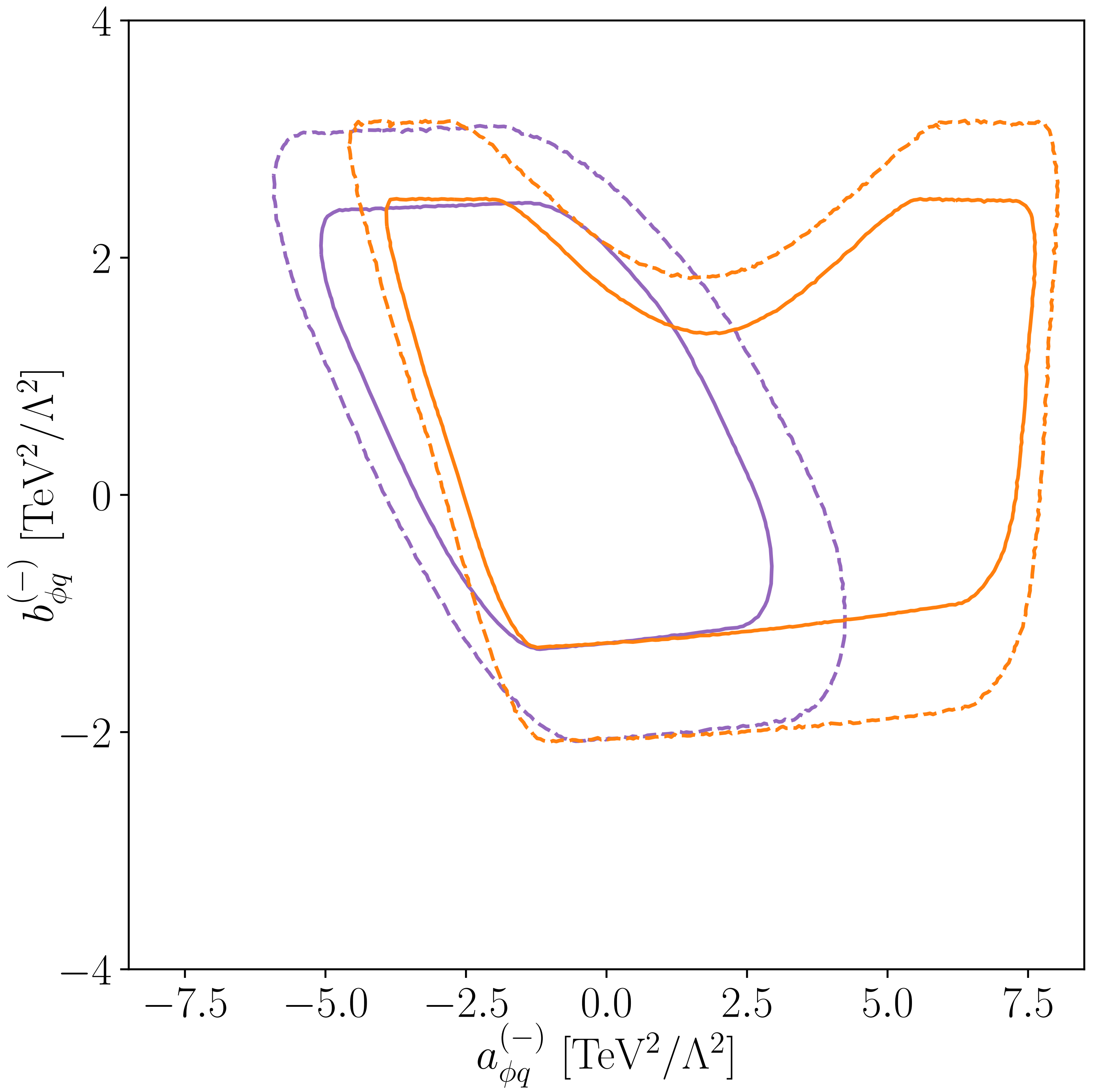
$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$



$A^{(-)}_{\phi q}$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$ $a^{(+)}_{\phi q}$, $a^{(-)}_{\phi q}$, $A^{(-)}_{\phi q}$

$$A = a + y_t^2 b$$

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$

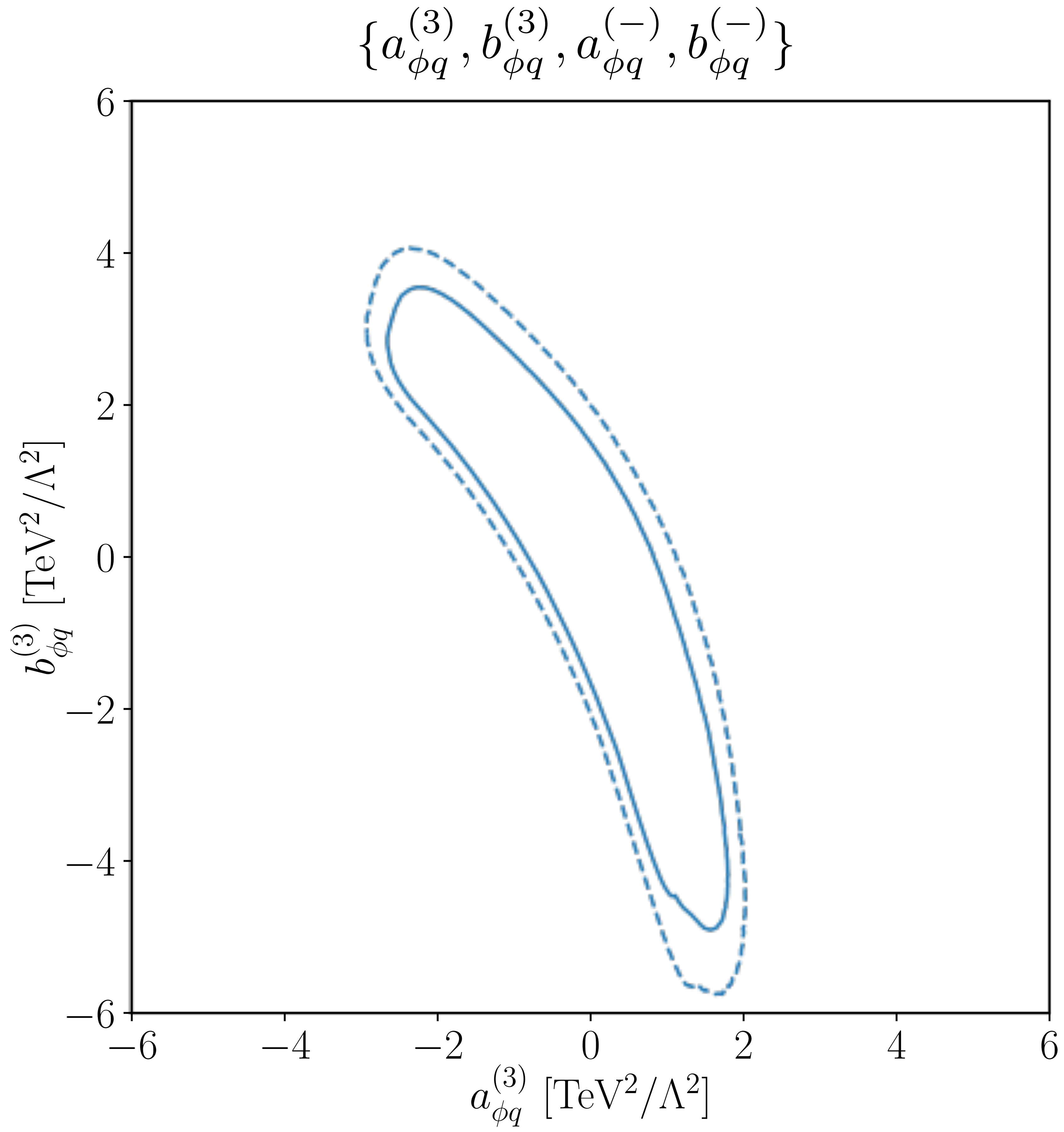


An Example: $C^1_{\phi Q}$ & $C^3_{\phi Q}$

Combined fit to top data

$$C^{(-)}_{\phi Q} = C^1_{\phi Q} - C^3_{\phi Q}$$

$$C^{(+)}_{\phi Q} = C^1_{\phi Q} + C^3_{\phi Q}$$



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Combined fit to top data & $\mathcal{B}(B_s \to \mu^+\mu^-)$

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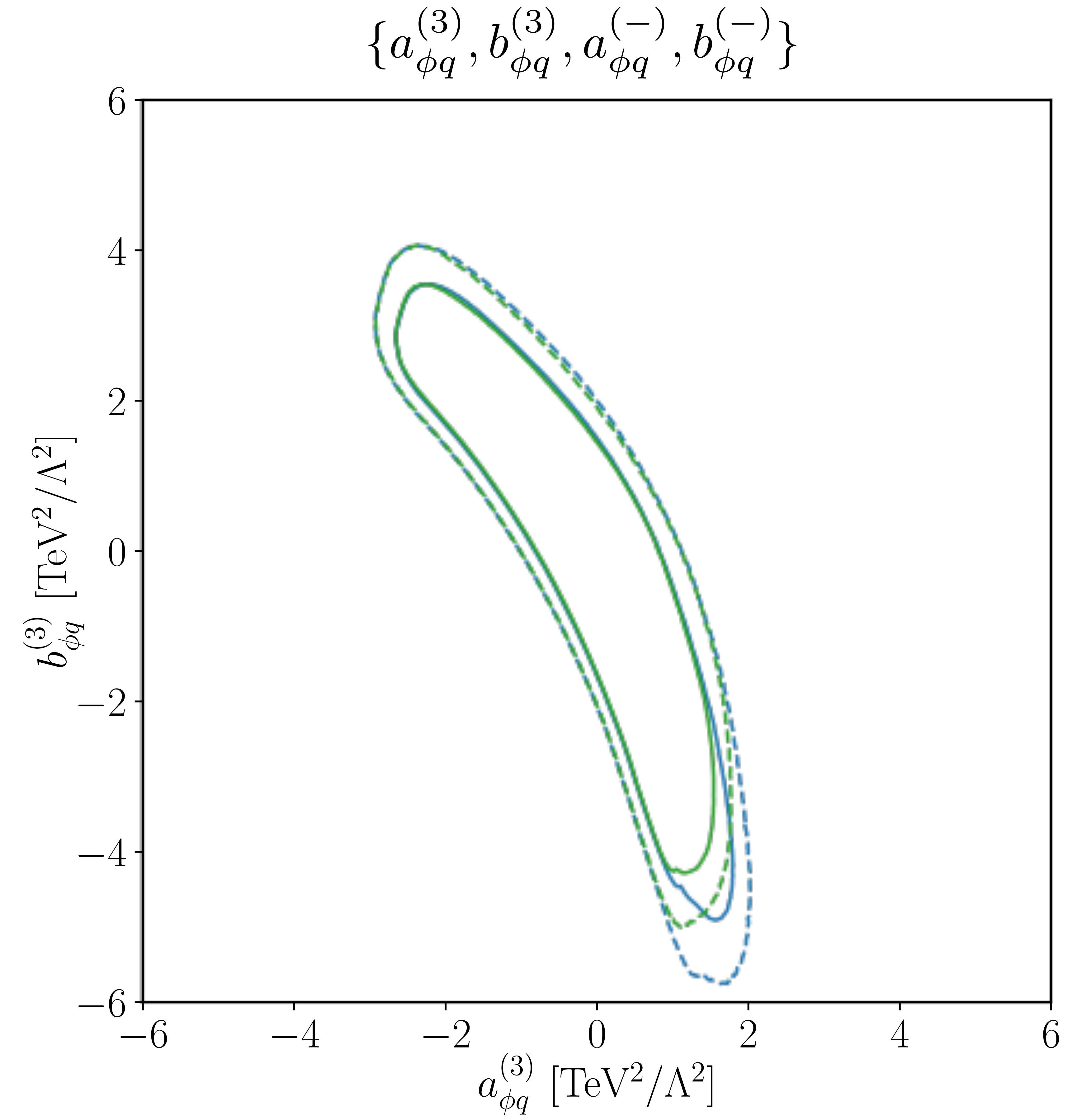

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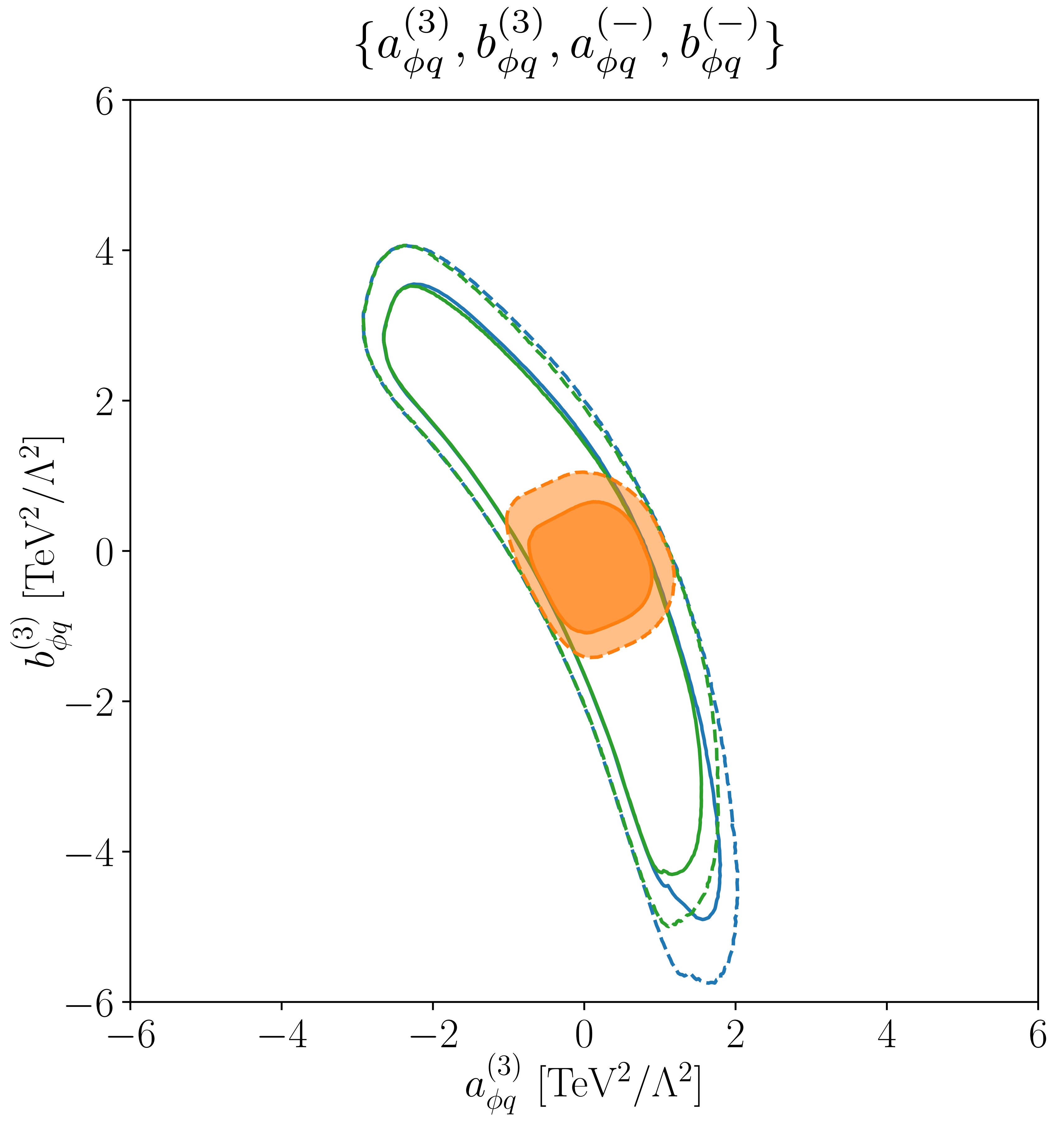

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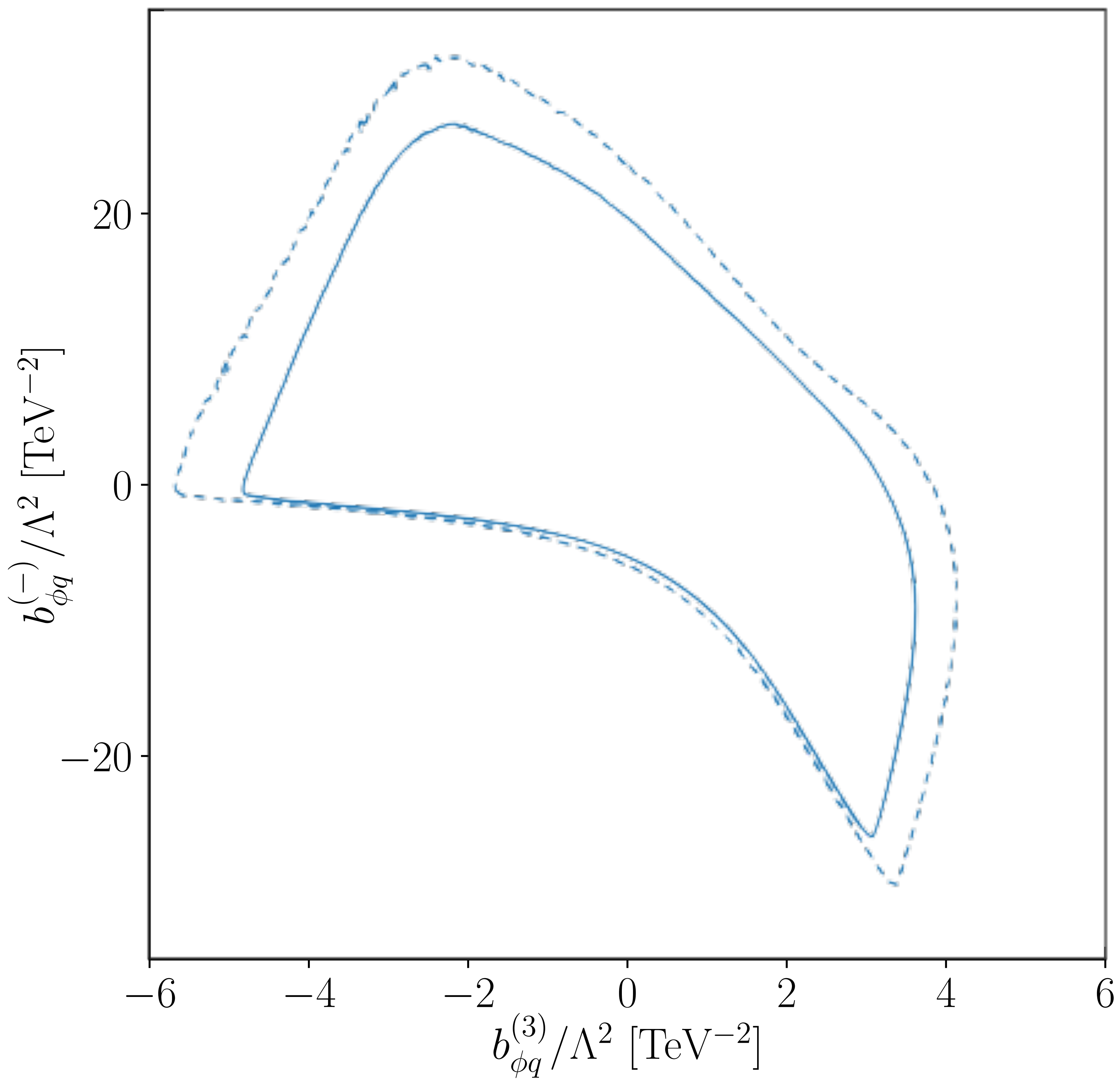
Combined fit to top data

$\{a^{(3)}_{\phi q}, b^{(3)}_{\phi q}, a^{(-)}_{\phi q}, b^{(-)}_{\phi q}\}$



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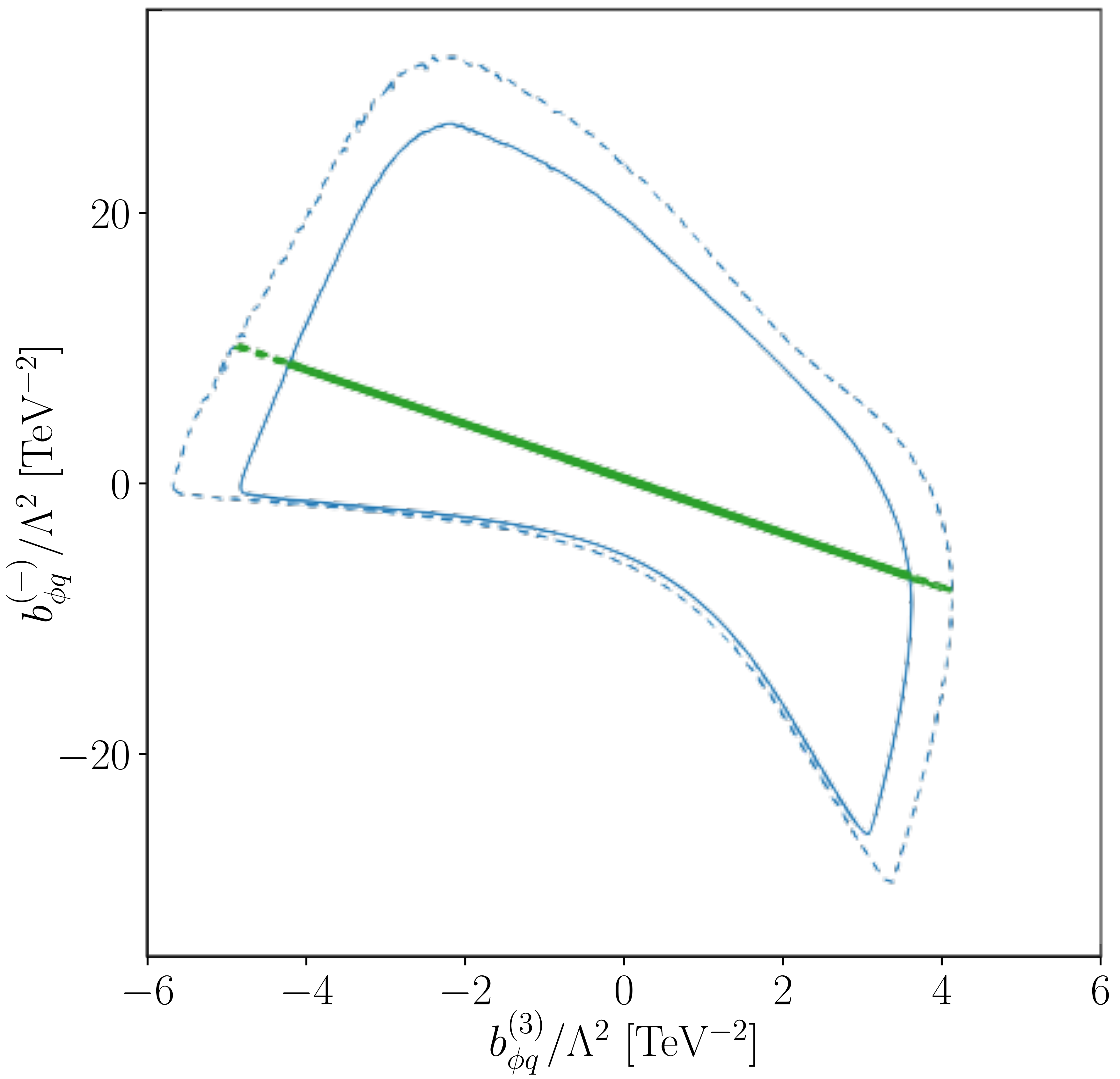
$\{a_{\phi q}^{(3)}, b_{\phi q}^{(3)}, a_{\phi q}^{(-)}, b_{\phi q}^{(-)}\}$



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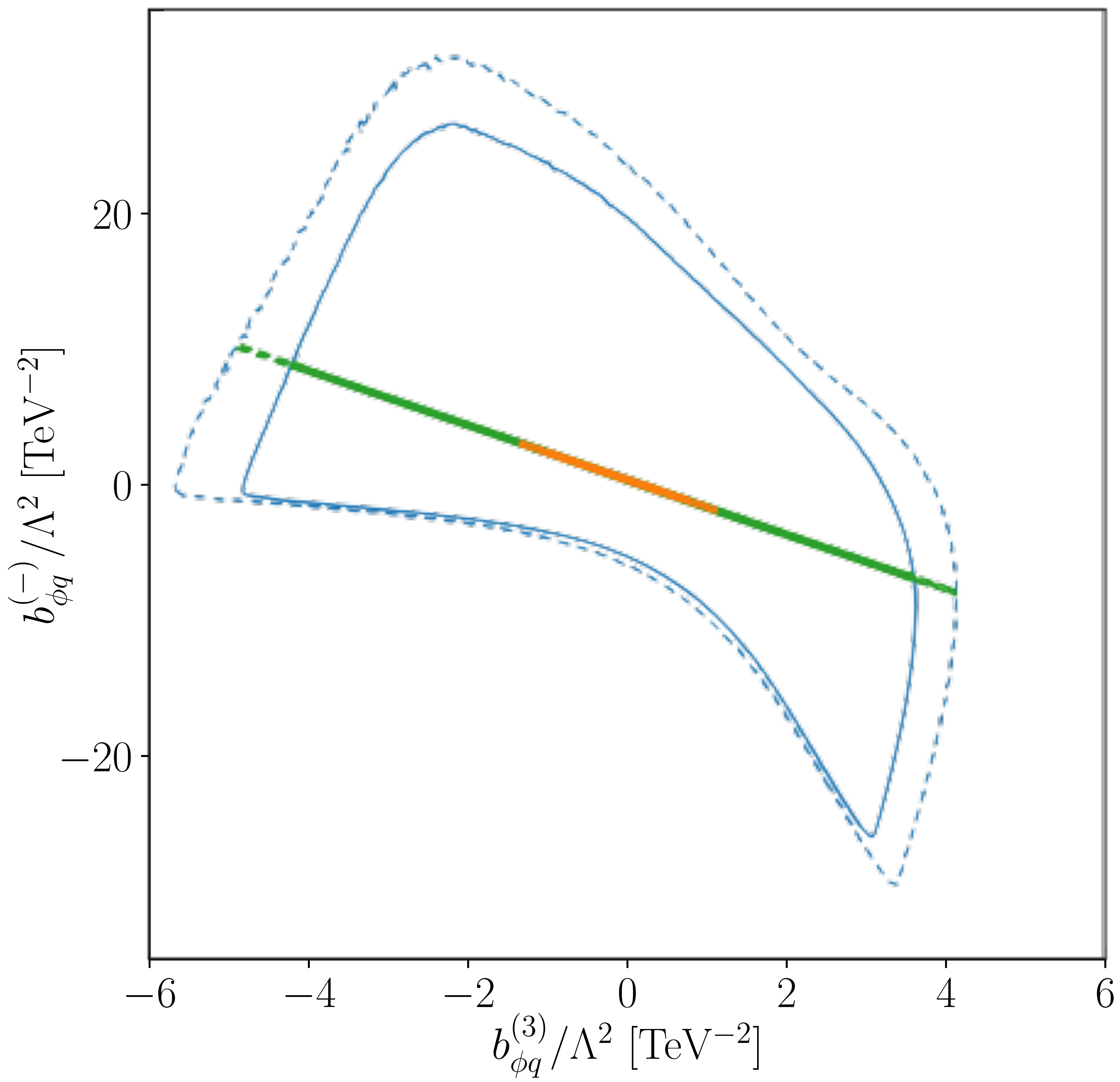

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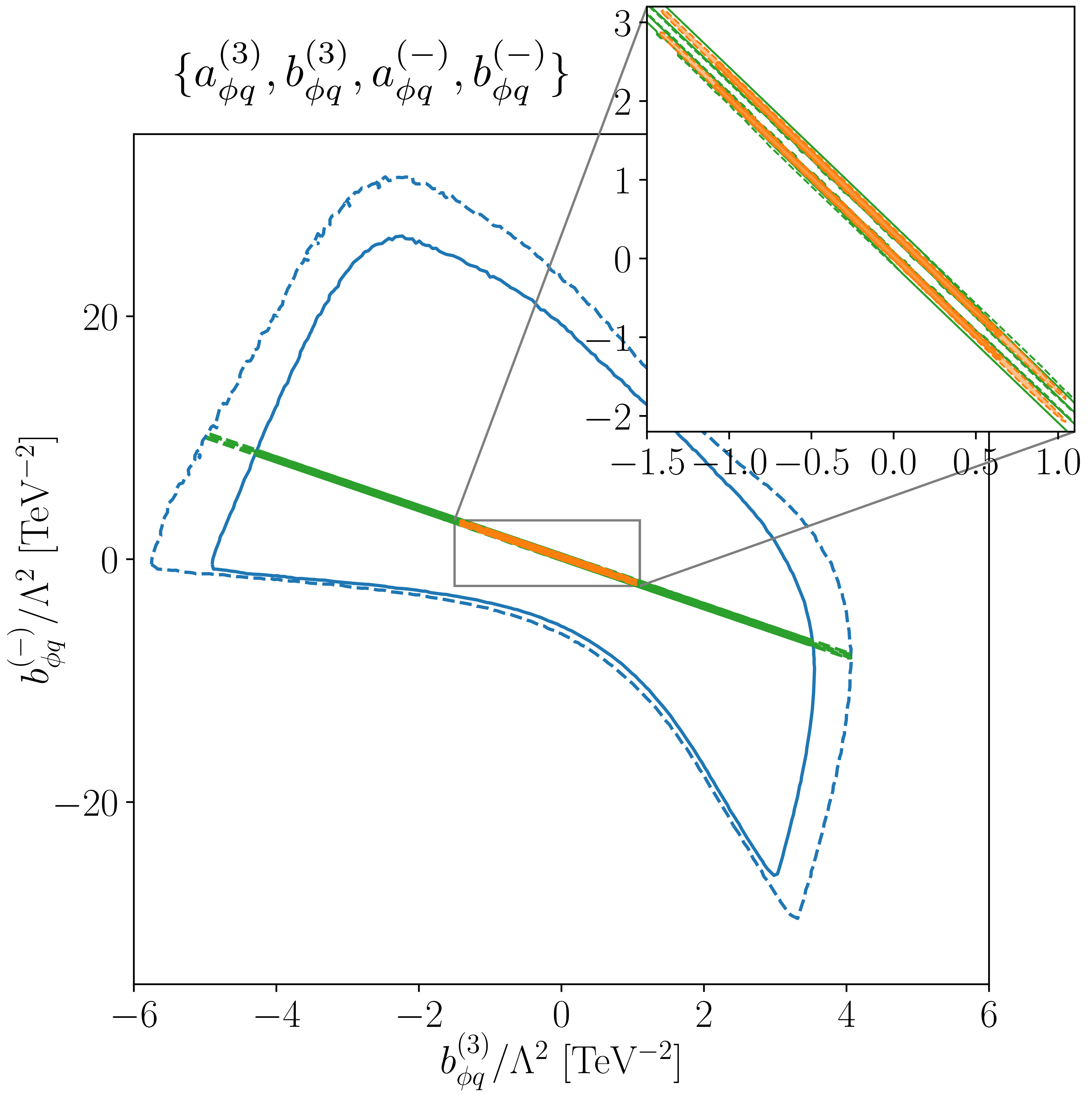

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Exampe: Four-quark couplings

$$O_{qq}^{(1)} = (\overline{Q}\gamma_\mu Q)(\overline{Q}\gamma^\mu Q)$$

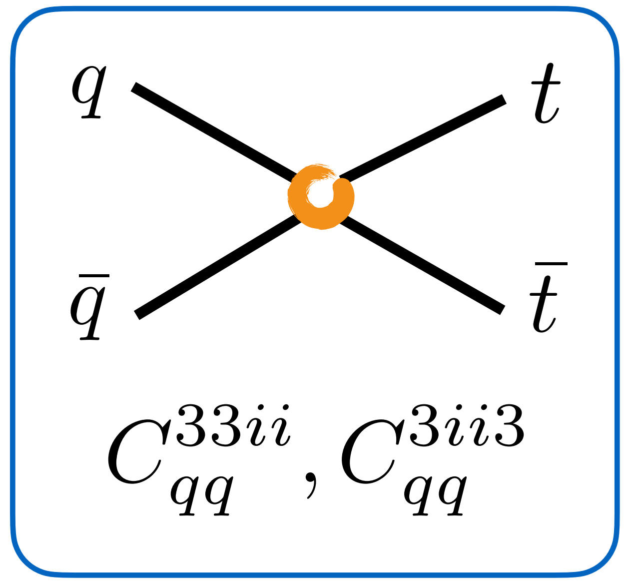
$$O_{qq}^{(3)} = (\overline{Q}\gamma_\mu \tau^a Q)(\overline{Q}\gamma^\mu \tau^a Q)$$

$$(C_{qq})^{33ii} = A_{qq} \qquad A_{qq} = (aa) + (ba)y_t^2$$

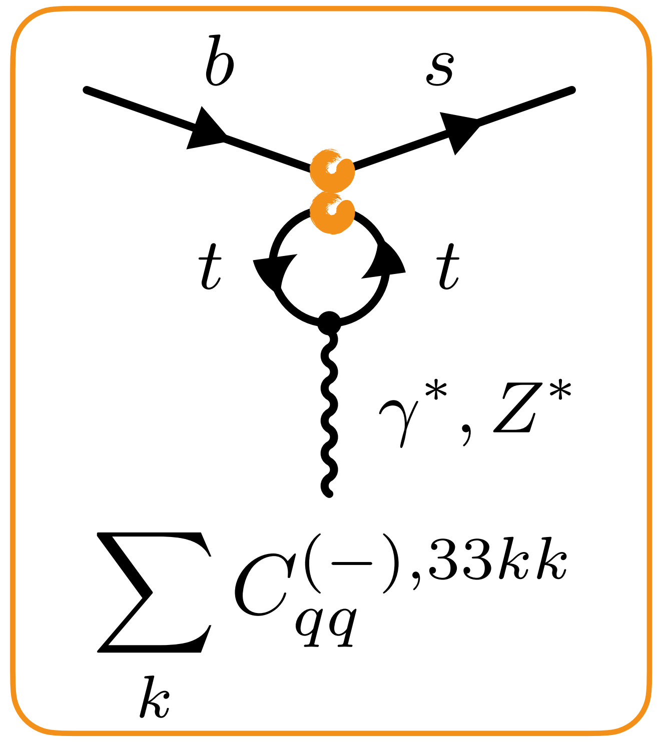
$$(C_{qq})^{3ii3} = \widetilde{A}_{qq} \qquad B_{qq} = (ba) + (\widetilde{ba})$$

$$(C_{qq})^{3333} = A_{qq} + \widetilde{A}_{qq} + B_{qq}$$

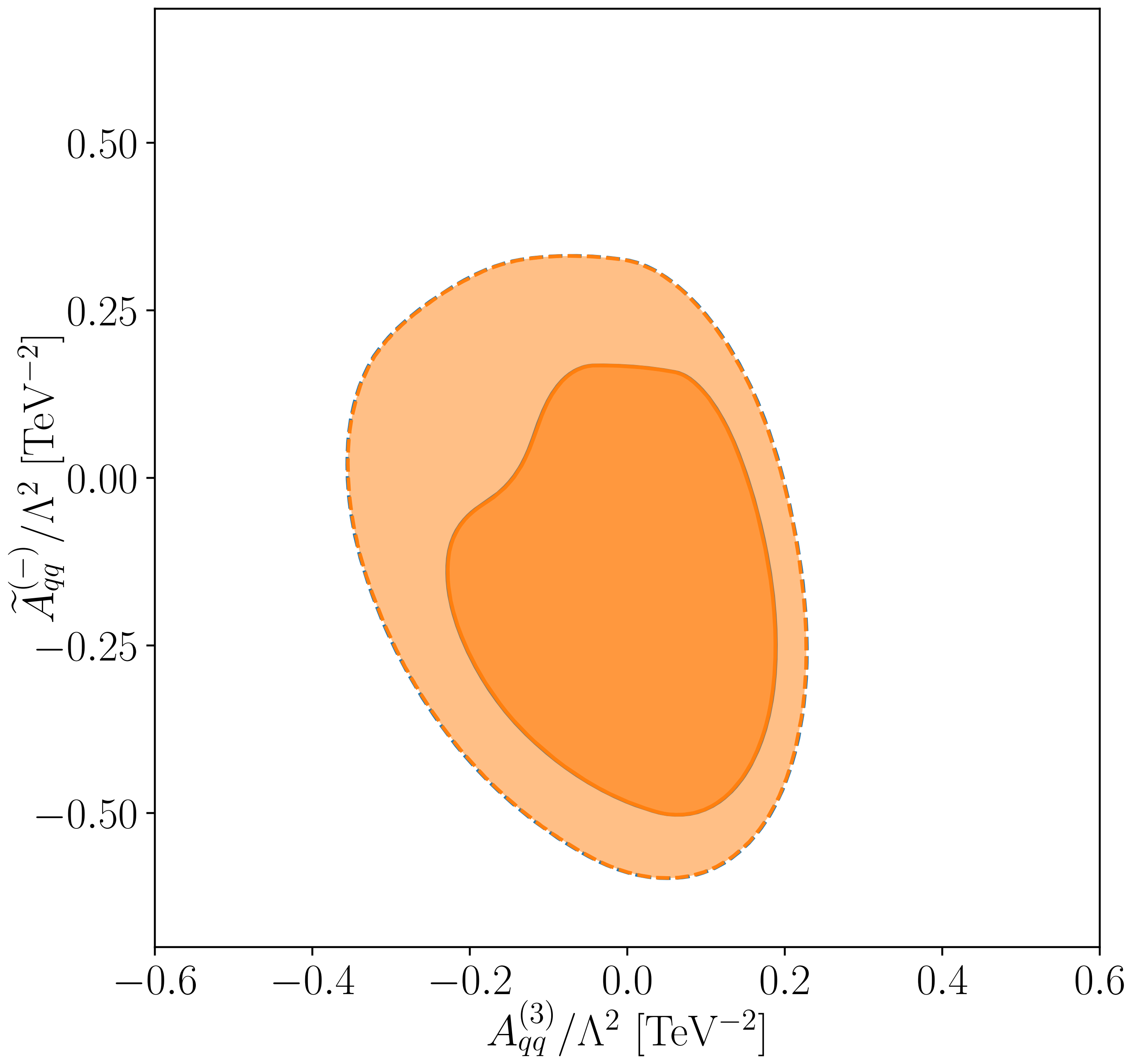
top

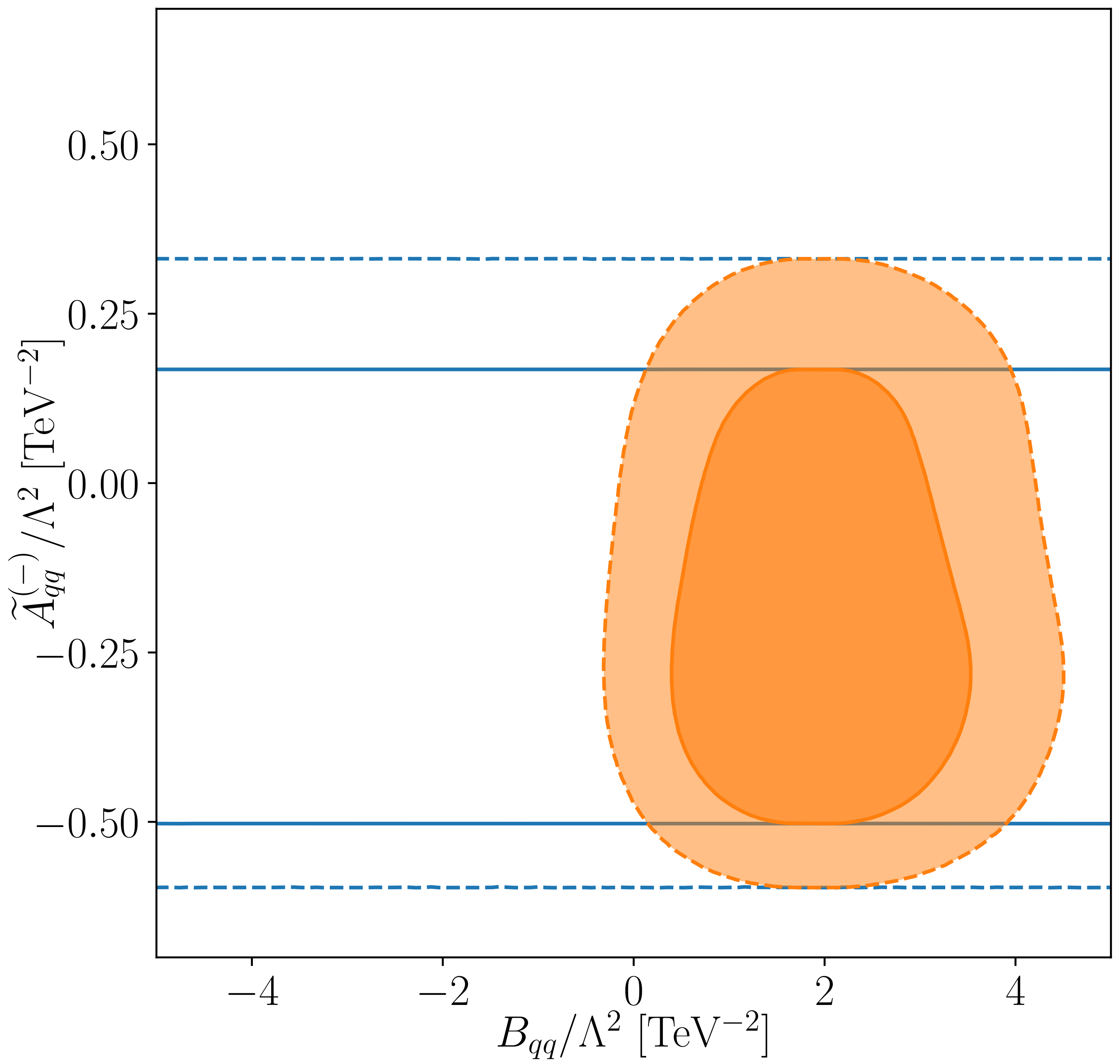


bottom



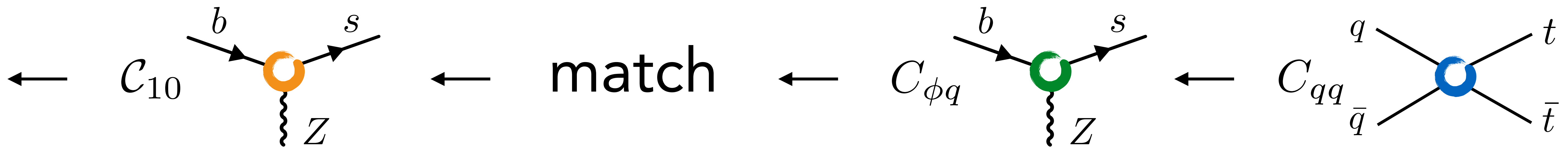
$$\{\widetilde{A}_{qq}^{(-)}, A_{qq}^{(3)}, B_{qq}\}$$

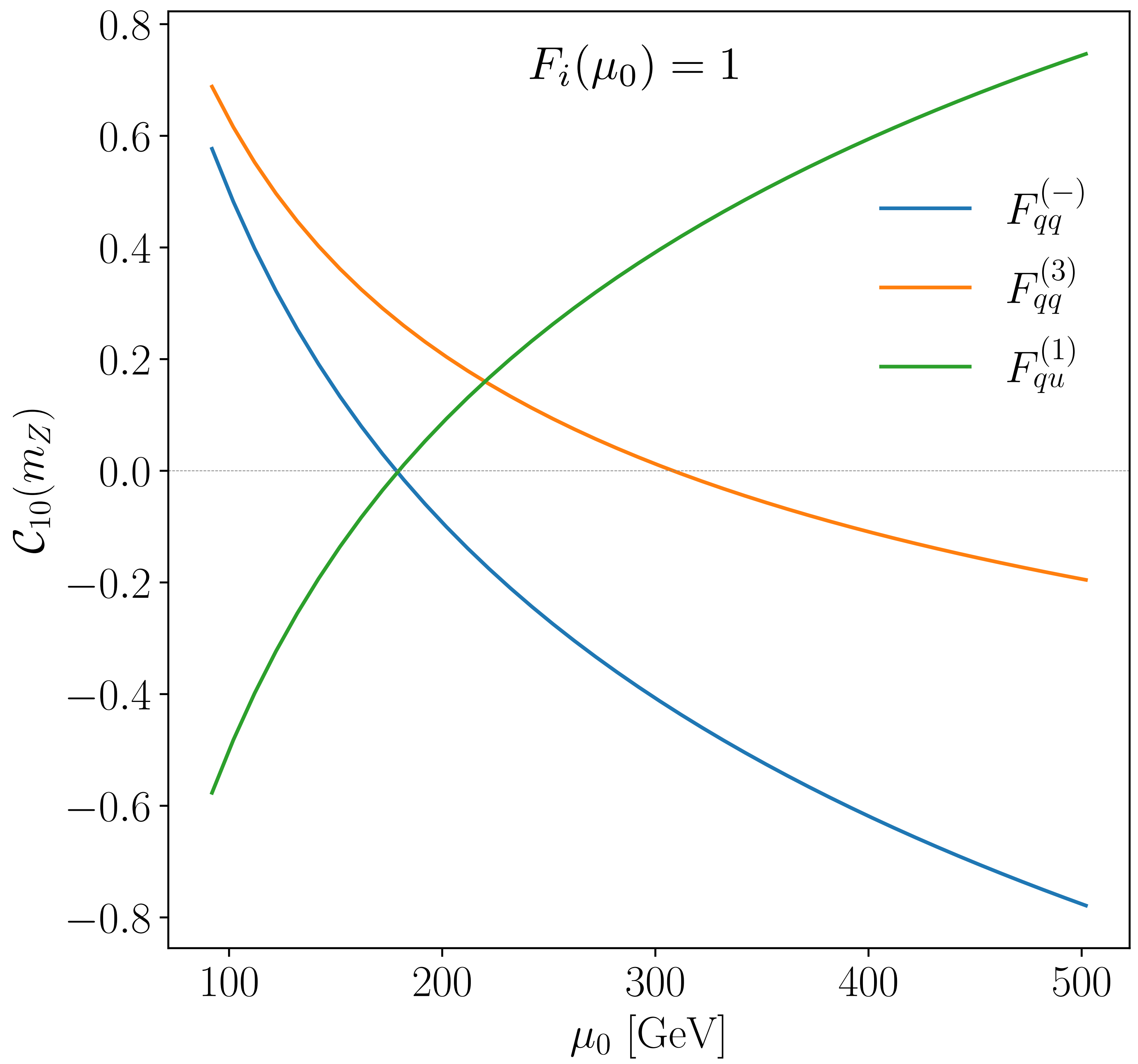


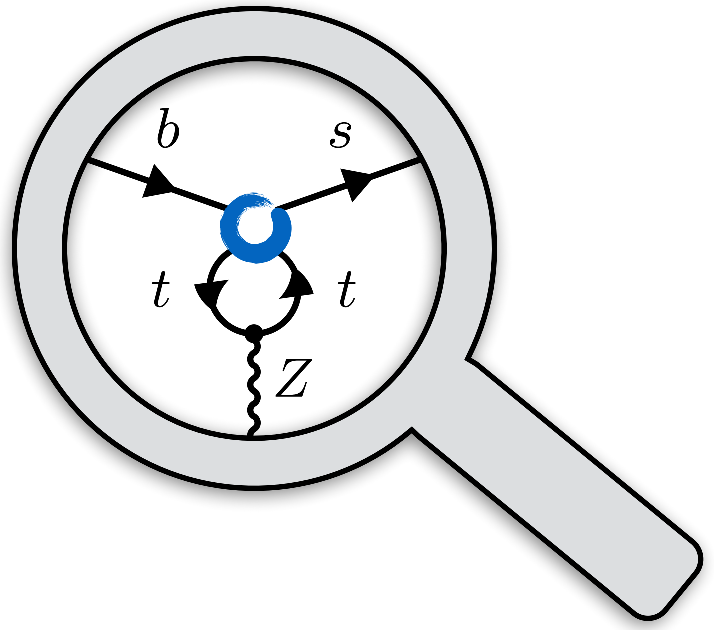


Stress test: top-bottom connection

$$\mathcal{C}_a(m_b) = \left(\mathcal{R}^{\mathrm{WET}}(m_b, m_Z)\right)_{ab} \left(\mathcal{M}(m_Z)\right)_{bc} \left(\mathcal{R}^{\mathrm{SMEFT}}(m_Z, m_t)\right)_{cd} C_d(m_t)$$







High sensitivity to operator mixing:

$$\mathcal{C}_{10} = F\left(\frac{4\pi}{\alpha} C_{\phi q}(m_t), C_{qq}(m_t)\right)$$

Slide from Susanne Westhoff