Project B2b
Operator Analysis of New Physics in Top-Quark Observables

1910.03606

I. Brivio, S. Bruggisser, F. Maltoni, R. Moutafis, T. Plehn, E. Vryonidou, S. Westhoff, C. Zhang

And ongoing work with S. Bruggisser, D. Van Dyk, R. Schaefer, S. Westhoff

PI

Presenter

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Why the Top-Sector?

Why the Top-Sector?

- Couples the strongest to the Higgs → Top-sector influences Higgs-sector and vice-versa → part of EW symmetry breaking?

Why the Top-Sector?

- Couples the strongest to the Higgs → Top-sector influences Higgs-sector and vice-versa → part of EW symmetry breaking?
- Many BSM models modify the Top-sector: Light Top partners in SUSY/Composite Higgs, etc.

Why the Top-Sector?

- Couples the strongest to the Higgs → Top-sector influences Higgs-sector and vice-versa → part of EW symmetry breaking?
- Many BSM models modify the Top-sector: Light Top partners in SUSY/Composite Higgs, etc.
- The LHC is a Top-factory → wealth of data to be explored.

Why now?

Why now?

- Existing top-fits:
  - TopFitter collaboration: 1512.03360, 1612.02294, 1901.03164
  - SMEFiT collaboration: 1901.05965

Why now?

- Existing top-fits:
  - TopFitter collaboration: 1512.03360, 1612.02294, 1901.03164
  - SMEFiT collaboration: 1901.05965

- What we can do:
  - Including ATLAS and CMS 13 TeV differential measurements
  - Studying the impact of NLO predictions
  - Detailed study of degeneracies
  - More honest treatment of theoretical uncertainties
  - Systematic study of the impact of uncertainties

The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \dots$$

The EFT

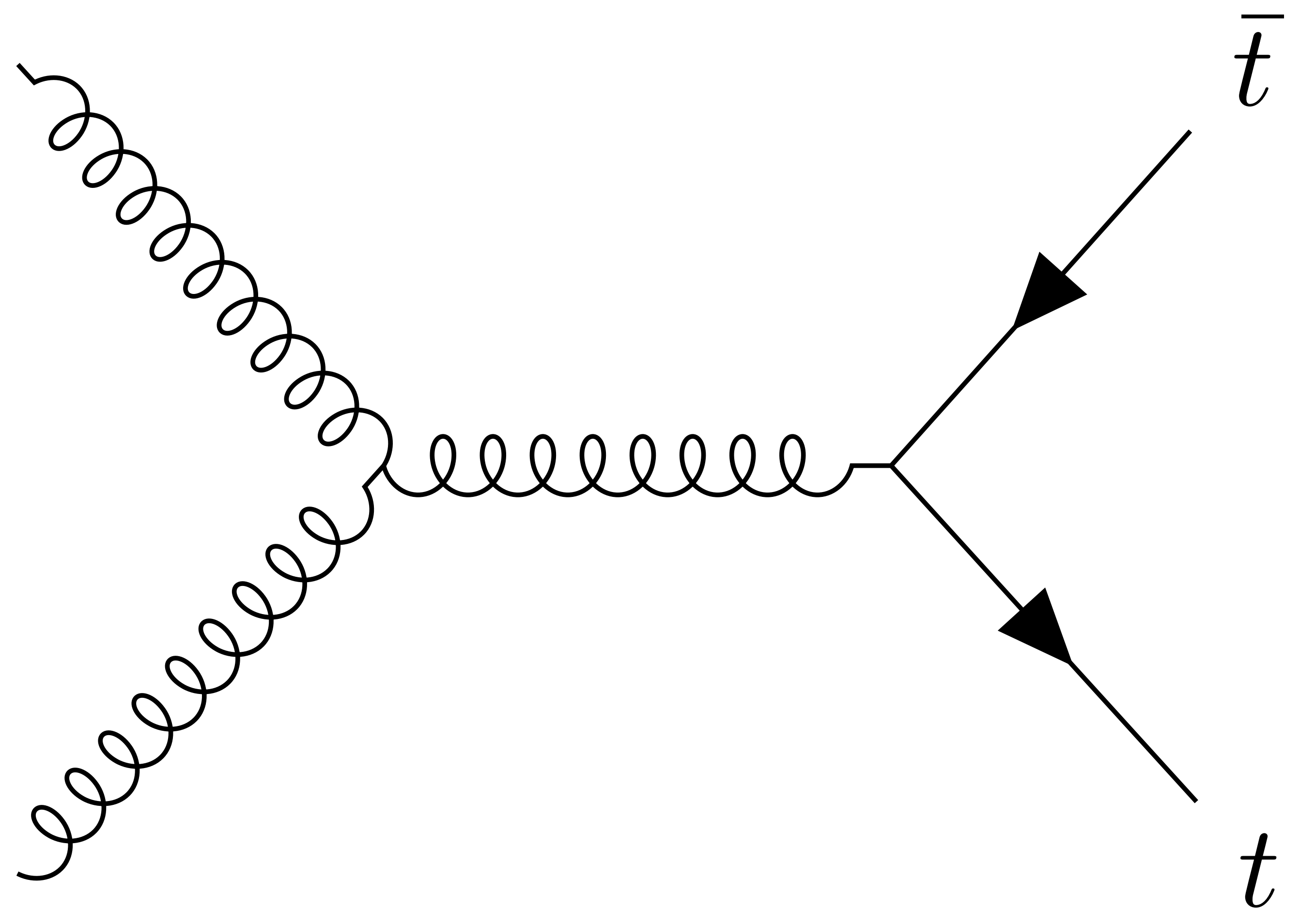
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

- All relevant (including at least one Top) operators up to d=6

The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \dots$$

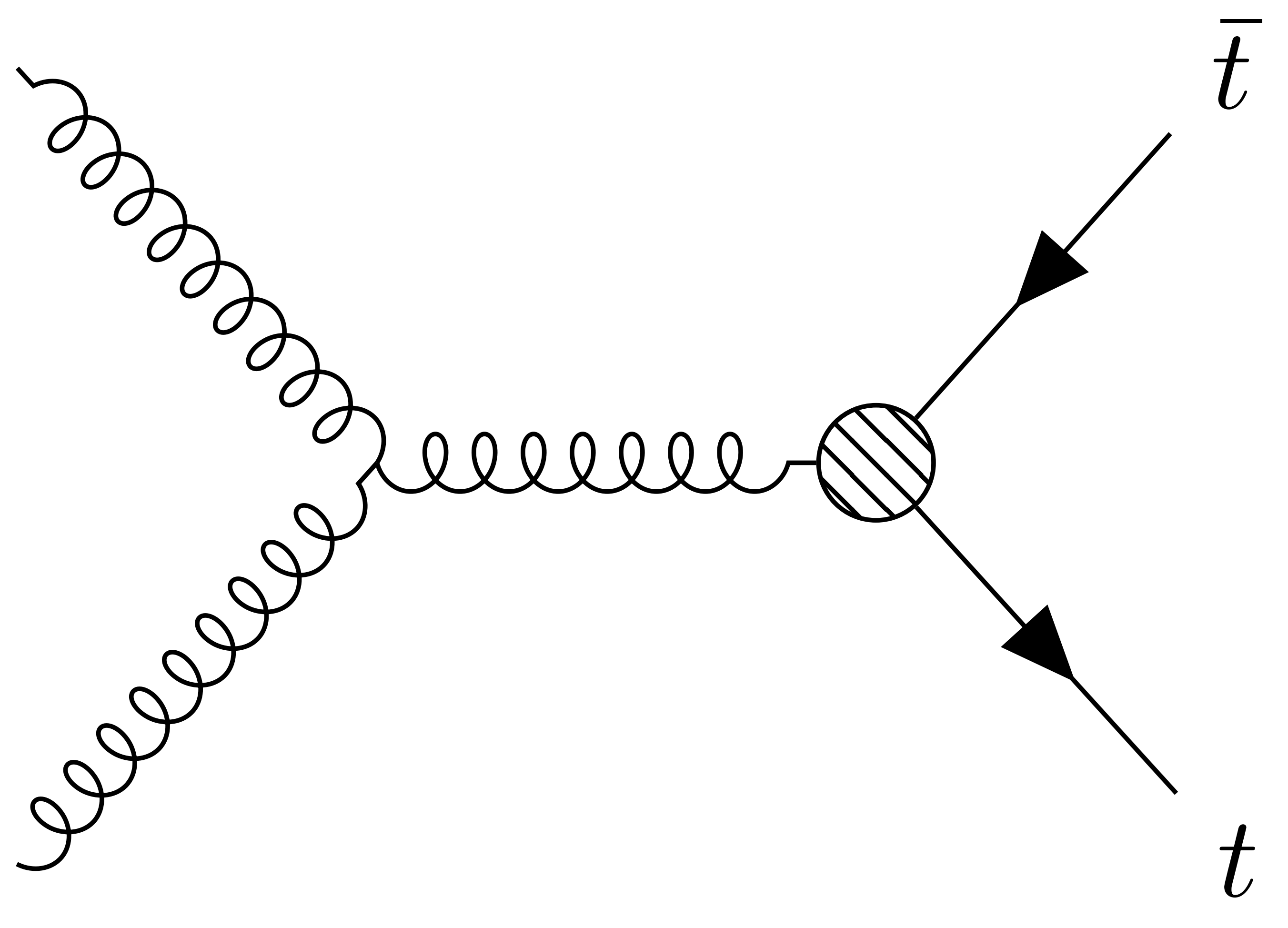
- All relevant (including at least one Top) operators up to d=6



The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

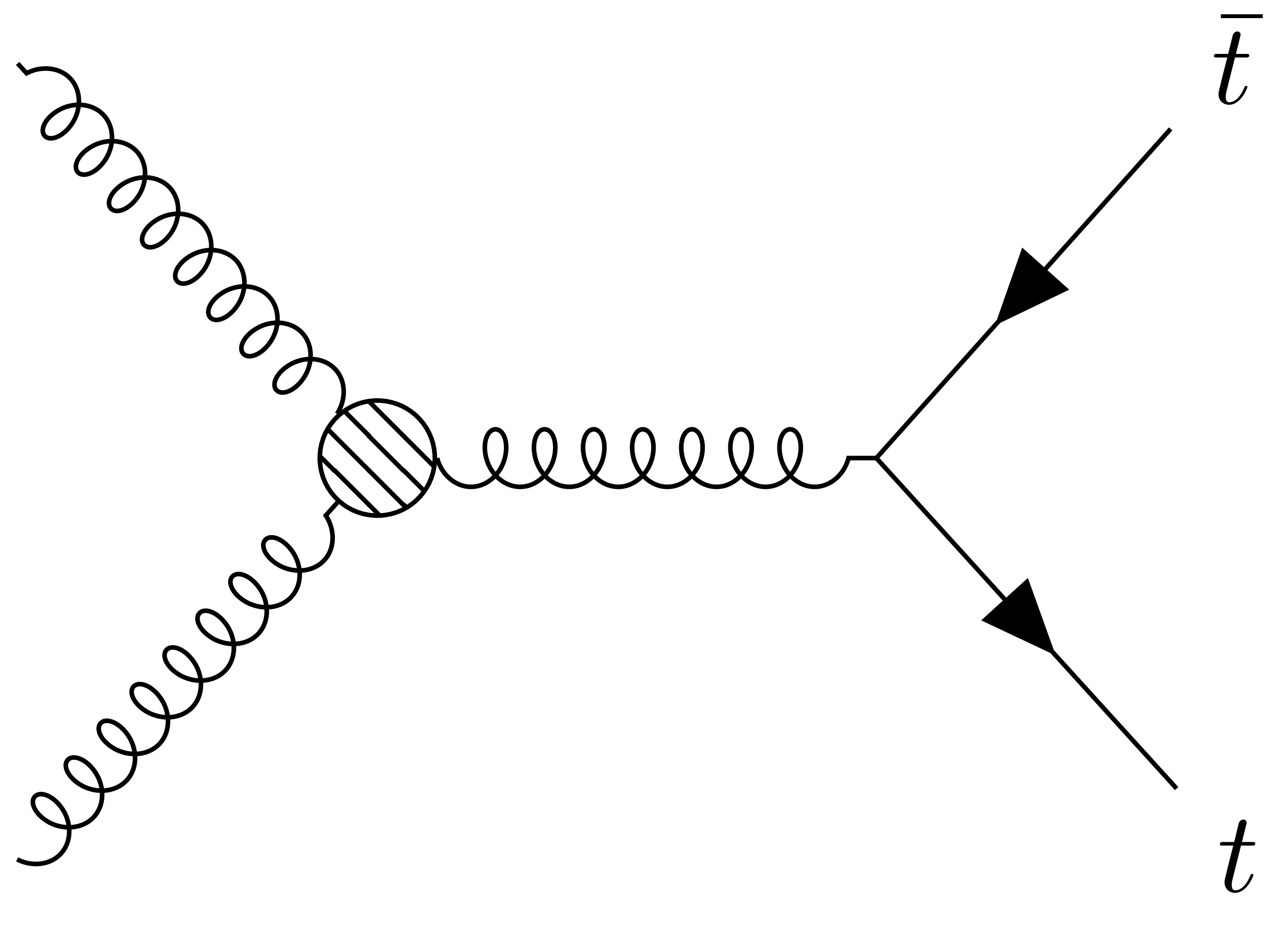
- All relevant (including at least one Top) operators up to d=6



The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4} \mathcal{O}_j^{d=8} + \dots$$

- All relevant (including at least one Top) operators up to d=6



The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

- All relevant (including at least one Top) operators up to d=6

The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \ldots$$

- All relevant (including at least one Top) operators up to d=6
- Assumptions:
  - $U(2)_u x U(2)_d x U(2)_Q$ flavour symmetry
  - Light quarks considered massless (Yukawa=0)
  - Diagonal CKM
  - CP conserving
  - Warsaw-basis operators or linear combinations thereof
  - Total of 22 operators considered

The Operators

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

The Operators

- Four-fermion vs. Two-fermion

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} [Λ^{-2}]	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{Qq}^{3,1}$	Λ^{-4} [Λ^{-2}]	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{tq}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	[Λ^{-2}]	Λ^{-2}	–	[Λ^{-2}]	Λ^{-2}	Λ^{-2}

The Operators

- Four-fermion vs. Two-fermion
- Gauge structure or Up vs. Down

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} [Λ^{-2}]	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{Qq}^{3,1}$	Λ^{-4} [Λ^{-2}]	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{tq}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	[Λ^{-2}]	Λ^{-2}	–	[Λ^{-2}]	Λ^{-2}	Λ^{-2}

The Operators

- Four-fermion vs. Two-fermion
- Gauge structure or Up vs. Down
- Chirality of the top

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

The Operators

- Four-fermion vs. Two-fermion
- Gauge structure or Up vs. Down
- Chirality of the top
- …

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

Event Kinematics

Or Rates vs. Tails

Event Kinematics

Or Rates vs. Tails

$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu}$$

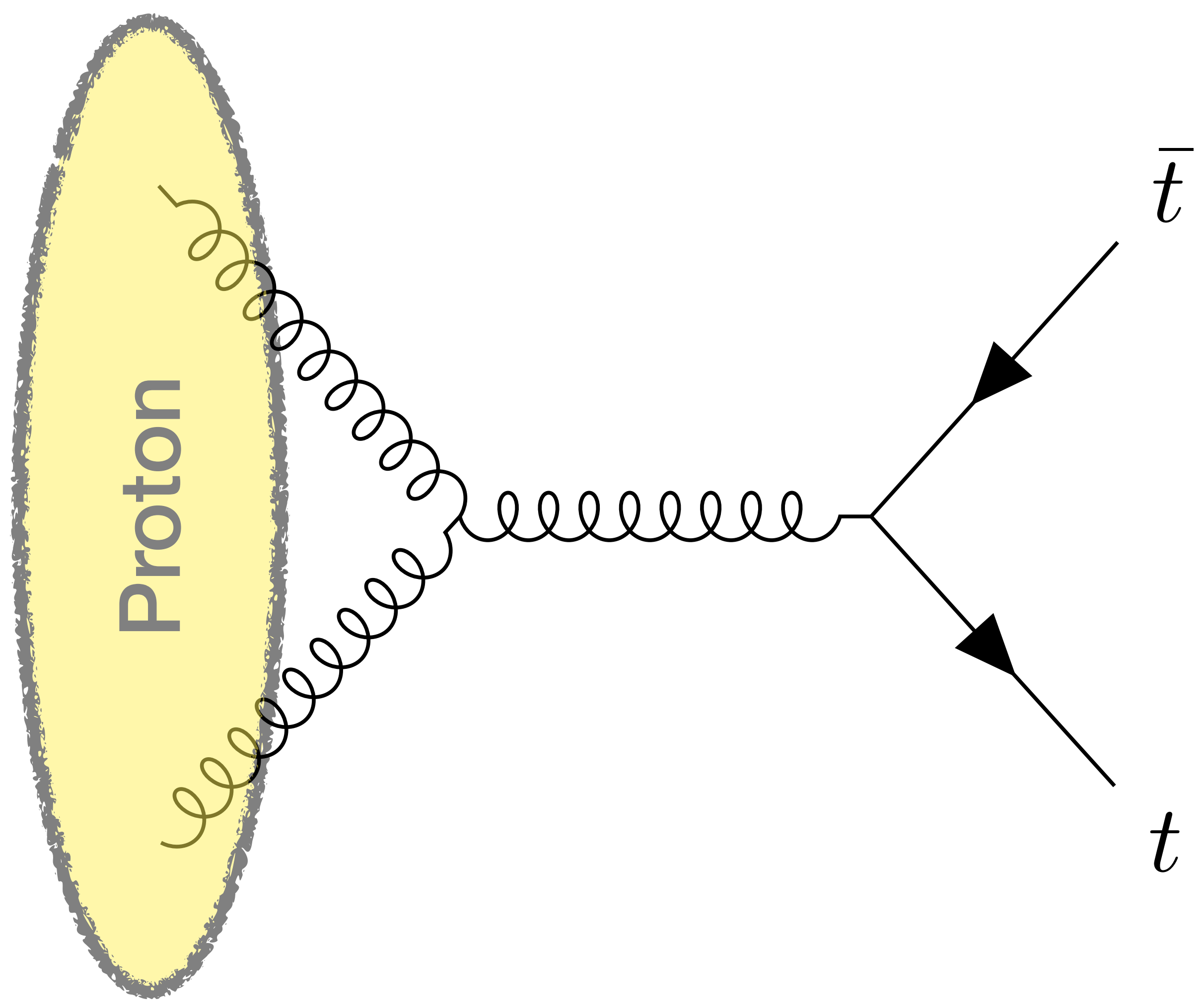
$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

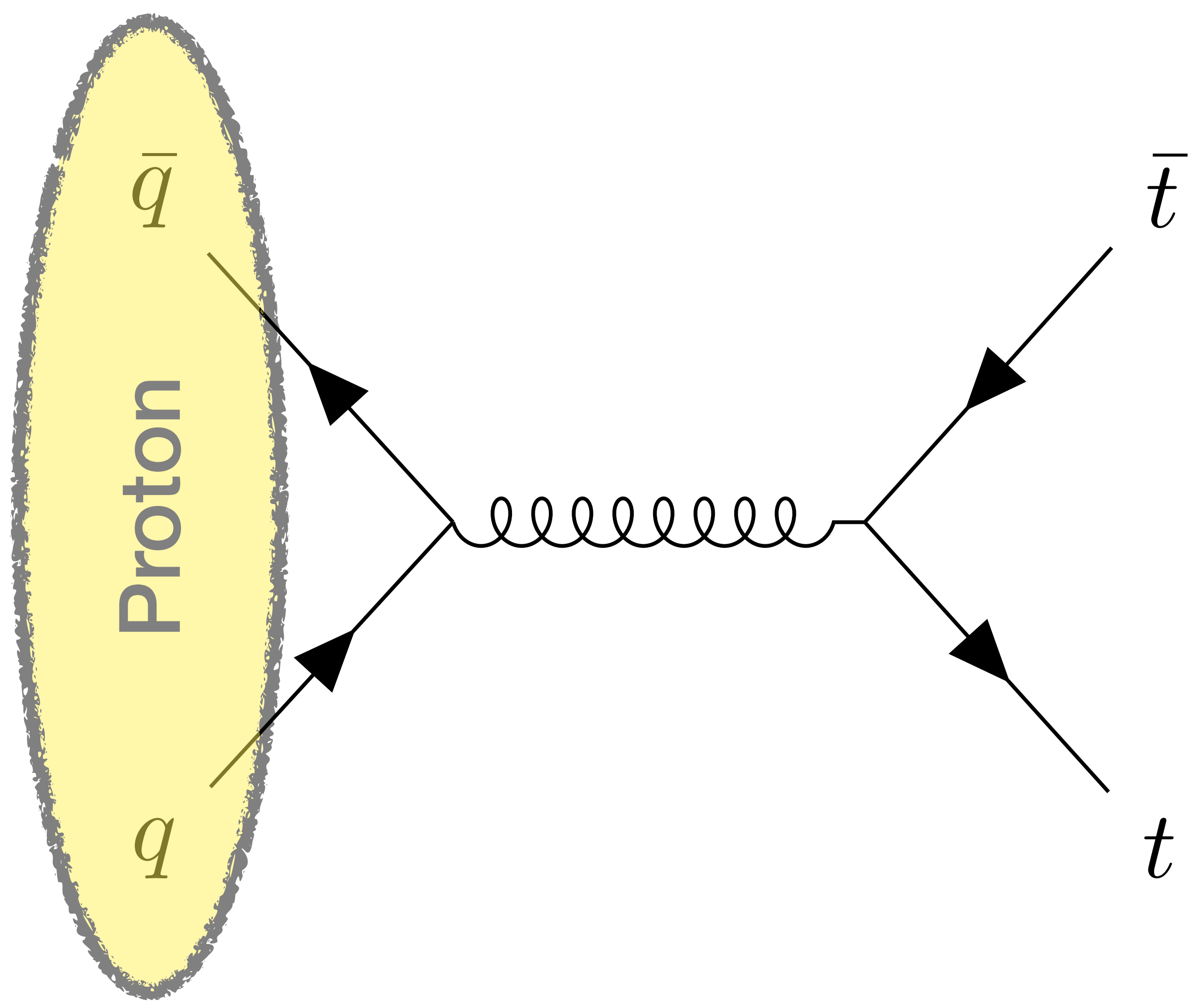
Event Kinematics

Or Rates vs. Tails

$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu}$$

$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$



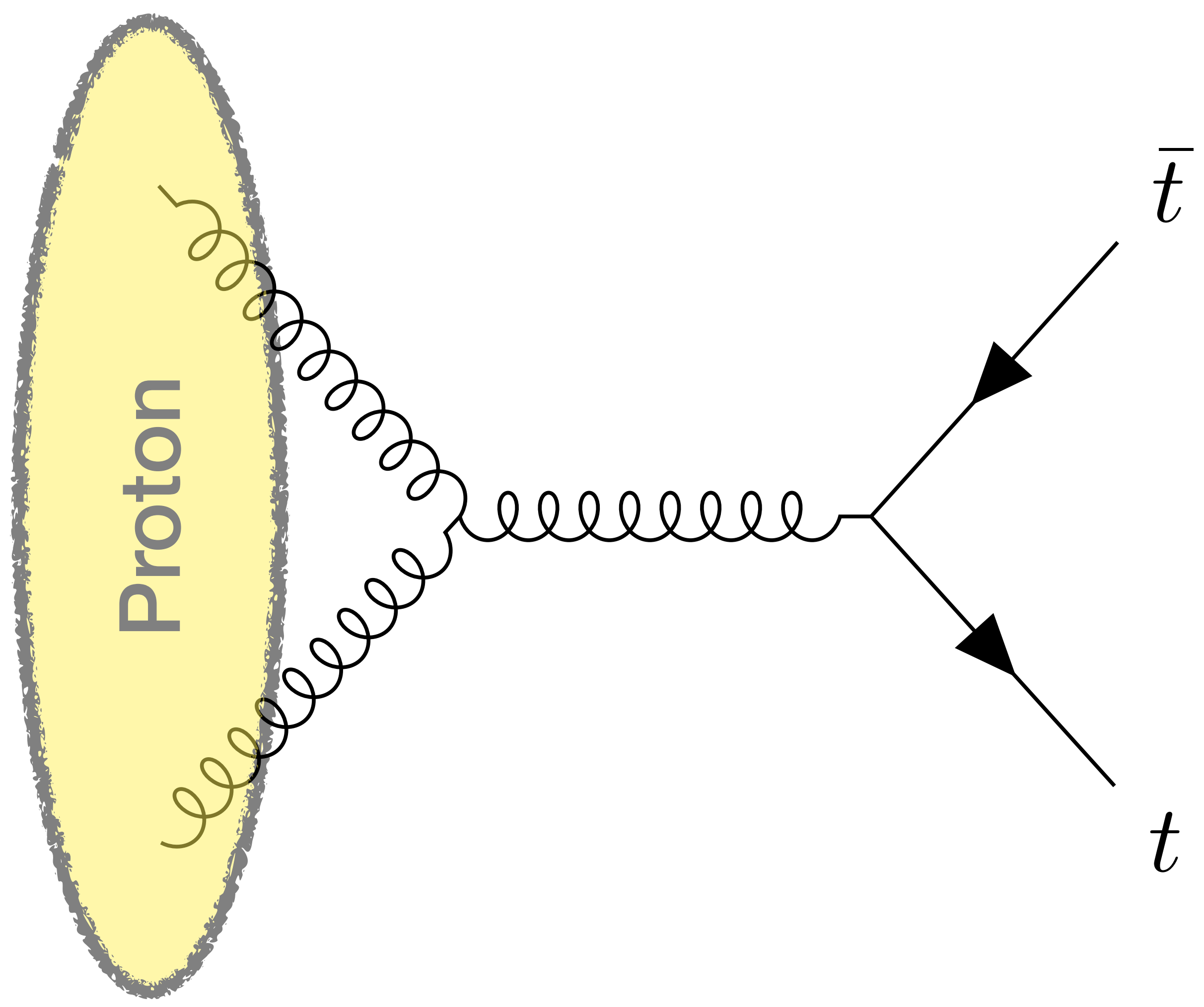


Event Kinematics

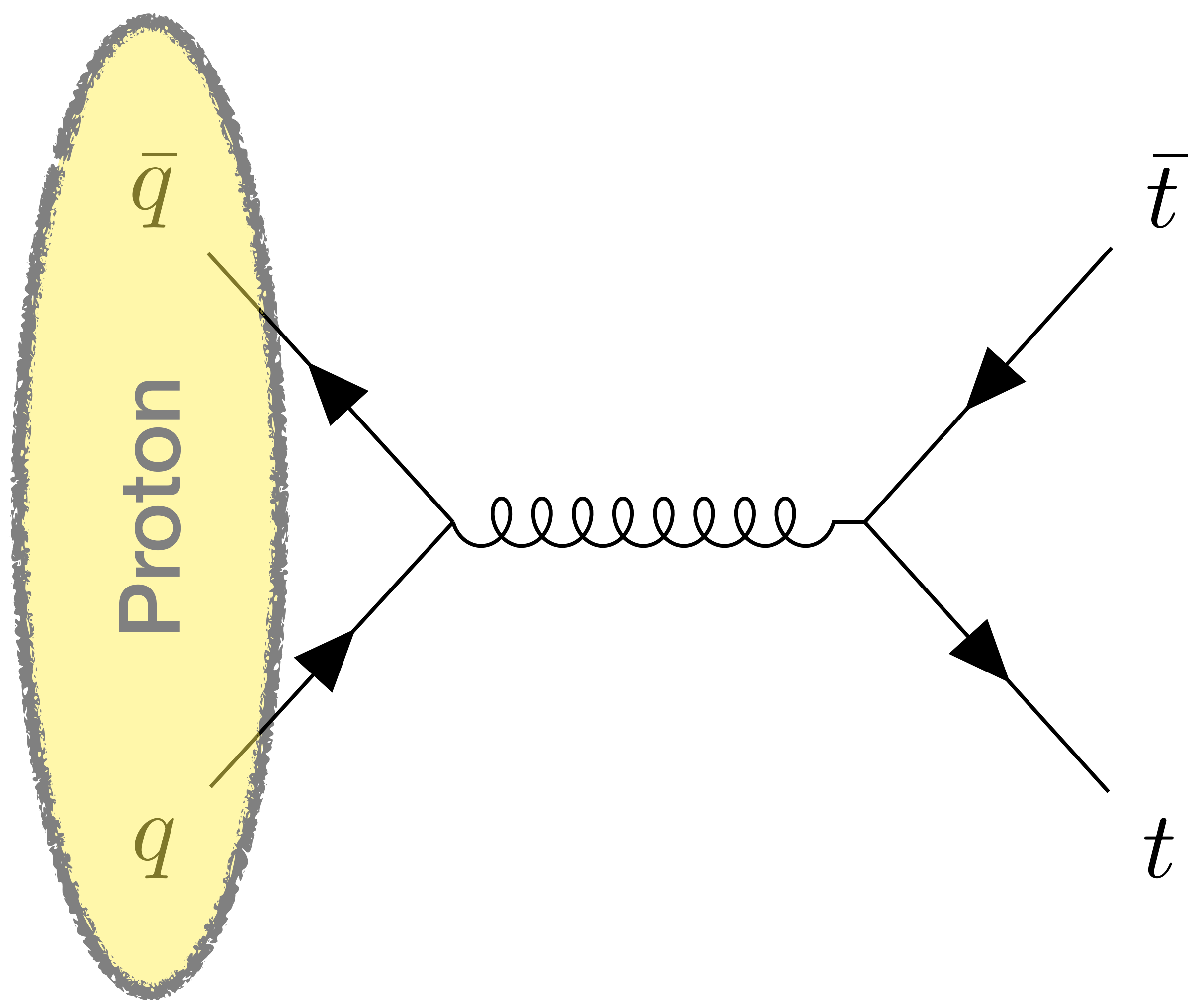
Or Rates vs. Tails

$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu}$$

$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$



$$\gg$$

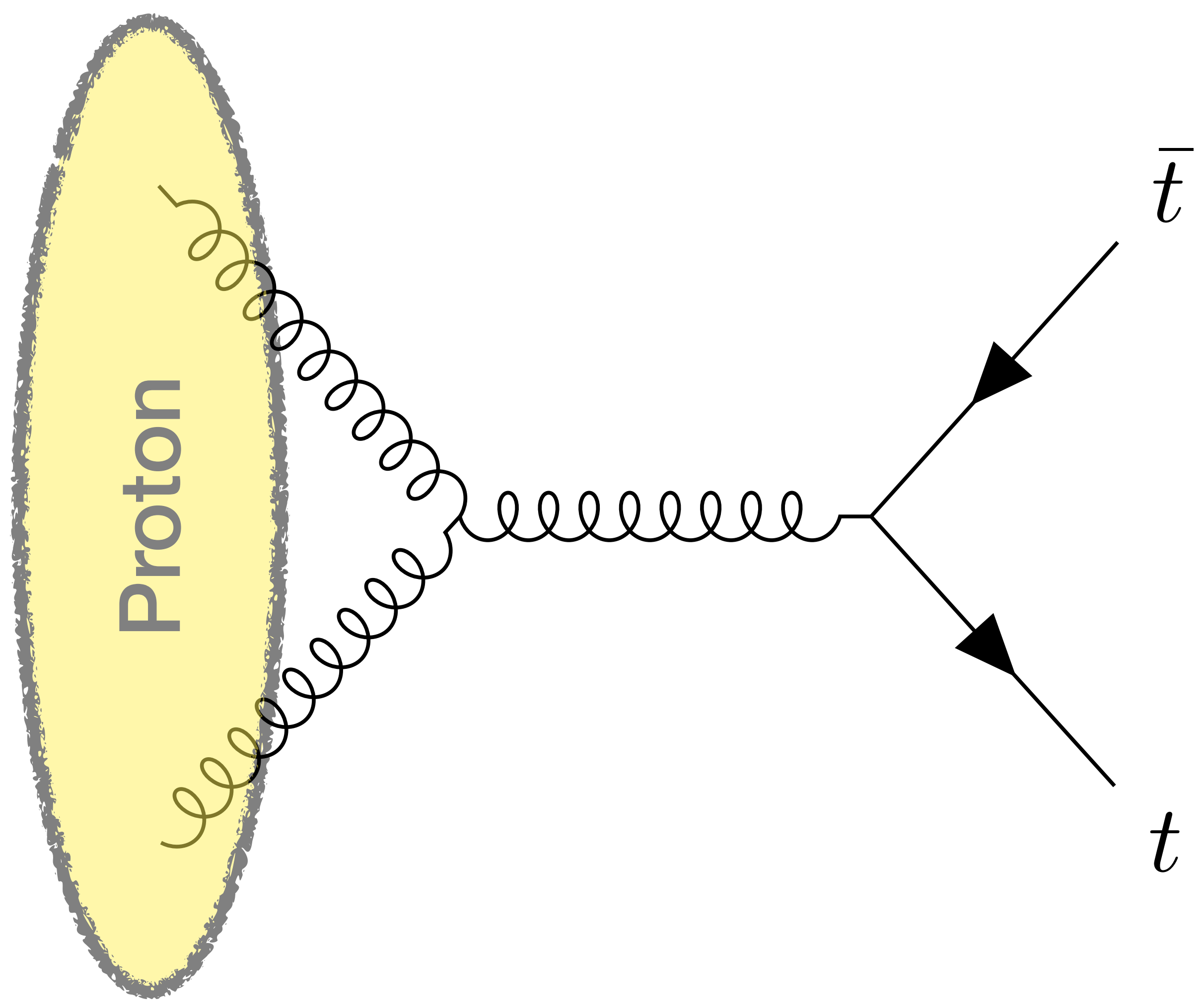


Event Kinematics

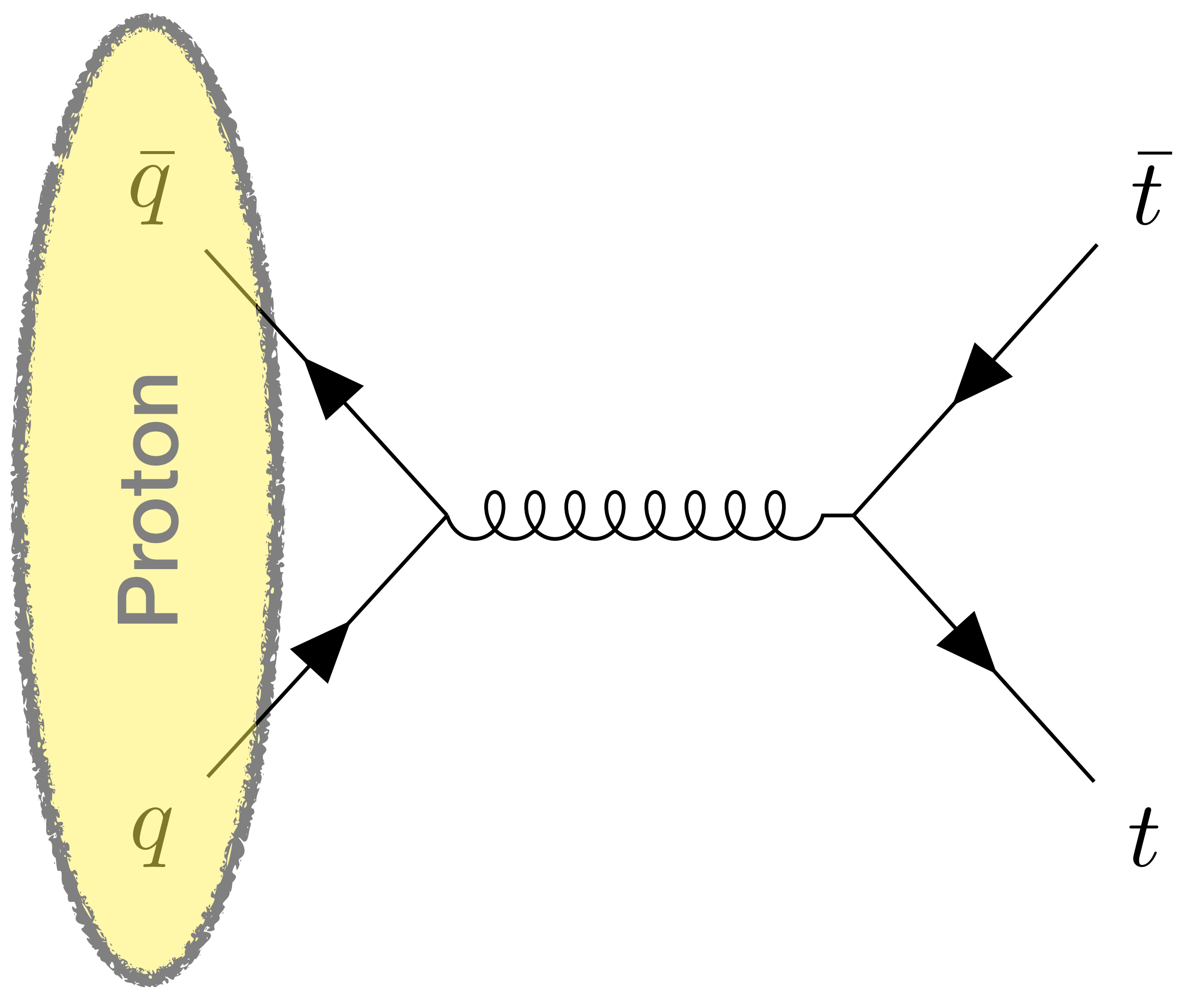
Or Rates vs. Tails

$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu} \qquad O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$



$$\gg$$



Event Kinematics

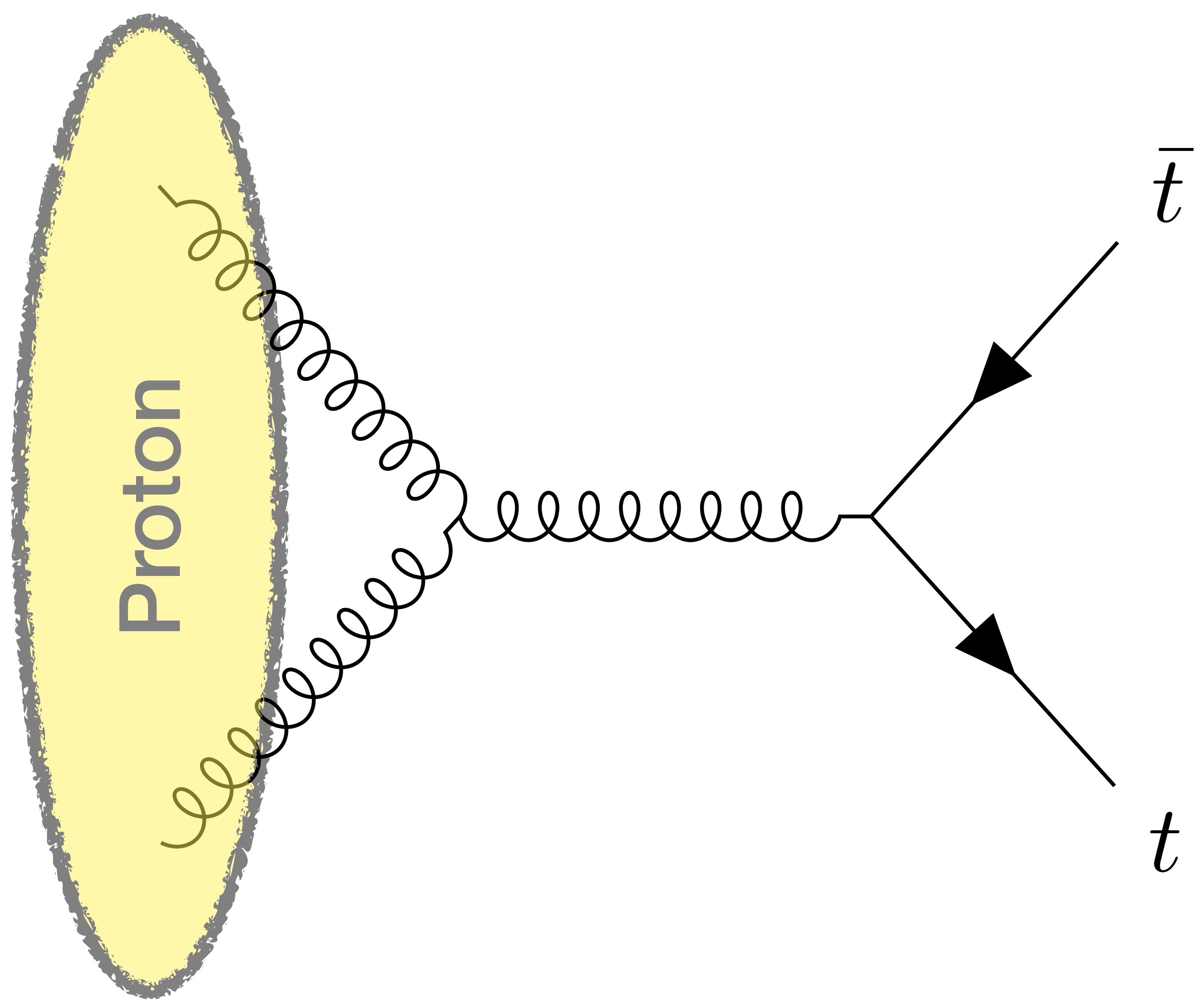
Or Rates vs. Tails

$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu}$$

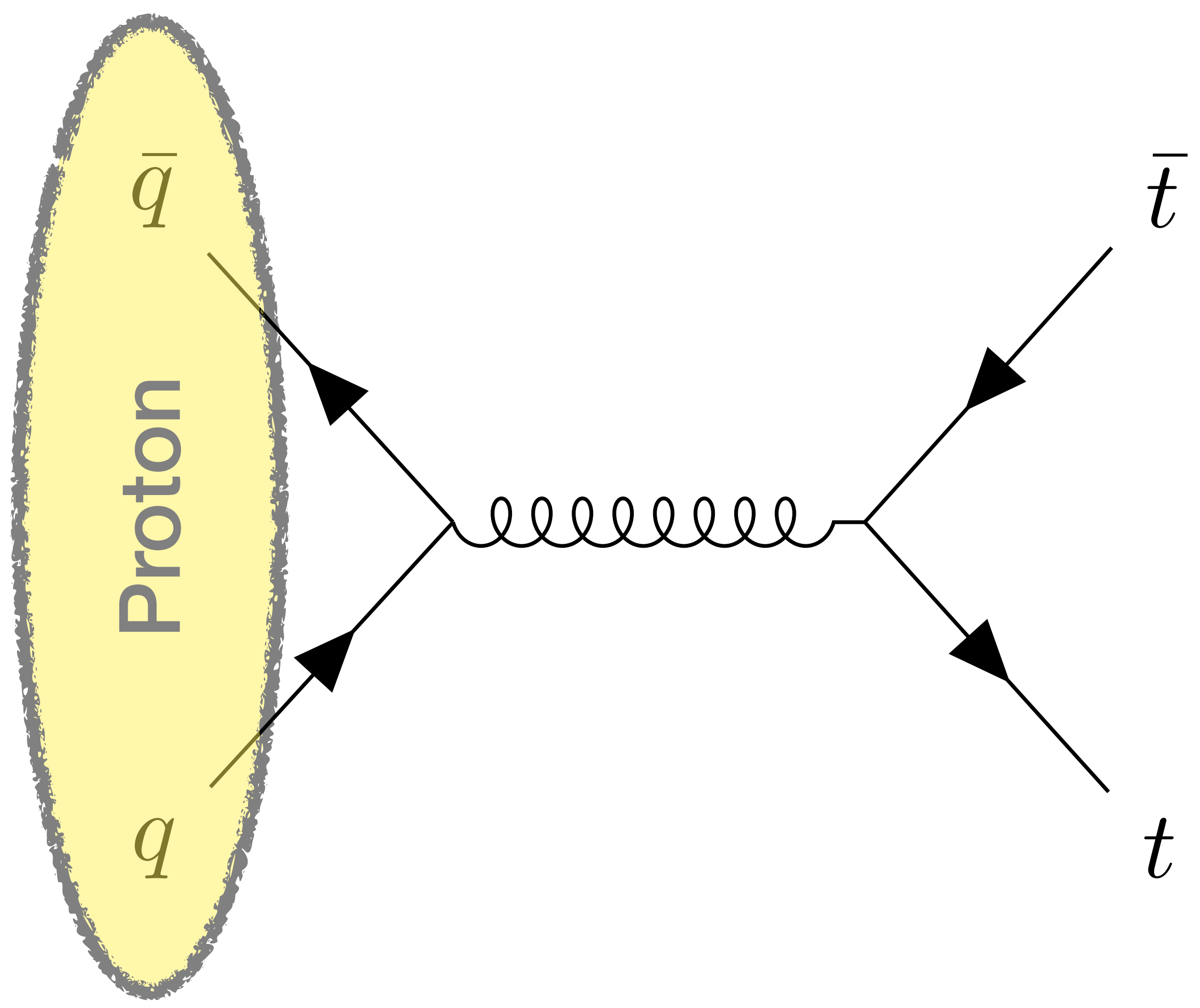
$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

Very small



$\gg$



Event Kinematics

Or Rates vs. Tails

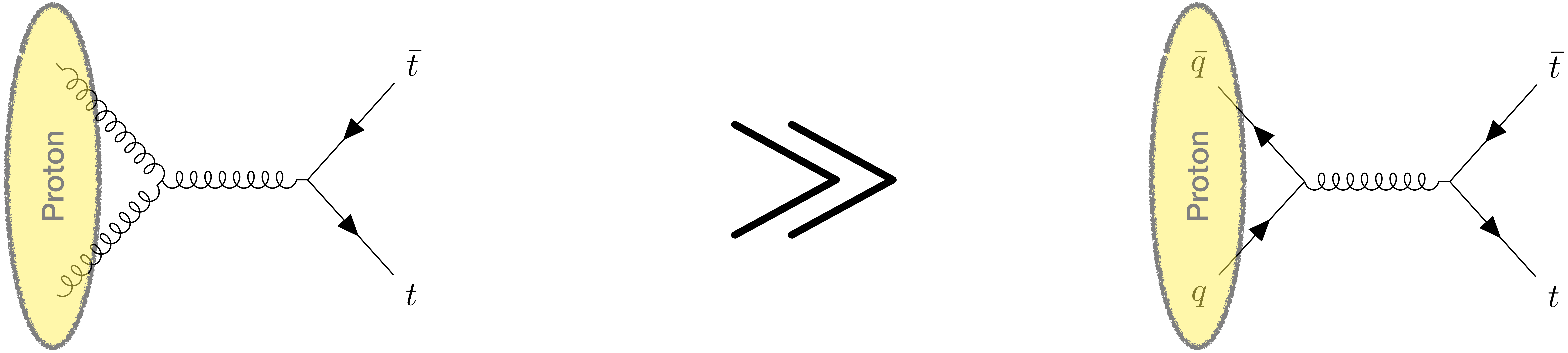
$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu}$$

$$O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

Very small

Very large
For high bins



Event Kinematics

Or Rates vs. Tails

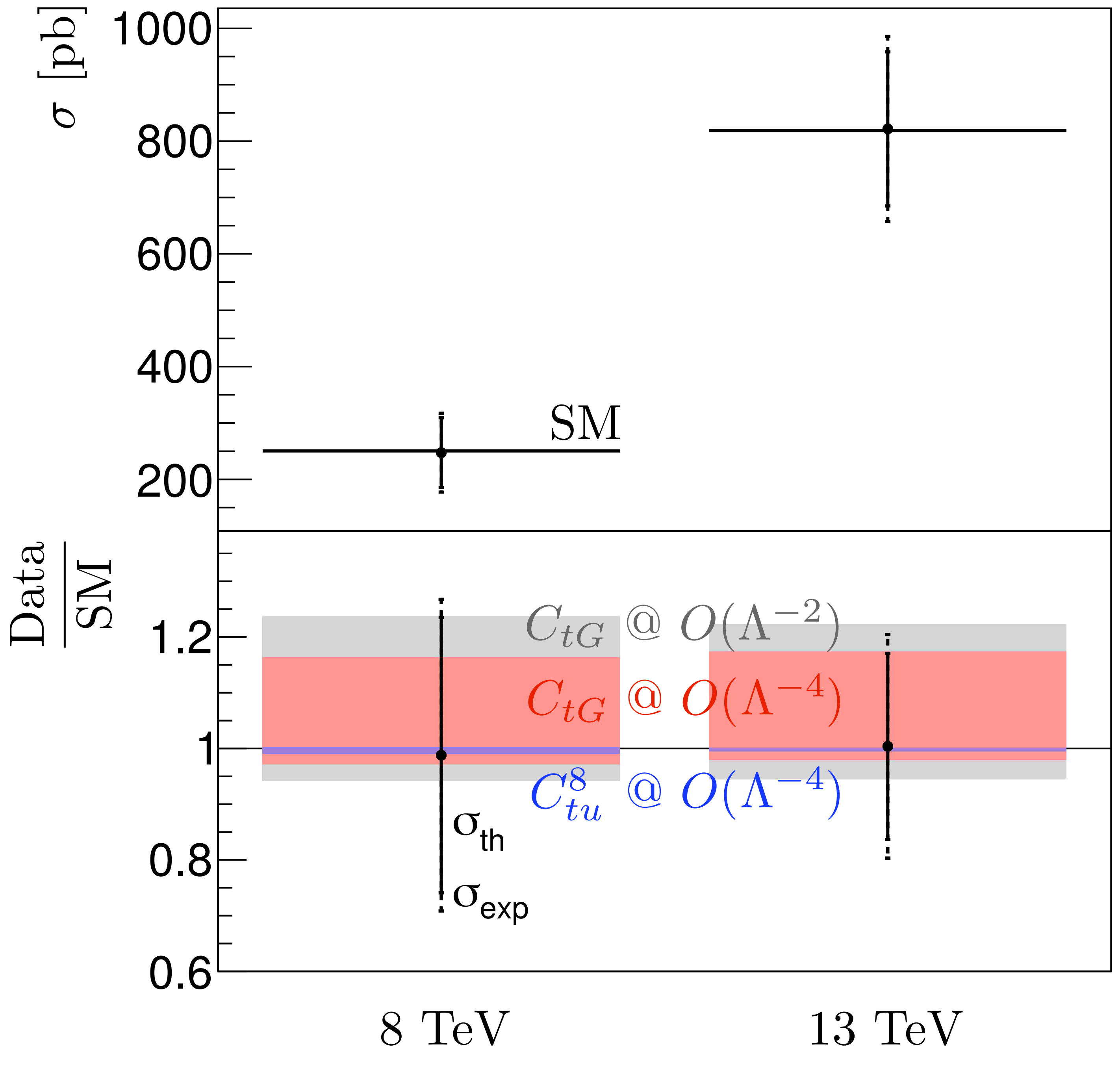
$$O_{tG} = C_{tG}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G^A_{\mu\nu}$$

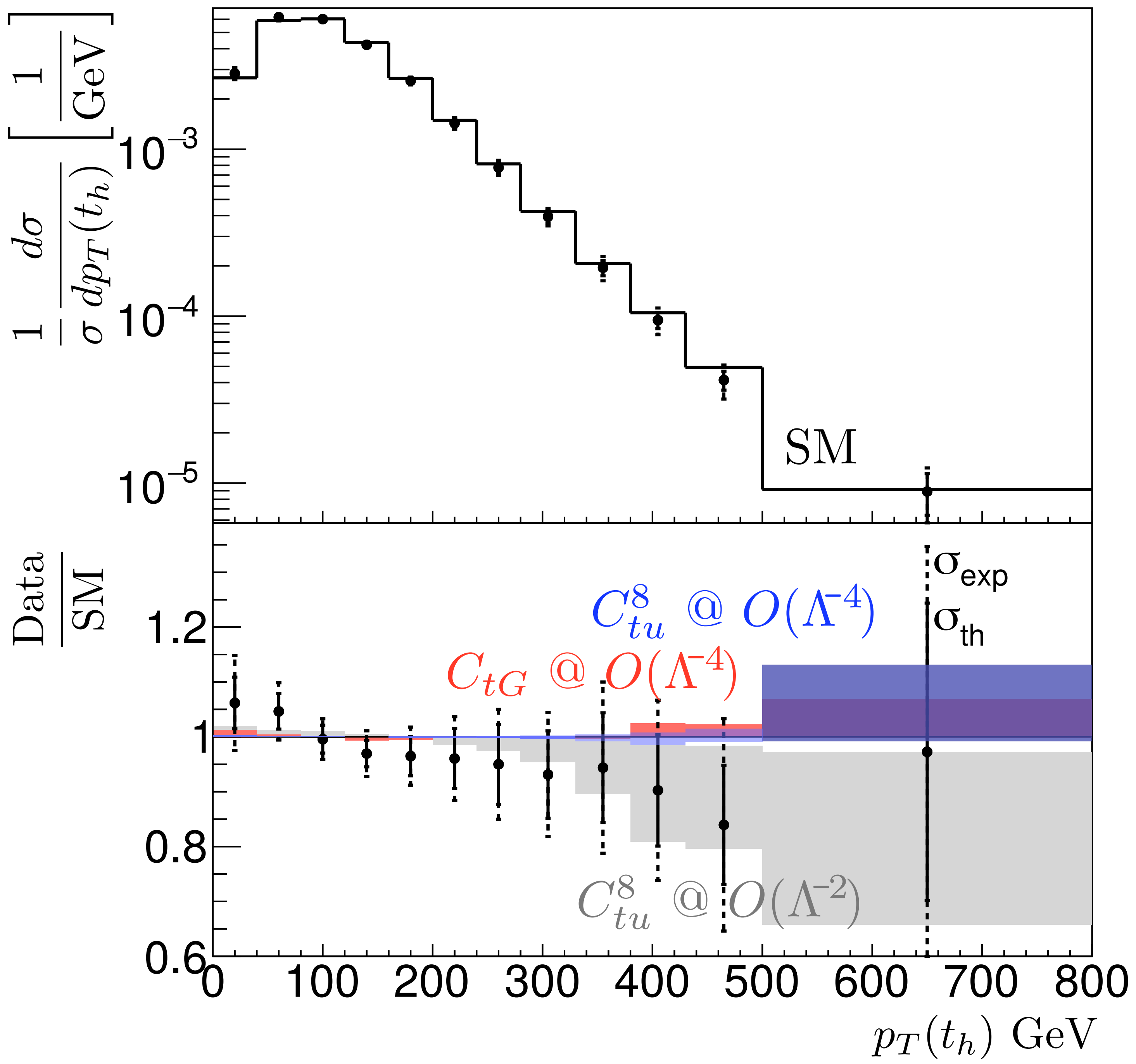
$$O^8_{tu} = C^8_{tu}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{u}_i\gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

Very small

Very large
For high bins





Up vs. Down

And Gauge Structure

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

Up vs. Down

And Gauge Structure

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

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

SU(2) Singlet
Sensitive to u+d initial state

Up vs. Down

And Gauge Structure

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

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

SU(2) Tripplet
Sensitive to u-d initial state

Up vs. Down

And Gauge Structure

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

Up vs. Down

And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)}$$

Up vs. Down

And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)}$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[(r+1)C_{Qq}^{1,8} + (r-1)C_{Qq}^{3,8}\right]$$

Up vs. Down

And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[(r+1)C_{Qq}^{1,8} + (r-1)C_{Qq}^{3,8}\right]$$

Up vs. Down

And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8}\right]$$

Up vs. Down

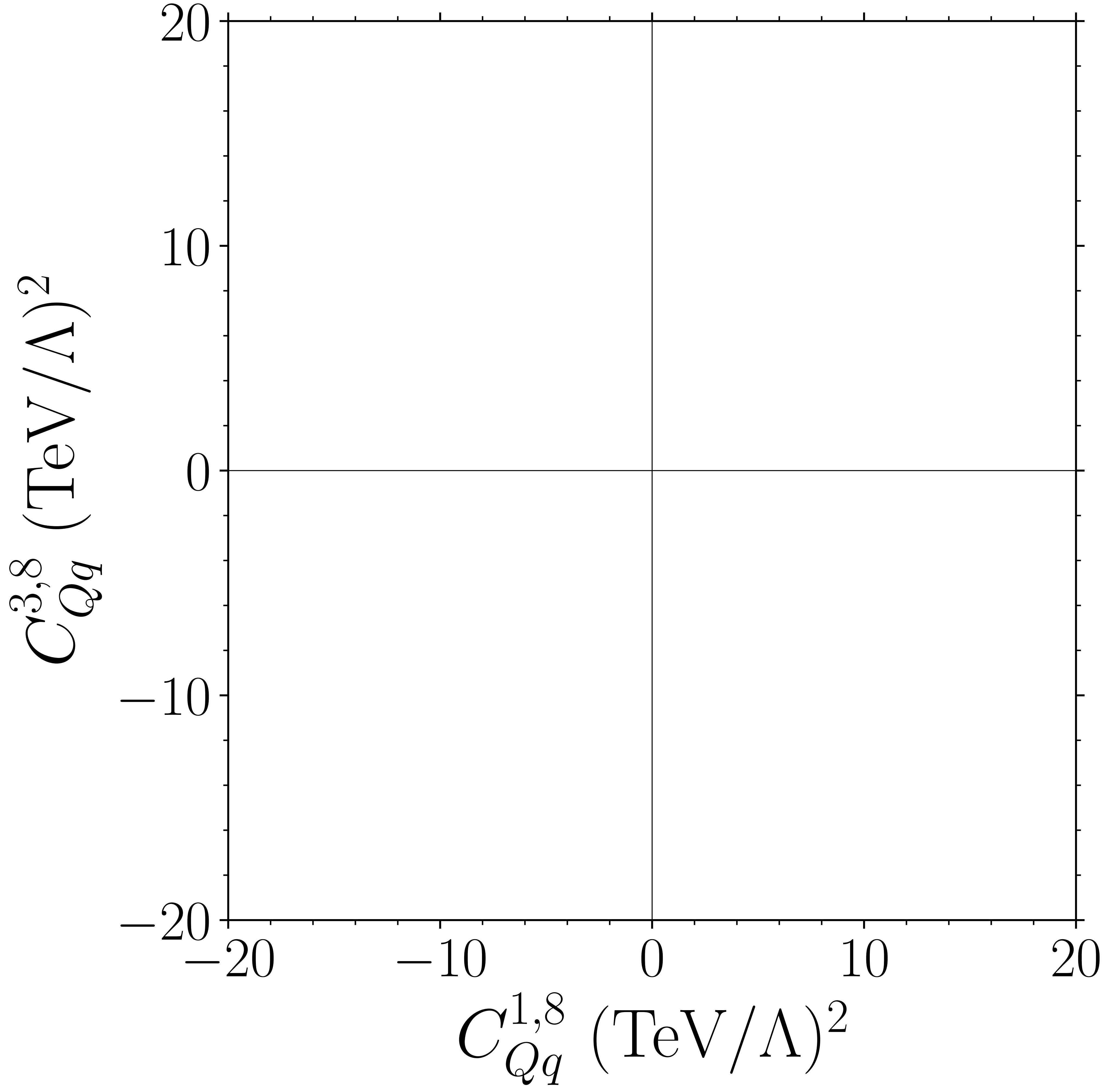
And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad \mathbf{3}\, C_{Qq}^{1,8} + \quad \mathbf{1}\, C_{Qq}^{3,8}\right]$$



Up vs. Down

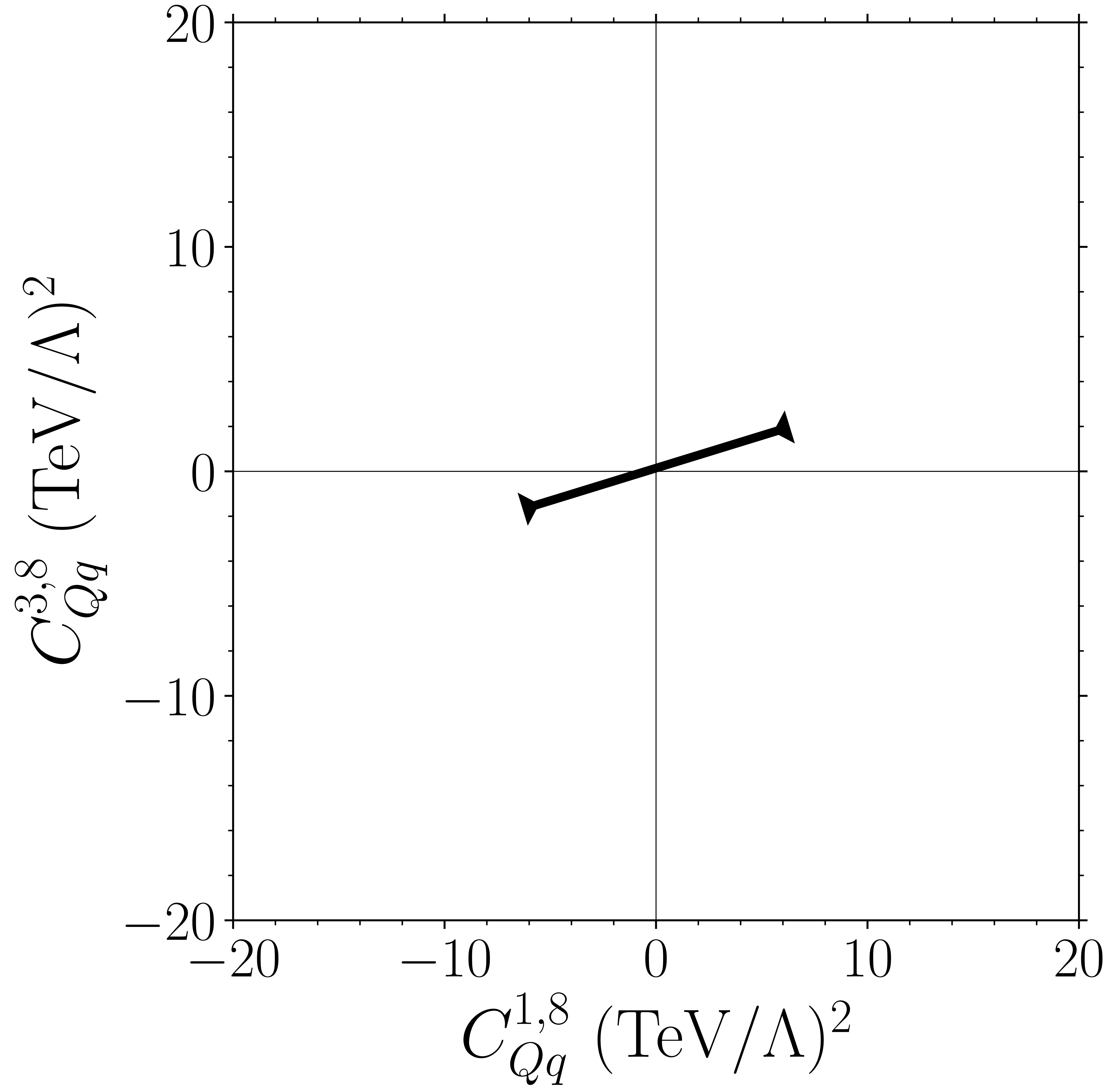
And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8}\right]$$



Up vs. Down

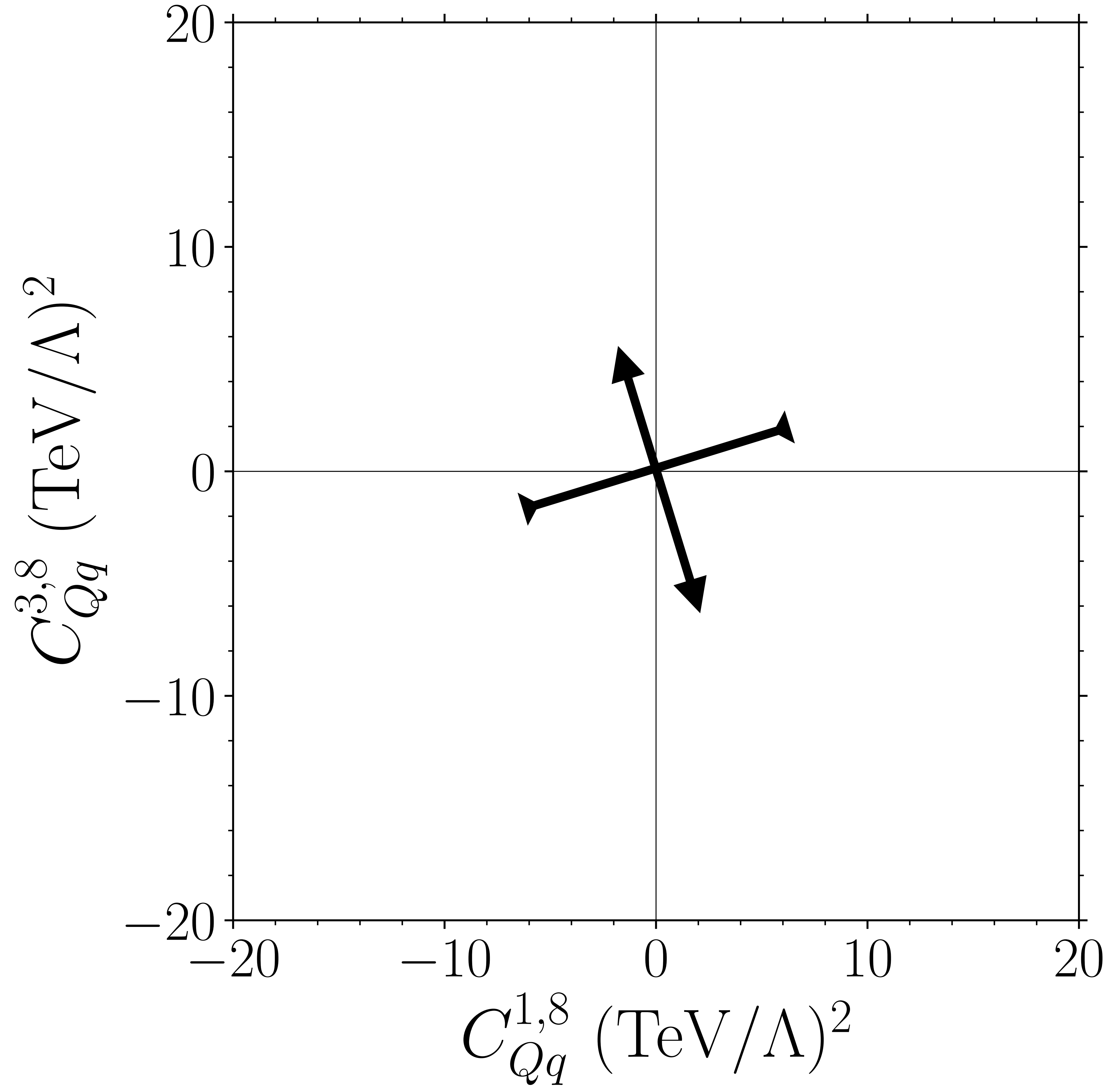
And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad \mathbf{3}\, C_{Qq}^{1,8} + \quad \mathbf{1}\, C_{Qq}^{3,8} \right]$$



Up vs. Down

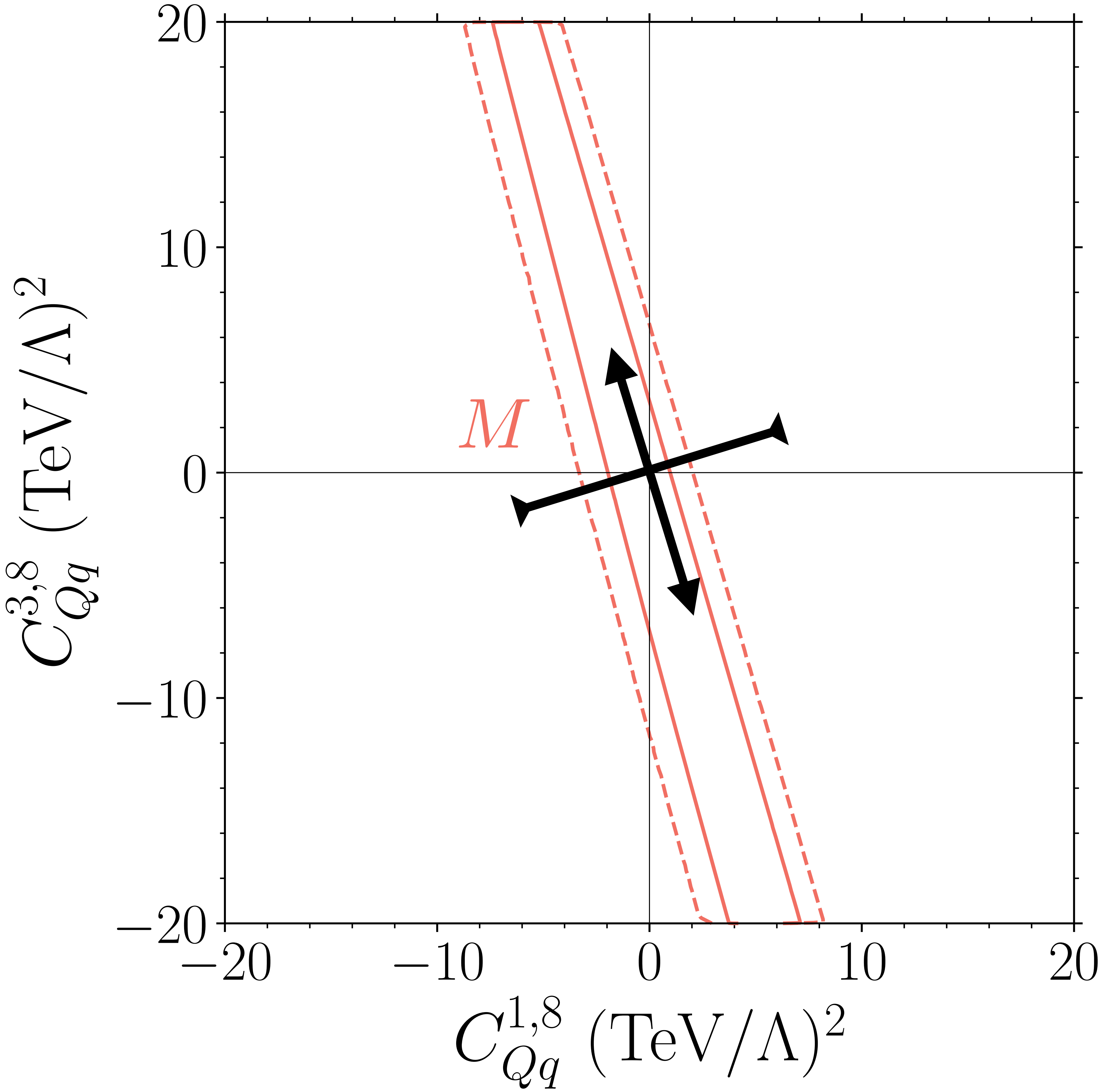
And Gauge Structure

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

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\,C_{Qq}^{1,8} + \quad 1\,C_{Qq}^{3,8}\right]$$



Up vs. Down

And Gauge Structure

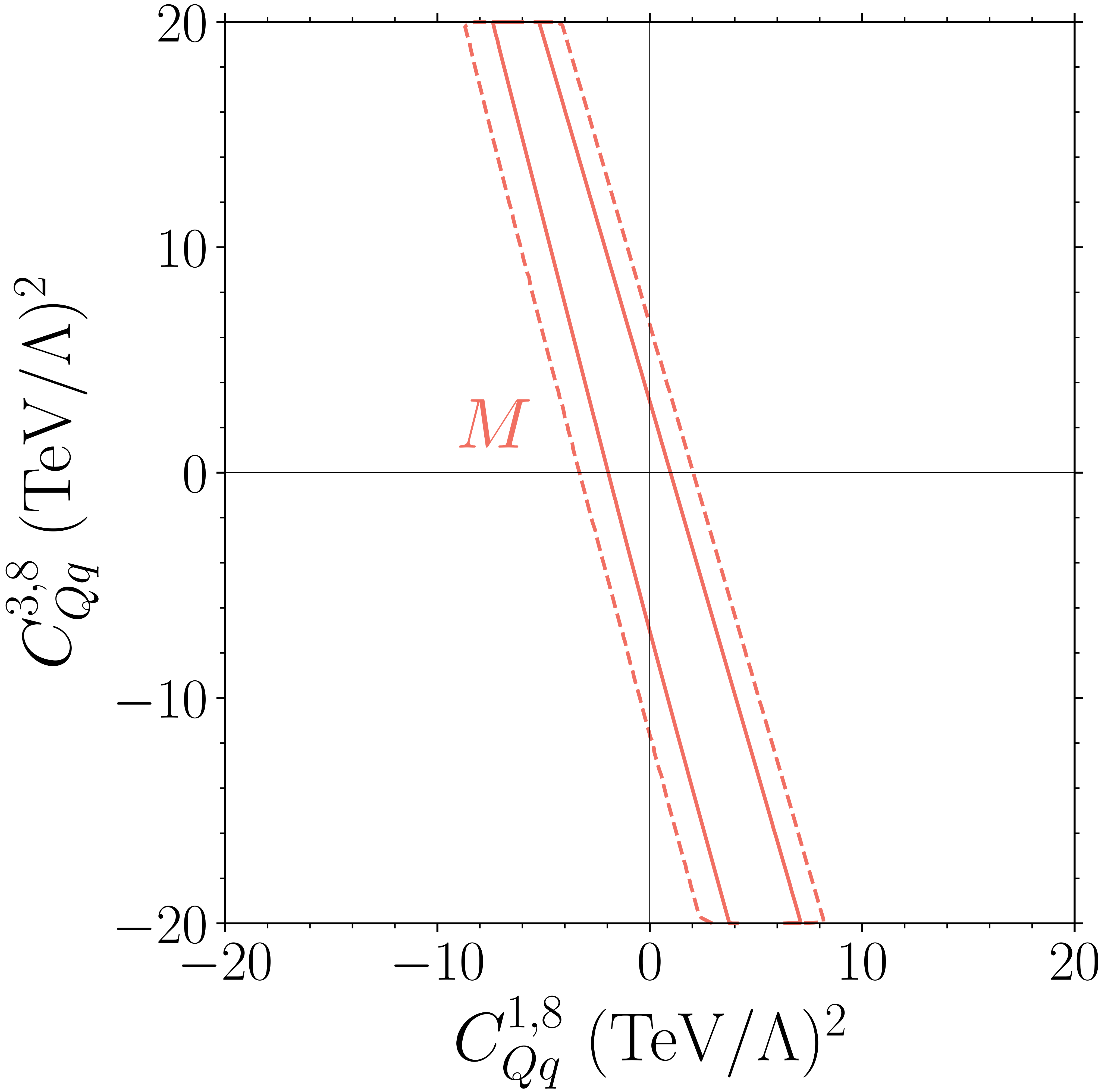
$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i) \qquad O_{Qq}^{3,8} = C_{Qq}^{3,8}(\bar{q}_3\gamma^\mu T^A \tau^I q_3)(\bar{q}_i\gamma_\mu T^A \tau^I q_i)$$

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\,C_{Qq}^{1,8} + \quad 1\,C_{Qq}^{3,8}\right]$$

Probe different r(x) in boosted regime



Up vs. Down

And Gauge Structure

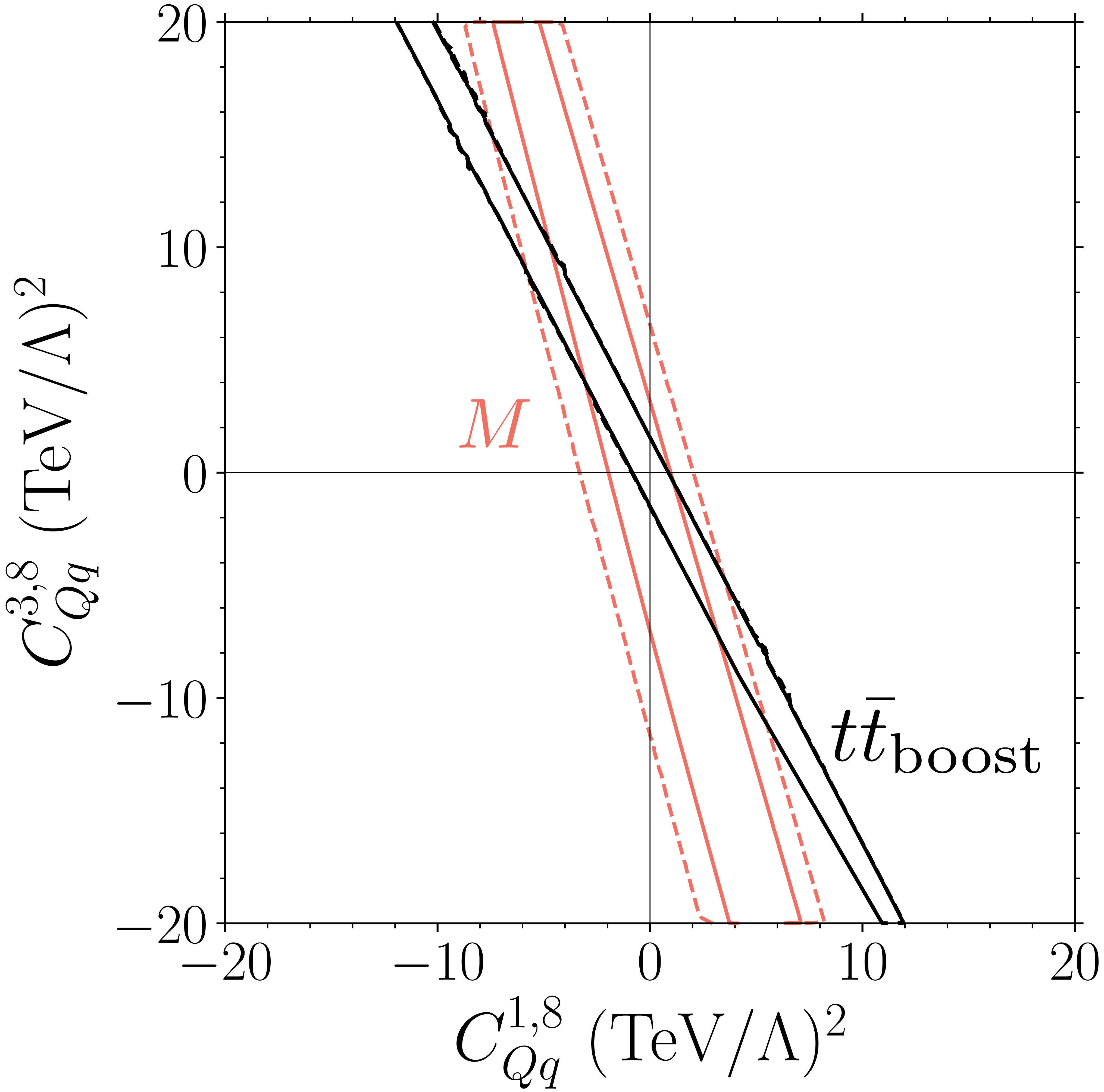
$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i) \qquad O_{Qq}^{3,8} = C_{Qq}^{3,8}(\bar{q}_3\gamma^\mu T^A \tau^I q_3)(\bar{q}_i\gamma_\mu T^A \tau^I q_i)$$

$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8} \right]$$

Probe different r(x) in boosted regime



Up vs. Down

And Gauge Structure

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

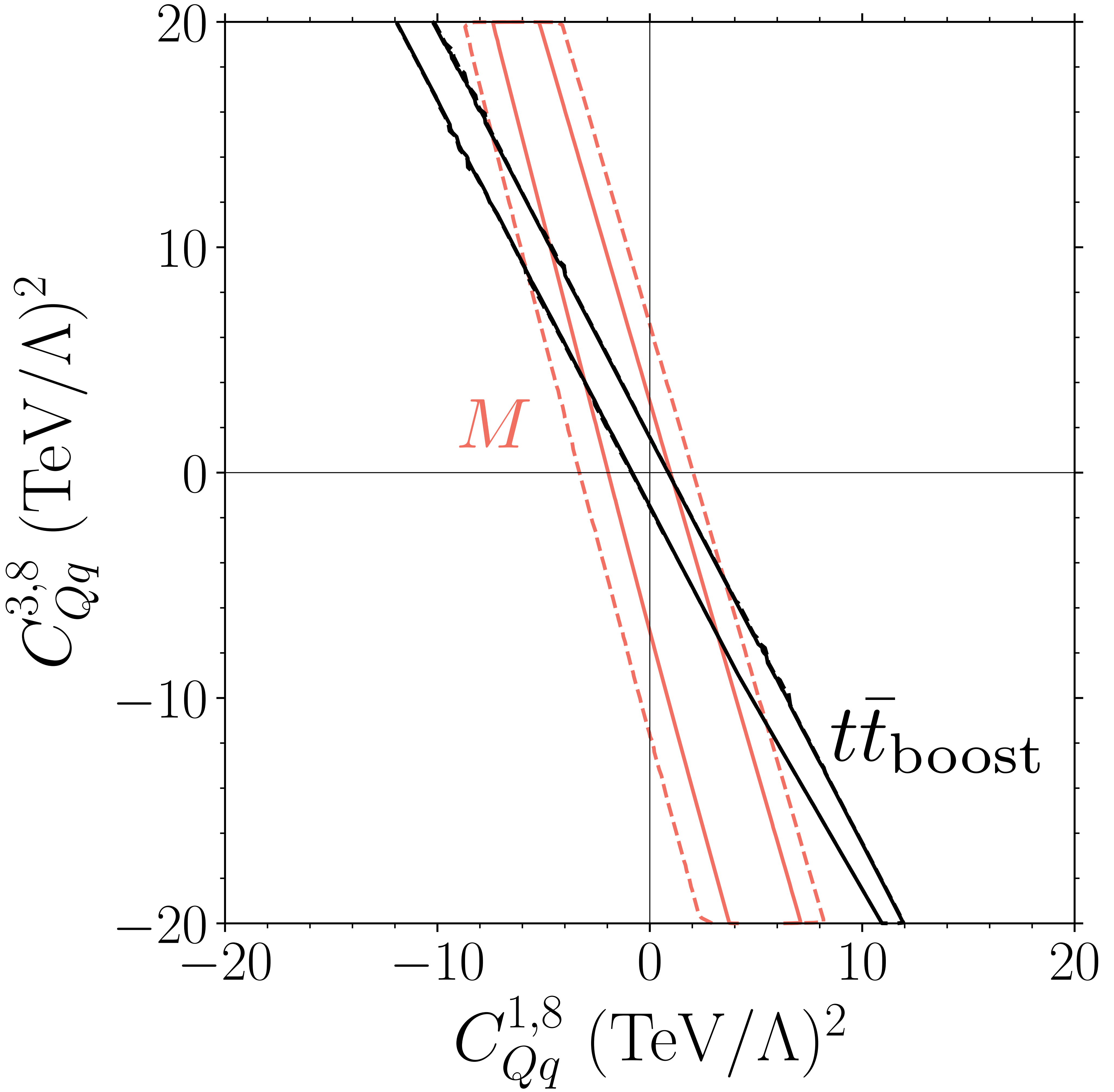
$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8}\right]$$

Probe different r(x) in boosted regime

Include ttZ and ttW measurements



Up vs. Down

And Gauge Structure

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

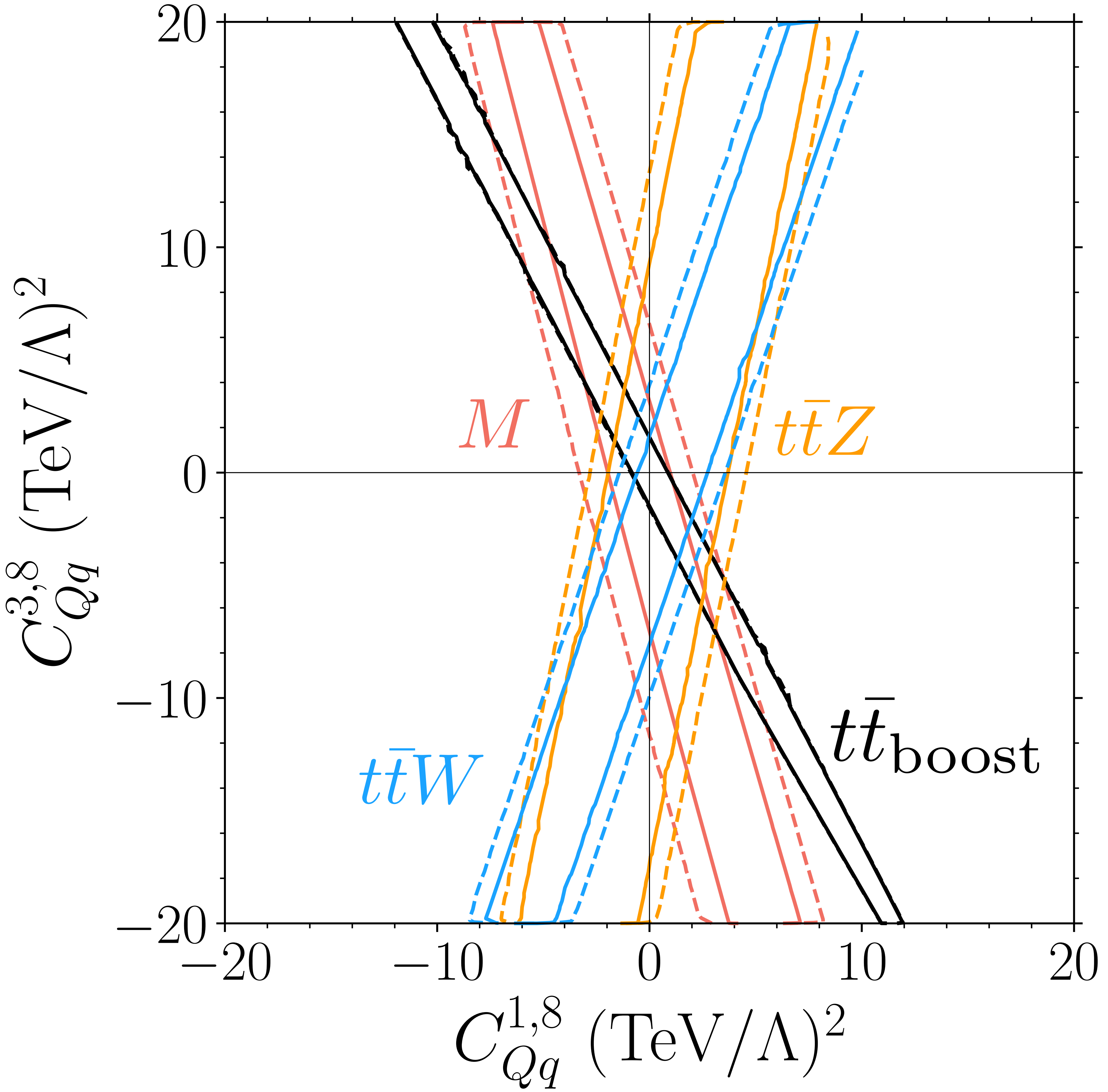
$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8}\right]$$

Probe different r(x) in boosted regime

Include ttZ and ttW measurements



Up vs. Down

And Gauge Structure

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

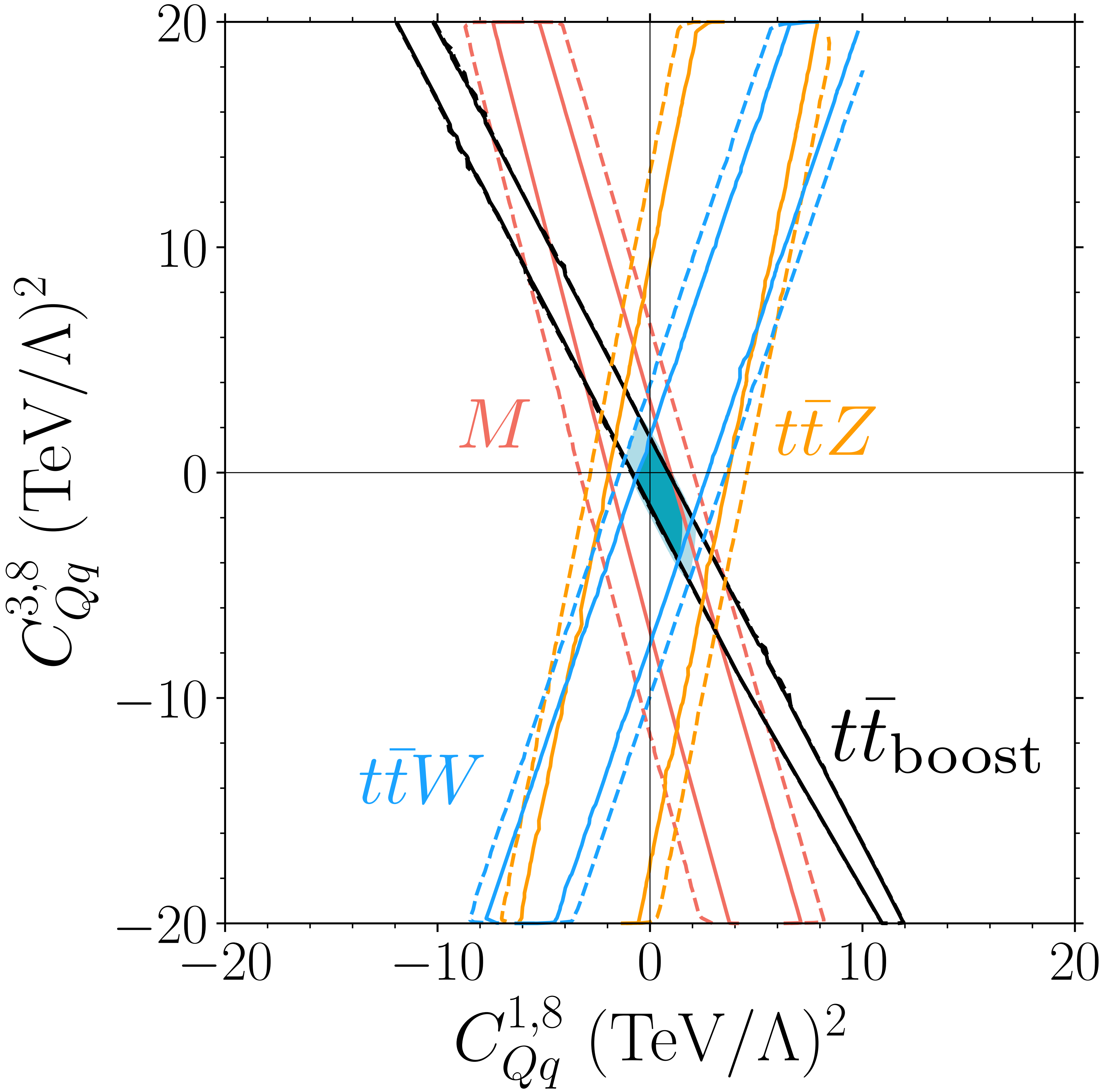
$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)} \sim 2$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3\, C_{Qq}^{1,8} + \quad 1\, C_{Qq}^{3,8} \right]$$

Probe different r(x) in boosted regime

Include ttZ and ttW measurements



Chirality

Or Left vs. Right

Chirality

Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

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

Chirality

Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

Right handed Top
in final state

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

Chirality

Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

Right handed Top
in final state

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

Left handed Top
in final state

Chirality

Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

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

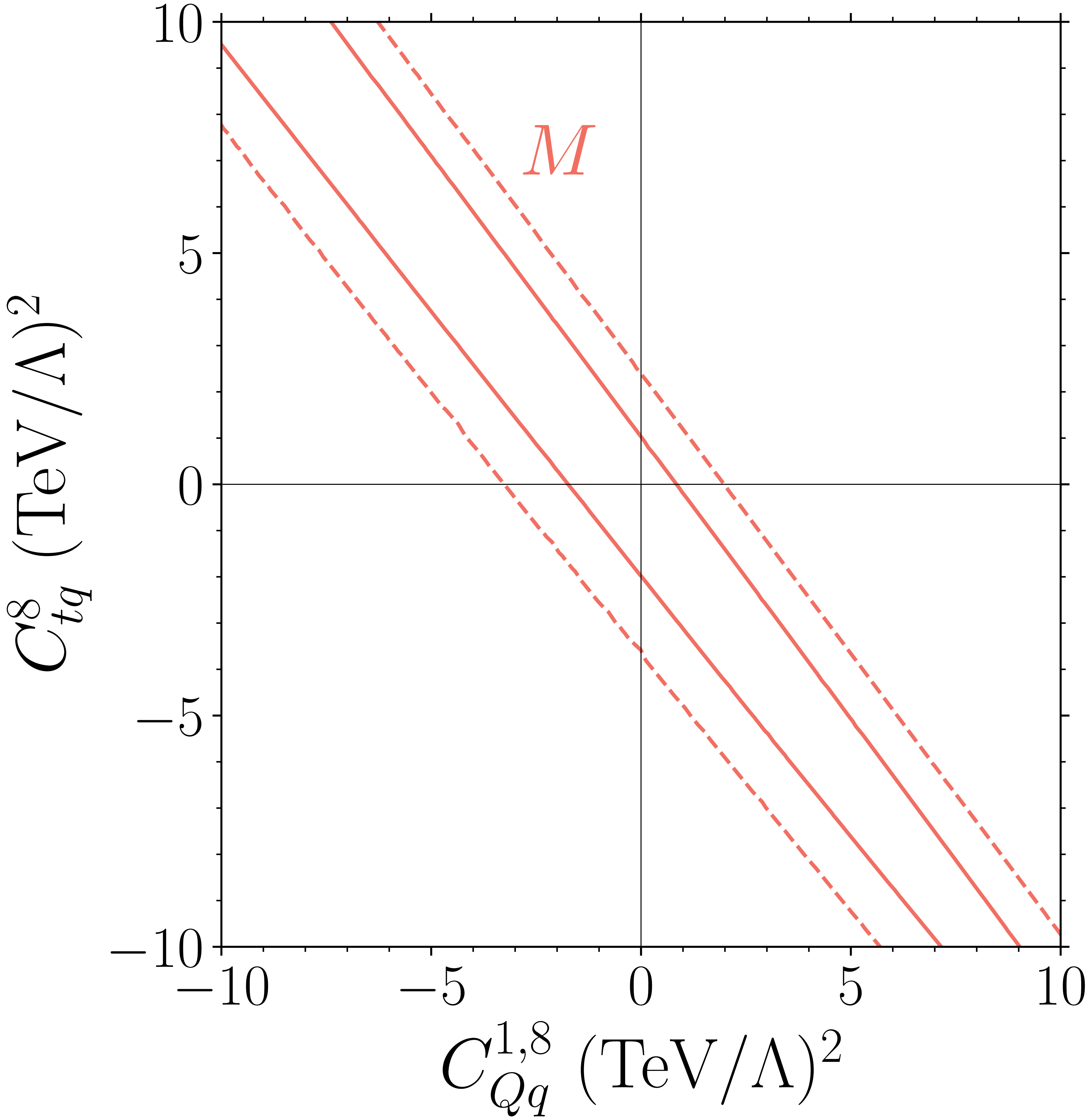
$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(\frac{C_{tq}^{8}}{\Lambda^2} + \frac{C_{Qq}^{1,8}}{\Lambda^2}\right)$$

Chirality
Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

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

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(\frac{C_{tq}^{8}}{\Lambda^2} + \frac{C_{Qq}^{1,8}}{\Lambda^2}\right)$$



Chirality

Or Left vs. Right

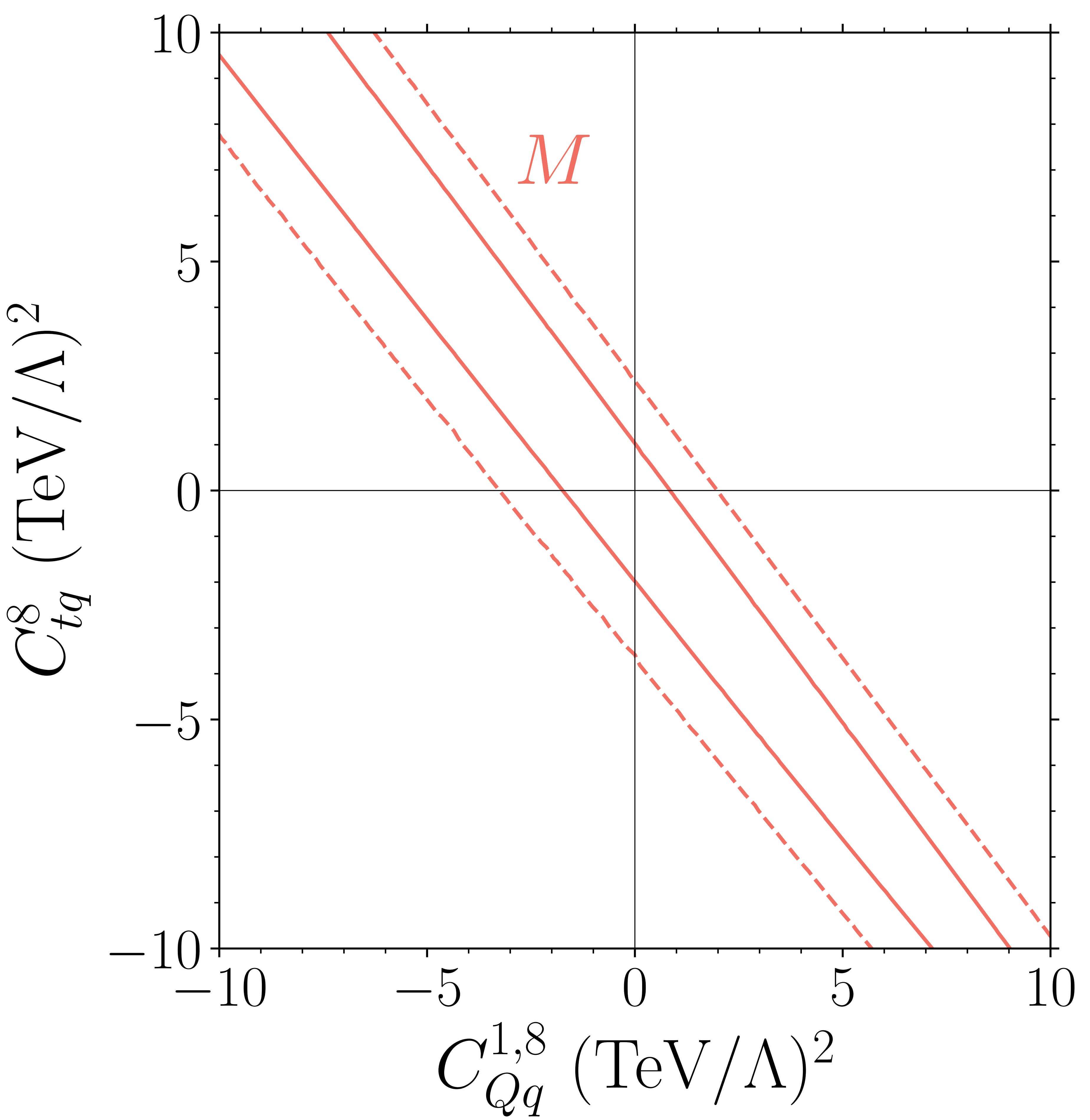
$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

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

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(\frac{C_{tq}^{8}}{\Lambda^2} + \frac{C_{Qq}^{1,8}}{\Lambda^2}\right)$$

$$A_C = \frac{\sigma\left(\Delta|y|>0\right) - \sigma\left(\Delta|y|>0\right)}{\sigma\left(\Delta|y|>0\right) + \sigma\left(\Delta|y|>0\right)} \quad \text{with} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(\frac{C_{Qq}^{1,8}}{\Lambda^2} - \frac{C_{tq}^{8}}{\Lambda^2}\right)}{\sigma_{t\bar{t}}}$$



Chirality
Or Left vs. Right

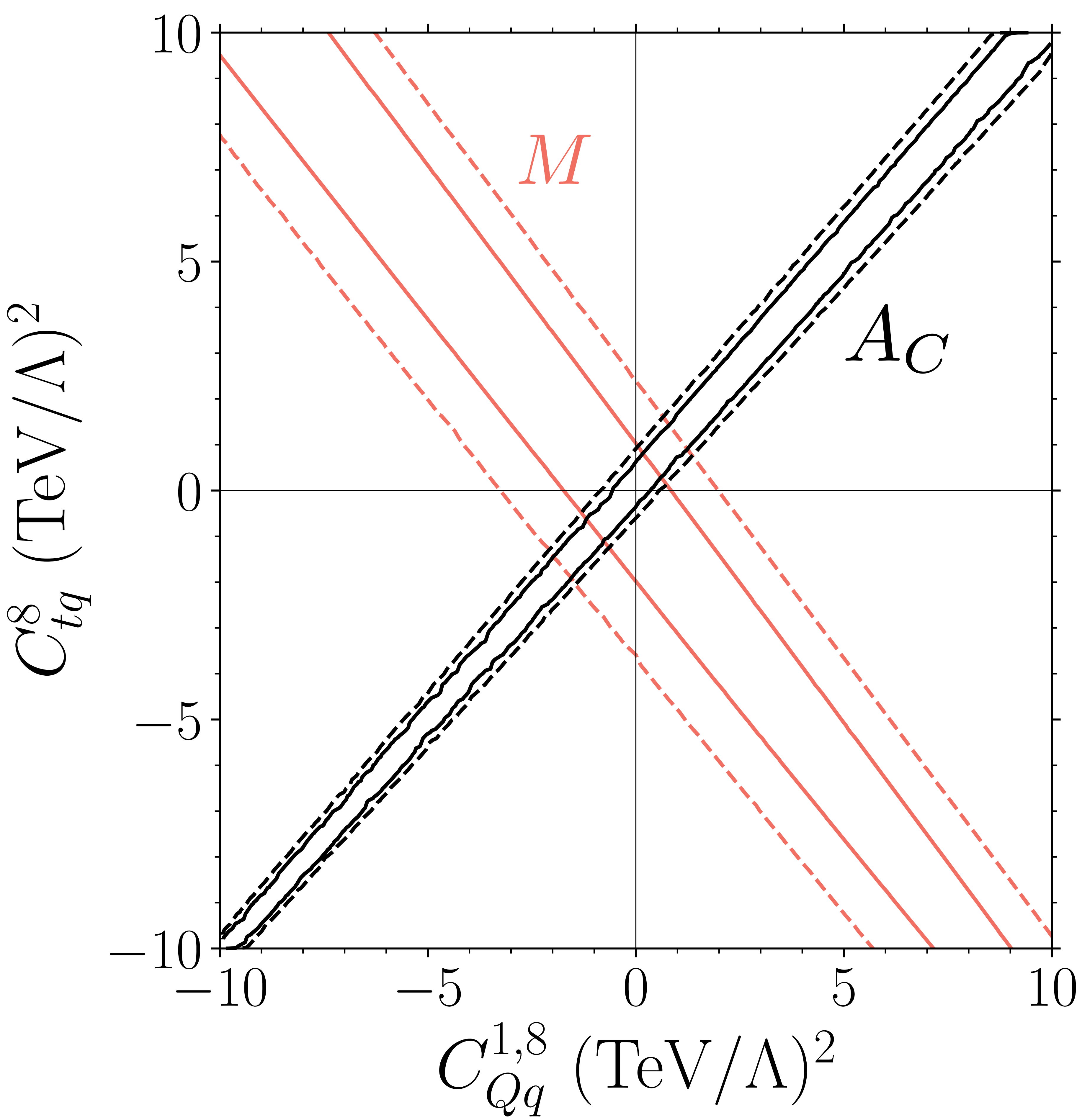
$$O^{8}_{tq} = C^{8}_{tq}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

$$O^{1,8}_{Qq} = C^{1,8}_{Qq}(\bar{q}_3\gamma^{\mu}T^{A}q_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

$$\sigma_{t\bar{t}} = \sigma^{SM}_{t\bar{t}} + \sigma^{NP,int}_{t\bar{t}}\left(\frac{C^{8}_{tq}}{\Lambda^2} + \frac{C^{1,8}_{Qq}}{\Lambda^2}\right)$$

$$A_C = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| > 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| > 0\right)} \quad \text{with} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{\sigma^{SM,A}_{t\bar{t}} + \sigma^{NP,A}_{t\bar{t}}\left(\frac{C^{1,8}_{Qq}}{\Lambda^2} - \frac{C^{8}_{tq}}{\Lambda^2}\right)}{\sigma_{t\bar{t}}}$$



Chirality

Or Left vs. Right

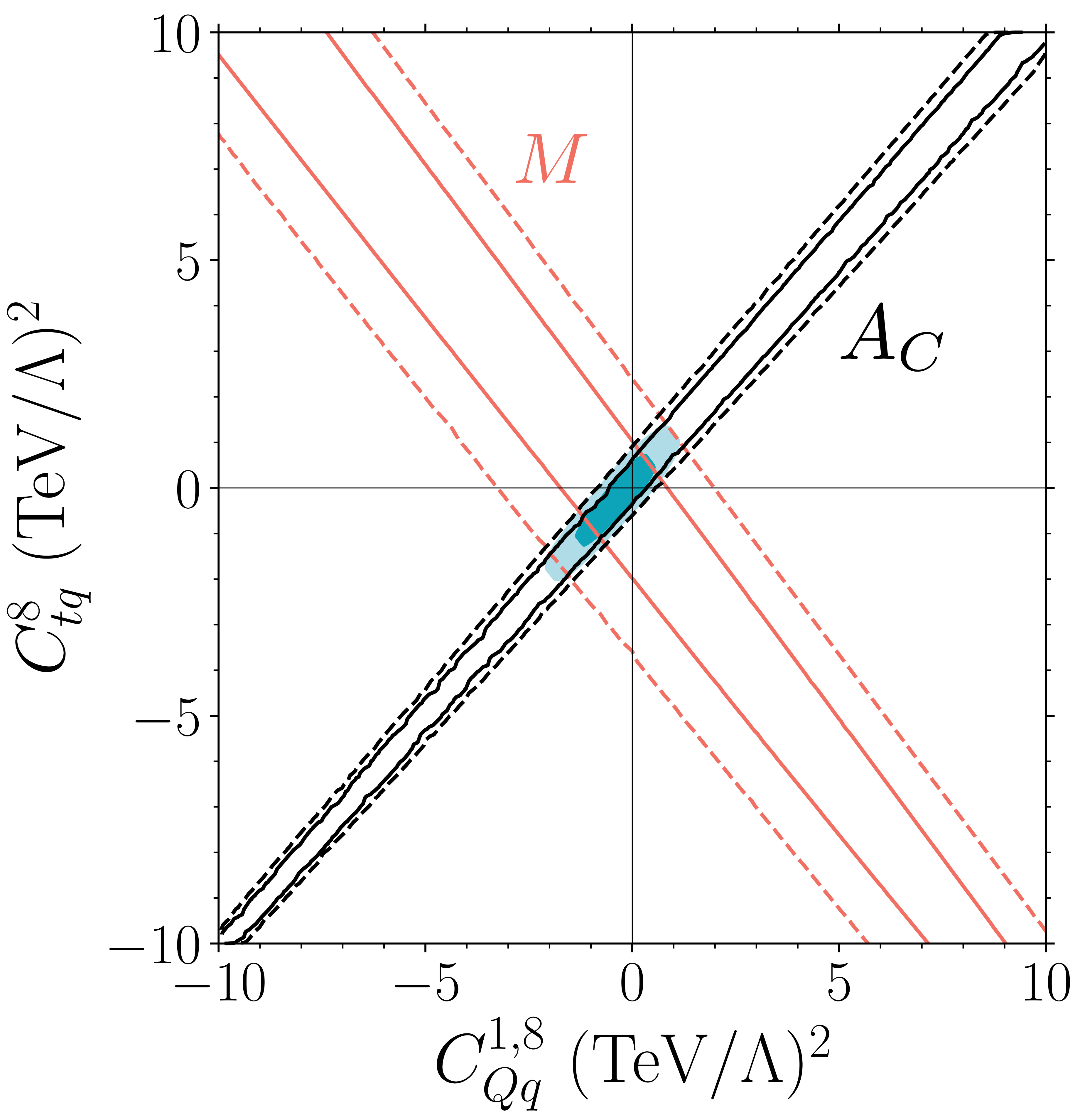
$$O^8_{tq} = C^8_{tq}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

$$O^{1,8}_{Qq} = C^{1,8}_{Qq}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

$$\sigma_{t\bar{t}} = \sigma^{SM}_{t\bar{t}} + \sigma^{NP,int}_{t\bar{t}}\left(\frac{C^8_{tq}}{\Lambda^2} + \frac{C^{1,8}_{Qq}}{\Lambda^2}\right)$$

$$A_C = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| > 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| > 0\right)} \quad \text{with} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{\sigma^{SM,A}_{t\bar{t}} + \sigma^{NP,A}_{t\bar{t}}\left(\frac{C^{1,8}_{Qq}}{\Lambda^2} - \frac{C^8_{tq}}{\Lambda^2}\right)}{\sigma_{t\bar{t}}}$$



Chirality

Or Left vs. Right

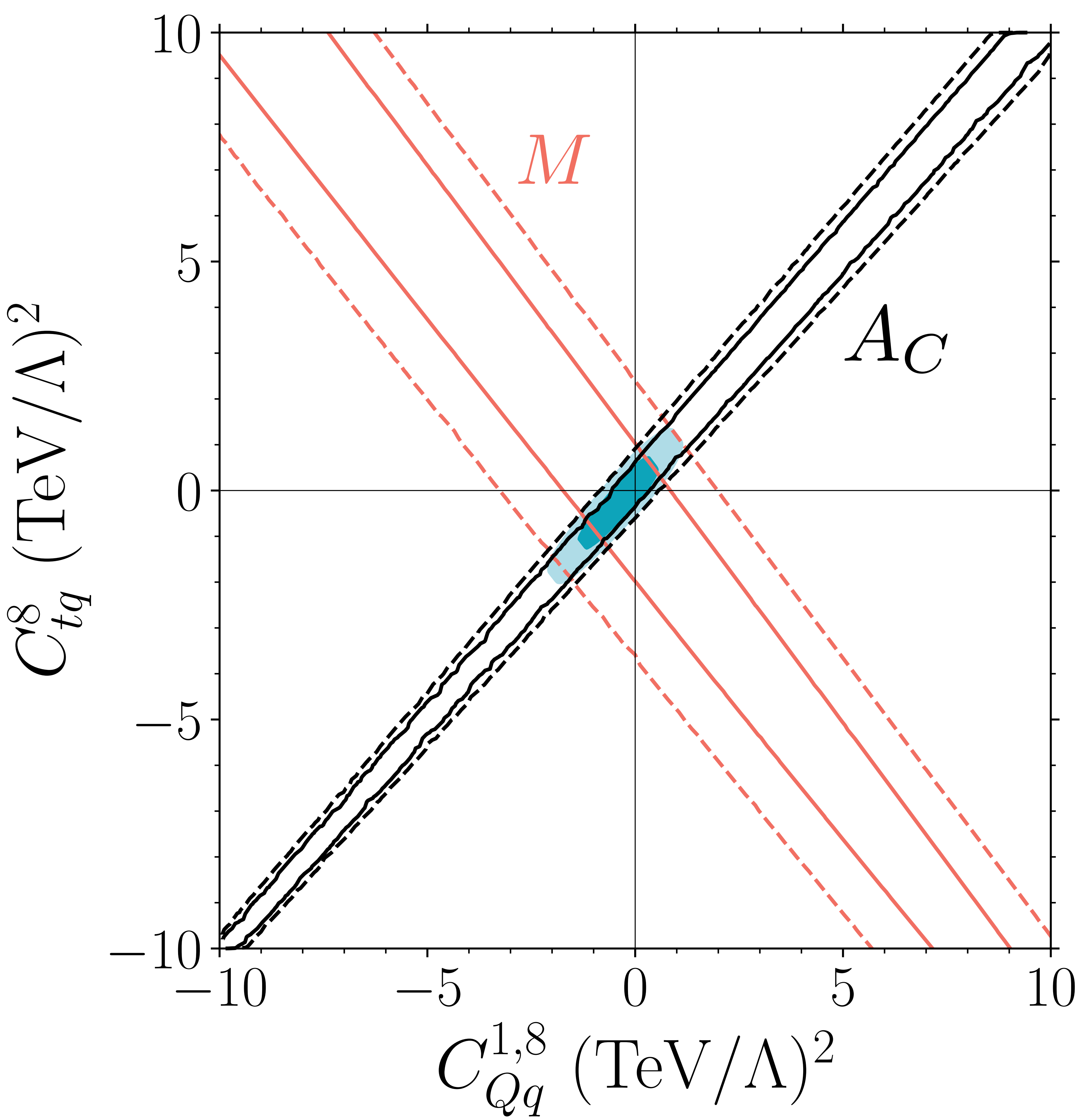
$$O^{8}_{tq} = C^{8}_{tq}(\bar{u}_3\gamma^{\mu}T^{A}u_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

$$O^{1,8}_{Qq} = C^{1,8}_{Qq}(\bar{q}_3\gamma^{\mu}T^{A}q_3)(\bar{q}_i\gamma_{\mu}T^{A}q_i)$$

$$\sigma_{t\bar{t}} = \sigma^{SM}_{t\bar{t}} + \sigma^{NP,int}_{t\bar{t}}\left(\frac{C^{8}_{tq}}{\Lambda^2} + \frac{C^{1,8}_{Qq}}{\Lambda^2}\right)$$

$$A_C = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| > 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| > 0\right)} \quad \text{with} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

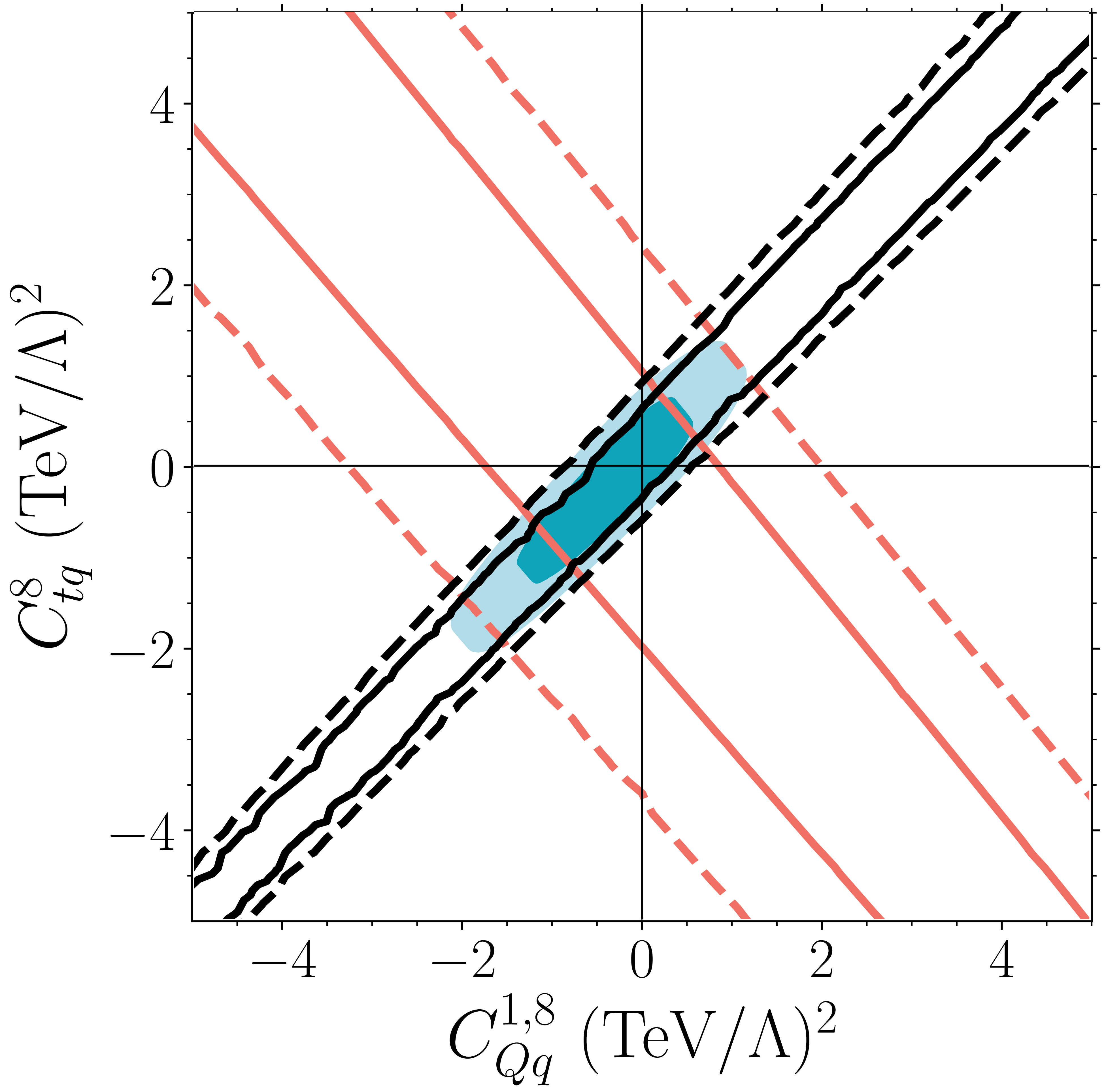
$$A_C = \frac{\sigma^{SM,A}_{t\bar{t}} + \sigma^{NP,A}_{t\bar{t}}\left(\frac{C^{1,8}_{Qq}}{\Lambda^2} - \frac{C^{8}_{tq}}{\Lambda^2}\right)}{\sigma_{t\bar{t}}}$$



NLO Corrections can also help to resolve this degeneracy

Quadratic Terms

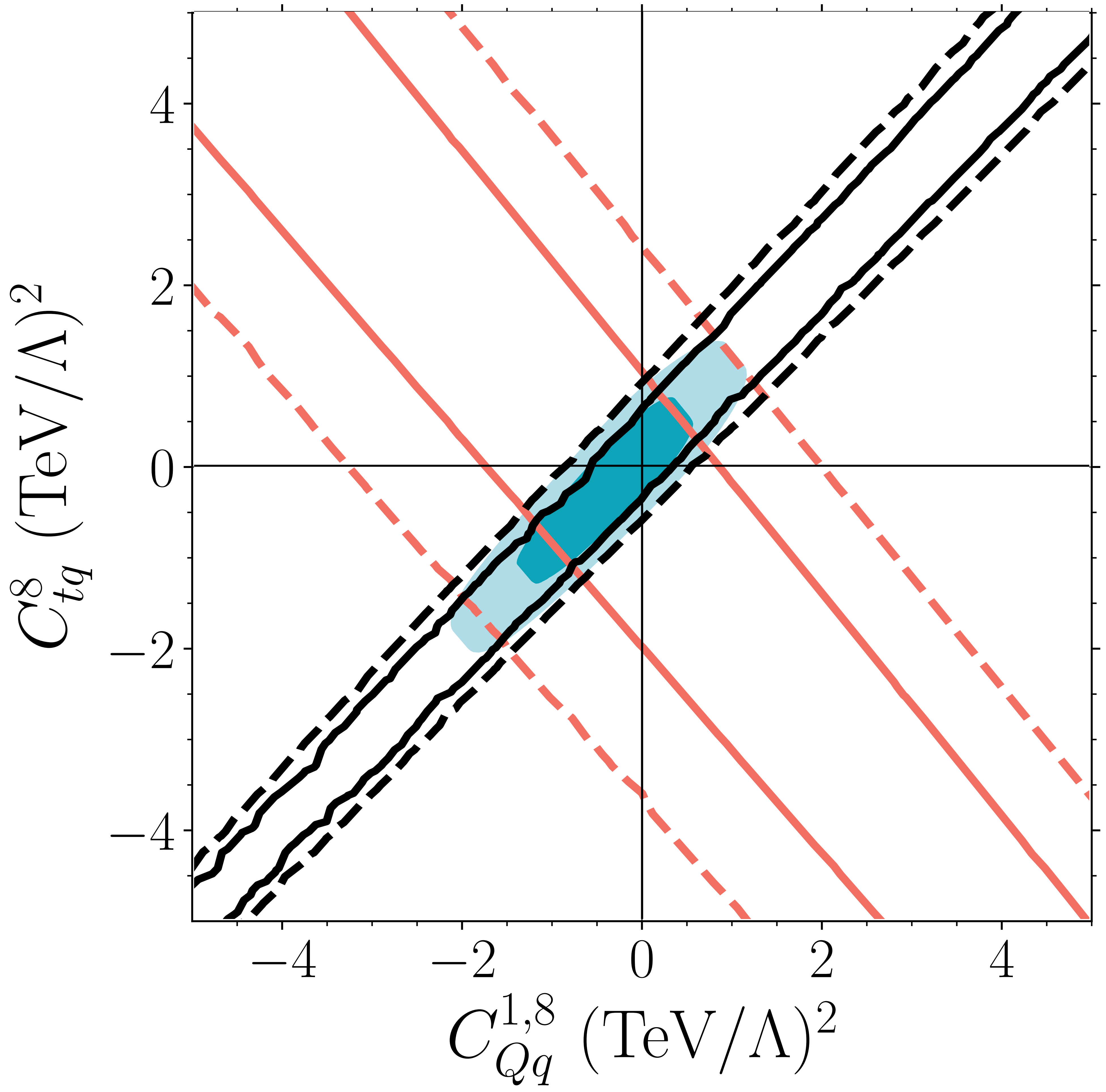
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$



Quadratic Terms

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

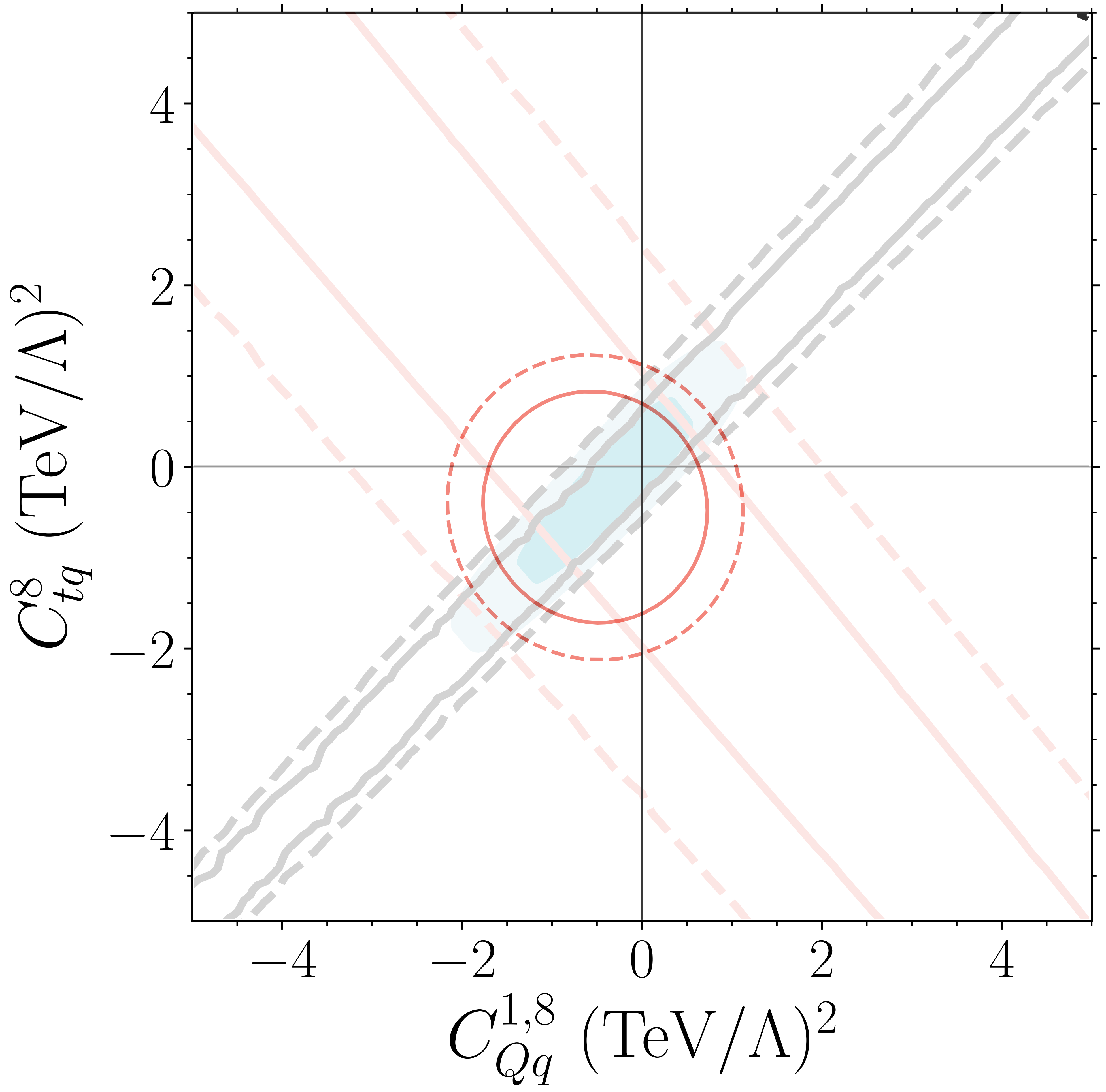
$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \dots$$



Quadratic Terms

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \ldots$$

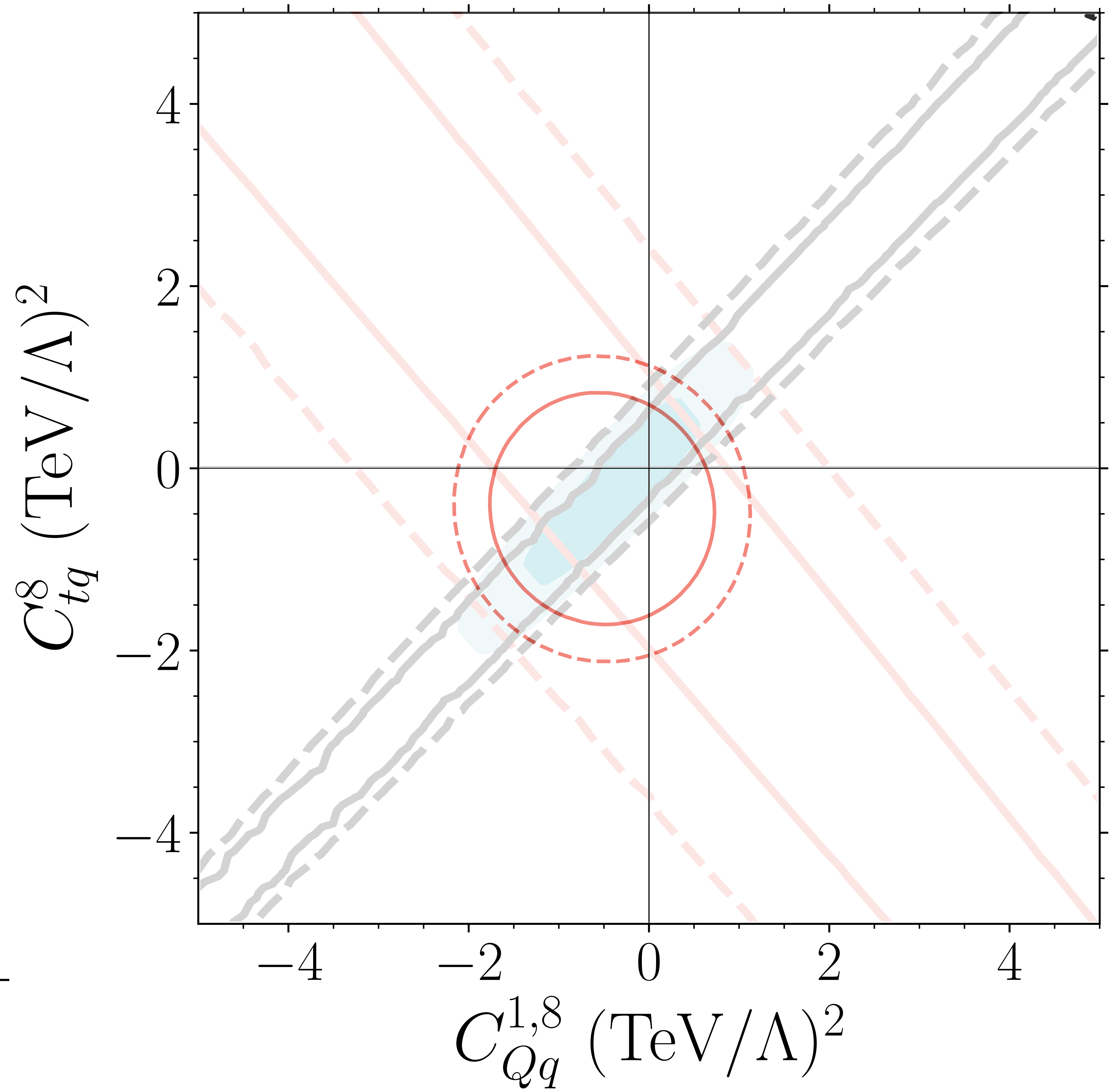


Quadratic Terms

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \ldots$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right) + \sigma_{t\bar{t}}^{NP^2,A}\left(\left(C_{Qq}^{1,8}\right)^2 - \left(C_{tq}^{8}\right)^2\right)}{\sigma_{t\bar{t}}}$$

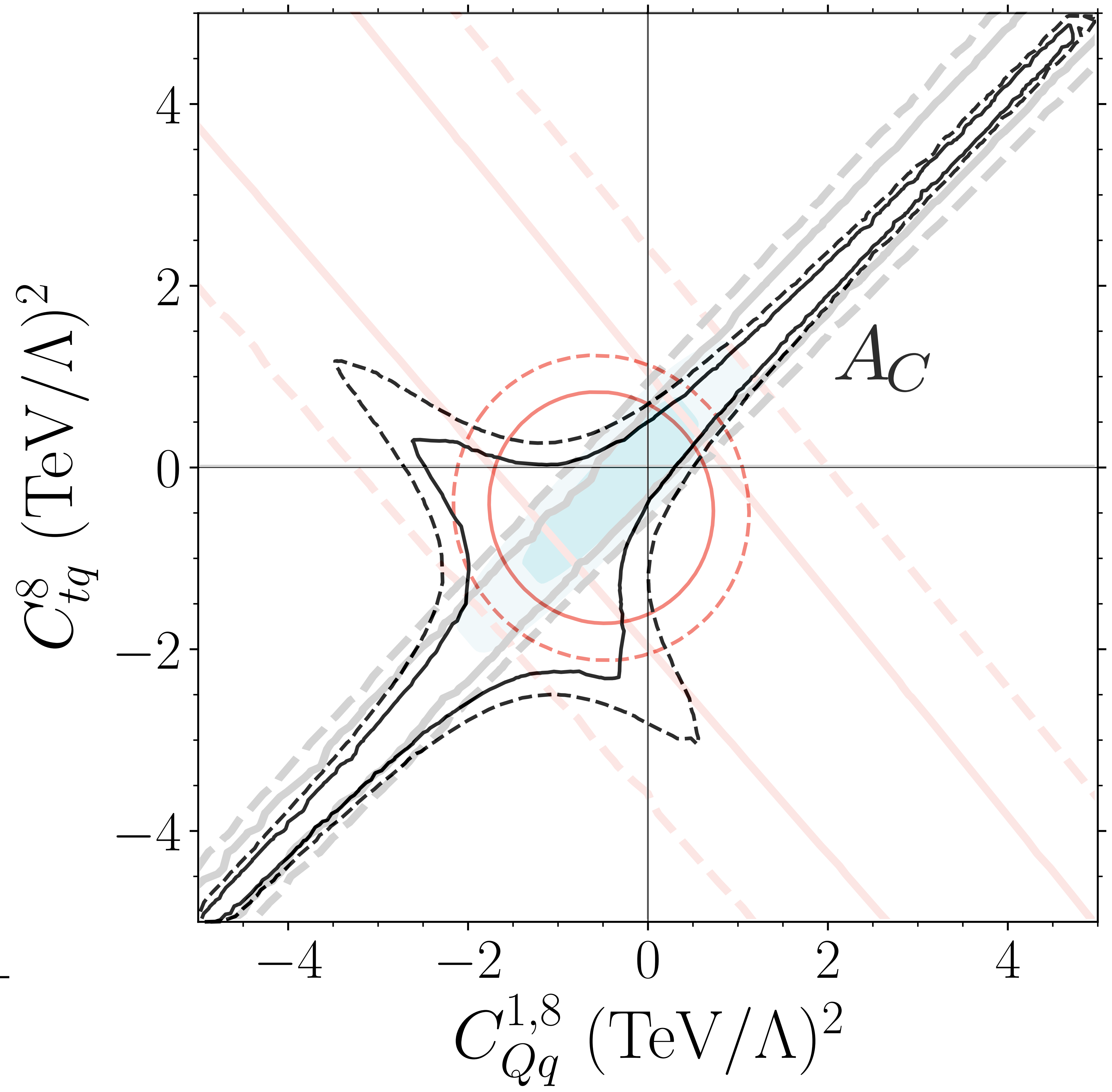


Quadratic Terms

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \dots$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right) + \sigma_{t\bar{t}}^{NP^2,A}\left(\left(C_{Qq}^{1,8}\right)^2 - \left(C_{tq}^{8}\right)^2\right)}{\sigma_{t\bar{t}}}$$

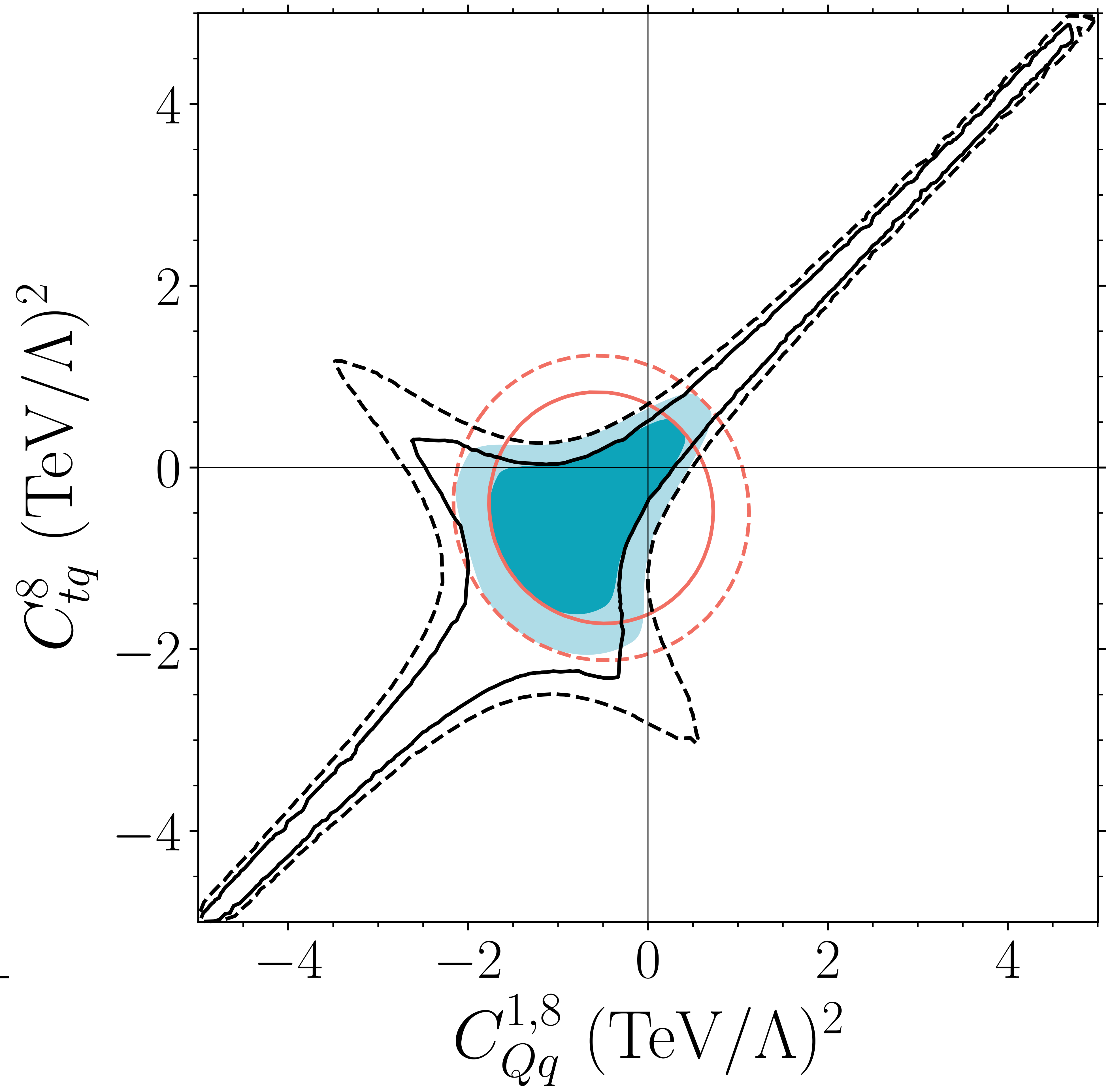


Quadratic Terms

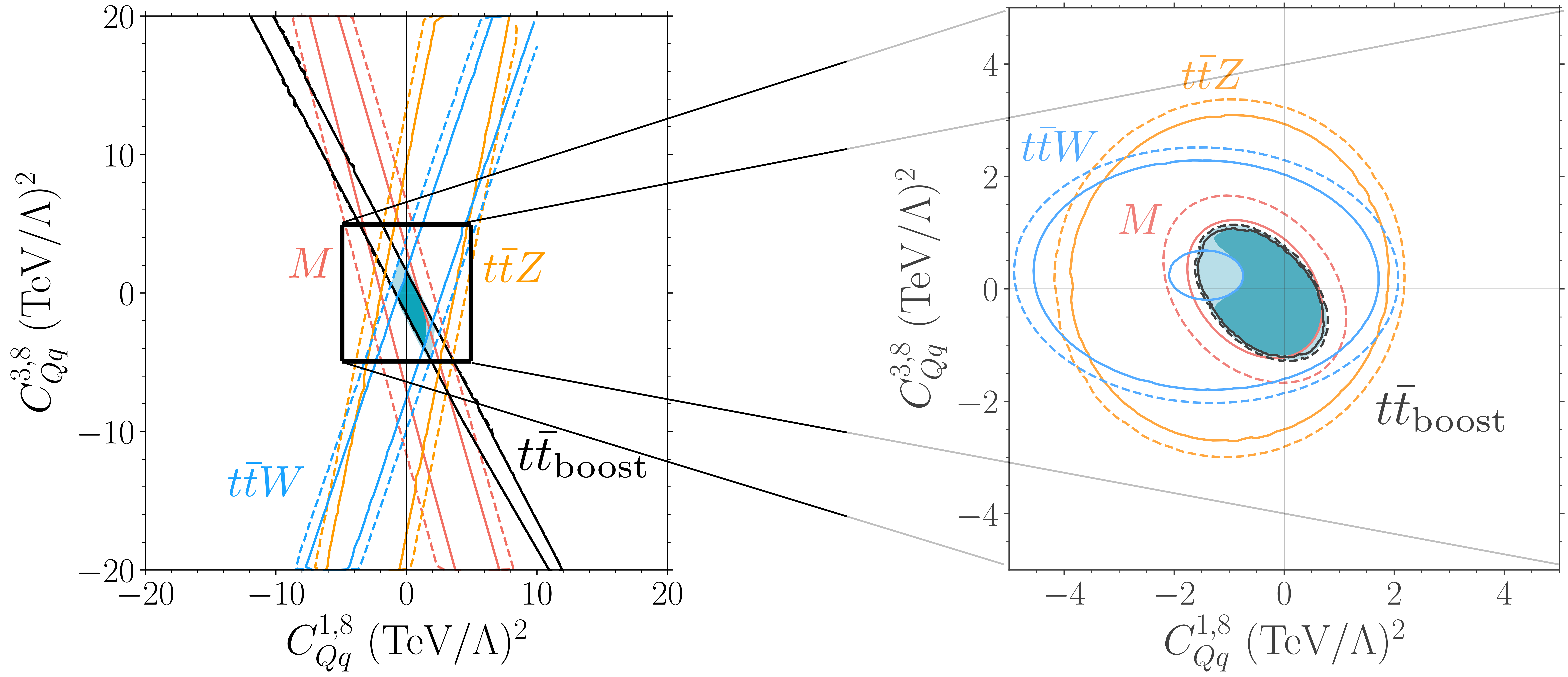
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \ldots$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right) + \sigma_{t\bar{t}}^{NP^2,A}\left(\left(C_{Qq}^{1,8}\right)^2 - \left(C_{tq}^{8}\right)^2\right)}{\sigma_{t\bar{t}}}$$



Quadratic Terms

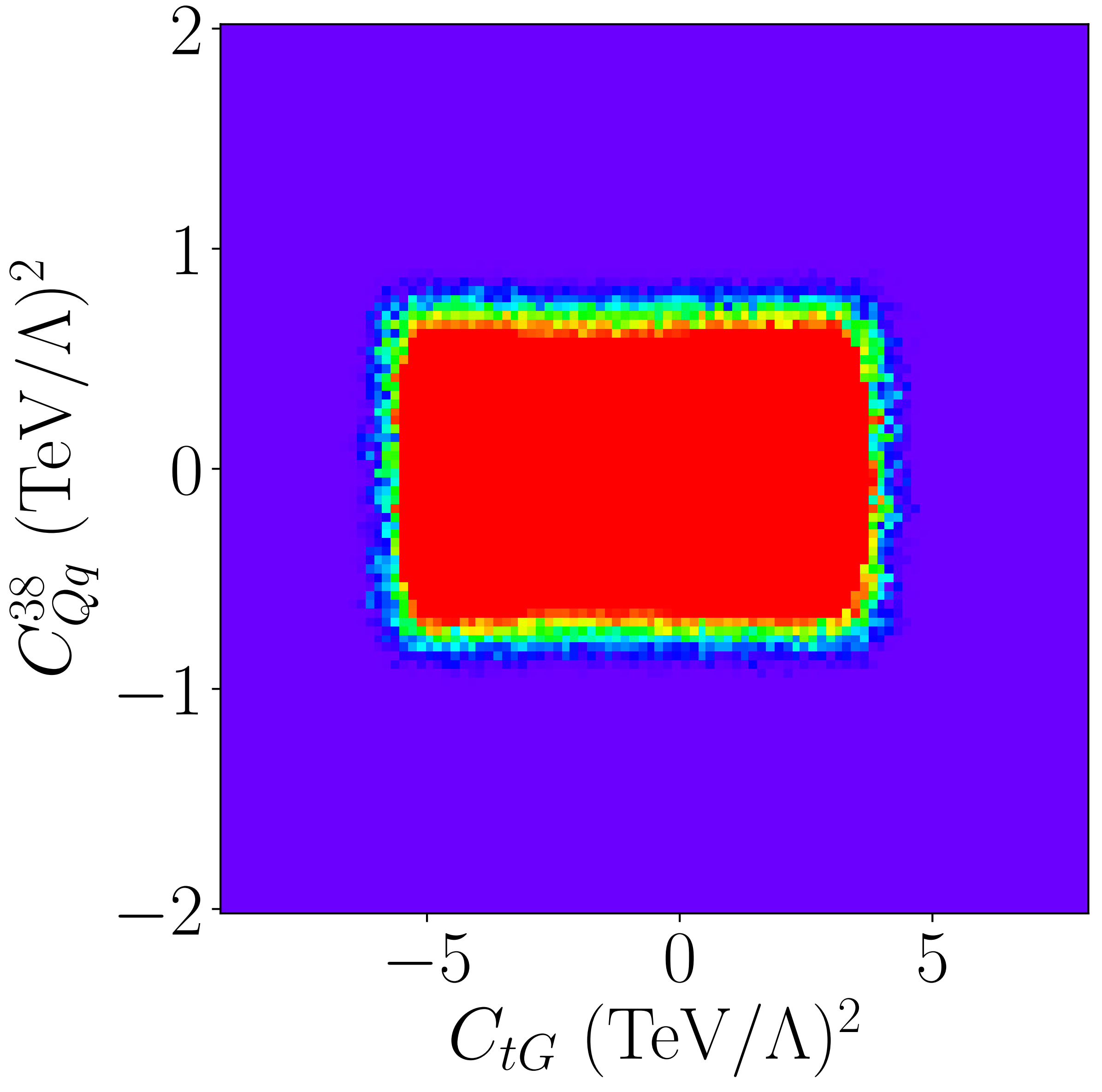


Single Top

Some aspects

Single Top

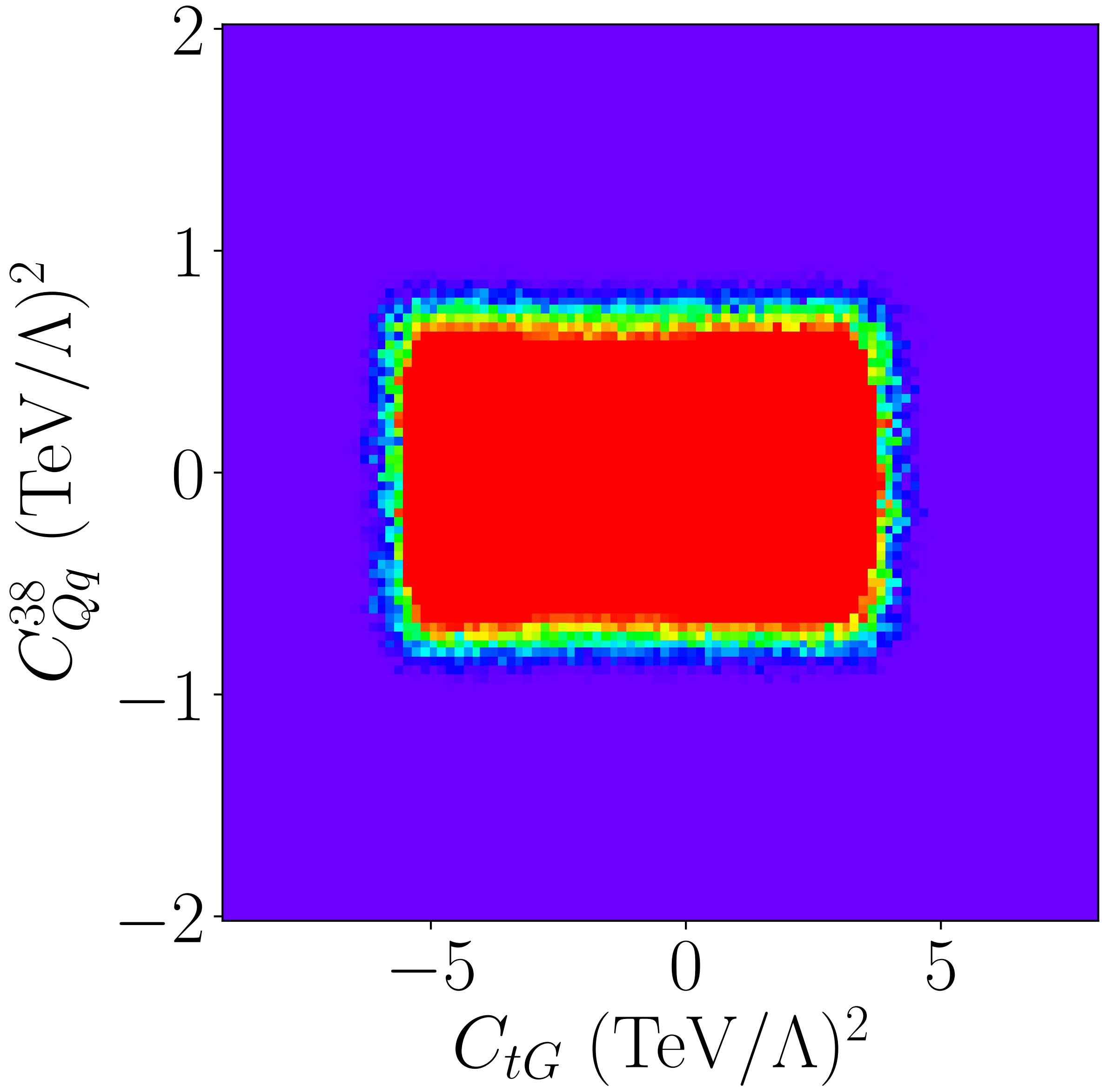
Some aspects

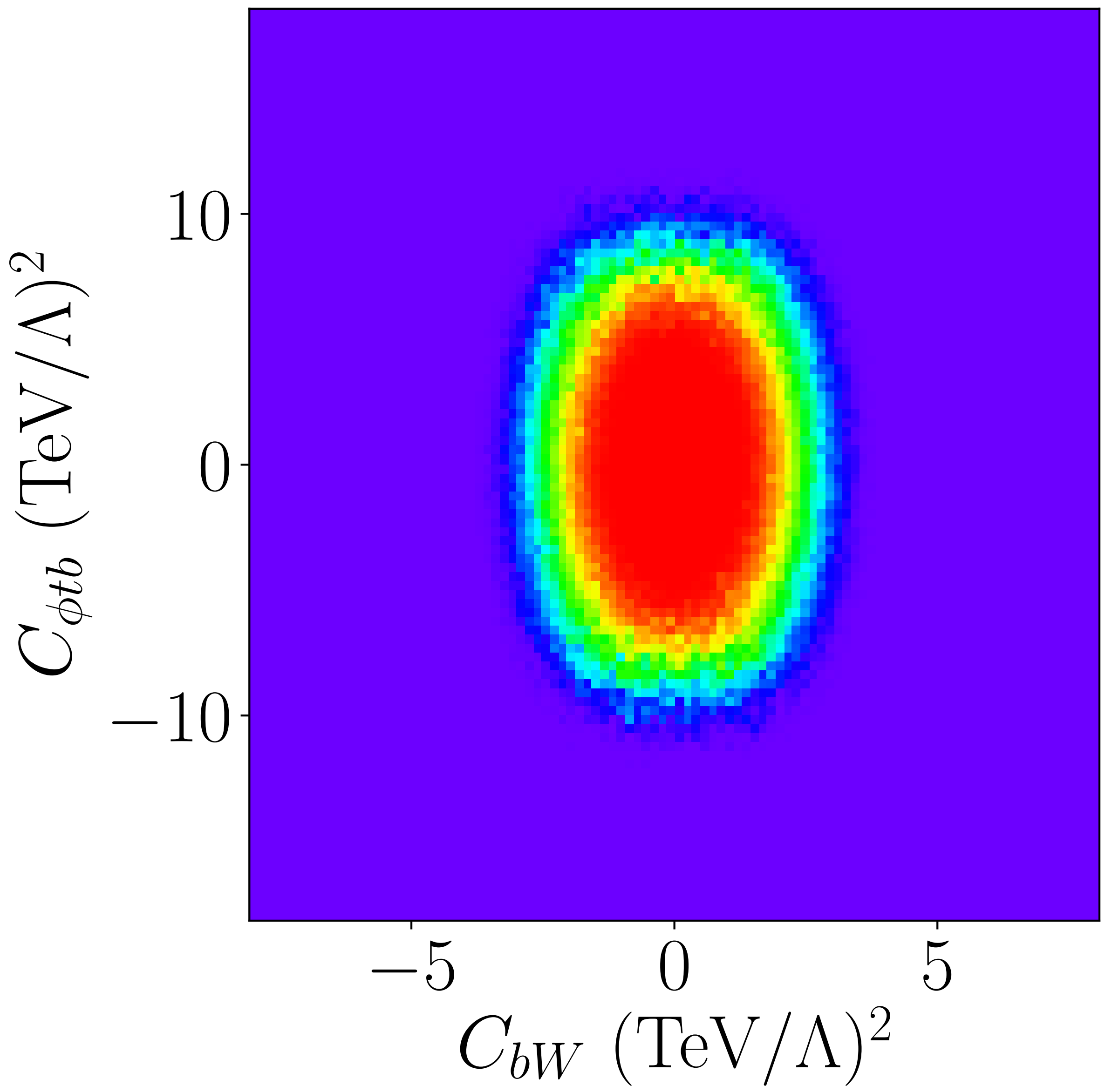


- Constrained by independent measurements

Single Top

Some aspects



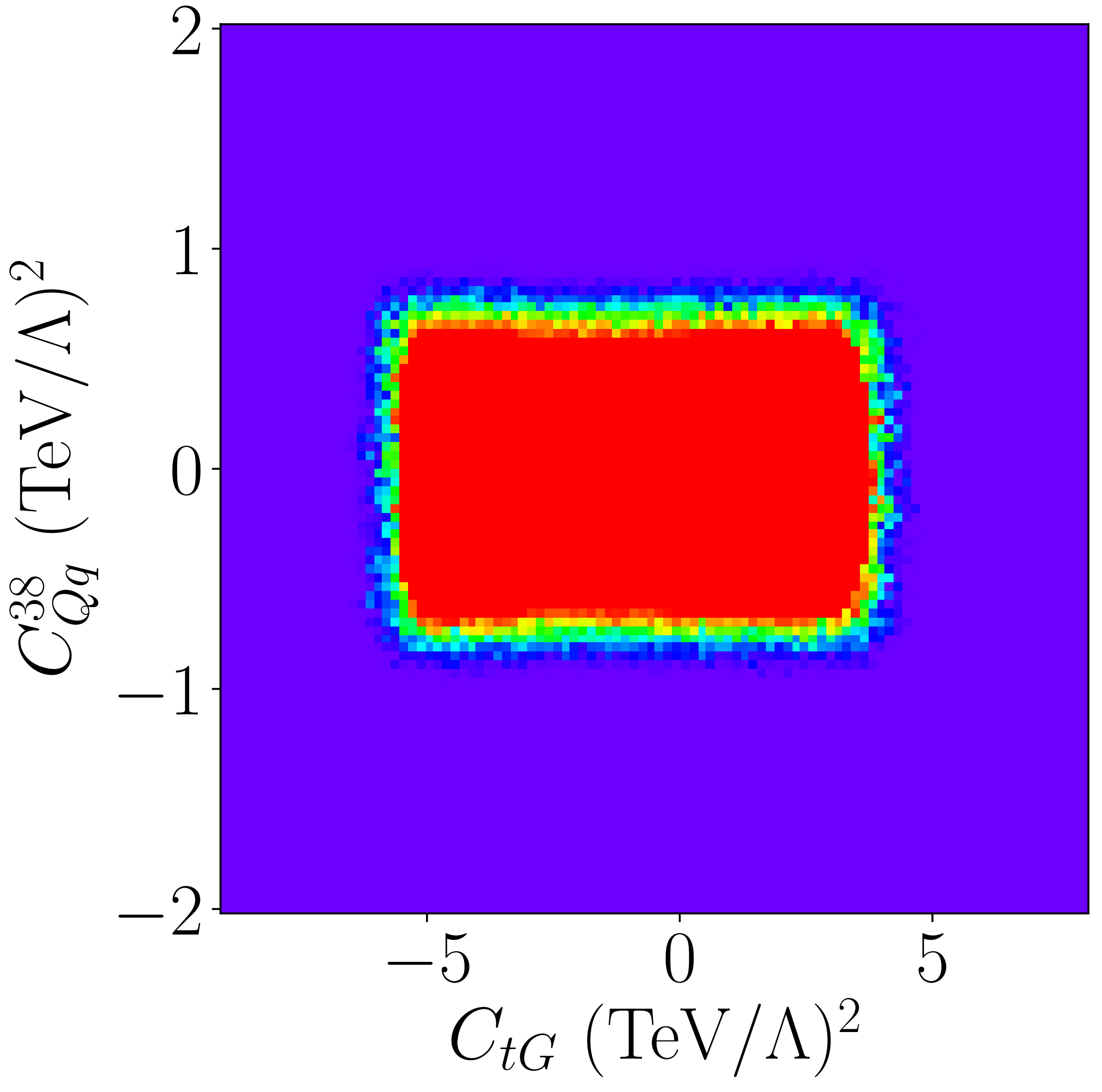


- Constrained by independent measurements

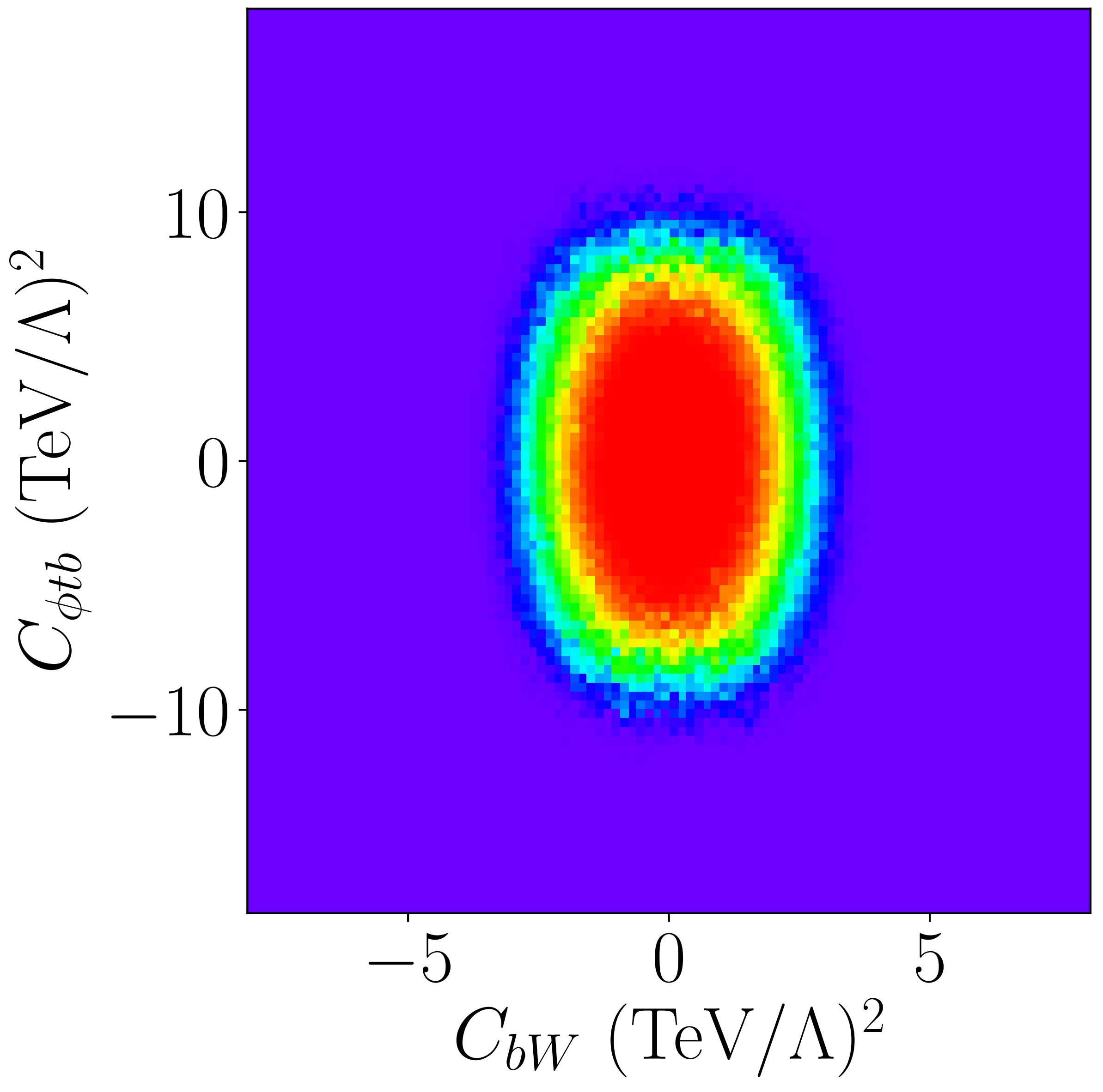
- Both contribute quadratically

Single Top

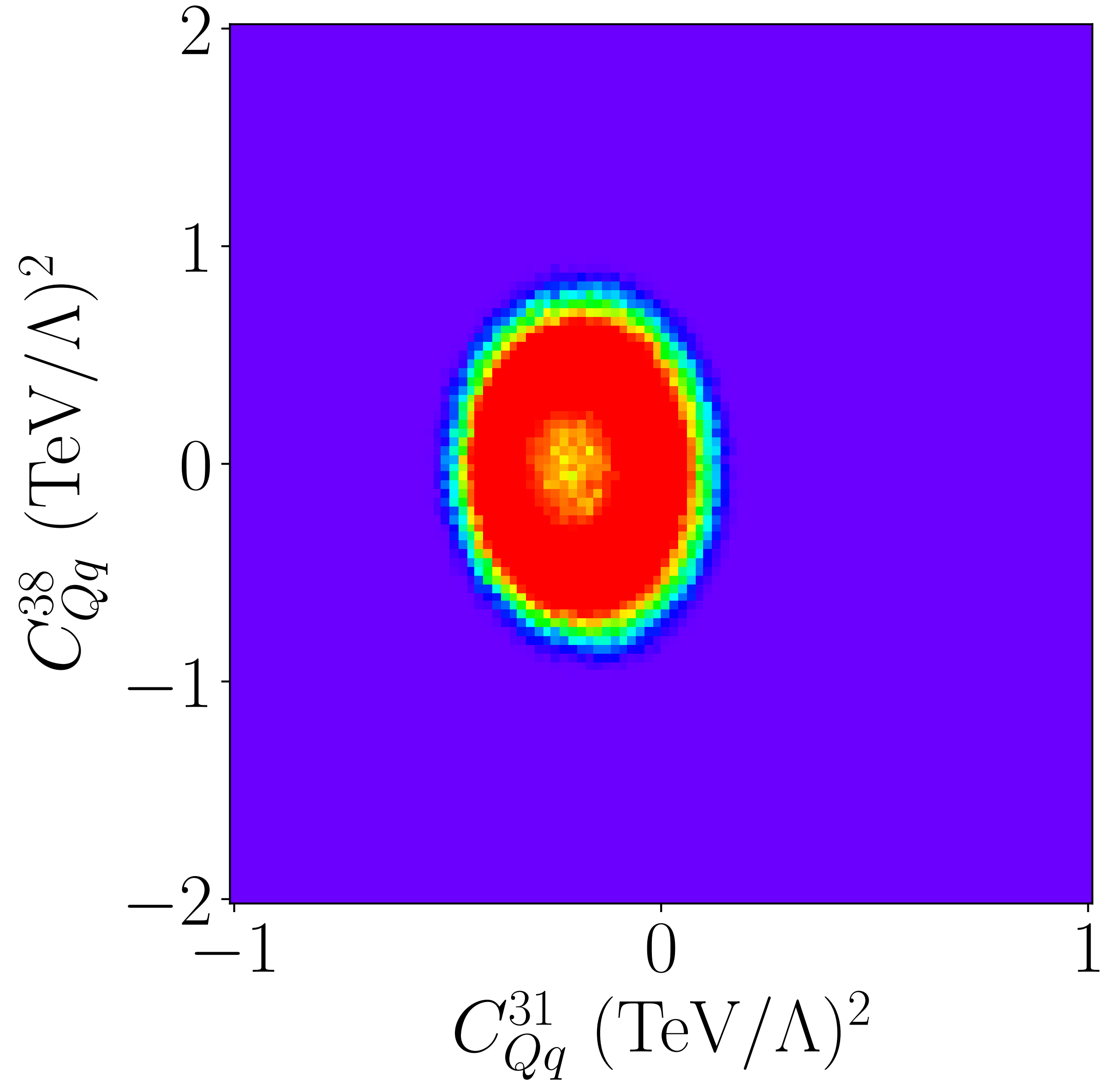
Some aspects



- Constrained by independent measurements

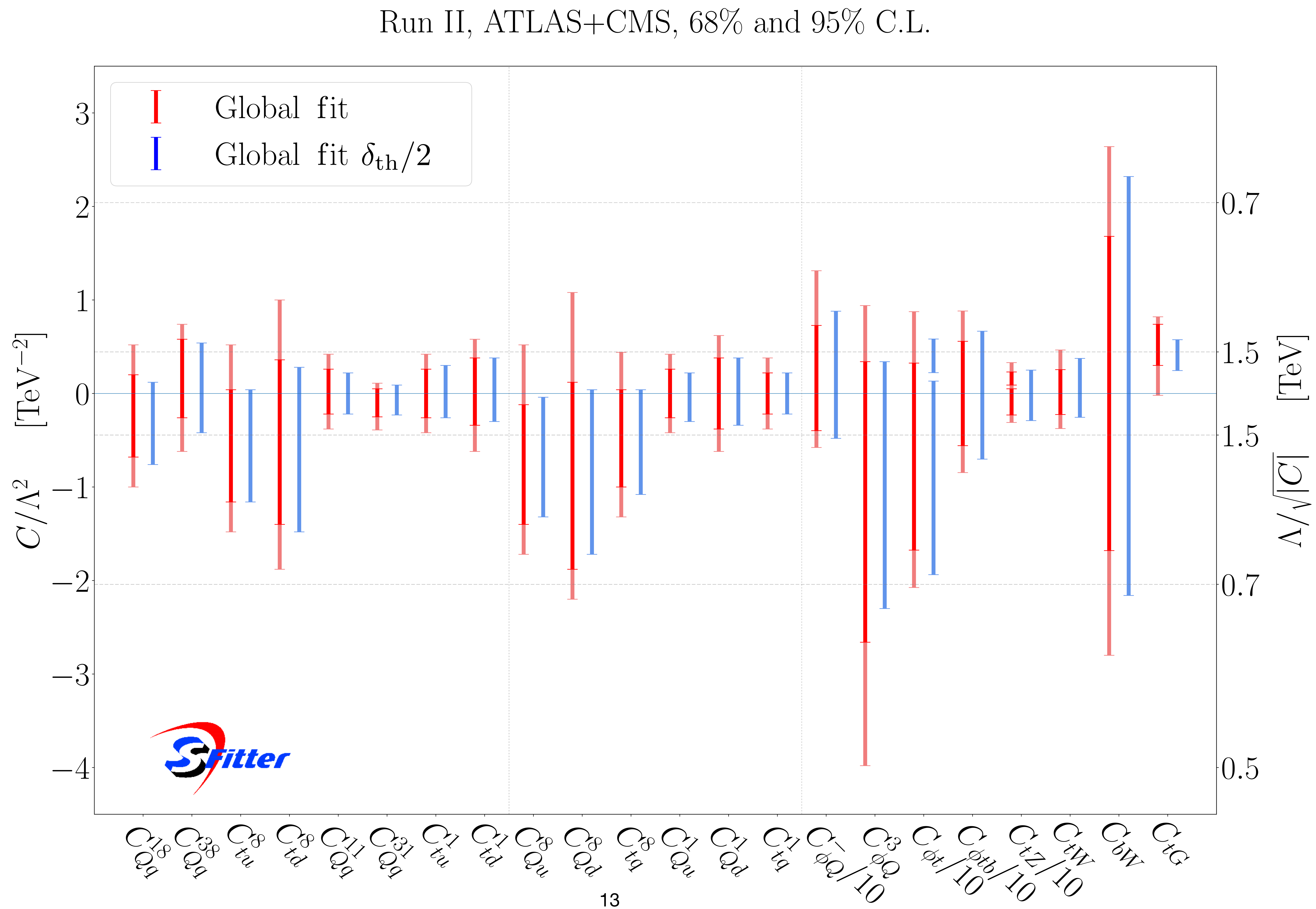


- Both contribute quadratically



- One linear and one quadratic contribution

Results



Run II, ATLAS+CMS, 68% and 95% C.L.
Global fit
Global fit $\delta_{th}/2$
C/Λ^2 [TeV^{-2}]
$\Lambda/\sqrt{|C|}$ [TeV]
3
2
1
0
−1
−2
−3
−4
0.7
1.5
1.5
0.7
0.5
C^{18}_{Qq}
C^{38}_{Qq}
C^{8}_{tu}
C^{8}_{td}
C^{11}_{Qq}
C^{31}_{Qq}
C^{1}_{tu}
C^{1}_{td}
C^{8}_{Qu}
C^{8}_{Qd}
C^{8}_{tq}
C^{1}_{Qu}
C^{1}_{Qd}
C^{1}_{tq}
$C^{-}_{\phi Q}/10$
$C^{3}_{\phi Q}$
$C_{\phi t}/10$
$C_{\phi tb}/10$
$C_{tZ}/10$
C_{tW}
C_{bW}
C_{tG}
SFitter

New Directions

New Observables (e.g. Energy asymmetry)

New Directions

New Observables (e.g. Energy asymmetry)

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

New Directions

New Observables (e.g. Energy asymmetry)

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

	$A_{\|y\|}$	A_E
Order	NLO	LO
Process	tt	ttj

New Directions

New Observables (e.g. Energy asymmetry)

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

	$A_{\|y\|}$	A_E
Order	NLO	LO
Process	tt	ttj

Resolve new directions in parameter space!

New Directions

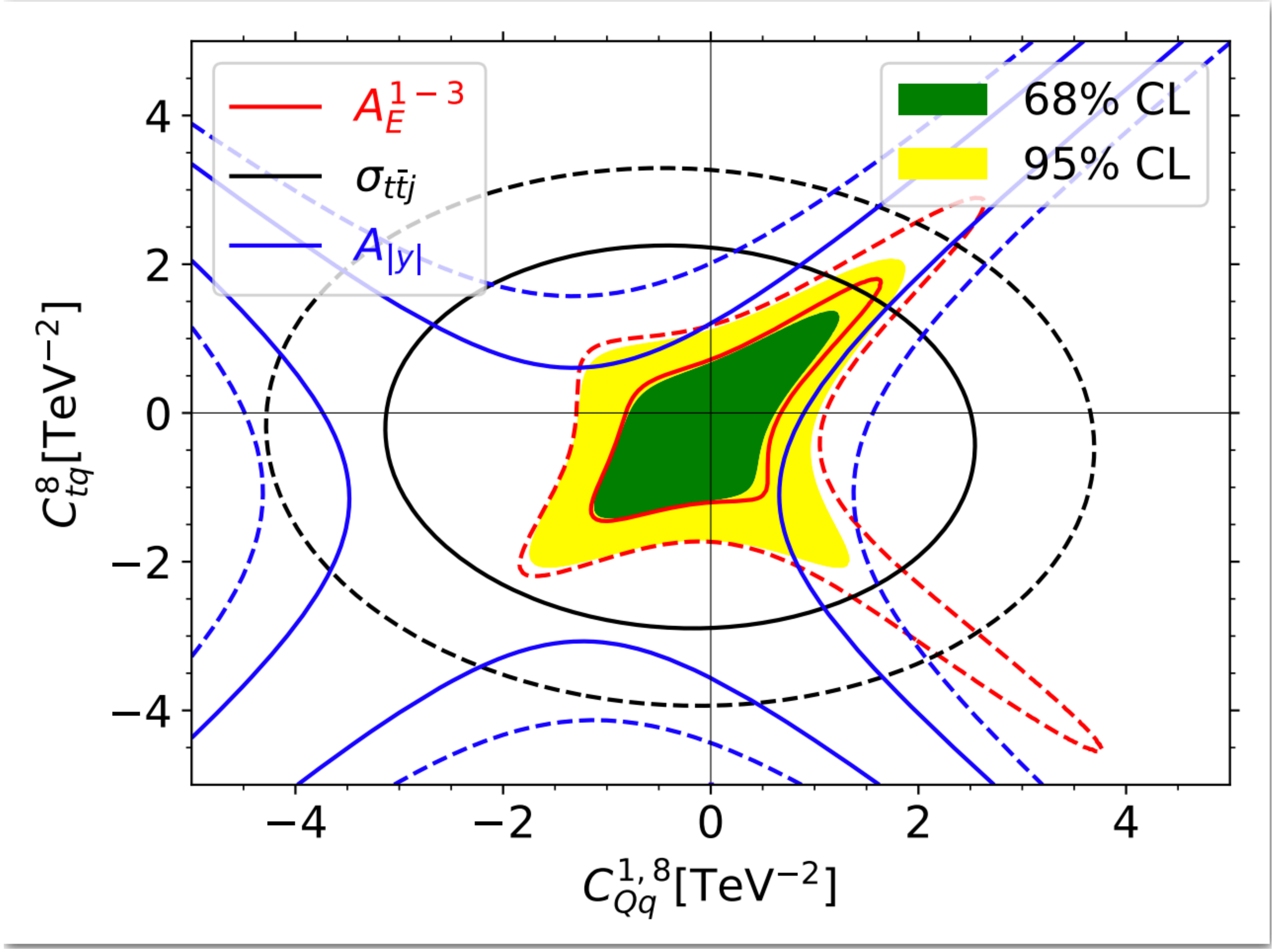
New Observables (e.g. Energy asymmetry)

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

	$A_{\lvert y \rvert}$	A_E
Order	NLO	LO
Process	tt	ttj

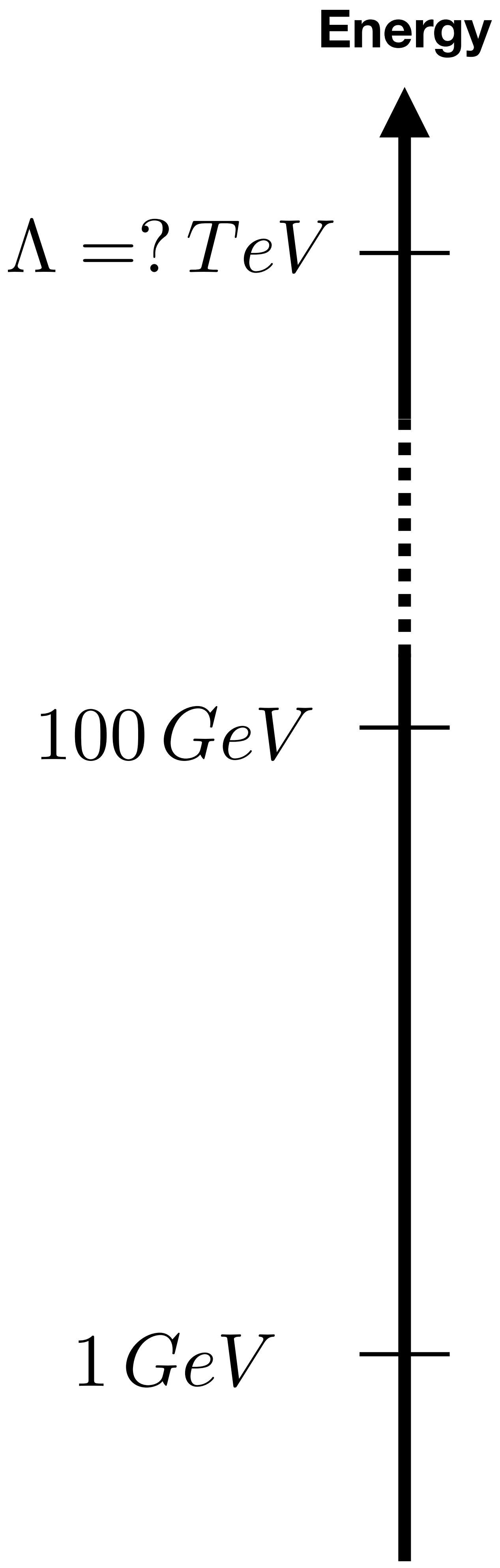
Resolve new directions in parameter space!



Basan, Berta, Masetti, Vryonidou, Westhoff: 2001.07225

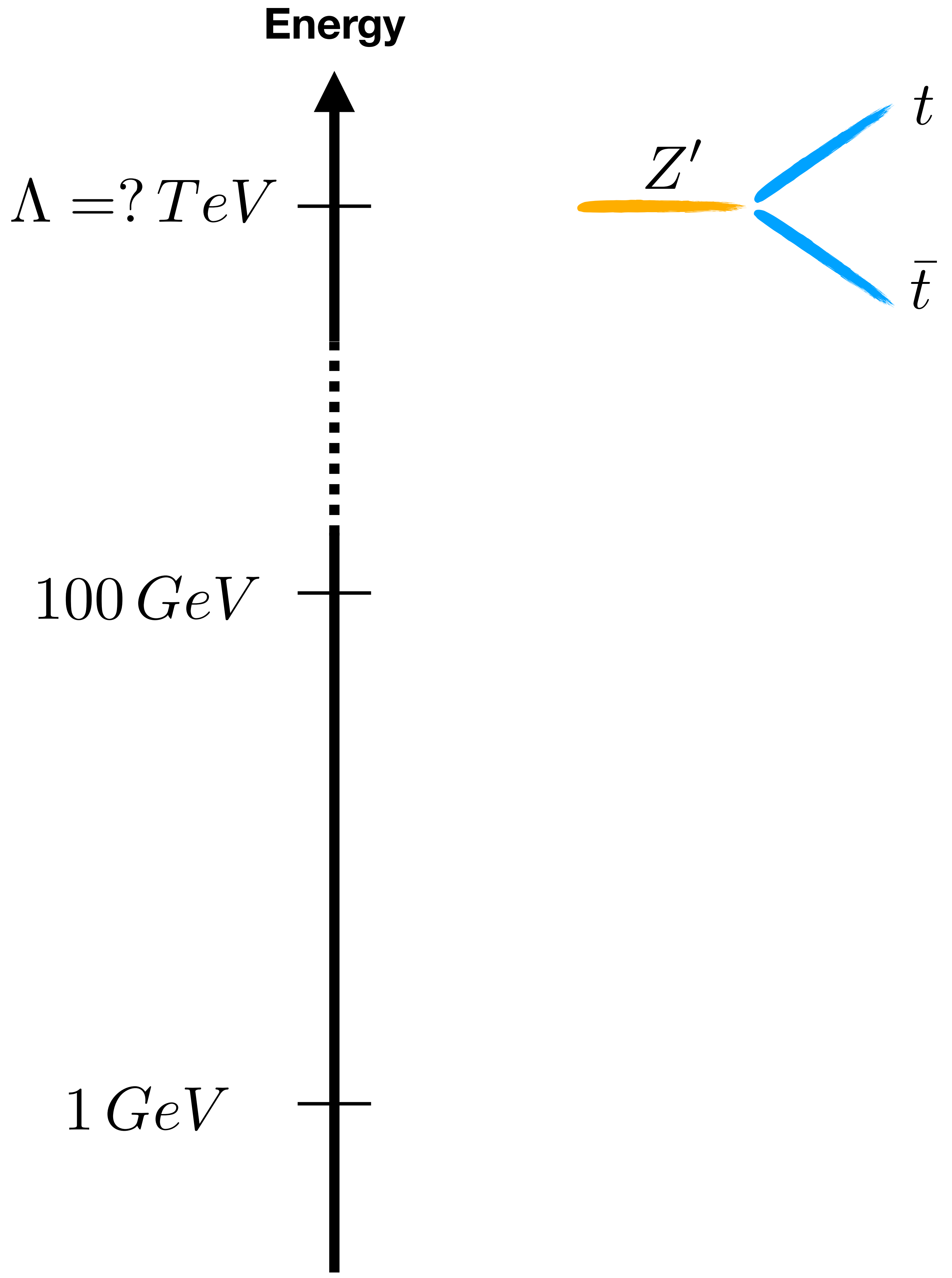
New Directions

Flavour (Work in Progress)



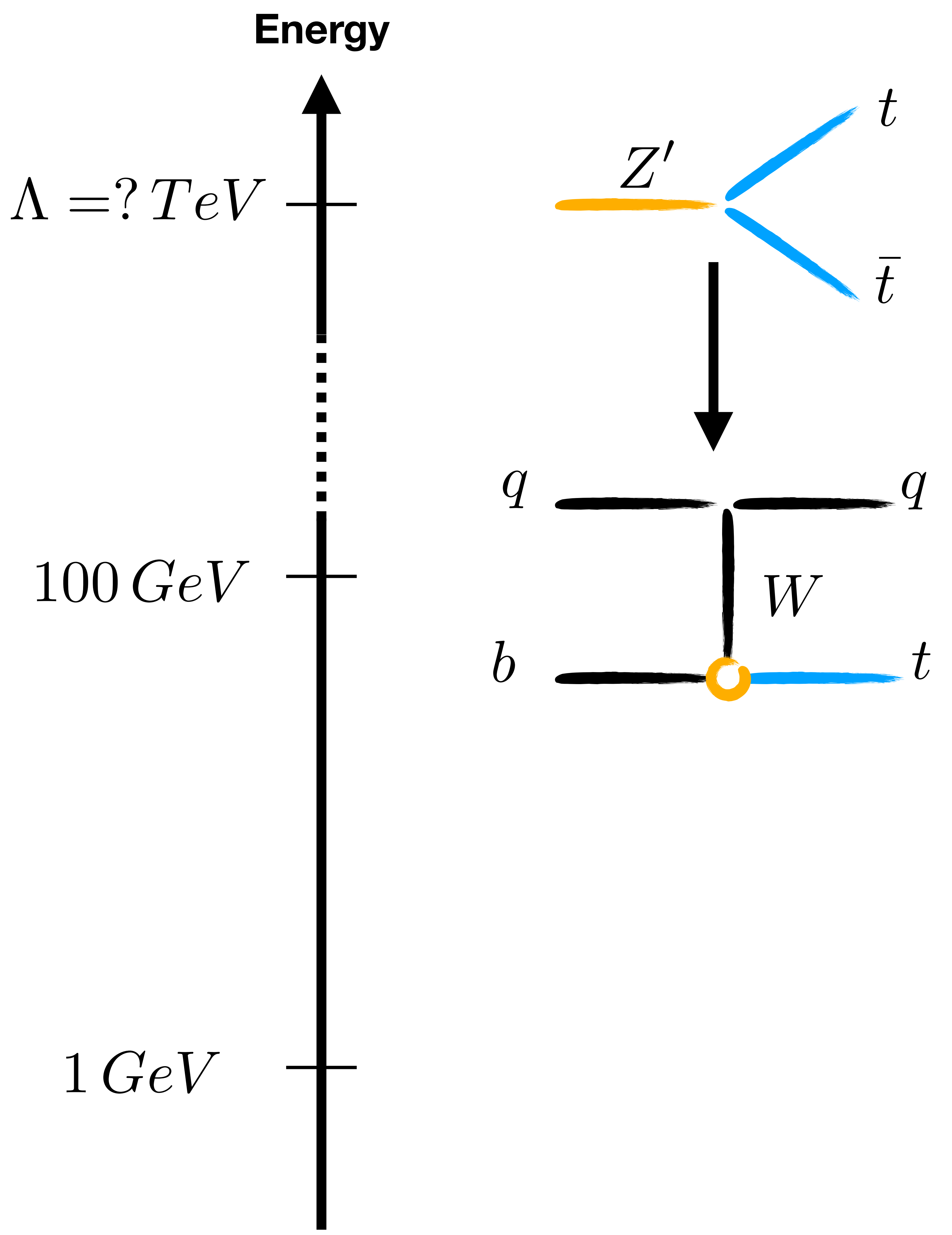
New Directions

Flavour (Work in Progress)



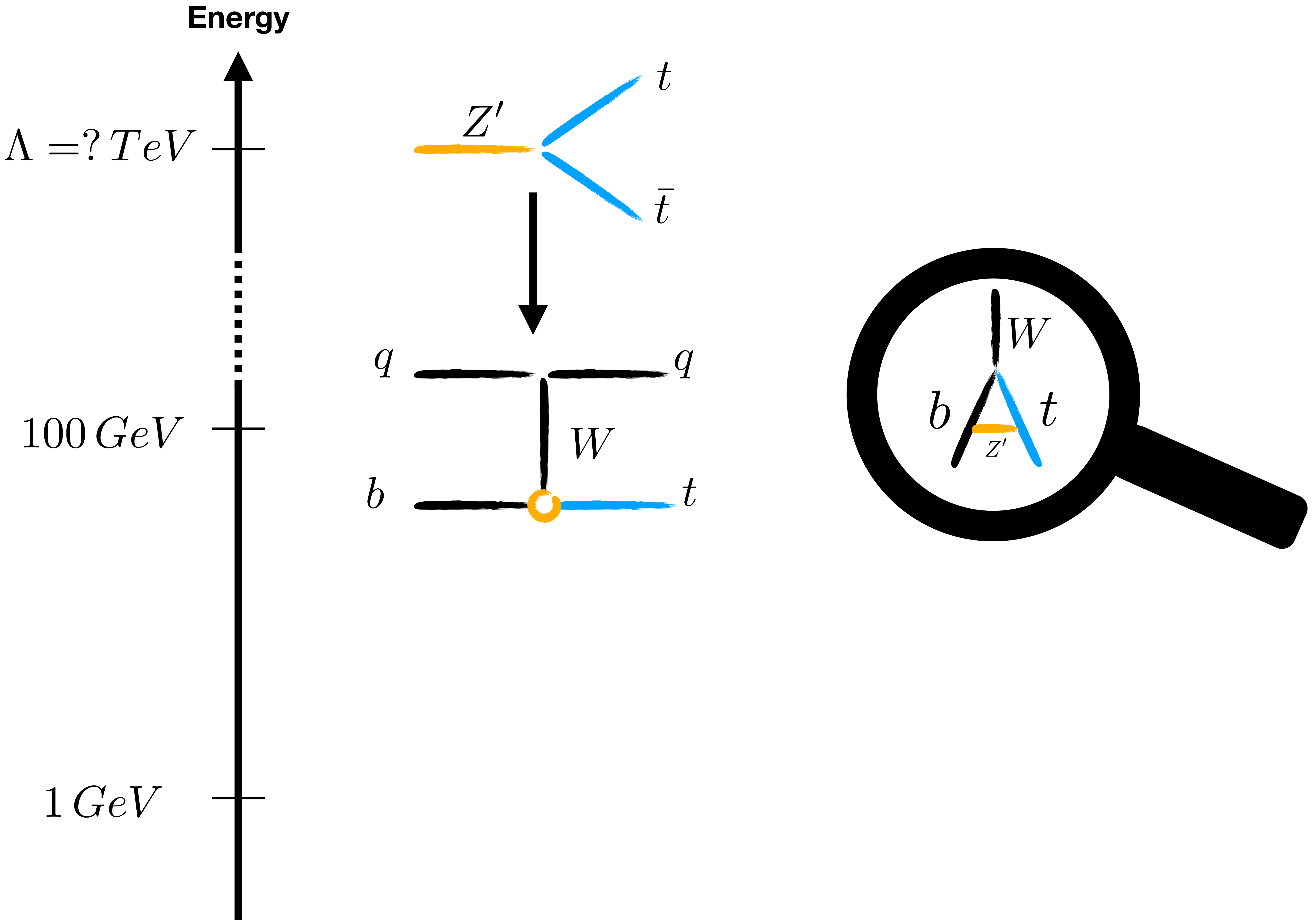
New Directions

Flavour (Work in Progress)



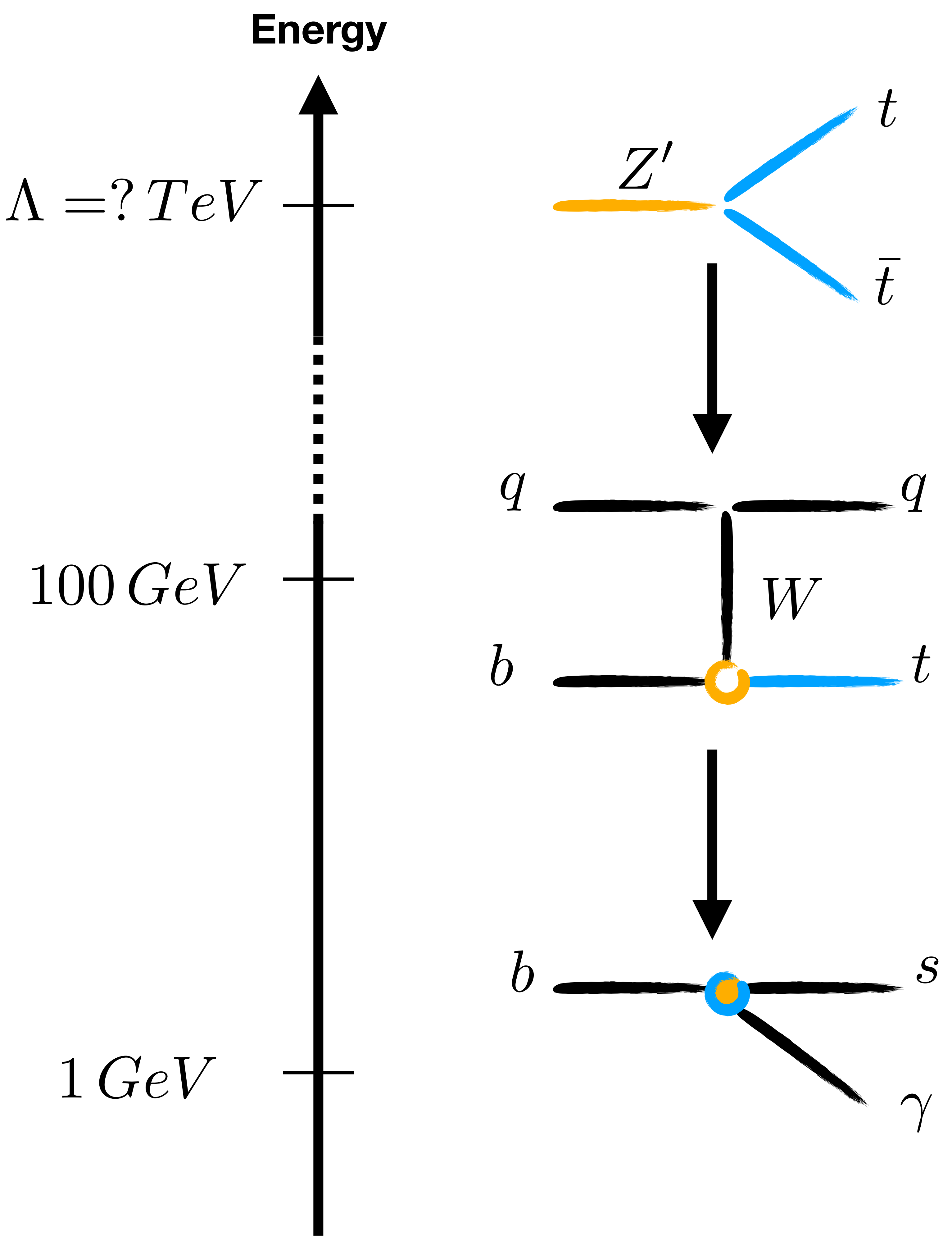
New Directions

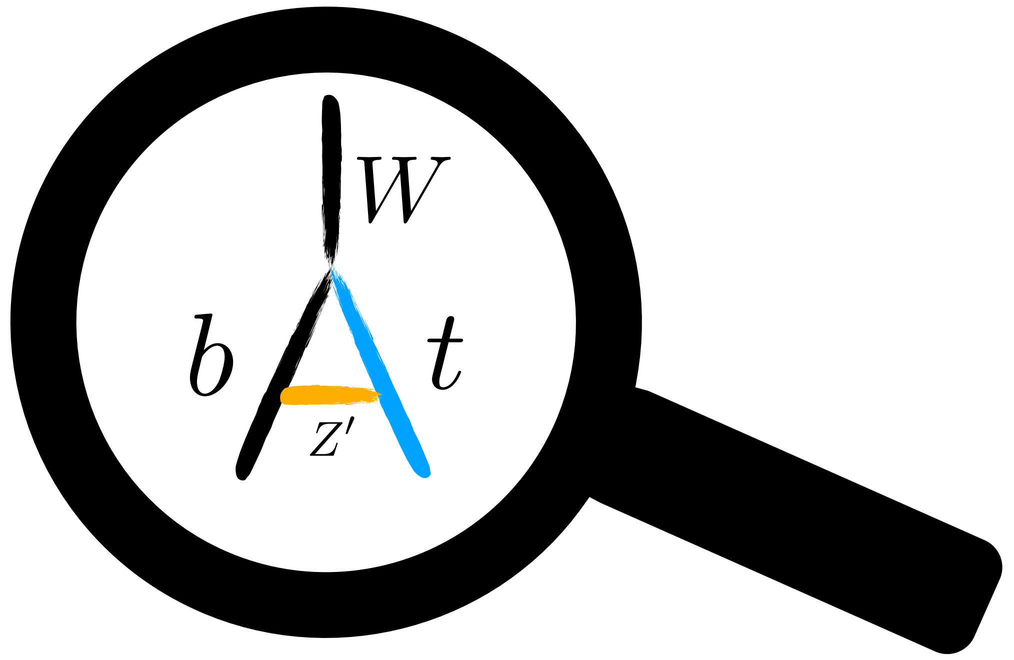
Flavour (Work in Progress)



New Directions

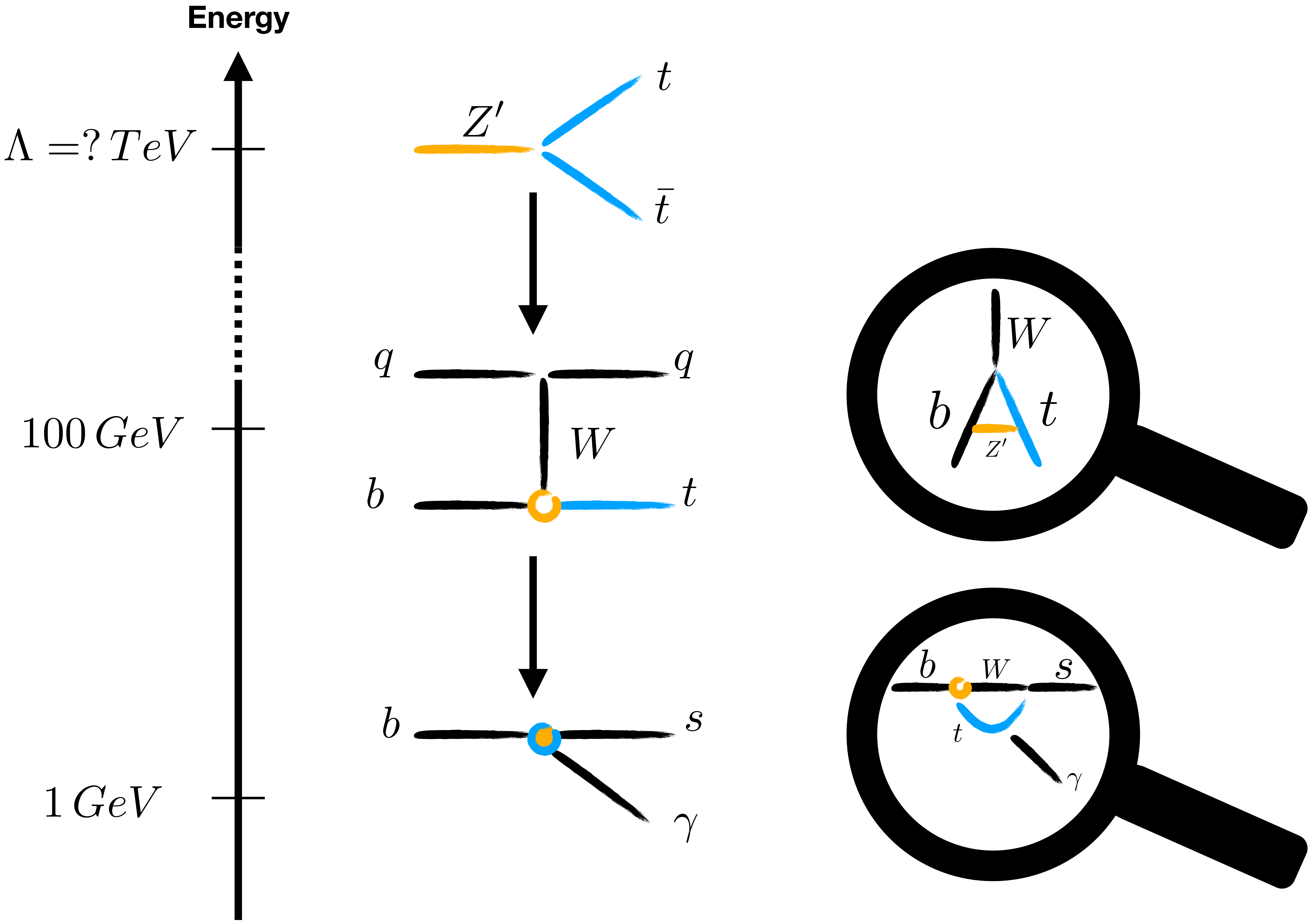
Flavour (Work in Progress)





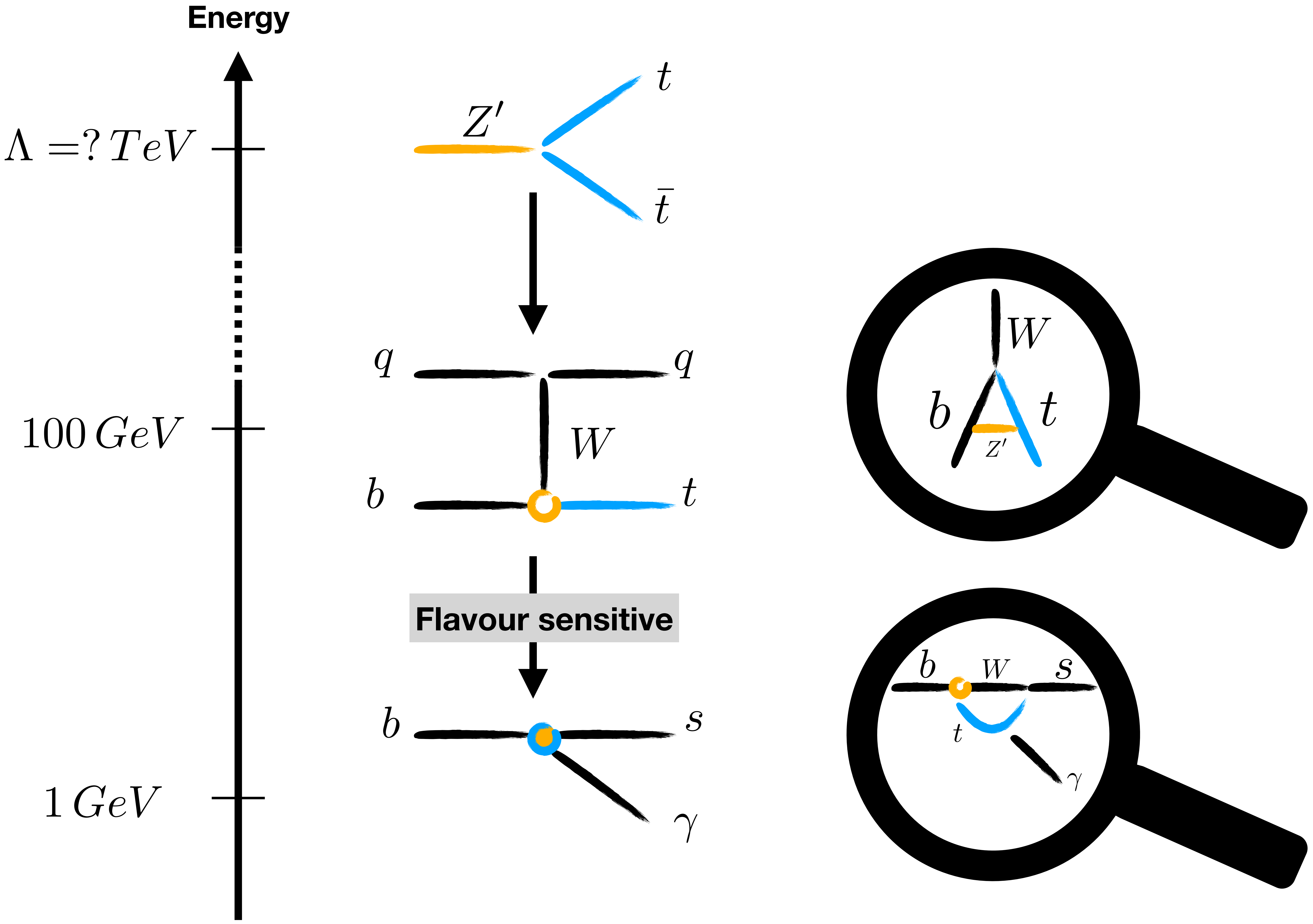
New Directions

Flavour (Work in Progress)



New Directions

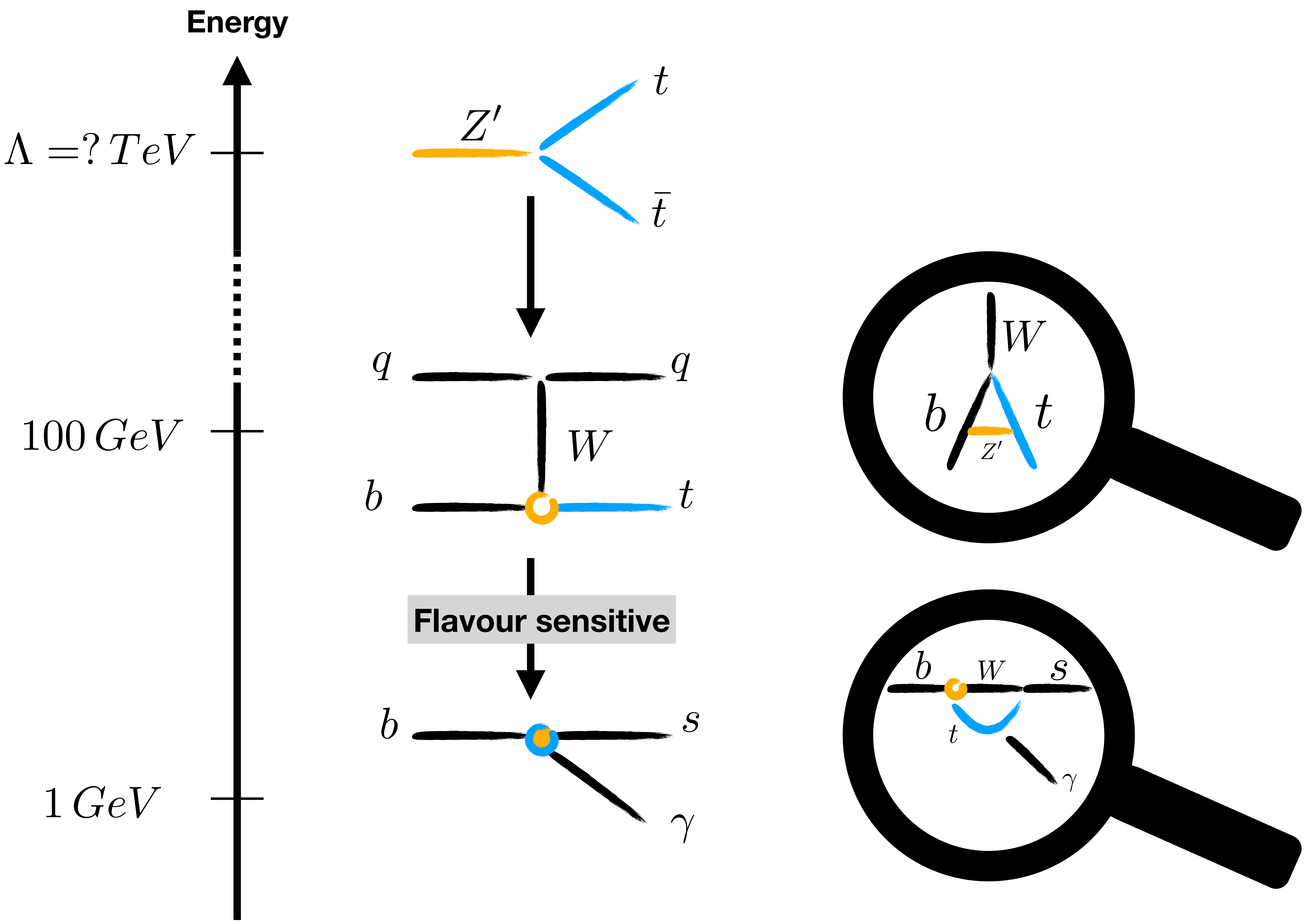
Flavour (Work in Progress)



New Directions

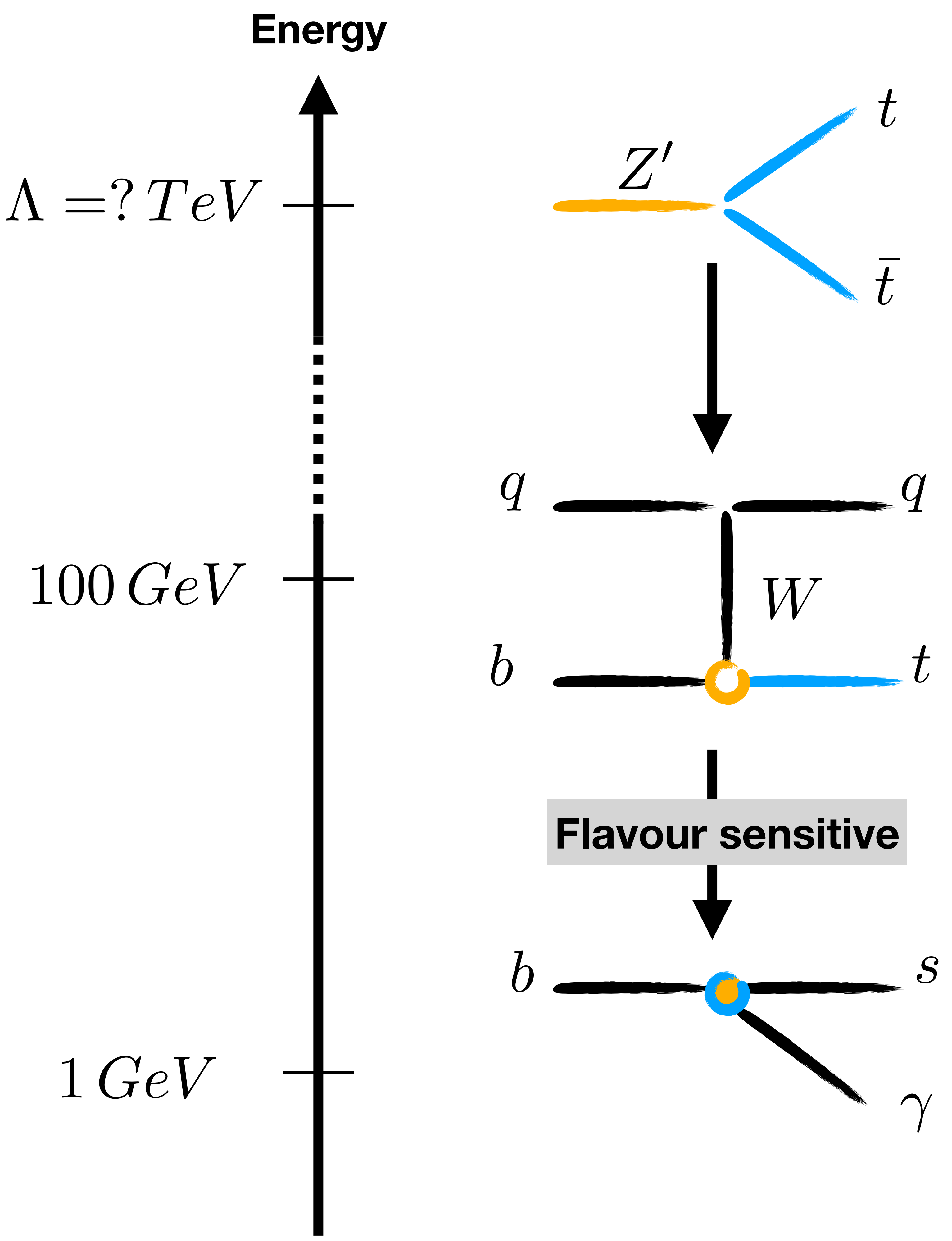
Flavour (Work in Progress)

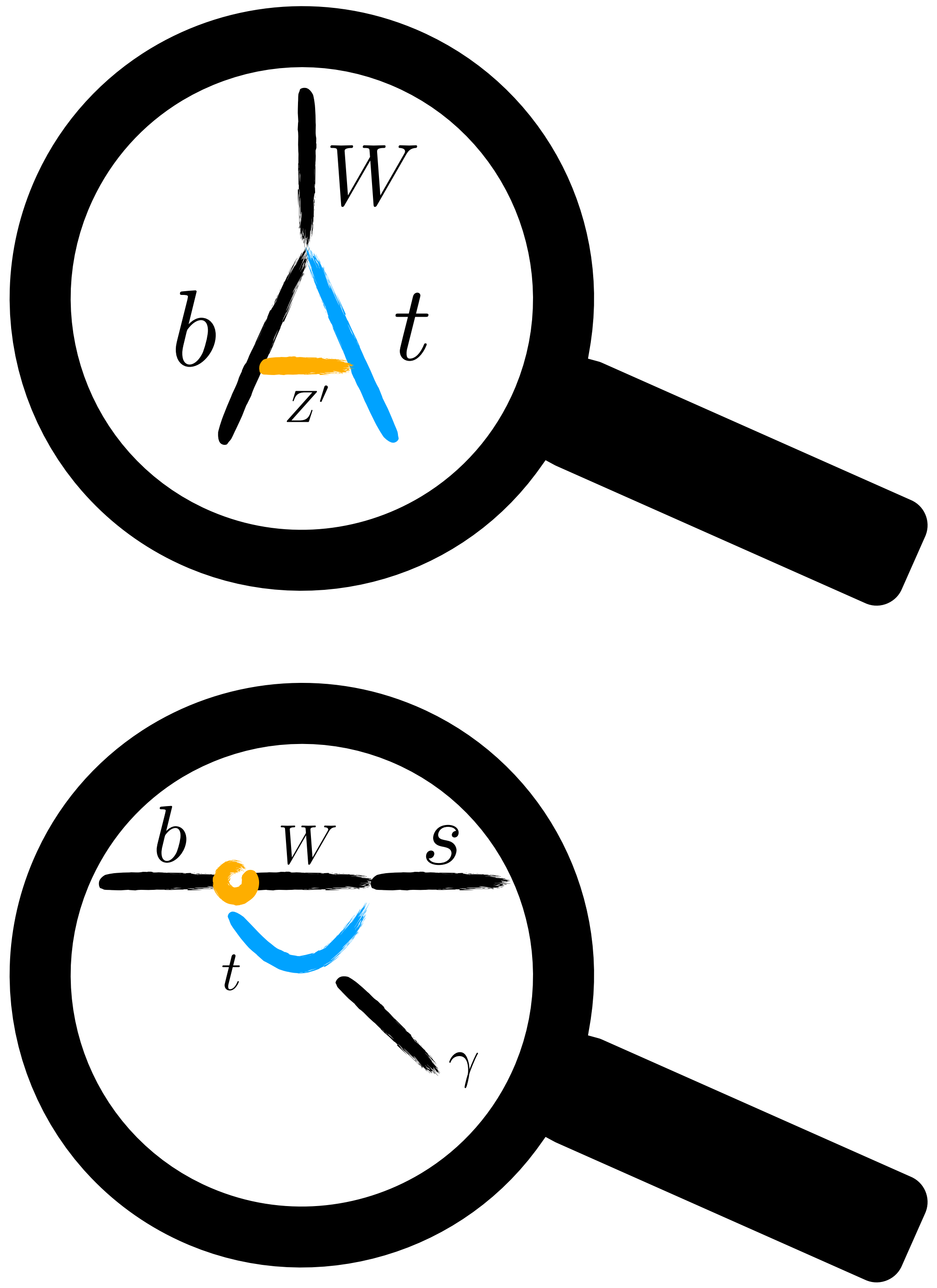
$$^{\ddagger}\mathcal{O}_{uW}^{ij} = \left(\bar{q}^{i}\sigma^{\mu\nu}u^{j}\right)\tau^{I}\tilde{\phi}W_{\mu\nu}^{I}$$



New Directions

Flavour (Work in Progress)

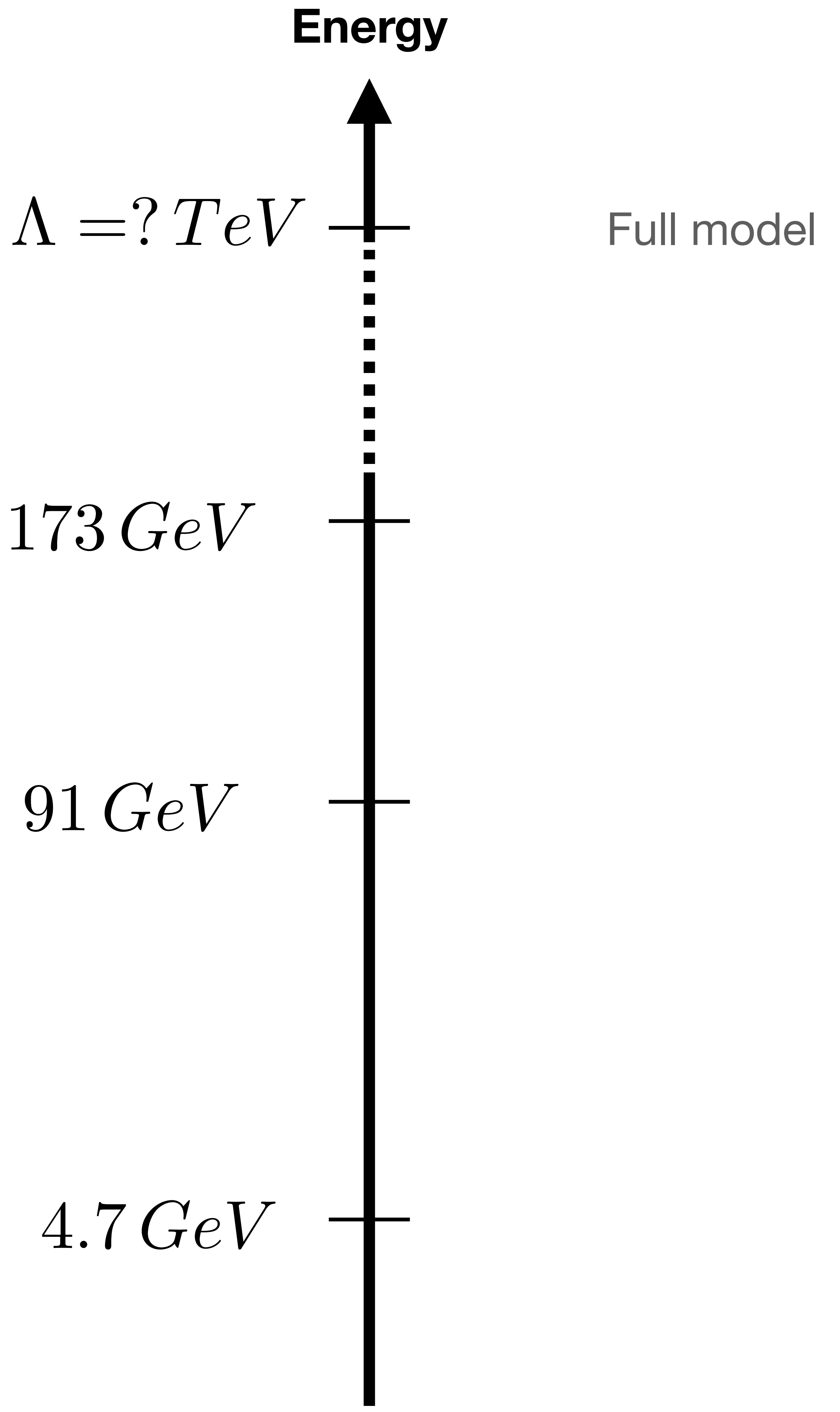




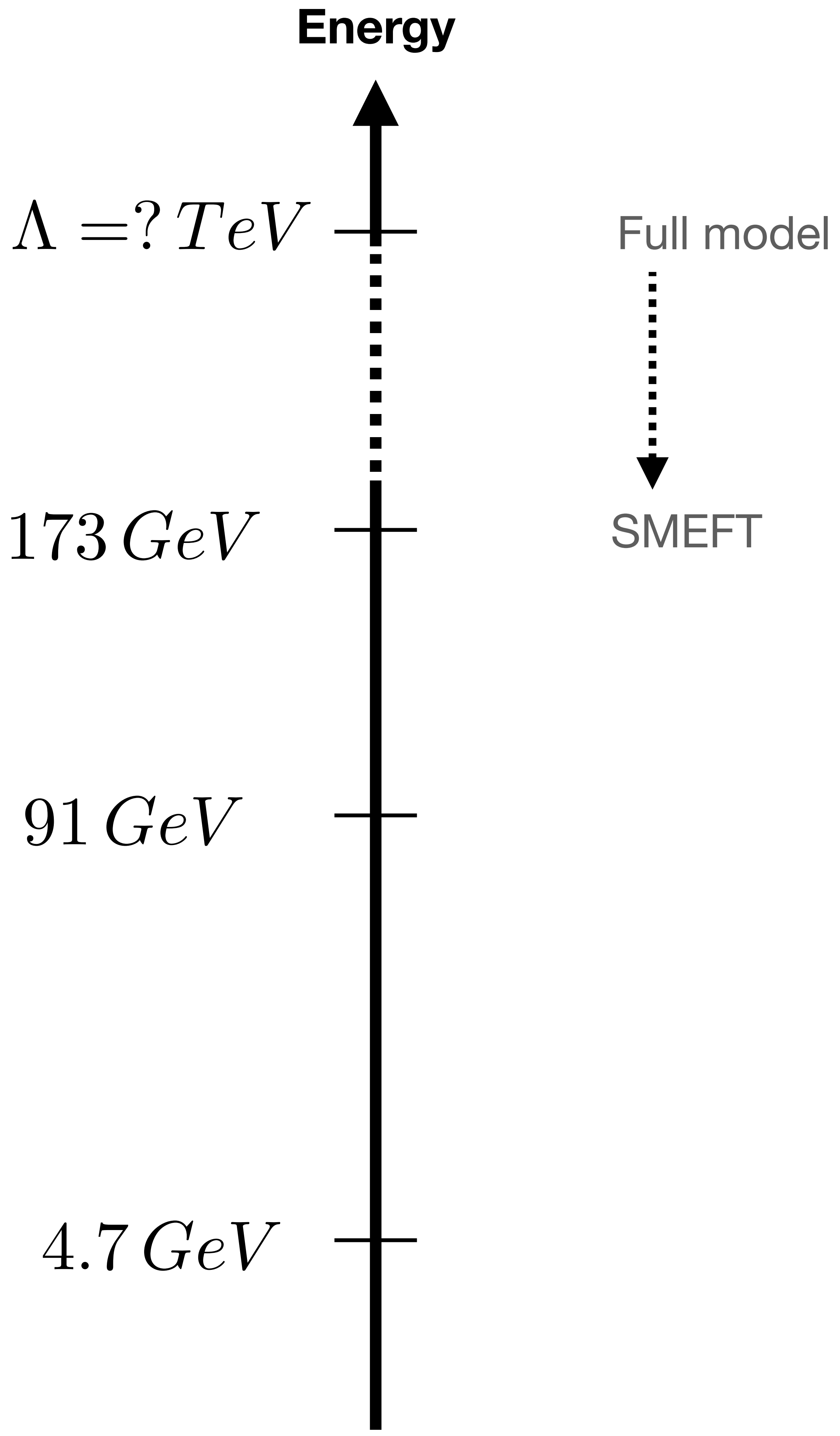
$$^{\ddagger}\mathcal{O}_{uW}^{ij} = \left(\bar{q}^i \sigma^{\mu\nu} u^j\right) \tau^I \tilde{\phi} W_{\mu\nu}^I$$

MFV	C_{uW}^{ij}
ii	0
33	$(a + y_t^2 b) y_t$
kj	0
$k3$	$c y_b^2 y_t V_{kb} V_{tb}^*$

New Directions
Flavour (Work in Progress)

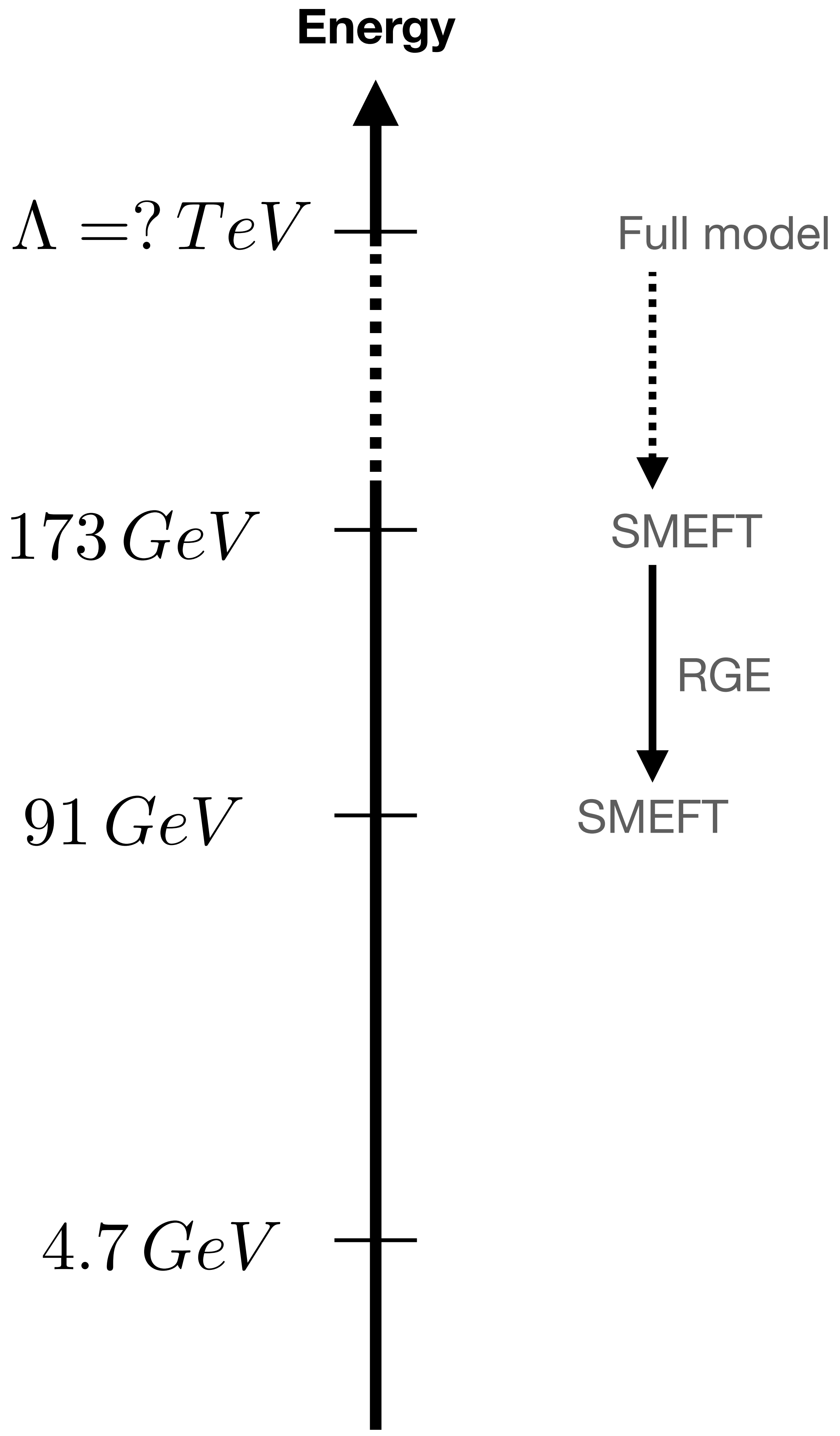


New Directions
Flavour (Work in Progress)



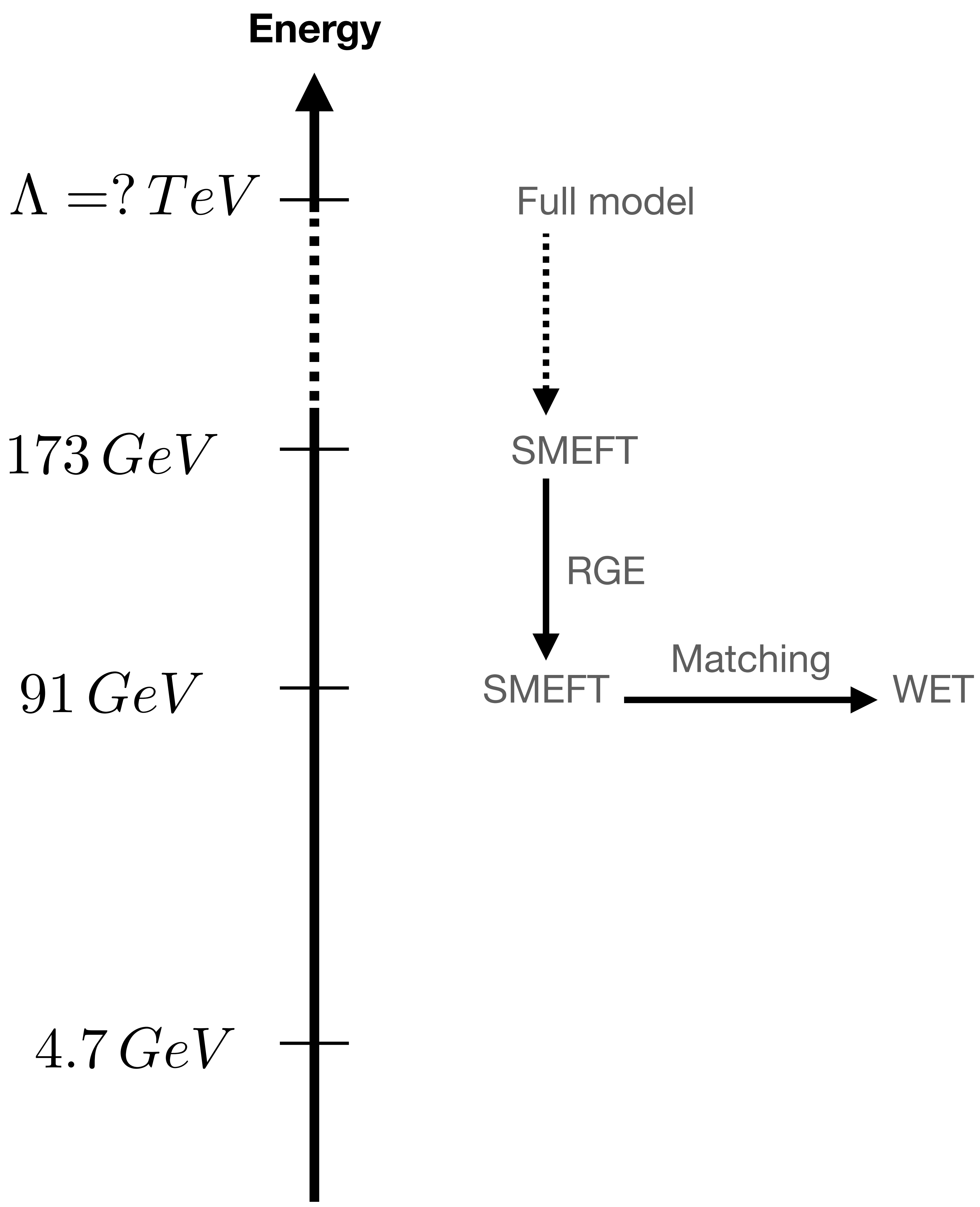
New Directions

Flavour (Work in Progress)



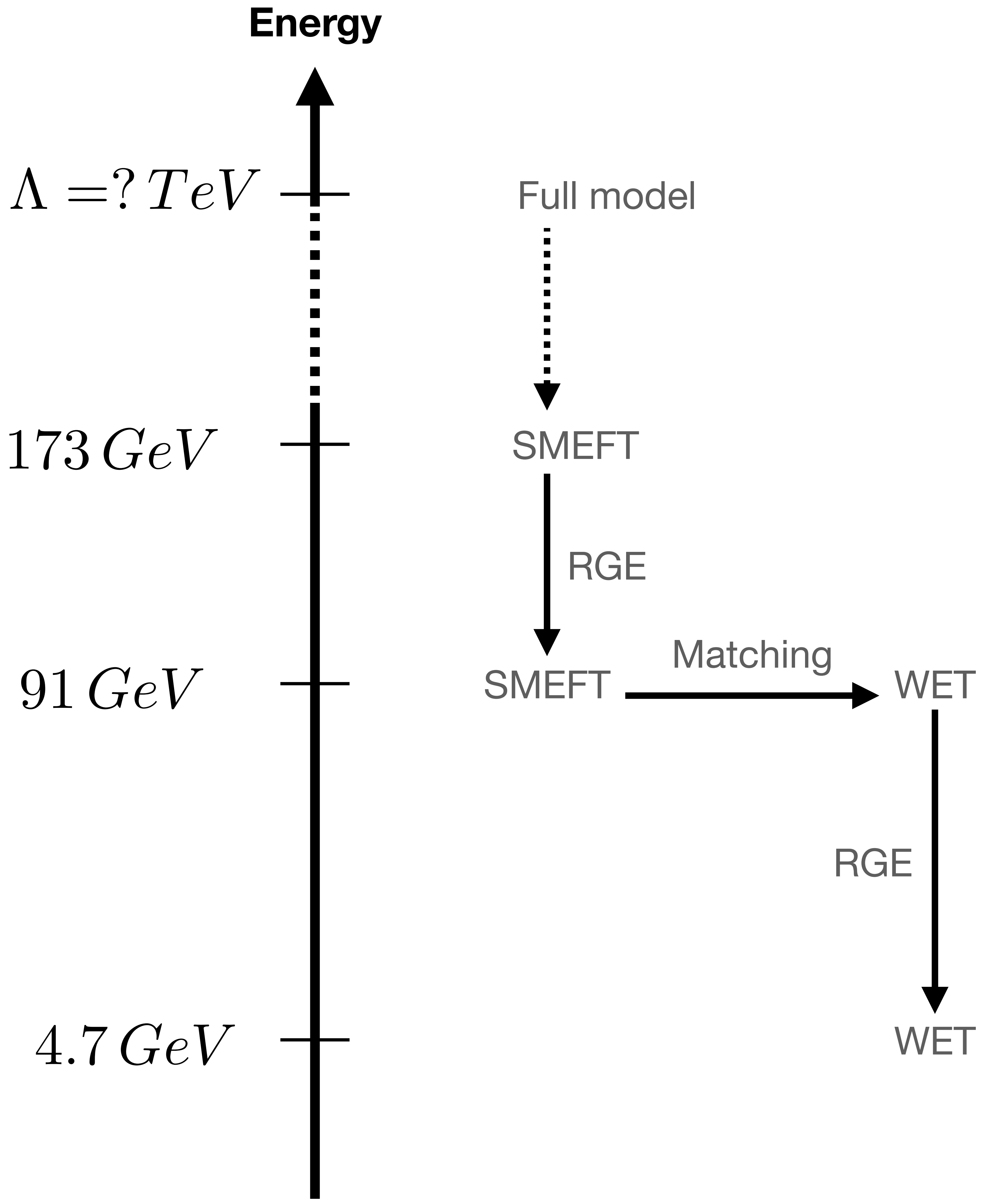
New Directions

Flavour (Work in Progress)



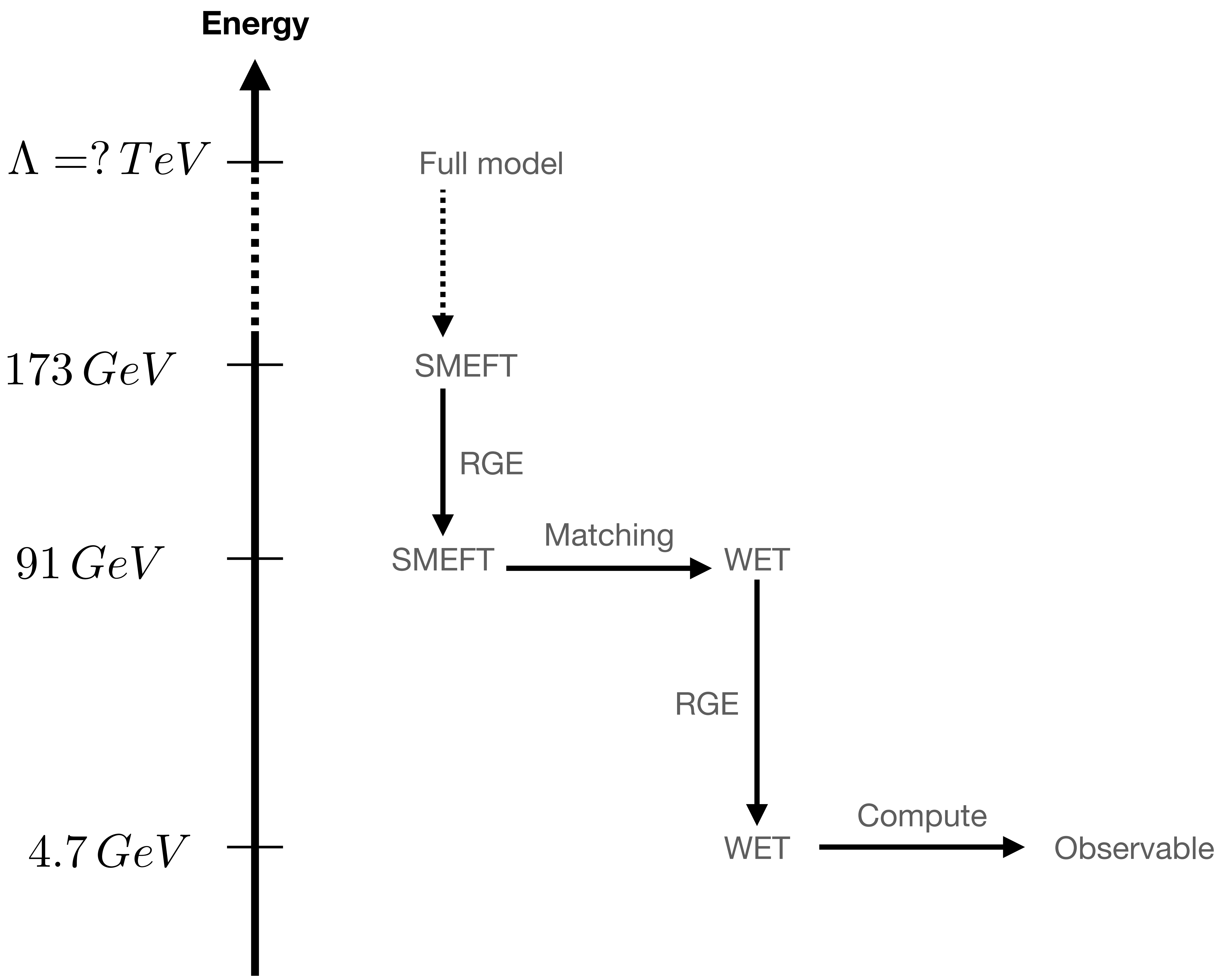
New Directions

Flavour (Work in Progress)



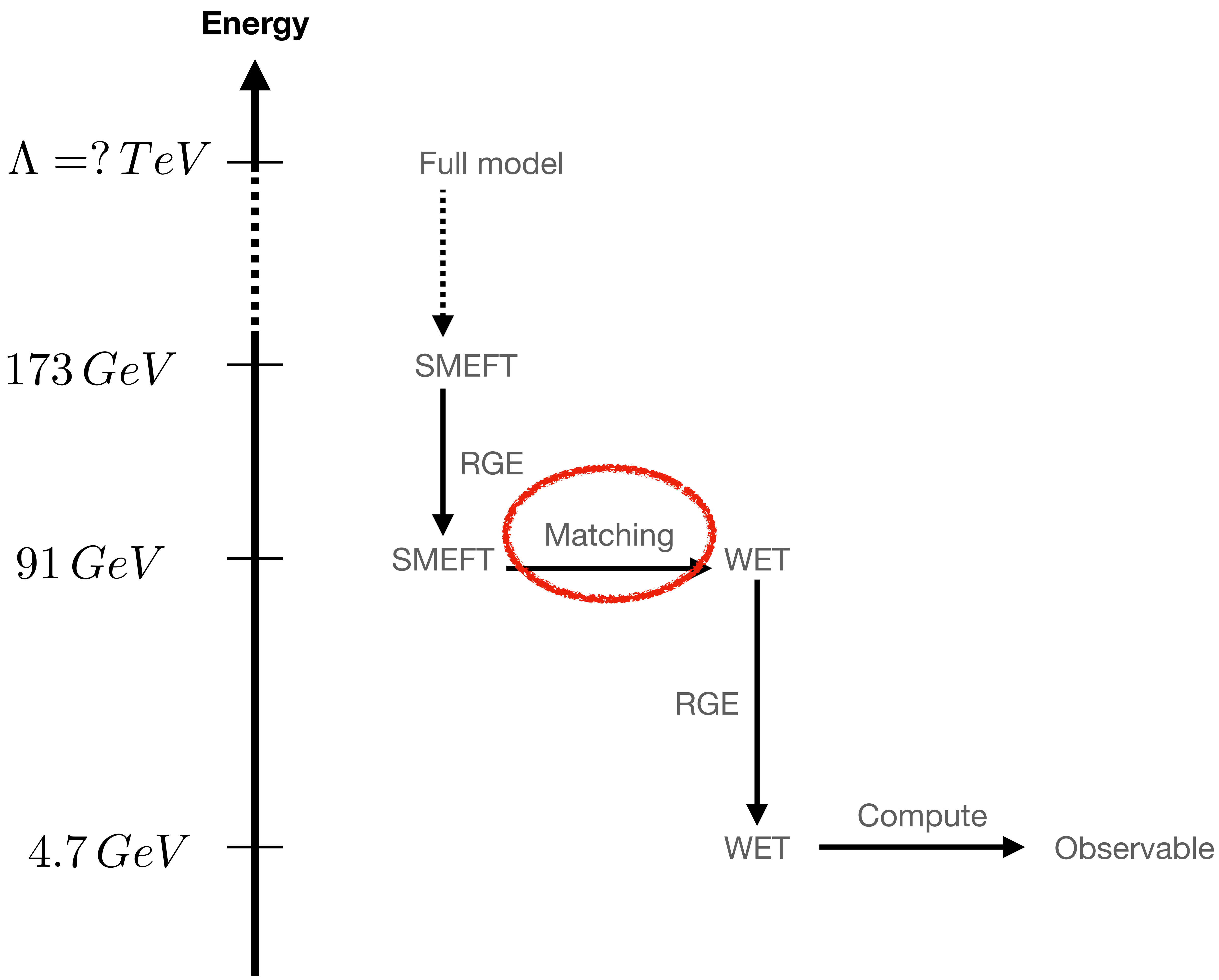
New Directions

Flavour (Work in Progress)



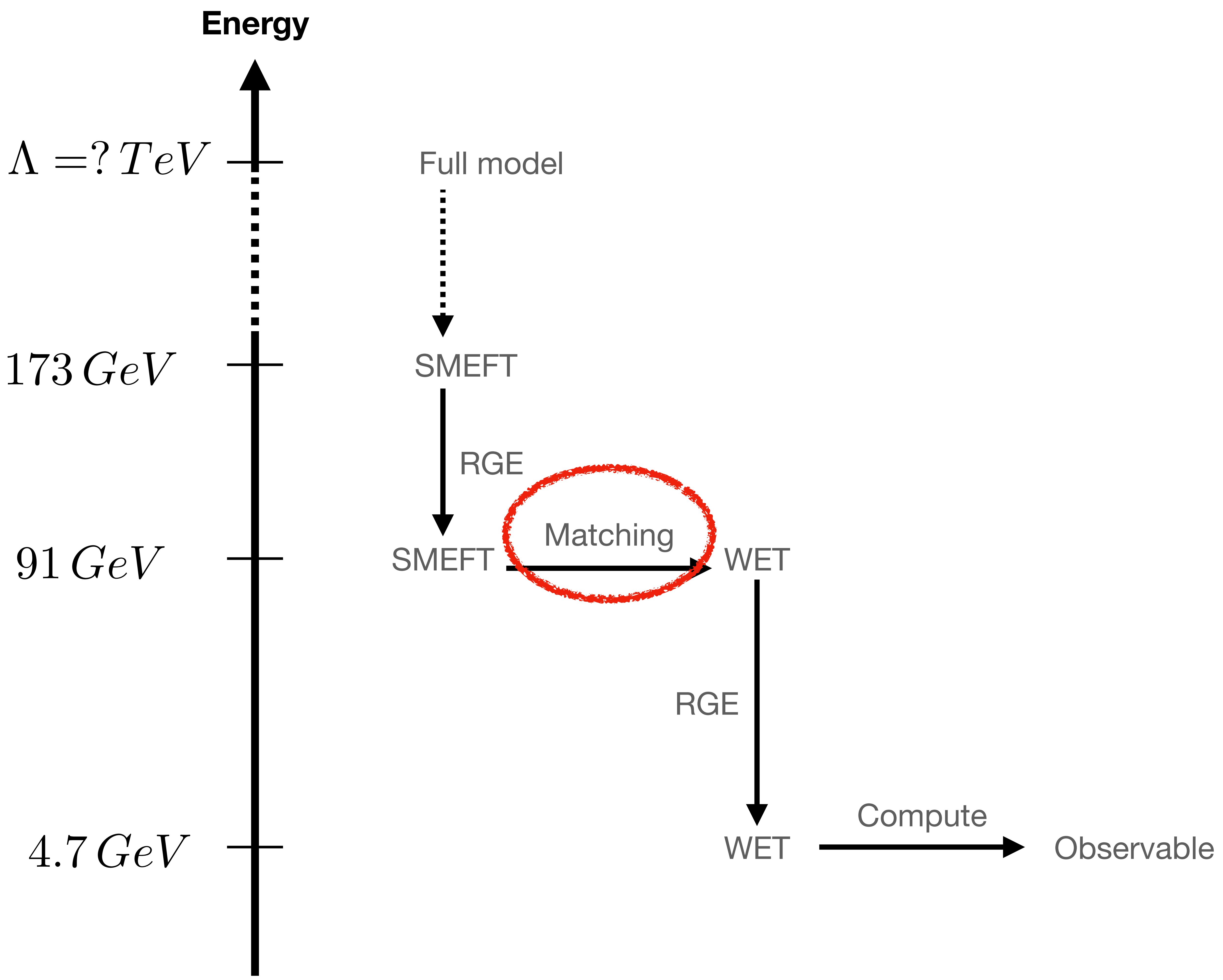
New Directions

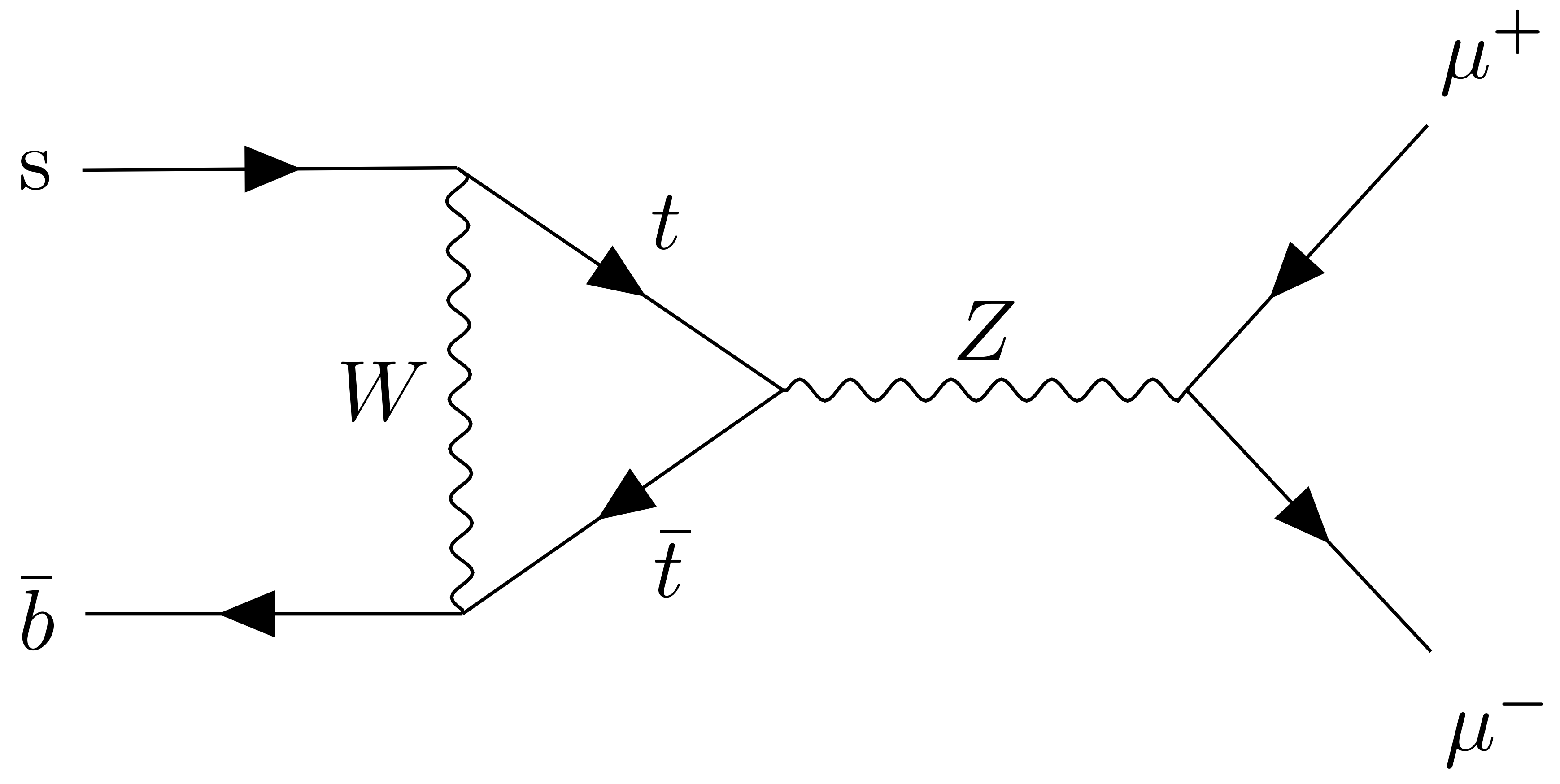
Flavour (Work in Progress)



New Directions

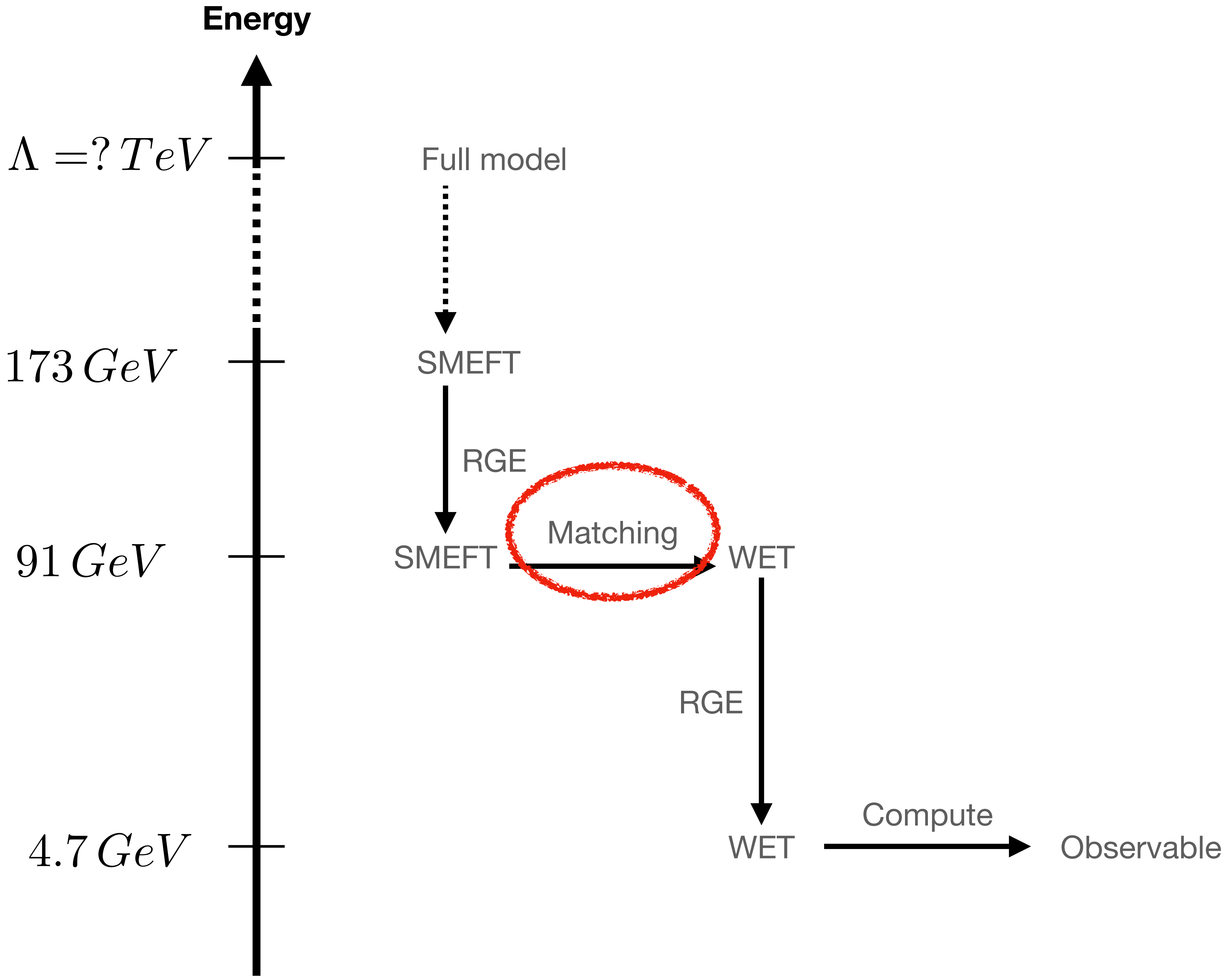
Flavour (Work in Progress)

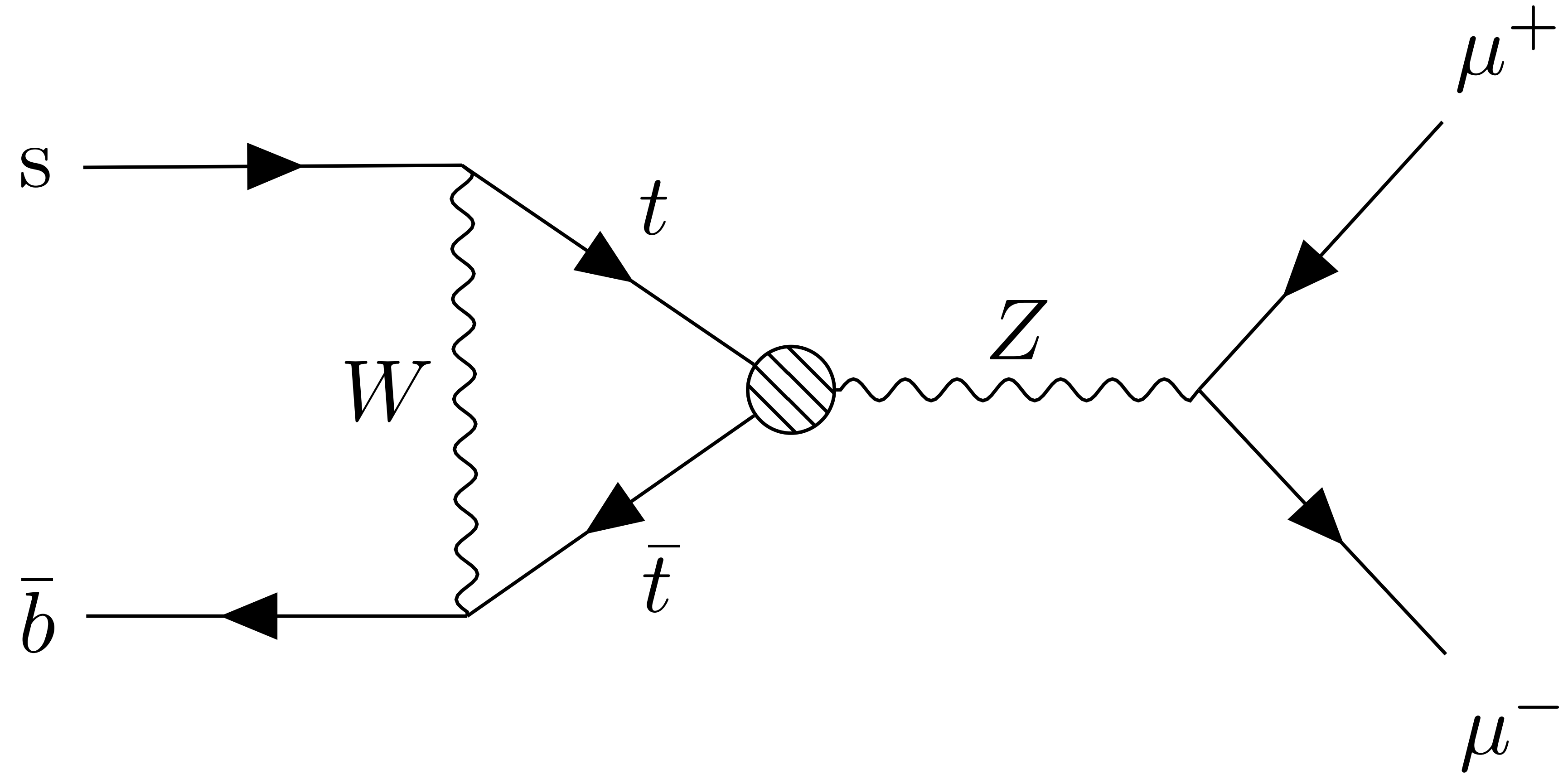




New Directions

Flavour (Work in Progress)

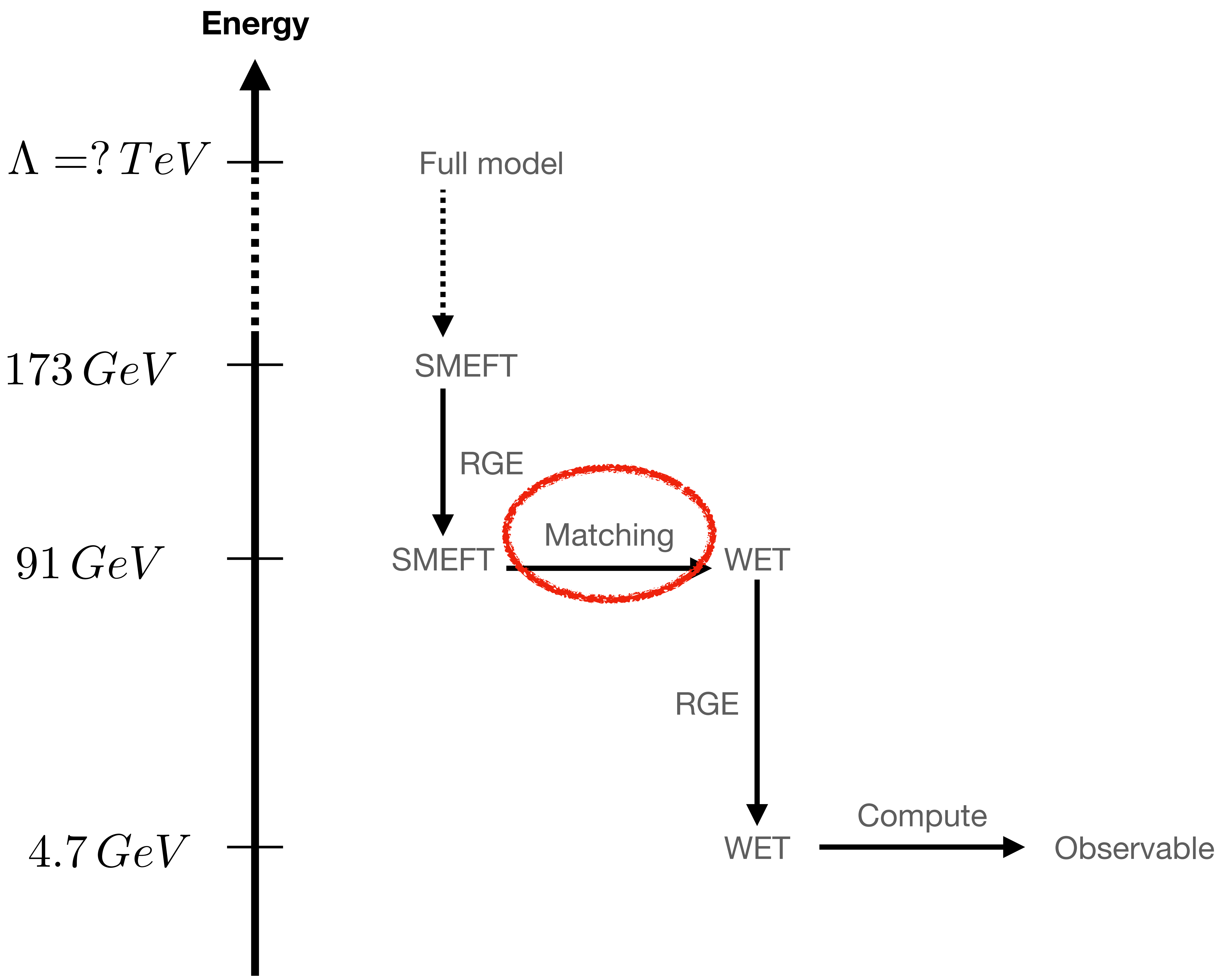


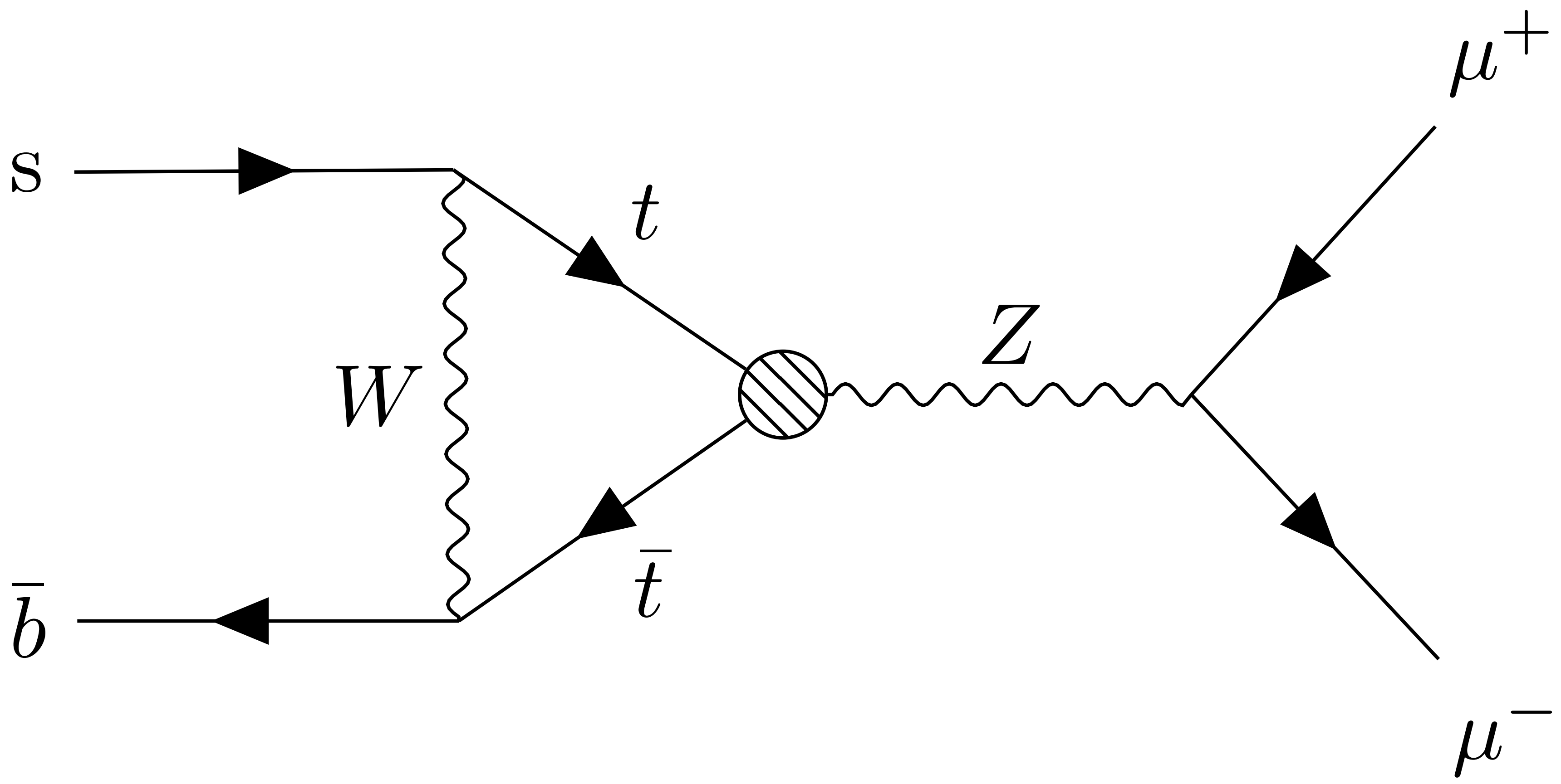


$$[\mathcal{O}^1_{\phi q}]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)(\bar{q}_i \gamma^\mu q_j)$$

New Directions

Flavour (Work in Progress)





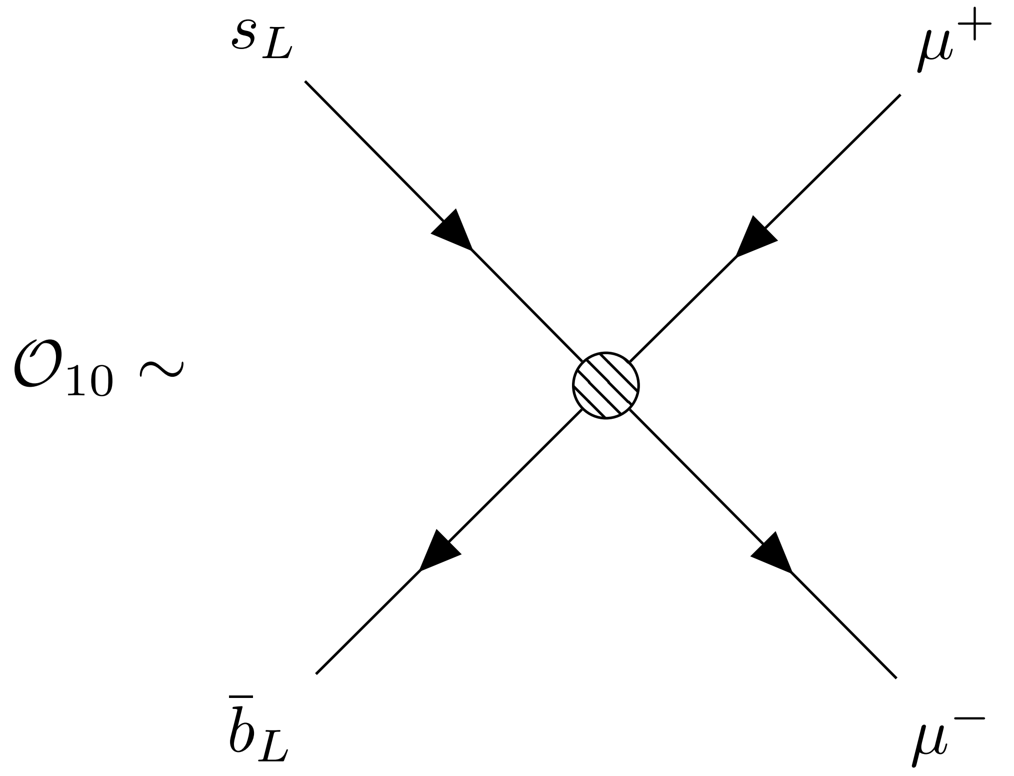
$$\left[\mathcal{O}^1_{\phi q}\right]_{ij} = \left(\phi^\dagger\, i\, \overleftrightarrow{D}_\mu\, \phi\right)(\bar{q}_i \gamma^\mu q_j)$$

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

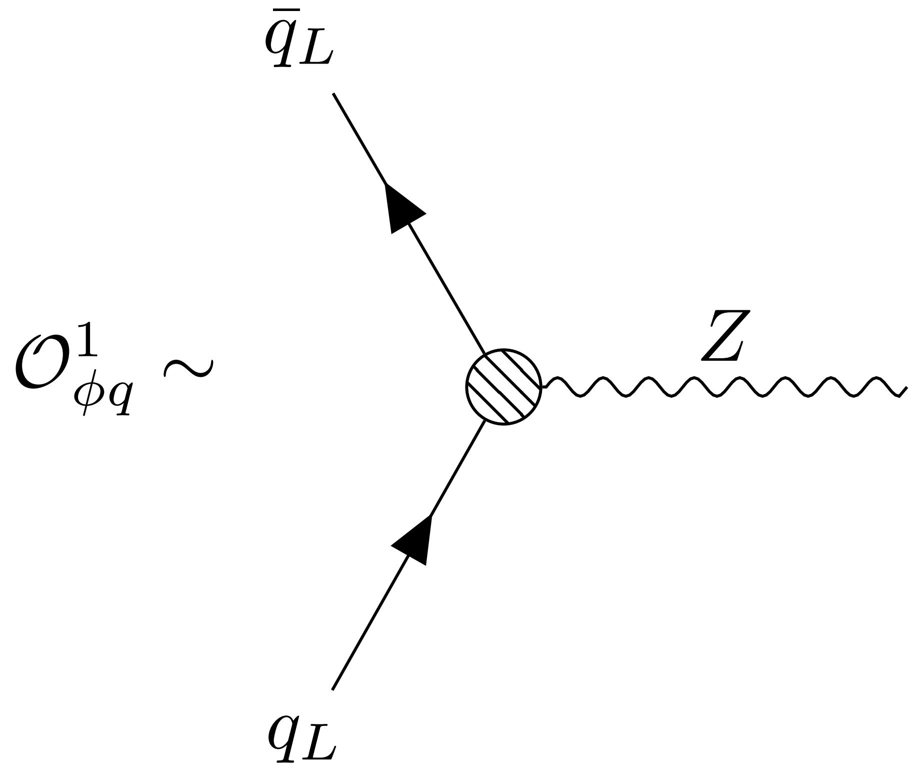
New Directions

Flavour (Work in Progress)

WET



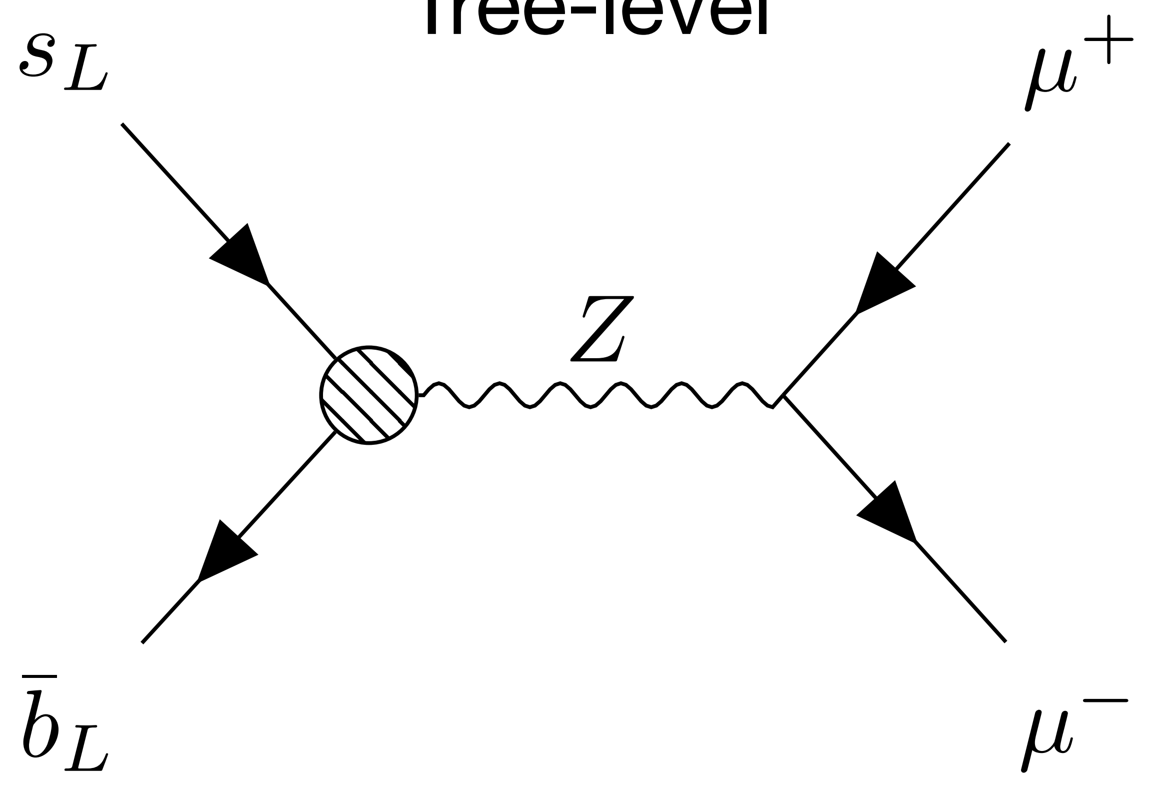
SMEFT



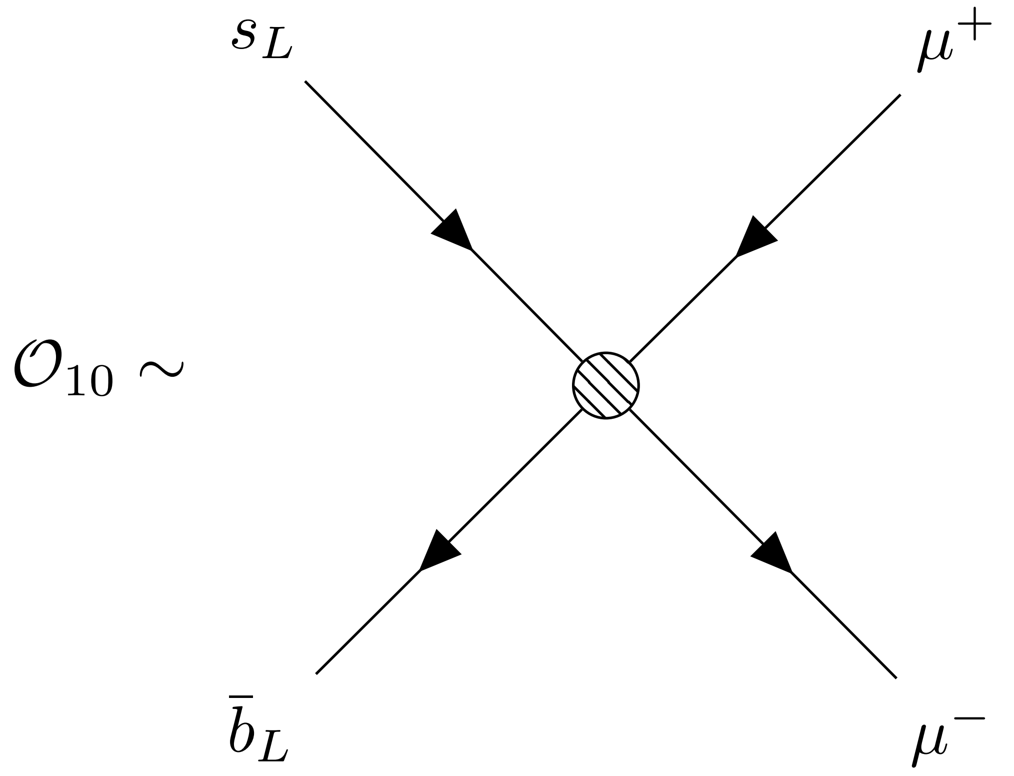
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

New Directions
Flavour (Work in Progress)

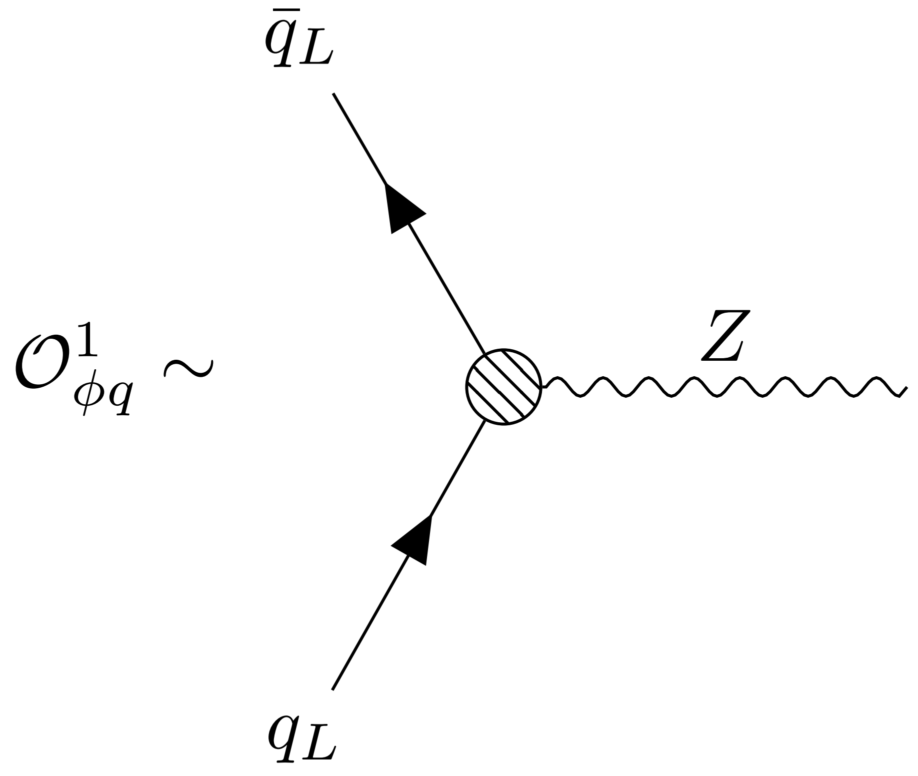
Tree-level



WET



SMEFT

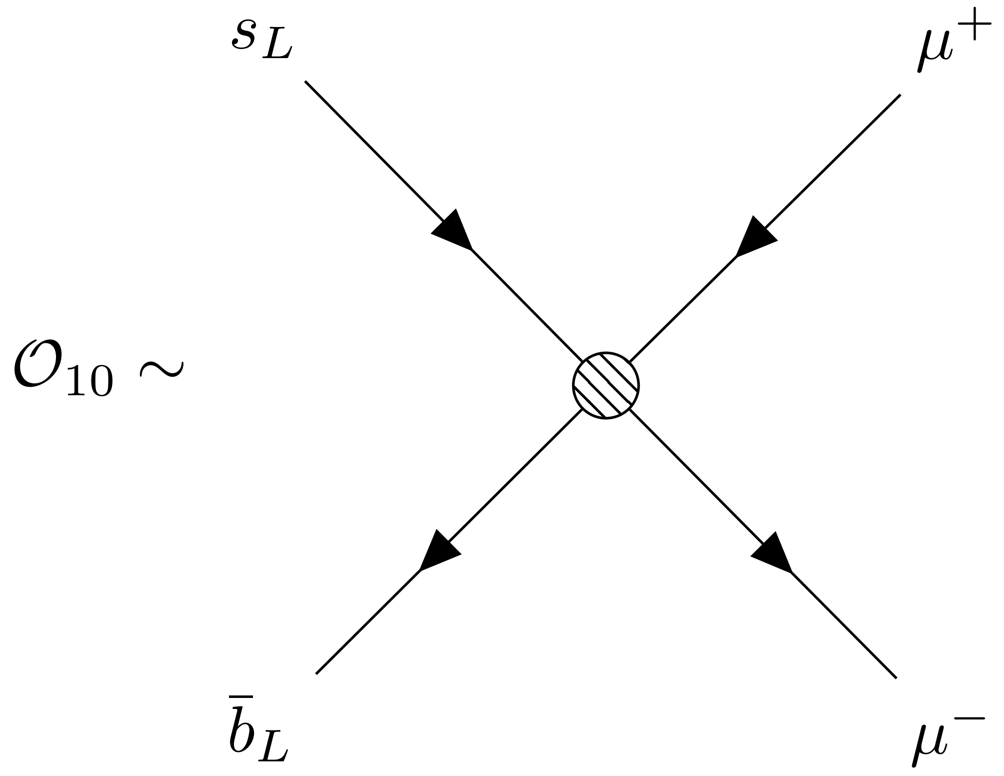


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

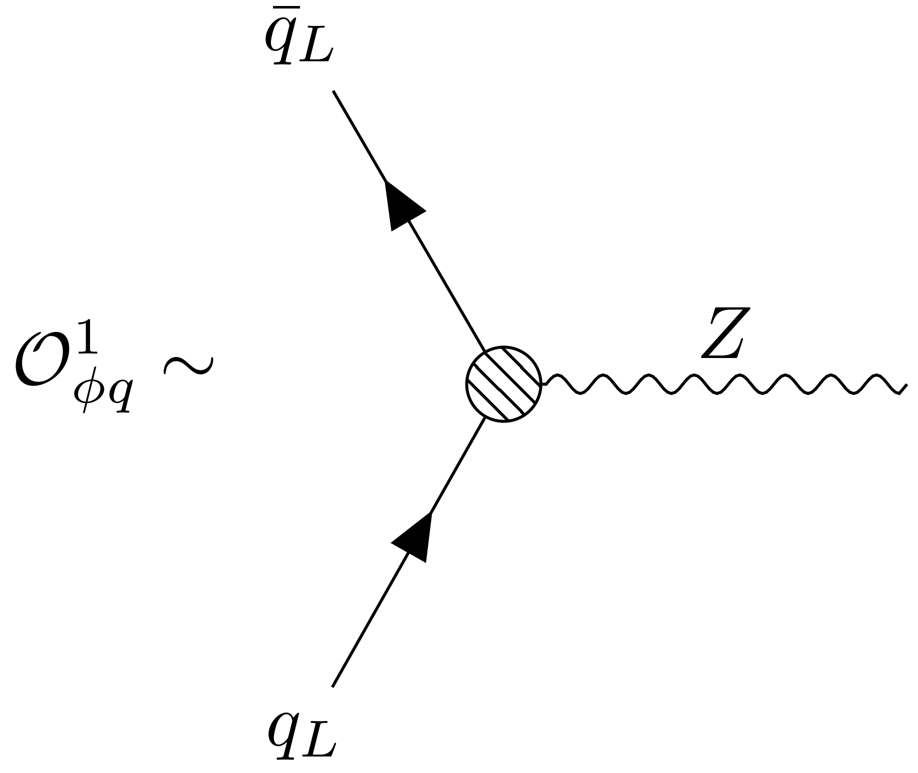
New Directions

Flavour (Work in Progress)

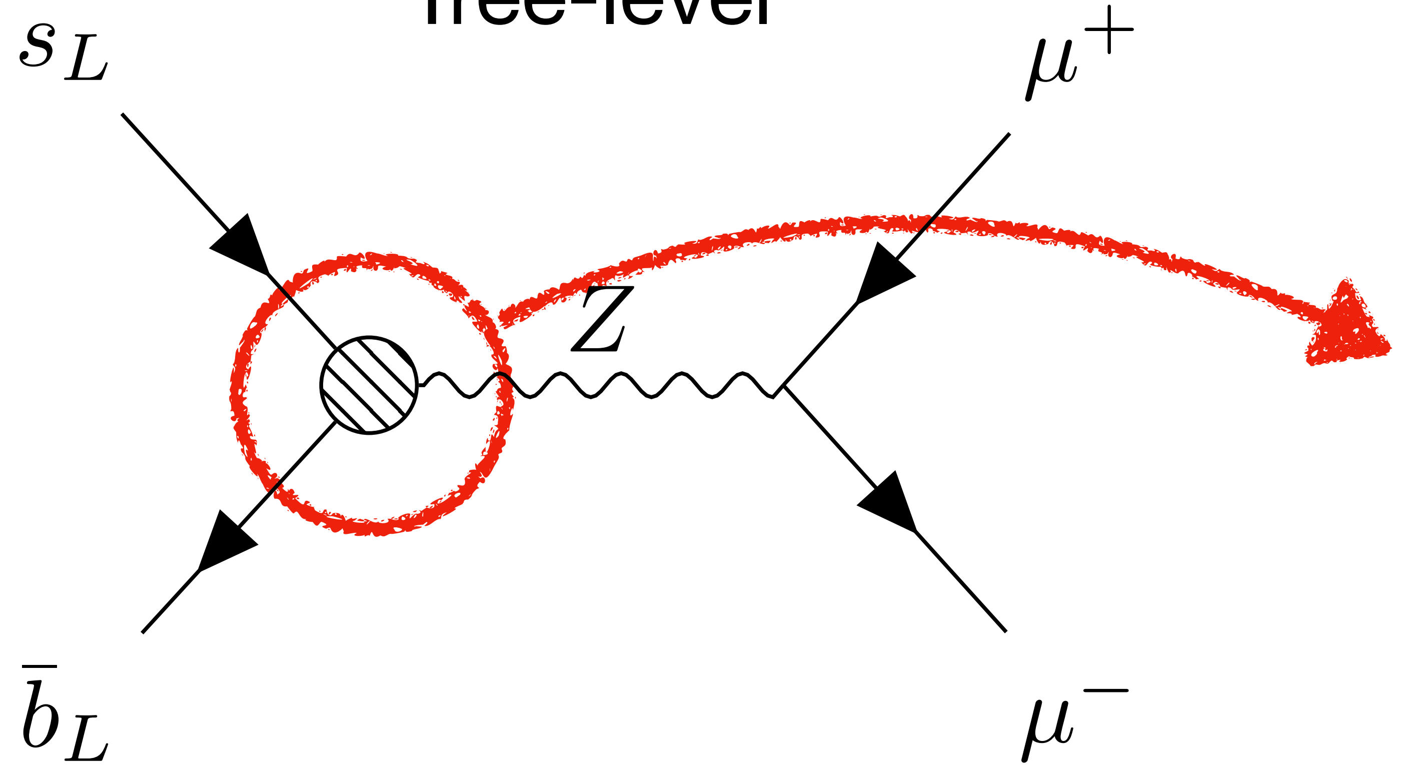
WET



SMEFT



Tree-level

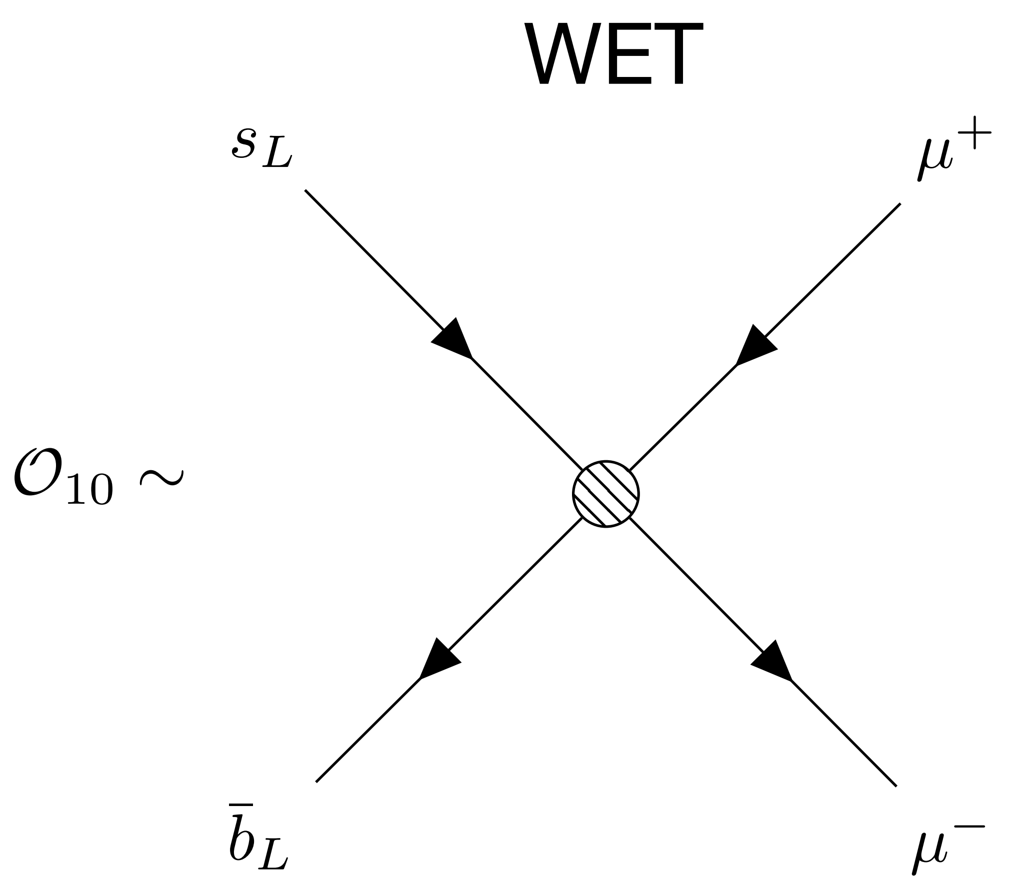


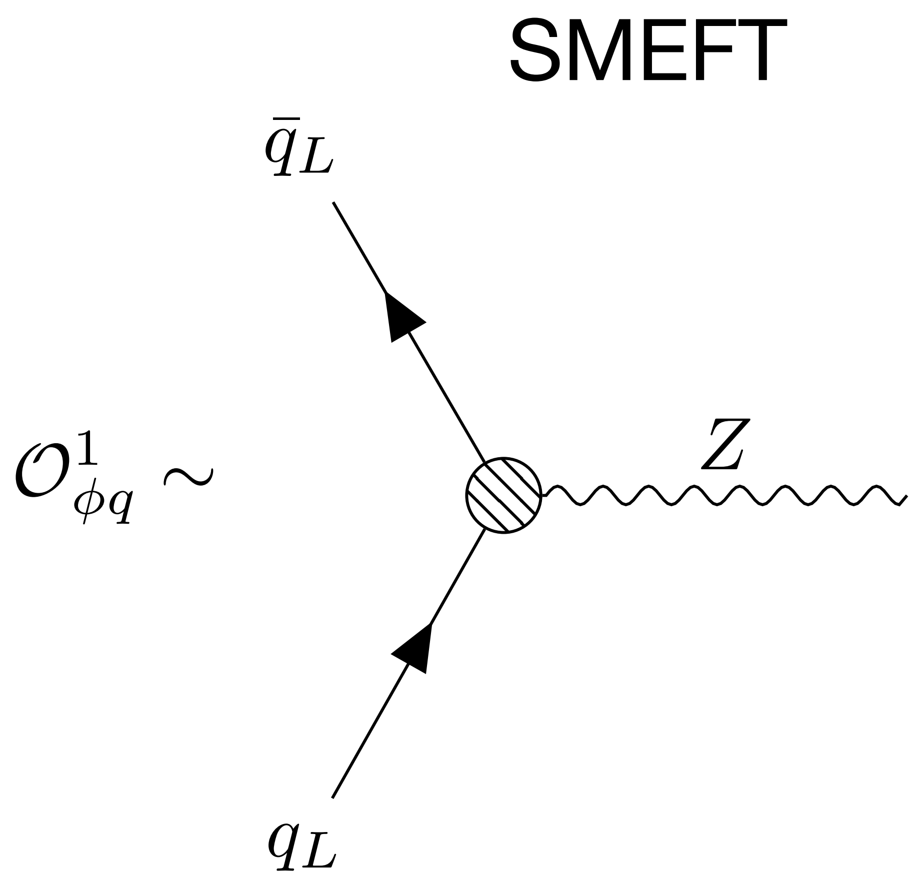
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

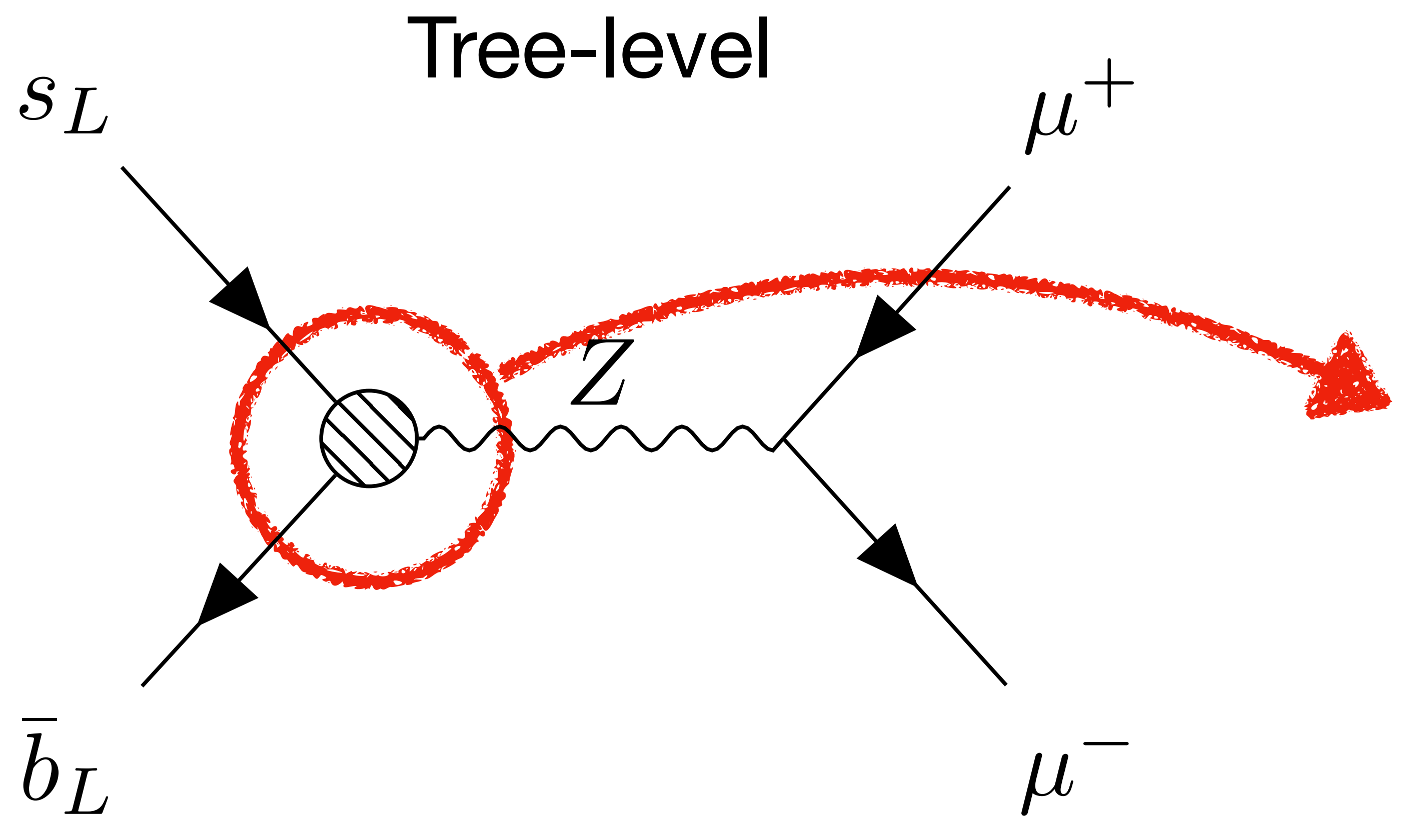
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

New Directions

Flavour (Work in Progress)





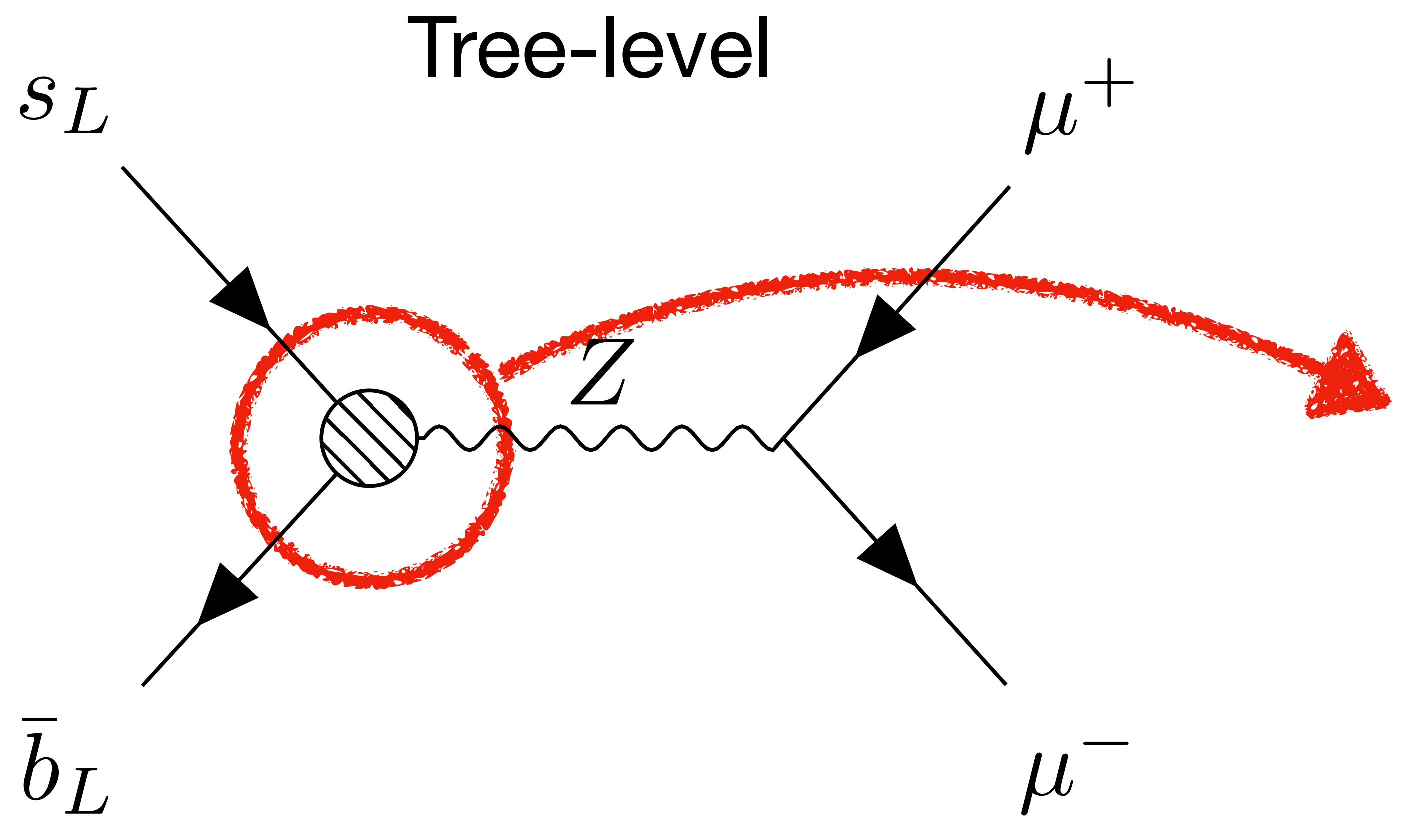


$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

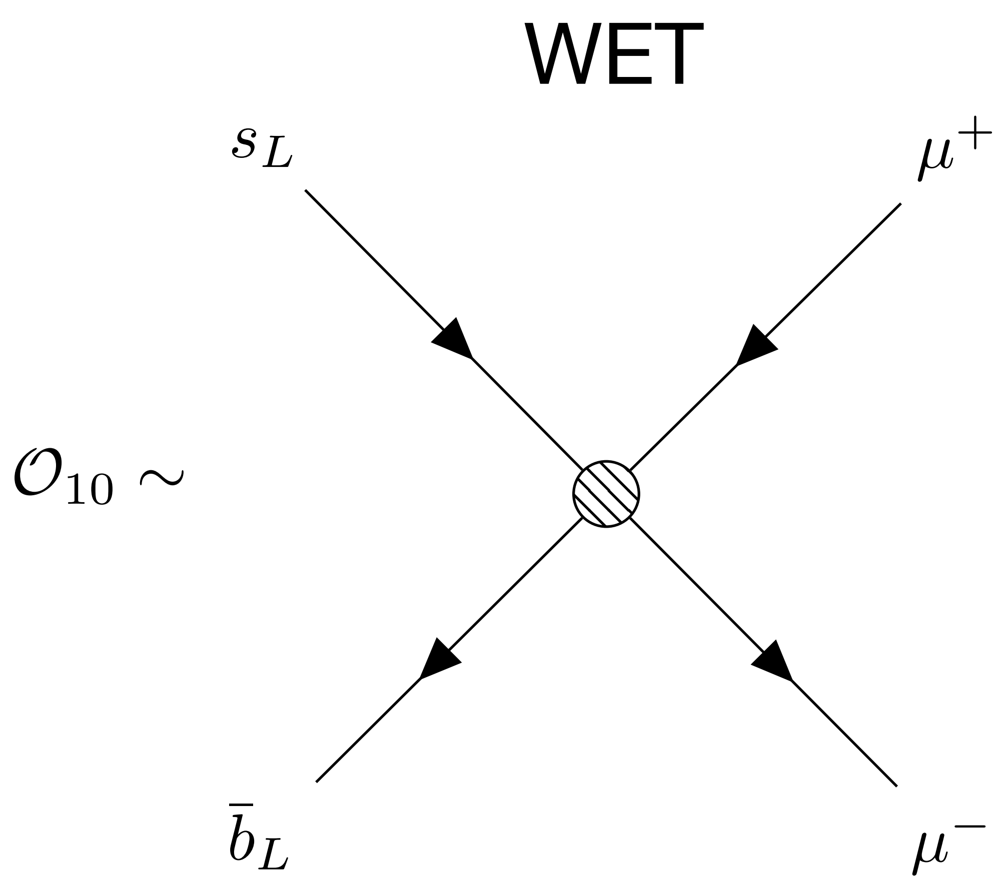
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

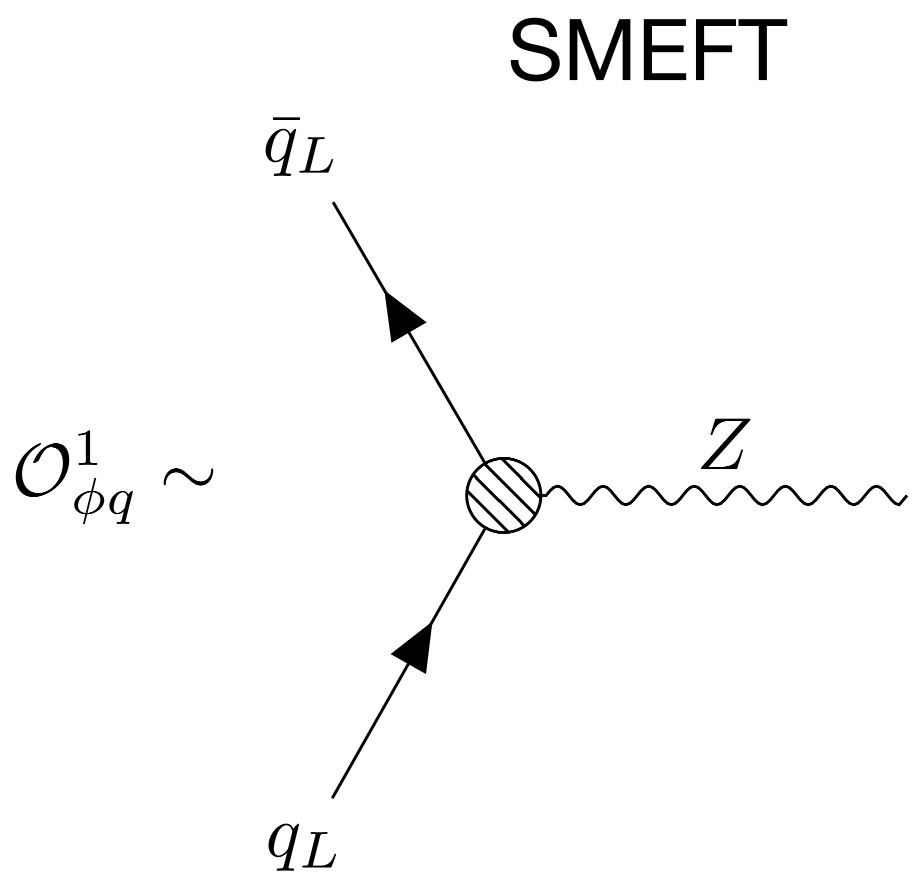
New Directions

Flavour (Work in Progress)



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





$\mathcal{C}_{10}$

b

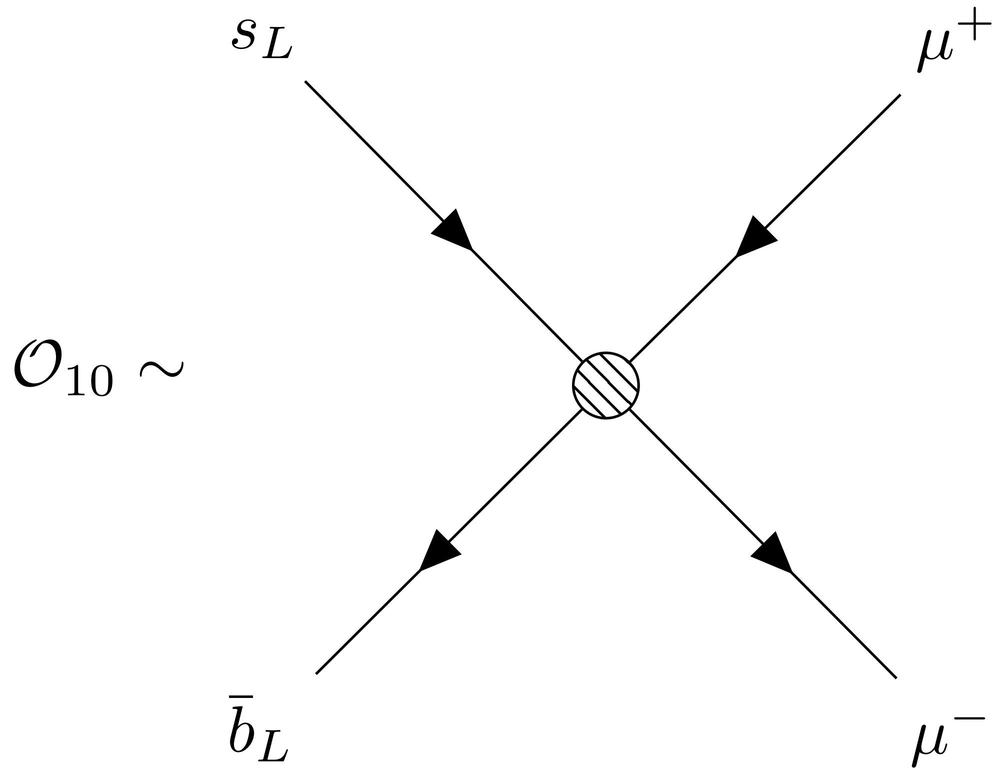
$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} \\ \text{Loop-level} \end{cases}$$

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

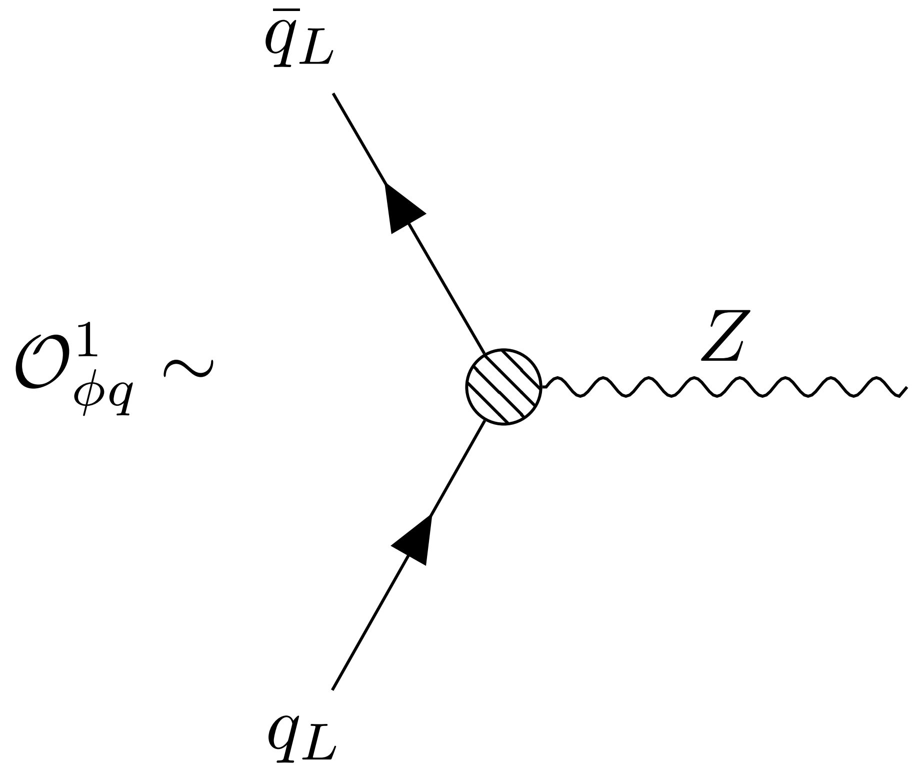
New Directions

Flavour (Work in Progress)

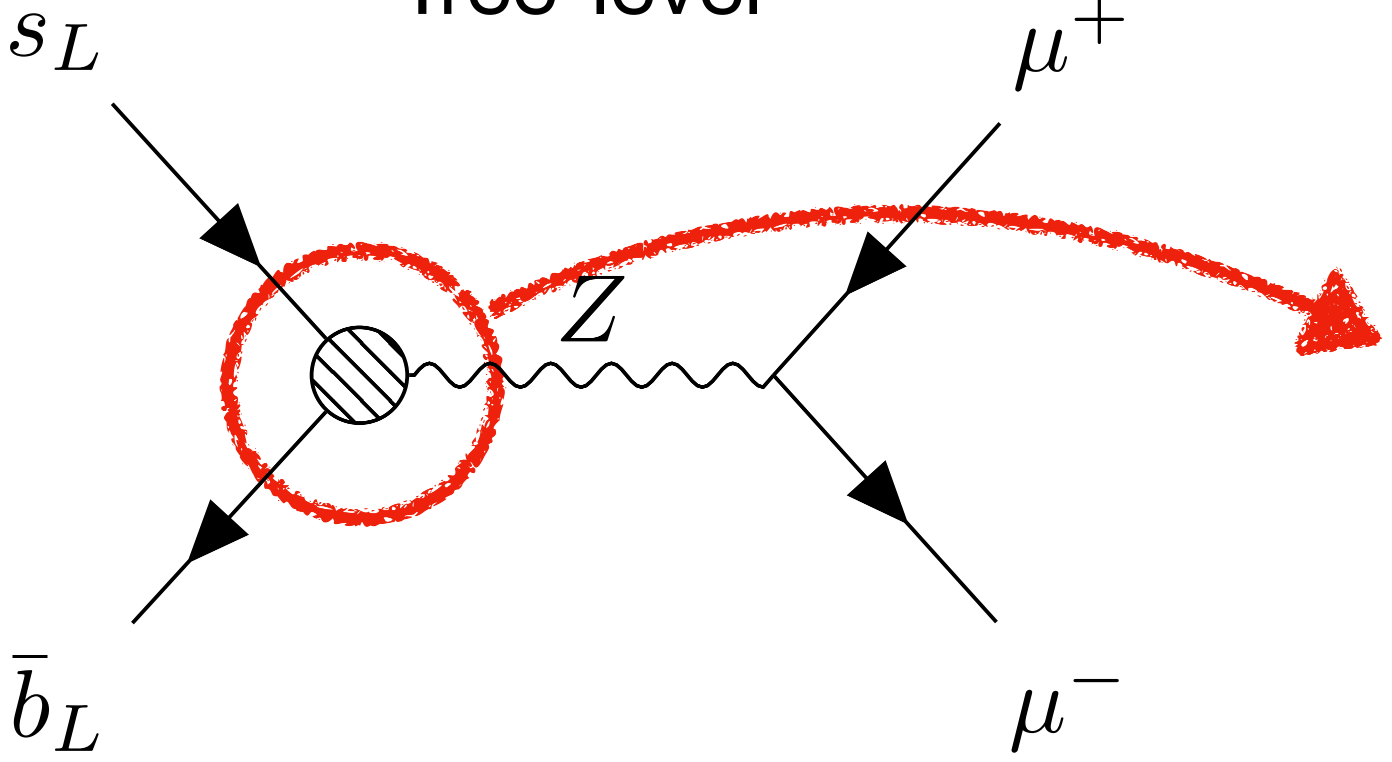
WET



SMEFT



Tree-level



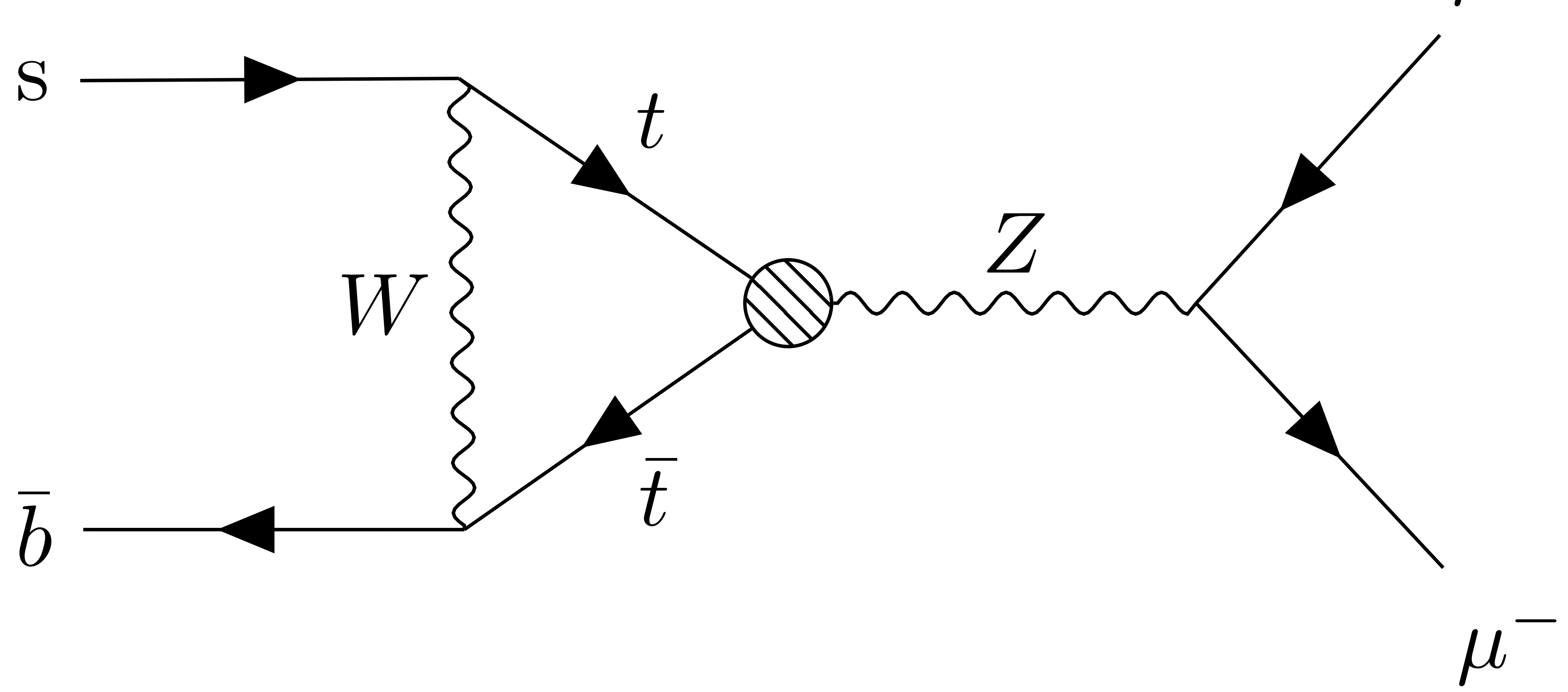
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

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

$$b$$

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

Loop-level

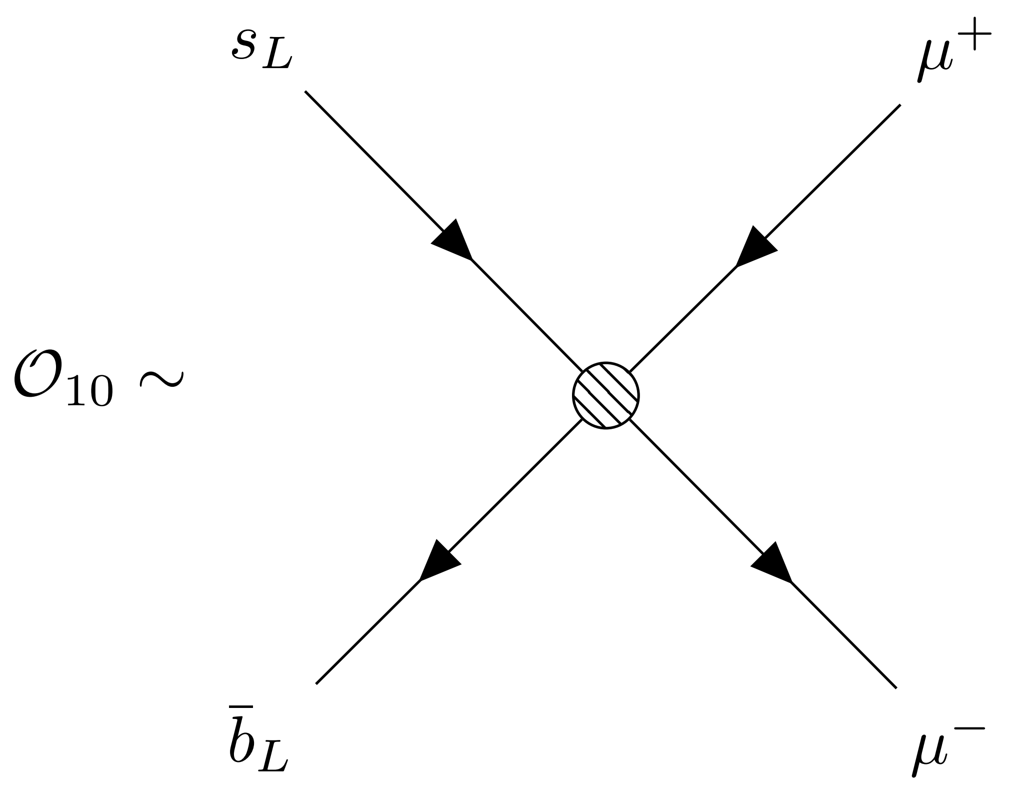


MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

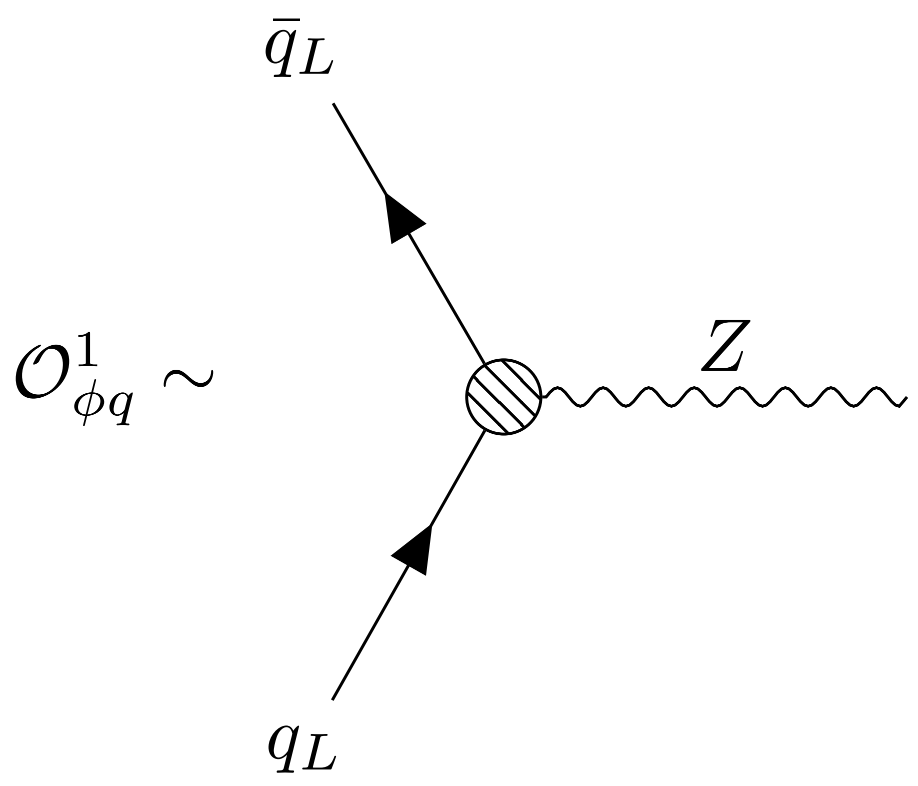
New Directions

Flavour (Work in Progress)

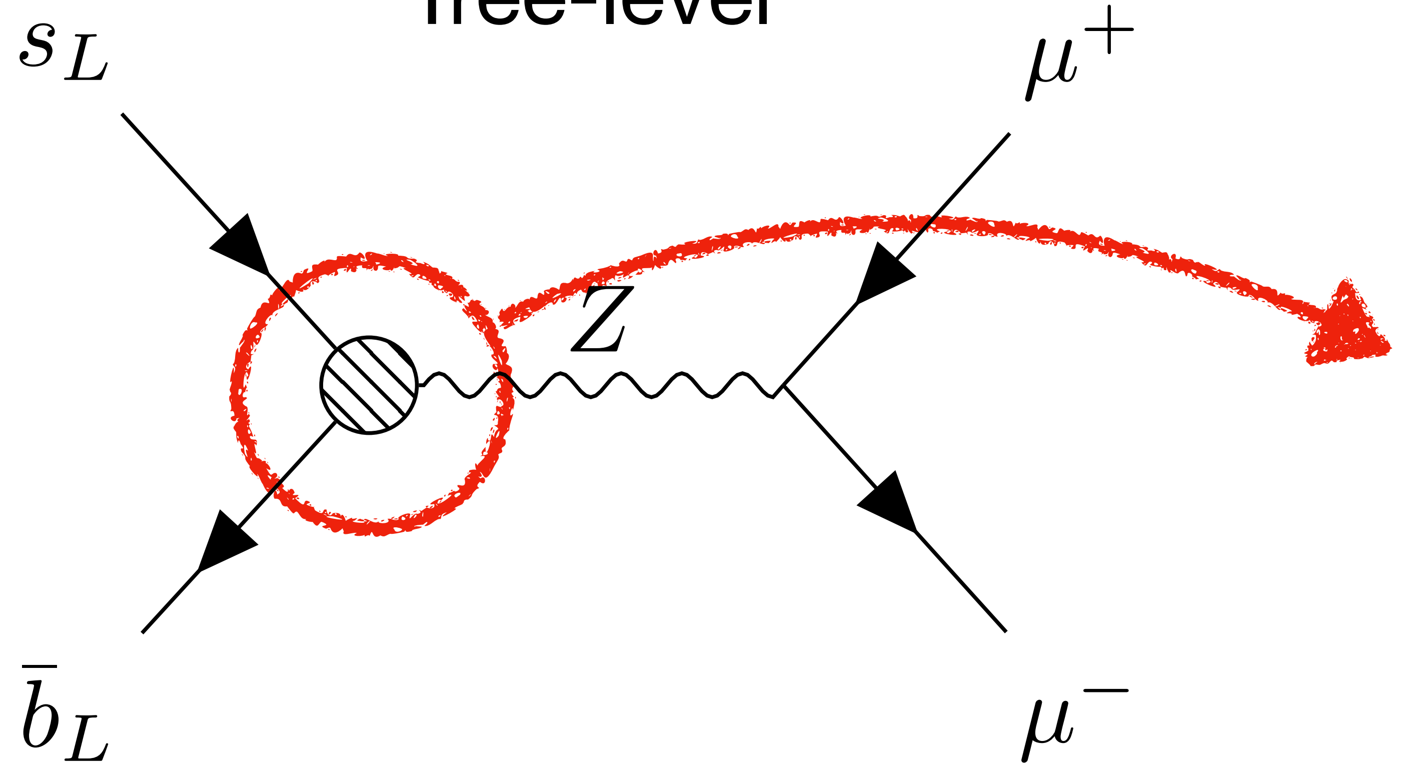
WET



SMEFT



Tree-level



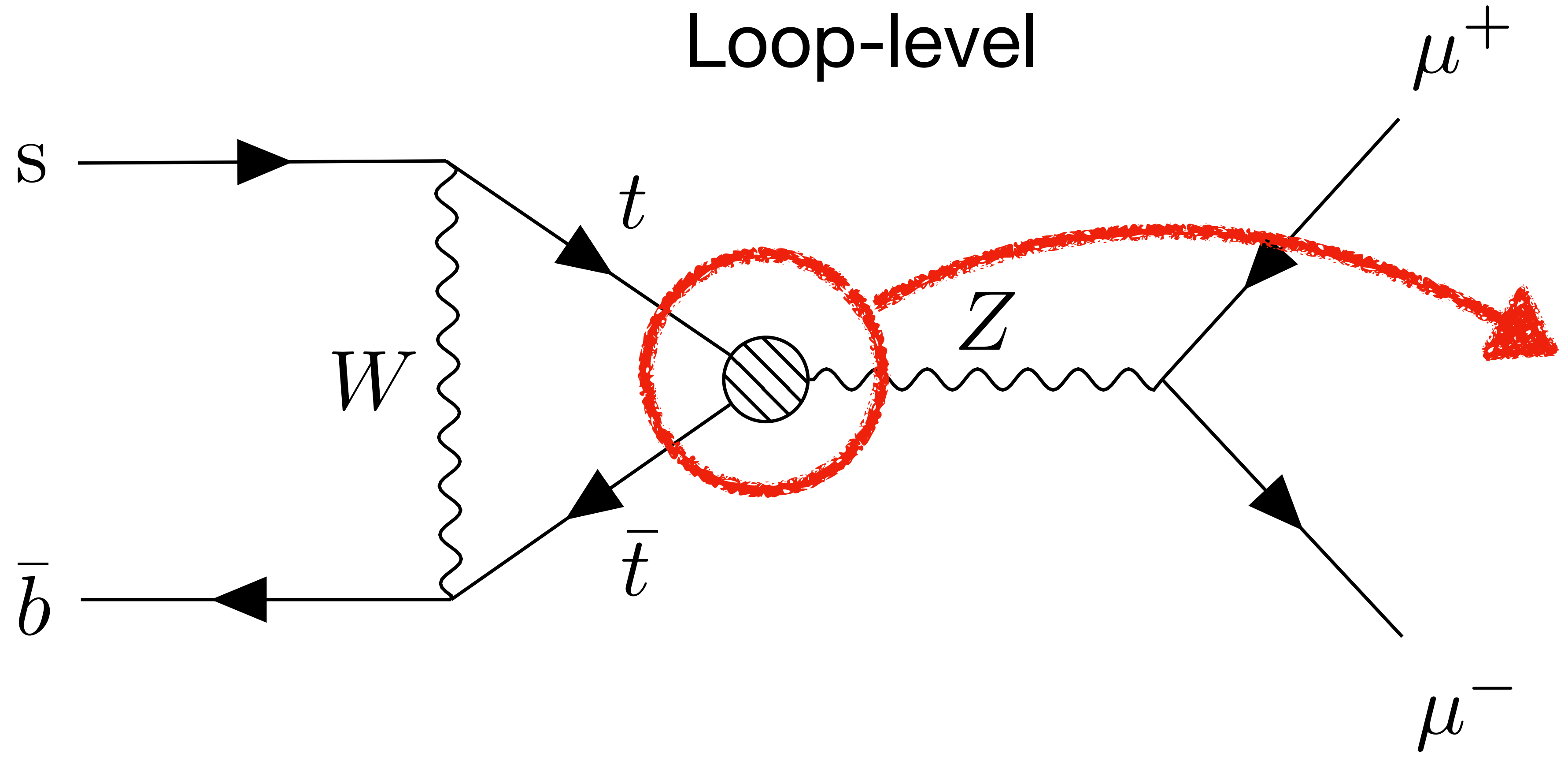
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

$\mathcal{C}_{10}$

b

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

Loop-level



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

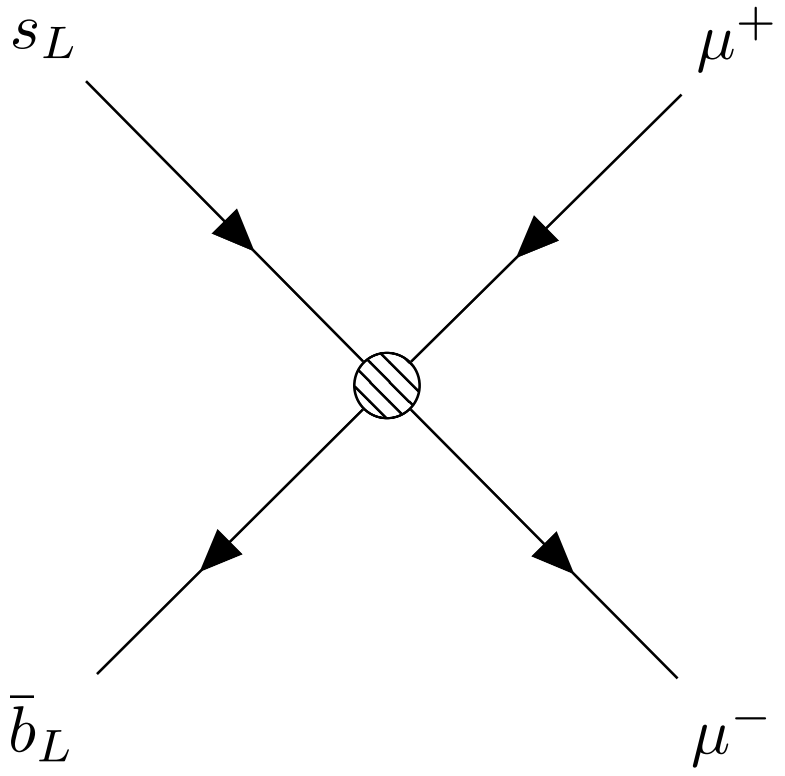
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

New Directions

Flavour (Work in Progress)

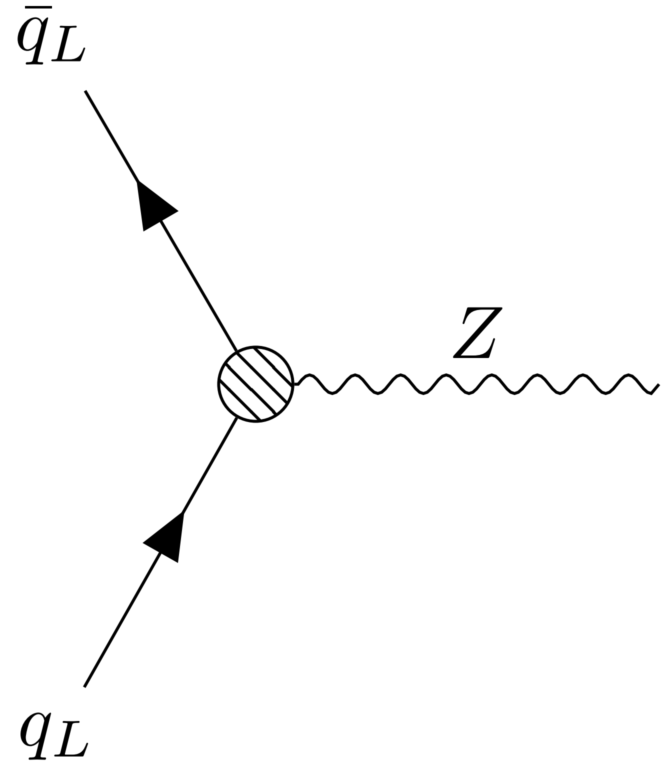
WET

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

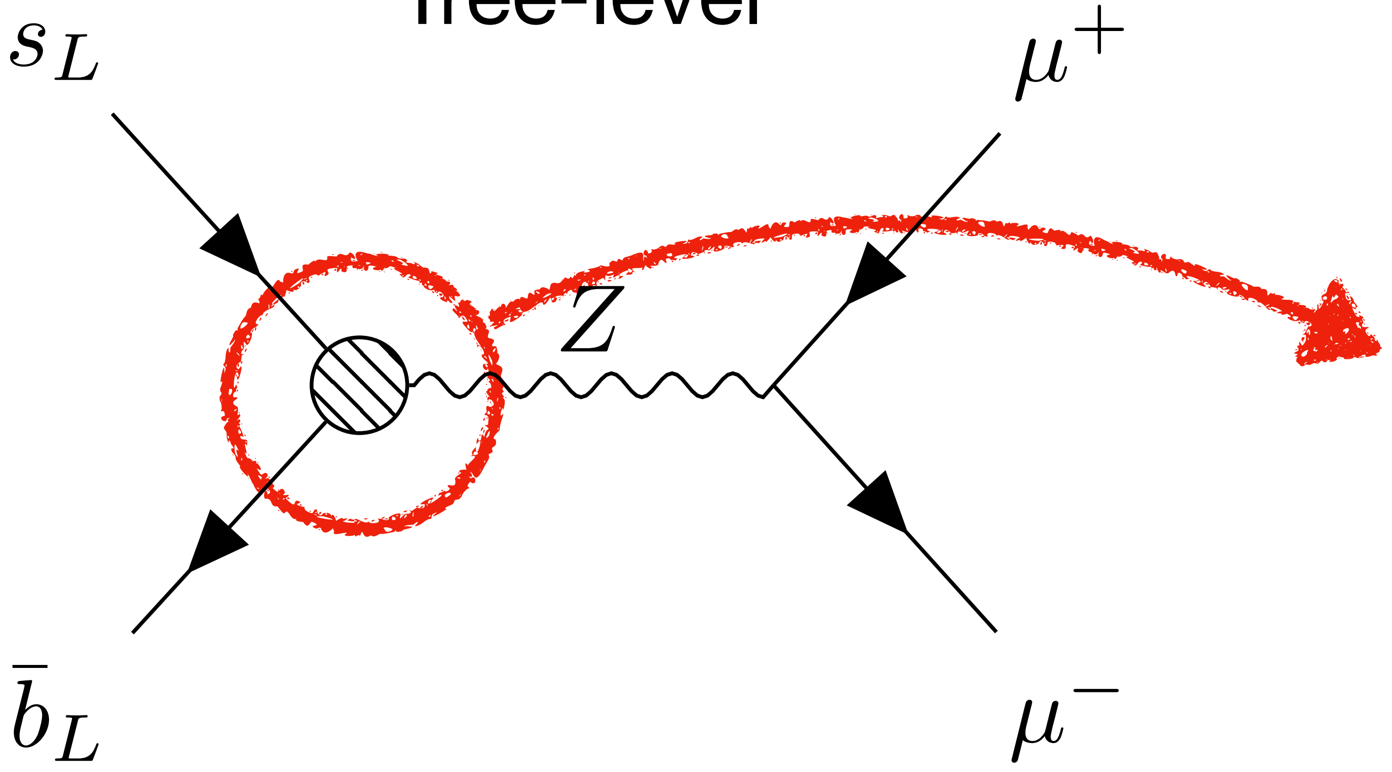


SMEFT

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



Tree-level

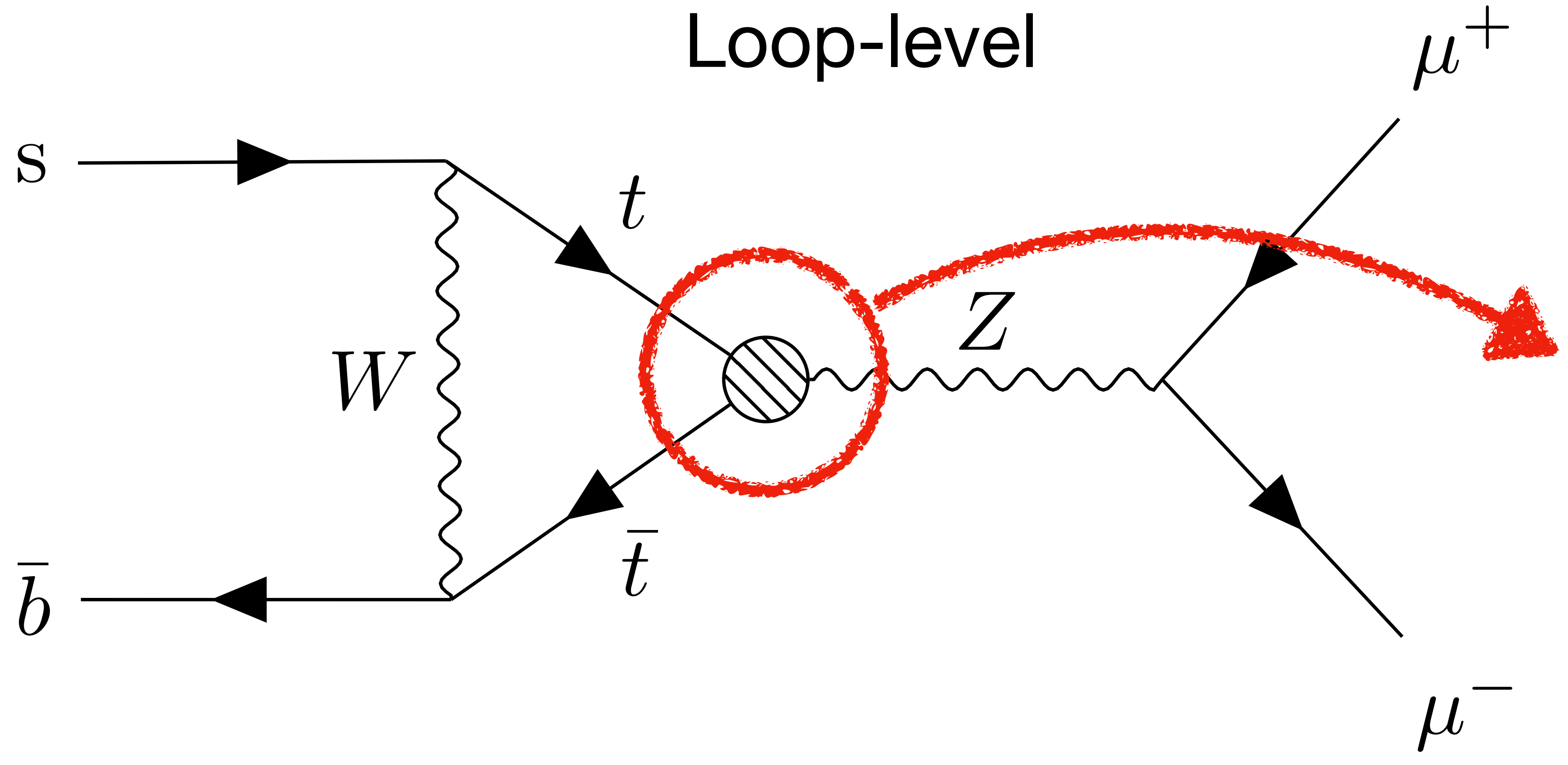


$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$

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

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

Loop-level



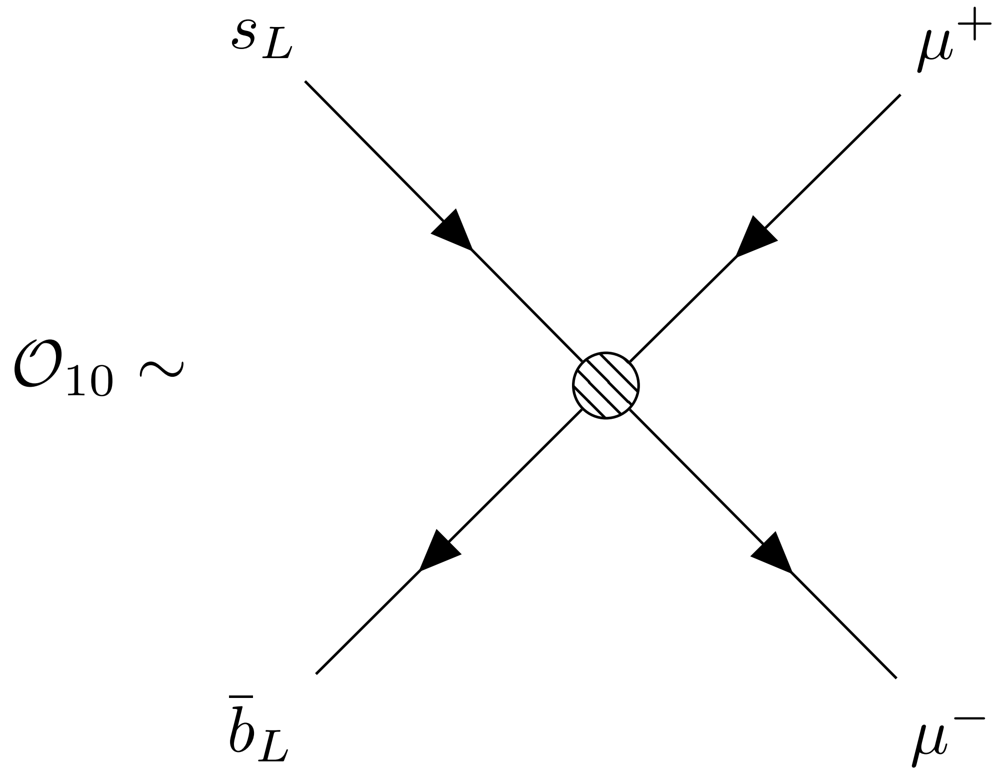
$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

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

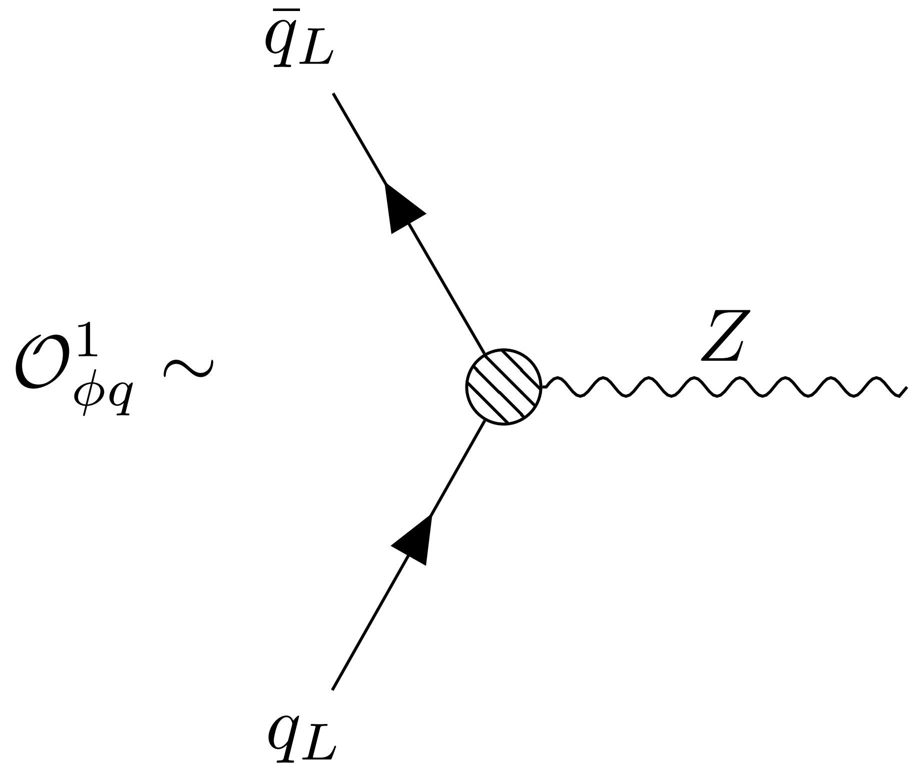
New Directions

Flavour (Work in Progress)

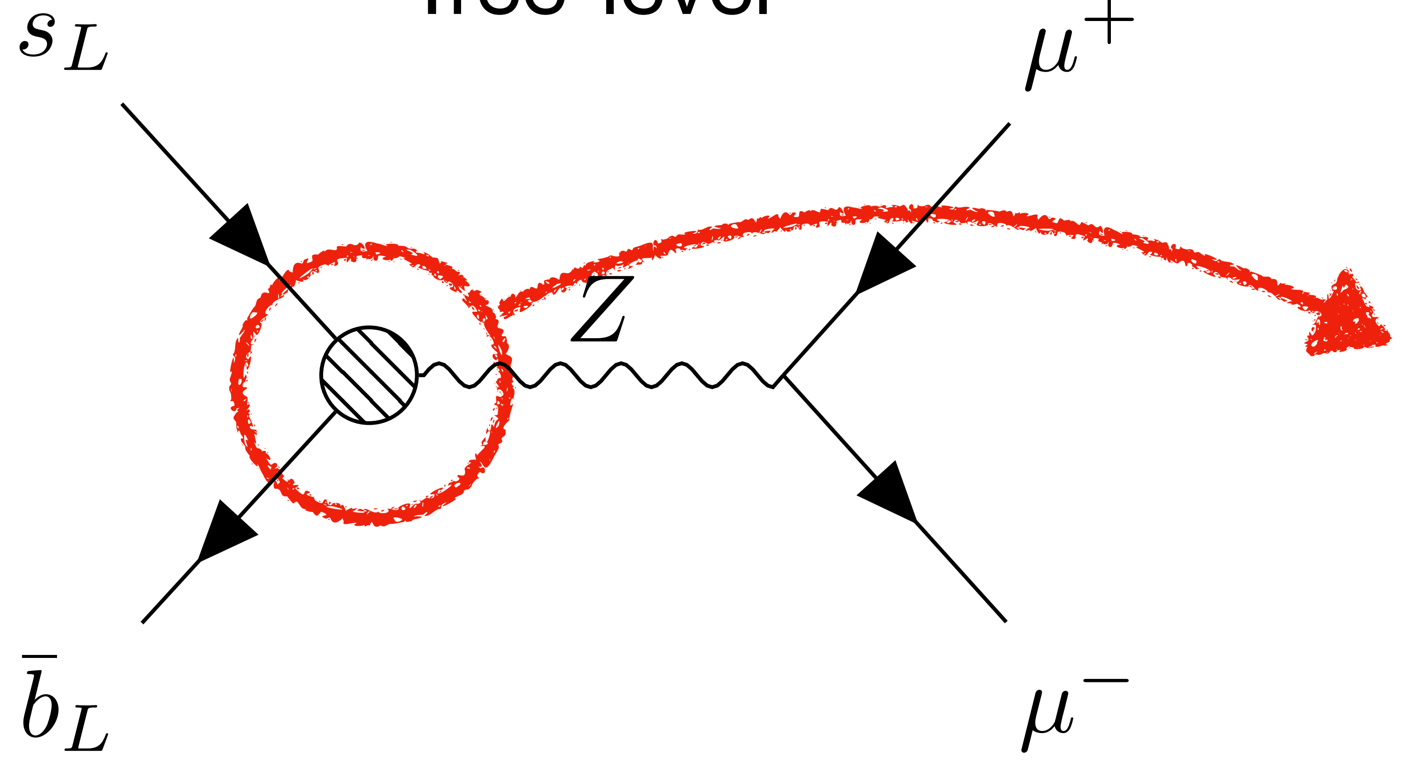
WET



SMEFT

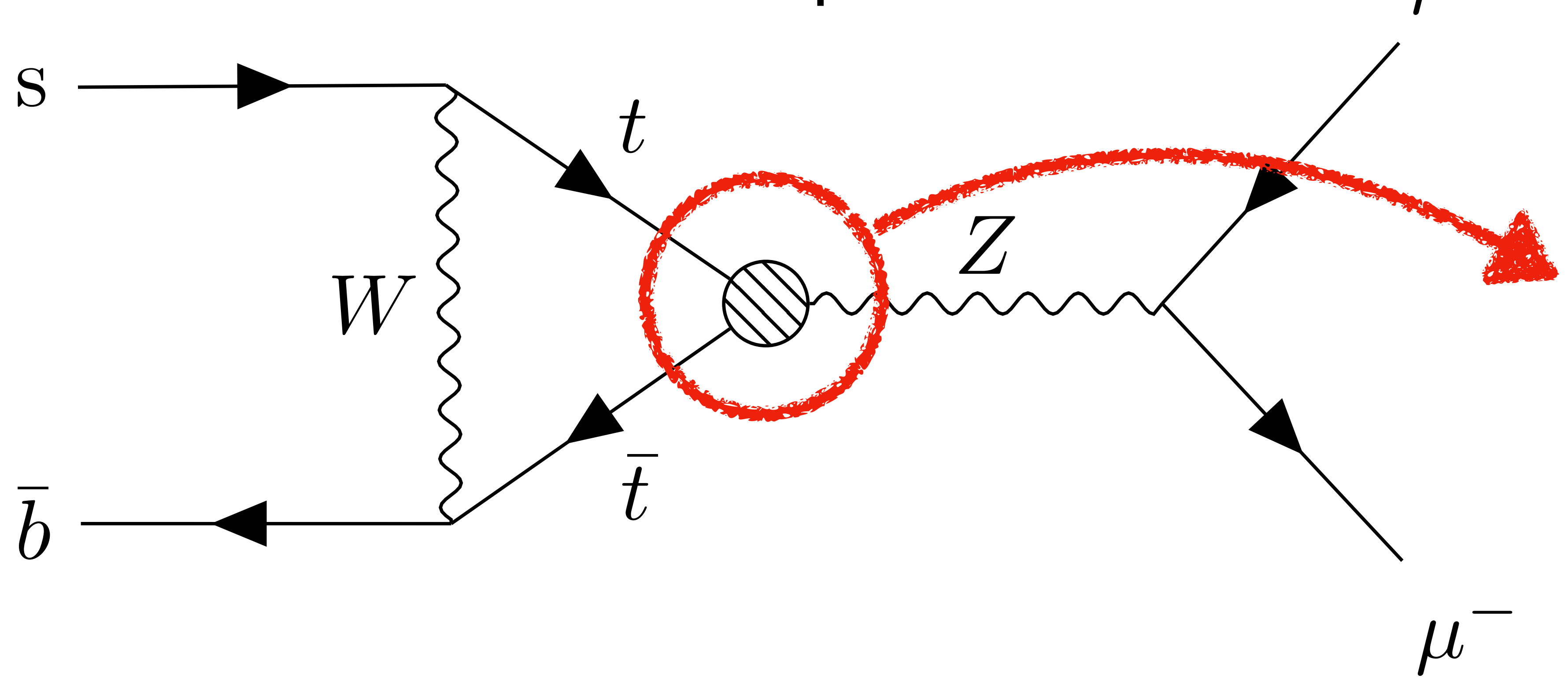


Tree-level



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

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

Conclusion

- Now is the time for Top-BSM
- Resolve degeneracies with different measurements
- Theorists can achieve allot by lowering the uncertainties
- Still opportunities for new observables
- Interesting playground for connecting high- and low-energy physics

The Operators

For full list see 1910.03606

Examples

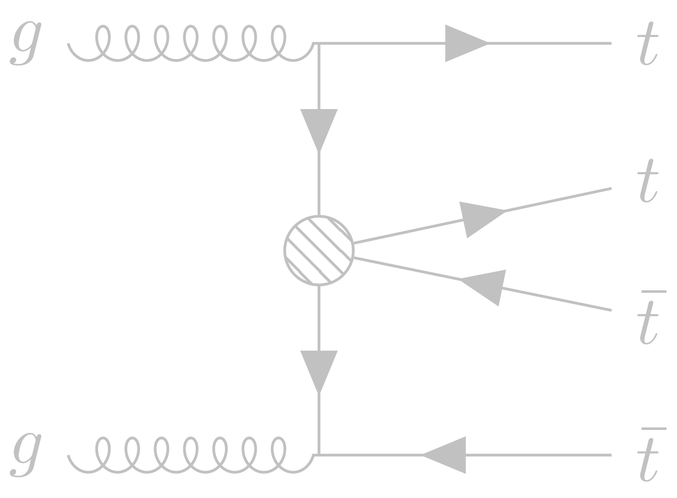
Processes

4 heavy fermions

$C_{qu}^{8(3333)}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{u}_3\gamma_\mu T^A u_3)$

$t\bar{t}t\bar{t}$

$t\bar{t}b\bar{b}$



2 heavy - 2 light fermions

$$Oqt8 = C_{qu}^{8(ii33)}(\bar{q}_i\gamma^\mu T^A q_i)(\bar{u}_3\gamma_\mu T^A u_3)$$

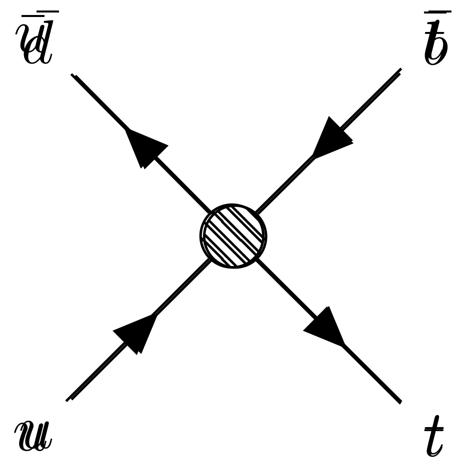
$$Oqt1 = C_{qu}^{1(ii33)}(\bar{q}_i\gamma^\mu q_i)(\bar{u}_3\gamma_\mu u_3)$$

$t\bar{t}$ production

single t production

tZ

$t\bar{t}Z/W/H$



2 heavy fermions - boson

$$OtG = \text{Re}\left\{C_{uG}^{(33)}\right\}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G_{\mu\nu}^A$$

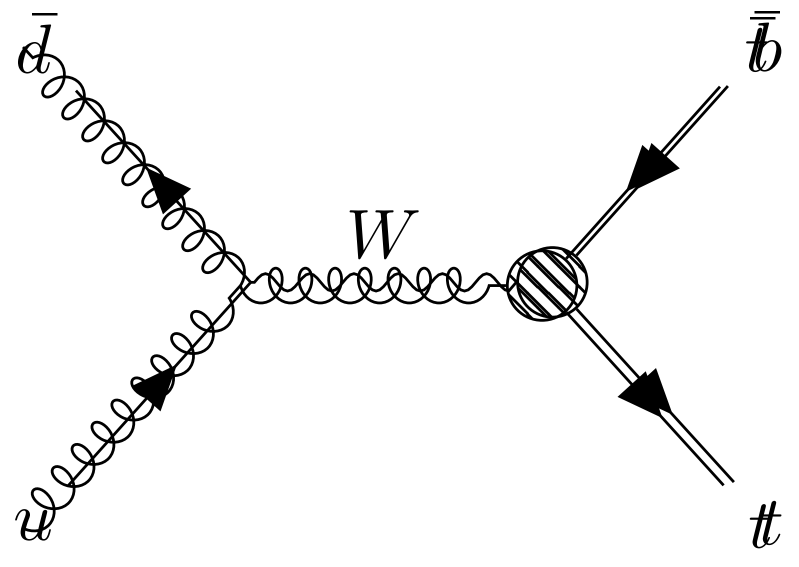
$$OtW = \text{Re}\left\{C_{uW}^{(33)}\right\}(\bar{q}_3\sigma^{\mu\nu}\tau^{\mathcal{I}} u_3)\tilde{\phi}W_{\mu\nu}^{\mathcal{I}}$$

$t\bar{t}$ production

single t production

tZ/W

$t\bar{t}Z/W/H$



Event Kinematics

Or Rates vs. Tails

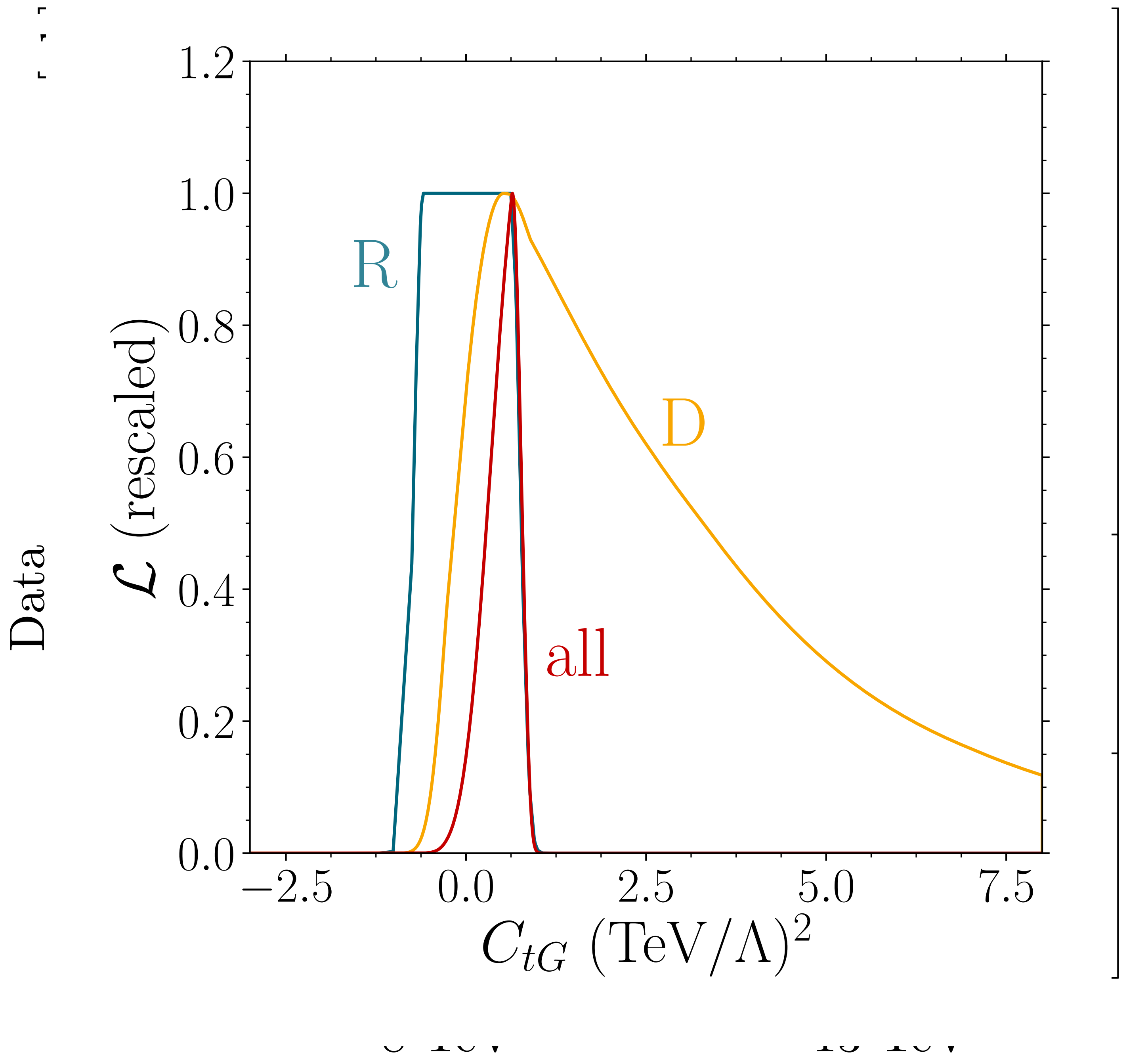
$$O_{tG} = C_{tG}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G^A_{\mu\nu}$$

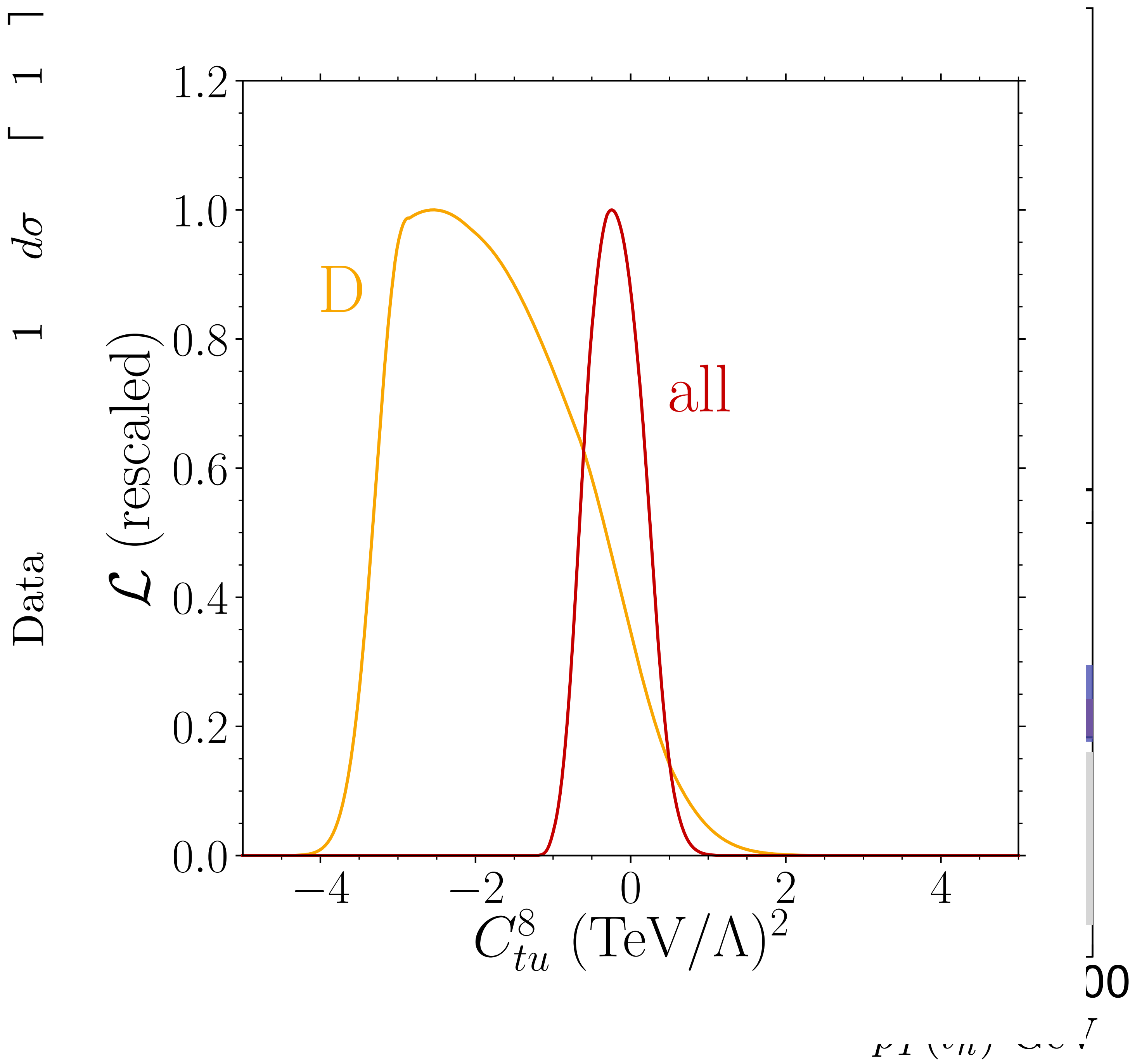
$$O^8_{tu} = C^8_{tu}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{u}_i\gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

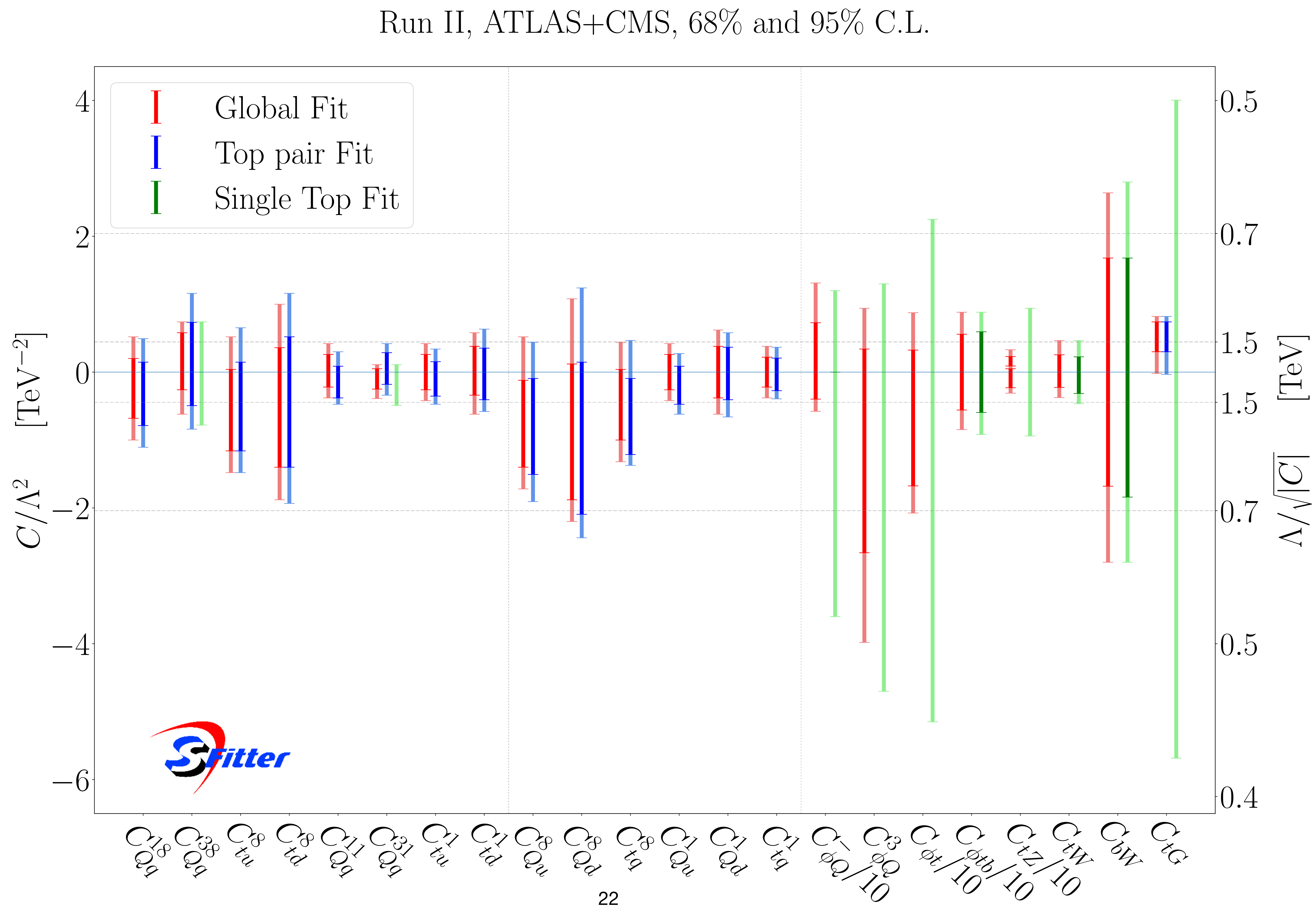
Very small

Very large
For high bins





Results



Run II, ATLAS+CMS, 68% and 95% C.L.
Global Fit
Top pair Fit
Single Top Fit
C/Λ^2 [TeV^{-2}]
$\Lambda/\sqrt{|C|}$ [TeV]
4
2
0
−2
−4
−6
0.5
0.7
1.5
1.5
0.7
0.5
0.4
C^{18}_{Qq} C^{38}_{Qq} C^{8}_{tu} C^{8}_{td} C^{11}_{Qq} C^{31}_{Qq} C^{1}_{tu} C^{1}_{td} C^{8}_{Qu} C^{8}_{Qd} C^{8}_{tq} C^{1}_{Qu} C^{1}_{Qd} C^{1}_{tq} $C^{-}_{\phi Q}/10$ $C^{3}_{\phi Q}$ $C_{\phi t}/10$ $C_{\phi tb}/10$ $C_{tZ}/10$ C_{tW} C_{bW} C_{tG}
SFitter

NLO Effects for chirality