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Probing squared four-fermion operators of SMEFT with meson-mixing

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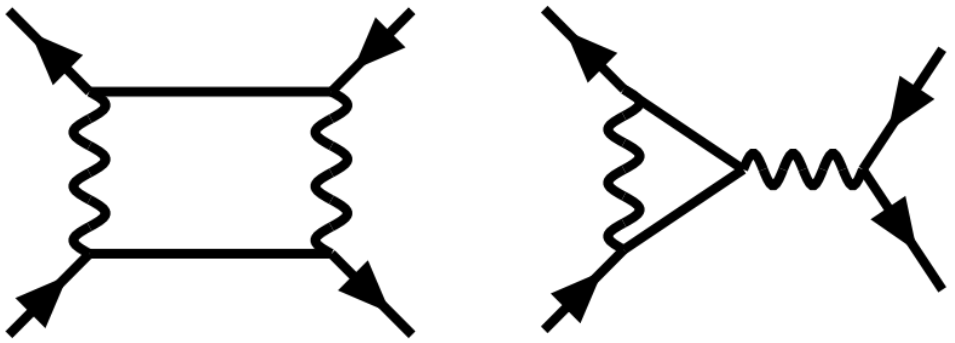
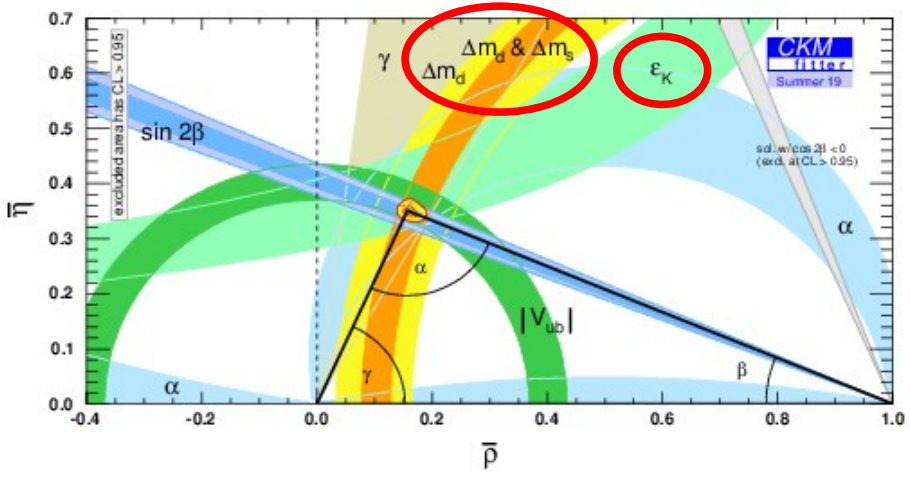
Looking for non-standard physics

- One **successful** approach (evidence of heavy quarks): observables that are predicted being suppressed
  - e.g., Flavour Changing Neutral Currents (FCNCs) in the SM
- Another approach is precision physics

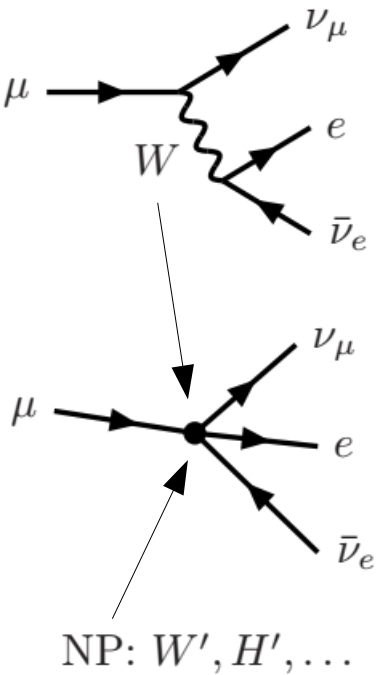
e.g., meson-mixing, rare decays





Manifestations of heavy NP

- At low energies, the effects of heavy d.o.f. are encoded in the Wilson coefficients of higher dimensional operators, e.g., μ decay in the SM



- **SMEFT**: consider the SM + non-renormalizable interactions, i.e., of dimension higher than four, suppressed by the characteristic scale of NP

$$\frac{C^{(5)} \times Q^{(5)}}{\Lambda}, \quad \frac{C^{(6)} \times Q^{(6)}}{\Lambda^2}, \quad \frac{C^{(7)} \times Q^{(7)}}{\Lambda^3}, \quad \frac{C^{(8)} \times Q^{(8)}}{\Lambda^4}, \quad \text{etc.}$$

Operators of dim.-6 and dim.-8

- Involve further SM fields (q_L,u_R,d_R,l_L,e_R,$X^{\mu\nu}$,H) and/or cov. derivatives (D)
- Use of algebraic identities, equations of motion, etc.
  - operators of dim.-6 (B preserving: #2,499): [Buchmuller, Wyler '86; Grzadkowski, Iskrzynski, Misiak, Rosiek '10]

$$\text{Warsaw: } X^3,\ H^6,\ H^4D^2,\ \psi^2H^3,\ X^2H^2,\ \psi^2XH,\ \psi^2H^2D,\ \psi^4$$

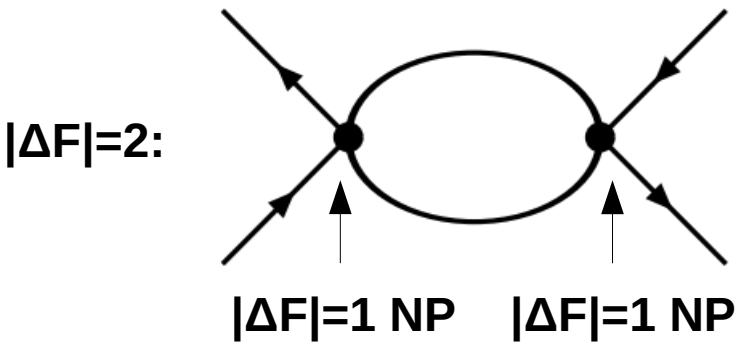
  - operators of dim.-8 (B preserving: #36,971): [Murphy '20; Li, Ren, Shu, Xiao, Yu, Zheng '20]

$$\text{bosonic } (X^4, \text{ etc.}),\ 2\text{-fermion } (\psi^2X^2H, \psi^2XH^3, \text{ etc.}),\ 4\text{-fermion } (\psi^4H^2, \psi^4X, \text{ etc.})$$

- **Flavour aspects of NP**: charged and neutral flavour changing currents, CP violation, violation of leptonic flavour universality, etc.

Double insertions of dim.-6 ops.

- Operators that change flavour by 1-unity naturally lead to contributions where flavour changes by 2-units



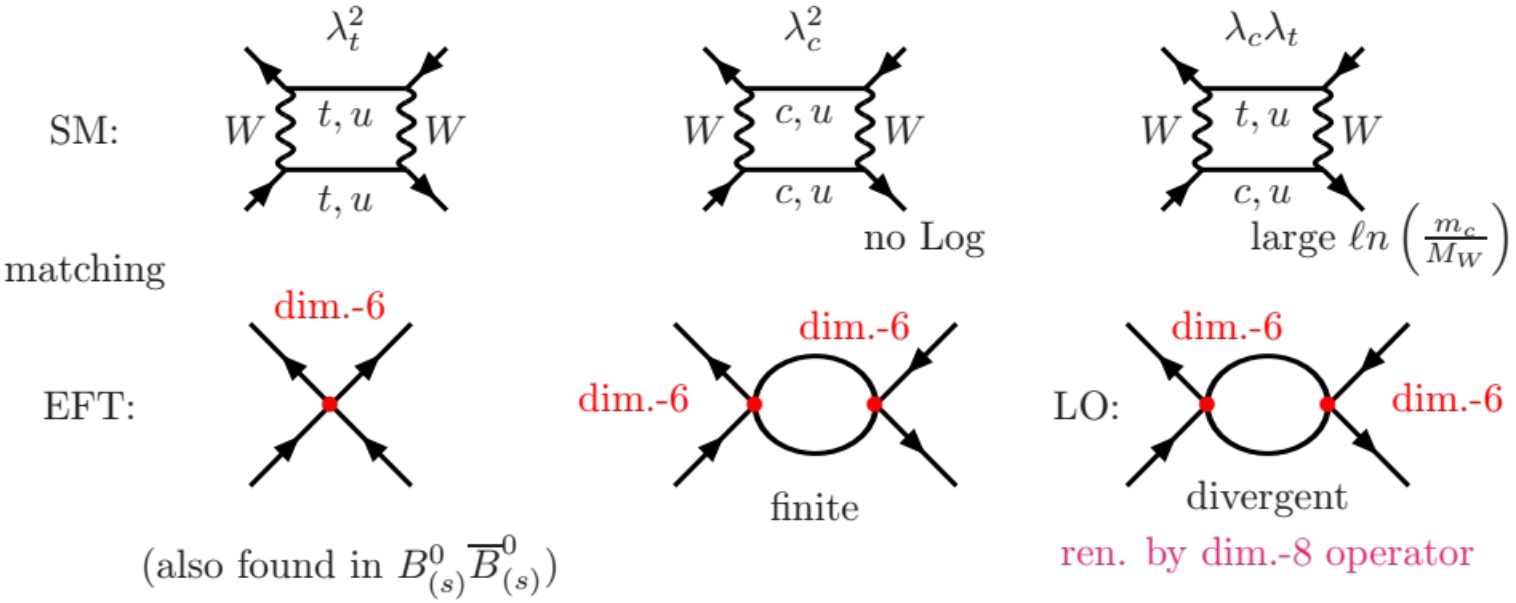
- **Here**:
  - renormalization by dim.-8 operators
  - phenomenological consequences

Weak interactions at low-energies

- Heavy d.o.f. exchanges encoded in effective field theory
- Example: neutral-Kaon meson-mixing in the SM
  - **GIM mechanism** plays a crucial role in controlling the size of contributions

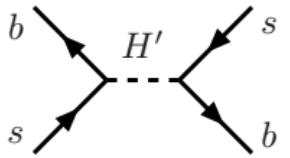
[Gilman, Wise ‘83]
[Herrlich, Nierste ‘94 ‘96]
[Brod, Gorbahn, Stamou ‘20]

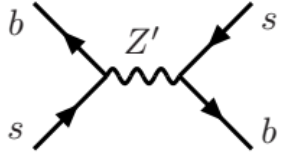
[Glashow, Iliopoulos, Maiani ‘70]

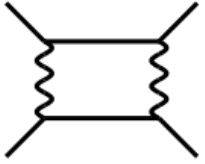


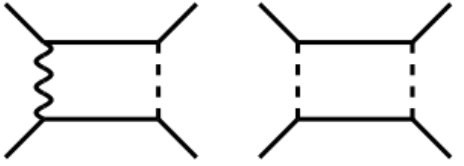
Analogous picture in SMEFT

- Consider a <u>case analogous to previous **SM-ct**</u>:
  - no/suppressed dim.-6 changing flavour by 2-units, e.g., no large tree-level effect
  - NP enhanced by large-Log & possible GIM-like mechanism in the NP sector does not eliminate large Logs => renormalization by dim.-8 is required
- <u>Under these assumptions</u>: renormalization of double-insertions capture most of the quantitative effects, i.e., the <u>Leading Order</u>







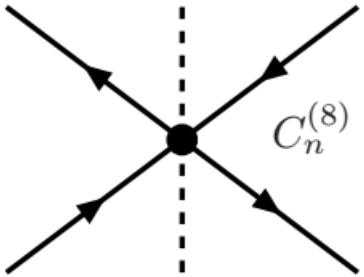


NP: $W', H', \mathrm{LQ}, \ldots$

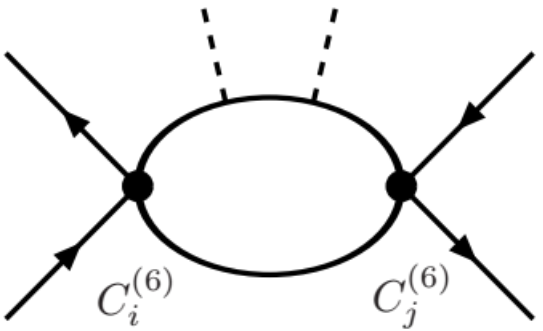
Renormalization group equations

- Anomalous Dimension Tensor $\gamma_{ij,n}$

[other cases, e.g.: Davidson, Gorbahn, Leak ‘18; Chala, Titov ‘21; Chala, Guedes, Ramos, Santiago ‘21]



$$\mu\frac{d}{d\mu}C_n^{(8)}(\mu) = \Sigma_{i,j}C_i^{(6)}(\mu)C_j^{(6)}(\mu)\gamma_{ij,n} + \Sigma_m C_m^{(8)}(\mu)\gamma_{mn}$$



- Previous assumptions: $C^{(8)}(\Lambda_{NP})$ is sub-leading
- Focus on double-insertions of four-fermions
- Double-insertions of the same operator, with the same flavour content
- Similar discussion applies to rare decays

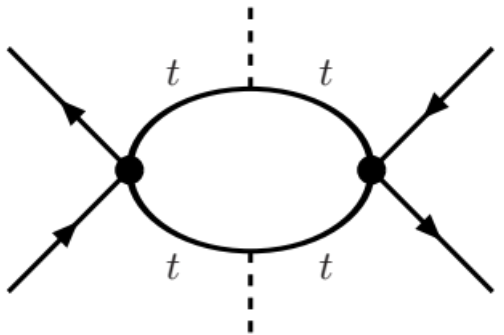
Example: top-quarks in loops

- Consider the following dim.-6 operators with |ΔF|=1:

dim.-6: $Q^{(\text{singlet})}_{quqd} = (\bar{q}^m u)\epsilon_{mn}(\bar{q}^n d)\,, \quad Q^{(\text{octet})}_{quqd} = (\bar{q}^m T^A u)\epsilon_{mn}(\bar{q}^n T^A d)$

dim.-8: $Q^{(\text{singlet})}_{q^2d^2H^2} = (\bar{q}dH)(\bar{q}dH)\,, \quad Q^{(\text{octet})}_{q^2d^2H^2} = (\bar{q}T^A dH)(\bar{q}T^A dH)$

$\left(\text{low-energies:} \quad \tilde{O}^{\psi\xi}_2 = (\bar{\psi}^\alpha R\xi^\alpha)\,(\bar{\psi}^\beta R\xi^\beta)\,, \quad \tilde{O}^{\psi\xi}_3 = (\bar{\psi}^\alpha R\xi^\beta)\,(\bar{\psi}^\beta R\xi^\alpha)\right)$



- Contributions are prop. to **large Yukawa coupling**
  - Kaon system: **chiral enhancement** $M^2/(m_s+m_d)^2$
  - color-group factor enhancements O(few)

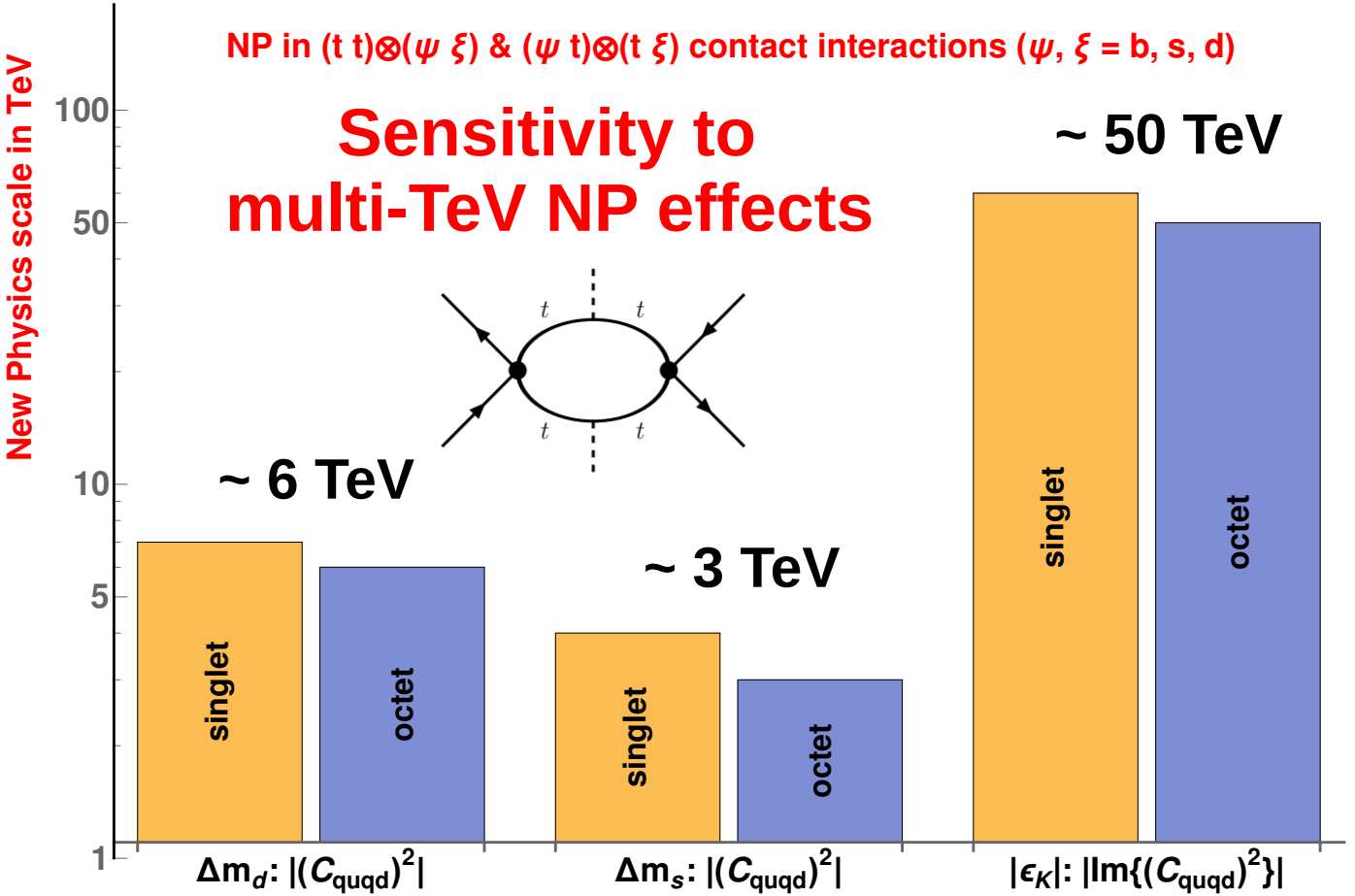
Example: top-quarks in loops

Bounds on NP Wilson coefficients at low-energy scale:

[Ligeti, Papucci, CKMfitter ‘14; Ligeti, Papucci, CKMfitter ‘20]

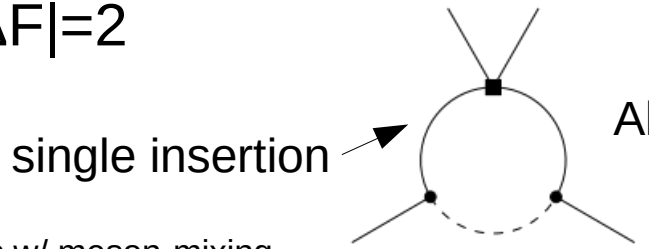
Bag parameters (non-pert. inputs):

[ETM ‘15; FNAL-MILC ‘16]



Example: top-quarks in loops

- Short-distance QCD effects of $|\Delta F|=2$ four-fermions below EW scale taken into account [Buras, Jager, Urban '01]
- Sub-leading effects may be numerically important if $\mathrm{Log}(\mu_{EW}/\Lambda_{NP})$ is not largely dominant: beyond leading-Log
- Competing effects in full pheno analysis: e.g., other dim.-6 operators radiatively generated @ 1-loop $\{\psi^2 H, \psi^2 H^3, \psi^4\}$
  - not four-fermion, not prop. to top-quark mass squared, or no contribution to $|\Delta F|=2$



[Jenkins, Manohar, Trott '13 '14; Alonso, Jenkins, Manohar, Trott '14]

Other operators and flavours

- Other contributions may involve: τ-, c- and b-loops, etc., thus also requiring the consideration of double insertions below the EW scale

$$b, c - \text{loop}: \; Q_{quqd}^{(\text{singlet})}, Q_{quqd}^{(\text{octet})}, \text{etc.}$$

$$\tau - \text{loop}: \; Q_{\ell edq}, Q_{ed}, Q_{\ell d}, Q_{qe}, Q_{\ell q}^{(1,3)}, \text{etc.}$$

- Dim.-8 operators ≠ $\psi^4 H^2$, {$\psi^4 HD$, $\psi^4 D^2$, $\psi^4 X$}: lead to contributions suppressed by ~ external quark masses

Conclusions

- SMEFT encodes the effects of heavy NP: universal description when considering energy scales much below NP scale
- Power of indirect constraints in probing flavour structure of NP: e.g., meson-mixing probes **very high energy scales**
- Discussed operators of dim.-6 that change flavour by 1-unity: naturally lead to processes in which flavour changes by 2-units
- Given precision in meson-mixing: loop-suppressed double-insertion contributions still lead to **powerful bounds on NP**

Pre-print to appear soon!

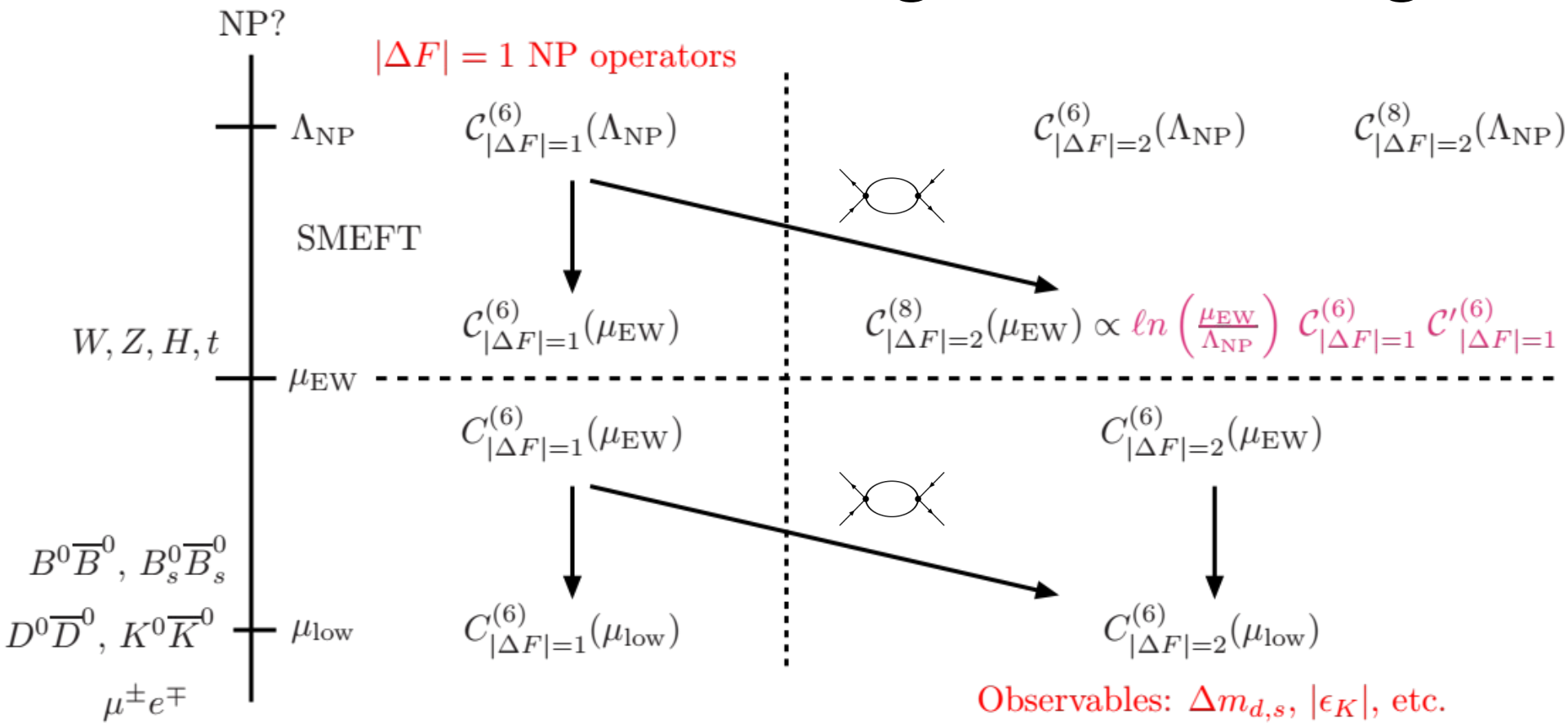
Thanks!

S. Weinberg (1933-2021)

"It often happens that condition of renormalizability is so stringent that the effective Lagrangian automatically obeys one or more symmetries, which are not symmetries of the underlying theory, and may therefore be violated by the suppressed non-renormalizable terms in the effective Lagrangian."

Pattern of running and mixing

App. 1



Some numerical results

	flavours	$B\ (f=b,\, i=d)$	$B_s\ (f=b,\, i=s)$	$K\ (f=s,\, i=d)$
singlet	$33fi\,,(33if)^\dagger$	$\lvert(\tilde{C}^{(1)}_{quqd})^2\rvert < \frac{1}{(7.5\,\mathrm{TeV})^4}$	$\lvert(\tilde{C}^{(1)}_{quqd})^2\rvert < \frac{1}{(4.1\,\mathrm{TeV})^4}$	$\lvert\mathrm{Im}\{(\tilde{C}^{(1)}_{quqd})^2\}\rvert < \frac{1}{(58\,\mathrm{TeV})^4}$
	$f33i\,,(i33f)^\dagger$	$\lvert(\tilde{C}^{(1)}_{quqd})^2\rvert < \frac{1}{(4.8\,\mathrm{TeV})^4}$	$\lvert(\tilde{C}^{(1)}_{quqd})^2\rvert < \frac{1}{(2.6\,\mathrm{TeV})^4}$	$\lvert\mathrm{Im}\{(\tilde{C}^{(1)}_{quqd})^2\}\rvert < \frac{1}{(37\,\mathrm{TeV})^4}$
octet	$33fi\,,(33if)^\dagger$	$\lvert(\tilde{C}^{(8)}_{quqd})^2\rvert < \frac{1}{(6.1\,\mathrm{TeV})^4}$	$\lvert(\tilde{C}^{(8)}_{quqd})^2\rvert < \frac{1}{(3.4\,\mathrm{TeV})^4}$	$\lvert\mathrm{Im}\{(\tilde{C}^{(8)}_{quqd})^2\}\rvert < \frac{1}{(47\,\mathrm{TeV})^4}$
	$f33i\,,(i33f)^\dagger$	$\lvert(\tilde{C}^{(8)}_{quqd})^2\rvert < \frac{1}{(6.1\,\mathrm{TeV})^4}$	$\lvert(\tilde{C}^{(8)}_{quqd})^2\rvert < \frac{1}{(3.4\,\mathrm{TeV})^4}$	$\lvert\mathrm{Im}\{(\tilde{C}^{(8)}_{quqd})^2\}\rvert < \frac{1}{(47\,\mathrm{TeV})^4}$

Table 1: 95% Confidence Level bounds.