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

arXiv: 2201.03038 [hep-ph]

FLASY (Lisbon)
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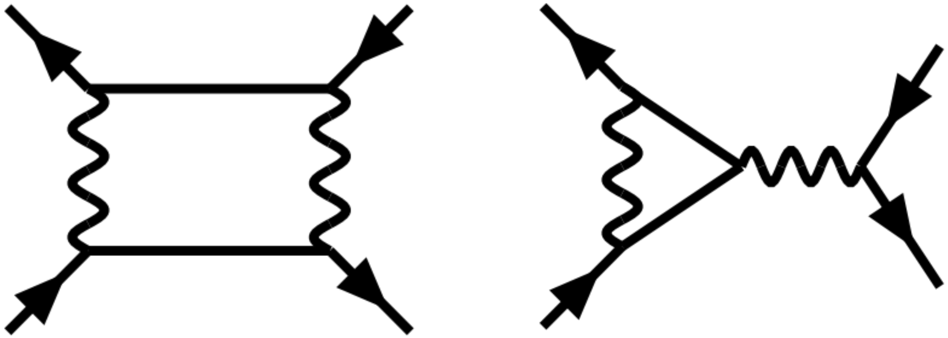
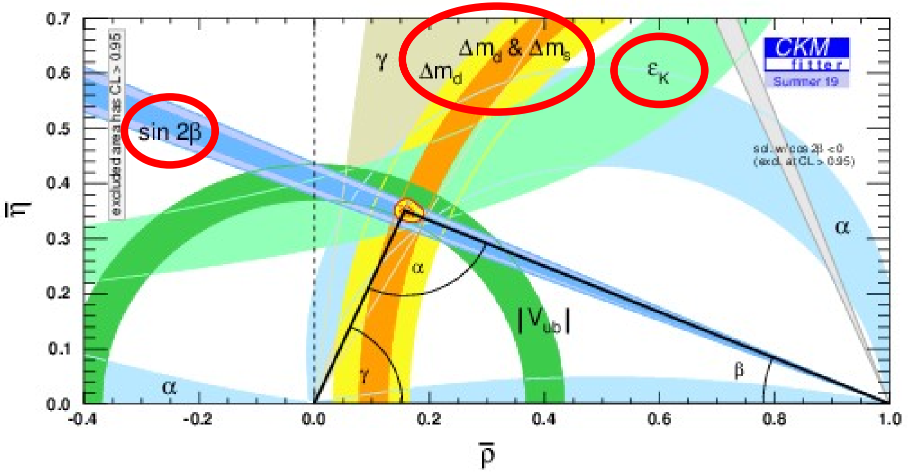
Looking for non-standard physics

- Focus here is on low-energy observables
- Observables that are predicted to be suppressed
  - e.g., Flavour Changing Neutral Currents (FCNCs) in the SM
- Another approach is precision physics

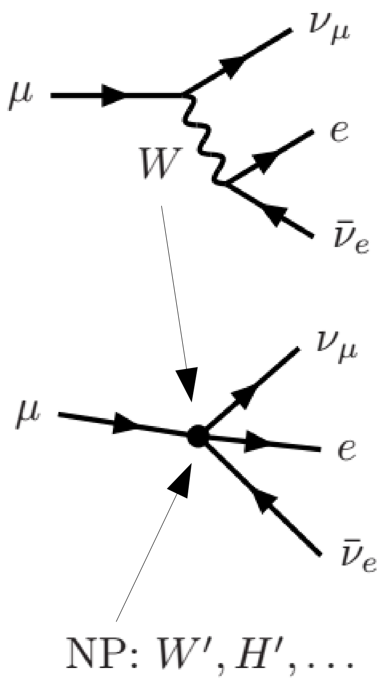
e.g., meson-mixing, rare decays





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

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

Operators of dim.-6 and dim.-8

- Involve SM fields ($q_L, u_R, d_R, l_L, e_R, X^{\mu\nu}, H$) and covariant 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]

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

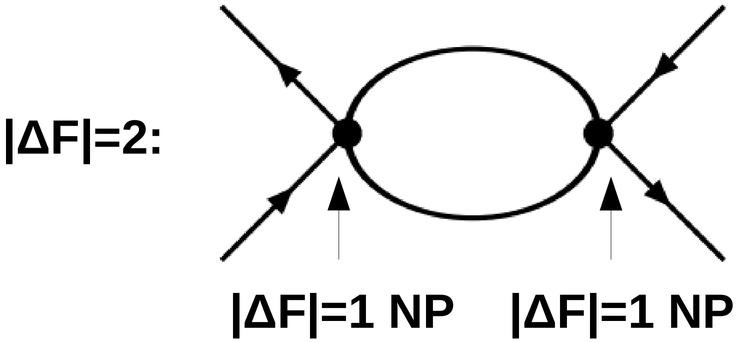
  - operators of dim.-8 (B preserving: #36,971): [Murphy '20; Li, Ren, Shu, Xiao, Yu, Zheng '20]

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

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

Double insertions of dim.-6 ops.

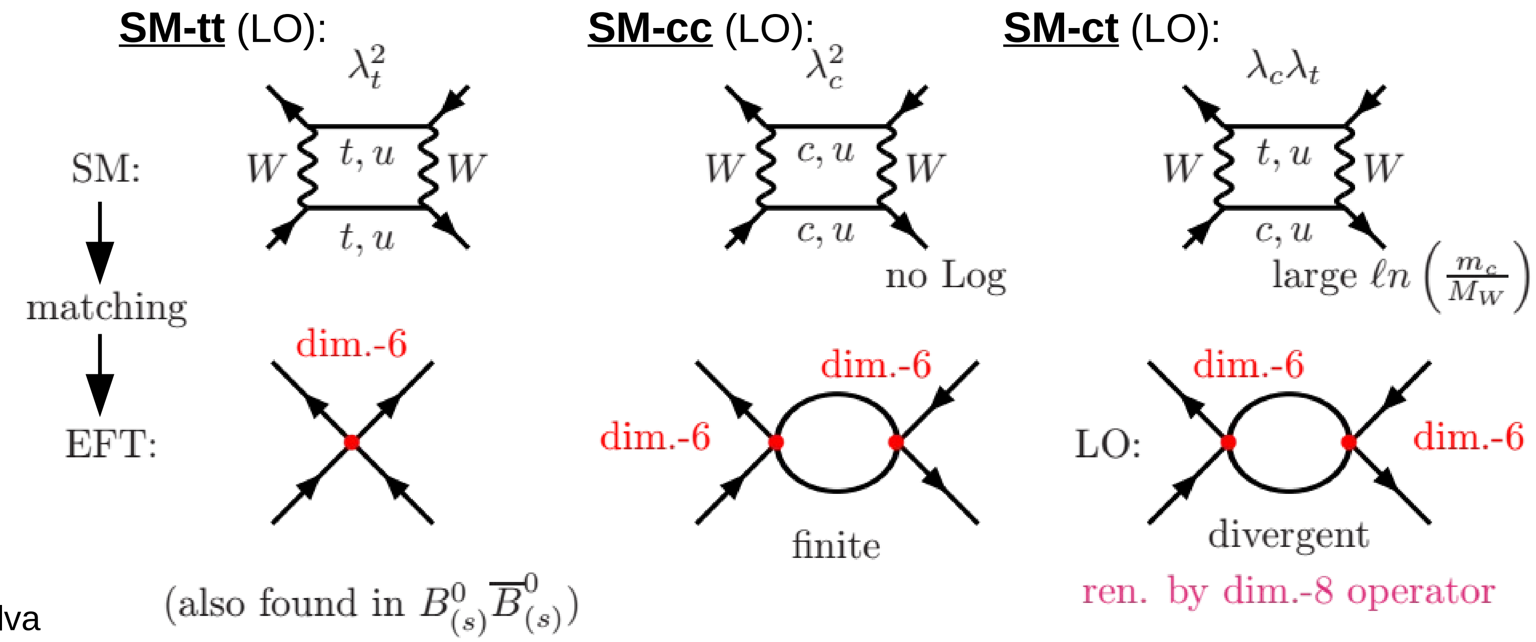
- Operators that change flavour by 1-unity naturally lead to contributions where flavour changes by 2-units



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

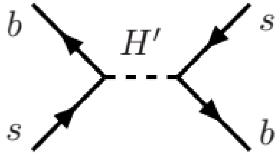
Weak interactions at low-energies

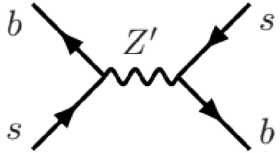
- Exchanges of heavy d.o.f. are encoded in effective field theory
- Example: neutral-Kaon meson-mixing in the SM [Glashow, Iliopoulos, Maiani ‘70]
  - **GIM mechanism** controls the sizes of contributions, and thus operators in the EFT



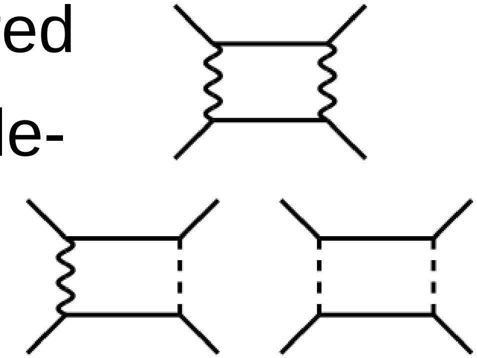
[Gilman, Wise ‘83]
[Herrlich, Nierste ‘94 ‘96]
[Brod, Gorbahn ‘10 ‘11]
[Brod, Gorbahn, Stamou ‘20]
[Brod, Kvedaraite, Polonsky ‘21]

Analogous picture in SMEFT





- Consider a case analogous to **SM-ct**:
  - No or suppressed dim.-6 operators 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
- Under these assumptions: renormalization of double-insertions captures most of the quantitative effects, i.e., the Leading Order

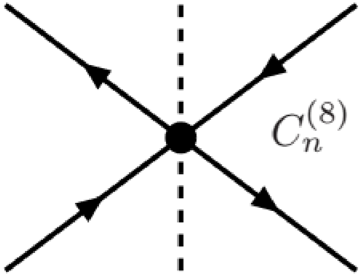


NP: $W', H', \mathrm{LQ}, \ldots$

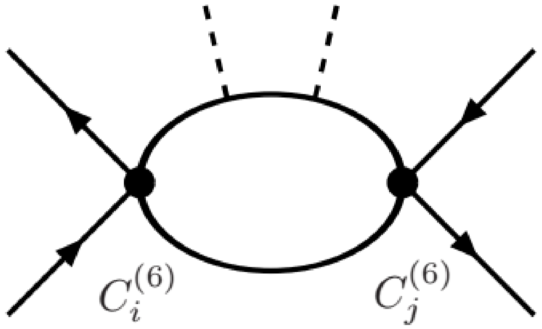
Renormalization group evolution

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

[other cases, e.g.: Davidson, Gorbahn, Leak ‘18; Chala, Titov ‘21; Chala, Guedes, Ramos, Santiago ‘21; Ardu, Davidson, Gorbahn ‘22]



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



- $C^{(8)}(\Lambda_{NP})$ is sub-leading: it does not contain large $\mathrm{Log}(\mu_{EW}/\Lambda_{NP})$
- Focus on double-insertions of four-fermion operators
- Double-insertions of the same operator, with the same flavour content: $\gamma_{ij,n}$ is found in [LVS, 2201.03038]
- Similar discussion applies to rare decays

Example: top-quarks in loops

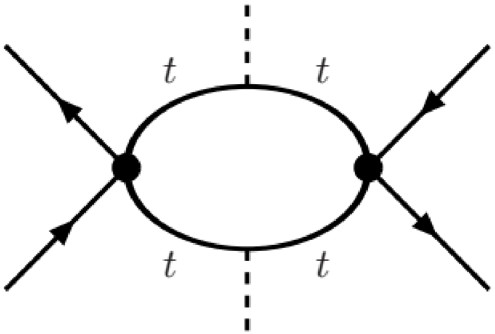
- Consider the following dim.-6 operators with |ΔF|=1:

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

d → d, s, b; u → t

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

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



- No tops below EW scale: |ΔF|=2 four-fermions operators
- Contributions are prop. to **large Yukawa coupling**

Kaon system: **chiral enhancement** $M^2/(m_s+m_d)^2$

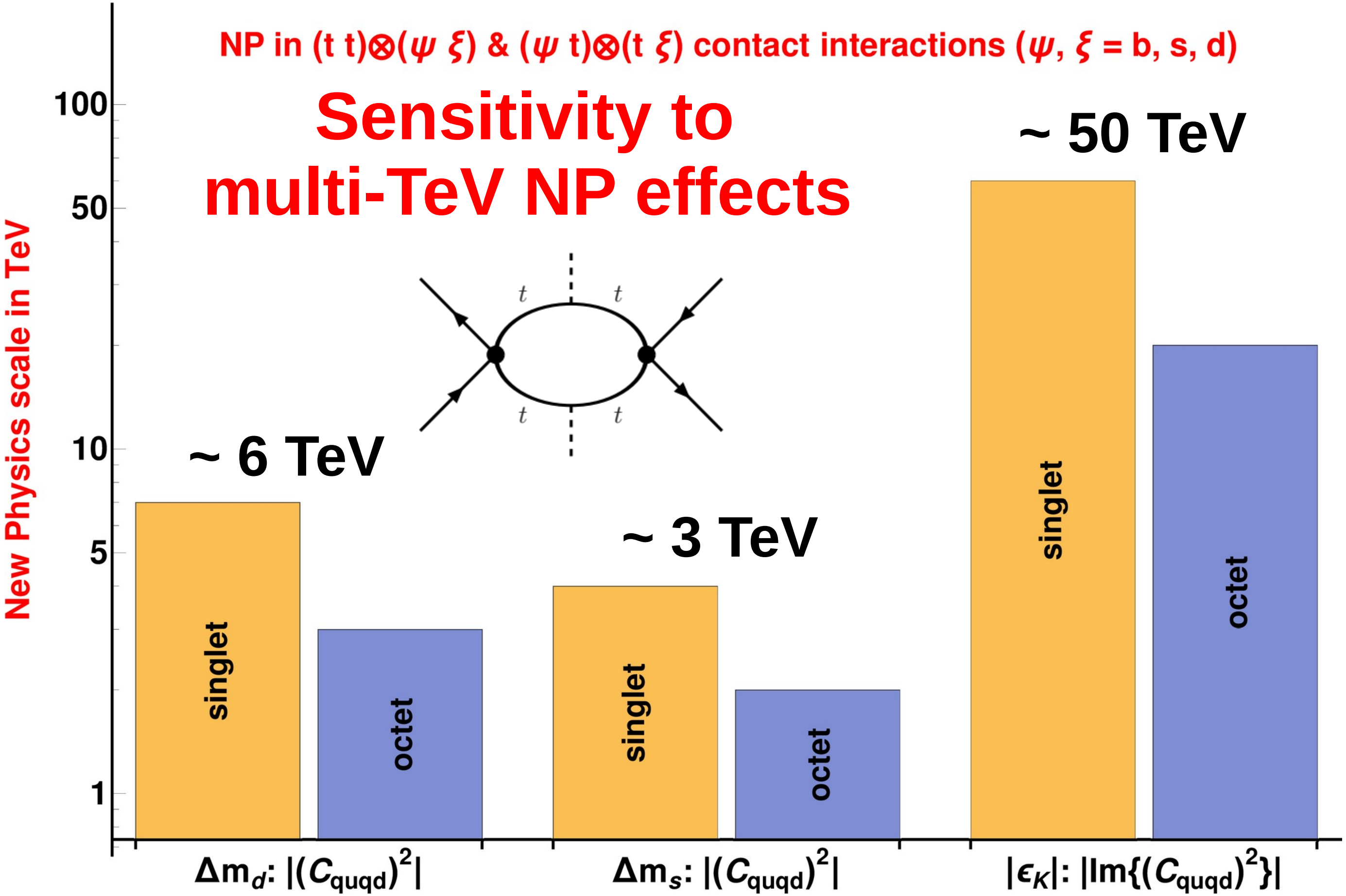
Example: top-quarks in loops

Bounds on generic NP contributions:

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

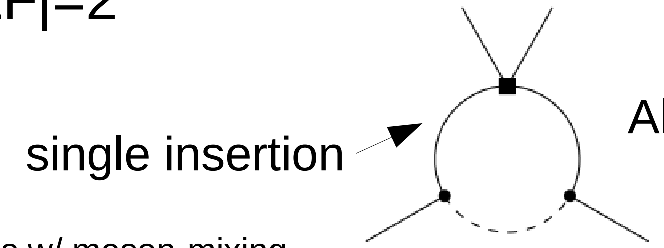
Bag parameters (non-pert. QCD inputs):

[ETM ‘15; HPQCD ‘19]



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
- Competing effects in full pheno analysis: e.g., other dim.-6 operators radiatively generated by ψ^4 @ 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 similar cases involving a top loop: $Q_{qu}^{(1)}$, $Q_{qq}^{(1,3)}$
- Other contributions may involve: τ-, c- and b-loops, etc., thus also requiring in general the consideration of <u>double insertions below the EW scale</u>

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

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

- Other dim.-8 operators ≠ $\psi^4 H^2$, {$\psi^4 HD$, $\psi^4 D^2$, $\psi^4 X$}: contributions suppressed by external quark mass scale

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**

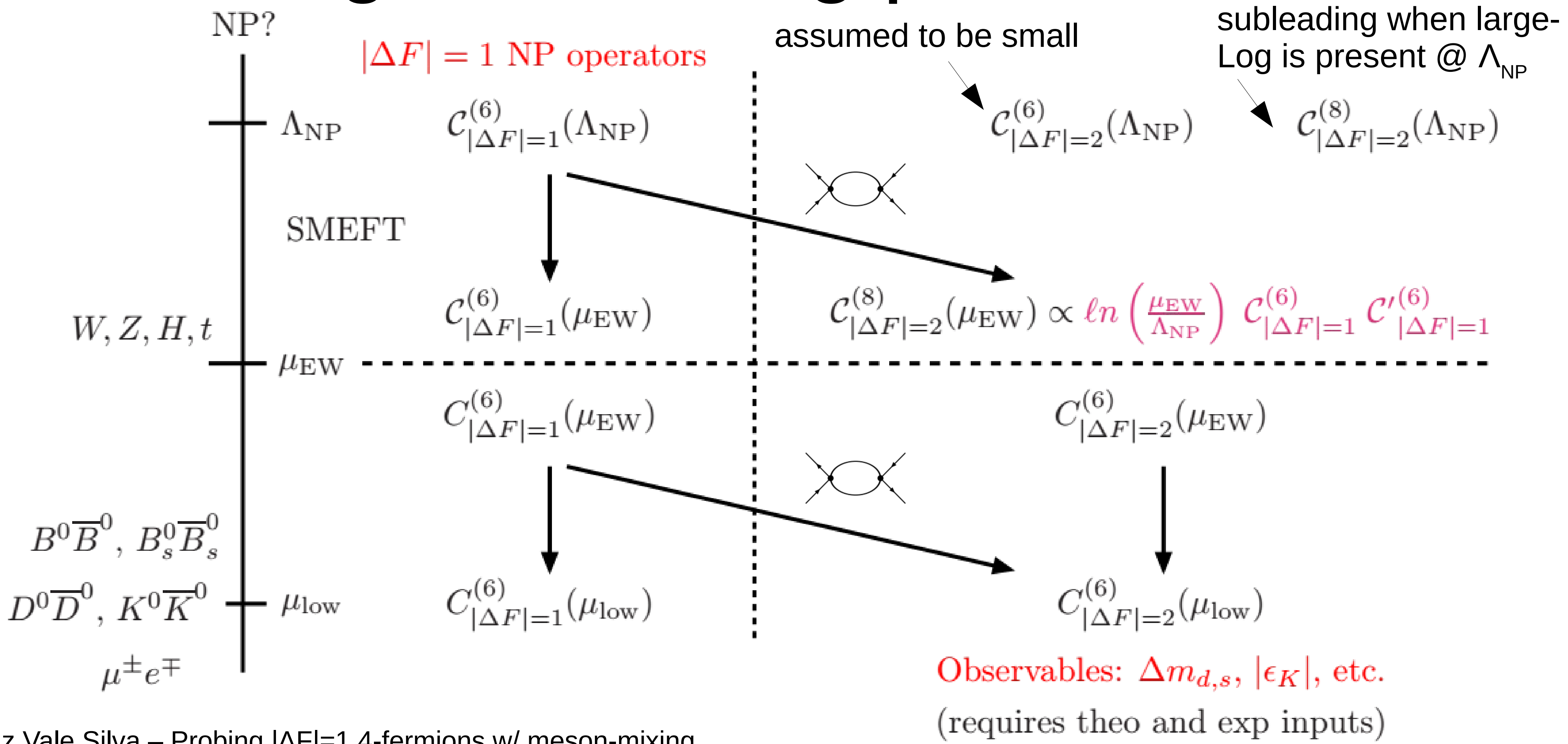
Thanks!, Obrigado!

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."

Running and mixing pattern @ LO

App. 1



Some numerical results

App. 2

WC	flavours	$B\ (f=3,\ i=1)$	$B_s\ (f=3,\ i=2)$	$K\ (f=2,\ i=1)$
$C^{(1)}_{quqd}$	$33fi\,,(33if)^*$	$\lvert C^2\rvert < (7\,\text{TeV})^{-4}$	$\lvert C^2\rvert < (4\,\text{TeV})^{-4}$	$\lvert\text{Im}\{C^2\}\rvert < (70\,\text{TeV})^{-4}$
	$f33i\,,(i33f)^*$	$\lvert C^2\rvert < (5\,\text{TeV})^{-4}$	$\lvert C^2\rvert < (3\,\text{TeV})^{-4}$	$\lvert\text{Im}\{C^2\}\rvert < (50\,\text{TeV})^{-4}$
$C^{(8)}_{quqd}$	$33fi\,,(33if)^*$	$\lvert C^2\rvert < (3\,\text{TeV})^{-4}$	$\lvert C^2\rvert < (2\,\text{TeV})^{-4}$	$\lvert\text{Im}\{C^2\}\rvert < (30\,\text{TeV})^{-4}$
	$f33i\,,(i33f)^*$	$\lvert C^2\rvert < (3\,\text{TeV})^{-4}$	$\lvert C^2\rvert < (2\,\text{TeV})^{-4}$	$\lvert\text{Im}\{C^2\}\rvert < (30\,\text{TeV})^{-4}$

TABLE III. Estimated bounds on the Wilson coefficients of the operators in Eq. (2). The first column indicates the Wilson Coefficient (WC) C being probed at the scale Λ_{NP}, together with its flavour indices (bounds correspond to the combination of the two cases provided, with no interference present). The three remaining columns give estimated bounds accordingly to the meson system.

Some numerical results

better probed by **single-insertions**, chirally enhanced contribution to meson mixing

better probed by **single-insertions**, chirally enhanced contribution to direct CPV

WC	flavours	K $(f=2,\ i=1)$
$C_{ud}^{(1)}$	$33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$
$C_{ud}^{(8)}$	$33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (10\,\mathrm{TeV})^{-4}$
$C_{qd}^{(1)}$	$33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$
$C_{qd}^{(8)}$	$33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (10\,\mathrm{TeV})^{-4}$
$C_{qu}^{(1)}$	$fi33$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$
$C_{qu}^{(8)}$	$fi33$	$\lvert\mathrm{Im}\{C^2\}\rvert < (10\,\mathrm{TeV})^{-4}$
$C_{qq}^{(1)}$	$fi33=33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$
$C_{qq}^{(3)}$	$fi33=33fi$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$
	$f33i=3if3$	$\lvert\mathrm{Im}\{C^2\}\rvert < (30\,\mathrm{TeV})^{-4}$

TABLE IV. See caption of Tab. III for comments. Additionally, the contribution of $Q^{(1)}_{qq;f33i}$ to double-insertions proportional to the Yukawa of the top-quark squared vanishes at this order.

$$Q_{ud}^{(1)} = (\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$$
$$Q_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$$

$$Q_{qx}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{x}\gamma^\mu x) \qquad x = u, d$$
$$Q_{qx}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{x}\gamma^\mu T^A x)$$

$$Q_{qq}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$
$$Q_{qq}^{(3)} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$$

Dominant or competitive <u>clean</u> bounds from double-insertions ($Q_{qq}^{(1,3)}$ contribute at tree level to charm-meson mixing)

$B_{(s)}$ cases: not shown due to the need to include contamination by NP in $\beta_{(s)}$ in global fit extractions of NP contributions

Counting of large-Logs

- Different NP scenarii may not have a large-Log in ct @ LO, or have it in a different case (i.e., cc) [e.g., LRM: Bernard, Descotes-Genon, LVS '15]

Order	$\widetilde{G}^c$	$\widetilde{G}^t$	$\widetilde{G}^{ct}$
LO	$(\alpha_s \ln x_c)^n$	$(\alpha_s \ln x_c)^n$	$(\alpha_s \ln x_c)^n \ln x_c$
NLO	$\alpha_s(\alpha_s \ln x_c)^n$	$\alpha_s(\alpha_s \ln x_c)^n$	$(\alpha_s \ln x_c)^n$
NNLO	$\alpha_s^2(\alpha_s \ln x_c)^n$	$\alpha_s^2(\alpha_s \ln x_c)^n$	$\alpha_s(\alpha_s \ln x_c)^n$
m_t dependence	none	in LO	in NLO

Tab. 1 from [Herrlich, Nierste '96]

Acknowledgements

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