

Probing New Physics through β -decay

At a loop level in the Standard Model Effective Field Theory

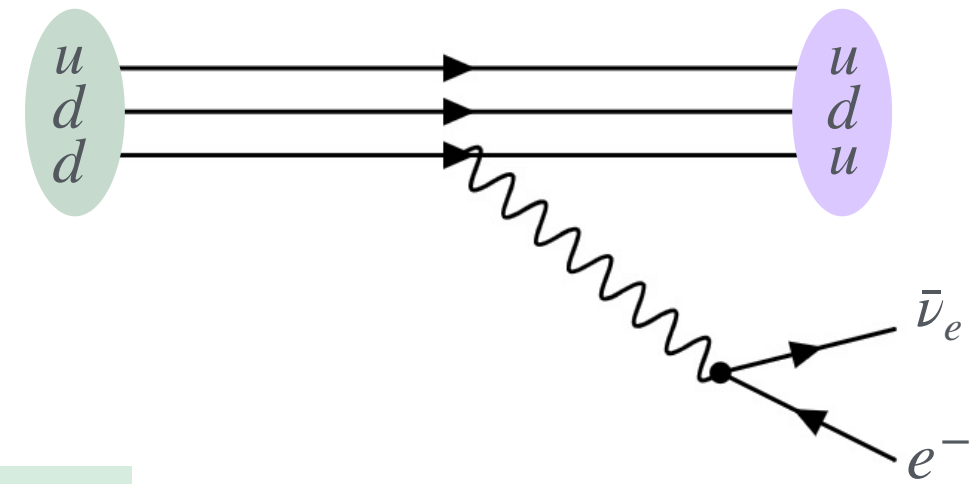


Maria Dawid



M.D., V. Cirigliano, W. Dekens
ArXiv: (2402.06723)

The CKM unitarity test

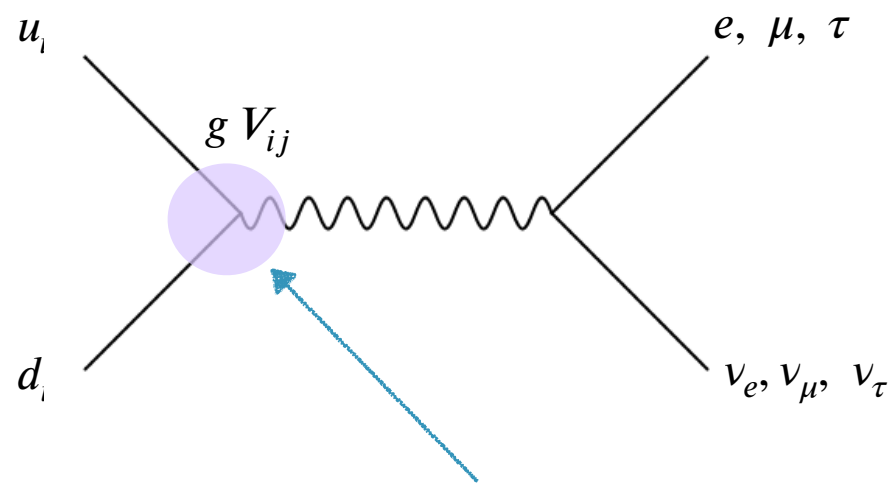


The Cabibbo-Kobayashi-Maskawa matrix

$$V_{\text{CKM}} V_{\text{CKM}}^\dagger = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = 1 ,$$

Unitarity

$$\Delta_{\text{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1 \approx 0$$



Global fit

$$\Delta_{\text{CKM}} = -1.48(53) \times 10^{-3}$$

$$V_{ud} = 0.973670(25)$$

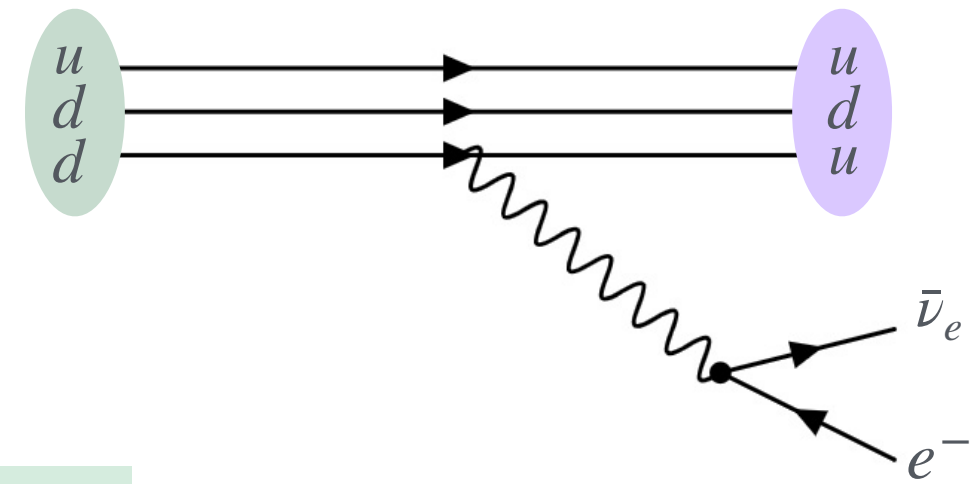
$$V_{us} = 0.2245(8)$$

$$\mathcal{L}_{EW} \subset \frac{g}{\sqrt{2}} W_\mu^+ \bar{d}_{iL} V_{ij} \gamma^\mu u_{jL}$$

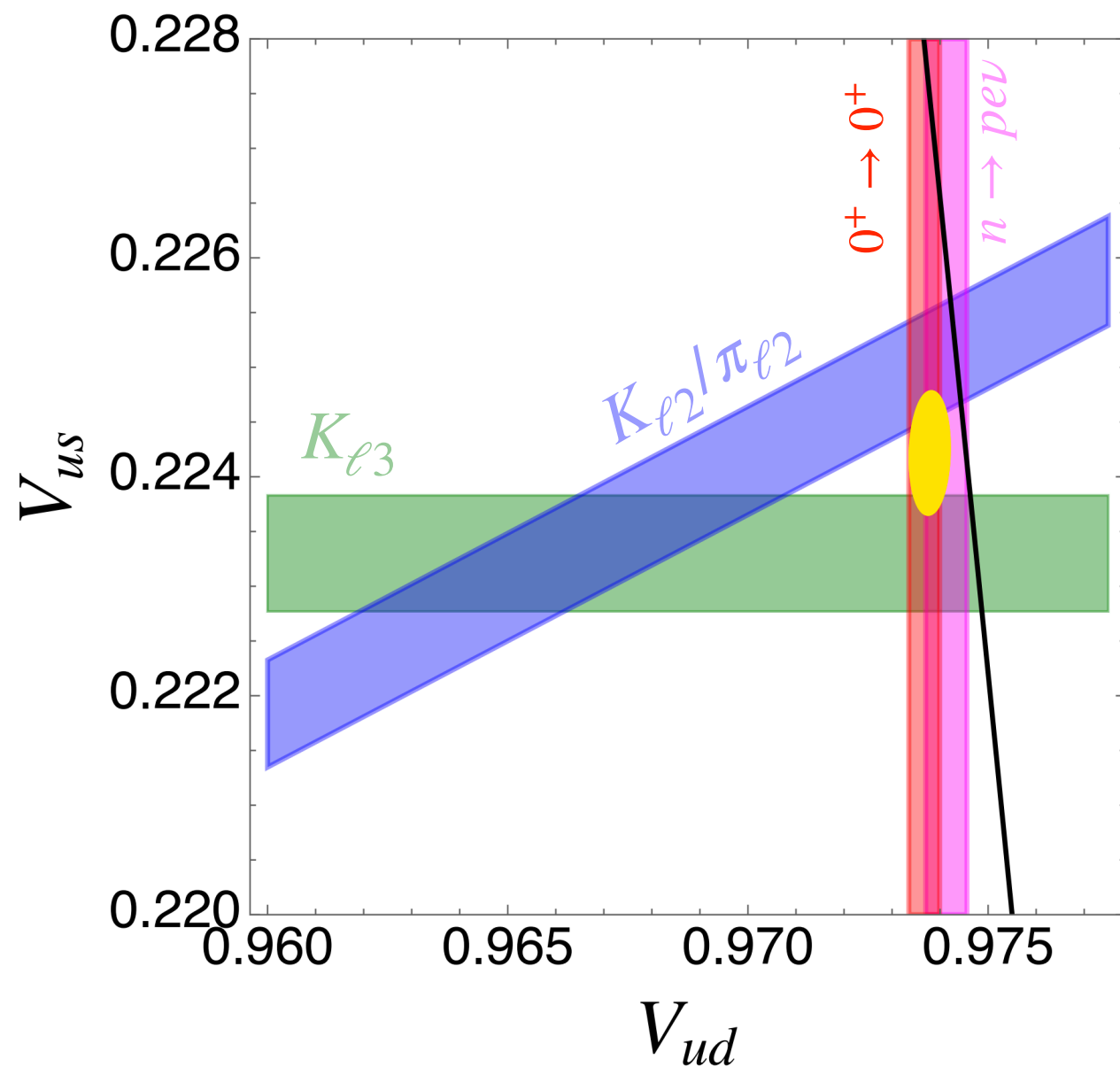
Discrepancy with SM

- Underestimated SM uncertainties?
- BSM physics?

The CKM unitarity test



The Cabibbo-Kobayashi-Maskawa matrix



Scrutinizing CKM unitarity with a new measurement of the $K_{\mu 3}/K_{\mu 2}$ branching fraction
V. Cirigliano et al. (arXiv: 2208.11707)

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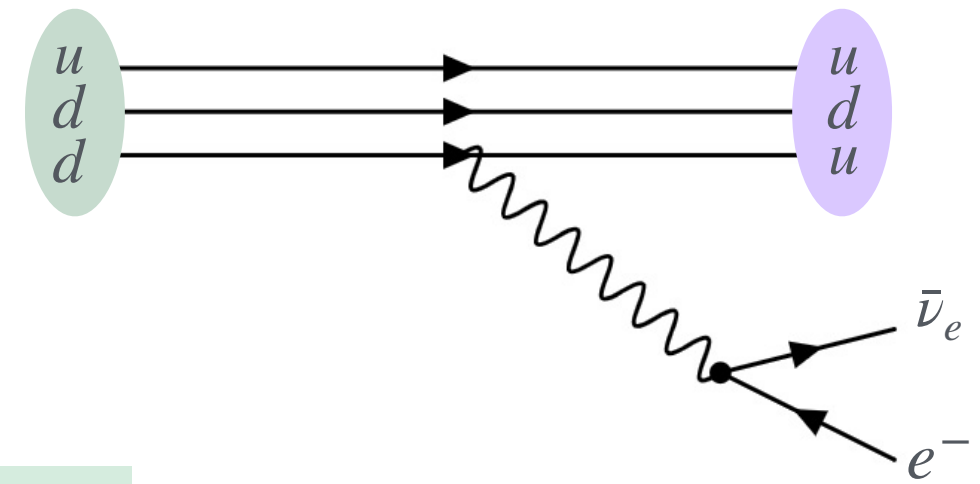
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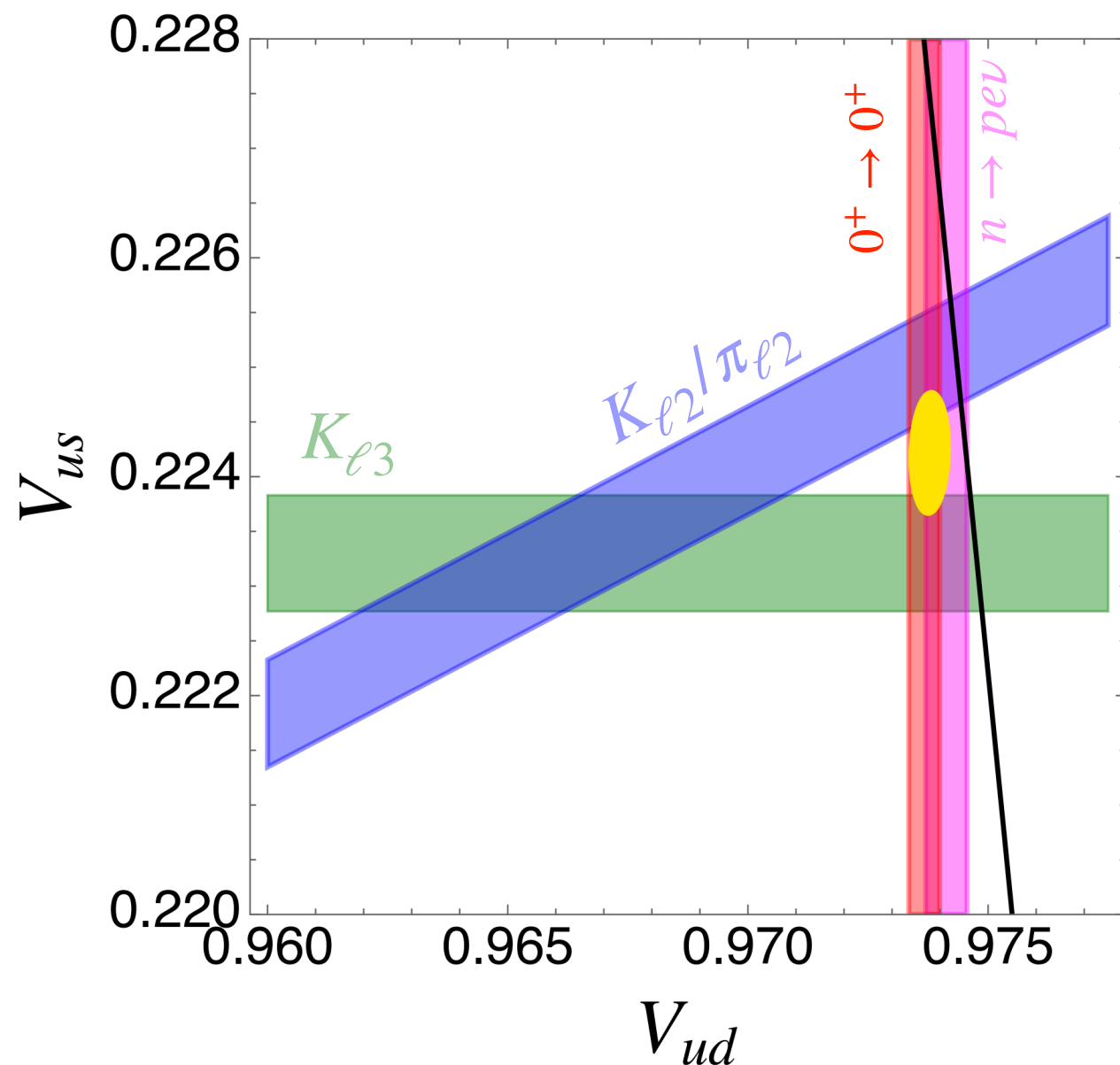
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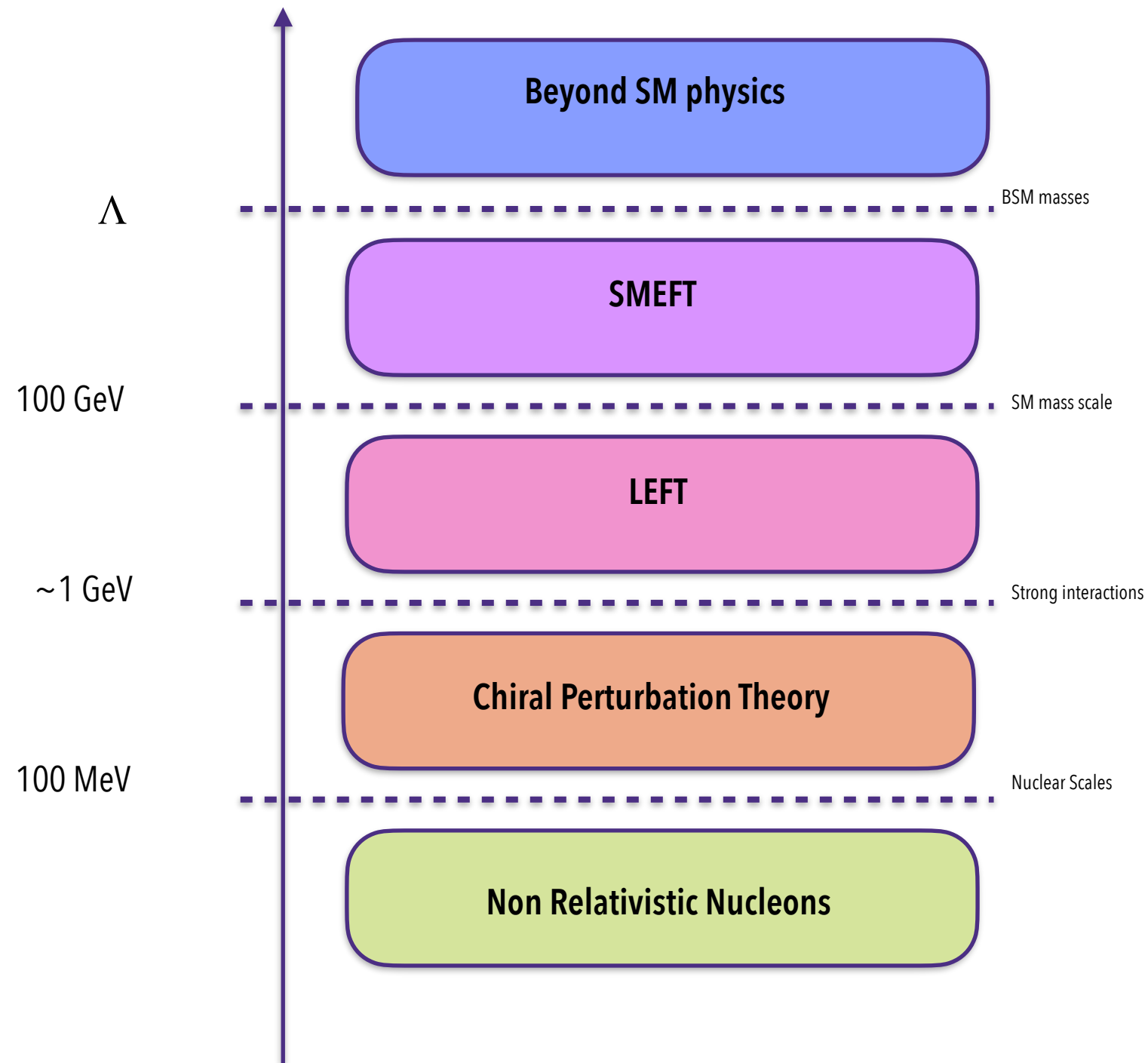
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Standard Model Effective Field Theory

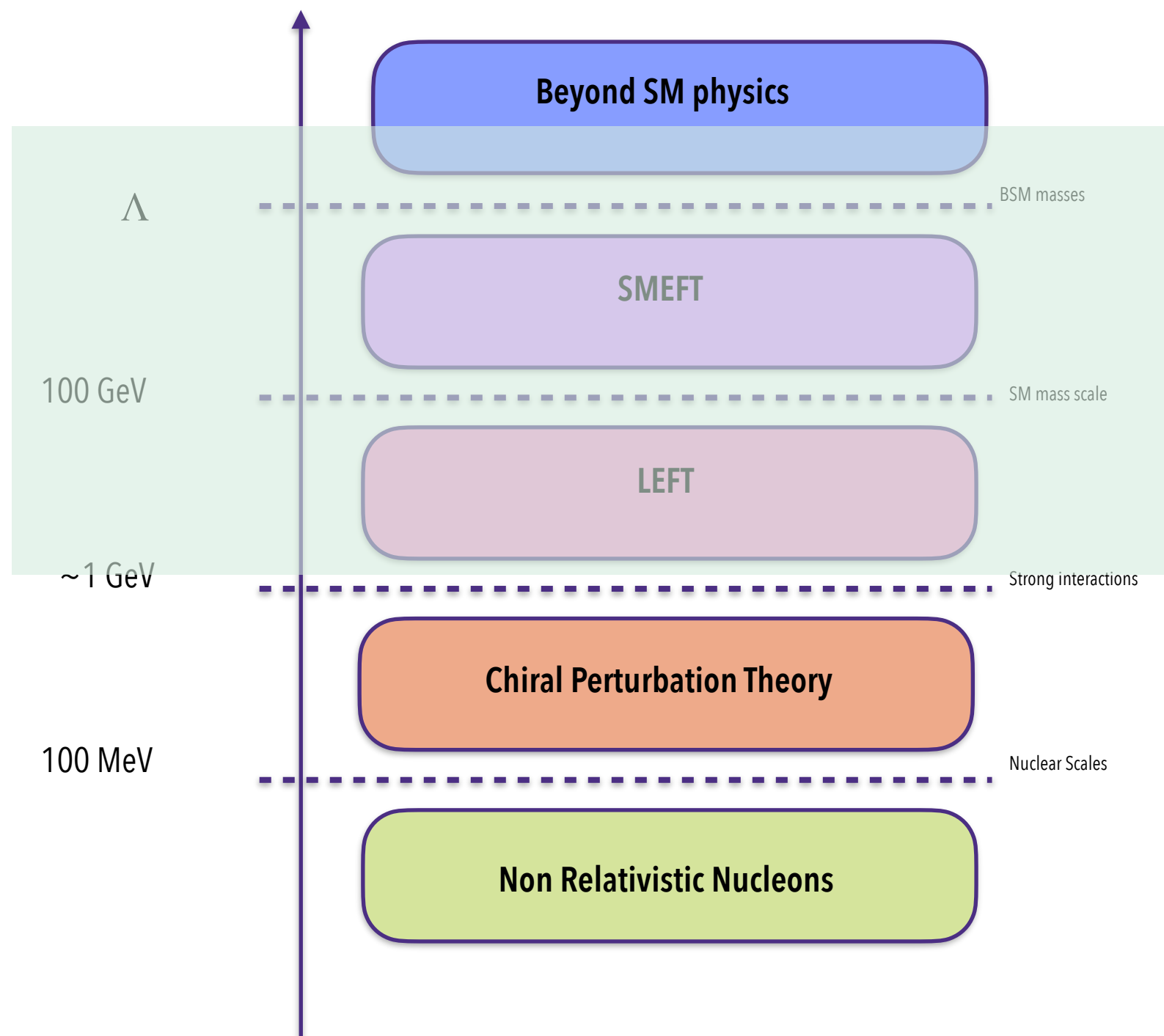
Effective Field Theories

To connect UV physics to beta decays, use EFT



Effective Field Theories

To connect UV physics to beta decays, use EFT



This talk

Standard Model EFT

The EFT constructed with Standard Model fields & symmetries

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{v} C^{(5)} Q^{(5)} + \frac{1}{v^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{v^3}\right) + \dots$$

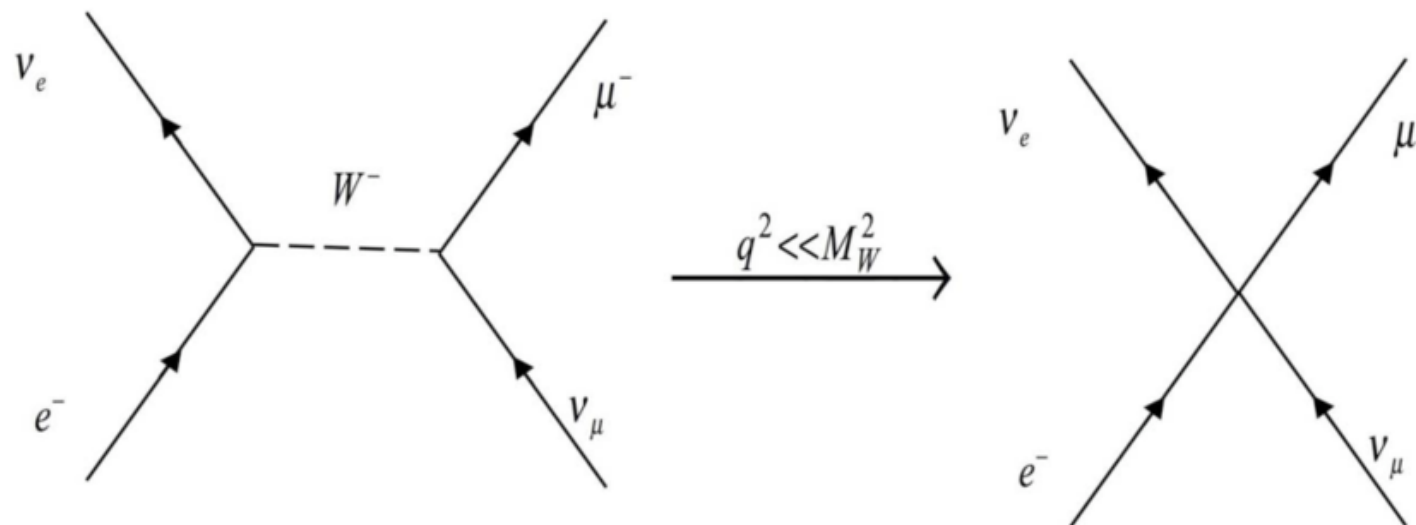
The Standard Model is a part of the leading order of SMEFT

With $C_k \sim v^2/\Lambda^2$

C - Wilson coefficients

Q - local interaction terms (operators)

Example: Fermi Theory



$$\frac{-g_{\mu\nu} + q_\mu q_\nu / M_W^2}{q^2 - M_W^2} \xrightarrow{q^2 \ll M_W^2} \frac{g_{\mu\nu}}{M_W^2}$$

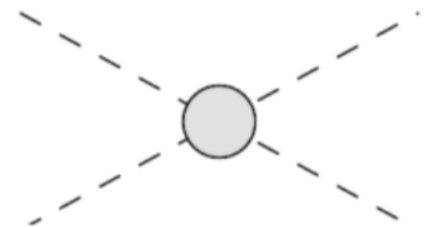
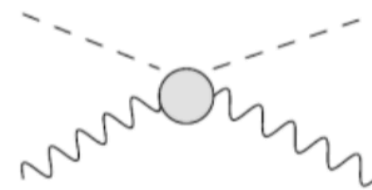
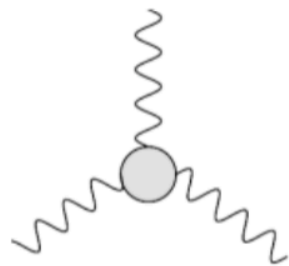
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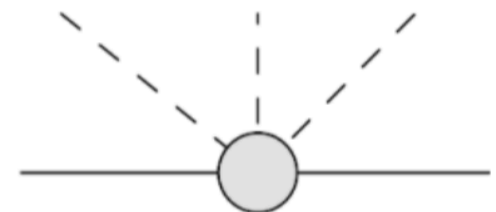
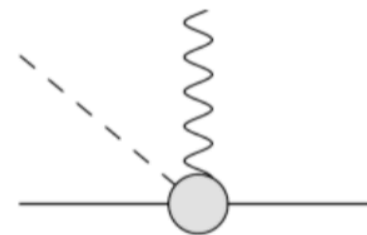
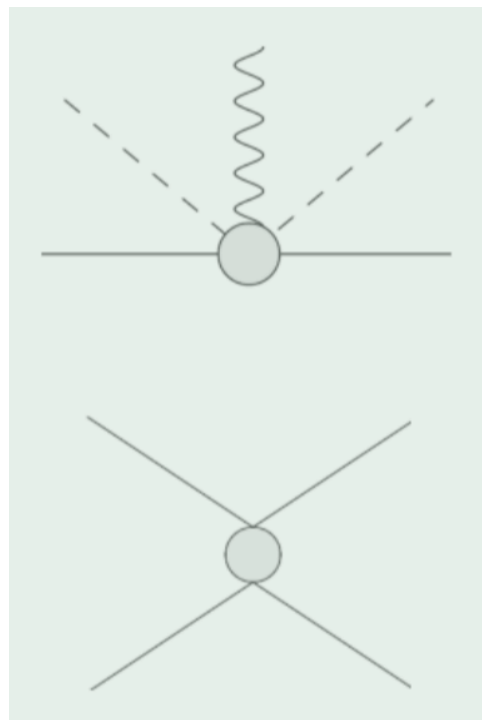
6-dim operators

No fermions

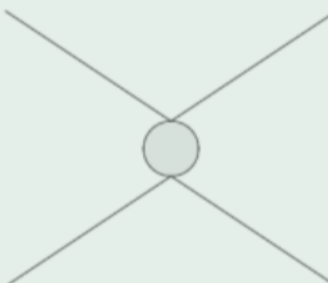


With $C_k \sim v^2/\Lambda^2$

Two fermions



Four fermions



Standard Model EFT

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The Standard Model is a part of the leading order of SMEFT

With $C_k \sim v^2/\Lambda^2$

C - Wilson coefficients

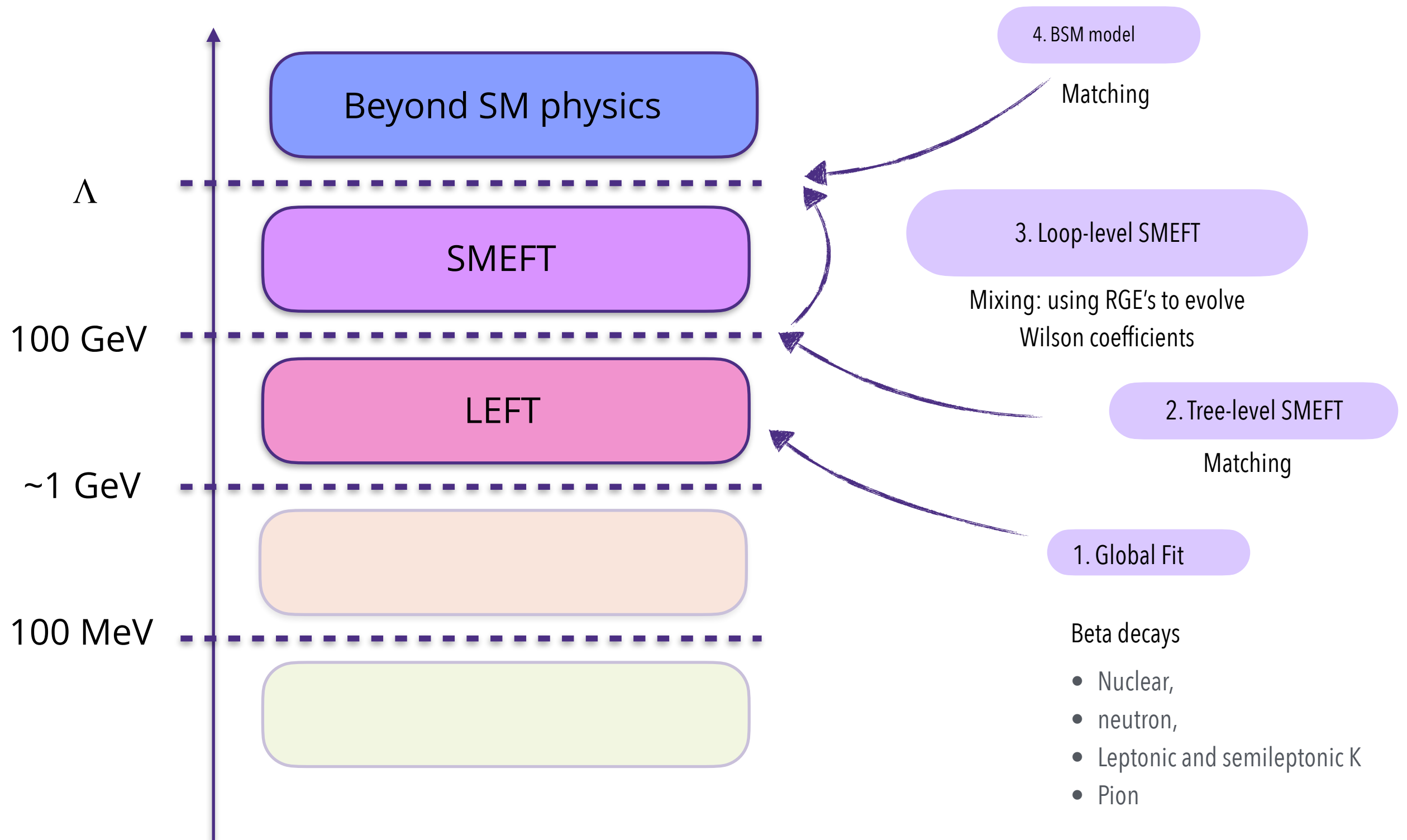
Q - local interaction terms (operators)

SMEFT contributions to beta decay are well-known at a tree level

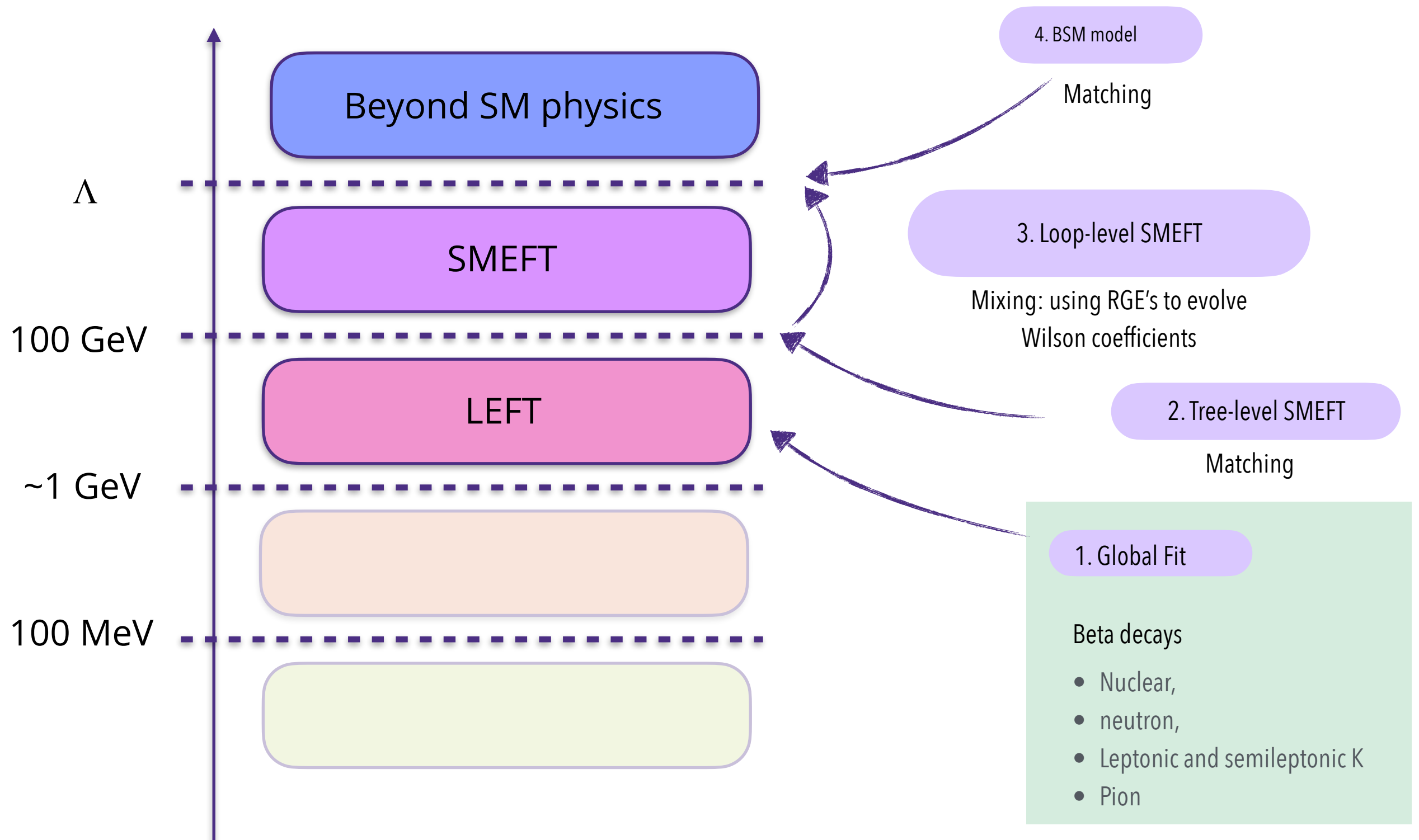
What about quantum fluctuations?

Goal of the work: identify leading contributions to beta decay at a one-loop level.

β -decay on loop level

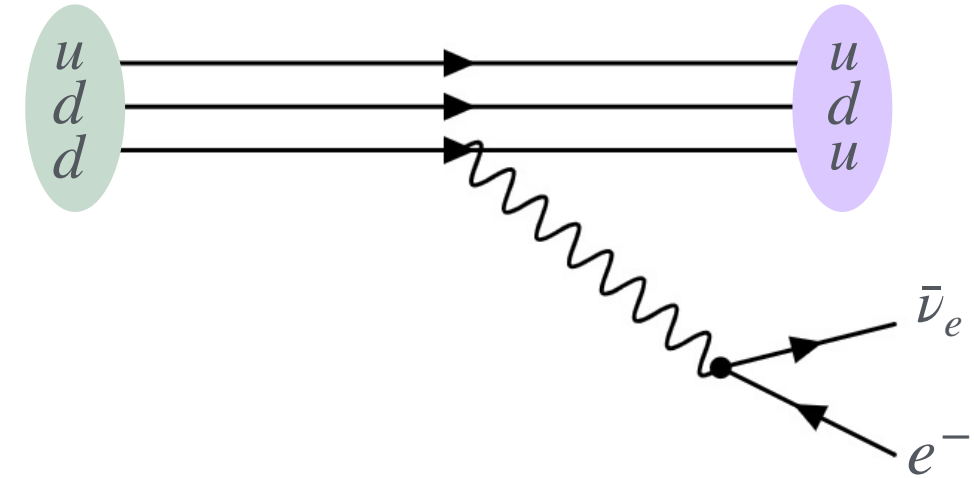


β -decay on loop level



GeV scale effective Lagrangian

$$d \rightarrow u l^- \bar{\nu}_l$$



From muon decay

$$\epsilon_L = \epsilon_L^\beta - \epsilon_L^\mu$$

$$\begin{aligned} \mathcal{L}_{LEFT} = & -\frac{G_F^0 V_{ud}}{\sqrt{2}} [(1 + \epsilon_L) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_l \bar{u} \gamma^\mu (1 - \gamma_5) d \\ & + \epsilon_R \bar{e} \gamma_\mu (1 - \gamma_5) \nu_l \bar{u} \gamma^\mu (1 + \gamma_5) d \\ & + \epsilon_S \bar{e} (1 - \gamma_5) \nu_l \bar{u} d \\ & - \epsilon_P \bar{e} (1 - \gamma_5) \nu_l \bar{u} \gamma_5 d \\ & + \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_l \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d] \end{aligned}$$

left quarks

right quarks

scalar

pseudo-scalar

tensor

ϵ_L^μ SMEFT correction to GF as extracted from muon decay

Global Fit

flavor-assumption-independent analysis

- Drell-Yan collider processes ('C')
- Low-energy charged current processes ('L')
 - Neutron and nuclear β decays
 - Kaon and pion decays ($\Gamma(K \rightarrow \mu\nu_\mu)$,
 $R_\pi = \Gamma(\pi \rightarrow e\nu_e)/\Gamma(\pi \rightarrow \mu\nu_\mu)$,
 $R_K = \Gamma(K \rightarrow e\nu_e)/\Gamma(K \rightarrow \mu\nu_\mu)$,
 $R_\mu = \Gamma(K \rightarrow \mu\nu_\mu)/\Gamma(\pi \rightarrow \mu\nu_\mu)$)
- electroweak precision observables ('EW')
 - observables measured at the Z pole (decay widths, asymmetries, hadronic cross section obtained from $e + e^- \rightarrow Z \rightarrow \bar{q}q$, W mass

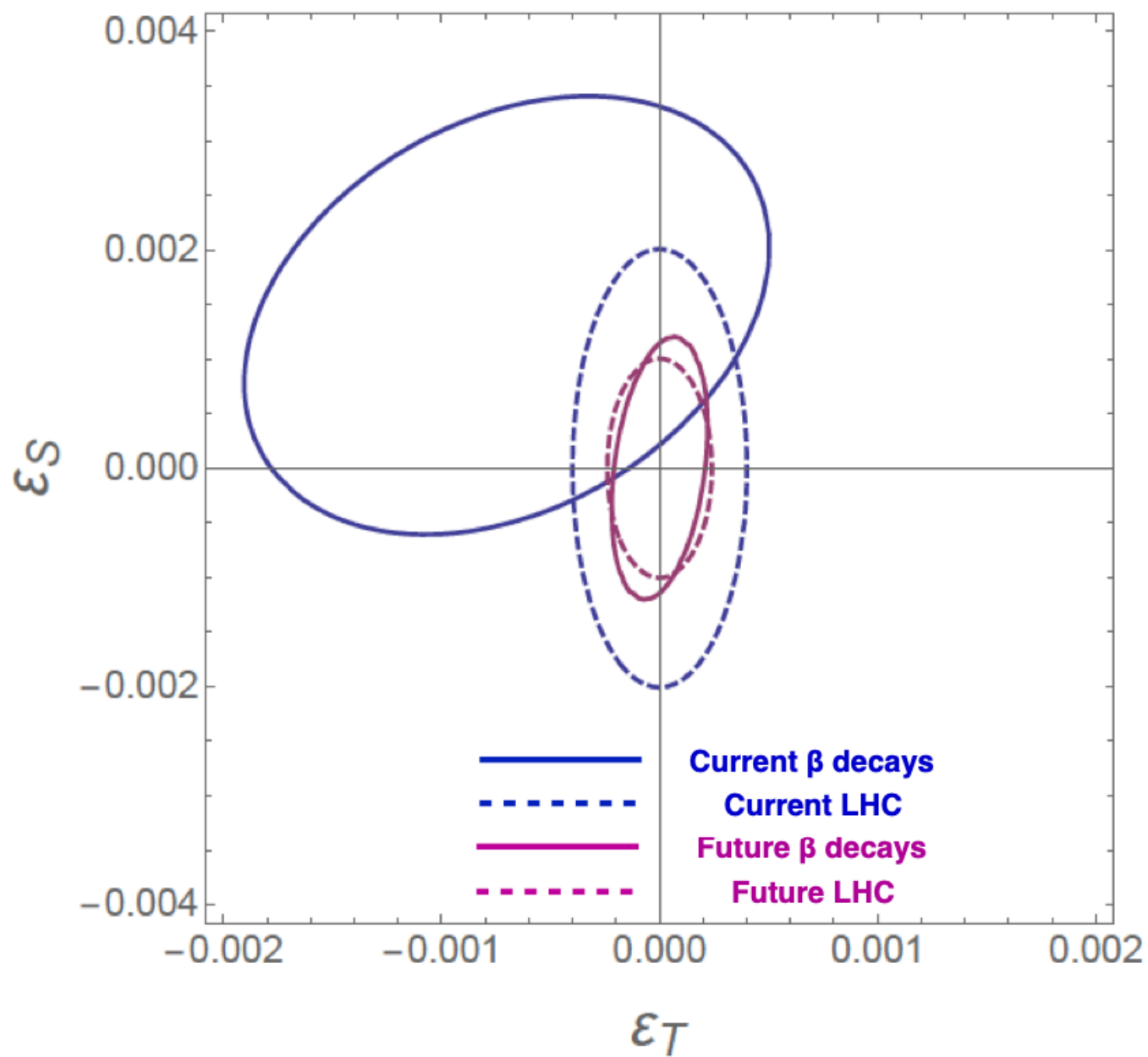
→ put constraints on ϵ_i 's

$$\sim v^2/\Lambda^2$$

$$\epsilon_L^{(\mu)}, \quad \epsilon_L^{(c)}, \quad \epsilon_L^{(v)} \approx -8.3 \pm 2.5 \times 10^{-4}$$

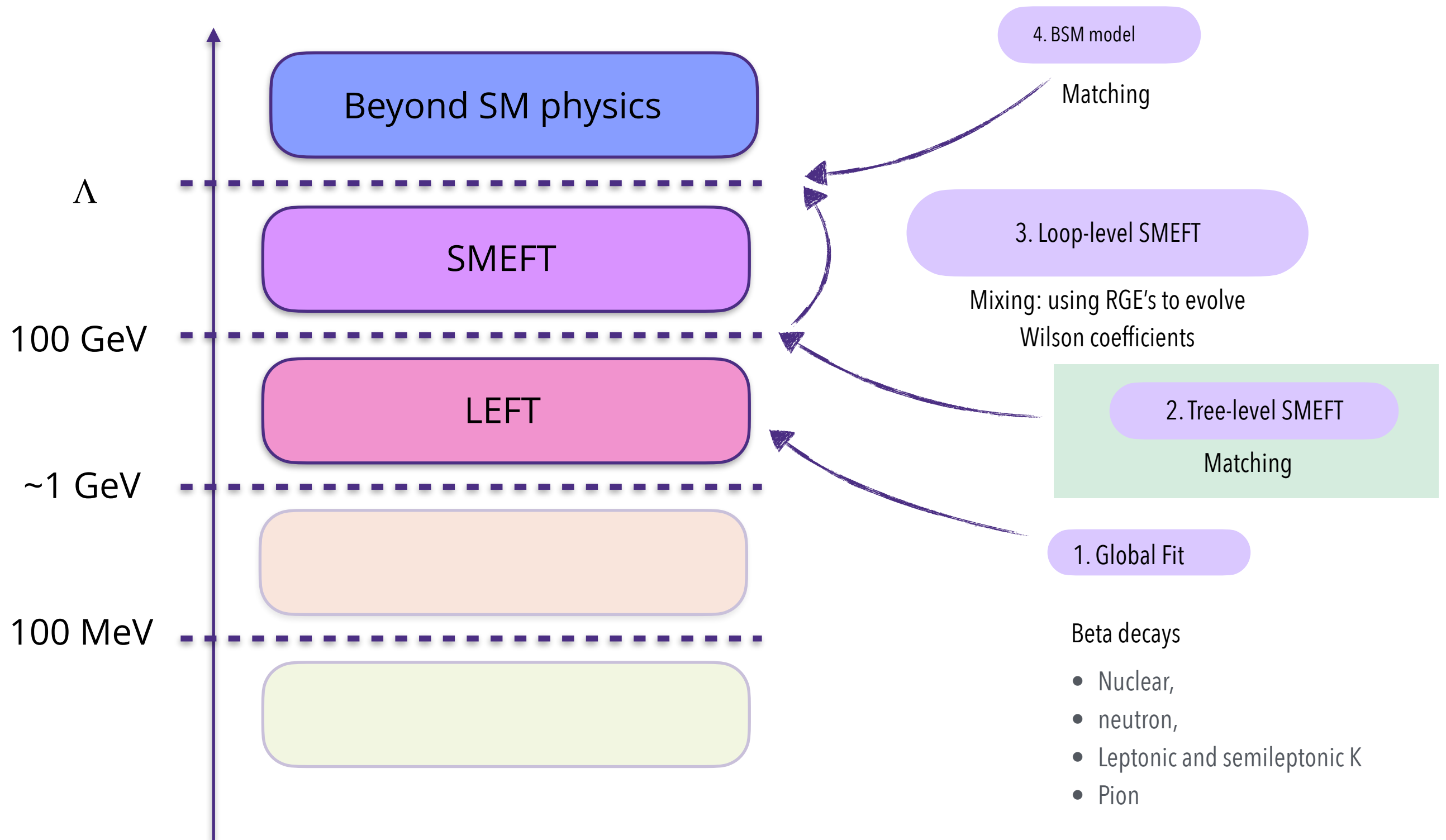
→ 20 TeV

Global Fit

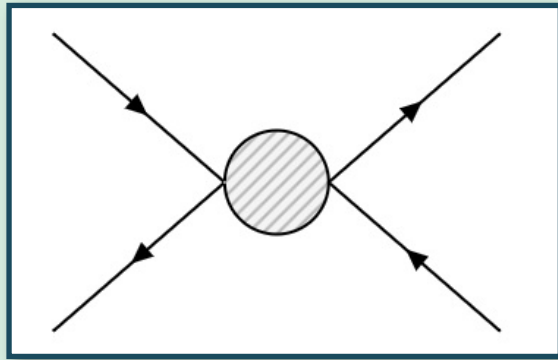


- Current and projected 90% C.L. constraints on ϵ_S and ϵ_T defined at 2 GeV in the $\overline{\text{MS}}$ scheme
- Obtained from arXiv:1803.08732
- LHC cannot constrain $\epsilon_{L'}$ and ϵ_R

β -decay on loop level

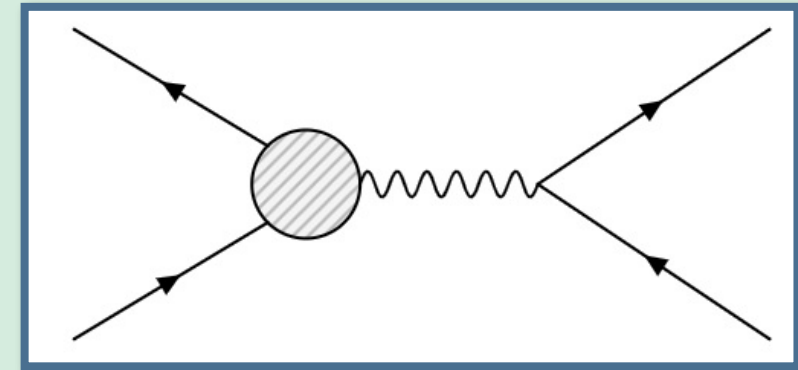


BETA DECAY AT THE TREE LEVEL



Four fermion operators

$$\begin{aligned}
 Q_{lq}^{(3)} &= (\bar{l}_p \gamma_\mu \tau^I l_r) (\bar{q}_s \gamma^\mu \tau^I q_t), \\
 Q_{ledq} &= (\bar{l}_p e_r) (\bar{d}_s q_t), \\
 Q_{lequ}^{(1)} &= (\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t), \\
 Q_{lequ}^{(3)} &= (\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t),
 \end{aligned}$$



Vertex correction

$$\begin{aligned}
 Q_{Hud} &= i(H^\dagger D_\mu H) (\bar{u}_p \gamma^\mu d_r), \\
 Q_{Hl}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{l}_p \tau^I \gamma^\mu l_r), \\
 Q_{Hq}^{(3)} &= (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r),
 \end{aligned}$$

p, r, s, t are flavor indices
here all 1

We work in the weak eigenstate basis

$$M_u = \text{diag}(m_u, m_c, m_t), M_d = \text{diag}(m_d, m_c, m_t) V^\dagger$$

$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}, \quad q^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}, \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix},$$

e, u, d – right-chiral fields,
 τ – $SU(2)$ generators,
 D_μ – covariant derivative

MUON DECAY

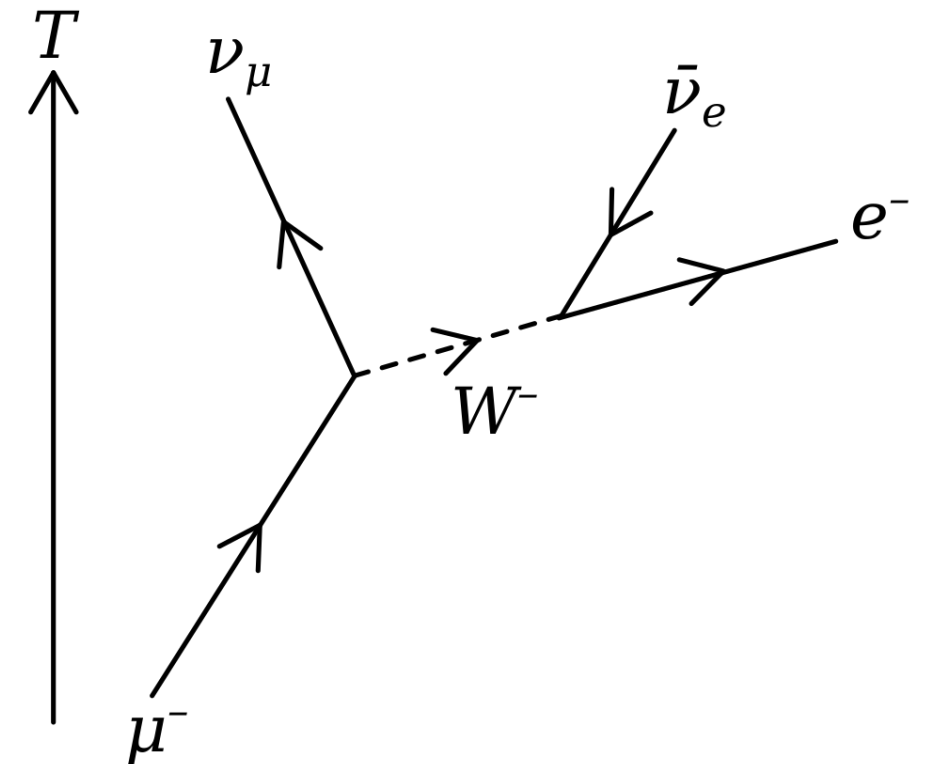
$\epsilon_L^{(\mu)}$ arises from the SMEFT correction to the Fermi constant extracted from muon decay and is given by

$$Q_{Hl}^{(3)} = \left(H^\dagger i \vec{D}_\mu^I H \right) (\bar{l}_p \tau^I \gamma^\mu l_r)$$

$$Q_{ll} = (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t)$$

flavour indices:
(1,2,2,1)

$$\epsilon_L^{(\mu)} = \left(C_{ll_{1221}} + C_{ll_{2112}} \right) - 2(C_{Hl_{11}}^{(3)} + C_{Hl_{22}}^{(3)})$$



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MATCHING AT THE ELECTRO-WEAK SCALE

$$[\mathcal{T}_{LEFT} = \mathcal{T}_{SMEFT}]_{\mu_W}$$

Vector interactions for left quarks:

- $\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)} - \epsilon_L^{(\mu)}$
- $\epsilon_L^{(v)} = 2 C_{Hl}^{(3)} + 2 \frac{[V C_{Hq}^{(3)}]_{11}}{V_{ud}} + 4 \frac{[V C_{Hl}^{(3)}]_{11}}{V_{ud}},$
- $\epsilon_L^{(c)} = -2 \frac{[V C_{lq}^{(3)}]_{11}}{V_{ud}},$
- $\epsilon_L^{(\mu)} = \left(C_{ll_{1221}} + C_{ll_{2112}} \right) - 2(C_{Hl_{11}}^{(3)} + C_{Hl_{22}}^{(3)})$

$\epsilon_L^{(v)}$ - vertex correction

$\epsilon_L^{(c)}$ - contact correction

$\epsilon_L^{(\mu)}$ - correction to muon decay

$$\epsilon_R = - \frac{[V C_{Hud}^{(3)}]_{11}}{V_{ud}},$$

$$\epsilon_s - \epsilon_P = -2 \frac{[V C_{ledq}^{(3)}]_{11}}{V_{ud}},$$

$$\epsilon_s + \epsilon_P = -2 \frac{[V C_{lequ}^{(1)}]_{11}}{V_{ud}},$$

$$\epsilon_T = - \frac{C_{lequ}^{(3)}}{V_{ud}}.$$

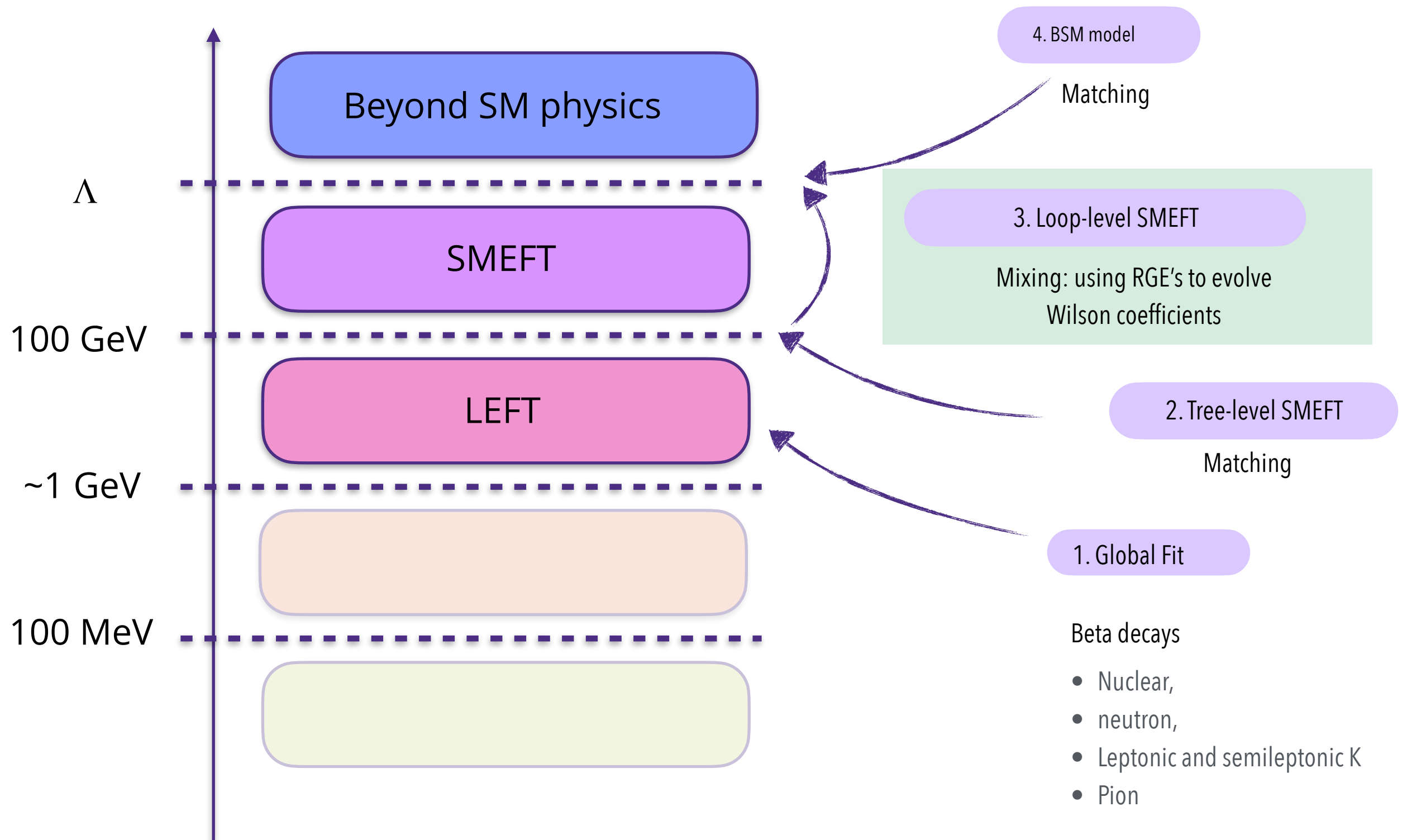
$$[V C_{Hq}^{(3)}]_{11} = C_{Hq_{11}}^{(3)} V_{11} + C_{Hq_{12}}^{(3)} V_{21} + C_{Hq_{13}}^{(3)} V_{31}$$

Bounds from beta decay (CKM unitarity)

$$\Delta_{CKM} = 2 |V_{ud}|^2 \epsilon_L^d + 2 |V_{us}|^2 \epsilon_L^s$$

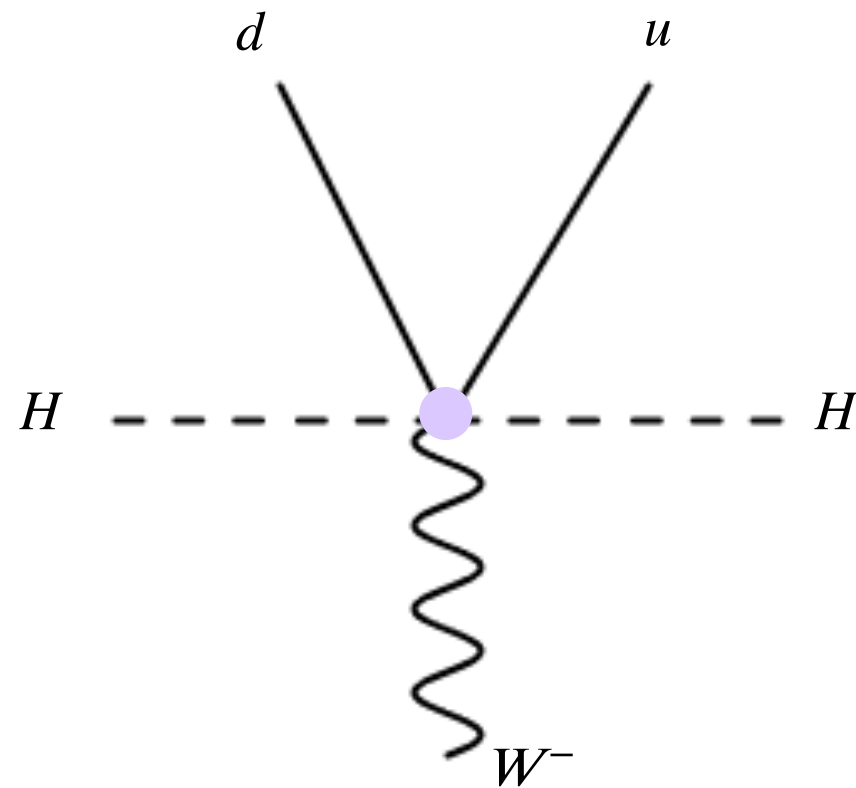
$$\epsilon_L^{(\mu)}, \epsilon_L^{(c)}, \epsilon_L^{(v)} \approx -8.3 \pm 2.5 \times 10^{-4},$$

β -decay on loop level



MIXING PROCEDURE

● - SMEFT operator

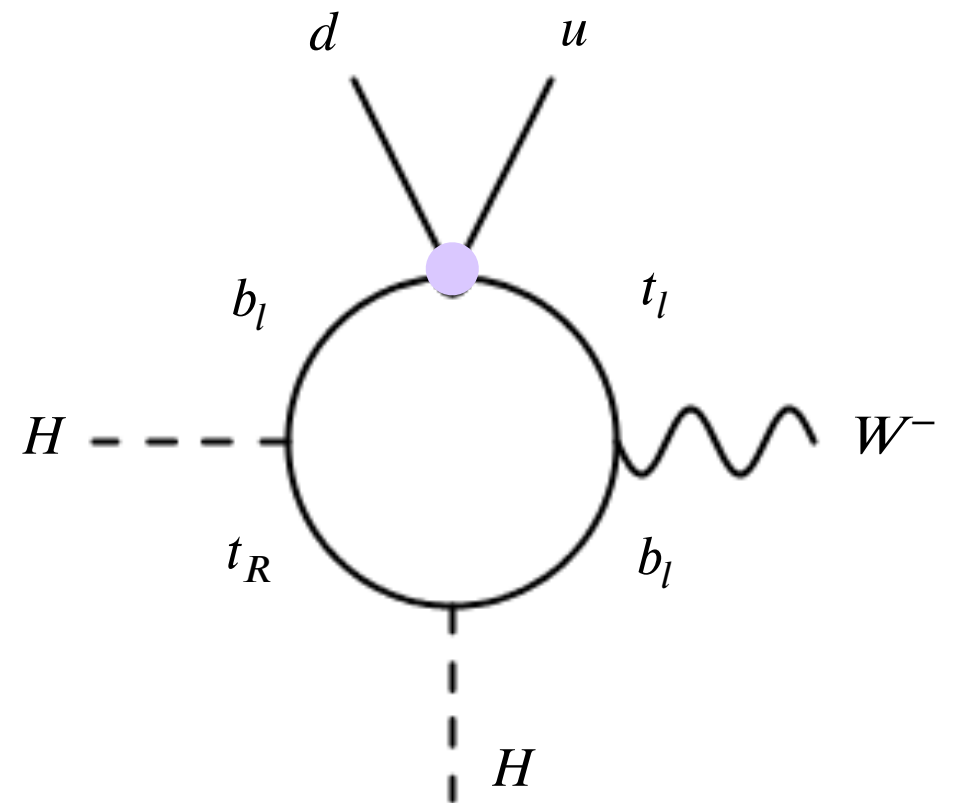


$Q_{Hq}^{(3)}$

Triplet

$$Q_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r)$$

2 quarks and boson



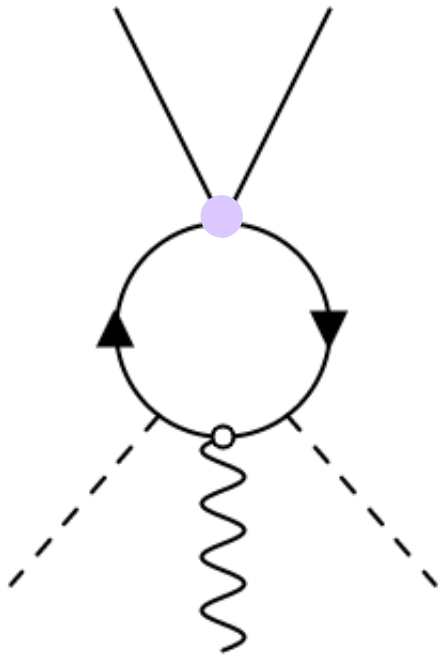
$Q_{qq}^{(3)} \rightarrow Q_{Hq}^{(3)}$

$$Q_{qq}^{(3)} = (\bar{q}_p \gamma_\mu \tau^I q_r) (\bar{q}_s \gamma^\mu \tau^I q_t)$$

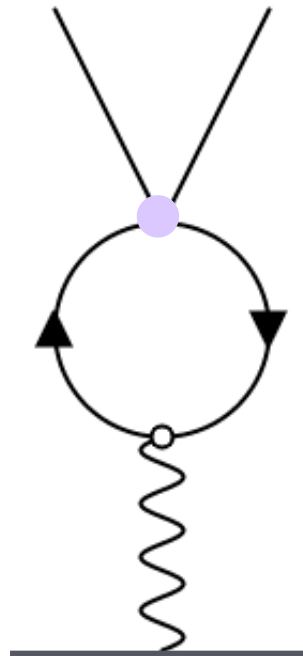
4 quarks

MORE EXAMPLES

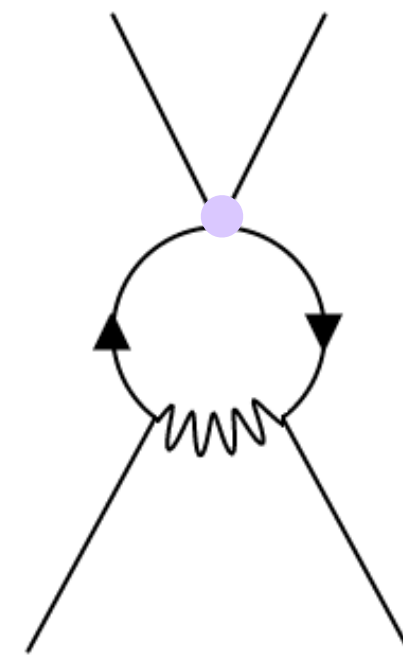
● - SMEFT operator



Contribution to $Q_{Hl}^{(3)}$ and $Q_{Hq}^{(3)}$
from $Q_{qq}^{(3)}$, $Q_{qq}^{(1)}$, $Q_{lq}^{(3)}$



Contribution to $Q_{lq}^{(3)}$
from $Q_{qq}^{(3)}$, $Q_{qq}^{(1)}$



Contribution to Q_u
from Q_u

RENORMALIZATION GROUP EQUATIONS

RGE

Tree level $\rightarrow$

Loop level $\rightarrow$

$$\begin{pmatrix} \dot{C}_\beta \\ \dot{C}_x \end{pmatrix} = \begin{pmatrix} \gamma_{\beta\beta} & \gamma_{\beta x} \\ \gamma_{x\beta} & \gamma_{xx} \end{pmatrix} \begin{pmatrix} C_\beta \\ C_x \end{pmatrix}$$

Initial conditions for $\Lambda = 5 \text{ TeV}$

$$C_\beta(\Lambda) = 0$$

$$C_x(\Lambda) = 1$$

Mixing of operators

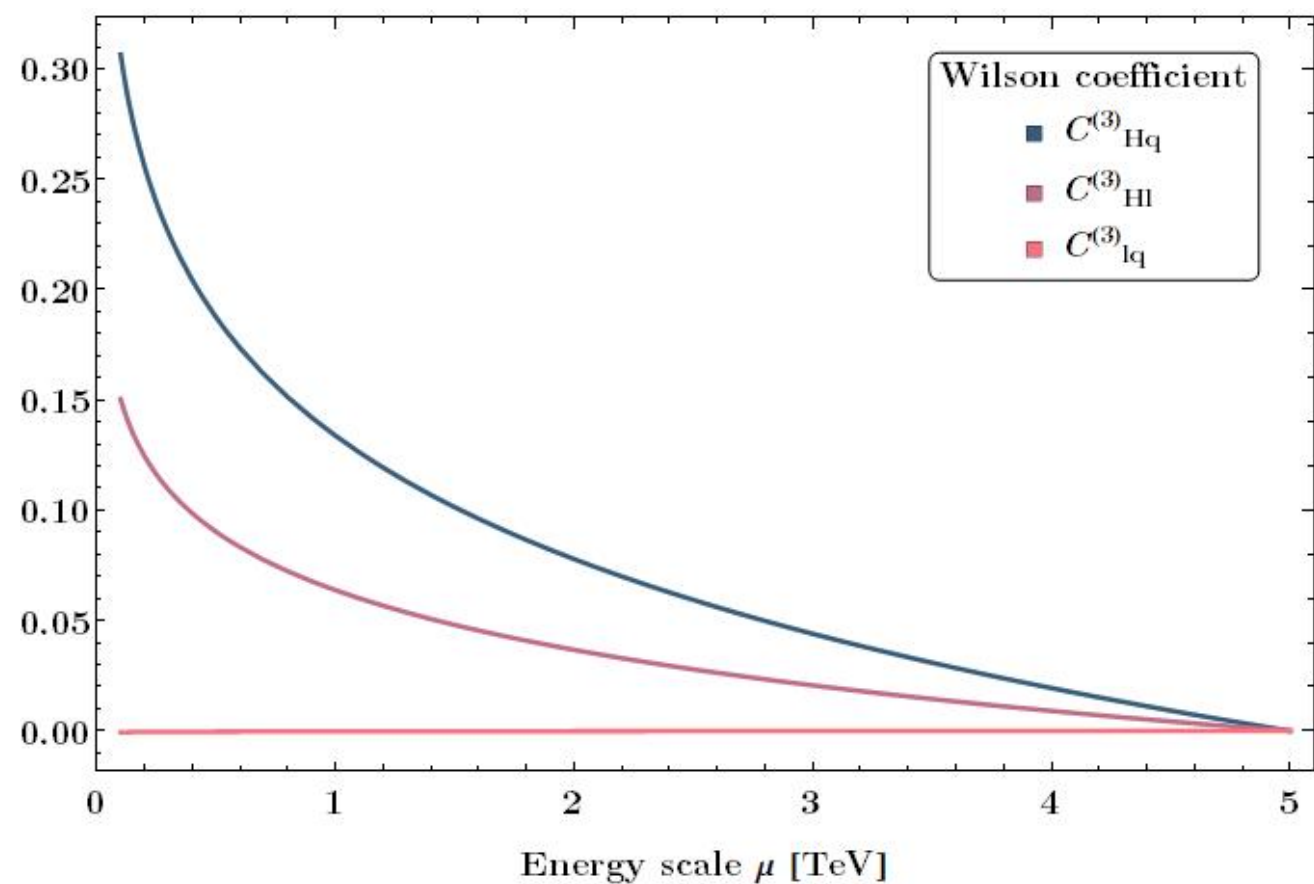
$$C_{\beta j}(\mu_W) = \sum_k U_{jk}(\mu_W, \Lambda) C_{xk}(\Lambda)$$

$$|\epsilon| = |\kappa_i C_i| \leq \bar{e}_L$$

mixing parameter
from RGE's

bound from
the experiment

Example of solutions of RGE's for $C_{Hq}^{(3)}$, $C_{Hl}^{(3)}$ and $C_{lq}^{(3)}$



RH, SCALAR, PSEUDOSCALAR, AND TENSOR TERMS

This class of couplings are suppressed by y_b

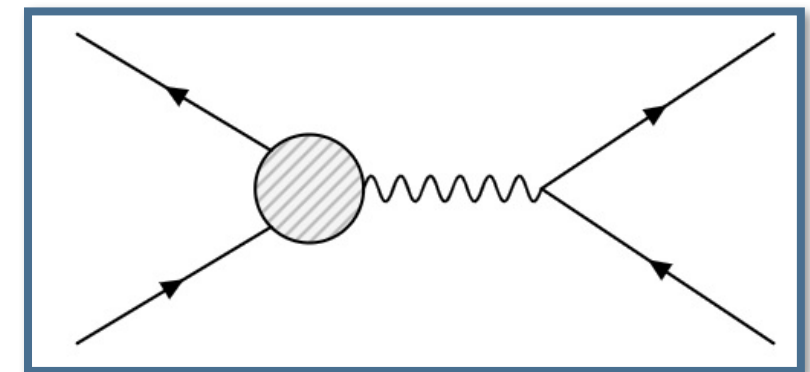
Example:

$$\dot{C}_{Hud}_{11} \subset 4 \left(C_{ud}_{1331}^{(1)} + \frac{4}{3} C_{ud}_{1331}^{(8)} \right) [Y_u Y_d^\dagger]_{33}$$

Solving RGE $\longrightarrow$ bounds of $\mathcal{O}(1)$

Results for ϵ_i at $\mu_W = 246$ GeV in terms of C_β and C_x at $\Lambda = 5$ TeV

$$\begin{aligned} \epsilon_R &= 0.950 \, C_{Hud} - 0.001 \, C_{ud}^{(1)} - 0.0011 \, C_{ud}^{(8)}, \\ \epsilon_P &= 0.603 \, C_{lequ}^{(1)} - 0.600 \, C_{ledq} + 0.143 \, C_{lequ}^{(3)} \\ \epsilon_S &= -0.603 \, C_{lequ}^{(1)} - 0.600 \, C_{ledq} + 0.143 \, C_{lequ}^{(3)} \\ \epsilon_T &= 0.003 \, C_{lequ}^{(1)} - 0.465 \, C_{lequ}^{(3)} \end{aligned}$$



Coefficients in blue are matched to a given ϵ_i at a tree level

LH CURRENTS

The largest contribution to ϵ_i at a loop level ($\kappa_{ij} > 10^{-2}$):

$$Q_{\beta_L}: \{Q_{ll}, Q_{lq}^{(3)}, Q_{Hl}^{(3)}, Q_{Hq}^{(3)}, Q_{qq}^{(1)}, Q_{qq}^{(3)}, Q_{H\Box}\}$$

$$\begin{aligned} Q_{qq}^{(1)} &= (\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t) \\ Q_{qq}^{(3)} &= (\bar{q}_p \gamma_\mu \tau^I q_r) (\bar{q}_s \gamma^\mu \tau^I q_t) \\ Q_{H\Box} &= (H^\dagger H) \Box (H^\dagger H) \end{aligned}$$

Results for ϵ_L at $\mu_W = 246$ GeV in terms of C_β and C_x at $\Lambda = 5$ TeV

$$\begin{aligned} \epsilon_L^{(d)} &= 0.946 C_{Hq_{11}}^{(3)} - 1.052 C_{lq_{1111}}^{(3)} + 1.012 C_{ll_{1221}} - 0.965 C_{Hl_{22}}^{(3)} \\ &+ 0.198 C_{qq_{1133}}^{(3)} - 0.026 C_{qq_{1331}}^{(3)} + 0.026 C_{qq_{1331}}^{(1)} - 0.0471 C_{ll_{1122}} - 0.100 C_{lq_{2233}}^{(3)}, \end{aligned} \quad \left. \vphantom{\epsilon_L^{(d)}} \right\} \text{Beta decay}$$

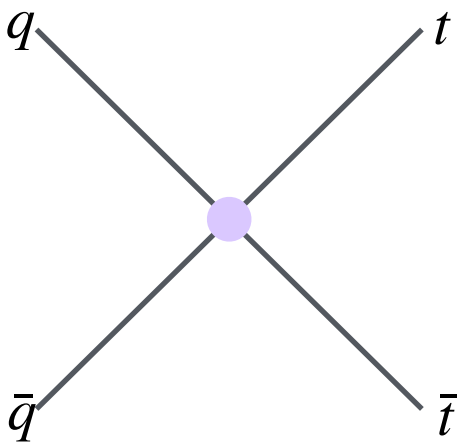
$$\begin{aligned} \epsilon_L^{(s)} &= \frac{0.942}{\lambda} C_{Hq_{12}}^{(3)} - \frac{1.052}{\lambda} C_{lq_{1112}}^{(3)} + 1.010 C_{ll_{1221}} - 0.960 C_{Hl_{22}}^{(3)} \\ &+ \frac{0.198}{\lambda} C_{qq_{1233}}^{(3)} - \frac{0.028}{\lambda} C_{qq_{1332}}^{(3)} + \frac{0.026}{\lambda} C_{qq_{1332}}^{(1)} - 0.099 C_{lq_{2233}}^{(3)} - 0.047 C_{ll_{1122}} \\ &+ 0.0144 (C_{Hq_{11}}^{(3)} + C_{Hq_{22}}^{(3)} + C_{Hq_{33}}^{(3)}) - 0.016 (C_{lq_{1111}}^{(3)} + C_{lq_{1122}}^{(3)} + C_{lq_{1133}}^{(3)}). \end{aligned} \quad \left. \vphantom{\epsilon_L^{(s)}} \right\} \text{Kaon decay}$$

RESULTS

With $C_k \sim v^2/\Lambda^2$

$C_x(\Lambda = 5 \text{ TeV})$	Constraint from β decays	Strongest constraints from other processes	Process
$C_{1133}^{(3)qq}$	-0.004 ± 0.0013	$-0.0073 \pm 0.006^{(1)}$ $\pm 0.00002^{(2)}$	Top production $K \rightarrow \pi \nu \bar{\nu}$
$C_{2233}^{(3)lq}$	0.008 ± 0.0025	$-0.00024 \pm 0.00021^{(2)}$	B decays (R_K)
C_{1122}^l	0.018 ± 0.005	-0.0018 ± 0.0029	Muon pair production
$C_{1331}^{(1)qq}$	-0.031 ± 0.009	$-0.035 \pm 0.027^{(1)}$ $\pm 0.0009^{(2)}$	Top production Δm_K
$C_{1331}^{(3)qq}$	0.03 ± 0.009	$-0.042 \pm 0.024^{(1)}$ $\pm 0.00004^{(2)}$	Top production $K \rightarrow \pi \nu \bar{\nu}$

Example of tree level
process, $t\bar{t}$ production at the LHC



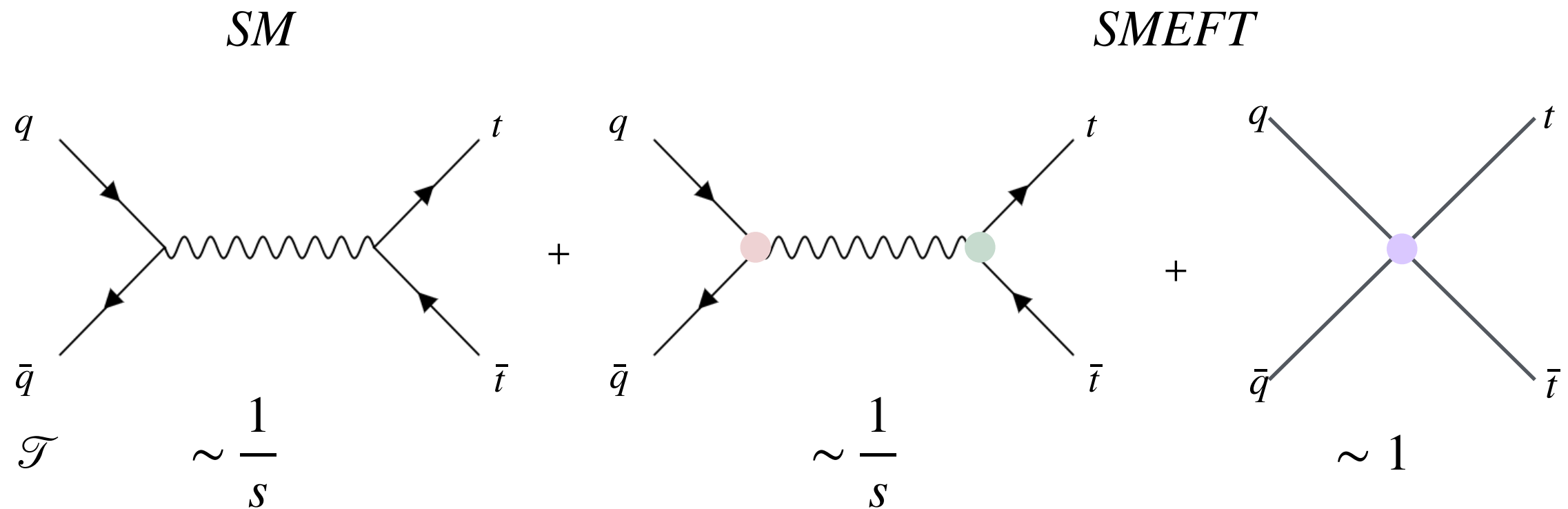
Result: Stronger constraints on BSM operators from loop-level processes than those achievable in other channels at tree level.

(1) indicates that the fit was performed assuming $U(3)_l \times U(3)_e \times U(3)_d \times U(2)_u \times U(2)_q$ symmetry

(2) indicates that the constraint would disappear if one used the weak basis in which the down-type quark mass matrix M_d is diagonal.

RESULTS VS LHC

Transverse mass distributions for events satisfying all selection criteria in the electron channels.



Scattering amplitude

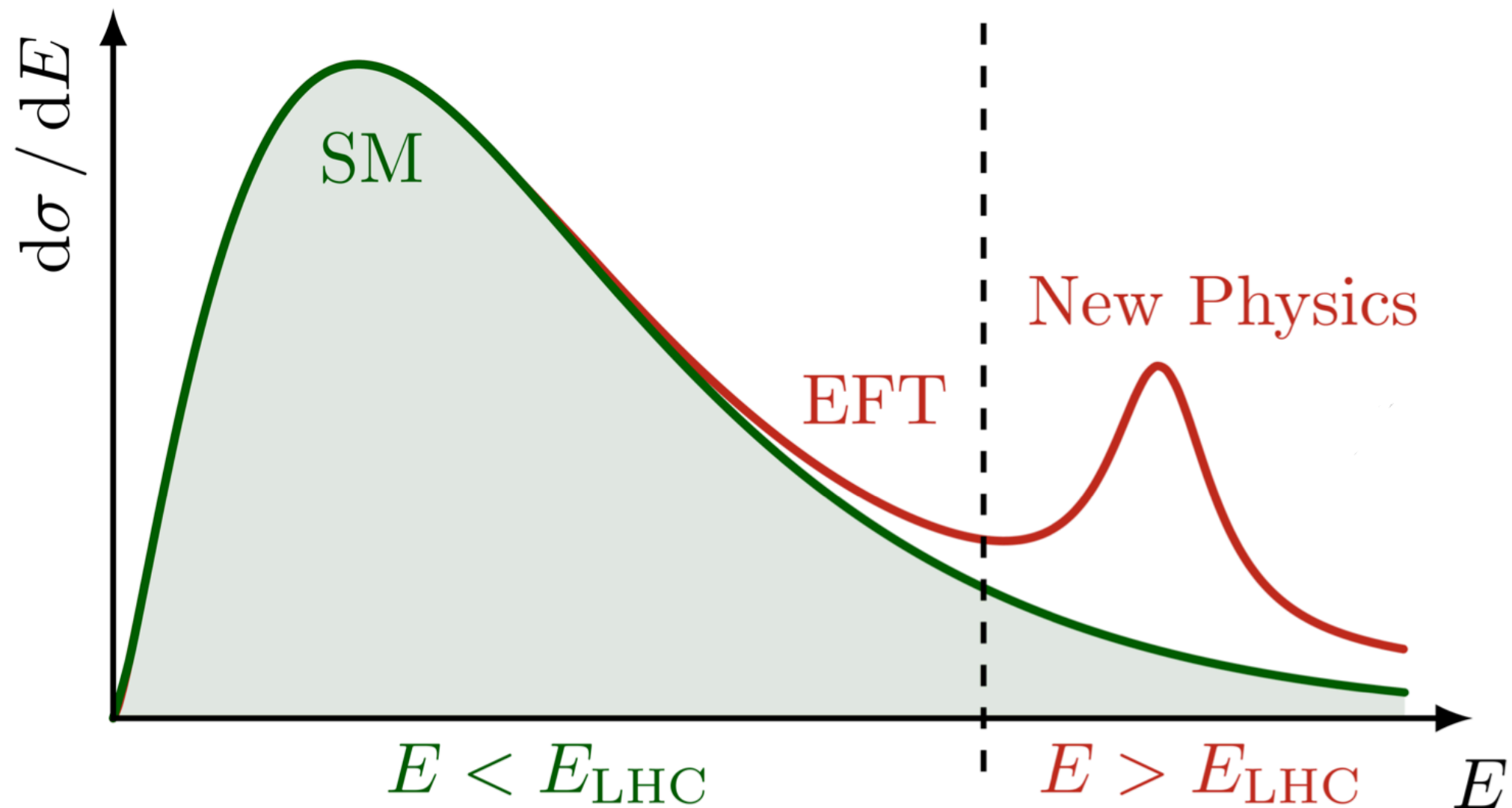
Cross-section

$$\mathcal{T} = \mathcal{T}_{SM} + \mathcal{T}_{SMEFT}$$

$$\sigma = \left| \mathcal{T}_{SM} \right|^2 + 2\text{Re} \left[\mathcal{T}_{SM} \times \mathcal{T}_{SMEFT} \right] + \left| \mathcal{T}_{SMEFT} \right|^2$$

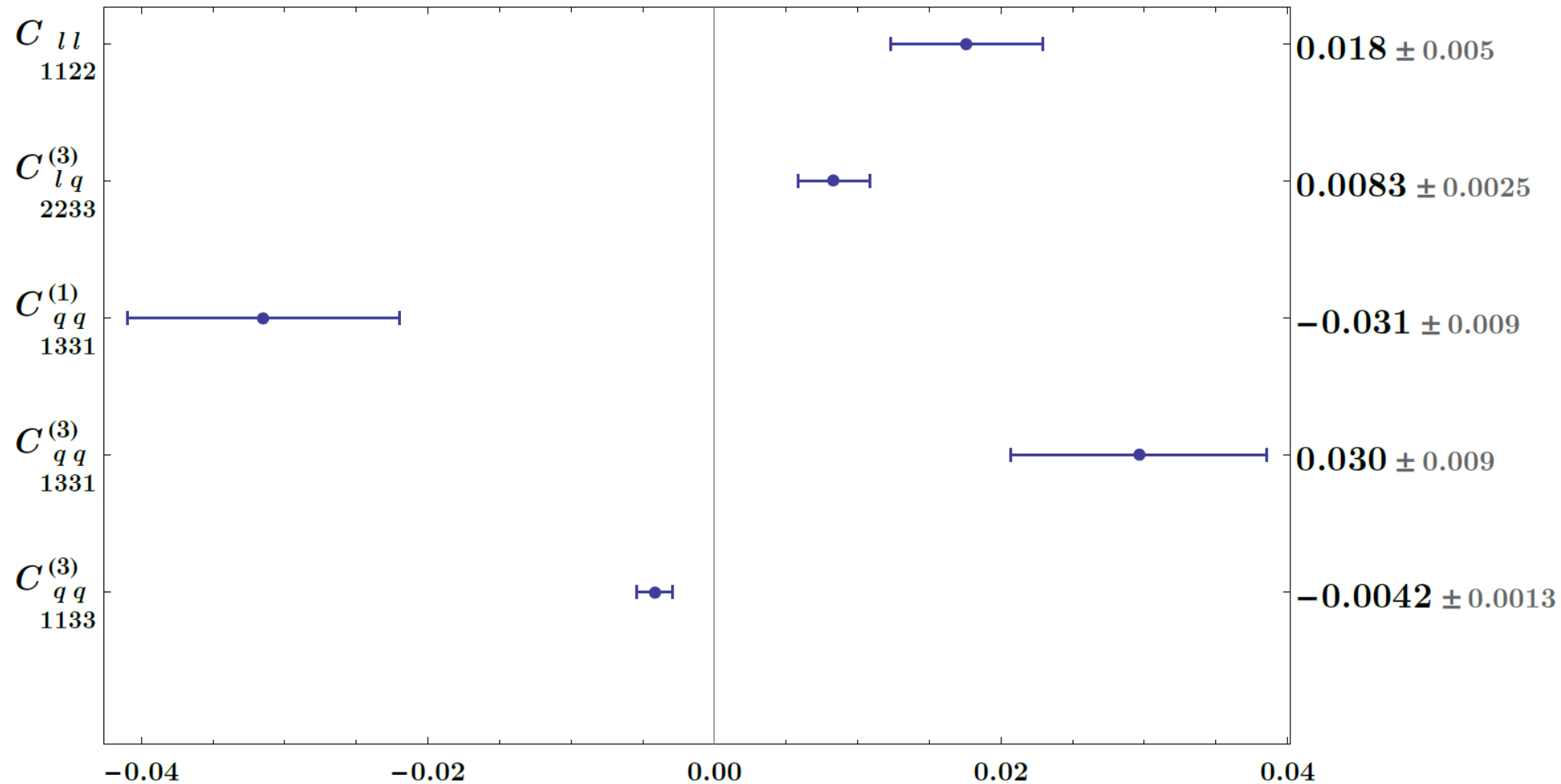
RESULTS VS LHC

Transverse mass distributions for events satisfying all selection criteria in the electron channels.



RESULTS

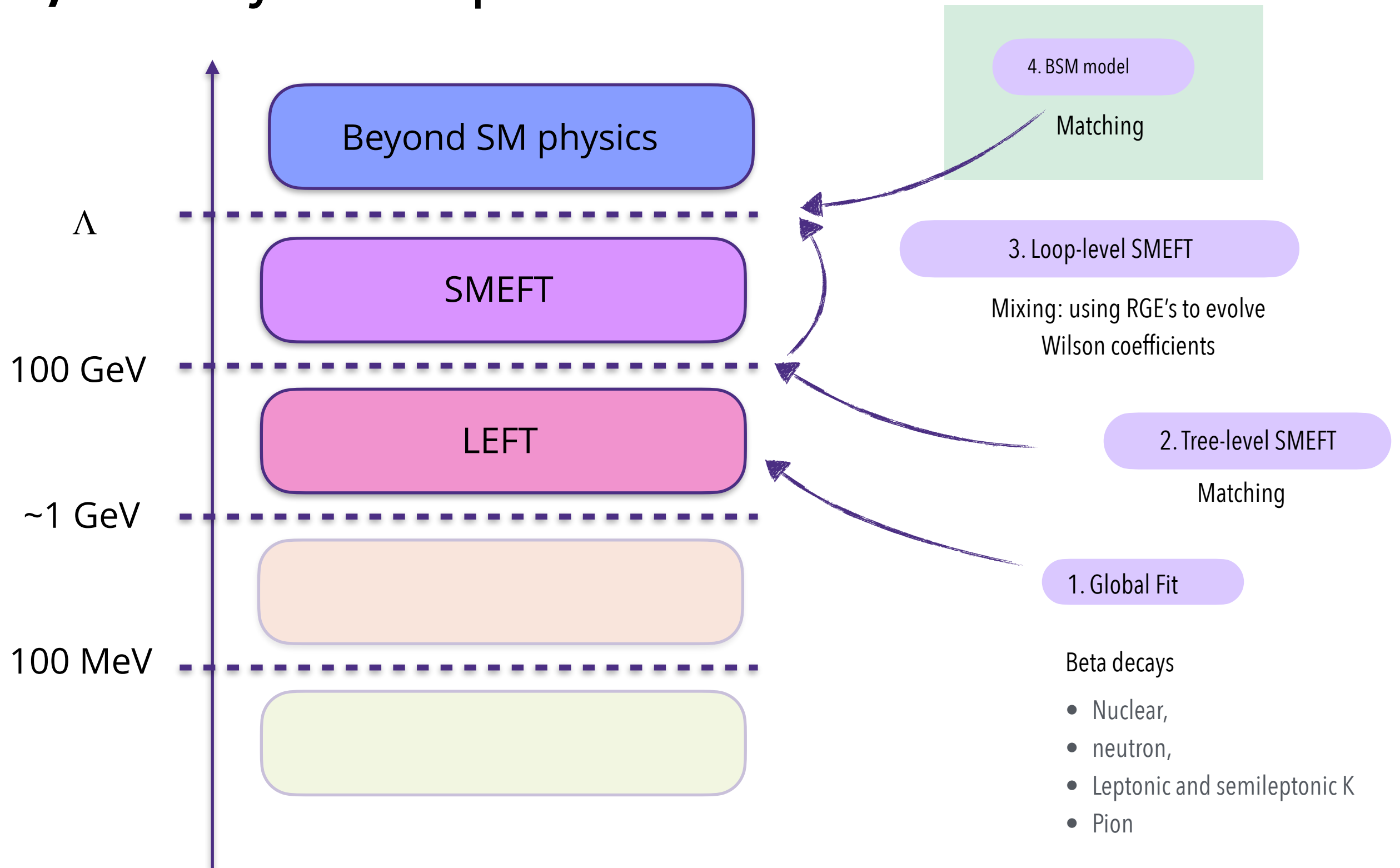
$$C \sim \frac{v^2}{\Lambda^2}$$



$\Lambda \sim 8 \text{ TeV}$

Result: Beta decay at loop level can probe higher energies (that correspond to masses of BSM particles) than other processes, e.g., from LHC

β -decay on loop level



Beyond the SM: a model above the high-energy scale

Assumption of BSM above the Λ scale

1. $\mathcal{L}_{BSM}$ is invariant under linearly-realized $SU(3)_C \times SU(2)_L \times U(1)_Y$.
2. $\mathcal{L}_{BSM}$ contains only particles of spin ≤ 1 .
3. Adding one new particle at a time.

Q_x operator	Heavy field						
$Q_{qq}^{(3)}$ Irrep	ω_1 $(3, 1)_{-\frac{1}{3}}$	ζ $(3, 3)_{-\frac{1}{3}}$	Ω_1 $(6, 1)_{\frac{1}{3}}$	Υ^* $(6, 3)_{\frac{1}{3}}$	$\mathcal{W}$ $(1, 1)_0$	$\mathcal{G},$ $(8, 1)_0$	$\mathcal{H}^*$ $(8, 3)_0$
$Q_{qq}^{(1)}$ Irrep	ω_1 $(3, 1)_{-\frac{1}{3}}$	ζ $(3, 3)_{-\frac{1}{3}}$	Ω_1 $(6, 1)_{\frac{1}{3}}$	Υ^* $(6, 3)_{\frac{1}{3}}$	$\mathcal{B}$ $(1, 3)_0$	$\mathcal{G},$ $(8, 1)_0$	$\mathcal{H}^*$ $(8, 3)_0$
$Q_{lq}^{(3)}$ Irrep	ω_1 $(3, 1)_{-\frac{1}{3}}$	ζ $(3, 3)_{-\frac{1}{3}}$	$\mathcal{W}$ $(1, 3)_0$	$\mathcal{U}_2$ $(3, 1)_0$	$\mathcal{X}$ $(3, 3)_{\frac{2}{3}}$		
Q_{ll} Irrep	$\mathcal{S}_1$ $(1, 1)_1$	Ξ $(1, 3)_1$	β $(1, 1)_0$	$\mathcal{W}$ $(1, 3)_0$			

Summary

- The CKM unitarity test is important for constraining ϵ_L and ϵ_R
- Beta decay probes BSM physics at a tree-level at ~ 20 TeV (needs experimental and theoretical scrutiny!)
- We put constraints on New Physics operators that include **top quarks** at ~ 8 TeV at a loop-level, which exceeds the LHC results!
- We connect these operators to the BSM model

FLAVOR-CHANGING NEUTRAL CURRENT OPERATORS

- At a loop level ($\Delta F = 2$):

$$\dot{C}_\beta = \gamma_{\beta x} C_x,$$

$$\dot{C}_{FCNC} = \gamma_{FCNC} C_x$$

- Rotation to the mass basis

The strongest constraints arise from the rare

$$\Delta S = 1 \text{ proces } K \rightarrow \pi \nu \bar{\nu}$$

$$[L_{VLL}^{\nu d}] < 0.97 \times 10^{-5} \text{ TeV}$$

$$v^2 [L_{VLL}^{\nu d}] = \tilde{C}_{ll12} + \lambda \left(\tilde{C}_{ll11} - \tilde{C}_{ll22} \right) +$$

$$\tilde{C}_{llij} = C_{lq}^{(1)} - C_{lq}^{(3)} + \delta_{ll} C_{Hq}^{(1)} + \delta_{ll} C_{Hq}^{(3)}$$

$\begin{matrix} \text{llij} & \text{llij} & \text{ij} & \text{ij} \end{matrix}$



$$C_{lq}^{(1)} < 2.0 \times 10^{-5}, \quad C_{qq}^{(1)} < 0.57 \times 10^{-3}$$

$$C_{lq}^{(3)} < 2.0 \times 10^{-5}, \quad C_{qq}^{(3)} < 0.37 \times 10^{-4}$$

$\begin{matrix} 1133 & 1331 \\ 1133 & 1331 \end{matrix}$

$$\text{With } C_k \sim v^2 / \Lambda^2$$