Probing dimension-8 SMEFT operators through neutral meson mixing

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第三届高能物理理论与实验融合发展研讨会

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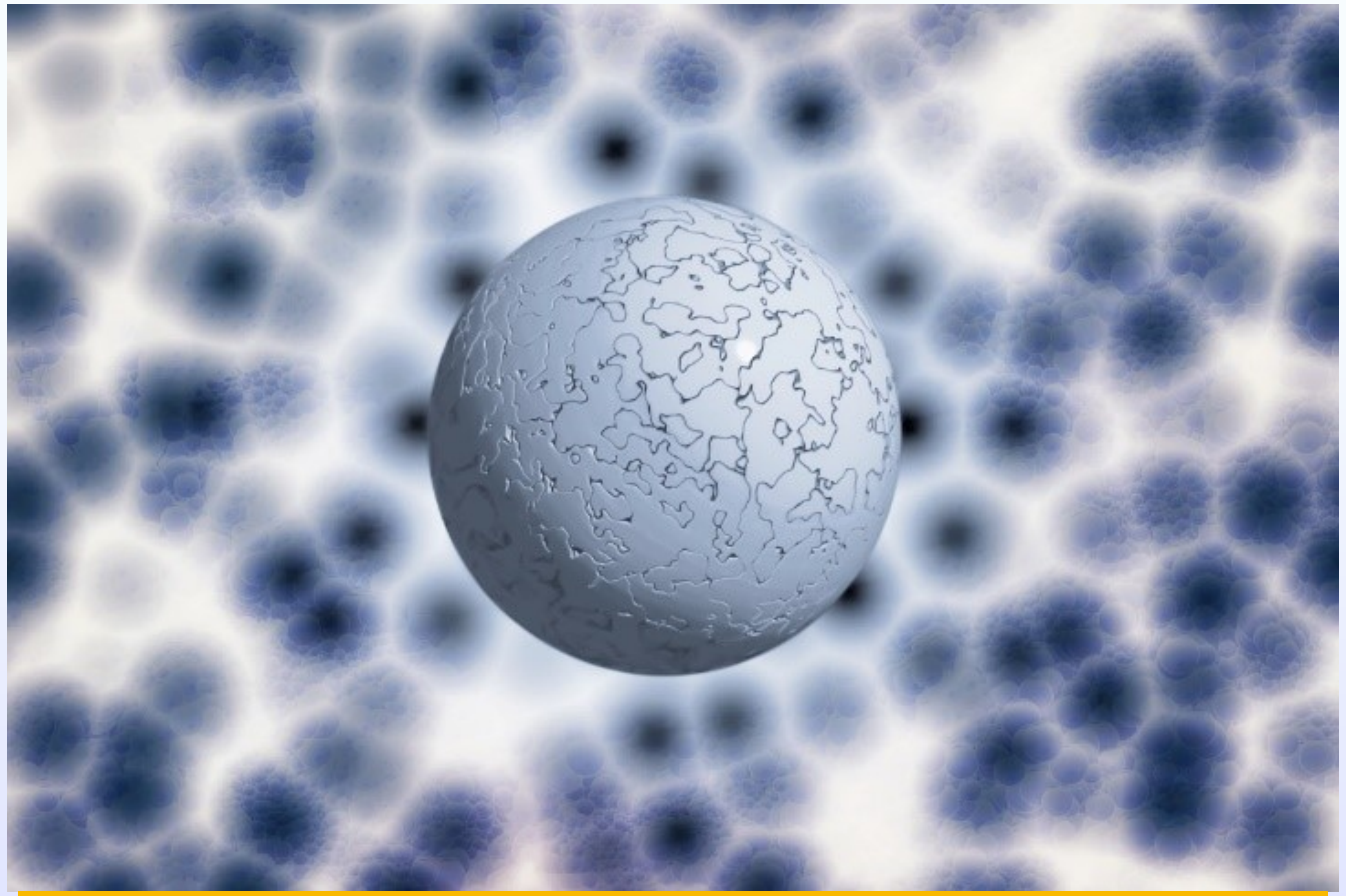
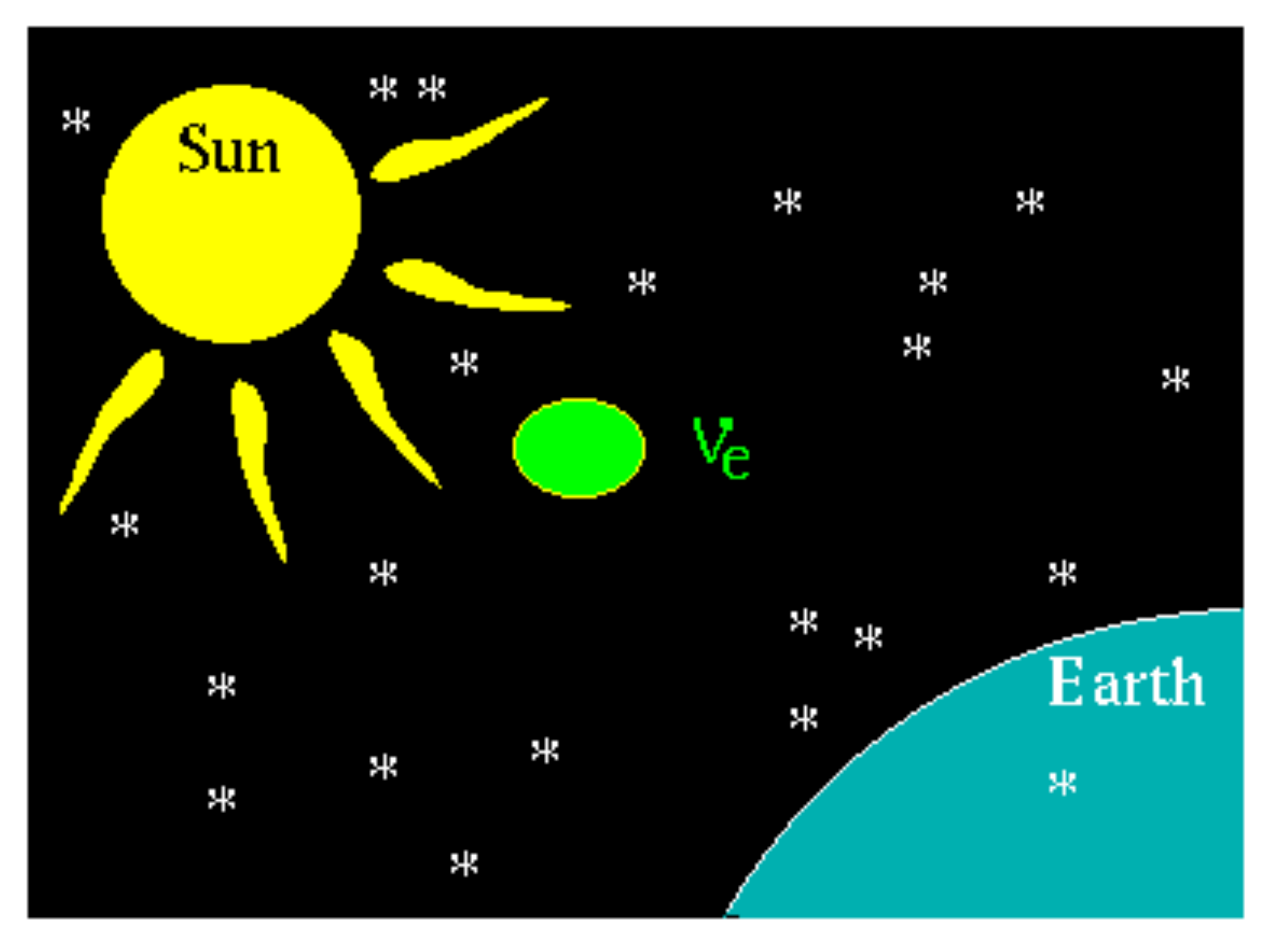
Yi Liao, XDM, Hao-Lin Wang: 2409.10305

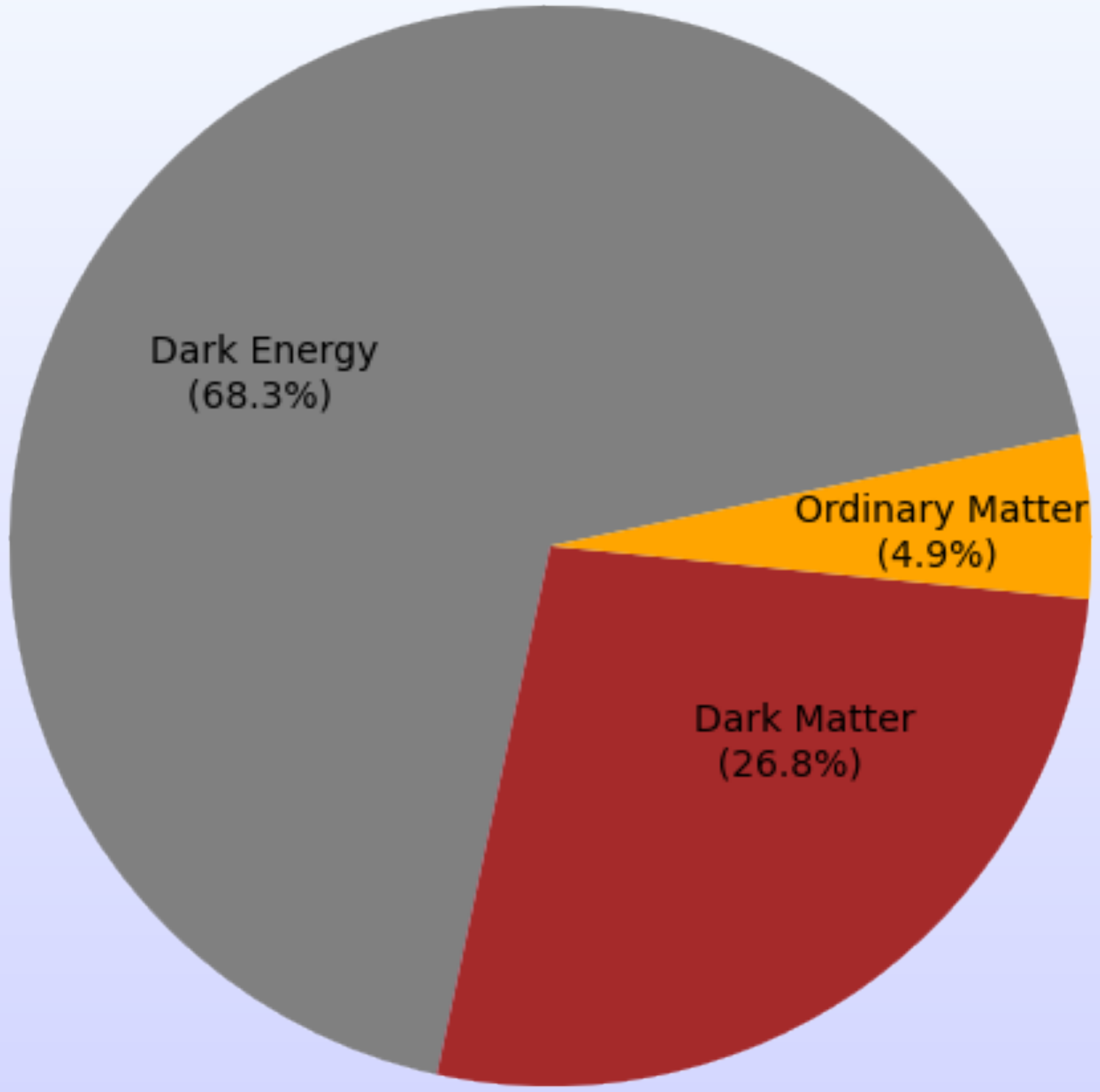
Evidence of physics beyond SM—NP

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Anomalies
  - Neutron lifetime τ_n
  - $B \to K\nu\bar{\nu}$
  - $K \to \pi\nu\bar{\nu}$
  - MiniBooNE ν_e
  - Gallium anomaly
  - ……
- 。。。。。。



https://www.iasgyan.in/daily-current-affairs/ghost-particles





Rare/forbidden processes are golden channels to NP search

SM forbidden processes: LFV, BNV, LNV, Lorentz violation, ...

$\ell_i \to \ell_j \gamma, \ell_i \to \ell_j \ell_k \ell_k$ $\quad N \to M\ell$ $\quad nn \to ppe^- e^-$

SM rare processes: FCNC

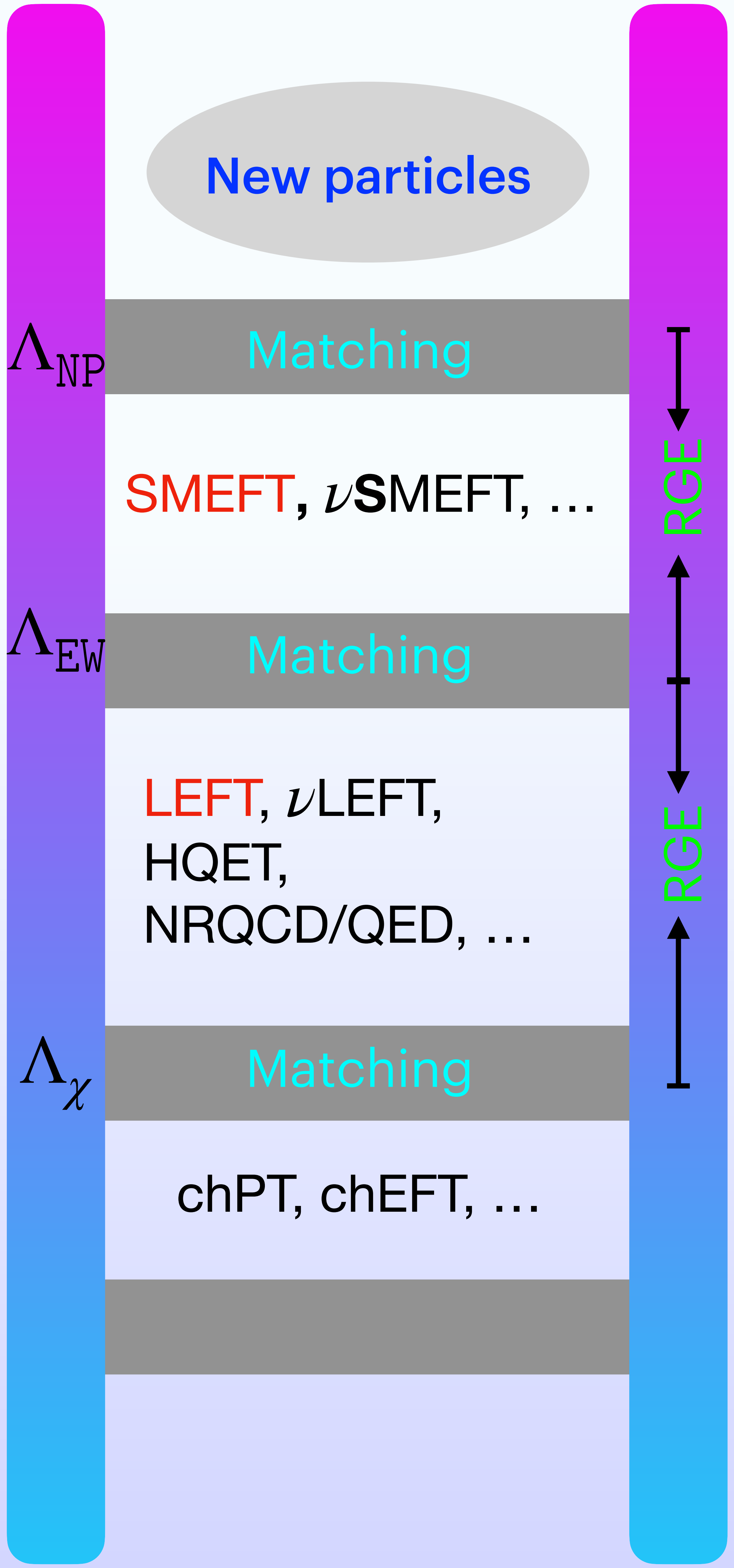
$\Delta F = 1$ processes: $H_1 \to H_2 + \ell^+\ell^- / \ell^- \bar{\nu} / \nu\bar{\nu}$ or $M \to \ell^+\ell^- / \ell^- \bar{\nu} / \nu\bar{\nu}$

$B \to K\nu\bar{\nu}$ BELLE-II: 2311.14647 $\quad K \to \pi\nu\bar{\nu}$ NA62 : EP seminar by Swallow

$\Delta F = 2$ processes: $M - \bar{M}$ mixing

$$K^0 - \bar{K}^0, D^0 - \bar{D}^0, B_d - \bar{B}_d, B_s - \bar{B}_s$$

Bottom-up EFT



$\boxed{\text{Assumption: scales are well separated with } \Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}}$

Parametrize the derivation of low energy observables w.r.t. the SM prediction by non-SM interactions based on SM particles and symmetries

$\boxed{\text{SMEFT-like framework}}$

Study NP effect in low energy observables indirectly

LEFT framework— SUSY basis

$$\mathcal{O}_1^{ij} = (\bar{q}_i^{\alpha}\gamma_\mu P_L q_j^{\alpha})(\bar{q}_i^{\beta}\gamma^\mu P_L q_j^{\beta}),$$

$$\mathcal{O}_2^{ij} = (\bar{q}_i^{\alpha} P_L q_j^{\alpha})(\bar{q}_i^{\beta} P_L q_j^{\beta}),$$

$$\mathcal{O}_3^{ij} = (\bar{q}_i^{\alpha} P_L q_j^{\beta})(\bar{q}_i^{\beta} P_L q_j^{\alpha}),$$

$$\mathcal{O}_4^{ij} = (\bar{q}_i^{\alpha} P_L q_j^{\alpha})(\bar{q}_i^{\beta} P_R q_j^{\beta}),$$

$$\mathcal{O}_5^{ij} = (\bar{q}_i^{\alpha} P_L q_j^{\beta})(\bar{q}_i^{\beta} P_R q_j^{\alpha}),$$

$$\tilde{\mathcal{O}}_{1,2,3}^{ij} = \mathcal{O}_{1,2,3}^{ij}\,|_{P_L \leftrightarrow P_R}$$

Gabbiani *et al*: 9604387
FLAG: 1902.08191

* $ij = ds, cu, db, sb$ for K^0, D^0, B_d, B_s mixing

* Eight operators for each system

* SM contribution only from $\mathcal{O}_1$

* NP @ dim6: only $\mathcal{O}_{1,4,5}$ and $\tilde{\mathcal{O}}_1$

* NP @ dim8: $\mathcal{O}_{1,4,5}$, $\tilde{\mathcal{O}}_1$ + $\mathcal{O}_{2,3}$ $\tilde{\mathcal{O}}_{2,3}$

SMEFT framework

Grzadkowski *et al*: 1008.4884
Murphy: 2005.00059;
Li *et al*: 2005.00008

Dim 6		Dim 8					
-		Type-I		#	Type-II		#
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$	$\mathcal{O}_{q^4H^2}^{(1)}$	$\mathcal{O}_{qq}^{(1)}(H^\dagger H)$	45	$\mathcal{O}_{q^4H^2}^{(2)}$	$(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu \tau^I q)(H^\dagger \tau^I H)$	81
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$	$\mathcal{O}_{q^4H^2}^{(3)}$	$\mathcal{O}_{qq}^{(3)}(H^\dagger H)$	45	$\mathcal{O}_{q^4H^2}^{(5)}$	$i\epsilon^{IJK}(\bar{q}\gamma^\mu \tau^I q)(\bar{q}\gamma_\mu \tau^J q)(H^\dagger \tau^K H)$	36
$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{q^2u^2H^2}^{(1)}$	$\mathcal{O}_{qu}^{(1)}(H^\dagger H)$	81	$\mathcal{O}_{q^2u^2H^2}^{(2)}$	$(\bar{q}\gamma^\mu \tau^I q)(\bar{u}\gamma_\mu u)(H^\dagger \tau^I H)$	81
$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$	$\mathcal{O}_{q^2u^2H^2}^{(3)}$	$\mathcal{O}_{qu}^{(8)}(H^\dagger H)$	81	$\mathcal{O}_{q^2u^2H^2}^{(4)}$	$(\bar{q}\gamma^\mu T^A \tau^I q)(\bar{u}\gamma_\mu T^A u)(H^\dagger \tau^I H)$	81
$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{q^2d^2H^2}^{(1)}$	$\mathcal{O}_{qd}^{(1)}(H^\dagger H)$	81	$\mathcal{O}_{q^2d^2H^2}^{(2)}$	$(\bar{q}\gamma^\mu \tau^I q)(\bar{d}\gamma_\mu d)(H^\dagger \tau^I H)$	81
$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$	$\mathcal{O}_{q^2d^2H^2}^{(3)}$	$\mathcal{O}_{qd}^{(8)}(H^\dagger H)$	81	$\mathcal{O}_{q^2d^2H^2}^{(4)}$	$(\bar{q}\gamma^\mu T^A \tau^I q)(\bar{d}\gamma_\mu T^A d)(H^\dagger \tau^I H)$	81
$\mathcal{O}_{uu}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{u^4H^2}$	$\mathcal{O}_{uu}(H^\dagger H)$	45	$\mathcal{O}_{q^2u^2H^2}^{(5)}, \ +\mathrm{H.c.}$	$(\bar{q}u\tilde{H})(\bar{q}u\tilde{H}), \ +\mathrm{H.c.}$	$45+45$
$\mathcal{O}_{dd}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{d^4H^2}$	$\mathcal{O}_{dd}(H^\dagger H)$	45	$\mathcal{O}_{q^2u^2H^2}^{(6)}, \ +\mathrm{H.c.}$	$(\bar{q}T^A u\tilde{H})(\bar{q}T^A u\tilde{H}), \ +\mathrm{H.c.}$	$45+45$
					$\mathcal{O}_{q^2d^2H^2}^{(5)}, \ +\mathrm{H.c.}$	$(\bar{q}dH)(\bar{q}dH), \ +\mathrm{H.c.}$	$45+45$
					$\mathcal{O}_{q^2d^2H^2}^{(6)}, \ +\mathrm{H.c.}$	$(\bar{q}T^A dH)(\bar{q}T^A dH), \ +\mathrm{H.c.}$	$45+45$

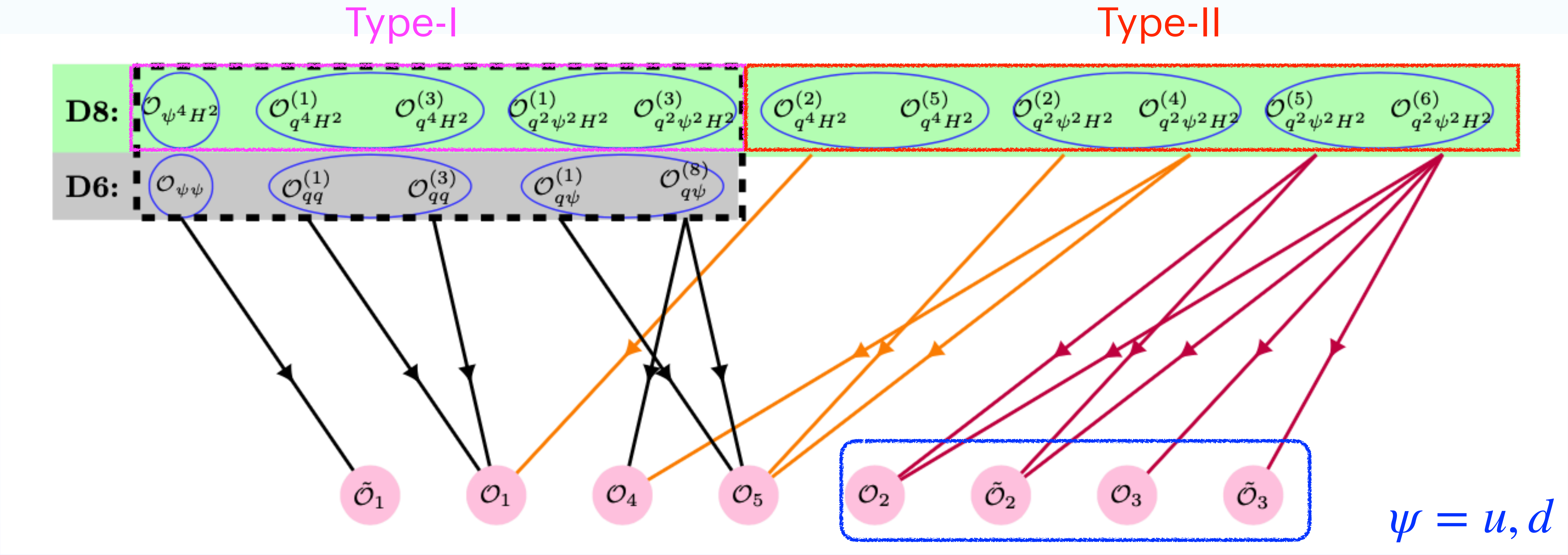
Type-I

Dim6 operator $\otimes$ $(H^\dagger H)$

Type-II

Non-trivial $\mathrm{SU}(2)_\mathrm{L}$ structure

SMEFT and LEFT correspondance



Tree-level matching results

LEFT operators	Matching results at electroweak scale Λ_{EW}
$\mathcal{O}_1^{ij} = (\bar{q}_i^\alpha \gamma_\mu P_L q_j^\alpha)(\bar{q}_i^\beta \gamma^\mu P_L q_j^\beta)$	$C_{1,dd}^{ij} = \left[\frac{v^2}{2}\left(C_{q^4H^2}^{(2),xyzw} + C_{q^4H^2}^{(1),xyzw} + C_{q^4H^2}^{(3),xyzw}\right) + C_{qq}^{(1),xyzw} + C_{qq}^{(3),xyzw}\right] V_{xi}^* V_{yj} V_{zi}^* V_{wj},$
	$C_{1,uu}^{ij} = -\frac{v^2}{2}\left(C_{q^4H^2}^{(2),ijij} - C_{q^4H^2}^{(1),ijij} - C_{q^4H^2}^{(3),ijij}\right) + C_{qq}^{(1),ijij} + C_{qq}^{(3),ijij},$
$\tilde{\mathcal{O}}_1^{ij} = (\bar{q}_i^\alpha \gamma_\mu P_R q_j^\alpha)(\bar{q}_i^\beta \gamma^\mu P_R q_j^\beta)$	$\tilde{C}_{1,dd}^{ij} = \frac{v^2}{2} C_{d^4H^2}^{ijij} + C_{dd}^{ijij},$
	$\tilde{C}_{1,uu}^{ij} = \frac{v^2}{2} C_{u^4H^2}^{ijij} + C_{uu}^{ijij},$
$\mathcal{O}_2^{ij} = (\bar{q}_i^\alpha P_L q_j^\alpha)(\bar{q}_i^\beta P_L q_j^\beta)$	$C_{2,dd}^{ij} = \frac{v^2}{2}\left(C_{q^2d^2H^2}^{(5),xizi*} - \frac{1}{6} C_{q^2d^2H^2}^{(6),xizi*}\right) V_{xj} V_{zj},$
	$C_{2,uu}^{ij} = \frac{v^2}{2}\left(C_{q^2u^2H^2}^{(5),jiji*} - \frac{1}{6} C_{q^2u^2H^2}^{(6),jiji*}\right),$
$\mathcal{O}_3^{ij} = (\bar{q}_i^\alpha P_L q_j^\beta)(\bar{q}_i^\beta P_L q_j^\alpha)$	$C_{3,dd}^{ij} = \frac{v^2}{4} C_{q^2d^2H^2}^{(6),xizi*} V_{xj} V_{zj},$
	$C_{3,uu}^{ij} = \frac{v^2}{4} C_{q^2u^2H^2}^{(6),jiji*},$
$\mathcal{O}_4^{ij} = (\bar{q}_i^\alpha P_L q_j^\alpha)(\bar{q}_i^\beta P_R q_j^\beta)$	$C_{4,dd}^{ij} = \left[-\frac{v^2}{2}\left(C_{q^2d^2H^2}^{(4),xyij} + C_{q^2d^2H^2}^{(3),xyij}\right) - C_{qd}^{(8),xyij}\right] V_{xi}^* V_{yj},$
	$C_{4,uu}^{ij} = \frac{v^2}{2}\left(C_{q^2u^2H^2}^{(4),ijij} - C_{q^2u^2H^2}^{(3),ijij}\right) - C_{qu}^{(8),ijij},$
$\mathcal{O}_5^{ij} = (\bar{q}_i^\alpha P_L q_j^\beta)(\bar{q}_i^\beta P_R q_j^\alpha)$	$C_{5,dd}^{ij} = \left[-v^2\left(C_{q^2d^2H^2}^{(2),xyij} - \frac{1}{6} C_{q^2d^2H^2}^{(4),xyij} + C_{q^2d^2H^2}^{(1),xyij} - \frac{1}{6} C_{q^2d^2H^2}^{(3),xyij}\right) - 2C_{qd}^{(1),xyij} + \frac{1}{3} C_{qd}^{(8),xyij}\right] V_{xi}^* V_{yj},$
	$C_{5,uu}^{ij} = v^2\left(C_{q^2u^2H^2}^{(2),ijij} - \frac{1}{6} C_{q^2u^2H^2}^{(4),ijij} - C_{q^2u^2H^2}^{(1),ijij} + \frac{1}{6} C_{q^2u^2H^2}^{(3),ijij}\right) - 2C_{qu}^{(1),ijij} + \frac{1}{3} C_{qu}^{(8),ijij}.$

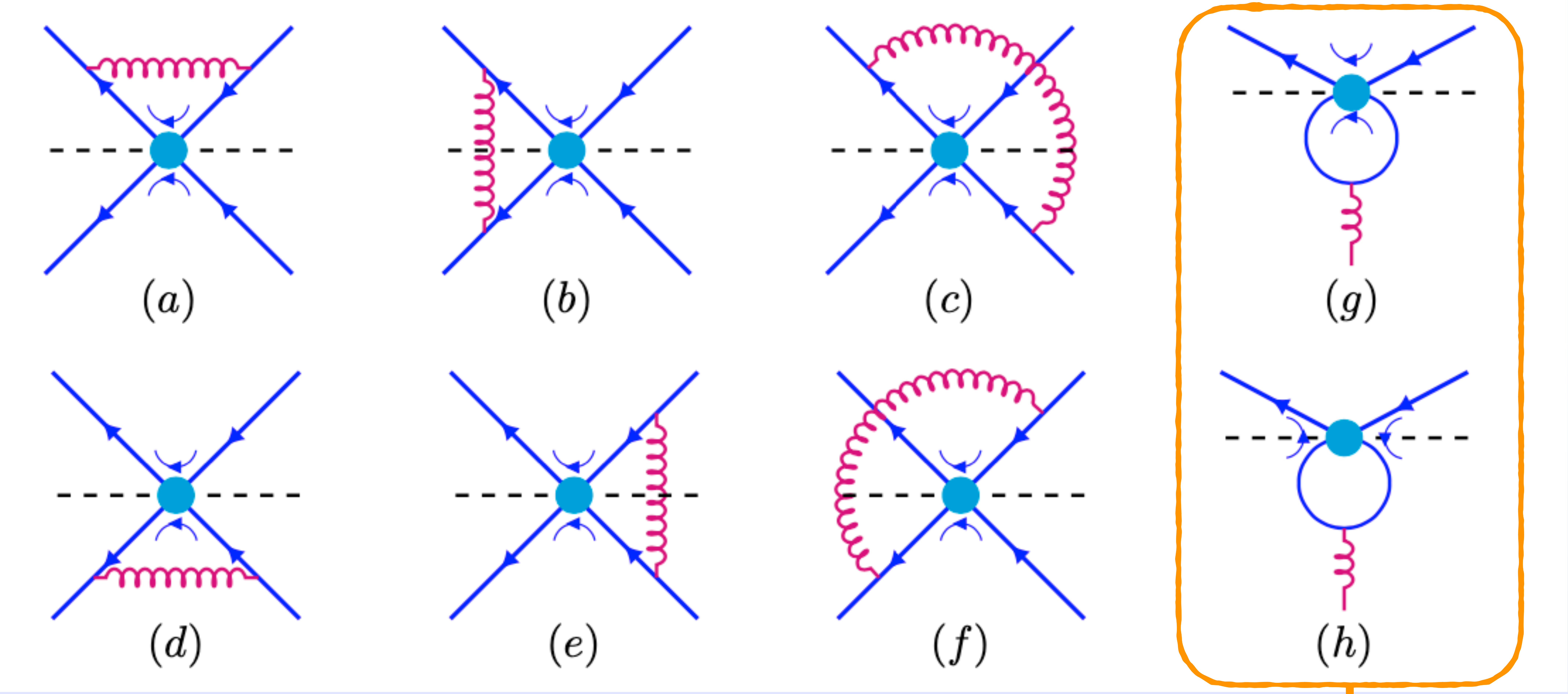
Up-type quark:

flavor basis = mass basis

Down-type quark:

$d_L^f = V_{\text{CKM}} d_L^m$

QCD running effect



No contribution to meson mixing: $\Delta F = 1$

RG equations for Type-II operators

Yi Liao, XDM, Hao-Lin Wang: 2409.10305

$$\mu\frac{d}{d\mu}\begin{pmatrix} C^{(2),xyzw}_{q^4H^2} \\ C^{(2),xwzy}_{q^4H^2} \\ C^{(2),zyxw}_{q^4H^2} \\ C^{(2),zwxy}_{q^4H^2} \\ C^{(5),xyzw}_{q^4H^2} \\ C^{(5),xwzy}_{q^4H^2} \end{pmatrix} = -\frac{\alpha_s}{2\pi}\begin{pmatrix} \frac{3}{N_c} & -\frac{3}{2} & -\frac{3}{2} & 0 & 0 & -6 \\ -\frac{3}{2} & \frac{3}{N_c} & 0 & -\frac{3}{2} & -6 & 0 \\ -\frac{3}{2} & 0 & \frac{3}{N_c} & -\frac{3}{2} & 6 & 0 \\ 0 & -\frac{3}{2} & -\frac{3}{2} & \frac{3}{N_c} & 0 & 6 \\ 0 & -\frac{3}{4} & \frac{3}{4} & 0 & \frac{3}{N_c} & 0 \\ -\frac{3}{2} & 0 & 0 & \frac{3}{4} & 0 & \frac{3}{N_c} \end{pmatrix}\begin{pmatrix} C^{(2),xyzw}_{q^4H^2} \\ C^{(2),xwzy}_{q^4H^2} \\ C^{(2),zyxw}_{q^4H^2} \\ C^{(2),zwxy}_{q^4H^2} \\ C^{(5),xyzw}_{q^4H^2} \\ C^{(5),xwzy}_{q^4H^2} \end{pmatrix},$$

$$\mu\frac{d}{d\mu}\begin{pmatrix} C^{(2),xyzw}_{q^2\psi^2H^2} \\ C^{(4),xyzw}_{q^2\psi^2H^2} \end{pmatrix} = -\frac{\alpha_s}{2\pi}\begin{pmatrix} 0 & \frac{3}{N_c}C_F \\ 6 & 6C_F - \frac{3}{N_c} \end{pmatrix}\begin{pmatrix} C^{(2),xyzw}_{q^2\psi^2H^2} \\ C^{(4),xyzw}_{q^2\psi^2H^2} \end{pmatrix},$$

$$\mu\frac{d}{d\mu}\begin{pmatrix} C^{(5),xyzw}_{q^2\psi^2H^2} \\ C^{(5),xwzy}_{q^2\psi^2H^2} \\ C^{(6),xyzw}_{q^2\psi^2H^2} \\ C^{(6),xwzy}_{q^2\psi^2H^2} \end{pmatrix} = -\frac{\alpha_s}{2\pi}\begin{pmatrix} 6C_F & \frac{4-4N_c^2}{N_c^2} & \frac{N_c^2-4C_FN_c-1}{N_c^2} & \frac{2(N_c^2-C_FN_c^3-1)}{N_c^3} \\ \frac{4-4N_c^2}{N_c^2} & 6C_F & \frac{2(N_c^2-C_FN_c^3-1)}{N_c^3} & \frac{N_c^2-4C_FN_c-1}{N_c^2} \\ -4 & \frac{8}{N_c} & -2C_F & -\frac{4}{N_c^2}-2 \\ \frac{8}{N_c} & -4 & -\frac{4}{N_c^2}-2 & -2C_F \end{pmatrix}\begin{pmatrix} C^{(5),xyzw}_{q^2\psi^2H^2} \\ C^{(5),xwzy}_{q^2\psi^2H^2} \\ C^{(6),xyzw}_{q^2\psi^2H^2} \\ C^{(6),xwzy}_{q^2\psi^2H^2} \end{pmatrix},$$

Such closed form can be solved analytically at 1-loop precision

Type-I operators: same as the corresponding dim6 ones

Alonso *et al*: 1312.2014

Solutions to the RG equations

$$C^{(2),xyzw}_{q^4H^2}(\Lambda_{\rm EW}) = 1.06C^{(2),xyzw}_{q^4H^2} - 0.08(C^{(2),xwzy}_{q^4H^2} + C^{(2),zyxw}_{q^4H^2}) - 0.31C^{(5),xwzy}_{q^4H^2},$$

$$C^{(5),xyzw}_{q^4H^2}(\Lambda_{\rm EW}) = -0.04(C^{(2),xwzy}_{q^4H^2} - C^{(2),zyxw}_{q^4H^2}) + 1.06C^{(5),xyzw}_{q^4H^2}$$

$$C^{(2),xyzw}_{q^2\psi^2H^2}(\Lambda_{\rm EW}) = 1.01C^{(2),xyzw}_{q^2\psi^2H^2} + 0.08C^{(4),xyzw}_{q^2\psi^2H^2},$$

$$C^{(4),xyzw}_{q^2\psi^2H^2}(\Lambda_{\rm EW}) = 0.36C^{(2),xyzw}_{q^2\psi^2H^2} + 1.43C^{(4),xyzw}_{q^2\psi^2H^2},$$

$$C^{(5),xyzw}_{q^2\psi^2H^2}(\Lambda_{\rm EW}) = 1.51C^{(5),xyzw}_{q^2\psi^2H^2} - 0.25C^{(5),xwzy}_{q^2\psi^2H^2} - 0.03C^{(6),xyzw}_{q^2\psi^2H^2} - 0.11C^{(6),xwzy}_{q^2\psi^2H^2},$$

$$C^{(6),xyzw}_{q^2\psi^2H^2}(\Lambda_{\rm EW}) = -0.25C^{(5),xyzw}_{q^2\psi^2H^2} + 0.19C^{(5),xwzy}_{q^2\psi^2H^2} + 0.88C^{(6),xyzw}_{q^2\psi^2H^2} - 0.10C^{(6),xwzy}_{q^2\psi^2H^2},$$

$\Lambda_{\rm EW} = 160\,\mathrm{GeV}$

Defined at $\Lambda_{\rm NP} = 5\,\mathrm{TeV}$

The mixing effect due to the QCD running can be significant in some cases

LEFT master formula

Effective Hamiltonian: $$-\mathscr{H}^{\mathtt{NP},ij}_{\Delta F=2}(\Lambda_{\mathtt{EW}}) = \sum_{a=1}^{5} C_a^{ij}\mathscr{O}_a^{ij} + \sum_{b=1}^{3} \tilde{C}_b^{ij}\tilde{\mathscr{O}}_b^{ij},$$

Off-shell transition: $$M_{12}^{ij} = \frac{\langle M^0 | \mathscr{H}^{ij}_{\Delta F=2} | \overline{M^0}\rangle}{2M_{M^0}} = [M_{12}^{ij}]_{\mathtt{SM}} + [M_{12}^{ij}]_{\mathtt{NP}},$$

Measured quantities: $\Delta M_{K^0} = 2\Re(M_{12}^{ds}),\ \Delta M_{B_i} = 2\,|\,M_{12}^{ib}\,|,\ \Delta M_{D^0} = 2\,|\,M_{12}^{cu}\,|$

$$\boxed{2[M_{12}^{ij}]_{\mathtt{NP}}^{\mathtt{LEFT}} = (\Delta M_{ij})_{\mathtt{exp}}\left[\sum_{a=1}^{5} P_a^{ij}(\Lambda_{\mathtt{EW}})C_a^{ij}(\Lambda_{\mathtt{EW}}) + \sum_{b=1}^{3} P_b^{ij}(\Lambda_{\mathtt{EW}})\tilde{C}_b^{ij}(\Lambda_{\mathtt{EW}})\right], \quad P_a^{ij}(\Lambda_{\mathtt{EW}}) = \frac{\langle M^0 | \mathscr{O}_a^{ij}(\Lambda_{\mathtt{EW}}) | \overline{M^0}\rangle}{M_{M^0}(\Delta M_{ij})_{\mathtt{exp}}}}$$

Aebischer *et al*: 2009.07276

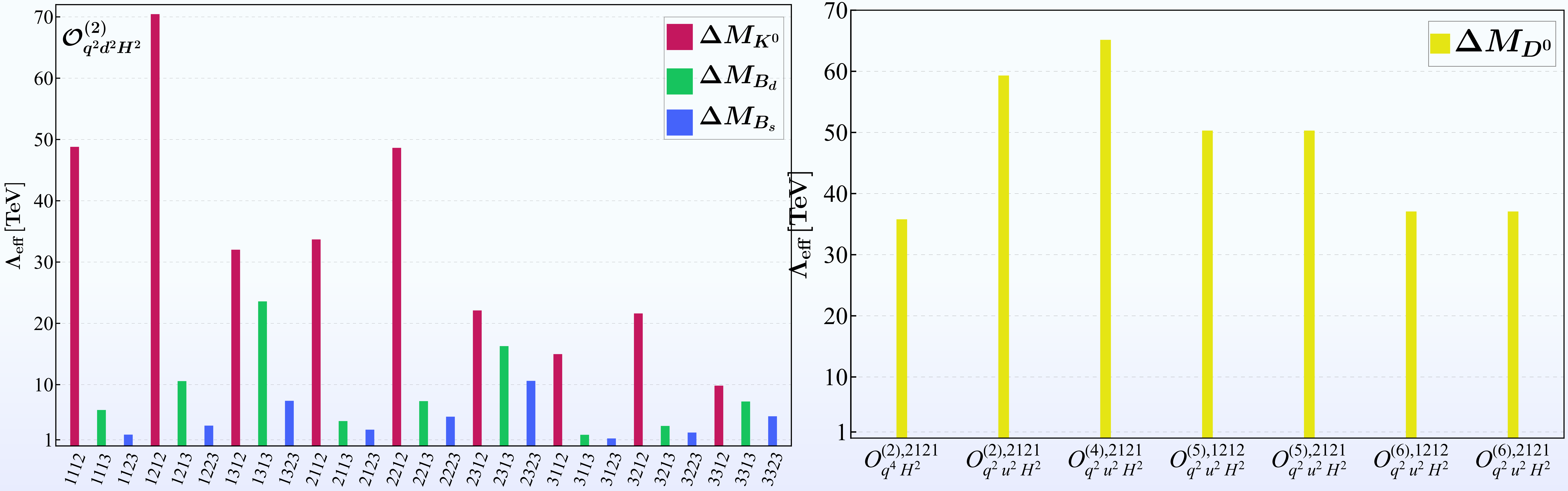
Numerical inputs

Meson	ΔM_{M^0} [GeV] PDG 2024		SUSY basis						
	SM prediction	Experiment	ij	$P_1^{ij}(\Lambda_{\text{EW}})$	$P_2^{ij}(\Lambda_{\text{EW}})$	$P_3^{ij}(\Lambda_{\text{EW}})$	$P_4^{ij}(\Lambda_{\text{EW}})$	$P_5^{ij}(\Lambda_{\text{EW}})$	units
K^0	$5.8(6)(2.3) \times 10^{-15}$	$3.484(6) \times 10^{-15}$	ds	$0.102(2)$	$-4.32(16)$	$1.09(5)$	$14.14(82)$	$4.28(14)$	10^7 TeV^2
D^0	10^{-17}–10^{-14}	$6.56(76) \times 10^{-15}$	cu	$0.54^{+0.17}_{-0.18}$	$-2.11^{+0.65}_{-0.69}$	$0.54^{+0.17}_{-0.18}$	$5.94^{+1.88}_{-1.96}$	$2.04^{+0.64}_{-0.67}$	10^7 TeV^2
B_d	$3.521(138) \times 10^{-13}$	$3.336(12) \times 10^{-13}$	db	$2.67(10)$	$-4.99(28)$	$1.12(8)$	$12.74(50)$	$5.15(27)$	10^5 TeV^2
B_s	$1.1999(415) \times 10^{-11}$	$1.1693(4) \times 10^{-11}$	sb	$1.15(4)$	$-2.24(13)$	$0.51(3)$	$5.22(21)$	$2.10(9)$	10^4 TeV^2

- $K^0, B_{d,s}$: SM prediction and experimental data show good consistency
- D^0: Large uncertainty for SM prediction

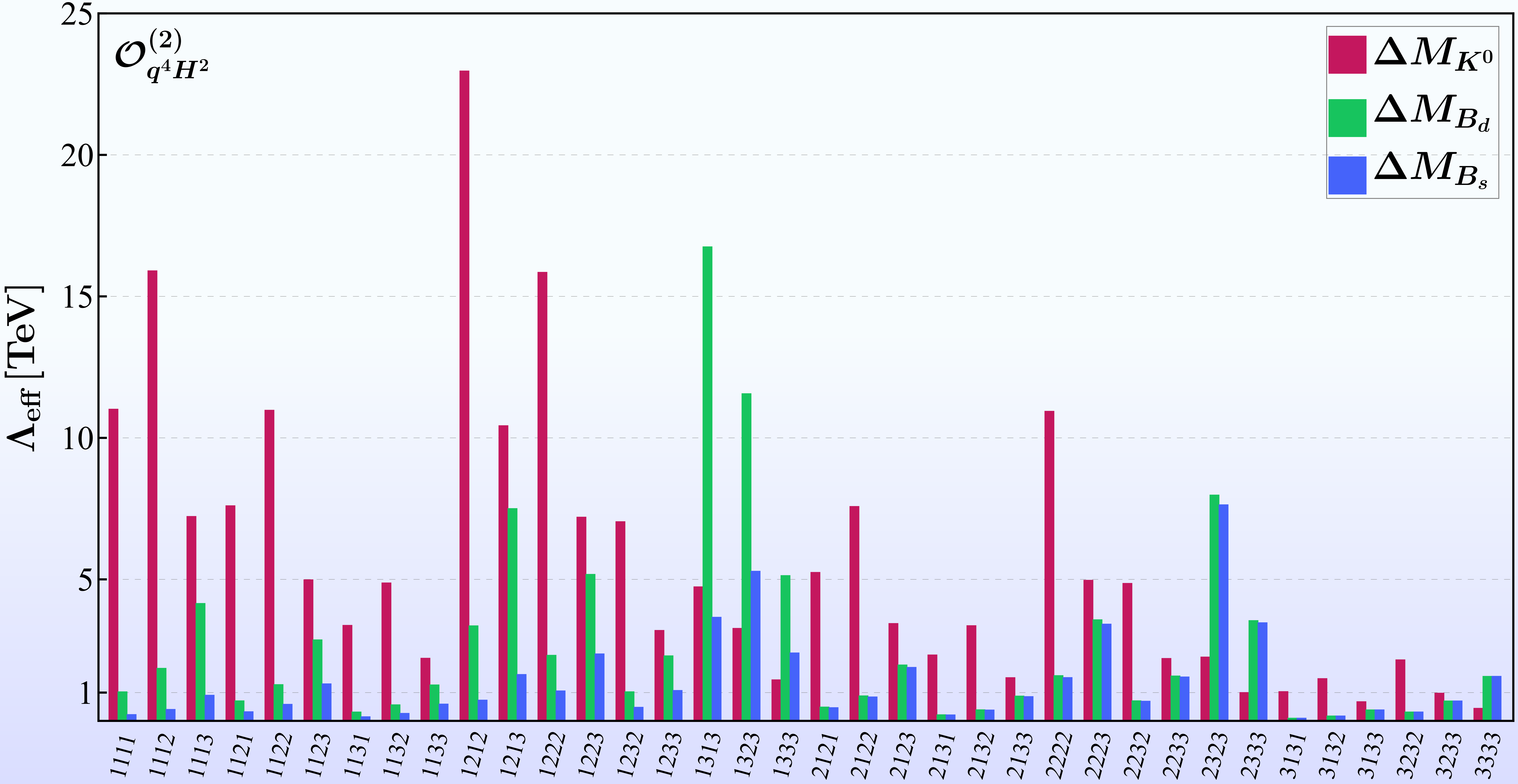
Numerical bound: $2[M_{12}^{ij}]_{\text{NP}}^{\text{LEFT}}/(\Delta M_{ij})_{\text{exp}} \lesssim 10\,\%$

Constraints on effective scale at Λ_{EW}



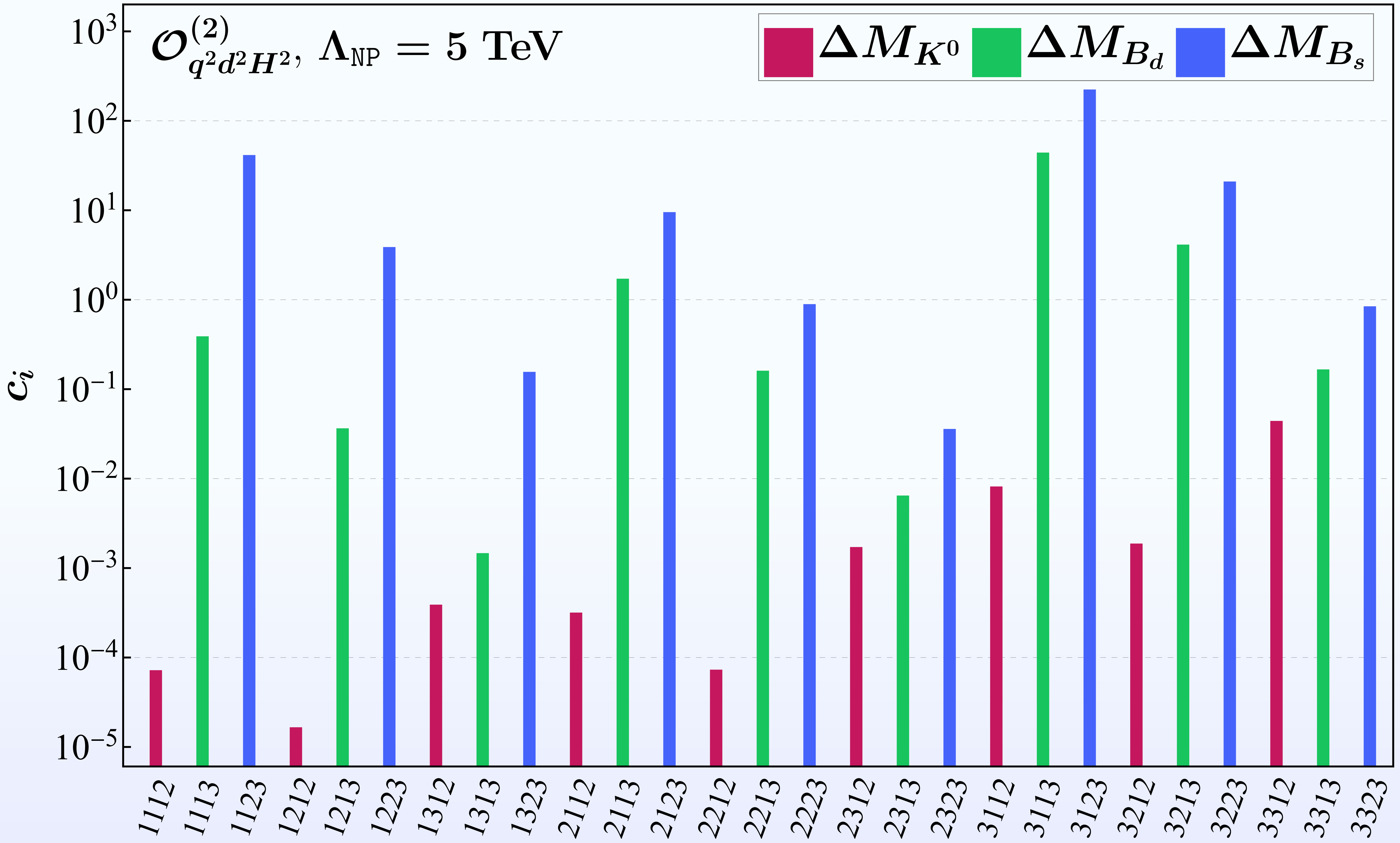
- Many generation combinations can be constrained
- Effective scale for most of operators can reach to tens of TeV

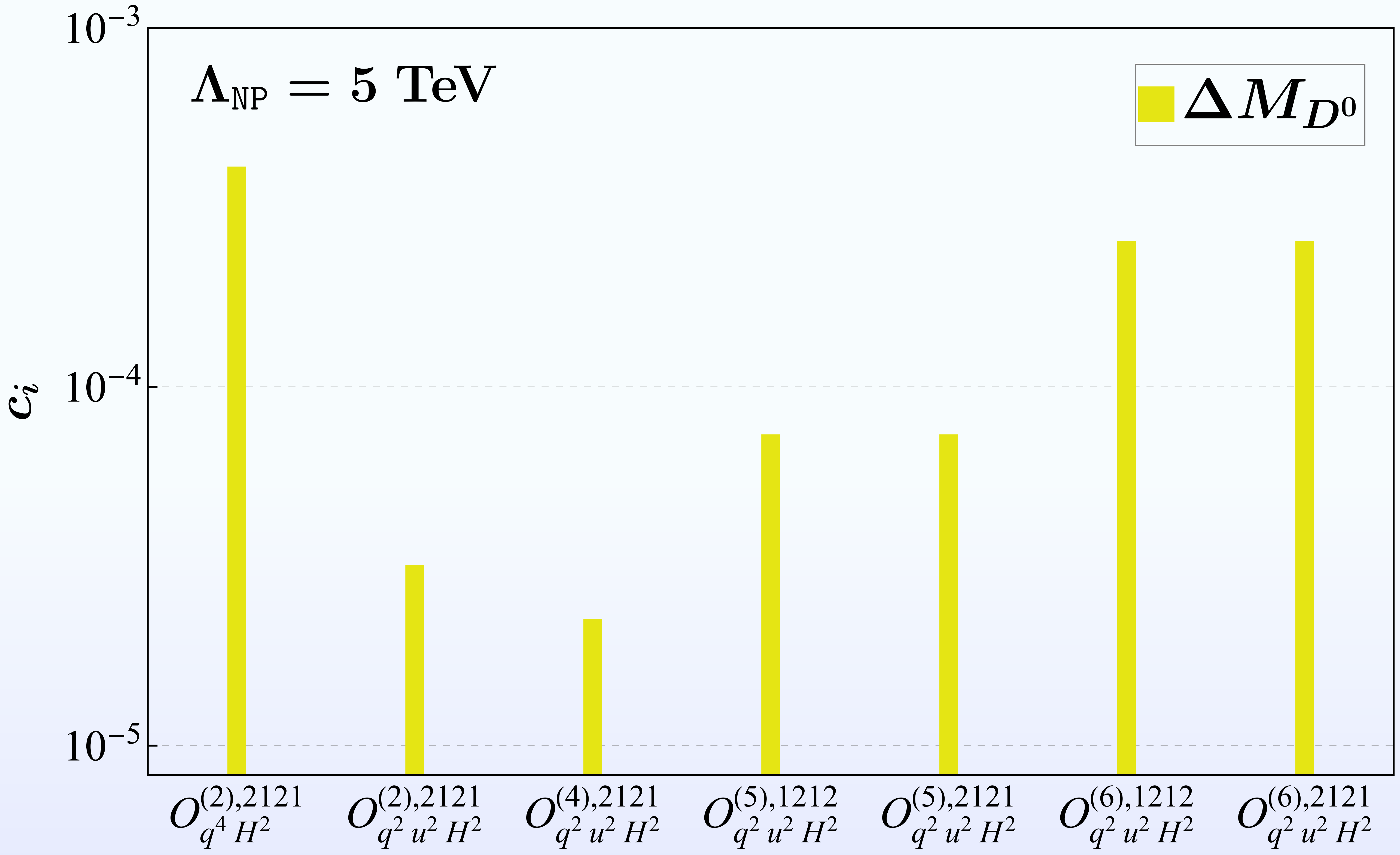
More generation combinations are constrained



CKM matrix's role

Constraints on dimensionless couplings at $\mu_\Lambda = 5\,\mathrm{TeV}$





Such bounds are much stronger than those from collider searches

$$\frac{c_i}{\Lambda^4_{\mathrm{NP}}}$$

A scalar DM model to $B \to K\nu\bar{\nu}$ anomaly

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\texttt{BelleII}} = (2.3 \pm 0.7) \times 10^{-5}$$
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\texttt{SM}} = (4.43 \pm 0.31) \times 10^{-6}$$

Belle-II: 2311.14647

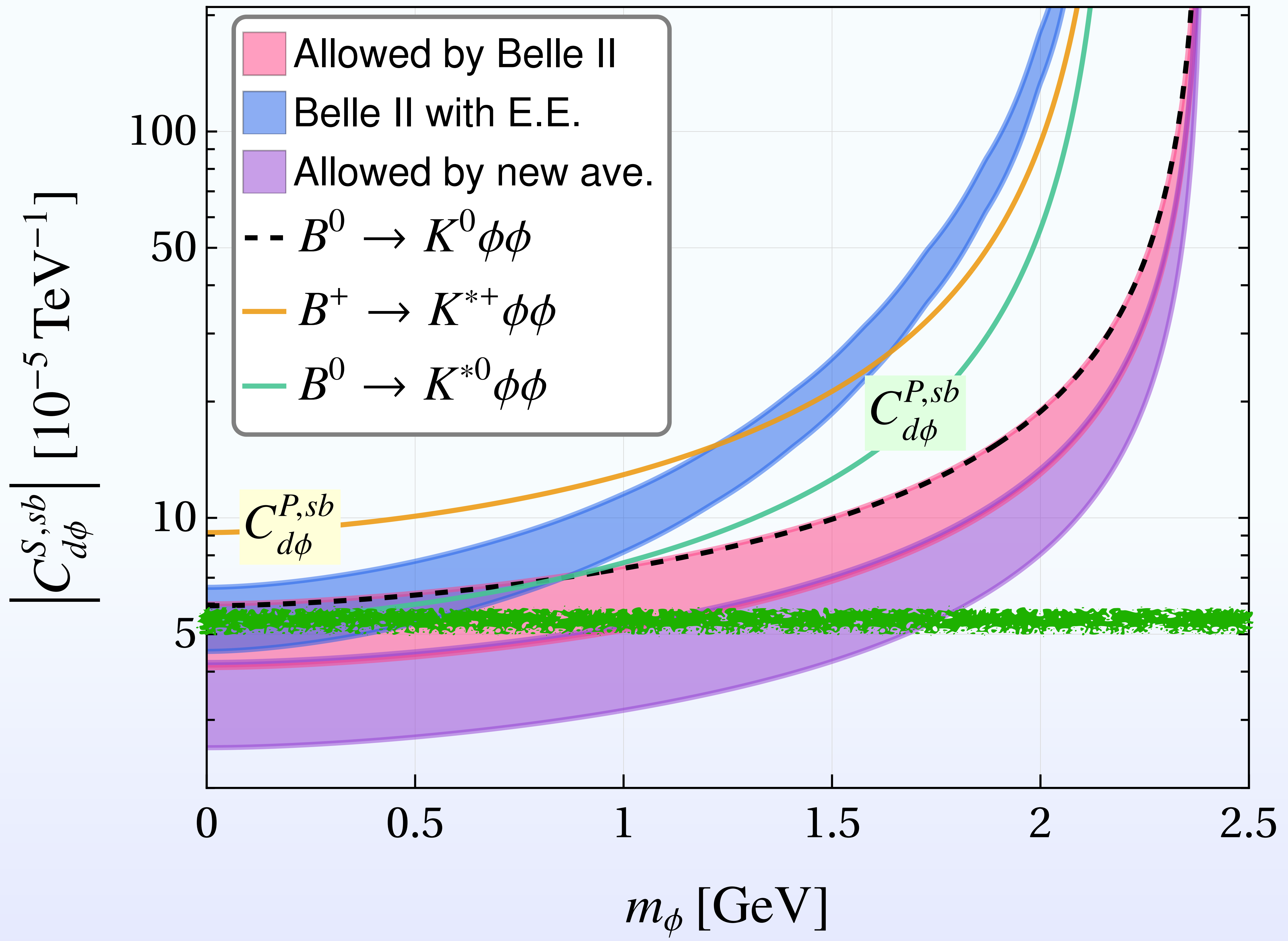
SM + a real scalar ϕ (DM)+ two vector-like quarks Q (q_L), $D(d_R)$

$\mathbb{Z}_2$ symmetry: odd of new particles

$$\mathcal{L}^{\rm NP}_{\texttt{kinetic}} = \bar{Q}i\not{D}Q - m_Q\bar{Q}Q + \bar{D}i\not{D}D - m_D\bar{D}D + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2,$$
$$\mathcal{L}^{\rm NP}_{\texttt{Yukawa}} = y_q^p\bar{q}_{Lp}Q_R\phi + y_d^p\bar{D}_Ld_{Rp}\phi - \boxed{y_1\bar{Q}_LD_RH} - y_2\bar{Q}_RD_LH + \text{h.c.}\ ,$$
$$V^{\rm NP}_{\texttt{potential}} = \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}\kappa\,\phi^2H^\dagger H\ ,$$

X.-G. He, XDM, M. A. Schmidt, G. Valencia and R. R. Volkas: 2403.12485

Belle II anomaly

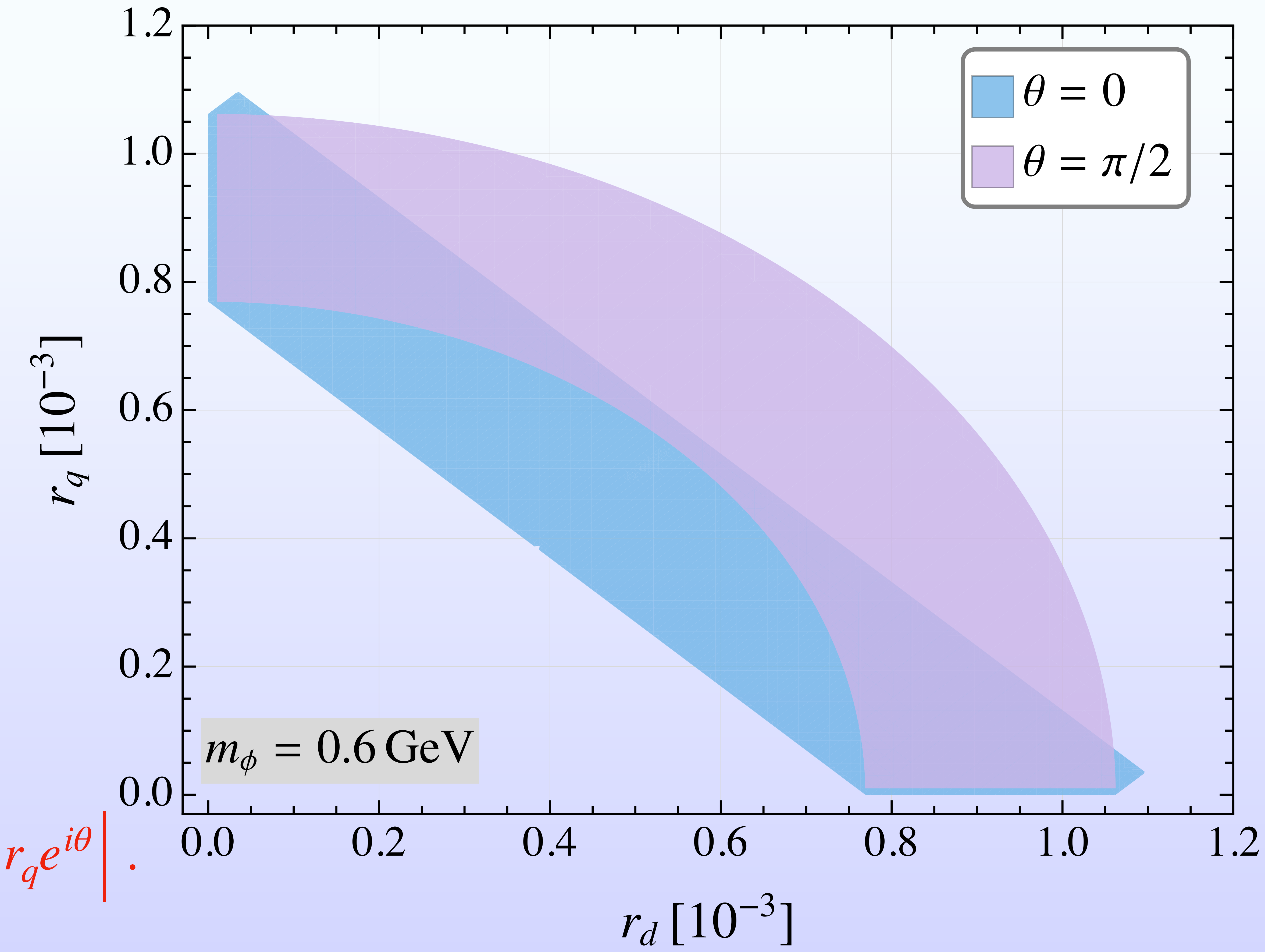


$$m_Q = m_D = 3\,\text{TeV} \quad |y_d^s| = |y_q^s| = 2$$

$$y_q^i \equiv |y_q^i| e^{-i\alpha_i}, \quad y_d^i \equiv |y_d^i| e^{-i\beta_i}$$

$$\alpha_s + \beta_s = \rho, \quad \alpha_b + \beta_b + \rho \equiv \theta$$

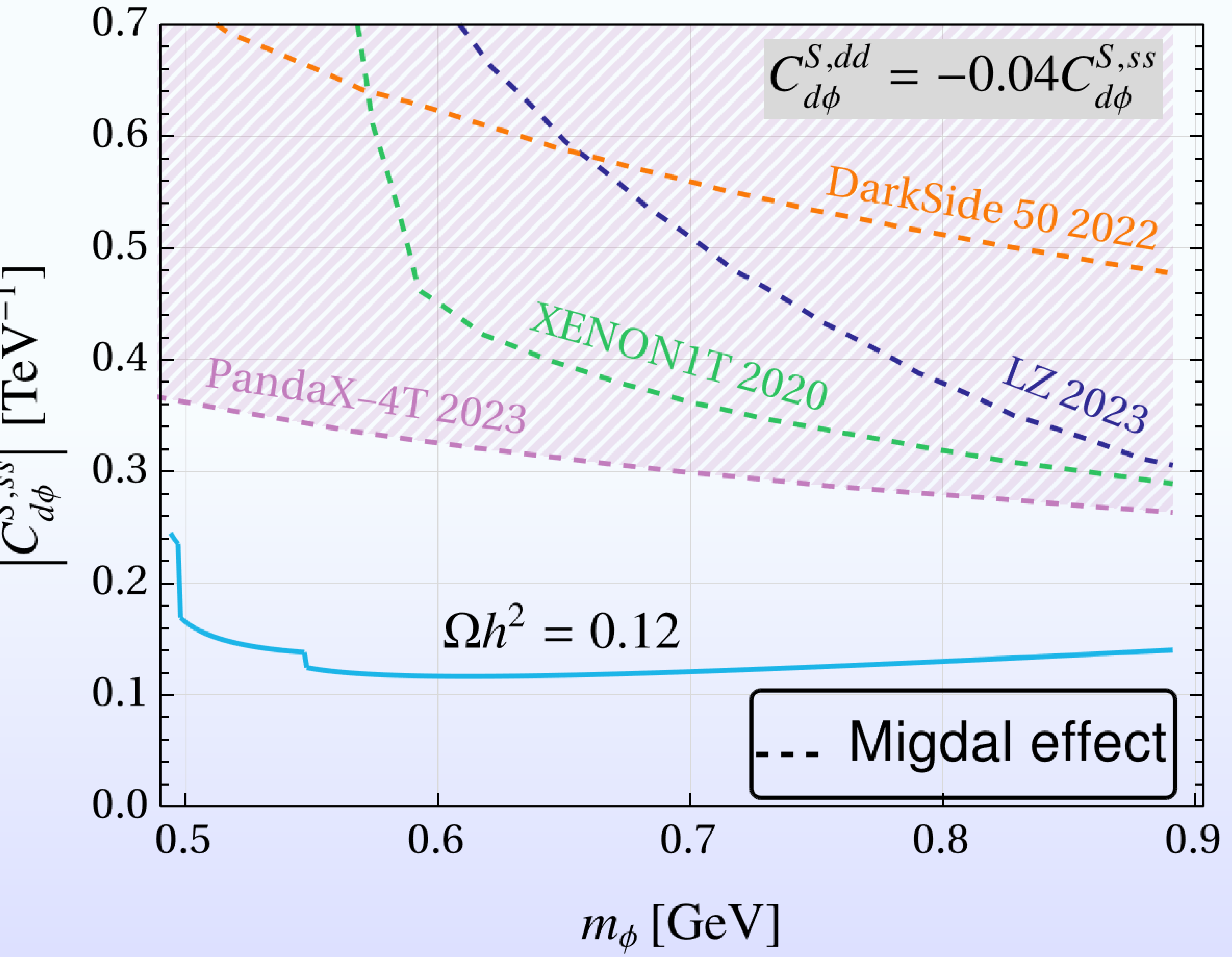
$$|y_d^b|/|y_d^s| \equiv r_d, \quad |y_q^b|/|y_q^s| \equiv r_q\,.$$

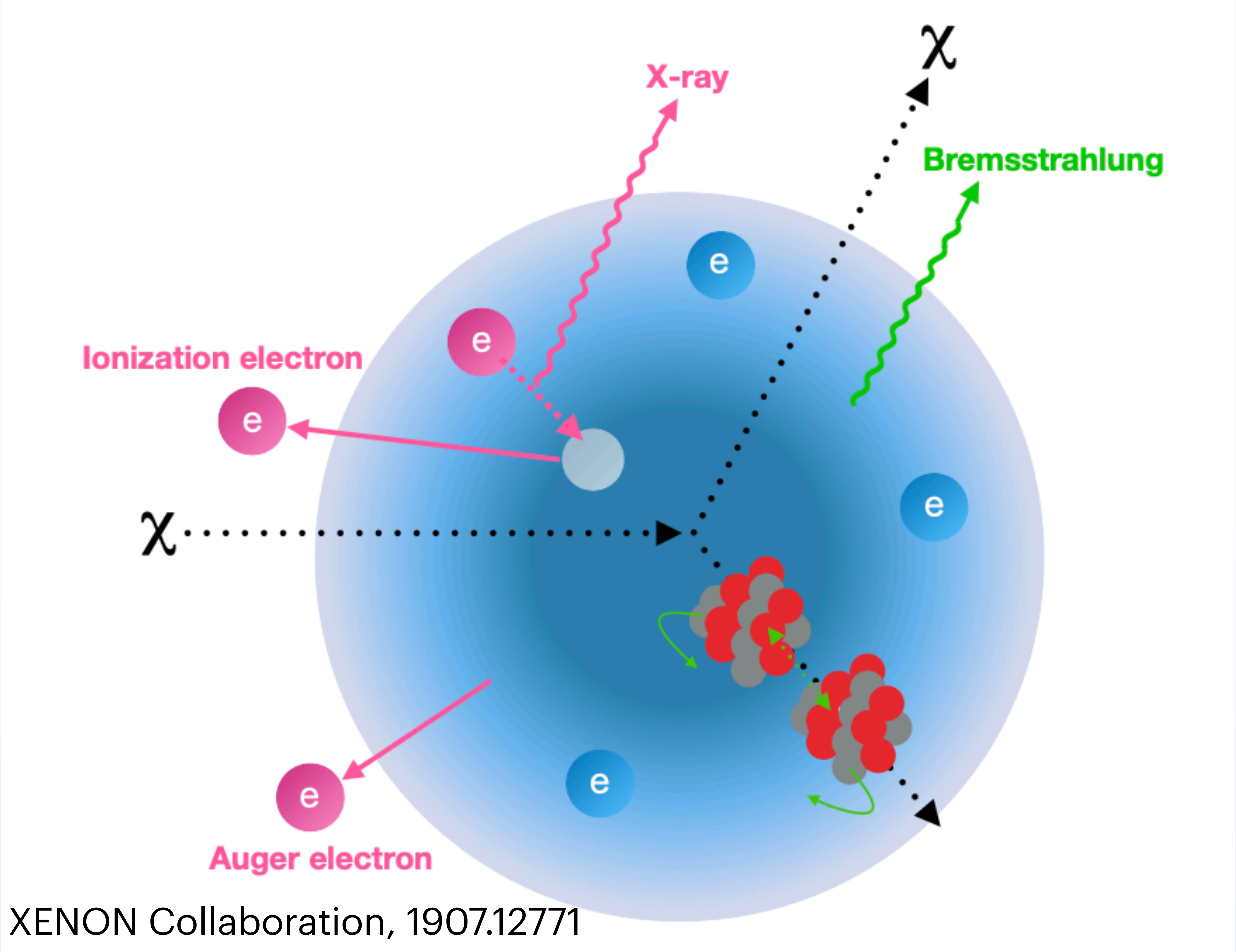


$$\mathcal{L}_{\phi\phi qq}^{\text{LEFT}} = \frac{1}{2} C_{d\phi}^{S,ij} (\bar{d}_i d_j)\phi^2 + \frac{1}{2} C_{d\phi}^{P,ij} (\bar{d}_i i\gamma_5 d_j)\phi^2 \,.$$

$$|C_{d\phi}^{S,ss}| \approx \frac{|y_q^s||y_d^s| y_1 v}{\sqrt{2} m_Q m_D} \left|1 + e^{i2\rho}\right|, \quad |C_{d\phi}^{S(P),sb}| \approx \frac{|y_q^s||y_d^s| y_1 v}{\sqrt{2} m_Q m_D} \left|r_d \pm r_q e^{i\theta}\right|.$$

DM relic density





- Isospin-violating DM scenario
- Safe from mono-γ search @ collider

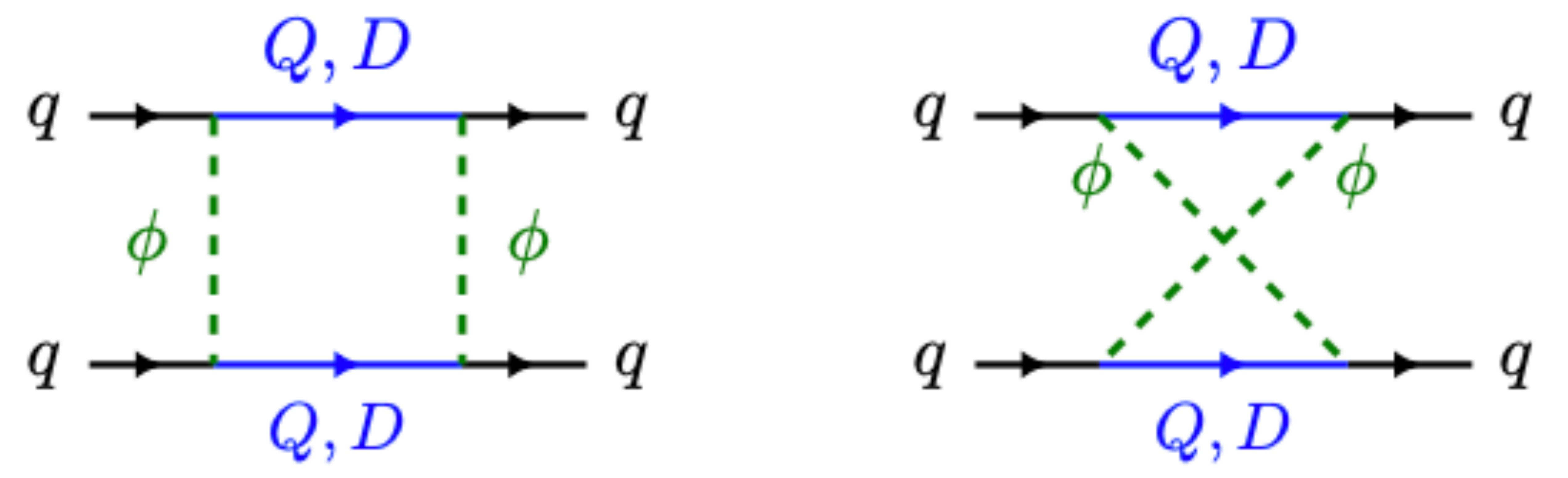
Thermal freezeout: $\phi\phi \to K\bar{K}$ and $\eta\eta$

New contributions to meson mixing

- **No dim-6 contribution**

  Cancellation for the two diagrams

- **Dim-8 contribution**



Type-I: $\mathcal{O}^{(1),(3)}_{q^2d^2H^2}$; Type-II: $\mathcal{O}^{(2),(4)}_{q^2d^2H^2}$ and $\mathcal{O}^{(5)}_{q^2d^2H^2}$

$h_{1,2}$: Loop functions

$$C^{(5),xyzw}_{q^2d^2H^2} = -\frac{y_q^x y_d^y y_q^z y_d^w y_1^2}{16\pi^2 m_Q^2 m_D^2} h_1, \quad C^{(3),xyzw}_{q^2d^2H^2} = \frac{y_q^x y_q^{y*} y_d^{z*} y_d^w |y_1|^2}{16\pi^2 m_Q^2 m_D^2} h_2,$$

$$C^{(1),xyzw}_{q^2d^2H^2} = \frac{1}{6} C^{(3),xyzw}_{q^2d^2H^2}, \; C^{(2),xyzw}_{q^2d^2H^2} = \frac{1}{6} C^{(3),xyzw}_{q^2d^2H^2}, \; C^{(4),xyzw}_{q^2d^2H^2} = C^{(3),xyzw}_{q^2d^2H^2}.$$

$$\left|\frac{2[M_{12}^{ds}]_{\mathtt{NP}}^{\mathtt{LEFT}}}{(\Delta M_{ds})_{\mathtt{exp}}}\right| = 471\left|\,|y_q^d|^2 e^{i\theta_{ds}} + |y_d^d|^2 e^{-i\theta_{ds}} - 4.49\,|y_q^d|\,|y_d^d|\,\right|\,|h_1|,$$

$$\left|\frac{2[M_{12}^{sb}]_{\mathtt{NP}}^{\mathtt{LEFT}}}{(\Delta M_{sb})_{\mathtt{exp}}}\right| = 0.24\left|\,|y_d^b|^2 e^{i\theta_{sb}} + |y_q^b|^2 e^{-i\theta_{sb}} - 3.20\,|y_d^b|\,|y_q^b|\,\right|\,|h_1|,$$

$$\left|\frac{2[M_{12}^{db}]_{\mathtt{NP}}^{\mathtt{LEFT}}}{(\Delta M_{db})_{\mathtt{exp}}}\right| = 1.36\left|\,|y_q^d|^2|y_d^b|^2 e^{i\theta_{db}} + |y_d^d|^2|y_q^b|^2 e^{-i\theta_{db}} - 3.50\,|y_q^d|\,|y_q^b|\,|y_d^d|\,|y_d^b|\,\right|\,|h_1|.$$

$< 10\,\%$

$\mathcal{O}(0.1)$ Yukawa couplings $\longrightarrow$ a stringent bound on $|h_1| \lesssim 10^{-3}$

Summary

- Meson mixing observables are sensitive to NP effect, and we apply them to probe dim-8 SMEFT operators and set stringent bound on the effective scale;

- The QCD running effect is calculated which is important when interpolating the low energy bound onto a higher NP scale;

- A UV model, which is built to explain the recent Belle-II $B \to K\nu\bar{\nu}$ excess and dark matter, is provided to generate dim-8 operators while avoid dim-6 ones responsible for neutral meson mixing.

Thank you for your time!