A bottom-up approach to nucleon decay RGEs, correlations and connection to UV

Arnau Bas i Beneito.14th of January, 2025

Baryon Number Violation:
From Nuclear Matrix Elements to BSM physics

Based on work in collaboration with J. Gargalionis, J. Herrero-García, M. A. Schmidt. A. Santamaria [2312.13361] (published in JHEP)

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Proton decay within the SM

$$\mathscr{L}_{SM}$$

$$SU(3)_C \times SU2)_L \times U(1)_Y$$

$$+$$

$$H,\ Q_L^i,\ u_R^i,\ d_R^i,\ L_L^i,\ e_R^i,\ i = 1,\ 2,\ 3$$

Individual Flavour Symmetries

$\downarrow$ Yukawa couplings

$$U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \times U(1)_B$$

$\downarrow$ ν oscillations *[Super-K 1999, KamLAND 2003...]*

$$U(1)_L \times U(1)_B$$

B and L accidentally conserved

(B + L violated in 3 units by sphaleron transitions)

$\downarrow$

Proton stable

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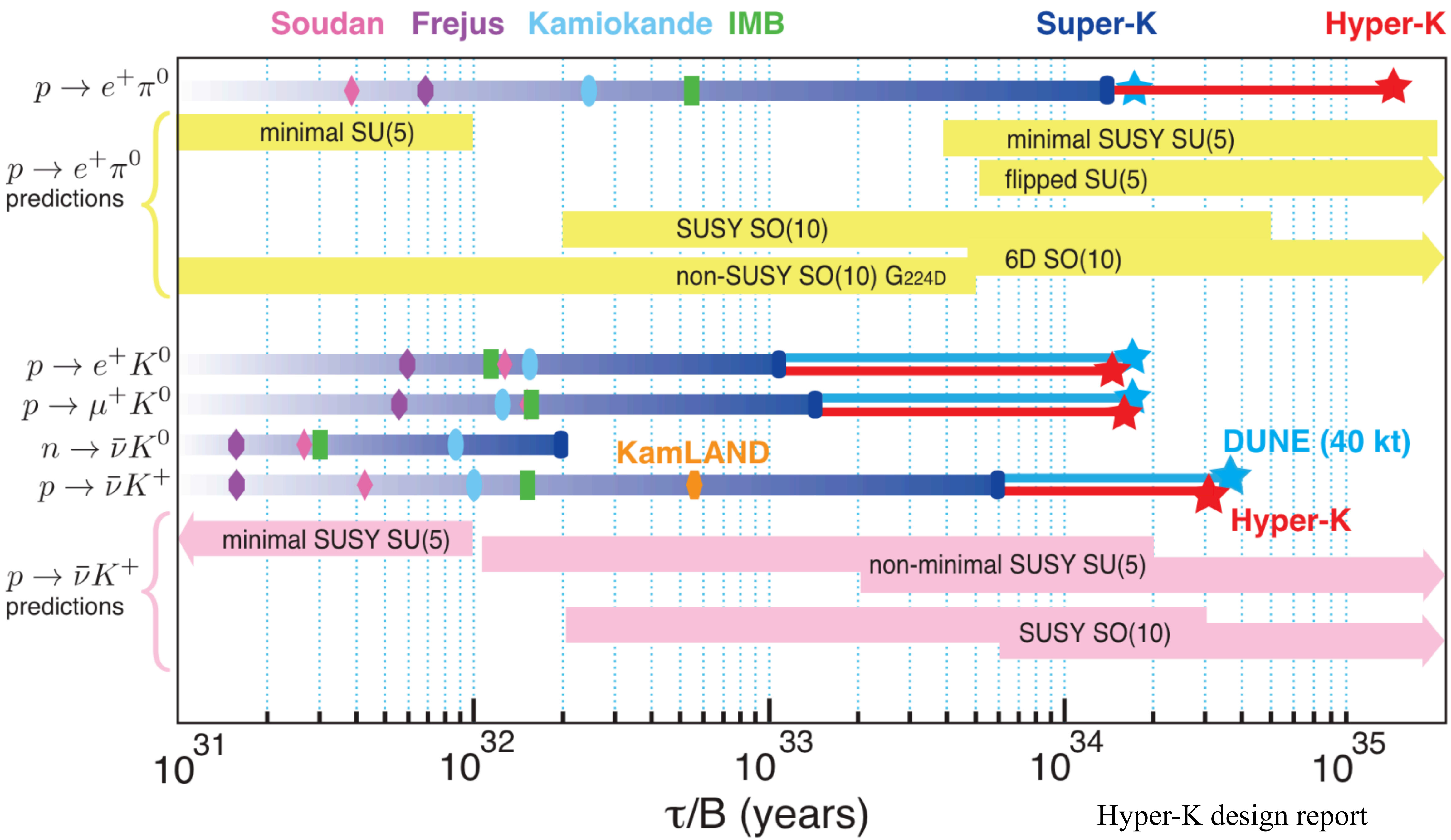
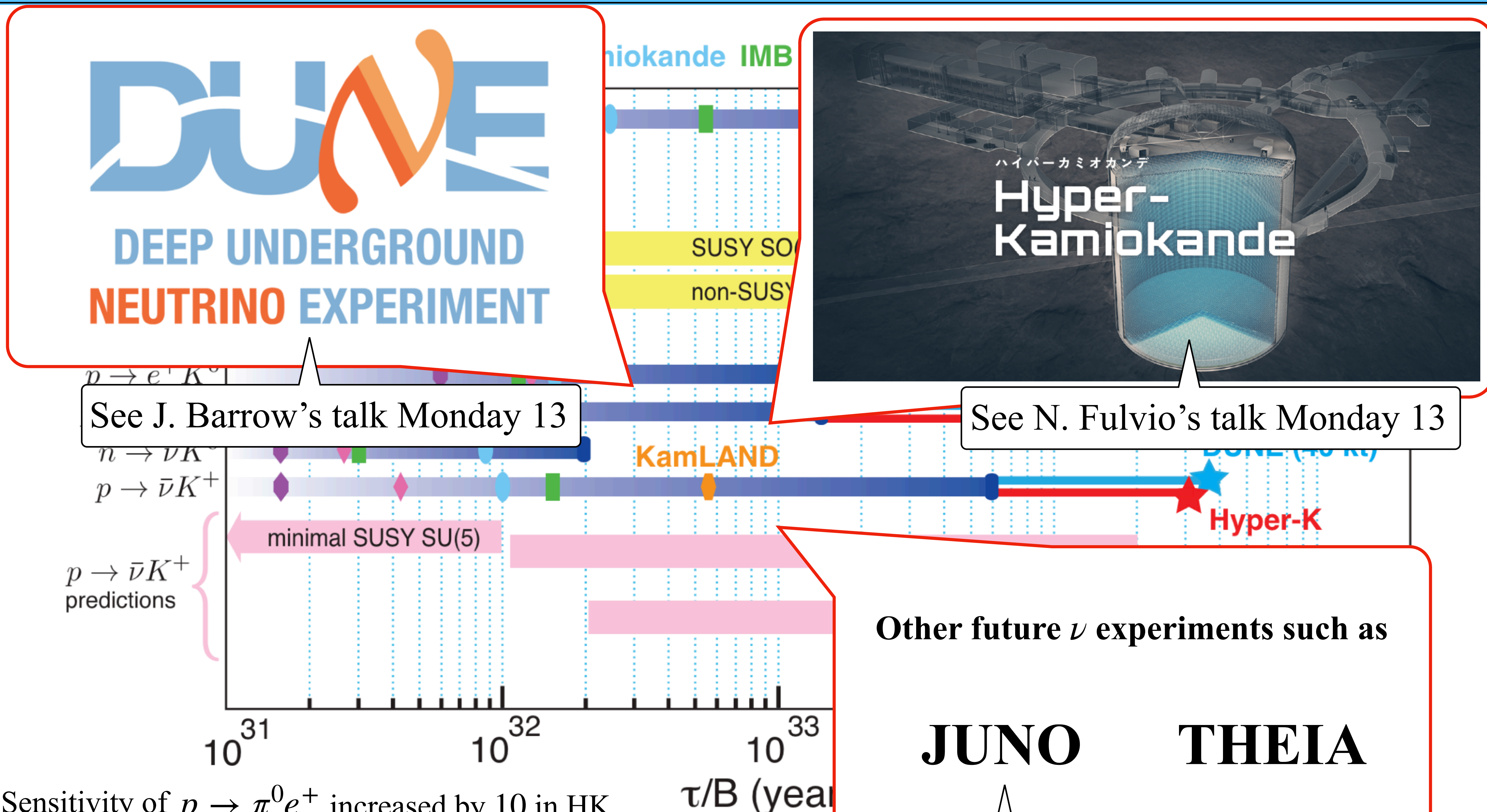
Proton stable

Experimental perspectives



Hyper-K design report

Experimental perspectives



See J. Barrow's talk Monday 13

See N. Fulvio's talk Monday 13

Other future ν experiments such as

JUNO THEIA

See C. Jiang's talk Monday 13

Sensitivity of $p \to \pi^0 e^+$ increased by 10 in HK

Sensitivity of $p \to K^+ \nu$ increased by 10 in HK/DUNE

Sensitivity of $n \to K^+ e^-$ increased by 10^3 in HK

BNV nucleon decay could be the next big discovery

Theoretical arguments

· **There is** **no fundamental reason** **to have B and L conserved (Leptoquarks, Seesaw particles, SUSY, GUTs…) → B and L conservation arise accidentally in the SM**

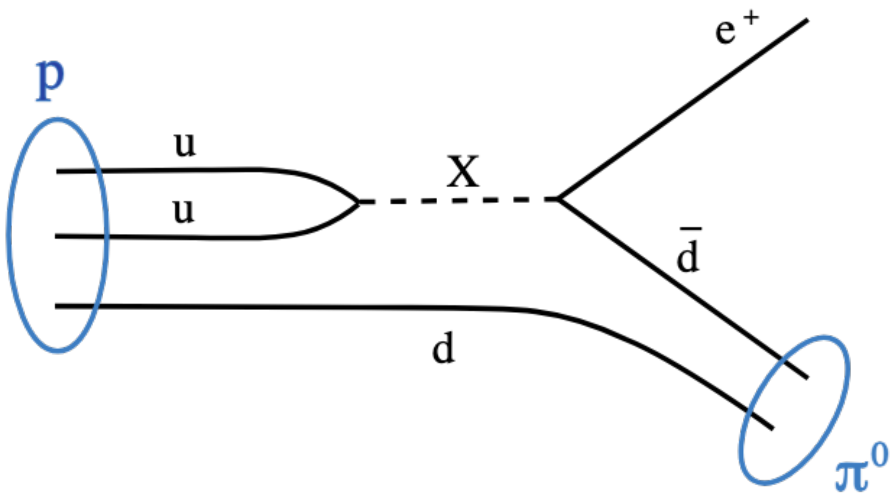
· **Experimental probes of BNV and LNV would constitute one of the** **strongest evidence** **for physics beyond SM (BSM) →Proton Decay will be searched in future experiments (HK, DUNE…)**

Grand Unified Theories (GUTs)
[*Georgi et. al. 1973, H. Fritzsch et al. 1975*]

Baryogenesis
[*Sakharov 1967*]

Baryon Number violation (BNV)

E.g. proton decay (PD), neutron-antineutron oscillations



Large number of UV theories predicting PD

↓

Systematic study of PD in a model-independent way (bottom-up)

BNV within the SMEFT

Parametrization of new physics through Effective operators (d > 4)
SM Effective Field Theory (SMEFT)

Bounds on SMEFT WCs serve as a bridge to specific UV models

[S. Weinberg 1979 ,
B. Grzadkowski et al. 2010,
W. Buchmuller et al. 1986,
Brivio et al. 2019,
B. Henning et al. 2016,
De Gouvea et al. 2014]

$$\mathscr{L} = \mathscr{L}_{SM} + \underbrace{\frac{c^{d=5}}{\Lambda}\mathcal{O}_W}_{\Delta L = 2} + \underbrace{\frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6}}_{\Delta(B-L)=0} + \underbrace{\frac{c^{d=7}}{\Lambda^3}\mathcal{O}^{d=7}}_{\Delta(B-L)=2} + \dots$$

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$\Delta L = 2$ → $\frac{c^{d=5}}{\Lambda}\mathcal{O}_W$

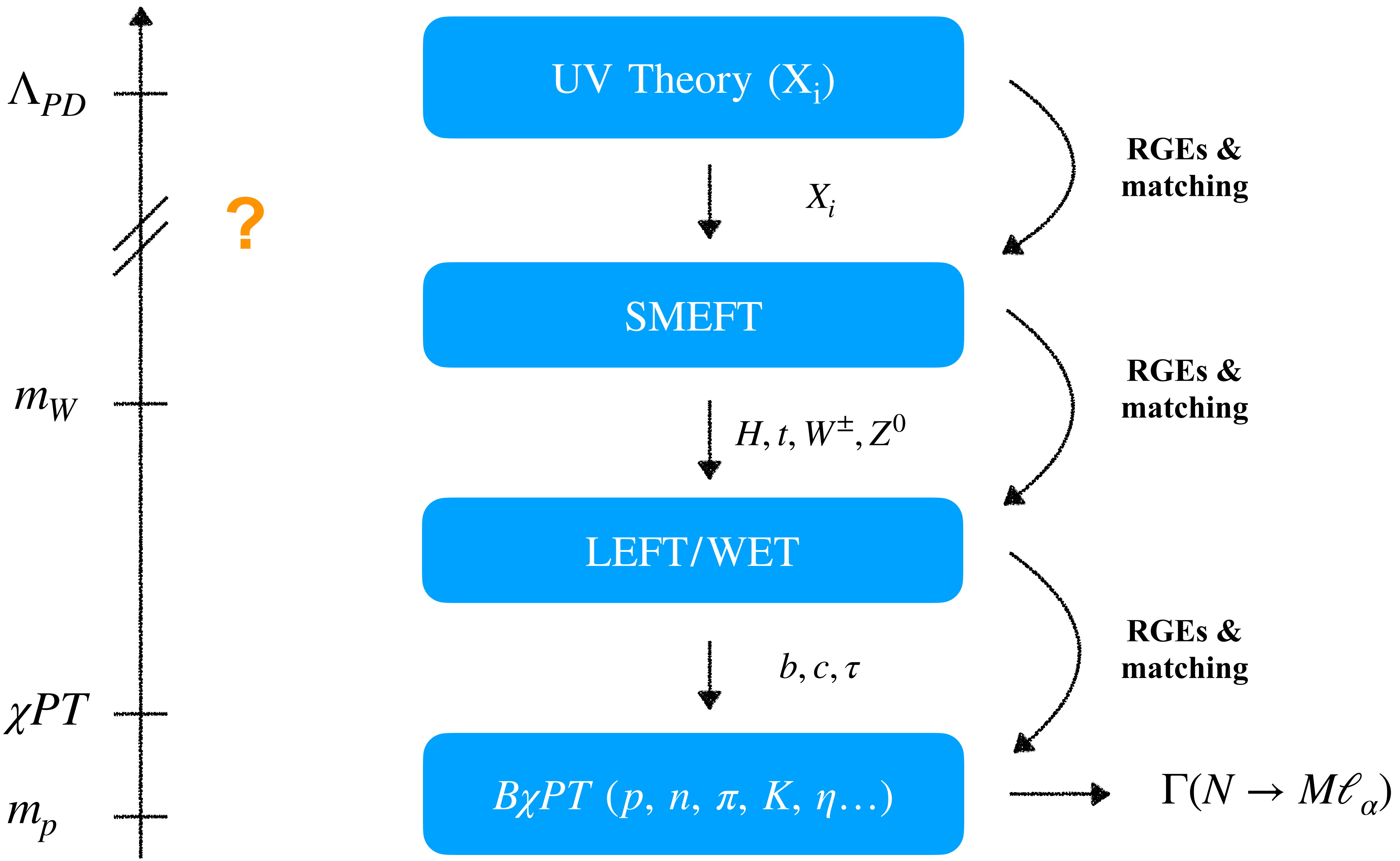
$\Delta(B-L) = 0$ → $\frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6}$ → $\Lambda \gtrsim 10^{15}$ GeV: $p \to \pi^0 e^+$, $\boxed{p \to K^+ \bar{\nu}}$

$\Delta(B-L) = 2$ → $\frac{c^{d=7}}{\Lambda^3}\mathcal{O}^{d=7}$ → $\Lambda \gtrsim 10^{10}$ GeV: $n \to \pi^+ e^-$, $\boxed{p \to K^+ \nu}$

Different phenomenology ⟶

Indistinguishable final states in detectors

BNV within the SMEFT



· **Assumptions: Energy Desert and no SUSY in the TeV scale/RpV**

[S. Antusch et al. 2021, H. Dreiner et al. 2020]

SMEFT

$d = 6 \rightarrow$ 4 operators $\rightarrow$ 273 independent components [L. F. Abbott et al. 1980, B. Grzadkowski et al. 2010]

$$\mathcal{O}_{qqql,pqrs} = (Q^i_p Q^j_q)(Q^l_r L^k_s)\epsilon_{ik}\epsilon_{jl}\,, \quad \mathcal{O}_{qque,pqrs} = (Q^i_p Q^j_q)(\bar{u}^\dagger_r \bar{e}^\dagger_s)\epsilon_{ij}\,,$$
$$\mathcal{O}_{duue,pqrs} = (\bar{d}^\dagger_p \bar{u}^\dagger_q)(\bar{u}^\dagger_r \bar{e}^\dagger_s)\,, \quad \mathcal{O}_{duql,pqrs} = (\bar{d}^\dagger_p \bar{u}^\dagger_q)(Q^i_r L^j_s)\epsilon_{ij}\,,$$

$d = 7 \rightarrow$ 6 operators $\rightarrow$ 297 independent components [L. Lehman 2014, Yi Liao et al. 2016]

$$\mathcal{O}_{\bar{l}dddH,pqrs} = (L^\dagger_p \bar{d}^\dagger_q)(\bar{d}^\dagger_r \bar{d}^\dagger_s)H\,, \quad \mathcal{O}_{\bar{l}dqq\tilde{H},pqrs} = (L^\dagger_p \bar{d}^\dagger_q)(Q_r Q^i_s)\tilde{H}^j\epsilon_{ij}\,,$$
$$\mathcal{O}_{\bar{e}qdd\tilde{H},pqrs} = (\bar{e}_p Q^i_q)(\bar{d}^\dagger_r \bar{d}^\dagger_s)\tilde{H}^j\epsilon_{ij}\,, \quad \mathcal{O}_{\bar{l}dud\tilde{H},pqrs} = (L^\dagger_p \bar{d}^\dagger_q)(\bar{u}^\dagger_r \bar{d}^\dagger_s)\tilde{H}\,,$$
$$\mathcal{O}_{\bar{l}qdDd,pqrs} = (L^\dagger_p \bar{\sigma}^\mu Q_q)(\bar{d}^\dagger_r i\overleftrightarrow{D}_\mu \bar{d}^\dagger_s)\,, \quad \mathcal{O}_{\bar{e}dddD,pqrs} = (\bar{e}_p \sigma^\mu \bar{d}^\dagger_q)(\bar{d}^\dagger_r i\overleftrightarrow{D}_\mu \bar{d}^\dagger_s)\,,$$

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$$\mathcal{O}_{\bar{e}qdd\tilde{H},pqrs} = (\bar{e}_p Q_q^i)(\bar{d}_r^\dagger \bar{d}_s^\dagger)\tilde{H}^j\epsilon_{ij}\,, \quad \mathcal{O}_{\bar{l}dud\tilde{H},pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(\bar{u}_r^\dagger \bar{d}_s^\dagger)\tilde{H}\,,$$
$$\cancel{\mathcal{O}_{\bar{l}qdDd,pqrs} = (L_p^\dagger \bar{\sigma}^\mu Q_q)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger)}\,, \quad \cancel{\mathcal{O}_{\bar{e}dddD,pqrs} = (\bar{e}_p \sigma^\mu \bar{d}_q^\dagger)(\bar{d}_r^\dagger i\overleftrightarrow{D}_\mu \bar{d}_s^\dagger)}\,,$$

Not Higgs-vev enhanced
Match onto d-7 LEFT ops.

Bounds in some components in
[J. Gargalionis et al. 2024]

$$\left.\begin{aligned} c^{d=6}(m_W) &\sim (2-4)\; c^{d=6}(10^{15}\ \text{GeV}) \\ c^{d=7}(m_W) &\sim (1-2)\; c^{d=7}(10^{11}\ \text{GeV}) \end{aligned}\right\}$$

From gauge interactions and y_t
(Operator mixing subdominant)

· **RGEs for d = 6 SMEFT** [A. Manohar et al. 2014]
· **RGEs for d = 7 SMEFT** [Yi Liao et al. 2016]

LEFT

6 $\Delta(B-L)=0$ operators → 288 independent components → 14 components

$\nu_\alpha \equiv \nu \quad L_\alpha \equiv e_L$

5 $|\Delta(B-L)|=2$ operators → 228 independent operators → 9 components

$\nu_\alpha \equiv \nu \quad L_\alpha \equiv e_L$

LEFT components involved in nucleon decay at tree level

Name [52]	SMEFT matching
$[\mathcal{O}^{S,LL}_{udd}]_{pqrs}$	$V_{q'q}V_{r'r}(C_{qqql,r'q'ps} - C_{qqql,q'r'ps} + C_{qqql,q'pr's})$
$[\mathcal{O}^{S,LL}_{duu}]_{pqrs}$	$V_{p'p}(C_{qqql,rqp's} - C_{qqql,qrp's} + C_{qqql,qp'rs})$
$[\mathcal{O}^{S,LR}_{duu}]_{pqrs}$	$-V_{p'p}(C_{qque,p'qrs} + C_{qque,qp'rs})$
$[\mathcal{O}^{S,RL}_{duu}]_{pqrs}$	$C_{duql,pqrs}$
$[\mathcal{O}^{S,RL}_{dud}]_{pqrs}$	$-V_{r'r}C_{duql,pqr's}$
$[\mathcal{O}^{S,RR}_{duu}]_{pqrs}$	$C_{duue,pqrs}$
$[\mathcal{O}^{S,LR}_{udd}]_{pqrs}$	$-V_{q'q}C_{\bar{l}dqq\tilde{H},rspq'}\frac{v}{\sqrt{2}\Lambda}$
$[\mathcal{O}^{S,LR}_{ddd}]_{pqrs}$	$V_{p'p}V_{q'q}(C_{\bar{l}dqq\tilde{H},rsq'p'} - C_{\bar{l}dqq\tilde{H},rsp'q'})\frac{v}{2\sqrt{2}\Lambda}$
$[\mathcal{O}^{S,RL}_{ddd}]_{pqrs}$	$V_{s's}(C_{\bar{e}qdd\tilde{H},rs'qp} - C_{\bar{e}qdd\tilde{H},rs'pq})\frac{v}{\sqrt{2}\Lambda}$
$[\mathcal{O}^{S,RR}_{udd}]_{pqrs}$	$C_{\bar{l}dud\tilde{H},rspq}\frac{v}{\sqrt{2}\Lambda}$
$[\mathcal{O}^{S,RR}_{ddd}]_{pqrs}$	$C_{\bar{l}dddH,rspq}\frac{v}{\sqrt{2}\Lambda}$

Name [52] ([12])	Operator	Flavour
$[\mathcal{O}^{S,LL}_{udd}]_{111r}$ (O^{ν}_{LL})	$(ud)(d\nu_r)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{udd}]_{121r}$ $(\tilde{O}^{\nu}_{LL1})$	$(us)(d\nu_r)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{udd}]_{112r}$ $(\tilde{O}^{\nu}_{LL2})$	$(ud)(s\nu_r)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{duu}]_{111r}$ (O^{e}_{LL})	$(du)(ue_r)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{duu}]_{211r}$ $(\tilde{O}^{e}_{LL})$	$(su)(ue_r)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LR}_{duu}]_{111r}$ (O^{e}_{LR})	$(du)(\bar{u}^\dagger\bar{e}_r^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{duu}]_{211r}$ $(\tilde{O}^{e}_{LR})$	$(su)(\bar{u}^\dagger\bar{e}_r^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,RL}_{duu}]_{111r}$ (O^{e}_{RL})	$(\bar{d}^\dagger\bar{u}^\dagger)(ue_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{duu}]_{211r}$ $(\tilde{O}^{e}_{RL})$	$(\bar{s}^\dagger\bar{u}^\dagger)(ue_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{dud}]_{111r}$ (O^{ν}_{RL})	$(\bar{d}^\dagger\bar{u}^\dagger)(d\nu_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{dud}]_{211r}$ $(\tilde{O}^{\nu}_{RL1})$	$(\bar{s}^\dagger\bar{u}^\dagger)(d\nu_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{dud}]_{112r}$ $(\tilde{O}^{\nu}_{RL2})$	$(\bar{d}^\dagger\bar{u}^\dagger)(s\nu_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{ddu}]_{[12]1r}$	$(\bar{d}^\dagger\bar{s}^\dagger)(u\nu_r)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RR}_{duu}]_{111r}$ (O^{e}_{RR})	$(\bar{d}^\dagger\bar{u}^\dagger)(\bar{u}^\dagger\bar{e}_r^\dagger)$	$(\mathbf{1},\mathbf{8})$
$[\mathcal{O}^{S,RR}_{duu}]_{211r}$ $(\tilde{O}^{e}_{RR})$	$(\bar{s}^\dagger\bar{u}^\dagger)(\bar{u}^\dagger\bar{e}_r^\dagger)$	$(\mathbf{1},\mathbf{8})$

Name	Operator	Flavour
$[\mathcal{O}^{S,LL}_{ddd}]_{[12]r1}$	$(ds)(\bar{e}_r d)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LR}_{udd}]_{11r1}$	$(ud)(\nu_r^\dagger\bar{d}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{udd}]_{12r1}$	$(us)(\nu_r^\dagger\bar{d}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{udd}]_{11r2}$	$(ud)(\nu_r^\dagger\bar{s}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{ddu}]_{[12]r1}$	$(ds)(\nu_r^\dagger\bar{u}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{ddd}]_{[12]r1}$	$(ds)(e_r^\dagger\bar{d}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
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$[\mathcal{O}^{S,LR}_{udd}]_{pqrs}$	$-V_{q'q}C_{\bar{l}dqq\tilde{H},rspq'}\frac{v}{\sqrt{2}\Lambda}$
$[\mathcal{O}^{S,LR}_{ddd}]_{pqrs}$	$V_{p'p}V_{q'q}(C_{\bar{l}dqq\tilde{H},rsq'p'}-C_{\bar{l}dqq\tilde{H},rsp'q'})\frac{v}{2\sqrt{2}\Lambda}$
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$[\mathcal{O}^{S,LR}_{udd}]_{11r2}$	$(ud)(\nu^\dagger_r\bar{s}^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
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Not generated at tree level by d = 6, 7 SMEFT ops.

· **RGEs for d = 6 LEFT** [A. Manohar et al. 2018]

- **RG effects universal in the LEFT**

$c(2\ \text{GeV}) \sim 1.26\ c(m_W)$

See L. Naterop's talk on 2-loops effects Tuesday 14

BχPT

$$M = \sum_{a=1}^{8} M_a \frac{\lambda_a}{\sqrt{2}} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$B = \sum_{a=1}^{8} B_a \frac{\lambda_a}{\sqrt{2}} = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}$$

$\xi \equiv e^{iM/f_\pi} \to L\xi U^\dagger = U\xi R^\dagger$

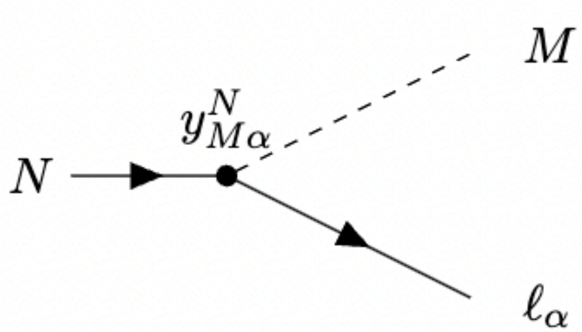
Flavour group $\mathrm{U(3)_L} \times \mathrm{U(3)_R}$

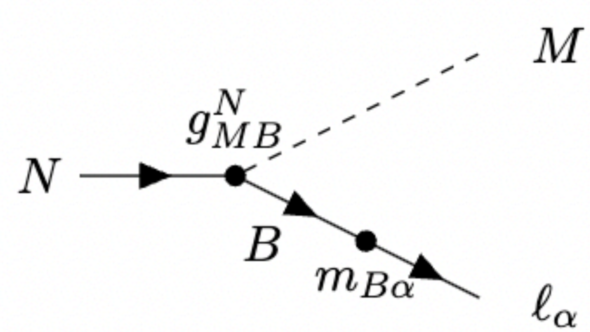
$B \to UBU^\dagger$

BNC interactions **BNV interactions**

$$\mathcal{L} = g^N_{MB}\overline{B}\gamma^\mu\gamma_5 N\partial_\mu M + m_{B\alpha,X}\overline{\ell_\alpha}P_{\bar{X}}B + iy^N_{M\alpha,X}\overline{\ell_\alpha}P_{\bar{X}}NM$$

[M. Claudson et al. 1981, P. Nath et al. 2007]





$\Gamma(N \to M\ell_\alpha)$

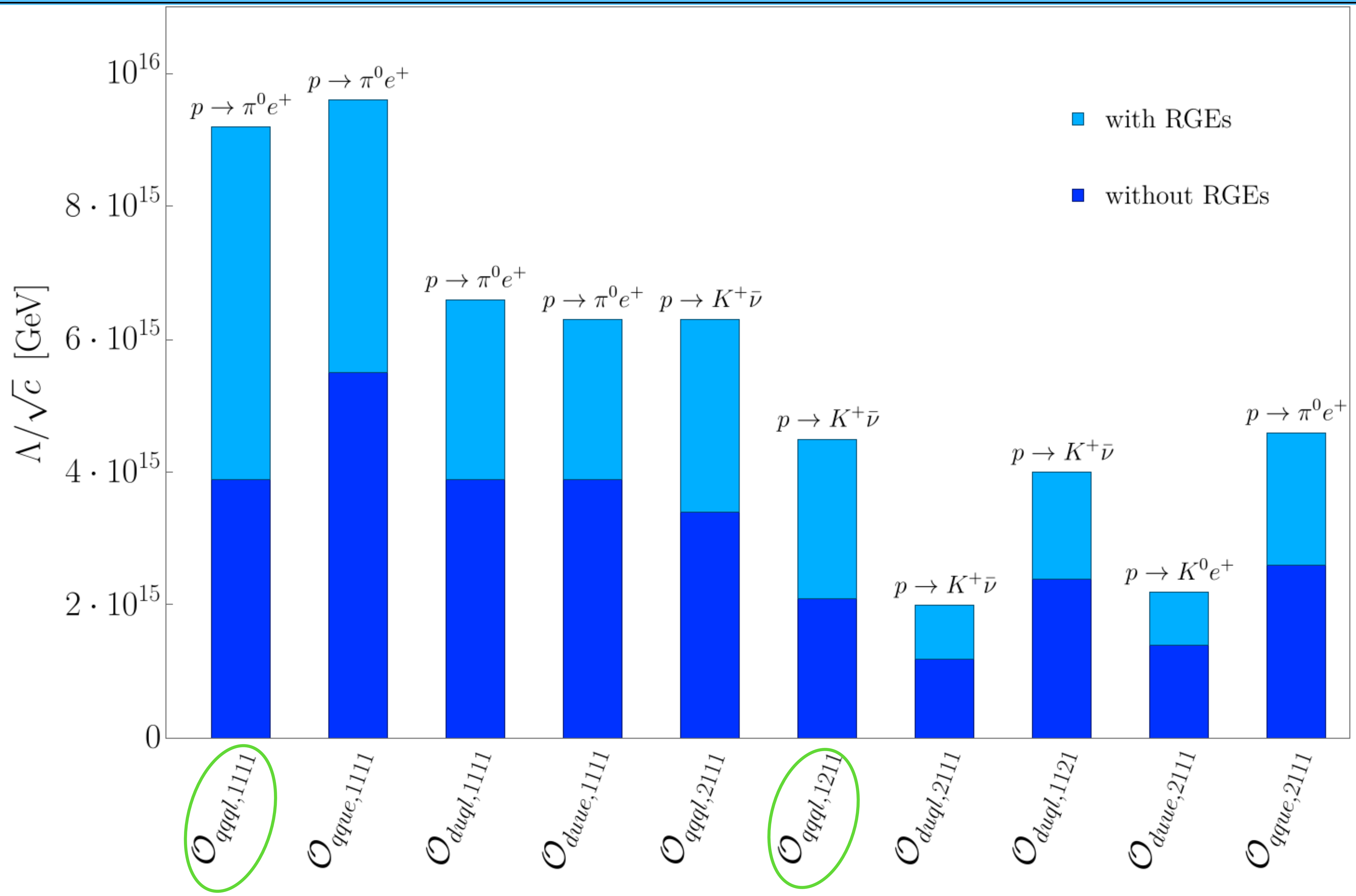
2 inputs from lattice α, β

See Y. Aoki's & Jun-Sik Yoo talks Wednesday 15

[JLQCD 2000, Y. Aoki et al. 2017,]

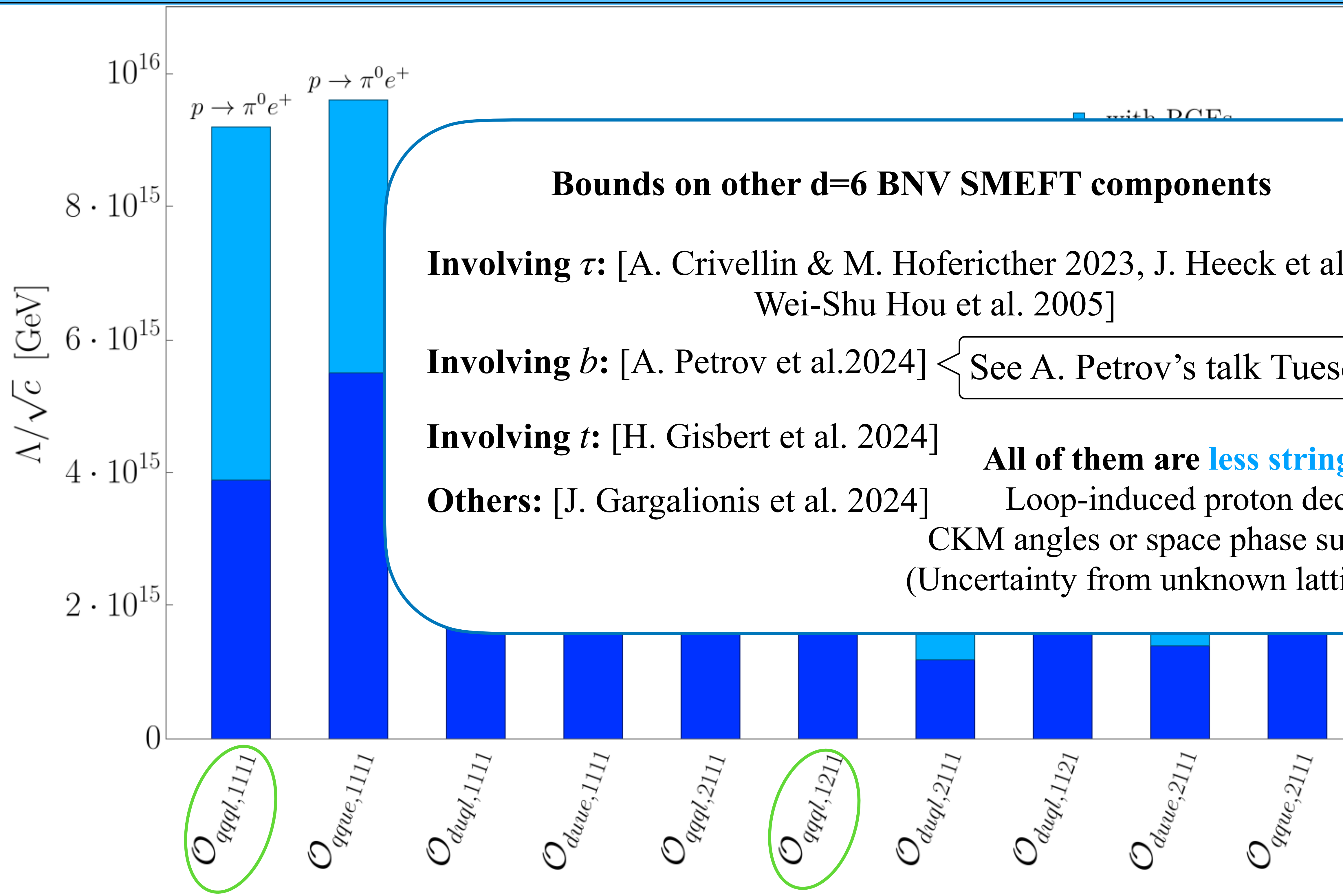
(First-time computation of $|\Delta(B-L)| = 2$ two-body decays in the BχPT formalism)

D = 6 limits



$$\Lambda/\sqrt{c} \sim (1 \ \sim \ 10) \ \times \ 10^{15} \text{ GeV}$$

D = 6 limits



Bounds on other d=6 BNV SMEFT components

Involving τ: [A. Crivellin & M. Hoferichter 2023, J. Heeck et al. 2024, Wei-Shu Hou et al. 2005]

Involving b: [A. Petrov et al.2024] See A. Petrov's talk Tuesday 14

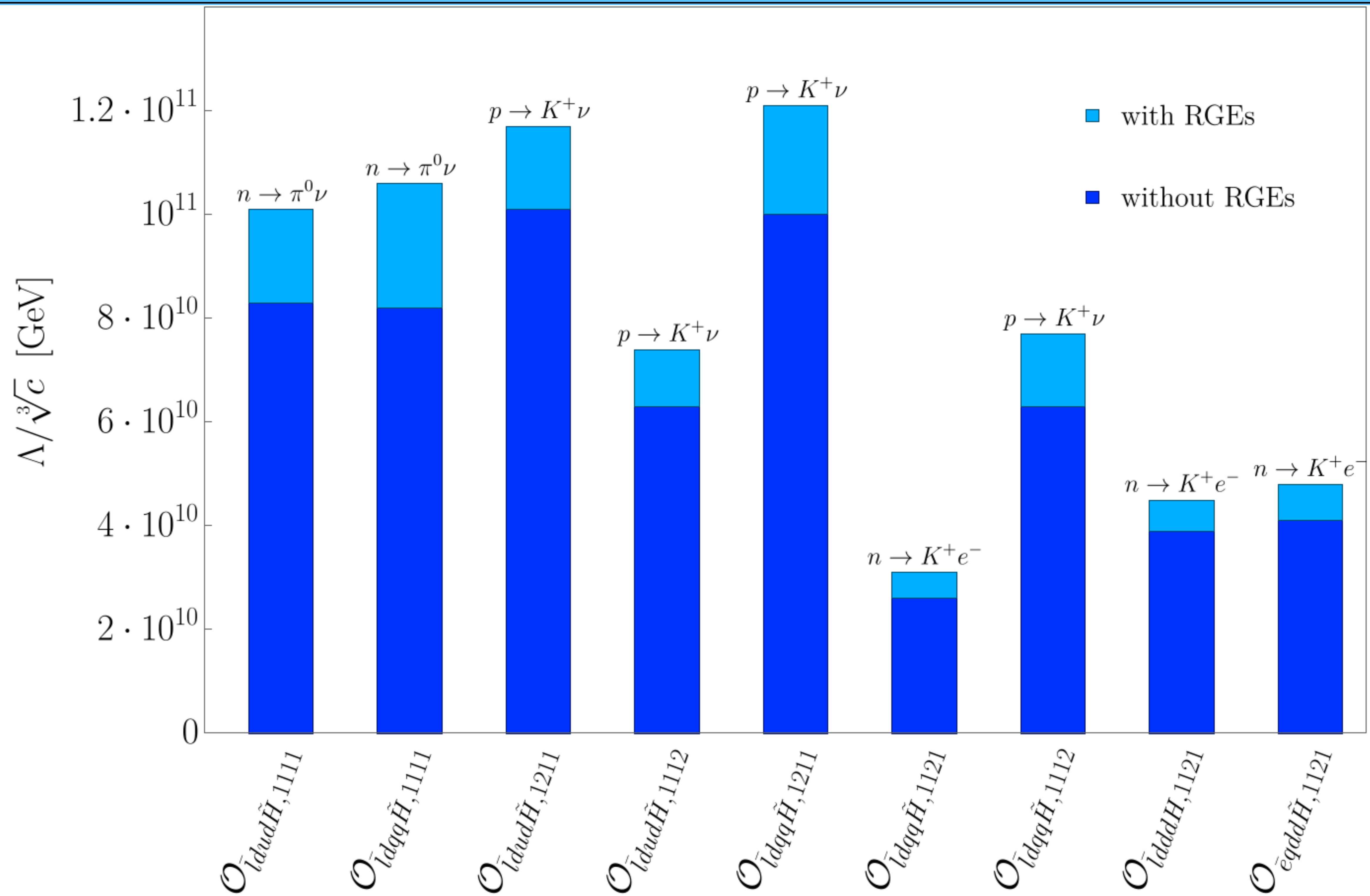
Involving t: [H. Gisbert et al. 2024]

Others: [J. Gargalionis et al. 2024]

All of them are less stringent:
Loop-induced proton decay,
CKM angles or space phase suppressed
(Uncertainty from unknown lattice results)

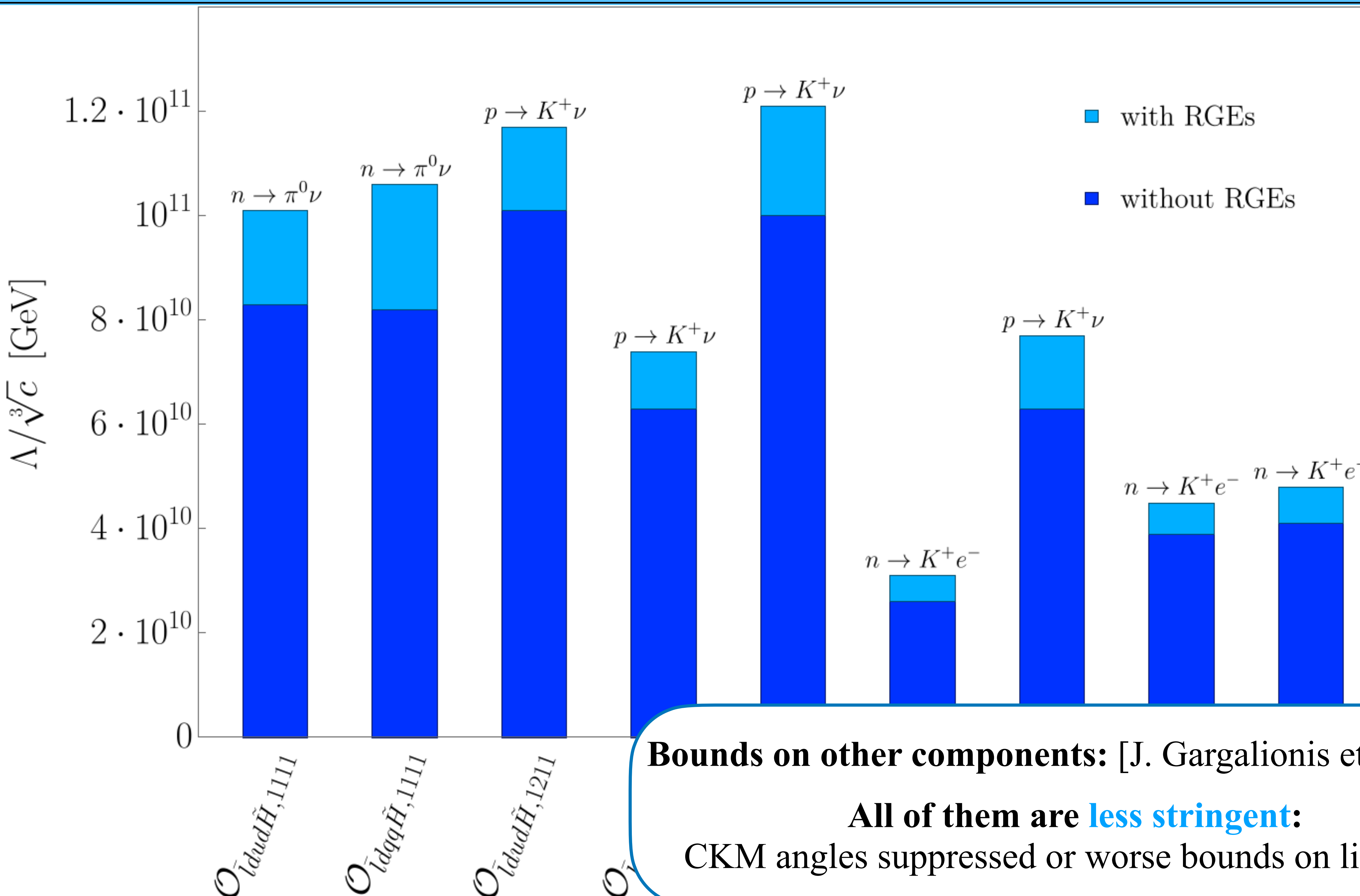
$$\Lambda/\sqrt{c} \sim (1 \sim 10) \times 10^{15}\ \text{GeV}$$

D = 7 limits



$\Lambda/\sqrt[3]{c} \sim (2 \sim 12) \times 10^{10}$ GeV

D = 7 limits

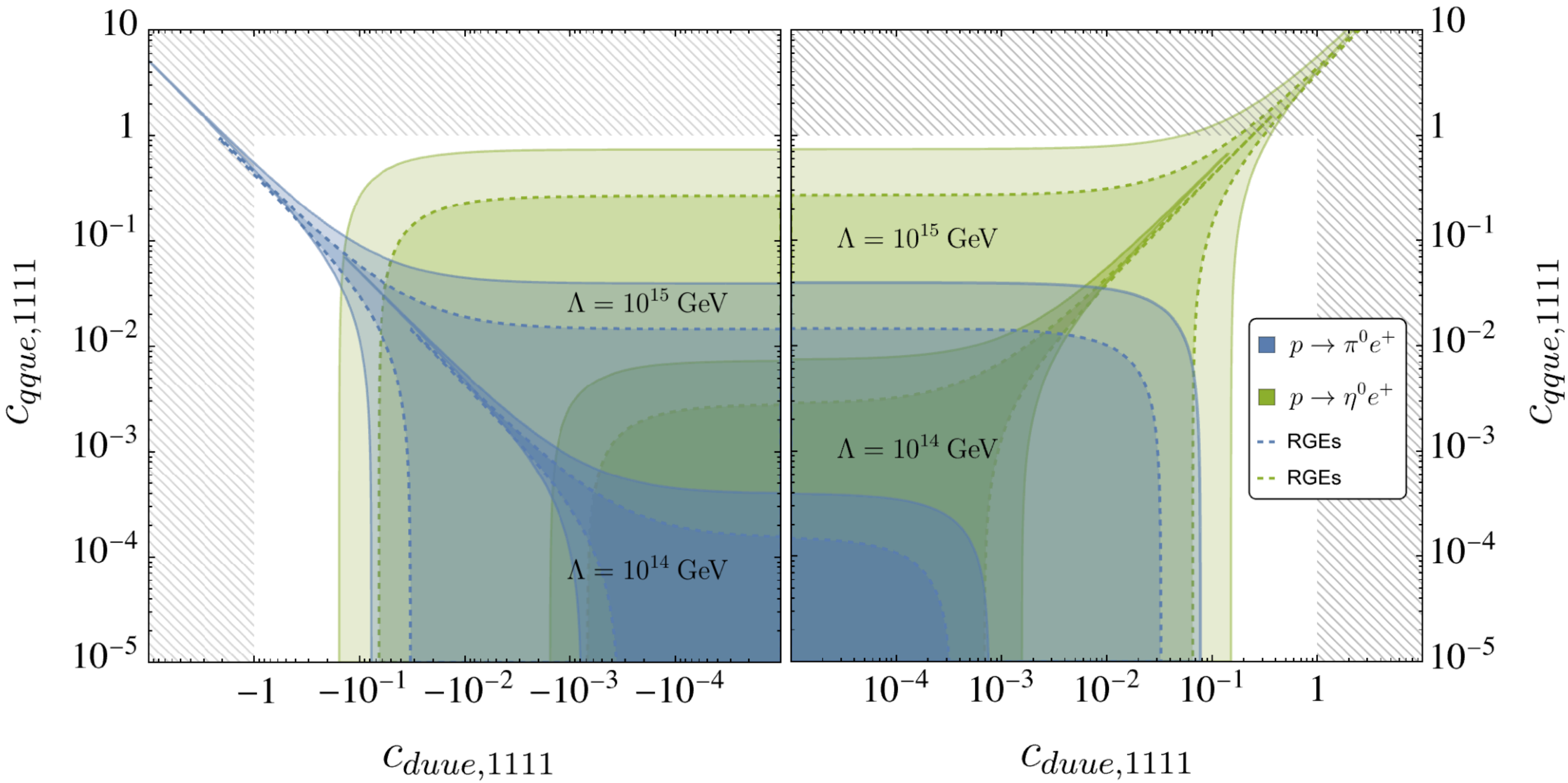


Bounds on other components: [J. Gargalionis et al. 2024]

All of them are less stringent:
CKM angles suppressed or worse bounds on lifetimes

$$\Lambda/\sqrt[3]{c} \sim (2 \sim 12) \times 10^{10}\ \text{GeV}$$

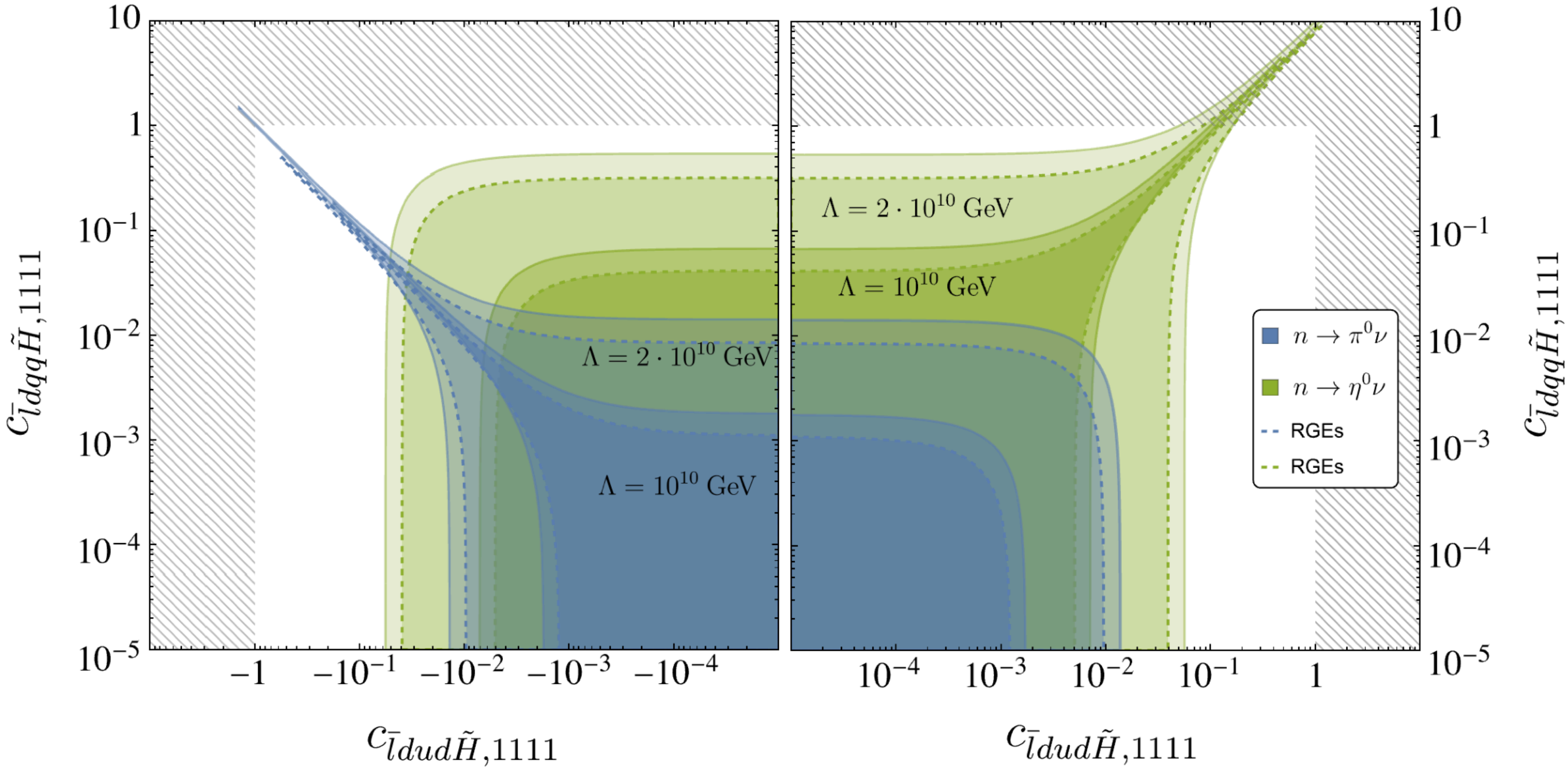
D = 6 pairs of WCs



· Different search channels provide complementary constraints

· No flat directions

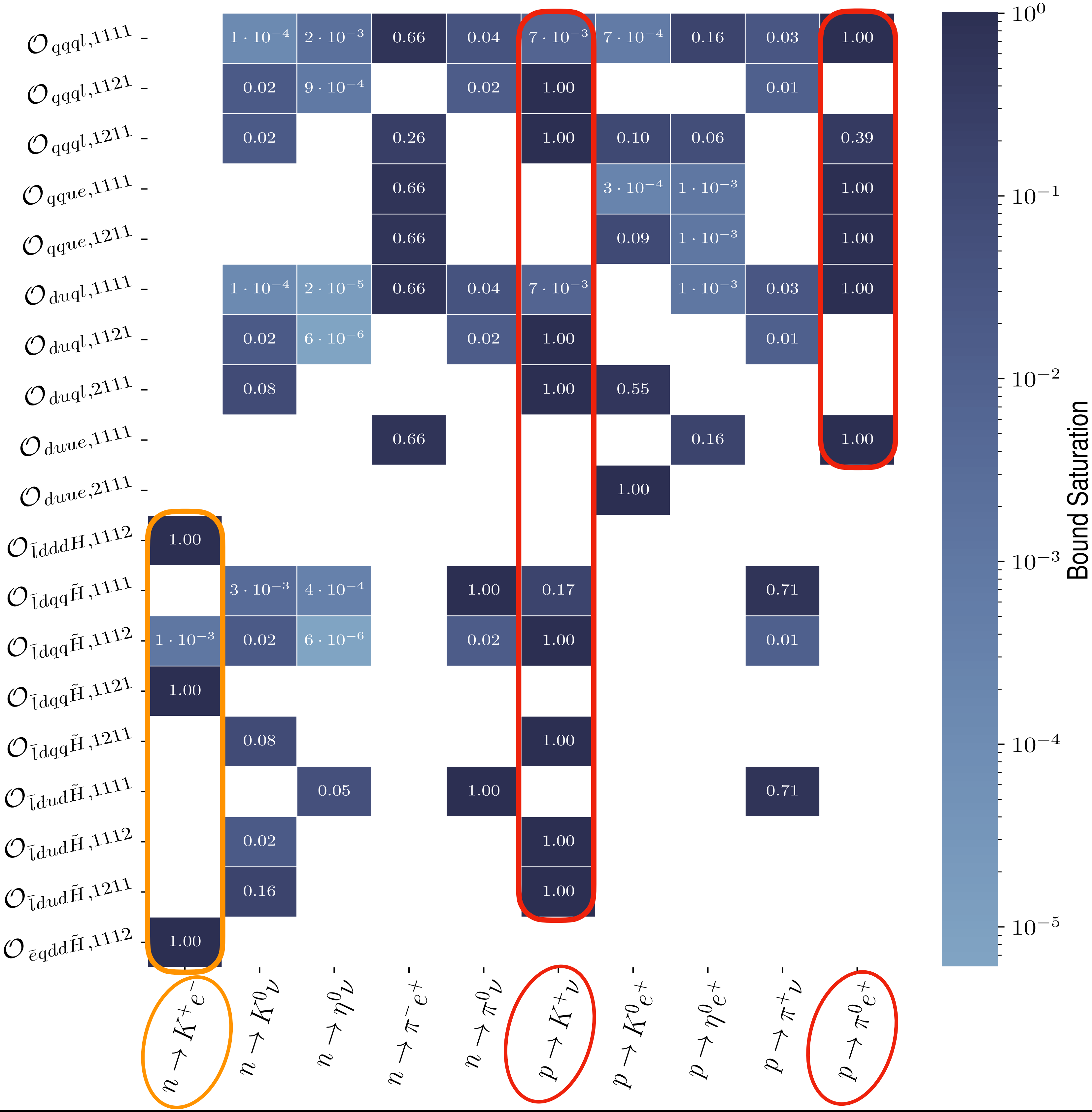
D = 7 pairs of WCs



· Different search channels provide complementary constraints

· No flat directions

Correlations

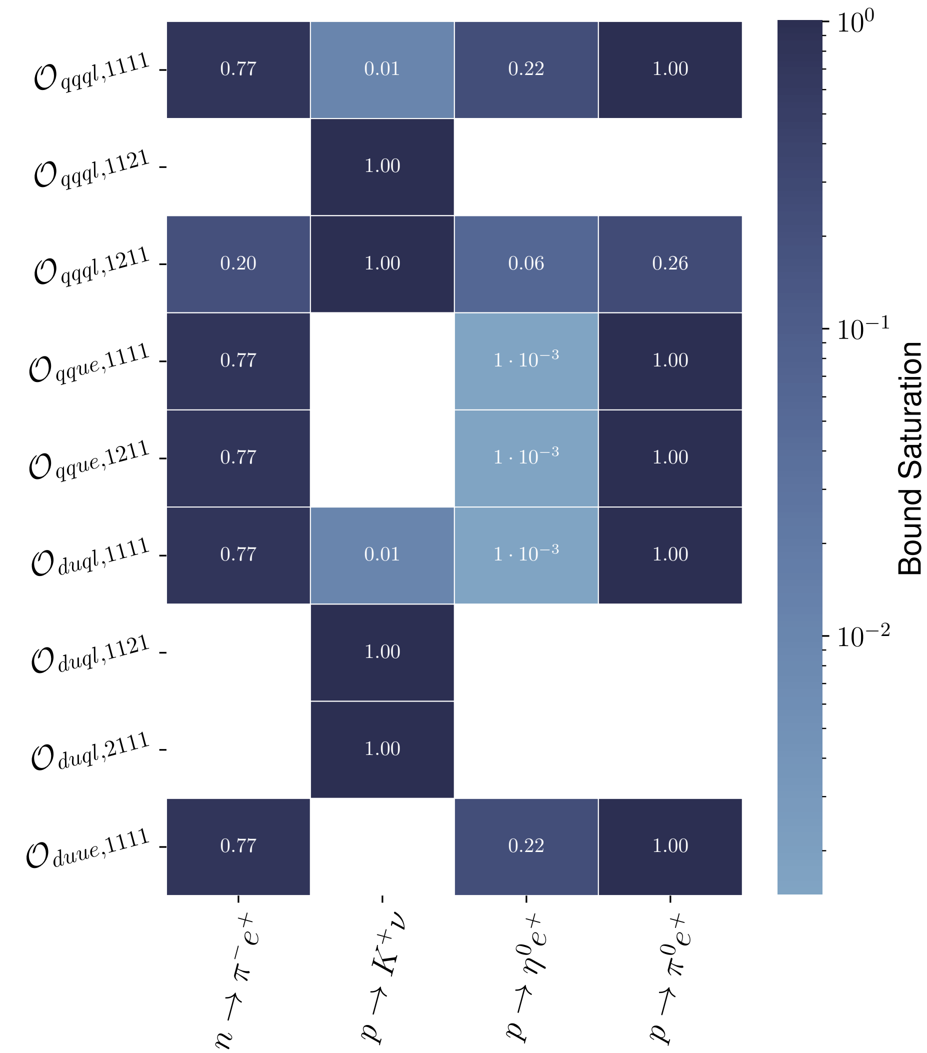


$$\text{Bound Saturation} \equiv \frac{\Gamma_{\text{i,th}}/\Gamma_{\text{max,th}}}{\Gamma_{\text{i,exp}}/\Gamma_{\text{max,exp}}}$$

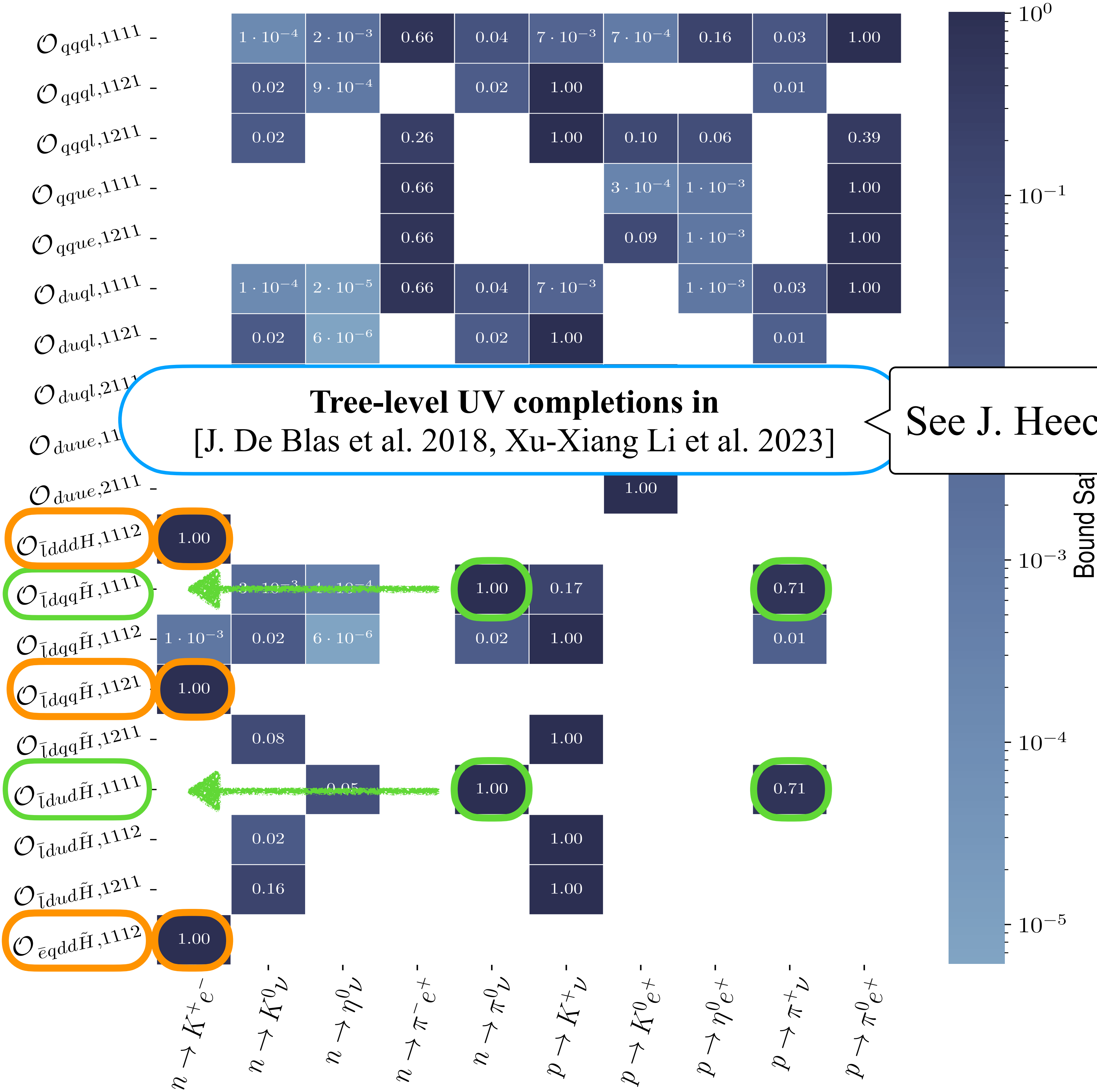
$$\tau_{p\to\pi^0 e^+} > 24 \cdot 10^{33} \text{ years}$$

$$\tau_{p\to K^+\nu} > 6.61 \cdot 10^{33} \text{ years}$$

$$\tau_{n\to K^+ e^-} > 0.032 \cdot 10^{33} \text{ years}$$



Correlations



Tree-level UV completions in
[J. De Blas et al. 2018, Xu-Xiang Li et al. 2023]

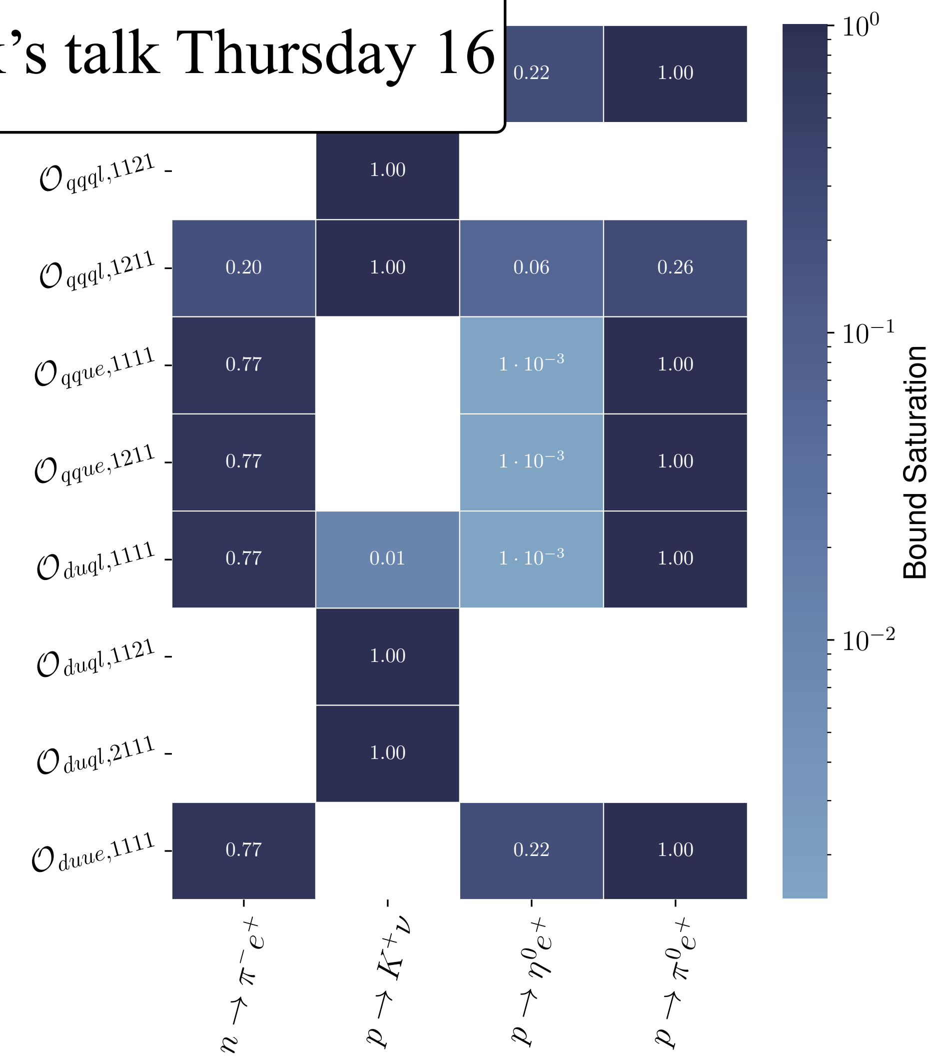
See J. Heeck's talk Thursday 16

$$\text{Bound Saturation} \equiv \frac{\Gamma_{\text{i,th}}/\Gamma_{\text{max,th}}}{\Gamma_{\text{i,exp}}/\Gamma_{\text{max,exp}}}$$

$\tau_{p\to\pi^0 e^+} > 24 \cdot 10^{33}$ years

$\tau_{p\to K^+\nu} > 6.61 \cdot 10^{33}$ years

$\tau_{n\to K^+ e^-} > 0.032 \cdot 10^{33}$ years



Phenomenological matrices

Numerical κ-matrices available online

$$\Gamma_{(i)}^{\Delta(B-L)=0} \equiv 10^{-4}\, c_j^* \boxed{\boldsymbol{\kappa}_{(i)}^{jk}}\, c_k \frac{m_p^5}{\Lambda^4} \quad \text{for} \quad i = p \to \pi^0 e^+, p \to K^+ \nu \dots \quad \text{(9 matrices)}$$

$$\Gamma_{(i)}^{|\Delta(B-L)|=2} \equiv c_j^* \boxed{\boldsymbol{\kappa}_{(i)}^{jk}}\, c_k \frac{m_p^7}{\Lambda^6} \quad \text{for} \quad i = p \to K^+ \nu, n \to K^+ e^- \dots \quad \text{(6 matrices)}$$

$c_{qque,1111} \sim -0.44\ c_{duue,1111}$

$p \to \pi^0 e^+$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	86.2		-44.4			-16.1				
$\mathcal{O}_{qque,1111}$		99.0		43.5						-22.9
$\mathcal{O}_{duql,1111}$	-44.4		22.9			8.31				
$\mathcal{O}_{duue,1111}$		43.5		19.1						-10.0
$\mathcal{O}_{qqql,2111}$										
$\mathcal{O}_{qqql,1211}$	-16.1		8.31			3.02				
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$										
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$		-22.9		-10.0						5.28

$c_{qque,1111} \sim 4.1\ c_{duue,1111}$

$p \to \eta^0 e^+$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	36.1		2.01			-6.76				
$\mathcal{O}_{qque,1111}$		0.48		-1.97						-0.11
$\mathcal{O}_{duql,1111}$	2.01		0.11			-0.38				
$\mathcal{O}_{duue,1111}$		-1.97		8.02						0.45
$\mathcal{O}_{qqql,2111}$										
$\mathcal{O}_{qqql,1211}$	-6.76		-0.38			1.27				
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$										
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$		-0.11		0.45						0.03

Phenomenological matrices

Numerical κ-matrices available online

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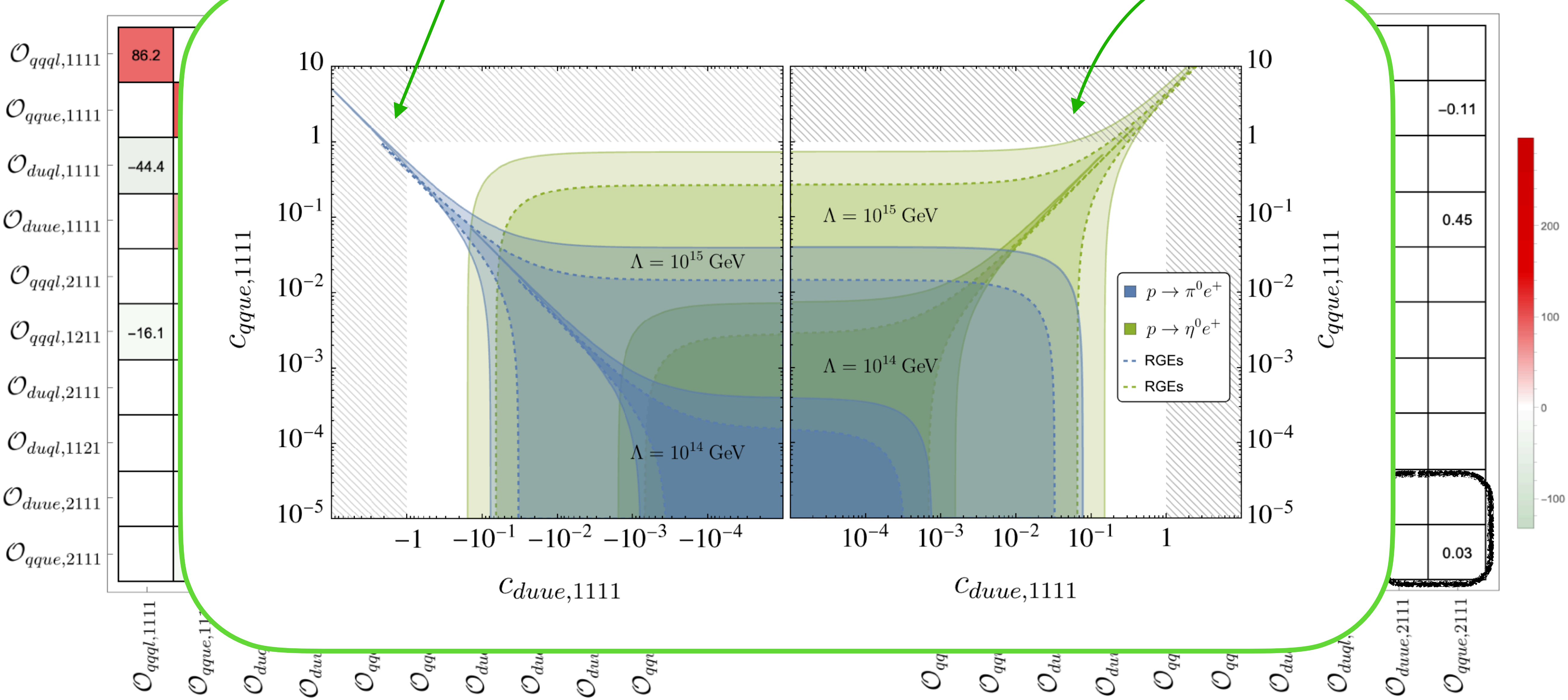
$c_{qque,1111} \sim -0.44\; c_{duue,1111}$

$c_{qque,1111} \sim 4.1\; c_{duue,1111}$

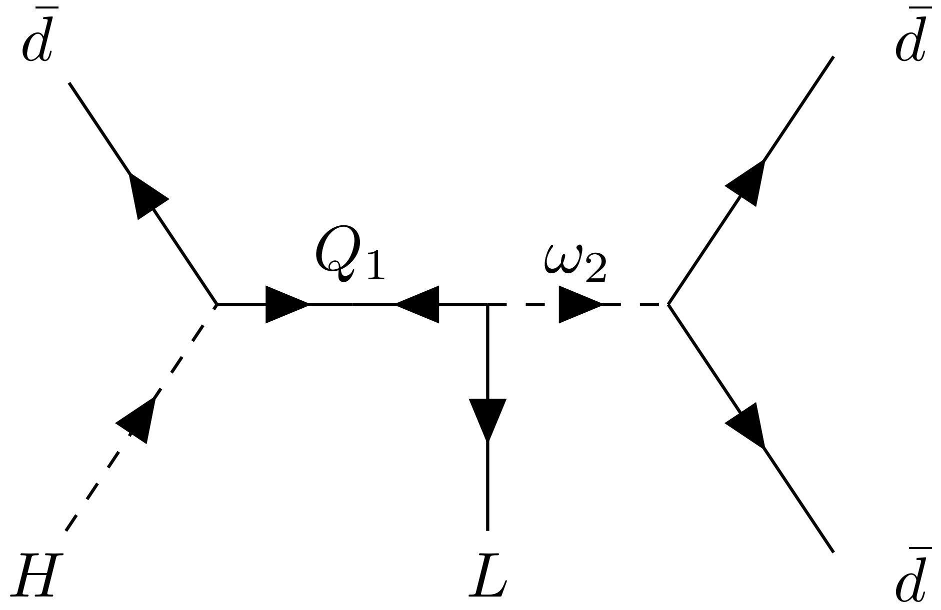


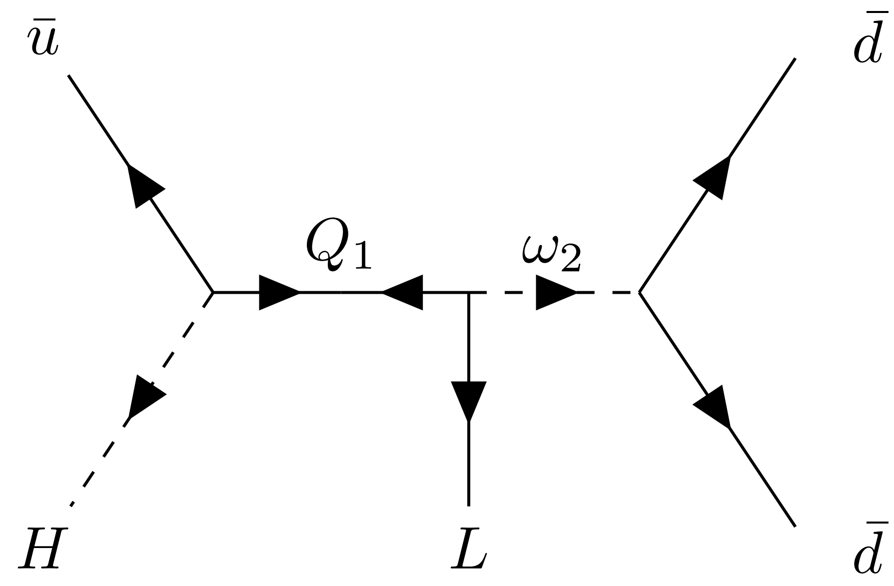
Example UV model

SM enhanced by a scalar LQ ω_2 and a VLF Q_1

$$\omega_2 \sim (3,\ 1,\ 2/3)\,,\ Q_1 + \bar{Q}_1^\dagger \sim (3,\ 2,\ 1/6)$$

$$\mathscr{L}_{\text{int}} = y_{1,ij}\omega_2 \bar{d}^{\dagger i}\bar{d}^{\dagger j} + y_{2,k}H^\dagger Q_1 \bar{d}^k + y_{3,k}\ Q_1 \epsilon H \bar{u}^k + y_{4,l}\ \omega_2 \bar{Q}_1 L^l + \mathrm{h.c.}$$





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$$\downarrow$$

$$\mathscr{L}_{\text{eff}} \supset C_{\bar{l}dddH,pqrs}\mathcal{O}_{\bar{l}dddH,pqrs} + C_{\bar{l}dud\tilde{H},pqrs}\mathcal{O}_{\bar{l}dud\tilde{H},pqrs} + \text{h.c.}$$

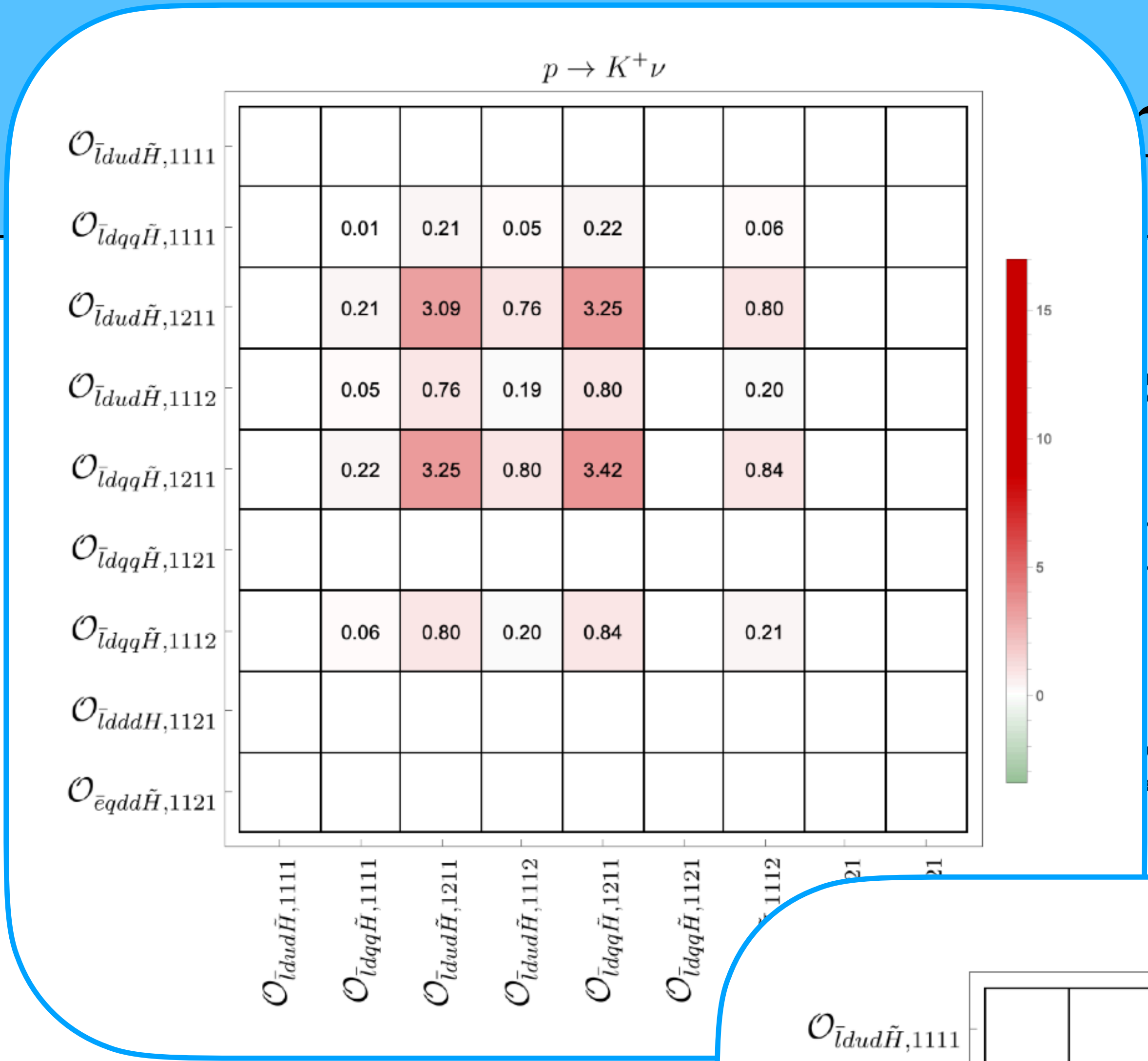
ble UV

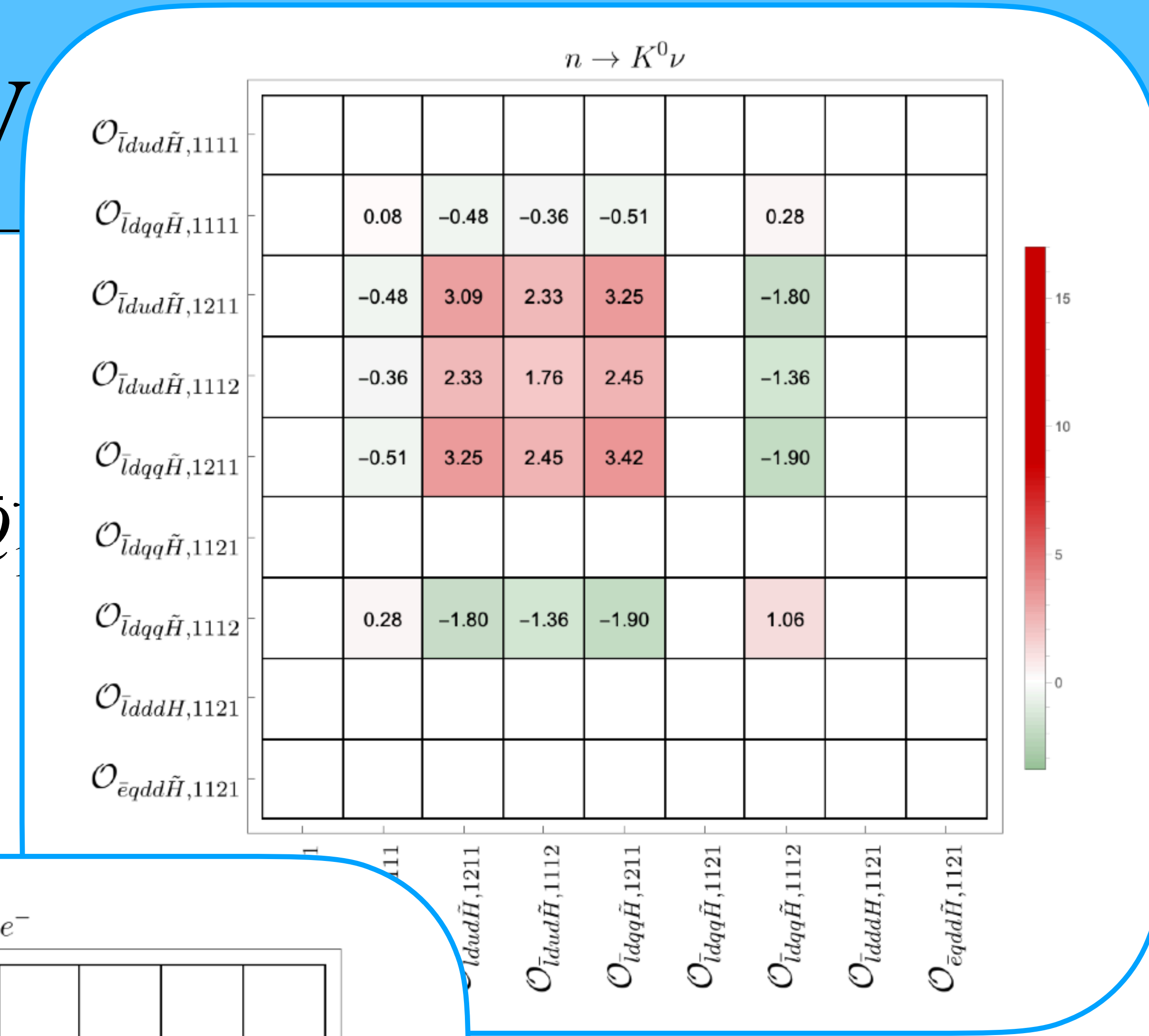
scalar LQ

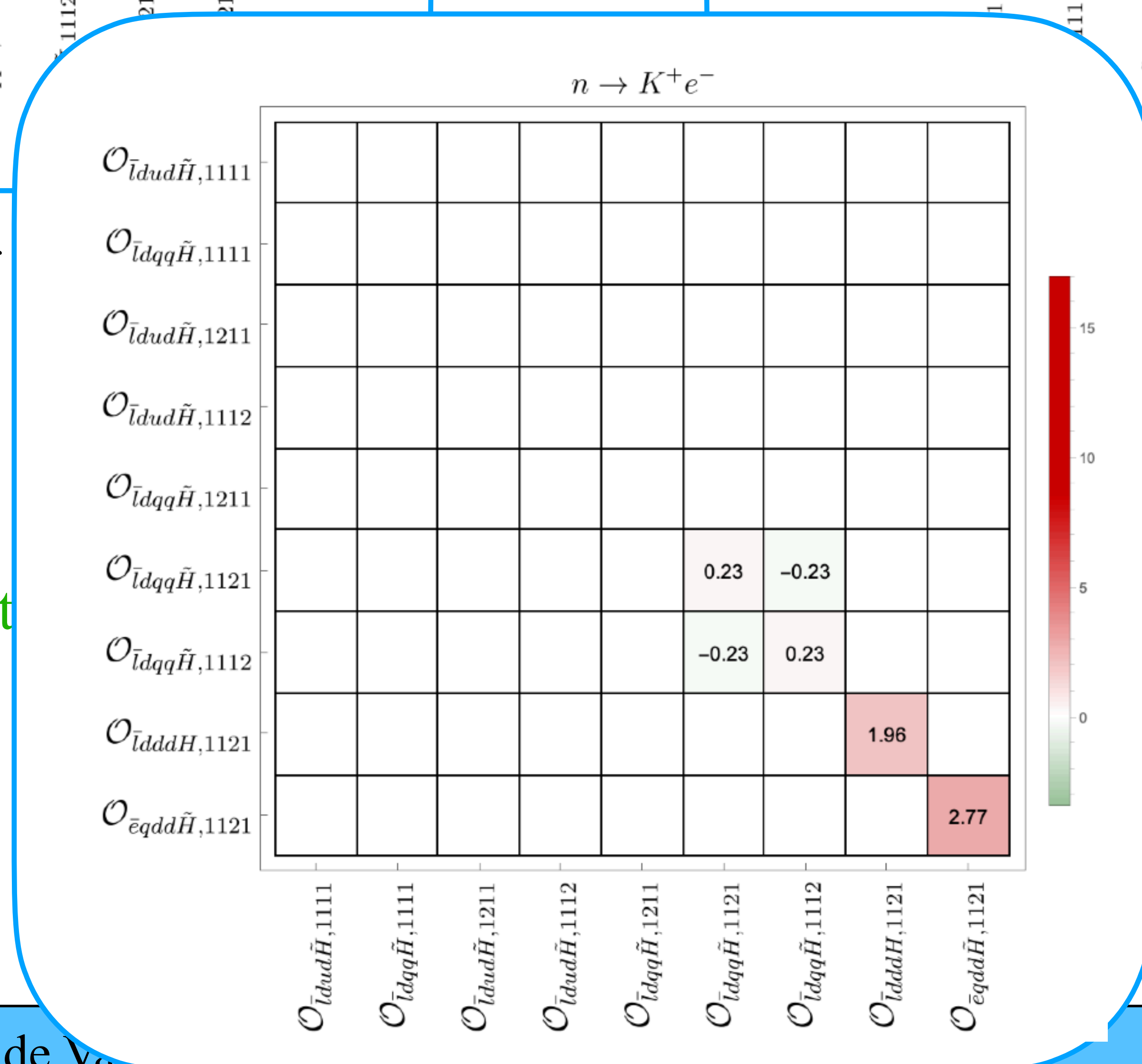
$), \ Q_1 + \bar{Q}$

$Q_1 \bar{d}^k + y_{3,k}$

$\mathscr{L}_{\text{eff}}$ + h.c.







K^+e^-

y_1 ant

Example UV model

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$$\mathscr{L}_{\rm int} = y_{1,ij}\omega_2 \bar{d}^{\dagger i}\bar{d}^{\dagger j} + y_{2,k} H^\dagger Q_1 \bar{d}^k + y_{3,k}\ Q_1 \epsilon H \bar{u}^k + y_{4,l}\ \omega_2 \bar{Q}_1 L^l + \mathrm{h.c.}$$

$$\downarrow$$

$$\mathscr{L}_{\rm eff} \supset C_{\bar{l}dddH,pqrs} \boxed{\mathcal{O}_{\bar{l}dddH,pqrs}} + C_{\bar{l}dud\tilde{H},pqrs} \boxed{\mathcal{O}_{\bar{l}dud\tilde{H},pqrs}} + \mathrm{h.c.}$$

y_1 antisymmetric
$$\left\{ \begin{array}{l} p \to K^+\nu \quad n \to K^0\nu \quad n \to K^+e^- \\ \\ C_{\bar{l}dud\tilde{H},1211} = - C_{\bar{l}dud\tilde{H},1112} \end{array} \right.$$

κ-matrices for the 3 processes above, compute Γ and compare with $\Gamma^{\rm exp}$ $\longrightarrow$ **$p \to K^+\nu$ the most constraining**

Main results of this work

· Model-independent analysis on nucleon decay

· RG effects important: limits enhanced by 30% - 130% (d=6) , and 20 - 30% (d=7)

· Complementary analysis → Correlations and flat directions

· κ-matrices: SMEFT WC at $\Lambda \leftrightarrow$ observables at m_p

· Positive signals in 2-3 channels → SMEFT operators → GUT/ UV models

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· κ-matrices: SMEFT WC at $\Lambda \leftrightarrow$ observables at m_p

· Positive signals in 2-3 channels → SMEFT operators → GUT/ UV models !

Exotic SM channels, Proton decay into BSM particles, BNV through third generation, inclusive searches… → The experiments will have the last word

Thank you!

Backup slides

RGEs

$\left(\dot{C}_i \equiv 16\pi^2\mu\frac{dC_i}{d\mu} = \sum_j \gamma_{ij}C_j\right)$

$$\dot{C}_{duue,prst} = \left(-4g_3^2 - 2g_1^2\right) C_{duue,prst} - \frac{20}{3}g_1^2\, C_{duue,psrt} + \dots$$

$$\dot{C}_{duq\ell,prst} = \left(-4g_3^2 - \frac{9}{2}g_2^2 - \frac{11}{6}g_1^2\right) C_{duq\ell,prst} + \dots$$

$$\dot{C}_{qque,prst} = \left(-4g_3^2 - \frac{9}{2}g_2^2 - \frac{23}{6}g_1^2\right) C_{qque,prst} + \dots$$

$$\dot{C}_{qqq\ell,prst} = \left(-4g_3^2 - 3g_2^2 - \frac{1}{3}g_1^2\right) C_{qqq\ell,prst} \boxed{- 4g_2^2\left(C_{qqq\ell,rpst} + C_{qqq\ell,srpt} + C_{qqq\ell,psrt}\right)} + \dots$$

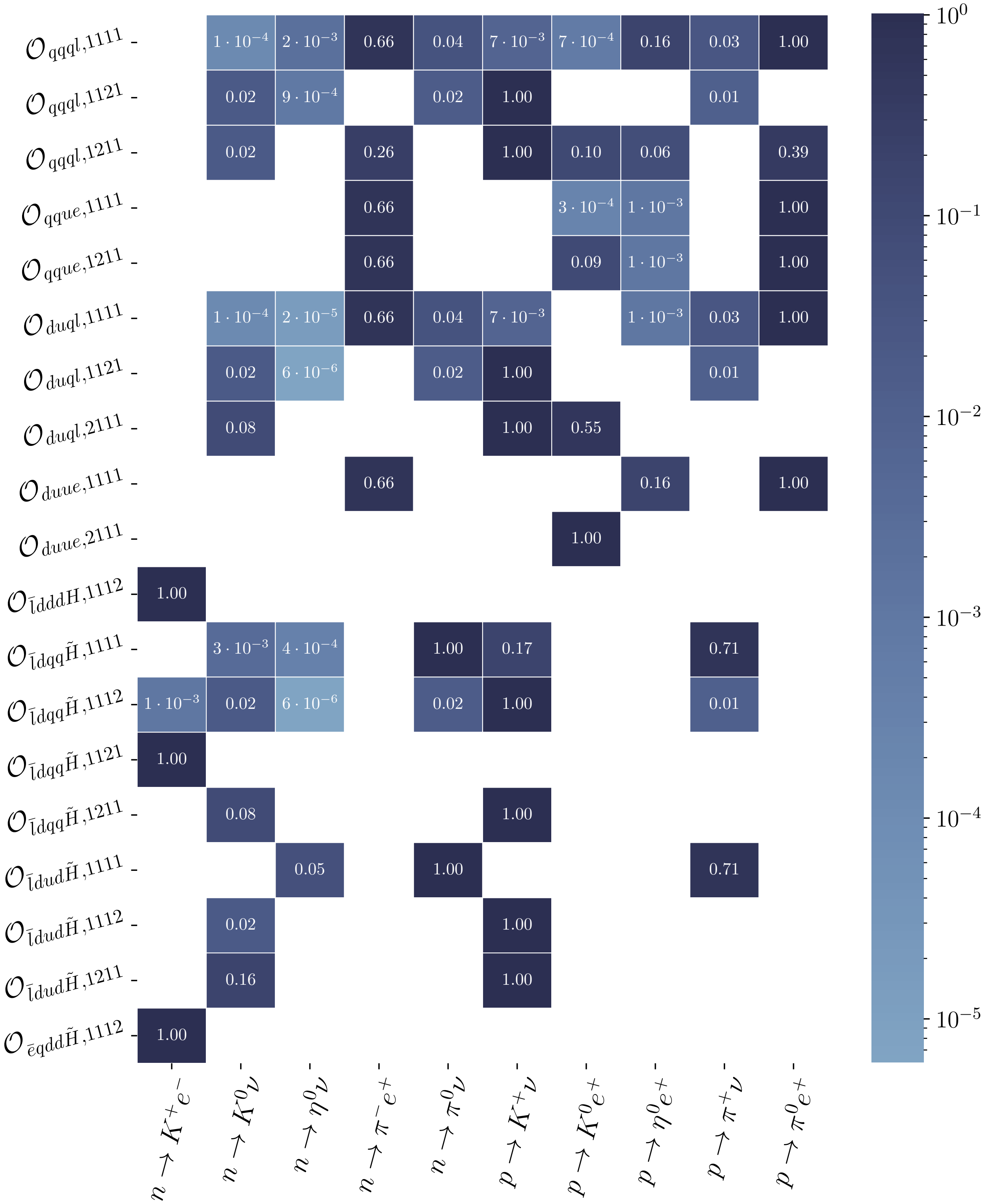
$$\dot{C}_{\bar{l}dud\tilde{H},prst} = \left(-4g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{12}g_1^2 \boxed{+ y_t^2}\right) C_{\bar{l}dud\tilde{H},prst} - \frac{10}{3}g_1^2\, C_{\bar{l}dud\tilde{H},ptsr}\,,$$

$$\dot{C}_{\bar{l}dddH,prst} = \left(-4g_3^2 - \frac{9}{4}g_2^2 - \frac{13}{12}g_1^2 \boxed{+ y_t^2}\right) C_{\bar{l}dddH,prst}\,,$$

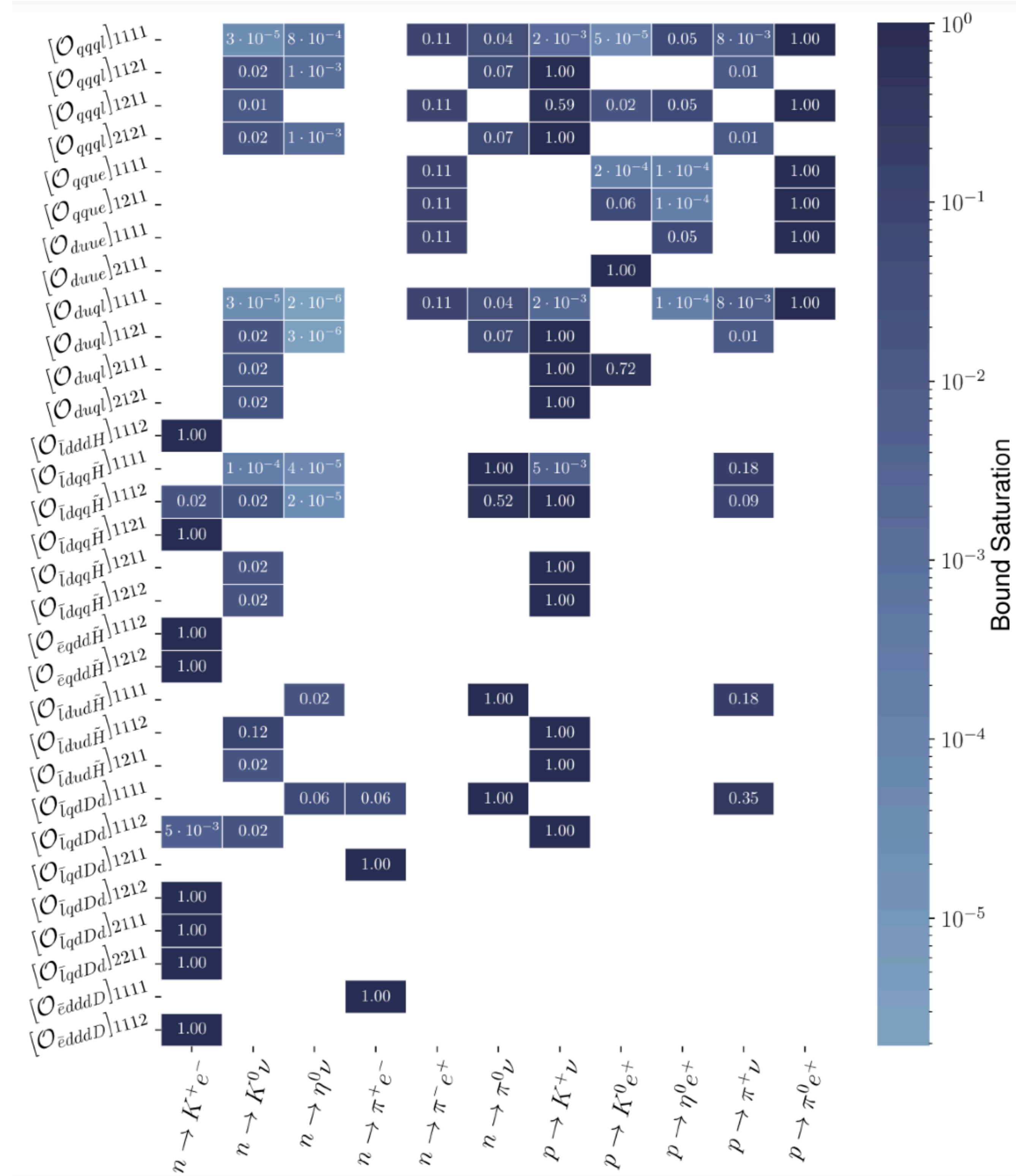
$$\dot{C}_{\bar{e}qdd\tilde{H},prst} = \left(-4g_3^2 - \frac{9}{4}g_2^2 + \frac{11}{12}g_1^2 \boxed{+ y_t^2}\right) C_{\bar{e}qdd\tilde{H},prst}\,,$$

$$\dot{C}_{\bar{l}dqq\tilde{H},prst} = \left(-4g_3^2 - \frac{15}{4}g_2^2 - \frac{19}{12}g_1^2 \boxed{+ y_t^2}\right) C_{\bar{l}dqq\tilde{H},prst} - 3g_2^2\, C_{\bar{l}dqq\tilde{H},prts}\,.$$

Direct and Indirect method



BχPT



Direct Method in [J. Gargalionis et al. 2024]

Direct and Indirect method

$$\Gamma(N \to M + \ell) = \frac{m_N}{32\pi}\left(1 - \frac{m_M^2}{m_N^2}\right)^2 \left|\sum_I C_I W_0^I(N \to M)\right|^2$$

$W_0^I(N \to M)$

computed in the lattice

(Several parameters)

$$\Gamma\left(p \to \pi^+ \nu_r\right) = (32\pi f_\pi^2 m_p^3)^{-1}(m_p^2 - m_\pi^2)^2 \left|\alpha \left[L_{udd}^{S,LR}\right]_{11r1} + \beta \left[L_{udd}^{S,RR}\right]_{11r1}\right|^2 (1 + D + F)^2$$

$$\Gamma\left(n \to K^+ e_r^-\right) = (32\pi f_\pi^2 m_n^3)^{-1}(m_n^2 - m_K^2)^2 \times$$
$$\left\{\left|\beta \left[L_{ddd}^{S,LL}\right]_{12r1} - \alpha \left[L_{ddd}^{S,RL}\right]_{12r1} + \frac{m_n}{m_\Sigma}\left(\alpha \left[L_{ddd}^{S,RL}\right]_{12r1} + \beta \left[L_{ddd}^{S,LL}\right]_{12r1}\right)(D - F)\right|^2\right.$$
$$\left. + \left|\beta \left[L_{ddd}^{S,RR}\right]_{12r1} - \alpha \left[L_{ddd}^{S,LR}\right]_{12r1} + \frac{m_n}{m_\Sigma}\left(\alpha \left[L_{ddd}^{S,LR}\right]_{12r1} + \beta \left[L_{ddd}^{S,RR}\right]_{12r1}\right)(D - F)\right|^2\right\}$$

$D,\ F, f_\pi$

low-energy BχPT constants

$$\Gamma\left(n \to K^0 \nu_r\right) = (32\pi f_\pi^2 m_n^3)^{-1}(m_n^2 - m_K^2)^2 \times$$
$$\left|-\alpha \left[L_{udd}^{S,LR}\right]_{12r1} + \beta \left[L_{udd}^{S,RR}\right]_{12r1} + \alpha \left[L_{udd}^{S,LR}\right]_{11r2} + \beta \left[L_{udd}^{S,RR}\right]_{11r2}\right.$$
$$- \frac{m_n}{2m_\Sigma}\left(\alpha \left[L_{udd}^{S,LR}\right]_{12r1} + \beta \left[L_{udd}^{S,RR}\right]_{12r1}\right)(D - F)$$
$$\left. + \frac{m_n}{6m_\Lambda}\left(\alpha \left[L_{udd}^{S,LR}\right]_{12r1} + \beta \left[L_{udd}^{S,RR}\right]_{12r1} + 2\alpha \left[L_{udd}^{S,LR}\right]_{11r2} + 2\beta \left[L_{udd}^{S,RR}\right]_{11r2}\right)(D + 3F)\right|^2$$

$\alpha,\ \beta$

computed in the lattice

κ-matrices

$\Gamma(p \to \pi^+\nu) = 2\,\Gamma(n \to \pi^0\nu)$

$\Gamma(n \to \pi^-e^+) = 3\,\Gamma(p \to \pi^0e^+)$

$n \to \pi^0\nu$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	81.9		−42.2		−23.5			9.74		
$\mathcal{O}_{qque,1111}$										
$\mathcal{O}_{duql,1111}$	−42.2		21.7		12.1			−5.02		
$\mathcal{O}_{duue,1111}$										
$\mathcal{O}_{qqql,2111}$	−23.5		12.1		6.76			−2.80		
$\mathcal{O}_{qqql,1211}$										
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$	9.74		−5.02		−2.80			1.16		
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$										

$n \to \eta^0\nu$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	34.3		1.91		−9.86			−0.44		
$\mathcal{O}_{qque,1111}$										
$\mathcal{O}_{duql,1111}$	1.91		0.11		−0.55			−0.02		
$\mathcal{O}_{duue,1111}$										
$\mathcal{O}_{qqql,2111}$	−9.86		−0.55		2.83			0.13		
$\mathcal{O}_{qqql,1211}$										
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$	−0.44		−0.02		0.13			0.006		
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$										

$n \to \pi^-e^+$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	258.5		−133.2			−48.4				
$\mathcal{O}_{qque,1111}$		297.1		130.5						−68.6
$\mathcal{O}_{duql,1111}$	−133.2		68.7			24.9				
$\mathcal{O}_{duue,1111}$		130.5		57.4						−30.1
$\mathcal{O}_{qqql,2111}$										
$\mathcal{O}_{qqql,1211}$	−48.4		24.9			9.06				
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$										
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$		−68.6		−30.1						15.8

$p \to \pi^+\nu$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	163.7		−84.4		−47.0			19.5		
$\mathcal{O}_{qque,1111}$										
$\mathcal{O}_{duql,1111}$	−84.4		43.5		24.2			−10.0		
$\mathcal{O}_{duue,1111}$										
$\mathcal{O}_{qqql,2111}$	−47.0		24.2		13.5			−5.60		
$\mathcal{O}_{qqql,1211}$										
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$	19.5		−10.0		−5.60			2.32		
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$										

$p \to K^0e^+$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	1.59					5.59	2.26			
$\mathcal{O}_{qque,1111}$		0.74							−2.21	3.20
$\mathcal{O}_{duql,1111}$										
$\mathcal{O}_{duue,1111}$										
$\mathcal{O}_{qqql,2111}$										
$\mathcal{O}_{qqql,1211}$	5.59					19.6	7.93			
$\mathcal{O}_{duql,2111}$	2.26					7.93	3.20			
$\mathcal{O}_{duql,1121}$										
$\mathcal{O}_{duue,2111}$		−2.21							6.63	−9.58
$\mathcal{O}_{qque,2111}$		3.20							−9.58	13.9

$p \to \pi^0e^+$

	$\mathcal{O}_{qqql,1111}$	$\mathcal{O}_{qque,1111}$	$\mathcal{O}_{duql,1111}$	$\mathcal{O}_{duue,1111}$	$\mathcal{O}_{qqql,2111}$	$\mathcal{O}_{qqql,1211}$	$\mathcal{O}_{duql,2111}$	$\mathcal{O}_{duql,1121}$	$\mathcal{O}_{duue,2111}$	$\mathcal{O}_{qque,2111}$
$\mathcal{O}_{qqql,1111}$	86.2		−44.4			−16.1				
$\mathcal{O}_{qque,1111}$		99.0		43.5						−22.9
$\mathcal{O}_{duql,1111}$	−44.4		22.9			8.31				
$\mathcal{O}_{duue,1111}$		43.5		19.1						−10.0
$\mathcal{O}_{qqql,2111}$										
$\mathcal{O}_{qqql,1211}$	−16.1		8.31			3.02				
$\mathcal{O}_{duql,2111}$										
$\mathcal{O}_{duql,1121}$										
$\mathcal{O}_{duue,2111}$										
$\mathcal{O}_{qque,2111}$		−22.9		−10.0						5.28

$$
\begin{aligned}
\mathcal{L}_0 \supset & \left(\frac{D-F}{f_\pi} \overline{\Sigma^+}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi} \overline{\Lambda^0}\gamma^\mu\gamma_5 n - \frac{D-F}{\sqrt{2}f_\pi} \overline{\Sigma^0}\gamma^\mu\gamma_5 n \right) \partial_\mu \bar{K}^0 \\
& + \left(\frac{D-F}{\sqrt{2}f_\pi} \overline{\Sigma^0}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi} \overline{\Lambda^0}\gamma^\mu\gamma_5 p + \frac{D-F}{f_\pi} \overline{\Sigma^-}\gamma^\mu\gamma_5 n \right) \partial_\mu K^- \\
& + \frac{3F-D}{2\sqrt{6}f_\pi} \left(\overline{p}\gamma^\mu\gamma_5 p + \overline{n}\gamma^\mu\gamma_5 n \right) \partial_\mu \eta \\
& + \frac{D+F}{f_\pi} \overline{p}\gamma^\mu\gamma_5 n \, \partial_\mu \pi^+ \\
& + \frac{D+F}{2\sqrt{2}f_\pi} \left(\overline{p}\gamma^\mu\gamma_5 p - \overline{n}\gamma^\mu\gamma_5 n \right) \partial_\mu \pi^0 + \text{h.c.} \, .
\end{aligned}
$$

$$\xi B \xi \to L \xi B \xi R^\dagger \qquad \xi^\dagger B \xi^\dagger \to R \xi^\dagger B \xi^\dagger L^\dagger$$

$$\xi B \xi^\dagger \to L \xi B \xi^\dagger L^\dagger \qquad \xi^\dagger B \xi \to R \xi^\dagger B \xi R^\dagger$$

$$\xi B \xi \sim (\mathbf{3}, \bar{\mathbf{3}}), \quad \xi^\dagger B \xi^\dagger \sim (\bar{\mathbf{3}}, \mathbf{3}), \quad \xi B \xi^\dagger \sim (\mathbf{8}, \mathbf{1}), \quad \xi^\dagger B \xi \sim (\mathbf{1}, \mathbf{8})$$

$$\alpha \cdot \nu \ \text{tr}(\xi B \xi^\dagger P_{32}) = -(du)(d\nu) = [\mathcal{O}_{udd}]^{S,LL}_{1111}$$

$$\langle 0 | \epsilon^{abc} (\bar{u}^\dagger_a \bar{d}^\dagger_b) u_c | p^{(s)} \rangle = \alpha P_L u_p^{(s)}$$

$$\langle 0 | \epsilon^{abc} (u_a d_b) u_c | p^{(s)} \rangle = \beta P_L u_p^{(s)}$$

Name	LEFT	Flavour/BχPT
$[\mathcal{O}^{S,LL}_{udd}]_{rstu}$	$(u_r d_s)(d_t \nu_u)$	$(\mathbf{8}, \mathbf{1})$
$[\mathcal{O}^{S,LL}_{udd}]_{111r}$	$(ud)(d\nu_r)$	$-\beta \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi^\dagger P_{32}) \supset -\beta \overline{\nu^c_{Lr}} n - \frac{i\beta}{f_\pi} \overline{\nu^c_{Lr}} \left(\sqrt{\frac{3}{2}} n\eta - \frac{1}{\sqrt{2}} n\pi^0 + p\pi^- \right)$
$[\mathcal{O}^{S,LL}_{udd}]_{121r}$	$(us)(d\nu_r)$	$-\beta \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi^\dagger \tilde{P}_{22}) \supset -\beta \overline{\nu^c_{Lr}} \left(-\frac{\Lambda^0}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} \right) - \frac{i\beta}{f_\pi} \overline{\nu^c_{Lr}} n \bar{K}^0$
$[\mathcal{O}^{S,LL}_{udd}]_{112r}$	$(ud)(s\nu_r)$	$-\beta \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi^\dagger P_{33}) \supset \beta \sqrt{\frac{2}{3}} \overline{\nu^c_{Lr}} \Lambda^0 - \frac{i\beta}{f_\pi} \overline{\nu^c_{Lr}} \left(n\bar{K}^0 + pK^- \right)$
$[\mathcal{O}^{S,LL}_{duu}]_{rstu}$	$(d_r u_s)(u_t e_u)$	$(\mathbf{8}, \mathbf{1})$
$[\mathcal{O}^{S,LL}_{duu}]_{111r}$	$(du)(ue_r)$	$-\beta \overline{e^c_{Lr}} \text{tr}(\xi B \xi^\dagger \tilde{P}_{31}) \supset \beta \overline{e^c_{Lr}} p + \frac{i\beta}{f_\pi} \overline{e^c_{Lr}} \left(\sqrt{\frac{3}{2}} p\eta + \frac{1}{\sqrt{2}} p\pi^0 + n\pi^+ \right)$
$[\mathcal{O}^{S,LL}_{duu}]_{211r}$	$(su)(ue_r)$	$-\beta \overline{e^c_{Lr}} \text{tr}(\xi B \xi^\dagger P_{21}) \supset -\beta \overline{e^c_{Lr}} \Sigma^+ + \frac{i\beta}{f_\pi} \overline{e^c_{Lr}} p\bar{K}^0$
$[\mathcal{O}^{S,LR}_{uud}]_{[rs]tu}$	$(u_r u_s)(\bar{d}^\dagger_t \bar{e}^\dagger_u)$	—
$[\mathcal{O}^{S,LR}_{duu}]_{rstu}$	$(d_r u_s)(\bar{u}^\dagger_t \bar{e}^\dagger_u)$	$(\bar{\mathbf{3}}, \mathbf{3})$
$[\mathcal{O}^{S,LR}_{duu}]_{111r}$	$(du)(\bar{u}^\dagger \bar{e}^\dagger_r)$	$\alpha \overline{e^c_{Rr}} \text{tr}(\xi^\dagger B \xi^\dagger \tilde{P}_{31}) \supset -\alpha \overline{e^c_{Rr}} p + \frac{i\alpha}{f_\pi} \overline{e^c_{Rr}} \left(-\frac{1}{\sqrt{6}} p\eta + \frac{1}{\sqrt{2}} p\pi^0 + n\pi^+ \right)$
$[\mathcal{O}^{S,LR}_{duu}]_{211r}$	$(su)(\bar{u}^\dagger \bar{e}^\dagger_r)$	$\alpha \overline{e^c_{Rr}} \text{tr}(\xi^\dagger B \xi^\dagger P_{21}) \supset \alpha \overline{e^c_{Rr}} \Sigma^+ - \frac{i\alpha}{f_\pi} \overline{e^c_{Rr}} p\bar{K}^0$
$[\mathcal{O}^{S,RL}_{uud}]_{[rs]tu}$	$(\bar{u}^\dagger_r \bar{u}^\dagger_s)(d_t e_u)$	—
$[\mathcal{O}^{S,RL}_{duu}]_{rstu}$	$(\bar{d}^\dagger_r \bar{u}^\dagger_s)(u_t e_u)$	$(\mathbf{3}, \bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{duu}]_{111r}$	$(\bar{d}^\dagger \bar{u}^\dagger)(ue_r)$	$-\alpha \overline{e^c_{Lr}} \text{tr}(\xi B \xi \tilde{P}_{31}) \supset \alpha \overline{e^c_{Lr}} p + \frac{i\alpha}{f_\pi} \overline{e^c_{Lr}} \left(-\frac{1}{\sqrt{6}} p\eta + \frac{1}{\sqrt{2}} p\pi^0 + n\pi^+ \right)$
$[\mathcal{O}^{S,RL}_{duu}]_{211r}$	$(\bar{s}^\dagger \bar{u}^\dagger)(ue_r)$	$-\alpha \overline{e^c_{Lr}} \text{tr}(\xi B \xi P_{21}) \supset -\alpha \overline{e^c_{Lr}} \Sigma^+ - \frac{i\alpha}{f_\pi} \overline{e^c_{Lr}} p\bar{K}^0$
$[\mathcal{O}^{S,RL}_{dud}]_{rstu}$	$(\bar{d}^\dagger_r \bar{u}^\dagger_s)(d_t \nu_u)$	$(\mathbf{3}, \bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{dud}]_{111r}$	$(\bar{d}^\dagger \bar{u}^\dagger)(d\nu_r)$	$\alpha \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi \tilde{P}_{32}) \supset -\alpha \overline{\nu^c_{Lr}} n + \frac{i\alpha}{f_\pi} \overline{\nu^c_{Lr}} \left(\frac{1}{\sqrt{6}} n\eta + \frac{1}{\sqrt{2}} n\pi^0 - p\pi^- \right)$
$[\mathcal{O}^{S,RL}_{dud}]_{211r}$	$(\bar{s}^\dagger \bar{u}^\dagger)(d\nu_r)$	$\alpha \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi P_{22}) \supset \alpha \overline{\nu^c_{Lr}} \left(\frac{\Lambda^0}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} \right) + \frac{i\alpha}{f_\pi} \overline{\nu^c_{Lr}} n\bar{K}^0$
$[\mathcal{O}^{S,RL}_{dud}]_{112r}$	$(\bar{d}^\dagger \bar{u}^\dagger)(s\nu_r)$	$\alpha \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi \tilde{P}_{33}) \supset \alpha \overline{\nu^c_{Lr}} \sqrt{\frac{2}{3}} \Lambda^0 - \frac{i\alpha}{f_\pi} \overline{\nu^c_{Lr}} \left(n\bar{K}^0 + pK^- \right)$
$[\mathcal{O}^{S,RL}_{dud}]_{212r}$	$(\bar{s}^\dagger \bar{u}^\dagger)(s\nu_r)$	$\alpha \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi P_{23}) \supset \alpha \overline{\nu^c_{Lr}} \Xi^0$
$[\mathcal{O}^{S,RL}_{ddu}]_{[rs]tu}$	$(\bar{d}^\dagger_r \bar{d}^\dagger_s)(u_t \nu_u)$	$(\mathbf{3}, \bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{ddu}]_{[12]1r}$	$(\bar{d}^\dagger \bar{s}^\dagger)(u\nu_r)$	$-\alpha \overline{\nu^c_{Lr}} \text{tr}(\xi B \xi P_{11}) \supset \alpha \overline{\nu^c_{Lr}} \left(\frac{\Lambda^0}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} \right) - \frac{i\alpha}{f_\pi} \overline{\nu^c_{Lr}} pK^-$
$[\mathcal{O}^{S,RR}_{duu}]_{rstu}$	$(\bar{d}^\dagger_r \bar{u}^\dagger_s)(\bar{u}^\dagger_t \bar{e}^\dagger_u)$	$(\mathbf{1}, \mathbf{8})$
$[\mathcal{O}^{S,RR}_{duu}]_{111r}$	$(\bar{d}^\dagger \bar{u}^\dagger)(\bar{u}^\dagger \bar{e}^\dagger_r)$	$\beta \overline{e^c_{Rr}} \text{tr}(\xi^\dagger B \xi \tilde{P}_{31}) \supset -\beta \overline{e^c_{Rr}} p + \frac{i\beta}{f_\pi} \overline{e^c_{Rr}} \left(\sqrt{\frac{3}{2}} p\eta + \frac{1}{\sqrt{2}} p\pi^0 + n\pi^+ \right)$
$[\mathcal{O}^{S,RR}_{duu}]_{211r}$	$(\bar{s}^\dagger \bar{u}^\dagger)(\bar{u}^\dagger \bar{e}^\dagger_r)$	$\beta \overline{e^c_{Rr}} \text{tr}(\xi^\dagger B \xi P_{21}) \supset \beta \overline{e^c_{Rr}} \Sigma^+ + \frac{i\beta}{f_\pi} \overline{e^c_{Rr}} p\bar{K}^0$

Name	LEFT	Flavour/BχPT
$[\mathcal{O}^{S,LL}_{udd}]_{rstu}$	$(u_r d_s)(d_t \nu_u)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{udd}]_{111r}$	$(ud)(d\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{32}) \supset -\beta\overline{\nu^c_{Lr}}n - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}\left(\sqrt{\frac{3}{2}}n\eta - \frac{1}{\sqrt{2}}n\pi^0 + p\pi^-\right)$
$[\mathcal{O}^{S,LL}_{udd}]_{121r}$	$(us)(d\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger\tilde{P}_{22}) \supset -\beta\overline{\nu^c_{Lr}}\left(-\frac{\Lambda^0}{\sqrt{6}}+\frac{\Sigma^0}{\sqrt{2}}\right) - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}n\bar{K}^0$
$[\mathcal{O}^{S,LL}_{udd}]_{112r}$	$(ud)(s\nu_r)$	$-\beta\overline{\nu^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{33}) \supset \beta\sqrt{\frac{2}{3}}\overline{\nu^c_{Lr}}\Lambda^0 - \frac{i\beta}{f_\pi}\overline{\nu^c_{Lr}}\left(n\bar{K}^0 + pK^-\right)$
$[\mathcal{O}^{S,LL}_{duu}]_{rstu}$	$(d_r u_s)(u_t e_u)$	$(\mathbf{8},\mathbf{1})$
$[\mathcal{O}^{S,LL}_{duu}]_{111r}$	$(du)(ue_r)$	$-\beta\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger\tilde{P}_{31}) \supset \beta\overline{e^c_{Lr}}p + \frac{i\beta}{f_\pi}\overline{e^c_{Lr}}\left(\sqrt{\frac{3}{2}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,LL}_{duu}]_{211r}$	$(su)(ue_r)$	$-\beta\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi^\dagger P_{21}) \supset -\beta\overline{e^c_{Lr}}\Sigma^+ + \frac{i\beta}{f_\pi}\overline{e^c_{Lr}}p\bar{K}^0$
$[\mathcal{O}^{S,LR}_{uud}]_{[rs]tu}$	$(u_r u_s)(\bar{d}_t^\dagger \bar{e}_u^\dagger)$	—
$[\mathcal{O}^{S,LR}_{duu}]_{rstu}$	$(d_r u_s)(\bar{u}_t^\dagger \bar{e}_u^\dagger)$	$(\bar{\mathbf{3}},\mathbf{3})$
$[\mathcal{O}^{S,LR}_{duu}]_{111r}$	$(du)(\bar{u}^\dagger \bar{e}_r^\dagger)$	$\alpha\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi^\dagger\tilde{P}_{31}) \supset -\alpha\overline{e^c_{Rr}}p + \frac{i\alpha}{f_\pi}\overline{e^c_{Rr}}\left(-\frac{1}{\sqrt{6}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,LR}_{duu}]_{211r}$	$(su)(\bar{u}^\dagger \bar{e}_r^\dagger)$	$\alpha\overline{e^c_{Rr}}\mathrm{tr}(\xi^\dagger B\xi^\dagger P_{21}) \supset \alpha\overline{e^c_{Rr}}\Sigma^+ - \frac{i\alpha}{f_\pi}\overline{e^c_{Rr}}p\bar{K}^0$
$[\mathcal{O}^{S,RL}_{uud}]_{[rs]tu}$	$(\bar{u}_r^\dagger \bar{u}_s^\dagger)(d_t e_u)$	—
$[\mathcal{O}^{S,RL}_{duu}]_{rstu}$	$(\bar{d}_r^\dagger \bar{u}_s^\dagger)(u_t e_u)$	$(\mathbf{3},\bar{\mathbf{3}})$
$[\mathcal{O}^{S,RL}_{duu}]_{111r}$	$(\bar{d}^\dagger \bar{u}^\dagger)(ue_r)$	$-\alpha\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi\tilde{P}_{31}) \supset \alpha\overline{e^c_{Lr}}p + \frac{i\alpha}{f_\pi}\overline{e^c_{Lr}}\left(-\frac{1}{\sqrt{6}}p\eta + \frac{1}{\sqrt{2}}p\pi^0 + n\pi^+\right)$
$[\mathcal{O}^{S,RL}_{duu}]_{211r}$	$(\bar{s}^\dagger \bar{u}^\dagger)(ue_r)$	$-\alpha\overline{e^c_{Lr}}\mathrm{tr}(\xi B\xi P_{21}) \supset -\alpha\overline{e^c_{Lr}}\Sigma^+ - \frac{i\alpha}{f_\pi}\overline{e^c_{Lr}}p\bar{K}^0$

Nucleon decay channels

$$\Gamma(N \to M\ell_\alpha) \quad \Delta(B-L)=0 \quad \begin{cases} n \to \eta^0\nu \\ n \to \pi^0\nu \\ p \to \pi^+\nu \\ n \to \pi^-e^+ \\ p \to \eta^0 e^+ \\ p \to \pi^0 e^+ \\ p \to K^0 e^+ \\ n \to K^0\nu \\ p \to K^+\nu \end{cases}$$

$$\Gamma(N \to M\ell_\alpha) \quad |\Delta(B-L)|=2 \quad \begin{cases} n \to \eta^0\nu \\ n \to \pi^0\nu \\ p \to \pi^+\nu \\ n \to K^0\nu \\ p \to K^+\nu \\ n \to K^+e^- \end{cases}$$

· **All 2-body PS decays except for** $p \to \bar{K}^0 e^+$ $n \to \bar{K}^0\nu$ $n \to K^-e^+$ $n \to \pi^+e^-$

· **No BχPT formalism developed for PD into vector mesons, e.g.** $p \to \rho^0 e^+$ **and** $p \to \omega^0 e^+$

Phenomenological matrices

$$\Gamma_{(i)}^{\Delta(B-L)=0} \equiv 10^{-4}\, c_j^* \boxed{\boldsymbol{\kappa}_{(i)}^{jk}}\, c_k \frac{m_p^5}{\Lambda^4}$$ **for** $i = p \to \pi^0 e^+, p \to K^+\nu \dots$ **(9 matrices)**

$$\Gamma_{(i)}^{|\Delta(B-L)|=2} \equiv c_j^* \boxed{\boldsymbol{\kappa}_{(i)}^{jk}}\, c_k \frac{m_p^7}{\Lambda^6}$$ **for** $i = p \to K^+\nu, n \to K^+e^- \dots$ **(6 matrices)**

$n \to K^0\nu$

	$\mathcal{O}_{\bar{l}dud\tilde{H},1111}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1111}$	$\mathcal{O}_{\bar{l}dud\tilde{H},1211}$	$\mathcal{O}_{\bar{l}dud\tilde{H},1112}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1211}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1121}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1112}$	$\mathcal{O}_{\bar{l}dddH,1121}$	$\mathcal{O}_{\bar{e}qdd\tilde{H},1121}$
$\mathcal{O}_{\bar{l}dud\tilde{H},1111}$									
$\mathcal{O}_{\bar{l}dqq\tilde{H},1111}$		0.08	−0.48	−0.36	−0.51		0.28		
$\mathcal{O}_{\bar{l}dud\tilde{H},1211}$		−0.48	3.09	2.33	3.25		−1.80		
$\mathcal{O}_{\bar{l}dud\tilde{H},1112}$		−0.36	2.33	1.76	2.45		−1.36		
$\mathcal{O}_{\bar{l}dqq\tilde{H},1211}$		−0.51	3.25	2.45	3.42		−1.90		
$\mathcal{O}_{\bar{l}dqq\tilde{H},1121}$									
$\mathcal{O}_{\bar{l}dqq\tilde{H},1112}$		0.28	−1.80	−1.36	−1.90		1.06		
$\mathcal{O}_{\bar{l}dddH,1121}$									
$\mathcal{O}_{\bar{e}qdd\tilde{H},1121}$									

$p \to K^+\nu$

	$\mathcal{O}_{\bar{l}dud\tilde{H},1111}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1111}$	$\mathcal{O}_{\bar{l}dud\tilde{H},1211}$	$\mathcal{O}_{\bar{l}dud\tilde{H},1112}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1211}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1121}$	$\mathcal{O}_{\bar{l}dqq\tilde{H},1112}$	$\mathcal{O}_{\bar{l}dddH,1121}$	$\mathcal{O}_{\bar{e}qdd\tilde{H},1121}$
$\mathcal{O}_{\bar{l}dud\tilde{H},1111}$									
$\mathcal{O}_{\bar{l}dqq\tilde{H},1111}$		0.01	0.21	0.05	0.22		0.06		
$\mathcal{O}_{\bar{l}dud\tilde{H},1211}$		0.21	3.09	0.76	3.25		0.80		
$\mathcal{O}_{\bar{l}dud\tilde{H},1112}$		0.05	0.76	0.19	0.80		0.20		
$\mathcal{O}_{\bar{l}dqq\tilde{H},1211}$		0.22	3.25	0.80	3.42		0.84		
$\mathcal{O}_{\bar{l}dqq\tilde{H},1121}$									
$\mathcal{O}_{\bar{l}dqq\tilde{H},1112}$		0.06	0.80	0.20	0.84		0.21		
$\mathcal{O}_{\bar{l}dddH,1121}$									
$\mathcal{O}_{\bar{e}qdd\tilde{H},1121}$									