Zuoz Summer School 2024:
“From low to high: Particle Physics at the Frontier”

Low Energy Physics (2)

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Flow of the lectures

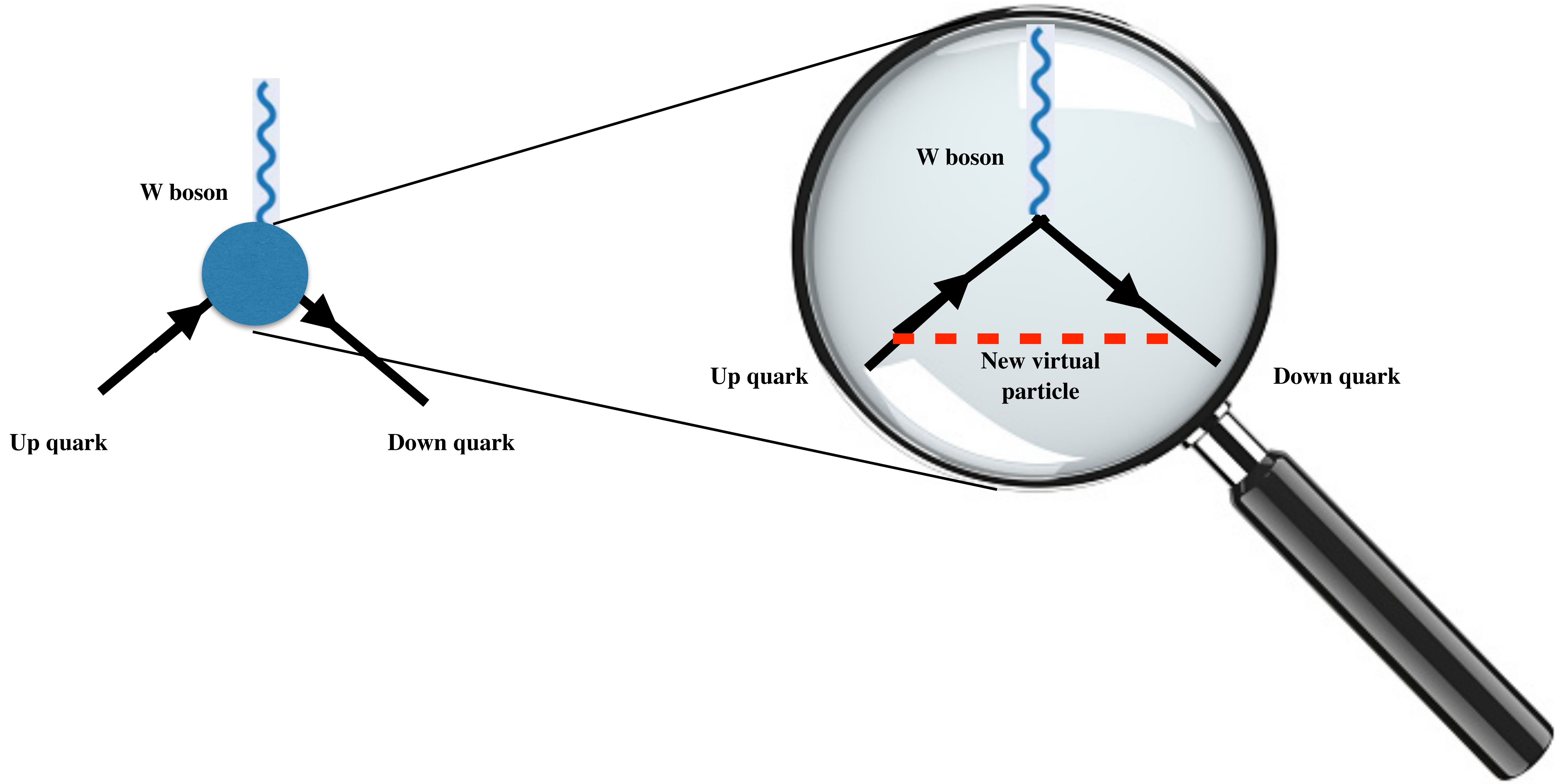
- The quest for new physics at the low-energy frontier
- How does the precision / intensity frontier work? (Theory perspective)
  - An example from history: the Standard Model itself!
  - Effective field theory (EFT) framework
  - Standard Model EFT landscape in the LHC era and beyond

Lecture 1

- "Zoom in" on selected low-energy probes: illustrate methods and impact
  - Precision measurements:
    - Weak charged current processes (beta decays)
  - Symmetry tests:
    - Lepton Number and Lepton Flavor Violation

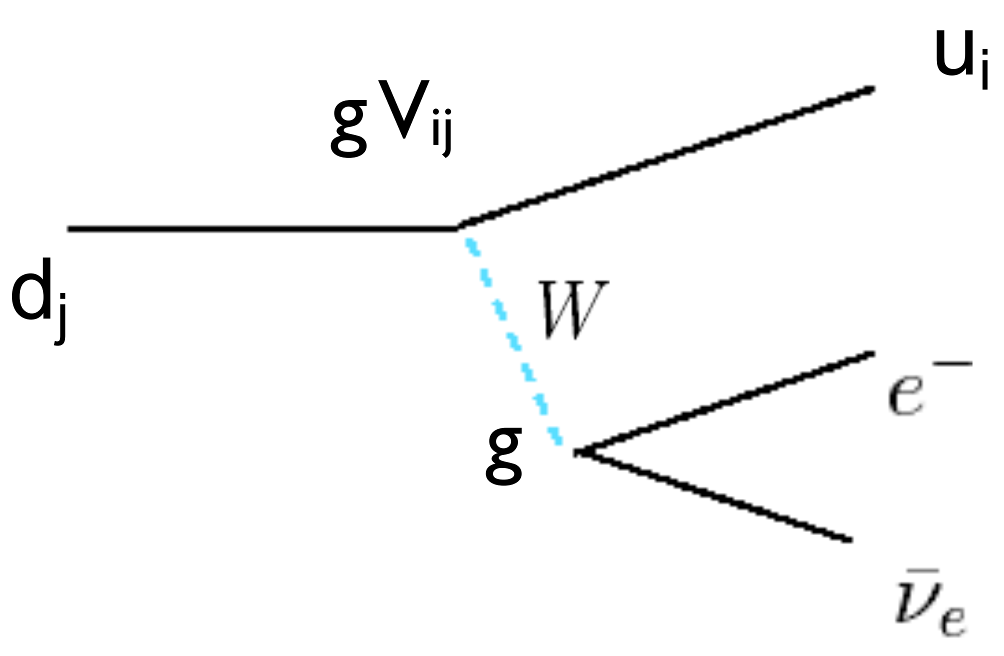
Lecture 2

Precision tests with weak charged currents



β decays in the SM and beyond

- In the SM, W exchange ⇒ only "V-A" + Cabibbo and lepton universality



$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa

Cabibbo Universality

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$$[G_F]_e/[G_F]_\mu = 1$$

Lepton Flavor Universality (LFU)

β decays in the SM and beyond

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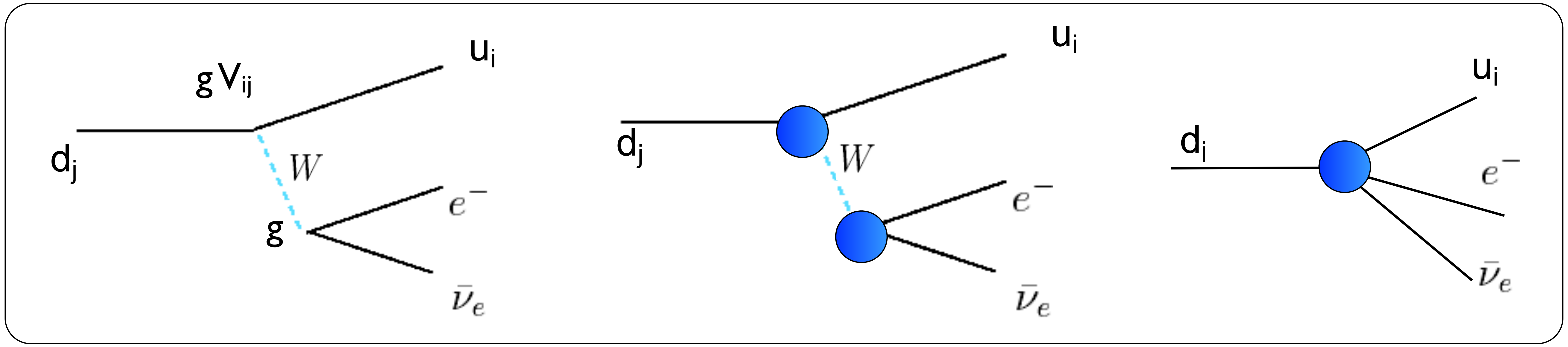


$G_F^{(\beta)} \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$ $\qquad 1/\Lambda^2 \qquad 1/\Lambda^2$

- New physics can spoil universality. With current precision of 0.1-0.01% we can probe Λ > 10 TeV

~0..95 ~0.05 ~1.5 × 10^{-5}

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$\delta V_{ud}/V_{ud} \sim 0.02\%$ $\delta V_{us}/V_{us} \sim 0.2\%$ $\delta V_{ub}/V_{ub} \sim 5\%$

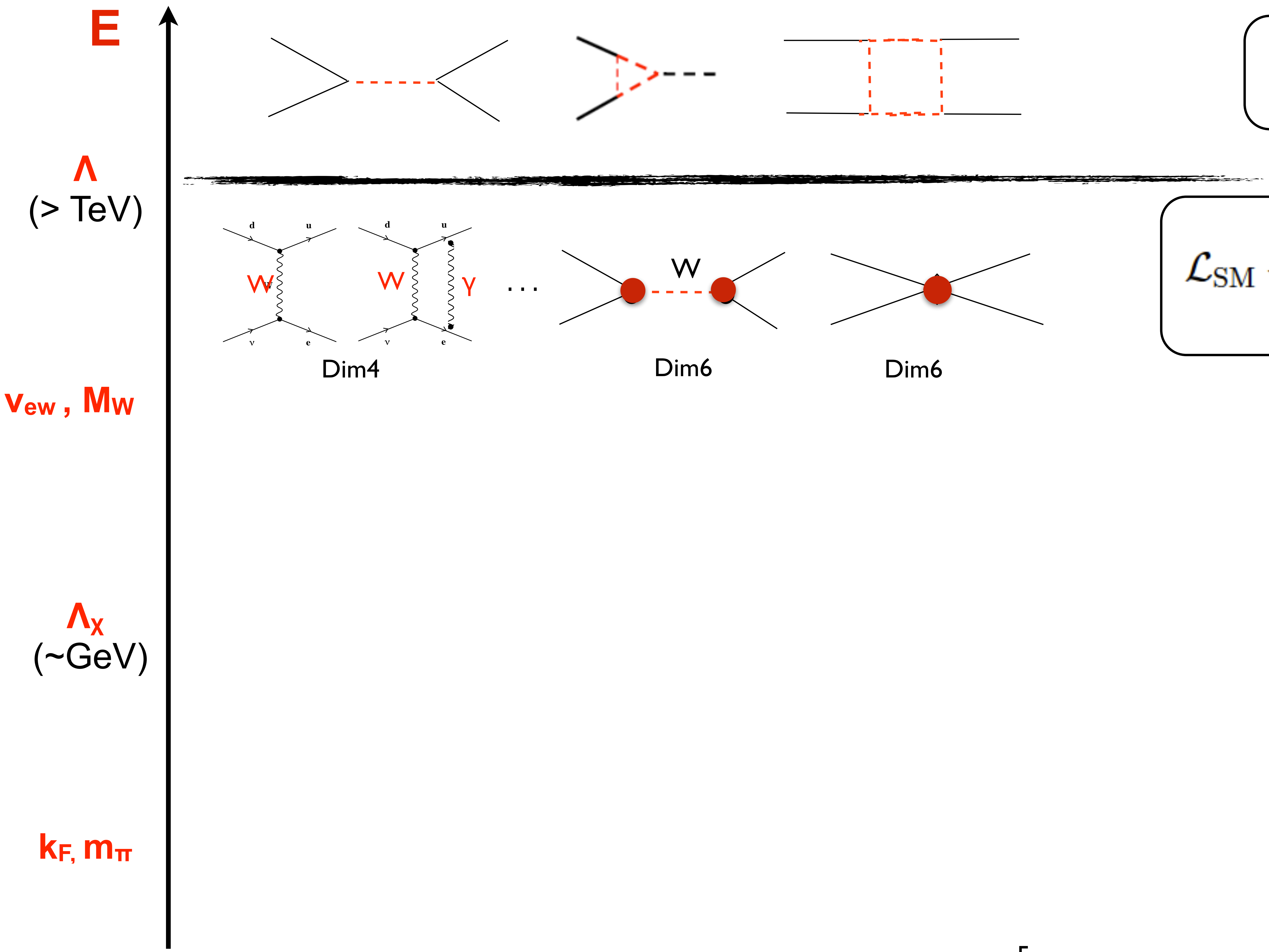
$R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$

$$R_{e/\mu}(\text{SM}) = 1.23524(015) \times 10^{-4} \qquad 0.01\%$$

$$R_{e/\mu}(\text{Exp}) = 1.23270(230) \times 10^{-4} \qquad 0.18\%$$

Bridging scales with EFT

To connect UV physics to hadronic decays, use multiple EFTs



$$\mathcal{L}_{\rm BSM}$$

BSM dynamics

$$\mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}$$

SM-EFT operators

$SU(3)_c \times SU(2)_W \times U(1)_Y$

V_{ew}/Λ

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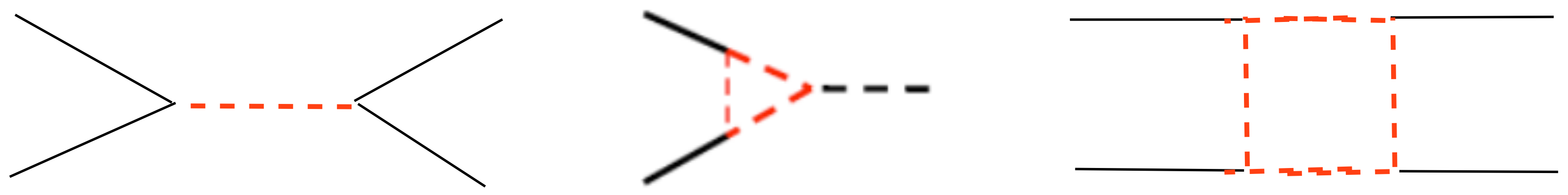

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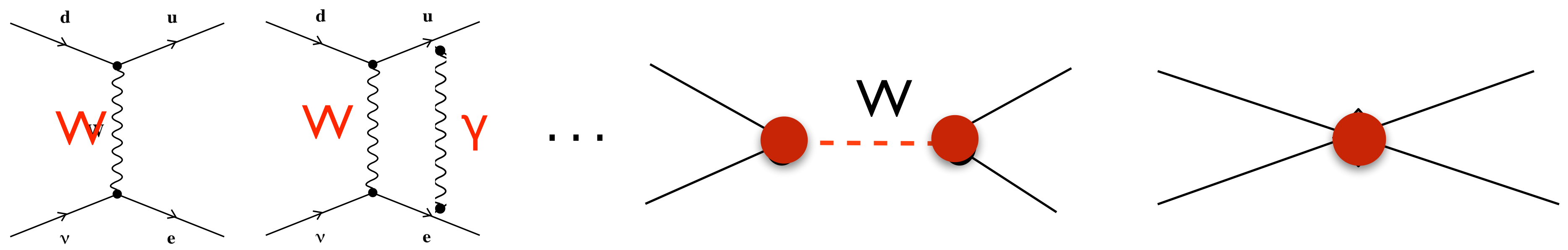
Λ (> TeV)



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SM-EFT operators

$SU(3)_c \times SU(2)_W \times U(1)_Y$

v_{ew}/Λ

v_{ew} , M_W

$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$
$$Q_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$
$$Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$$

$$O_{qde} = (\bar{\ell} e)(\bar{d} q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^t = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$$
$$O_{lq}^{(3)} = \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q$$
$$O_{ll} = \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l$$

Λ_χ (~GeV)

k_F, m_π

Eight SU(3)xSU(2)xU(1)-invariant dim 6 operators (up to flavor indices) affect beta decays (3 vertex corrections and 5 four-fermion)

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To connect UV physics to hadronic decays, use multiple EFTs

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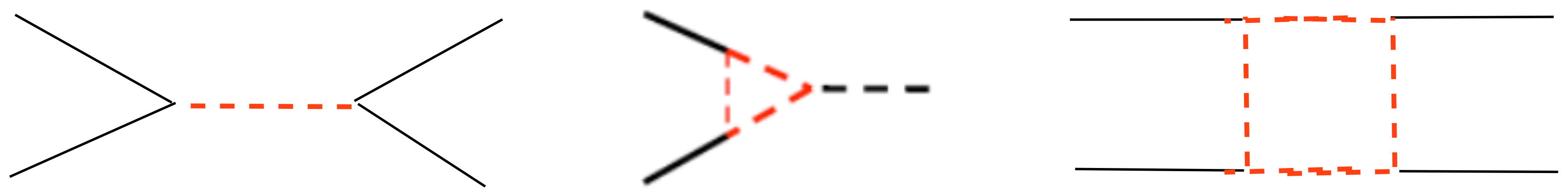

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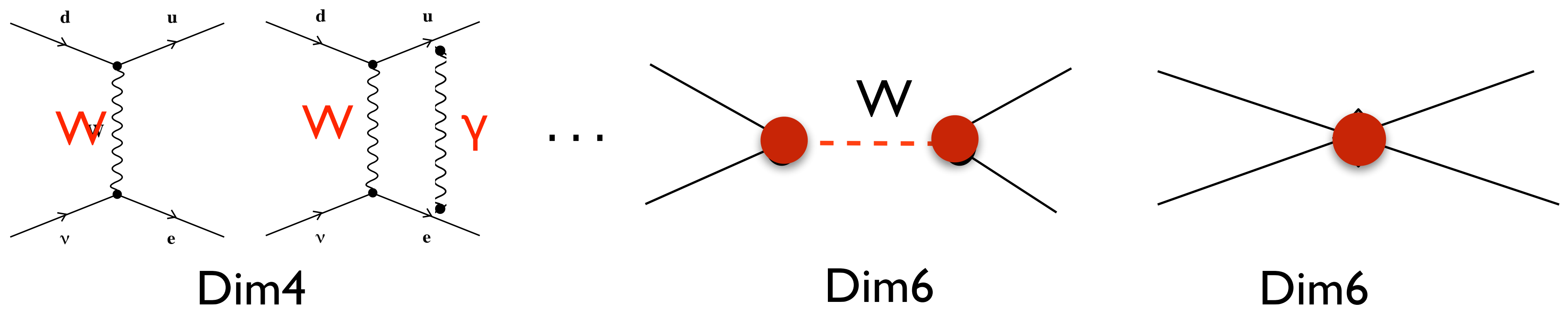

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SM-EFT operators

$SU(3)_c \times SU(2)_W \times U(1)_Y$

V_{ew}/Λ

v_{ew} , M_W

$$\mathcal{L}_{\rm Fermi} - \frac{G_F V_{u_i d_j}}{\sqrt{2}} \sum_n \epsilon_n O_n + \mathcal{L}_{QCD} + \mathcal{L}_{QED}$$

LEFT operators

$SU(3)_c \times U(1)_{EM}$

E/V_{ew}

Λ_χ (~GeV)

k_F, m_π

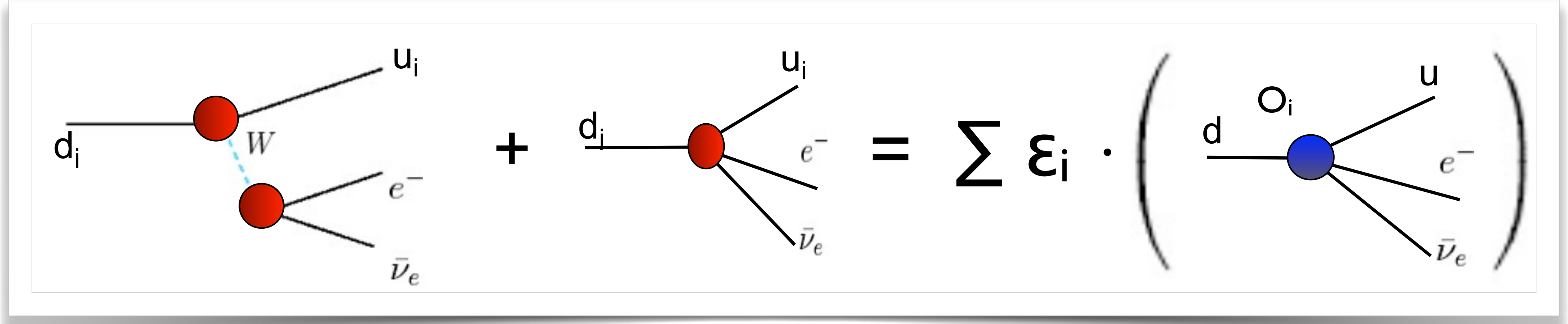
$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\mu - \frac{G_F V_{u_i d_j}}{\sqrt{2}} C_\beta(\mu)\, \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}_i \gamma^\mu (1-\gamma_5) d_j$$

6 SU(3)xU(1)-invariant dim 6 operators affect analysis of beta decays (all four-fermion)

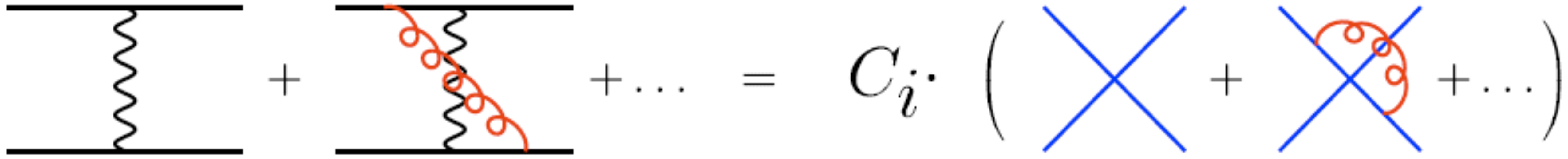
$$
\begin{aligned}
O_L^{abij} &= \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}_i \gamma^\mu (1-\gamma_5) d_j \\
O_R^{abij} &= \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}_i \gamma^\mu (1+\gamma_5) d_j \\
O_S^{abij} &= \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u}_i d_j \\
O_P^{abij} &= \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u}_i \gamma_5 d_j \\
O_T^{abij} &= \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5)\nu_b \cdot \bar{u}_i \sigma^{\mu\nu} (1-\gamma_5) d_j \\
O_{\rm lept}^{abcd} &= \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{\nu}_c \gamma^\mu (1-\gamma_5) e_d
\end{aligned}
$$

SMEFT → LEFT matching

- Wilson coefficients determined from the matching condition $A_{SMEFT} = A_{LEFT}$
- Tree-level matching for BSM operators determines $\varepsilon_{L,R,S,P,T}$



- Loop-level matching for SM operators (QED / QCD loops needed for precision)



"Full" theory (higher scale EFT) "Effective theory" (lower scale EFT)

$$\mathcal{L}_{\rm CC} \;\to\; -\frac{G_F V_{ud}}{\sqrt{2}}\, C_\beta(\mu)\; \bar{e}_a \gamma_\alpha (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\alpha(1-\gamma_5) d + \ldots$$

$$C_\beta(\mu) = 1 + \frac{\alpha}{\pi} \log \frac{M_Z}{\mu} + \ldots$$

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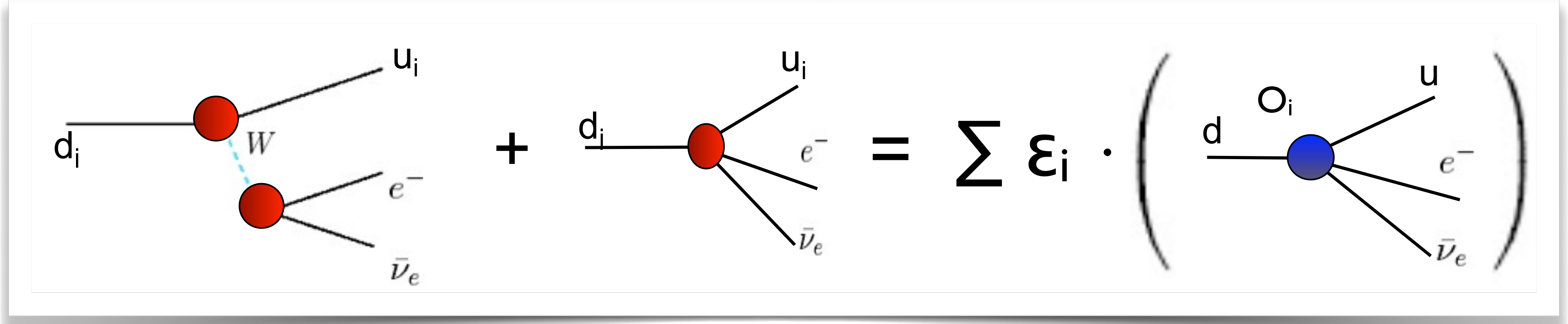

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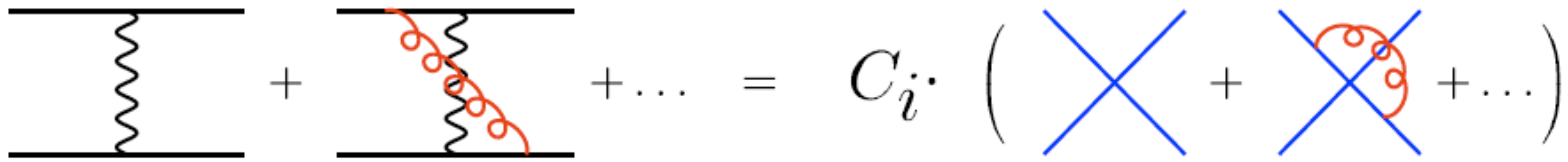

"Full" theory (higher scale EFT) "Effective theory" (lower scale EFT)

$$\mathcal{L}_{\rm CC} \to -\frac{G_F V_{ud}}{\sqrt{2}} \, C_\beta(\mu) \, \bar{e}_a \gamma_\alpha (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\alpha (1-\gamma_5) d + \dots$$

$$C_\beta(\mu) = 1 + \frac{\alpha}{\pi} \log \frac{M_Z}{\mu} + \dots$$ ⟵ Large log @ $\mu << M_Z$

Renormalization Group "Running" (1)

- At scale μ (process) < Λ (matching), QED and QCD corrections to the Wilson coefficients can spoil perturbation theory

QED

$1 + \#\ \alpha/\pi \,\mathrm{Log}\,(\Lambda/\mu)$

@ μ~1GeV ↓ Λ~M_Z

~1%

Mandatory to include these for SM operator (BSM effect < 1%)

QCD

$1 + \#\ \alpha_s/\pi \,\mathrm{Log}\,(\Lambda/\mu)$

↓ Λ~M_Z

~40%

Include these for SM and BSM operators (O(1) impact on extraction of BSM parameters)

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~1%

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↓ $\Lambda \sim M_Z$

~40%

Include these for SM and BSM operators (O(1) impact on extraction of BSM parameters)

- Use RGEs to re-organize perturbation series.
  Pert. theory expands "by rows": NLO, N^{2}LO, ...
  RGE: expands "by columns": LL, NLL, ...

$$\ell = \log \frac{\Lambda}{\mu} \qquad \alpha_s\, \ell \sim O(1)$$

	LL	NLL	N^2LL	...
NLO	$\alpha_s\, \ell$	α_s		
N^{2}LO	$\alpha_s^2\, \ell^2$	$\alpha_s^2\, \ell$	α_s^2	
N^{3}LO	$\alpha_s^3\, \ell^3$	$\alpha_s^3\, \ell^2$	$\alpha_s^3 \ell$	α_s^3
	...	...	...	
	$O(1)$	$O(\alpha_s)$	$O(\alpha_s^2)$	

Renormalization Group "Running" (2)

- RG equations:

$$\frac{d}{d(\ln\mu)}C_i = \gamma_i C_i \qquad \frac{d}{d(\ln\mu)}g = \beta(g)$$

$$\gamma_i = \frac{g^2}{16\pi^2}\gamma_i^{(0)} + \dots \qquad \beta(g) = -\beta_0\frac{g^3}{16\pi^2} + \dots \qquad \alpha(\mu) = \frac{\alpha(\Lambda)}{1 - \frac{\beta_0\alpha(\Lambda)}{2\pi}\log\frac{\Lambda}{\mu}}$$

$$\frac{C_i(\mu)}{C_i(\Lambda)} = \exp\left[\int_{g(\Lambda)}^{g(\mu)} dg' \frac{\gamma_i(g')}{\beta(g')}\right] \rightarrow \left[\frac{\alpha(\Lambda)}{\alpha(\mu)}\right]^{\frac{\gamma_i^{(0)}}{2\beta_0}}$$

With one-loop anomalous dimensions, sum the leading log (LL) series

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With one-loop anomalous dimensions, sum the leading log (LL) series

- For the V-A operator the anomalous dimension is known beyond one loop

Solution gives LL~ $(\alpha \ln(M_W/\mu))^n$ and NLL~ $\alpha\, (\alpha_s \ln(M_W/\mu))^n$, $\alpha\, (\alpha \ln(M_W/\mu))^n$

$$\mu \frac{\mathrm{d}C_\beta^r(a,\mu)}{\mathrm{d}\mu} = \gamma(\alpha,\alpha_s)\, C_\beta^r(a,\mu)\,,$$

$$\gamma(\alpha,\alpha_s) = \gamma_0 \frac{\alpha}{\pi} + \gamma_1 \left(\frac{\alpha}{\pi}\right)^2 + \gamma_{se}\frac{\alpha}{\pi}\frac{\alpha_s}{4\pi} + \cdots$$

$$\gamma_0 = -1 \qquad \gamma_1^{NDR}(a) = \frac{\tilde{n}}{18}(2a+1)\,, \qquad \tilde{n} = \sum_f n_f Q_f^2 \qquad \gamma_{se} = +1$$

Renormalization Group “Running” (2)

- RG equations:

$$\frac{d}{d(\ln\mu)}C_i = \gamma_i C_i \qquad \frac{d}{d(\ln\mu)} g = \beta(g)$$

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$$\frac{C_i(\mu)}{C_i(\Lambda)} = \exp\left[\int_{g(\Lambda)}^{g(\mu)} dg' \,\frac{\gamma_i(g')}{\beta(g')}\right] \rightarrow \left[\frac{\alpha(\Lambda)}{\alpha(\mu)}\right]^{\frac{\gamma_i^{(0)}}{2\beta_0}}$$

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$$\mu\frac{dC^r_\beta(a,\mu)}{d\mu} = \gamma(\alpha,\alpha_s)\, C^r_\beta(a,\mu)\,,$$

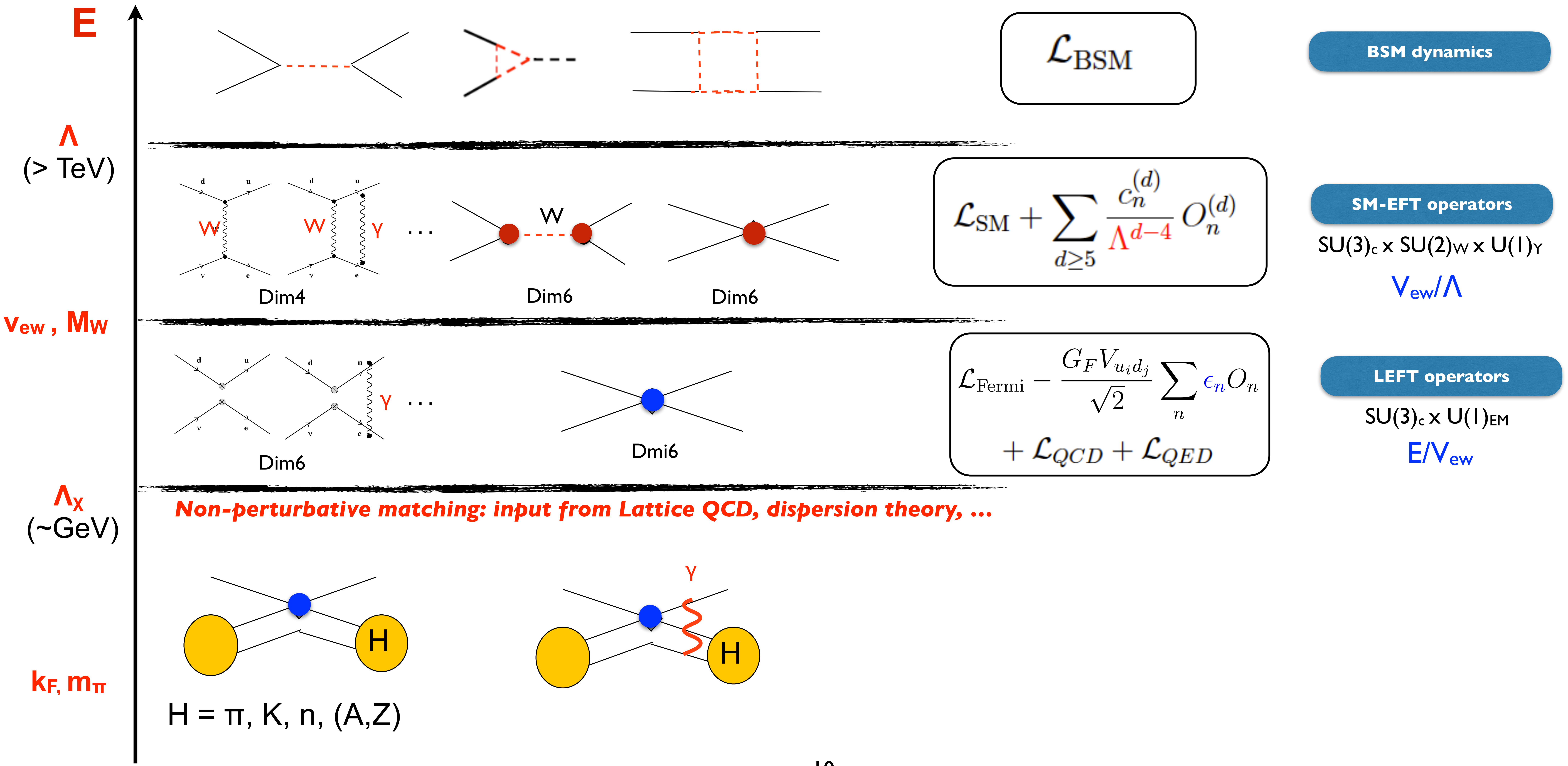
$$\gamma(\alpha,\alpha_s) = \gamma_0\frac{\alpha}{\pi} + \gamma_1\left(\frac{\alpha}{\pi}\right)^2 + \gamma_{se}\frac{\alpha}{\pi}\frac{\alpha_s}{4\pi} + \cdots$$

Beyond one loop C_i and γ_i depend on other choices (‘scheme dependence’) Physics does not care about our calculations choices

$$\gamma_0 = -1 \qquad \gamma_1^{NDR}(a) = \frac{\tilde{n}}{18}(2a+1)\,, \qquad \tilde{n} = \sum_f n_f Q_f^2 \qquad \gamma_{se} = +1$$

Bridging scales with EFT

To connect UV physics to hadronic decays, use multiple EFTs



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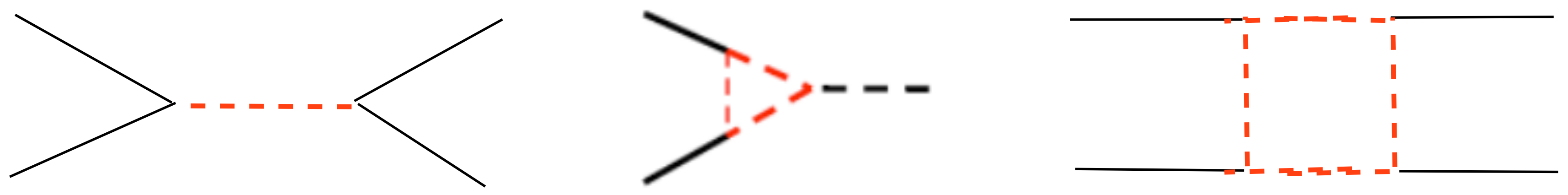
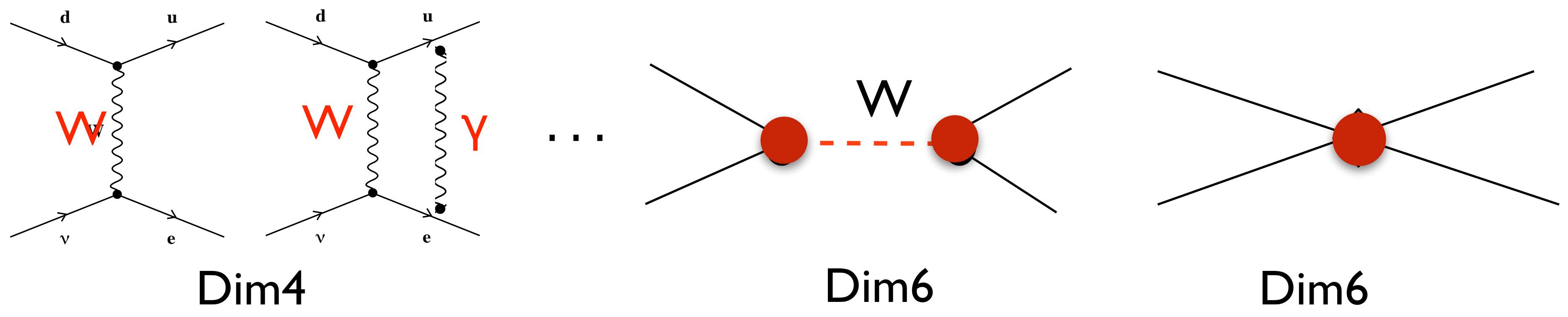


$$\mathcal{L}_{\rm BSM}$$

BSM dynamics

Λ (> TeV)



$$\mathcal{L}_{\rm SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} O_n^{(d)}$$

SM-EFT operators

$SU(3)_c \times SU(2)_W \times U(1)_Y$

v_{ew}/Λ

v_{ew} , M_W

$$\mathcal{L}_{\rm Fermi} - \frac{G_F V_{u_i d_j}}{\sqrt{2}} \sum_n \epsilon_n O_n + \mathcal{L}_{QCD} + \mathcal{L}_{QED}$$

LEFT operators

$SU(3)_c \times U(1)_{EM}$

E/v_{ew}

Λ_χ (~GeV)

Non-perturbative matching: input from Lattice QCD, dispersion theory, …

- Degrees of freedom: mesons and nucleons
- Symmetries: Lorentz (or Galileo) + symmetries of QCD (in particular chiral symmetry) and LEFT
- Power counting: expansion in energy over scale of QCD resonances (~GeV)

$\mathcal{L}_{\pi,K,\eta}$ ← Goldstone bosons of Chiral SB

$\mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$

Chiral EFT (N,π, K…)

p/Λ_χ, k_F/Λ_χ, $m_{\pi,K}/\Lambda_\chi$

k_F, m_π

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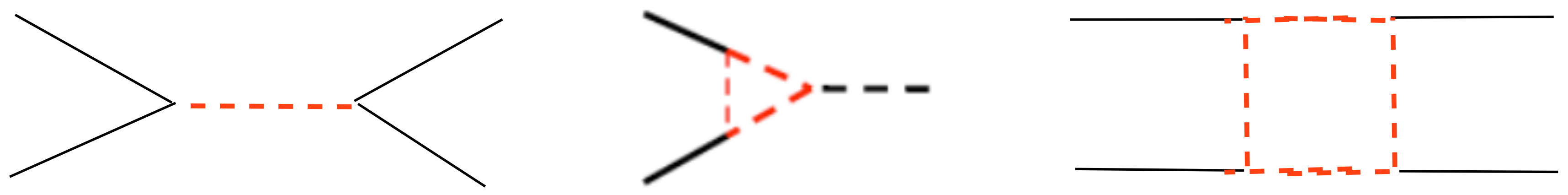

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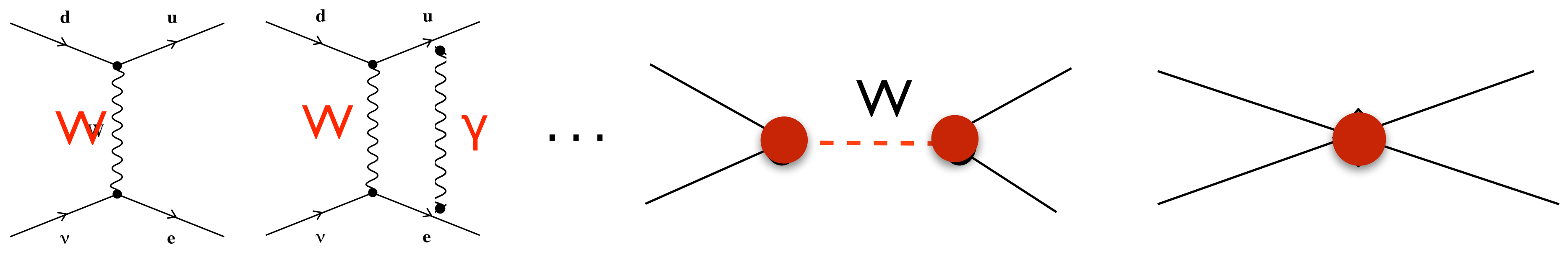

Dim4 Dim6 Dim6

v_{ew} , M_W

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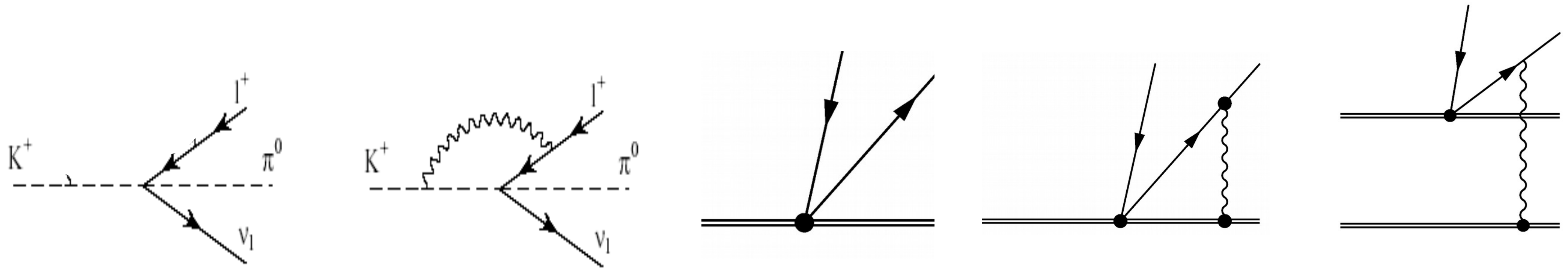

k_F, m_π

$$\mathcal{L}_{\pi,K,\eta} \longleftarrow \text{Goldstone bosons of Chiral SB}$$

$$\mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

Chiral EFT (N,π, K…)

p/Λ_χ, k_F/Λ_χ, $m_{\pi,K}/\Lambda_\chi$

To a given order, loops + LECs (determined by experiment, LQCD, dispersive methods, models…)

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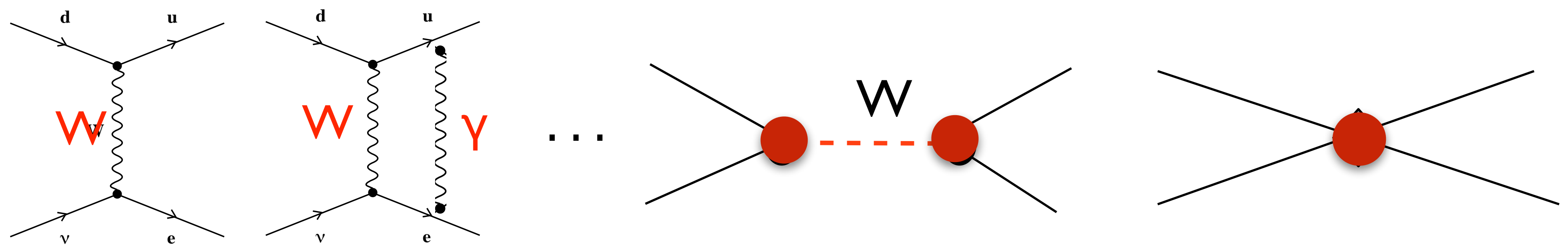

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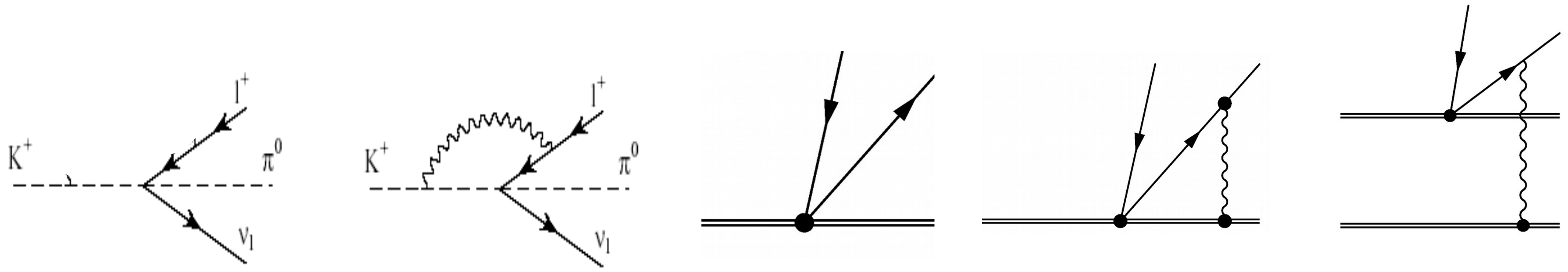

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p/Λ_χ, k_F/Λ_χ, $m_{\pi,K}/\Lambda_\chi$

k_F, m_π

$$H_{\rm Nuclear} + H_{\rm weak} + H_{\rm EM}$$

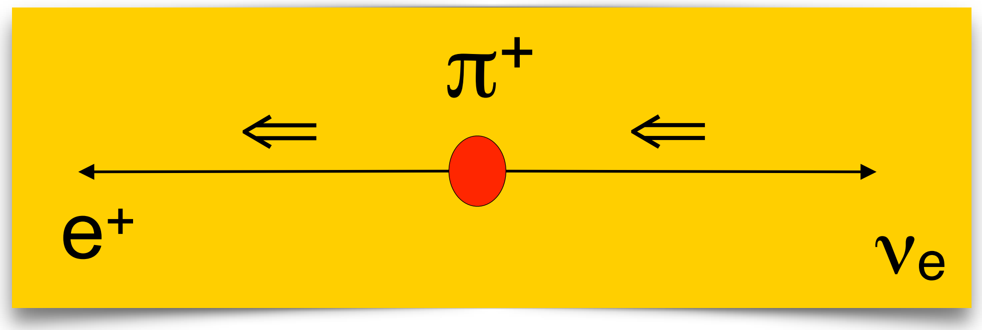
Pion-less EFT and H_{nucl}

m_e/m_π , q_{ext}/m_π

To a given order, loops + LECs (determined by experiment, LQCD, dispersive methods, models…)

Probing LFU with $R_{e/\mu}^{(\pi)}$

- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$



- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

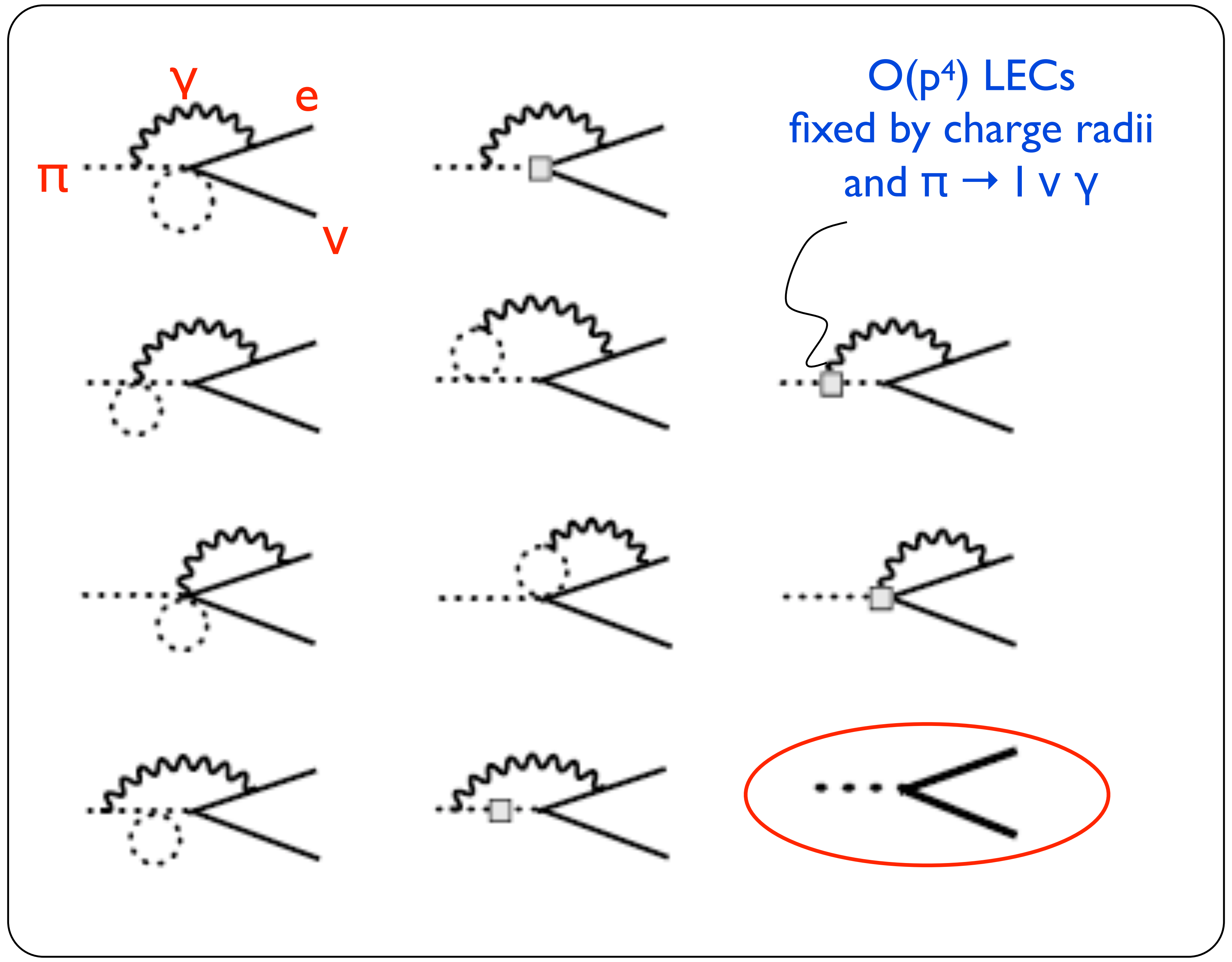
VC-Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

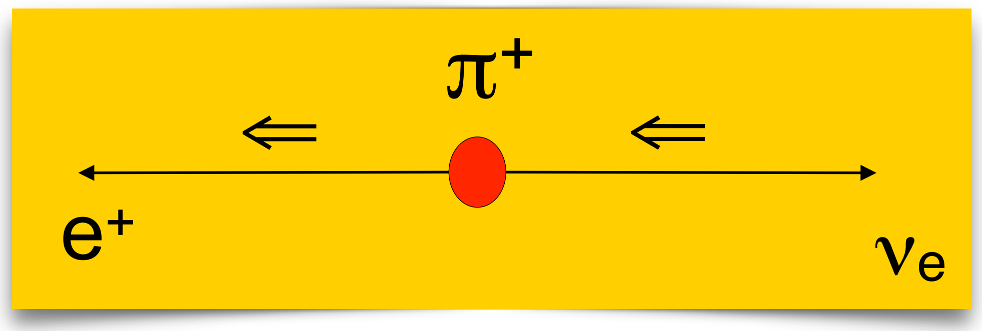
- Result known to $O(\alpha Q^4)$, with $Q \sim m_{\pi, K, \mu}/\Lambda_\chi$

- Many uncertainties cancel in the ratio



Probing LFU with $R_{e/\mu}(\pi)$

- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ helicity suppressed the SM (V-A), zero if $m_e \to 0$



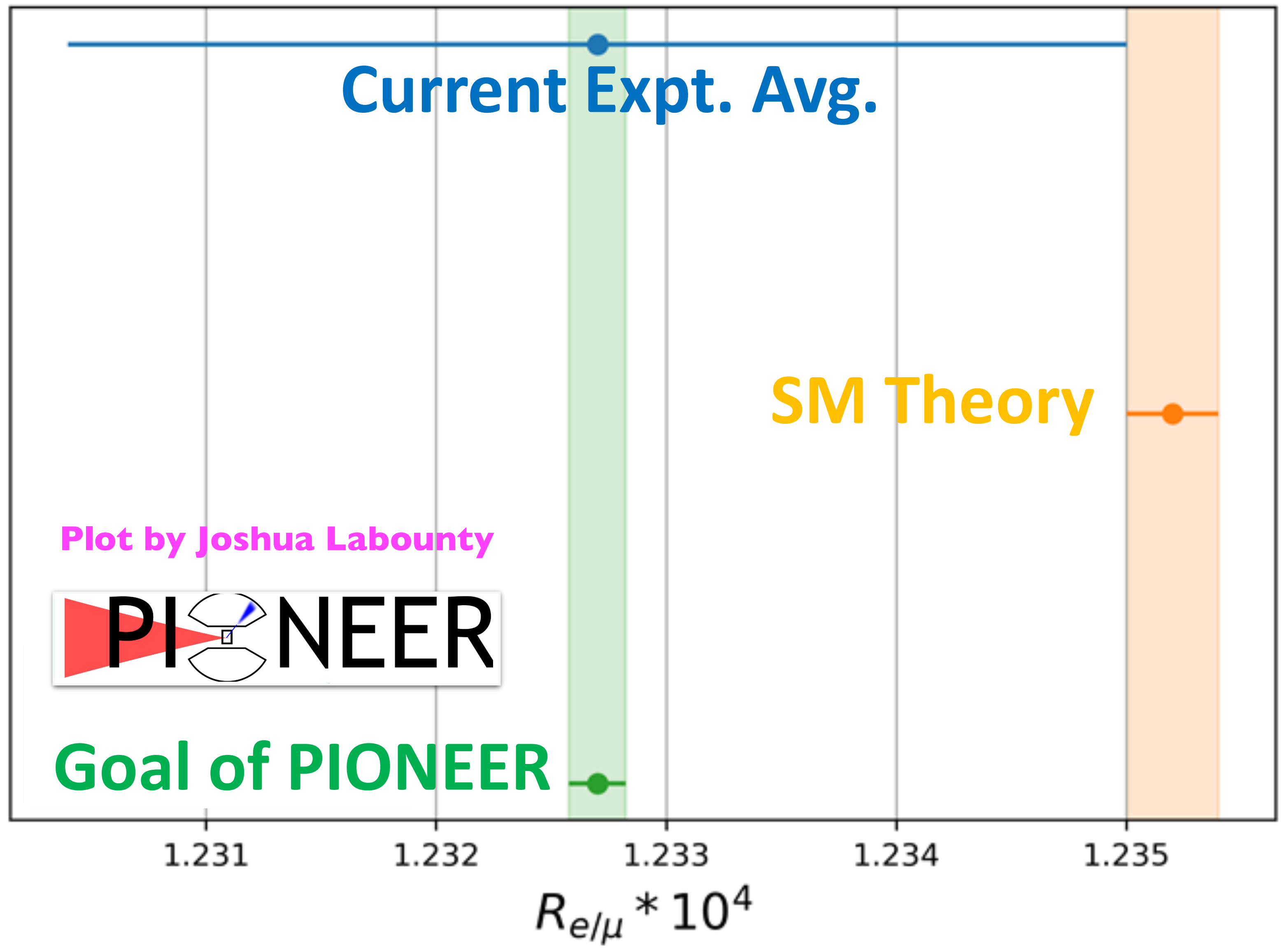
- $\sigma_{exp} \sim 15\sigma_{th} \Rightarrow$ pristine LFU test possible

VC-Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$
$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

- PIONEER @ PSI will match theoretical uncertainty. Order of magnitude gap — room for surprises!



Status of LFU test

$$\frac{R_{e/\mu}^{(\pi)}}{\left[R_{e/\mu}^{(\pi)}\right]^{\rm SM}} = \frac{\left|1+\epsilon_L^{ee}-\epsilon_R-\frac{B_0}{m_e}\epsilon_P^{ee}\right|^2}{\left|1+\epsilon_L^{\mu\mu}-\epsilon_R-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right|^2}+\cdots$$

Non-interfering terms with 'wrong' neutrino flavor

- BSM axial-current contribution

$$-1.9\times10^{-3} < \epsilon_A^{ee}-\epsilon_A^{\mu\mu} < -0.1\times10^{-3} \qquad \epsilon_A \equiv \epsilon_L - \epsilon_R$$

Λ_A ~ 5.5 TeV → ~ 22 TeV with PIONEER

Status of LFU test

$$\frac{R^{(\pi)}_{e/\mu}}{\left[R^{(\pi)}_{e/\mu}\right]^{\mathrm{SM}}} = \frac{\left|1+\epsilon_L^{ee}-\epsilon_R-\frac{B_0}{m_e}\epsilon_P^{ee}\right|^2}{\left|1+\epsilon_L^{\mu\mu}-\epsilon_R-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right|^2}+\cdots$$

Non-interfering terms with 'wrong' neutrino flavor

- BSM pseudoscalar contribution
  - Not helicity suppressed! $B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu)+m_d(\mu)}$ → $B_0/m_e = 3.6 \times 10^3$ @ μ = 2 GeV
  - LFU violation ↔ $[\epsilon_P]^{\alpha\alpha} \neq \kappa\, m_\alpha$

$$\epsilon_P^{ee} < 5.4 \times 10^{-7}$$

Λ_P ~ 350 TeV → ~1500 TeV with PIONEER

Cabibbo universality tests

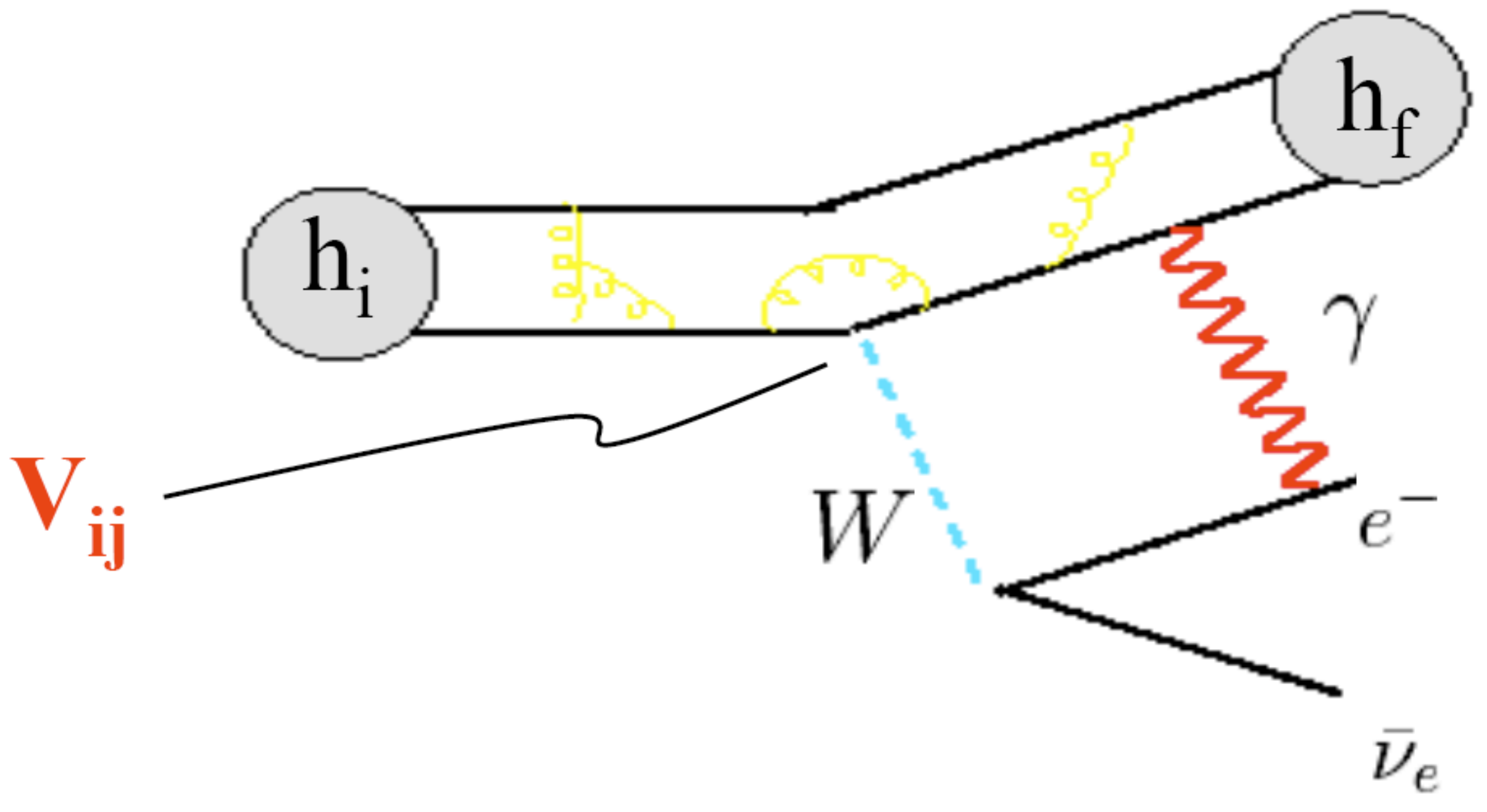
Extract $V_{ud}=\cos\theta_C$ and $V_{us}=\sin\theta_C$ from various decays

$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections: $(\alpha/\pi) \sim 2. \times 10^{-3}$ and smaller effects



Cabibbo universality tests

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Channel-dependent effective CKM element

Hadronic matrix element

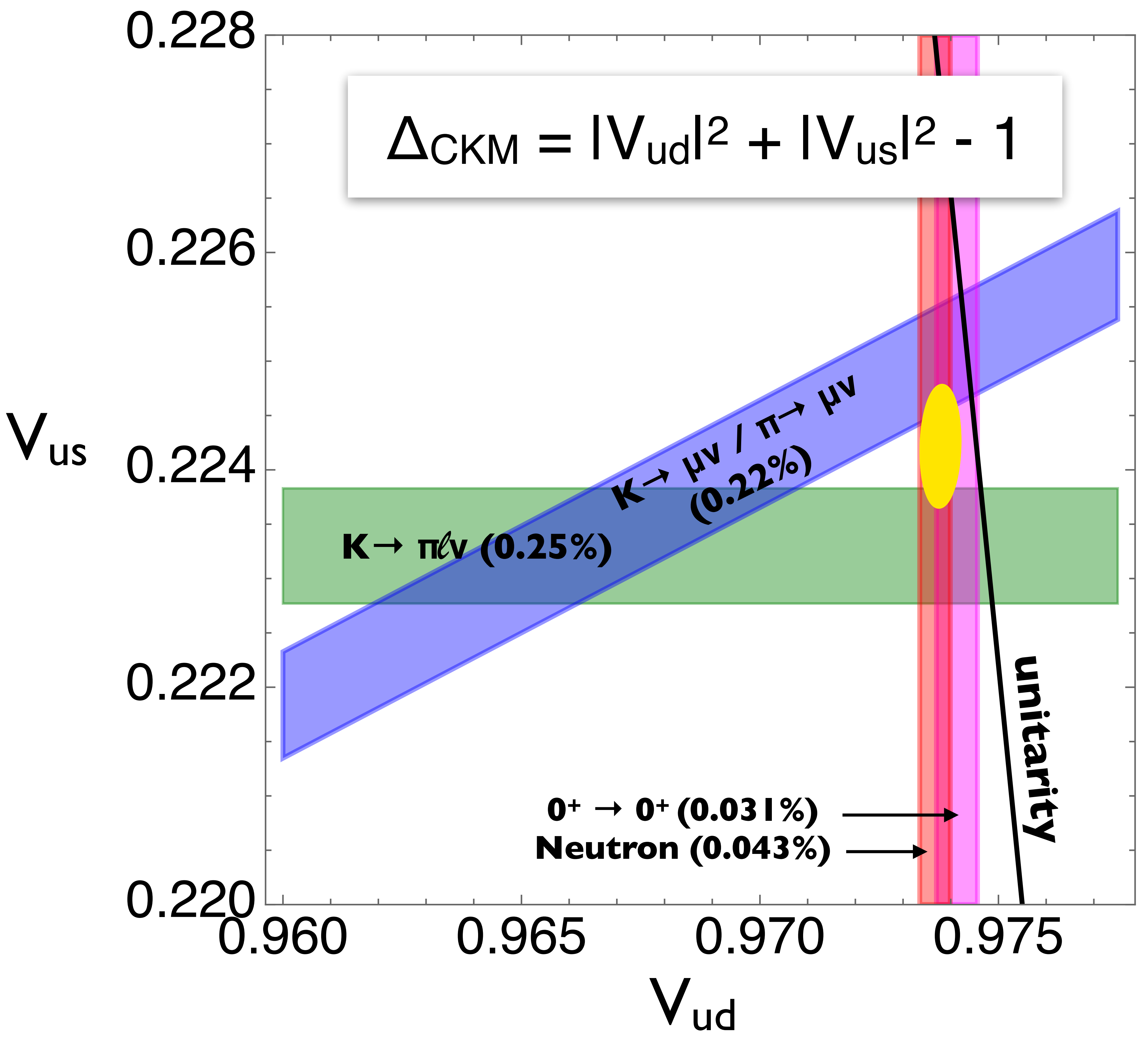
Radiative corrections: $(\alpha/\pi) \sim 2. \times 10^{-3}$ and smaller effects

Unitarity test, with input from many experiments and many theoretical papers

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

Status of Cabibbo universality test

VC-Crivellin-Hoferichter-Moulson 2208.11707
And references therein



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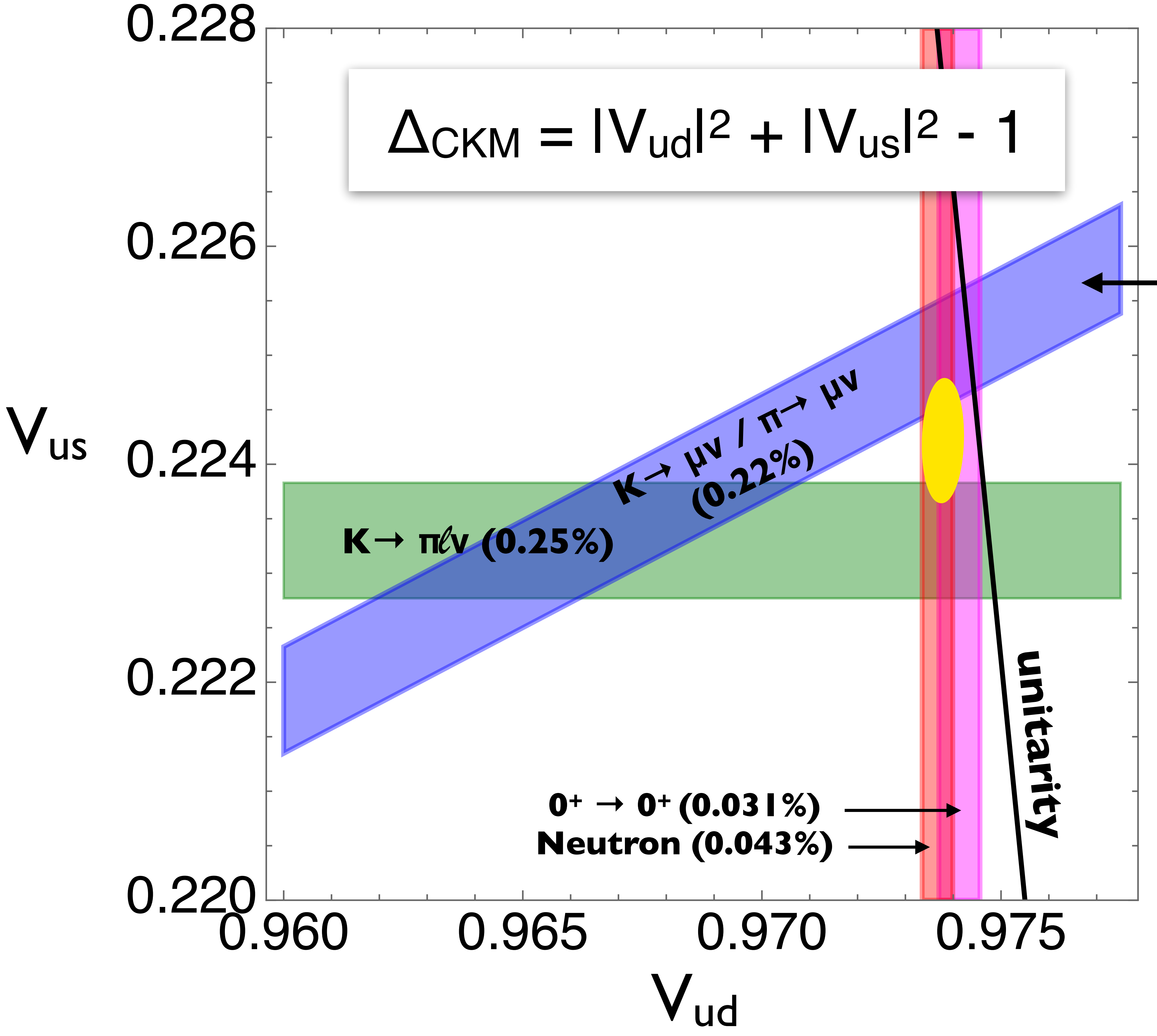
And references therein



Ratio of decay constants s from Lattice QCD

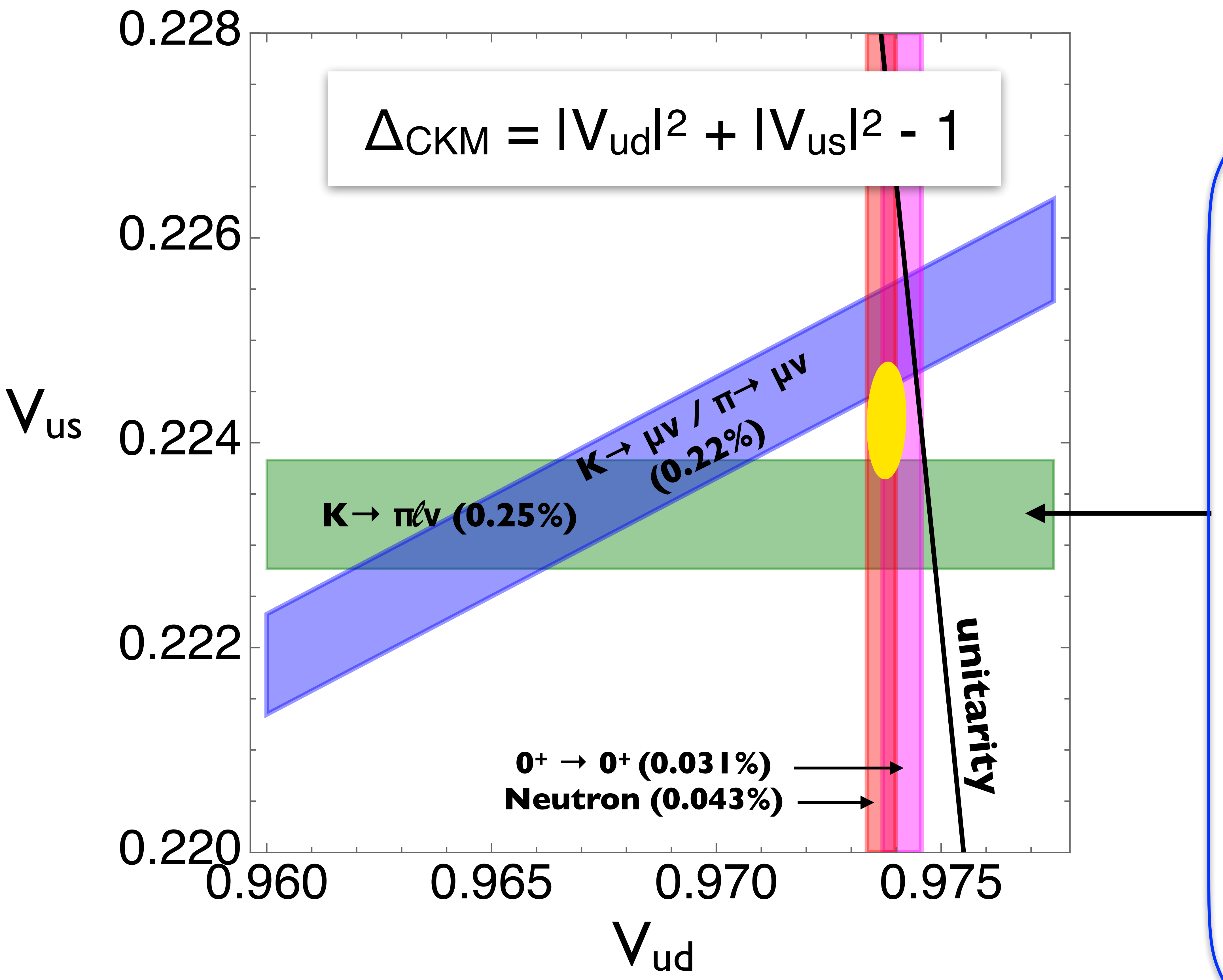
QED + strong isospin-breaking: Lattice QCD and ChPT

ChPT: VC-Neufeld, 1102.0563
LQCD:
FLAG: 2111.09849
Di Carlo et al., 1904.08731
Boyle et al., 2211.12865

No contact (LEC): contribution cancels in the ratio!

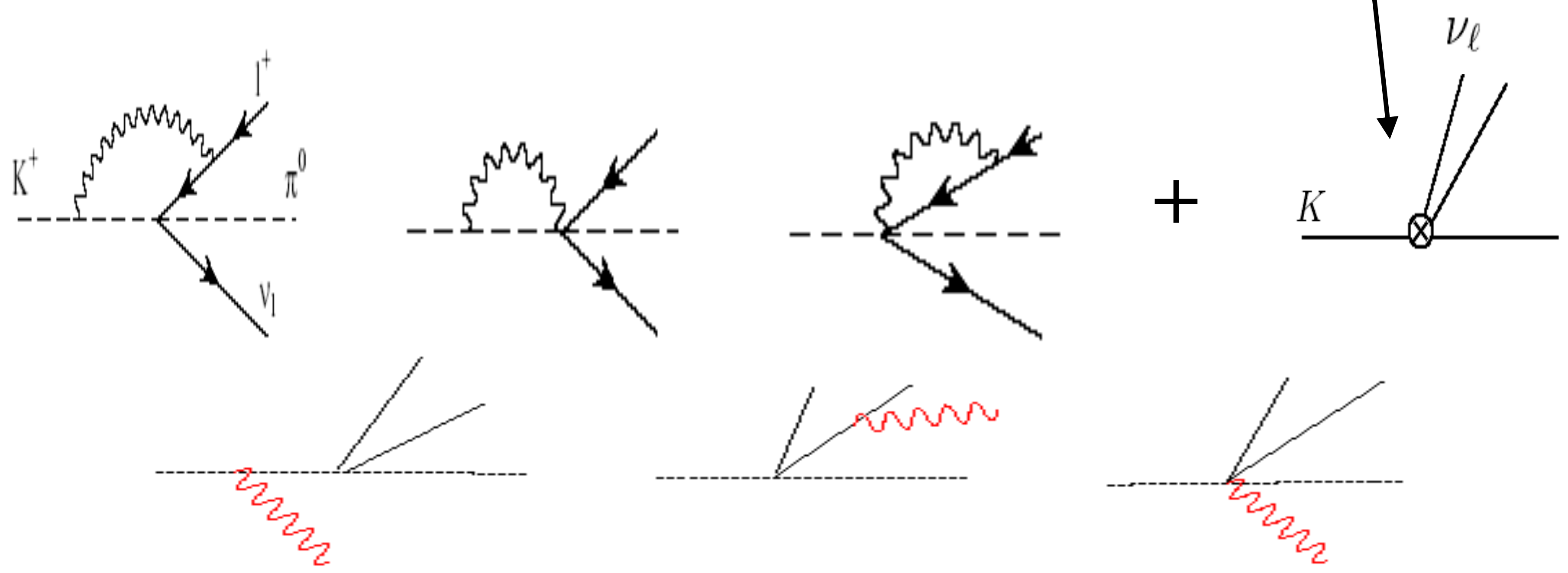
Status of Cabibbo universality test

VC-Crivellin-Hoferichter-Moulson 2208.11707
And references therein



<π |V|K> form factor from Lattice QCD FLAG: 2111.09849

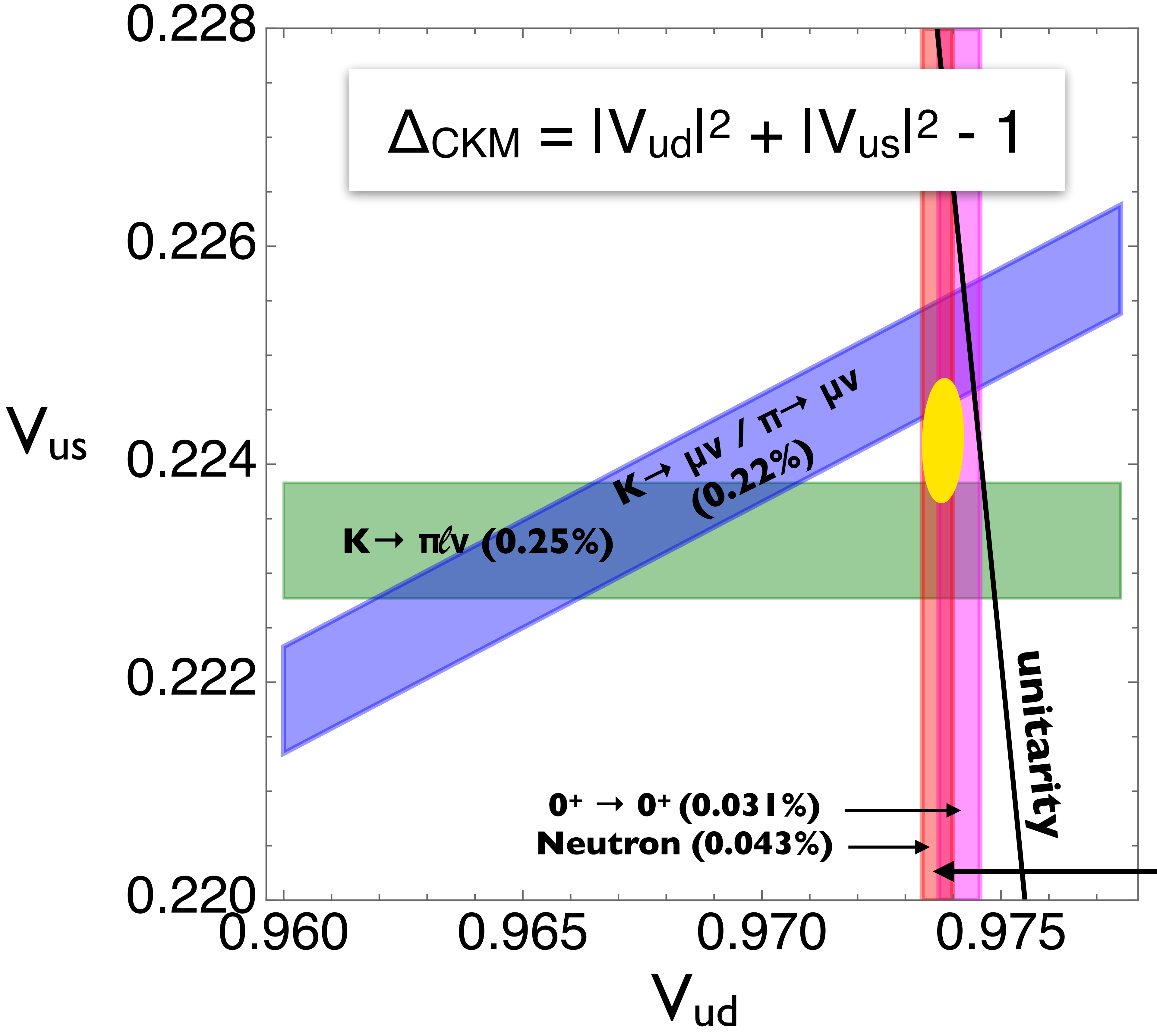
QED + strong isospin-breaking: ChPT + LECs estimated with dispersive methods and LQCD



VC, Giannotti, Neufeld 0807.4607
Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217. Ma et al. 2102.12048

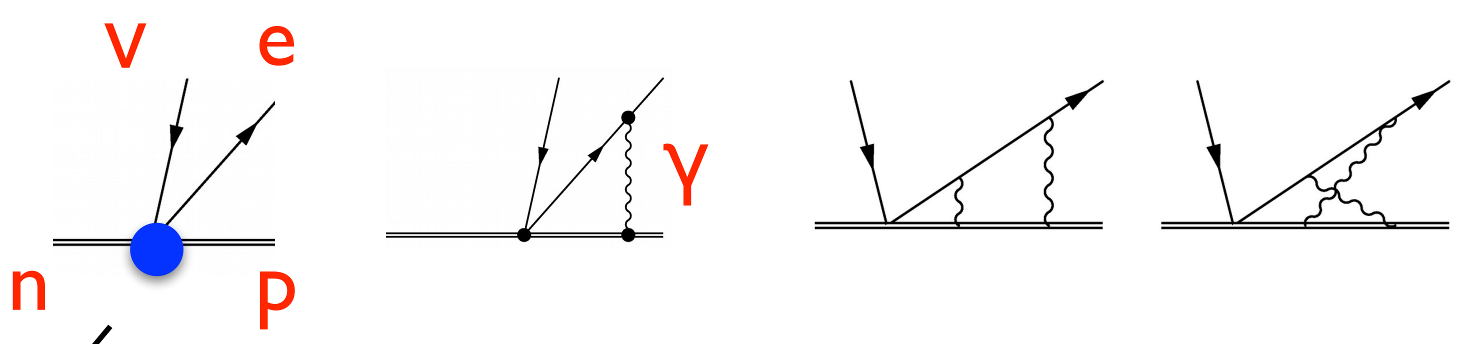
Status of Cabibbo universality test

VC-Crivellin-Hoferichter-Moulson 2208.11707
And references therein



<p|A|n> form experiment

<p|V|n> with QED: ChPT + LECs estimated with dispersive methods and LQCD

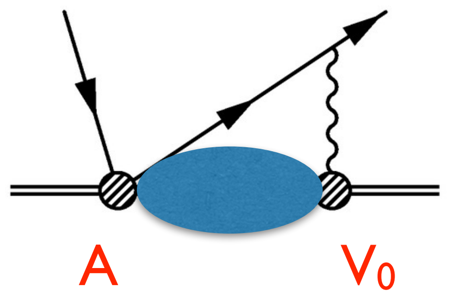


$$g_V(\mu_e) = U(\mu_e, \Lambda_\chi) \left[1 + \overline{\Box}^V_{\rm Had} + \frac{\alpha(\Lambda_\chi)}{\pi} \kappa \right] U(\Lambda_\chi, \mu_W)\; C_\beta(\mu_W)$$

NLL RGE in ChPT and pion-less EFT

Non-perturbative contribution

NLL RGE in LEFT

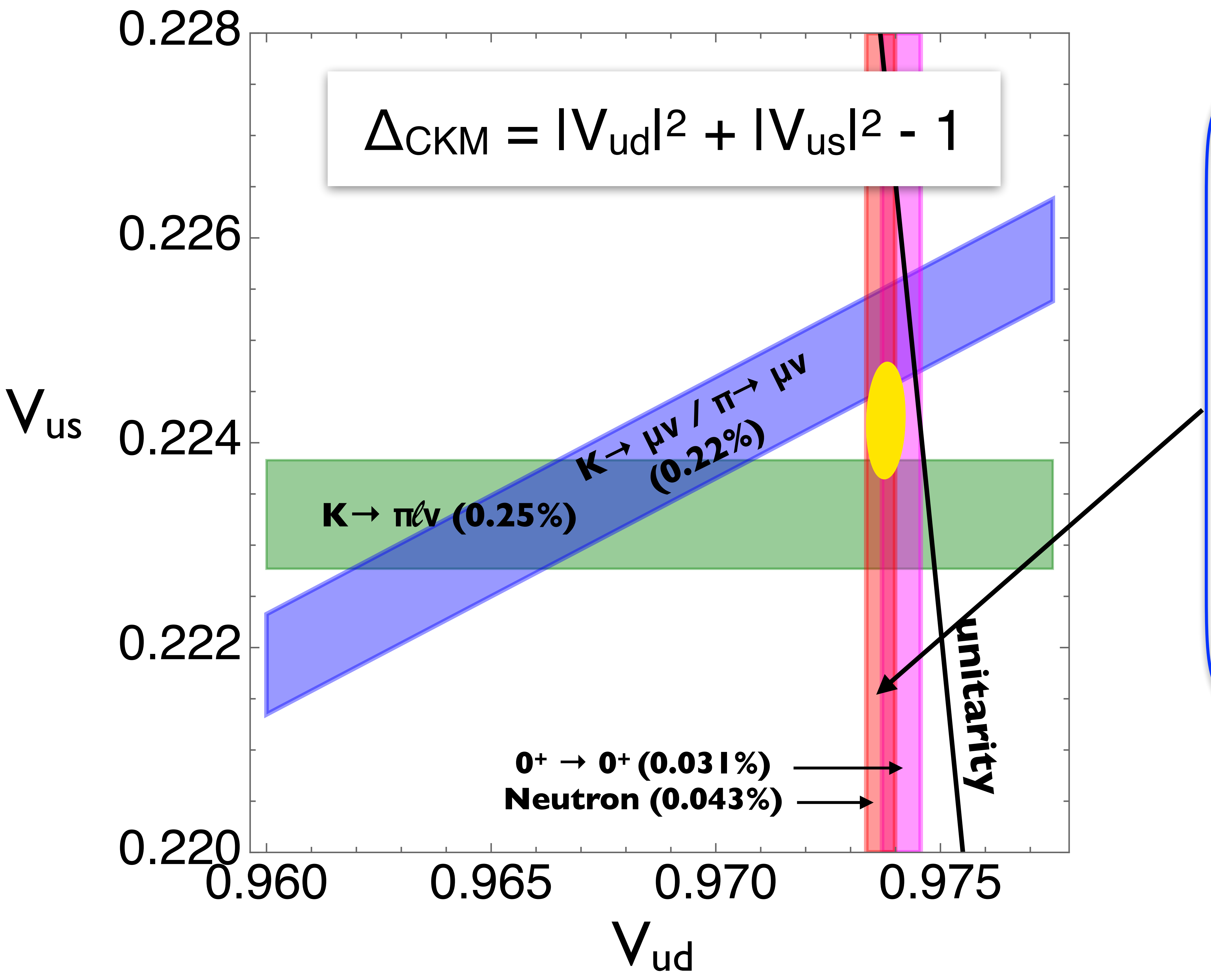


Wilson Coefficient at $\mu_W \sim m_W$

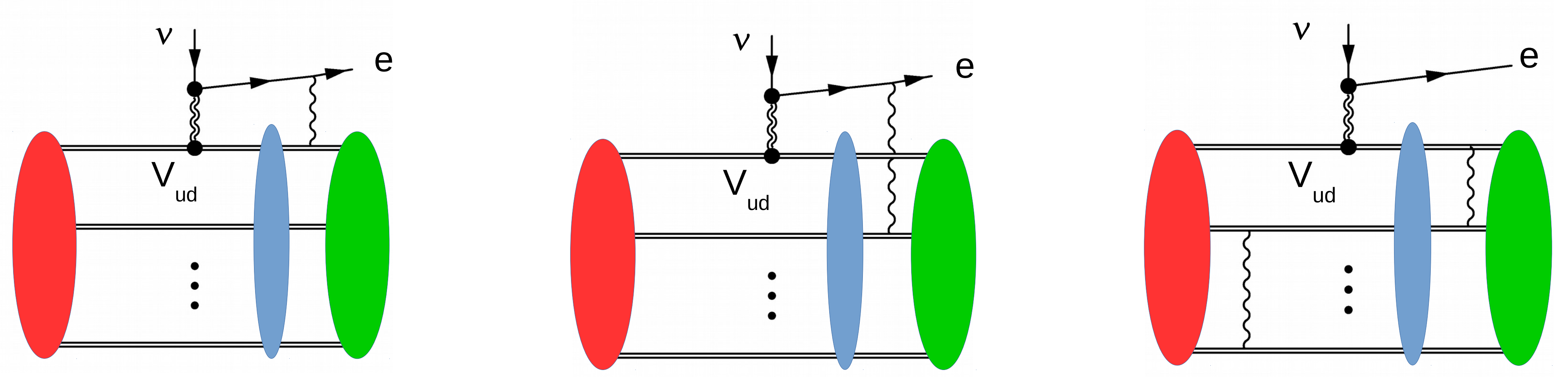
Matching and running: VC-Dekens-Mereghetti-Tomalak 2306.03138
Input from dispersive theory and LQCD
[Seng et al. 1807.10197, 2308.16755]

Status of Cabibbo universality test

VC-Crivellin-Hoferichter-Moulson 2208.11707
And references therein



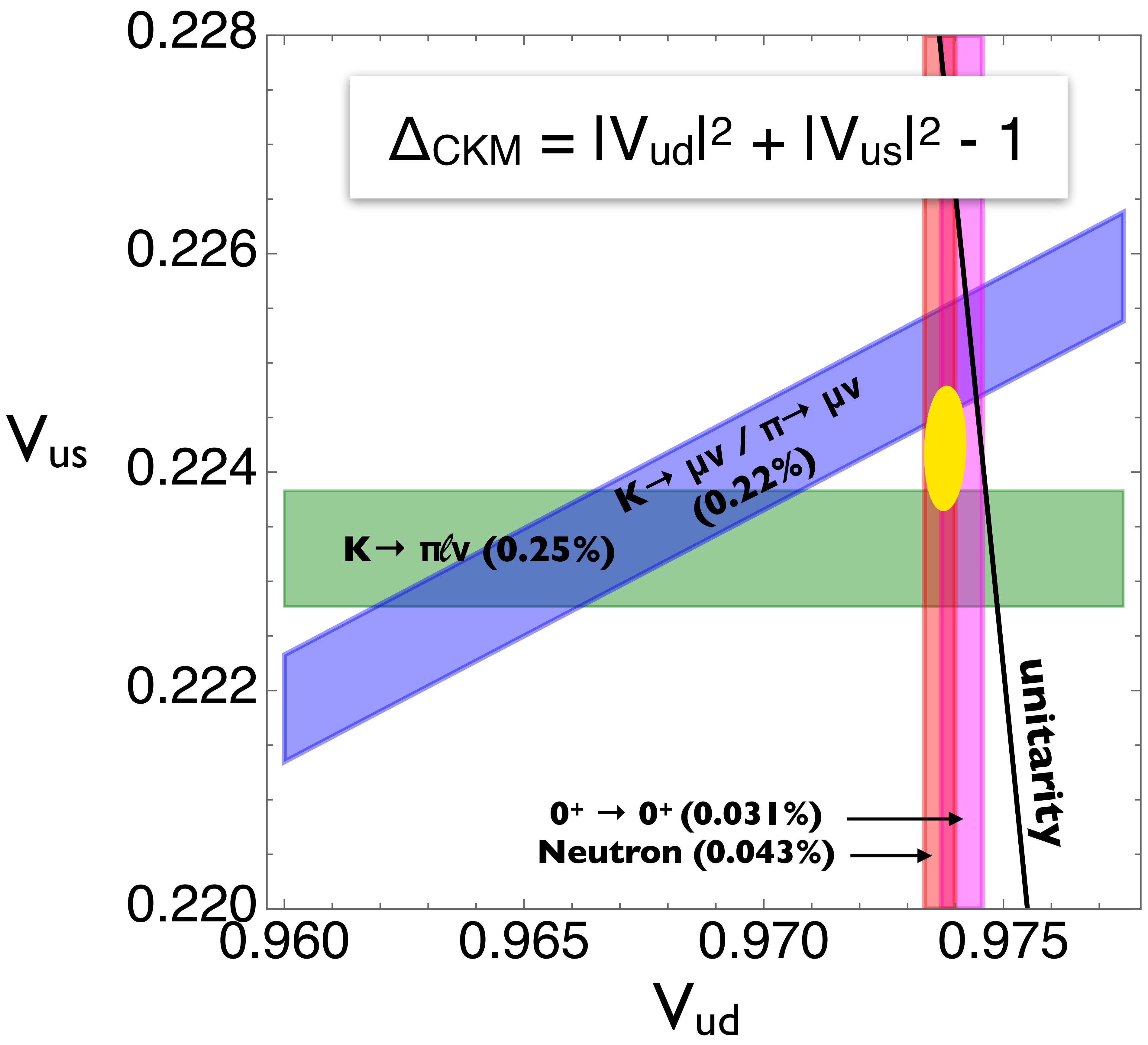
Long history. Current bottleneck from nuclear-structure dependent radiative corrections



Towner-Hardy 2020 PRC
Gorchtein, Seng 2311.00044 and references therein

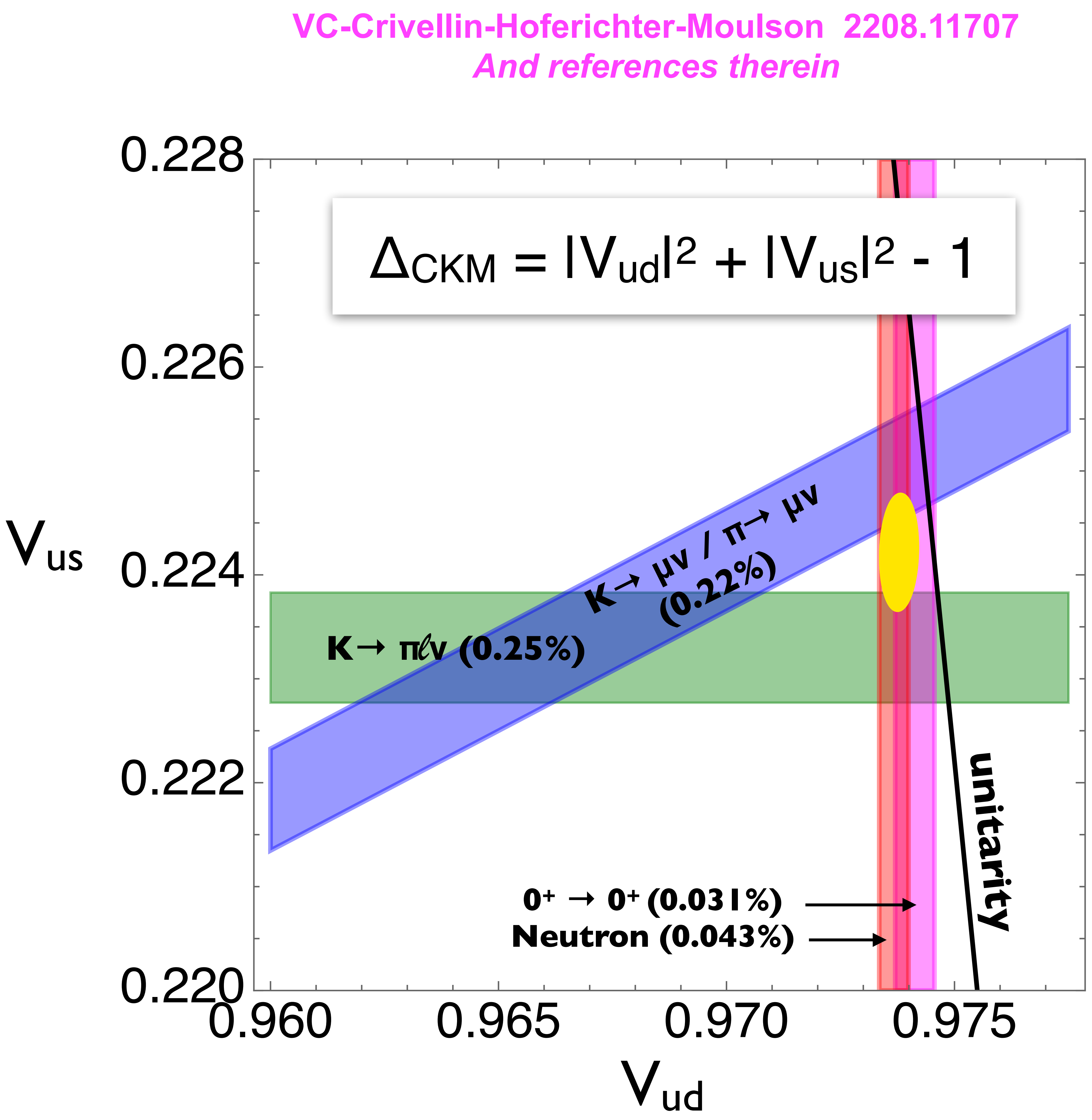
Status of Cabibbo universality test

VC-Crivellin-Hoferichter-Moulson 2208.11707
And references therein



- Tensions
  - ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)
  - ~3σ problem in meson sector (Kl2 vs Kl3)

Status of Cabibbo universality test



- Expected experimental improvements
  - neutron decay (will match nominal nuclear uncertainty)
  - pion beta decay (3x to 10x at PIONEER phases II, III)
  - new $K_{\mu 3}/K_{\mu 2}$ BR measurement at NA62
- Ongoing / future theoretical scrutiny
  - Radiative corrections in lattice QCD to Kl3 and neutron decay
  - EFT and first-principles nuclear structure for radiative corrections in nuclear decay

Implications for new physics

- Start with LEFT

$$|\bar{V}_{ud}|_i^2 = |V_{ud}|^2 \left(1 + \sum_\alpha C_{i\alpha}\epsilon_\alpha\right)$$

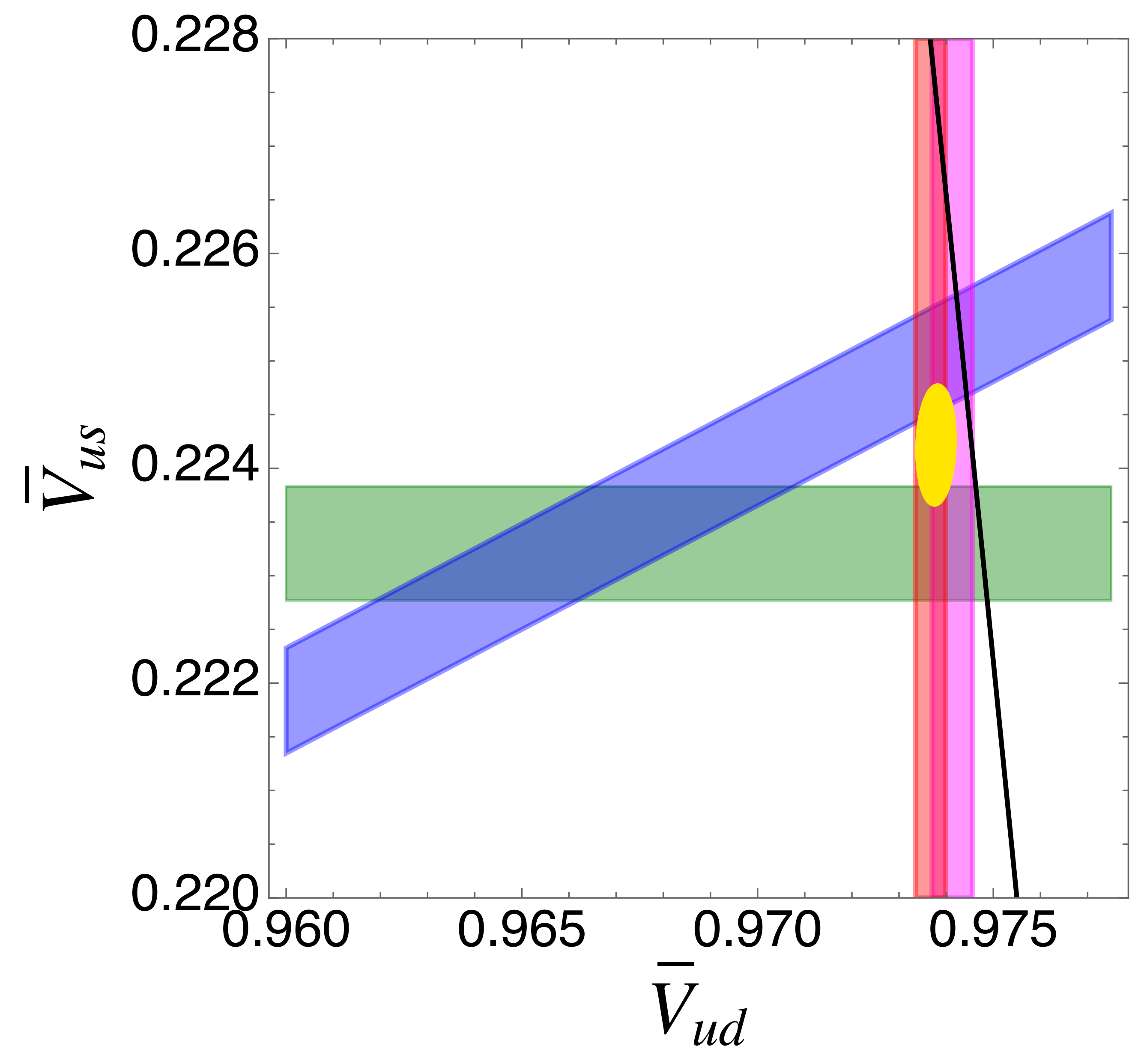
$$|\bar{V}_{us}|_j^2 = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

Channel-dependent CKM elements extracted in the 'SM-like analysis'

Elements of the unitary CKM matrix

Known coefficients

LEFT couplings



Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Implications for new physics

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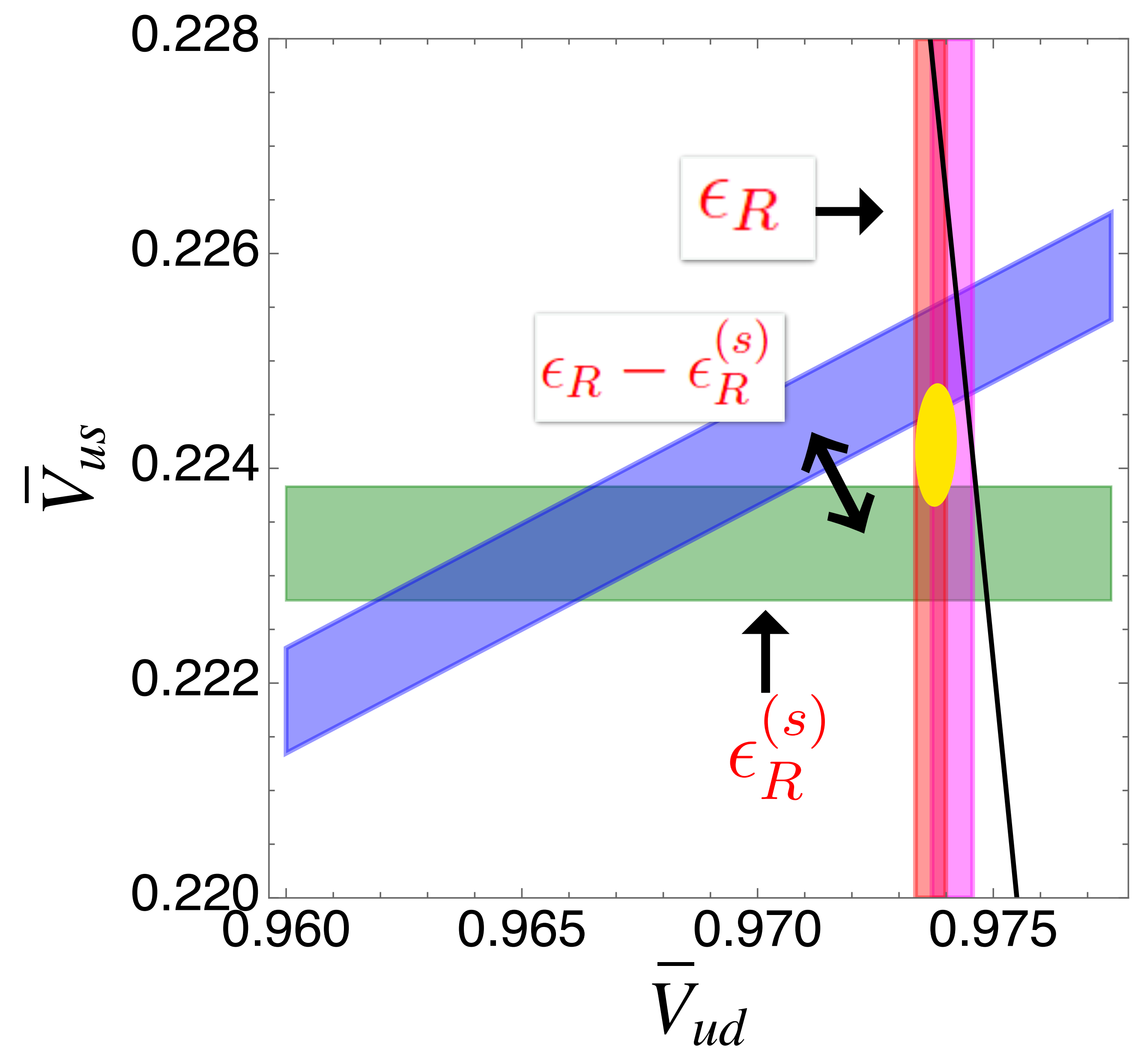


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Simplest 'solution': right-handed (V+A) quark currents

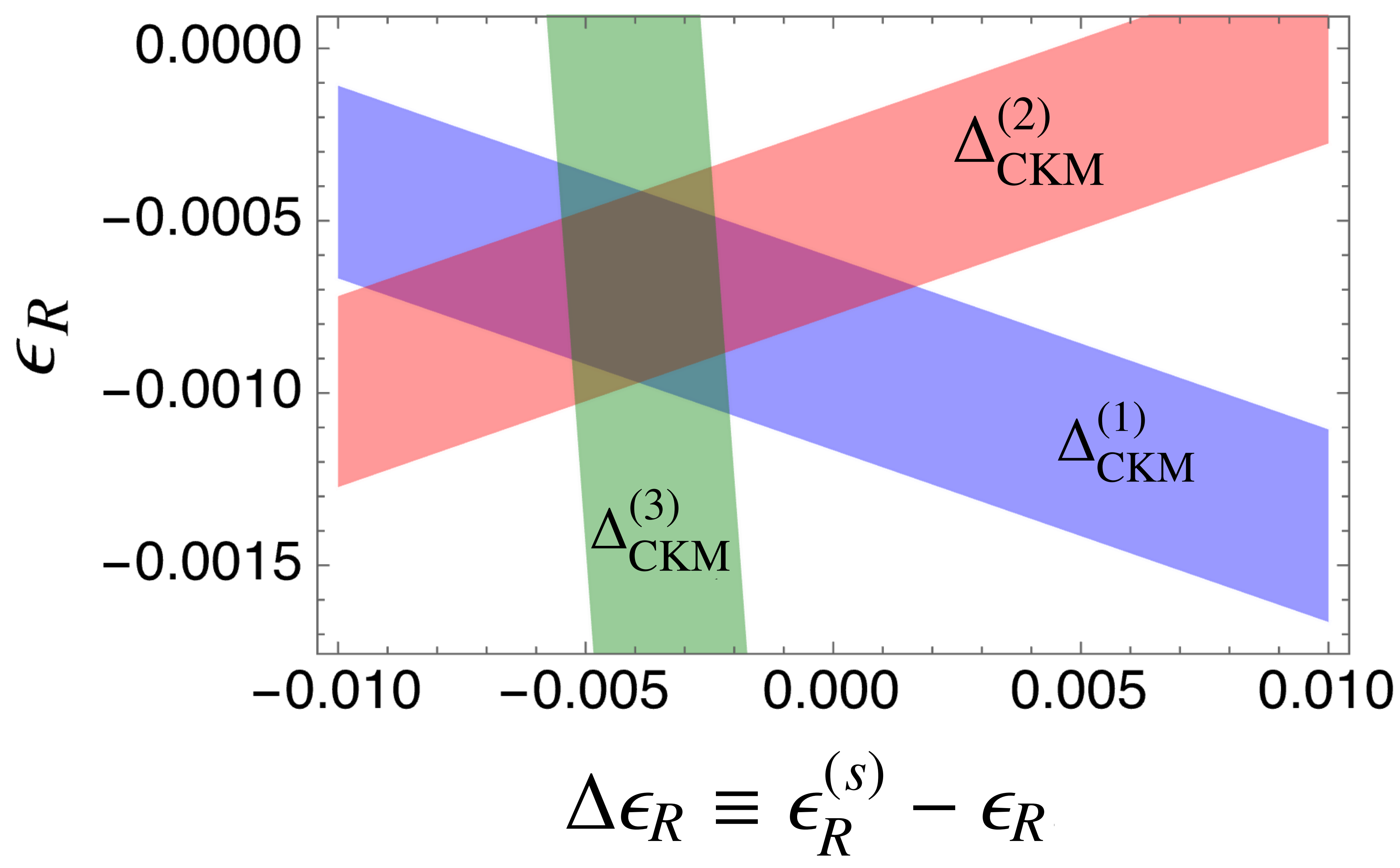
CKM elements from vector (axial) channels are shifted by $1+\epsilon_R$ ($1-\epsilon_R$).

V_{us}/V_{ud} , V_{ud} and V_{us} shift in correlated way, can resolve all tensions!

Alioli et al 1703.04751 Grossman-Passemar-Schacht 1911.07821
VC-Crivellin-Hoferichter-Moulson 2208.11707
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



$$
\begin{aligned}
\Delta^{(1)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.76(56) \times 10^{-3} \\
\Delta^{(2)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 2}/\pi_{\ell 2},\beta}|^2 - 1 \\
&= -0.98(58) \times 10^{-3} \\
\Delta^{(3)}_{CKM} &= |V_{ud}^{K_{\ell 2}/\pi_{\ell 2},K_{\ell 3}}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.64(63) \times 10^{-2}
\end{aligned}
$$

↓

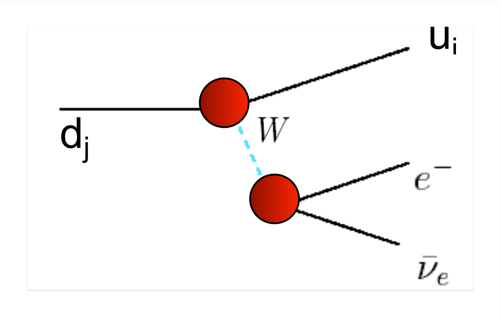
$$\epsilon_R = -0.69(27) \times 10^{-3}$$

$$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$$

Λ_R ~ 5-10 TeV

- Preferred ranges are not in conflict with constraints from other low-E probes
- Does the R-handed current explanation survive after taking into account high energy data?

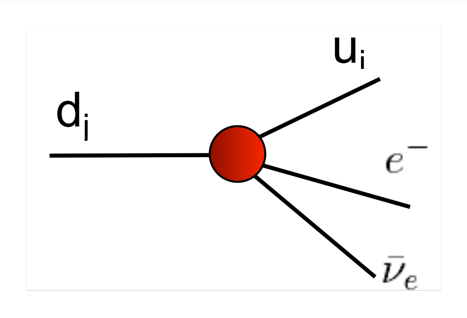
High Energy constraints



ε_R $$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

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

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



$\varepsilon_{S,P}$ $$O_{qde} = (\bar{\ell} e)(\bar{d} q) + \text{h.c.}$$

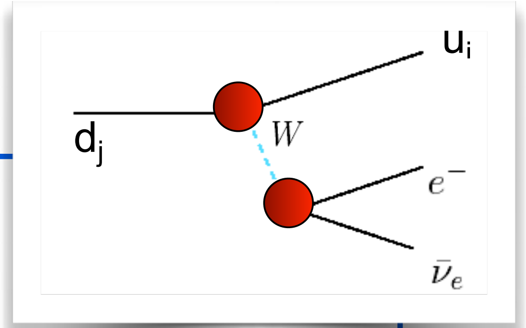
$\varepsilon_{S,P}$ $$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

ε_T $$O_{lq}^t = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$$

ε_L $$O_{lq}^{(3)} = \bar{l}\gamma_\mu \sigma^a l \; \bar{q}\gamma^\mu \sigma^a q$$

ε_L $$O_{ll} = \bar{l}\gamma_\mu l \; \bar{l}\gamma^\mu l$$

High Energy constraints



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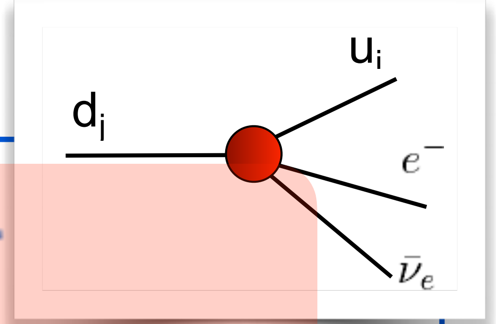

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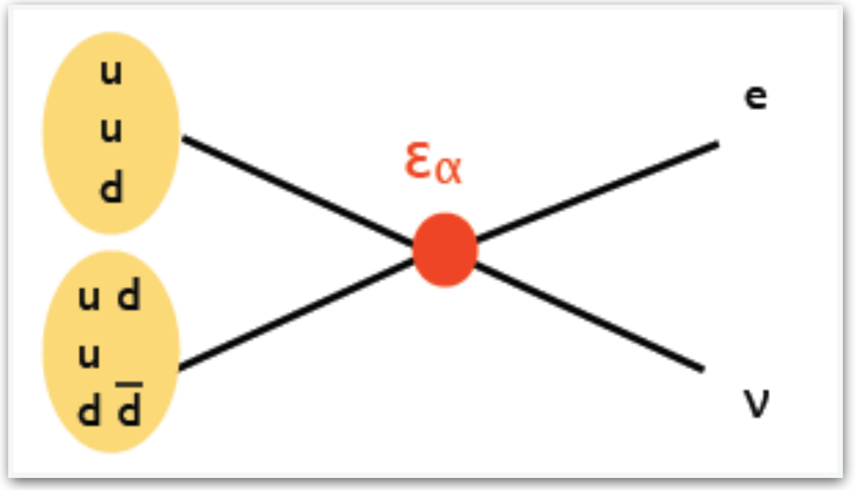
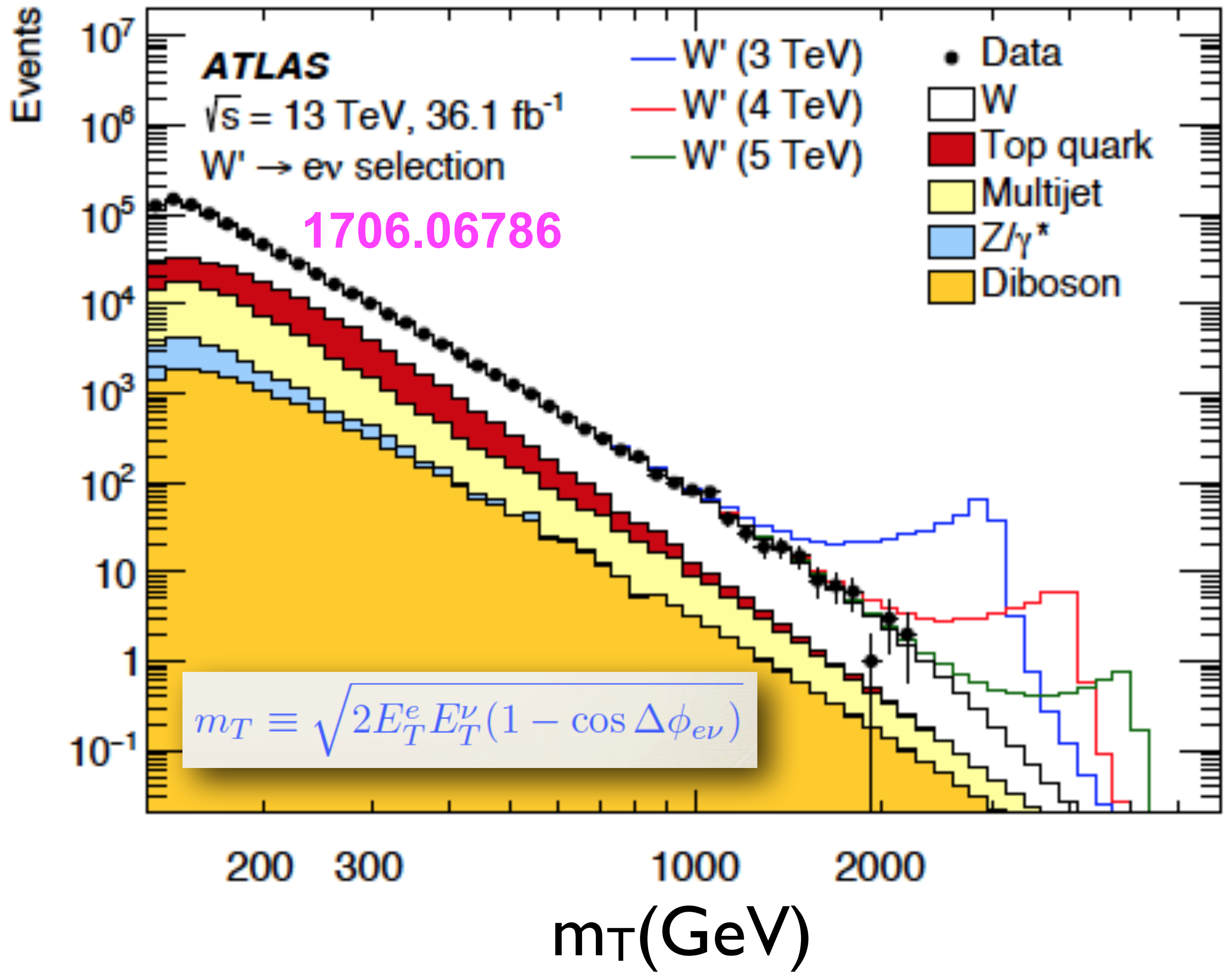
Constrained by pp → eν+X and pp → e⁺e⁻ +X at the LHC

LHC: pp → eν + X



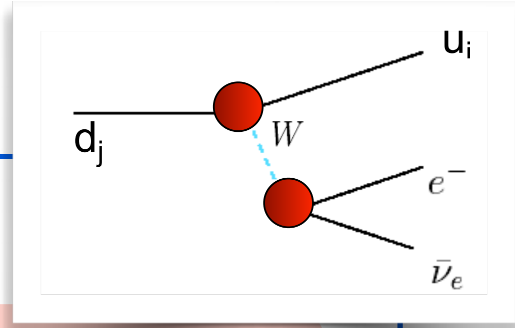
Vertex corrections essentially unconstrained



$\varepsilon_\alpha \sim 10^{-3} - 10^{-4}$

VC, Graesser, Gonzalez-Alonso 1210.4553
Alioli-Dekens-Girard-Mereghetti 1804.07407
Gupta et al. 1806.09006
Boughezal-Mereghetti-Petriello 2106.05337
...

High Energy constraints



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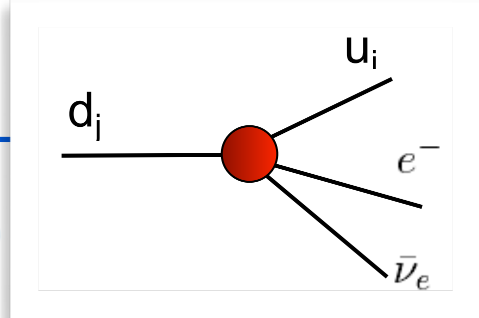

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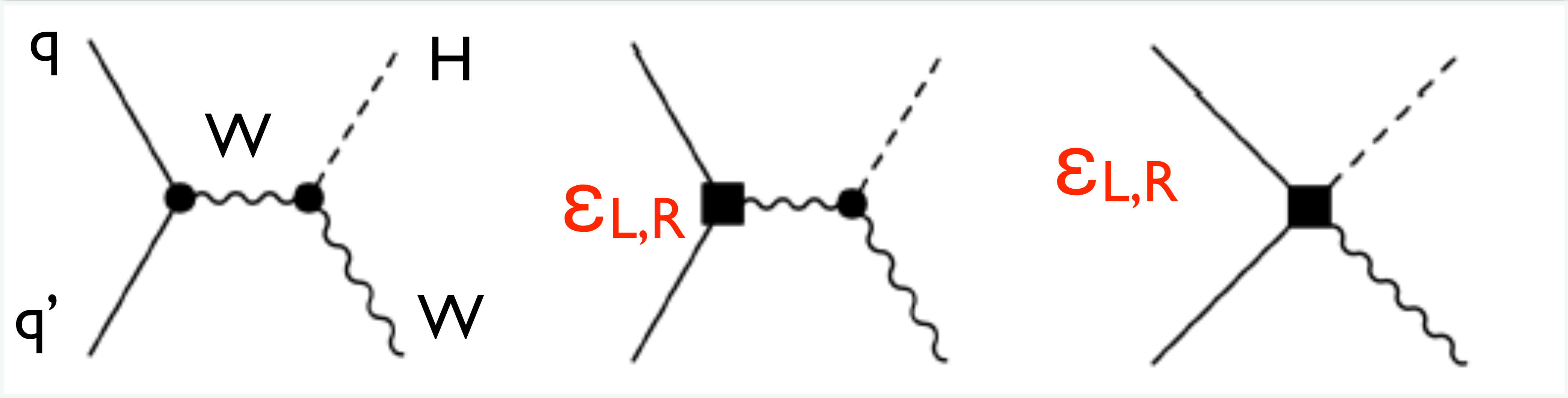
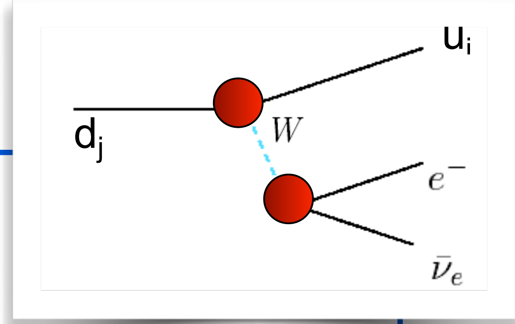
Can be probed at the LHC by associated Higgs + W production (5-10%)



S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

LHC run 2 projection would lead to $\varepsilon_{L,R} \sim$ 3-4%

High Energy constraints



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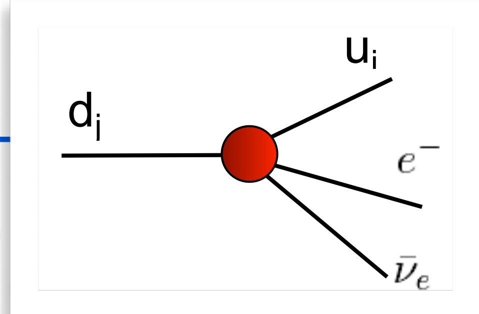

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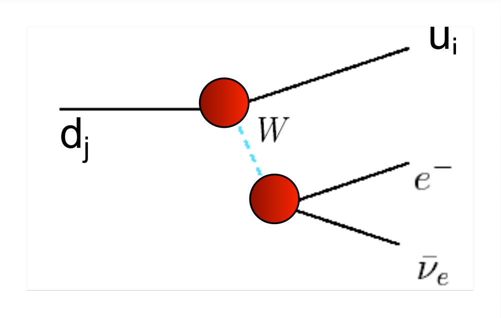
Contribute to Z-pole and other EW observables, including** M_W

High Energy constraints



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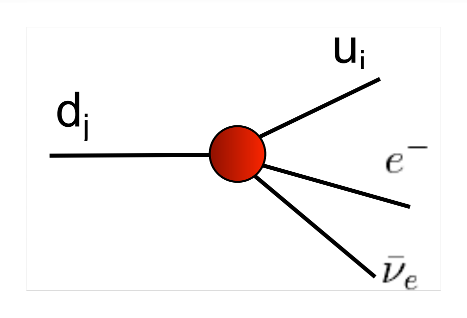

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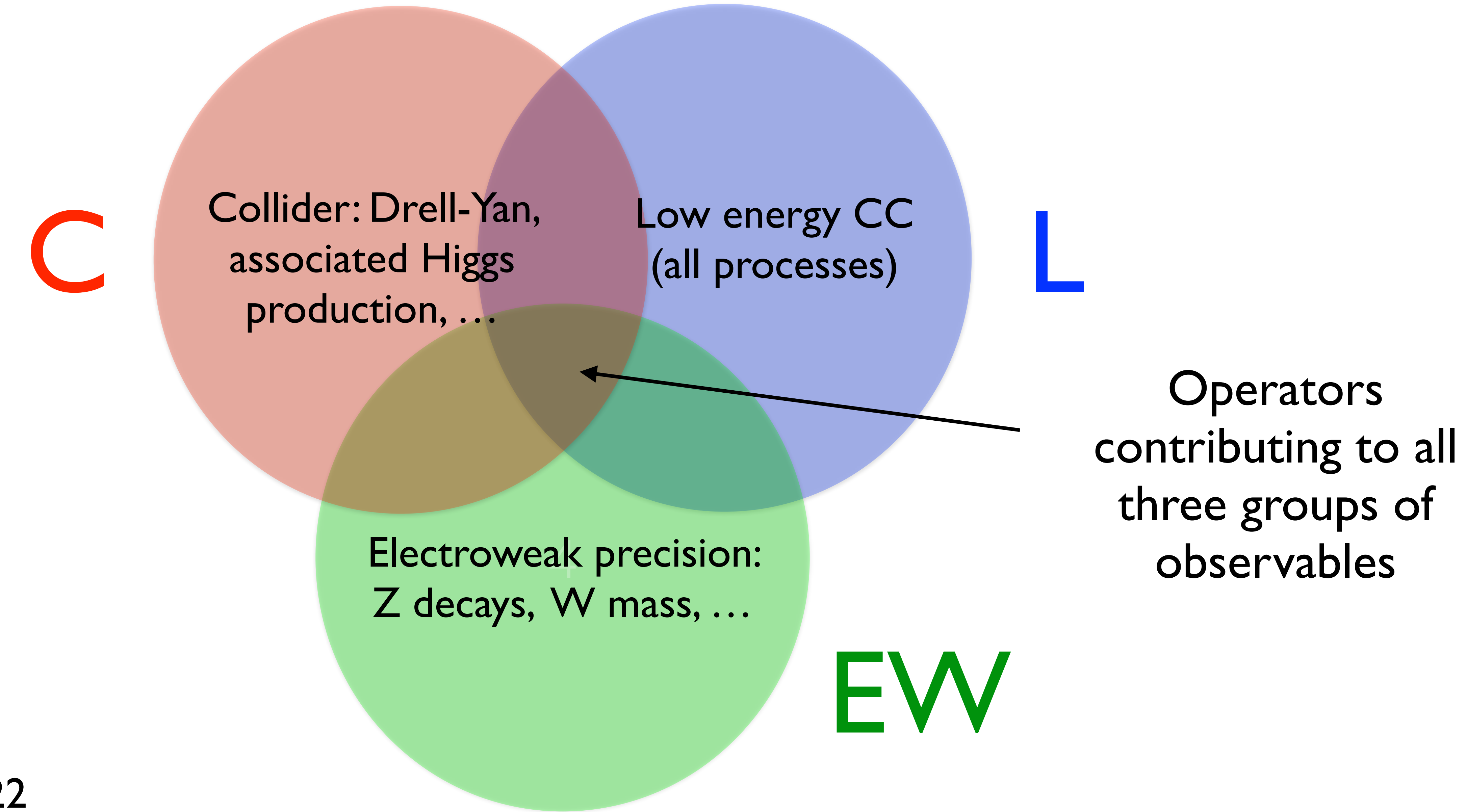
Contribute to Z-pole and other EW observables, including** M_W

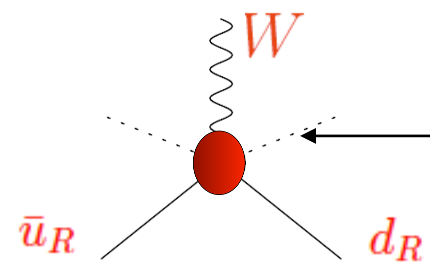
- A consistent analysis of beta decays in the SM-EFT requires using data from, Collider, Low energy, and ElectroWeak tests
- Requires 37 dim-6 operators



'Global' analysis

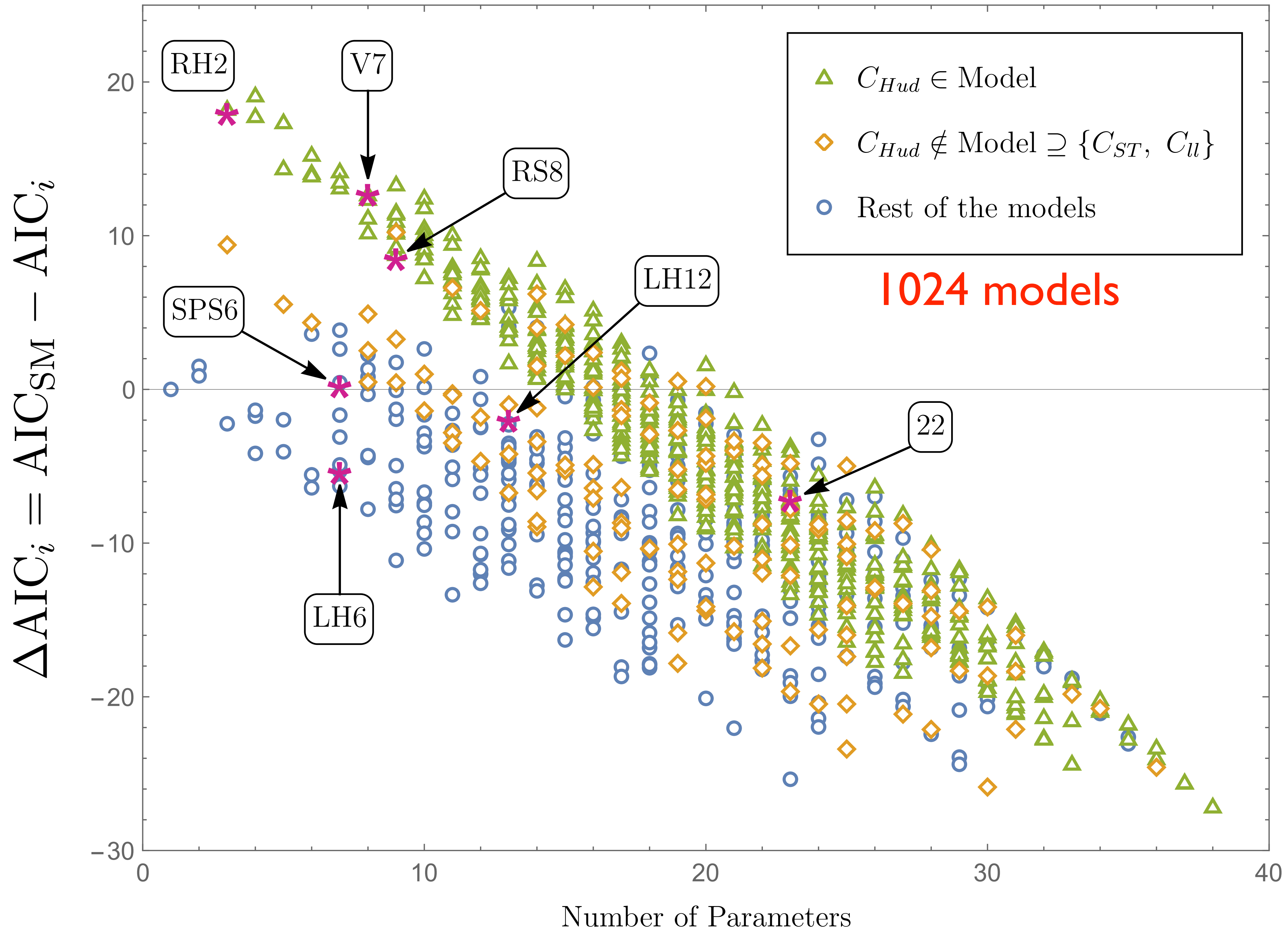
- Performed 'CLEWed' analysis within SMEFT. Scanned model space by 'turning on' certain classes of effective couplings

- Model selection? Akaike Information Criterion [AIC = 2k - ln(L)) favors models with Right-Handed Charged Currents of quarks (V+A)



C_{Hud}

VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, JHEP 03 (24) 33, arXiv: 2311.00021



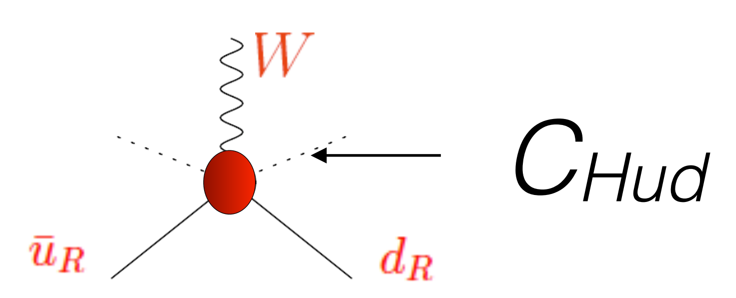
More favored models

Standard Model

Less favored models

‘Global’ analysis

- Performed ‘CLEWed’ analysis within SMEFT. Scanned model space by ‘turning on’ certain classes of effective couplings
- Model selection? Akaike Information Criterion [AIC = 2k - ln(L)) favors models with Right-Handed Charged Currents of quarks (V+A)



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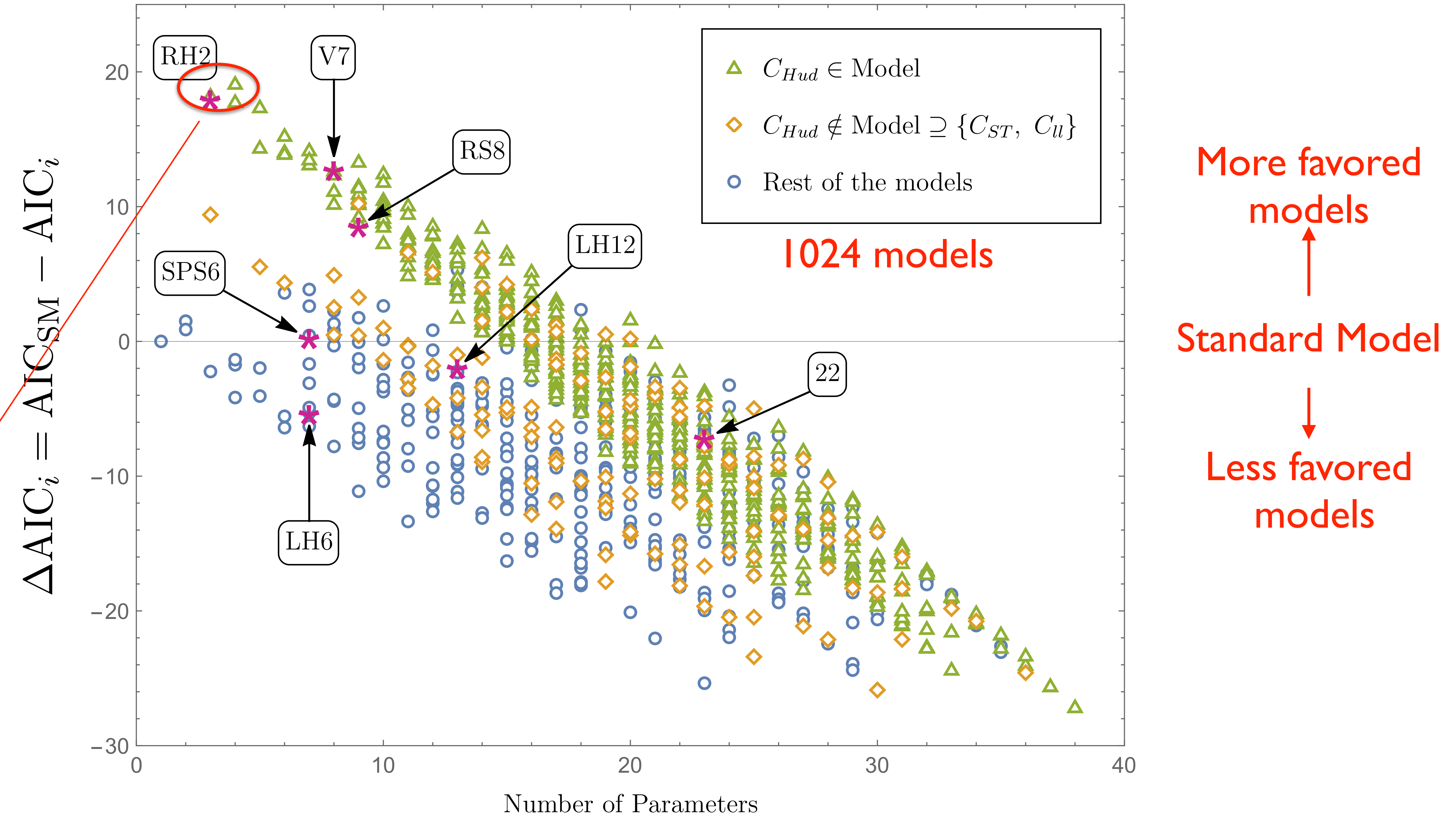


- Best fit to CLEW data: two RH CC vertex corrections and the S parameter

CKM “anomaly” not ruled out by other data.
Unitarity test provides relevant input to unravel possible new physics

Precision tests: lessons

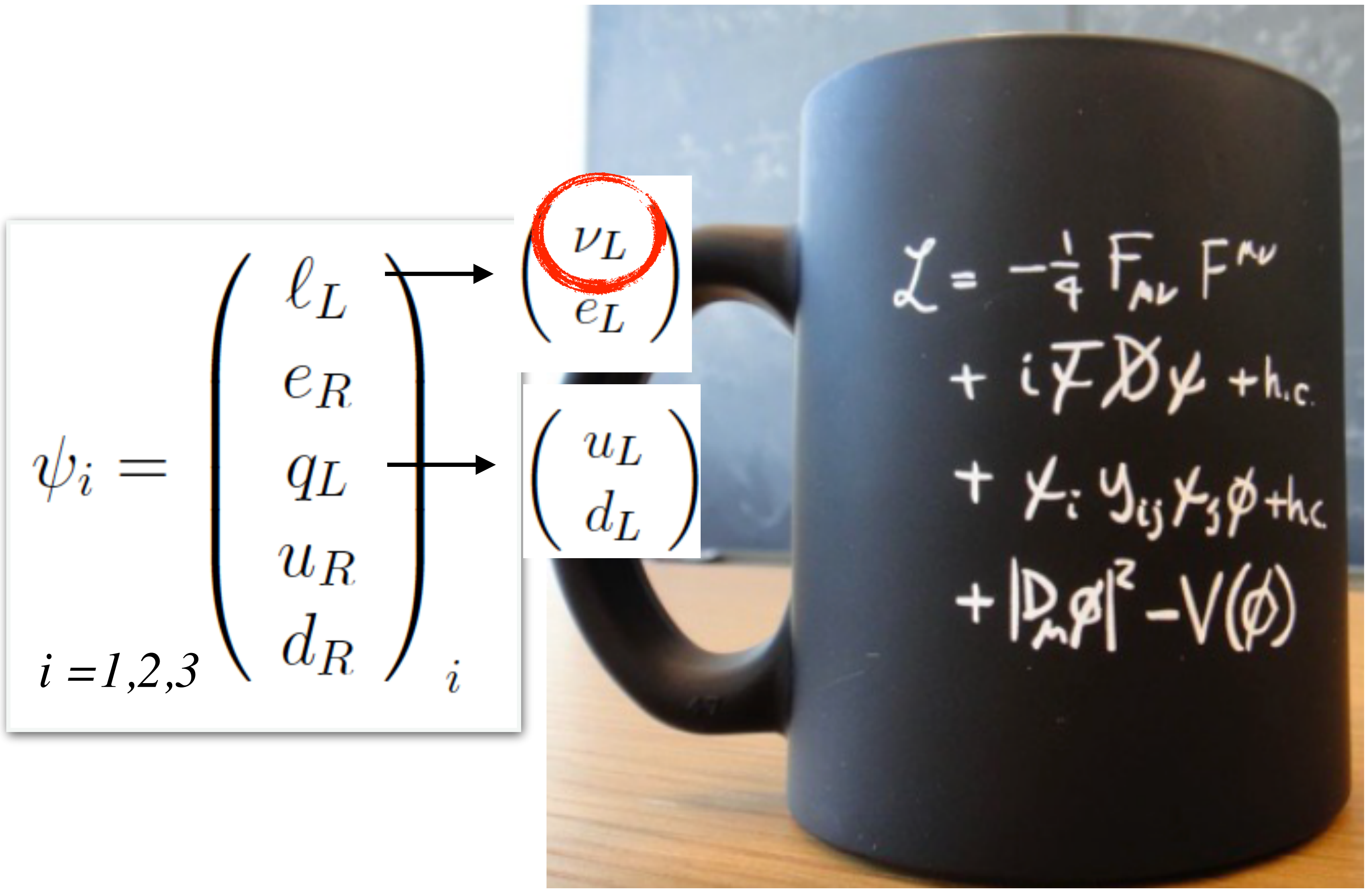
- Illustrated with (semi)leptonic charged currents some general features o precision tests at low energy
- Impactful tests require:
    - Ability to compute the SM prediction to high accuracy
    - Ability to measure to high precision (similar to theory)
    - Framework to interpret possible deviations in light of ‘everything else’, including high-energy searches

Lepton Number Violation
&
Neutrinoless double beta decay

Neutrino mass and new physics

- Neutrino masses not accounted in the Standard Model

The Standard Model



No neutrino mass

Understanding origin and nature of neutrino mass is an open problem, with implications for baryogenesis, DM, structure formation, …

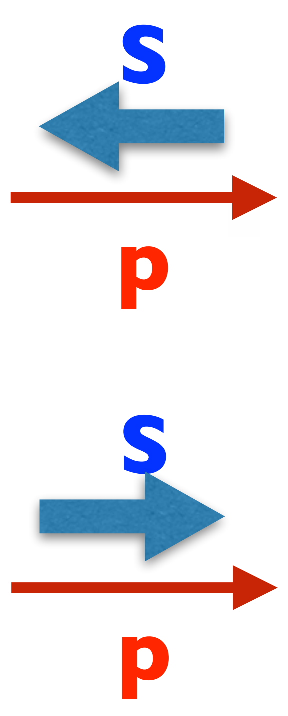
Neutrino mass and symmetries

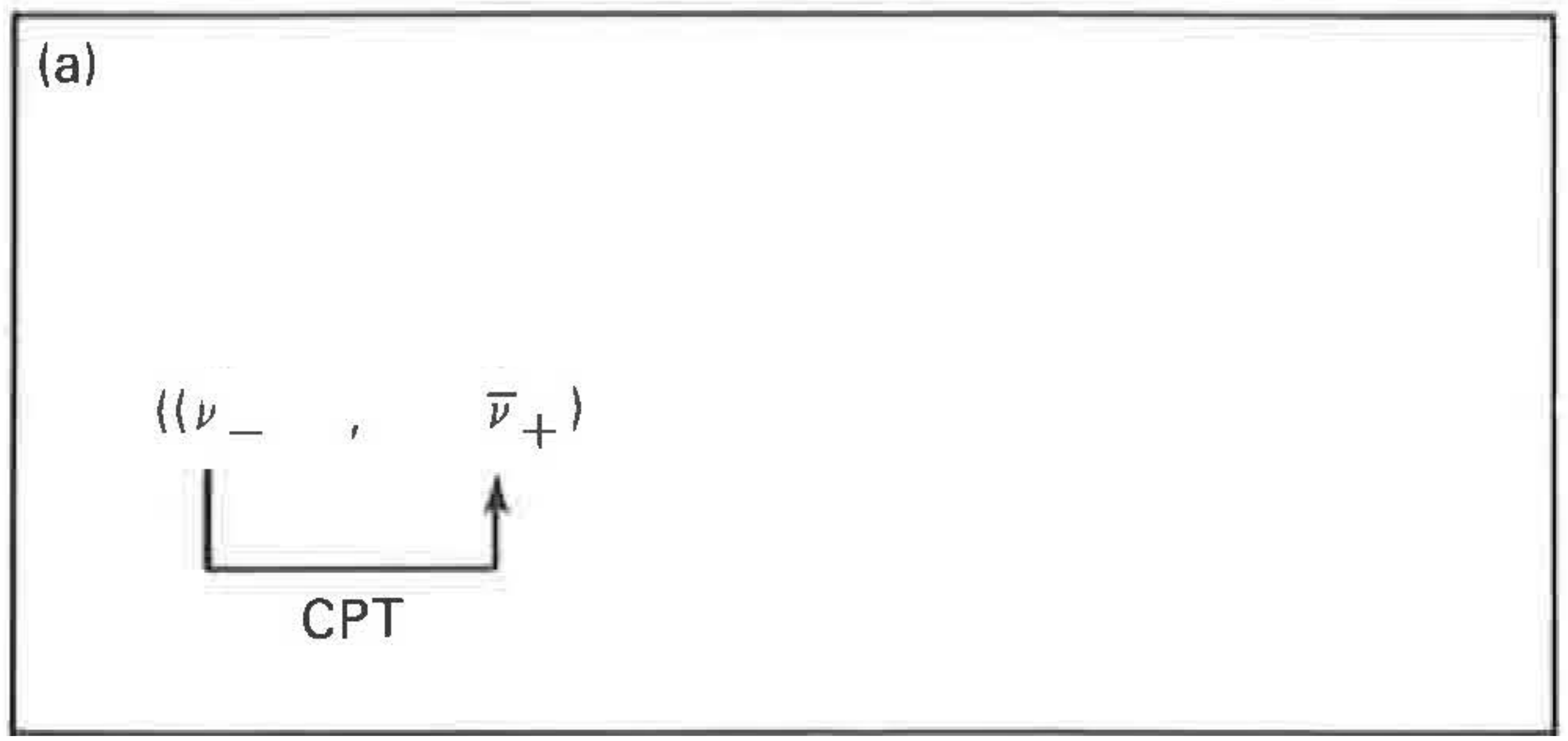
- Lorentz invariance ⇒ two options: Dirac or Majorana

B. Kayser 1984

$\nu(L)=\nu_-$

$\nu(R)=\nu_+$





Dirac:
4 states

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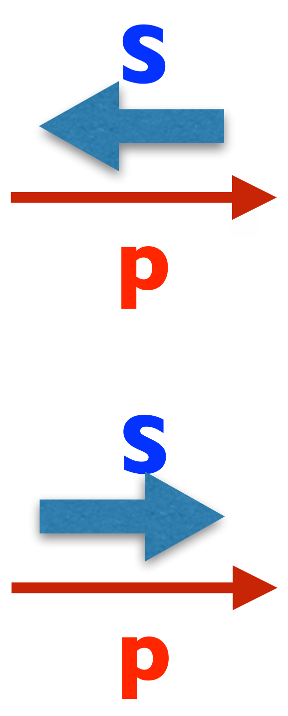
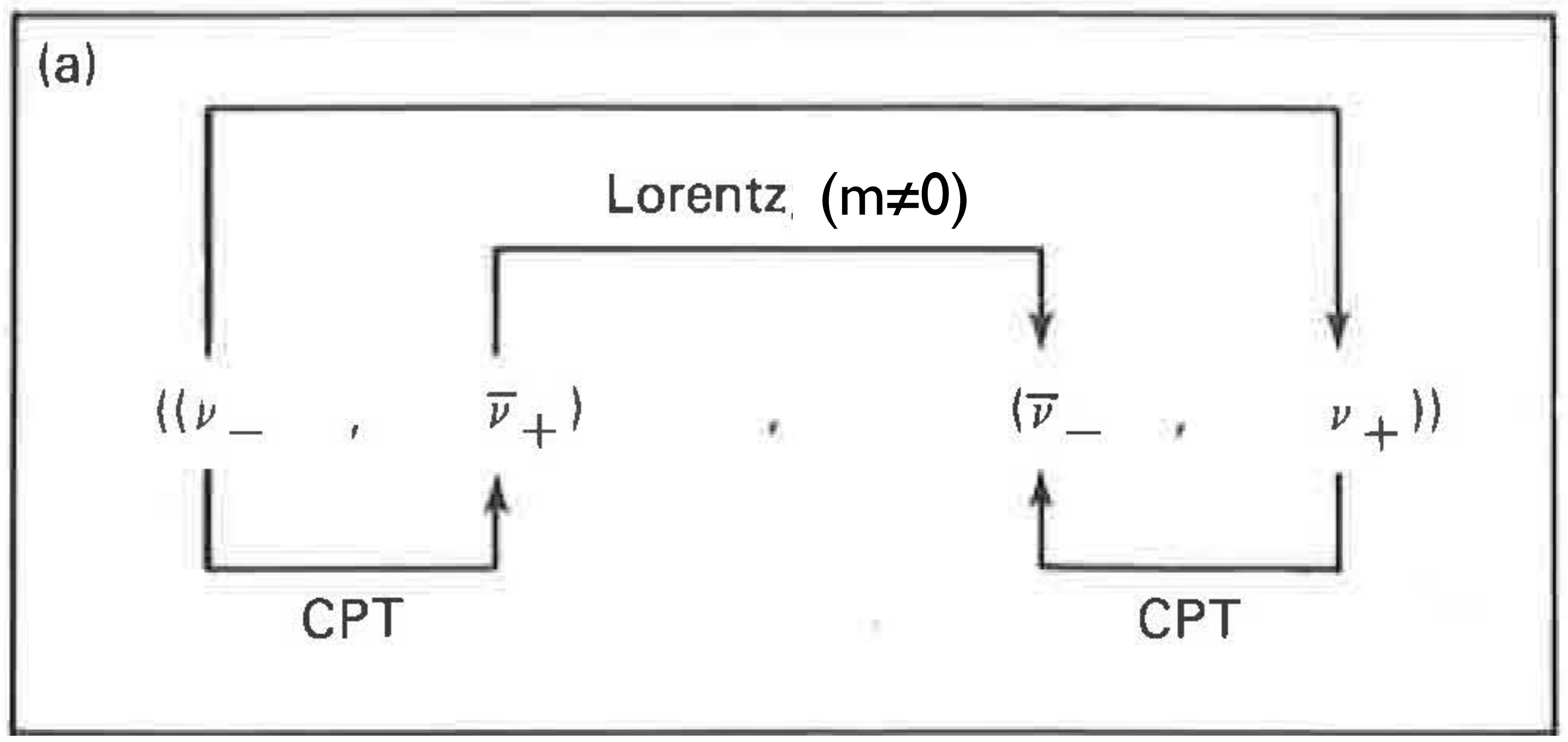


B. Kayser 1984



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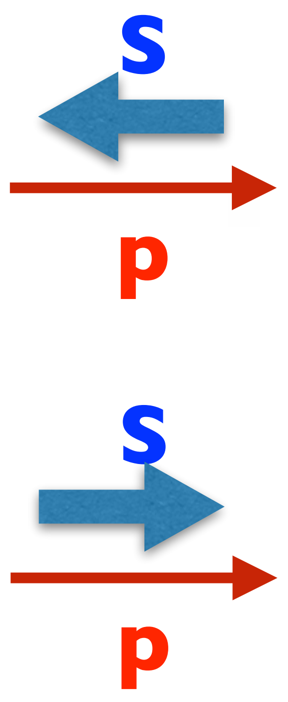

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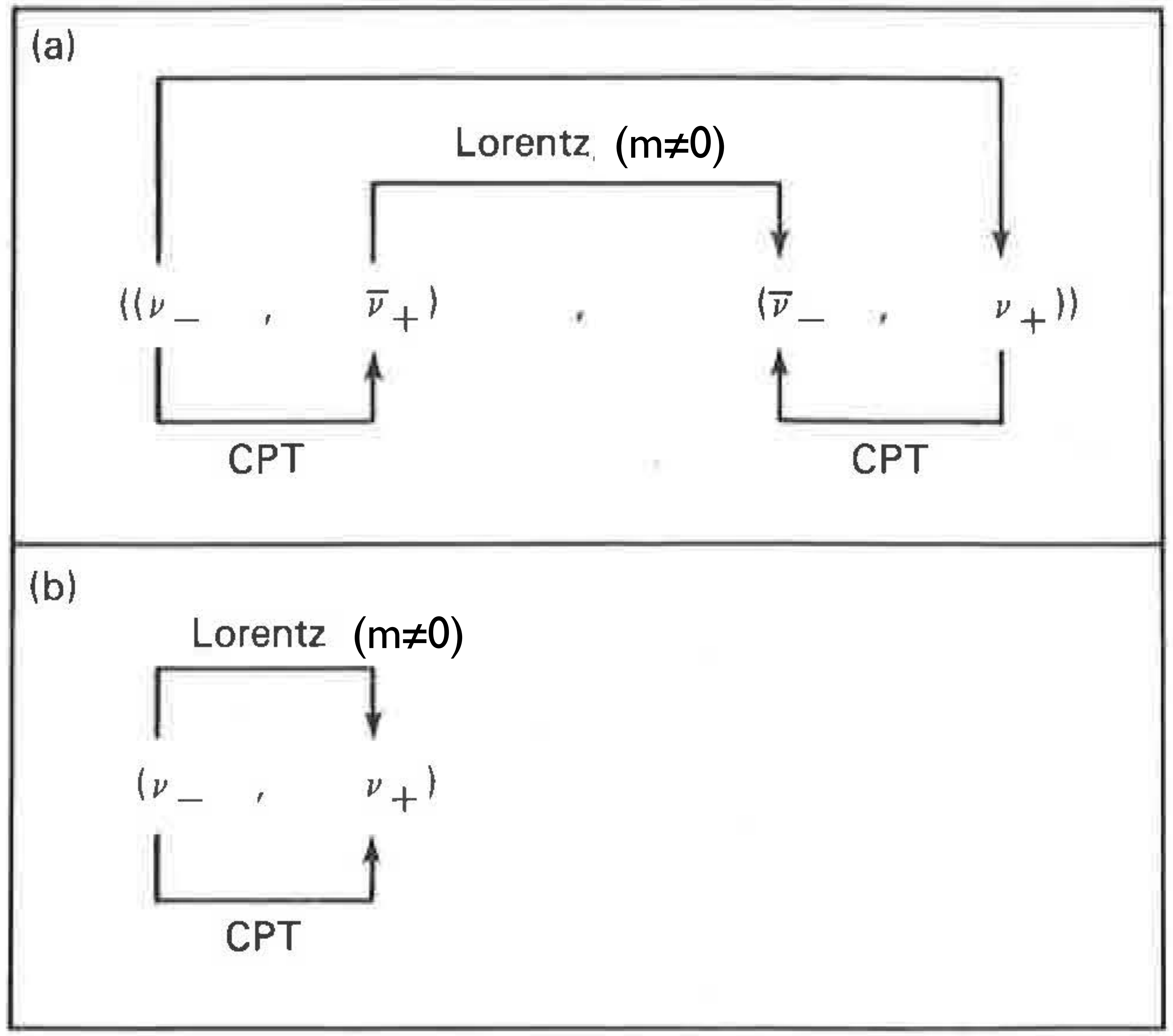

Dirac:
4 states

Majorana:
2 states

Only possible if there no internal quantum number that flips sign under "C"

Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana

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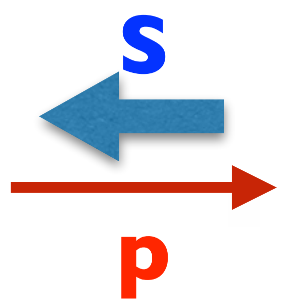
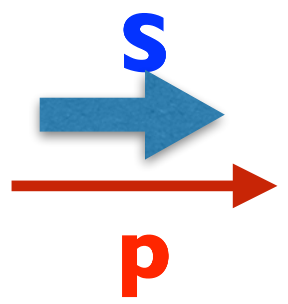


$\nu(R)=\nu_+$



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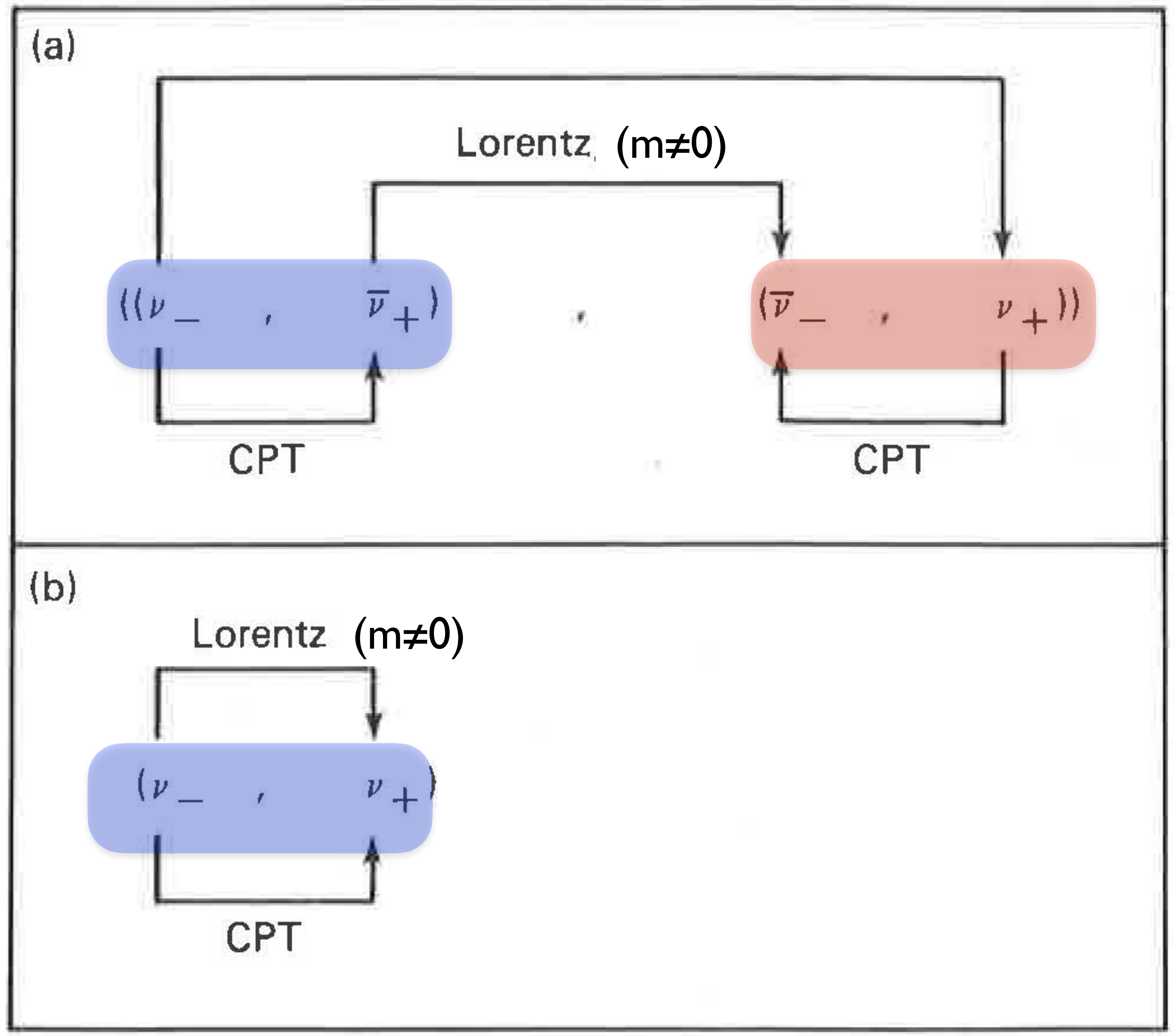

Dirac:
4 states

Majorana:
2 states

Only possible if there no internal quantum number that flips sign under "C"

$\nu_L(x)$: takes part in weak interactions

$\nu_R(x)$: no interactions in the SM

Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana

Dirac mass:

$$m\,\bar{\nu}_R \nu_L$$

Majorana mass:

$$m\,\nu_L^T C \nu_L$$

Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana

- Lorentz (Dirac case) and weak isospin (Majorana case) ⇒ need new degrees of freedom

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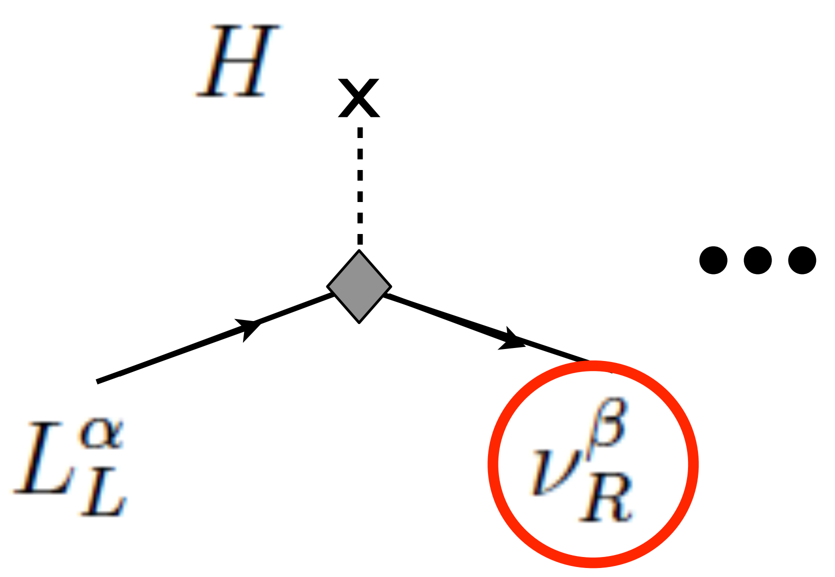

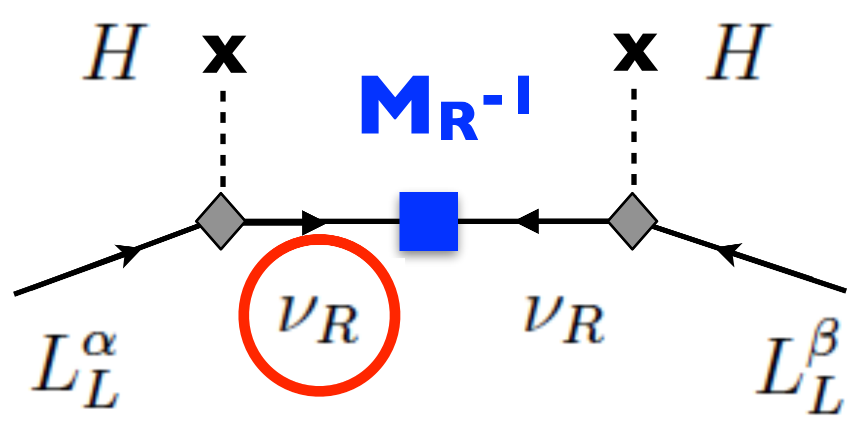

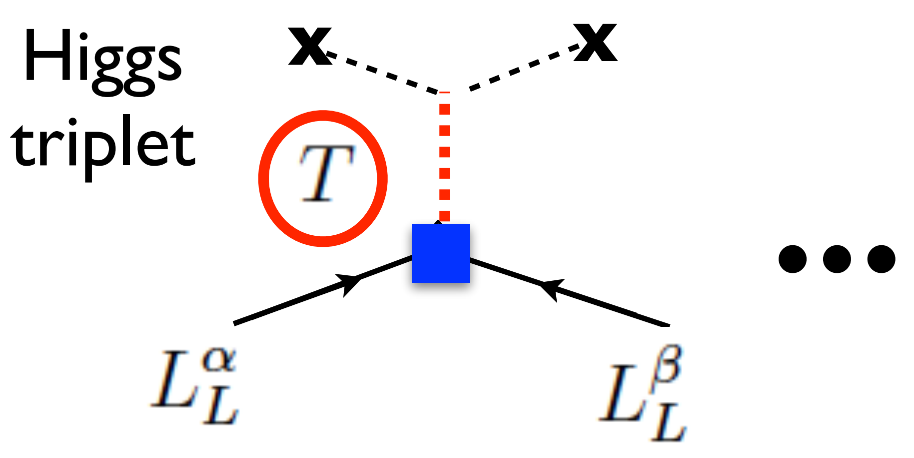

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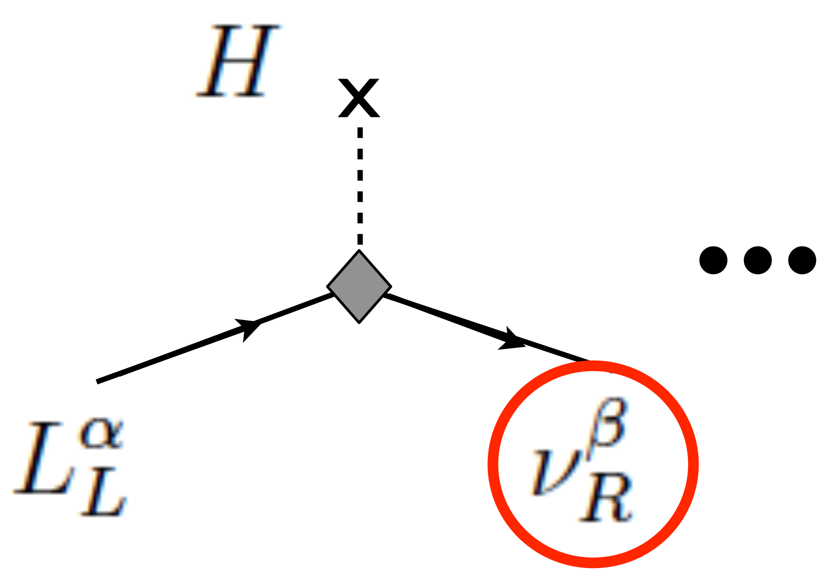

Violates $L_{e,\mu,\tau}$, conserves L

Majorana mass:

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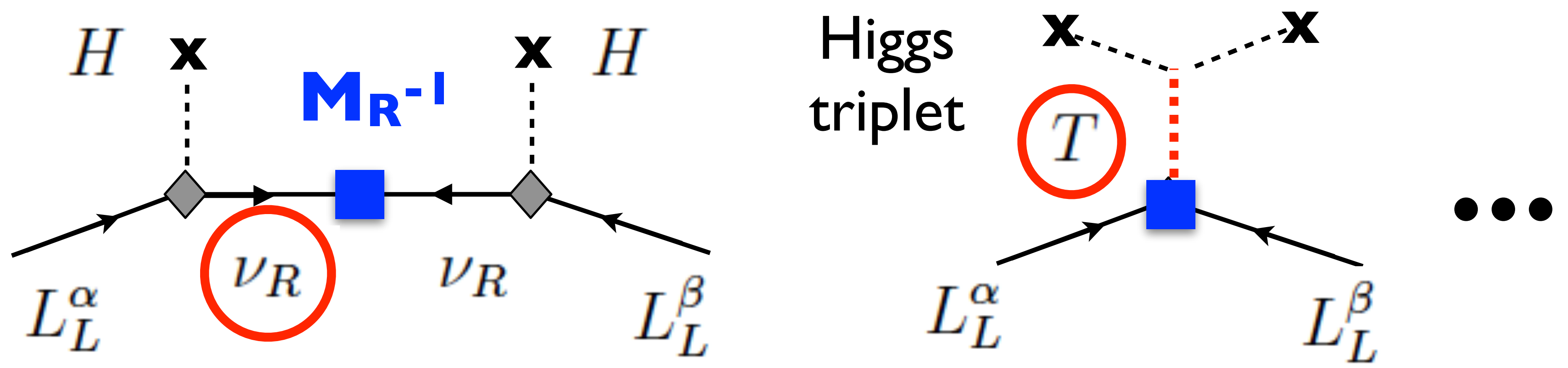


Violates $L_{e,\mu,\tau}$ and L ($\Delta L=2$)

Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana
- Lorentz (Dirac case) and weak isospin (Majorana case) ⇒ need new degrees of freedom

Dirac mass:

$$m\,\bar{\nu}_R \nu_L$$

Majorana mass:

$$m\,\nu_L^T C \nu_L$$

Which option is realized in nature?

- Smallness of ν mass and chiral nature of the weak interactions implies that *neutrino-less* processes are the best probes of ΔL=2 interactions
- 0νββ provides in many scenarios the strongest sensitivity to LNV interactions ("Avogadro's number wins", P. Vogel)

…

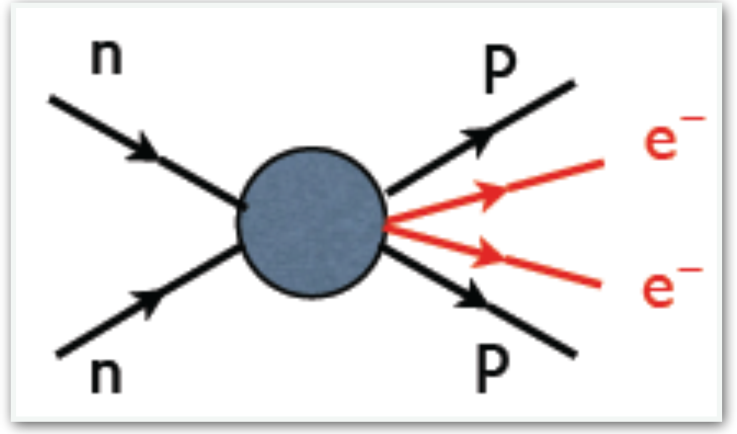
Violates $L_{e,\mu,\tau}$, conserves L

Violates $L_{e,\mu,\tau}$ and L (ΔL=2)

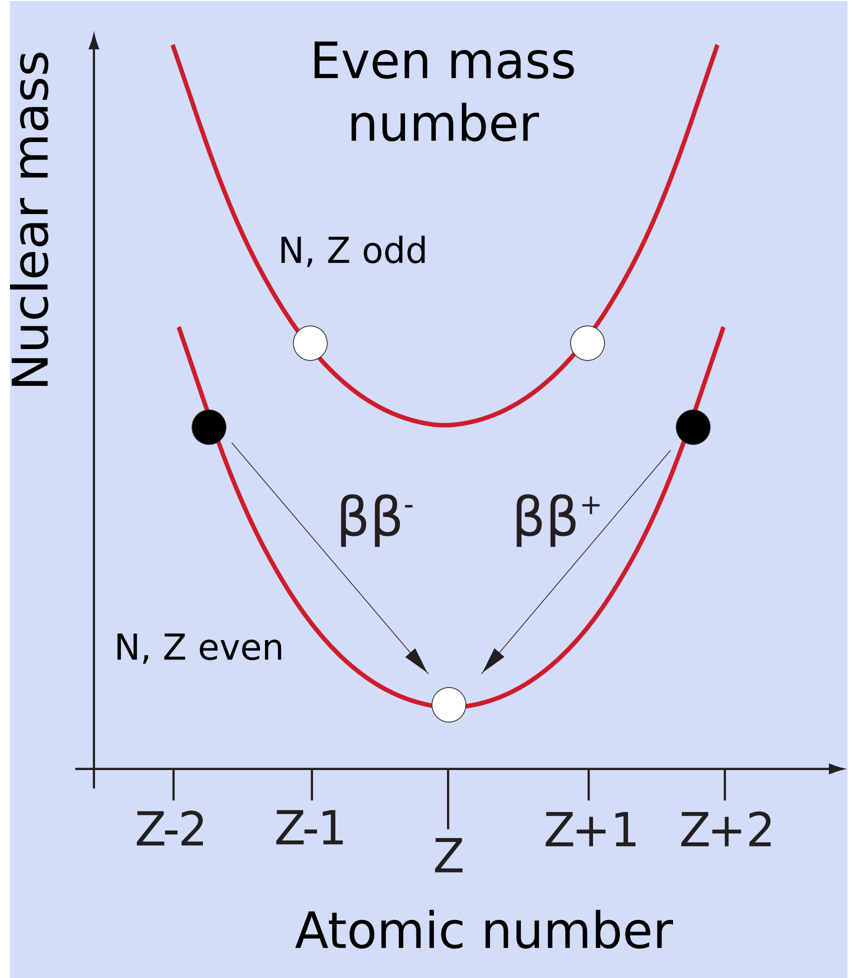
Neutrinoless double beta decay

$$(N,Z) \to (N-2, Z+2) + e^- + e^-$$

$$T_{1/2} > \# 10^{25}\mathrm{yr}$$



ΔL=2



Potentially observable in even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …) for which single beta decay is energetically forbidden

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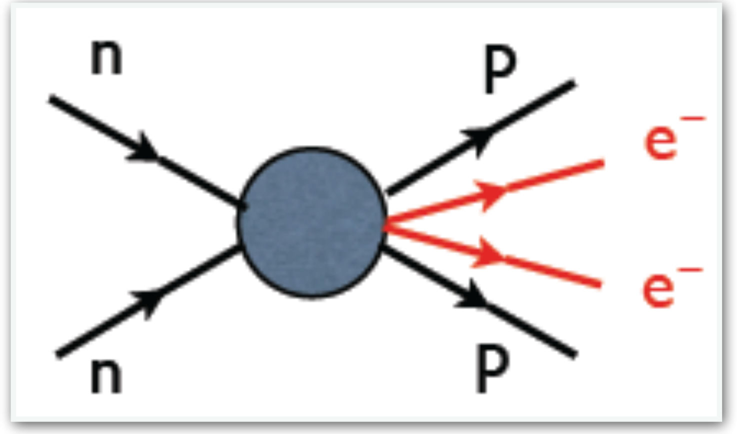

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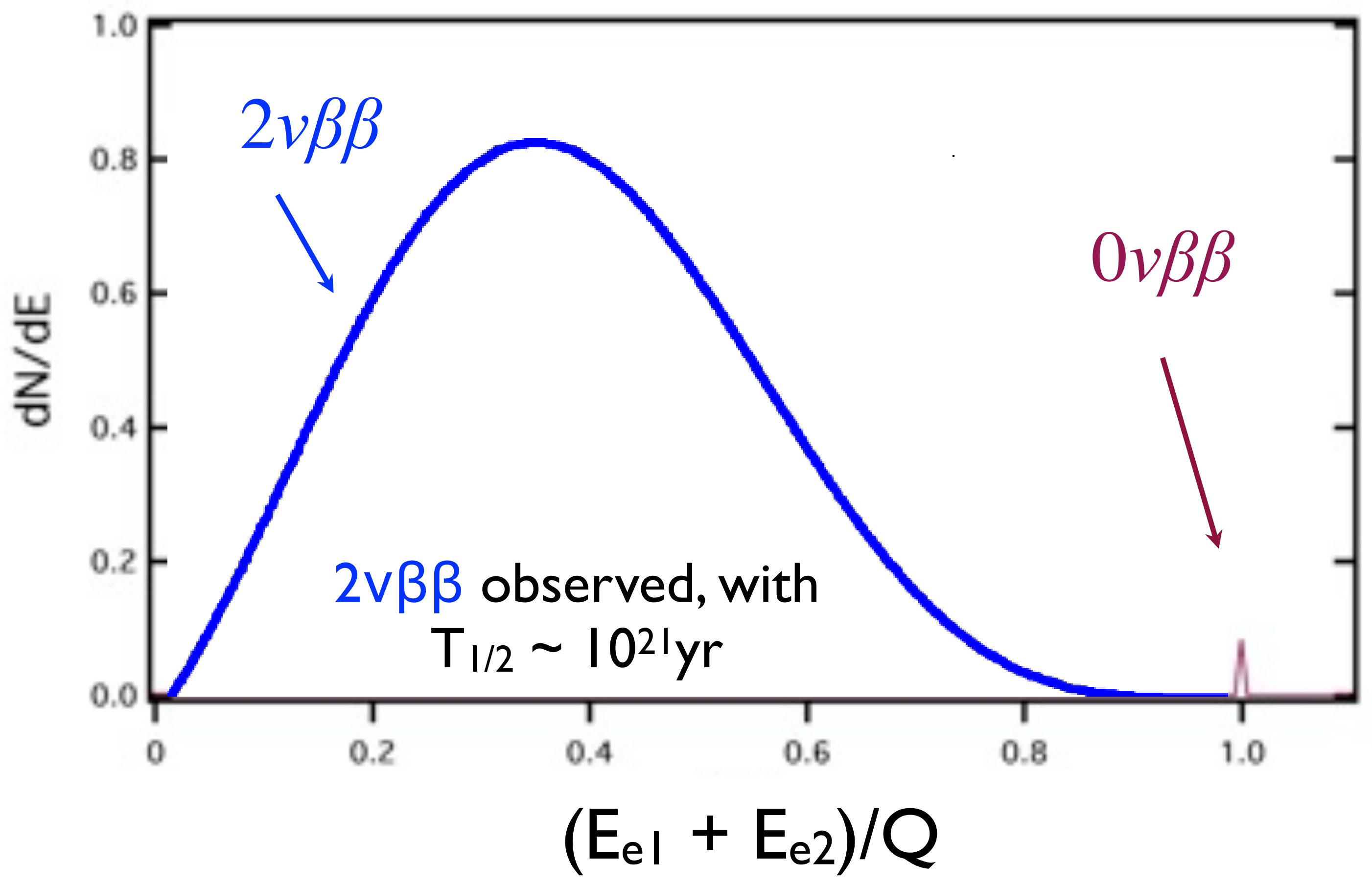

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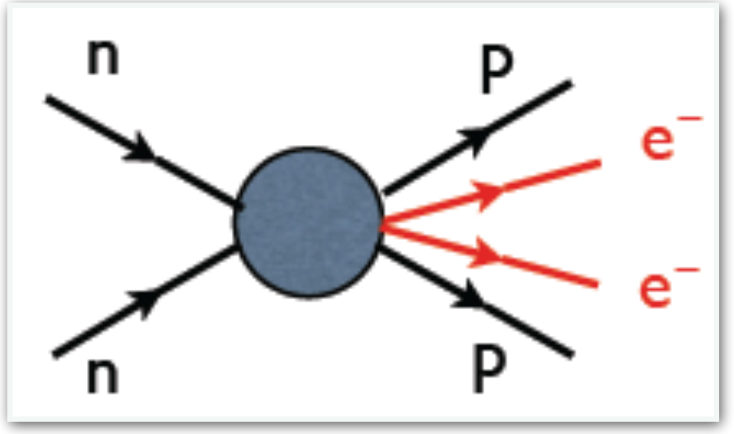

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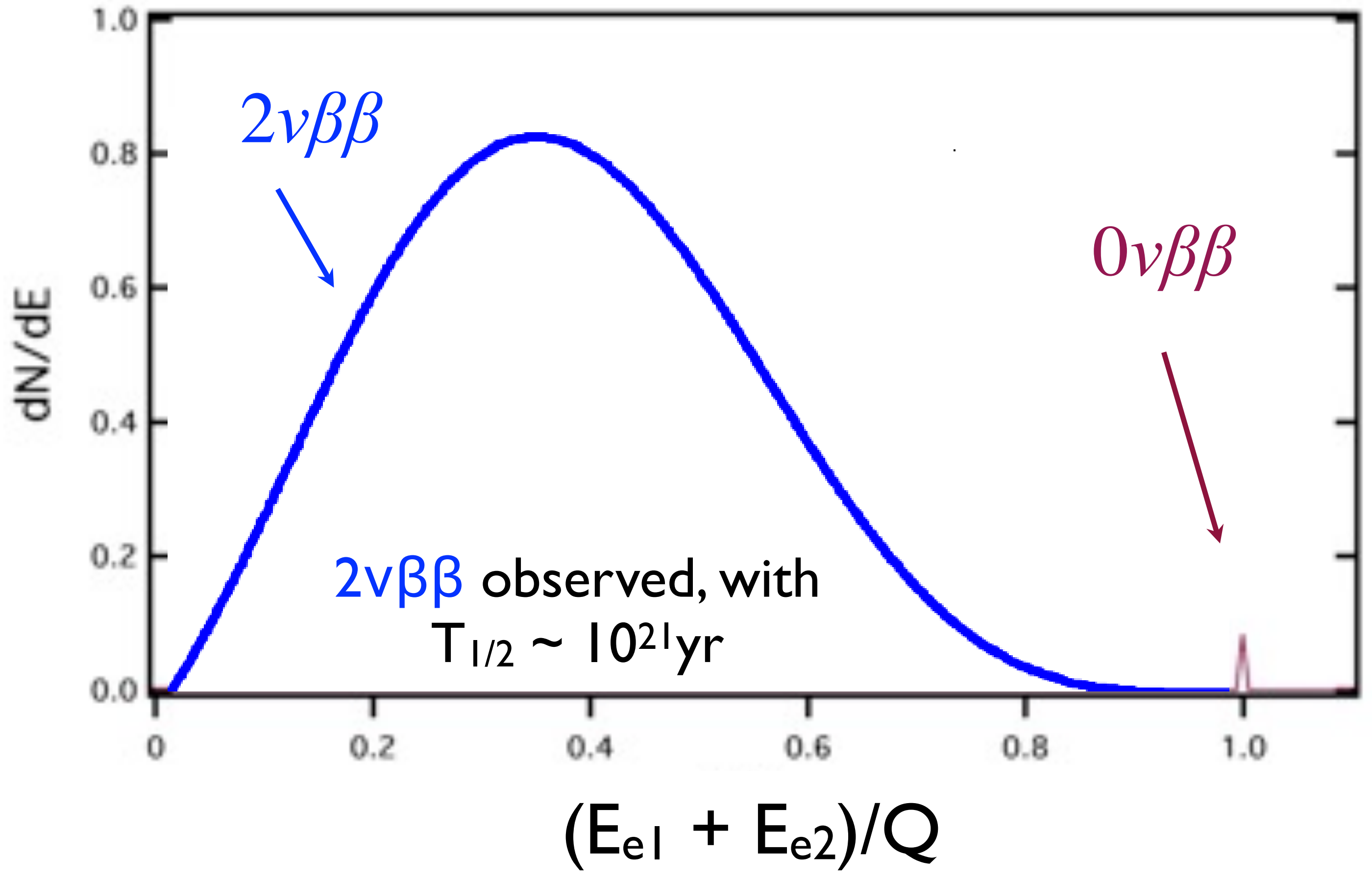

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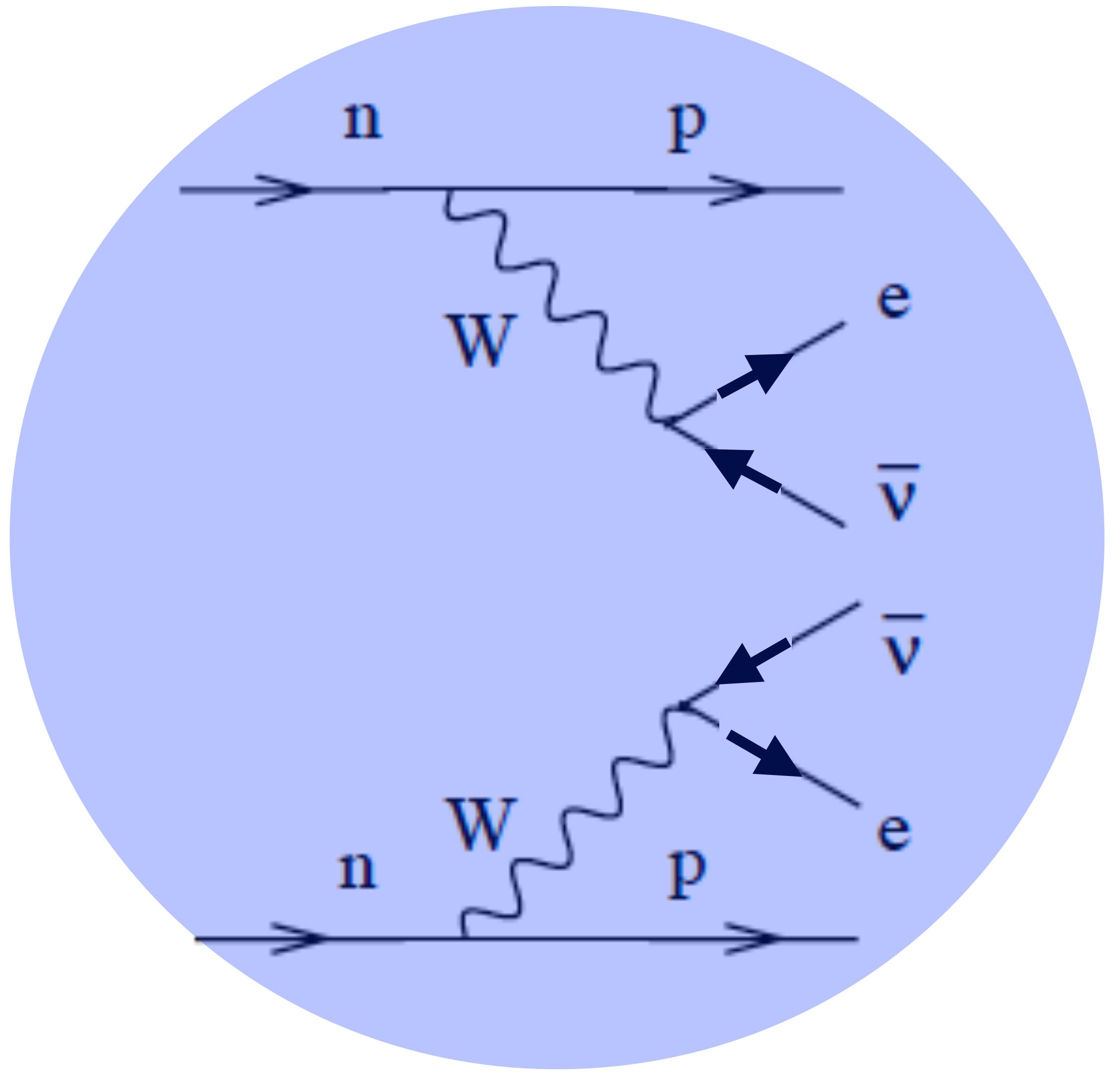
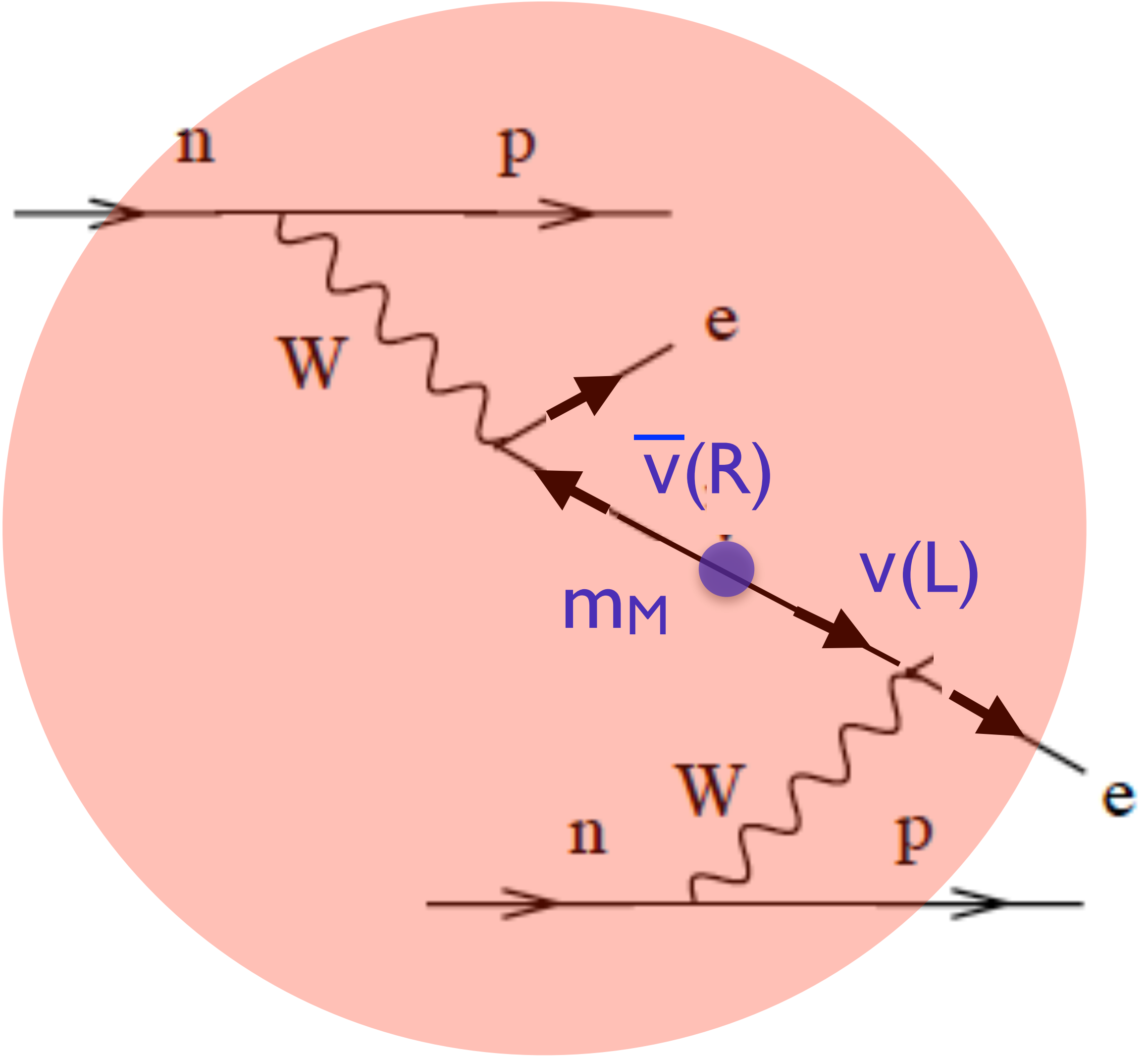


Simplest mechanism: Majorana mass term

But not the only one!

Furry 1939



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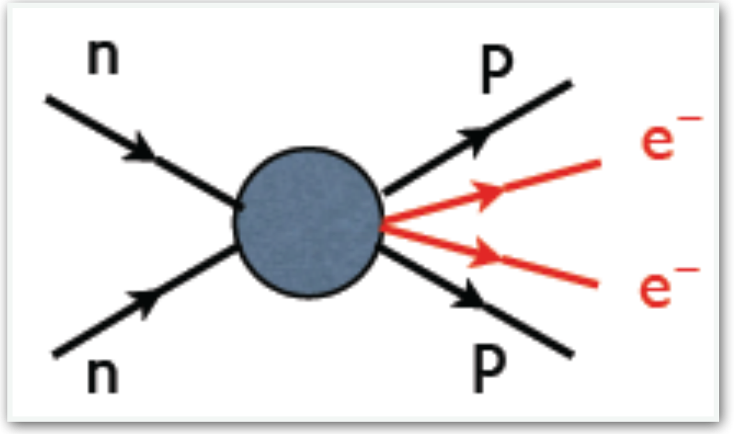
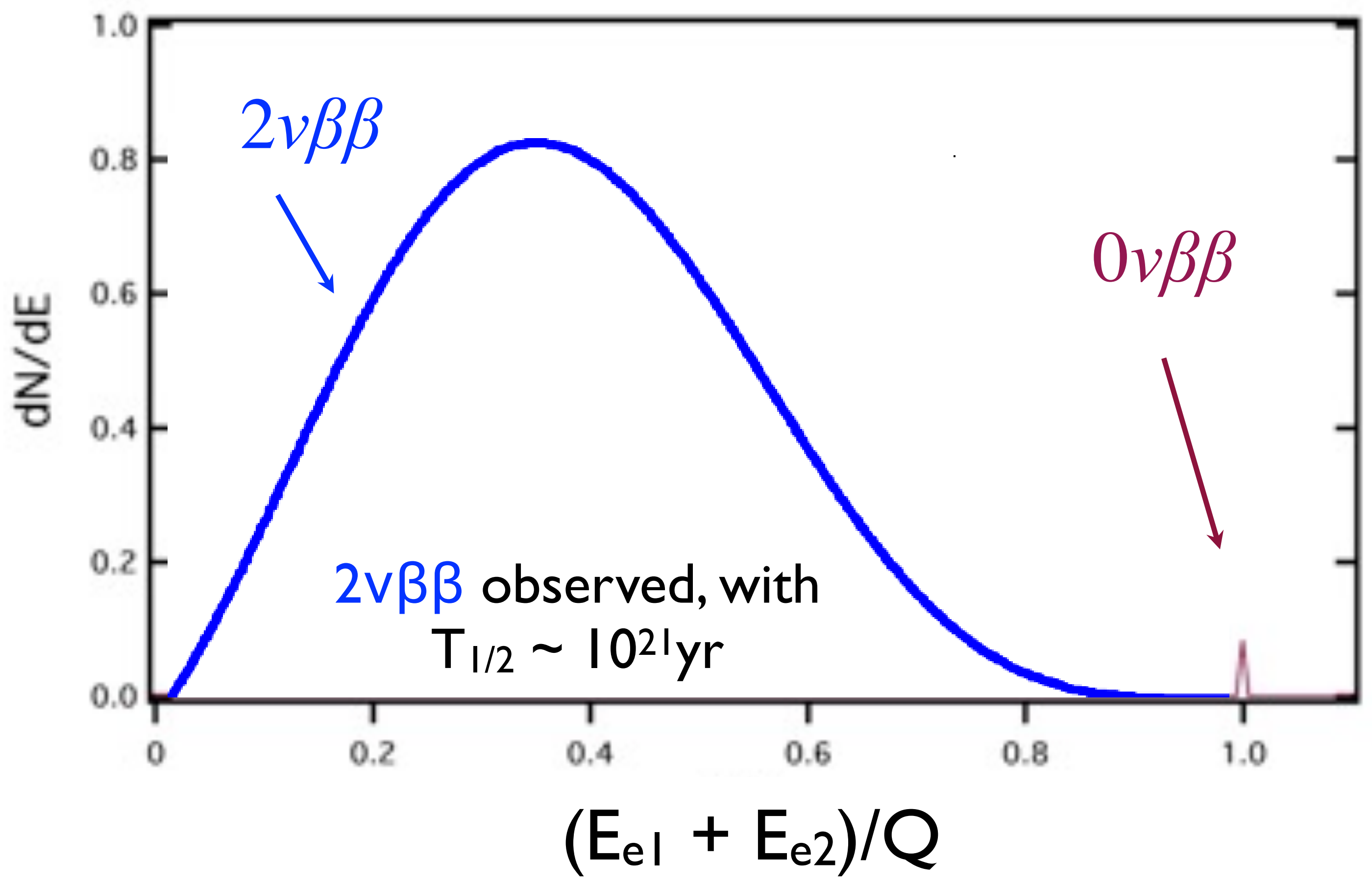


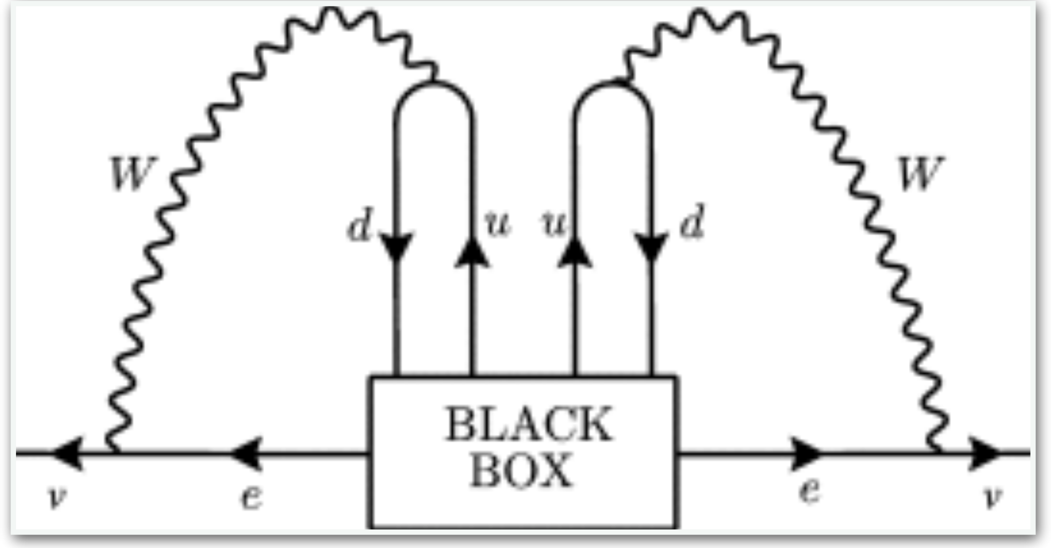
ΔL=2



Potentially observable in even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …) for which single beta decay is energetically forbidden

- Observation would have far-reaching implications
  - Demonstrate that neutrinos are Majorana fermions
  - Establish LNV, key ingredient to generate the baryon asymmetry via leptogenesis

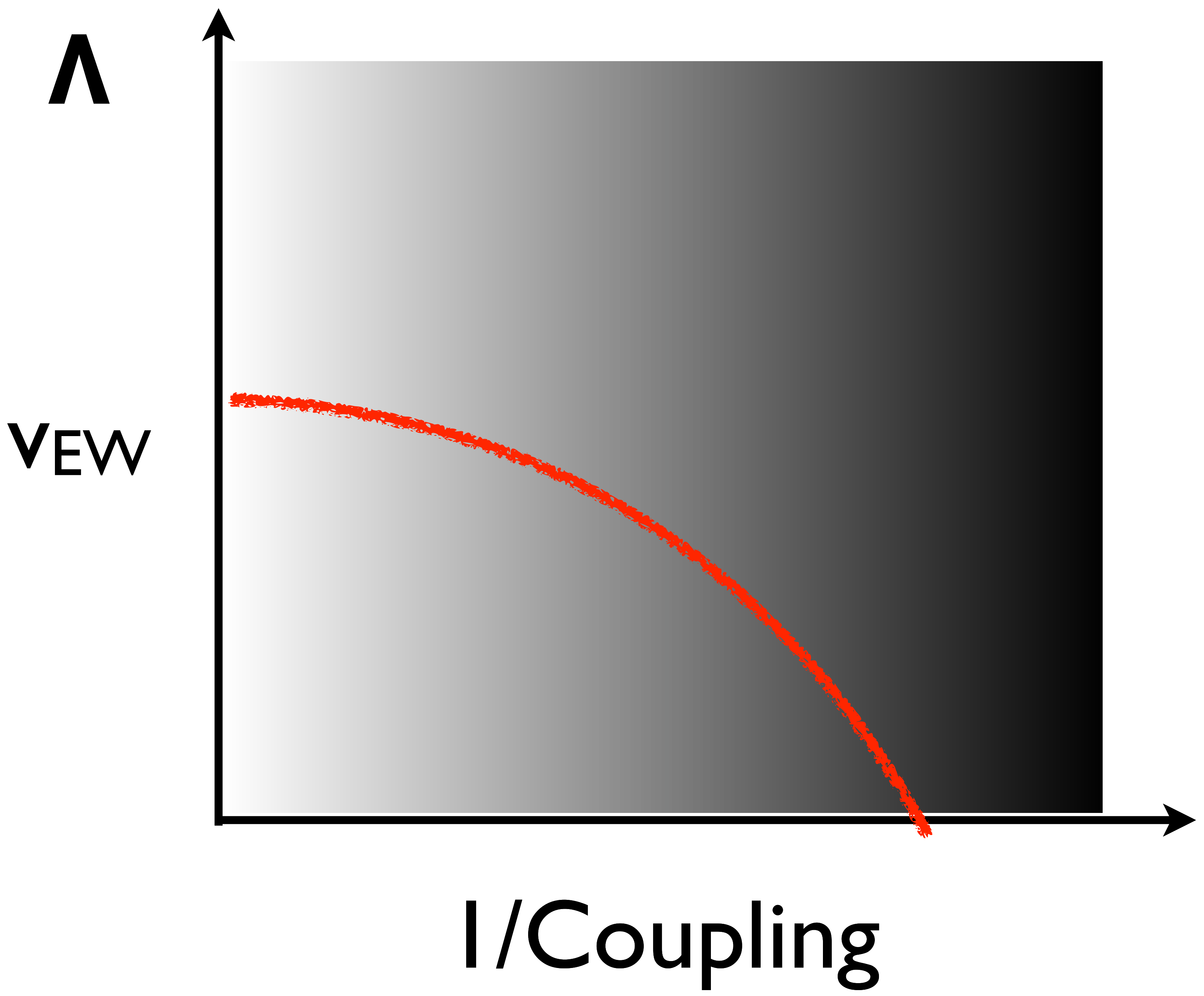
Fukugita-Yanagida 1987

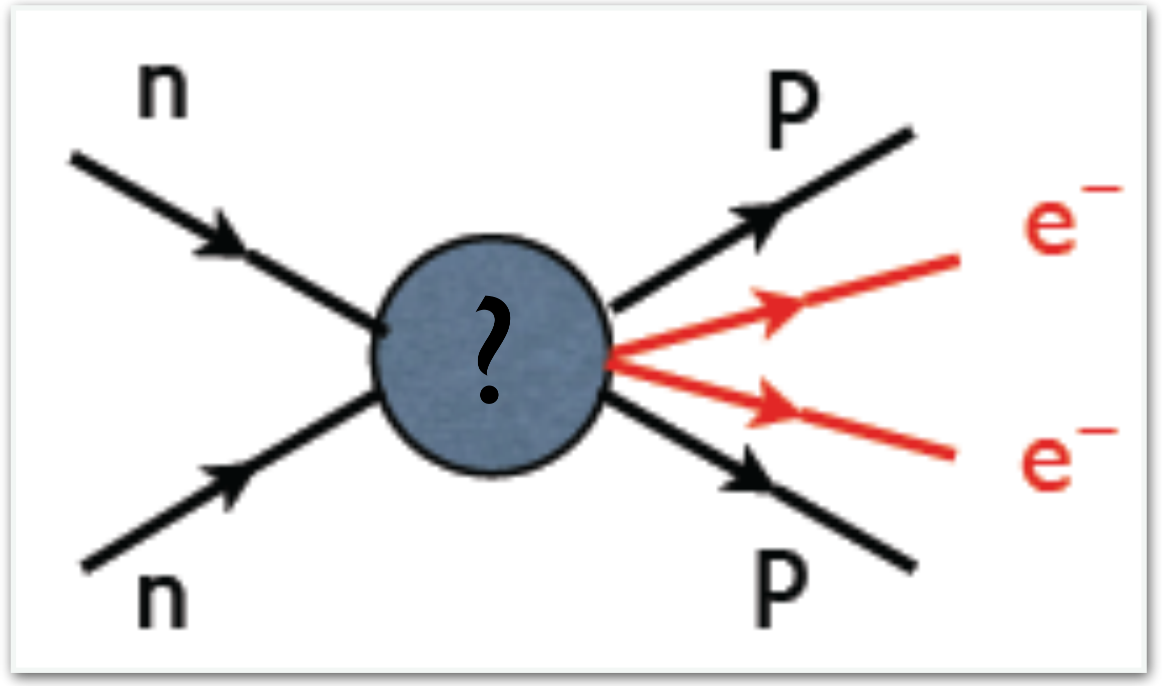


Shechter-Valle 1982

0νββ physics reach

- 0νββ searches @ $T_{1/2} > 10^{27\text{-}28}$ yr will have broad sensitivity to LNV mechanisms





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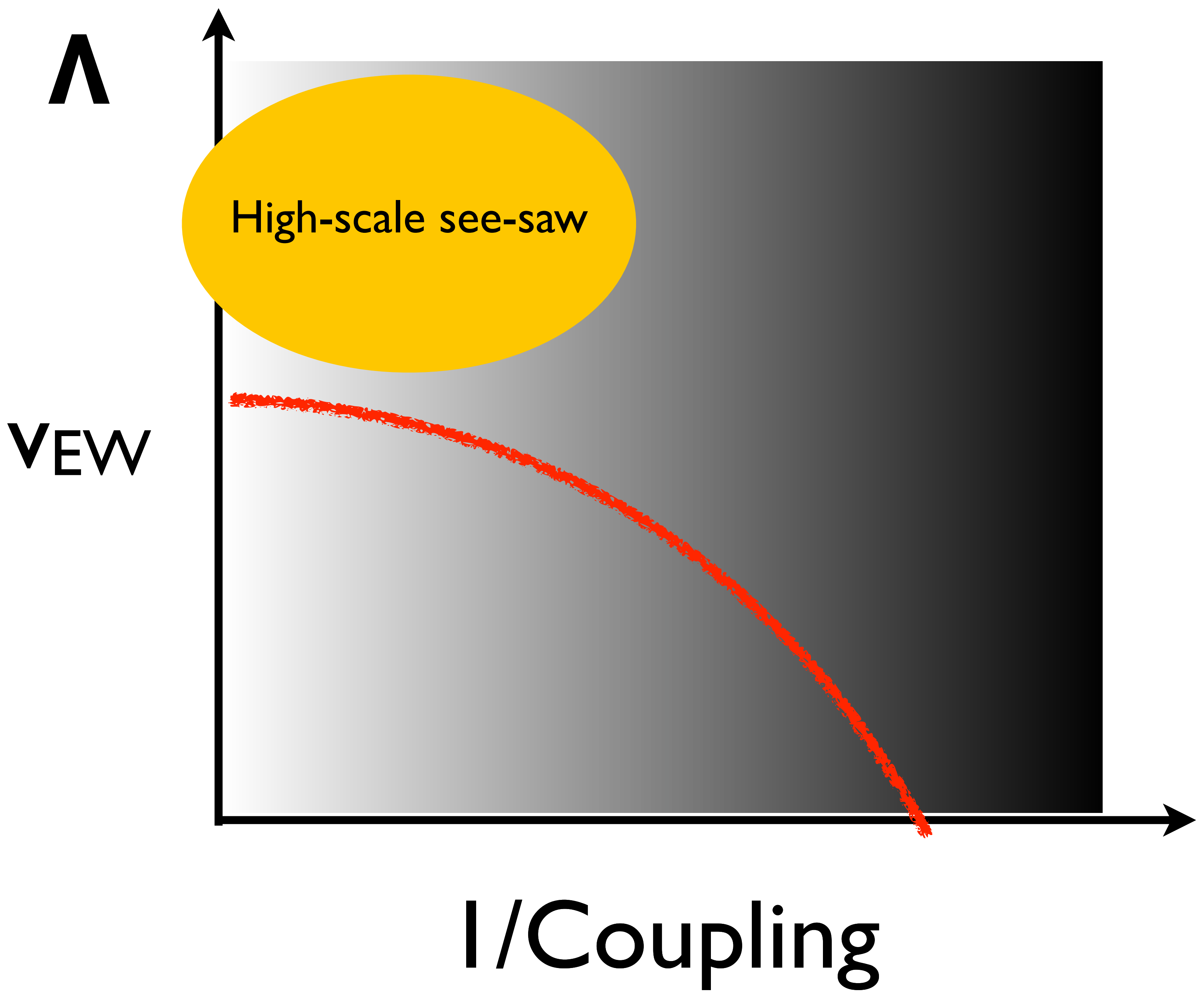

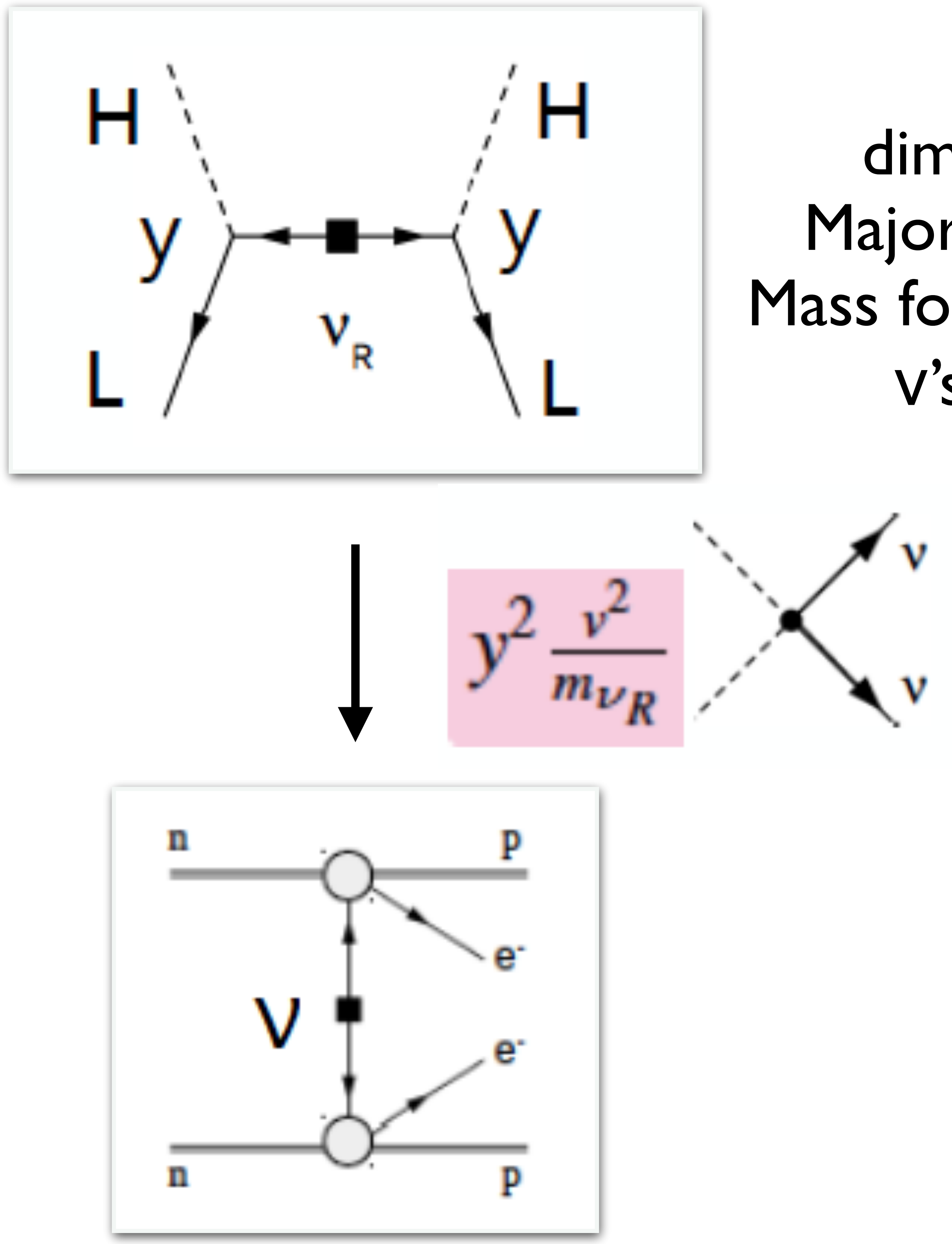

dim5 Majorana Mass for light ν's

Only low-E remnant of LNV is the neutrino mass

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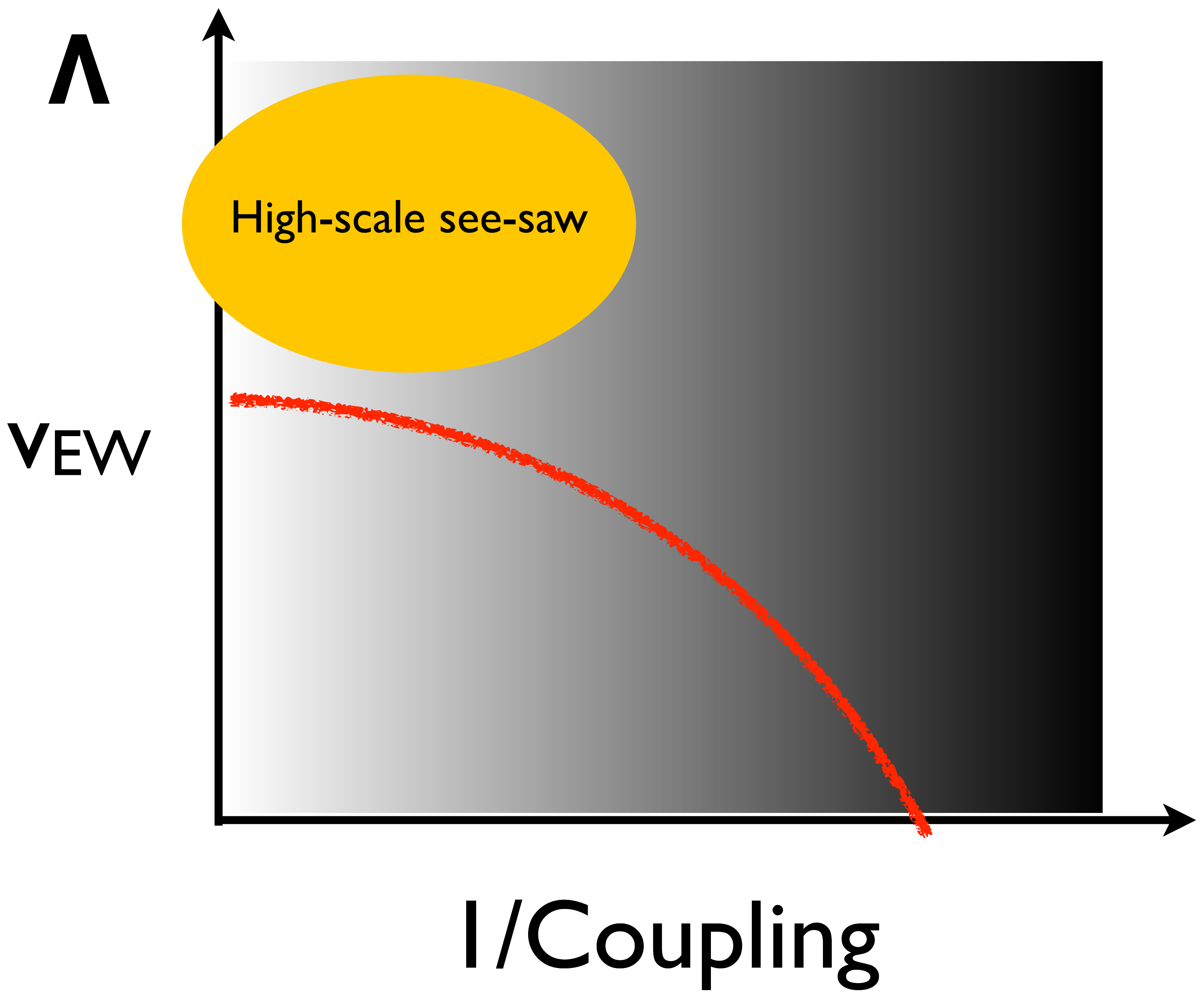
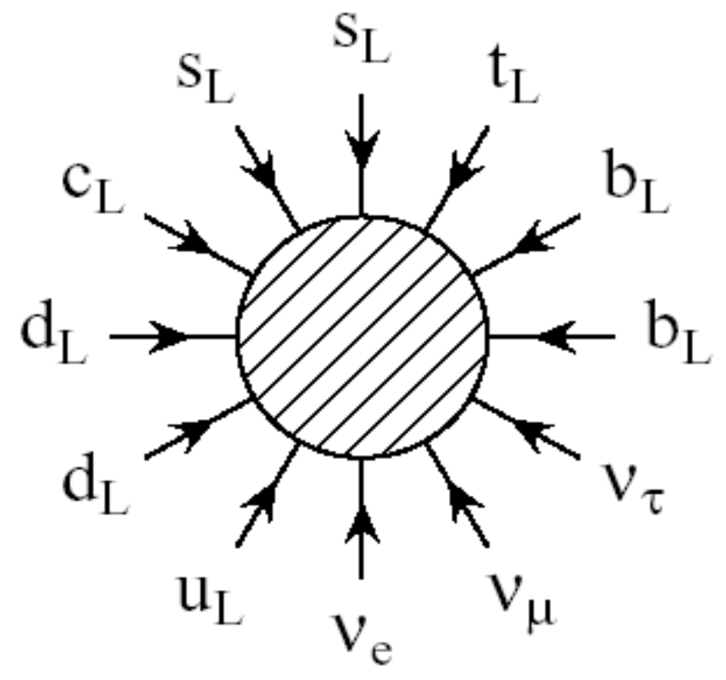


Baryogengesis via Leptogenesis

1) CP- and L- violating out-of-equilibrium decays of heavy $\nu_{Ri} \Rightarrow n_L$

$$\Gamma(\nu_R \to H^* \ell) \neq \Gamma(\nu_R \to H \bar{\ell})$$

2) EW sphalerons $\Rightarrow n_B = \# \, n_L$



Fukugita-Yanagida 1987

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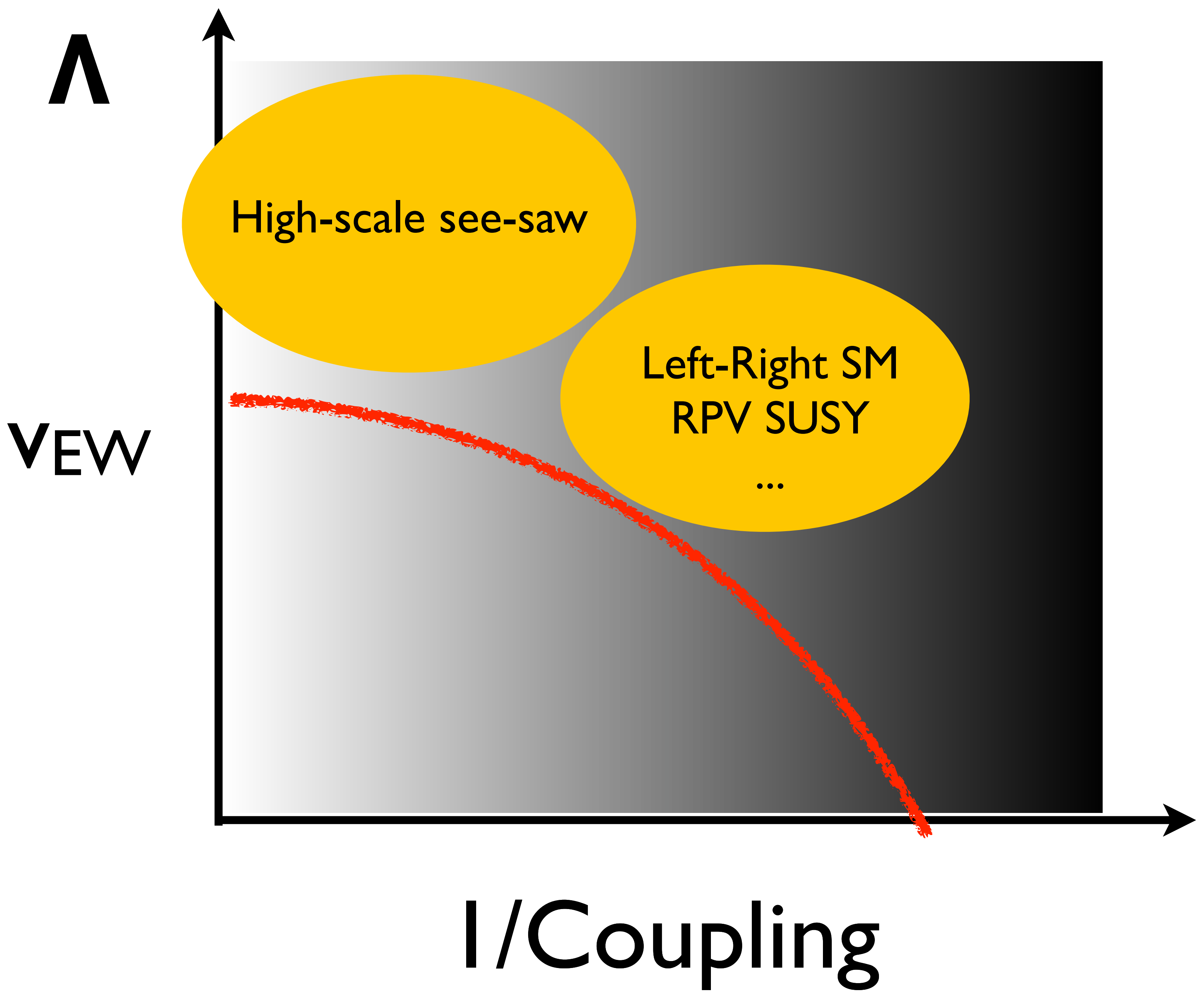
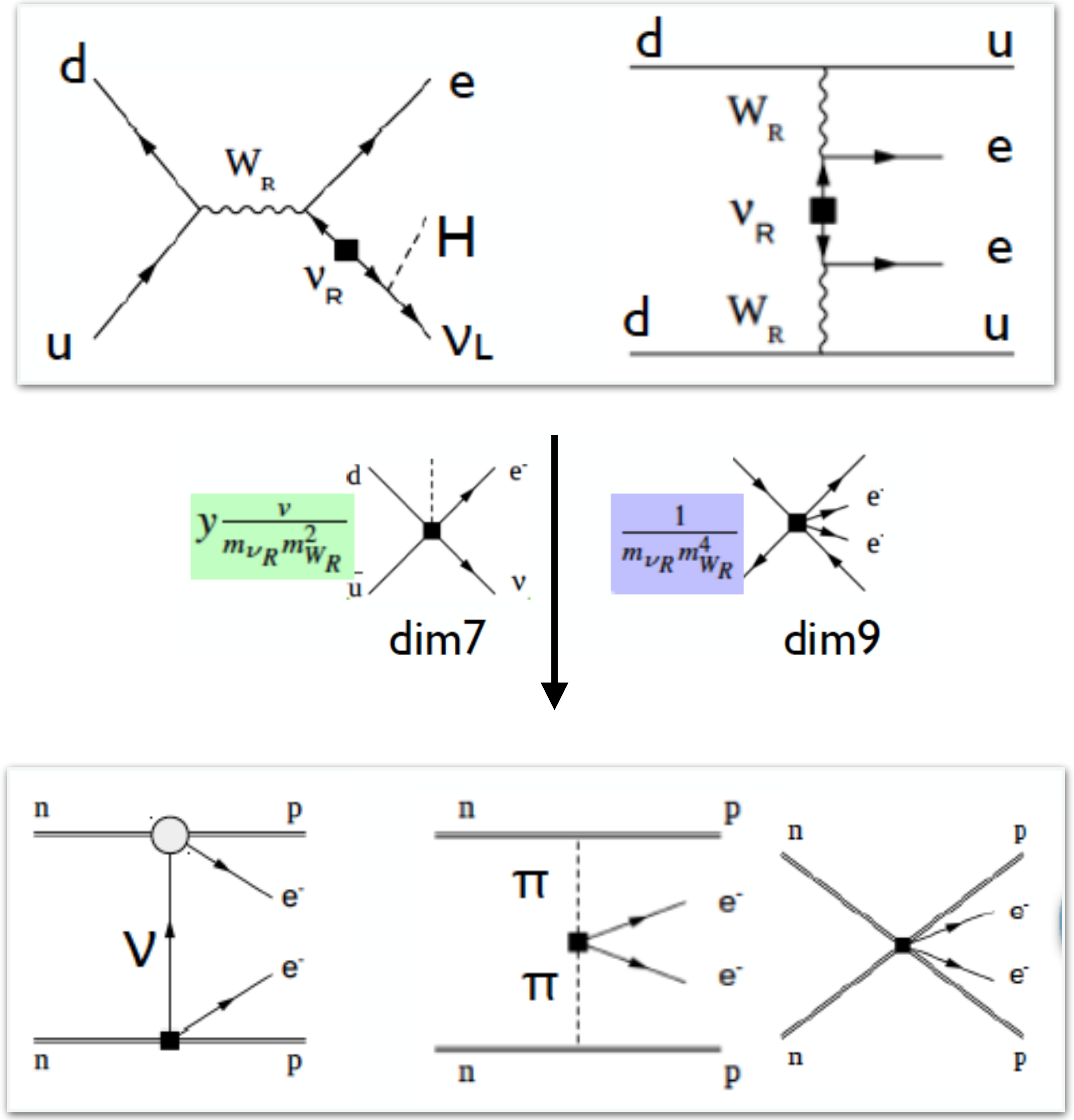


These contributions can compete if scale is not too high (10-100 TeV) and lead to new mechanisms at the nuclear scale



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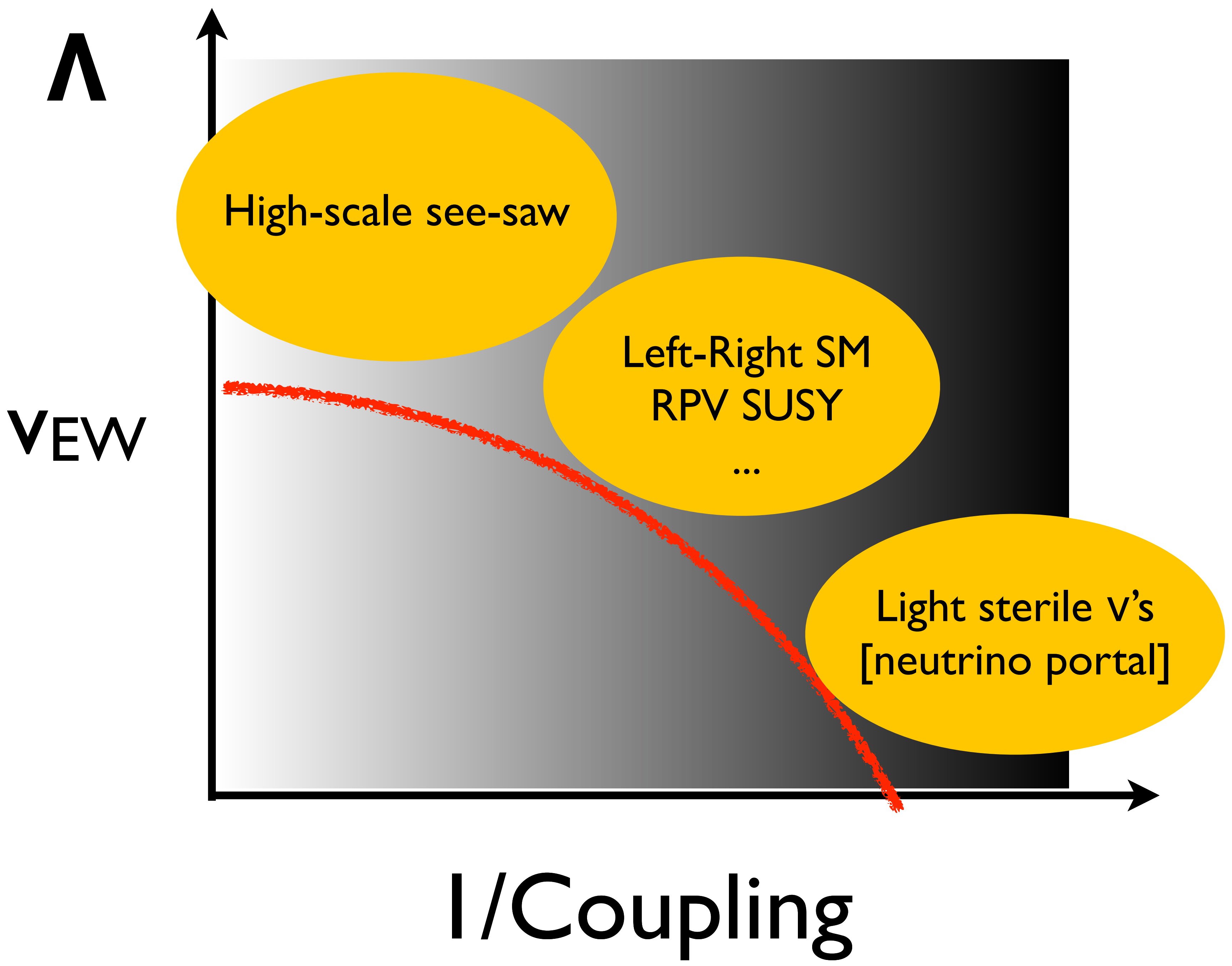
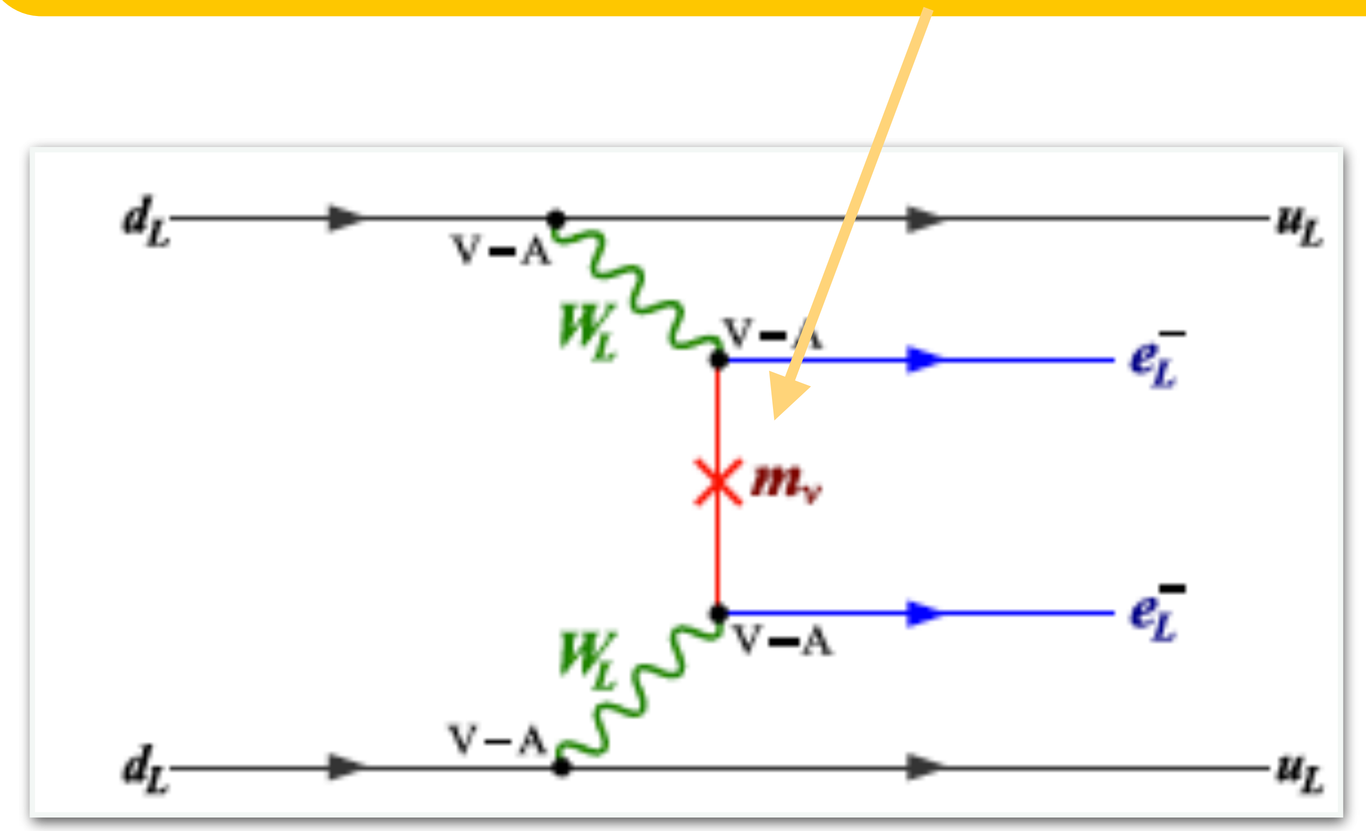
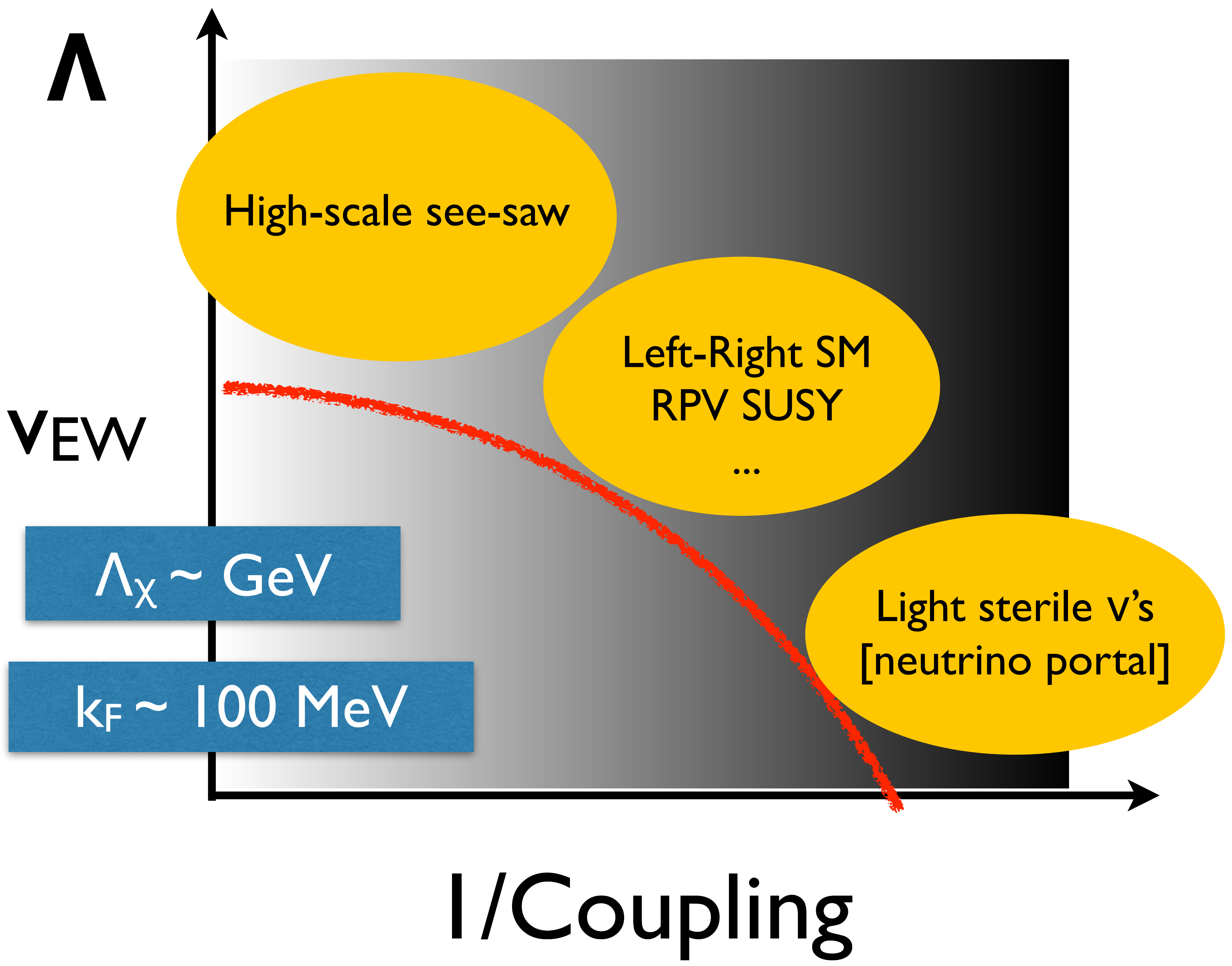


Light (nearly sterile) Majorana neutrinos



$0\nu\beta\beta$ physics reach

- $0\nu\beta\beta$ searches @ $T_{1/2} > 10^{27\text{-}28}$ yr will have broad sensitivity to LNV mechanisms



- Multi-scale problem best tackled through 'end-to-end' EFT: only chance to achieve controllable uncertainty
- Synergy of EFT, Lattice QCD, and first-principles nuclear structure

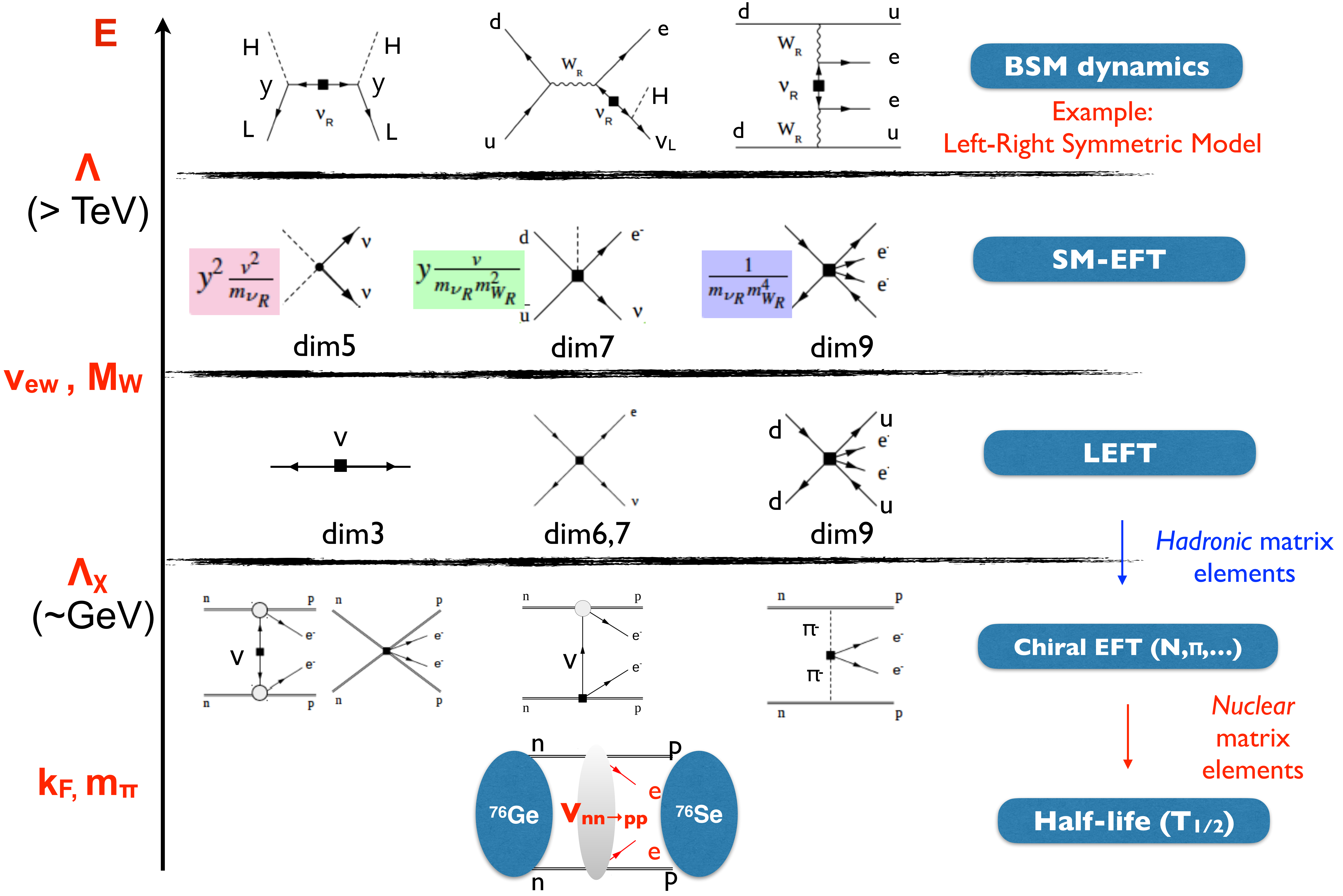
SMEFT LEFT Chiral EFT

$$T_{1/2} \propto (m_W/\Lambda)^A \, (\Lambda_\chi/m_W)^B \, (k_F/\Lambda_\chi)^C$$

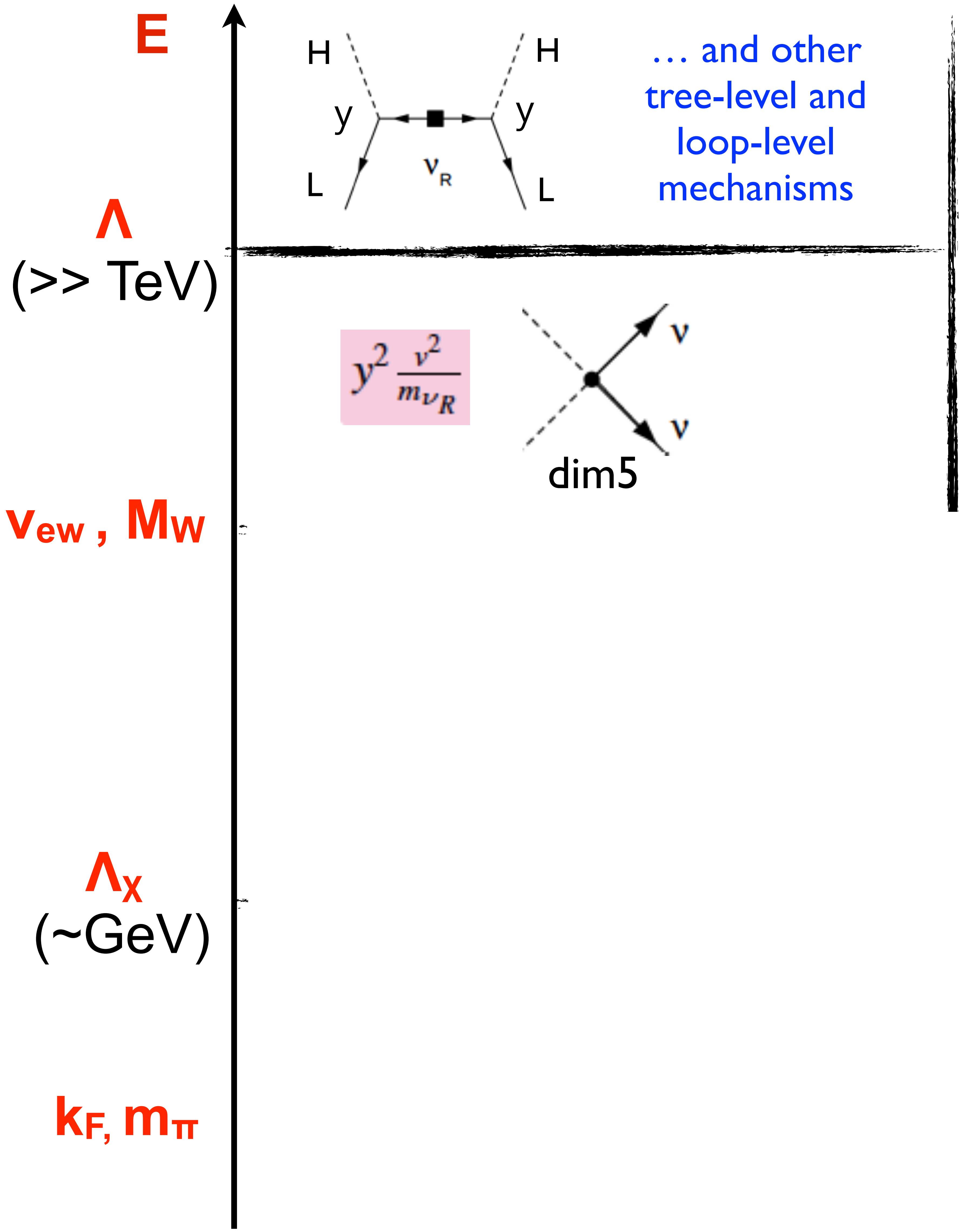
White paper 2203. 21169 and refs therein

‘End-to-end’ EFT framework

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]



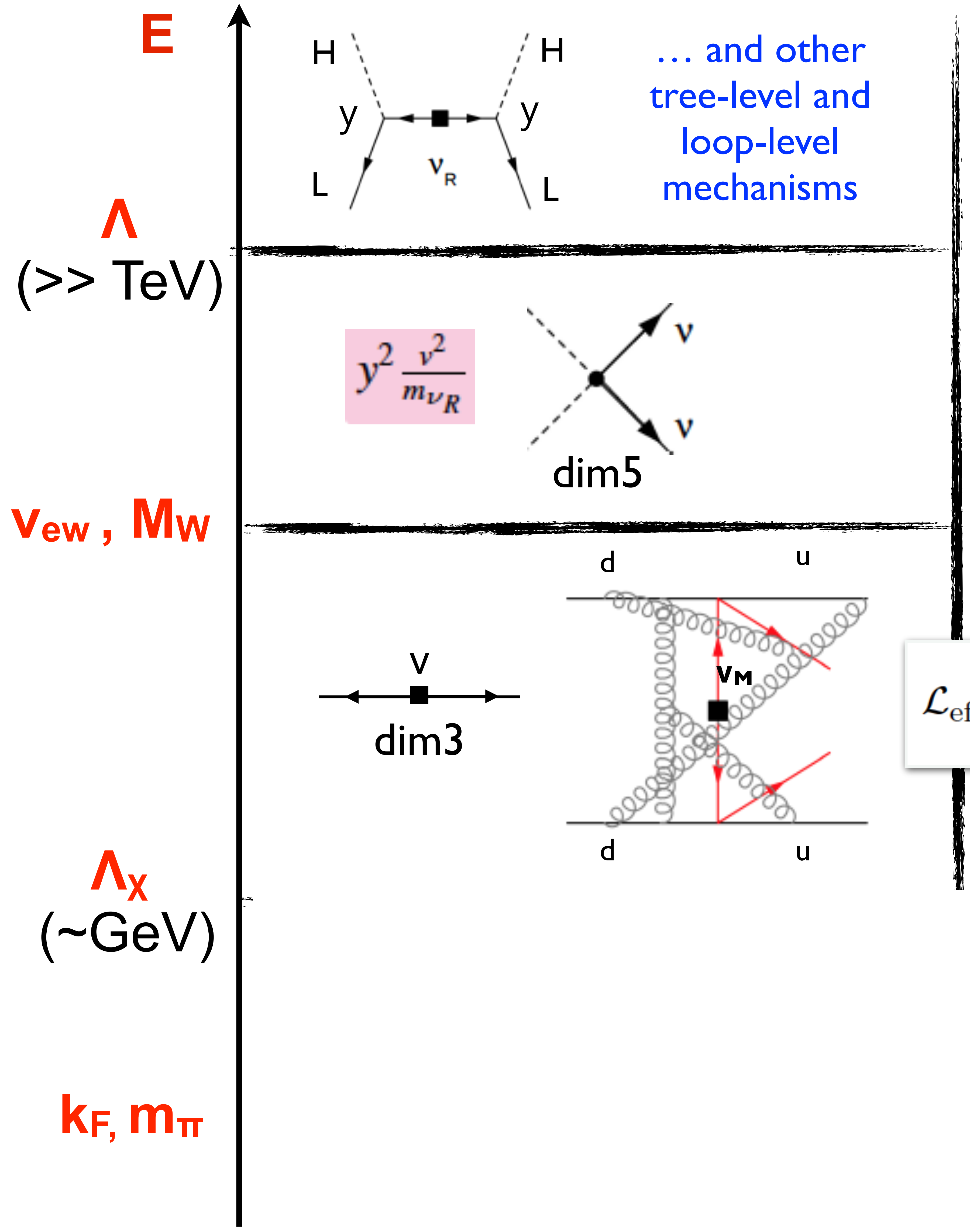
High scale LNV



- LNV originates at very high scale (Λ >> v) → dominant low-energy remnant is Weinberg's dim-5 operator:

$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L_\alpha^T C \epsilon H \, H^T \epsilon L_{\alpha'}$$

High scale LNV



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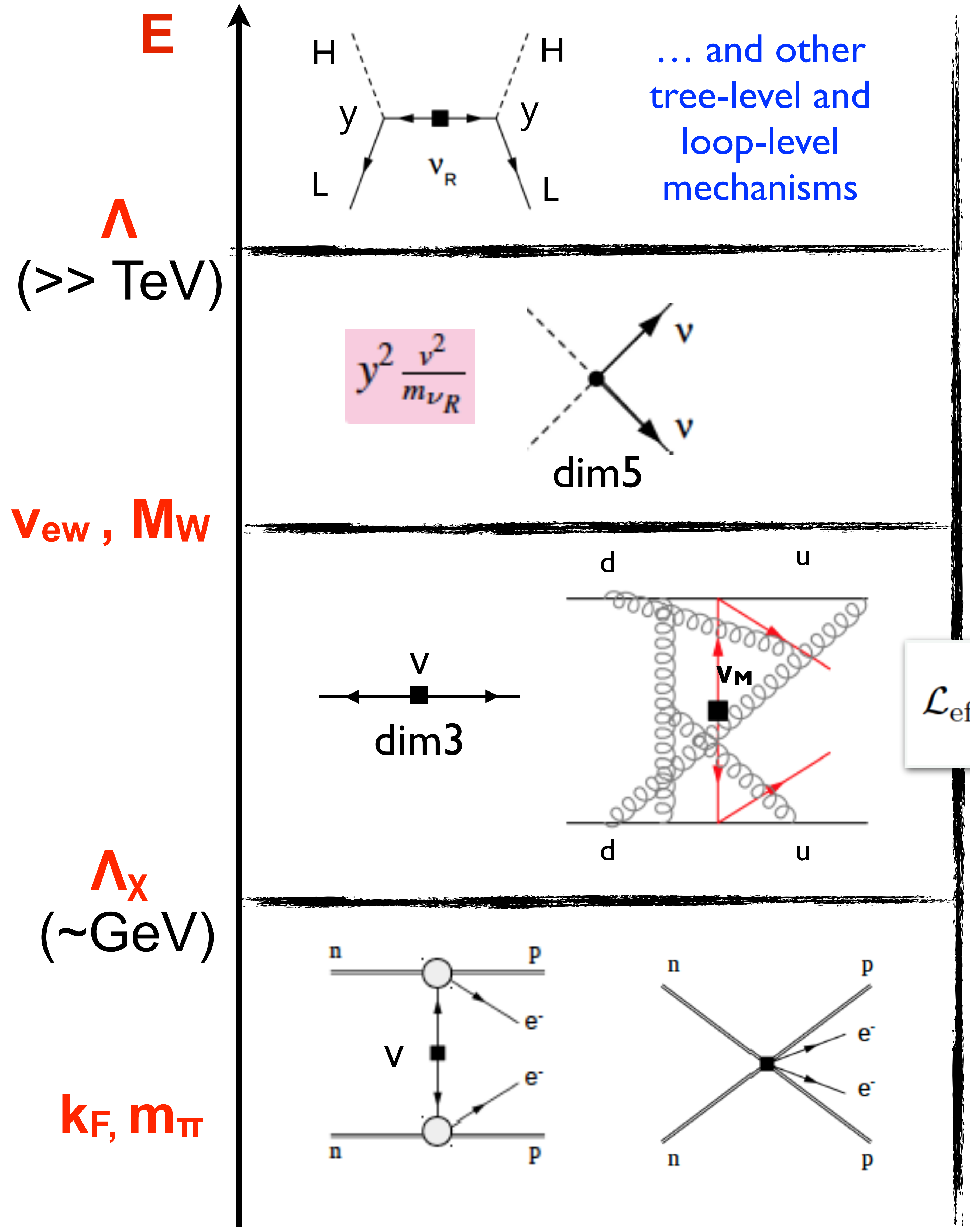
- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee}\, v^2/\Lambda$)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}} V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \text{H.c.}$$

High scale LNV



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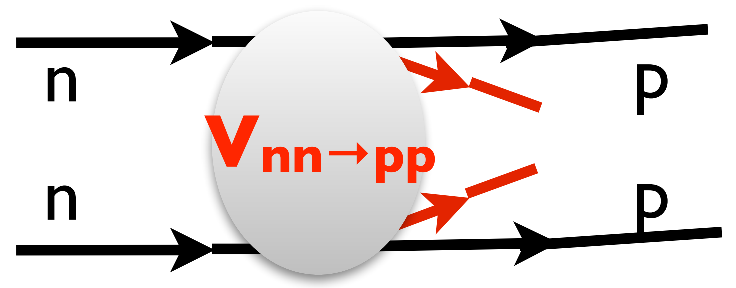
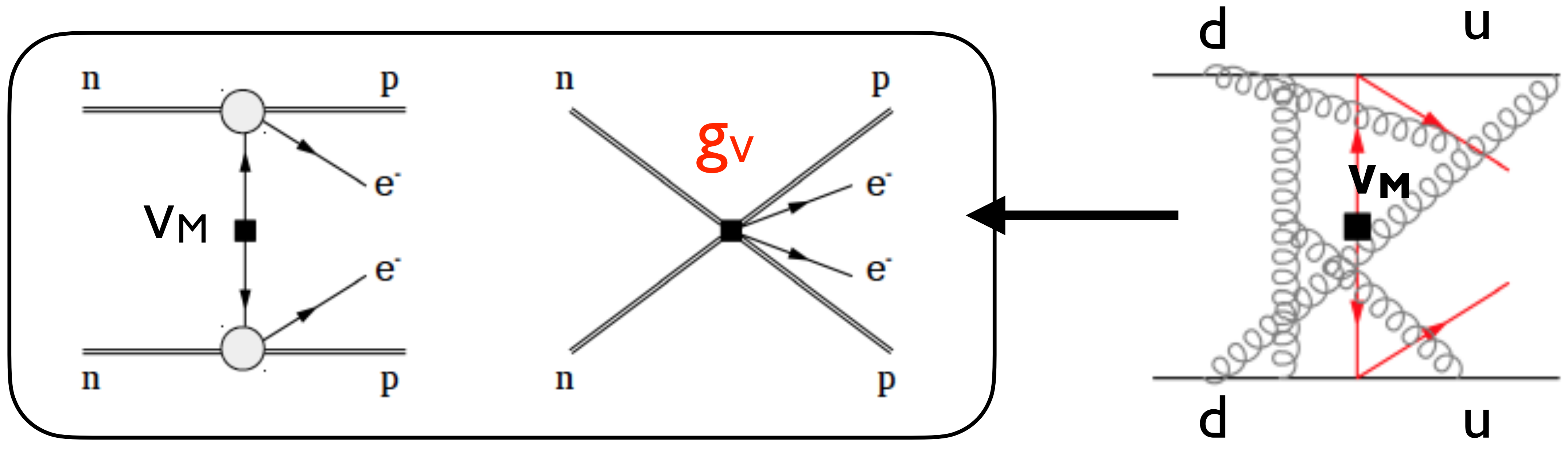
- 0νββ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$



Recent theoretical developments

- Insight from EFT: new NN contact interaction to leading order in Q/Λ_χ

$Q \sim k_F \sim m_\pi$
$\Lambda_\chi \sim \mathrm{GeV}$



VC, W. Dekens, J. de Vries, M. Graesser,
E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

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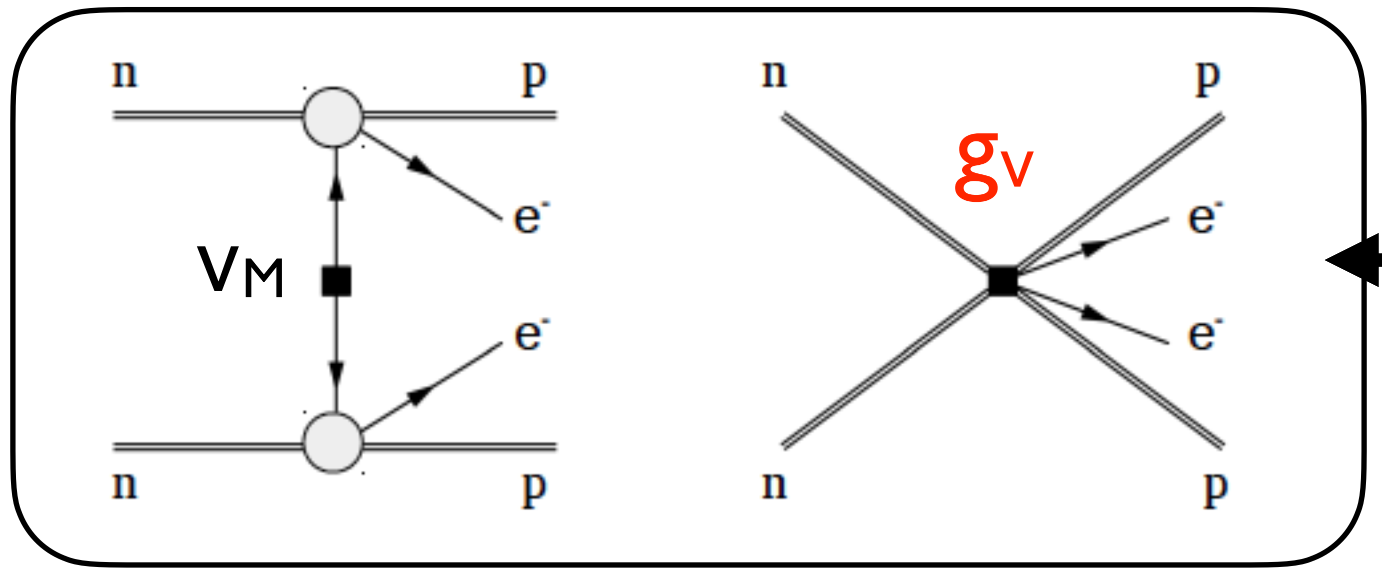

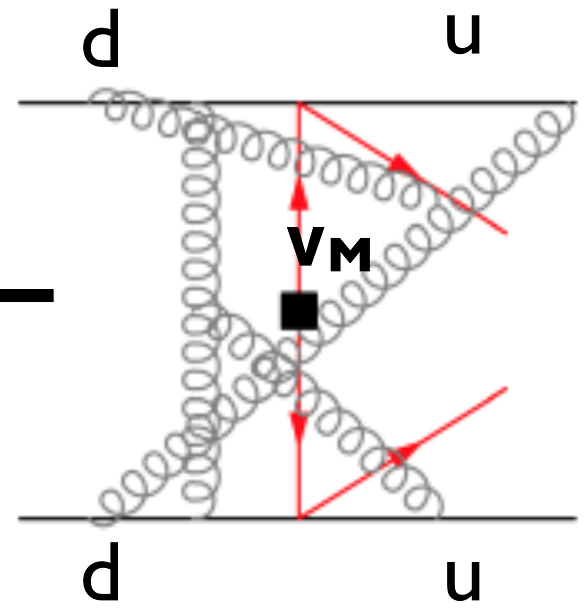

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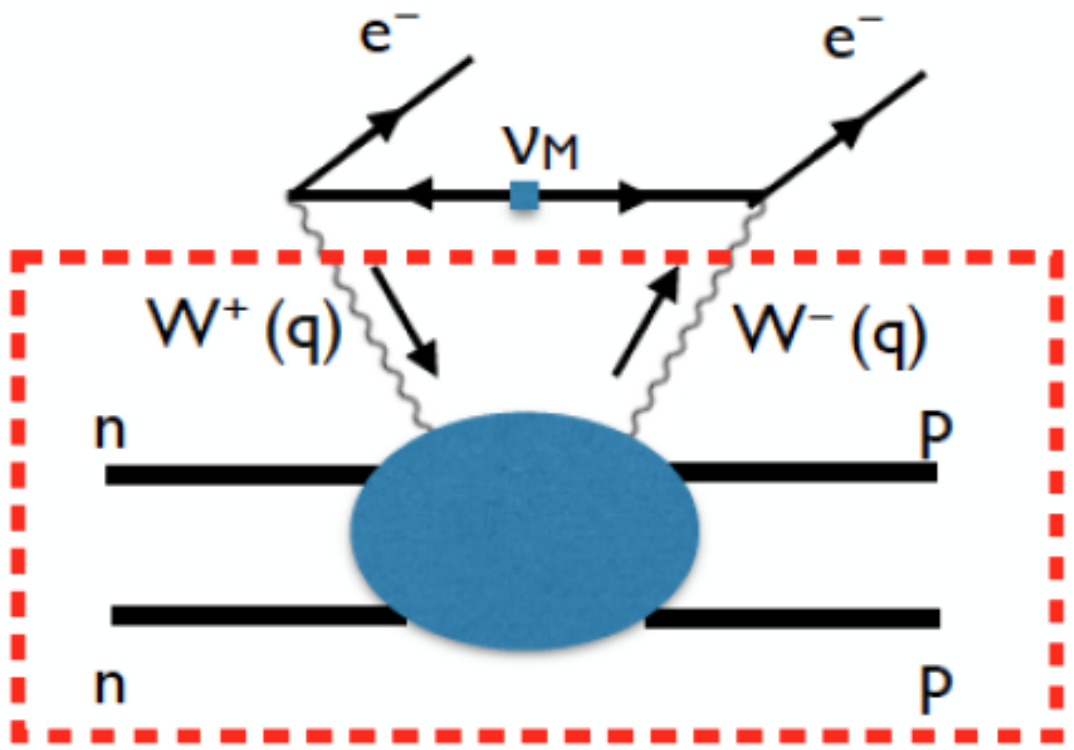
E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- g_ν estimated through dispersive analysis [1] and used in first-principles calculation [2] of $^{48}Ca \rightarrow {}^{48}Ti$: contact term enhances n.m.e. by ~50%



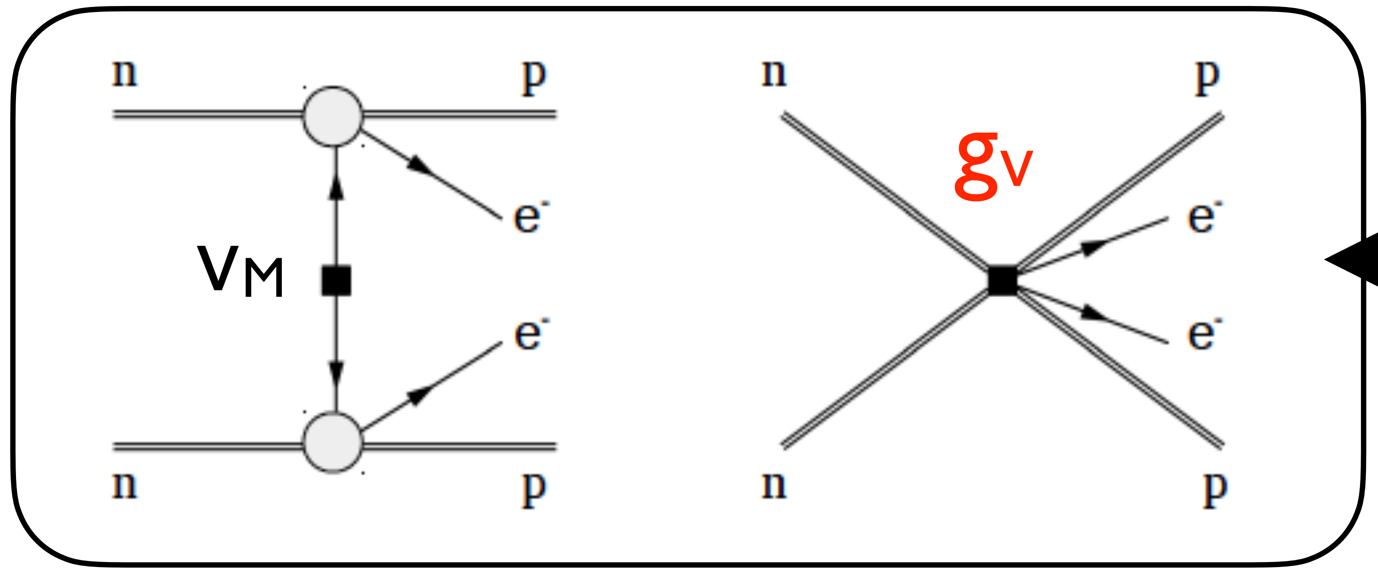
[1] VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

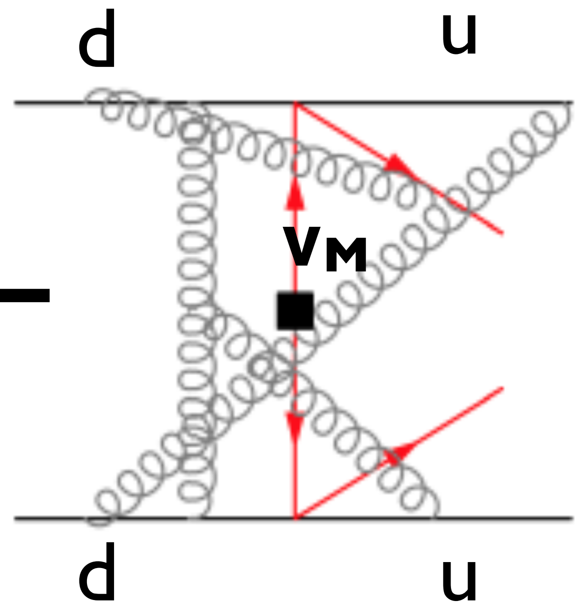
[2] Wirth, Yao, Hergert, 2105.05415. See also Belley et al, 2307.15156, 2308.15634

Recent theoretical developments

- Insight from EFT: new NN contact interaction to leading order in Q/Λ_χ

$Q \sim k_F \sim m_\pi$
$\Lambda_\chi \sim GeV$





VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

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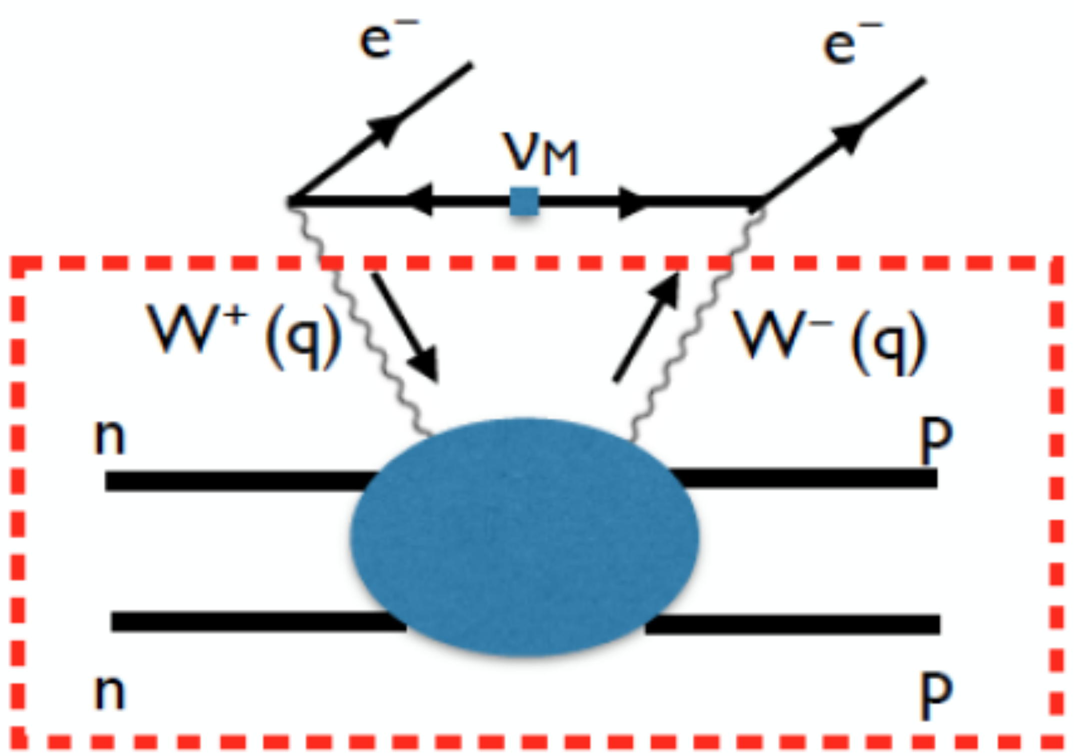

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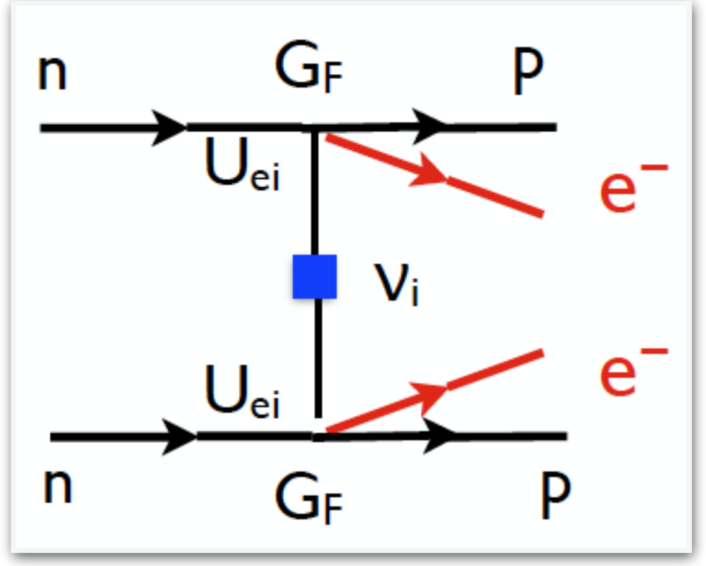
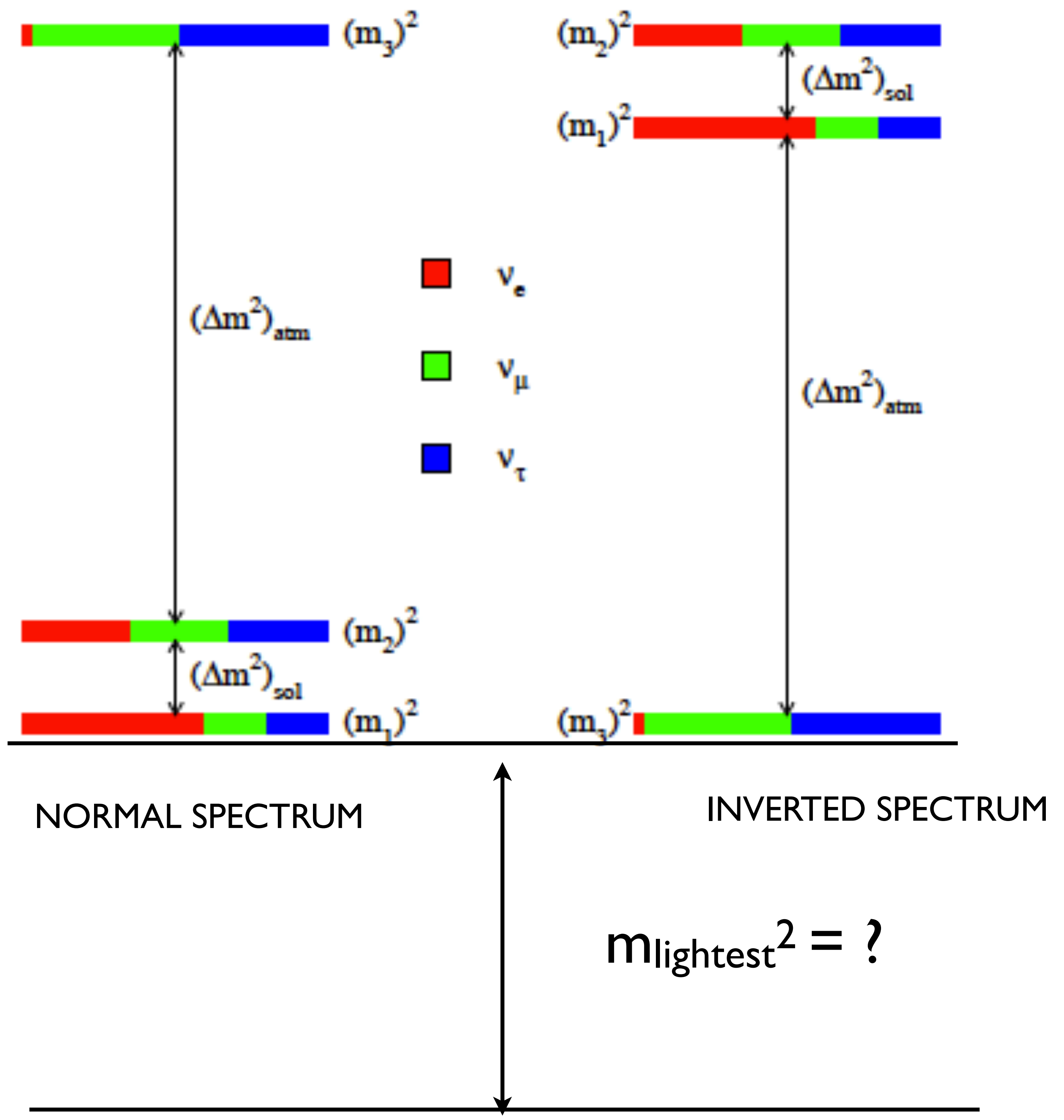
Overall, uncertainties still sizable. Progress requires theoretical activity at the interface of EFT, lattice QCD, and nuclear structure

Discovery potential / target

- Within the high-scale seesaw, $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$





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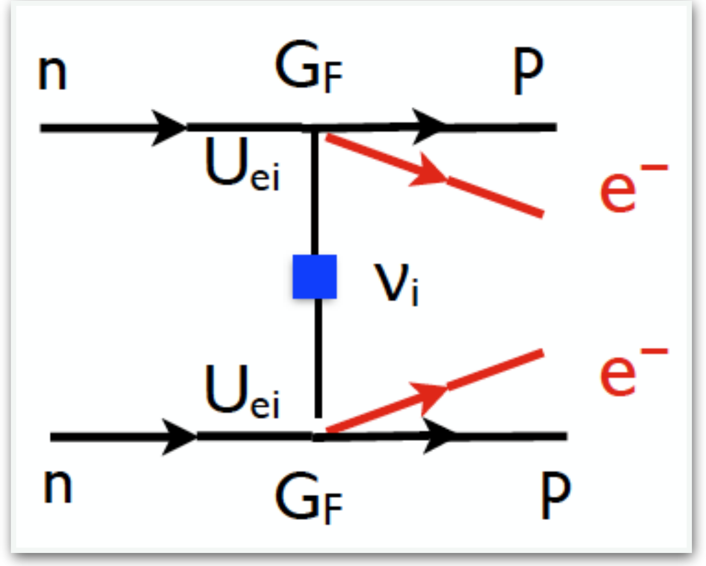
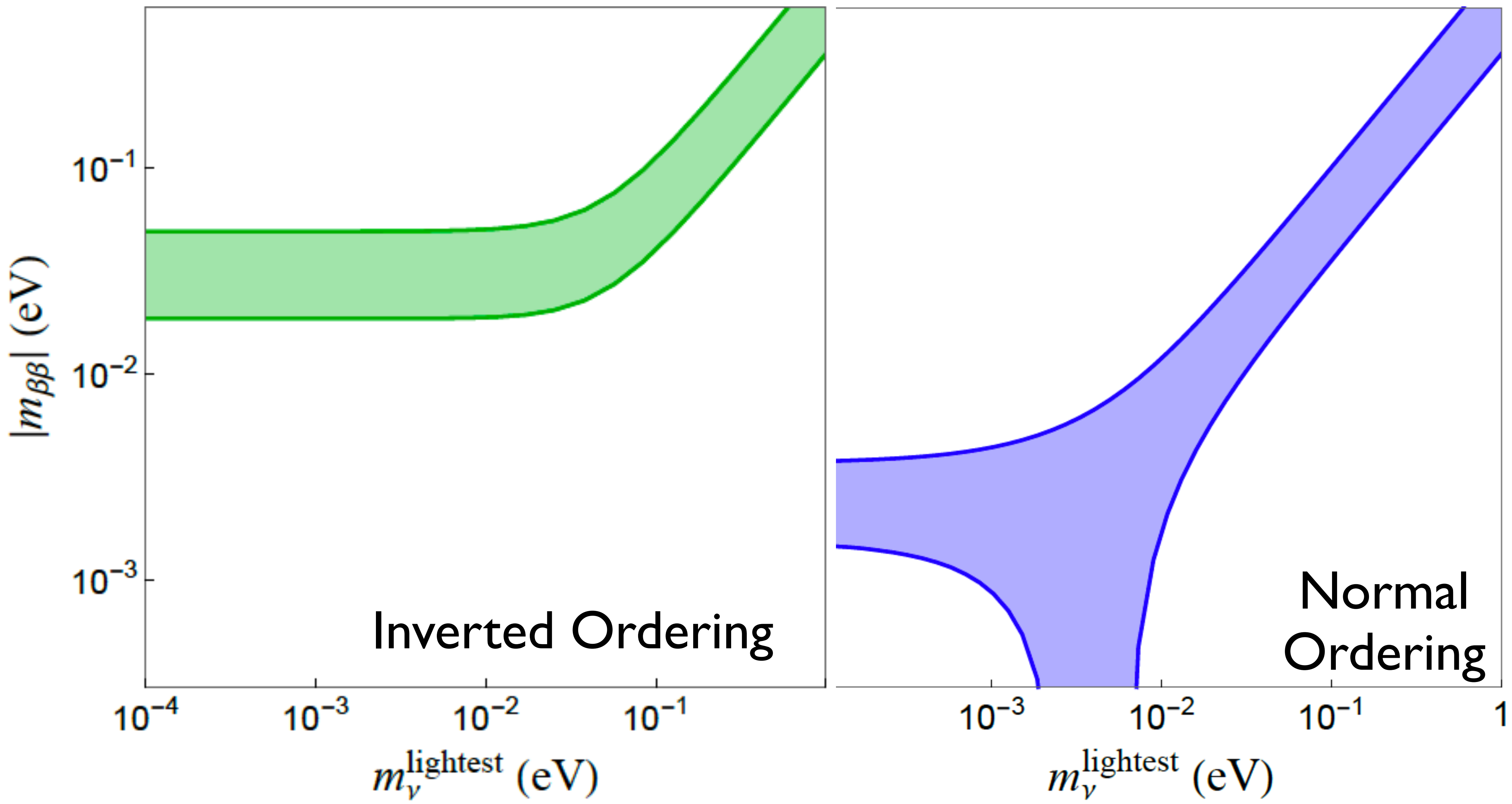


Bands: unknown Majorana phases



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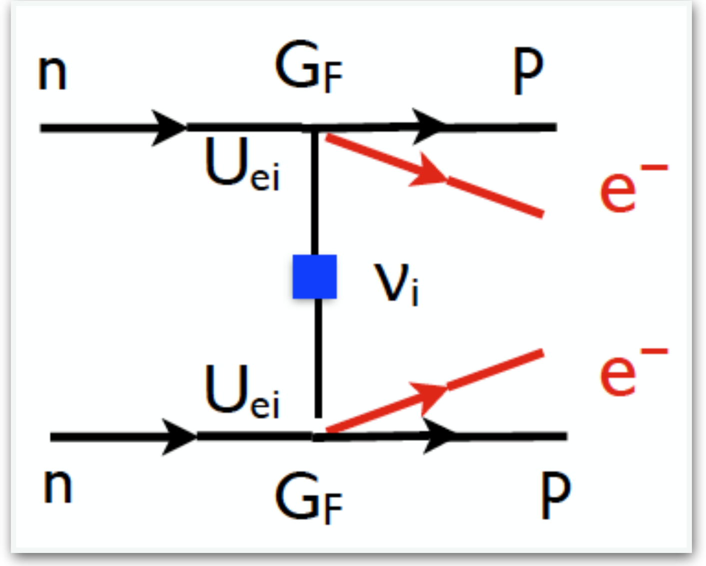

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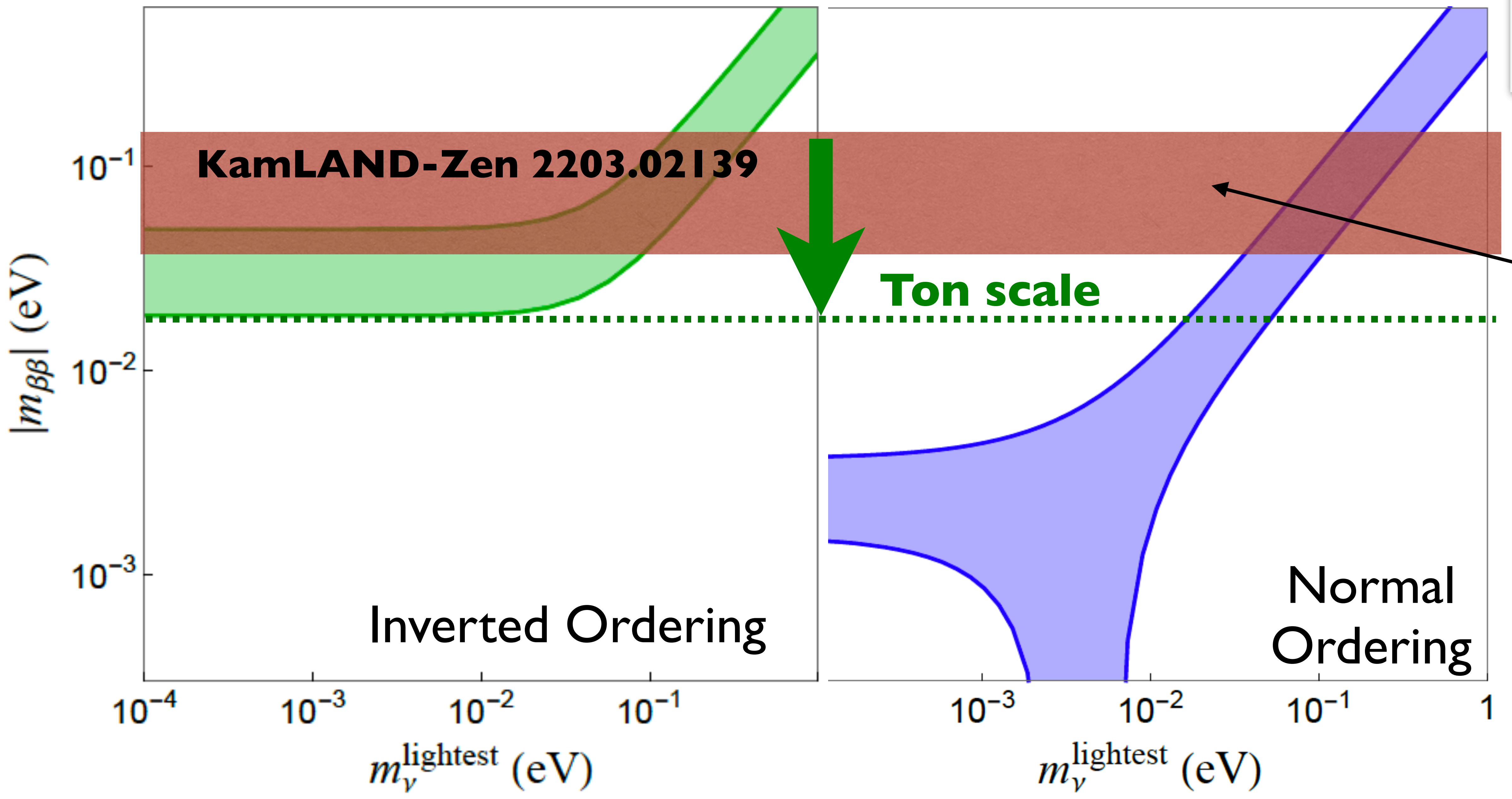

Assume range for nuclear matrix elements from different nuclear calculations

Assuming current range for matrix elements, discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

Discovery potential / target

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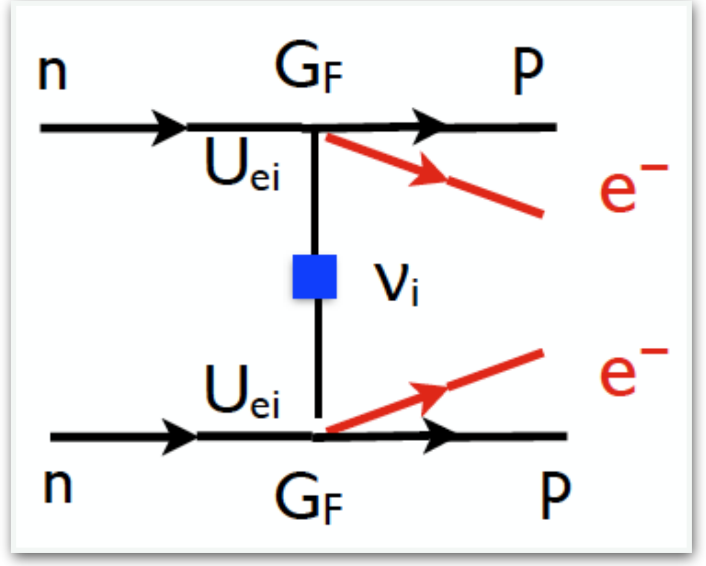

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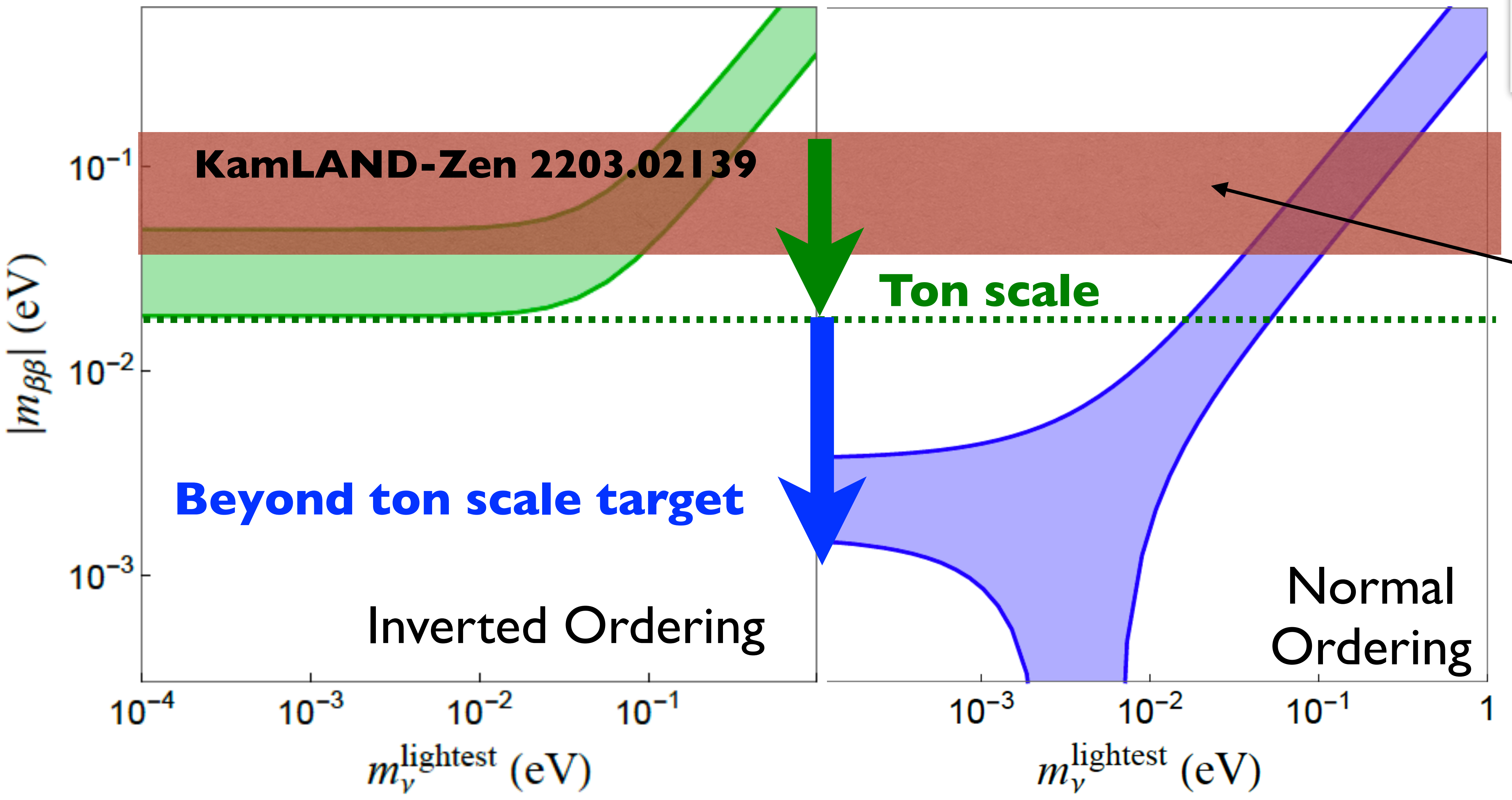


Assume range for nuclear matrix elements from different nuclear calculations

Natural (but challenging!) beyond ton-scale target is $m_{\beta\beta} \sim$ meV

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes
- Future data coupled with improved theory can challenge the 3-neutrino paradigm, unravel new LNV sources or physics beyond "ΛCDM + m_ν"

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

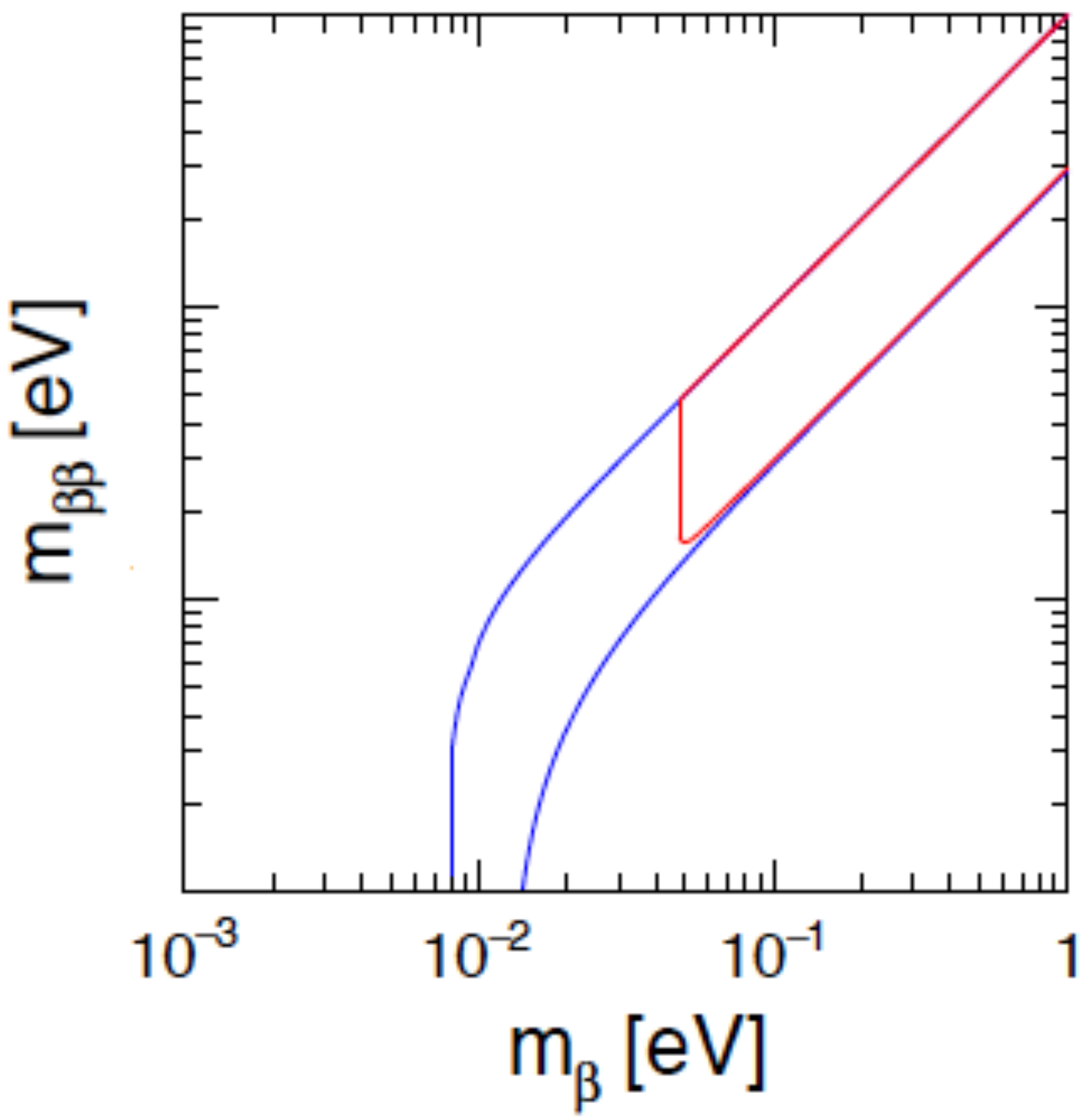
0νββ decay

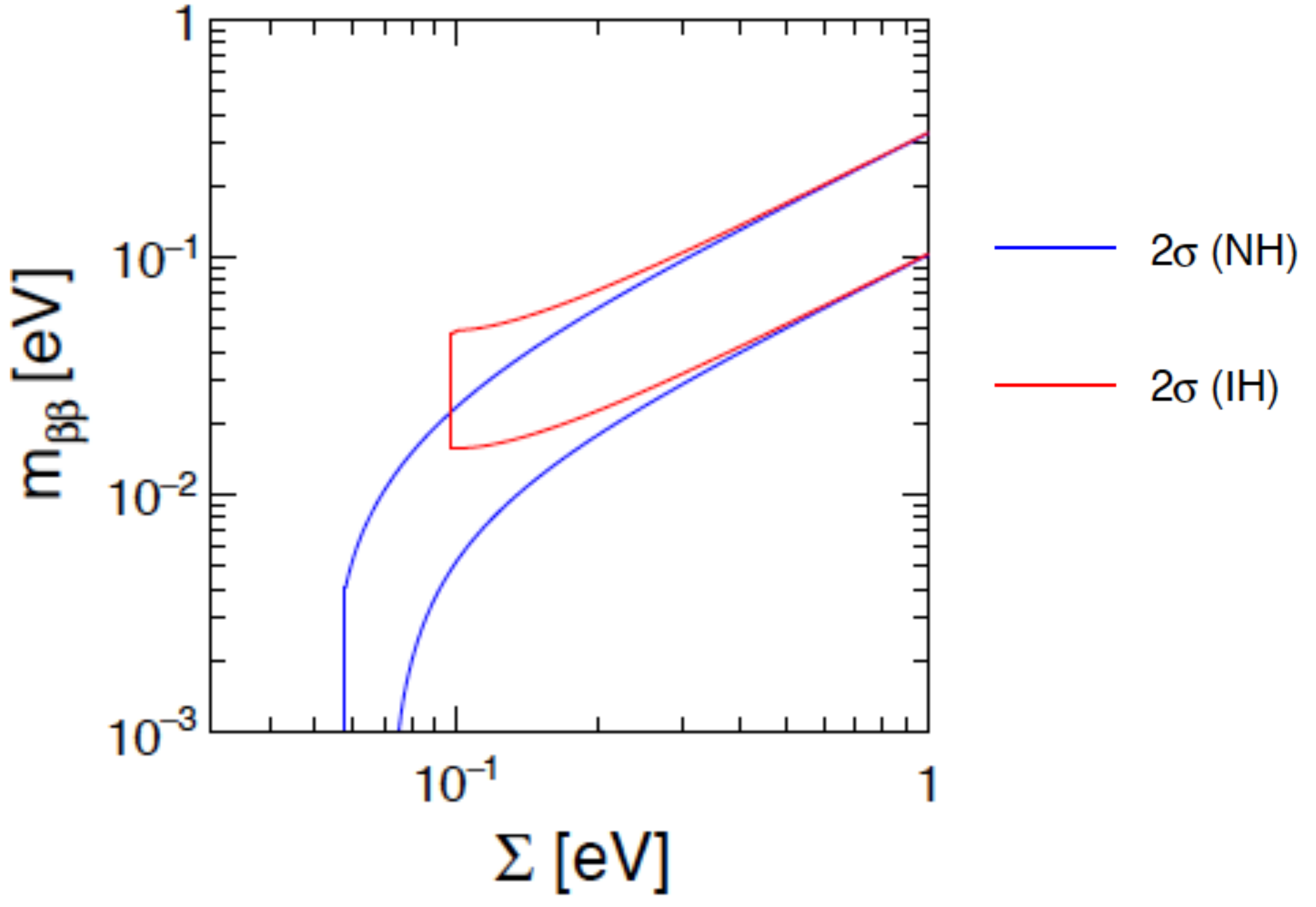
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





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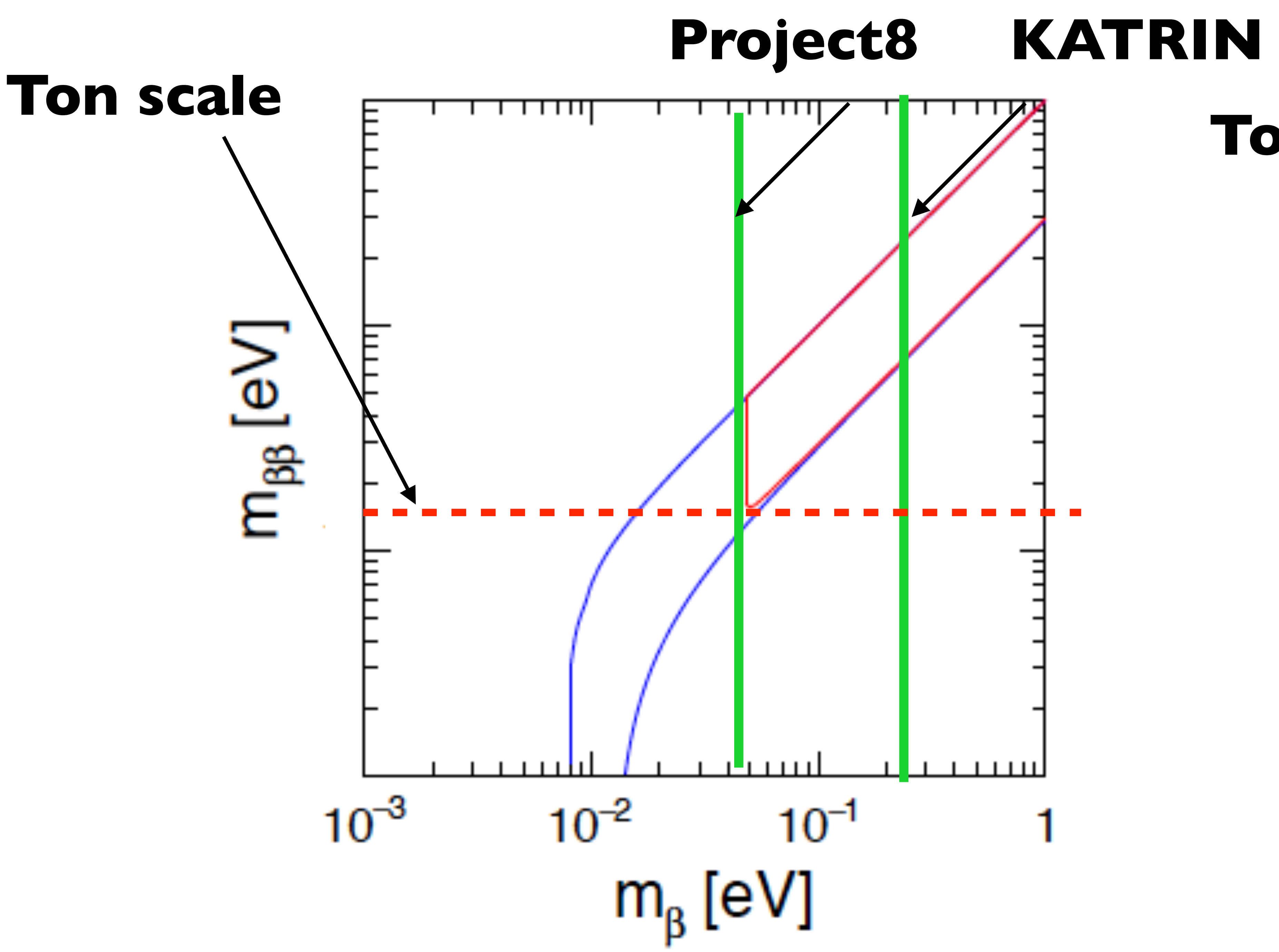
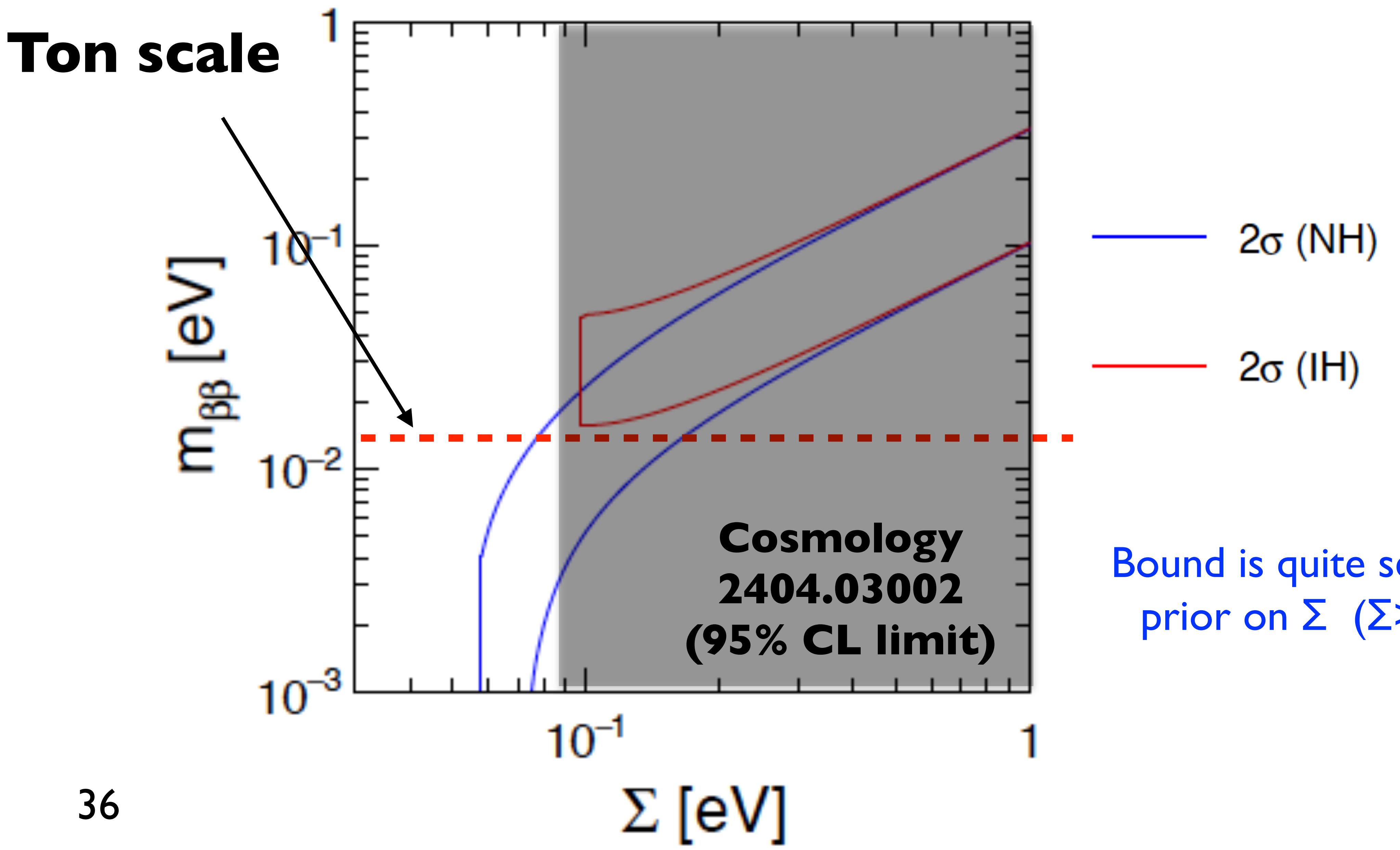
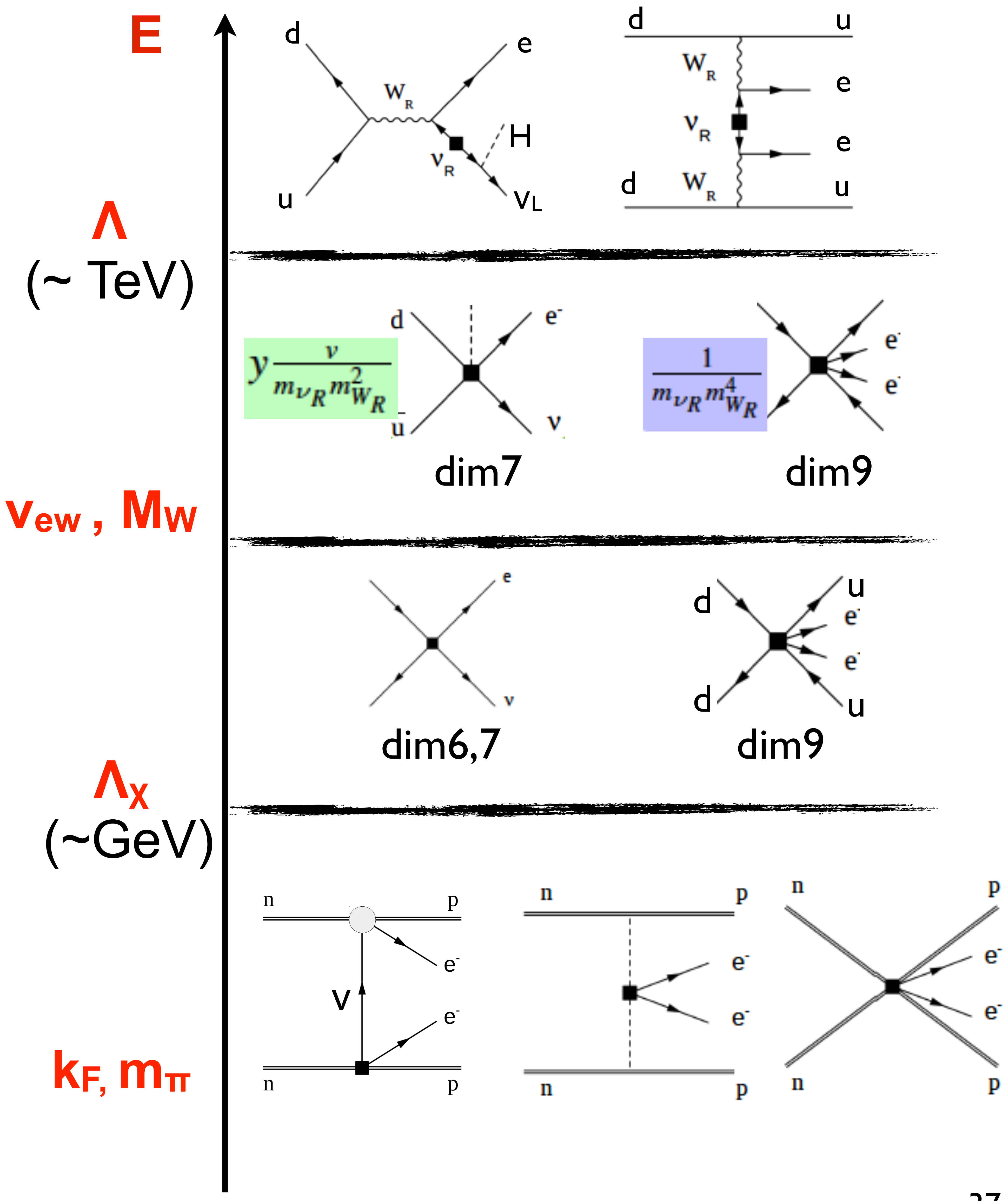




Bound is quite sensitive to prior on Σ (Σ>0 used)

~TeV-scale LNV



- Higher dim operators arise in well motivated models. Can compete with Dim=5 operator if $\Lambda \sim O(1\text{-}10\ \text{TeV})$

- 31 operators up to dimension 9

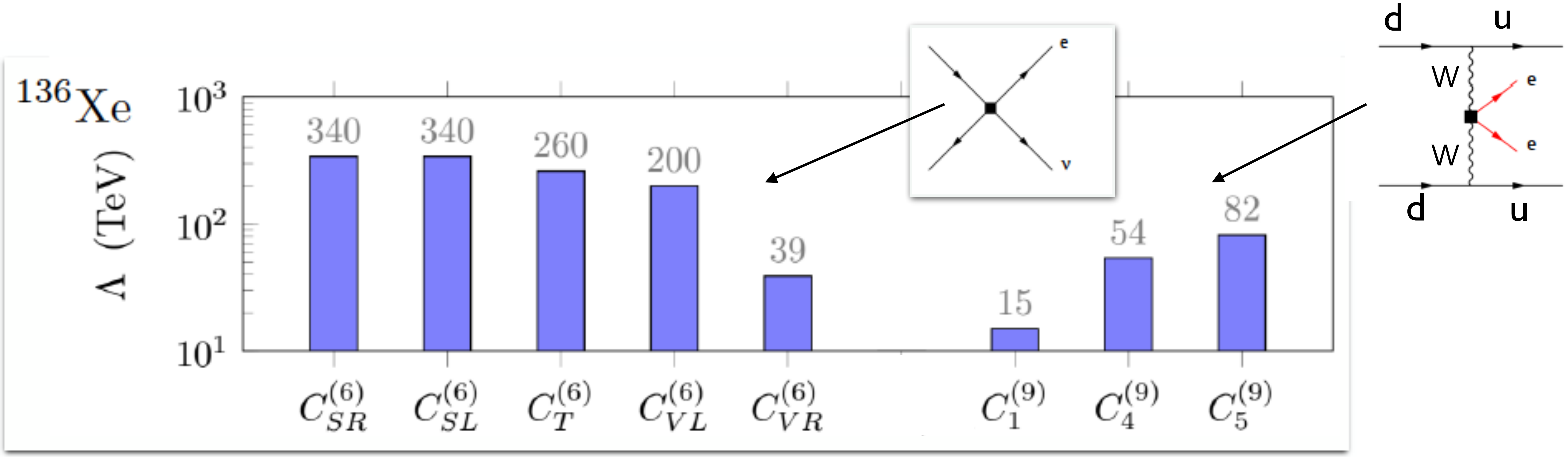
- New mechanisms at the hadronic scale: need appropriate chiral EFT treatment. Not including pion-range effects leads to factor $\sim (Q/\Lambda_\chi)^2 \sim 1/100$ reduction in sensitivity to short-distance couplings!

What scales are we probing?

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

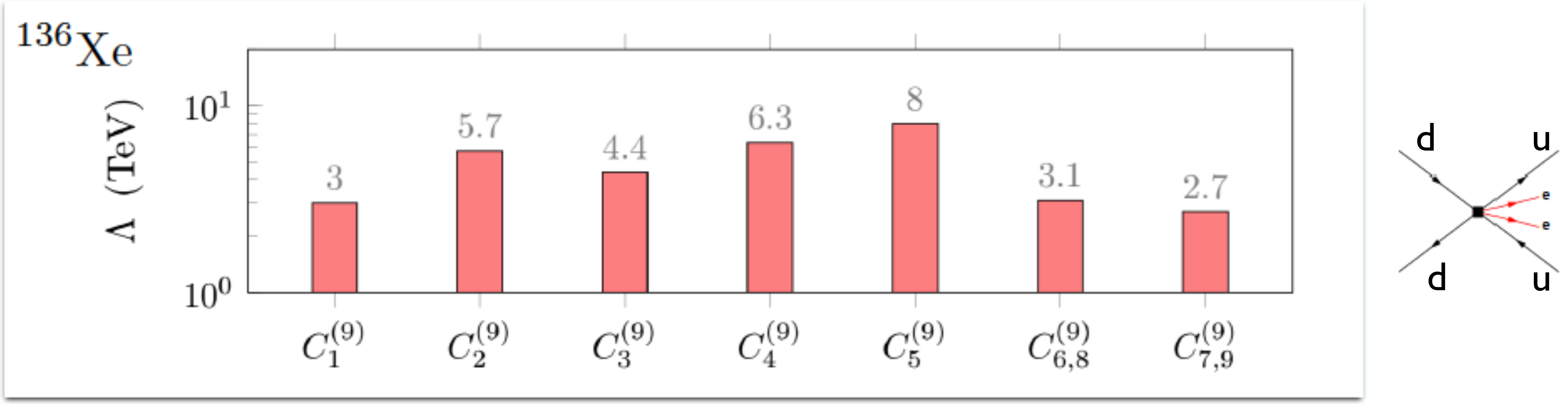
Dim 7 in SM-EFT

$(v/\Lambda)^3$



Dim 9 in SM-EFT

$(v/\Lambda)^5$

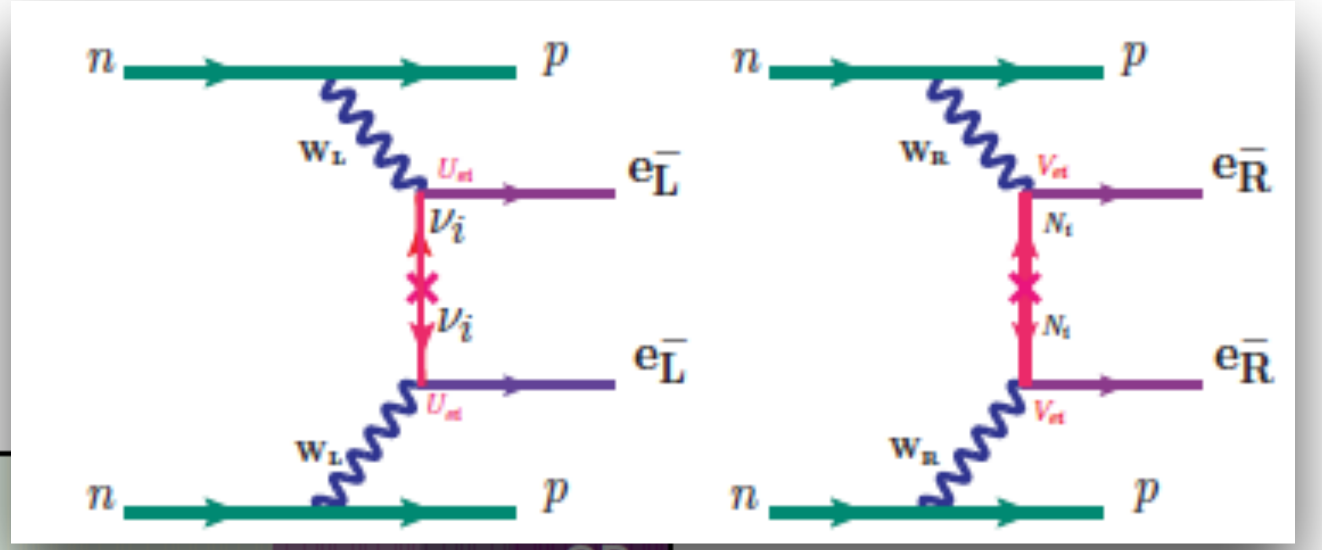


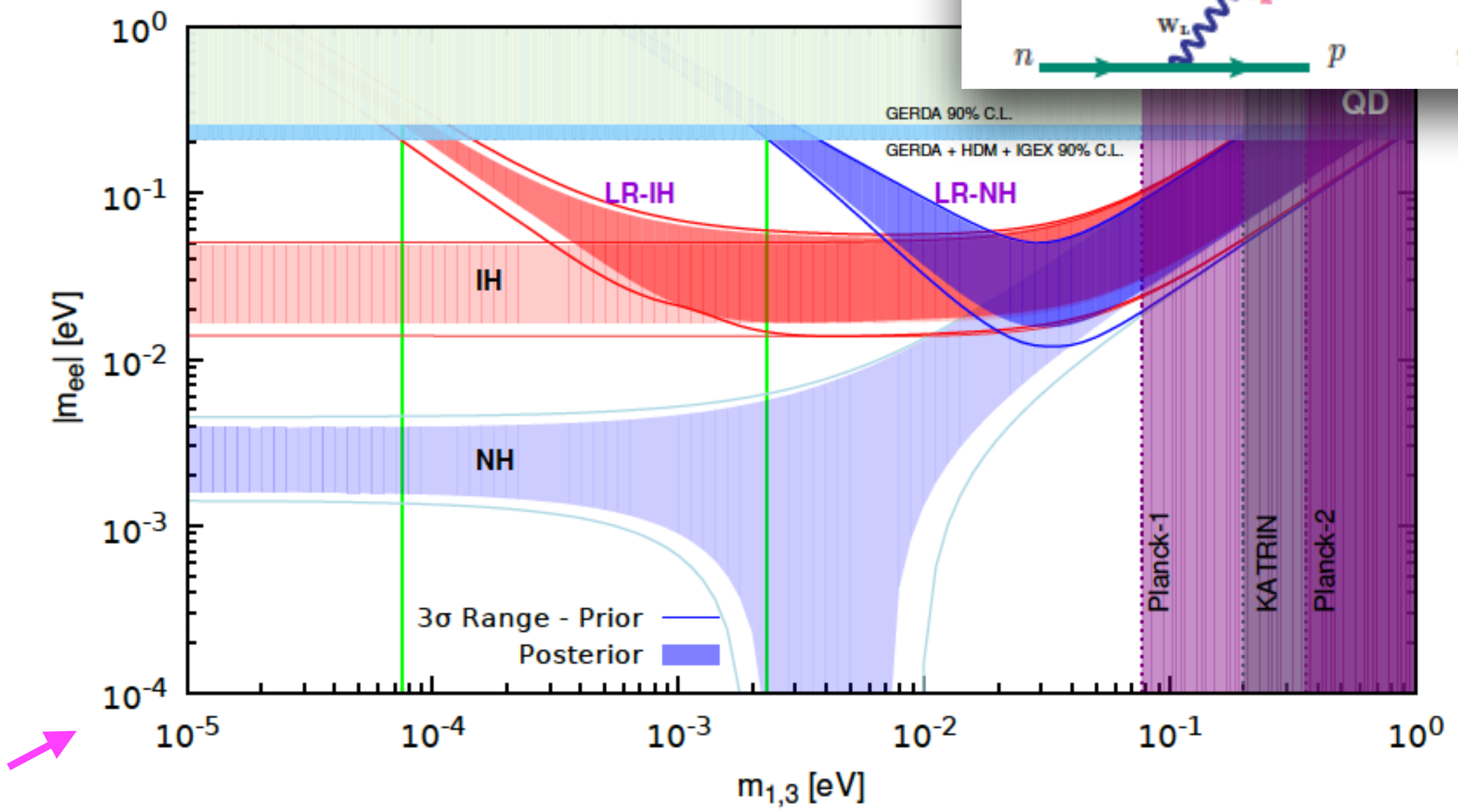
Bounds reflect dependence on Λ_χ / Λ and Q/Λ_χ

Phenomenological interest (1)

- TeV-scale LNV induces *contributions to 0νββ not directly related to the exchange of light neutrinos*, within reach of planned experiments

Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_i}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_i}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522

Ge-Lindner-Patra 1508.07286

...

Phenomenological interest (2)

- May lead to correlated (or precursor!) signal at LHC: pp →ee jj

Keung-Senjanovic ’83

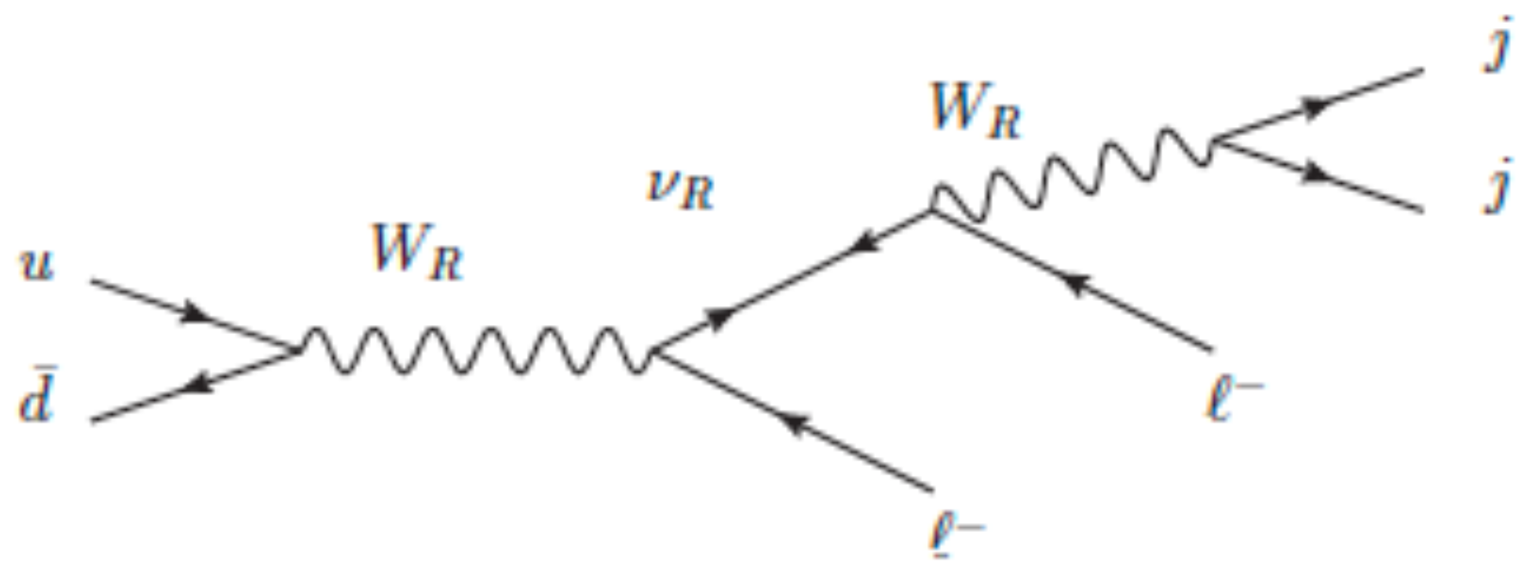
Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

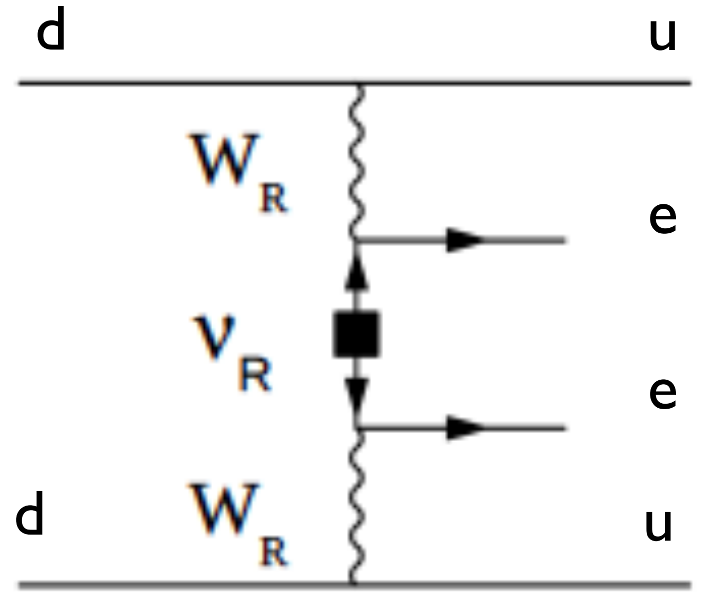
Cai, Han, Li, Ruiz 1711.02180

…

Classic LRSM example



LHC



0νββ

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- May lead to correlated (or precursor!) signal at LHC: pp →ee jj

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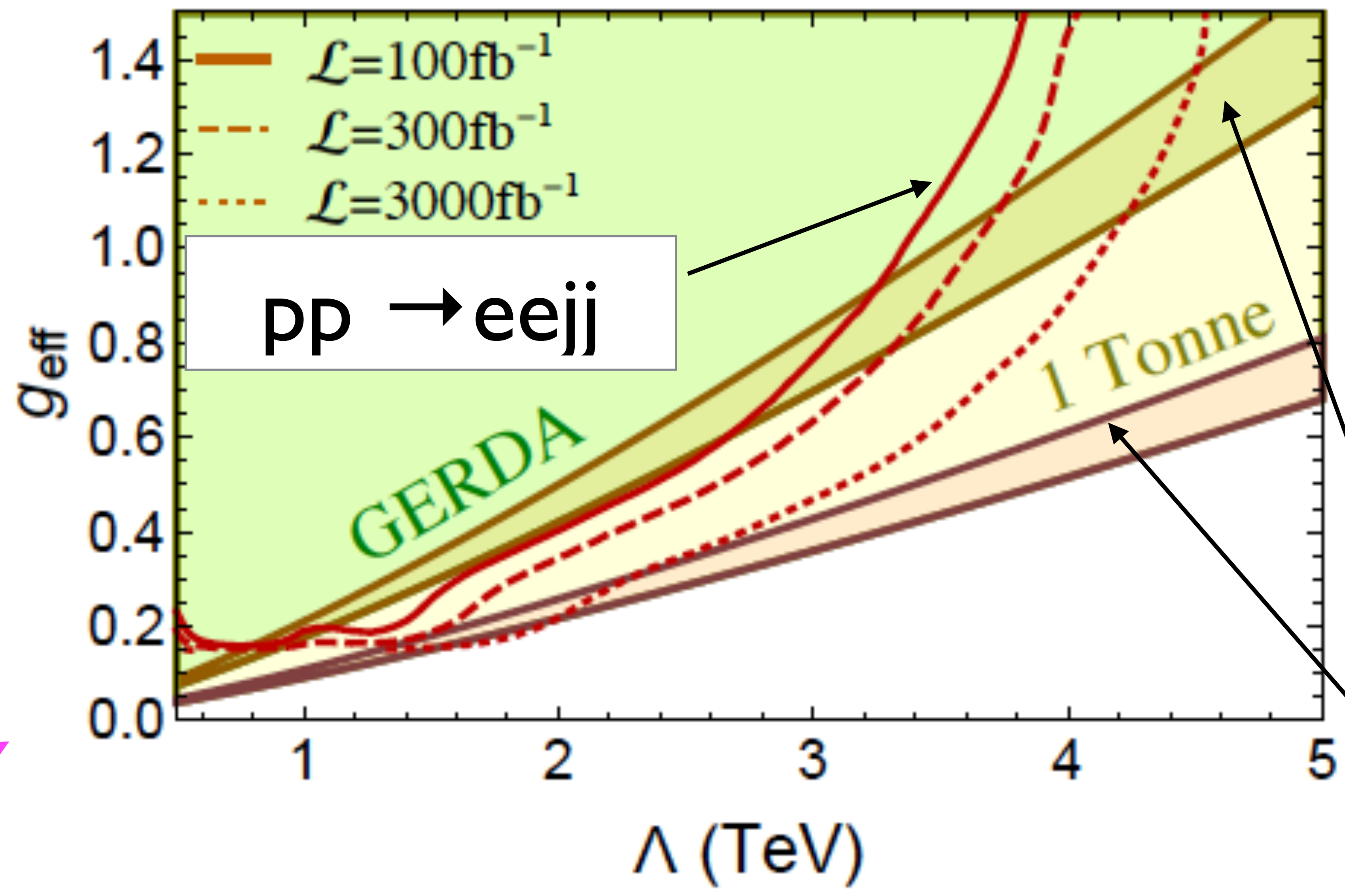
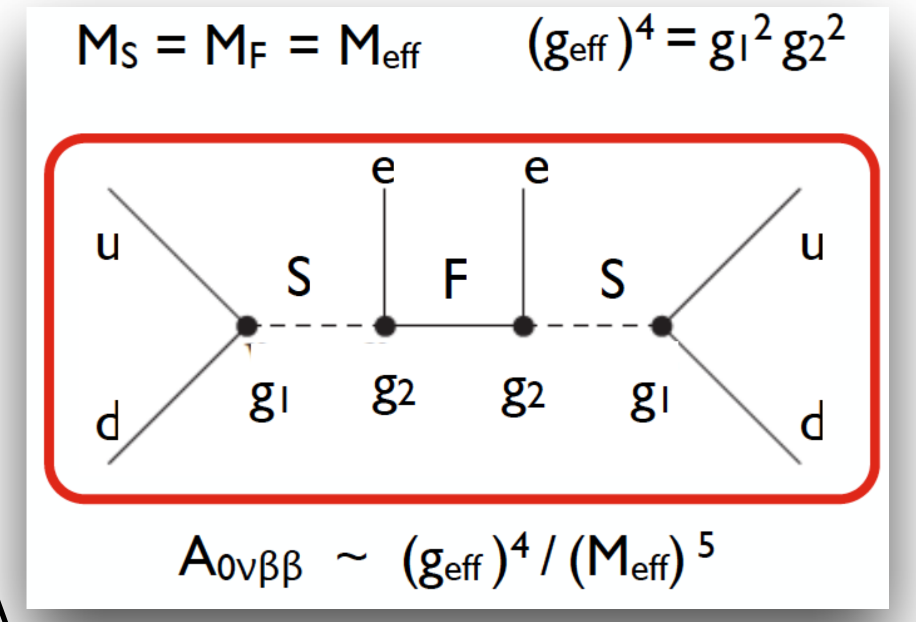
...



Simplified model



Hadronic / nuclear uncertainty

- LHC searches important to unravel origin of LNV and implications for letpogenesis

Deppisch-Harz-Hirsch 1312.4447, Deppisch-Graf-Harz-Huang 1711.10432, Harz, Ramsey-Musolf, et al 2106.10838 , ...

Outlook on 0νββ and LNV

- Ton-scale 0νββ searches have significant discovery potential — we simply don't know the origin of m_ν and the scale Λ associated with LNV

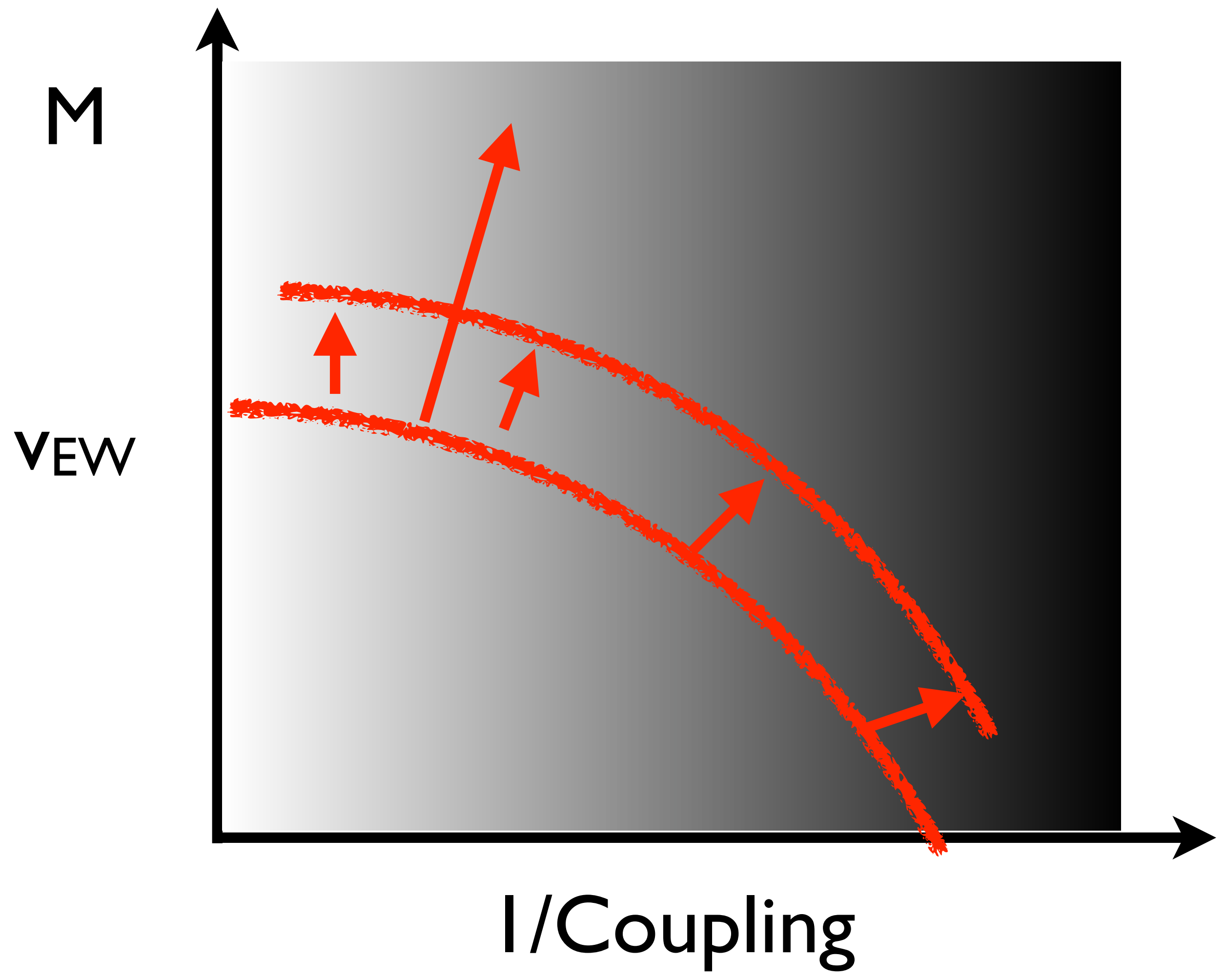
- EFT approach provides a general framework to:

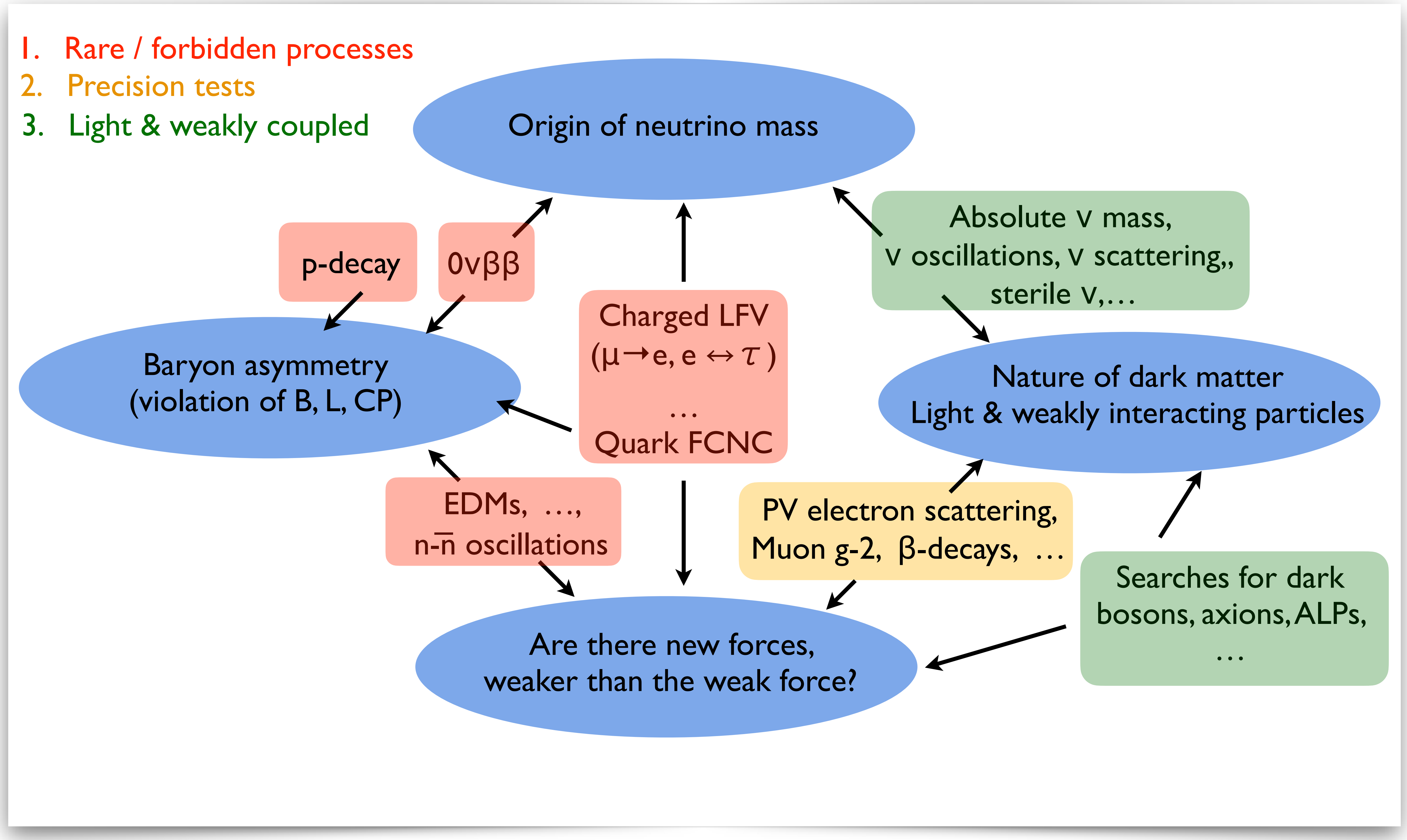
1. Relate 0νββ to underlying LNV dynamics (and collider & cosmology)
2. Organize contributions to hadronic and nuclear matrix elements

Improving the theory uncertainty is challenging, but there are good prospects thanks to advances in EFT, lattice QCD, and nuclear structure

Concluding comments

- Experiments at the low-energy Precision / Intensity Frontier are exploring uncharted territory in the search for new physics, in a complementary way to other frontiers





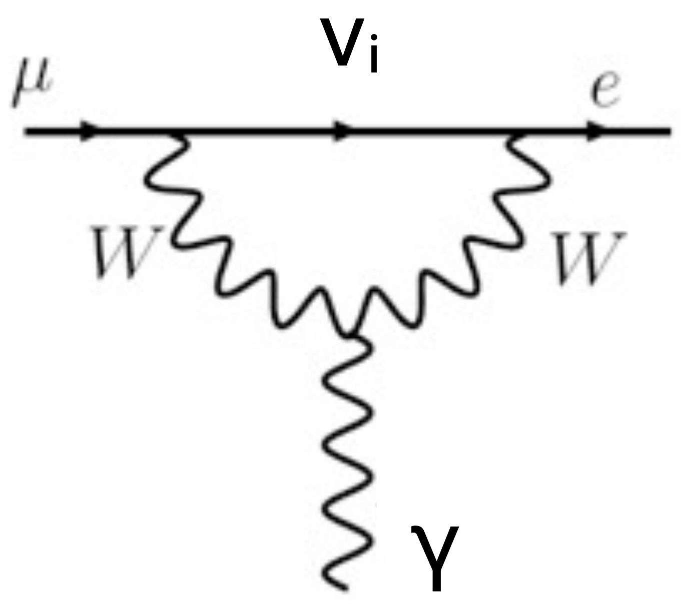
- The low-energy frontier probes BSM physics related to the 'big questions'

- Theoretical challenges addressed by a combination of EFT, lattice QCD and other non-perturbative methods

Probing
Lepton Flavor Violation
with charged leptons

LFV and new physics (1)

- ν oscillations ⇒ $L_{e,\mu,\tau}$ not conserved
- In SM + massive ν, Charged-LFV decays suppressed to unobservable level



$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}}$$

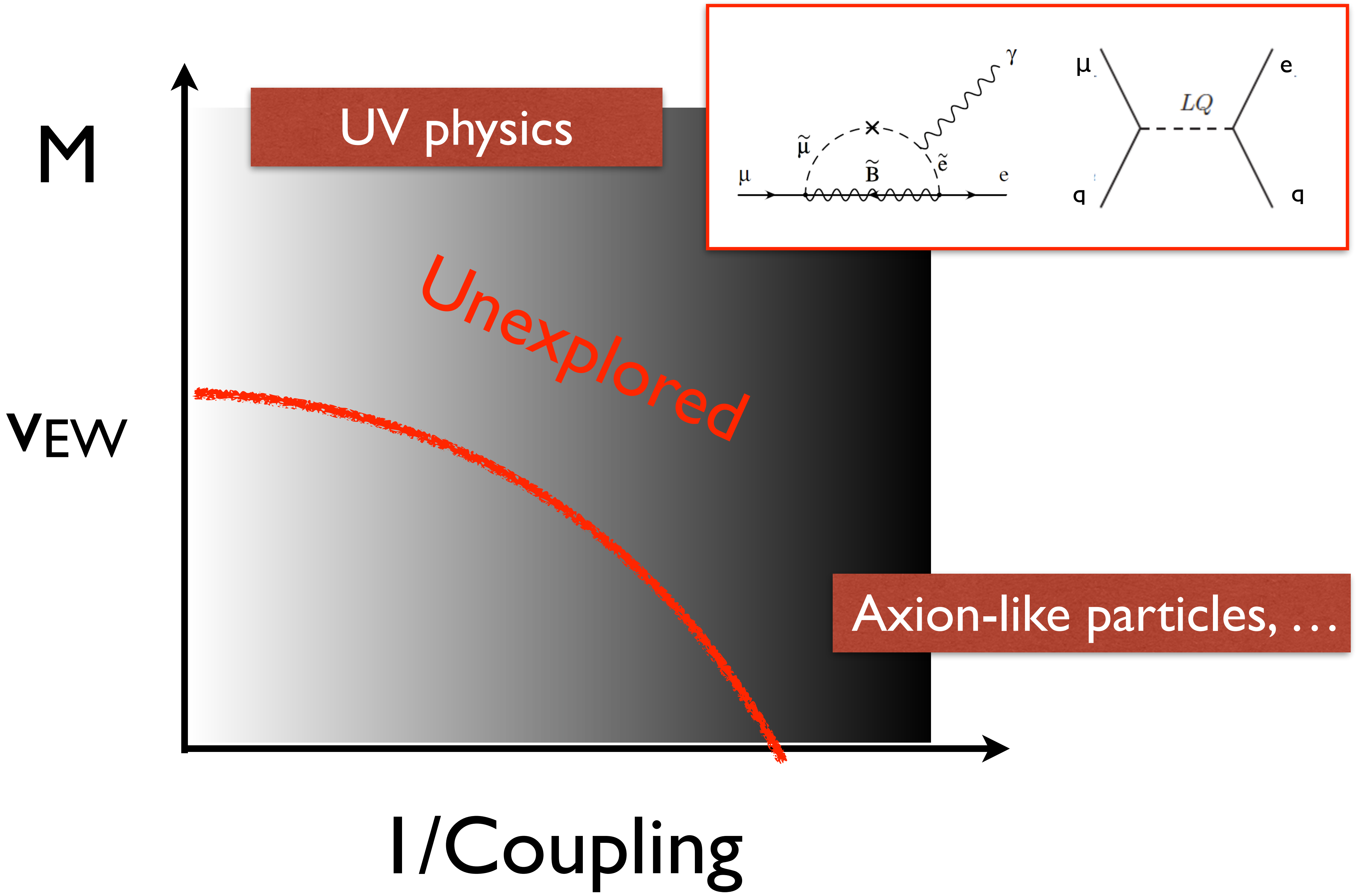
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77, Shrock '77…

- Observation of CLFV processes would unambiguously indicate BSM physics, related to the origin of leptonic 'flavor' & possibly neutrino mass

LFV and new physics (2)

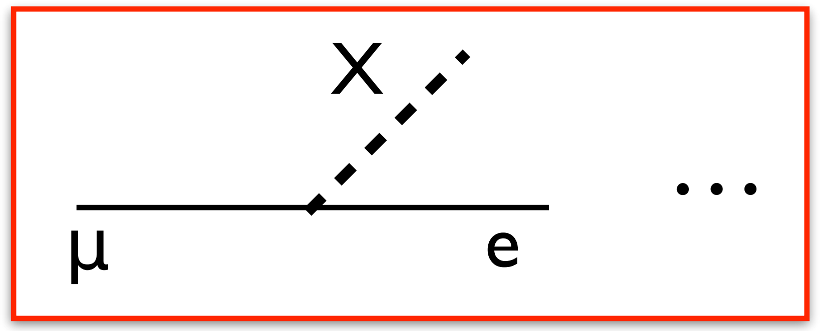
- Sensitivity to broad spectrum of new physics: both heavy and light + weakly coupled



→

$$\mathcal{L}_{\rm SMEFT} \supset \sum_n \frac{C_n}{\Lambda^2} O_n^{\rm LFV} + \ldots$$

$\Lambda/\sqrt{C}$ up to ~ $10^{4\text{-}5}$ TeV



$$\mathcal{L}_{\rm portals} \supset \frac{1}{F^{\Gamma}_{\alpha\beta}} \partial_\mu a \, \bar{\ell}_\alpha \Gamma^\mu \ell_\beta + \ldots$$

$F_{\alpha\beta}$ up to ~ $10^{6\text{-}7}$ TeV

LFV probes across energy scales

- Decays of μ, τ (and mesons)

(K →πμe; B → Kμτ, Kμe; B_s → μτ, μe, quarkonia , … not discussed in detail here)

$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z) \qquad M_\mu - \overline{M}_\mu \qquad \mu \to ea$$

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell\, Y \qquad Y = P, S, V, P\bar{P}, \ldots$$

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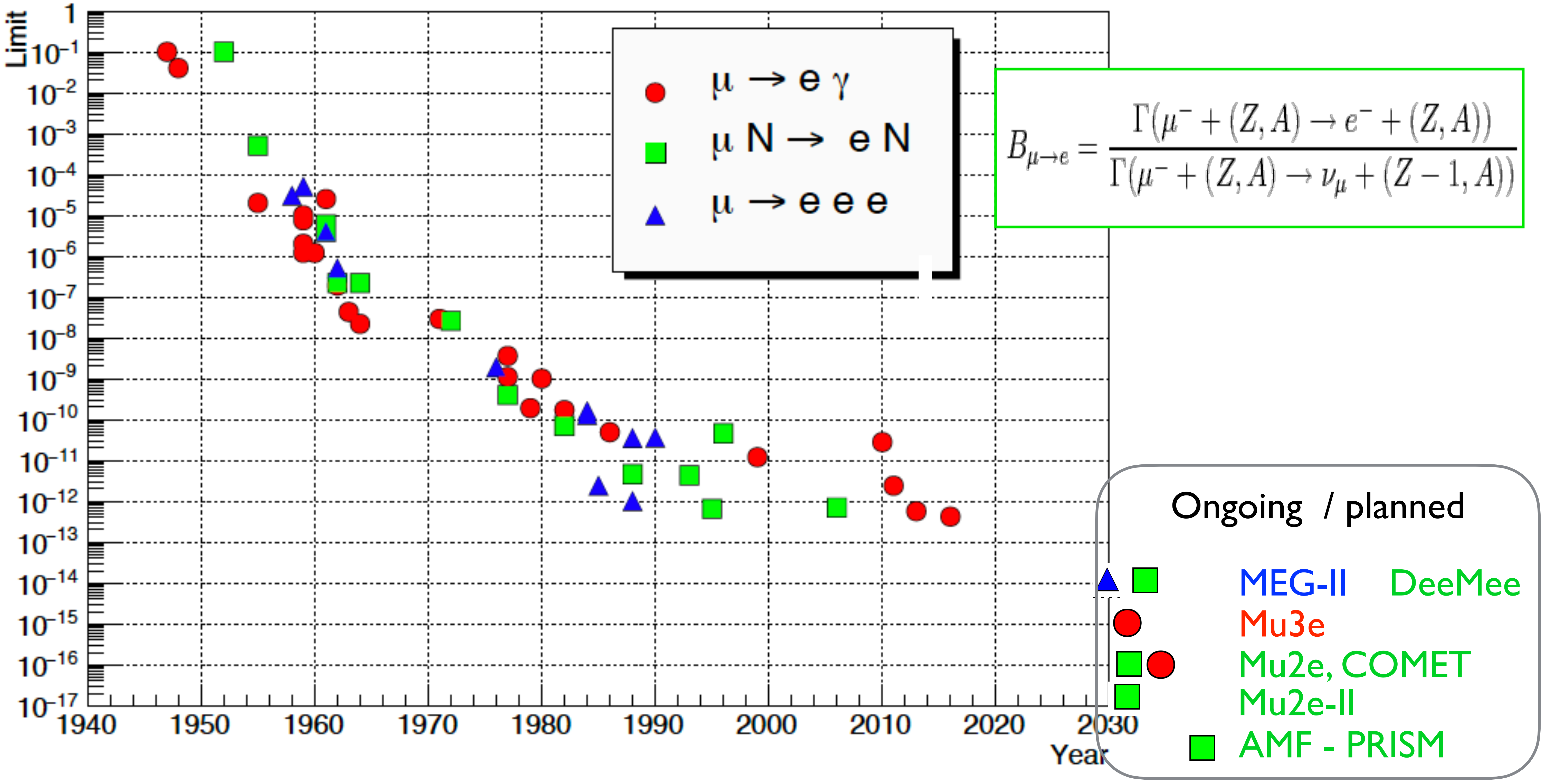
Modified from Calibbi-Signorelli 1709.00294



$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

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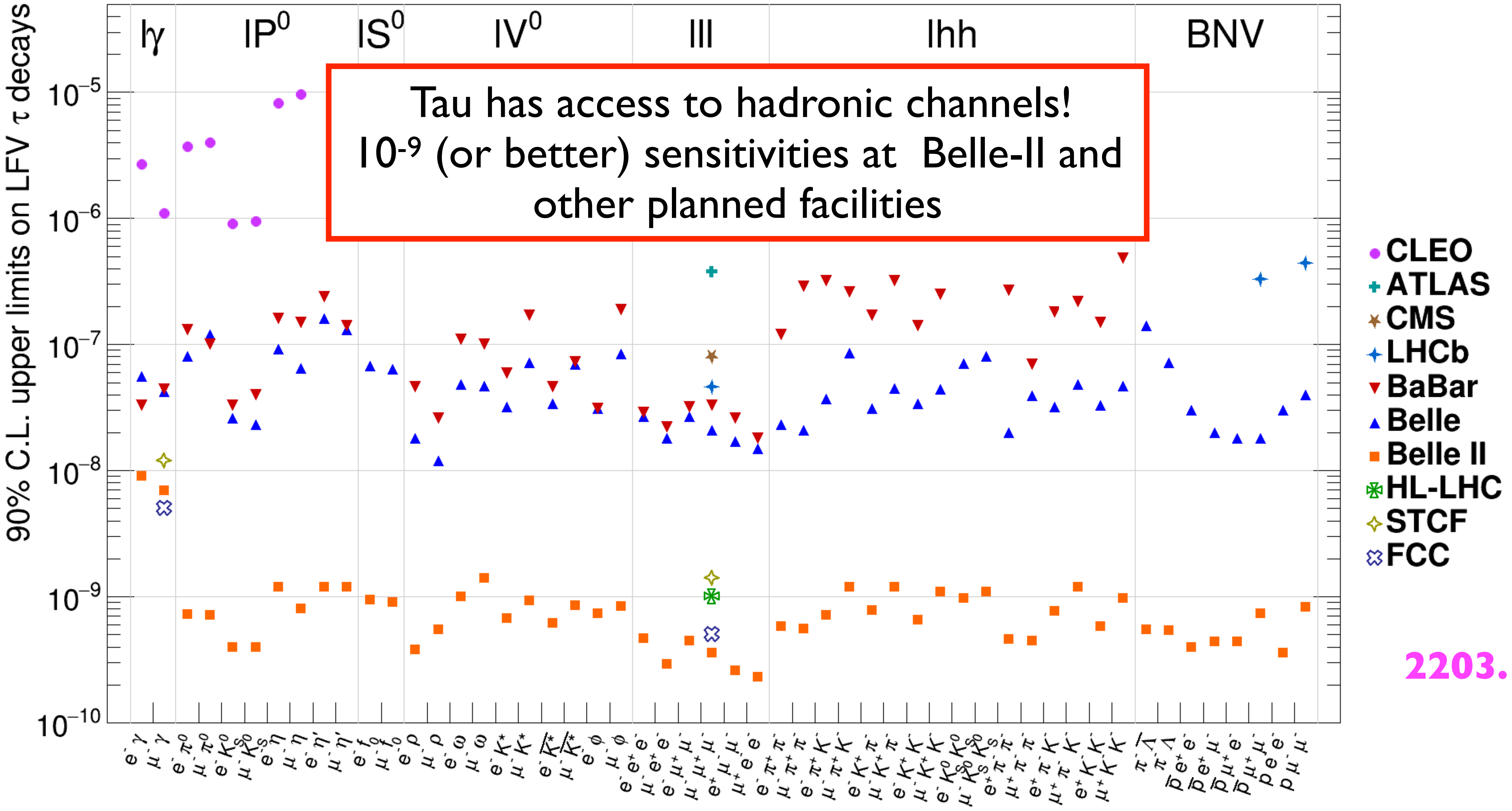

Tau has access to hadronic channels!
10^{-9} (or better) sensitivities at Belle-II and other planned facilities

2203.14919

LFV probes across energy scales

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- Collider processes:

LHC

$$pp \to R \to \ell_\alpha \bar{\ell}_\beta + X \qquad R = Z, h, \tilde{\nu}, \ldots.$$

$$pp \to \ell_\alpha \bar{\ell}_\beta + X$$

HERA, EIC

$$ep \to \ell + X$$

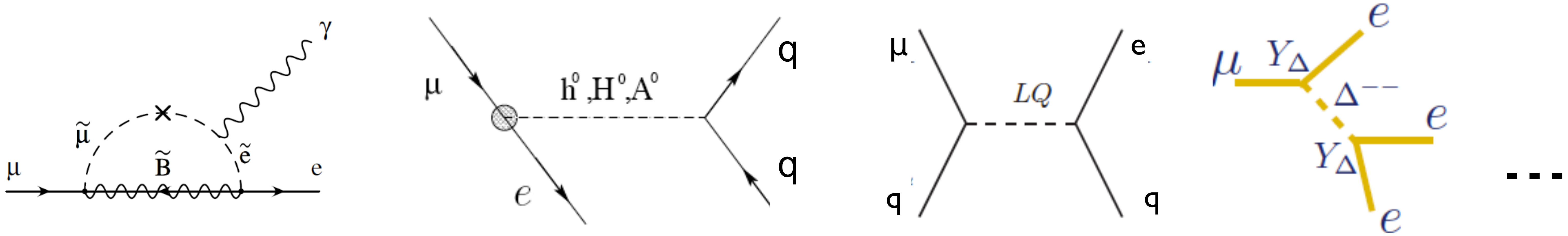
Connecting scales with EFT

M

Λ

v_{ew}

Λ_{QCD}



Dipole: SUSY-GUT and SUSY see-saw scenarios, …

Scalar: RPV SUSY and RPC SUSY for large tan(β) and low m_A, leptoquarks, …

Vector Type III seesaw, LRSM, leptoquarks, …

4-lepton: Type II seesaw, RPV SUSY, LRSM, …

$$\mathcal{L}_{d=6} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta F^{\mu\nu} + \sum_\Gamma \frac{C_\Gamma^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \, \bar{q} \Gamma q + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \, \bar{\ell} \tilde{\Gamma} \ell$$

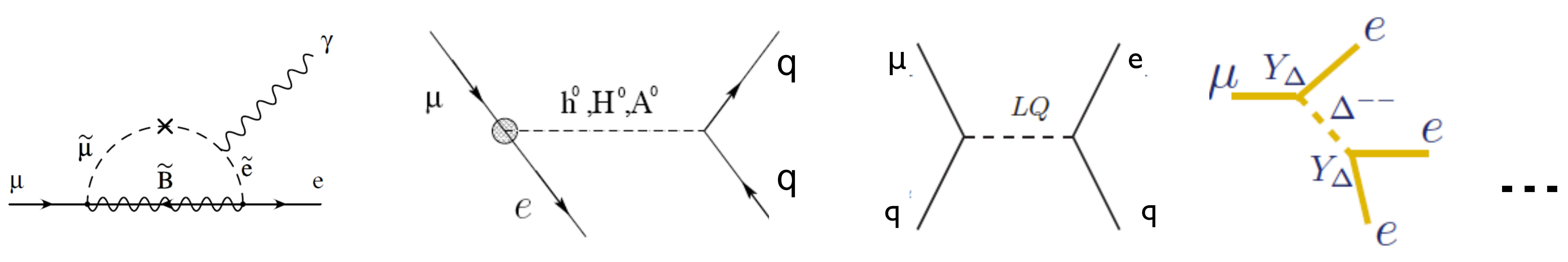
Connecting scales with EFT

M

Λ

v_{ew}

Λ_{QCD}



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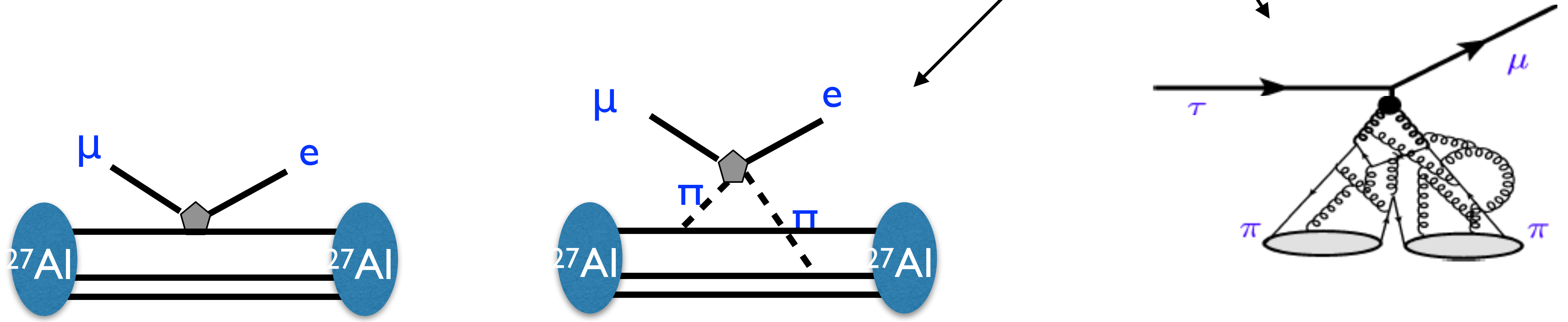


CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{vC_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\sigma_{\mu\nu}\ell^\beta + \sum_{\tilde{\Gamma}}\frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\tilde{\Gamma}\ell^\beta\bar{\ell}\tilde{\Gamma}\ell + \sum_{\Gamma}\frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\Gamma\ell^\beta\bar{q}\Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}}\,\partial_\mu a\,\bar{\ell}^\alpha\Gamma^\mu\ell^\beta$$

Each model generates a specific pattern of operators

→ multiple CLFV measurements needed to extract the underlying physics

CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{vC_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\sigma_{\mu\nu}\ell^\beta + \sum_{\tilde{\Gamma}}\frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\tilde{\Gamma}\ell^\beta\bar{\ell}\tilde{\Gamma}\ell + \sum_{\Gamma}\frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha\Gamma\ell^\beta\bar{q}\Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}}\partial_\mu a\,\bar{\ell}^\alpha\Gamma^\mu\ell^\beta$$

Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

- New physics mass scale through any process

$$BR_{\alpha\to\beta} \sim (v_{ew}/\Lambda)^4 * |(C_n)^{\alpha\beta}|^2$$

μ-e sector:	$\Lambda/\sqrt{C} \sim 10^{4\text{-}5}$ TeV	(Muon decays)
τ-μ(e) sector:	$\Lambda/\sqrt{C} \sim 10^{2}$ TeV	(Tau decays)

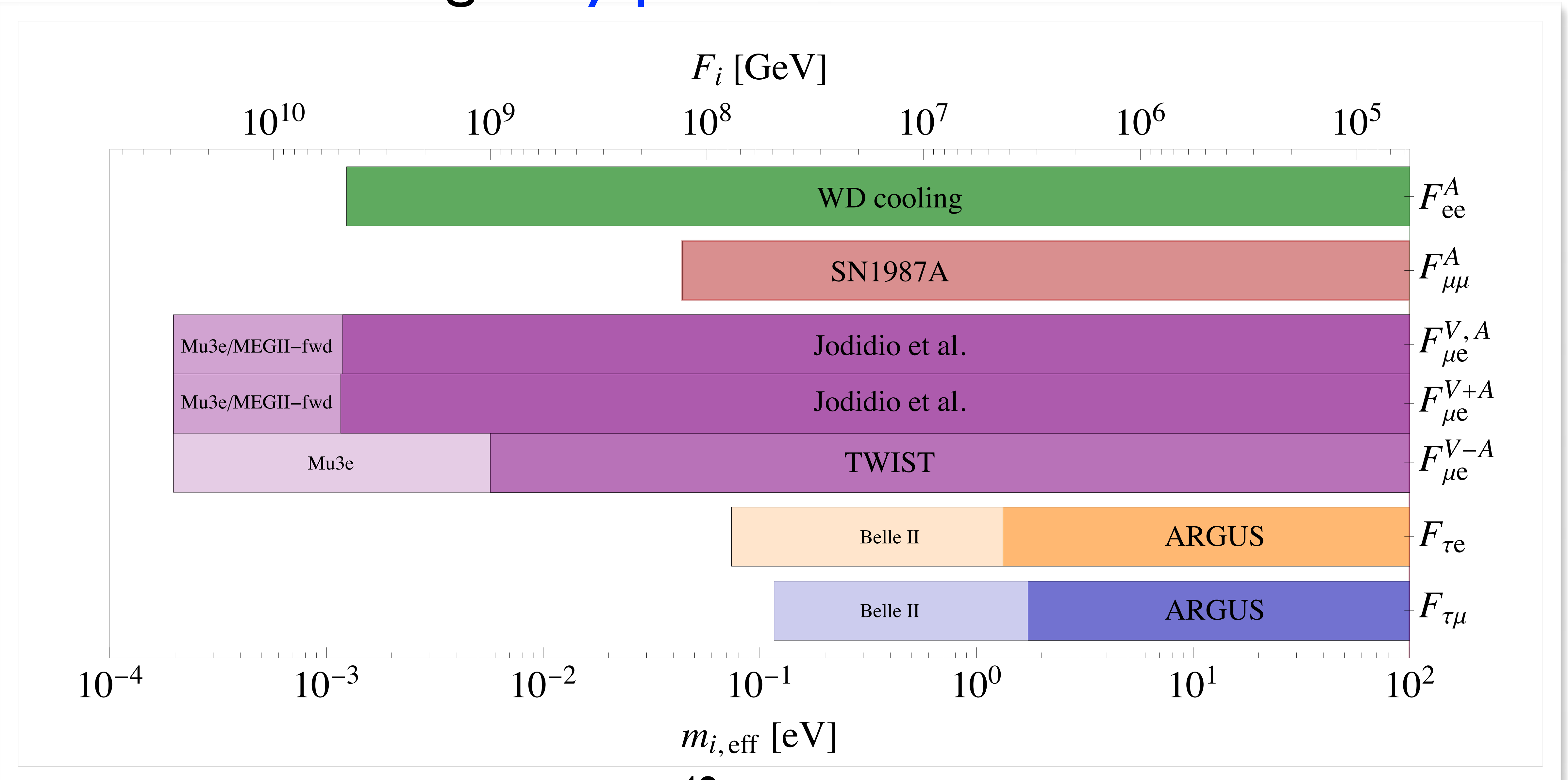
CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \sigma_{\mu\nu}\ell^\beta + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \tilde{\Gamma}\ell^\beta \bar{\ell}\tilde{\Gamma}\ell + \sum_{\Gamma}\frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \Gamma \ell^\beta \bar{q}\Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}}\partial_\mu a\, \bar{\ell}^\alpha \Gamma^\mu \ell^\beta$$

Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

- New physics mass scale through any process

BR($l_\alpha \to l_\beta\, a$) ~ $((v_{ew})^2/(m_\alpha F_{\alpha\beta}))^2$



Calibbi-Redigolo-Ziegler-Zupan
2006.04795

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- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through $\mu \to 3e$ versus $\mu \to e\gamma$ versus $\mu \to e$ conversion ⇒ Mediators, mechanism

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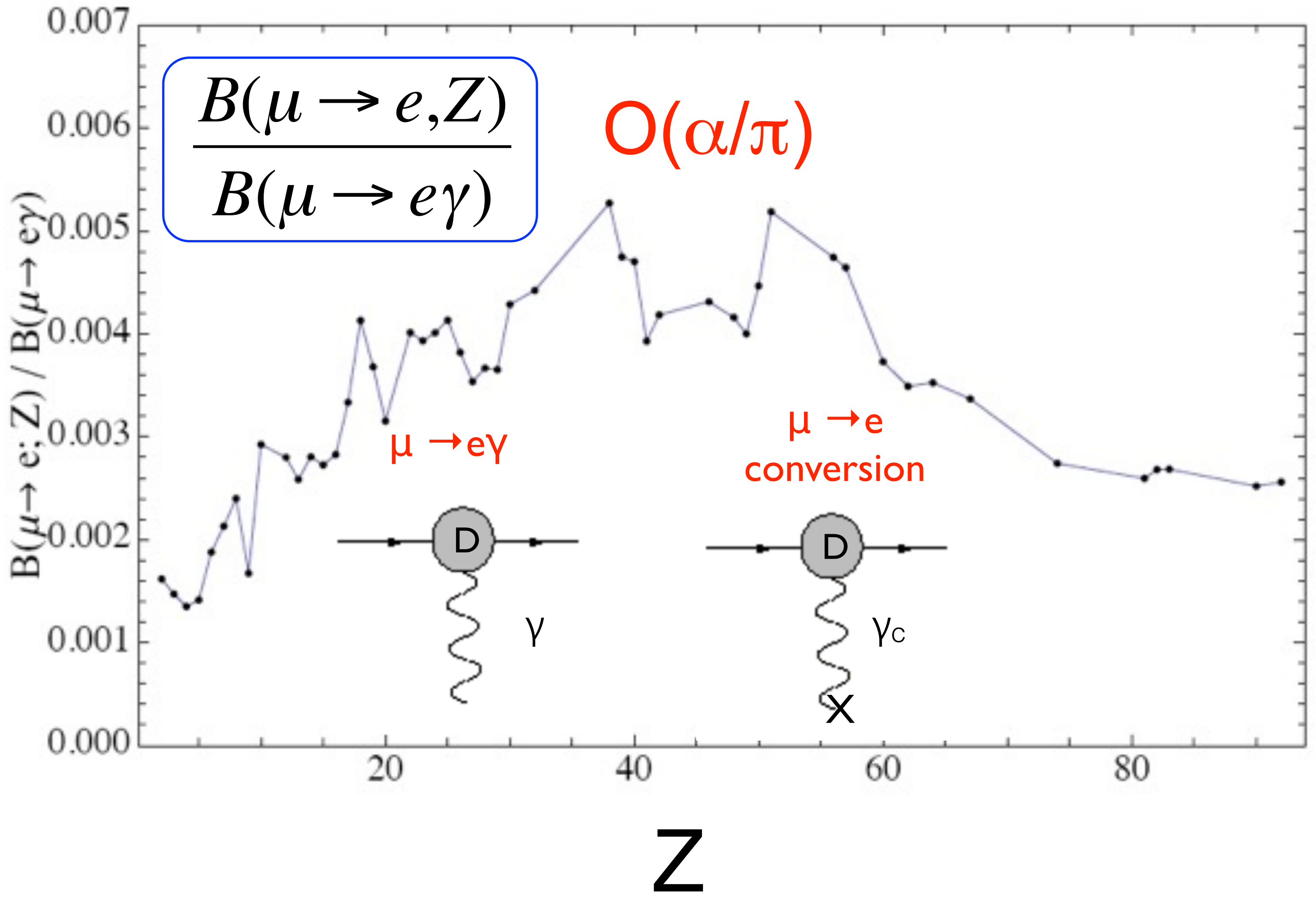
- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through $\mu \to 3e$ versus $\mu \to e\gamma$ versus $\mu \to e$ conversion ⇒ Mediators, mechanism

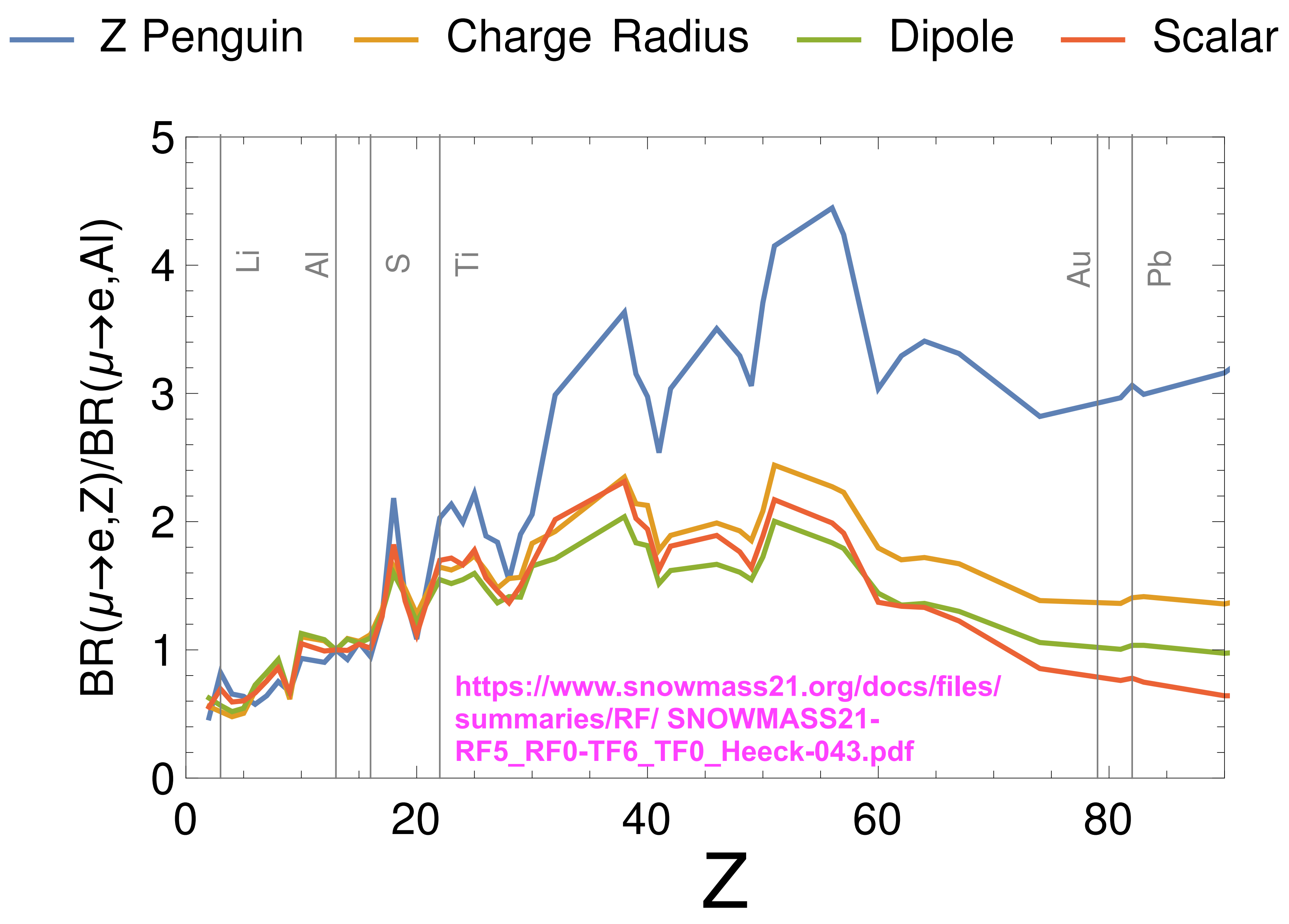
- Flavor structure of couplings ($[C_D]^{e\mu}$ vs $[C_D]^{\tau\mu}$…) through $\mu \to e$ versus $\tau \to \mu$ versus $\tau \to e$ ⇒ Sources of flavor breaking

μ-e sector: diagnosing tools (I)

- Extract info on effective couplings by comparing μ →e to μ →eγ and through target-dependence of μ →e conversion

Dipole dominance





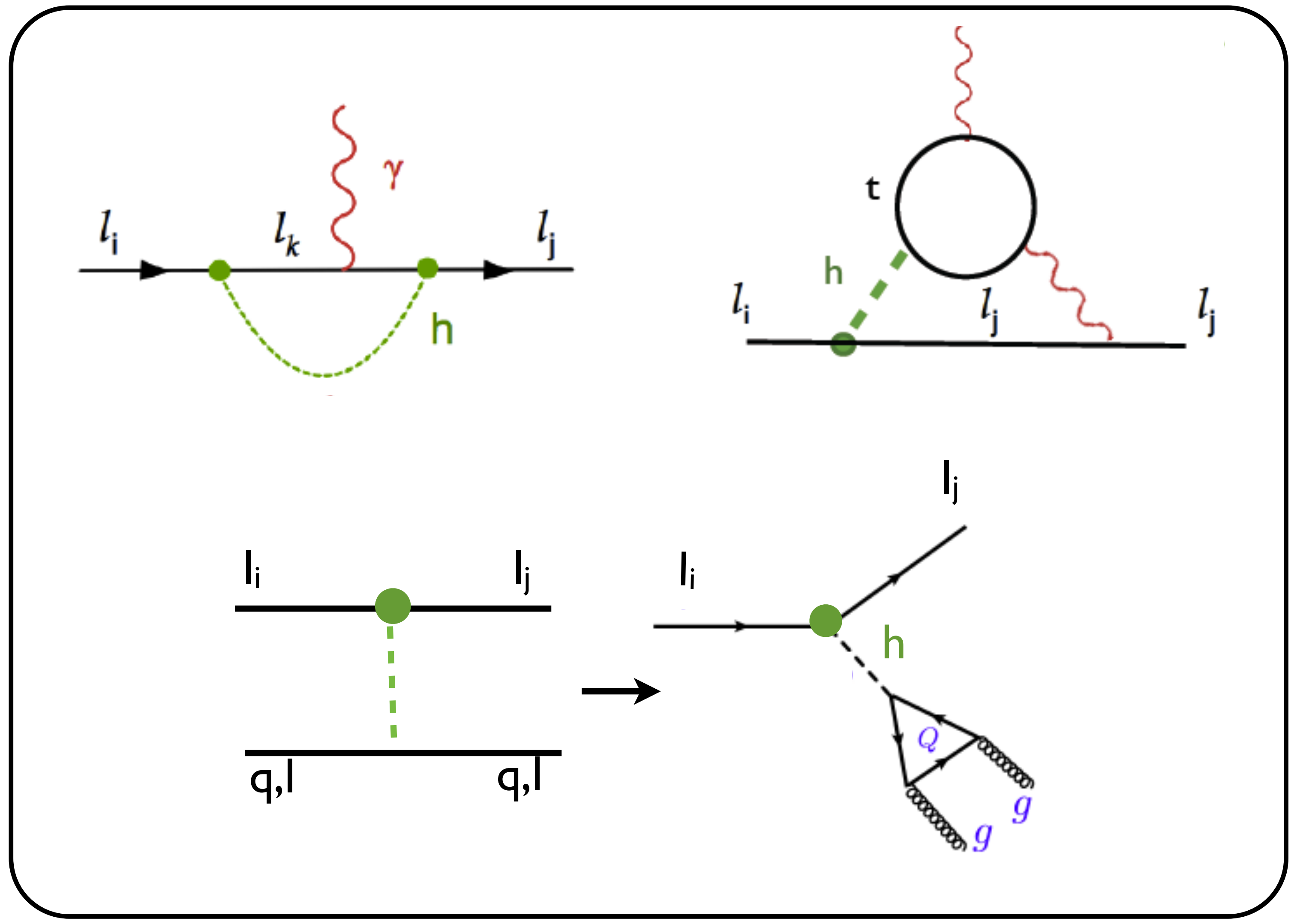
Kitano-Koike-Okada hep-ph/0203110, VC-Kitano-Okada-Tuzon 0904.0957, Heek-Szafron-Uesaka 2203.00702, ...

μ-e sector: diagnosing tools (2)

- Illustration: Higgs-mediated LFV, e.g. from dim-6 operator

Harnik-Kopp-Zupan 1209.1397, ...

$$\Delta\mathcal{L} \supset Y_{ij}\, \bar{e}_L^i\, e_R^j\, h \; + \; \text{H.c.}$$



- μ→eγ is currently probing $|Y_{\mu e}| \sim 10^{-6}$ $(BR(h\to\mu e) < 10^{-9})$

- Correlated signals in μ→e transitions**

BR(μ→e,Al) / BR(μ→eγ) = 8.7(3) 10^{-3}

BR(μ→e,Ti) / BR(μ→e,Al) = 1.5(1)

VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

(See also Crivellin et al. 1404.7134)

μ-e sector: diagnosing tools (2)

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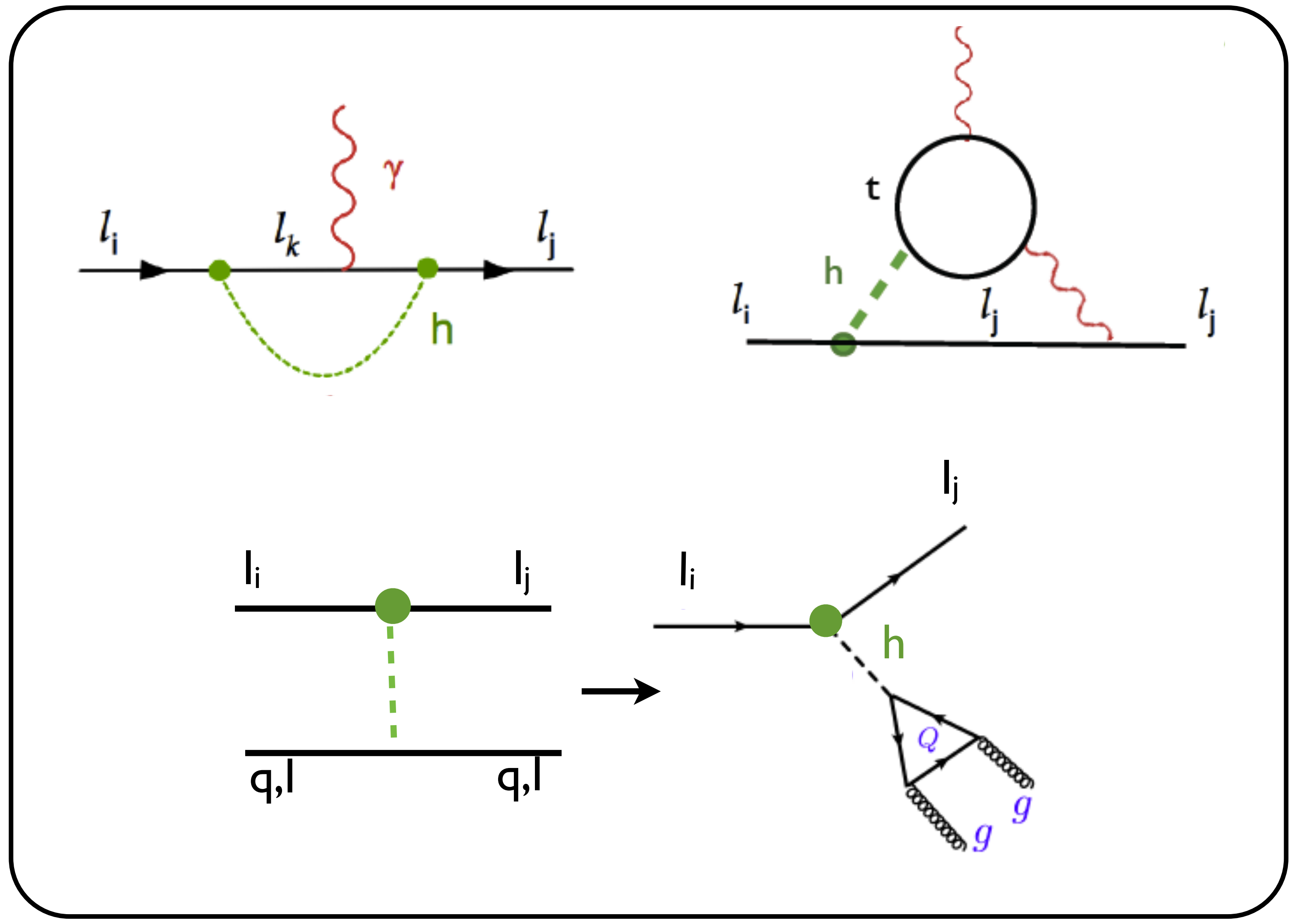

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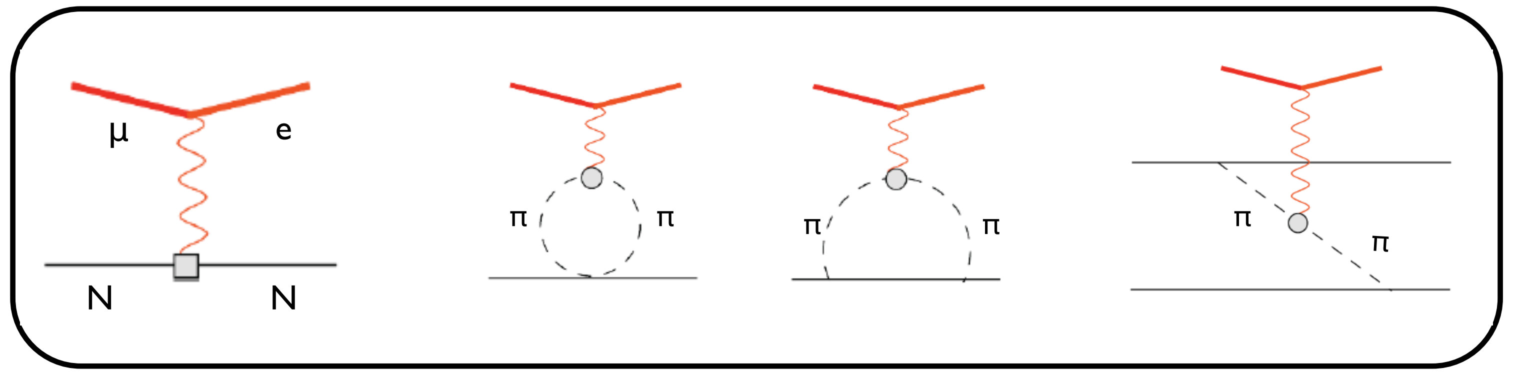


** Included NLO chiral EFT corrections in computation of conversion rate.

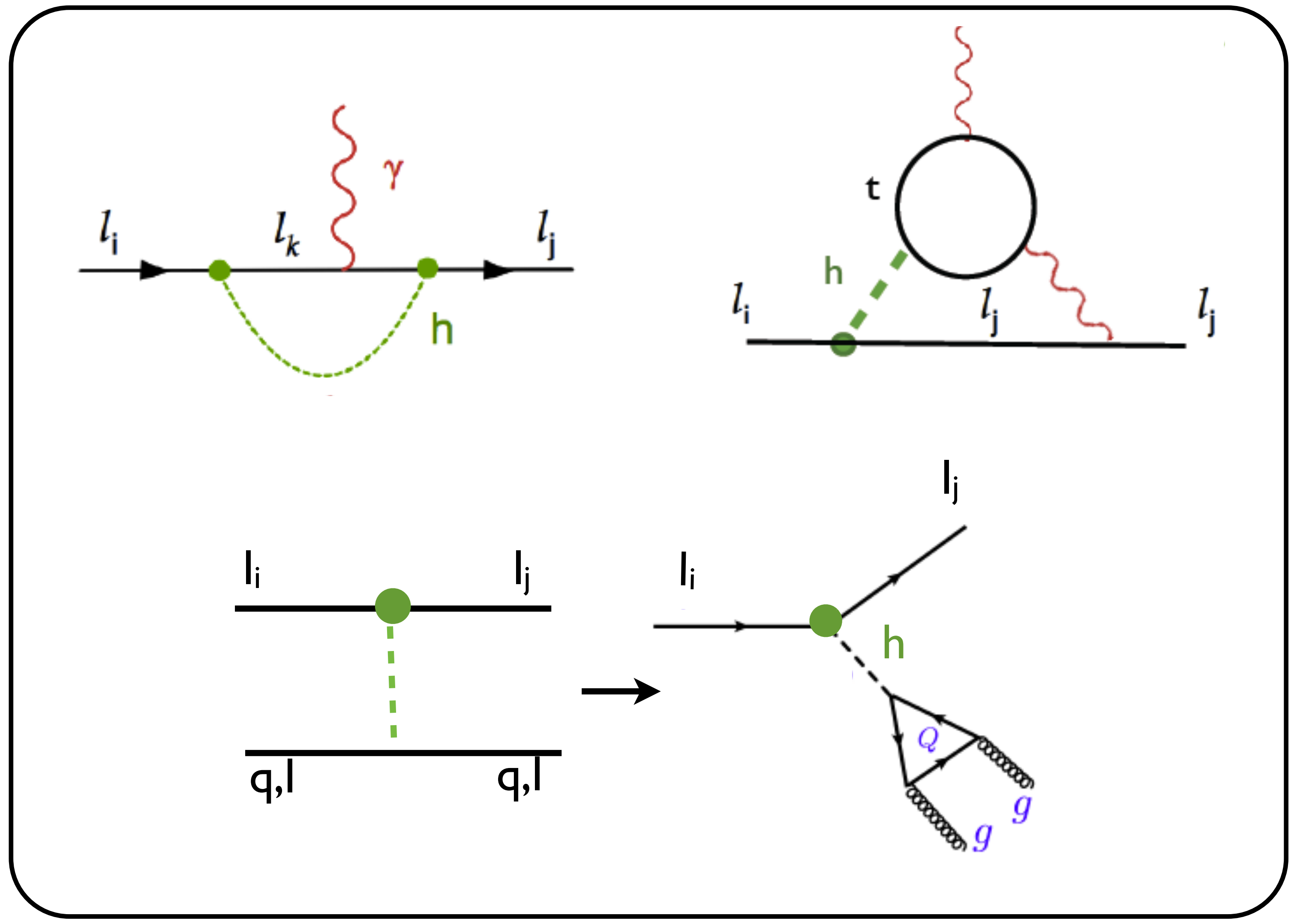
For NR nuclear EFT approach see Rule et al, 2109.13503

μ-e sector: diagnosing tools (2)

- Illustration: Higgs-mediated LFV, e.g. from dim-6 operator

Harnik-Kopp-Zupan 1209.1397, …

$$\Delta\mathcal{L} \supset Y_{ij}\, \bar{e}^i_L\, e^j_R\, h \; + \; \text{H.c.}$$



- $\mu\to e\gamma$ is currently probing $|Y_{\mu e}| \sim 10^{-6}$ ($BR(h\to\mu e) < 10^{-9}$)

- Correlated signals in $\mu\to e$ transitions**

$BR(\mu\to e,Al)\; /\; BR(\mu\to e\gamma) = 8.7(3)\; 10^{-3}$

$BR(\mu\to e,Ti)\; /\; BR(\mu\to e,Al) = 1.5(1)$

VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

(See also Crivellin et al. 1404.7134)

- Muon decays provide clean probe of LFV Higgs couplings!

Probing the flavor-breaking pattern: μ vs τ

- Smaller samples of taus compared to muons $\Rightarrow$ $BR_\tau \sim 10^{-8}$ while $BR_\mu \sim 10^{-13}$

- Well motivated flavor-breaking patterns (leptonic MFV, GUTs, U(2) symmetries, …) suppress $\mu \to e$ compared to $\tau \to \mu$:

Leptonic MFV:	$BR(\mu \to e\gamma) \,/\, BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma) \,/\, BR(\tau \to \mu\gamma) \sim |V_{us}|^6 \sim 10^{-4}$

VC-Grinstein-Isidori-Wise, hep-ph/0507001, hep-ph/0608123, …

Barbieri-Hall-Strumia, hep-ph/9501334

- This underlies the importance of searches in multiple channels

Backup

(Incomplete) List of acronyms

- ALPs: Axion-Like Particles
- BNV: Baryon Number Violation
- CC: (weak) charged current
- CKM: Cabibbo-Kobayashi-Maskawa
- CP: Charge-Parity
- CPV: CP Violation
- EDM: Electric Dipole Moment
- EFT: Effective Field Theory
- FCNC: Flavor Changing Neutral Currents
- LEFT: Low Energy EFT (below the weak scale)
- LFU: Lepton Flavor Universality
- LFV: Lepton Flavor Violation
- LNV: Lepton Number Violation
- NC: (weak) neutral current
- RGEs: Renormalization Group Equations
- SMEFT: Standard Model EFT
- UV: ultraviolet

Backup: methods

Renormalization

- Use dimensional regularization (define theory in $d=4-\varepsilon$ dims)
- Dimensionless action integral → gauge couplings acquire mass dimension $\varepsilon/2$
- Introduce arbitrary dimensionful scale μ (renormalization scale) to work with dimensionless couplings: $g \to \mu^{\varepsilon/2}\, g$
- The scale μ appears only in logarithms ($\mu^\varepsilon = 1 + \varepsilon \log(\mu) + \ldots$), so it cannot upset EFT power counting (no powers of μ/Λ appear)
- Physics does not depend on μ.
- Renormalization: UV divergences appear as poles in ε. Subtract only the $1/\varepsilon^n$ pole terms (minimal subtraction)

Renormalization Group "Running"

- RGEs: exploit the fact that physics does not depend on the renormalization scale

$$\mathcal{L}_{CC} = \frac{G_F V_{ud}}{\sqrt{2}} \times \sum_i C_i \, O_i$$

- Bare operators do not depend on μ

$$\frac{d}{d(\ln \mu)} O_i^{(0)} = 0 \longrightarrow \frac{d}{d(\ln \mu)} O_i = -\gamma_i \, O_i$$

$$O_i^{(0)} = Z_i \, O_i$$

$$\gamma_i \equiv \frac{1}{Z_i} \frac{d}{d(\ln \mu)} Z_i = \frac{g^2}{16\pi^2} \gamma_i^{(0)} + \ldots$$

- Physical amplitudes do not depend on μ

$$\frac{d}{d(\ln \mu)} [C_i \, \langle Q_i \rangle] = 0 \longrightarrow \frac{d}{d(\ln \mu)} C_i = \gamma_i \, C_i$$

Chiral symmetry

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu,a} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R - \bar{q}_L m_q q_R - \bar{q}_R m_q^\dagger q_L$$

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \qquad q_{L,R} = \left(\frac{1 \mp \gamma_5}{2}\right) q \qquad m_q = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

Chiral symmetry

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu,a} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R - \bar{q}_L m_q q_R - \bar{q}_R m_q^\dagger q_L$$

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- For $m_q = 0$, invariant under independent U(3) transformations of left- and right-handed quarks:

$$\underbrace{SU(3)_L \times SU(3)_R}_{\text{Chiral group G}} \times [U(1)_V \times U(1)_A]$$

L,R ∈ *SU(3)*

$$q_L \to L\, q_L \qquad q_R \to R\, q_R$$

Chiral symmetry

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + i\bar{q}_L \gamma^\mu D_\mu q_L + i\bar{q}_R \gamma^\mu D_\mu q_R - \bar{q}_L m_q q_R - \bar{q}_R m_q^\dagger q_L$$

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L,R ∈ SU(3)

$$q_L \to L\, q_L \qquad q_R \to R\, q_R$$

- Symmetry is broken explicitly by $m_q \neq 0$ and “spontaneously”

$$\partial_\mu \left(\bar{q}\gamma^\mu T^a q\right) = \bar{q}\,[T^a, m_q]\, q \qquad \partial_\mu \left(\bar{q}\gamma^\mu \gamma^5 T^a q\right) = \bar{q}\,\{T^a, m_q\}\, i\gamma_5\, q$$

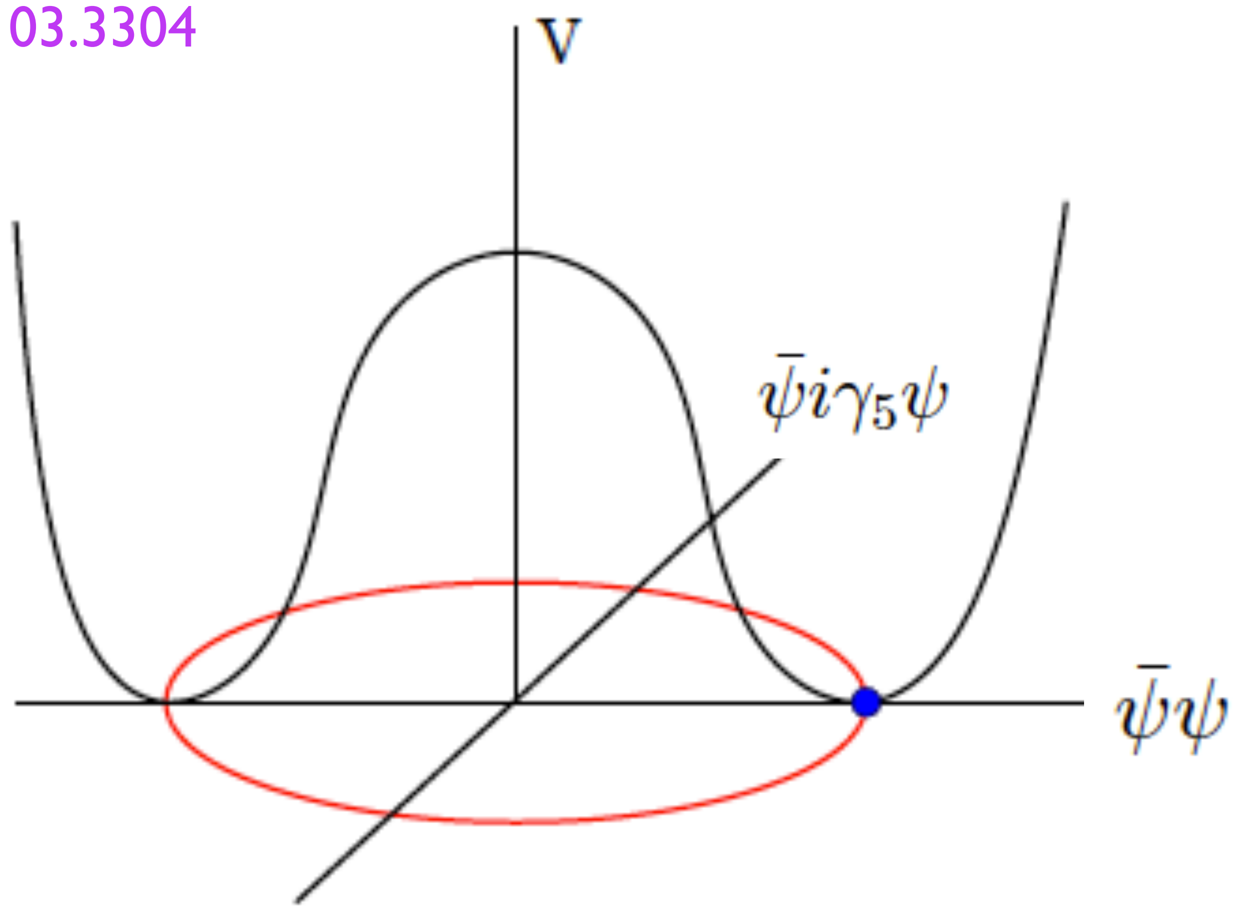
SSB of chiral SU(3)

- Empirical & theoretical evidence of breaking pattern

$$G = SU(3)_L \times SU(3)_R \;\rightarrow\; H = SU(3)_{V=L+R}$$

$$q_L \rightarrow L\, q_L \qquad q_R \rightarrow R\, q_R$$

Figure from M. Creutz 1103.3304



$$\langle 0|\bar q q|0\rangle = \langle 0|\bar q_L q_R|0\rangle + \langle 0|\bar q_R q_L|0\rangle \neq 0$$

- Vector subgroup $SU(3)_V$ (L=R) unbroken and symmetry is approximately manifest in the QCD spectrum
- Axial generators broken (no parity doublets, pseudoscalar mesons are the lightest hadrons)

- Goldstone's theorem: massless states appear in the spectrum, in one-to-one correspondence with the broken generators. Identified π,K,η

Low-energy EFT for GBs

- At low-E, the only d.o.f. are fluctuations along the vacuum manifold (Goldstone modes)
- Even though $M_{\pi,K,\eta} \neq 0$ (due to $m_q \neq 0$), π,K,η are still the lightest hadrons
- Use EFT methods to analyze the low-energy dynamics:
  - Identify relevant d.o.f: GBs plus possibly matter fields
  - Write down all interactions consistent with chiral symmetry
  - Order interactions according to power counting

Relevant ratio of scales (EFT expansion parameter): E/Λ, $M_{\pi,K}/\Lambda$

Λ: scale of lowest QCD resonances ~ O(1 GeV)

Chiral perturbation theory (1)

Describes low-energy interactions of light PS mesons (π,K,η), nucleons (n,p) and other light particles (e, μ, ν, γ)

- Special role of π,K,η: Goldstone bosons associated with spontaneous breaking of chiral symmetry (symmetry broken explicitly by m_q)

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + i \bar{q}_L \gamma^\mu D_\mu q_L + i \bar{q}_R \gamma^\mu D_\mu q_R - \bar{q}_L m_q q_R - \bar{q}_R m_q^\dagger q_L$$

$$SU(3)_L \times SU(3)_R \xrightarrow{\langle \bar{q}\, q \rangle \neq 0} SU(3)_V$$

- Even in presence of quark masses, π,K,η are the lightest hadrons (can integrate out heavy states). Interactions dictated by spontaneous and explicit χSB

- The symmetry dictates that GB have derivative interactions with all fields: GBs interact weakly at low energy. GBs determine the leading long-distance interactions among nucleons (multi N theory = chiral EFT)

Chiral perturbation theory (2)

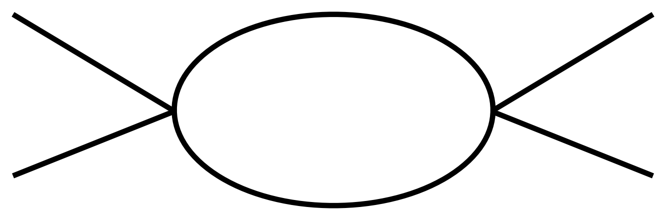
Weinberg '79, Gasser-Leutwyler '84-85, Weinberg '91, Jenkins-Manohar '92, Benard-Kaiser-Kambor-Meissner '92 van Kolck '94, Kaplan-Savage-Wise '96-98…..

- In ChPT / chiral EFT, Lagrangian and amplitudes are expanded in p/Λ, $M_{\pi,K}/\Lambda$, where p is the soft momentum and Λ~ GeV is the scale of QCD resonances.

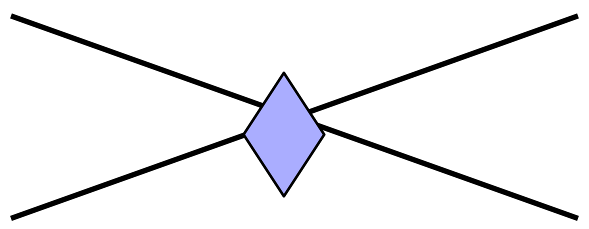
- Counting rules for ChPT: $\partial \sim p$, $m_q \sim p^2$ (because $M_{PS}^2 \sim B\, m_q$)

- To a given order in the chiral expansion:

  - Loops: leading IR singularities, perturbative unitarity.
    Except for NN EFT, higher loops imply higher suppression



  - "Contact" terms, LECs: UV div.+ finite part, encoding
    short distance (QCD) physics, to be determined from expt.
    or via non-perturbative techniques (LQCD, dispersion relations, …).
    As couplings in any QFT, the LECs satisfy appropriate RGEs.



- EFT has been extended to include dynamical photons and light leptons

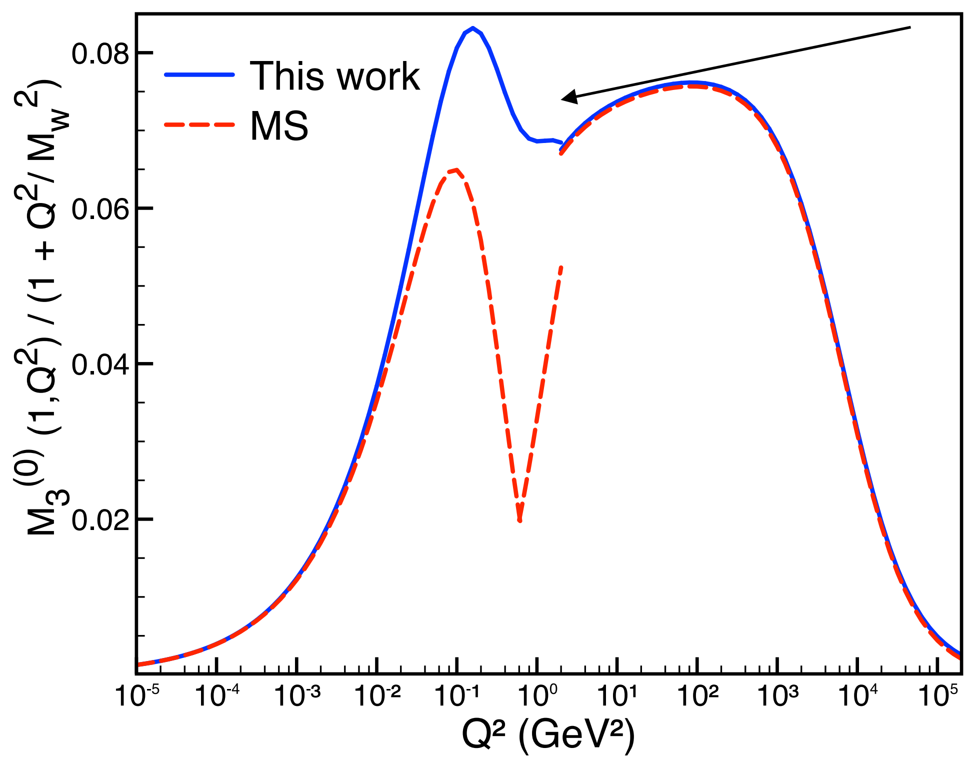
Backup: beta decays

β decays: pre-EFT radiative corrections

- Long history, starting in the 1950's. Modern approaches build upon Sirlin current algebra formulation from the '60 & '70s

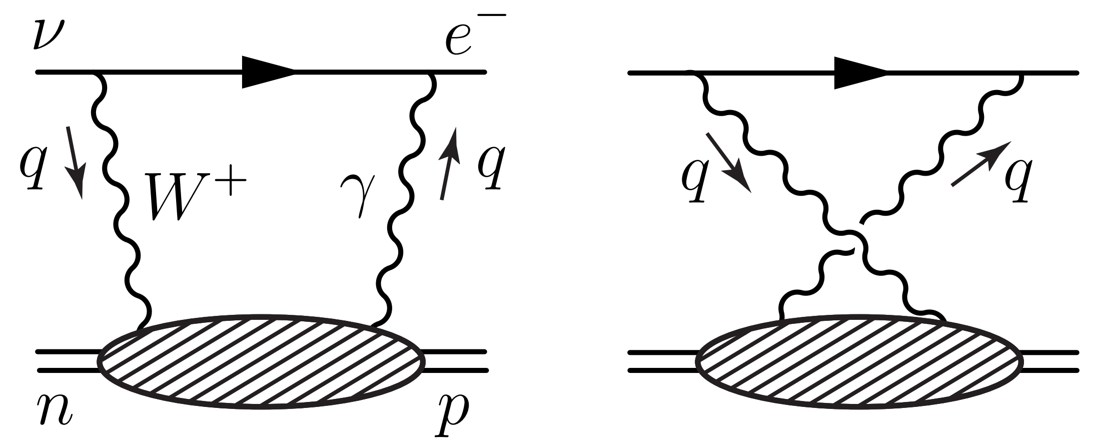
- Recent new development: dispersive approach to the non-perturbative input (γ-W box) for neutron, pion, and kaon semileptonic decays & connection to LQCD

- Example: EM correction to n→p vector coupling



Lattice QCD calculation confirms this behavior 2308.16755

Seng et al. 1807.10197, Czarnecki et al, 1907.06737, Shiells et al. 2012.01580
Hayen 2010.07262 , Gorchtein-Seng 2106.09185



Gorchtein, Feng, Jin, Seng, …
2003.09798, 2003.11264, 2102.12048, 2308.16755

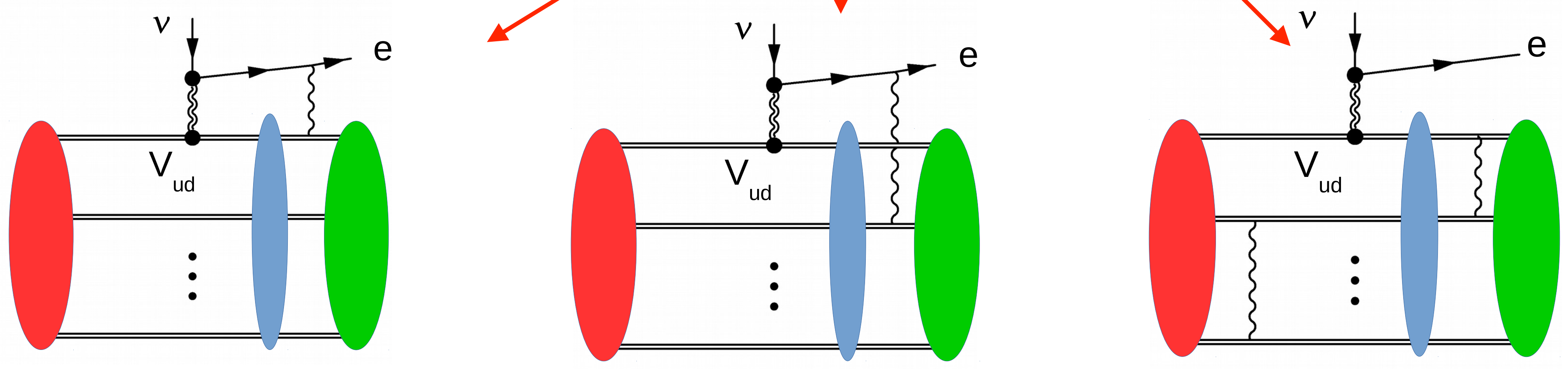
Larger correction, smaller error
It also affects nuclear decays

Ref.	Δ_R^V
Marciano, Sirlin 2006	0.02361(38)
Seng, Gorchtein, Patel, Ramsey-Musolf 2018	0.02467(22)
Czarnecki, Marciano, Sirlin 2019	0.02426(32)
Seng, Feng, Gorchtein, Jin 2020	0.02477(24)
Hayen 2020	0.02474(31)
Shiells, Blunden, Melnitchouk 2021	0.02472(18)
Combined	0.02467(27)

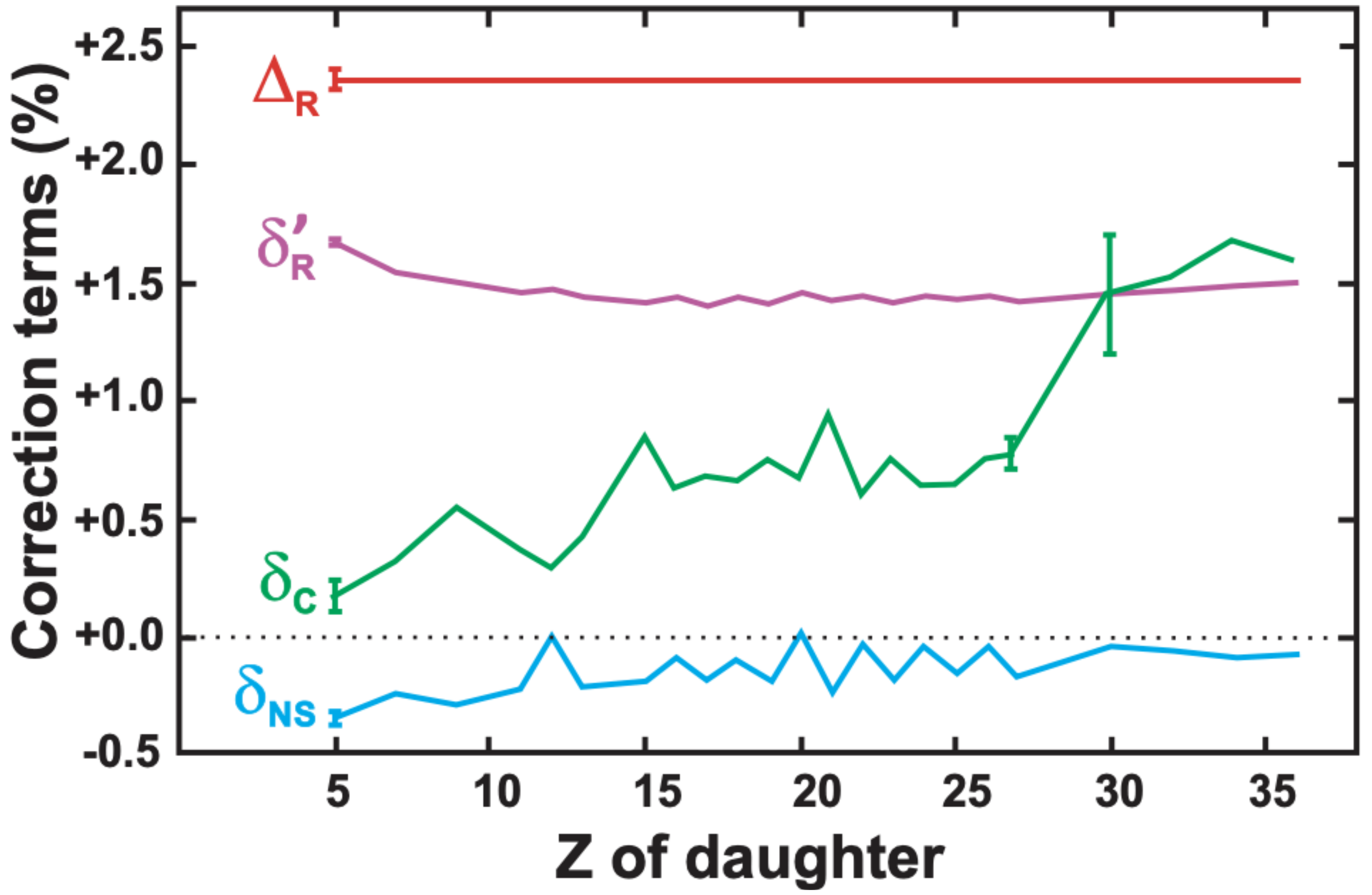
V_{ud} from nuclear $0^+ \rightarrow 0^+$ beta decays

$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1 + \delta'_R + \delta_{NS} - \delta_C + \Delta_R^V\right)}$$

Point-like nucleus
'outer corrections'
(Z, $(E_e)^{max}$)



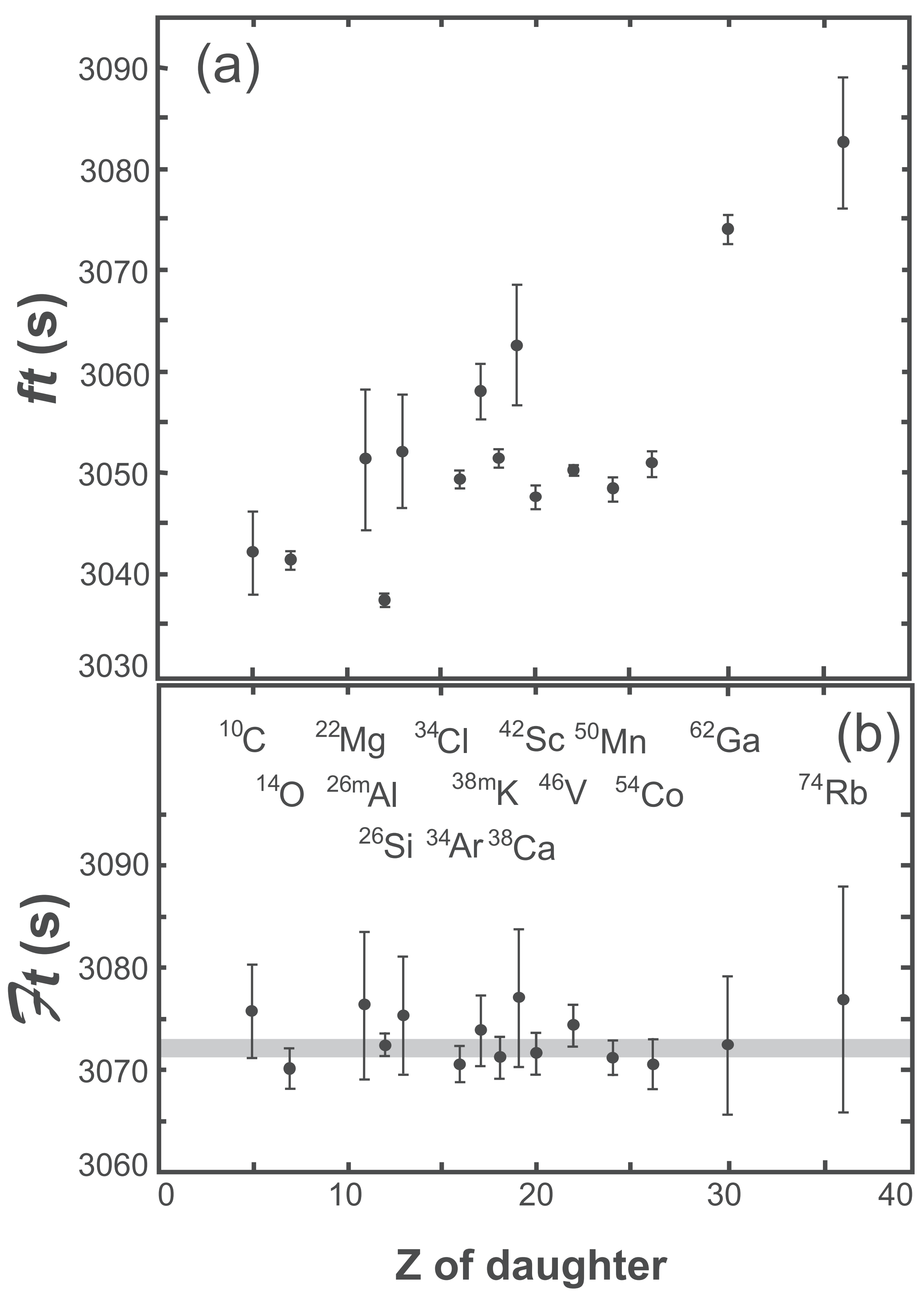
Single nucleon
`γ-W box'



Hardy-Towner, PRC 2020

V_{ud} from nuclear $0^+ \to 0^+$ beta decays

Hardy-Towner, PRC 2020



$$|V_{ud}|^2 = \frac{2984.432(3)\, s}{ft\left(1+\delta'_R+\delta_{NS}-\delta_C+\Delta^V_R\right)}$$

$\mathcal{F}t$

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta^V_R}(27)_{\rm NS}[32]_{\rm total}$$

Lots of activity

- New analysis of nuclear weak form factors and phase space f
- New approaches towards structure dependent corrections $\delta_{C,NS}$
- Controlled uncertainties will be achieved for a range of A=10, 14, …

Gorchtein, Seng 2311.00044 and references therein

V_{ud} from neutron decay

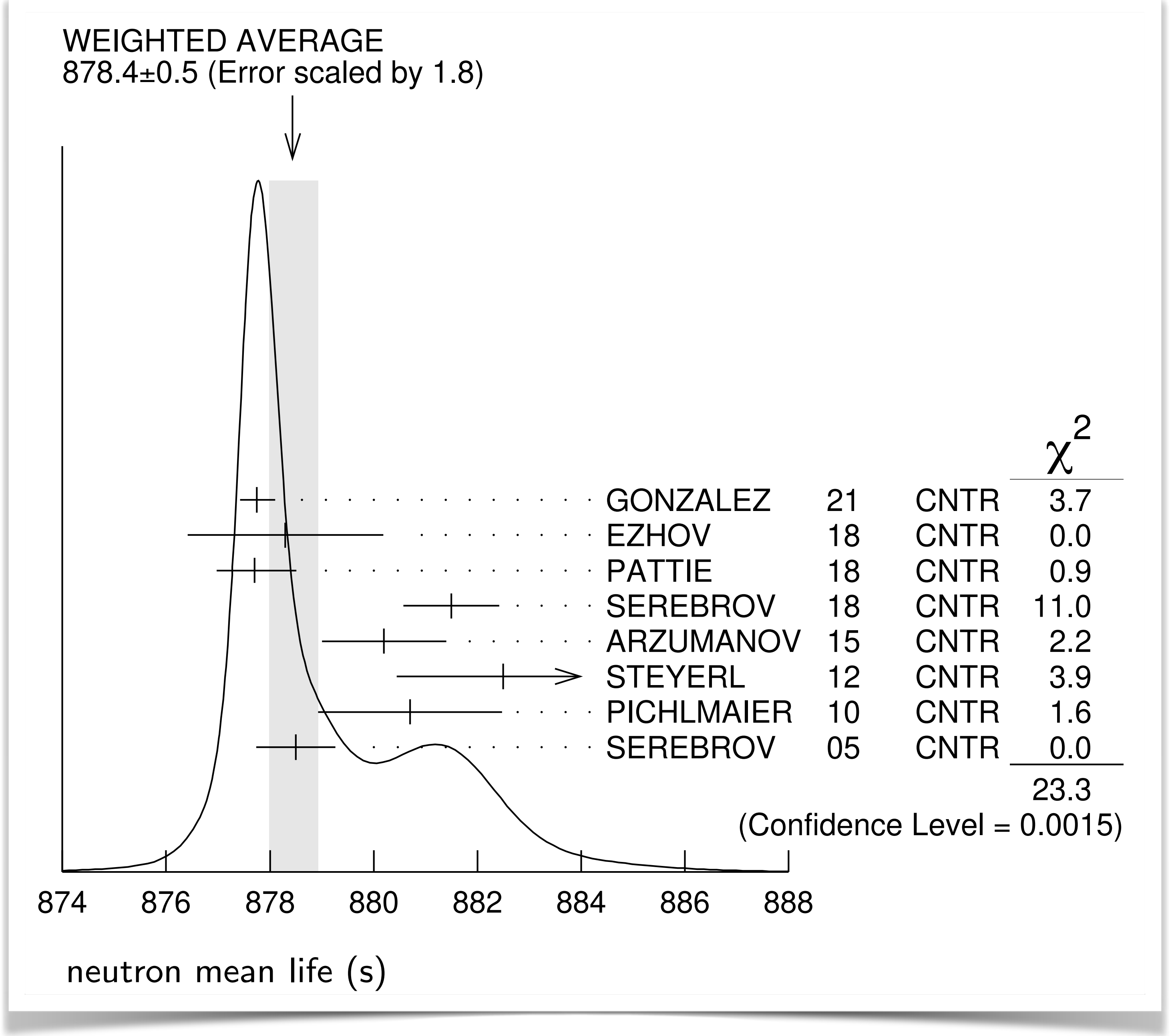
λ=g_A/g_V

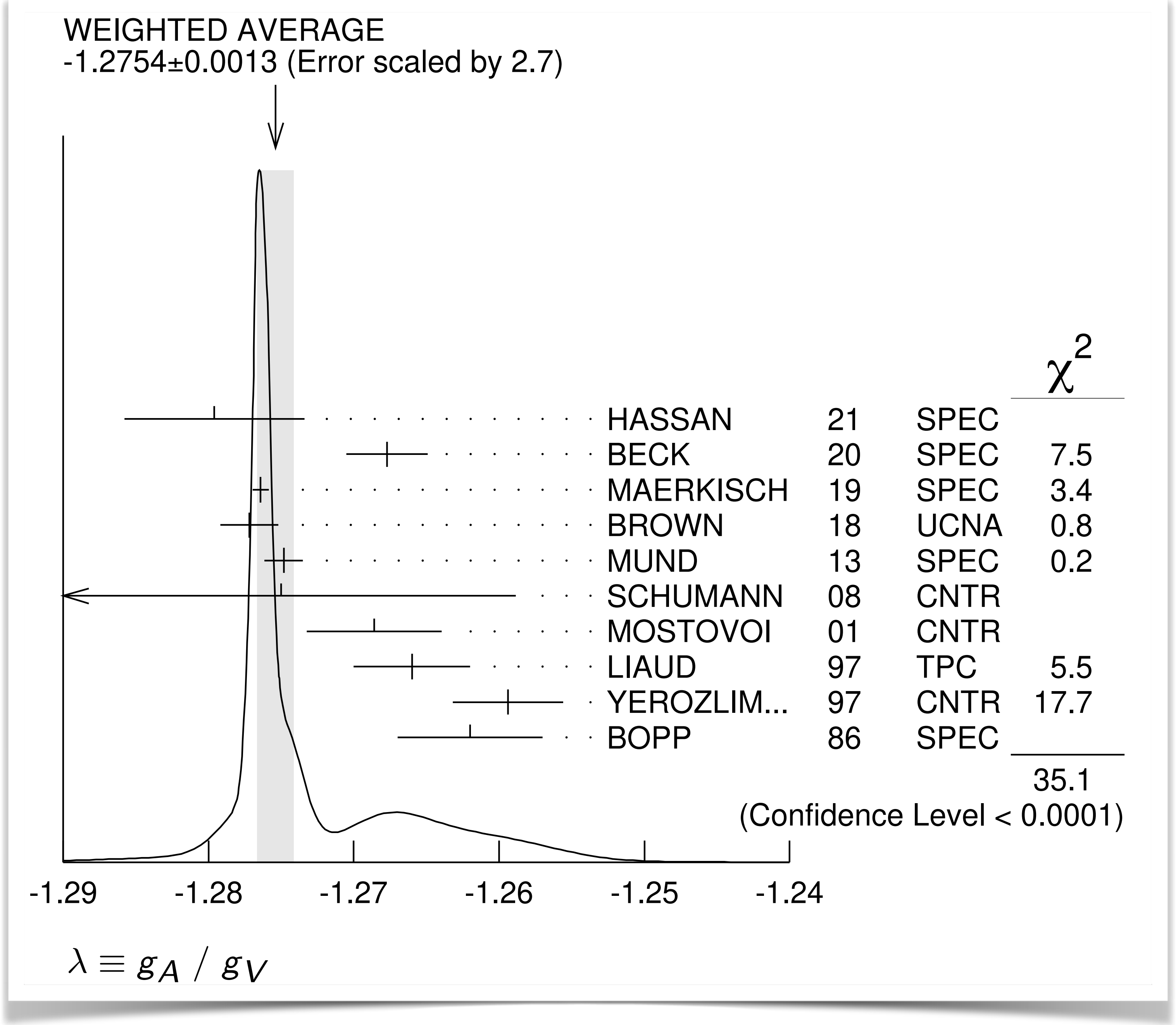
$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1 + 3\lambda^2) \cdot f_0 \cdot (1 + \Delta_f) \cdot (1 + \Delta_R),$$

$$\Delta_R = 4.044(27)\%$$
$$\Delta_f = 3.573(5)\%$$

VC, W. Dekens, E. Mereghetti, O. Tomalak, 2306. 03138

- Radiative corrections: NLL setup + LECs in terms of 'γ-W box' (dispersive & Lattice QCD)
- Experimental input: PDG averages include large scale factor, particularly for g_A / g_V





V_{ud} from neutron decay

$\lambda = g_A/g_V$

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- Experimental input: PDG averages include large scale factor, particularly for g_A / g_V

$$V_{ud}^{\mathrm{n,PDG}} = 0.97430(2)_{\Delta_f}(13)_{\Delta_R}(82)_\lambda(28)_{\tau_n}[88]_{\mathrm{total}}$$

$$V_{ud}^{\mathrm{n,best}} = 0.97402(2)_{\Delta_f}(13)_{\Delta_R}(35)_\lambda(20)_{\tau_n}[42]_{\mathrm{total}}$$

Single most precise measurements of lifetime and λ imply very competitive V_{ud}!

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

Need improvements in lifetime and g_A / g_V. Within reach in next 5 years

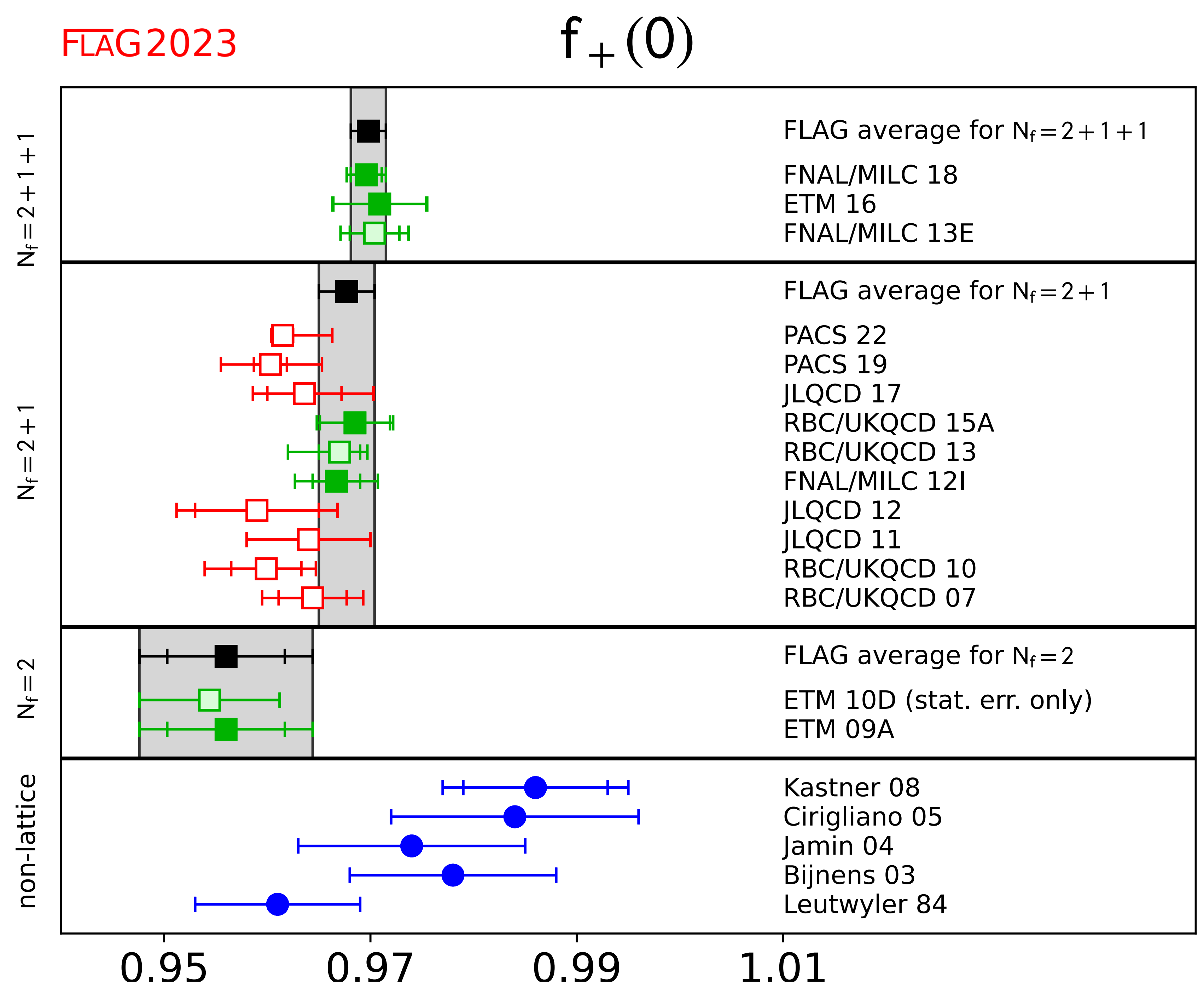
V_{us} from $K \rightarrow \pi l \nu$ decays

$$\Gamma_{K\to\pi\ell\nu(\gamma)} = \frac{C_K^2 G_F^2 S_{EW} |V_{us}|^2 M_K^5}{192\pi^3} |f_+^{K\pi}(0)|^2 I_{K\ell} \left(1 + 2\Delta_{K\ell}^{EM} + 2\Delta_K^{IB}\right)$$

- Lattice calculations of <π|V|K> @ 0.2%: $f_+^{K\pi}(0) = 0.9698(17)$
- New radiative corrections based on current algebra + lattice QCD. Consistent with ChPT, with much smaller uncertainties

	Cirigliano et al. '08	Seng et al. '21
$\Delta^{EM}(K^0{}_{e3})$ [%]	0.50 ± 0.11	**0.580 ± 0.016**
$\Delta^{EM}(K^+{}_{e3})$ [%]	0.05 ± 0.12	**0.105 ± 0.023**
$\Delta^{EM}(K^+{}_{\mu3})$ [%]	0.70 ± 0.11	**0.770 ± 0.019**
$\Delta^{EM}(K^0{}_{\mu3})$ [%]	0.01 ± 0.12	**0.025 ± 0.027**

NEW: Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217. Ma et al. 2102.12048
OLD: VC, Giannotti, Neufeld 0807.4607



V_{us} from K →πlv decays

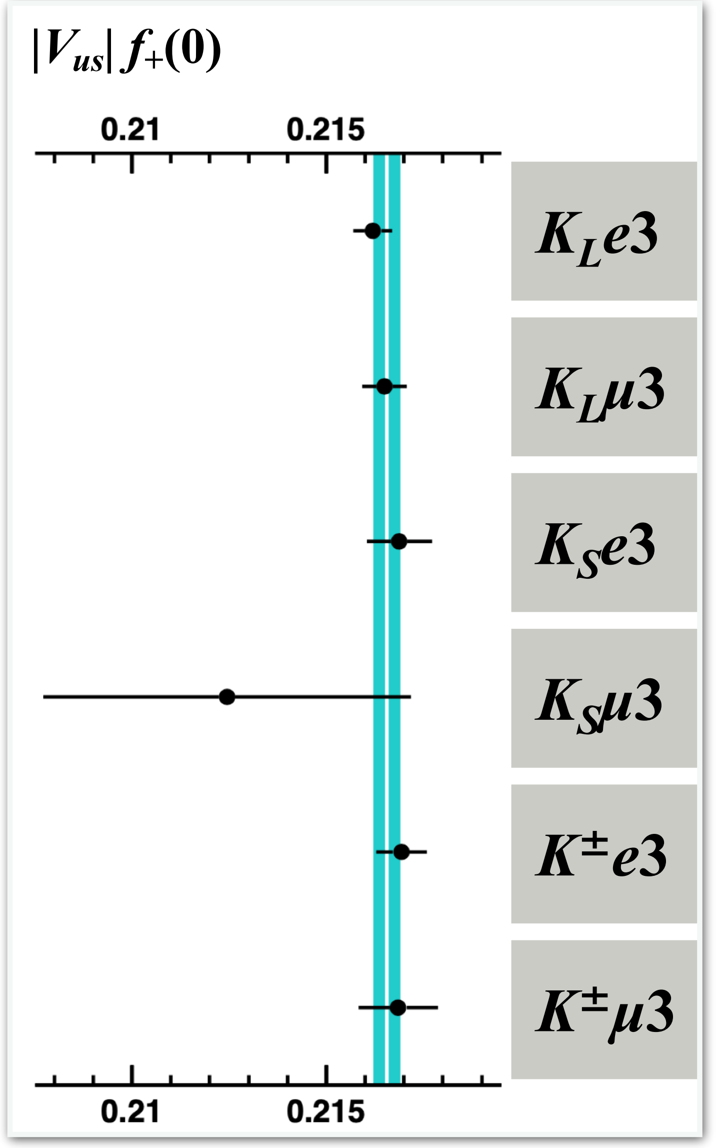
$$\Gamma_{K\to\pi\ell\nu(\gamma)} = \frac{C_K^2 G_F^2 S_{EW} |V_{us}|^2 M_K^5}{192\pi^3} |f_+^{K\pi}(0)|^2 I_{K\ell} \left(1 + 2\Delta_{K\ell}^{EM} + 2\Delta_K^{IB}\right)$$

- Lattice calculations of <π|V|K> @ 0.2%: $f_+^{K\pi}(0) = 0.9698(17)$

- New radiative corrections based on current algebra + lattice QCD. Consistent with ChPT, with much smaller uncertainties

- Experimental input has received only small updates since 2010

Flavianet WG, 1005.2323 Moulson 1704.04104



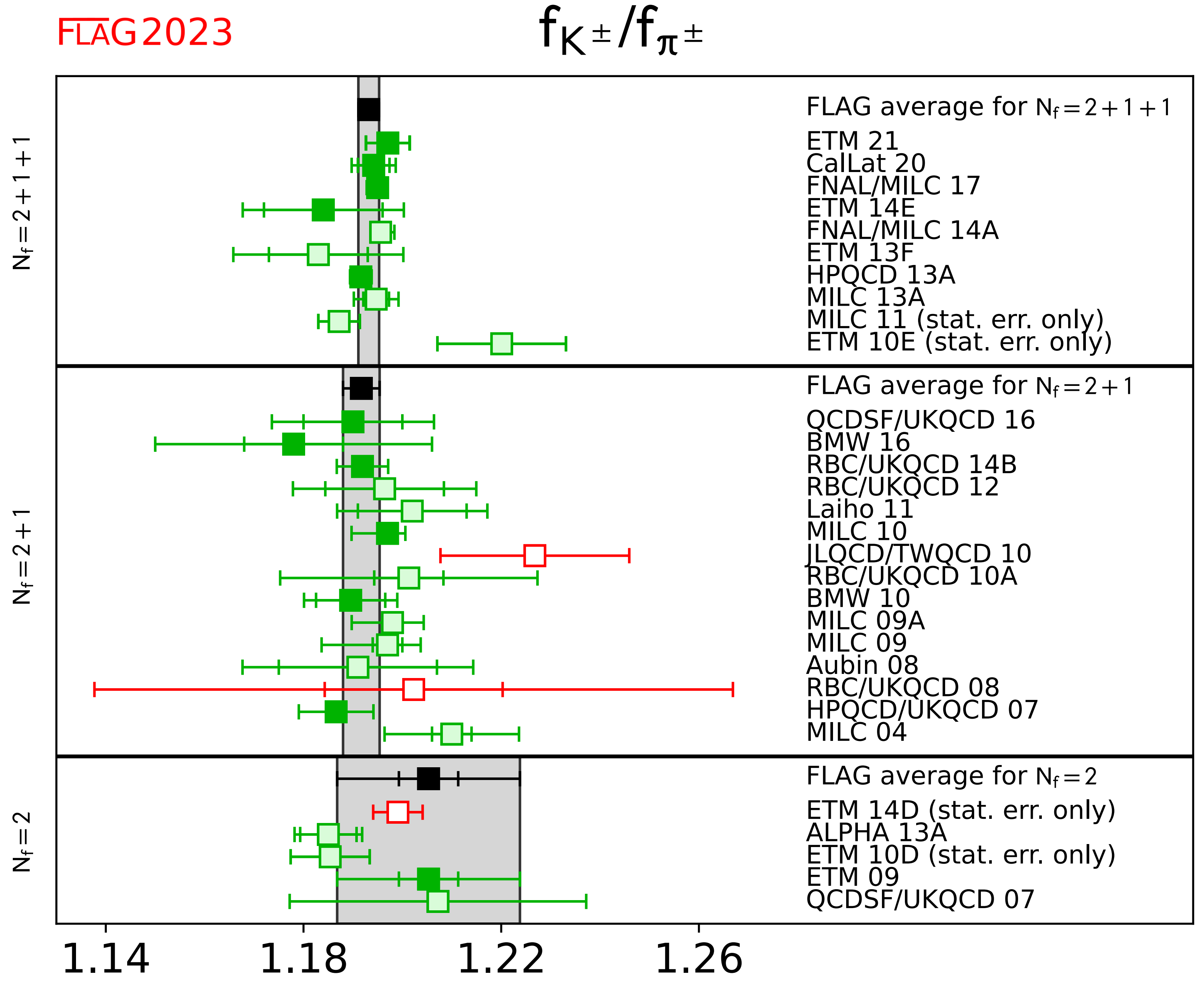
$$V_{us}^{K_{\ell 3}} = 0.22330(35)_{\rm exp}(39)_{f_+}(8)_{\rm RC+IB}[53]_{\rm total}$$

Potential issue: definition of 'isosymmetric QCD' in lattice ($f_+(0)$) vs calculations of $\Delta^{EM, IB}$

V_{us} from $K \to \mu\nu$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K\to\mu\nu(\gamma)}}{\Gamma_{\pi\to\mu\nu(\gamma)}}\frac{m_{\pi^\pm}}{m_{K^\pm}}\right)^{1/2}\frac{1-m_\mu^2/m_{\pi^\pm}^2}{1-m_\mu^2/m_{K^\pm}^2}\left(1-\frac{\Delta^{K\pi}_{\mathrm{RC+IB}}}{2}\right)$$

- Lattice QCD calculations of F_K/F_π are at the 0.2% level
- First calculation of radiative and isospin-breaking corrections in LQCD.** Compatible with ChPT, factor of ~2 more precise



ChPT: VC-Neufeld, 1102.0563	** LQCD1: Di Carlo et al., 1904.08731	LQCD2: Boyle et al., 2211.12865
$\Delta^{K\pi}_{\mathrm{RC+IB}} = -1.12(21)\%$	$\Delta^{K\pi}_{\mathrm{RC+IB}} = -1.26(14)\%$	$\Delta^{K\pi}_{\mathrm{RC+IB}} = -0.86(40)\%$

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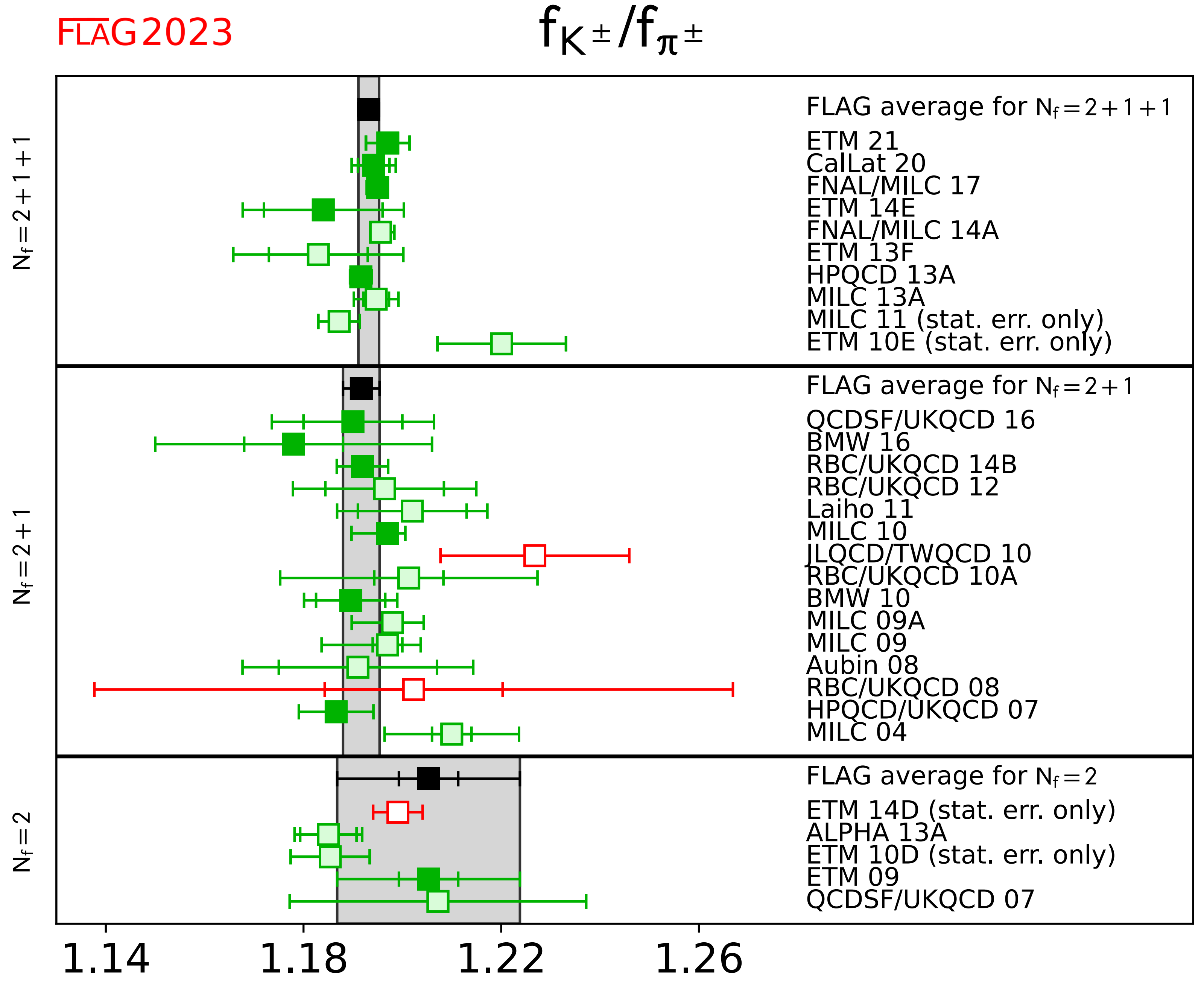

Potential issue (1):

Kmu2 BR dominated by one measurement (KLOE)

Km3/Kmu2 BR measurement at 0.2% would have significant impact

$$\left.\frac{V_{us}}{V_{ud}}\right|_{K_{\ell 2}/\pi_{\ell 2}} = 0.23108(23)_{\mathrm{exp}}(42)_{F_K/F_\pi}(16)_{\mathrm{RC+IB}}[51]_{\mathrm{total}}$$

Potential issue (2):

Isospin scheme dependence

LEFT Lagrangian for CC processes

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}} \left(1 + \epsilon_L^{(\mu)}\right) \bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma_\rho (1-\gamma_5)\mu \ + \ \ldots$$

Semi-leptonic interactions

$$\begin{aligned}
\mathcal{L}_{\rm CC} \ = \ & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[\left(\delta^{ab} + \epsilon_L^{ab}\right) \ \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\
& + \ \epsilon_R^{ab} \ \bar{e}_a \gamma_\mu (1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu (1+\gamma_5) d \\
& + \ \epsilon_S^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u} d \\
& - \ \epsilon_P^{ab} \ \bar{e}_a (1-\gamma_5)\nu_b \cdot \bar{u}\gamma_5 d \\
& + \ \epsilon_T^{ab} \ \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5)\nu_b \cdot \bar{u}\sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.}
\end{aligned}$$

$\varepsilon_i \sim (v/\Lambda)^2$

For global analysis of beta decays in this framework see:

Falkowski, Gonzalez-Alonso, Naviliat-Cuncic, 2010.13797

LEFT Lagrangian for CC processes

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

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From SM →LEFT matching at tree level

$$\frac{G_F^{(\mu)} V_{ud}}{\sqrt{2}} \left(1 - \epsilon_L^{(\mu)}\right)$$

Semi-leptonic interactions

$$\begin{aligned}
\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[& \left(\delta^{ab} + \epsilon_L^{ab}\right) \bar{e}_a\gamma_\mu(1-\gamma_5)\nu_b \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
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& + \epsilon_T^{ab} \; \bar{e}_a\sigma_{\mu\nu}(1-\gamma_5)\nu_b \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
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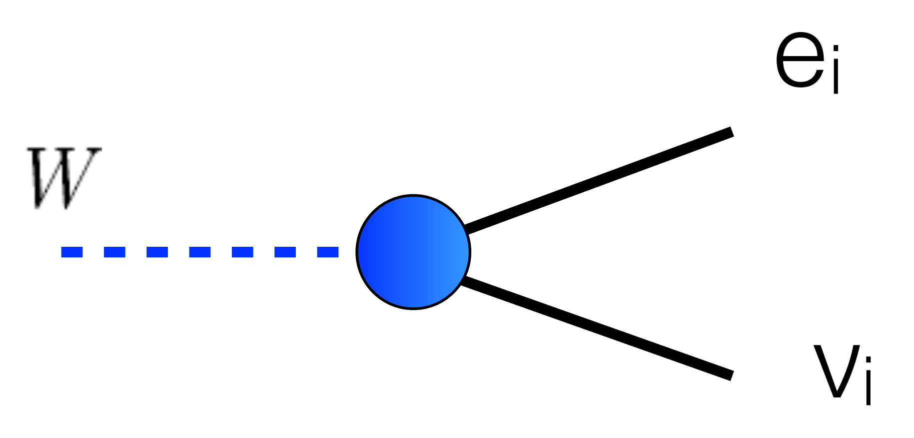
$R_{e/\mu}^{(\pi)}$ vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ, K, π

A. Pich, 2012.07099
Bryman, VC, Crivellin, Inguglia, 2111.05338, ARNPS

$$\mathcal{L} \supset -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu^- \left(\delta_{ij} + \epsilon_{ij}\right) + \text{h.c.}$$



$$g_\ell \equiv g_2\,(1 + \epsilon_{\ell\ell})$$

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0009 ± 0.0018
$B_{W\to\mu}/B_{W\to e}$	1.001 ± 0.003

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0011 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9964 ± 0.0038
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.001 ± 0.010

$R_{e/\mu}^{(\pi)}$ gives strongest constraint on ee − μμ combination

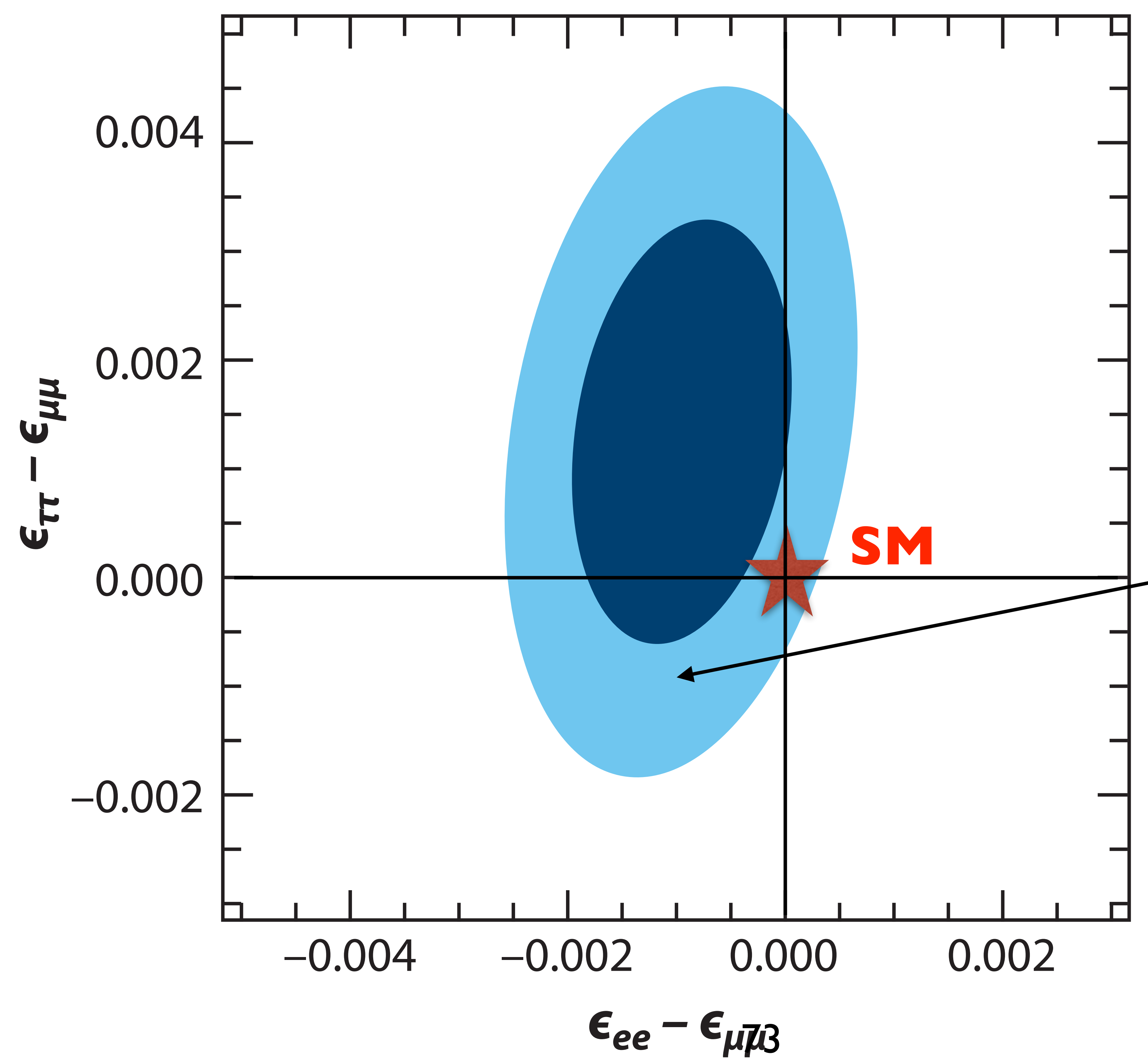
$|g_\tau / g_e|$

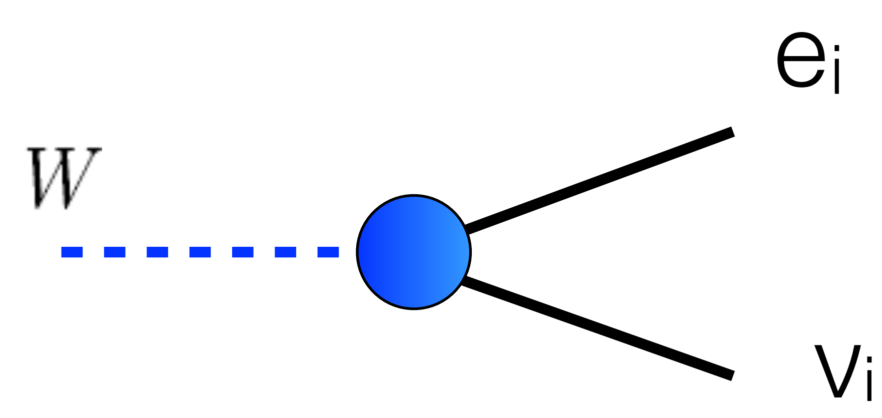
$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.008 ± 0.012

$R_{e/\mu}^{(\pi)}$ vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ, K, π
- Global fit [except for B decays]:

Bryman, VC, Crivellin, Inguglia, 2111.05338, ARNPS





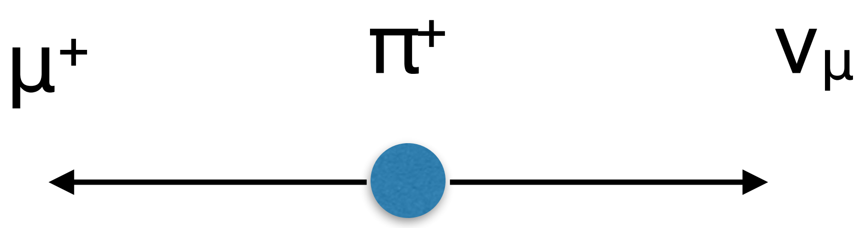
$$g_\ell \equiv g_2 \left(1 + \epsilon_{\ell\ell}\right)$$

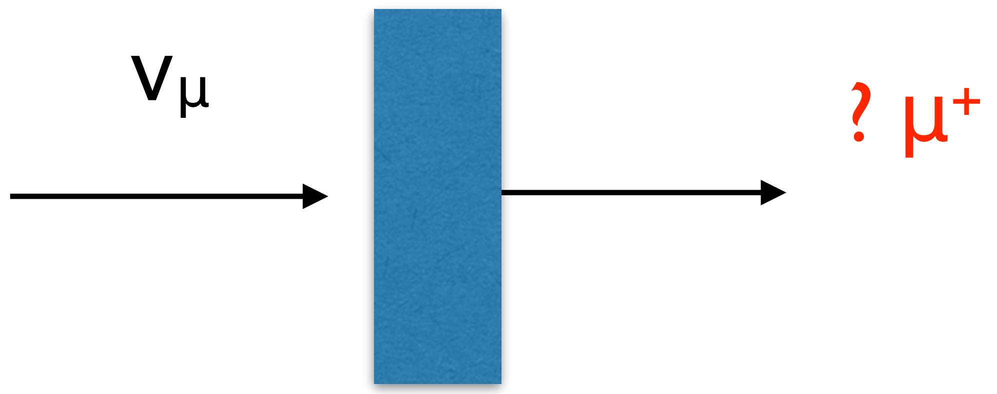
PIONEER will have strong impact on the horizontal scale in this plot

Backup: LNV

Dirac vs Majorana with ν beams?

- Simple test (B. Kayser): generate ν beam from $\pi^+ \to \mu^+ \nu_\mu$ and check whether it produces μ^+ on a target downstream





A Dirac neutrino won't do that.
A Majorana neutrino with helicity=+1 ($\nu(R)=\nu_+$) will produce μ^+.
But fraction of $\nu(R)=\nu_+$ produced in $\pi^+ \to \mu^+ \nu_\mu$ is $\sim(m_\nu/E_\nu)^2 < 10^{-16}$!!

Dirac vs Majorana with ν beams?

- Simple test (B. Kayser): generate ν beam from $\pi^+ \to \mu^+ \nu_\mu$ and check whether it produces μ^+ on a target downstream

Smallness of ν mass and V-A nature of the weak interactions imply that

Neutrinoless probes of ΔL=2 dynamics are our best bet!

Dirac vs Majorana with ν beams?

- Simple test (B. Kayser): generate ν beam from $\pi^+ \to \mu^+ \nu_\mu$ and check whether it produces μ^+ on a target downstream

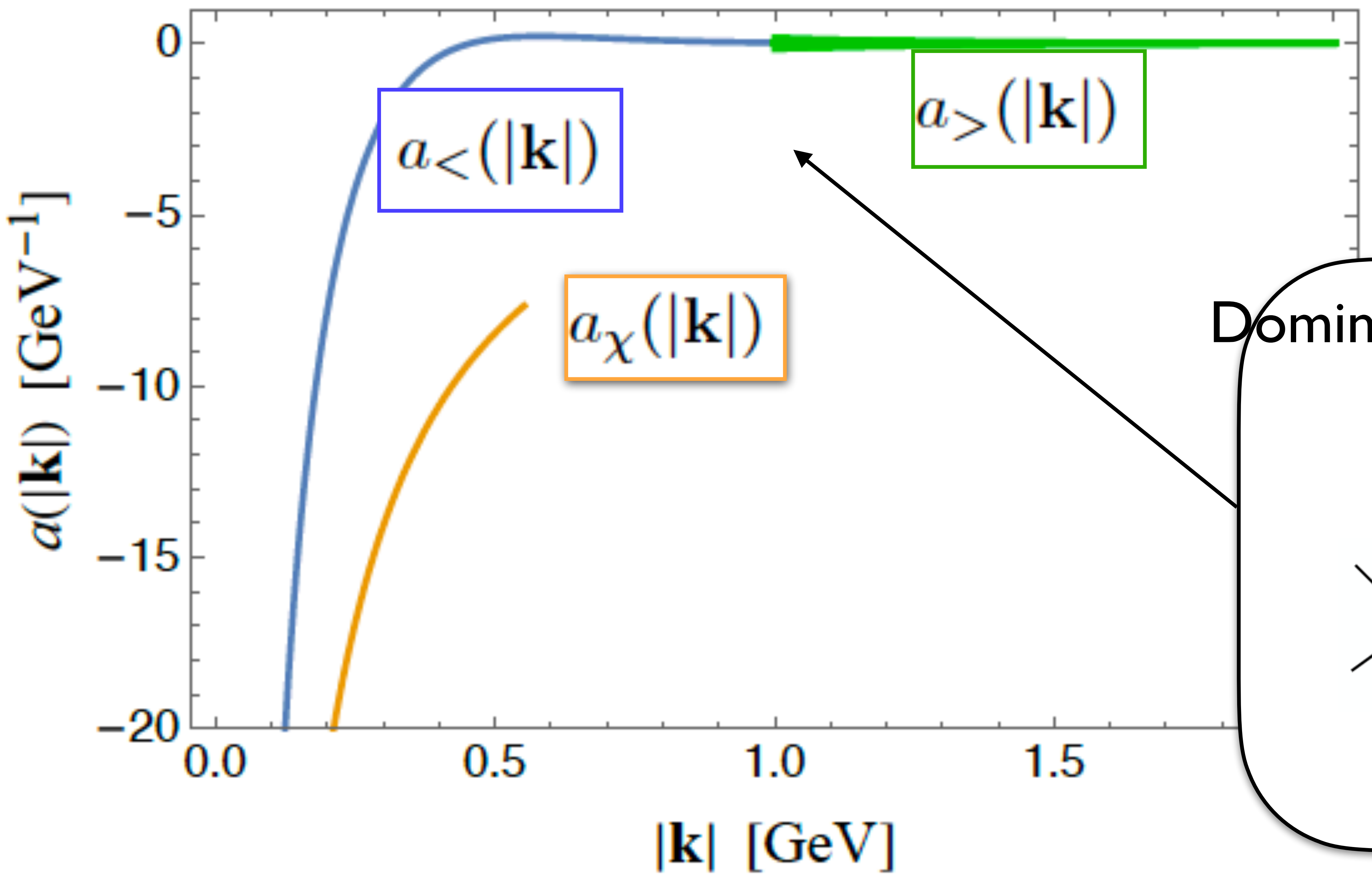
Among $\Delta L=2$ *neutrinoless* processes ($nn \to ppe^-e^-$, $K^+ \to \pi^- e^+ e^+$, $pp \to e^+e^+$ +2 jets ,…), $0\nu\beta\beta$ decay is the strongest* probe — "Avogadro's number wins"(P. Vogel)

Estimating the contact term

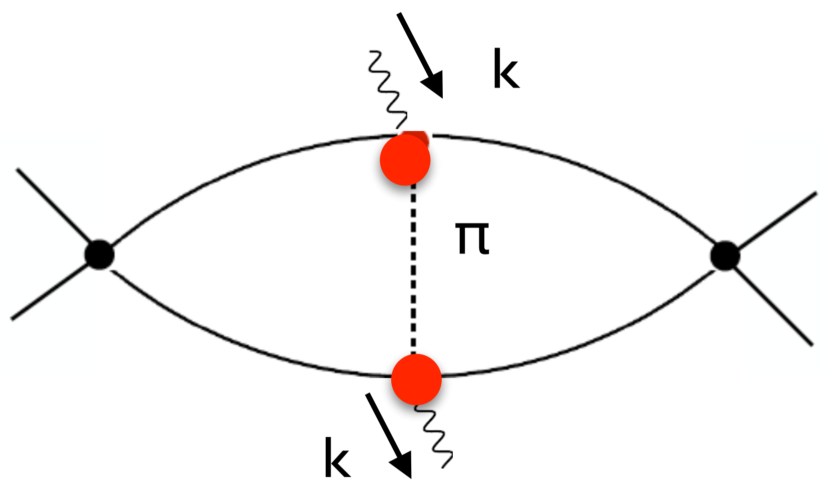
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\ a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\ a_>(|\mathbf{k}|)$$



Dominant uncertainty from inelastic channels (NNπ , …):



Estimating the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

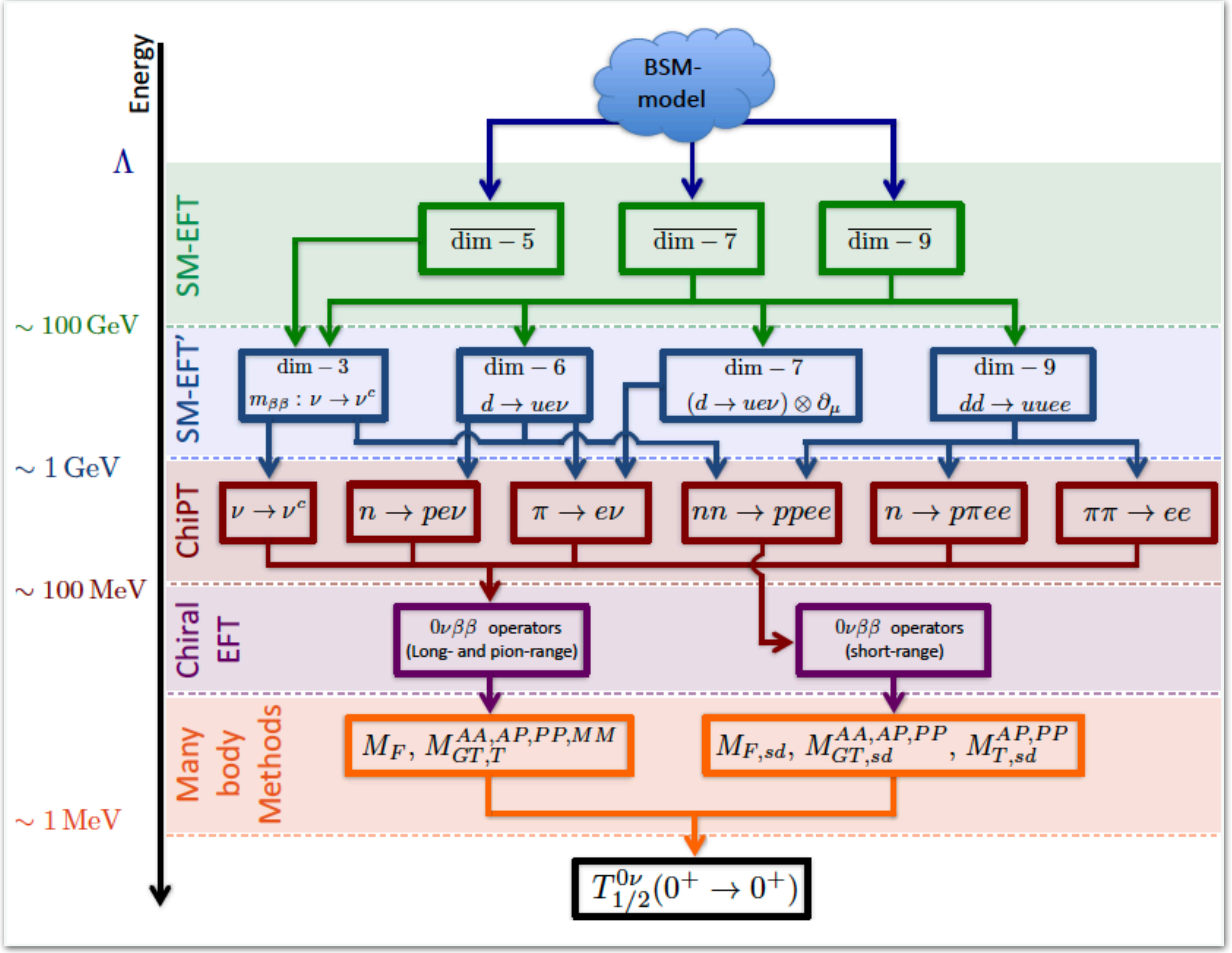
- Provided 'synthetic data' for the nn→pp amplitude at threshold

- First calculation of $^{48}Ca \rightarrow {}^{48}Ti$ with contact fitted to synthetic data ⇒ contact term enhances nuclear matrix element by (43±7)%

Wirth, Yao, Hergert, 2105.05415

EFT-based master formula

- Framework to interpret 0νββ searches in terms of any high-scale model and possibly unravel the underlying mechanism in case of discovery



V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]