TAU 2018 - The 15th International Workshop on Tau Lepton Physics
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Neutrino-less double beta decay — theory

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Outline

- Neutrino mass and Lepton Number Violation
    - LNV probes: $0\nu\beta\beta$, meson & lepton decays, LHC

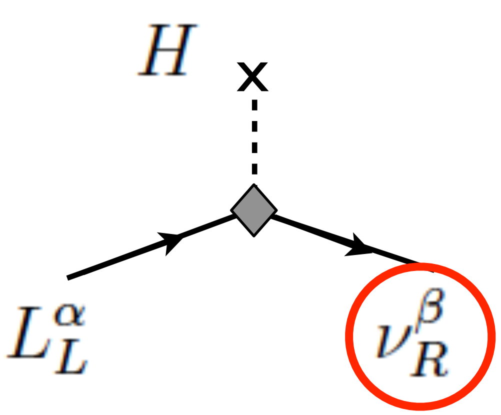
- EFT framework for LNV and $0\nu\beta\beta$ physics reach:
    - $0\nu\beta\beta$ from light Majorana ν exchange
    - $0\nu\beta\beta$ from (multi)TeV-scale dynamics & collider connections

Neutrino mass and new physics

- Neutrino mass requires introducing new degrees of freedom

Dirac mass:

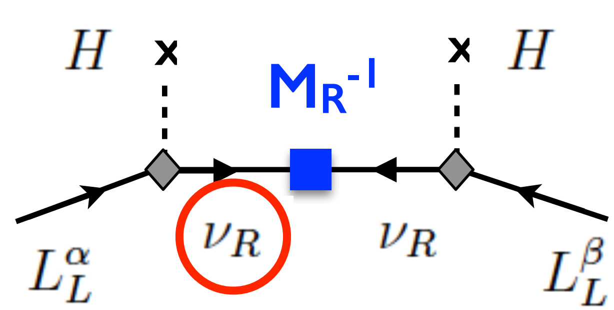
$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$

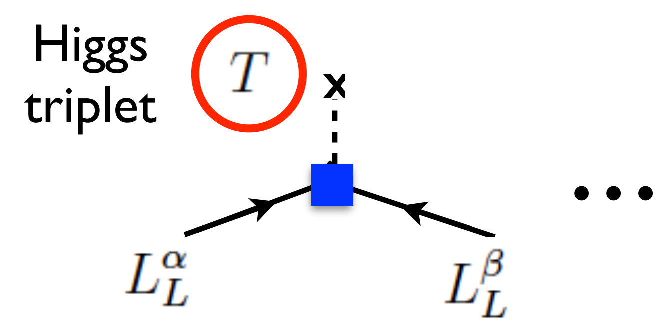


- Violates $L_{e,\mu,\tau}$, conserves L

Majorana mass:

$$m_M \, \psi_L^T \, C \psi_L \; + \; \text{h.c.}$$





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

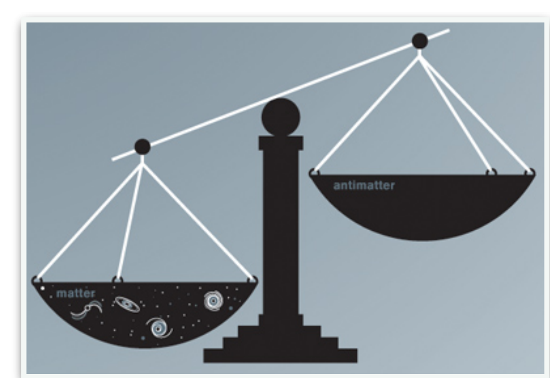
Neutrino mass and new physics

- Neutrino mass requires introducing new degrees of freedom

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

- Key question:
    - Are neutrino Majorana particles? Or equivalently:
    - Is Lepton Number a good symmetry of the new dynamics?

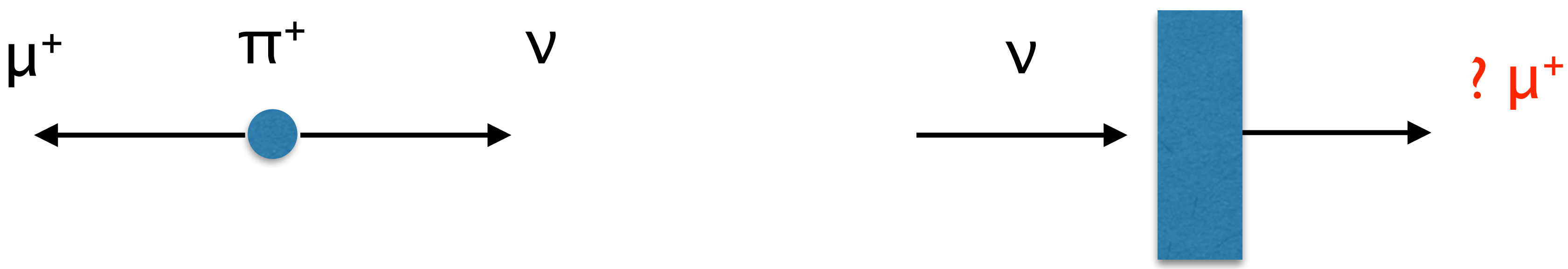
- Implications:
    - Model building
    - Generation of baryon asymmetry via "Leptogenesis" (need LNV)



Fukujgita-Yanagida
1987

Dirac vs Majorana: simple test?

- Thought experiment (B. Kayser): generate ν beam from $\pi^+ \to \mu^+ \nu$ and check whether it produces μ^+ on a target downstream:
  - A Dirac neutrino in either helicity state won't do that
  - A Majorana neutrino with helicity=+1 (R-handed) will do that



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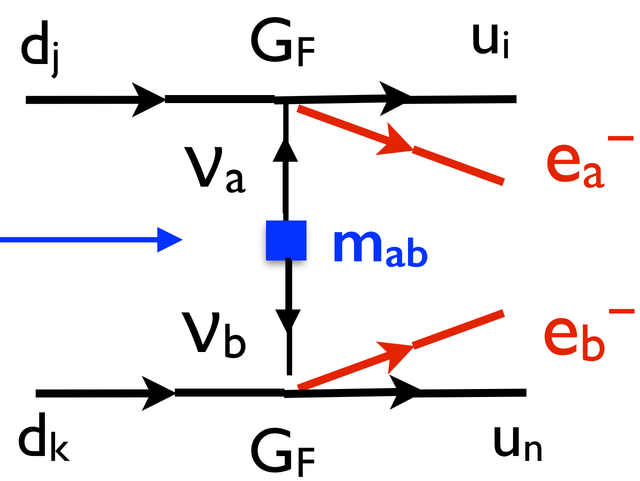
  - A Dirac neutrino in either helicity state won't do that
  - A Majorana neutrino with helicity=+1 (R-handed) will do that

- But fraction of R-helicity ν's produced in $\pi^+ \rightarrow \mu^+ \nu$ is $\sim(m_\nu/E_\nu)^2 < 10^{-16}$!!

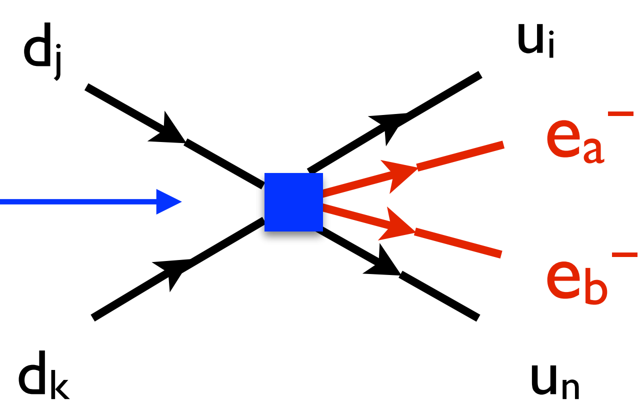
Neutrinoless processes are our best bet!

Neutrinoless probes of ΔL=2 dynamics

Minimal setup:
Majorana mass
insertion



Heavier neutrinos or other
particles can also mediate LNV.
Six-fermion (dim9) operator
$\sim 1/\Lambda^5$ at low energy



Neutrinoless probes of ΔL=2 dynamics

Minimal setup:
Majorana mass
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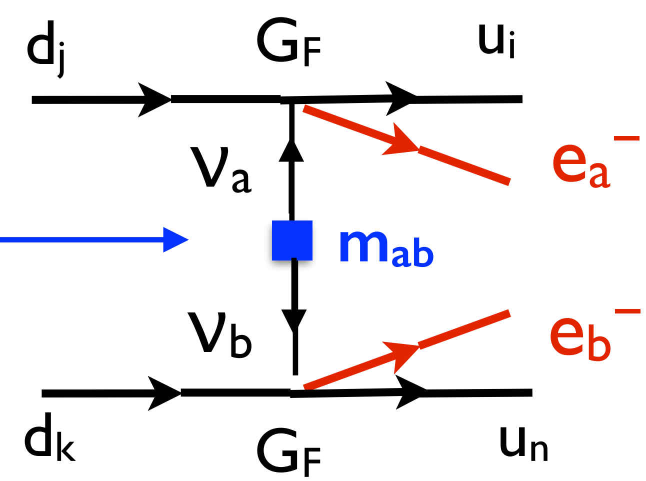
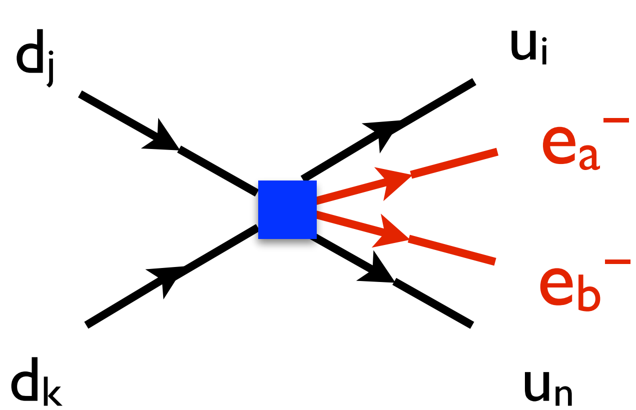
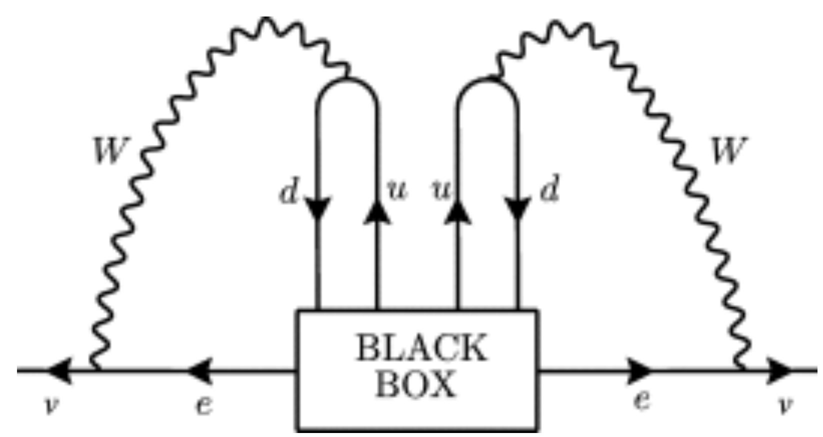




Observation of any of these processes (regardless of the mechanism) would demonstrate that neutrinos are Majorana fermions



Shechter-Valle 1982

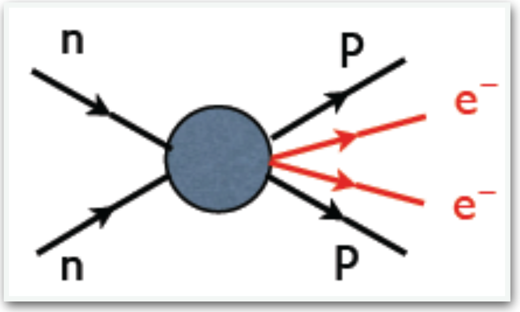
Neutrinoless probes of ΔL=2 dynamics

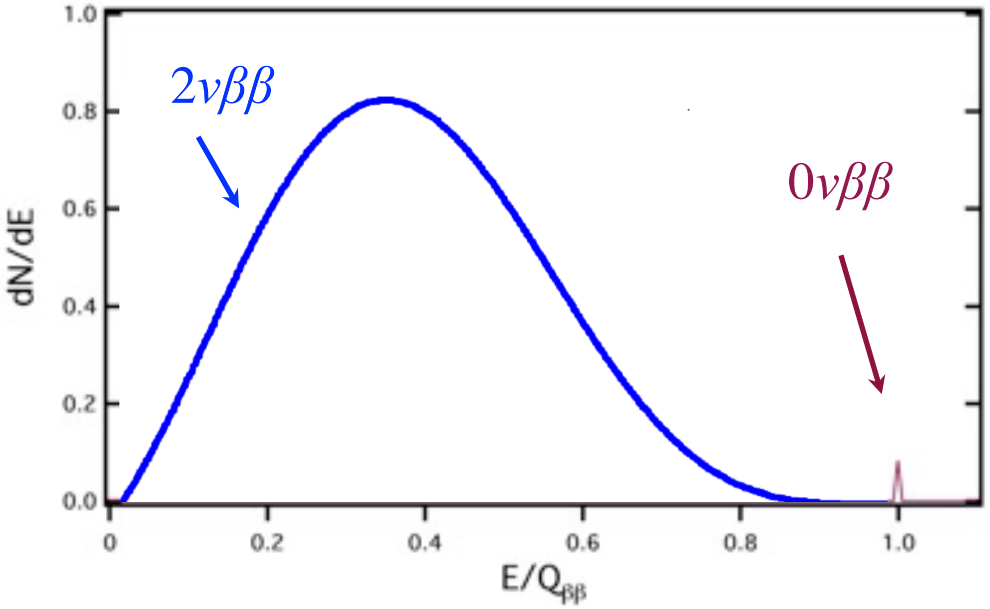
- Neutrinoless double beta decay

See talk by L. Cardani

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

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





Observable in certain even-even nuclei for which single beta decay is energetically forbidden

Neutrinoless probes of ΔL=2 dynamics

- Neutrinoless double beta decay

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

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

- Decays of mesons or leptons

See talk by A. Teixeira

$$K^+ \to \pi^- \ell_1^+ \ell_2^+$$

$$\ell_{1,2} = e, \mu$$

$$\boxed{\mathrm{BRs} < \# 10^{-10}}$$

$$B^+ \to h^- \ell_1^+ \ell_2^+$$

$$h = \pi, K \qquad \ell_{1,2} = e, \mu$$

$$\boxed{\mathrm{BR}\ (\pi^- \mu^+ \mu^+) < \# 10^{-9}}$$

$$\tau^- \to \ell^+ h_1^- h_2^-$$

$$\ell = e, \mu \qquad h_{1,2} = \pi, K$$

$$\boxed{\mathrm{BRs} < \# 10^{-8}}$$

($\mu^- \to e^+$ conversion BR at 10^{-12} level)

Neutrinoless probes of ΔL=2 dynamics

- Neutrinoless double beta decay

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

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

- Decays of mesons or leptons

See talk by A. Teixeira

$$K^+ \to \pi^- \ell_1^+ \ell_2^+ \qquad \ell_{1,2} = e, \mu$$

$$B^+ \to h^- \ell_1^+ \ell_2^+ \qquad h = \pi, K \quad \ell_{1,2} = e, \mu$$

$$\tau^- \to \ell^+ h_1^- h_2^- \qquad \ell = e, \mu \quad h_{1,2} = \pi, K$$

$$\boxed{\mathrm{BRs} < \# 10^{-10}} \qquad \boxed{\mathrm{BR}\ (\pi^- \mu^+ \mu^+) < \# 10^{-9}} \qquad \boxed{\mathrm{BRs} < \# 10^{-8}}$$

($\mu^- \to e^+$ conversion BR at 10^{-12} level)

- Same sign di-lepton production at LHC

$$pp \to \ell\ell + 2\ \mathrm{jets} \qquad \ell = e, \mu, \tau$$

Neutrinoless probes of $\Delta L=2$ dynamics

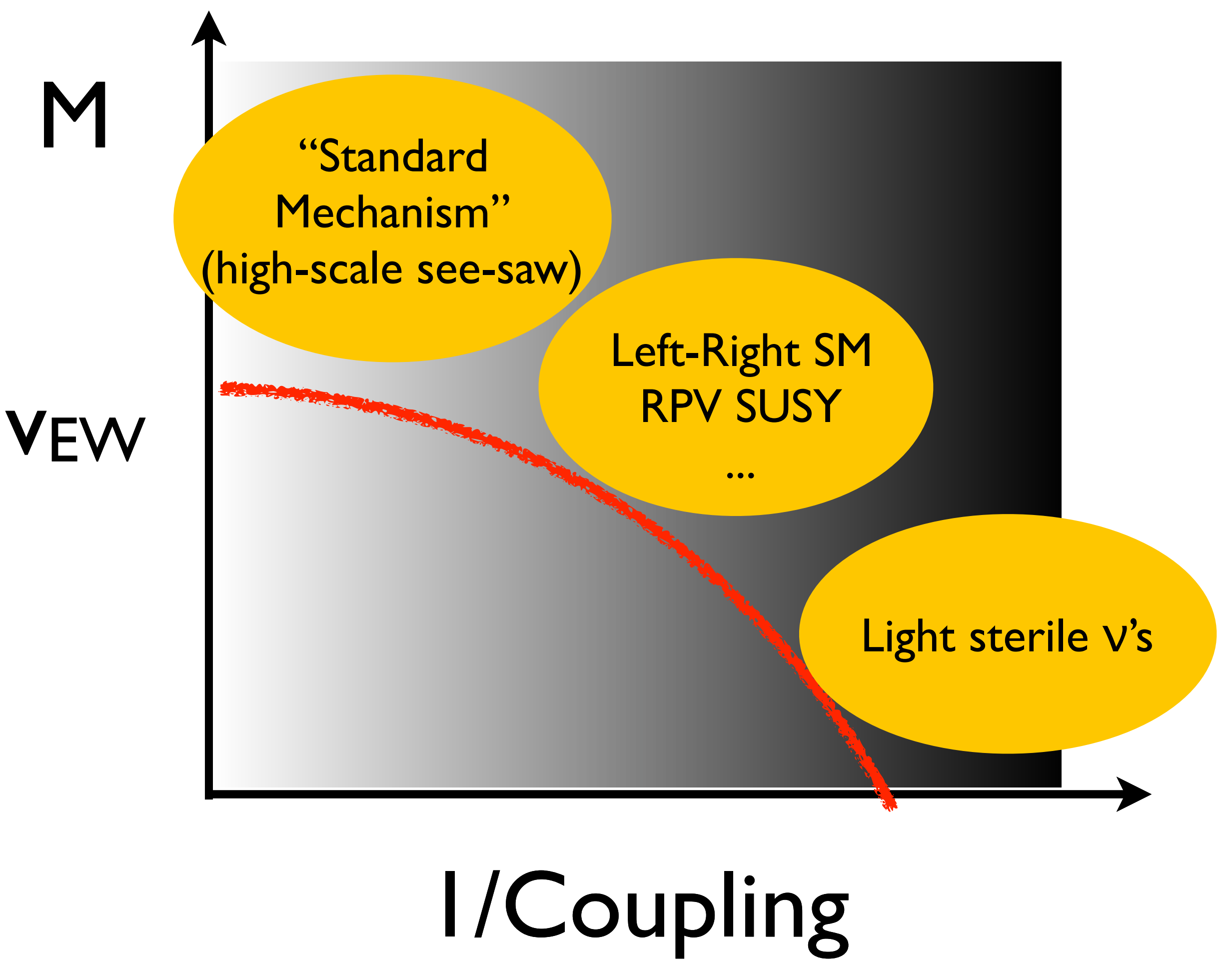
- Neutrinoless double beta decay
  - Currently probing $m_{ee} \equiv m_{\beta\beta} \sim 0.1$ eV and $\Lambda_{6\text{-fermion}} \sim$ few TeV
- Decays of mesons or leptons
  - Not competitive in high-scale LNV models: probing $m_{ab} \sim$ eV and $\Lambda_{6\text{-fermion}} \sim$ TeV requires BRs $\sim 10^{-30}$. (Avogadro number wins!)
  - Competitive for low-scale LNV models

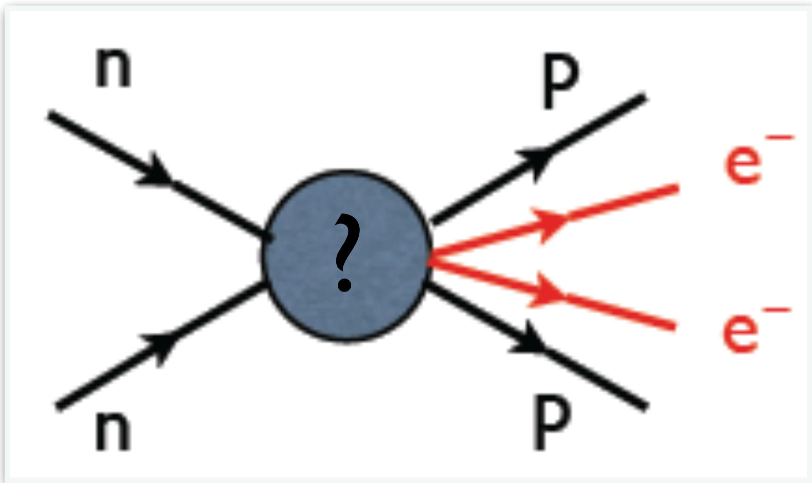
A. Teixeira et al. 1712.03984

- Same sign di-lepton production at LHC
  - Competitive probe of LNV mechanism at the TeV scale

$0\nu\beta\beta$ and Lepton Number Violation

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) probe at unprecedented levels LNV from a variety of mechanisms

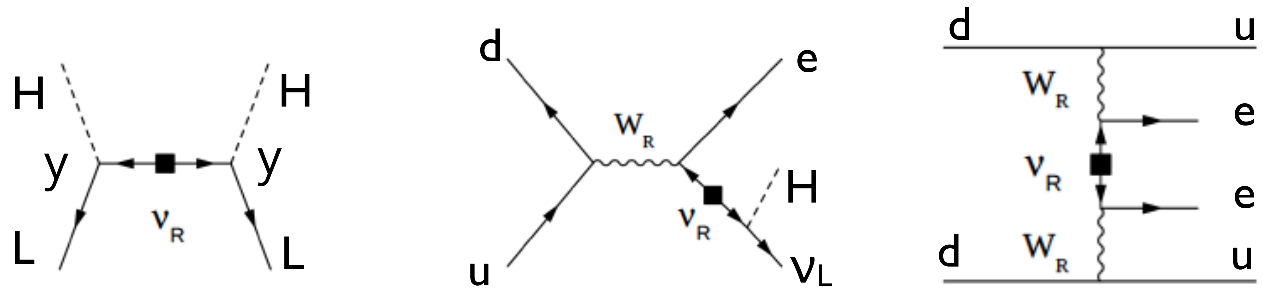




Impact of $0\nu\beta\beta$ searches most efficiently analyzed in EFT framework

EFT framework

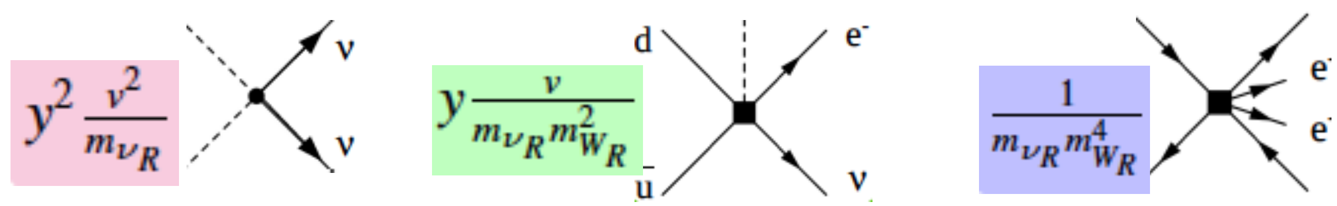
E



BSM dynamics

Example:
Left-Right Symmetric Model

Λ
(> TeV)



SM-EFT

dim5 dim7 dim9

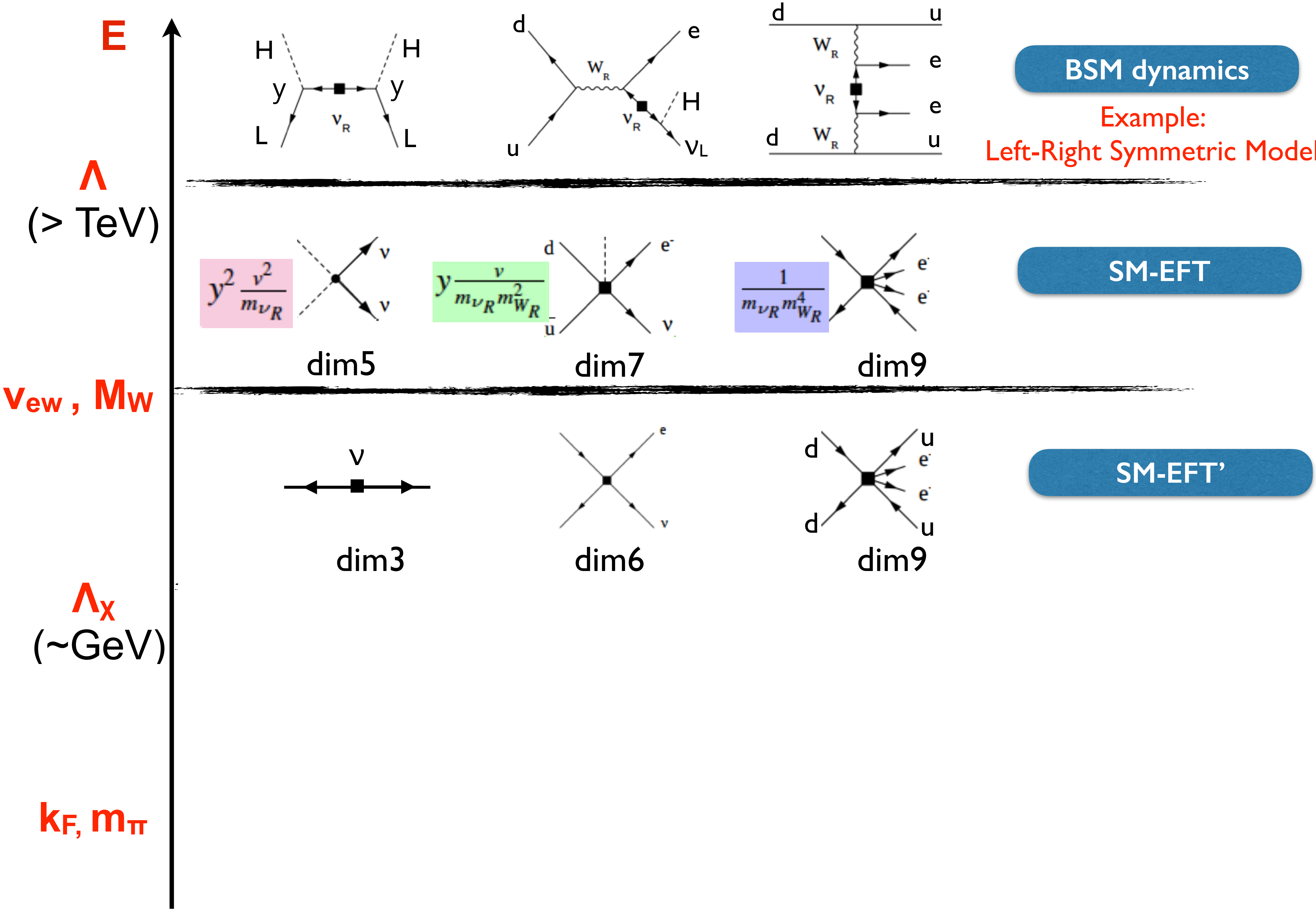
v_{ew} , M_W

Λ_X
(~GeV)

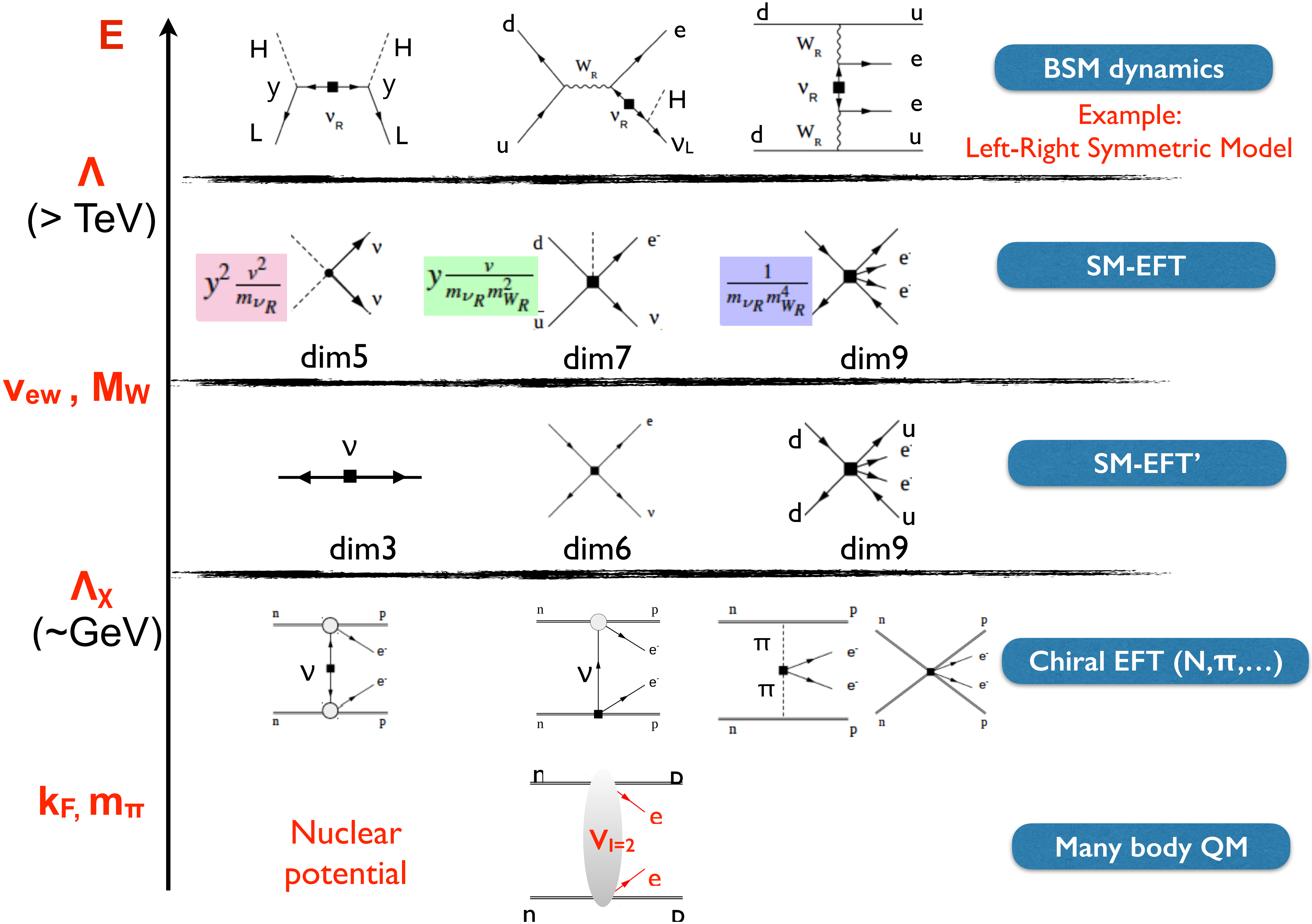
k_F, m_π

- $\Delta L=2$ operators appear only at odd dimension — A. Kobach 1604.05726
- Insertions of small dimensionless (Yukawa) coupling can make dim=5,,7,9 operators equally important for $\Lambda\sim$ TeV
- ν_R with mass < M_W can be included in the framework

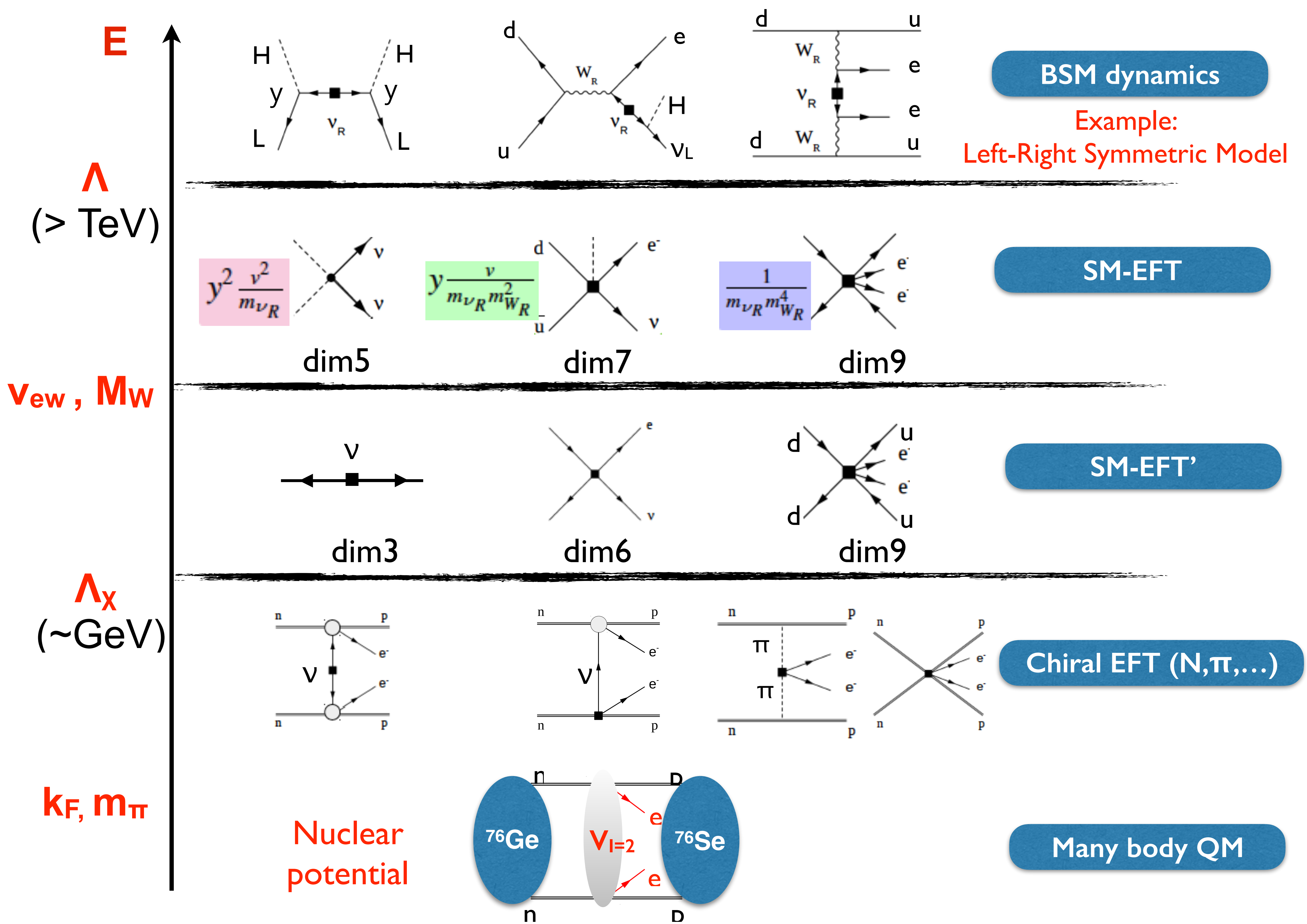
EFT framework



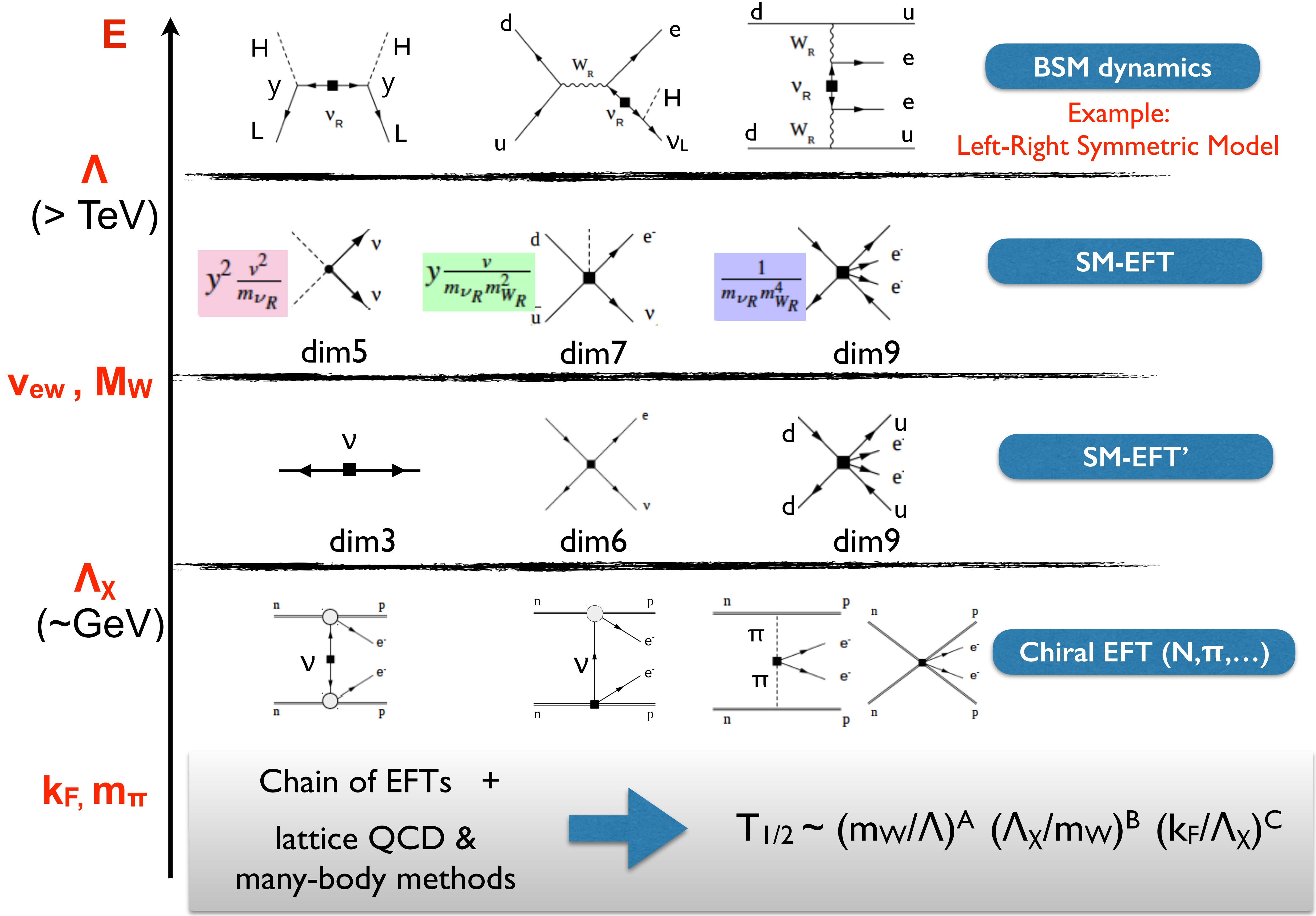
EFT framework



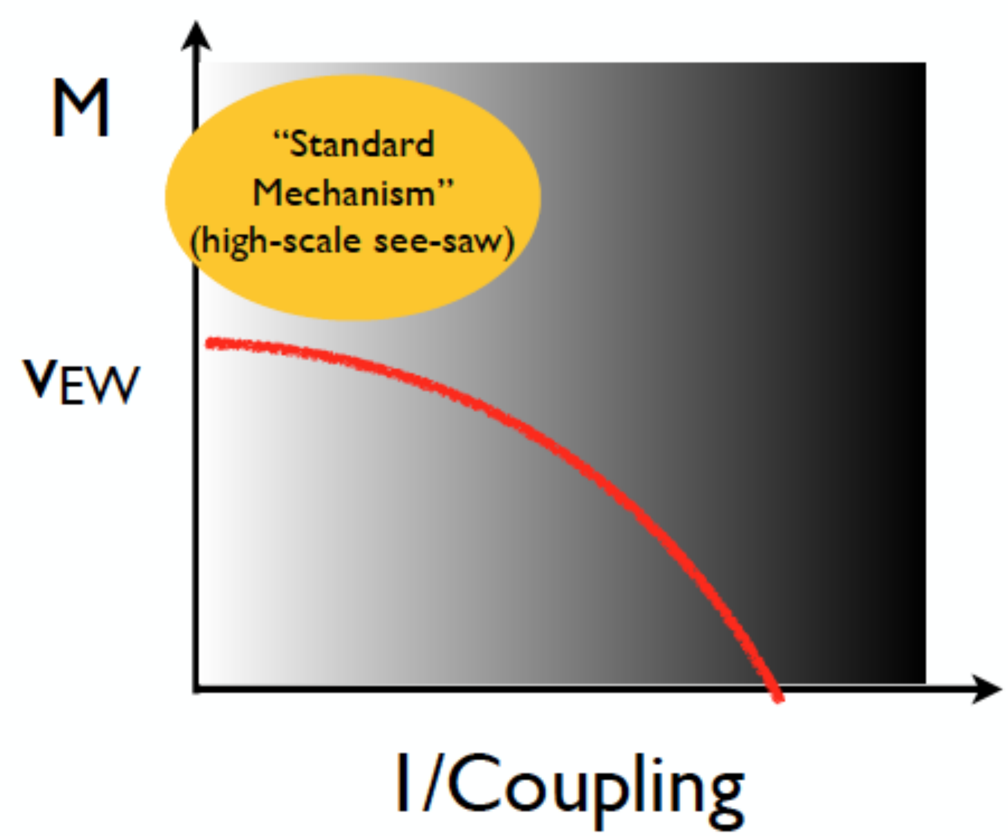
EFT framework



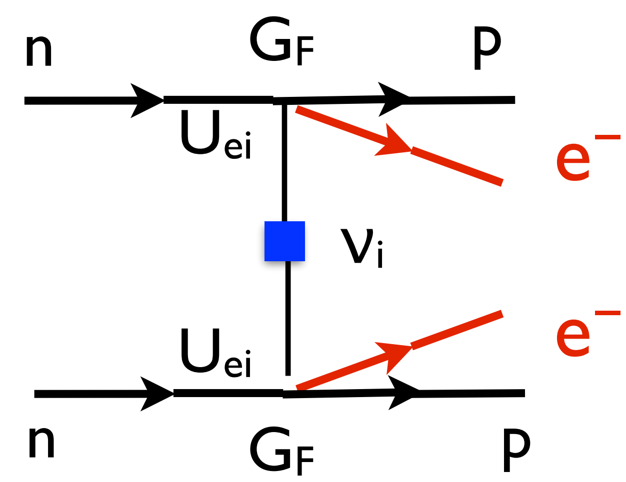
EFT framework



$0\nu\beta\beta$ from light Majorana neutrino exchange (dim-5 operator)



$0\nu\beta\beta$ from light ν_M exchange



Decay amplitude

$$\boxed{A \;\propto\; m_{\beta\beta}\, \langle f|\, \sum_{a,b} V_\nu^{(a,b)}\, |i\rangle}$$

$m_{\beta\beta} = \sum U_{ei}^2\, m_i$

$$\boxed{V_\nu^{(a,b)} = \tau^{+,a}\tau^{+,b}\,\frac{1}{\mathbf{q}^2}\,\Big(J_V^{(a)}(\mathbf{q})J_V^{(b)}(-\mathbf{q}) + J_A^{(a)}(\mathbf{q})J_A^{(b)}(-\mathbf{q})\Big)}$$

$$J_V \sim 1$$
$$J_A \sim g_A\,\sigma$$

In this case $0\nu\beta\beta$ is a *direct* probe of ν mass and mixing: $\Gamma \propto |M_{0\nu}|^2\,(m_{\beta\beta})^2$

$m_{\beta\beta}$ phenomenology

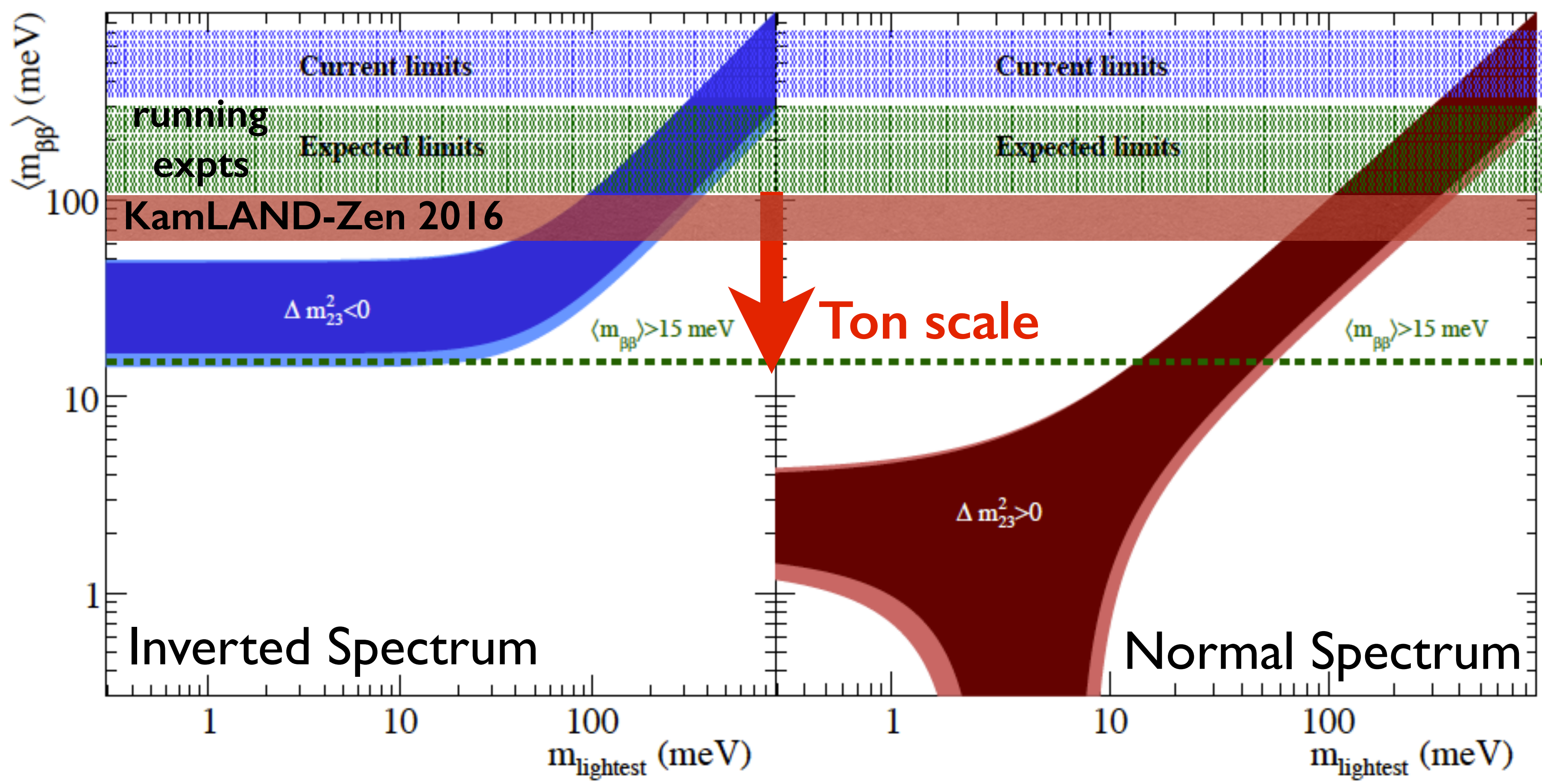
- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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

See talk by L. Cardani

Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)



Plot by K. Heger

- Assuming current range for matrix elements, discovery *possible* for inverted spectrum or $m_{lightest}$ > 50 meV (regardless of mass ordering)

$m_{\beta\beta}$ phenomenology

- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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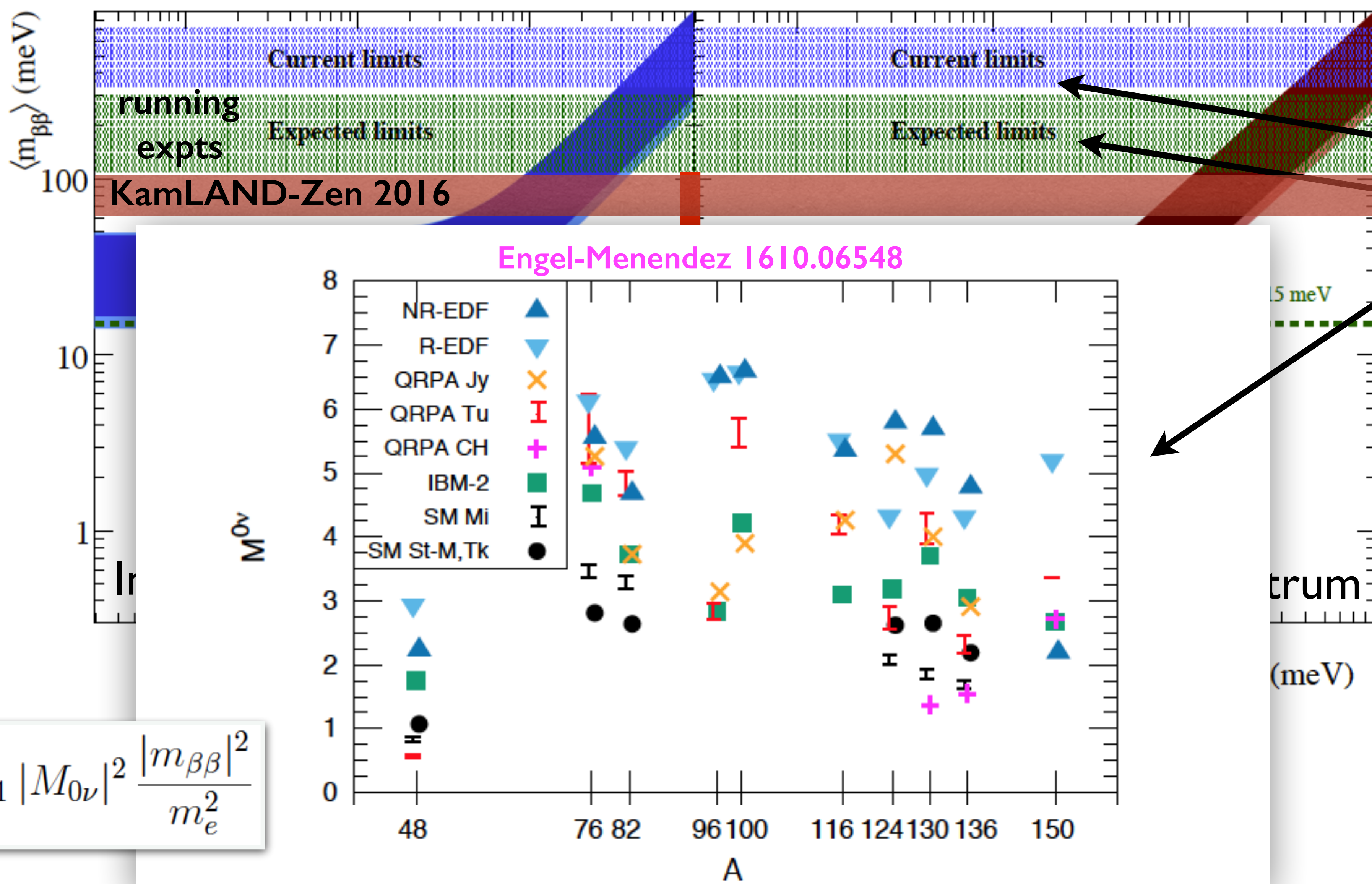


Assume range for nuclear matrix elements from different many-body methods

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, G_{01}\, |M_{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Room for theory improvement?

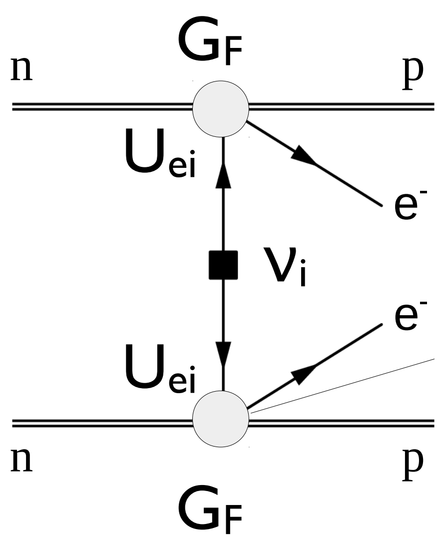
- Steps towards controllable uncertainties in matrix elements:
  - Use chiral EFT as guiding principle
  - Use first-principles results in light nuclei (A=12) as a benchmark

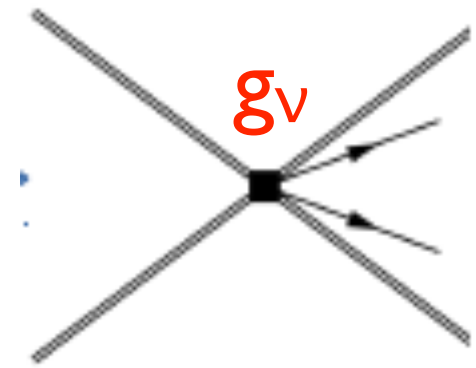
    S. Pastore et al., 1710.05026

  - First principles nuclear structure calculations in sight for ^{48}Ca and ^{76}Ca, with QCD-rooted chiral potentials

    G. Hagen, T. Papenbrock et al., to appear

Light ν_M exchange in chiral EFT





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

1802.10097

- Leading order (LO) term in Q/Λ_χ ($Q \sim k_F \sim m_\pi$): tree-level ν_M exchange

$$V_\nu^{(a,b)} = \frac{J^{(a)}(\mathbf{q})\, J^{(b)}(-\mathbf{q})}{\mathbf{q}^2}\, \tau^{(a)+}\tau^{(b)+}$$

- Renormalization of $nn \to ppee$ amplitude in presence of LO strong potential requires a LO short-range coupling $g_\nu \sim 1/F_\pi^2 \sim 1/k_F^2$!

$$V_{\nu,CT}^{(a,b)} = -2\, g_\nu\, \tau^{(a)+}\tau^{(b)+}$$

Estimating finite part of g_ν

1) Match χEFT & lattice QCD calculation of hadronic amplitude nn→pp

$$S_{\rm eff}^{\Delta L=2} = \frac{i8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, T\Big(\bar{u}_L\gamma_\mu d_L(x)\, \bar{u}_L\gamma_\mu d_L(y)\Big) g^{\mu\nu}$$

Scalar massless propagator
(remnant of ν propagator)

Estimating finite part of g_ν

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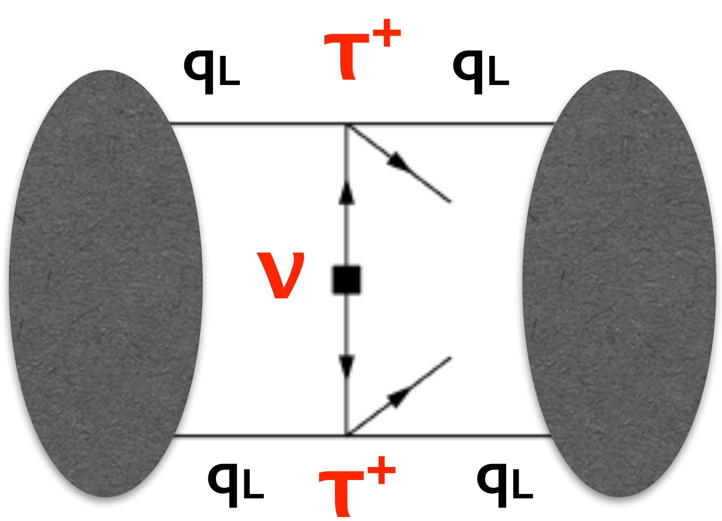
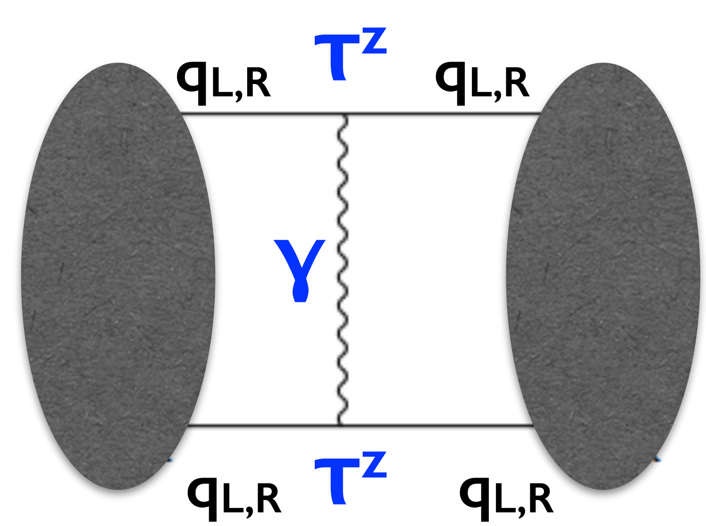
Scalar massless propagator
(remnant of ν propagator)

$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2) Chiral symmetry relates g_ν to one of two I=2 EM LECs





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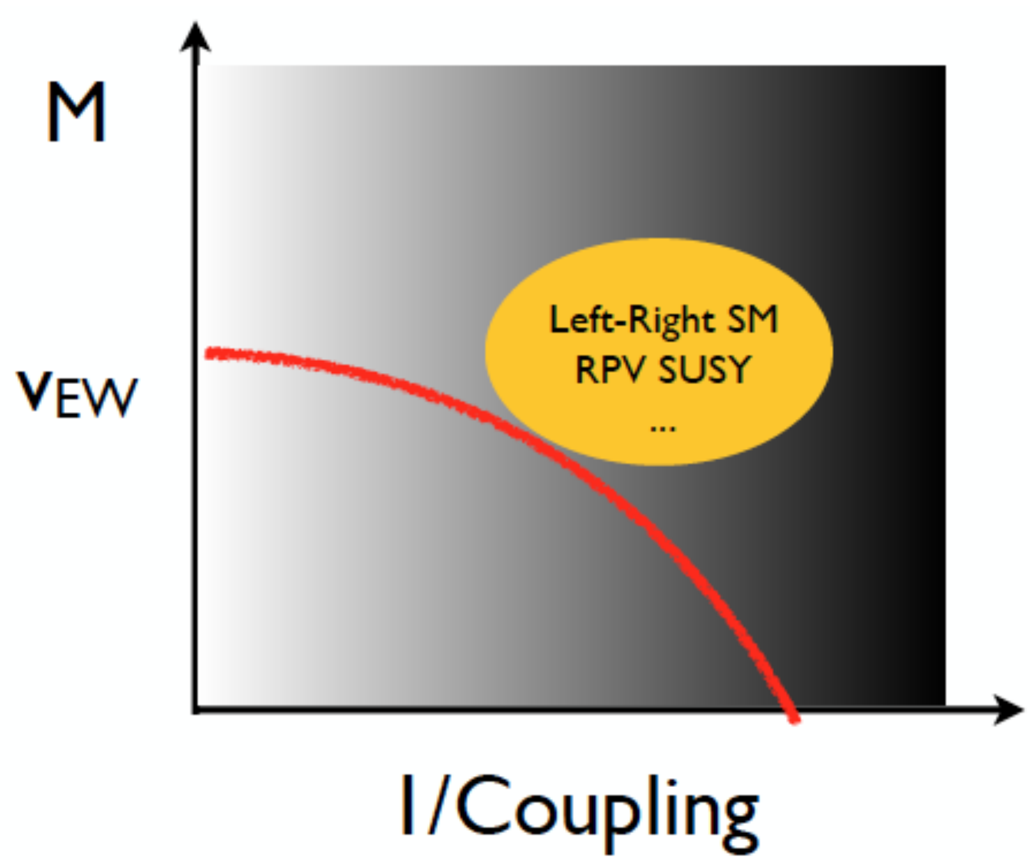
Scalar massless propagator
(remnant of ν propagator)

$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2) Chiral symmetry relates g_ν to one of two I=2 EM LECs

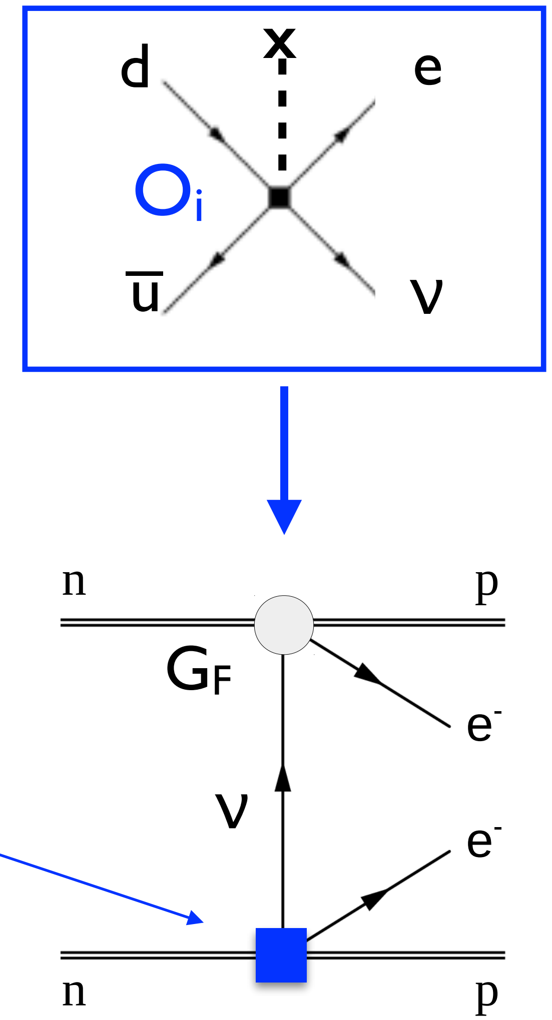
- Only one combination of the EM constants fixed by NN scattering
- Using this as rough estimate of g_ν, we get O(50%) shift for the matrix element in light nuclei (A=12)
- Strong motivation to pursue lattice QCD calculation

0νββ from higher-dimensional operators



$0\nu\beta\beta$ from $\mathcal{L}^{(7)}_{\Delta L=2}$

Long range effect:
ν exchange *without*
mass insertion



LNV vertex

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

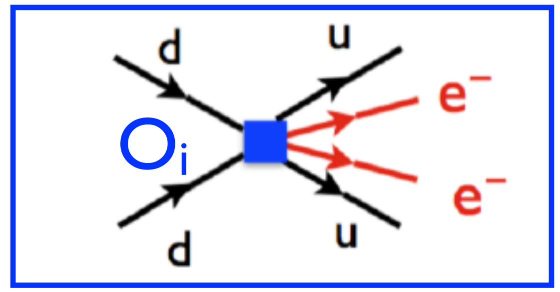
Horoi and Neacsu, 1706.05391 and refs therein

Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999

Doi, Kotani, Takasugi 1985

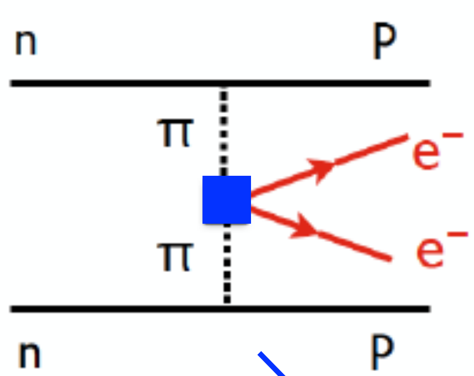
- Hadronic input in good shape: isovector nucleon charges (V, A, S, P, T)
- Nuclear m.e. related to the one needed for light ν_M exchange

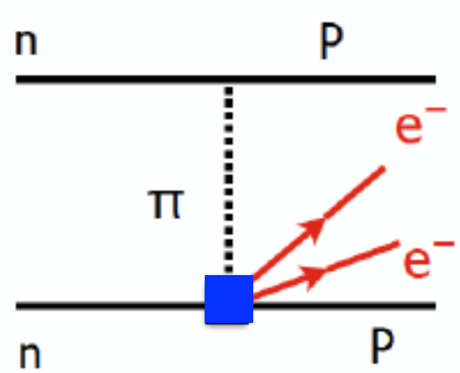
$0\nu\beta\beta$ from $\mathcal{L}^{(9)}_{\Delta L=2}$

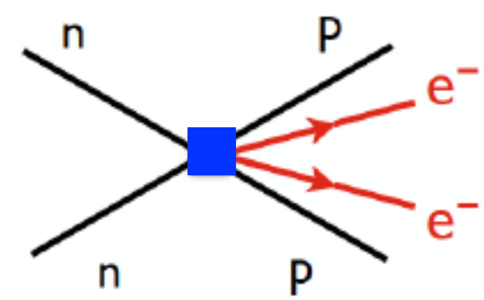


Pion-range effects

Short-range effects







$$V_{I=2} \supset \left(c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN}\right)$$

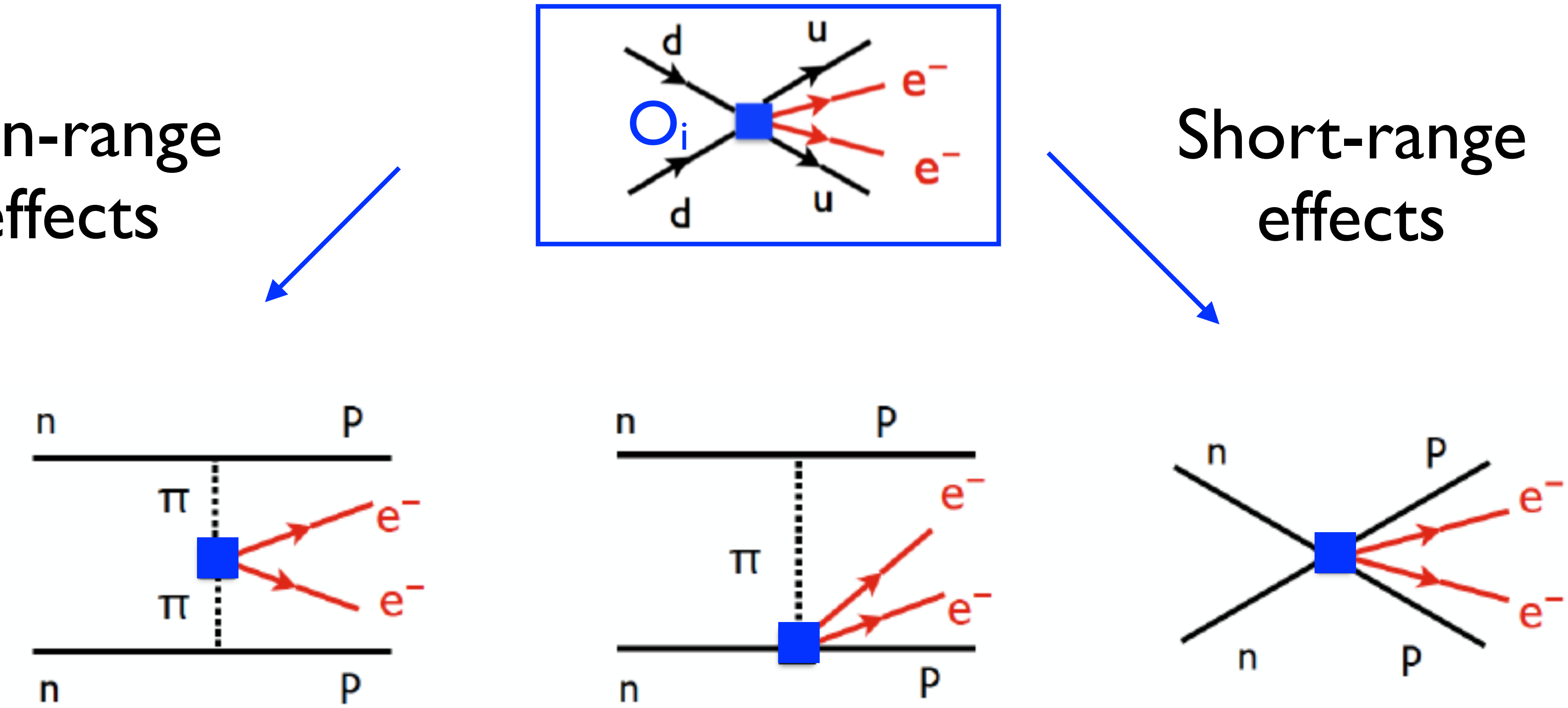
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

$c_\alpha \sim$ short-distance coupling (model-dep.) × hadronic matrix element

$0\nu\beta\beta$ from $\mathcal{L}^{(9)}_{\Delta L=2}$

Pion-range effects

Short-range effects



- Relative importance of $V_{\pi\pi,\,\pi N,NN}$ depends on O_i's chiral properties
- Non-perturbative renormalization → $V_{\pi\pi}$ and V_{NN} are both leading
- $<\pi^+|O_i|\pi^->$ known from lattice QCD

Nicholson et al., 1805/02634

- $<pp|O_i|nn>$ not yet known from LQCD (only factorization model)
- Nuclear matrix elements related to the ones for light ν_M exchange

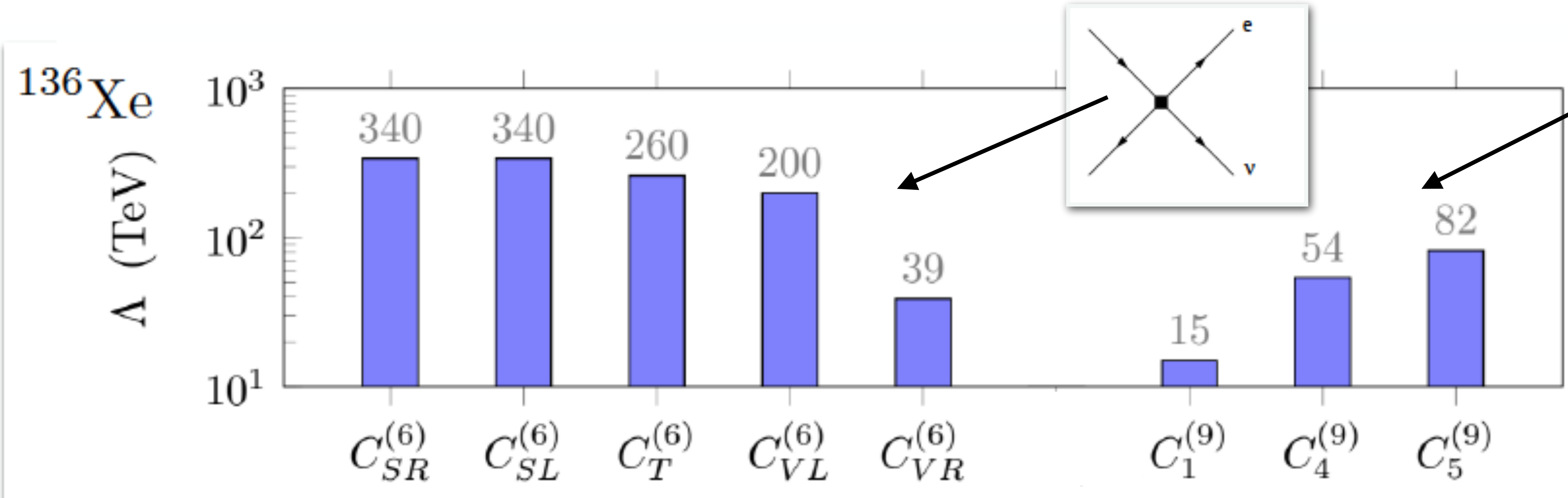
VC, Dekens, et al. 1806.02780

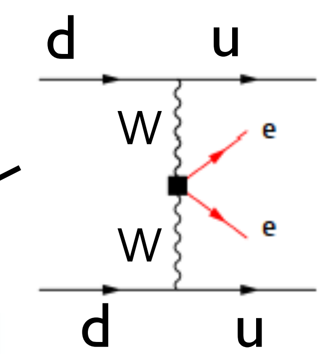
What scales are being probed?

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

Dim 7 in SM-EFT

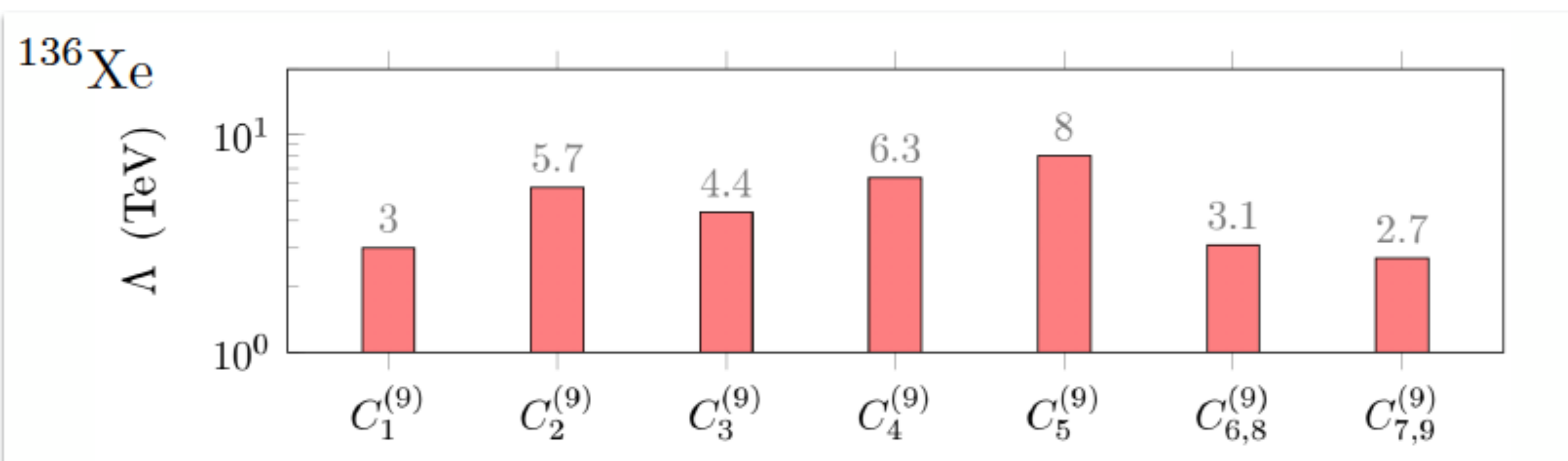
$(v/\Lambda)^3$

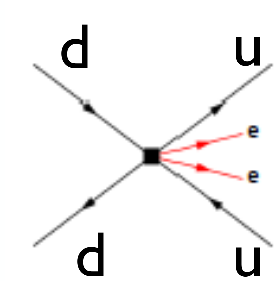




Dim 9 in SM-EFT

$(v/\Lambda)^5$

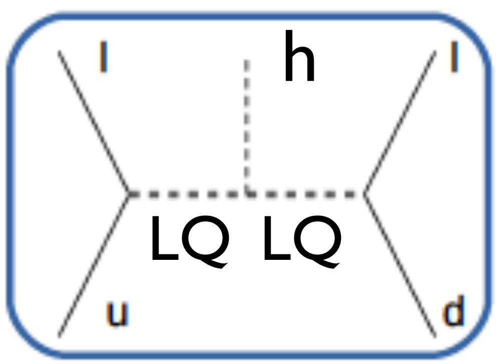




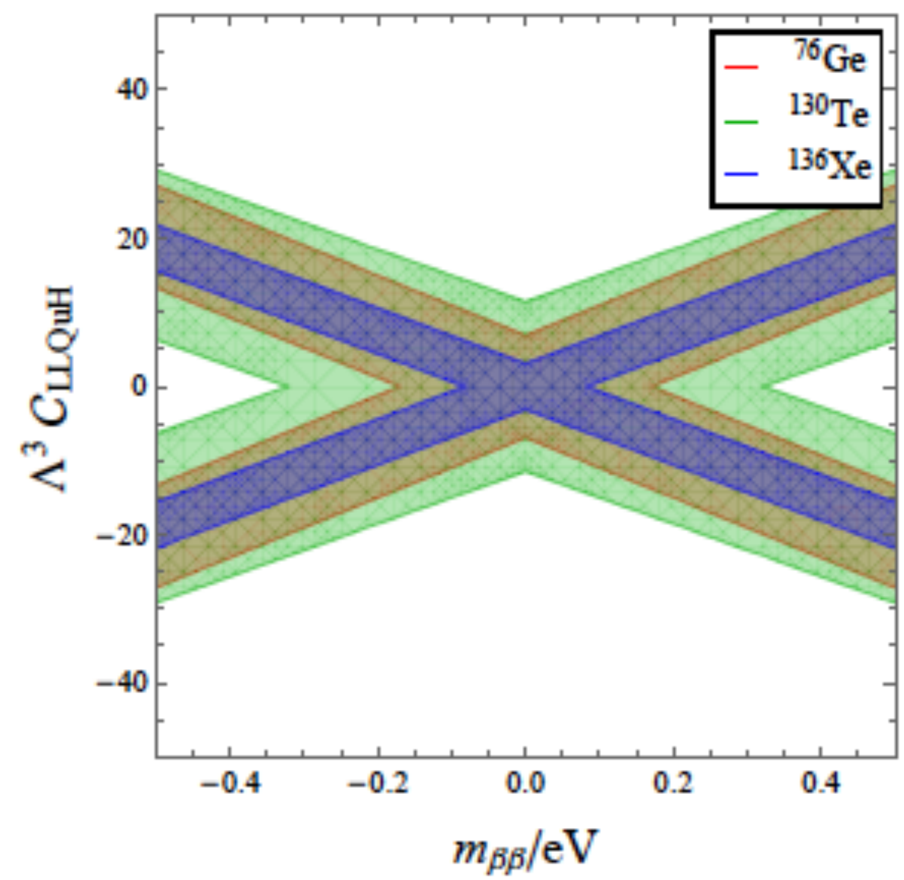
Bounds reflect dependence on Λ_χ / Λ and Q/Λ_χ

Dim-7 phenomenology (I)

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (leptoquark-induced)



e.g. leptoquarks



$$C_{LL\bar{Q}uH}\,\epsilon_{ij}\,(\bar{Q}_m u)\,(L_m^T C L_i)\,H_j$$

$$\Lambda = 600\ \text{TeV}$$

Nuclear matrix elements from Hyvarinen-Suhonen PRC 91 024613 (2015)

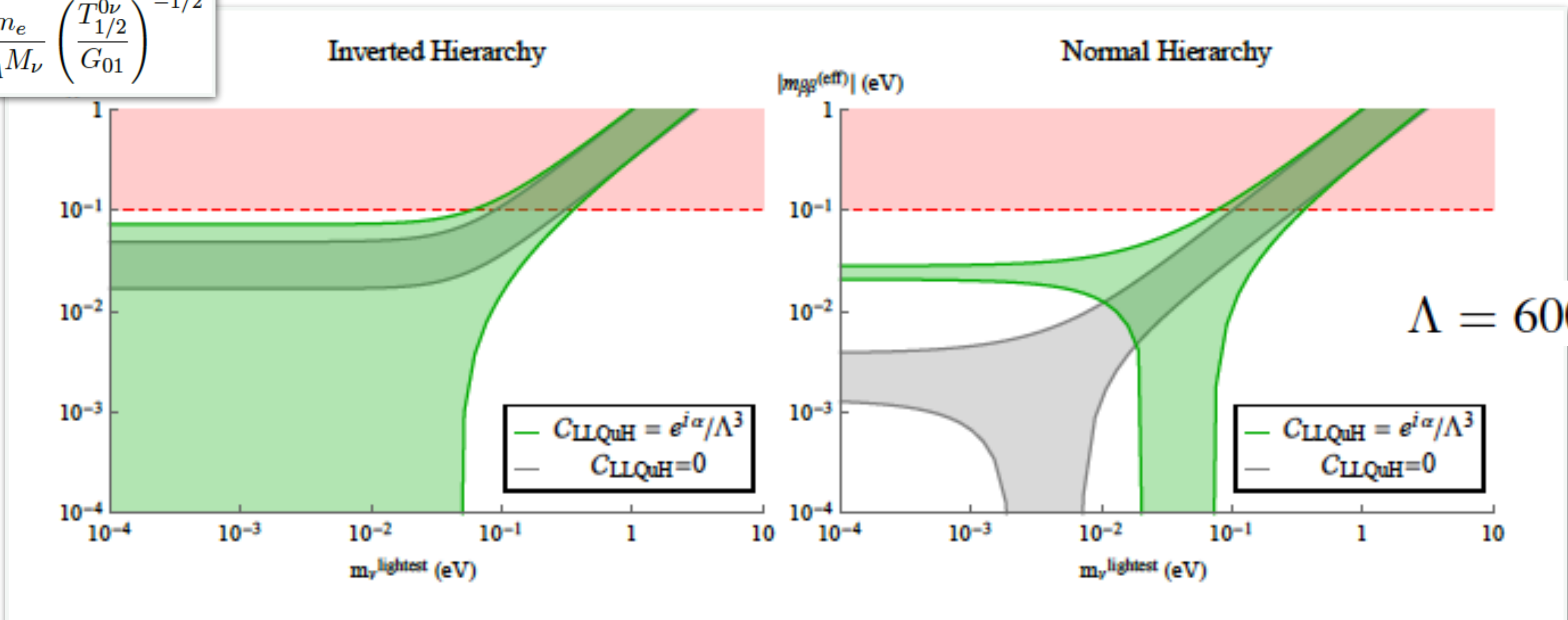
- Same leptonic structure as in ν_M exchange: can cancel $m_{\beta\beta}$!!

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Dim-7 phenomenology (1)

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (leptoquark-induced)

$$m_{\beta\beta}^{(\text{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$



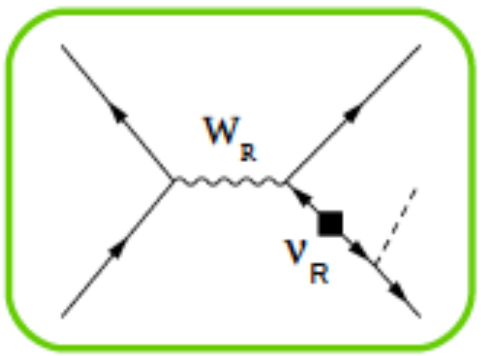
$\Lambda = 600$ TeV

- Same leptonic structure as in ν_M exchange: can cancel $m_{\beta\beta}$!!

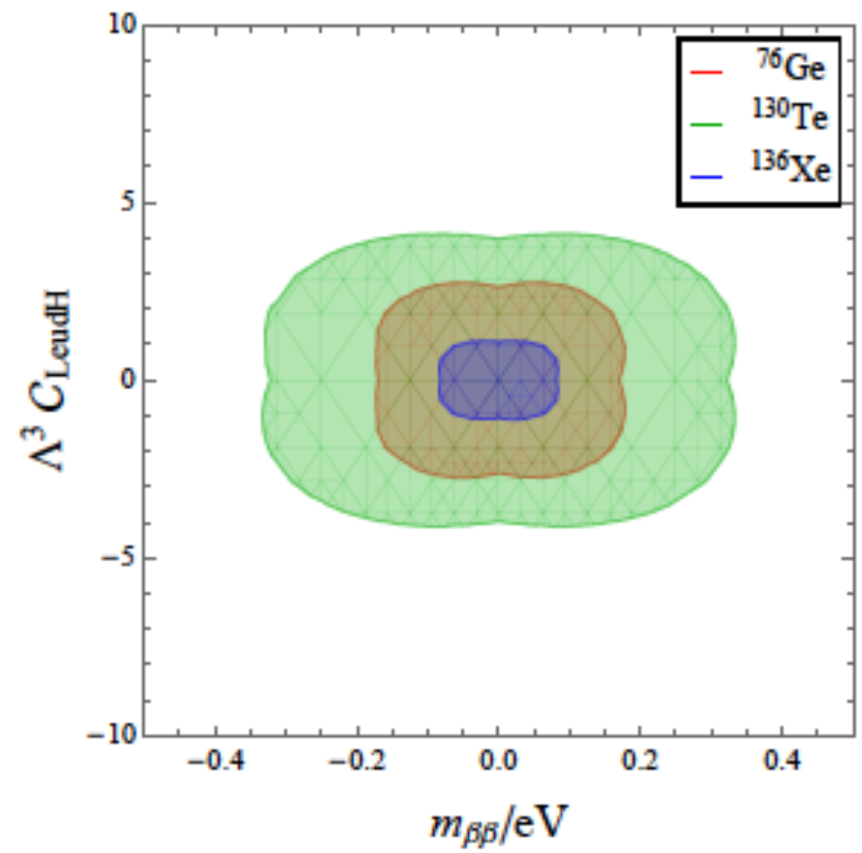
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Dim-7 phenomenology (2)

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (LRSM-induced)



e.g. LR models



$$\mathcal{C}_{LeudH}\, \epsilon_{ij}\, (\bar{d}\gamma^{\mu} u)\, (L_m^T C \gamma_{\mu} e)\, H_j$$

$$\Lambda = 40 \text{ TeV}$$

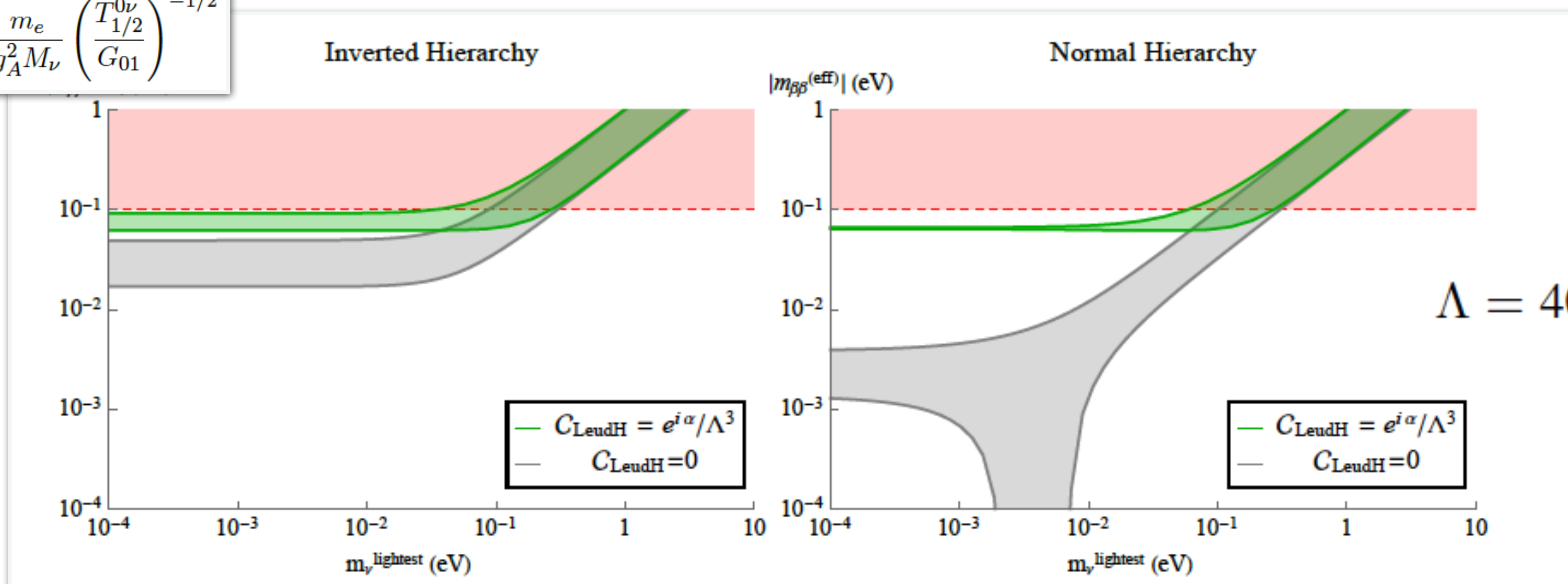
- Different leptonic structure from light ν_M exchange: no cancellation

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Dim-7 phenomenology (2)

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (LRSM-induced)

$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$



$\Lambda = 40$ TeV

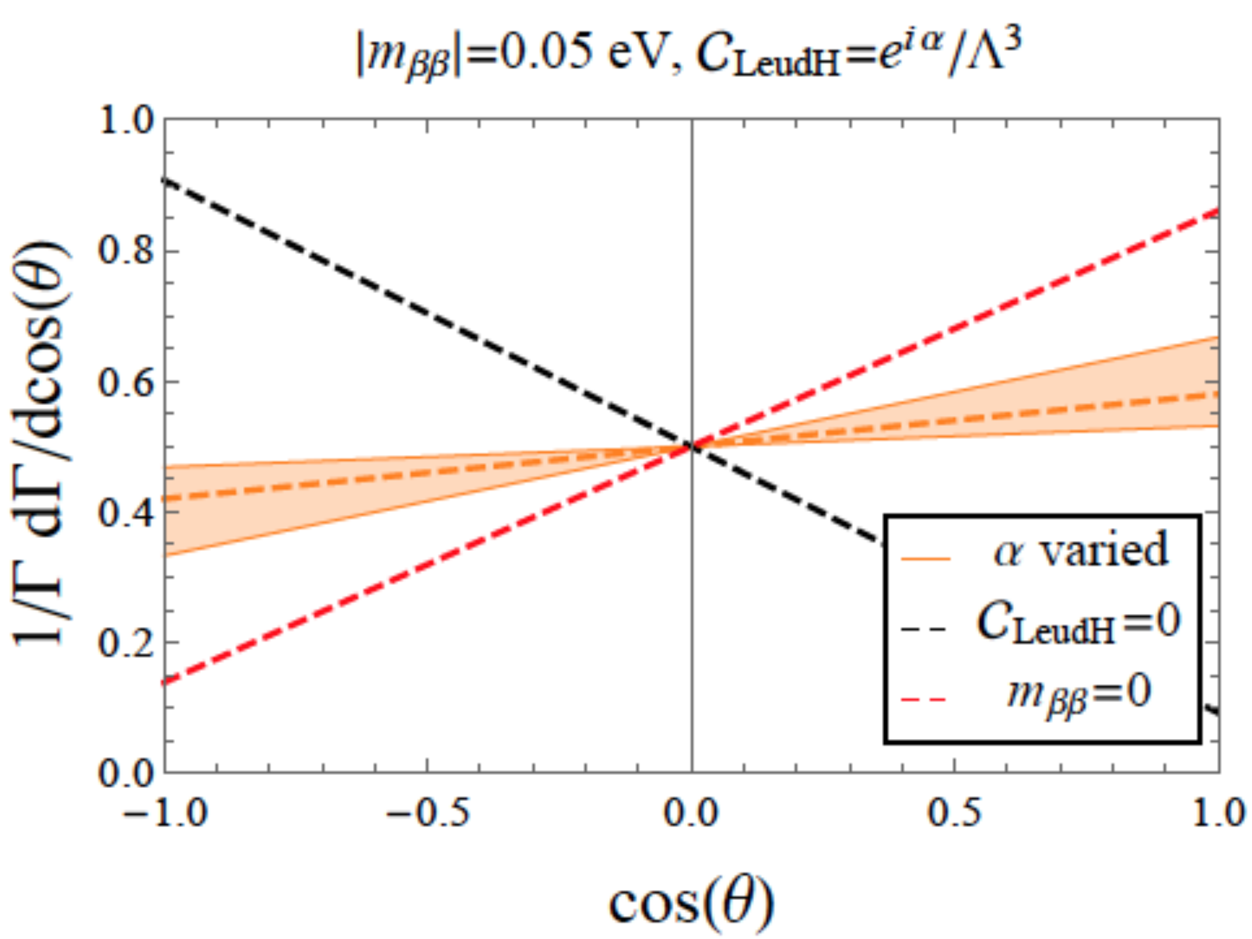
- Different leptonic structure from light ν_M exchange: no cancellation

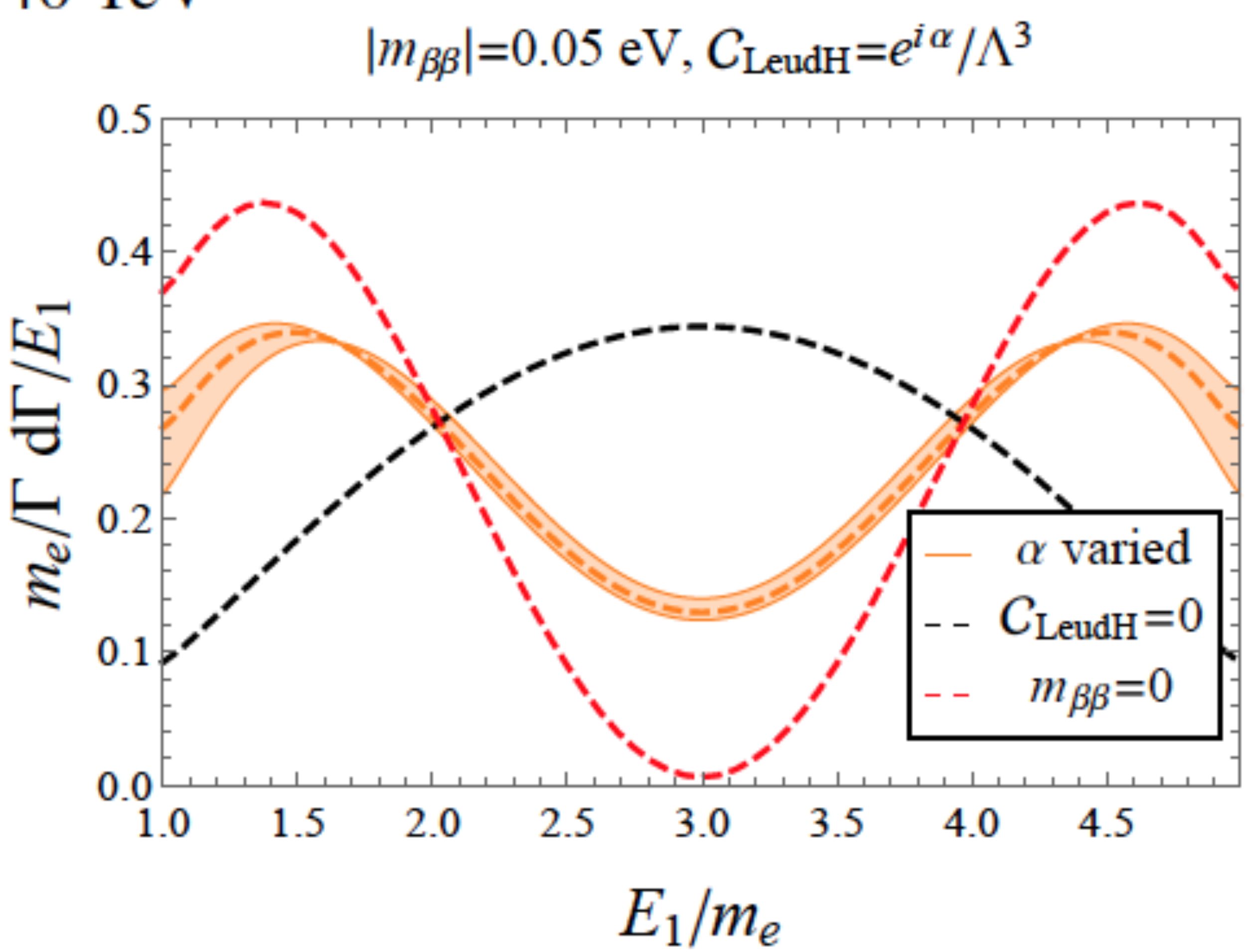
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Dim-7 phenomenology (2)

- Dim-5 ($m_{\beta\beta}$) + Dim-7 operator (LRSM-induced)
- In this case, electron θ and E distributions distinguish dim5 and dim7

$\Lambda = 40$ TeV



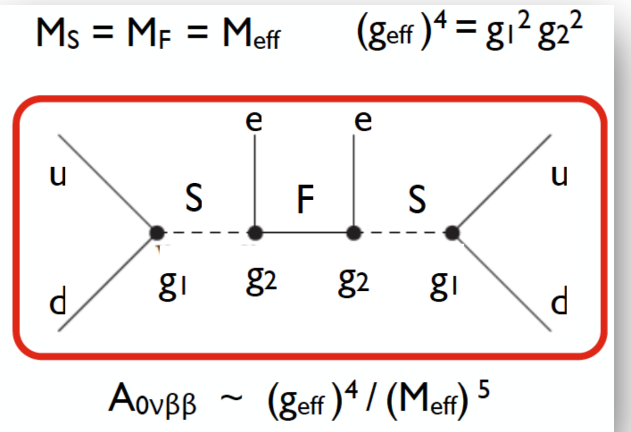


VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

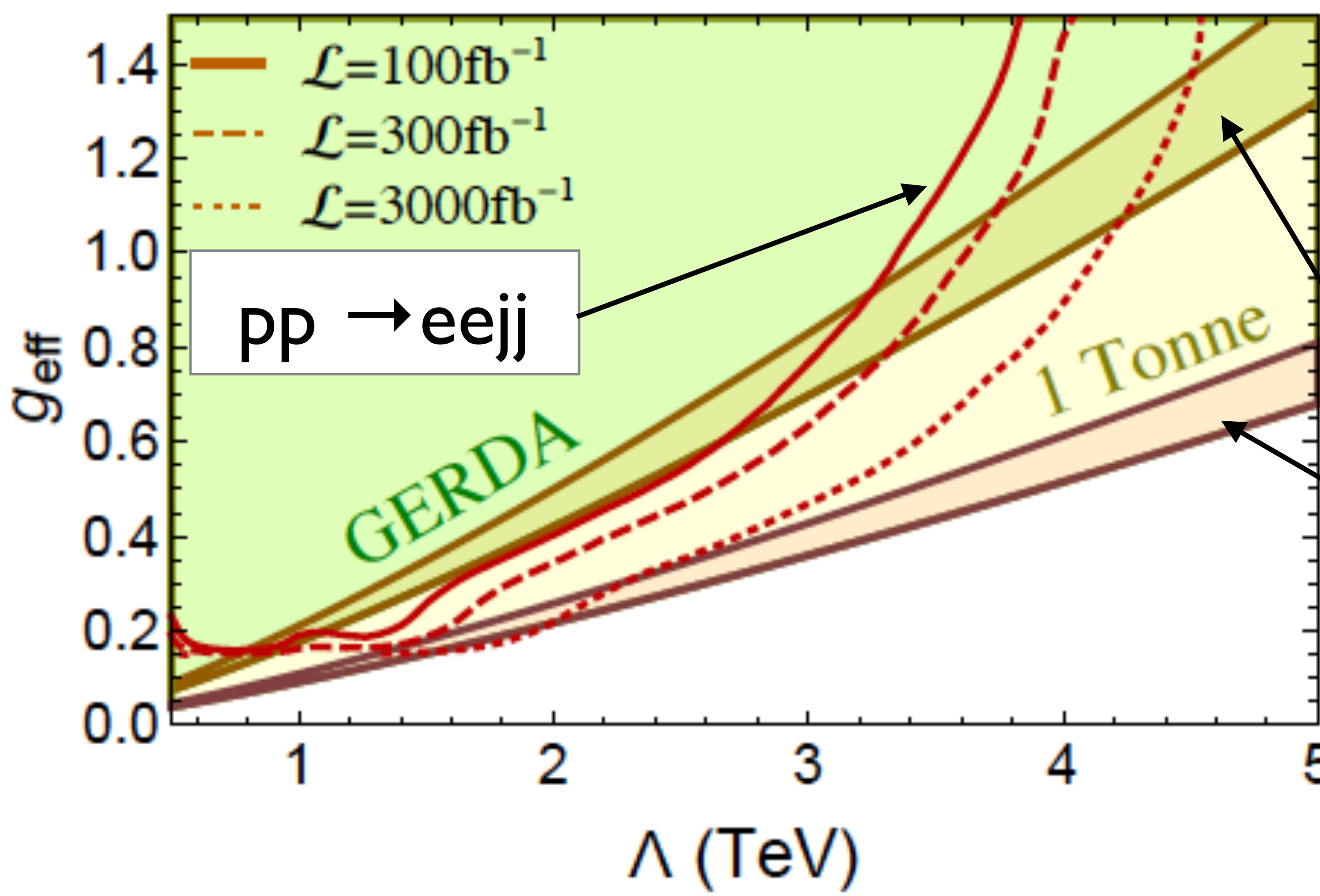
Simplified RPV-SUSY-like model

- Sensitivity study: 0νββ vs LHC

Peng, Ramsey-Musolf, Winslow, 1508.0444



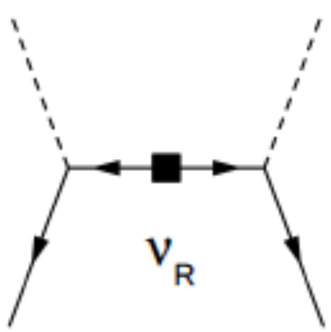
Dim-9 ΔL=2 six-fermion operator at low energy

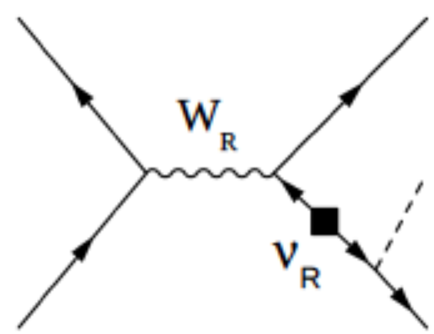


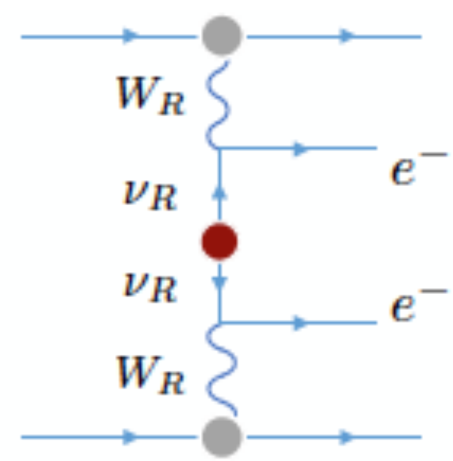
Plot assumes 30% uncertainty in the nuclear & hadronic matrix elements and VSA for ππ matrix element *(~ 2 x lattice result)*

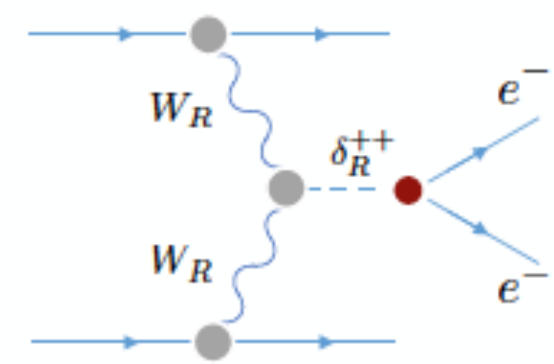
Left-Right symmetric model

- Generates ops. at dim-5 ($m_{\beta\beta}$) + dim-7 & dim-9

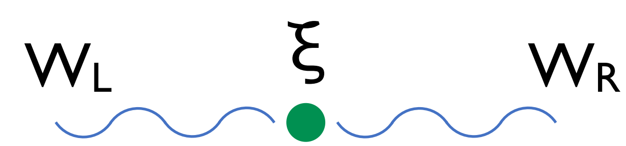








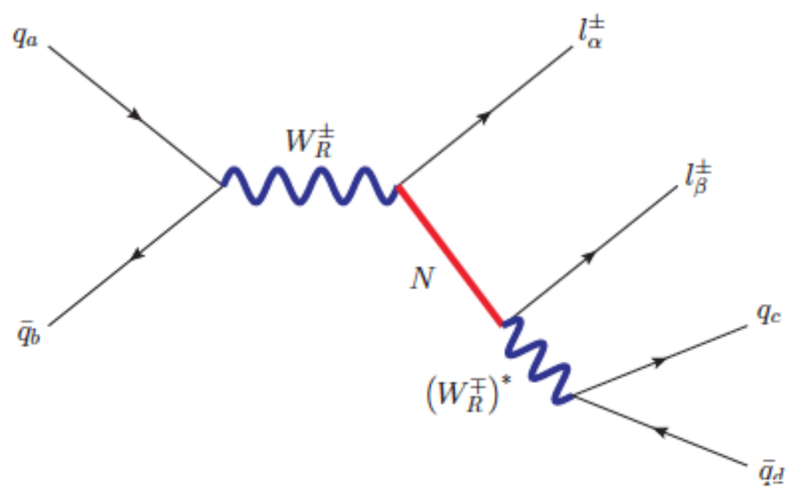
Chirally enhanced for ($\xi \neq 0$)



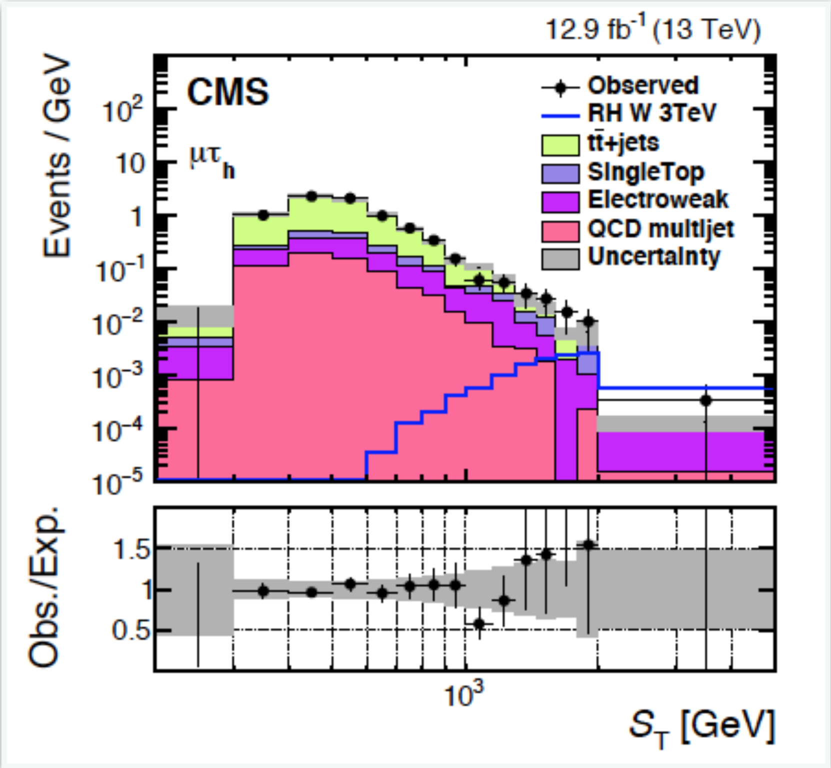
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

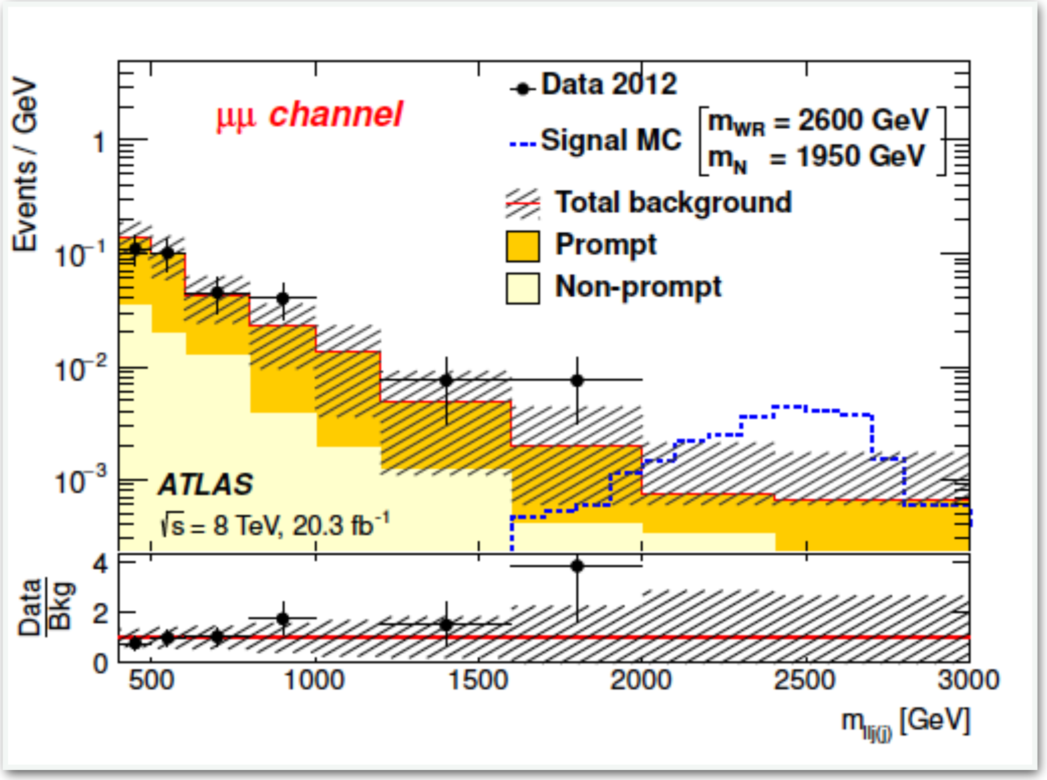
Left-Right symmetric model

- Generates ops. at dim-5 ($m_{\beta\beta}$) + dim-7 & dim-9
- LHC bounds exist



$\tau_h\tau_\mu$ channel





1703.03995

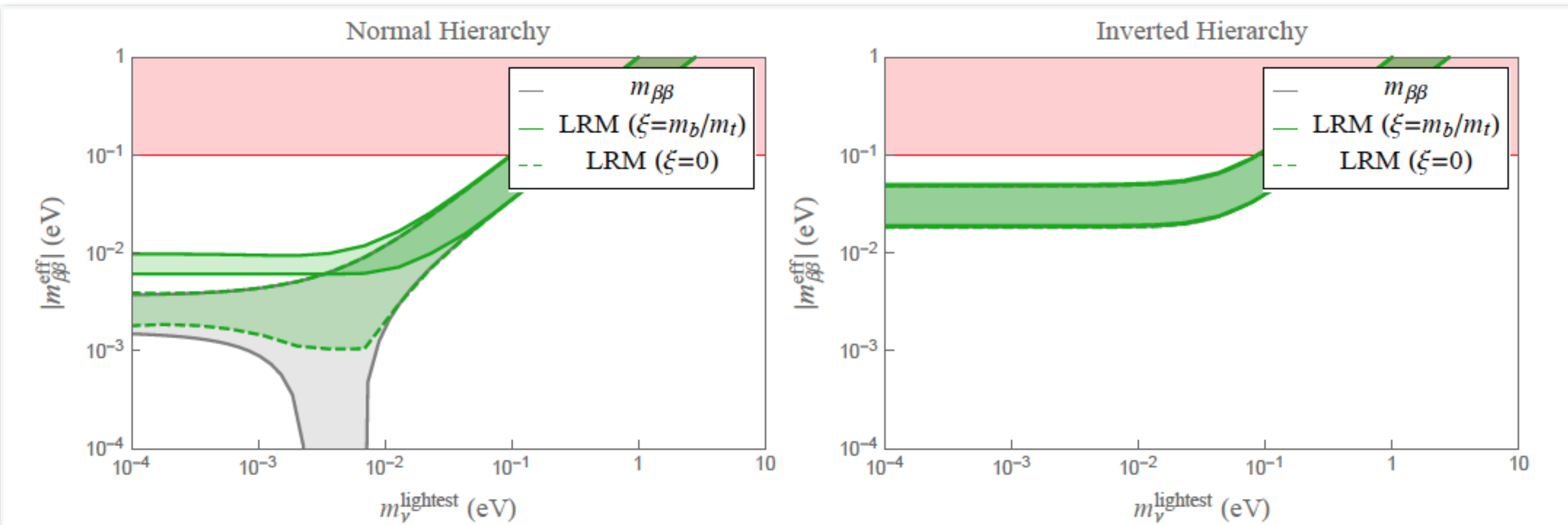
1506.06020

Left-Right symmetric model

- Generates ops. at dim-5 ($m_{\beta\beta}$) + dim-7 & dim-9
- Dim-9 contribution sizable in NH

Illustrative LHC-safe parameters

$$m_{W_R} = 4.5 \text{ TeV} \quad m_{\Delta_R} = 10 \text{ TeV} \quad m_{\nu_R} = O(10 \text{ TeV}) \quad U_R = U_{\text{PMNS}}$$



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

Conclusions

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe LNV from a variety of mechanisms — please don't get stuck on "Ah, but if it's normal hierarchy we'll never see anything…"

- EFT approach provides a general framework to:

1. Relate $0\nu\beta\beta$ to underlying LNV dynamics (and collider processes)
    - Illustrated by studying dim 7 and dim 9 operators in the SM-EFT and simple models (~LRSM, RPV-SUSY)
2. Organize contributions to hadronic and nuclear matrix elements
    - Leading potentials from dim5 & dim9 LNV involve new "contacts"

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

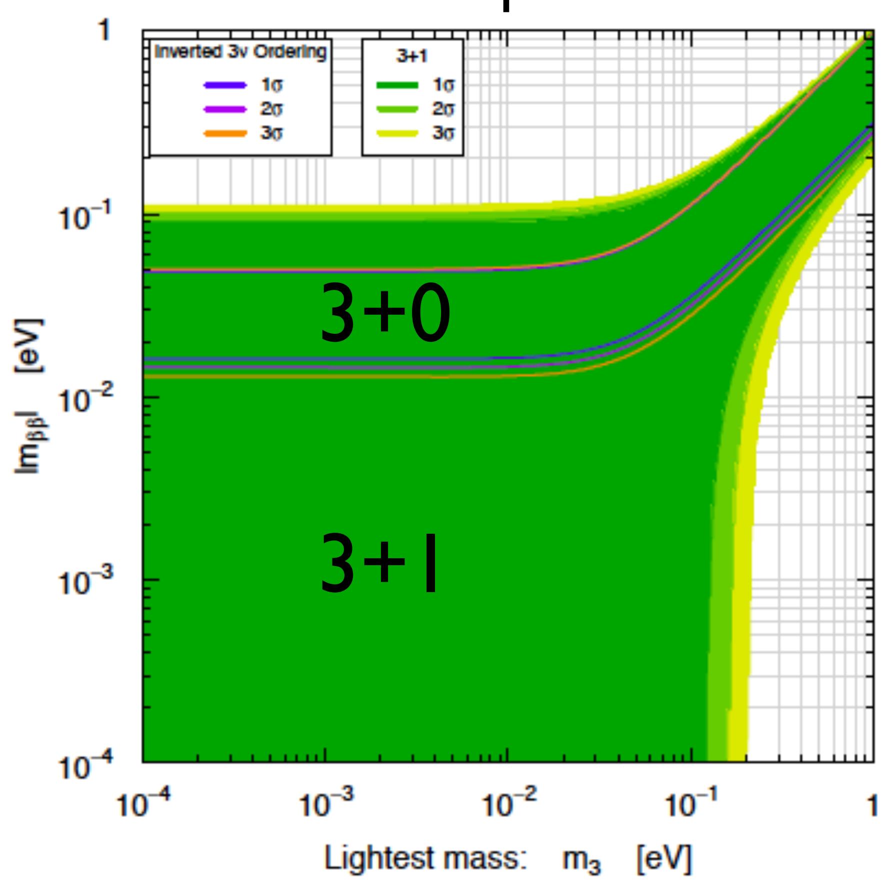
Backup

Low scale LNV

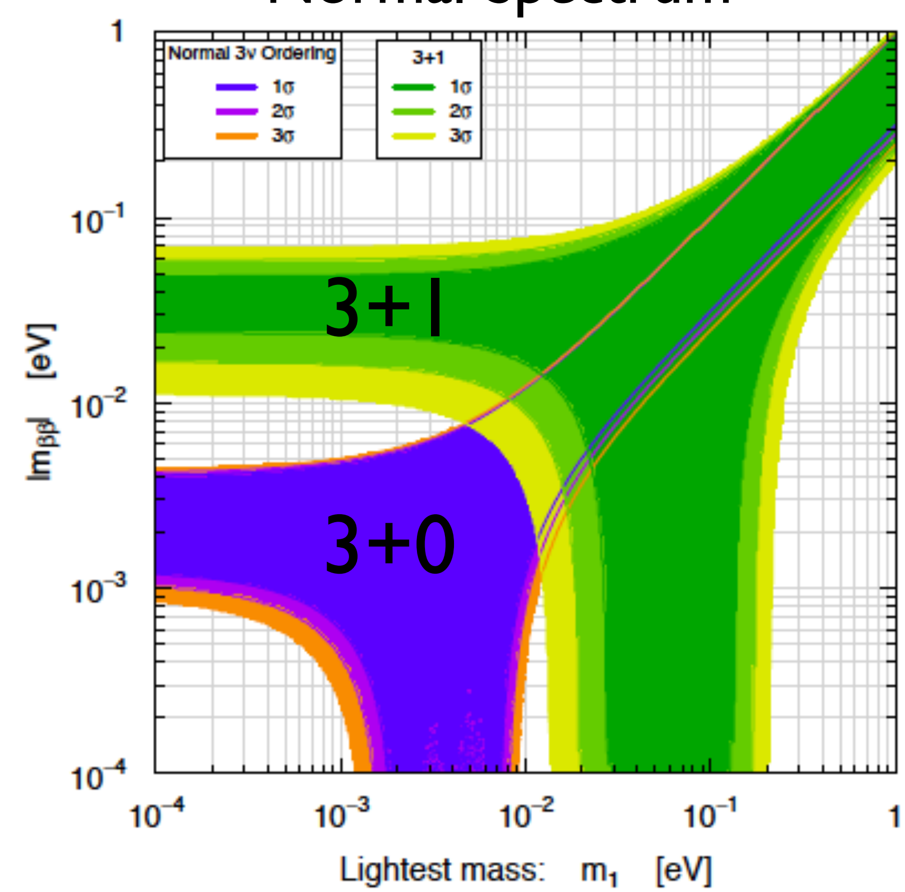
- Low scale seesaw: intriguing example with one light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies
- Extra contribution to effective mass

$$m_{\beta\beta} = m_{\beta\beta}|_{\text{active}} + |U_{e4}|^2 \, e^{2i\Phi} \, m_4$$

Inverted Spectrum



Normal Spectrum



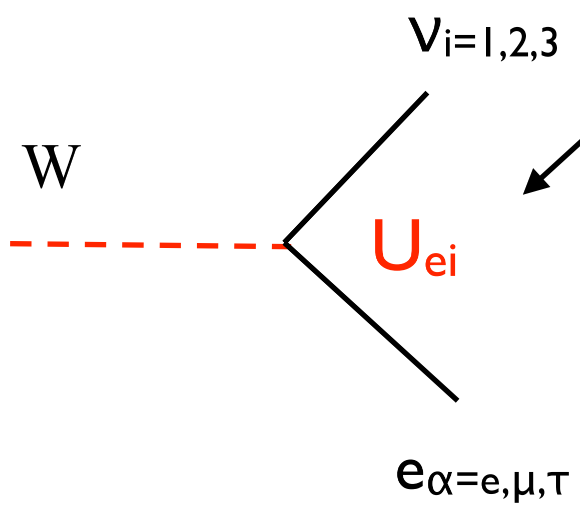
Giunti-Zavanin
1505.00978

Usual phenomenology turned around !

$m_{\beta\beta}$ phenomenology

- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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



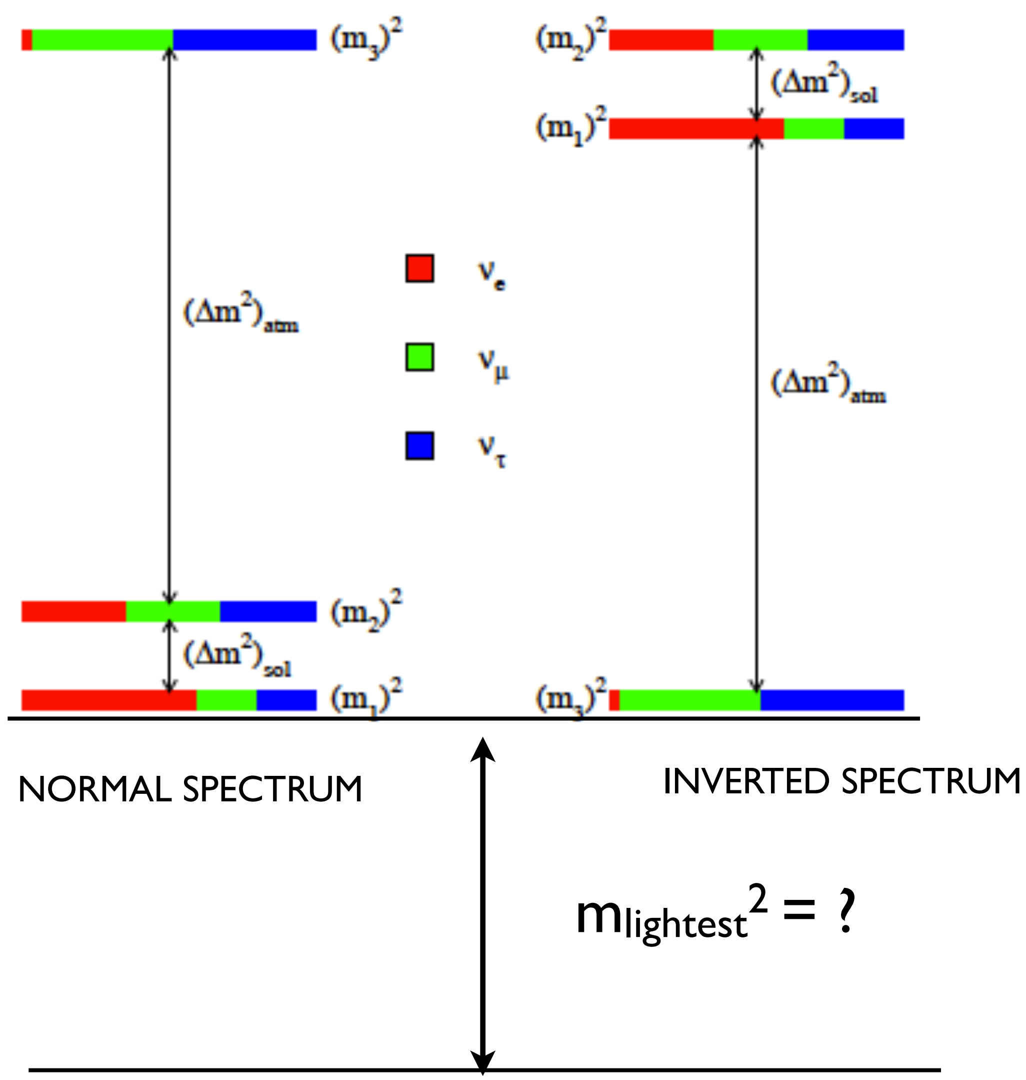
$$\frac{g}{\sqrt{2}} W_\mu^- \, \bar{e}_L^\alpha \, \gamma^\mu U^{\alpha i} \, \nu_L^i$$

Unitary mixing in CC vertex:
3 angles (known), 1+2 phases (unknown)

$m_{\beta\beta}$ phenomenology

- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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

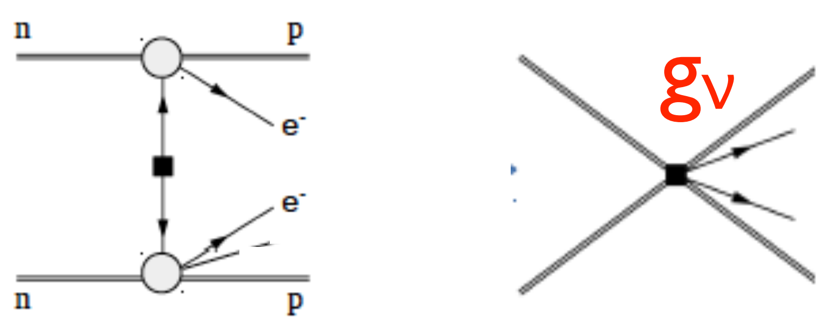


Mass ordering still not fixed by oscillation data

Anatomy of 0νββ amplitude from light ν exchange

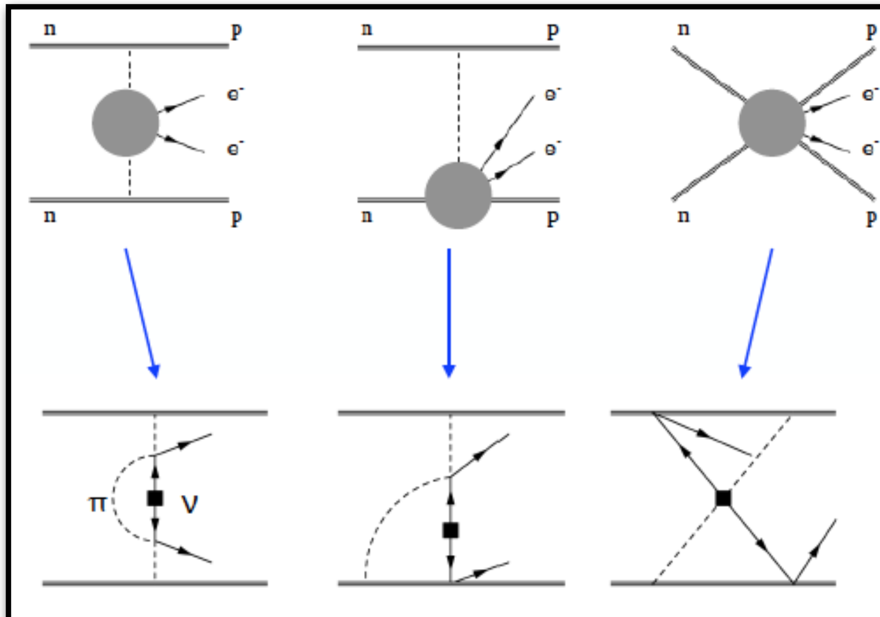
Expansion parameter Q/Λ_χ
with $Q \sim k_F \sim m_\pi$ and $\Lambda_\chi \sim M_n$

Leading order



$V_{I=2}$

N2LO



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

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

N2LO

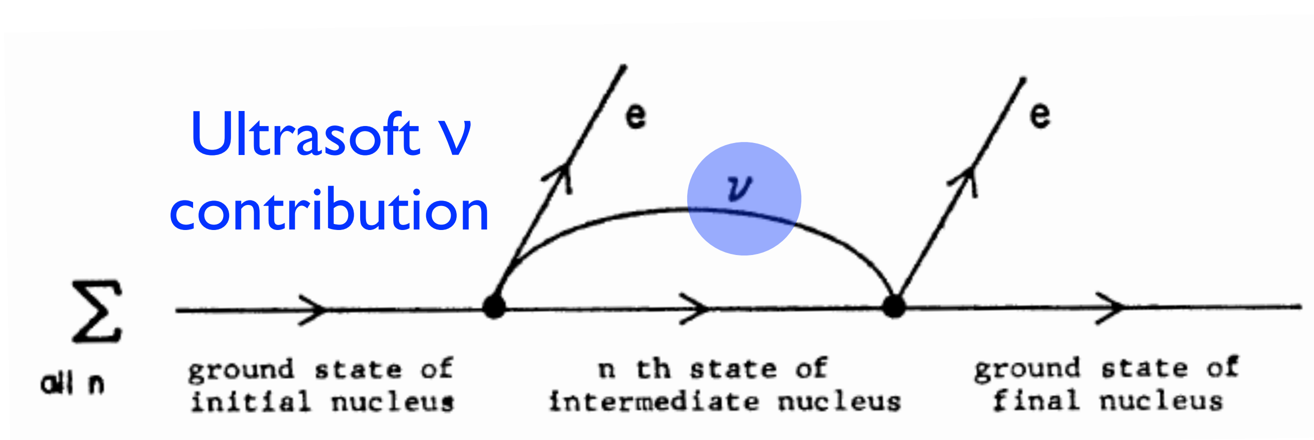
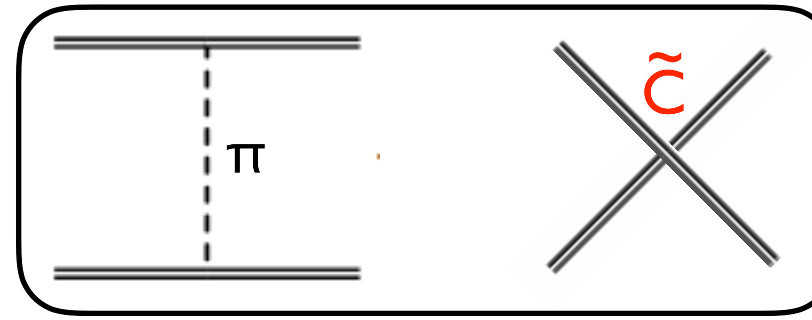


Figure adapted from Primakoff-Rosen 1969

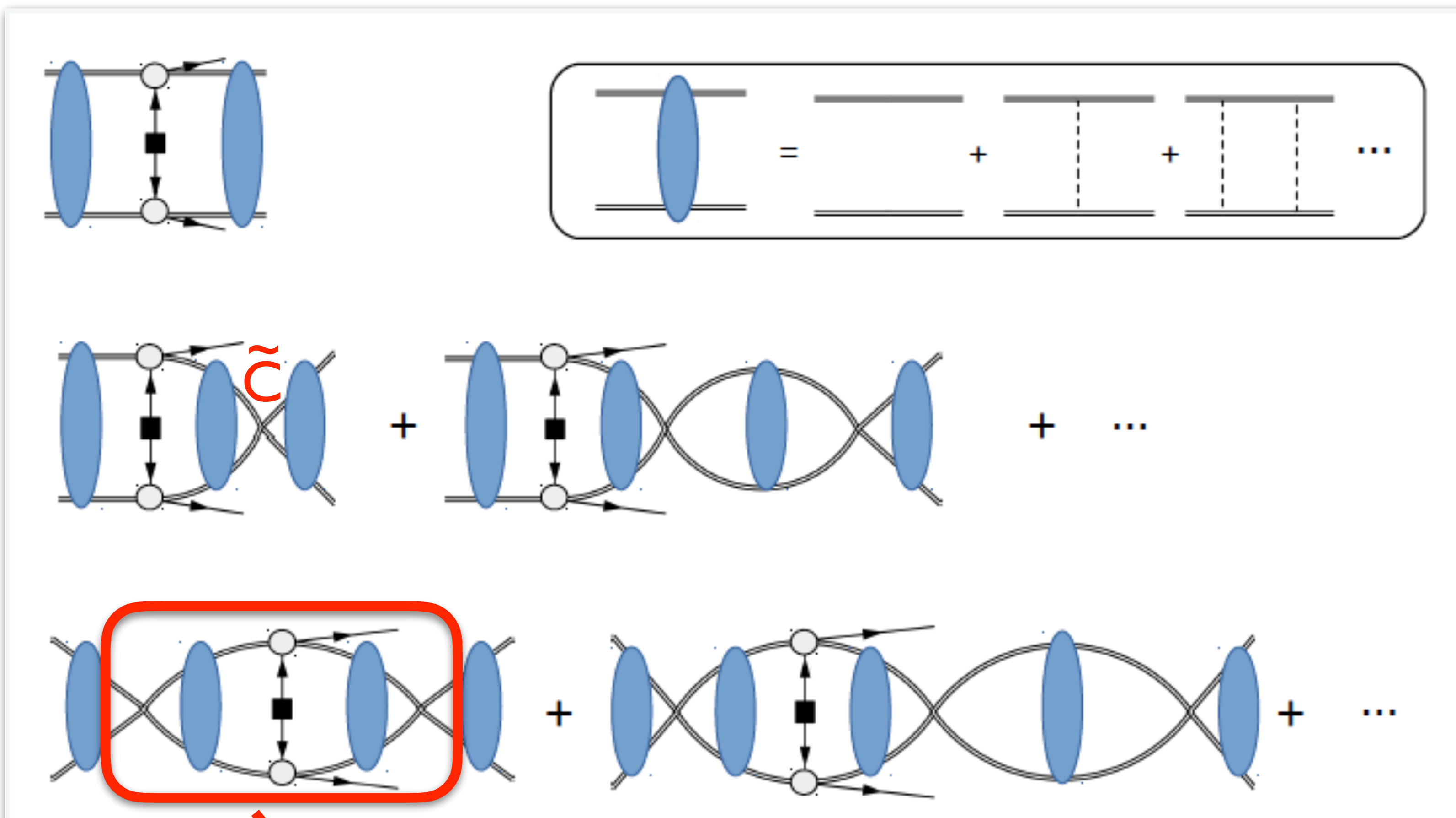
Related to matrix elements and excitation energies needed to predict 2νββ decay

Scaling of contact term in 0νββ

- nn→ppee amplitude with LO strong potential



Weinberg 1991



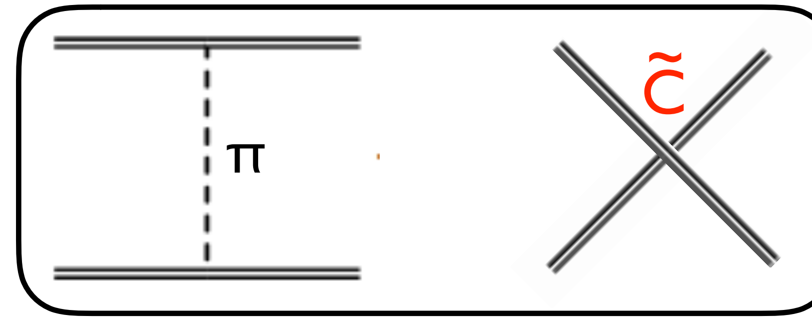
$\tilde{C} \sim 1/F_\pi^2$ from fit to a_{NN}

UV divergence $$\boxed{\sim \frac{1}{2}(1+2g_A^2)\left(\frac{m_N\tilde{C}}{4\pi}\right)^2}\left(\frac{1}{4-d}+\log\mu^2\right)$$

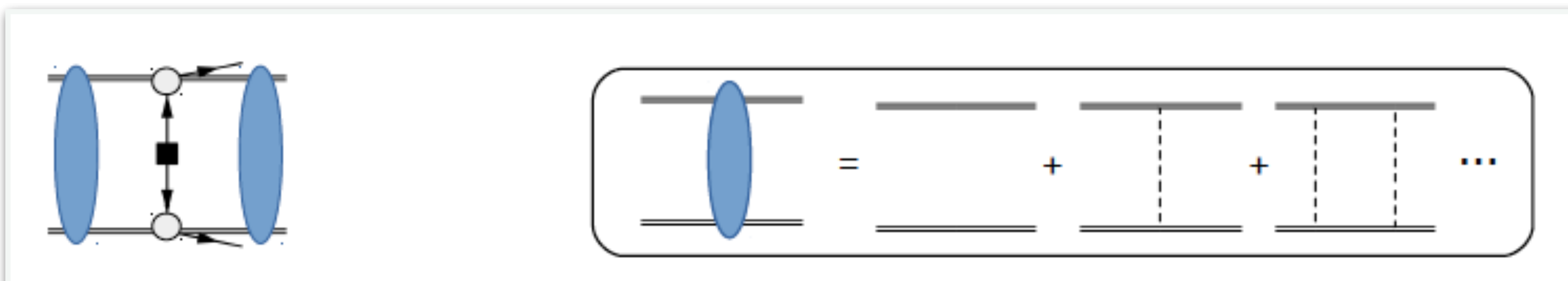
$\sim 1/F_\pi^2$

Scaling of contact term in 0νββ

- nn→ppee amplitude with LO strong potential



Weinberg 1991



$\tilde{C} \sim 1/F_\pi^2$ from fit to a_{NN}

- This effect is not included in current nuclear m.e. calculations
- Finite part of the "low-energy coupling" g_V is currently unknown

UV divergence $$\boxed{\sim \frac{1}{2}(1+2g_A^2)\left(\frac{m_N \tilde{C}}{4\pi}\right)^2}\left(\frac{1}{4-d}+\log\mu^2\right)$$

$\sim 1/F_\pi^2$

Estimating finite part of g_ν

1) Match χEFT & lattice QCD calculation of hadronic amplitude nn→pp

$$S_{\rm eff}^{\Delta L=2} = \frac{i8G_F^2V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x\, \bar{e}_L(x)e_L^c(x) \int d^4y\, S(x-y)\, T\Big(\bar{u}_L\gamma_\mu d_L(x)\, \bar{u}_L\gamma_\mu d_L(y)\Big) g^{\mu\nu}$$

Scalar massless propagator

($J_+ \times J_+$) vs ($J_{EM} \times J_{EM}$) $_{I=2}$

2) Chiral symmetry relates g_ν to I=2 electromagnetic LECs (hard ν vs γ)

$$\mathcal{Q}_L = \frac{\tau^z}{2},\ \mathcal{Q}_R = \frac{\tau^z}{2}$$

$$e^2 C_1 \left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$
$$e^2 C_2 \left(\bar{N}\mathcal{Q}_L N \bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L\mathcal{Q}_R]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$

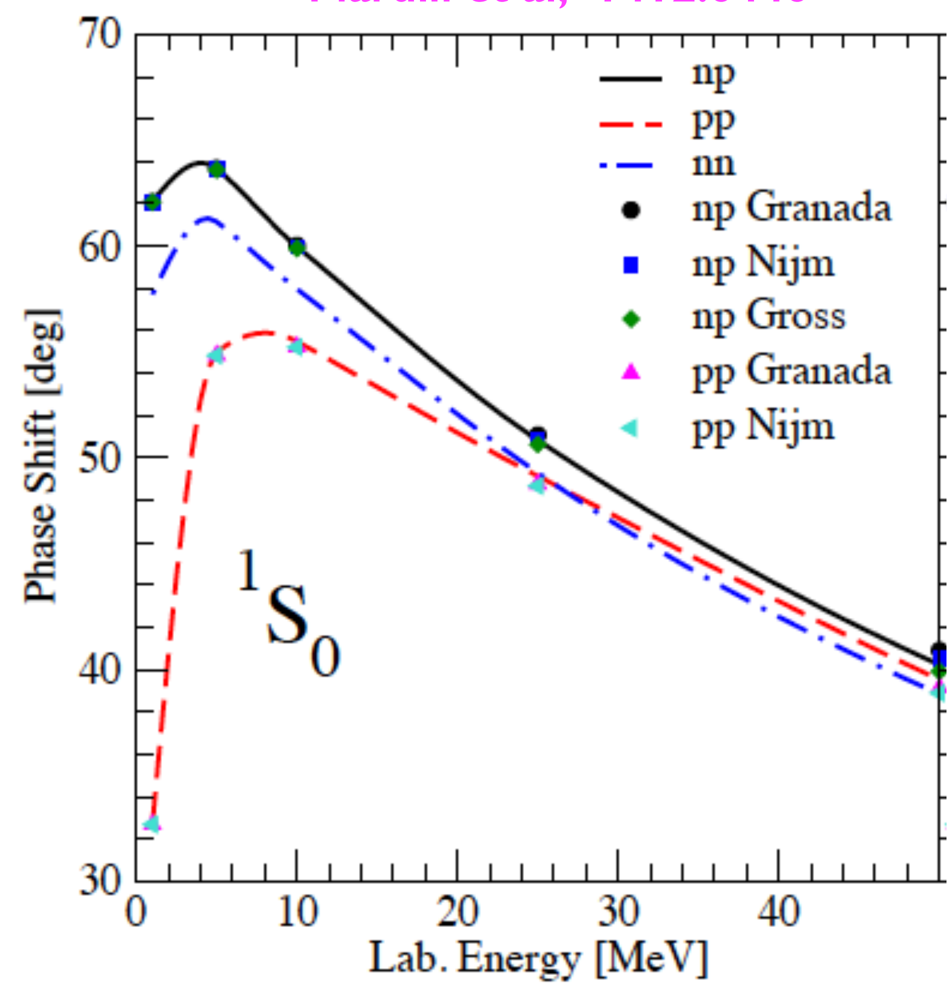
$$\mathcal{Q}_L = u^\dagger Q_L u$$
$$\mathcal{Q}_R = u Q_R u^\dagger$$
$$u = 1 + \frac{i\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{2F_\pi} + \ldots$$

Two I=2 NN non-derivative operators: chiral symmetry ⇒ $g_\nu = C_1$

$0\nu\beta\beta$ vs EM isospin breaking

- NN observables cannot disentangle C_1 from C_2 (need pions), but provide data-based estimate of C_1+C_2

Piarulli et al, 1412.6446



- $C_1 + C_2$ controls CIB combination of $^1S_0$ scattering lengths $a_{nn} + a_{pp} - 2\, a_{np}$

- Fit to data, including Coulomb potential, pion EM mass splitting, and contact terms confirms that $C_1 + C_2 \sim 1/F_\pi^2 >> 1/(4\pi F_\pi)^2$

Estimating numerical impact

- Assume $C_1 = C_2$ and hence $g_V = (C_1 + C_2)/2$ at some scale R_S
- Compute effect in light nuclei: use wave-functions obtained via Variational Monte Carlo from AV18 (NN) + U9 (NNN) potentials — short range correlations included
- Hybrid calculation at this stage: can't expect R_S-independence

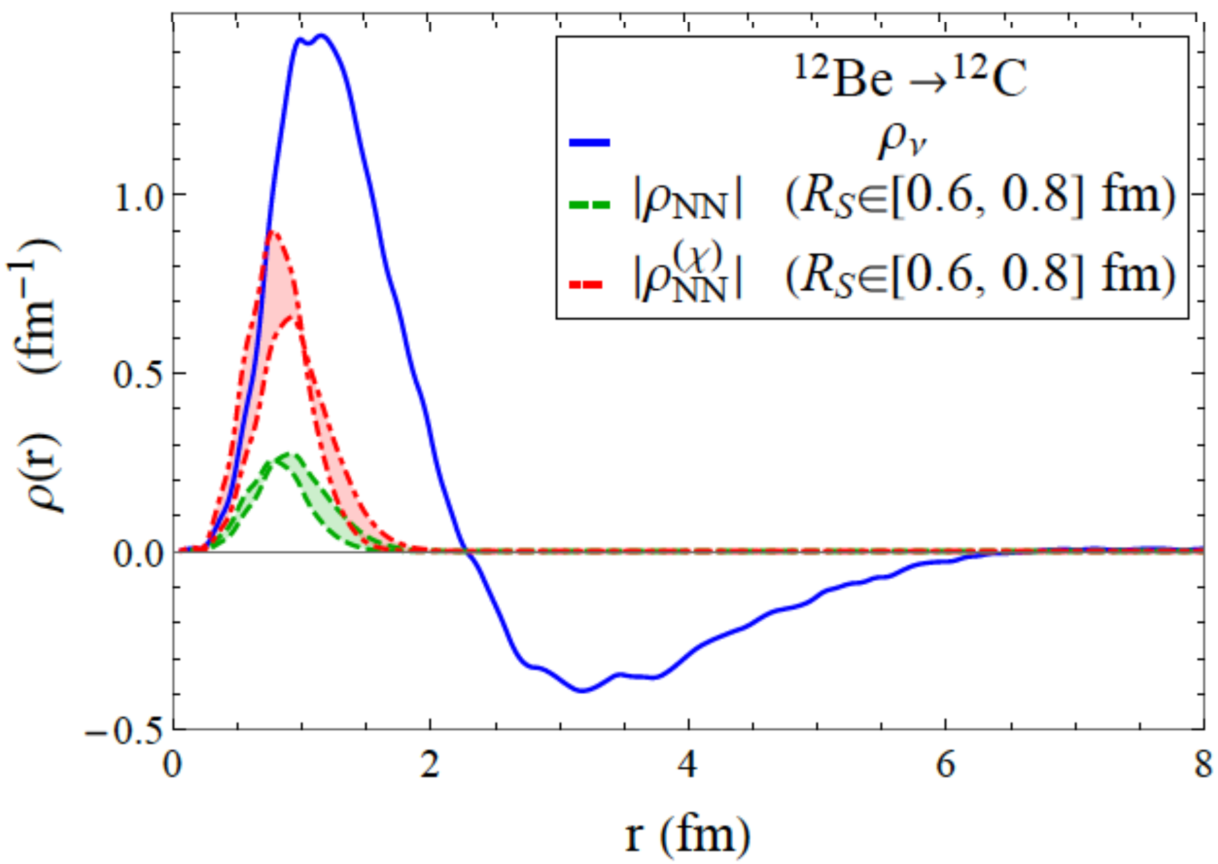
Plot matrix element densities $\rho(r)$

$$\boxed{A = \int dr \;\; \rho(r)}$$

Estimating numerical impact of g_ν

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

$^{12}\mathrm{Be} \to {}^{12}\mathrm{C}$ ΔI=2



$g_\nu \sim (C_1+C_2)/2$ taken from fit to NN data (ours vs Piarulli et al. 1606.06335)

g_ν contribution sizable in ΔI=2 transition (due to node): for A=12, A_{NN}/A_ν = 25%-55%

Transitions of experimental interest (^{76}Ge→ ^{76}Se, …) have ΔI=2 (and node) ⇒ expect significant effect

$0\nu\beta\beta$ from $\mathcal{L}^{(9)}_{\Delta L=2}$

- Example: scalar operators

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

$$\boxed{\begin{array}{ll} \mathcal{O}_1 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \gamma_\mu d_L & \\ \mathcal{O}_2 = \bar{u}_L d_R \, \bar{u}_L \, d_R, & \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha \\ \mathcal{O}_4 = \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \gamma_\mu d_R, & \mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta \, \bar{u}_R^\beta \gamma_\mu d_R^\alpha \end{array}}$$

- Hadronic realization depends on O_i's chiral properties

$$\mathcal{L}_{NN} = \left(g_1^{NN} C_{1L}^{(9)} + g_2^{NN} C_{2L}^{(9)} + g_3^{NN} C_{3L}^{(9)} + g_4^{NN} C_{4L}^{(9)} + g_5^{NN} C_{5L}^{(9)} \right) (\bar{p}n)\,(\bar{p}n)\, \frac{\bar{e}_L C \bar{e}_L^T}{v^5}$$

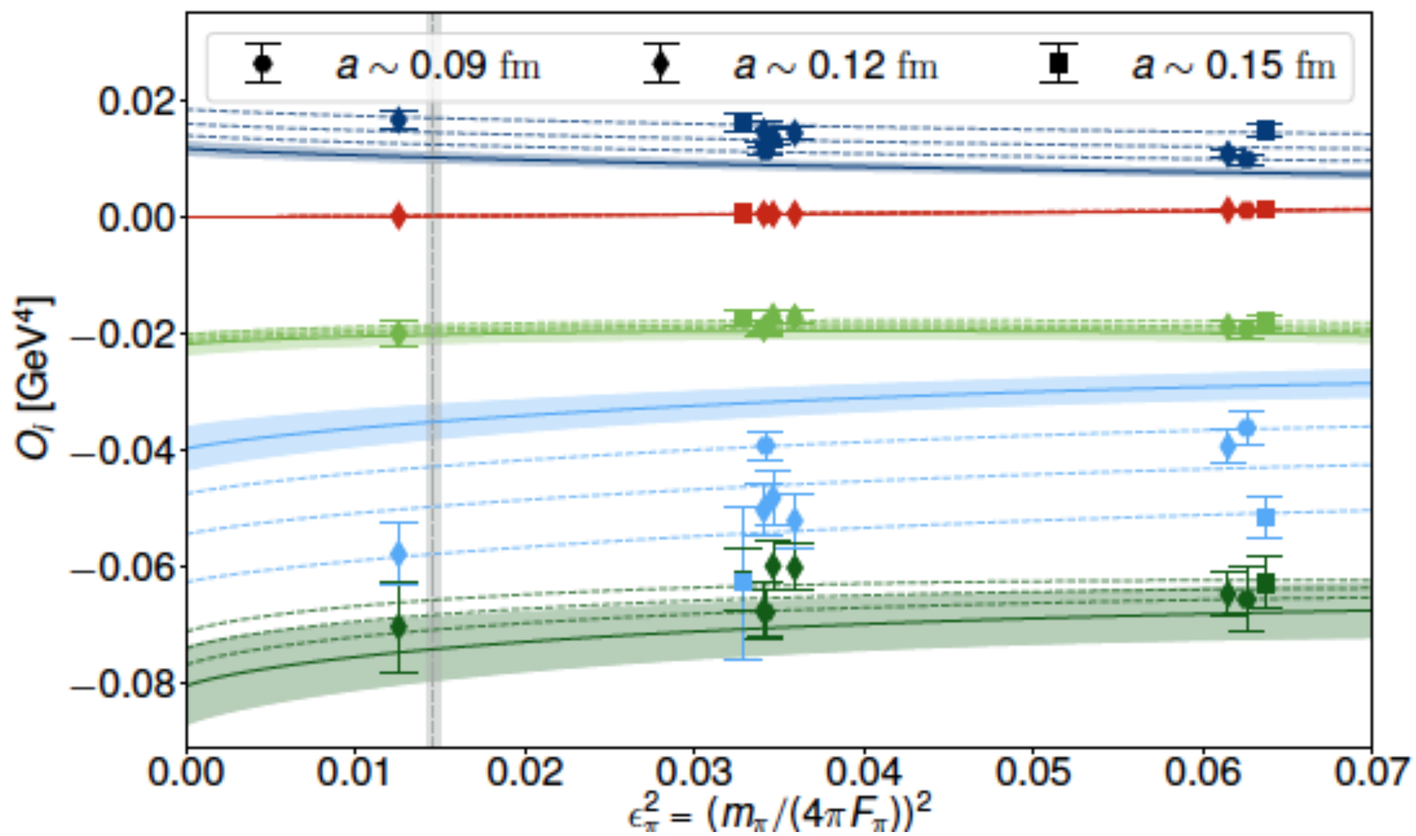
$$\mathcal{L}_\pi = \frac{F_0^2}{2} \left[\frac{5}{3} g_1^{\pi\pi} C_{1L}^{(9)} \partial_\mu \pi^- \partial^\mu \pi^- + \left(g_4^{\pi\pi} C_{4L}^{(9)} + g_5^{\pi\pi} C_{5L}^{(9)} - g_2^{\pi\pi} C_{2L}^{(9)} - g_3^{\pi\pi} C_{3L}^{(9)} \right) \pi^- \pi^- \right] \times \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \ldots$$

$$g_1^{\pi\pi} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{\pi\pi} \sim \mathcal{O}(\Lambda_\chi^2) \qquad\qquad g_1^{NN} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{NN} \sim \mathcal{O}\left(\frac{\Lambda_\chi^2}{F_\pi^2}\right)$$

Pion matrix elements from LQCD

Nicholson et al., 1805/02634

$\langle \pi^+ | O_i | \pi^- \rangle$



MS-bar at μ=2GeV

$g_1^{\pi\pi} = +0.4$

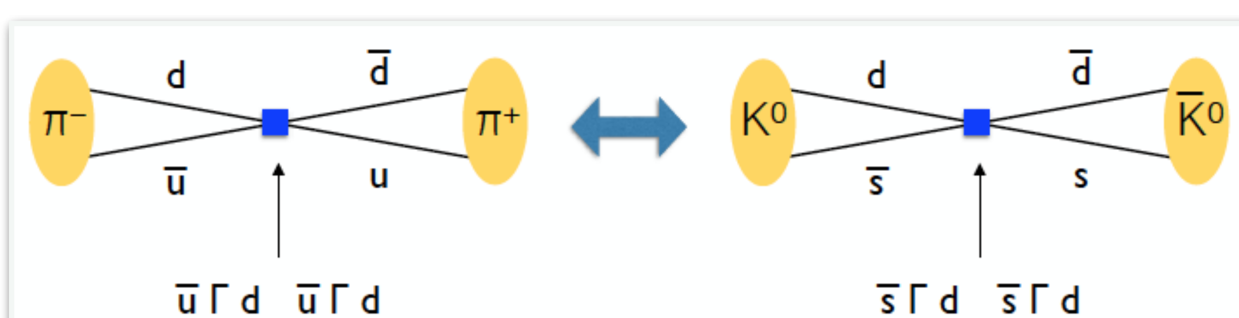
$g_2^{\pi\pi} = -(1.8\,\mathrm{GeV})^2$

$g_3^{\pi\pi} = +(1.0\,\mathrm{GeV})^2$

$g_4^{\pi\pi} = -(1.7\,\mathrm{GeV})^2$

$g_5^{\pi\pi} = -(3.6\,\mathrm{GeV})^2$

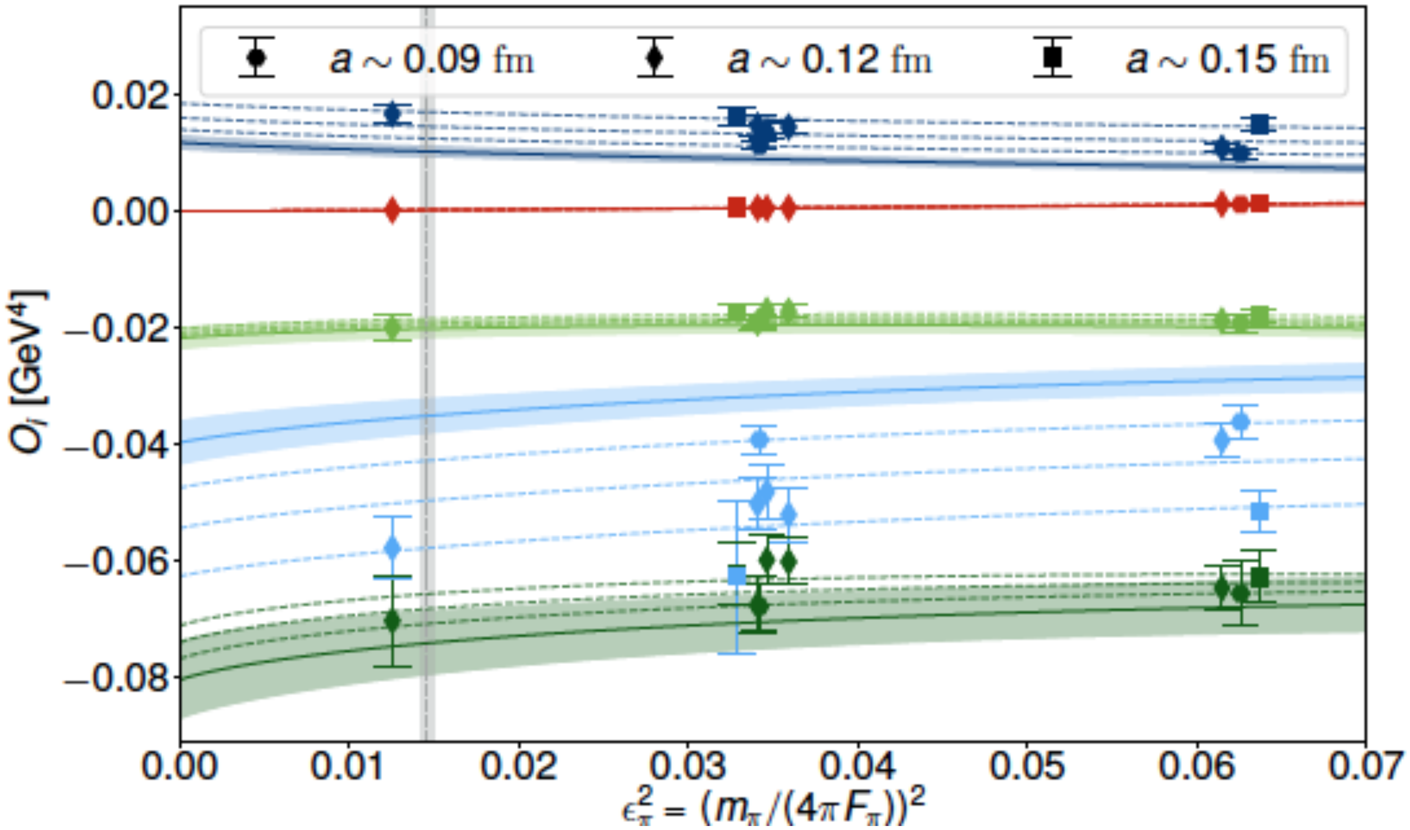
- Quite consistent with result obtained from kaon m.e. via chiral SU(3)



VC , W. Dekens, M. Graesser, E. Mereghetti 1701.01443

Pion matrix elements from LQCD

Nicholson et al., 1805/02634



$\langle\pi^+|O_i|\pi^-\rangle$

MS-bar at μ=2GeV

$g_1^{\pi\pi} = +0.4$

$g_2^{\pi\pi} = -(1.8\,\mathrm{GeV})^2$

$g_3^{\pi\pi} = +(1.0\,\mathrm{GeV})^2$

$g_4^{\pi\pi} = -(1.7\,\mathrm{GeV})^2$

$g_5^{\pi\pi} = -(3.6\,\mathrm{GeV})^2$

- Result is < 1/2 x "vacuum insertion approximation", commonly used in literature!
- $\langle pp|O_i|nn\rangle$ ($\langle p\pi^+|O_i|n\rangle$) not yet known from LQCD (only factorization model)
- In some instances, using "wrong hadronization" (e.g. no pion range) leads to factor >10 change in sensitivity to short-distance couplings