DOE Topical Collaboration Meeting, Amherst, Feb 3-4 2017

Neutrinoless double beta decay and chiral SU(3)

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Outline

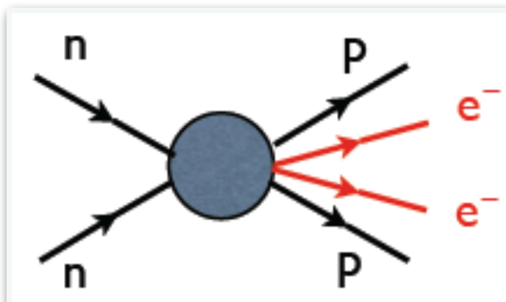
- Neutrinoless double beta decay and TeV sources of LNV
    - Generalities and EFT approach
    - Operator Basis
    - Leading pionic matrix elements from (i) chiral SU(3) and (ii) lattice QCD kaon matrix elements
    - Conclusion

Based on arXiv:1701.01443

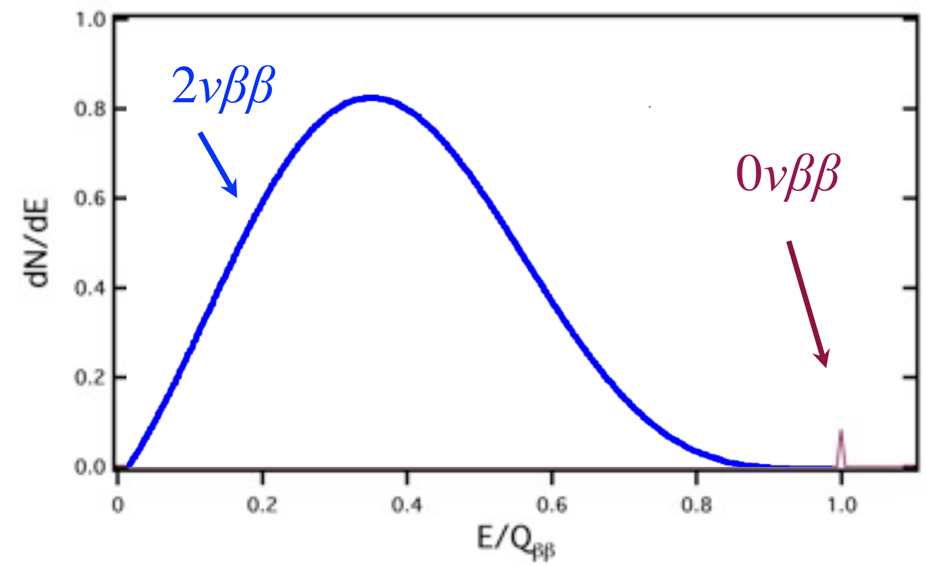
VC, W. Dekens, M. Graesser, E. Mereghetti

0νββ and Lepton Number Violation

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



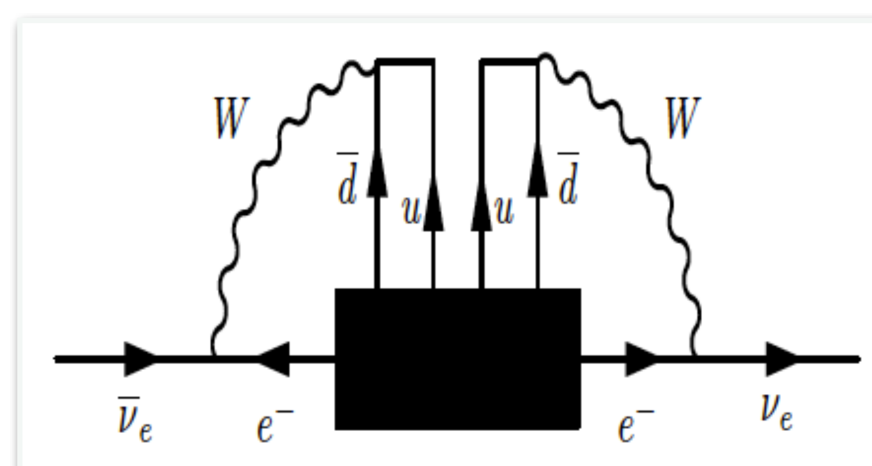
Lepton number changes by two units: ΔL=2



- B-L conserved in SM → new physics, with far-reaching implications

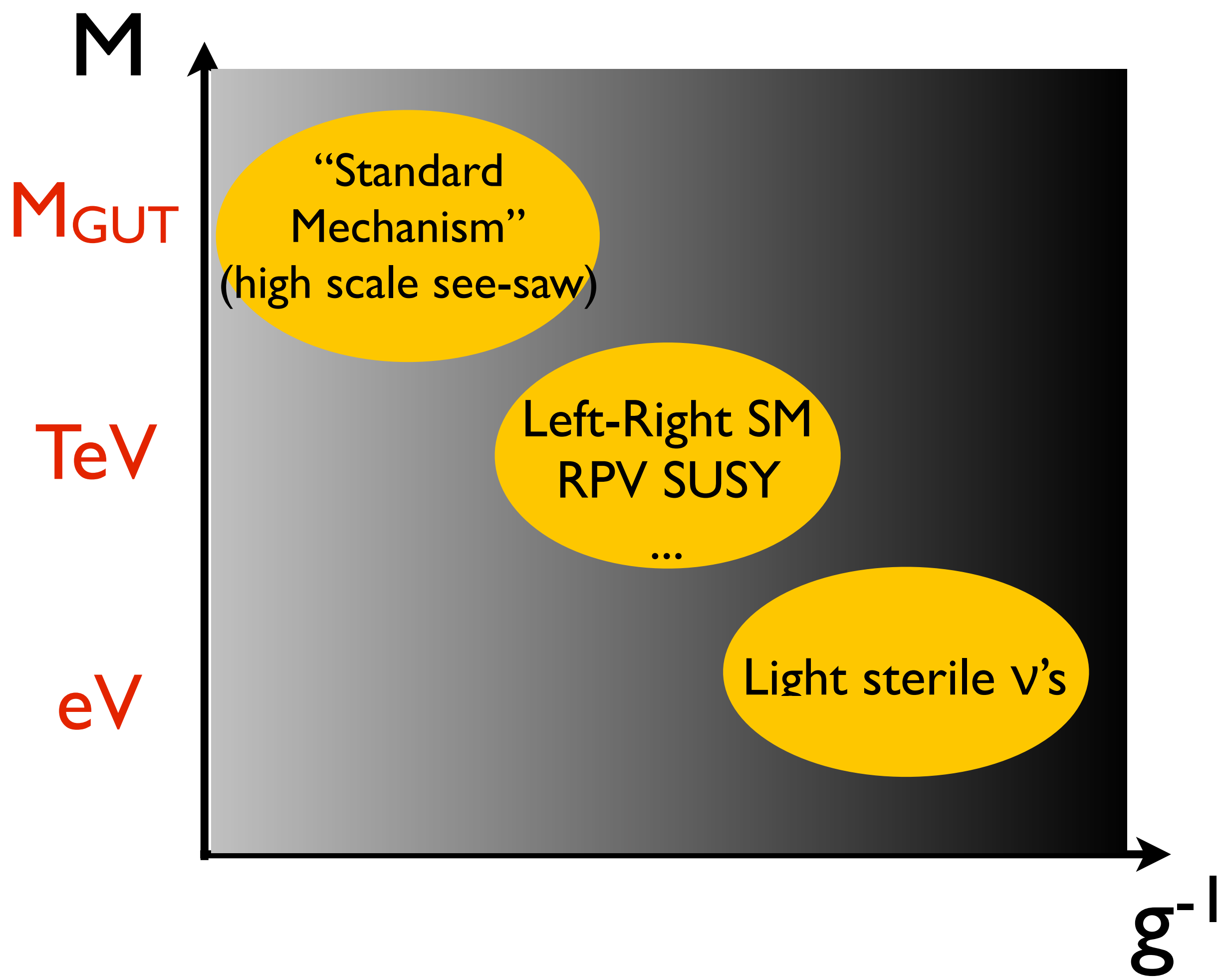
- No matter what the underlying mechanism, observation would demonstrate that neutrinos are their own antiparticles

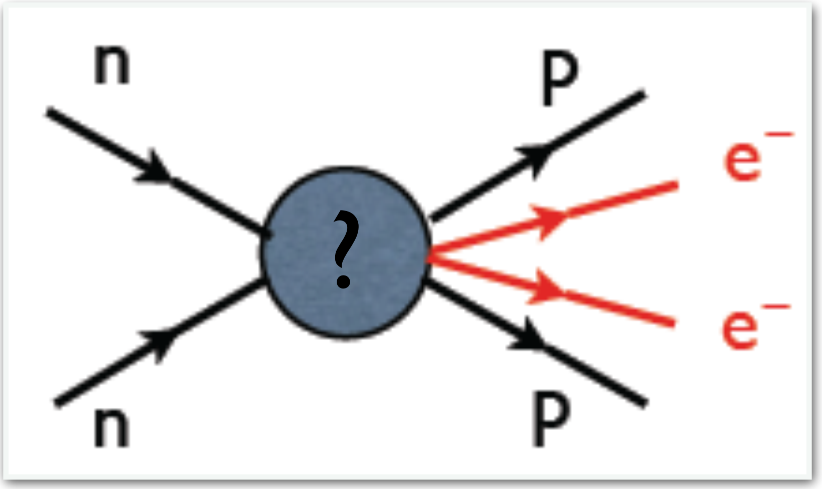
Shechter-Valle 1982



0νββ and Lepton Number Violation

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) sensitive to LNV from a variety of mechanisms





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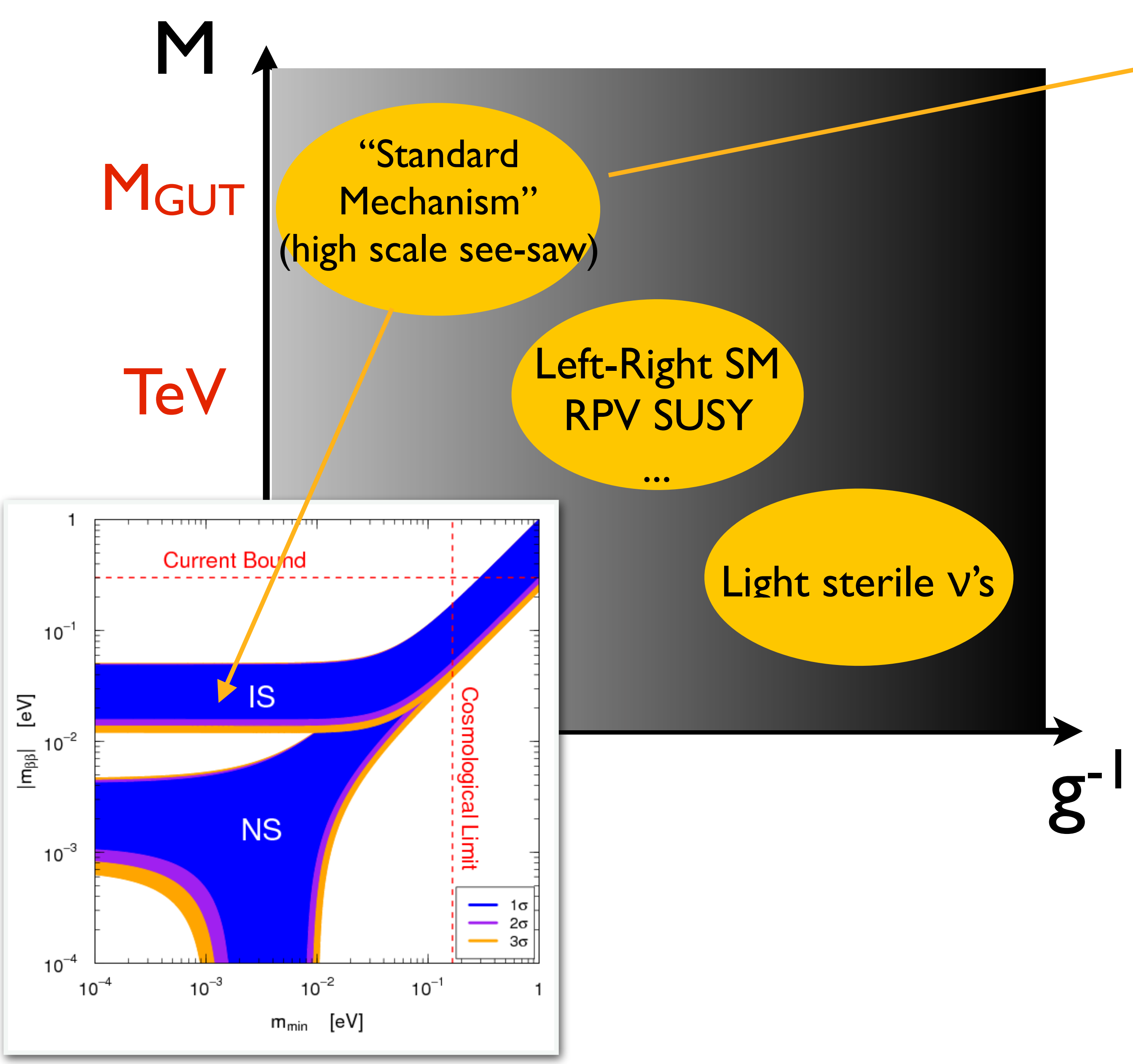
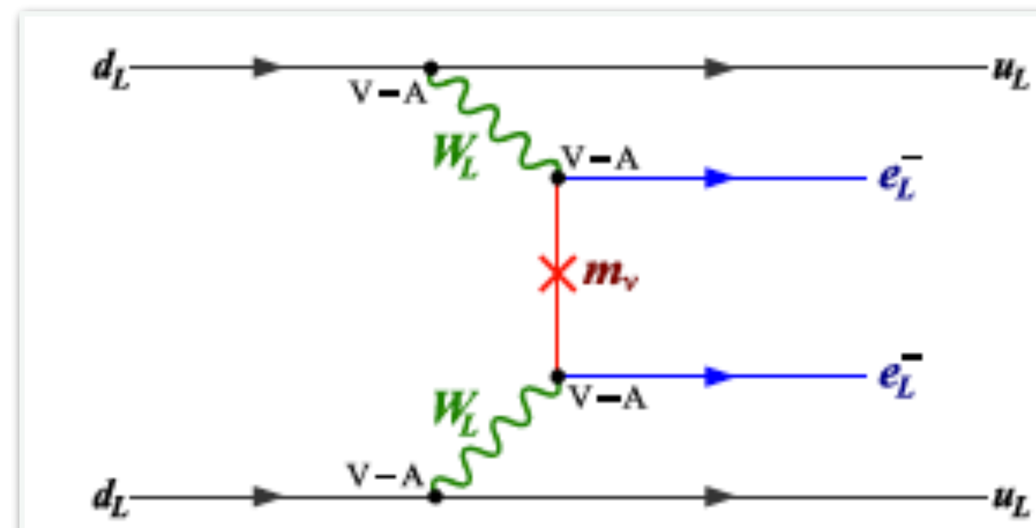


LNV dynamics at M >> TeV:
leaves as the only low-energy footprint
light Majorana neutrino



Clear interpretation framework and sensitivity goals ("inverted hierarchy"). Requires difficult nuclear matrix elements.

But only limited class of models!

0νββ and Lepton Number Violation

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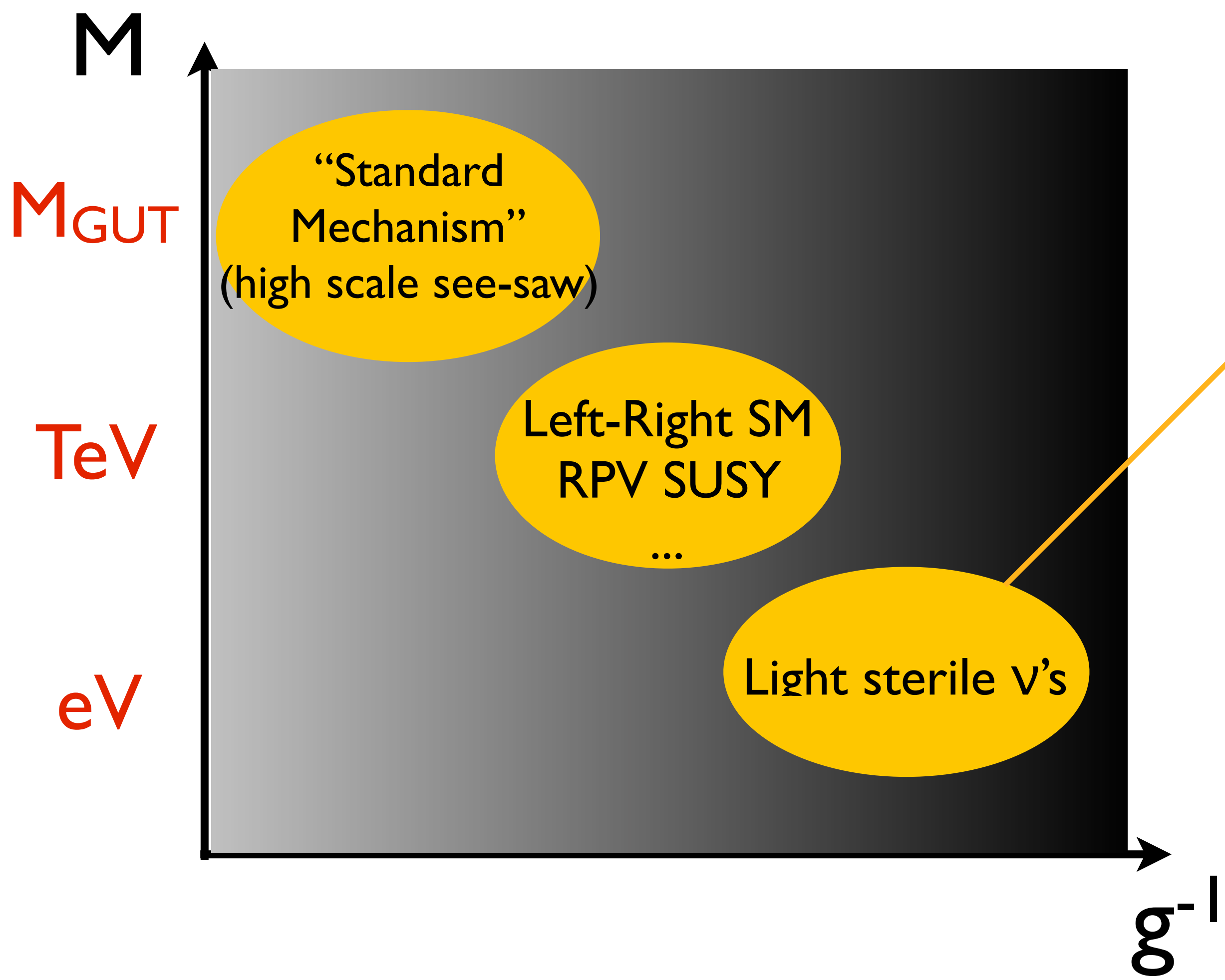
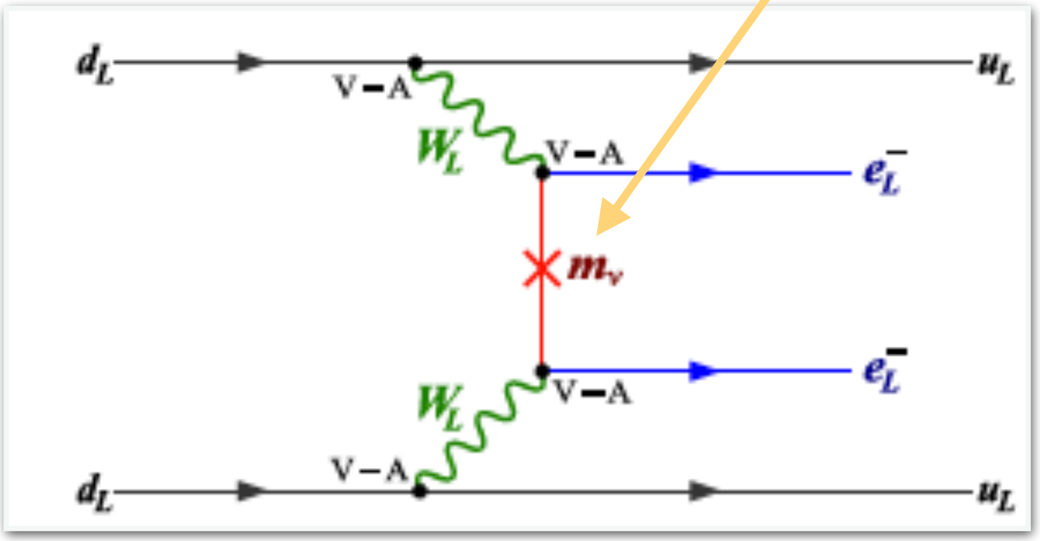
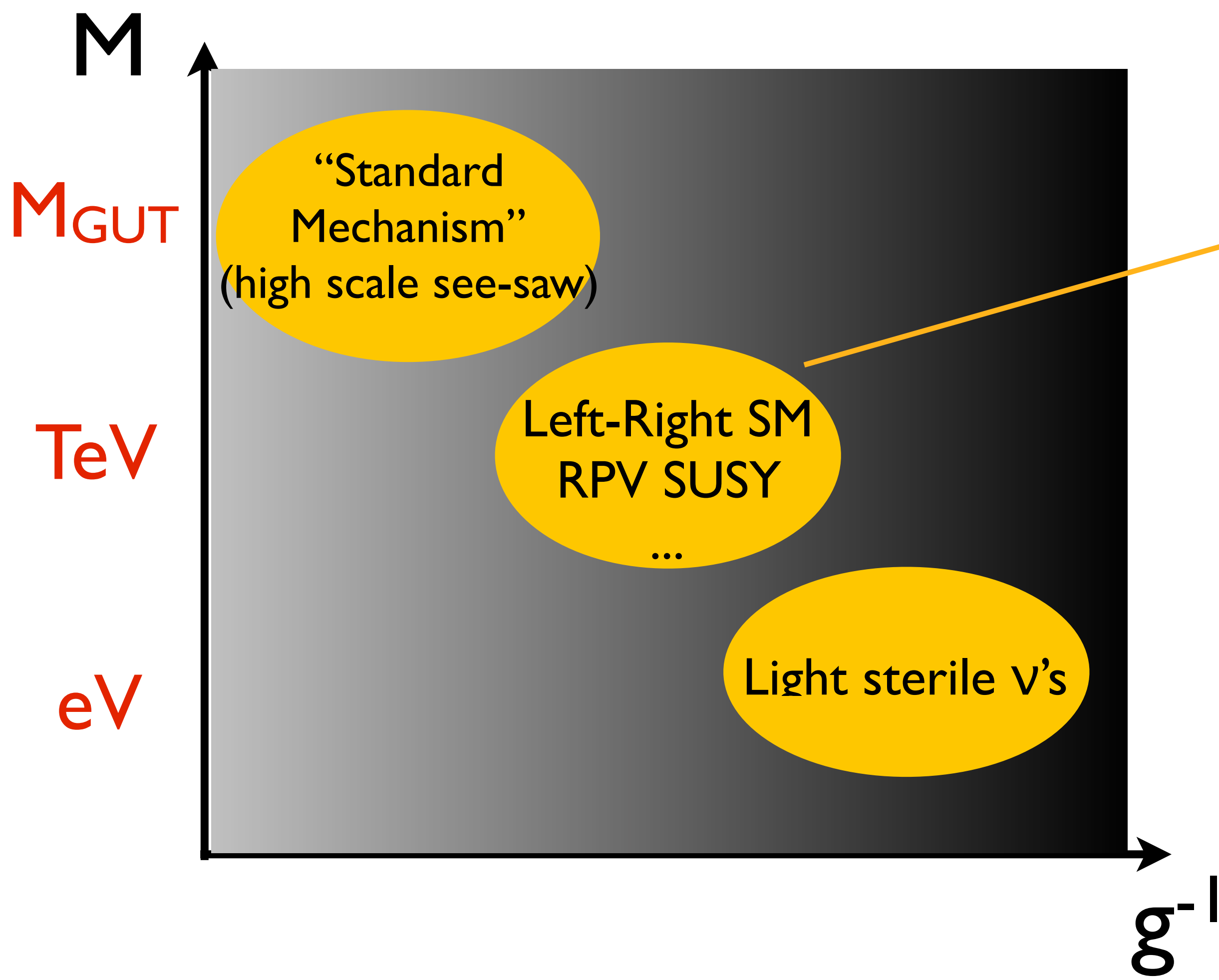


LNV dynamics at M_R : eV → GeV: additional light Majorana states

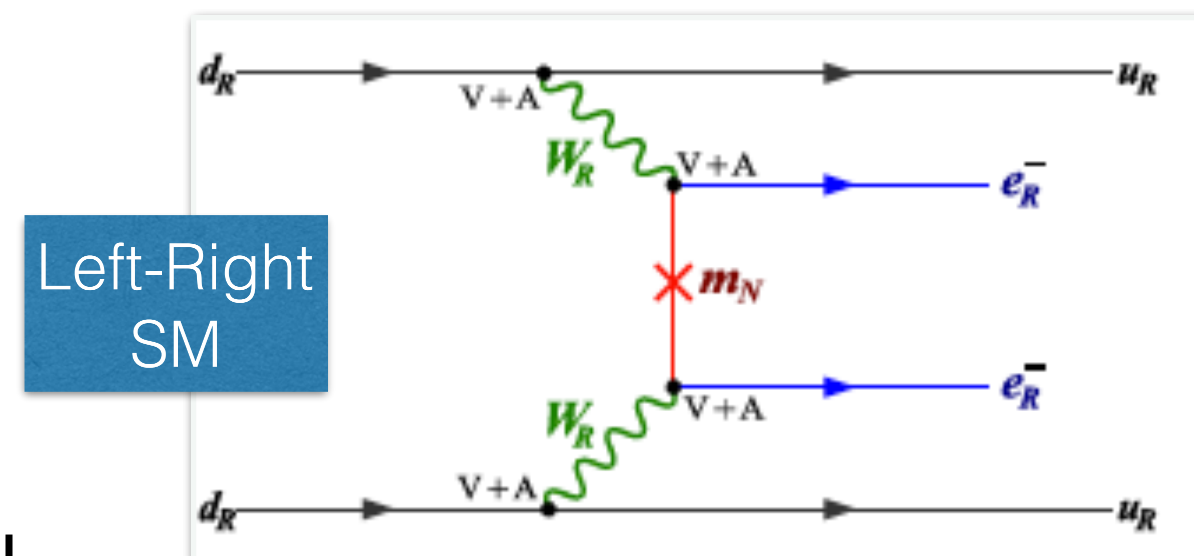


0νββ and Lepton Number Violation

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) sensitive to LNV from a variety of mechanisms



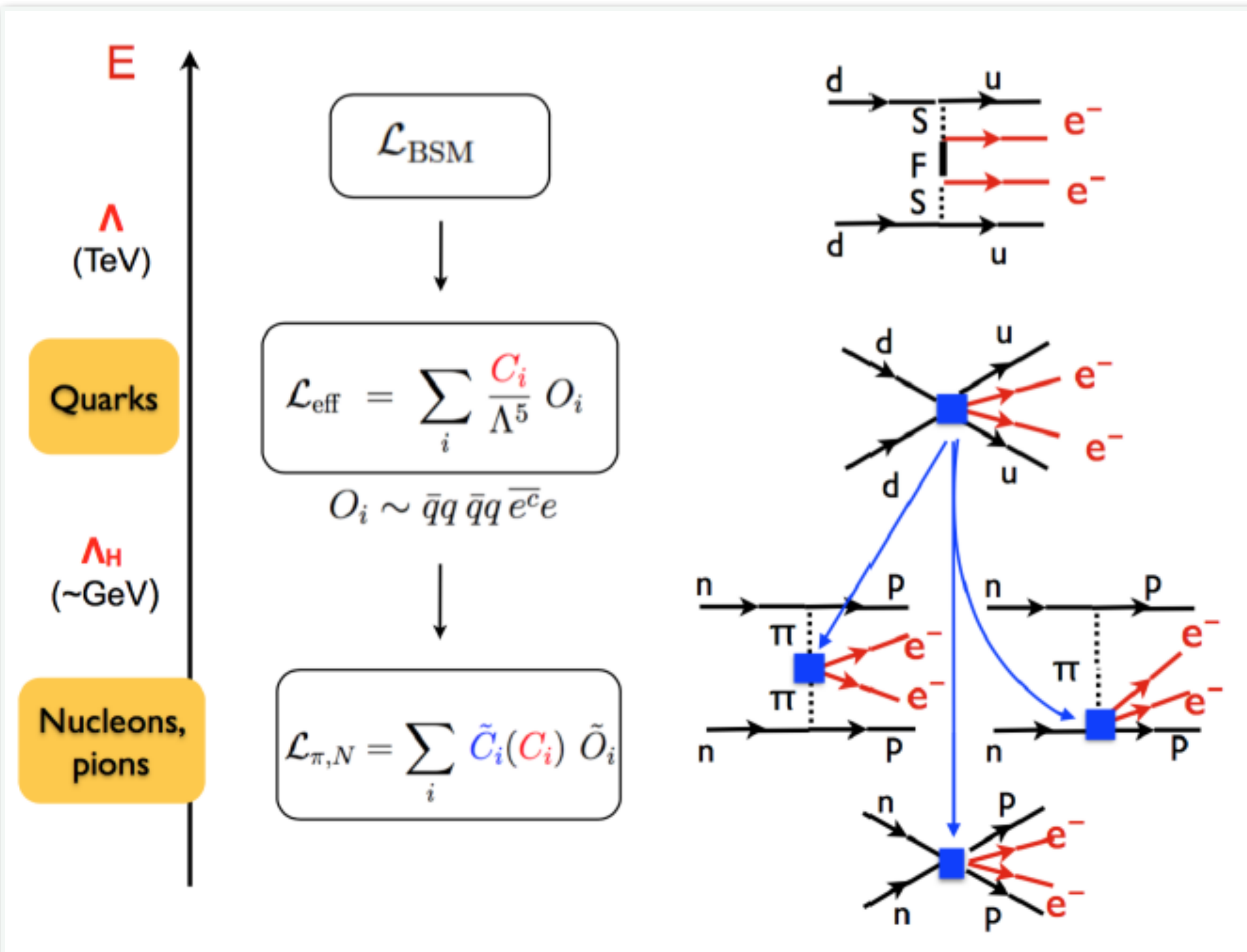
LNV dynamics at M ~ TeV:
1) new contribution to 0νββ not related to light neutrino mass;
2) pp → eejj at the LHC



Interpretation framework and sensitivity goals not yet systematically developed

Different set of hadronic and nuclear matrix elements

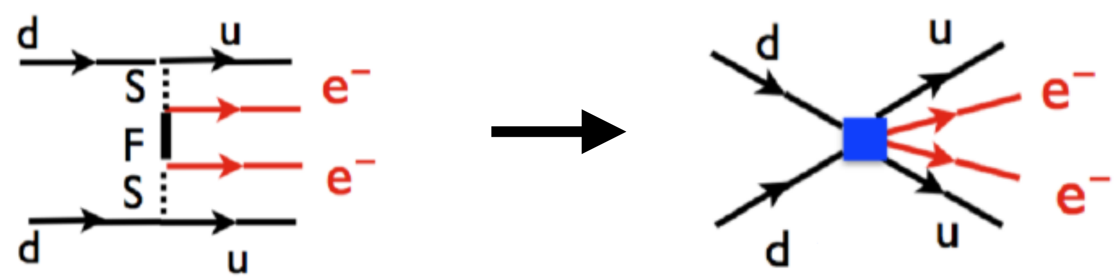
Connecting TeV-scale LNV to nuclei



- Identify leading (dim-9) gauge-invariant operators characterizing *any* model with LNV at the TeV scale
- Renormalization group evolution from TeV to GeV scale of effective couplings
- Map quark operators onto pion and nucleon operators using chiral EFT
- Hadronic matrix elements → estimate chiral EFT couplings $\tilde{C}_i$ [C_j]
- Nuclear matrix elements → $T_{1/2}$ [$\tilde{C}_i$ [C_j]]

Operator basis

- Identification of leading (dim-9) ΔL=2 gauge-invariant operators



- Low-scale: impose only $SU(3)_C \times U(1)_{EM}$ invariance

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^5_{\rm LNV}} \left[\sum_{i=\rm scalar} \left(c_{i,S}\, \bar{e} e^c + c'_{i,S}\, \bar{e}\gamma_5 e^c \right) O_i \;+\; \bar{e}\gamma_\mu\gamma_5 e^c \sum_{i=\rm vector} c_{i,V}\, O_i^\mu \right]$$

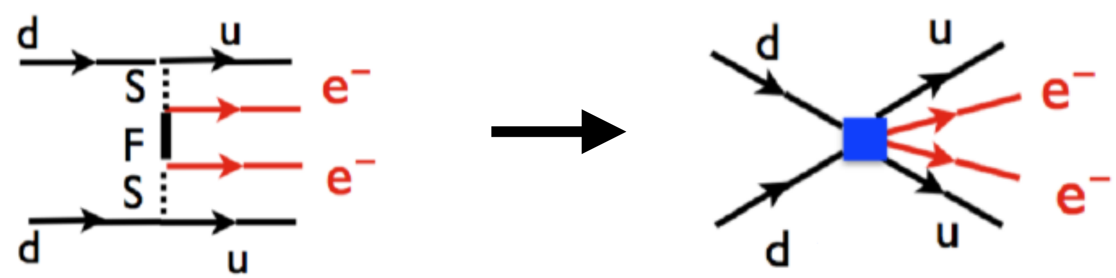
M. Graesser, 1606.04549
** Prezeau, Ramsey-Musolf, Vogel
hep-ph/0303205

8 (5**) scalar operators

8 (4**) vector operators

Operator basis

- Identification of leading (dim-9) $\Delta L=2$ gauge-invariant operators



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$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^5_{\rm LNV}} \left[\sum_{i={\rm scalar}} \left(c_{i,S}\, \bar{e} e^c + c'_{i,S}\, \bar{e}\gamma_5 e^c \right) O_i \; + \; \bar{e}\gamma_\mu\gamma_5 e^c \sum_{i={\rm vector}} c_{i,V}\, O_i^\mu \right]$$

M. Graesser, 1606.04549
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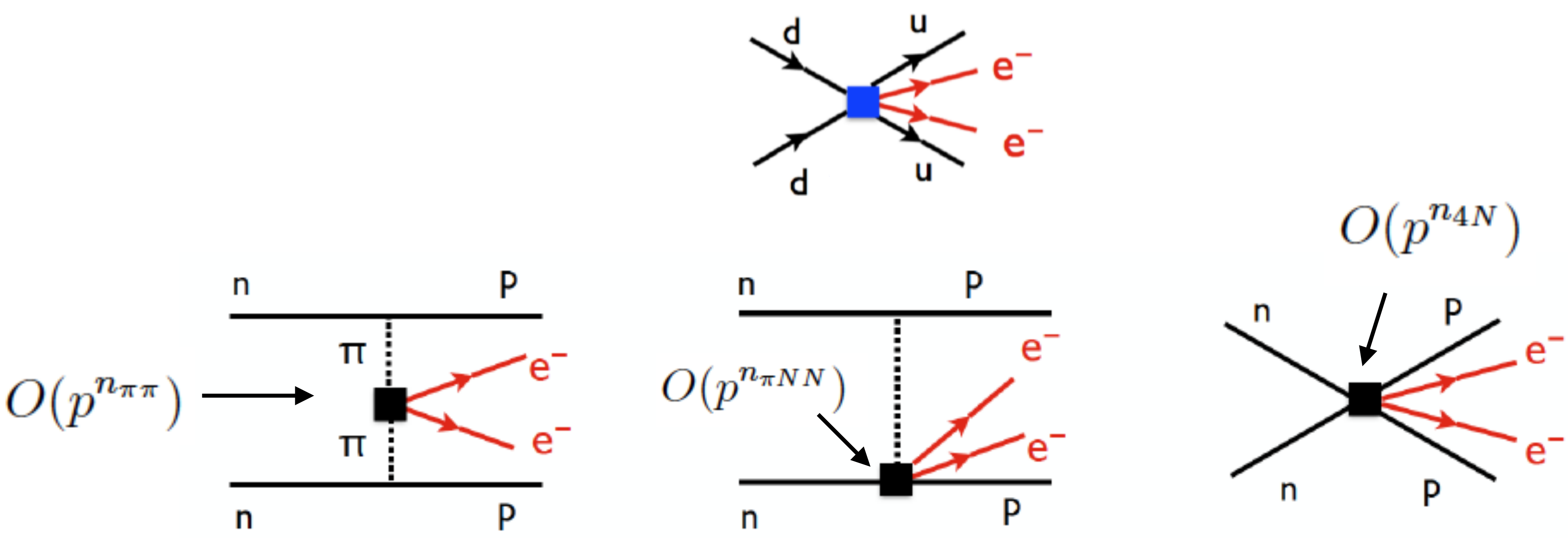
8 (5**) scalar operators

8 (4**) vector operators

- 7 (scalar) + 4 (vector) remnant of dim-9 SU(3)xSU(2)xU(1) invariant operators. Others suppressed by $(v_{EW}/\Lambda_{LNV})^n$ with n = 2, 4

Matching to pions and nucleons

- For a given quark operator O_j , chiral symmetry determines form of π and N operators $\tilde{O}_i$ and their chiral order ($\partial \sim O(p)$, $m_q \sim O(p^2)$)



$p^{n_{\pi\pi}-2}$ $p^{n_{\pi NN}-1}$ $p^{n_{4N}}$

Matching to pions and nucleons

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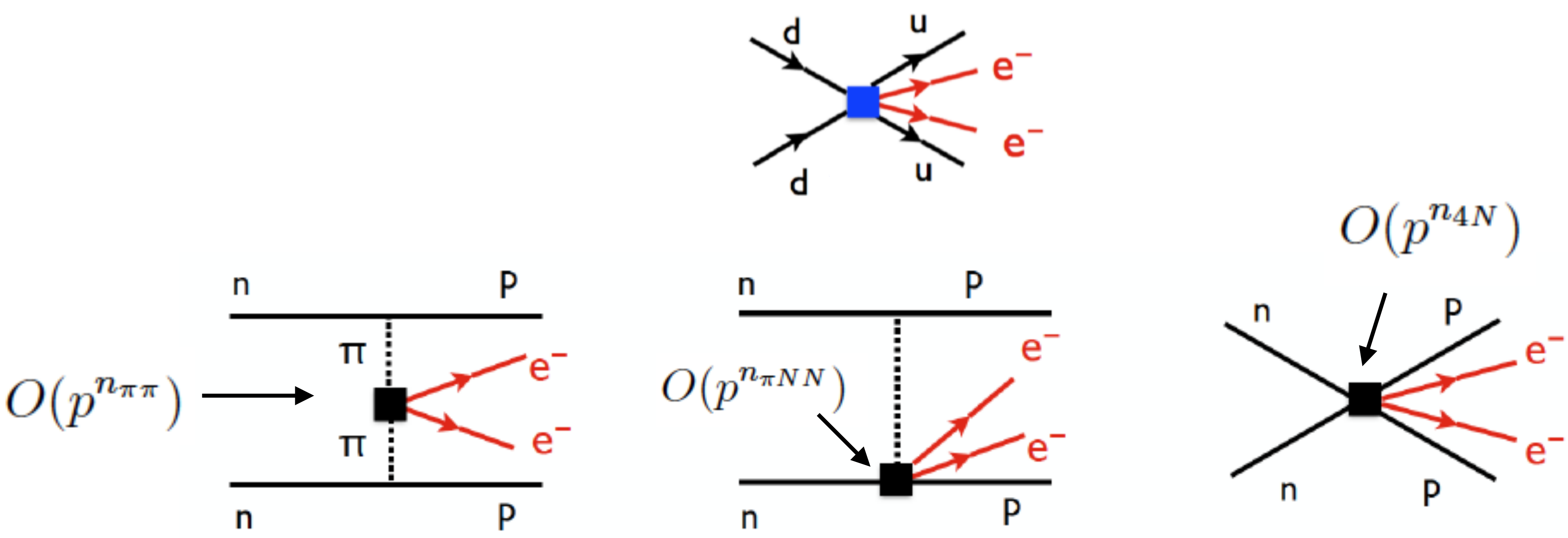
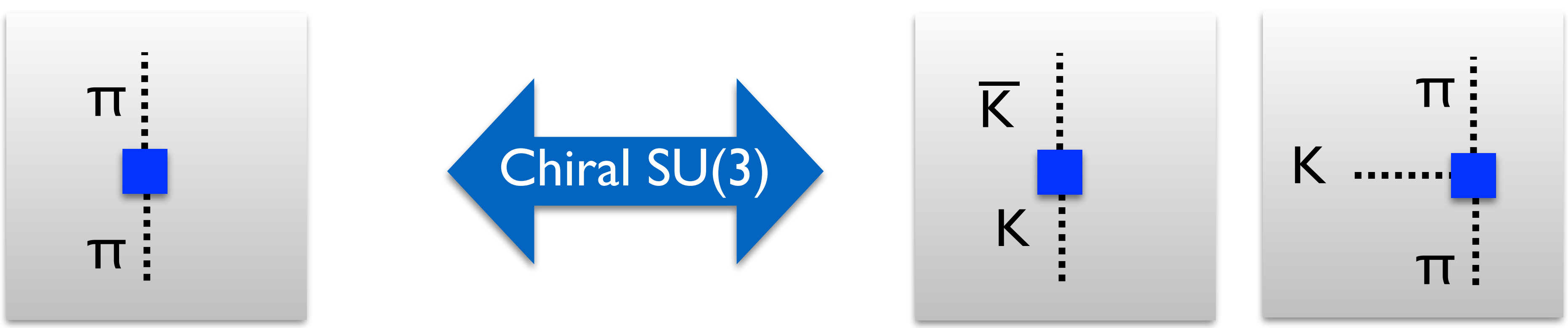


$p^{n_{\pi\pi}-2}$ $\quad$ $p^{n_{\pi NN}-1}$ $\quad$ $p^{n_{4N}}$

- Chiral power counting implies dominance of pion-exchange (if $n_{\pi\pi} = 0$)
- $<\pi^+|O_j|\pi^->$ is the key *hadronic* input for LO calculations of $T_{1/2}$

Matching to pions and nucleons

- Our strategy:
  - Use SU(3) chiral symmetry to relate $\langle \pi^+|O_i|\pi^-\rangle$ to the matrix element of the chiral partner of O_i between K^0 and $\bar{K}^0$
  - Use lattice QCD results for kaon matrix elements



A closer look at "scalar operators"

- Basis of 8 independent ΔI=2 operators

M. Graesser, 1606.04549
Gabbiani et al, hep-ph/9604378
Buras-Misiak-Urban hep-ph/0005183

α,β: color indices

$$
\begin{aligned}
O_1 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta \\
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \tau^+ q_L^\beta \\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \tau^+ q_L^\alpha \\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha
\end{aligned}
$$

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$$\tau^+ = T^1 + iT^2$$

$O'_{1,2,3}$: $O_{1,2,3}$ with L ↔ R

$$\langle \pi^+ | O'_{1,2,3} | \pi^- \rangle = \langle \pi^+ | O_{1,2,3} | \pi^- \rangle$$

Chiral transformation properties

- Chiral symmetry properties

$$\boxed{\begin{array}{ccc} q_L & \rightarrow & L\, q_L \\ q_R & \rightarrow & R\, q_R \end{array}}$$

$L,R \in SU(3)$

$$\begin{array}{lcll} O_1 & = & \bar{q}_L^{\alpha}\gamma_\mu\tau^+ q_L^{\alpha} \;\; \bar{q}_L^{\beta}\gamma^\mu\tau^+ q_L^{\beta} & \mathbf{27}_L \times \mathbf{1}_R \\ O_2 & = & \bar{q}_R^{\alpha}\tau^+ q_L^{\alpha} \;\; \bar{q}_R^{\beta}\tau^+ q_L^{\beta} & \\ O_3 & = & \bar{q}_R^{\alpha}\tau^+ q_L^{\beta} \;\; \bar{q}_R^{\beta}\tau^+ q_L^{\alpha} & \\ O_4 & = & \bar{q}_L^{\alpha}\gamma_\mu\tau^+ q_L^{\alpha} \;\; \bar{q}_R^{\beta}\gamma^\mu\tau^+ q_R^{\beta} & \\ O_5 & = & \bar{q}_L^{\alpha}\gamma_\mu\tau^+ q_L^{\beta} \;\; \bar{q}_R^{\beta}\gamma^\mu\tau^+ q_R^{\alpha} & \end{array}$$

M. Savage
nucl-th/9811087

Chiral transformation properties

- Chiral symmetry properties

$$\begin{array}{lcl} q_L & \to & L\, q_L \\ q_R & \to & R\, q_R \end{array}$$

L,R ∈ *SU(3)*

O_1	$=$	$\bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta$	$\mathbf{27}_L \times \mathbf{1}_R$
O_2	$=$	$\bar{q}_R^\alpha \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \tau^+ q_L^\beta$	$\mathbf{6}_L \times \bar{\mathbf{6}}_R$
O_3	$=$	$\bar{q}_R^\alpha \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \tau^+ q_L^\alpha$	
O_4	$=$	$\bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta$	
O_5	$=$	$\bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha$	

Chiral transformation properties

- Chiral symmetry properties

$$\begin{array}{ccc} q_L & \to & L\, q_L \\ q_R & \to & R\, q_R \end{array}$$

L,R $\in$ *SU(3)*

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Chiral transformation properties

- Chiral symmetry properties $\boxed{\begin{array}{lcl} q_L & \to & L\, q_L \\ q_R & \to & R\, q_R \end{array}}$ $L,R \in SU(3)$

$O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta$	$\mathbf{27}_L \times \mathbf{1}_R$
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$O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta$ $O_5 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha$	$\mathbf{8}_L \times \mathbf{8}_R$

- Focus on $O_{2,3,4,5}$ first and later revisit O_1

Leading chiral realization

- Unique non-derivative realization

$$O^{a,b}_{6\times\bar{6}} = \bar{q}_R T^a q_L \;\; \bar{q}_R T^b q_L \Big|_{6\times\bar{6}} \;\; \rightarrow \;\; g_{6\times\bar{6}} \frac{F_0^4}{8} \left[\mathrm{Tr}\left(T^a U T^b U\right) + \mathrm{Tr}\left(T^a U\right) \mathrm{Tr}\left(T^b U\right) \right]$$

$$O^{a,b}_{8\times 8} = \bar{q}_L T^a \gamma_\mu q_L \;\; \bar{q}_R T^b \gamma^\mu q_R \;\; \rightarrow \;\; g_{8\times 8} \frac{F_0^4}{4} \mathrm{Tr}\left(T^a U T^b U^\dagger\right)$$

Same non-perturbative input for all flavor structures

Chiral Symmetry relates ΔI=2 to ΔS= 2 and ΔS= 1 matrix elements

$$U = \exp\left(\frac{\sqrt{2} i \pi}{F_0}\right), \qquad \pi = \begin{pmatrix} \frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi_3}{\sqrt{2}} + \frac{\pi_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\pi_8 \end{pmatrix}$$

$$U \rightarrow L U R^\dagger \qquad L, R \in SU(3)$$

Leading chiral realization

- Unique non-derivative realization

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Same non-perturbative input for all flavor structures

- $g_{6\times\bar{6}}$ from K-$\bar{\text{K}}$ mixing
- $g_{8\times 8}$ from K-$\bar{\text{K}}$ mixing *and* K $\rightarrow\pi\pi$

Leading chiral realization

- Unique non-derivative realization

$$O^{a,b}_{6\times\bar{6}} = \bar{q}_R T^a q_L \;\; \bar{q}_R T^b q_L \Big|_{6\times\bar{6}} \;\; \rightarrow \;\; g_{6\times\bar{6}} \frac{F_0^4}{8} \left[\mathrm{Tr}\left(T^a U T^b U\right) + \mathrm{Tr}\left(T^a U\right)\mathrm{Tr}\left(T^b U\right)\right]$$

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Same non-perturbative input for all flavor structures

- Leading order symmetry relation

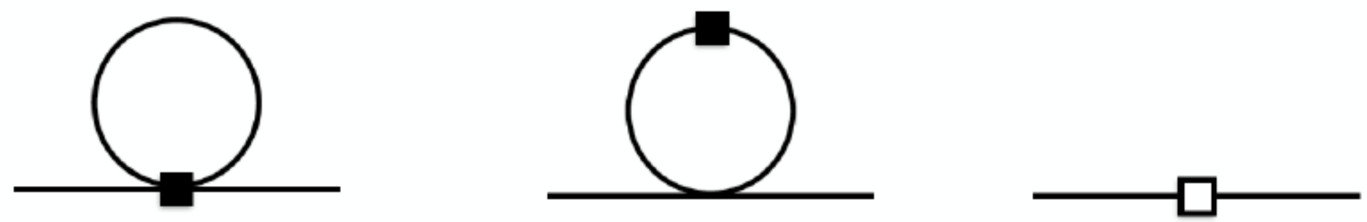
$$\mathcal{M}^{\pi\pi}_{6\times\bar{6}} \equiv \langle \pi^+ | O^{1+i2,1+i2}_{6\times\bar{6}} | \pi^- \rangle \;\; = \;\; \langle \bar{K}^0 | O^{6-i7,6-i7}_{6\times\bar{6}} | K^0 \rangle \equiv \mathcal{M}^{K\bar{K}}_{6\times\bar{6}}$$

$$\mathcal{M}^{\pi\pi}_{8\times 8} \equiv \langle \pi^+ | O^{1+i2,1+i2}_{8\times 8} | \pi^- \rangle \;\; = \;\; \langle \bar{K}^0 | O^{6-i7,6-i7}_{8\times 8} | K^0 \rangle \equiv \mathcal{M}^{K\bar{K}}_{8\times 8}$$

Matrix elements we want for NLDBD

Computed in LQCD by several groups

NLO chiral relations



$$\mathcal{M}^{\pi\pi}_{8\times 8} = \mathcal{M}^{K\bar{K}}_{8\times 8} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{8\times 8})$$

$$\mathcal{M}^{\pi\pi}_{6\times \bar{6}} = \mathcal{M}^{K\bar{K}}_{6\times \bar{6}} \times \frac{F_\pi^2}{F_K^2} \times (1+\Delta_{6\times \bar{6}})$$

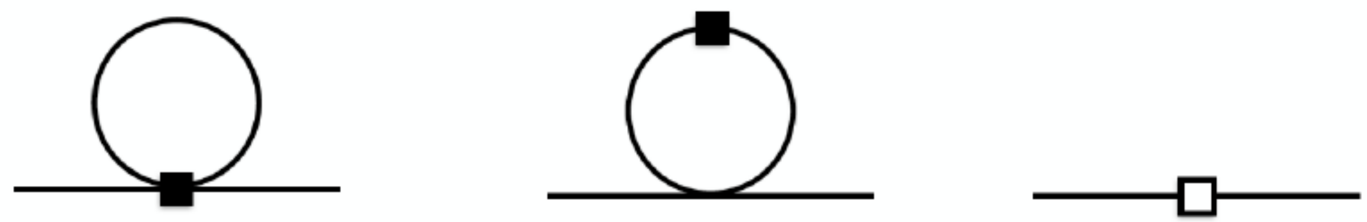
$$\Delta_{8\times 8} = \frac{1}{(4\pi F_0)^2}\left[\frac{m_\pi^2}{4}(-4+5L_\pi) - m_K^2(-1+2L_K) + \frac{3}{4}m_\eta^2 L_\eta - a_{8\times 8}\,(m_K^2 - m_\pi^2)\right]$$

$$\Delta_{6\times \bar{6}} = \frac{1}{(4\pi F_0)^2}\left[-\frac{m_\pi^2}{4}(4-3L_\pi) - m_K^2(-1+2L_K) + \frac{5}{4}m_\eta^2 L_\eta - a_{6\times \bar{6}}\,(m_K^2 - m_\pi^2)\right]$$

$$L_{\pi,K,\eta} \equiv \log \mu_\chi^2 / m^2_{\pi,K,\eta}$$

LEC can be determined in principle by studying $m_{u,d}$ and m_s dependence of K-$\bar{\text{K}}$ matrix element

NLO chiral relations



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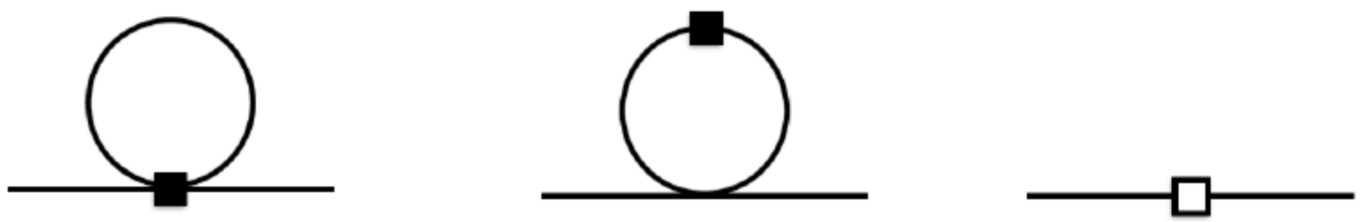
$$L_{\pi,K,\eta} \equiv \log \mu_\chi^2 / m^2_{\pi,K,\eta}$$

In practice set these to zero at $\mu_\chi = m_\rho$
and take as error maximum between NDA and

$$\Delta_n^{(\mathrm{ct})} = \pm|d\Delta_n^{(\mathrm{loops})}/d(\log \mu_\chi)|$$

NLO chiral relations



$$\mathcal{M}^{\pi\pi}_{8\times 8} = \mathcal{M}^{K\bar{K}}_{8\times 8} \times \frac{F_\pi^2}{F_K^2} \times (1 + \Delta_{8\times 8})$$

$$\mathcal{M}^{\pi\pi}_{6\times \bar{6}} = \mathcal{M}^{K\bar{K}}_{6\times \bar{6}} \times \frac{F_\pi^2}{F_K^2} \times (1 + \Delta_{6\times \bar{6}})$$

$$\Delta_{8\times 8} = 0.02(30)$$

$$\Delta_{6\times \bar{6}} = 0.07(20)$$

- Dominant chiral corrections captured by $(F_\pi/F_K)^2 = 0.71$

Results for $\langle \pi^+ | O_{2,3,4,5} | \pi^- \rangle$

- Input: K-$\bar{\text{K}}$ matrix elements at μ = 3 GeV in $\overline{\text{MS}}$ scheme
- Use conservative range from FLAG 2016 review

Aoki et al., 1607.00299

$$
\begin{aligned}
\langle \pi^+ | O_2 | \pi^- \rangle &= -(2.7 \pm 0.3 \pm 0.5) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_3 | \pi^- \rangle &= (0.9 \pm 0.1 \pm 0.2) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_4 | \pi^- \rangle &= -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_5 | \pi^- \rangle &= -(11 \pm 2 \pm 3) \times 10^{-2}\ \text{GeV}^4
\end{aligned}
$$

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$$\begin{aligned}
\langle \pi^+ | O_2 | \pi^- \rangle &= -(2.7 \pm 0.3 \pm 0.5) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_3 | \pi^- \rangle &= (0.9 \pm 0.1 \pm 0.2) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_4 | \pi^- \rangle &= -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \text{GeV}^4 \\
\langle \pi^+ | O_5 | \pi^- \rangle &= -(11 \pm 2 \pm 3) \times 10^{-2}\ \text{GeV}^4
\end{aligned}$$

First error:
lattice QCD input

Results for $\langle \pi^+ | O_{2,3,4,5} | \pi^- \rangle$

- Input: K-$\bar{K}$ matrix elements at μ = 3 GeV in $\overline{MS}$ scheme
- Use conservative range from FLAG 2016 review

Aoki et al., 1607.00299

$$\langle \pi^+ | O_2 | \pi^- \rangle = -(2.7 \pm 0.3 \pm 0.5) \times 10^{-2}\ \mathrm{GeV}^4$$
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$$\langle \pi^+ | O_5 | \pi^- \rangle = -(11 \pm 2 \pm 3) \times 10^{-2}\ \mathrm{GeV}^4$$

First error: lattice QCD input

Second error: chiral corrections

$\langle \pi^+|O_{4,5}|\pi^-\rangle$ (8_Lx8_R) from K $\rightarrow\pi\pi$

- Can extract g_{8x8} from "electroweak penguin" matrix elements

$$\langle(\pi\pi)_{I=2}|Q_{7,8}|K^0\rangle$$

- Lattice input + chiral corrections in both K $\rightarrow\pi\pi$ and $\pi\rightarrow\pi$

Blum et al, 1502.00263 VC + E. Golowich, hep-ph/9912513 & hep-ph/0109265

$\langle \pi^+ | O_{4,5} | \pi^- \rangle$ $(8_L \times 8_R)$ from $K \to \pi\pi$

- Can extract $g_{8\times8}$ from "electroweak penguin" matrix elements

$$\langle (\pi\pi)_{I=2} | Q_{7,8} | K^0 \rangle$$

- Lattice input + chiral corrections in both $K \to \pi\pi$ and $\pi \to \pi$

Blum et al, 1502.00263 VC + E. Golowich, hep-ph/9912513 & hep-ph/0109265

2.7

$$\begin{aligned}
\langle \pi^+ | O_4 | \pi^- \rangle &= -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \mathrm{GeV}^4 \\
\langle \pi^+ | O_5 | \pi^- \rangle &= -(11 \pm 2 \pm 3) \times 10^{-2}\ \mathrm{GeV}^4
\end{aligned}$$

12.7

Remarkable agreement (sanity check)

Revisiting $\langle \pi^+ | O_1 | \pi^- \rangle$ ($27_L \times 1_R$)

Donoghue, Golowich, Holstein 1982

$$Q_2 = \bar{s}\gamma_\mu(1-\gamma_5)u\,\bar{u}\gamma^\mu(1-\gamma_5)d = Q_2^{(27\times1)} + Q_2^{(8\times1)}$$

$$O_{\Delta S=2} = \bar{s}\gamma_\mu(1-\gamma_5)d\,\bar{s}\gamma^\mu(1-\gamma_5)d$$

$$O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta$$

Savage 1998

belong to same representation

Revisiting $\langle\pi^+|O_1|\pi^-\rangle$ $(27_L \times 1_R)$

$$Q_2^{(27\times 1)} \rightarrow g_{27\times 1} F_0^4 \left(L_{\mu 32} L^\mu_{11} + \frac{2}{3} L_{\mu 31} L^\mu_{12} \right)$$

$$O_{\Delta S=2} \rightarrow \frac{5}{3} g_{27\times 1} F_0^4 \; L_{\mu 32} L^\mu_{32}$$

$$4\, O_1 \rightarrow \frac{5}{3} g_{27\times 1} F_0^4 \; L_{\mu 12} L^\mu_{12} \; ,$$

$$L^\mu_{ij} = i(U^\dagger \partial^\mu U)_{ij}$$

- Chiral operators start at $O(p^2)$ → smaller matrix elements
- One non-perturbative parameter at this order
- $\Delta S=2$ matrix element suffers from large chiral corrections

Bijnens-Sonoda-Wise 1984

Revisiting $\langle \pi^+|O_1|\pi^-\rangle$ ($27_L \times 1_R$)

$$
\begin{aligned}
Q_2^{(27\times 1)} &\rightarrow g_{27\times 1}\, F_0^4 \left(L_{\mu 32} L_{11}^{\mu} + \frac{2}{3} L_{\mu 31} L_{12}^{\mu} \right) \\
O_{\Delta S=2} &\rightarrow \frac{5}{3}\, g_{27\times 1}\, F_0^4\; L_{\mu 32} L_{32}^{\mu} \\
4\, O_1 &\rightarrow \frac{5}{3}\, g_{27\times 1}\, F_0^4\; L_{\mu 12} L_{12}^{\mu} \,,
\end{aligned}
$$

$$L_{ij}^{\mu} = i(U^{\dagger}\partial^{\mu} U)_{ij}$$

- Use instead…

$$
\begin{aligned}
\langle \pi^+|O_1|\pi^-\rangle &= \frac{5}{3}\, g_{27\times 1}\, m_\pi^2 F_\pi^2 \left\{ 1 + \frac{m_\pi^2}{(4\pi F_0)^2}(-1 + 3L_\pi) + \delta_{27\times 1}^{\pi\pi} \right\} . \\
\langle \pi^+\pi^0|iQ_2|K^+\rangle &= \frac{5}{3}\, g_{27\times 1}\, F_\pi\; (m_K^2 - m_\pi^2)\; \left\{ 1 + \Delta_{27}^{K^+\pi^+\pi^0} \right\} .
\end{aligned}
$$

- …and LQCD input on $\langle \pi^+\pi^0|Q_2|K^+\rangle$ + chiral corrections

Blum et al, 1502.00263 VC-Ecker-Neufeld-Pich hep-ph/0310351

Revisiting $\langle \pi^+ | O_1 | \pi^- \rangle$ ($27_L \times 1_R$)

$$Q_2^{(27\times 1)} \rightarrow g_{27\times 1} F_0^4 \left(L_{\mu 32} L_{11}^{\mu} + \frac{2}{3} L_{\mu 31} L_{12}^{\mu} \right)$$

$$O_{\Delta S=2} \rightarrow \frac{5}{3} g_{27\times 1} F_0^4 \, L_{\mu 32} L_{32}^{\mu}$$

$$4\, O_1 \rightarrow \frac{5}{3} g_{27\times 1} F_0^4 \, L_{\mu 12} L_{12}^{\mu} \, ,$$

$$L_{ij}^{\mu} = i(U^{\dagger}\partial^{\mu} U)_{ij}$$

- At μ = 3 GeV in $\overline{\mathrm{MS}}$ scheme, extract $g_{27\times 1} = 0.34\,(3)_{LQCD}\,(2)_{\chi}$
- Good agreement with M. Savage (nucl-th/9811087) after realizing that $g^{(\mathbf{27})} = (5/12) g_{27\times 1}$

$$\boxed{\langle \pi^+ | O_1 | \pi^- \rangle = (1.0 \pm 0.1 \pm 0.2) \times 10^{-4}\ \mathrm{GeV}^4}$$

Lattice QCD input

Chiral corrections

Summary

Matrix elements in MS-bar renormalization scheme at μ = 3 GeV

$$
\begin{aligned}
\langle \pi^+ | O_1 | \pi^- \rangle &= (1.0 \pm 0.1 \pm 0.2) \times 10^{-4}\ \mathrm{GeV}^4 \\
\langle \pi^+ | O_2 | \pi^- \rangle &= -(2.7 \pm 0.3 \pm 0.5) \times 10^{-2}\ \mathrm{GeV}^4 \\
\langle \pi^+ | O_3 | \pi^- \rangle &= (0.9 \pm 0.1 \pm 0.2) \times 10^{-2}\ \mathrm{GeV}^4 \\
\langle \pi^+ | O_4 | \pi^- \rangle &= -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \mathrm{GeV}^4 \\
\langle \pi^+ | O_5 | \pi^- \rangle &= -(11 \pm 2 \pm 3) \times 10^{-2}\ \mathrm{GeV}^4
\end{aligned}
$$

First error: LQCD

Second error: chiral corrections

- First controlled estimate of $\langle \pi^+ | O_i | \pi^- \rangle$ for all scalar, dim-6, ΔI=2 operators relevant to $0\nu\beta\beta$ — based on chiral SU(3) + lattice QCD

- Qualitative agreement with un-renormalized CalLat results

Nicholson et al., 1608.04793

- Robust input to be combined with nuclear structure calculations of leading pion exchange operator → estimate of $T_{1/2}$ from TeV-scale LNV

Backup

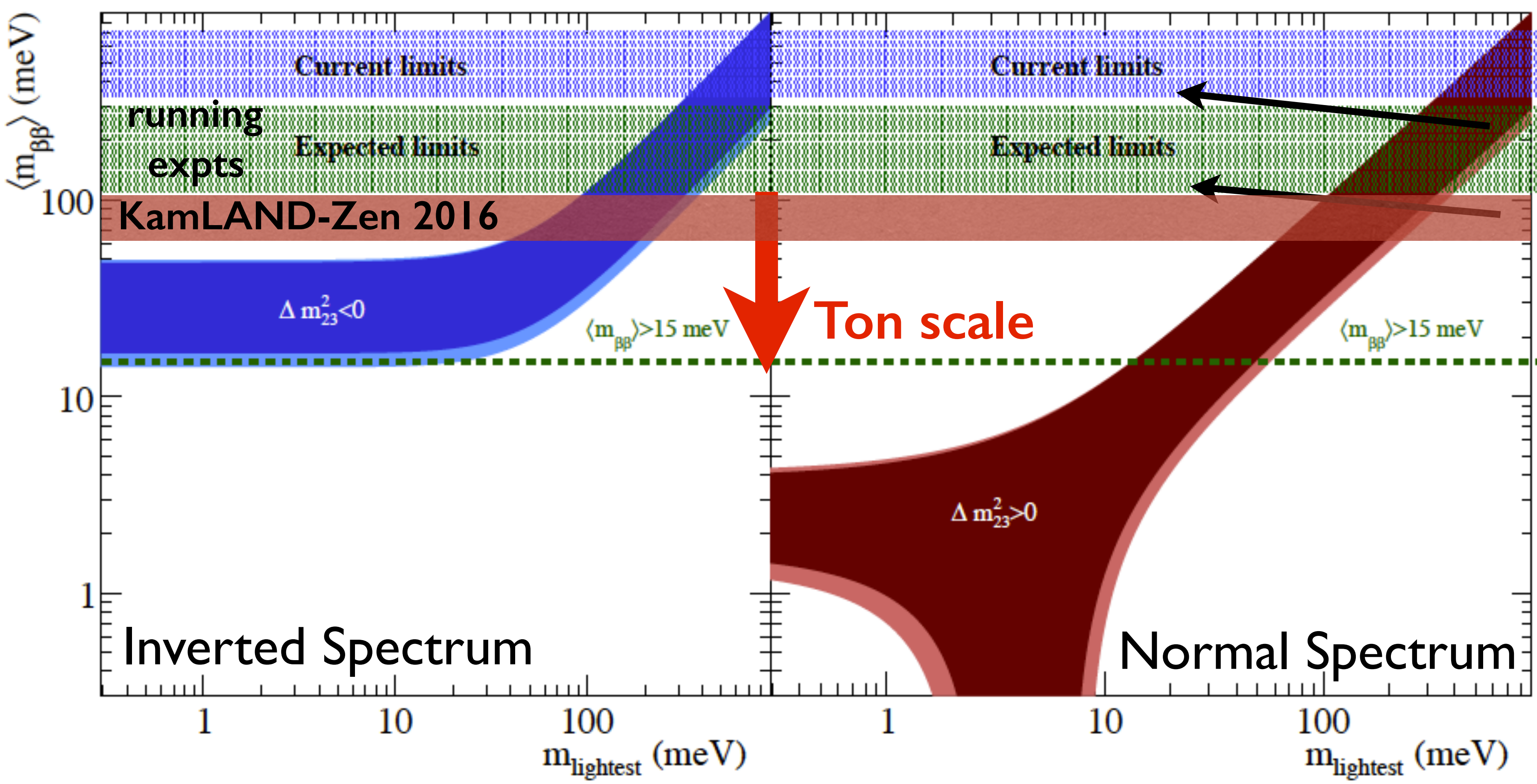
High-scale seesaw

- Strong correlation of 0νββ with neutrino phenomenology: $\Gamma \propto (m_{\beta\beta})^2$

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

Dark bands: unknown phases

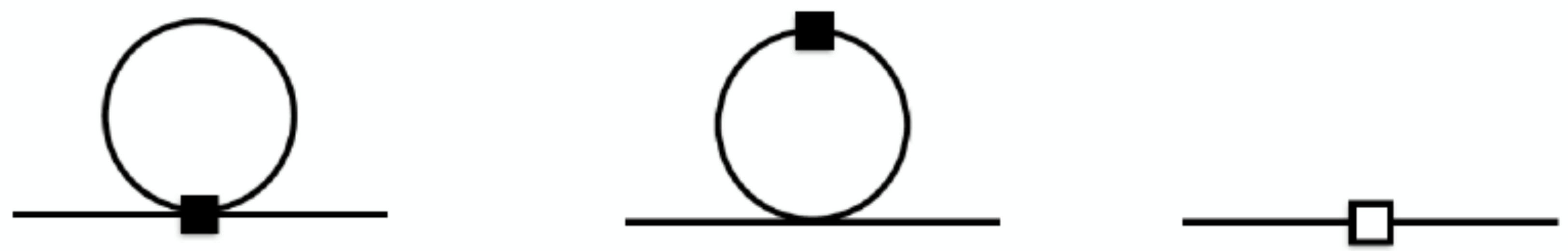
Light bands: uncertainty from oscillation parameters(90% CL)



Assume most “pessimistic” values for nuclear matrix elements

- Discovery *possible* for inverted spectrum OR $m_{lightest}$ > 50 meV

NLO chiral corrections: details



- Lessons from K physics: NLO chiral corrections can be large!

$$L_{\pi,K,\eta} \equiv \log \mu_\chi^2 / m_{\pi,K,\eta}^2$$

$$\begin{aligned}
\mathcal{M}_{8\times 8}^{K\bar{K}} &= g_{8\times 8}\, F_K^2 \left\{ 1 + \frac{1}{(4\pi F_0)^2} \left(m_K^2 \left(-1 + 2L_K\right) - \frac{m_\pi^2}{4} L_\pi - \frac{3}{4} m_\eta^2 L_\eta + \delta_{8\times 8}^{K\bar{K}} \right) \right\} \\
\mathcal{M}_{8\times 8}^{\pi\pi} &= g_{8\times 8}\, F_\pi^2 \left\{ 1 + \frac{1}{(4\pi F_0)^2} \left(m_\pi^2 \left(-1 + L_\pi\right) + \delta_{8\times 8}^{\pi\pi} \right) \right\} .
\end{aligned}$$

$$\delta_{8\times 8}^{\pi\pi} = a_{8\times 8}\, m_\pi^2 + b_{8\times 8} \left(m_K^2 + \frac{1}{2} m_\pi^2 \right) \qquad \delta_{8\times 8}^{K\bar{K}} = a_{8\times 8}\, m_K^2 + b_{8\times 8} \left(m_K^2 + \frac{1}{2} m_\pi^2 \right)$$

- Low-energy constants can be extracted from kaon mixing calculation at different values of $m_{u,d}$ and m_s

Results for $\langle\pi^+|O_{2,3,4,5}|\pi^-\rangle$: details

- Input: K-$\bar{K}$ matrix elements at μ = 3 GeV in $\overline{MS}$ scheme
- Use conservative range from FLAG 2016 review

Aoki et al., 1607.00299

$$
\begin{aligned}
\langle\pi^+|O_2|\pi^-\rangle &= -\frac{5}{12} B_2\, K \times R_{6\times\bar{6}} \\
\langle\pi^+|O_3|\pi^-\rangle &= \frac{1}{12} B_3\, K \times R_{6\times\bar{6}} \\
\langle\pi^+|O_4|\pi^-\rangle &= -\frac{1}{3} B_5\, K \times R_{8\times 8} \\
\langle\pi^+|O_5|\pi^-\rangle &= -B_4\, K \times R_{8\times 8}\ ,
\end{aligned}
$$

$$K = \frac{2\, F_K^2\, m_K^4}{(m_d + m_s)^2}$$

Input: bag factors from kaon mixing

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	running	B_2	B_3	B_4	B_5
ETM 15	[42]	2+1+1	A	★	○	○	★	a	0.46(1)(3)	0.79(2)(5)	0.78(2)(4)	0.49(3)(3)
SWME 15A	[45]	2+1	A	★	○	★	○†	–	0.525(1)(23)	0.772(6)(35)	0.981(3)(62)	0.751(7)(68)
SWME 14C	[416]	2+1	C	★	○	★	○†	–	0.525(1)(23)	0.774(6)(64)	0.981(3)(61)	0.748(9)(79)
SWME 13A‡	[401]	2+1	A	★	○	★	○†	–	0.549(3)(28)	0.790(30)	1.033(6)(46)	0.855(6)(43)
RBC/ UKQCD 12E	[411]	2+1	A	■	○	★	★	b	0.43(1)(5)	0.75(2)(9)	0.69(1)(7)	0.47(1)(6)
ETM 12D	[46]	2	A	★	○	○	★	c	0.47(2)(1)	0.78(4)(2)	0.76(2)(2)	0.58(2)(2)

† The renormalization is performed using perturbation theory at one loop, with a conservative estimate of the uncertainty.

a B_i are renormalized nonperturbatively at scales $1/a \sim 2.2 - 3.3\,\text{GeV}$ in the $N_f = 4$ RI/MOM scheme using two different lattice momentum scale intervals, with values around $1/a$ for the first and around 3.5 GeV for the second one. The impact of these two ways to the final result is taken into account in the error budget. Conversion to $\overline{\text{MS}}$ is at one loop at 3 GeV.

b The B parameters are renormalized nonperturbatively at a scale of 3 GeV.

c B_i are renormalized nonperturbatively at scales $1/a \sim 2 - 3.7\,\text{GeV}$ in the $N_f = 2$ RI/MOM scheme using two different lattice momentum scale intervals, with values around $1/a$ for the first and around 3 GeV for the second one.

‡ The computation of B_4 and B_5 has been revised in Refs. [45] and [416].