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Lepton Number Violation: connecting the TeV scale to nuclei

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EST. 1943

Outline

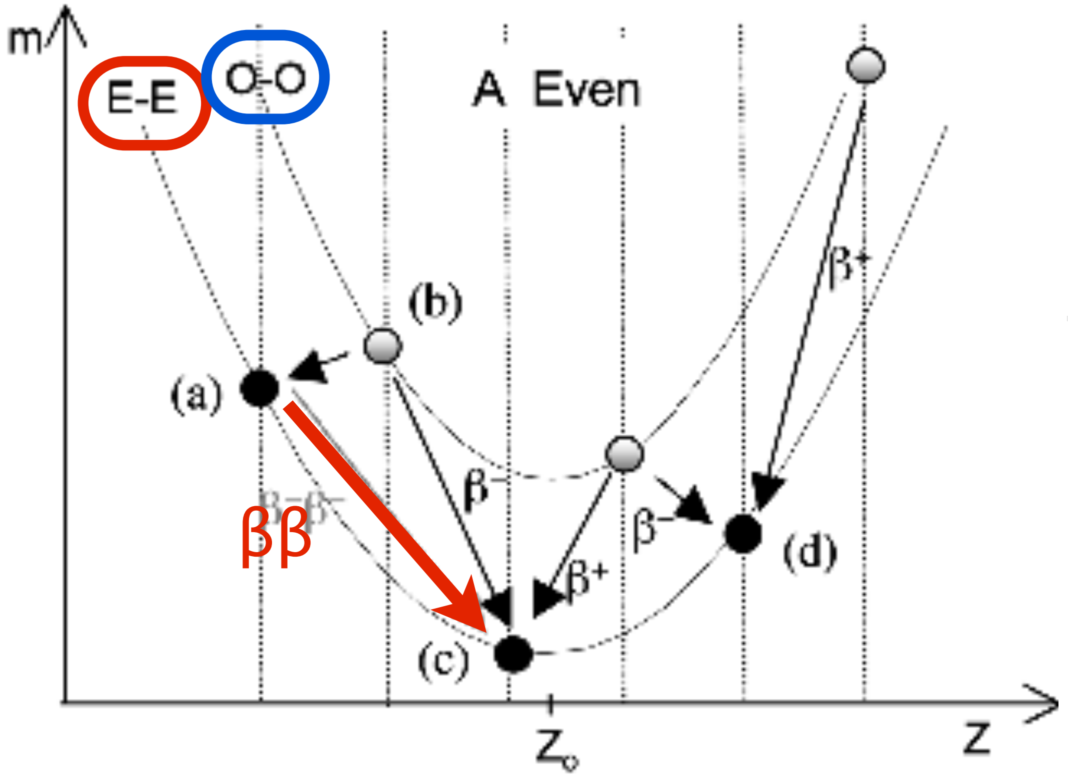
- Introduction: $0\nu\beta\beta$ and Lepton Number Violation (LNV)
- $0\nu\beta\beta$ and TeV sources of LNV
  - Examples
  - EFT approach
  - Leading *pion-pion* matrix elements from chiral SU(3) + lattice QCD *kaon* matrix elements
- Conclusions

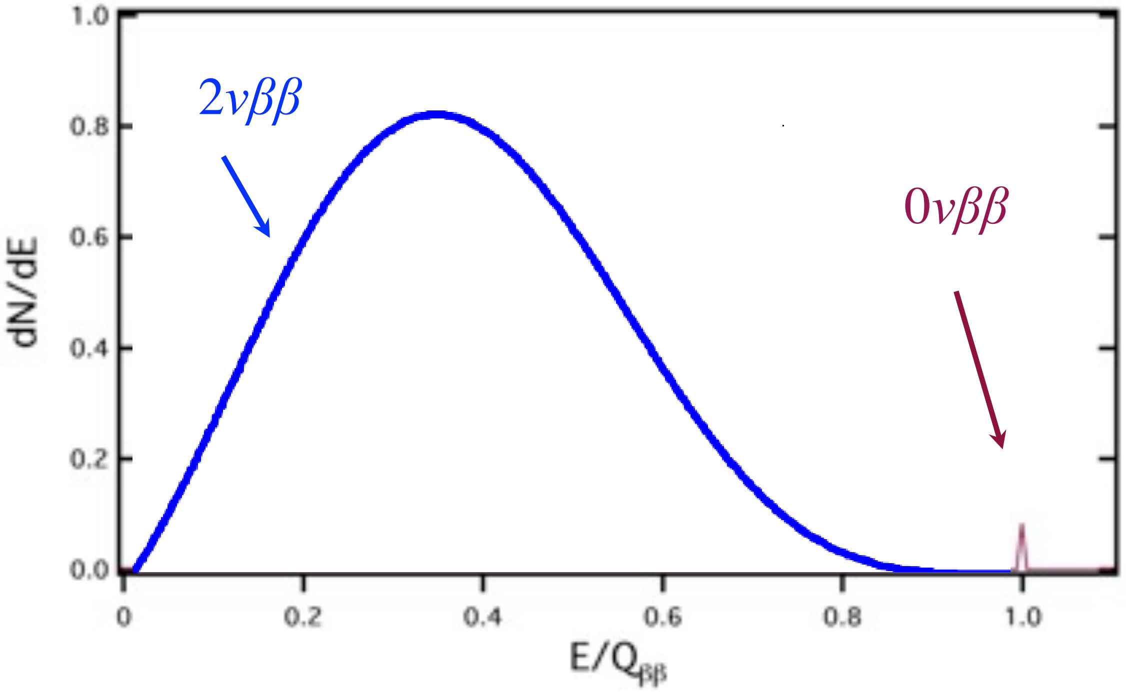
Based on arXiv:1701.01443 → PLB

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

0νββ and Lepton Number Violation

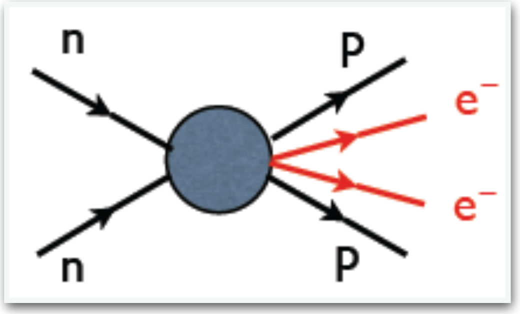
- For certain nuclei, single beta decay is energetically forbidden
- 2νββ is a (very rare) 2nd order weak process, expected in the Standard Model and observed
- 0νββ is quite special



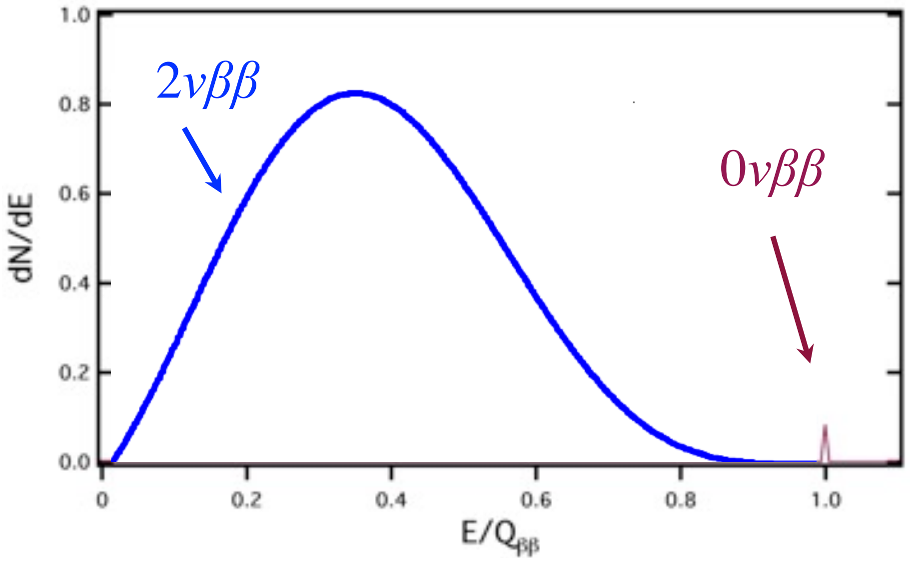


0νββ and Lepton Number Violation

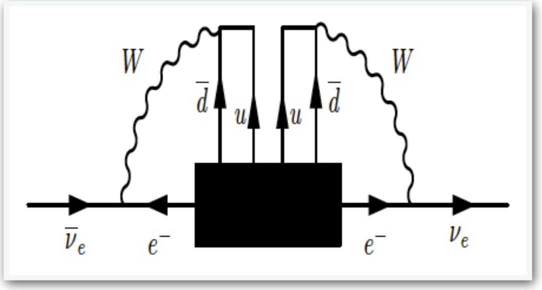
$$\boxed{(N,Z) \rightarrow (N-2, Z+2) + \ e^- + \ e^-}$$



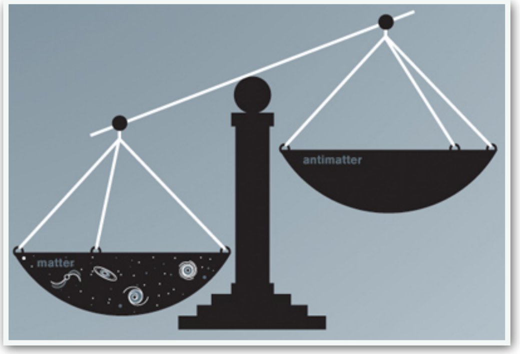
Lepton number changes by two units: ΔL=2



- B-L conserved in SM → new physics, with far-reaching implications
    - Demonstrate that neutrinos are their own antiparticles
    - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



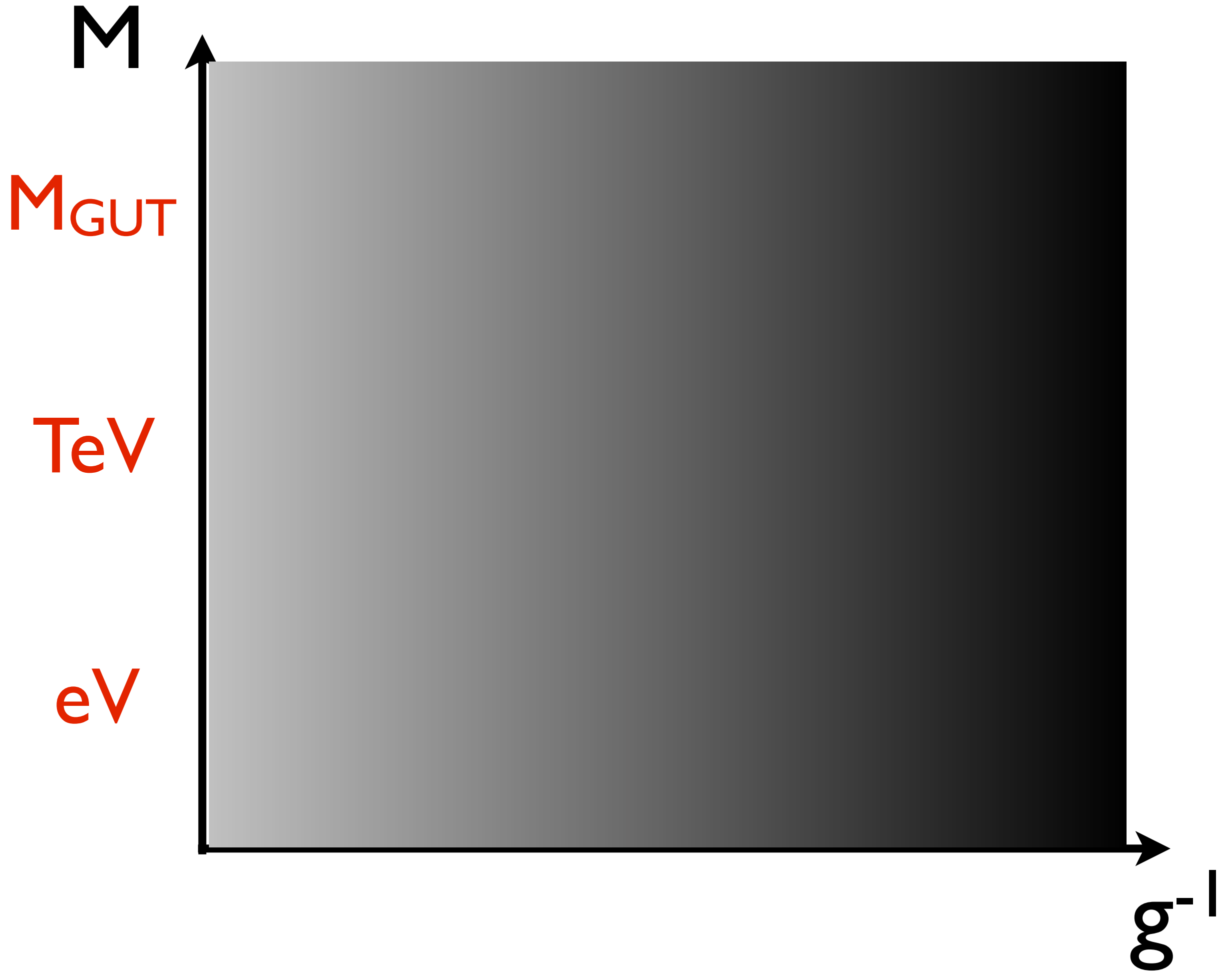
Shechter-Valle 1982

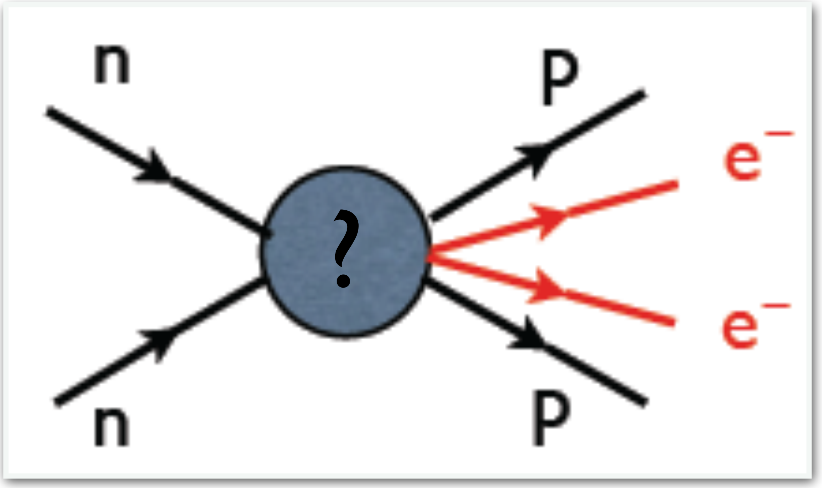


Fukujgita-Yanagida 1987

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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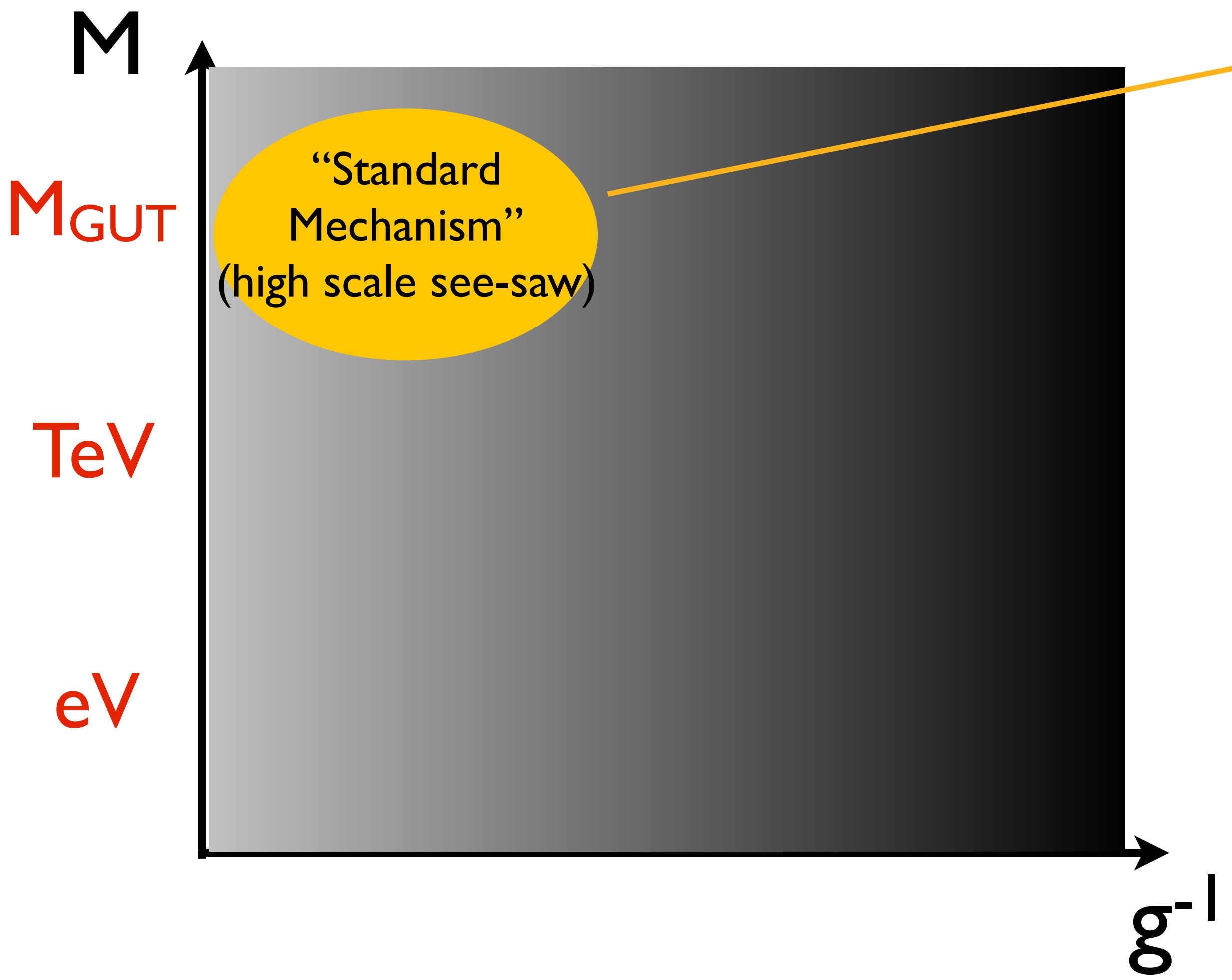
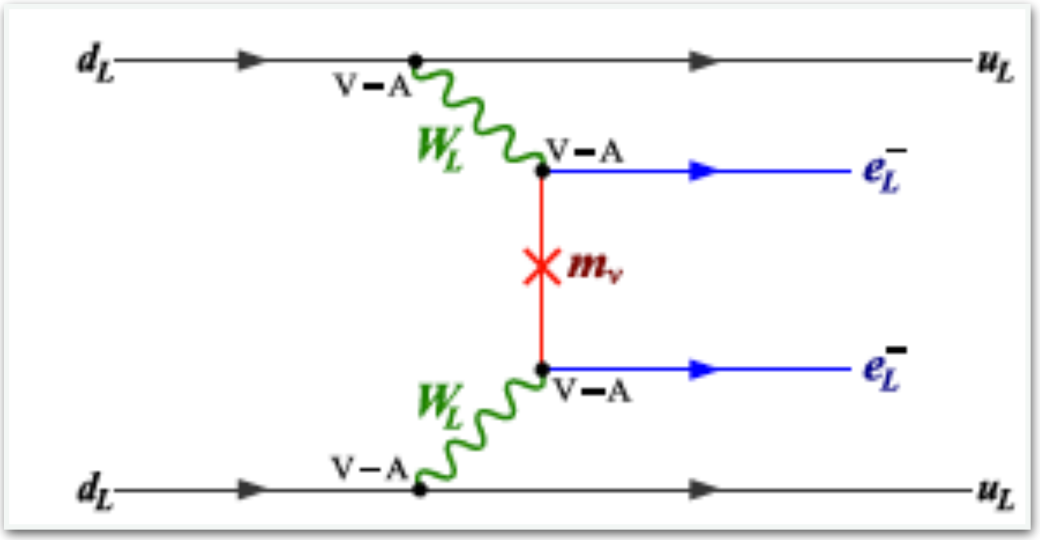
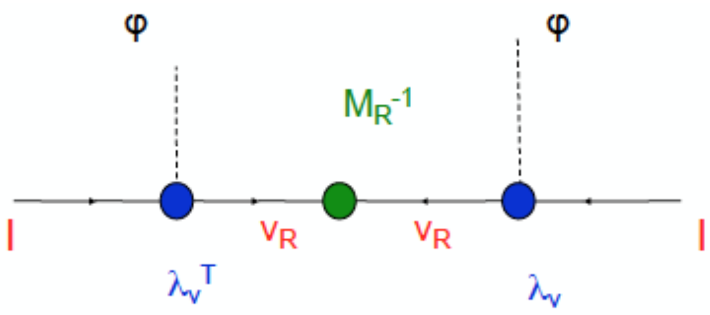


LNV dynamics at M >> TeV:
leaves as the only low-energy footprint
light Majorana neutrino





$m_\nu \sim v_{ew}^2 \, \lambda_\nu^T M_R^{-1} \lambda_\nu$

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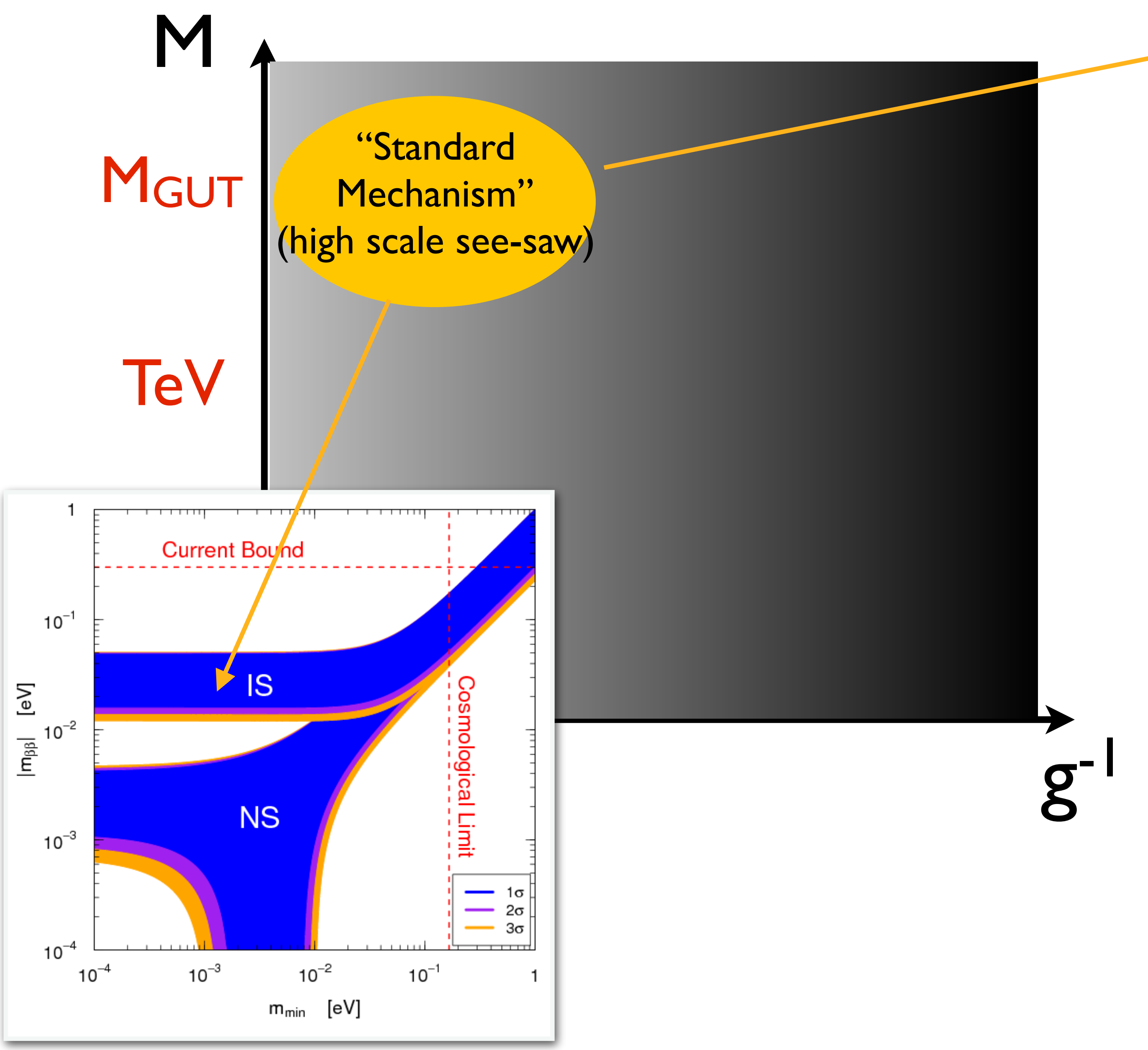

"Standard Mechanism" (high scale see-saw)

LNV dynamics at M >> TeV:
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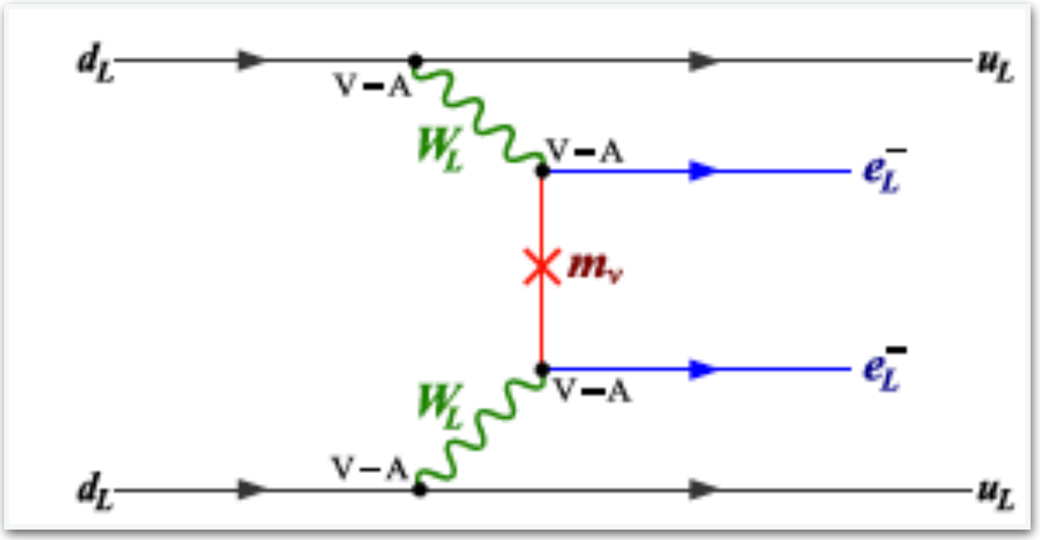

Clear interpretation framework and sensitivity goals ("inverted hierarchy"). Requires difficult nuclear matrix elements.

But only limited class of models!

0νββ and Lepton Number Violation

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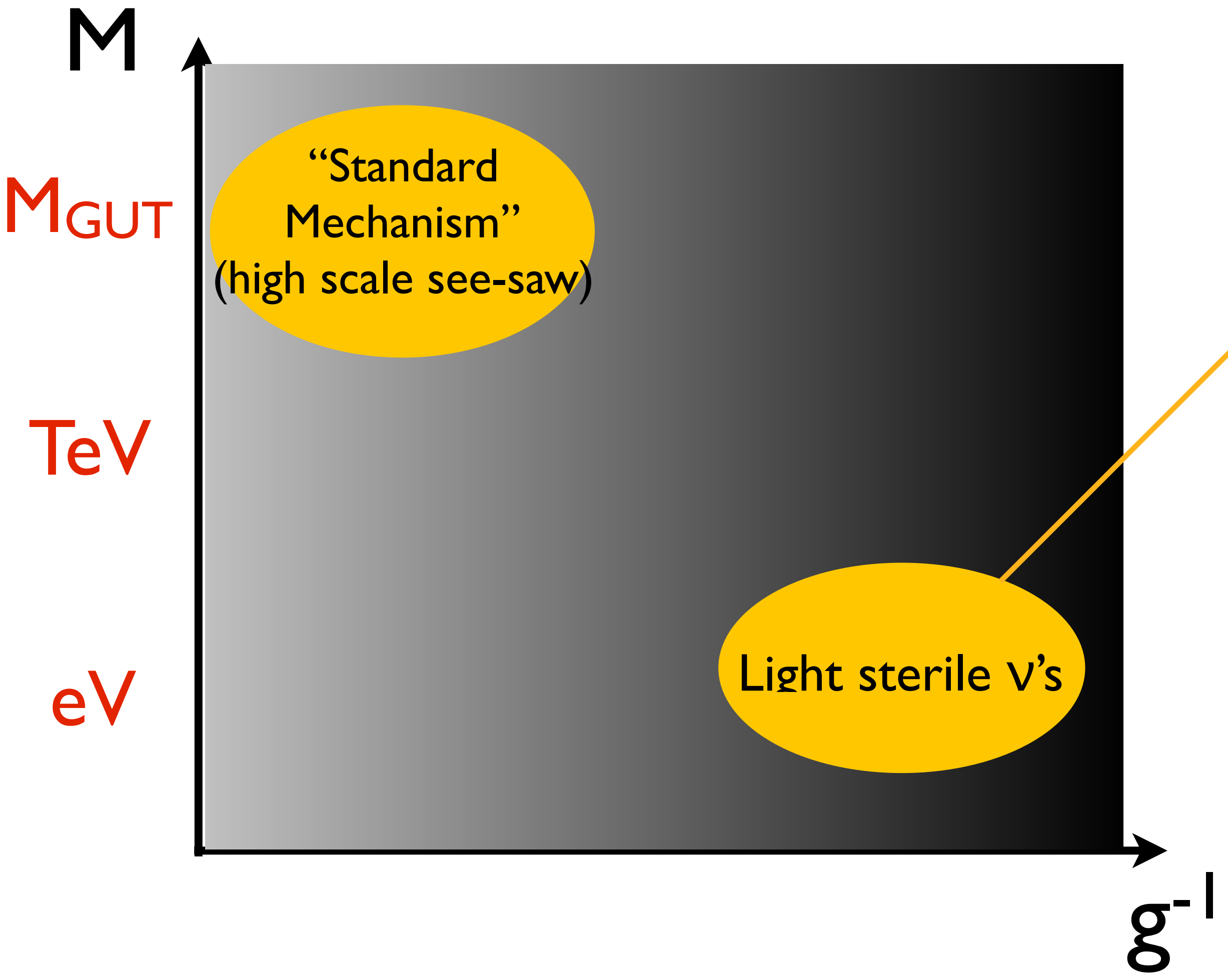
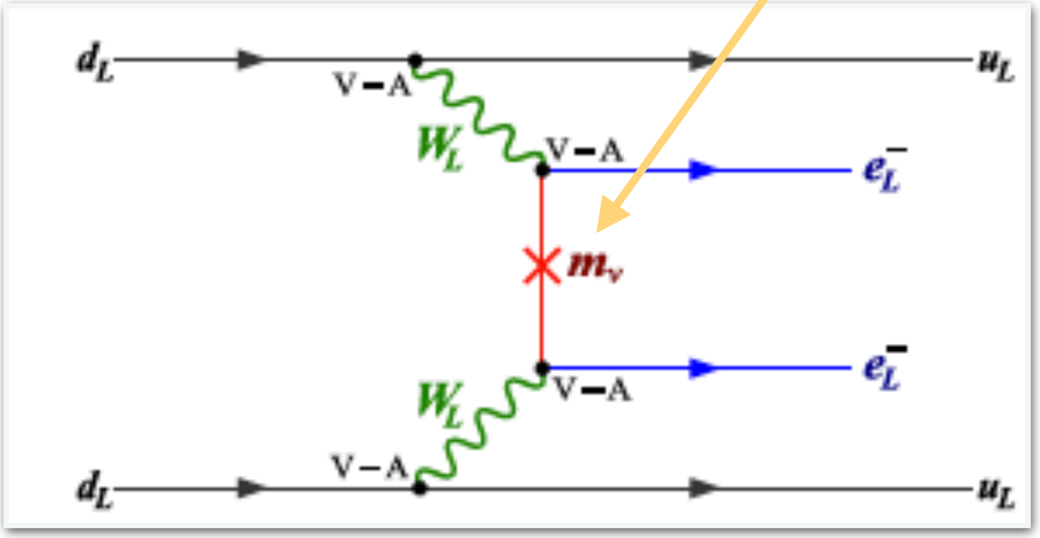


LNV dynamics at M_R ~ eV → GeV: additional light Majorana states



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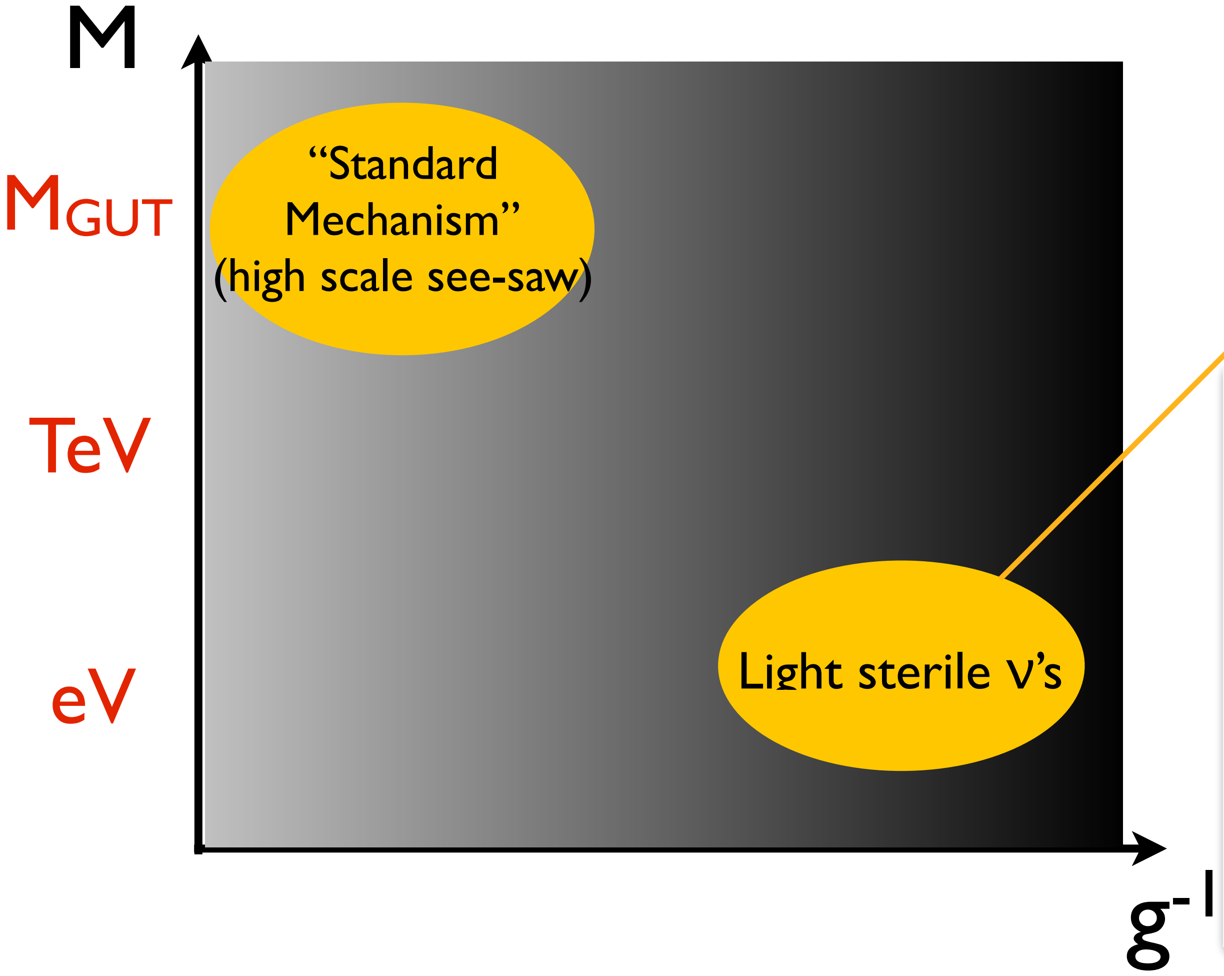

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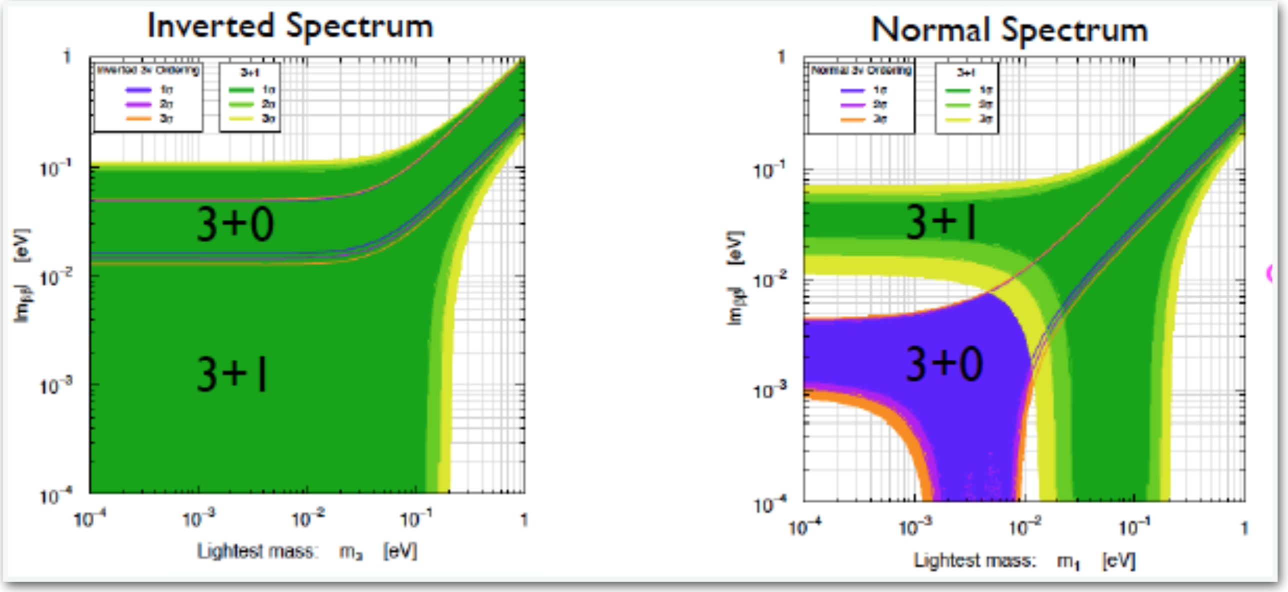

Giunti-Zavanin 1505.00978

Usual phenomenology turned around if there is a light sterile ν_R with mass (~eV) and mixing (~0.1) to fit short baseline anomalies

0νββ and Lepton Number Violation

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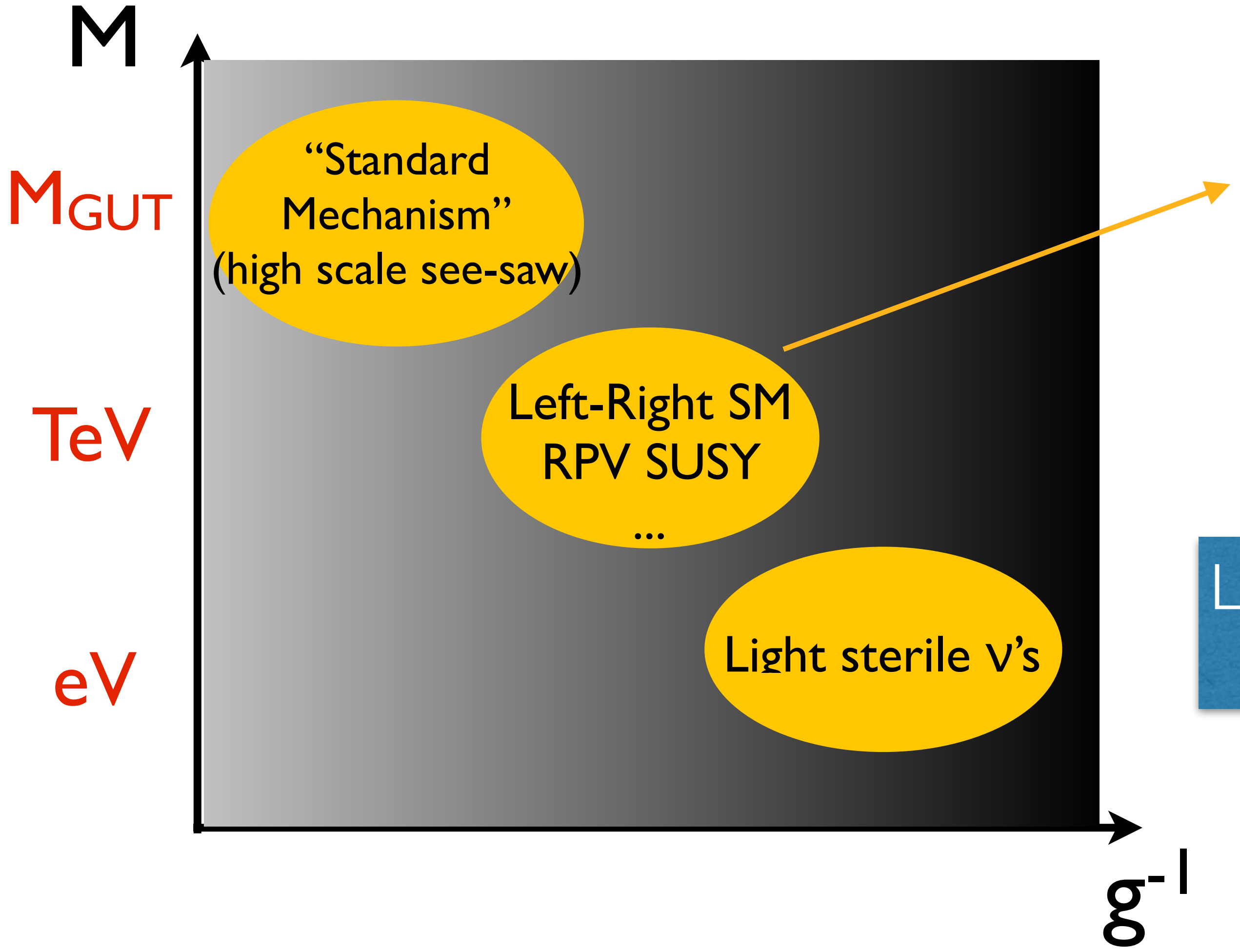
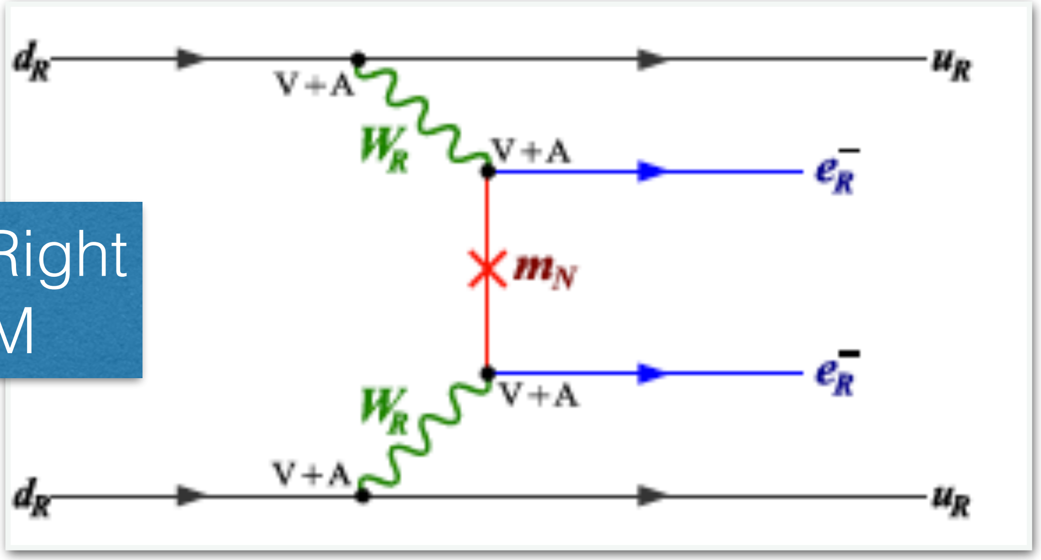


LNV dynamics at M ~ TeV:
1) new contribution to 0νββ not directly related to light neutrino mass;
2) pp → eejj at the LHC

Left-Right SM

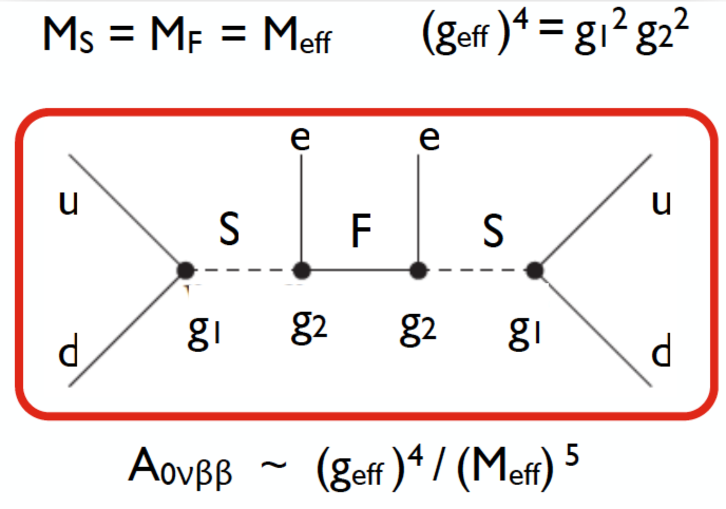


Interpretation framework and sensitivity goals not *systematically* developed

Different set of (difficult) hadronic and nuclear matrix elements

TeV scale LNV: examples

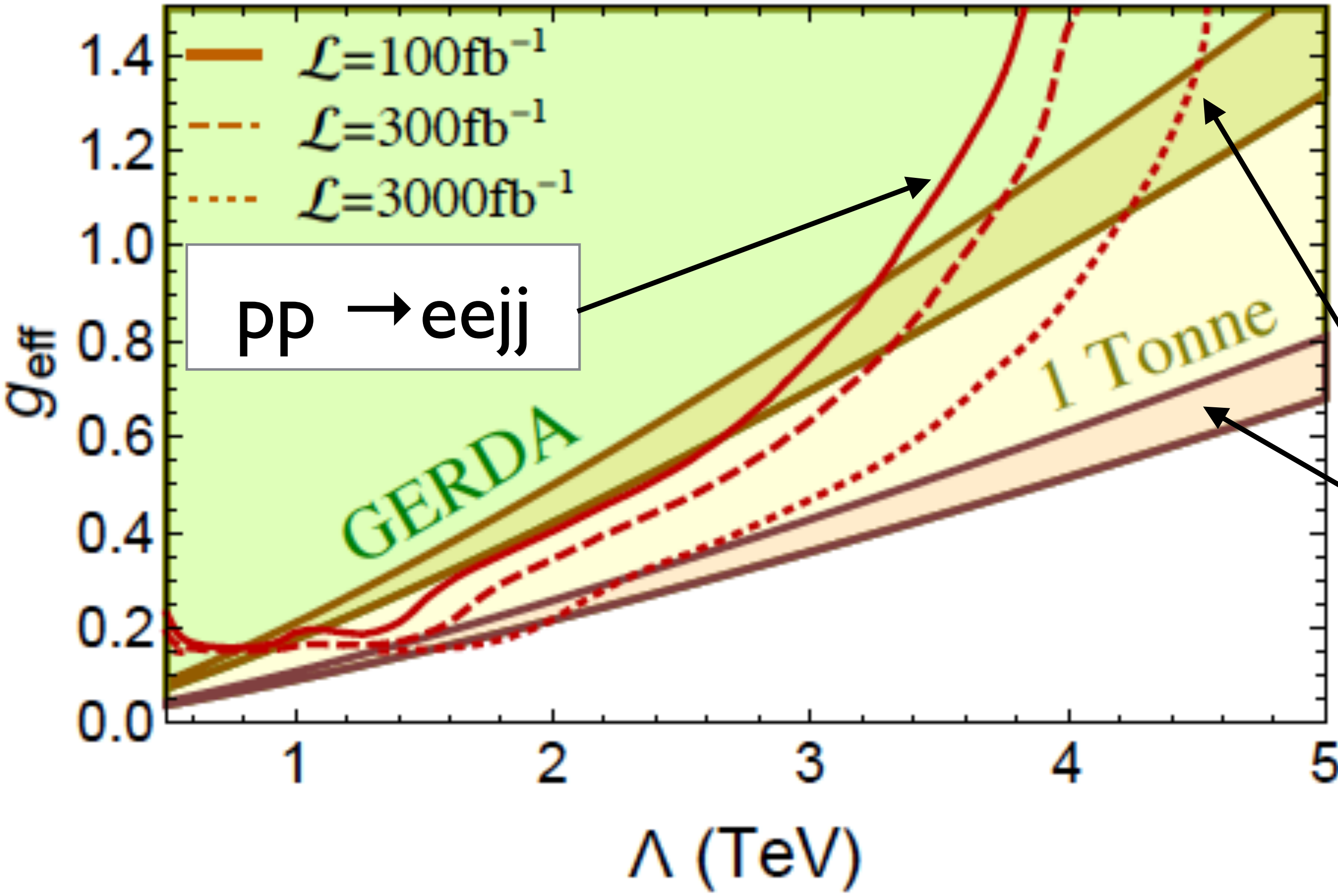
Simplified model
~ RPV-SUSY



$M_S = M_F = M_{eff}$ $(g_{eff})^4 = g_1^2 g_2^2$

$A_{0\nu\beta\beta} \sim (g_{eff})^4 / (M_{eff})^5$

For other studies see:
Helo et al: 1307.4849
Deppisch et al: 1208.0727
(and references therein)



Ton-scale NLDBD extends mass reach (multi TeV) and covers LHC-inaccessible regions

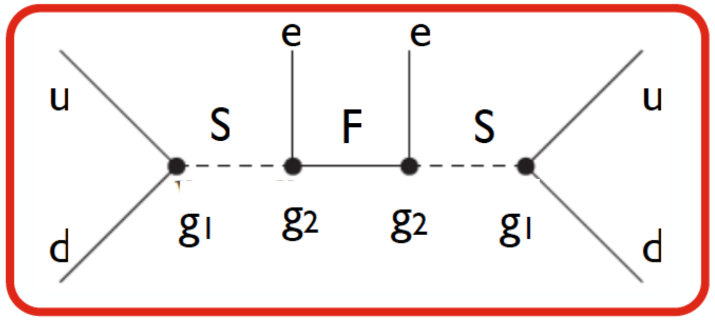
Plot assumes factor of 2 variation (~30% uncertainty!) in the hadronic & nuclear matrix elements

Peng, Ramsey-Musolf, Winslow, 1508.0444

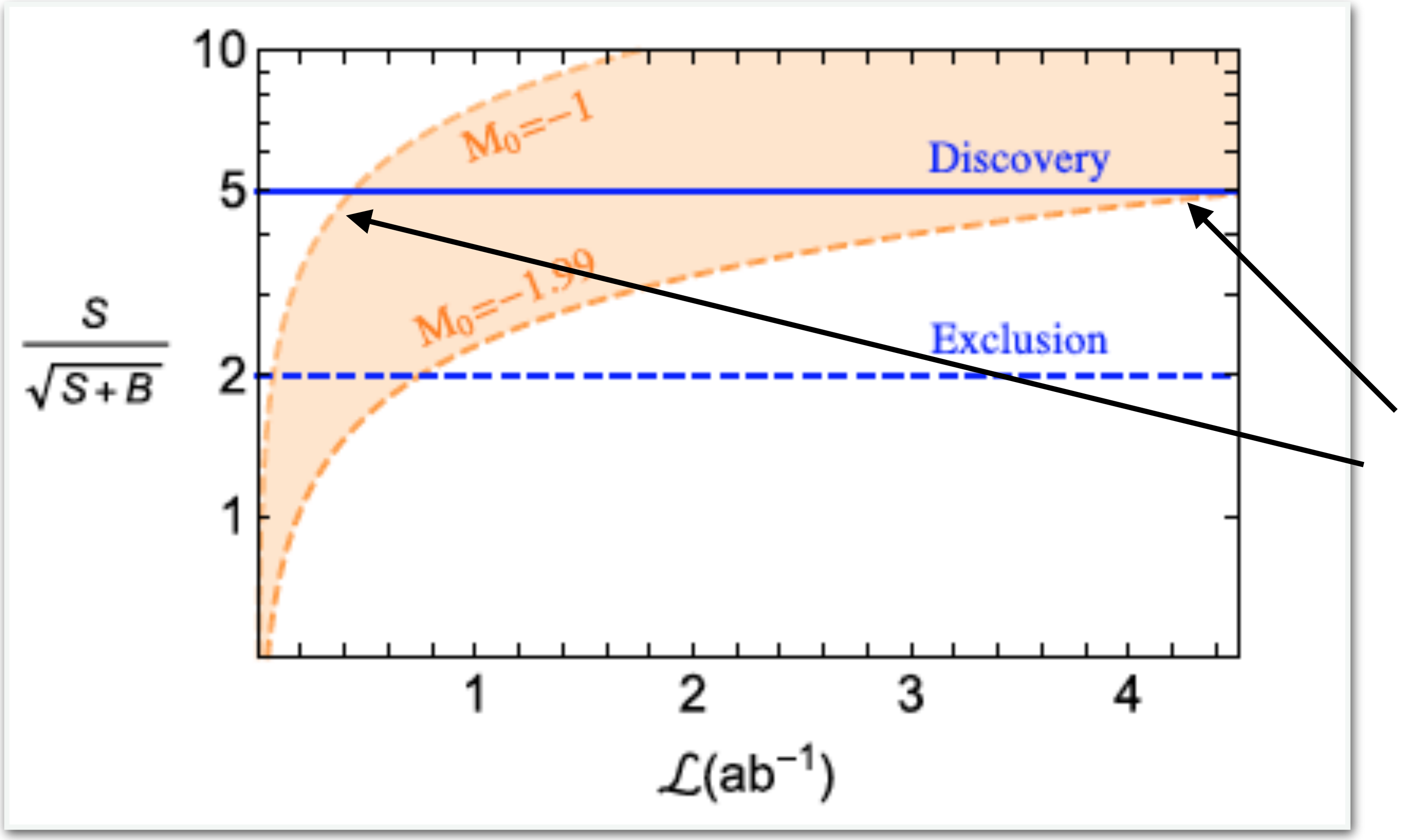
TeV scale LNV: examples

Simplified model
~ RPV-SUSY

$M_S = M_F = M_{eff}$ $(g_{eff})^4 = g_1^2\, g_2^2$



$A_{0\nu\beta\beta} \sim (g_{eff})^4 / (M_{eff})^5$

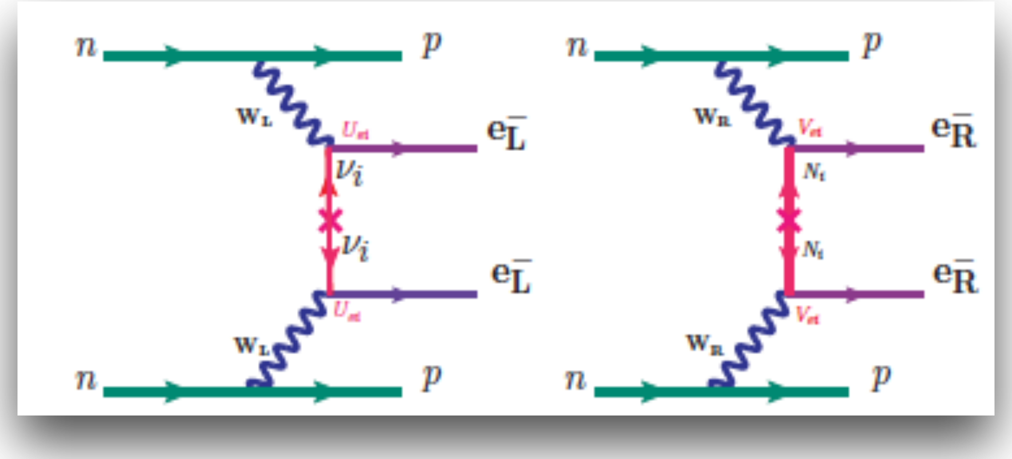


It translates into a factor of 10 in the integrated luminosity needed for LHC to compete with 0νββ

Peng, Ramsey-Musolf, Winslow, 1508.0444

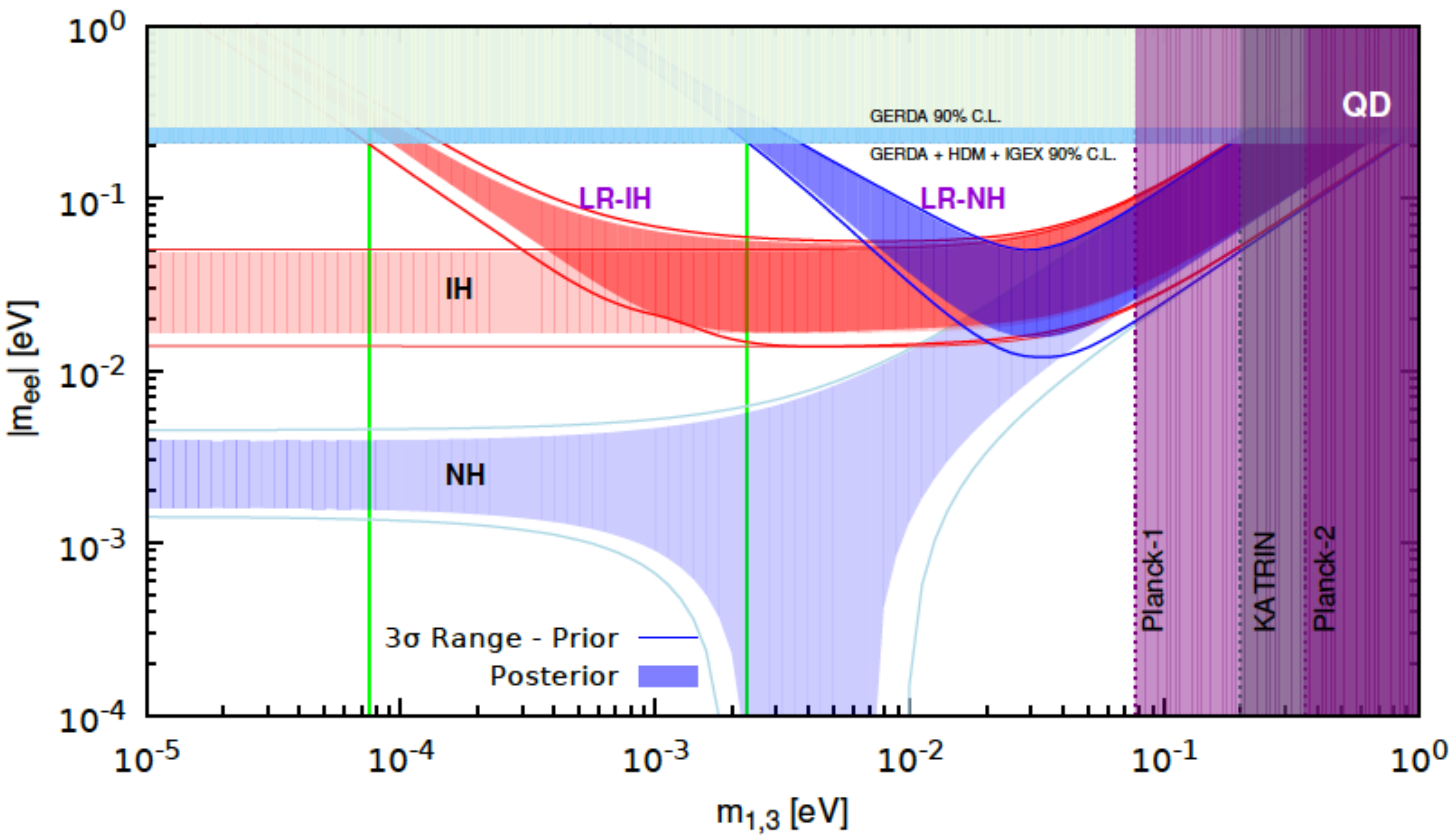
TeV scale LNV: examples

Left-Right
Symmetric Model
with type-II seesaw



$$M_i \propto m_i$$

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



$$M_i = \frac{m_i}{m_3} M_3, \text{ for NH}$$

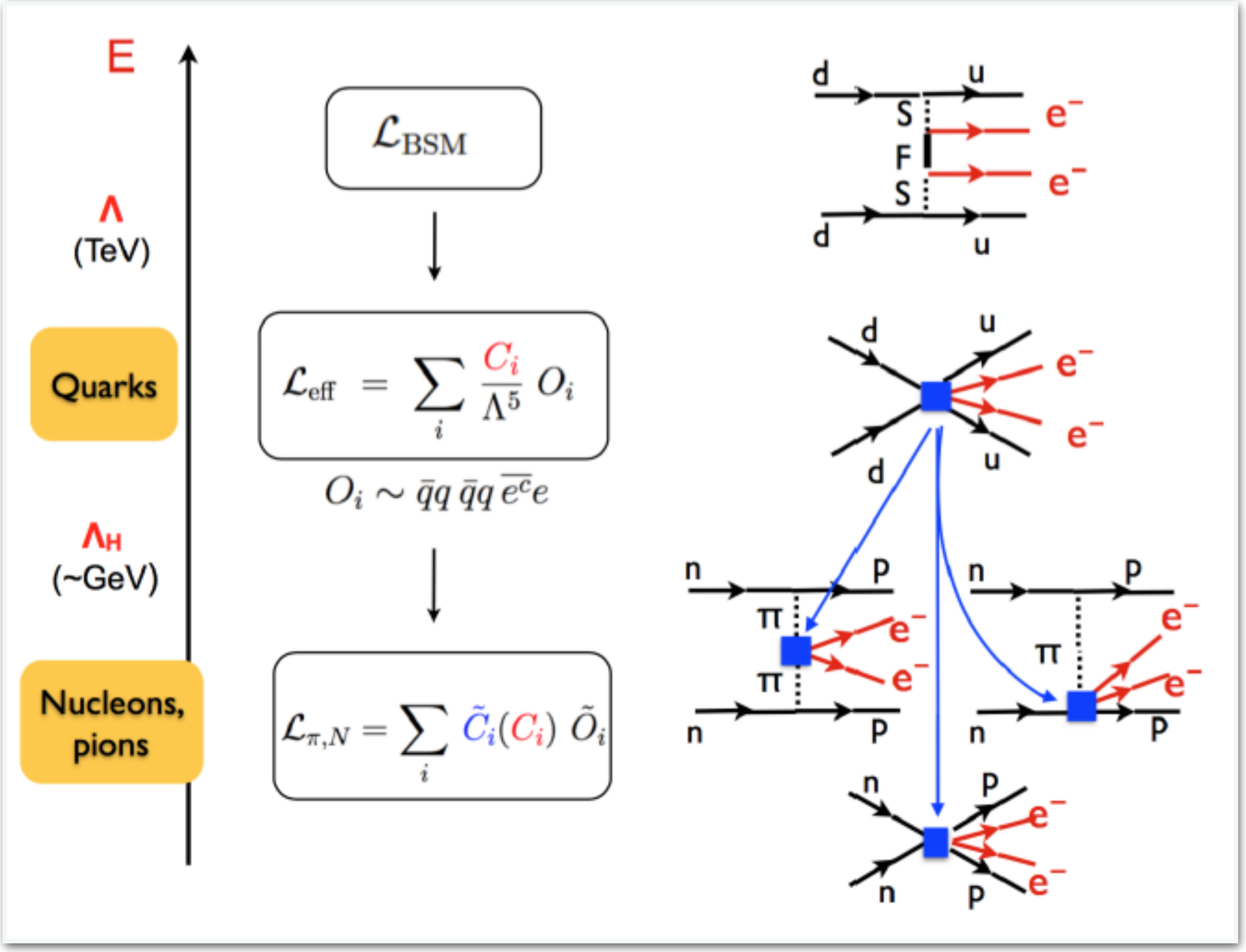
$$M_i = \frac{m_i}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV
M_{WR} = 2 TeV

Plot assumes crude estimate of the ratio of matrix elements

Ge-Lindner-Patra 1508.07286

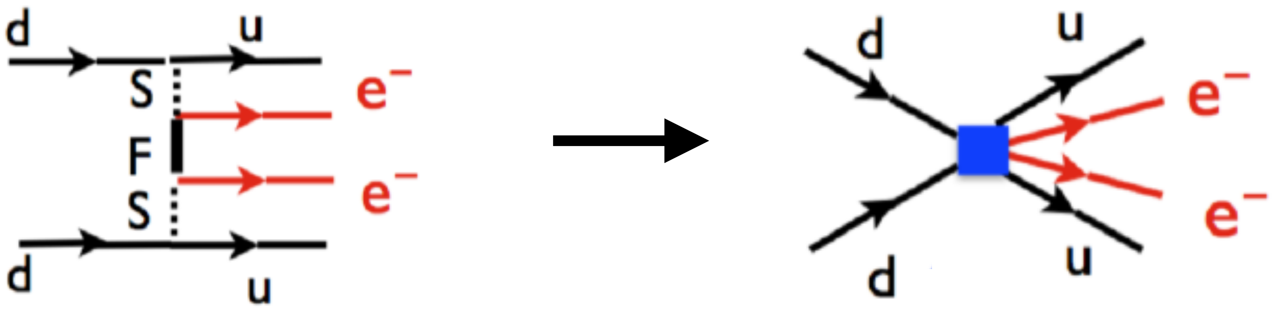
Connecting TeV-scale LNV to nuclei



- 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

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

M. Graesser, 1606.04549

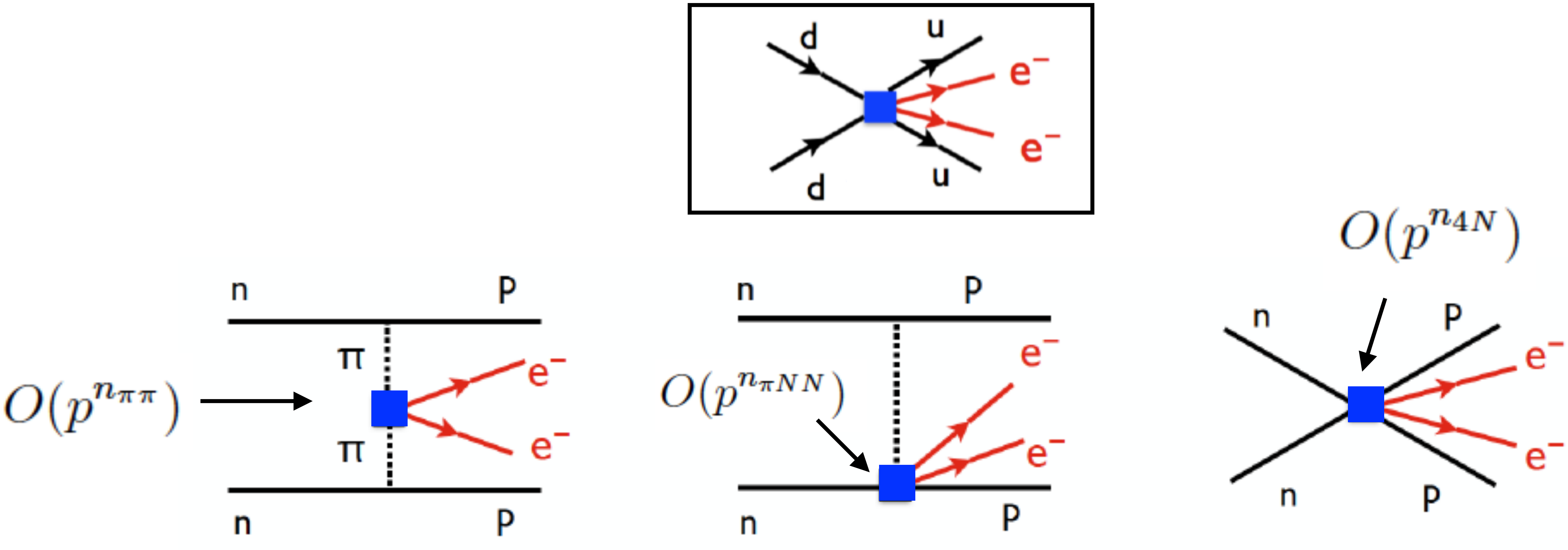
** Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

8 (5**) scalar 4-quark operators

8 (4**) vector 4-quark operators

Matching to pions and nucleons

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



$p^{n_{\pi\pi}-2}$ $\quad$ $p^{n_{\pi NN}-1}$ $\quad$ $p^{n_{4N}}$ $\quad$ $p \sim m_\pi/\Lambda_\chi$

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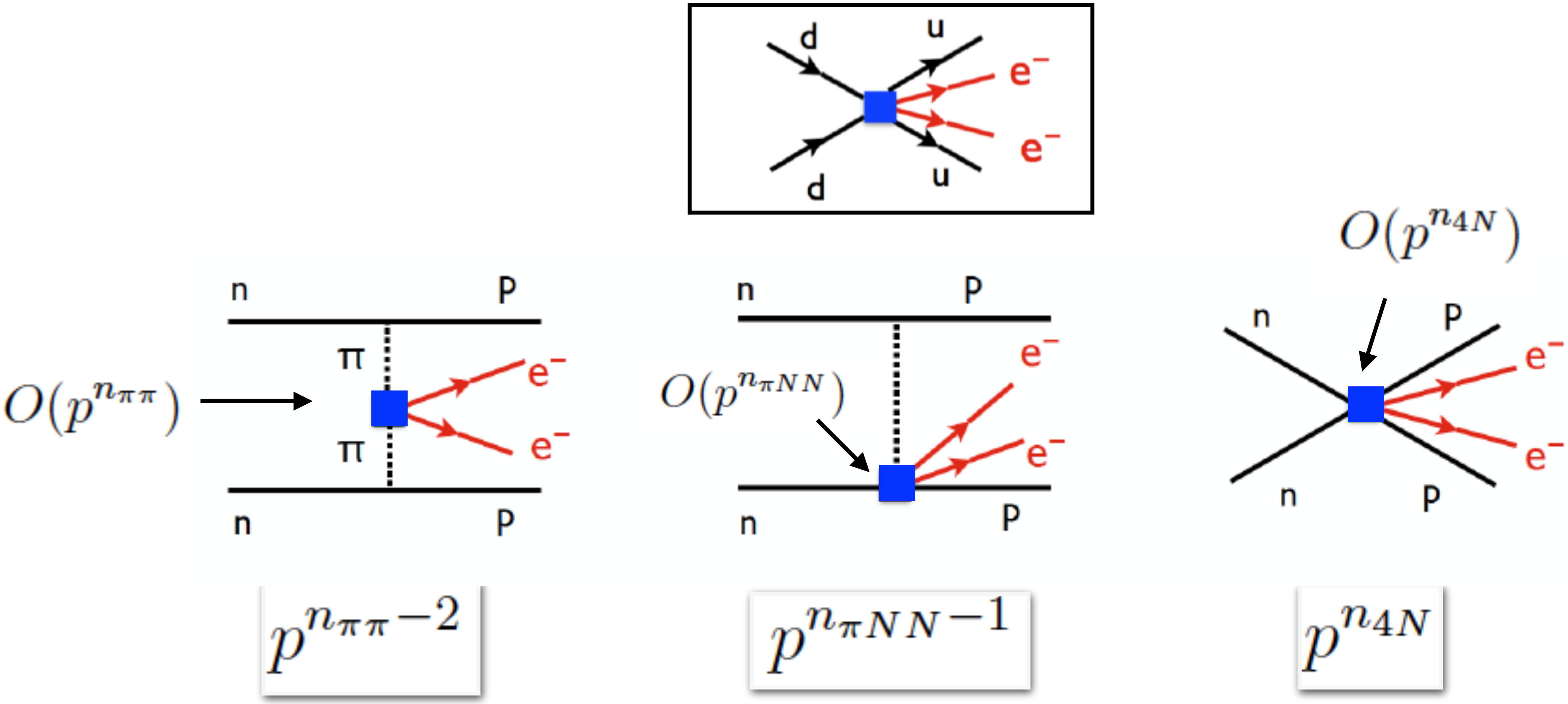
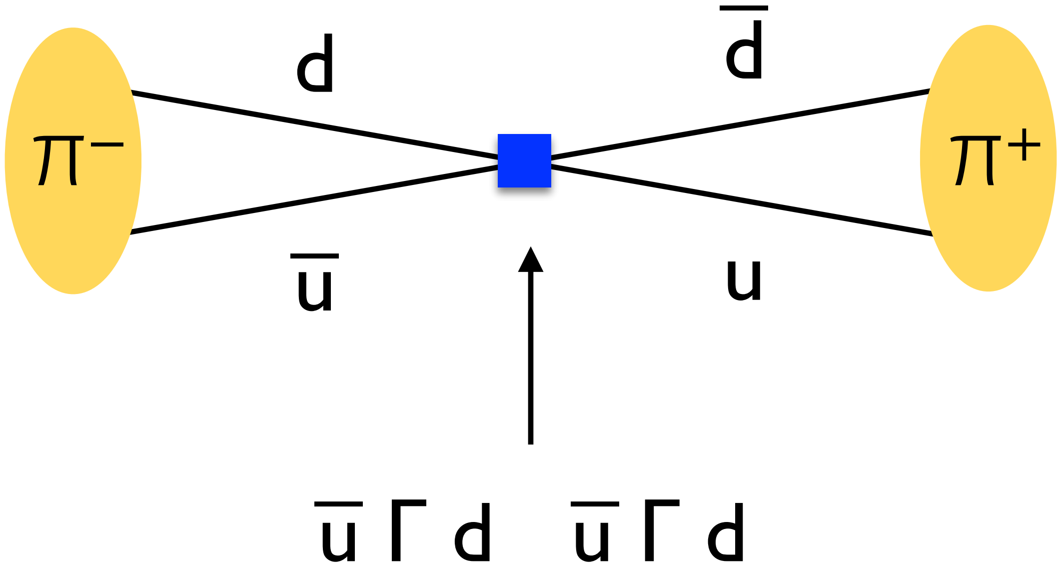


$p \sim m_\pi/\Lambda_\chi$

- Chiral power counting implies dominance of pion-exchange (if $n_{\pi\pi} = 0$)
- $\langle \pi^+ | O_j | \pi^- \rangle$ 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 $<\pi^+|O_i|\pi^->$ to the matrix element of the chiral partner of O_i between K^0 and $\overline{K}^0$
    - Use *existing* lattice QCD results for kaon matrix elements



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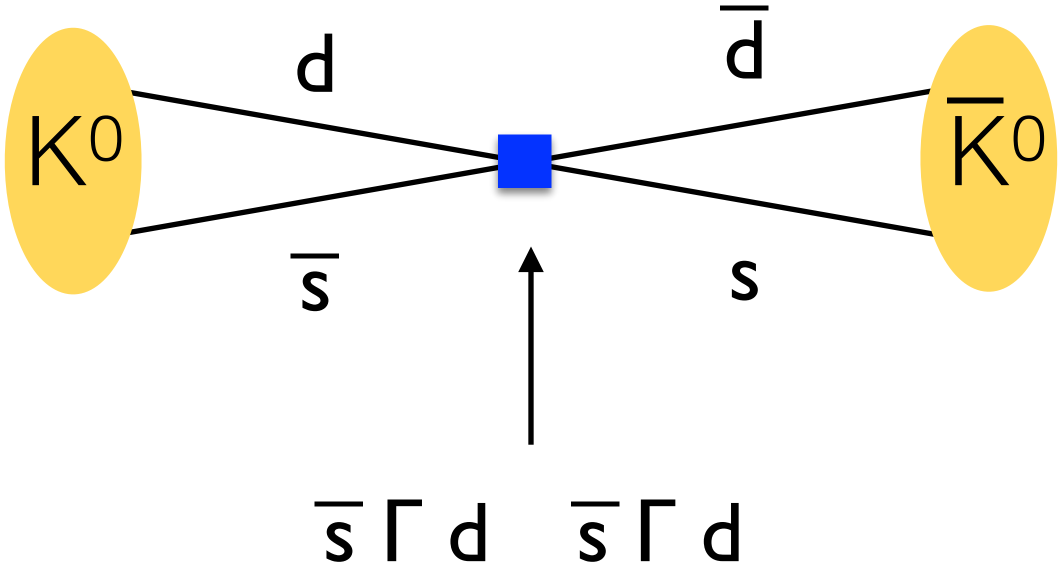

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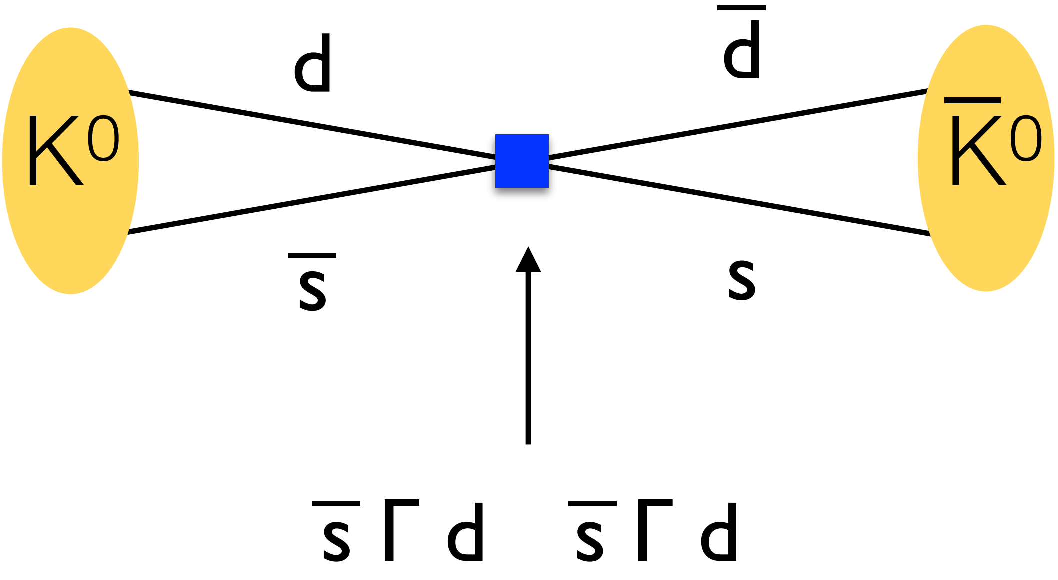


- Competition: direct lattice QCD calculation by Berkeley group (CalLat)

Nicholson et al., 1608.04793

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

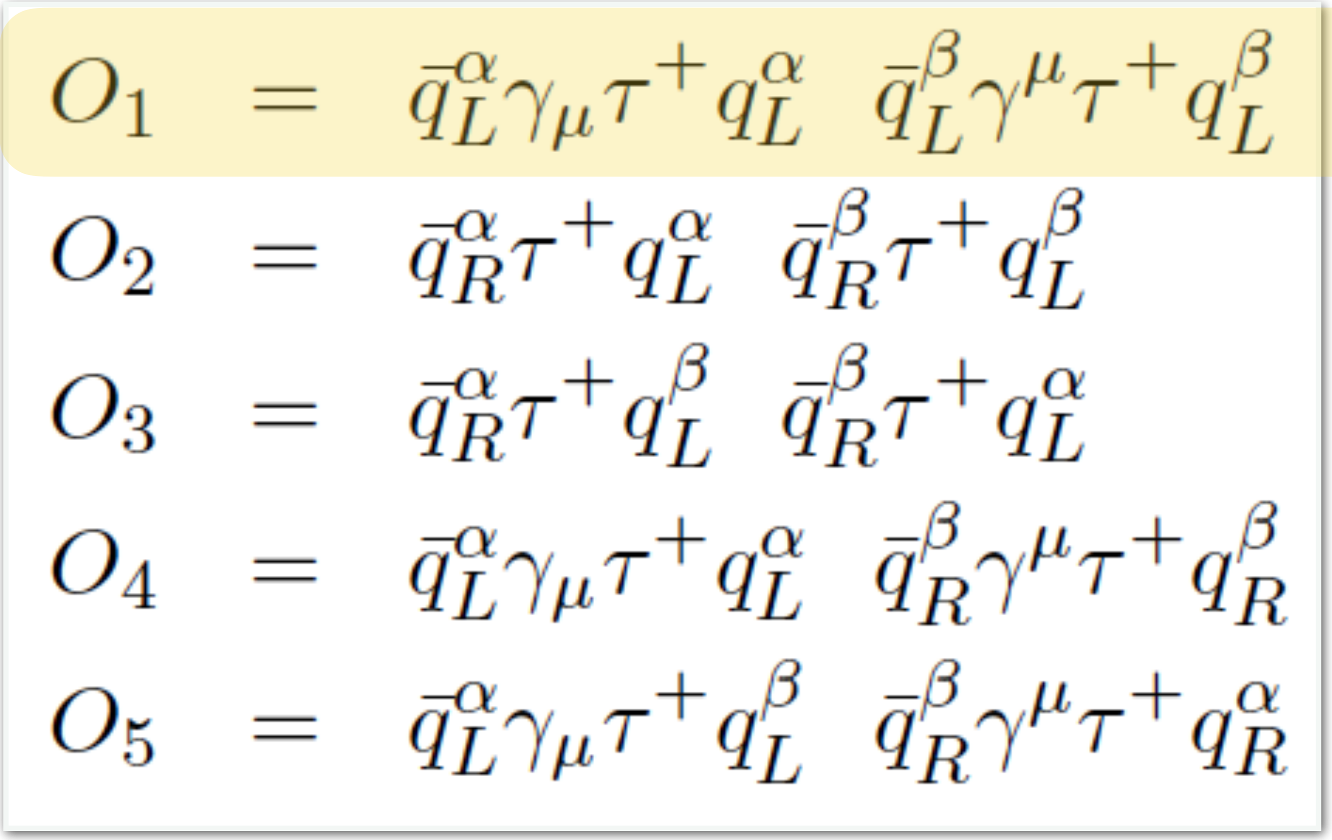
$$\langle \pi^+ | O'_{1,2,3} | \pi^- \rangle = \langle \pi^+ | O_{1,2,3} | \pi^- \rangle$$

Chiral transformation properties

- Chiral symmetry properties

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

$L,R \in SU(3)$



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\end{aligned}$$

$\mathbf{27}_L \times \mathbf{1}_R$

M. Savage
nucl-th/9811087

Chiral transformation properties

- Chiral symmetry properties

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

$L,R \in SU(3)$

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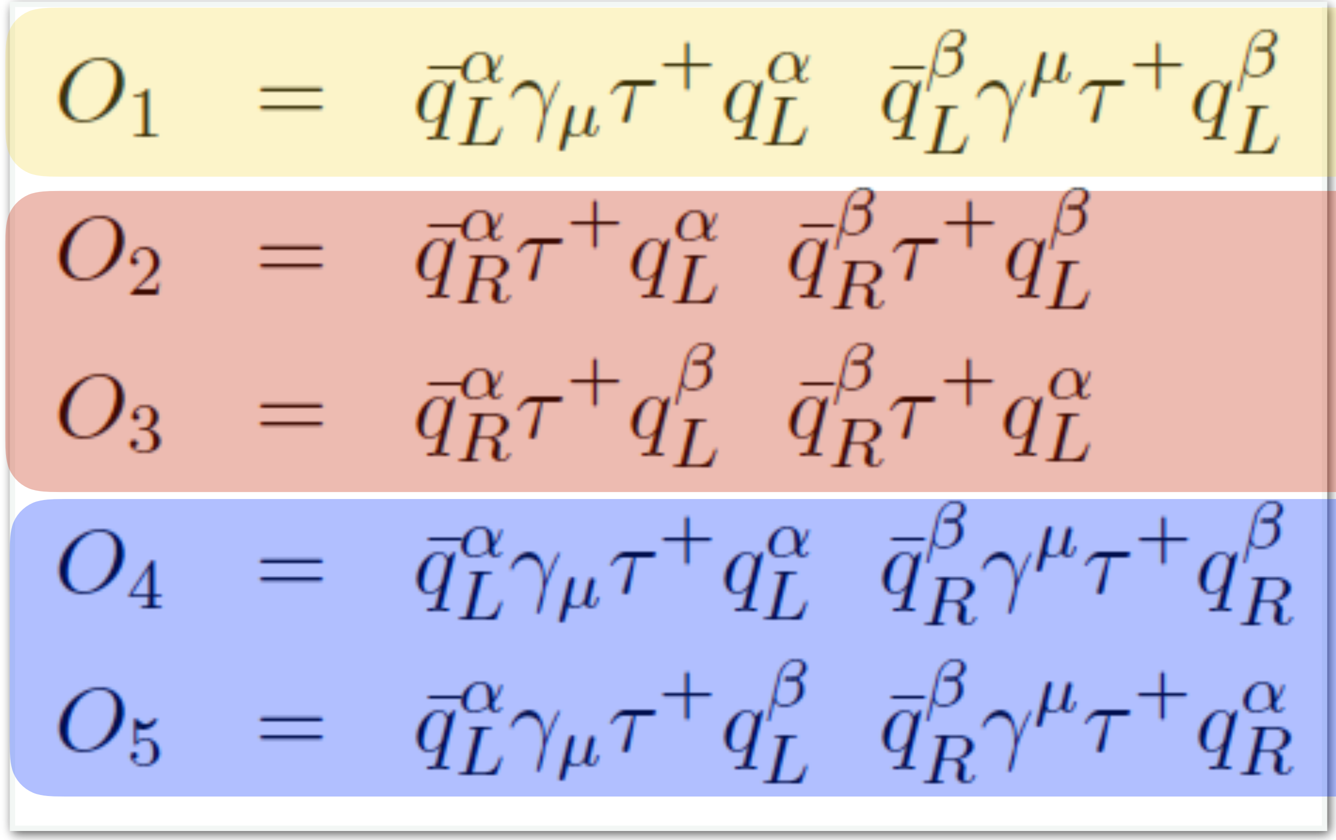

$O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta$	$\mathbf{27}_L \times \mathbf{1}_R$
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Chiral transformation properties

- Chiral symmetry properties

$$\boxed{\begin{aligned} q_L &\to L\, q_L \\ q_R &\to R\, q_R \end{aligned}}$$

L,R ∈ *SU(3)*

$$\begin{array}{lll} O_1 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta & & \mathbf{27}_L \times \mathbf{1}_R \\ O_2 = \bar{q}_R^\alpha \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \tau^+ q_L^\beta & & \\ O_3 = \bar{q}_R^\alpha \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \tau^+ q_L^\alpha & & \mathbf{6}_L \times \bar{\mathbf{6}}_R \\ O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta & & \\ O_5 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \;\; \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha & & \mathbf{8}_L \times \mathbf{8}_R \end{array}$$

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

Leading chiral realization

- Unique non-derivative realization

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

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

Same non-perturbative coupling for all flavor structures
Chiral Symmetry relates ΔI=2 to ΔS= 2 and ΔS= 1 matrix elements

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

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

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 coupling for all flavor structures
Chiral Symmetry relates ΔI=2 to ΔS= 2 and ΔS= 1 matrix elements

- $g_{6\times\bar{6}}$ from K-$\overline{\text{K}}$ mixing
- $g_{8\times 8}$ from K-$\overline{\text{K}}$ mixing *and* K →ππ

Leading chiral realization

- Unique non-derivative realization

$$\begin{aligned} O^{a,b}_{6\times\bar{6}} &= \bar{q}_R T^a q_L \ \ \bar{q}_R T^b q_L \Big|_{6\times\bar{6}} \ \ \rightarrow \ \ g_{6\times\bar{6}} \frac{F_0^4}{8}\left[\mathrm{Tr}\left(T^a U T^b U\right) + \mathrm{Tr}\left(T^a U\right)\mathrm{Tr}\left(T^b U\right)\right] \\ O^{a,b}_{8\times 8} &= \bar{q}_L T^a \gamma_\mu q_L \ \ \bar{q}_R T^b \gamma^\mu q_R \ \ \rightarrow \ \ g_{8\times 8} \frac{F_0^4}{4}\mathrm{Tr}\left(T^a U T^b U^\dagger\right) \end{aligned}$$

Same non-perturbative input for all flavor structures

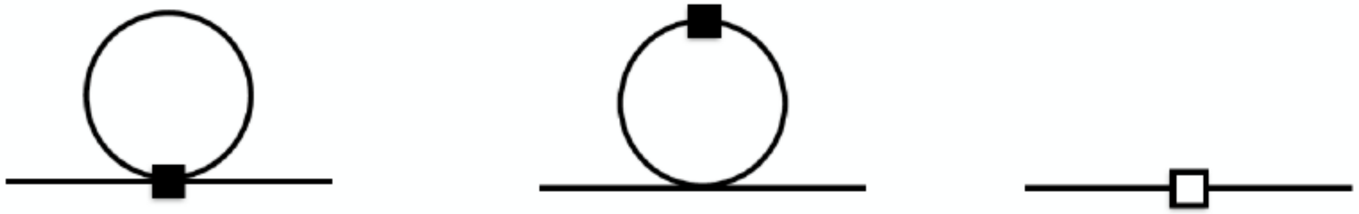
- Leading order symmetry relation

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

Matrix elements we want for NLDBD

Computed in LQCD by several groups

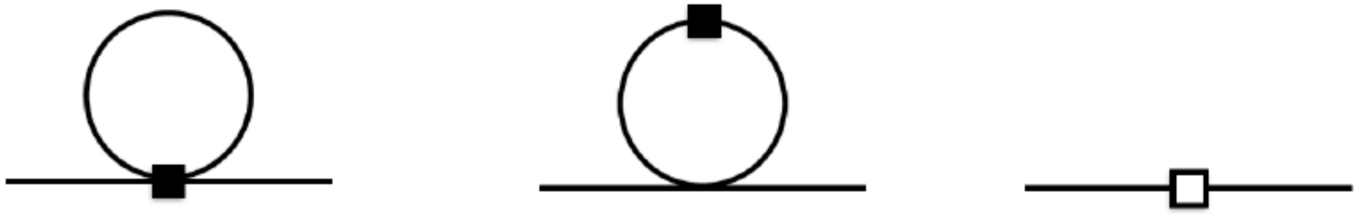
NLO chiral relations



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

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

NLO chiral relations



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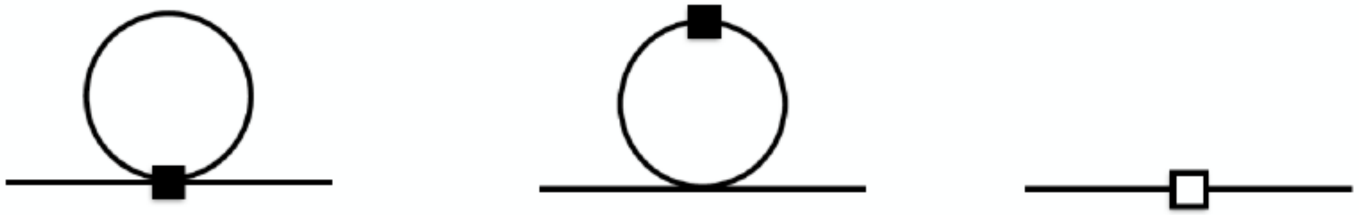
$$\Delta_{8\times8} = \frac{1}{(4\pi F_0)^2}\left[\frac{m_\pi^2}{4}(-4+5L_\pi) - m_K^2(-1+2L_K) + \frac{3}{4}m_\eta^2 L_\eta - a_{8\times8}\left(m_K^2 - m_\pi^2\right)\right]$$

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

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

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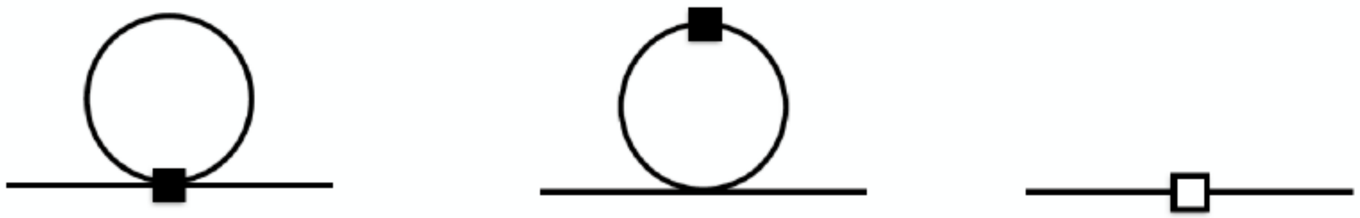
$L_{\pi,K,\eta} \equiv \log \mu_\chi^2 / m^2_{\pi,K,\eta}$

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

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

NLO chiral relations



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

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

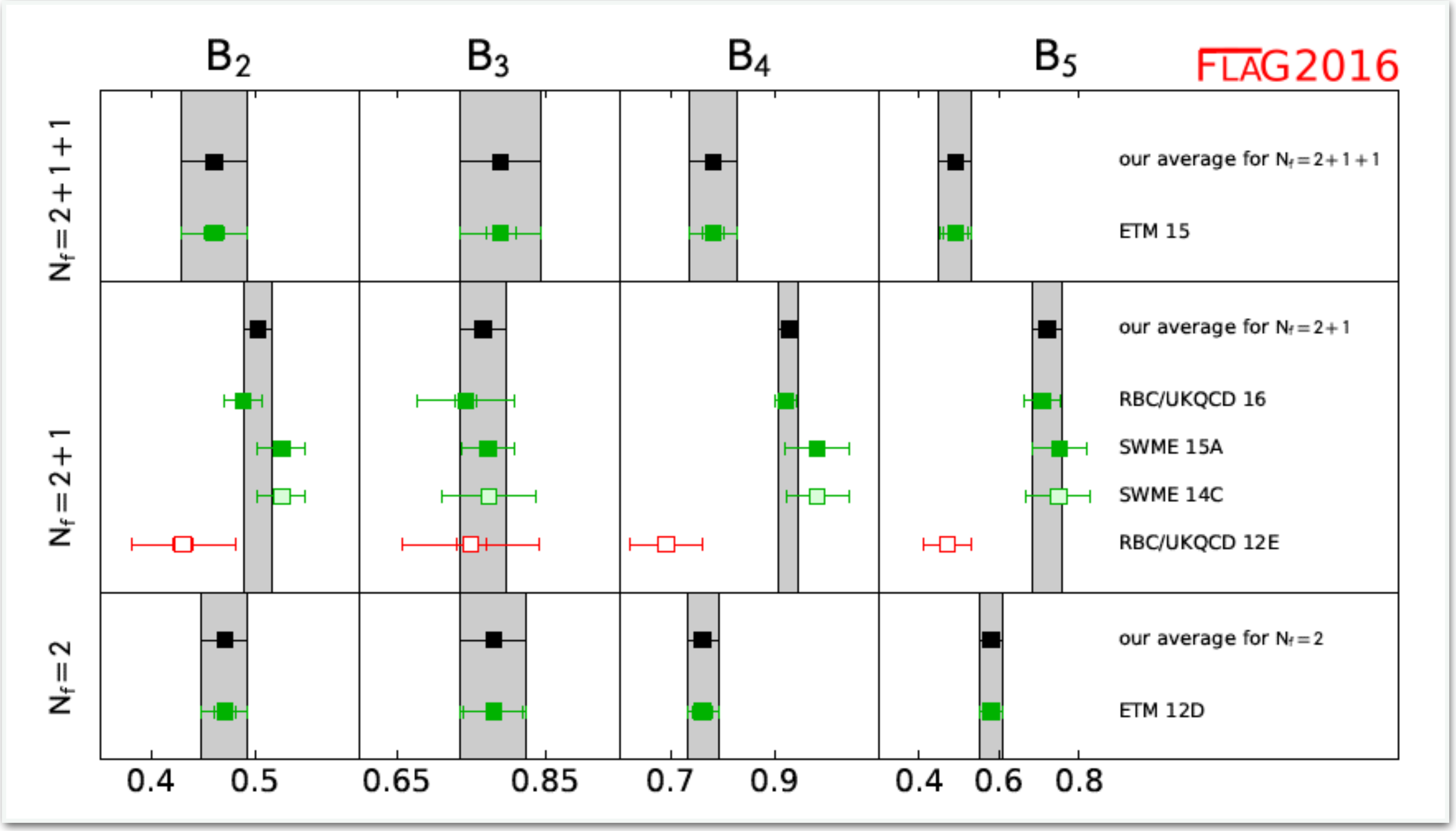
$$\Delta_{6\times \bar{6}} = 0.07(20)$$

- 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-$\overline{\text{K}}$ matrix elements ($M^{KK} \propto B_i$) at μ = 3 GeV in $\overline{\text{MS}}$ scheme
- Use conservative range from FLAG 2016 review

Aoki et al., 1607.00299



$6_L \times \bar{6}_R$

$8_L \times 8_R$

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

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

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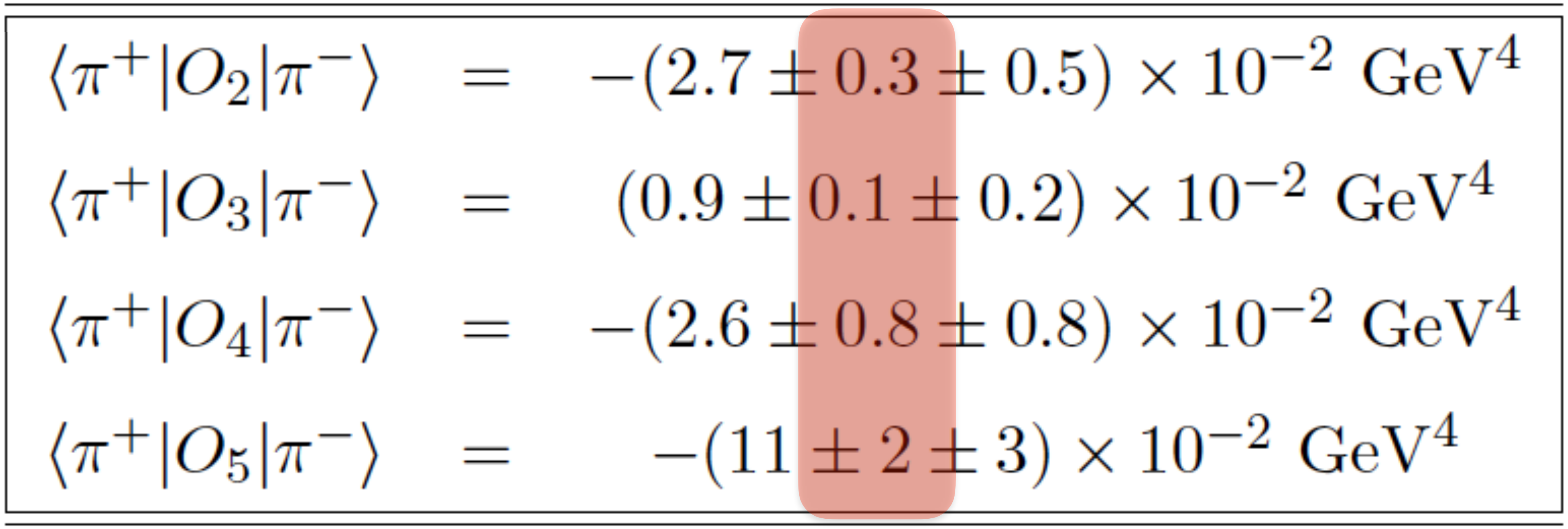

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$$

First error: lattice QCD input

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

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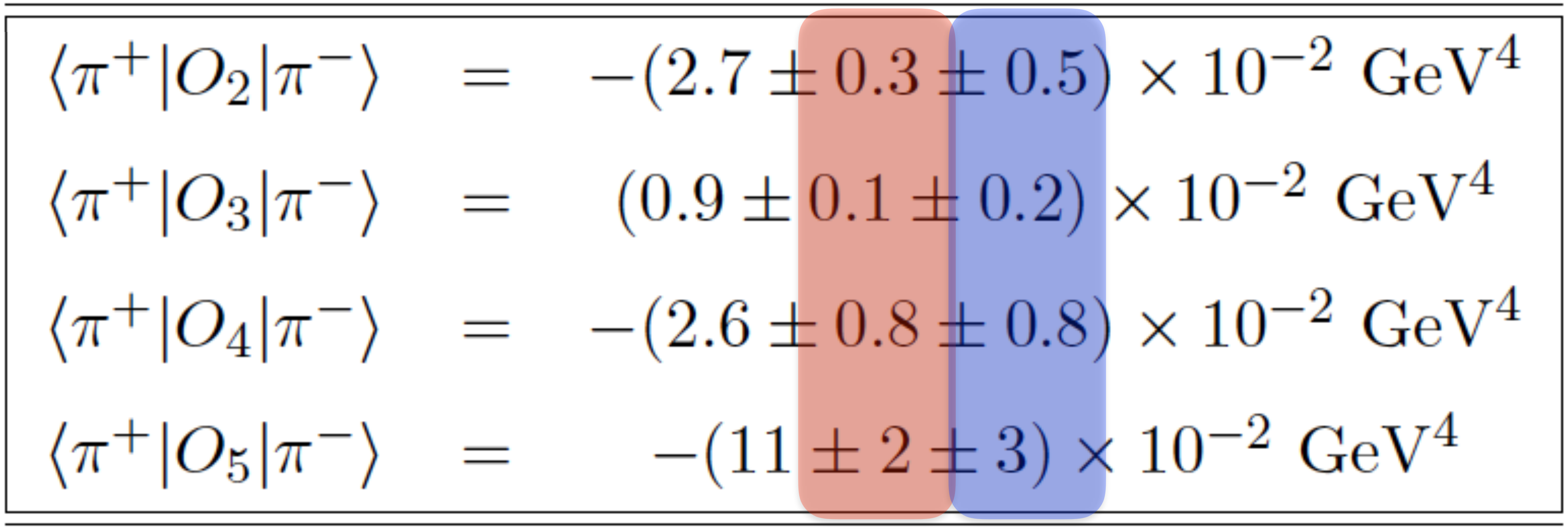
Aoki et al., 1607.00299



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First error:
lattice QCD input

Second error:
chiral corrections

⟨π⁺|O₄,₅|π⁻⟩ (8ʟx8ʀ) from K→ππ

- 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 →ππ and π→π

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

2.7

$$\langle \pi^+ | O_4 | \pi^- \rangle = -(2.6 \pm 0.8 \pm 0.8) \times 10^{-2}\ \mathrm{GeV}^4$$

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

12.7

Remarkable agreement

$\langle \pi^+ | O_1 | \pi^- \rangle$ $(27_L \times 1_R)$ from K→ππ

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

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

● belong to same representation

M. Savage 1998

$\langle \pi^+ | O_1 | \pi^- \rangle$ ($27_L \times 1_R$) from K→ππ

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

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

- Chiral operators start at $O(p^2)$ → smaller matrix elements

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

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

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- Chiral operators start at $O(p^2)$ → smaller matrix elements
- Use 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

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

Lattice QCD input Chiral corrections

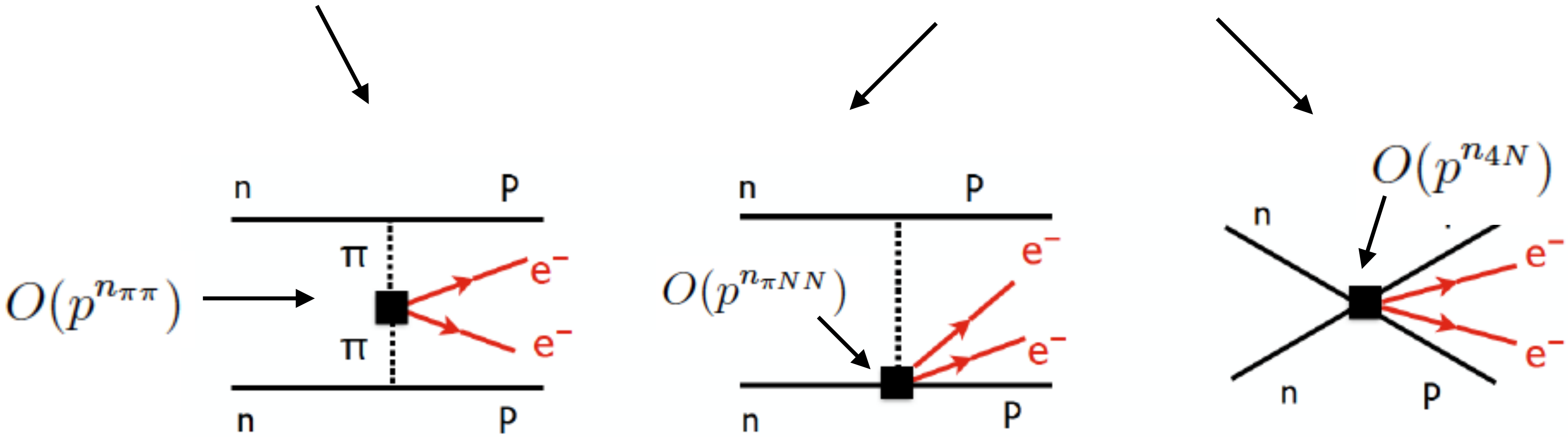
Good agreement with M. Savage (nucl-th/9811087), who used experimental input on $g_{27\times1}$

Future directions

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

Leading π-π operators
ready for nuclear
structure calculations

Impact of one-π and 4N operators:
leading order for O_1 but sub-leading for $O_{i\neq 1}$.
LQCD + nuclear structure: check chiral power counting!

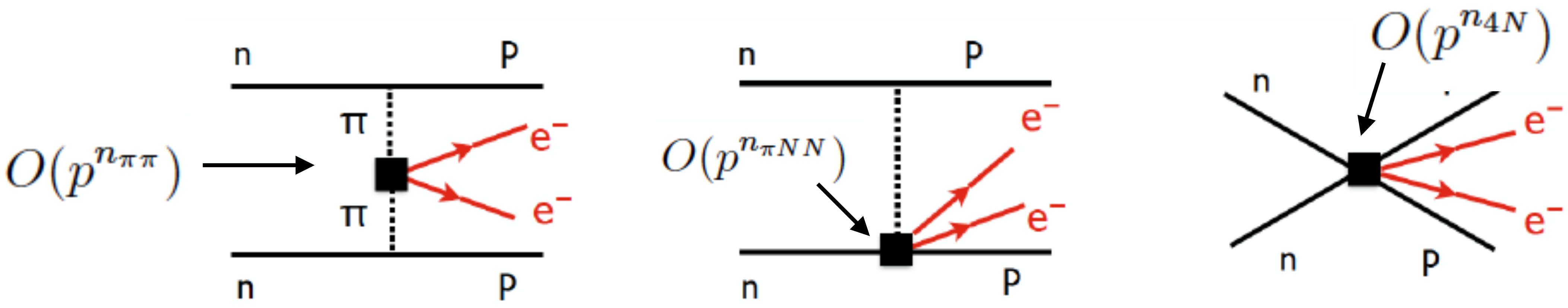


Future directions

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

π-π operators negligible: matrix elements are proportional to m_e

Impact of one-π and 4N operators:
Chiral symmetry relations + LQCD + nuclear structure



Future directions

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Robust estimates of half-life in terms of TeV-scale couplings → map out discovery potential and benchmark scenarios

Need integration of model-building, EFT, lattice QCD, nuclear structure

$T_{1/2}\, [c_i]$

Summary

- TeV sources of LNV can be probed by next generation $0\nu\beta\beta$ experiments *and* the LHC ⇒ important to control uncertainties in this multi-scale problem

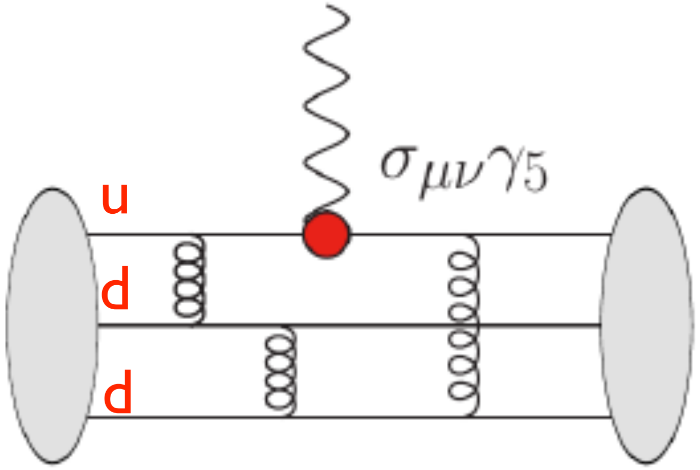
- First *controlled* estimate of $\langle\pi^+|O_i|\pi^-\rangle$ for all scalar, dim-6, $\Delta I=2$ operators relevant to $0\nu\beta\beta$ — based on chiral SU(3) + lattice QCD

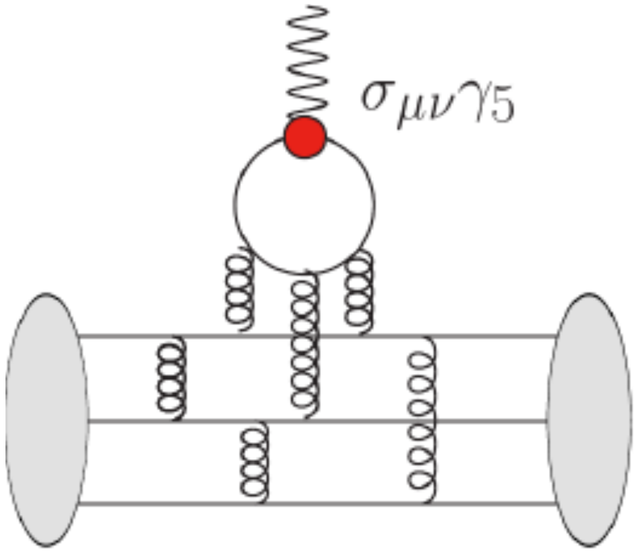
- Step towards robust estimate of $T_{1/2}$ from TeV-scale LNV (of increasing phenomenological importance in the years to come)

Neutron EDM from quark EDMs

- Quarks couple directly to photon (in a CP-odd way)

$$\mathcal{L} = -\frac{i}{2}\sum_{q=u,d,s} d_q \; \bar{q}\sigma_{\mu\nu}\gamma_5 q \; F^{\mu\nu}$$





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$$\mathcal{L} = -\frac{i}{2} \sum_{q=u,d,s} d_q \; \bar{q} \sigma_{\mu\nu} \gamma_5 q \; F^{\mu\nu}$$

- Problem “factorizes”: need so-called tensor charge of the neutron

$$\boxed{d_N = d_u \, g_T^{(N,u)} + d_d \, g_T^{(N,d)} + d_s \, g_T^{(N,s)}}$$

$$\langle N | \, \bar{q} \sigma_{\mu\nu} q \, | N \rangle \equiv g_T^{(N,q)} \; \bar{\psi}_N \sigma_{\mu\nu} \psi_N$$

Neutron EDM from quark EDMs

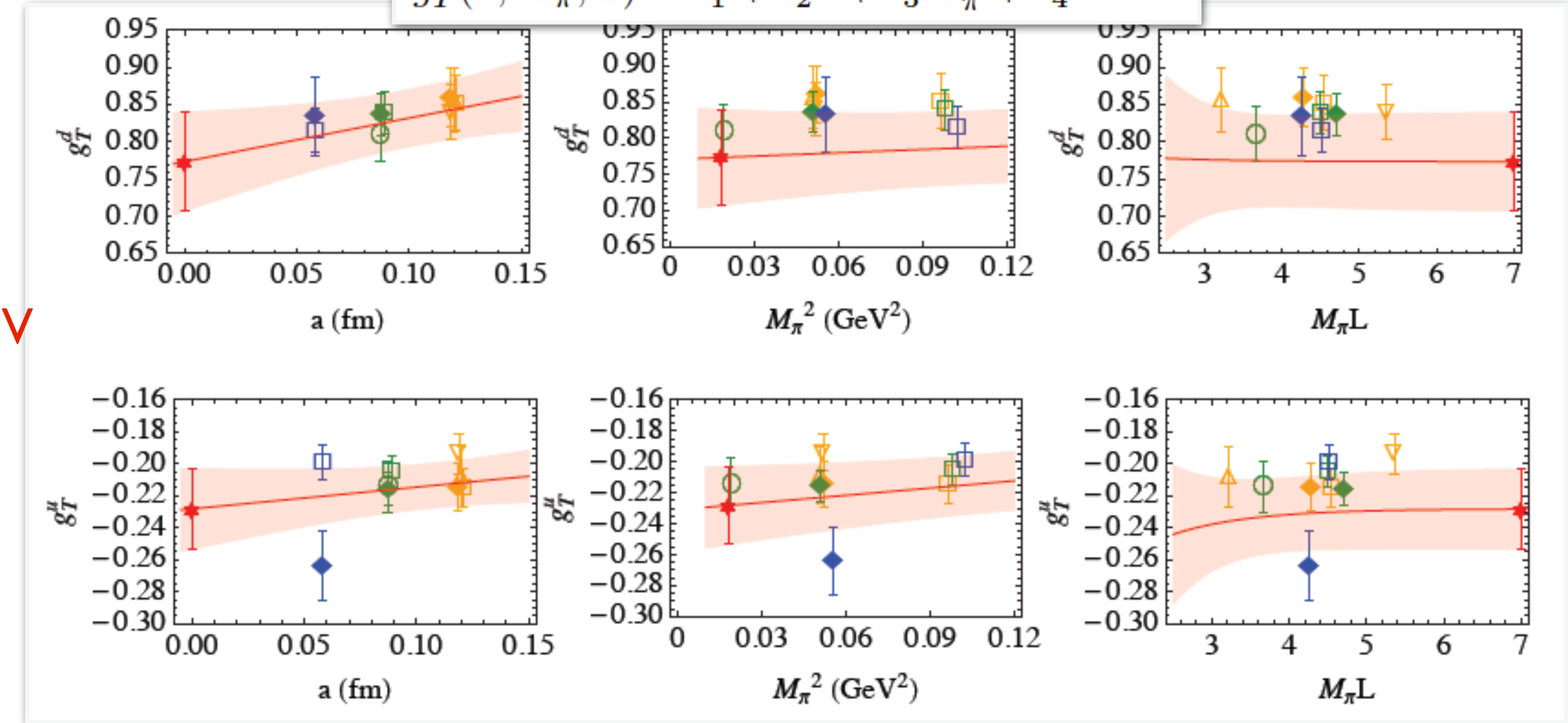
$g_T^{(n,u)} = -0.23(3)$

$g_T^{(n,d)} = 0.77(7)$

$g_T^{(s)} = 0.008(9)$

$g_T(a, M_\pi, L) = c_1 + c_2 a + c_3 M_\pi^2 + c_4 e^{-M_\pi L}$

$\overline{\text{MS}}$ @ 2 GeV



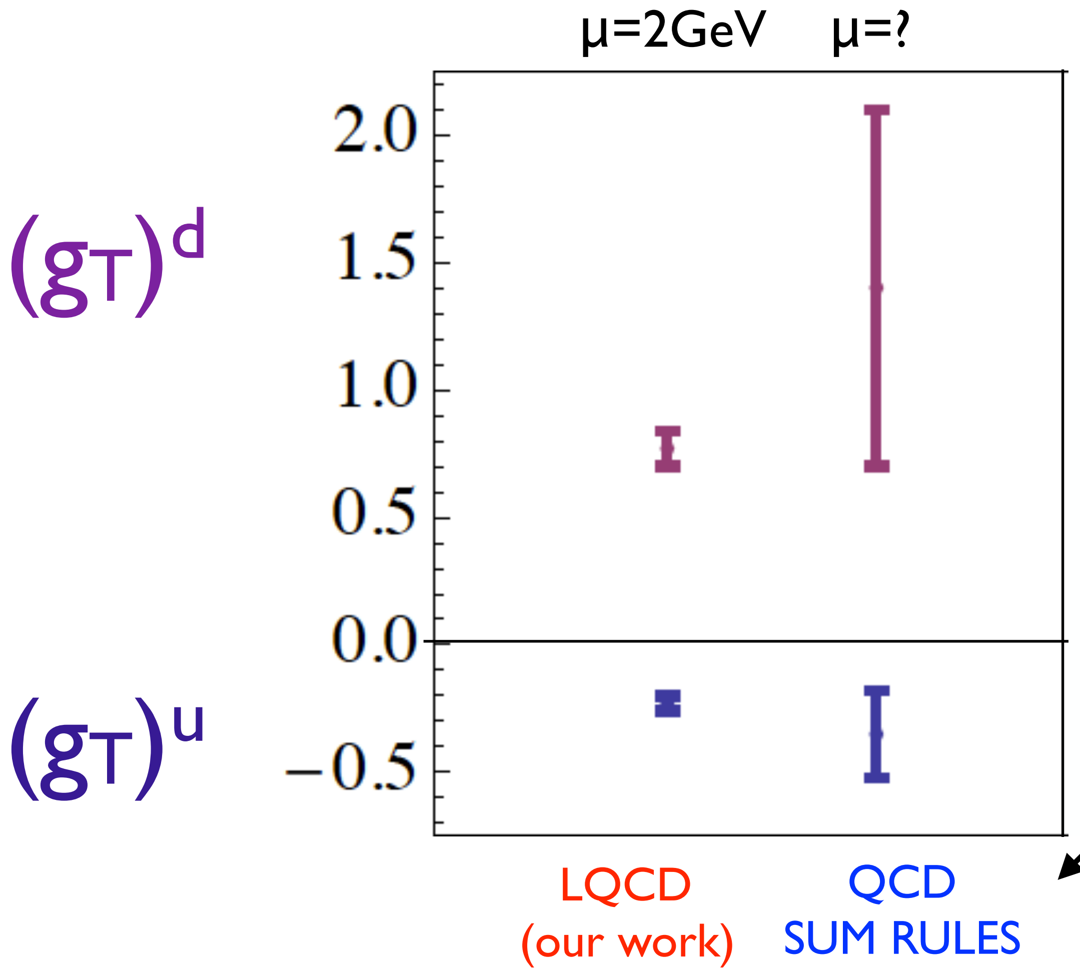
Bhattacharya, VC, Gupta, Lin, Yoon, PRL 115 (2015) 212002 [1506.04196]

O(10%) error** including all systematics: excited states, continuum, quark masses, volume

** Except for strange quark

Neutron EDM from quark EDMs

- Impact of Lattice results:



Widely used in BSM studies of neutron EDM (Pospelov-Ritz hep-ph/0504231)

Smaller (50% → 10%) & controlled error; scale/scheme dependence.
Smaller central values of g_T's ⇒ d_n "less sensitive" to new physics in d_q

Neutron EDM from quark EDMs

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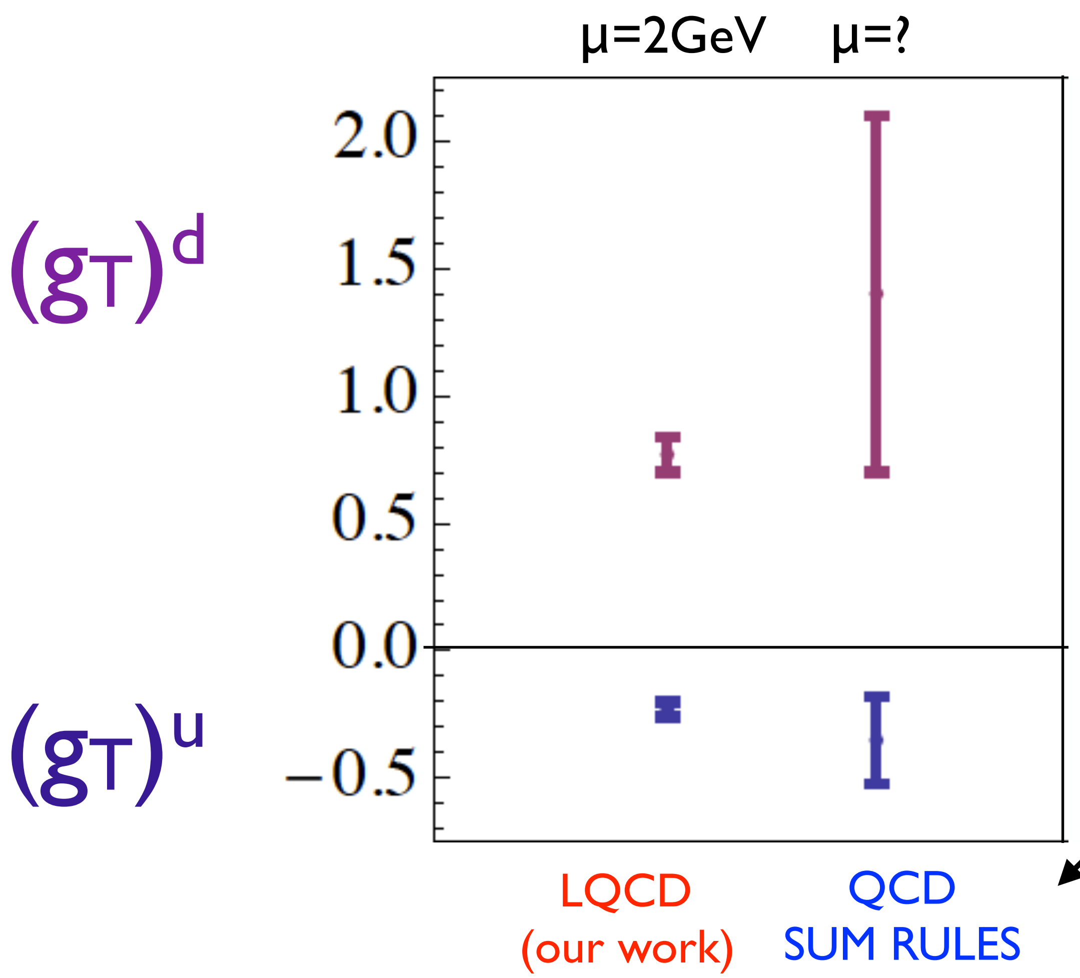

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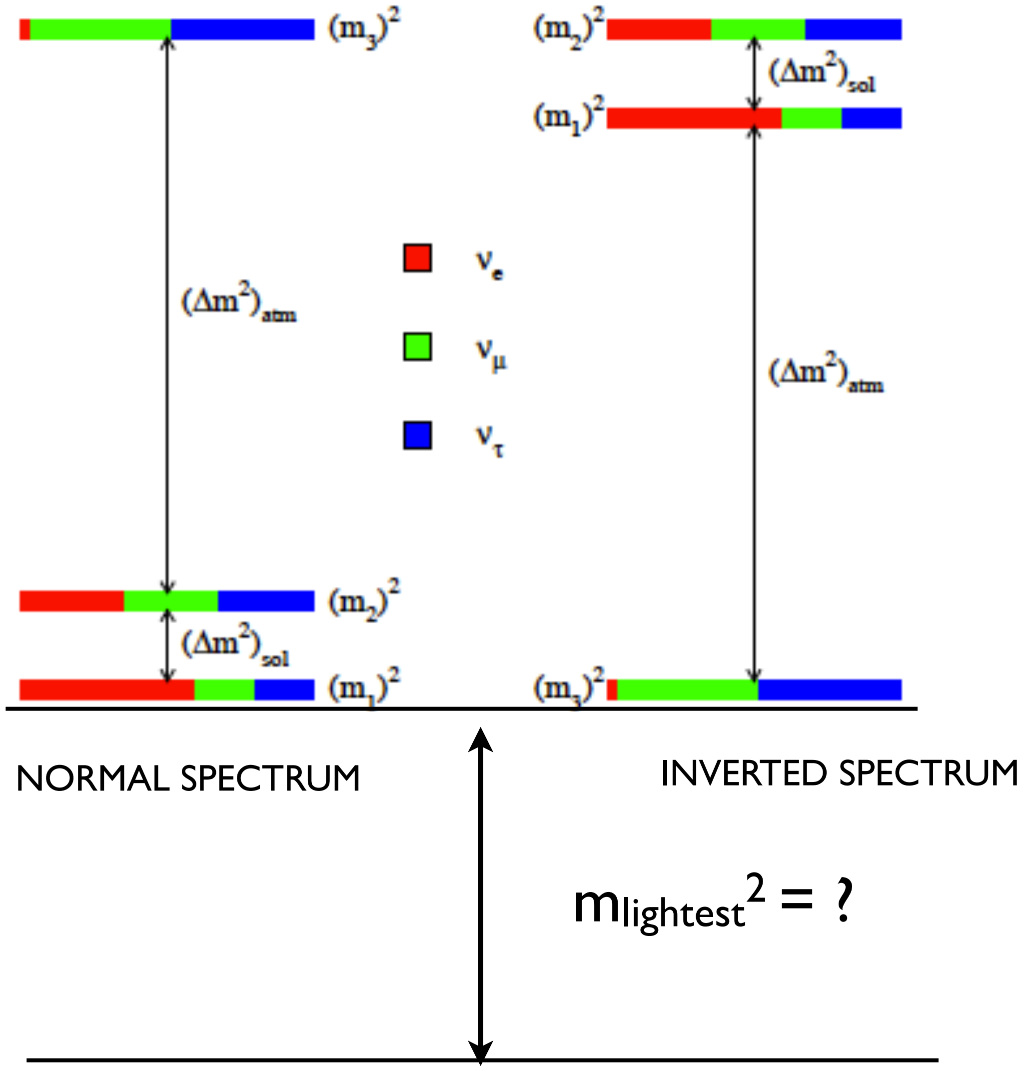
Ongoing efforts by LANL, BNL, LBL groups to tackle other operators

Backup

High-scale seesaw

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

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



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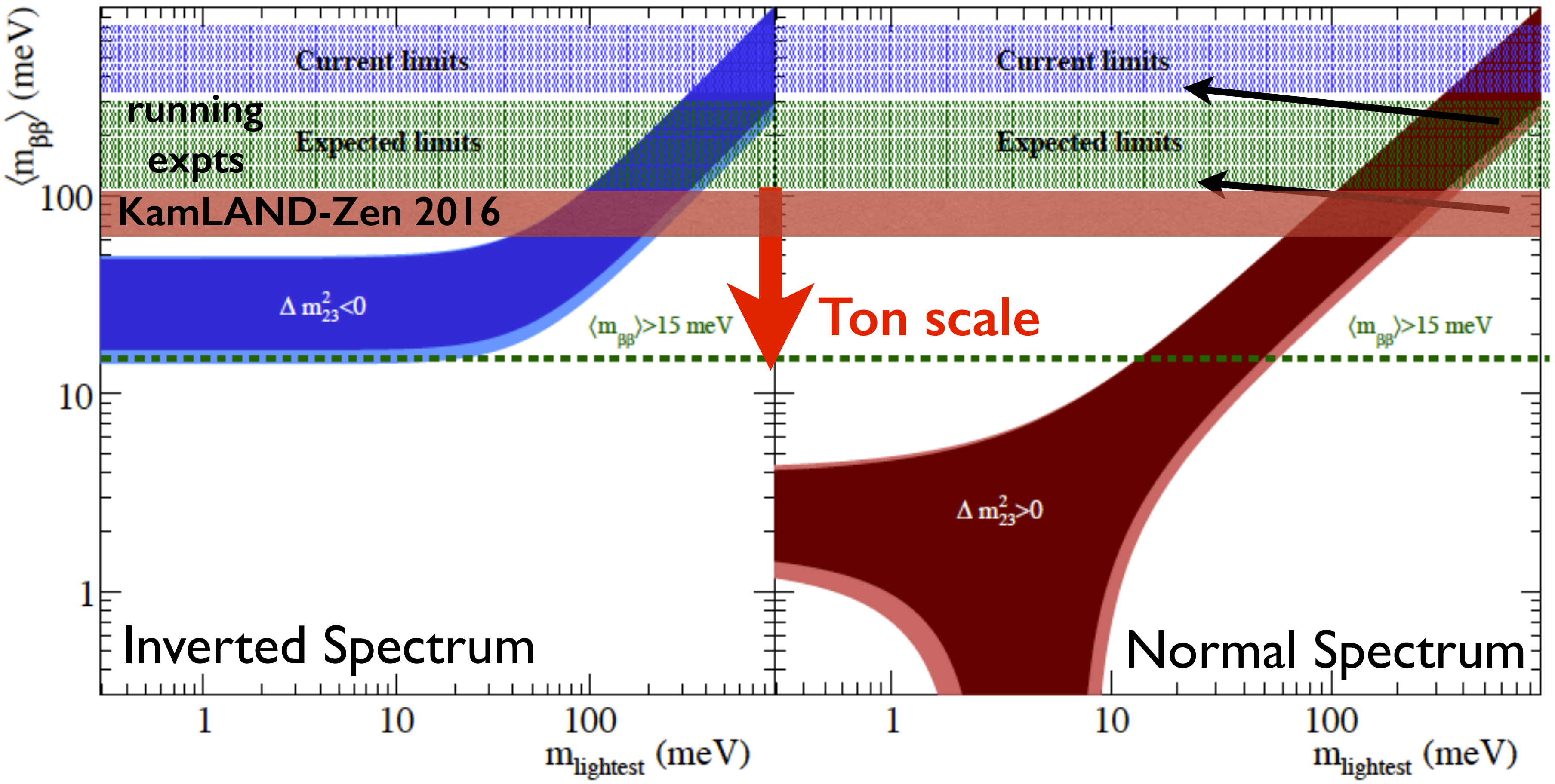


Dark bands: unknown phases

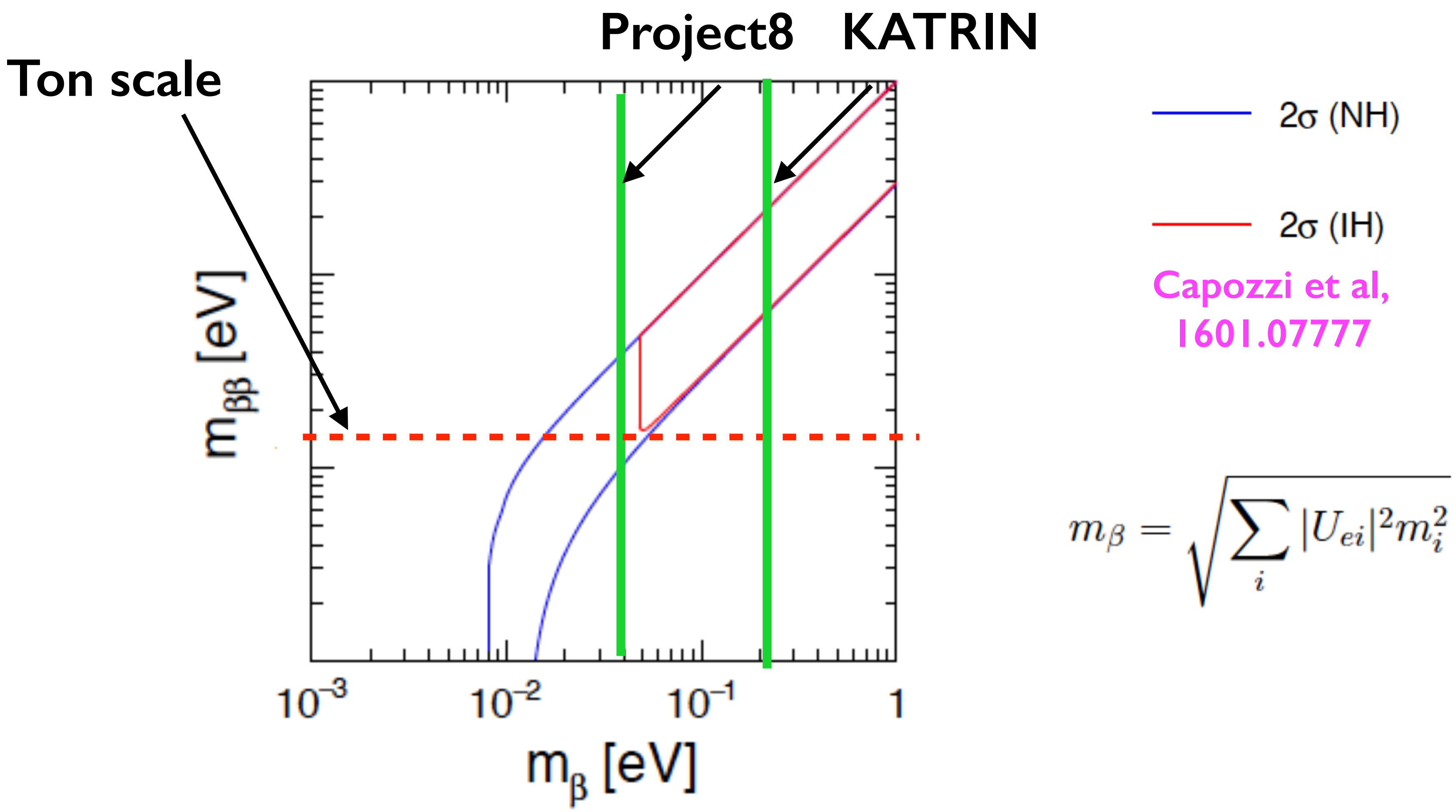
Light bands: uncertainty from oscillation parameters(90% CL)

Assume most "pessimistic" values for nuclear matrix elements

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

High-scale seesaw

- Correlation with other mass probes will contribute to the interpretation of positive or null result



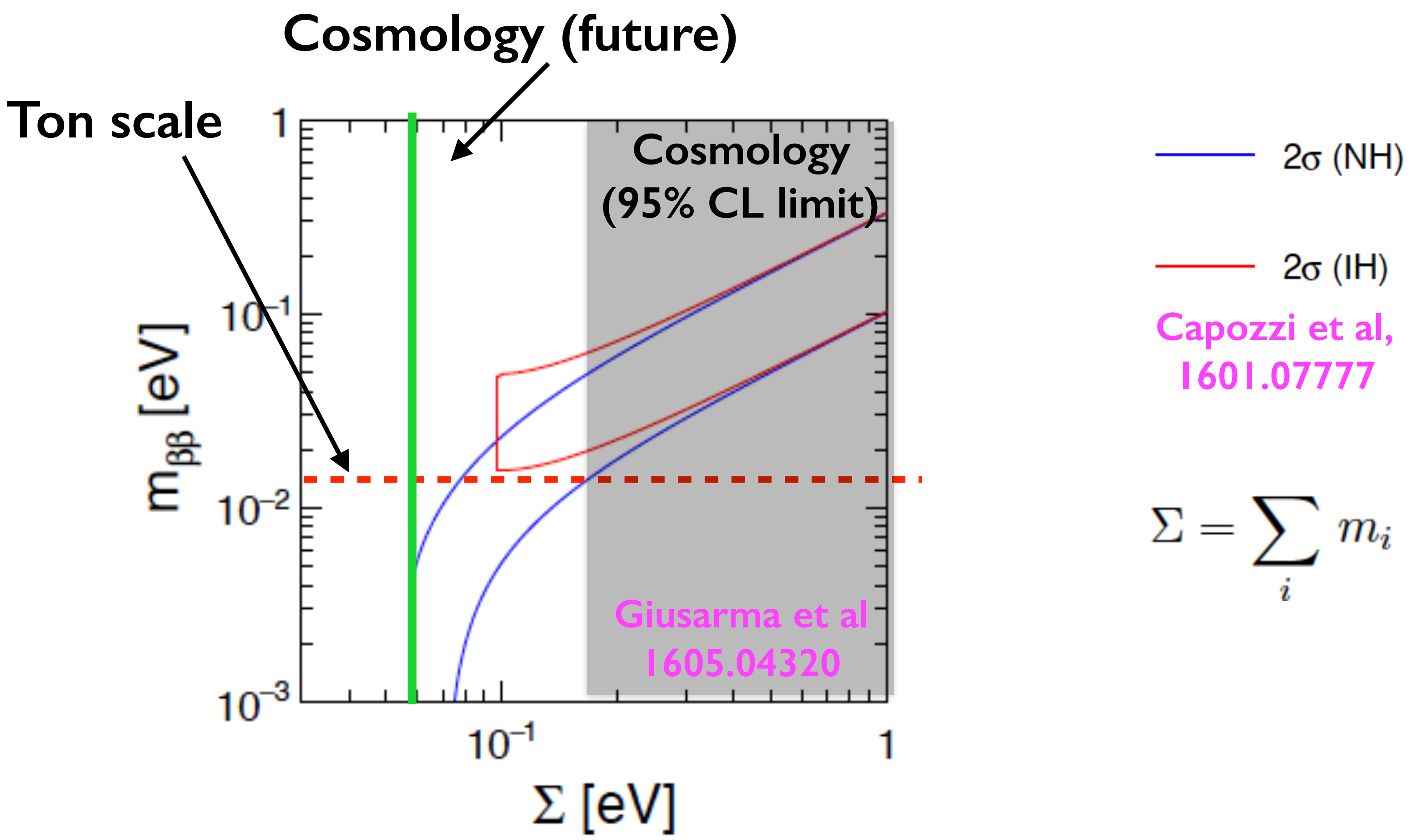
Capozzi et al, 1601.07777

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

- Tritium decay: in this framework, positive result in KATRIN, Project8 would imply 0νββ within reach

High-scale seesaw

- Correlation with other mass probes will contribute to the interpretation of positive or null result



$$\Sigma = \sum_i m_i$$

- Interplay with cosmic frontier: expose potential new physics in cosmology (is "ΛCDM + m_ν" the full story?) or in 0νββ (LNV)