# Chiral EFT for $0\nu\beta\beta$

Wouter Dekens

with

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K. Fuyuto, V. Cirigliano, J. de Vries, M.L. Graesser,
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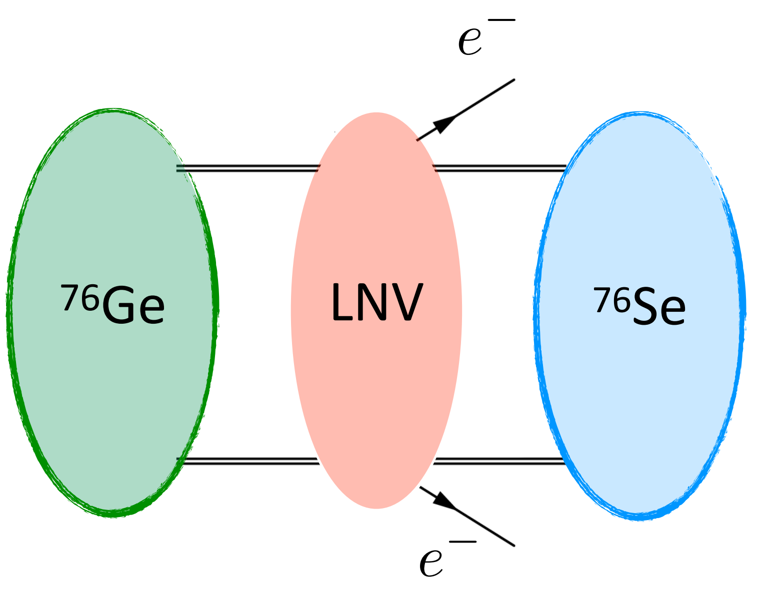
UC San Diego

# Introduction



0νββ




- Violates lepton number, ΔL=2

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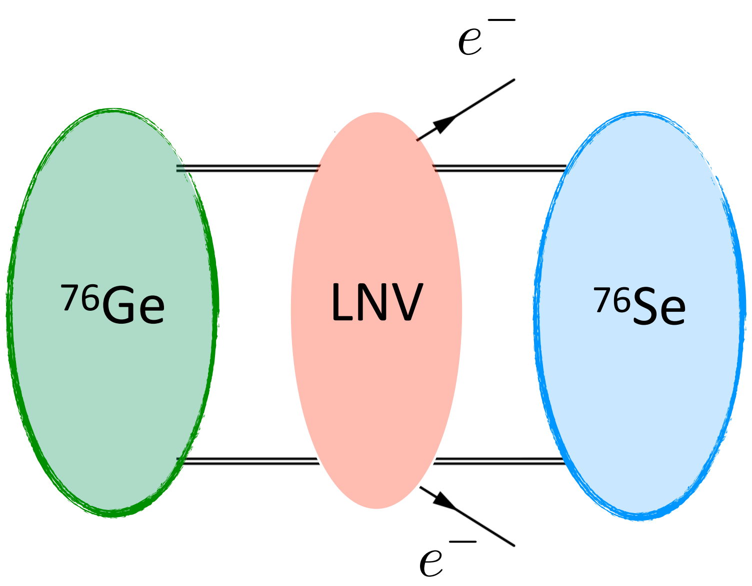


- Violates lepton number, ΔL=2

- Stringently constrained experimentally
  - To be improved by 1-2 orders

| $T_{1/2}^{0\nu}(^{76}\mathrm{Ge})$ Gerda | $T_{1/2}^{0\nu}(^{130}\mathrm{Te})$ Cuore | $T_{1/2}^{0\nu}(^{136}\mathrm{Xe})$ KamLAND-zen |
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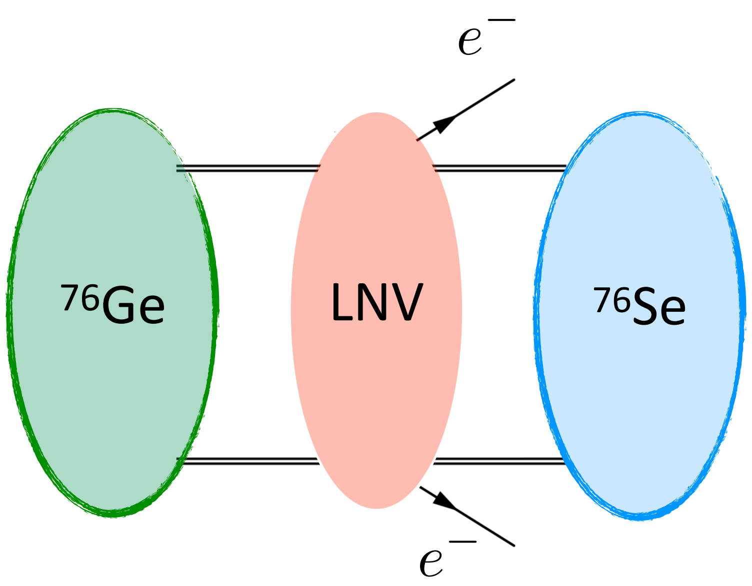


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  - Physics beyond the SM

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Schechter, Valle, `82

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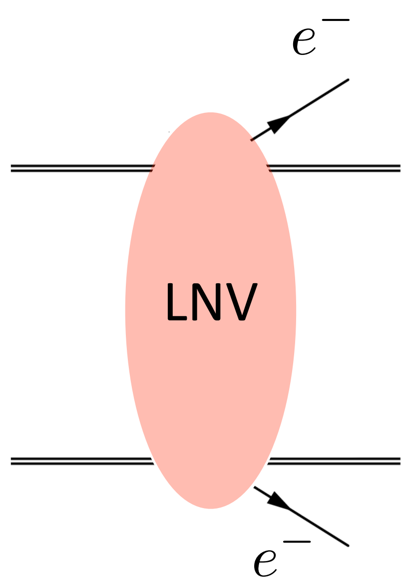


= **BSM physics**

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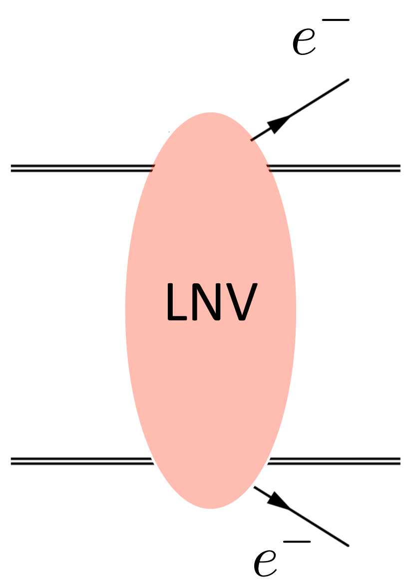


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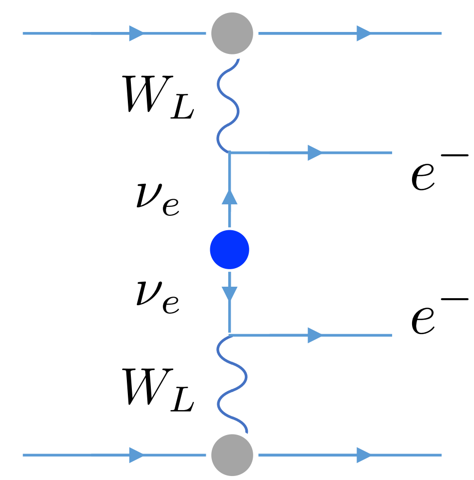
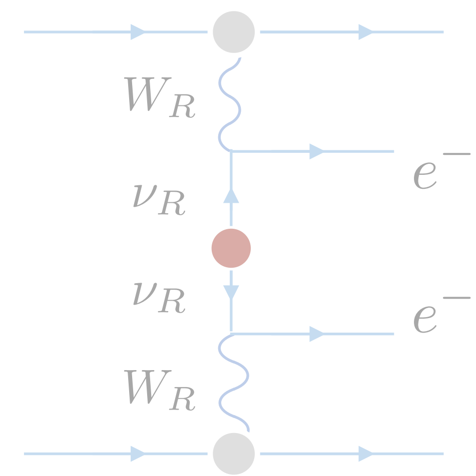
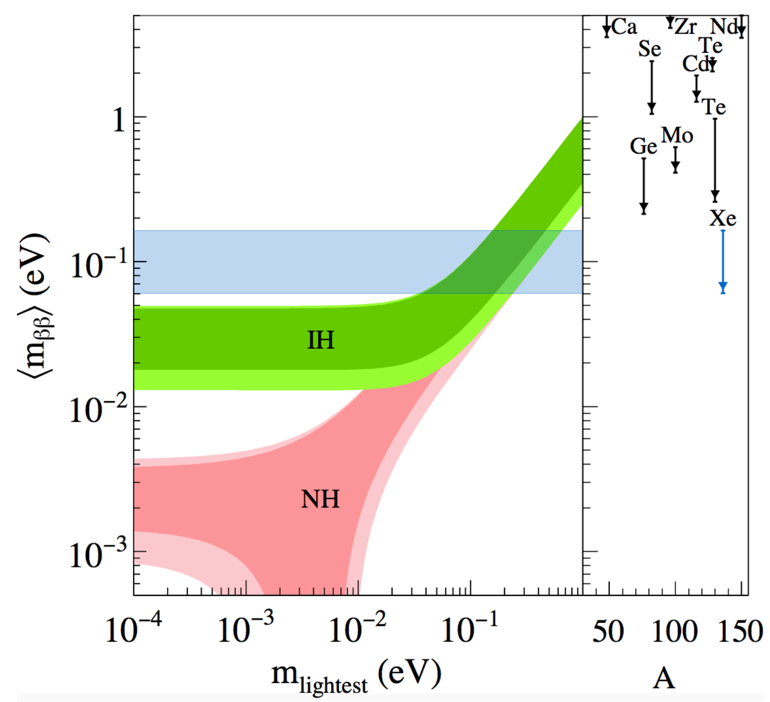



Left-right model?




+ ??

## Well-known Majorana mass mechanism




- Implications for the mass hierarchy

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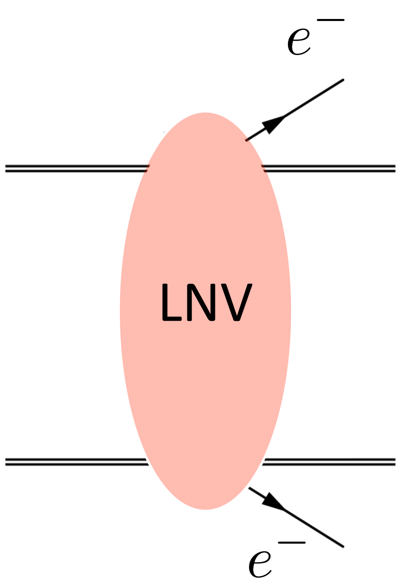
## 0νββ

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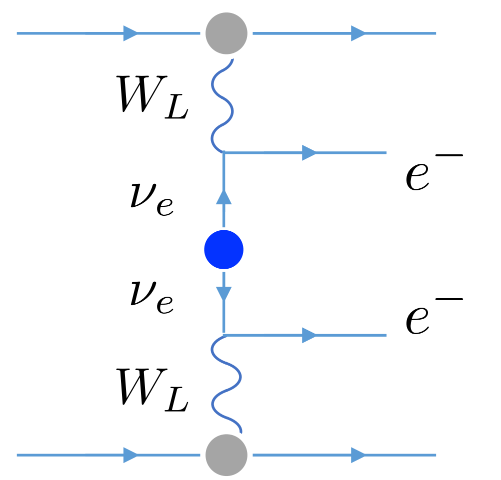


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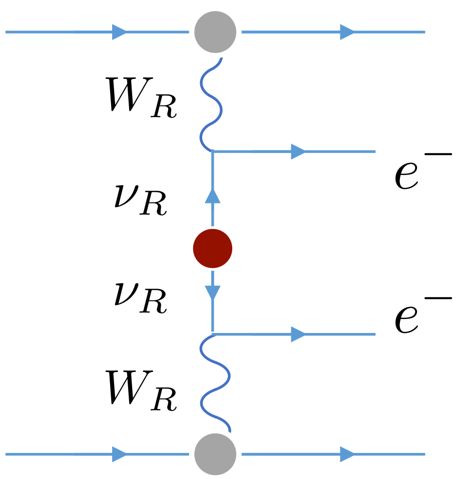


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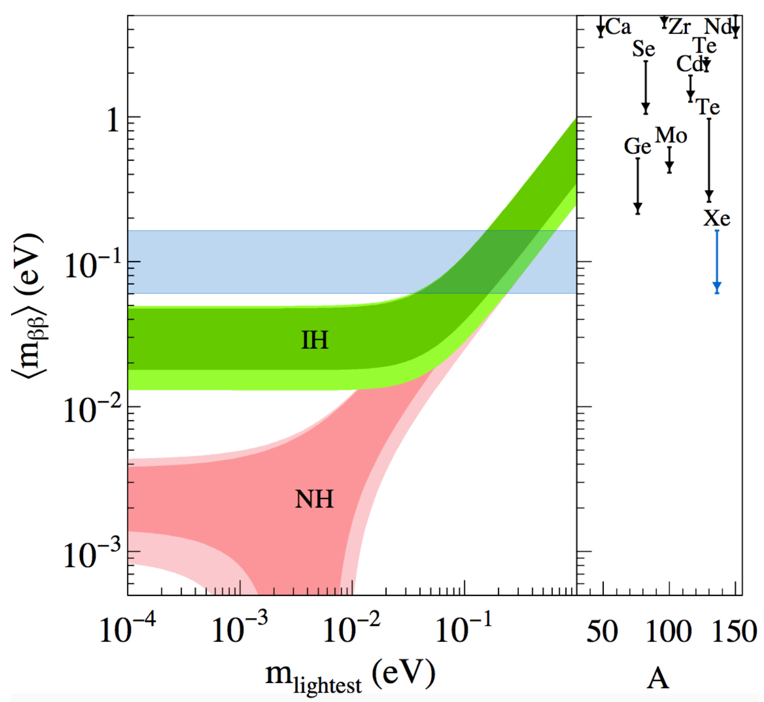


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- Many possible scenarios
  - Left-right model,
  - R-parity violating SUSY
  - Leptoquarks…

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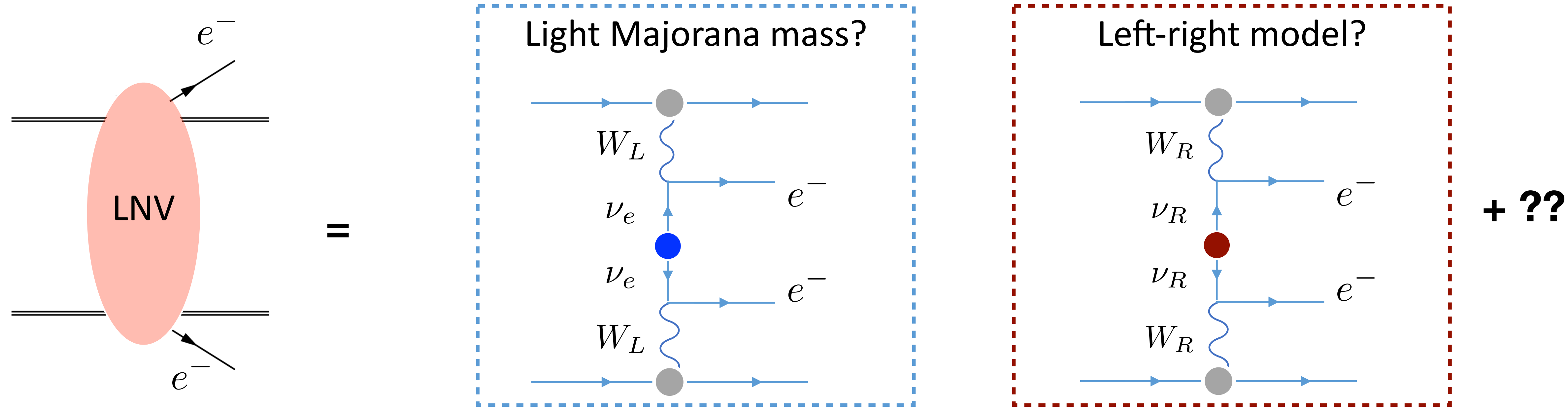


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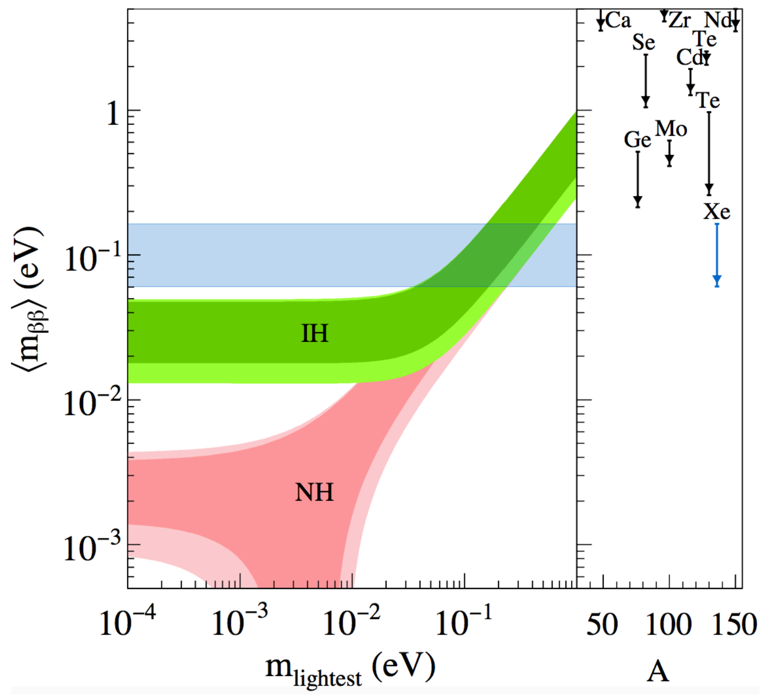


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  - Left-right model,
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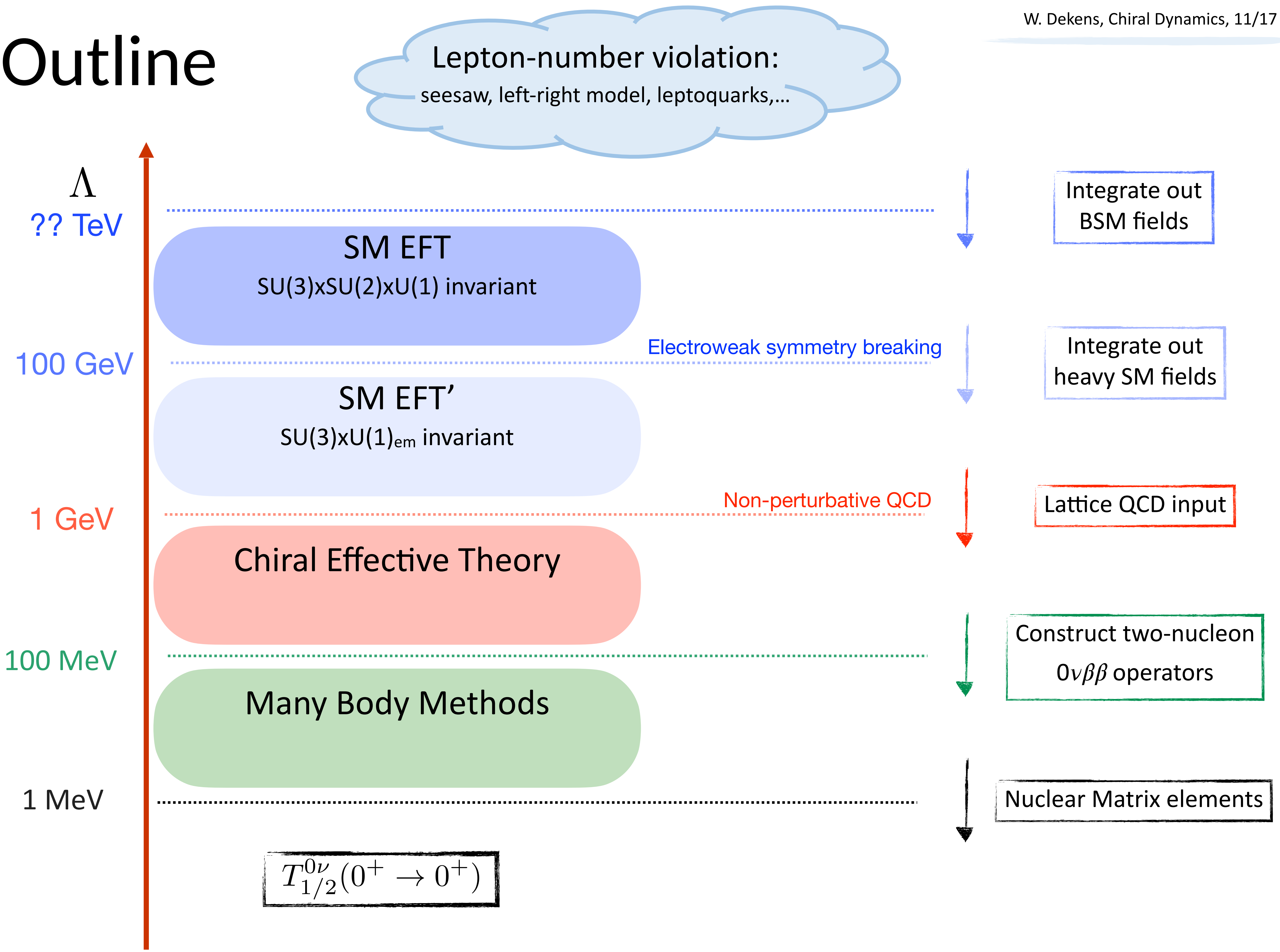
  - Leptoquarks…
- How to describe all LNV sources systematically?

# Outline


Lepton-number violation:
seesaw, left-right model, leptoquarks,...
$\Lambda$
?? TeV
SM EFT
SU(3)xSU(2)xU(1) invariant
100 GeV
Electroweak symmetry breaking
SM EFT'
$SU(3)xU(1)_{em}$ invariant
1 GeV
Non-perturbative QCD
Chiral Effective Theory
100 MeV
Many Body Methods
1 MeV
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

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Construct two-nucleon $0\nu\beta\beta$ operators

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$T^{0\nu}_{1/2}(0^+ \to 0^+)$

# Effective Field Theory

From heavy $\Delta L = 2$ physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)} + \dots$$

### Dimension-five

$$\mathcal{L}_5 = \frac{c_5}{\Lambda}(L^T C\tilde{H})(\tilde{H}^T L)$$

### Dimension-seven

- 12 ΔL=2 operators

| $1:\ \psi^2 H^4 + \text{h.c.}$ | |
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- Consider subset of operators

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## Interactions involving light $\nu_R$

- Can be described in the same framework ($\nu$SMEFT):

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- Majorana mass (L violating)

Zhou, Fuyuto, de Vries, Mereghetti, WD, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

# Effective Field Theory



From heavy $\Delta L = 2$ physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)} + \ldots$$

## Interactions involving light $\nu_R$

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Liao & Ma, '17

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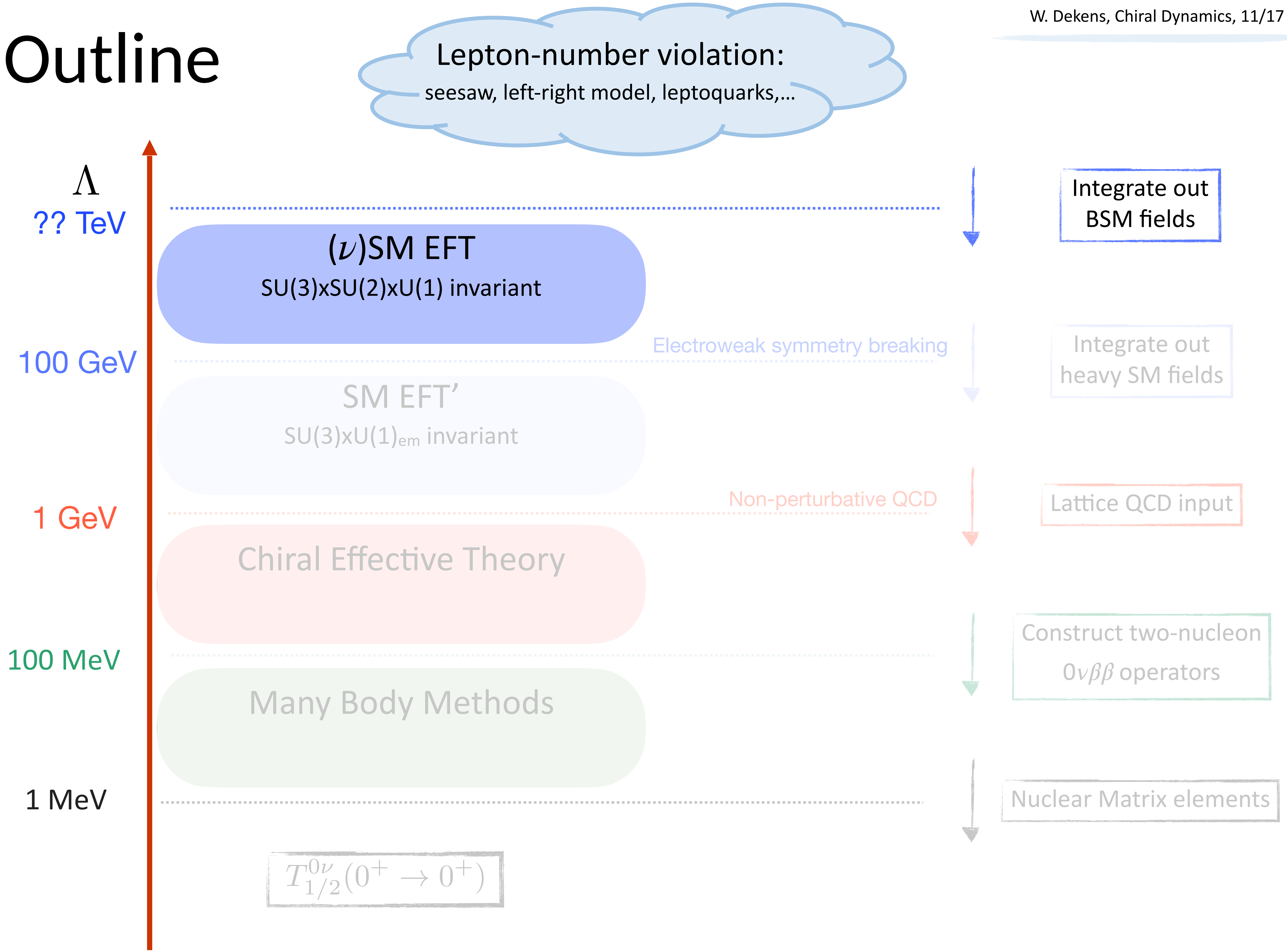
- Majorana mass (L violating)

- Dirac mass (L conserving)

- Dimension-6 (L-conserving)
- Dimension-7 operators (L-violating)
- Induced by heavy BSM physics

Zhou, Fuyuto, de Vries, Mereghetti, WD, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

# Outline


Lepton-number violation:
seesaw, left-right model, leptoquarks,...
$\Lambda$
?? TeV
100 GeV
1 GeV
100 MeV
1 MeV
($\nu$)SM EFT
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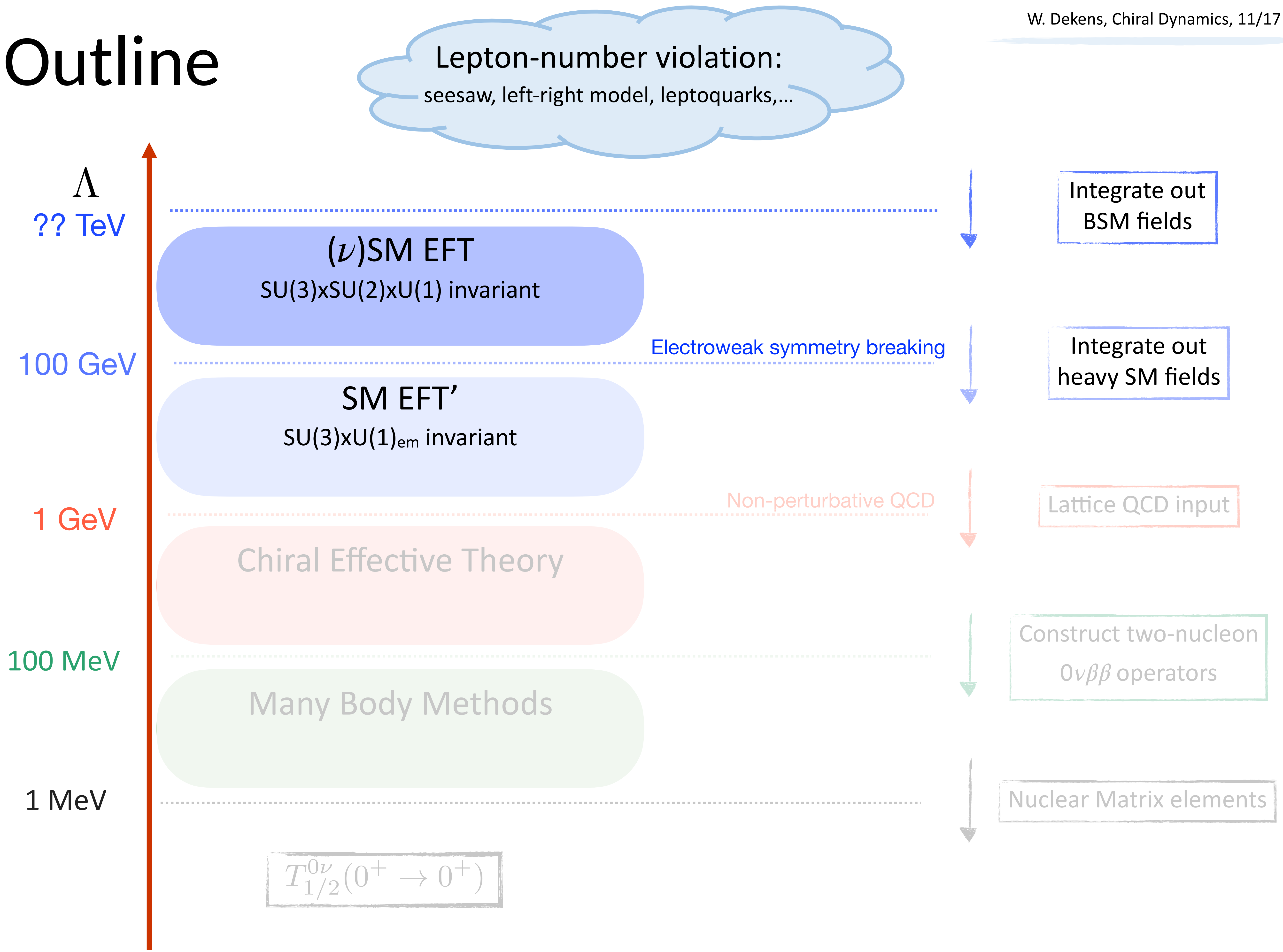
Chiral Effective Theory
Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

# Outline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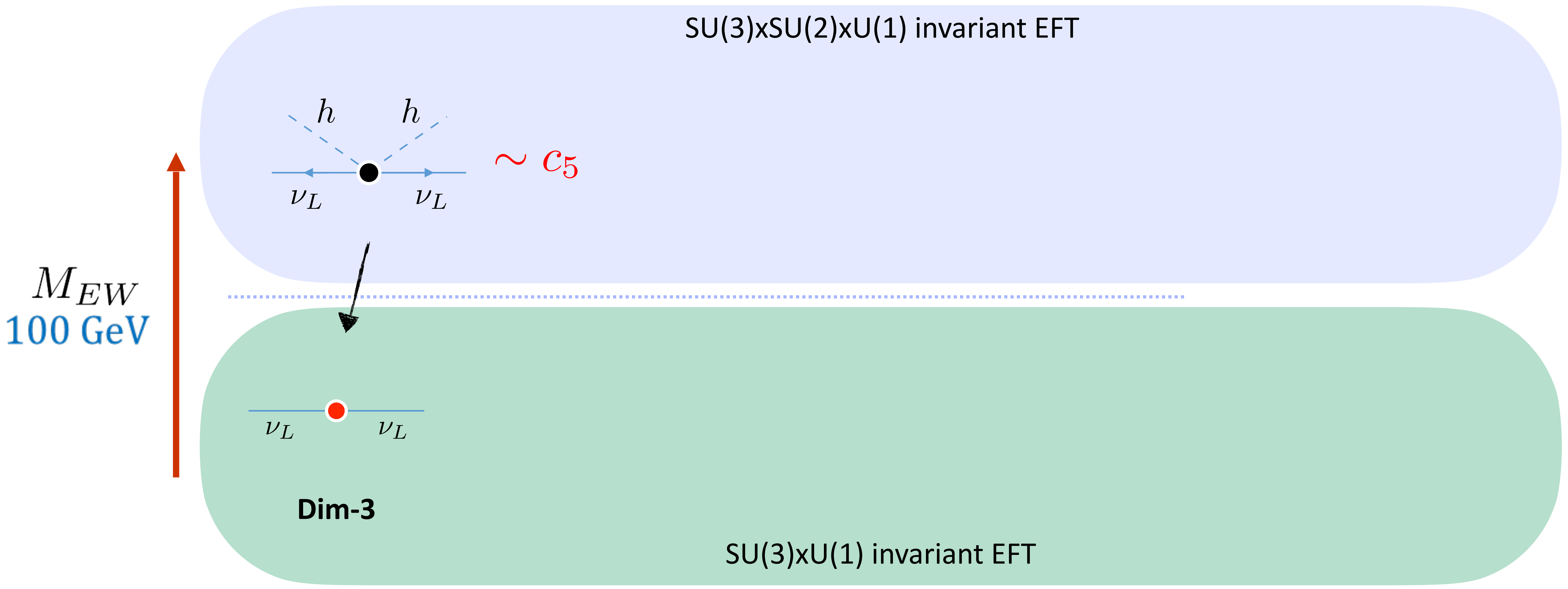
# Low-energy operators

## At/below the weak scale*




* very similar for operators involving $\nu_R$

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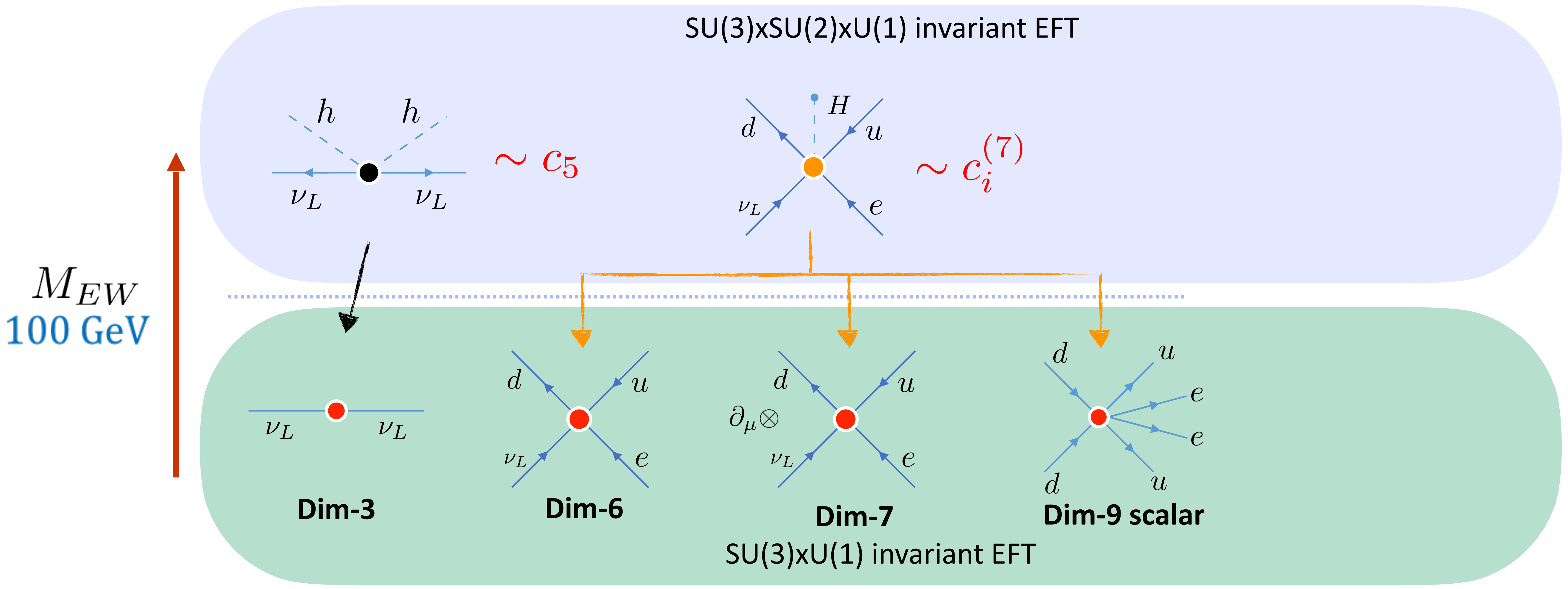


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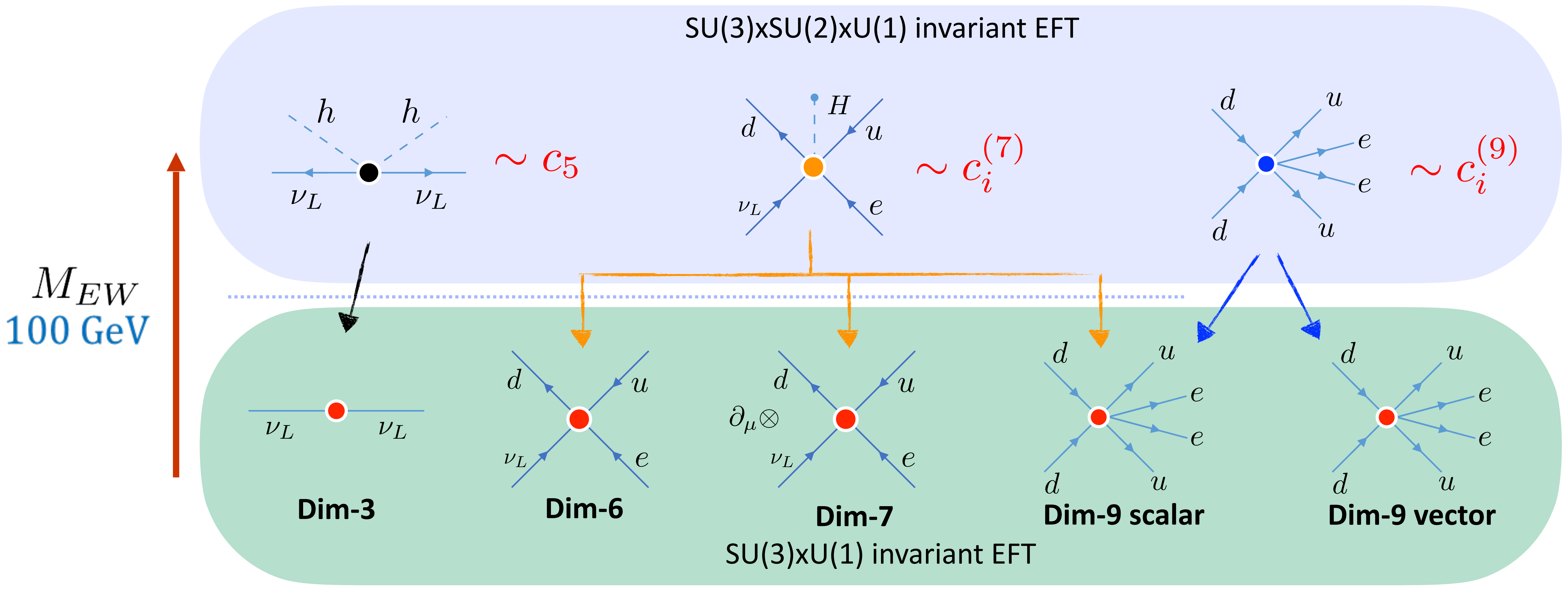


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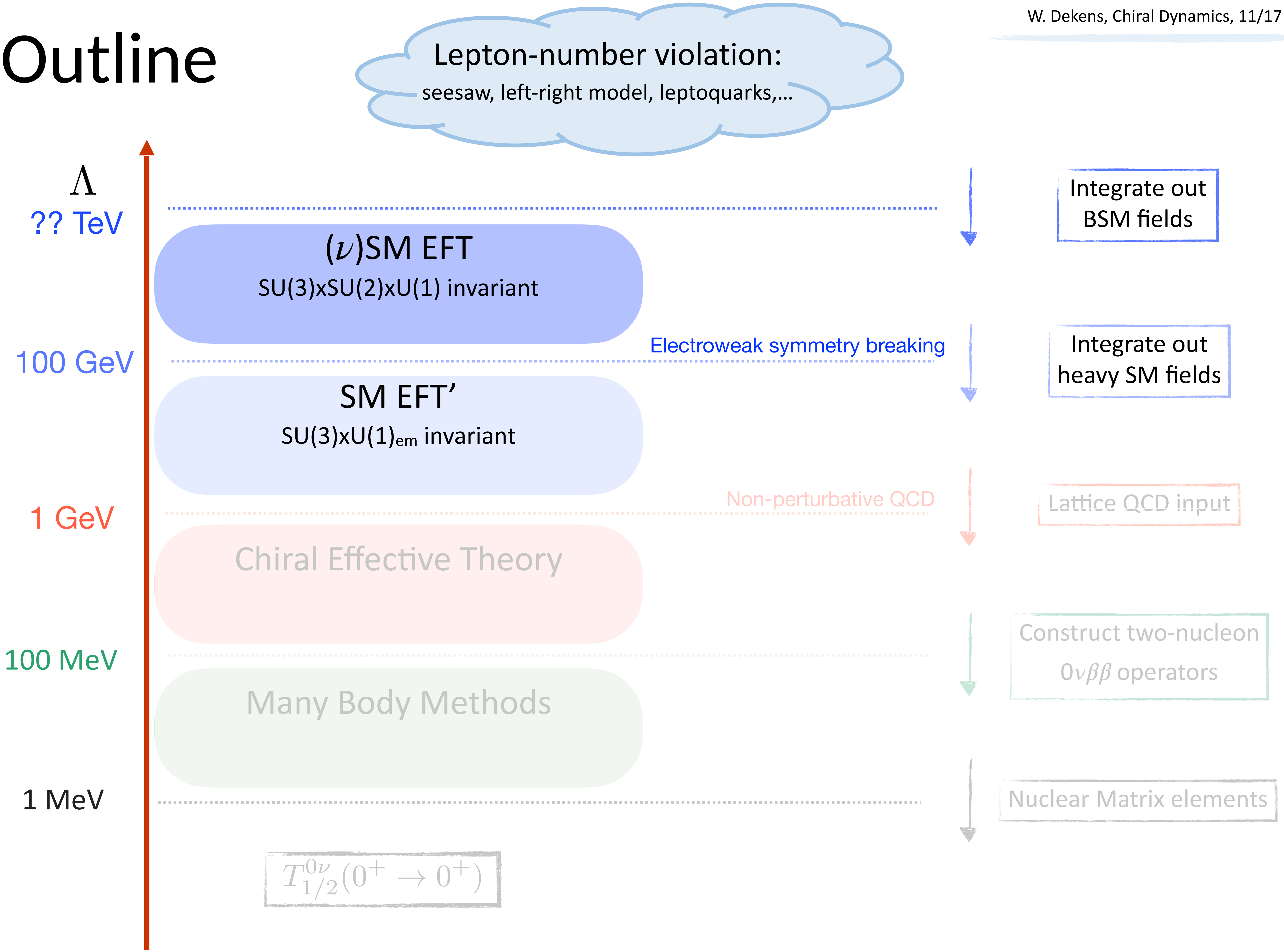
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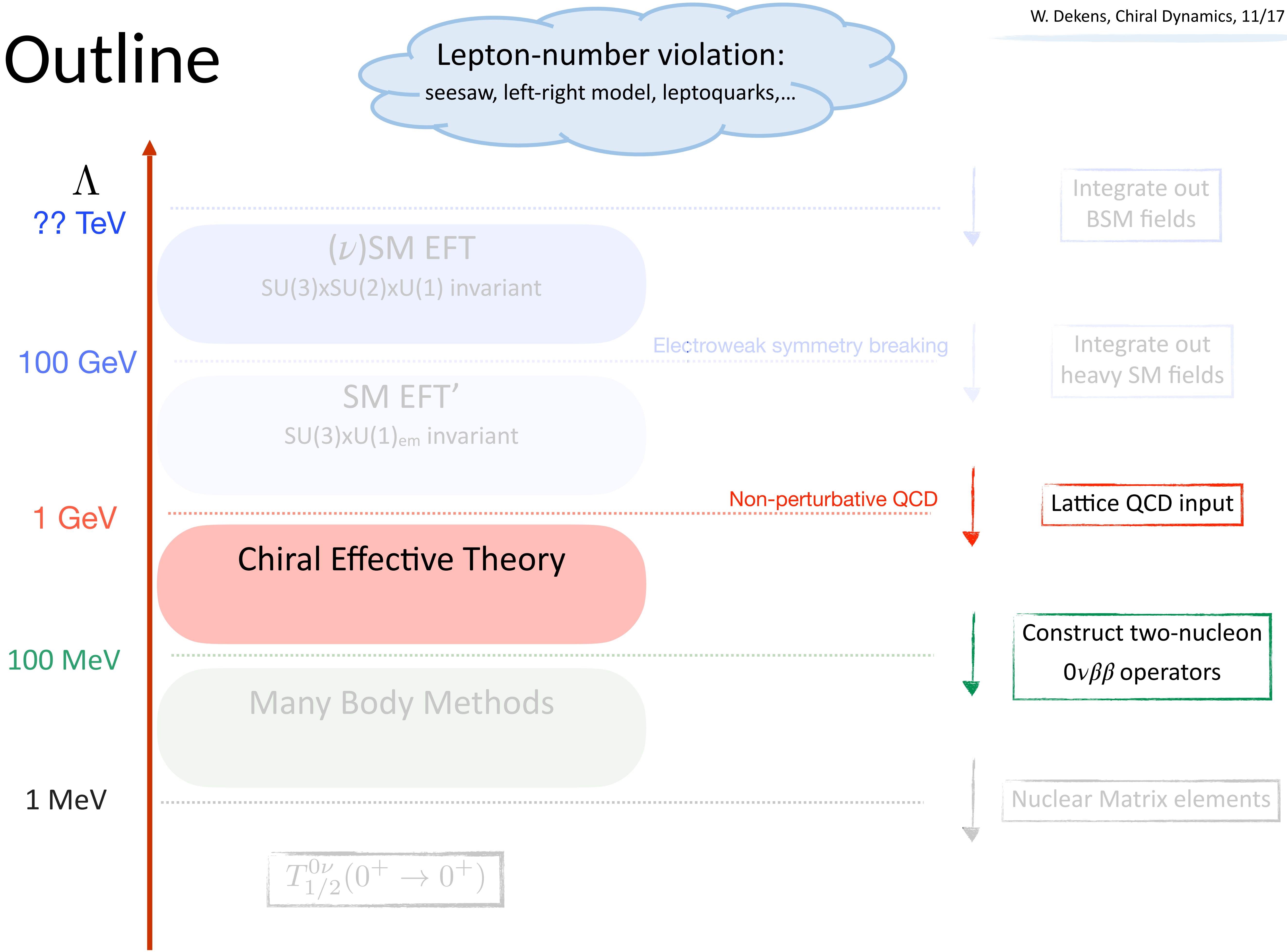
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# Matching to Chiral EFT

$M_{QCD}$
1 GeV

## SM EFT'

SU(3)xU(1)$_{em}$ invariant

In terms of quarks, gluons, leptons $\mathcal{L}(u, d, g, \nu, e)$

## Chiral Effective Theory

In terms of nucleons, pions, leptons $\mathcal{L}_{\chi PT}(N, \pi, \nu, e)$

Form of operators determined by chiral symmetry

The operators come with unknown constants (LECs)

Need a power-counting scheme

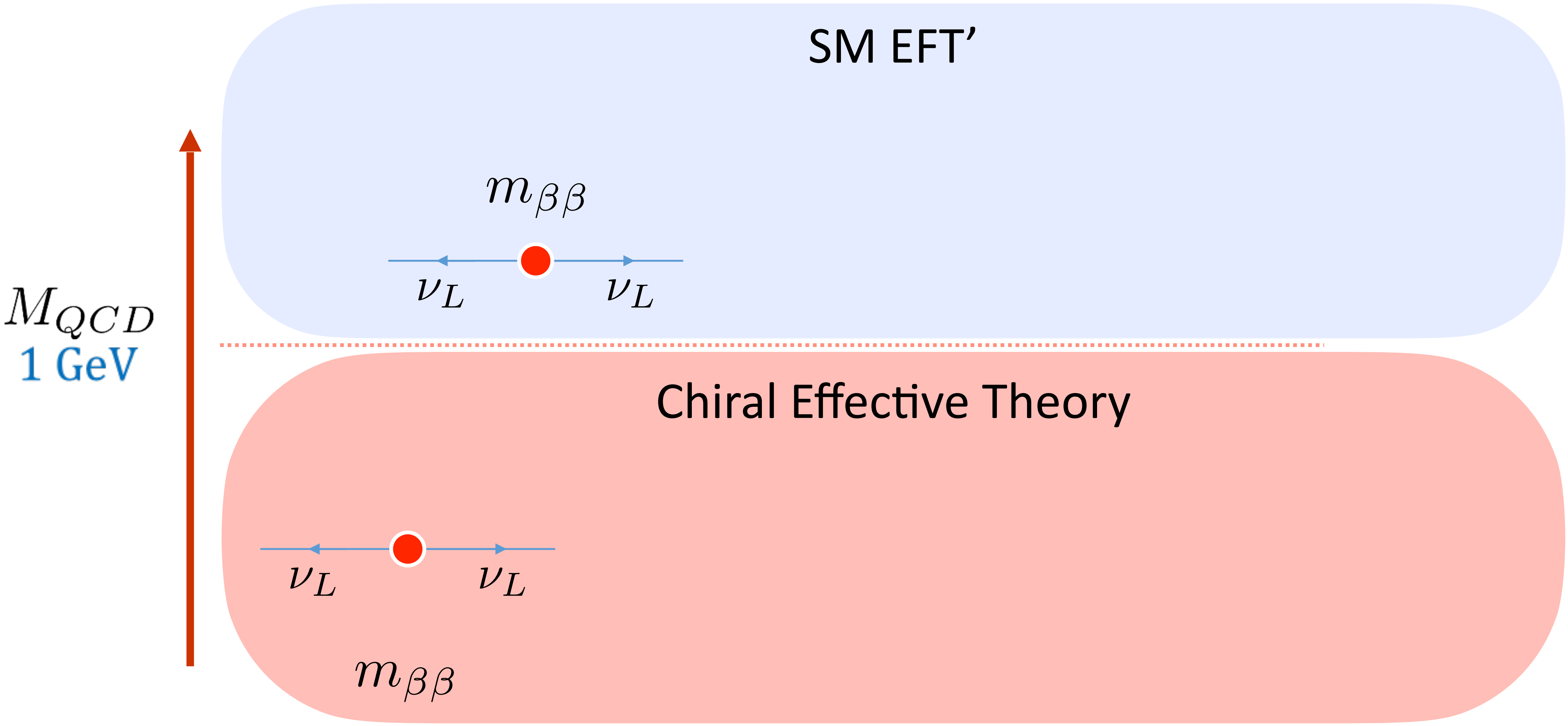
- Start by assuming Naive dimensional analysis (NDA)
- Will come back to whether it breaks down

Manohar, Georgi, `84; Weinberg, `90, `91

# Matching to Chiral EFT

Dimension-3

Warning: Based on NDA



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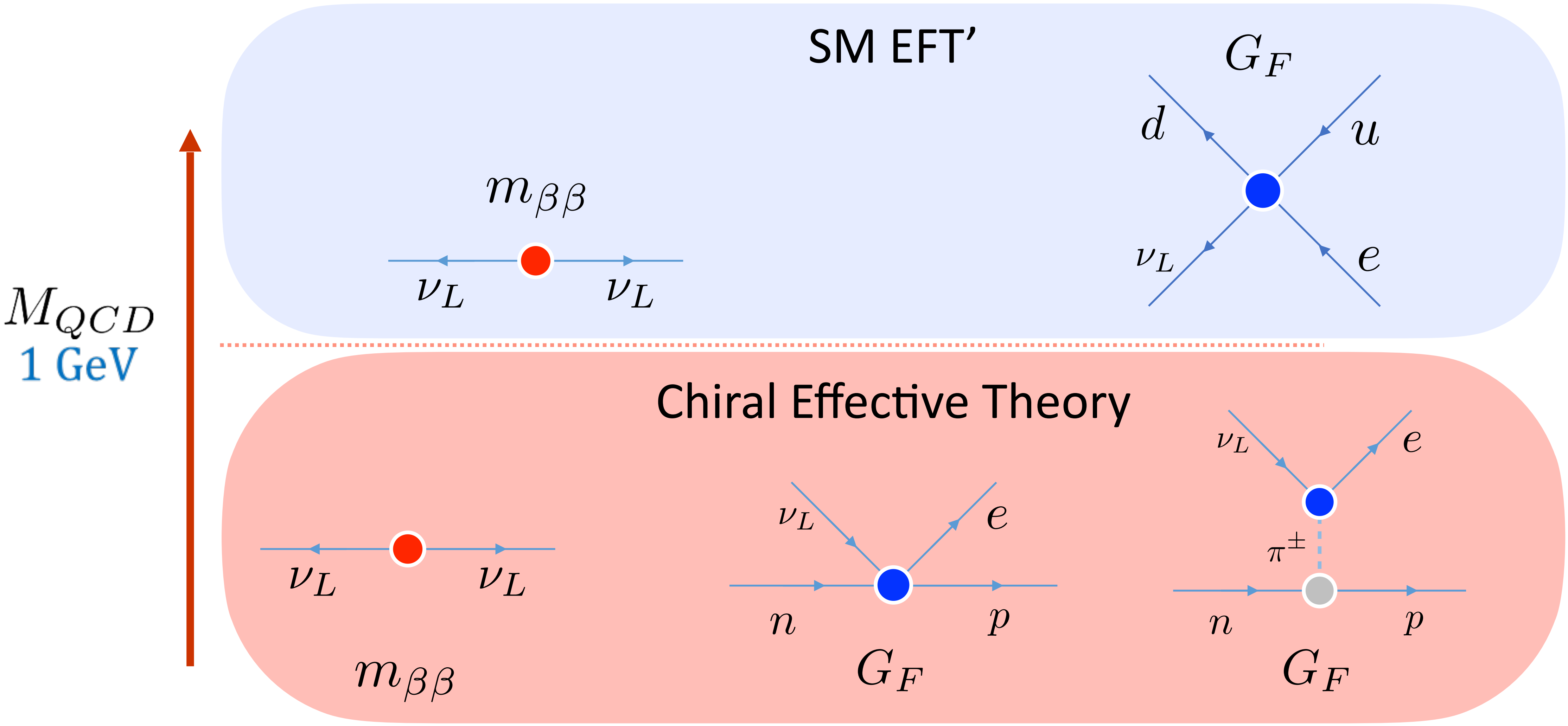

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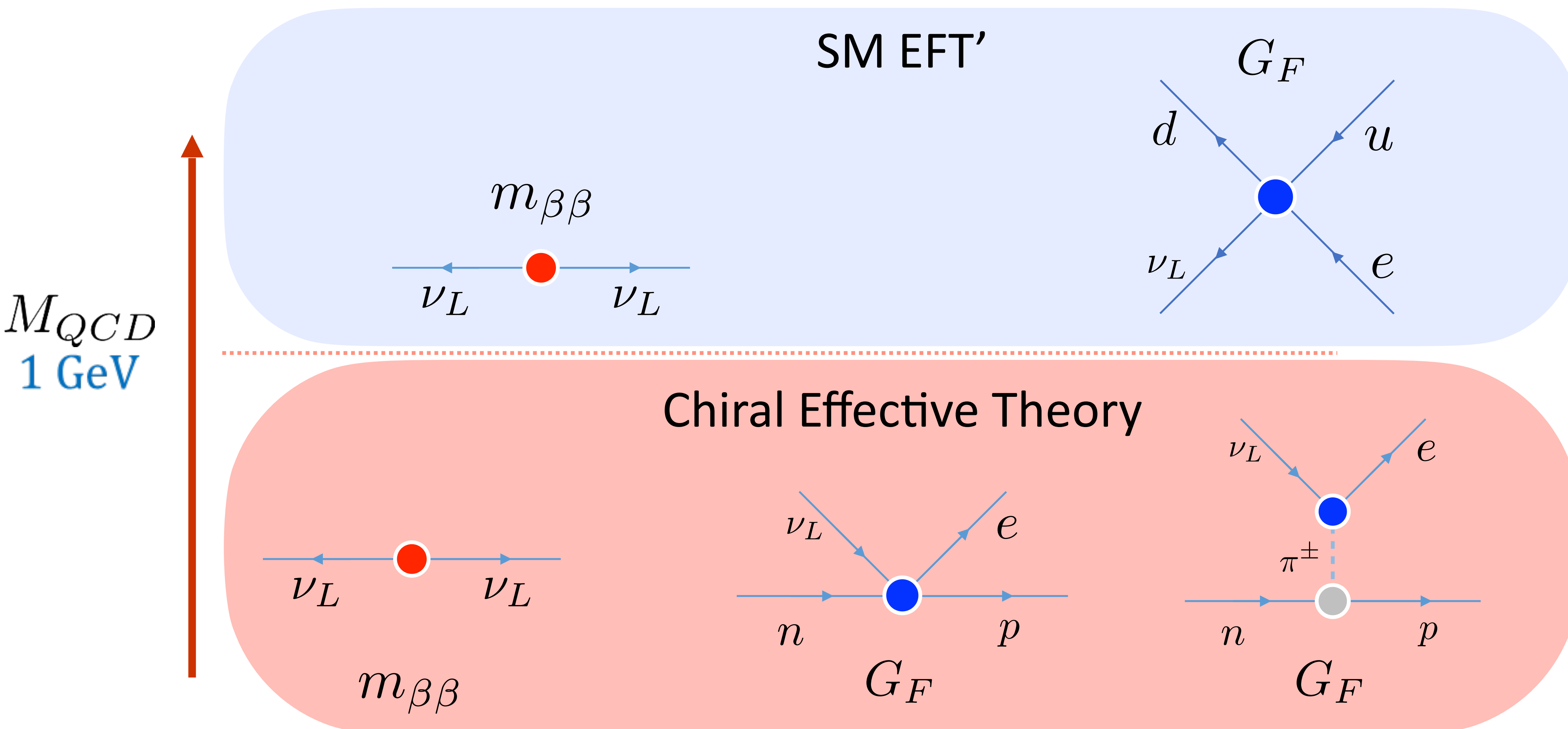
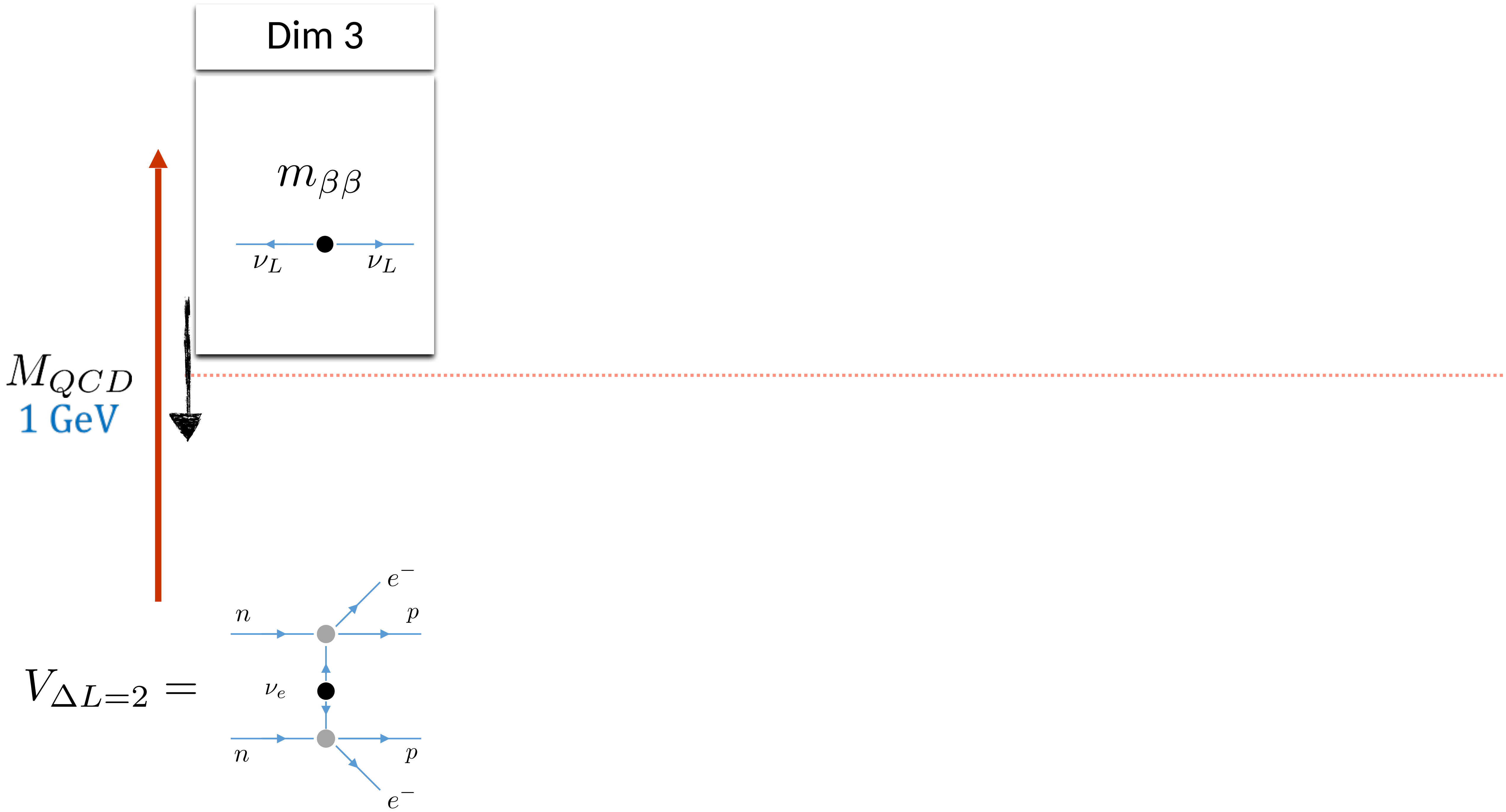


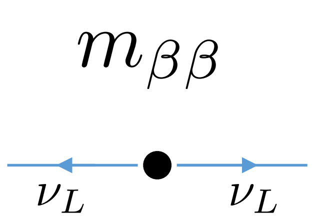

- At LO in Weinberg counting, only need the nucleon one-body currents
- Needed low-energy constants are known from experiment / Lattice QCD

# Chiral EFT

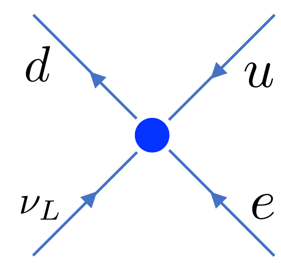


# Chiral EFT

## Dim 3

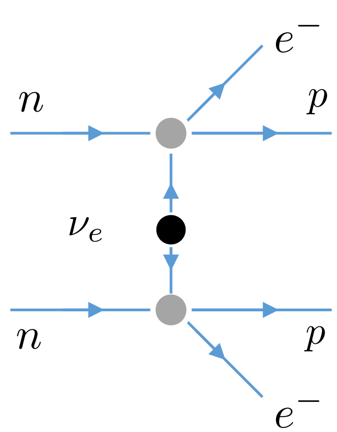


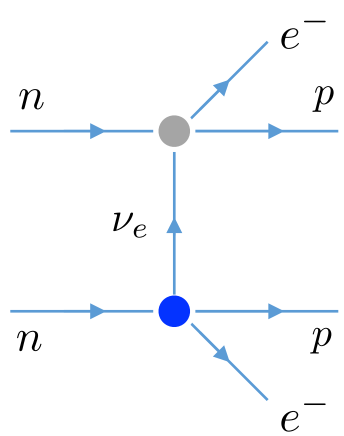

## Dim 6 & 7




$M_{QCD}$
1 GeV

$V_{\Delta L=2} =$

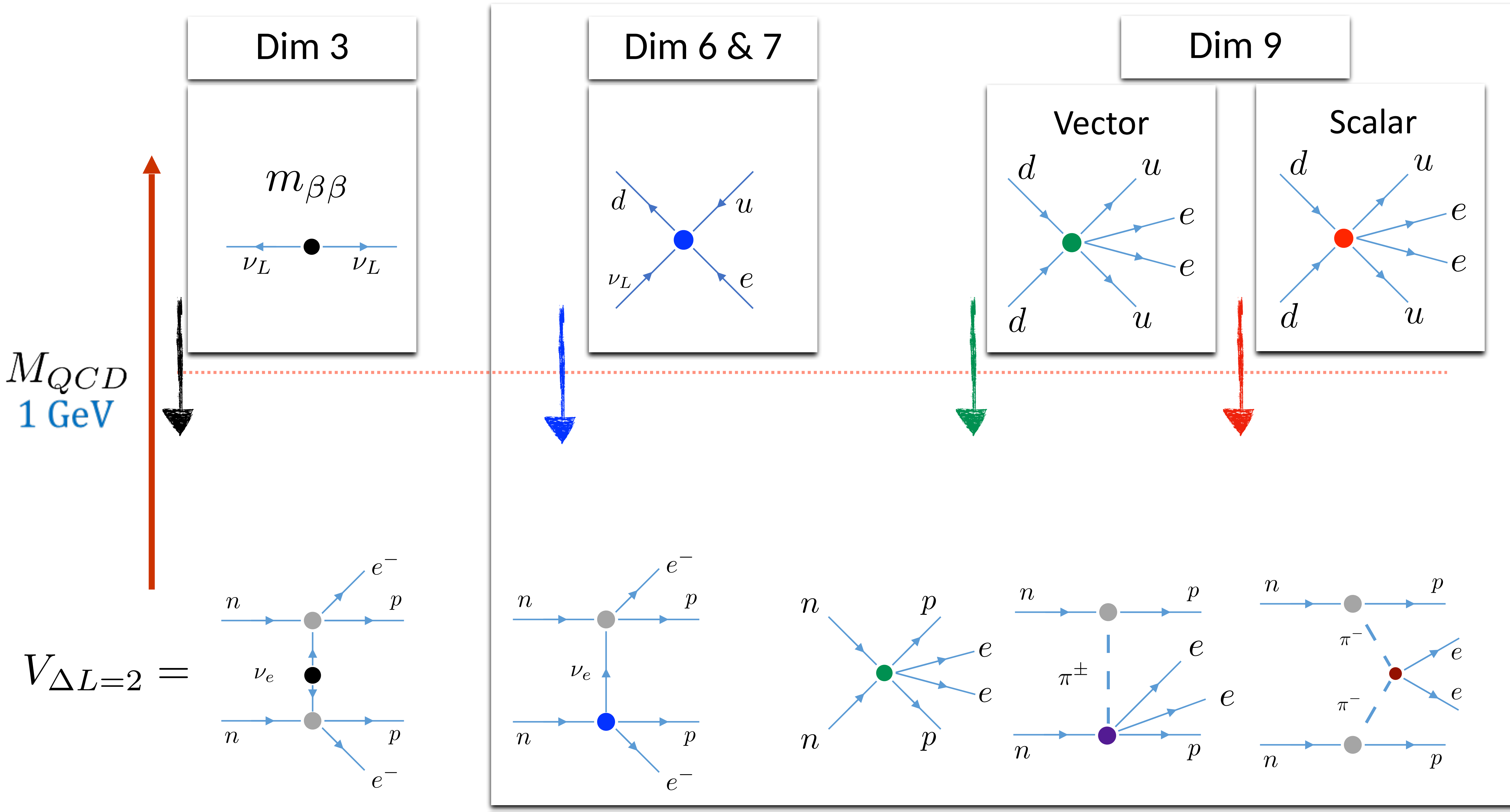



- Additional $N$-currents $\pi\pi$, $\pi N$, $NN$ interactions and LECs
- LECs for the $N$-currents and $\pi\pi$ interactions are partially known

Nicholson et al.'18; Cirigliano et al. '17

# Chiral EFT

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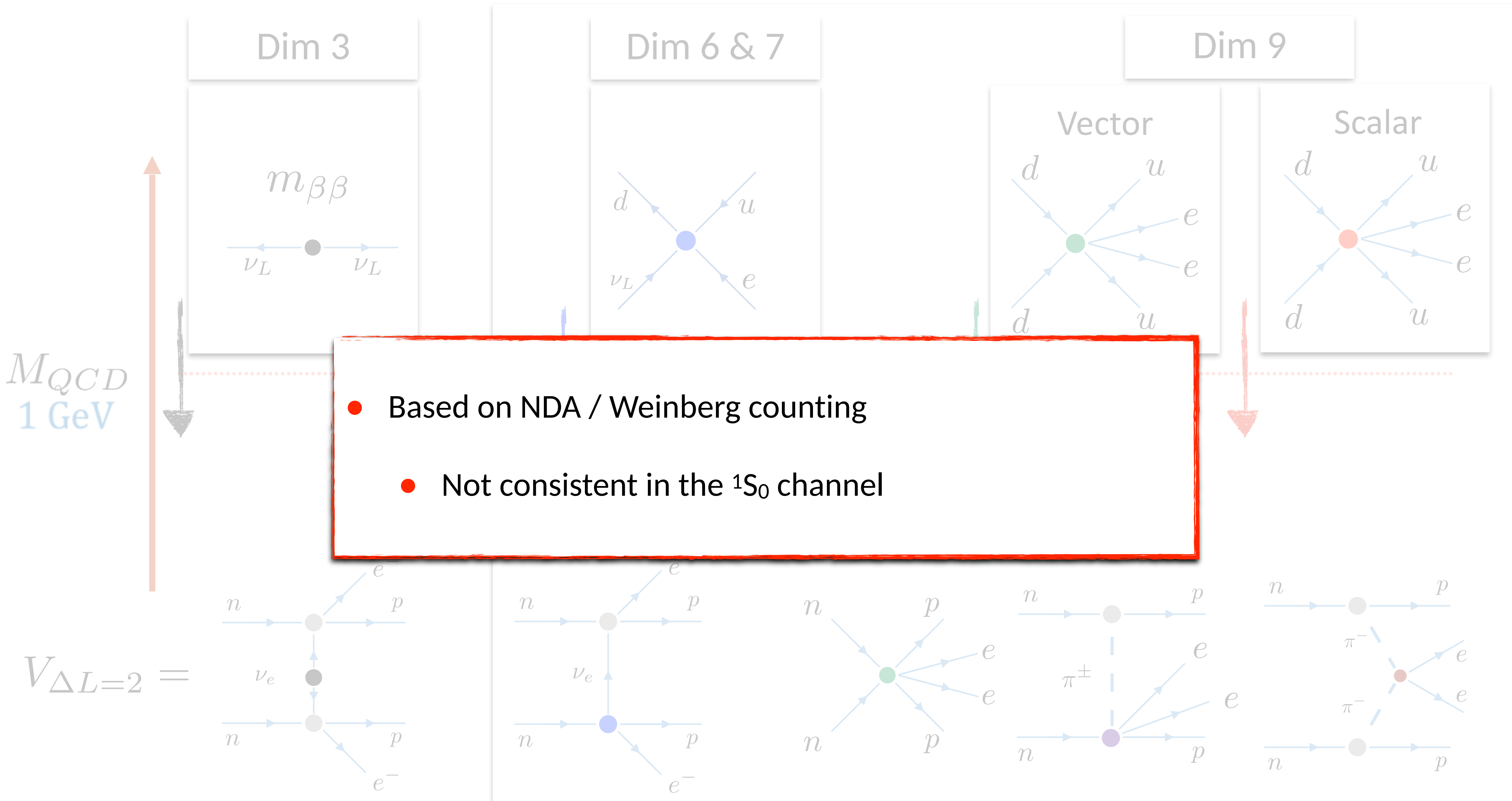



- Based on NDA / Weinberg counting
  - Not consistent in the $^1S_0$ channel

- Additional $N$-currents $\pi\pi$, $\pi N$, $NN$ interactions and LECs
- LECs for the $N$-currents and $\pi\pi$ interactions are partially known

Kaplan, Savage, Wise, '96; Beane, Bedaque, Savage, van Kolck, '03, Nogga, Timmermans, van Kolck, '05, Long, Yang, '12;

# Checking the power counting



Dimension-3

Check that $\mathcal{A}(nn \to ppee)$ is finite

# Checking the power counting

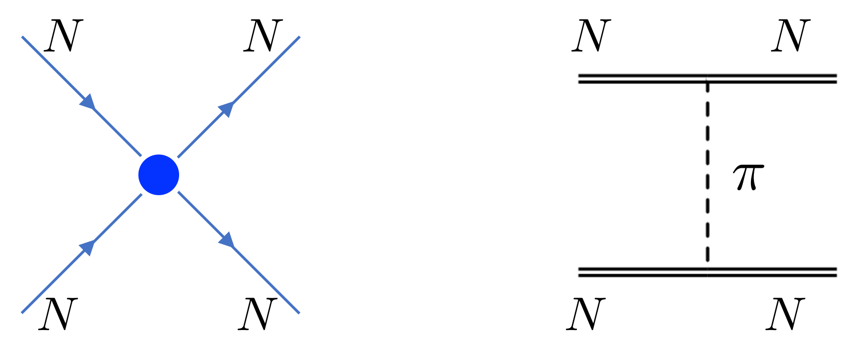


## Dimension-3

Check that $\mathcal{A}(nn \to ppee)$ is finite

- Requires inclusion of the strong interaction

$$\mathcal{L}_\chi = C\left(N^T P_{{}^1S_0} N\right)^\dagger N^T P_{{}^1S_0} N - \frac{g_A}{2F_\pi}\nabla\pi \cdot \bar{N}\tau\boldsymbol{\sigma}N$$



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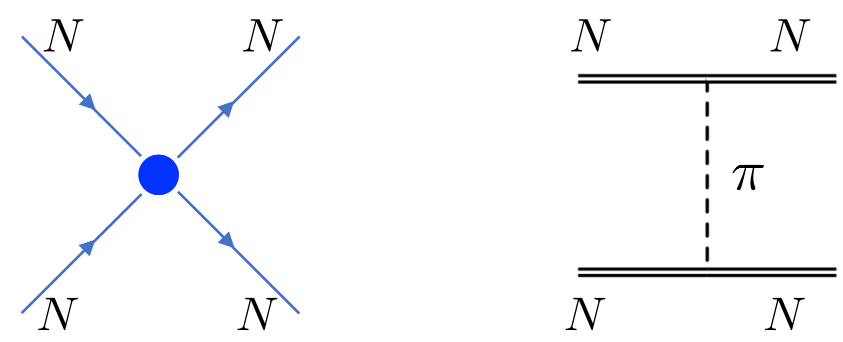
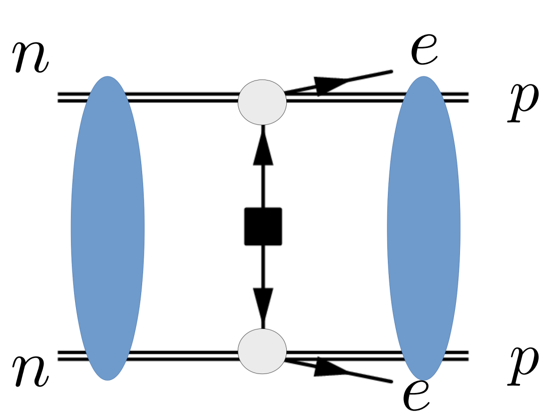
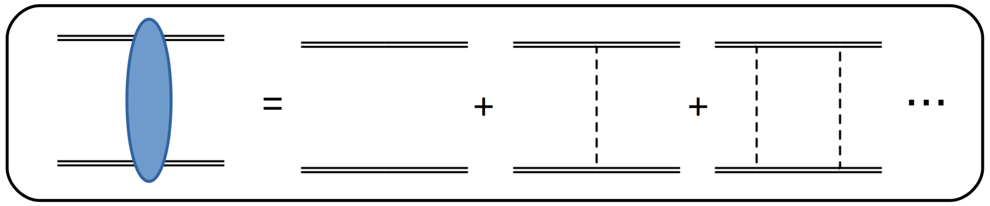



Dress the ΔL=2 potential with (renormalized) strong interactions:




✓ finite

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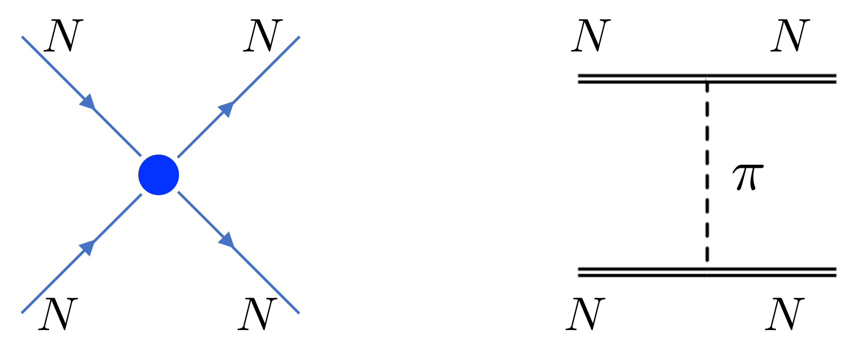


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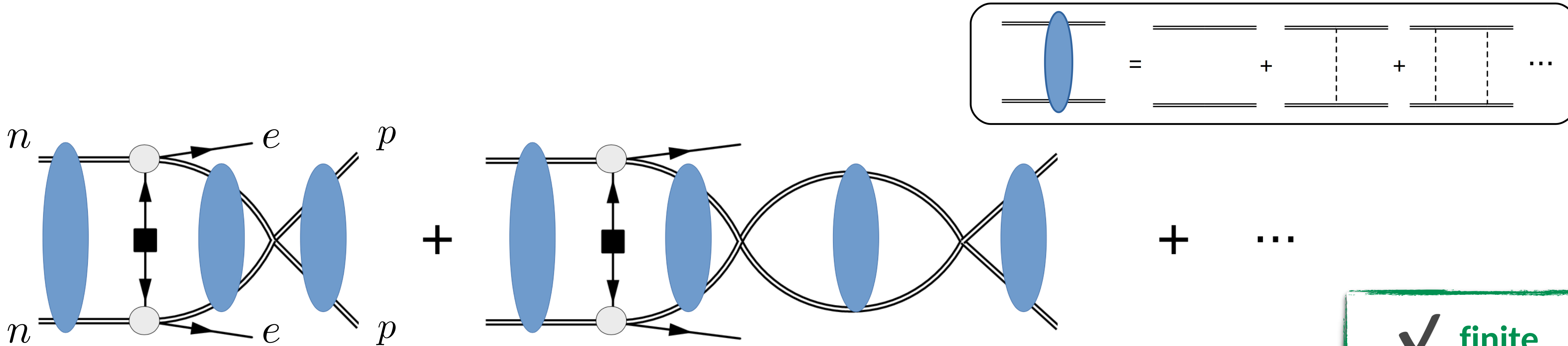


✓ finite

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## Dimension-3

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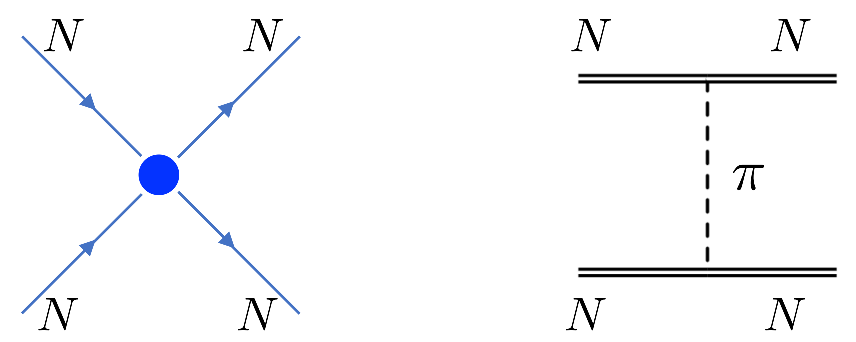


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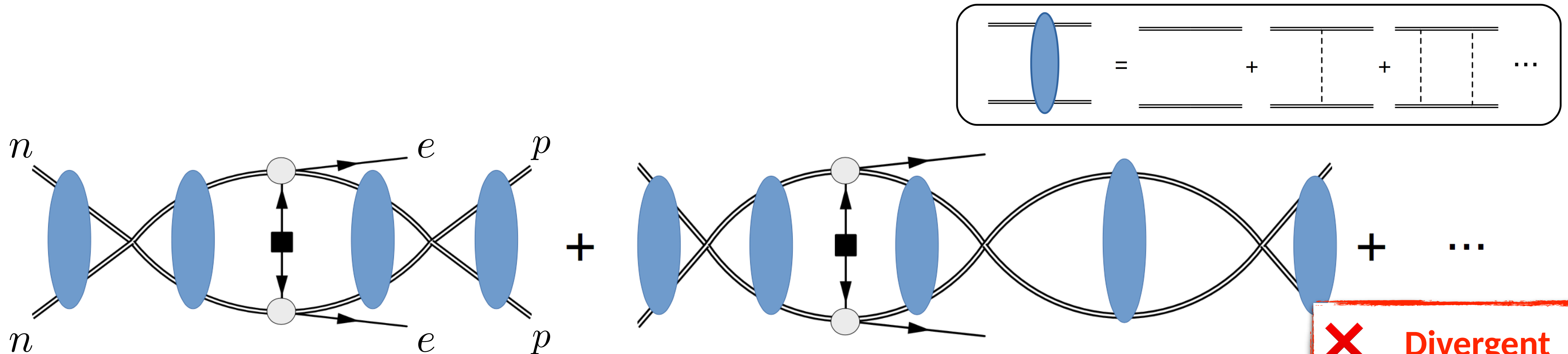


❌ Divergent

# Checking the power counting



Dimension-3

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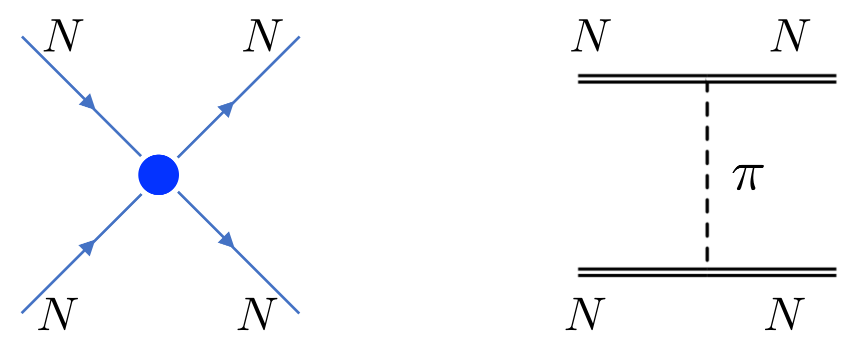
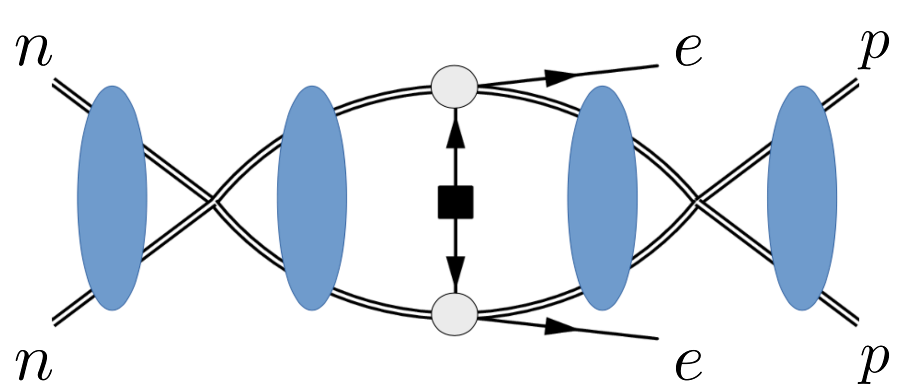



Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

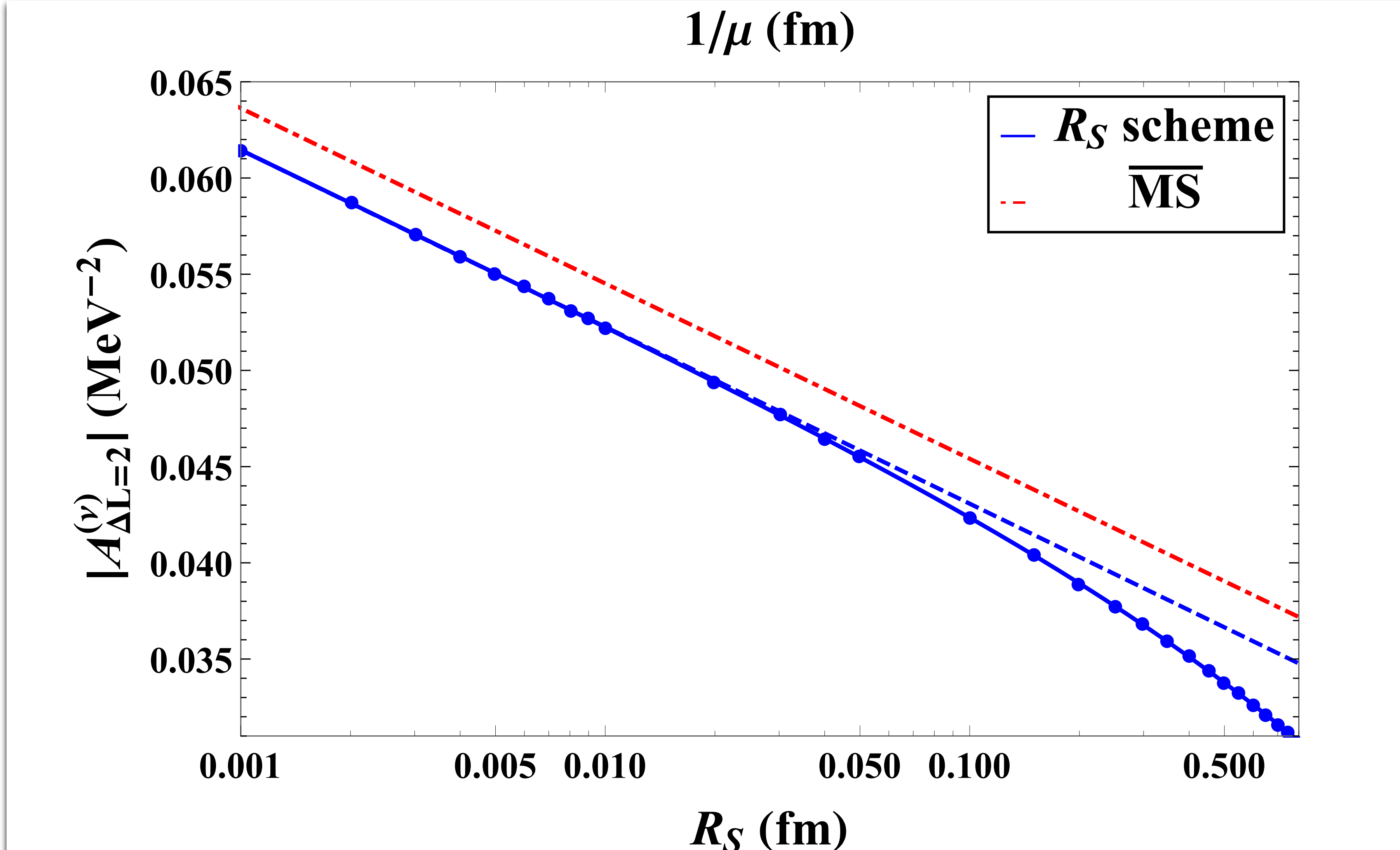



$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+$finite

Regulator dependent

# Numerical results




- Amplitudes obtained using
  - MS-bar
  - Coordinate-space cut-off

$$\tilde{C}\,\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right)$$

- Clear $\mu$ or $R_S$ dependence

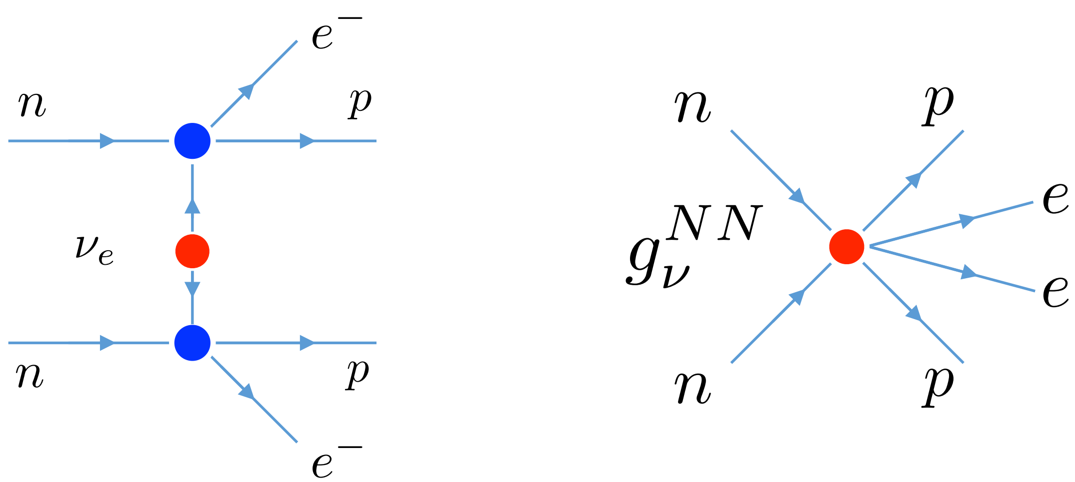
# Need for a counter term



- Need a new contact interaction at leading order to get physical amplitudes:

$$\mathcal{L}_{CT} = 2G_F^2 V_{ud}^2 m_{\beta\beta}\, g_\nu^{NN}\, \bar{p}n\, \bar{p}n\, \bar{e}_L C \bar{e}_L^T$$

$$V_{\Delta L=2} = V_\nu + V_{\nu,CT} =$$



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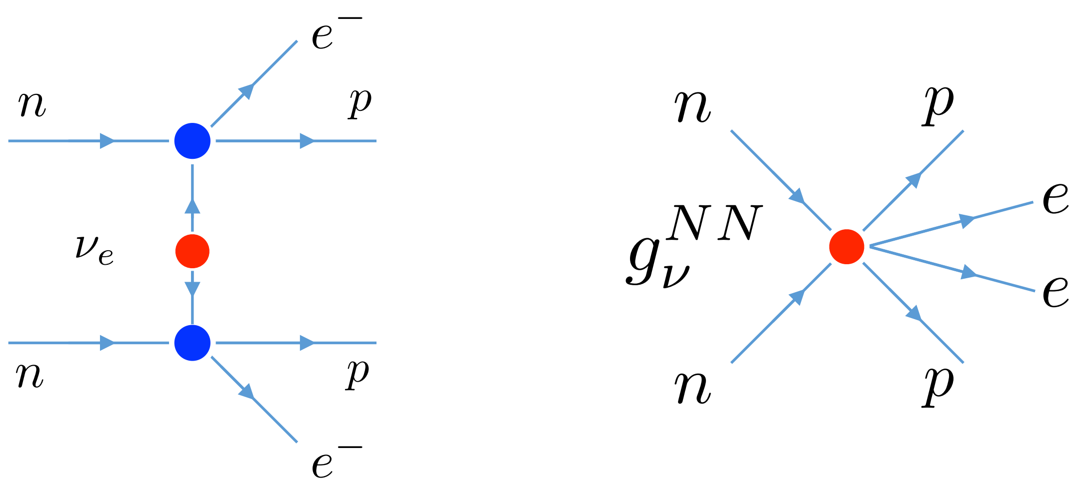



- $g_\nu^{NN}$ be determined from a lattice calculation of $\mathcal{A}(nn \to ppe^- e^-)$
  - Area of active research

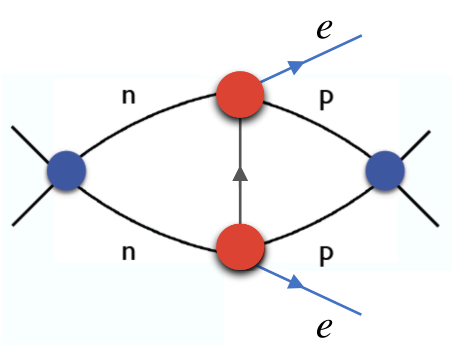
Davoudi and Kadam, '20; Feng et al, '20

# Determination of the counterterm

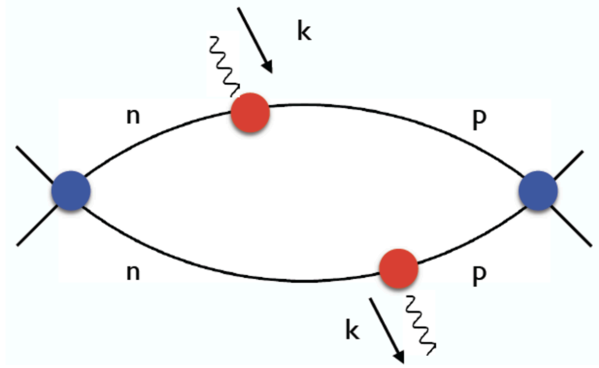
- Analogy to the Cottingham approach for pion/nucleon mass differences

Cirigliano et al, '20, '21

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2 + i\epsilon} \int d^4x\, e^{ik\cdot x} \langle pp | T\{ j^\mu_{\rm w}(x) j^\nu_{\rm w}(0)\} | nn \rangle$$

$\mathcal{A}_\nu =$ 


$$\propto \int dk\, a(k) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + i\epsilon}$$




W. Cottingham '63; H. Harari, '66

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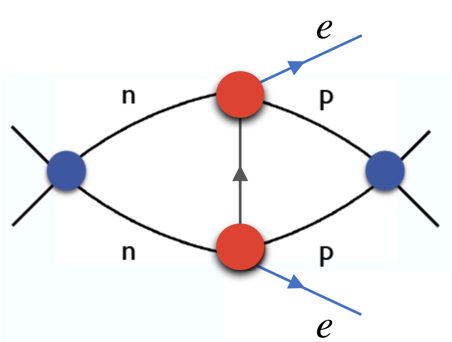
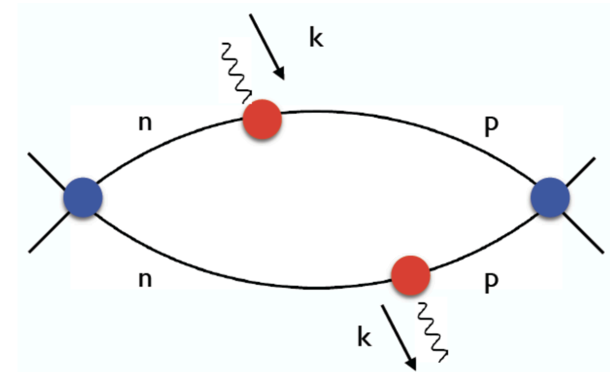
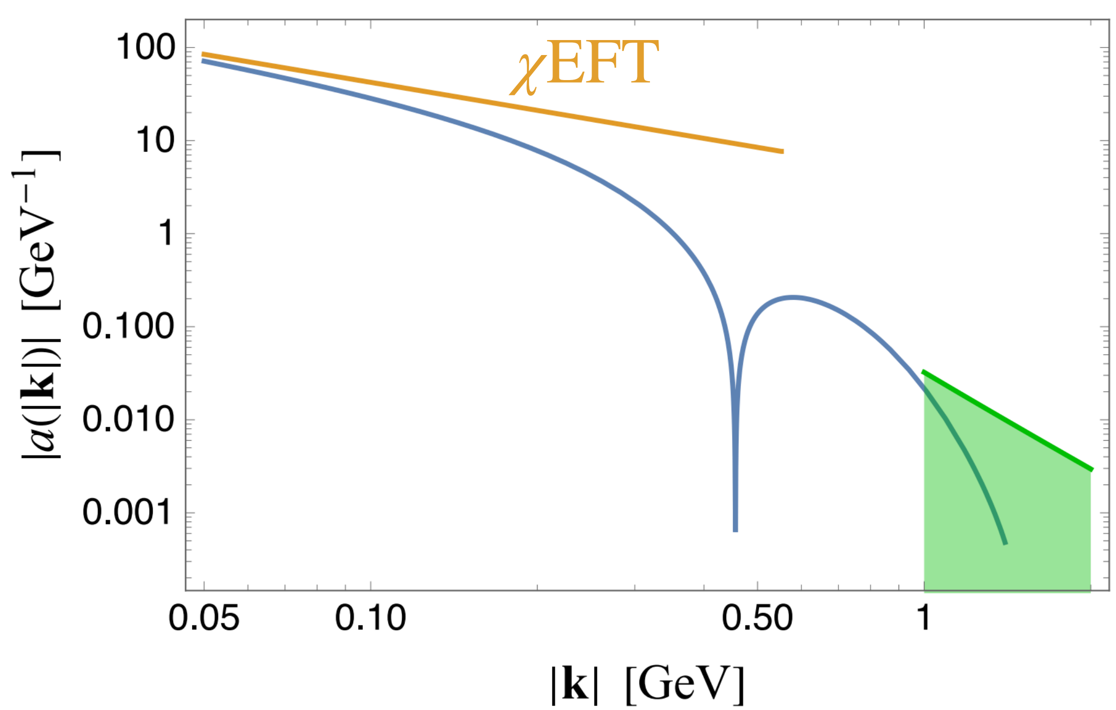
$\mathcal{A}_\nu =$ 

$\propto \int dk\, a(k) = \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2+i\epsilon}$ 


- Estimate the $A_\nu$ by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by $\chi$EFT

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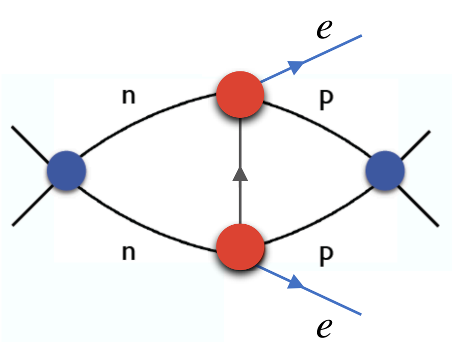
$\mathcal{A}_\nu =$ 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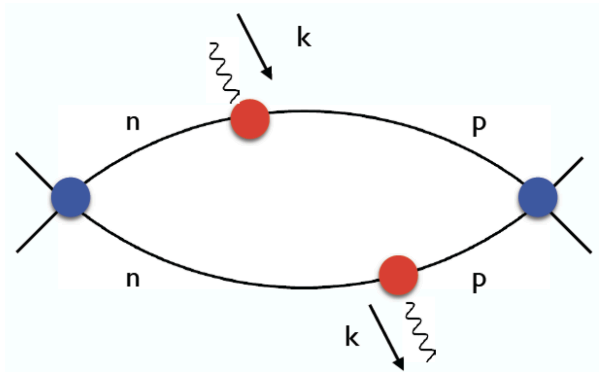


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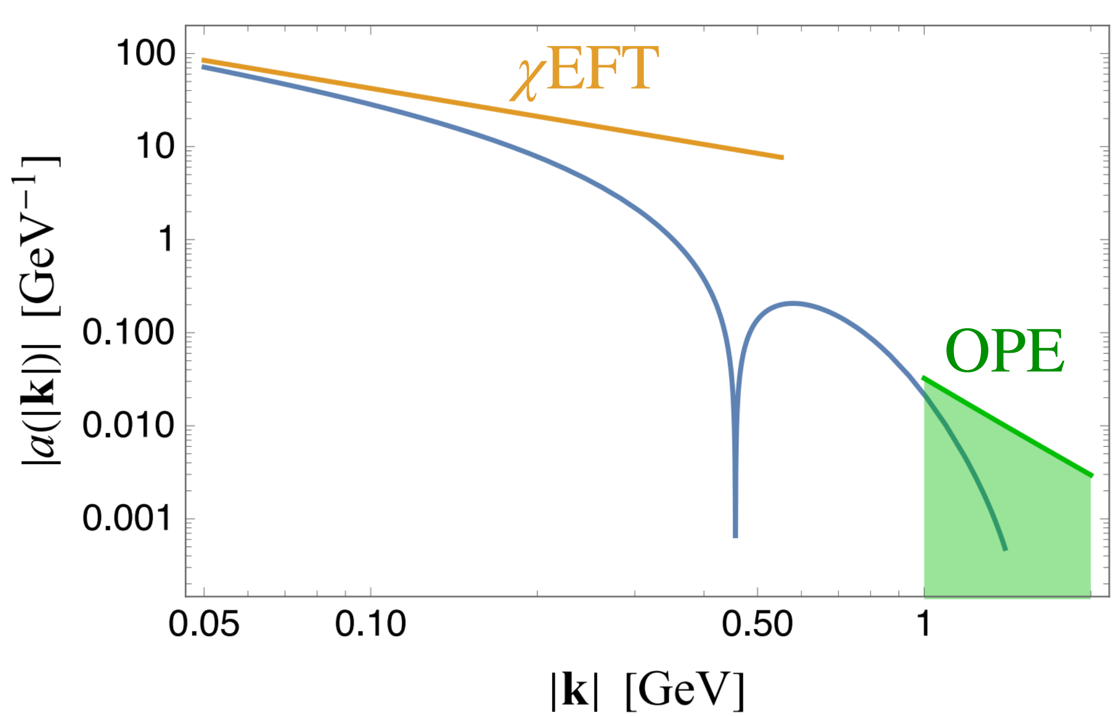


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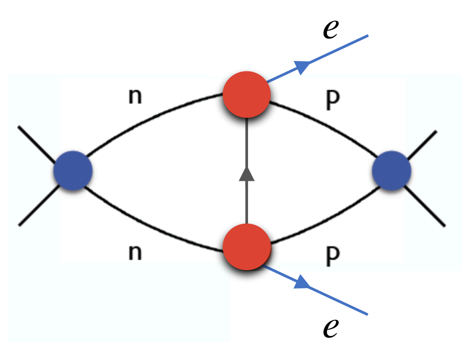
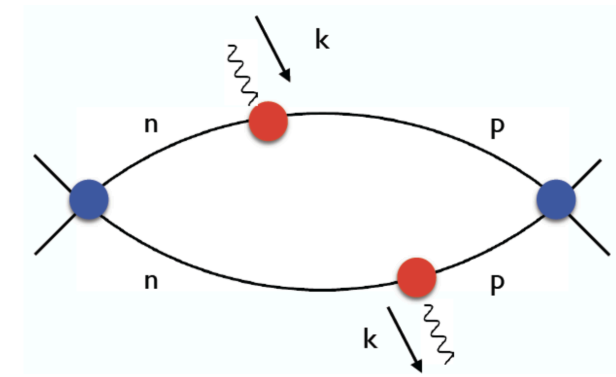
$\mathcal{A}_\nu =$ 

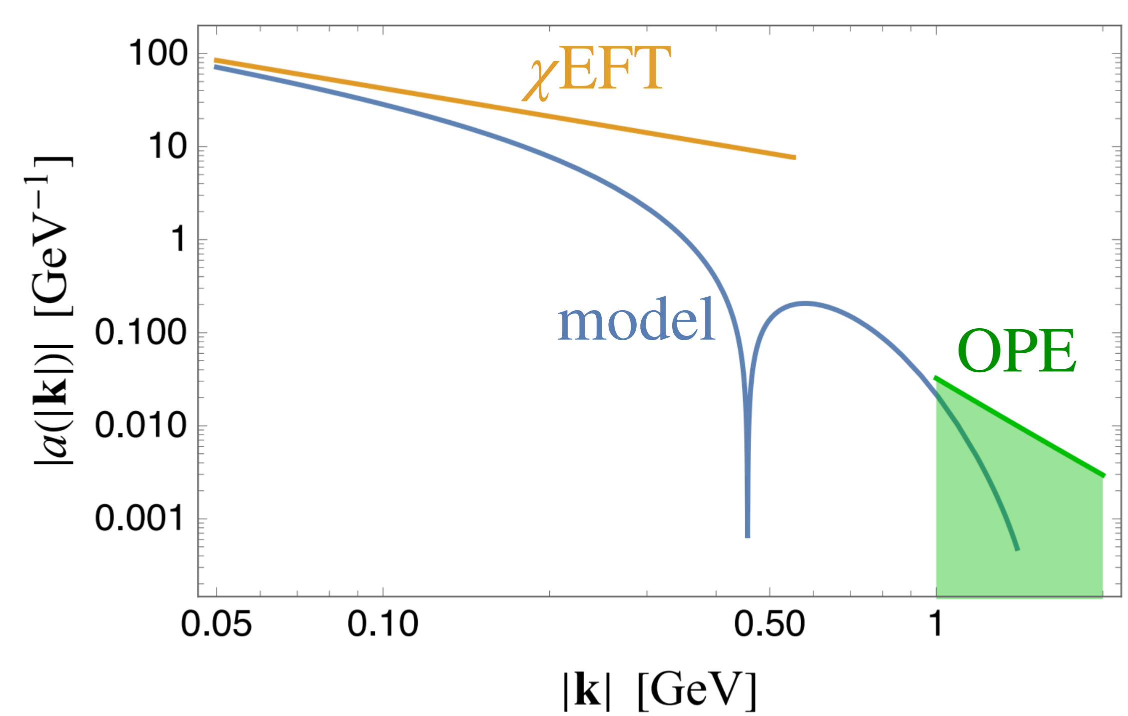


$$\propto \int dk\, a(k) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + i\epsilon}$$





- Estimate the $A_\nu$ by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by $\chi$EFT
  - $k \gg \mathrm{GeV}$ region determined by OPE
  - Model intermediate region using:
    - Form factors
    - Off-shell effects from $NN$ intermediate states





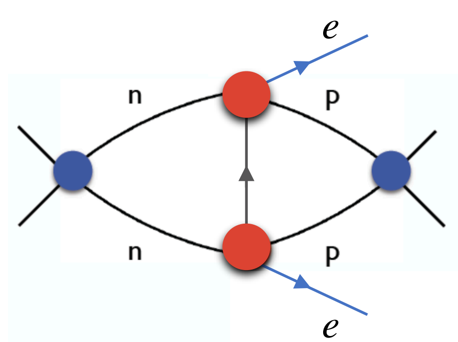
W. Cottingham '63; H. Harari, '66

# Determination of the counterterm

- Analogy to the Cottingham approach for pion/nucleon mass differences

Cirigliano et al, '20, '21

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2 + i\epsilon} \int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\rm w}^\mu(x) j_{\rm w}^\nu(0) \} | nn \rangle$$

$\mathcal{A}_\nu =$ 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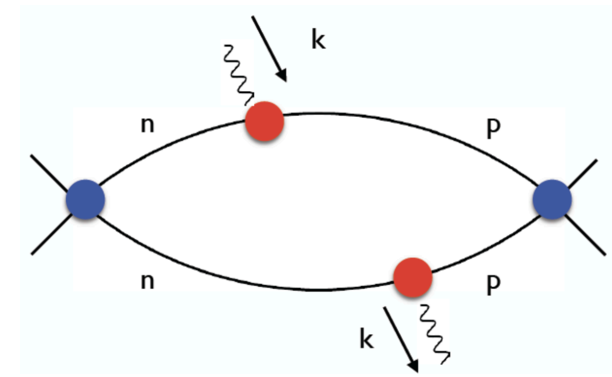
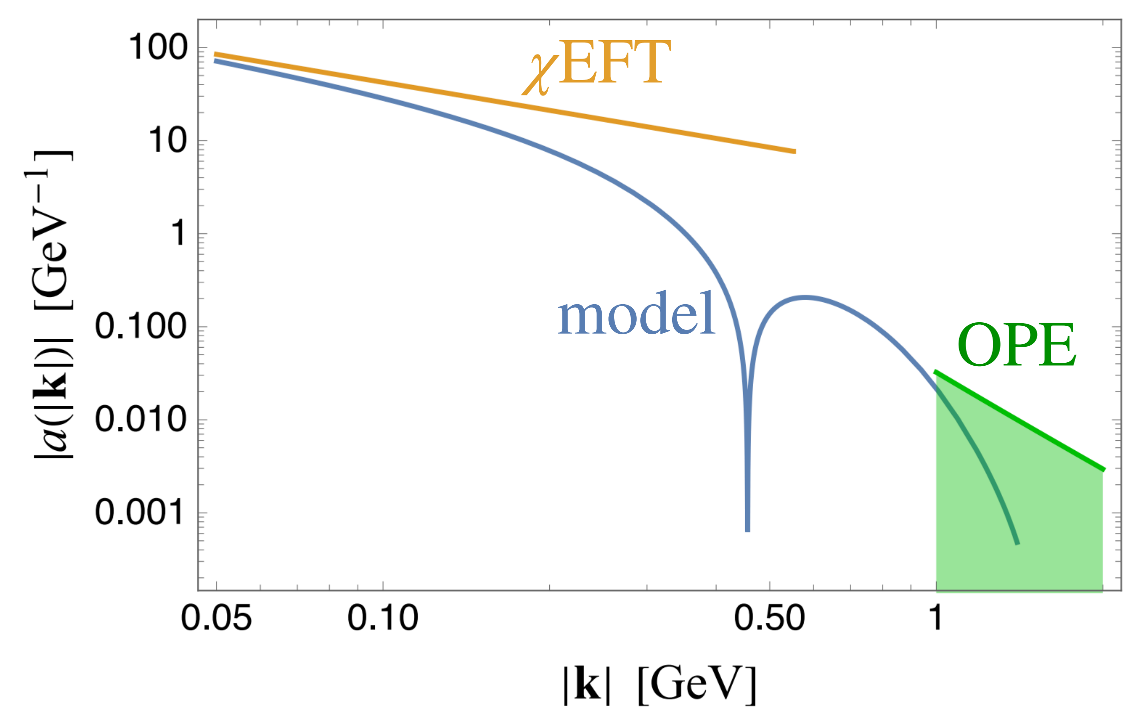



- Gives $\tilde{g}_\nu^{NN}(\mu = m_\pi) = 1.3(6)$ in $\overline{\rm MS}$

- Estimated 30% uncertainty
  - Validated in isospin-breaking observables $j_W^\mu \to j_{\rm EM}^\mu$
  - Consistent with large-Nc estimate

Richardson et al, '21

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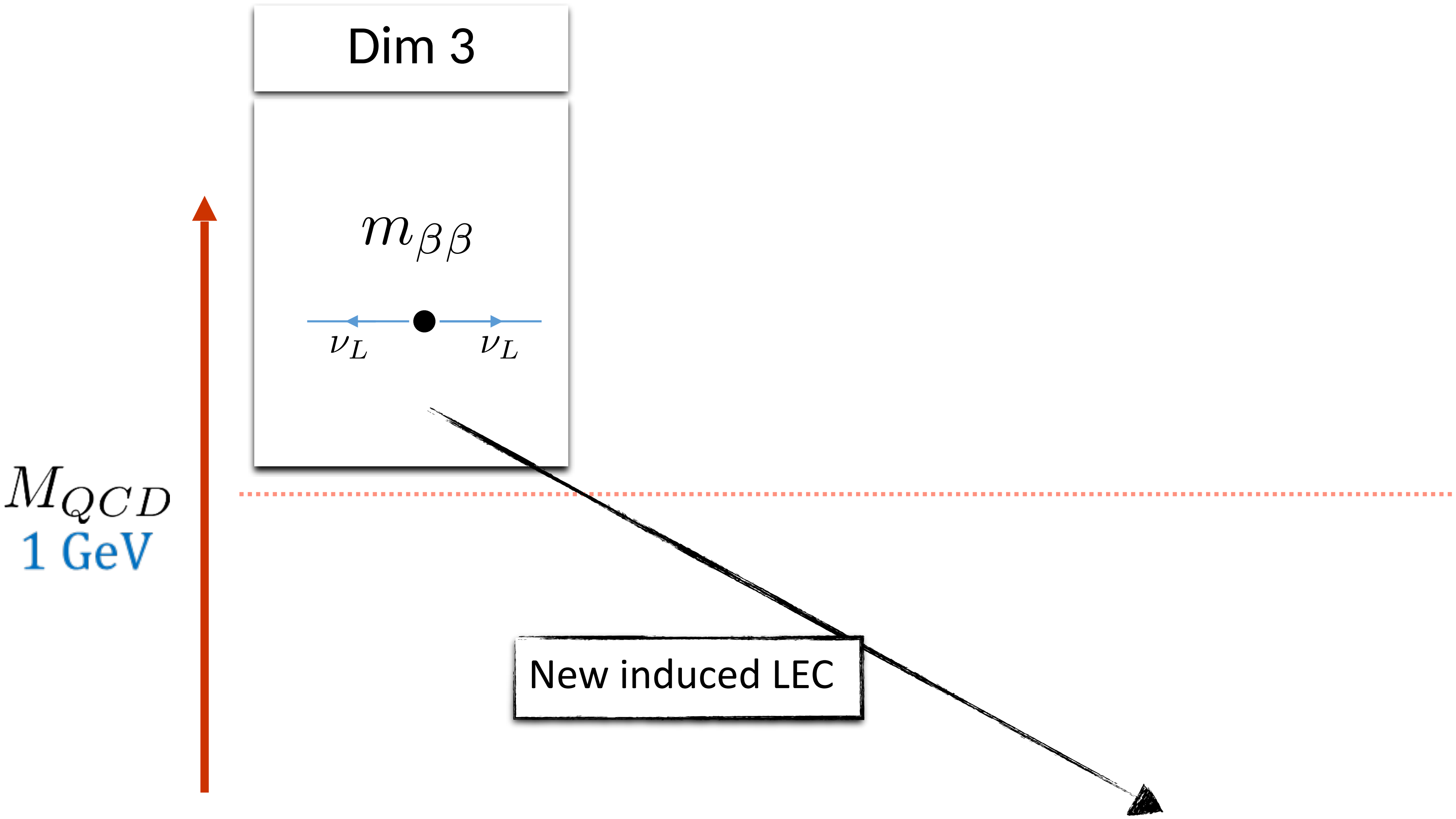
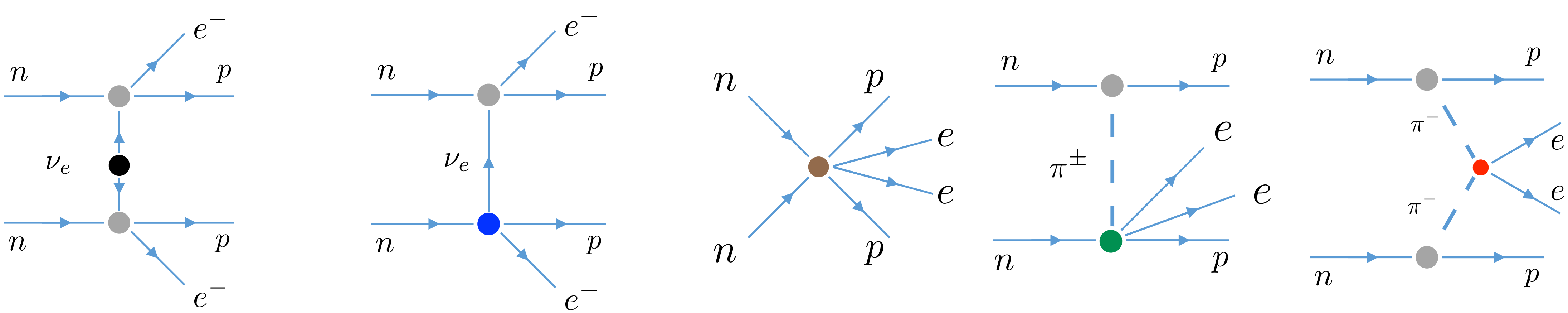
# Chiral EFT

## Non-Weinberg counting

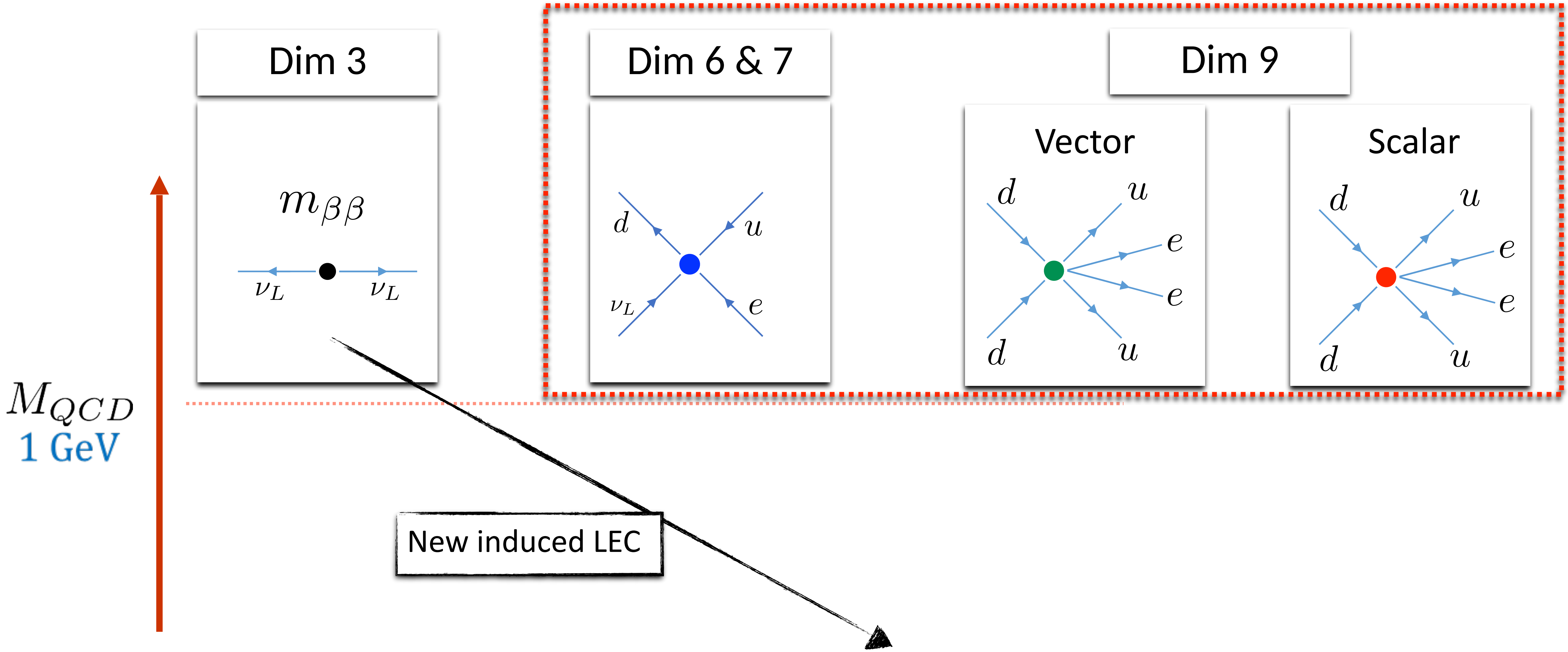



$V_{\Delta L=2} =$



# Chiral EFT

Non-Weinberg counting affects higher dimensional interactions as well

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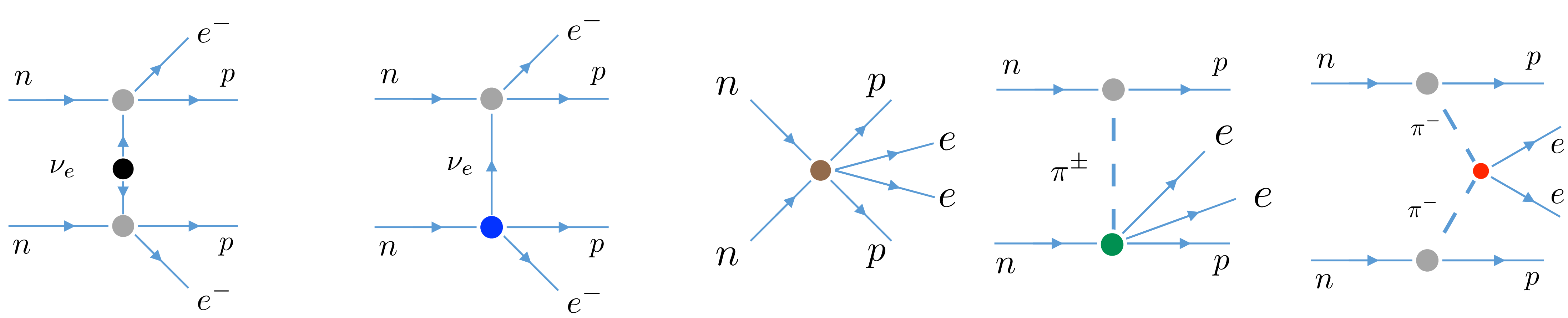

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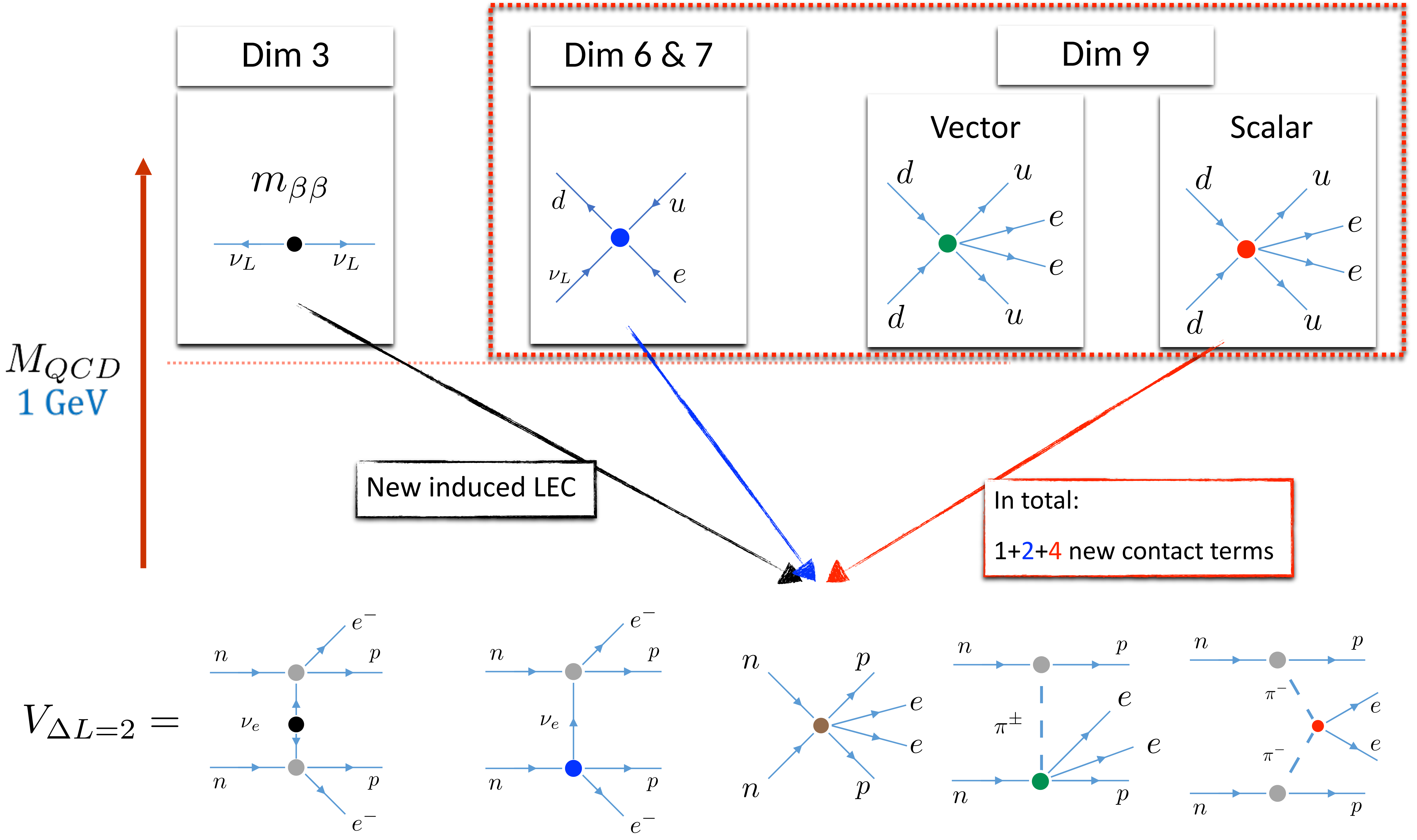
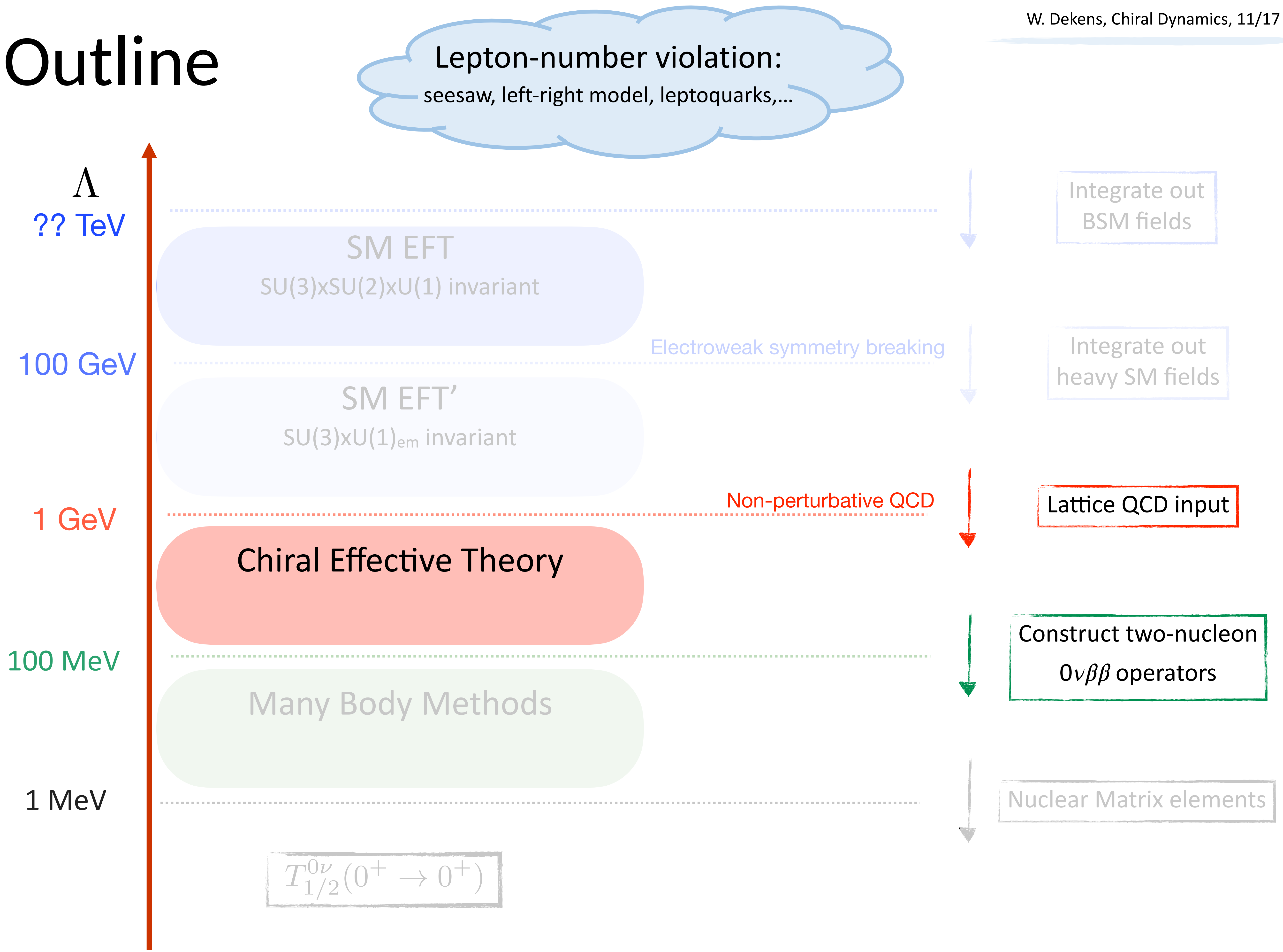


# Outline


Lepton-number violation:
seesaw, left-right model, leptoquarks,...
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100 GeV
1 GeV
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Chiral Effective Theory
Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

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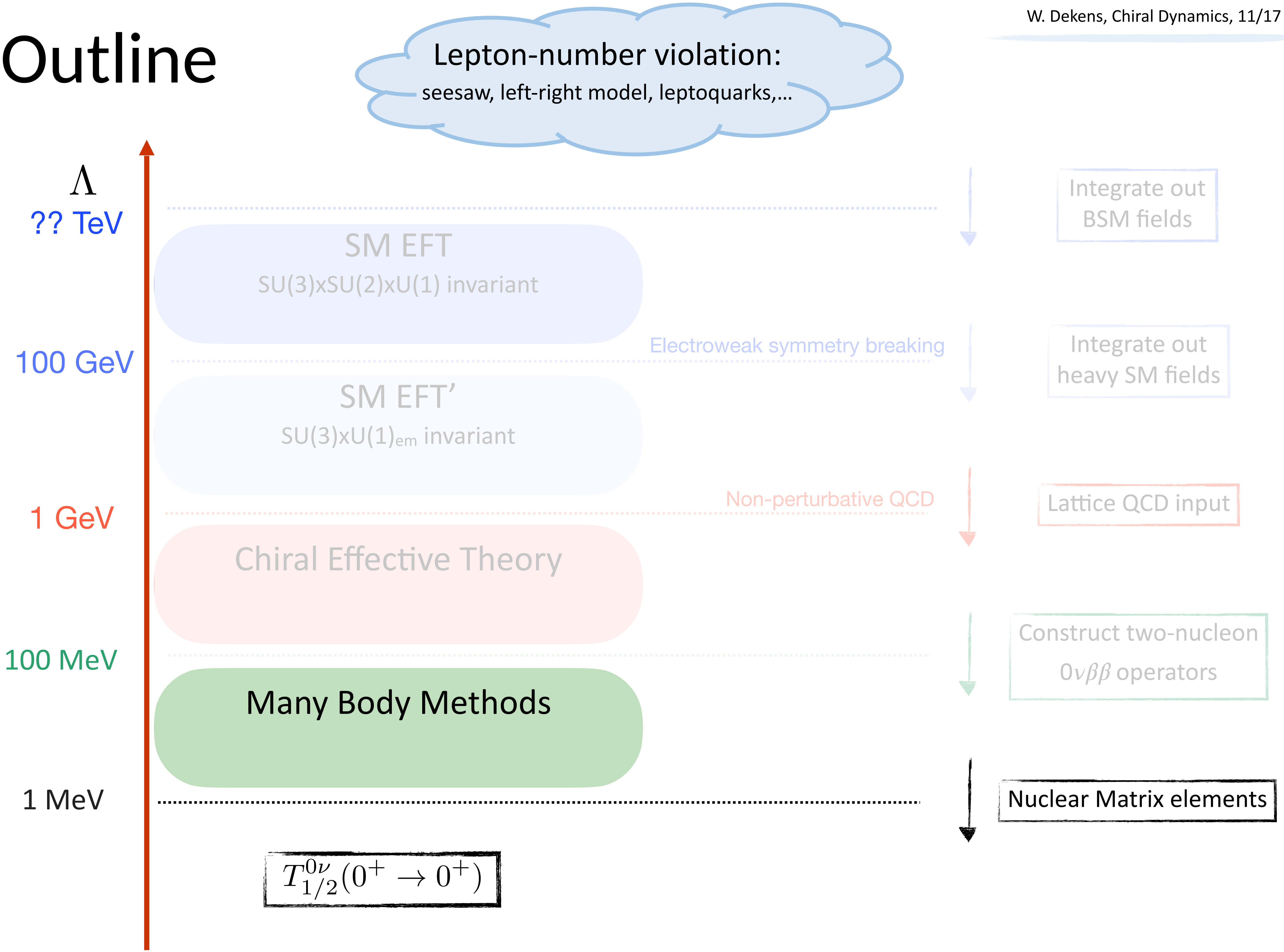
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# Nuclear matrix elements

*More complicated for $\nu_R$ with $m_{\nu_R} \sim 1$ GeV

- All NMEs can be obtained from literature*
  - 9 long-distance & 6 short-distance
  - Have been determined in literature

- Follow ChiPT expectations fairly well
  - E.g. all $O(1)$ and

$$M_{GT,sd}^{PP} = -\frac{1}{2}M_{GT,sd}^{AP} - M_{GT}^{PP}, \qquad M_{T,sd}^{PP} = -\frac{1}{2}M_{T,sd}^{AP} - M_{T}^{PP},$$

$$M_{GT,sd}^{AP} = -\frac{2}{3}M_{GT,sd}^{AA} - M_{GT}^{AP}, \qquad M_{GT}^{MM} = \frac{g_M^2 m_\pi^2}{6 g_A^2 m_N^2} M_{GT,sd}^{AA},$$

| NMEs | $^{76}$Ge | | | |
|---|---|---|---|---|
| | [74] | [31] | [81] | [82, 83] |
| $M_F$ | -1.74 | -0.67 | -0.59 | -0.68 |
| $M_{GT}^{AA}$ | 5.48 | 3.50 | 3.15 | 5.06 |
| $M_{GT}^{AP}$ | -2.02 | -0.25 | -0.94 | |
| $M_{GT}^{PP}$ | 0.66 | 0.33 | 0.30 | |
| $M_{GT}^{MM}$ | 0.51 | 0.25 | 0.22 | |
| $M_{T}^{AA}$ | – | – | – | |
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| NMEs | $^{76}$Ge | | | |
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| $M_{GT,\,sd}^{PP}$ | 1.99 | 0.85 | 0.82 | 0.42 |
| $M_{T,\,sd}^{AP}$ | -0.85 | 0.01 | -0.05 | -0.97 |
| $M_{T,\,sd}^{PP}$ | 0.32 | 0.00 | 0.02 | 0.38 |

Barea et al. '15; Hyvarinen et al, '15; Horoi et al. '17, Menendez et al, '18

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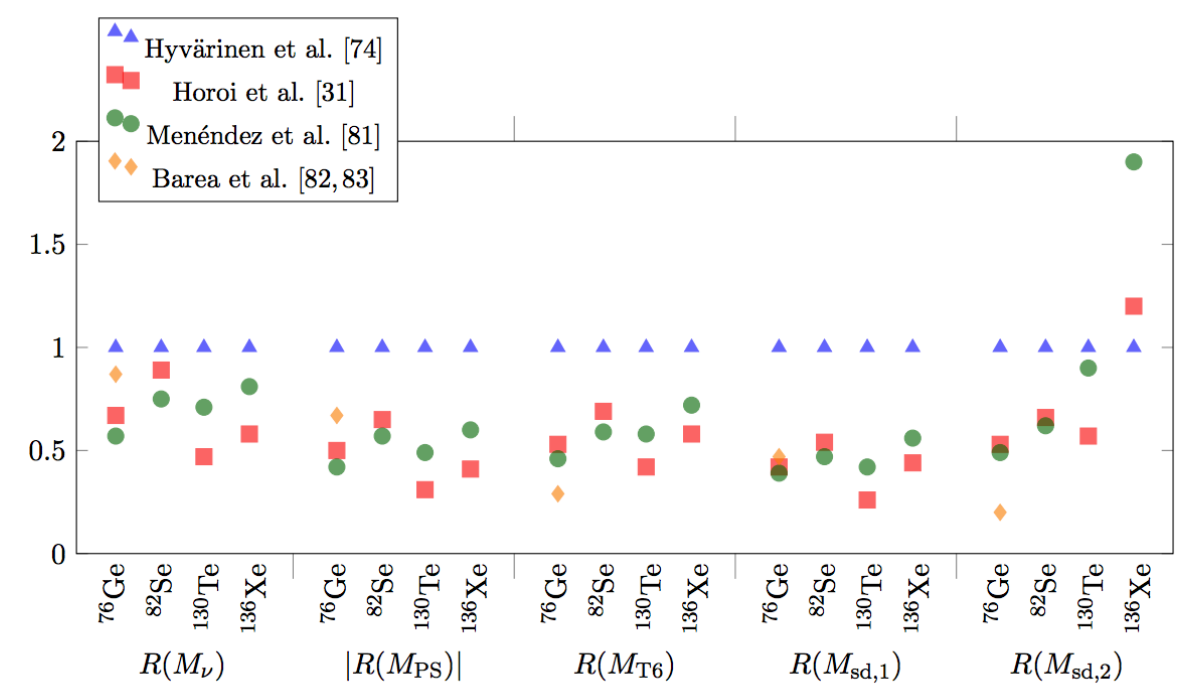
- The NMEs differ by a factor 2-3 between methods
  - For Majorana-mass term & other LNV sources




- *Ab initio* NMEs for $A \geq 48$ are starting to appear
  - e.g. Belley et al '20; Yao et al '20; Wirth, Yao, Hegert '21

Barea et al. '15; Hyvarinen et al, '15; Horoi et al. '17, Menendez et al, '18

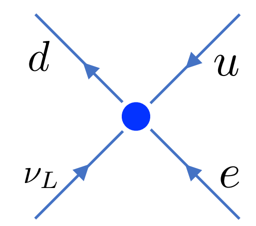
# Phenomenology

# Phenomenology

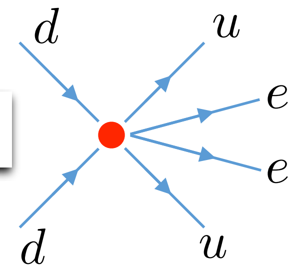


## From heavy new physics

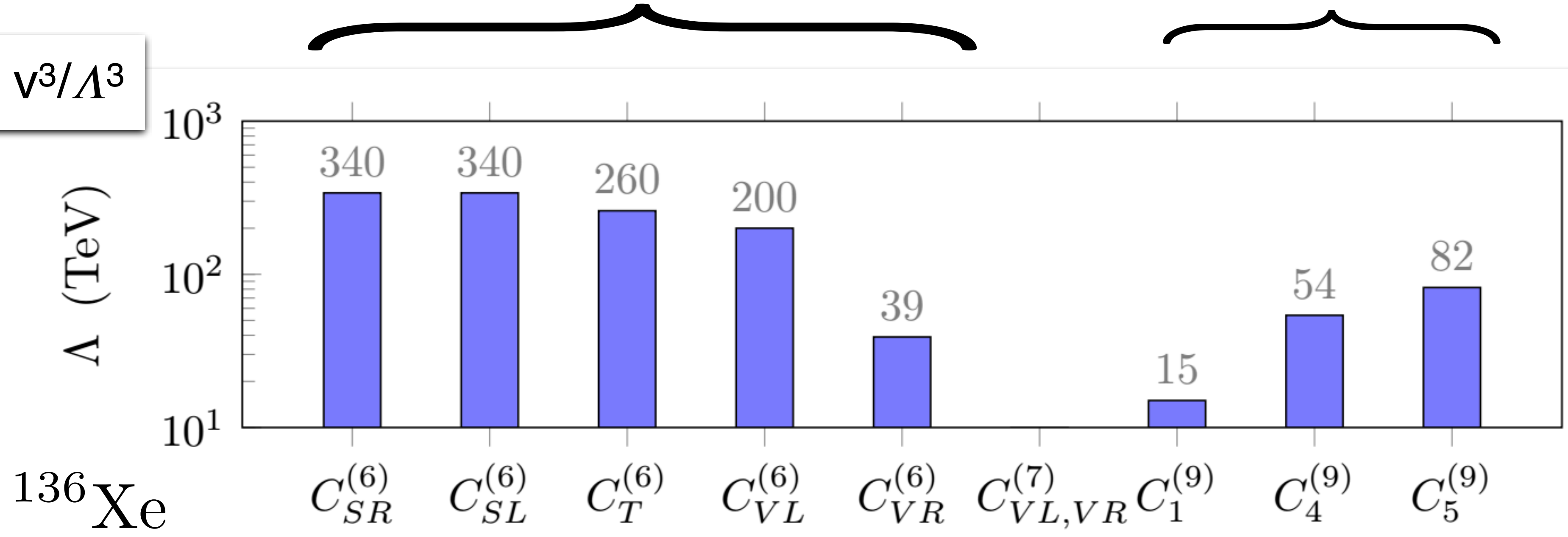
Dim 6 & 7




Dim 9




- Couplings with $C_i \sim v^3/\Lambda^3$



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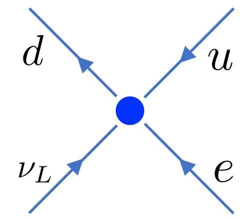


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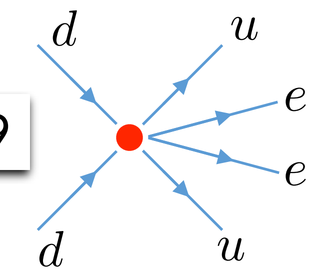


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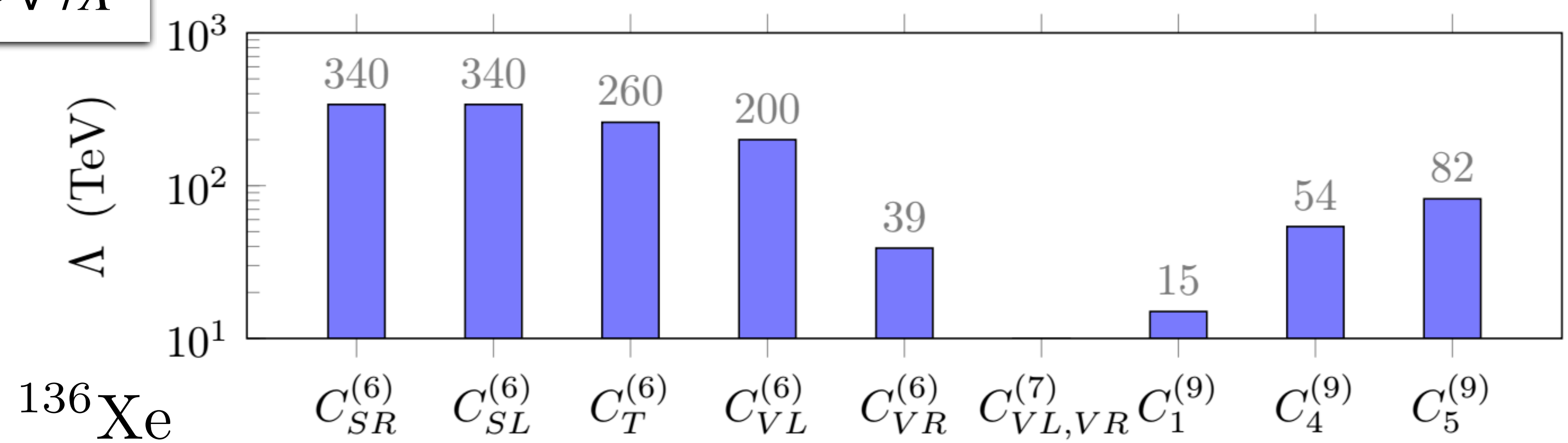
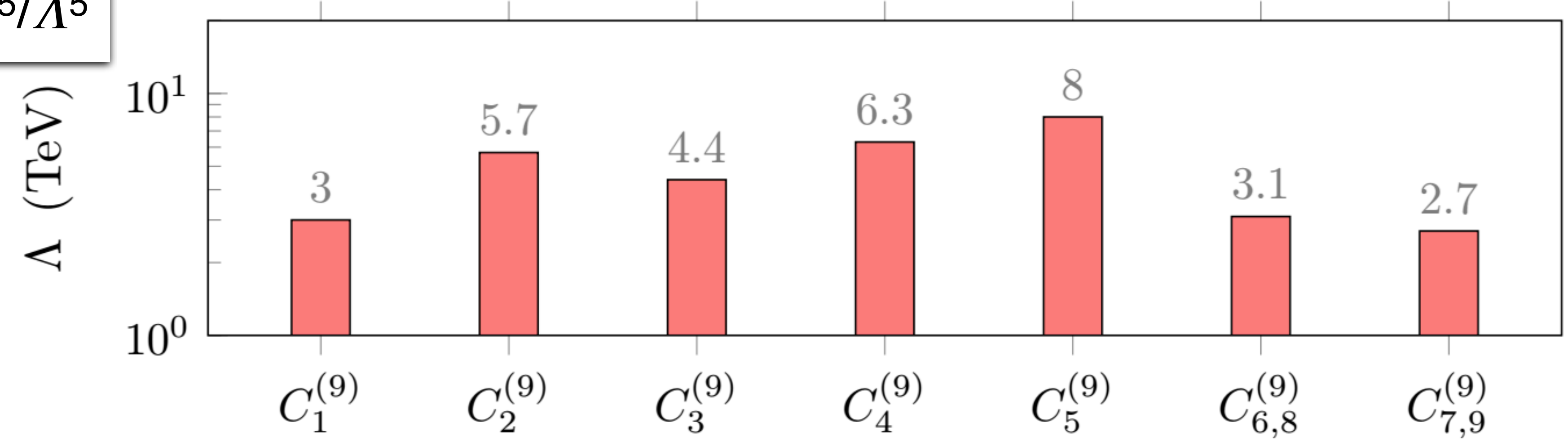



- Couplings with $C_i \sim v^5/\Lambda^5$

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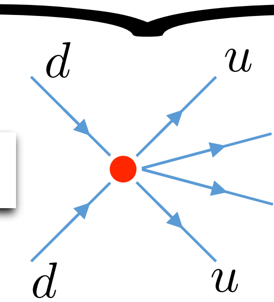

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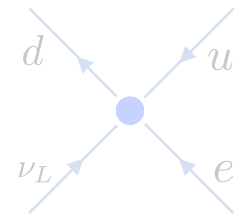


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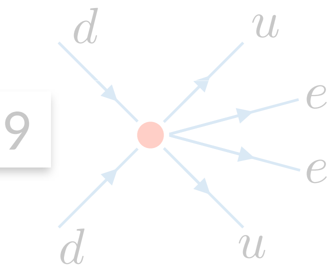


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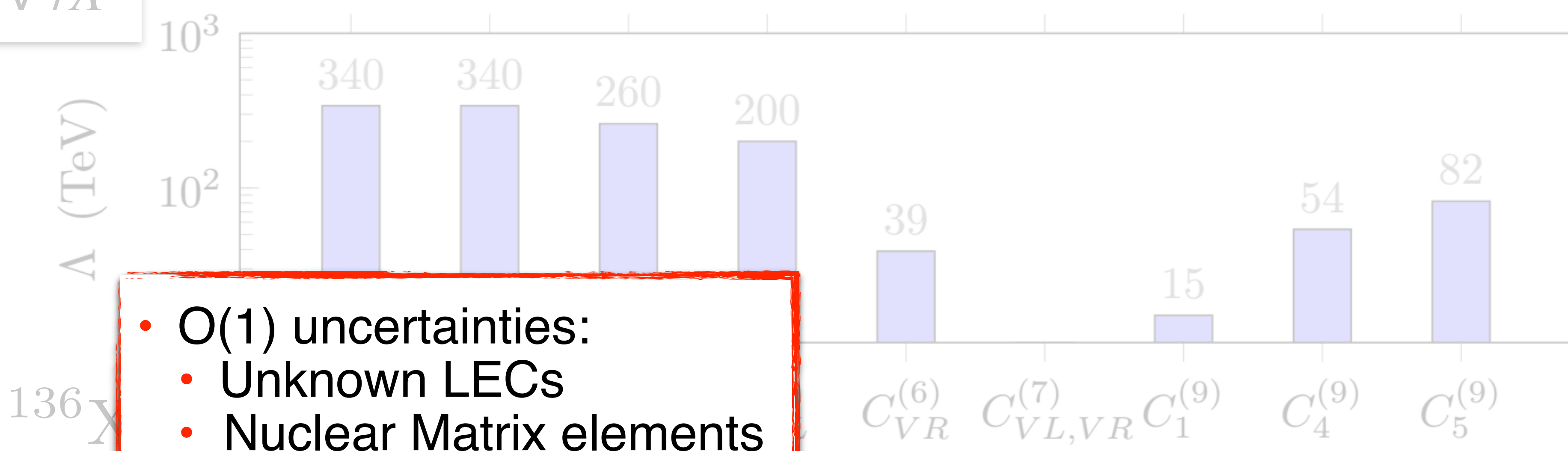
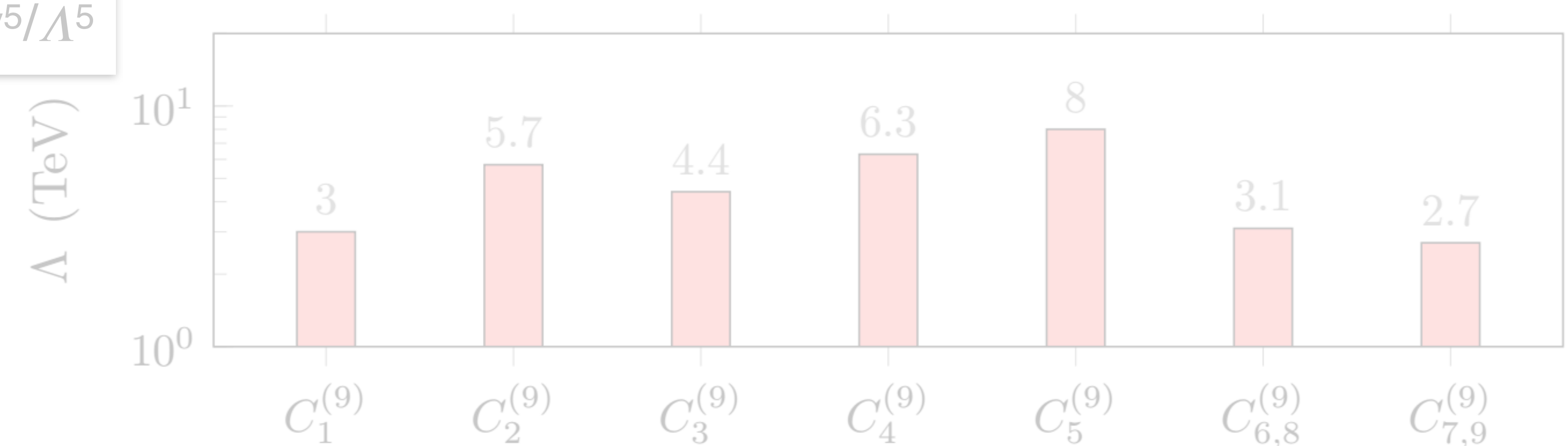



- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

- Couplings with $C_i \sim v^5/\Lambda^5$

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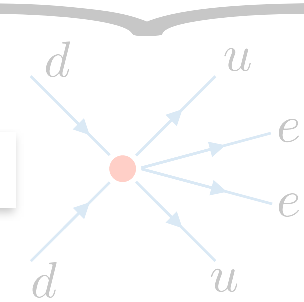


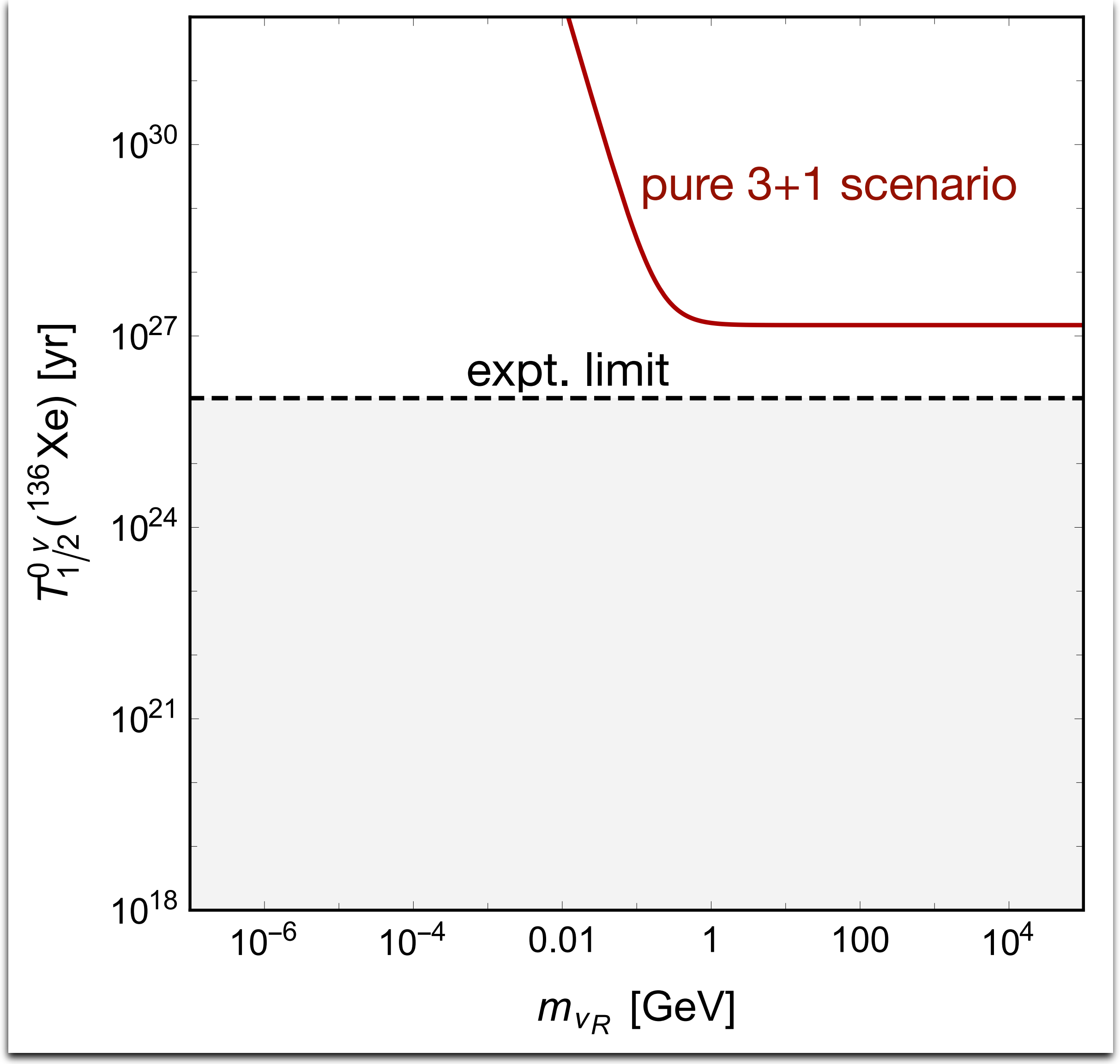
# Phenomenology

## From heavy new physics + light $\nu_R$

Example with $\nu_R$

O(100%) uncertainties not shown

- Toy Model
  - SM + 1 light $\nu_R$



# Phenomenology



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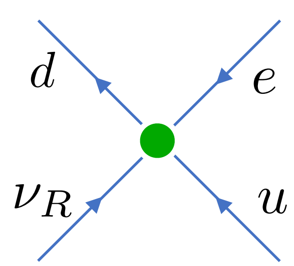
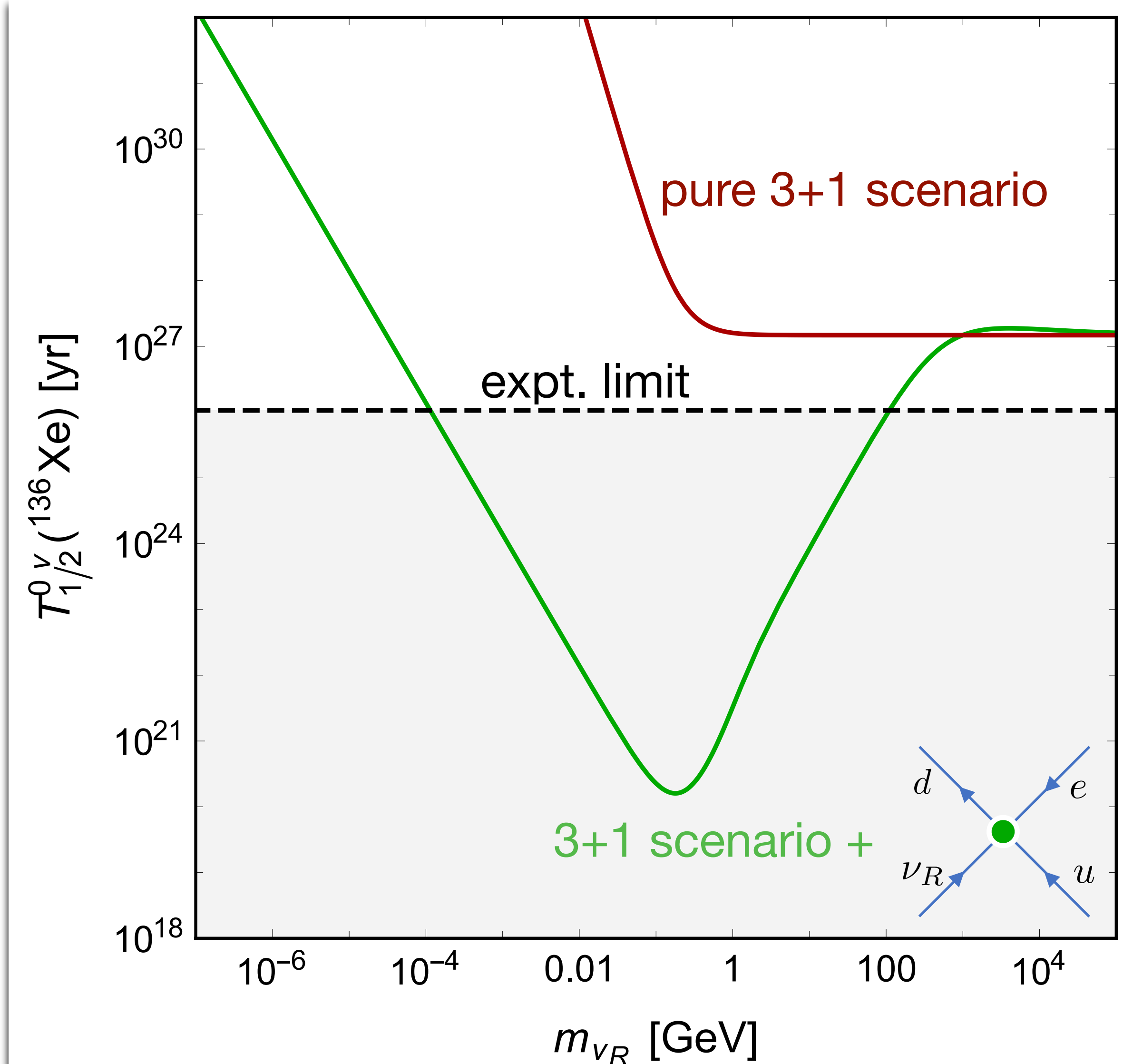
- Added dimension-six interaction
  - SM + 1 light $\nu_R$ +




$\Lambda = 10\,\mathrm{TeV}$



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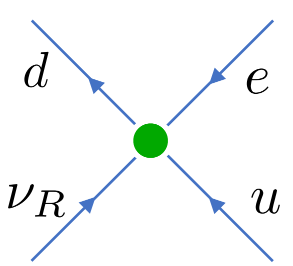


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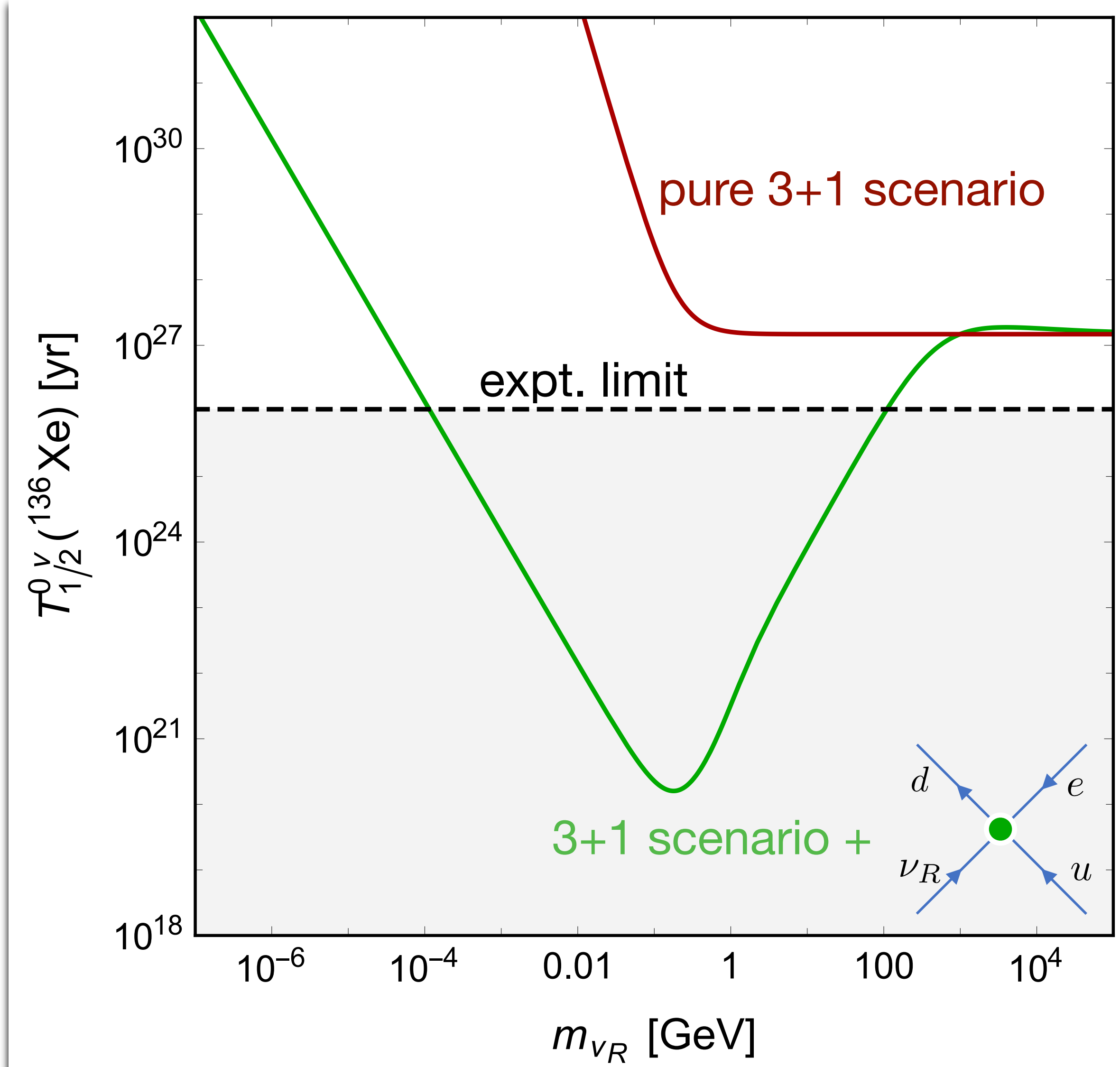
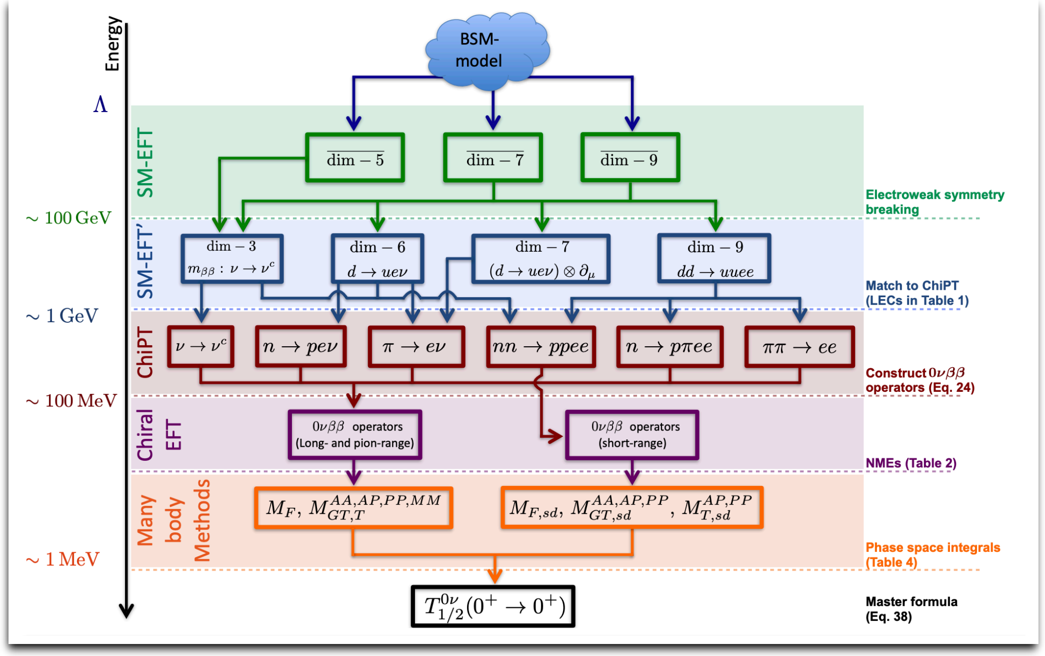



- Higher dimensional $\nu_R$ terms can have a large impact!

# Summary



- EFTs allow one to systematically describe ΔL=2 sources
  - Standard mechanism (dim-5)
  - Dimension-7 & -9 sources
  - Effects from $\nu_R$



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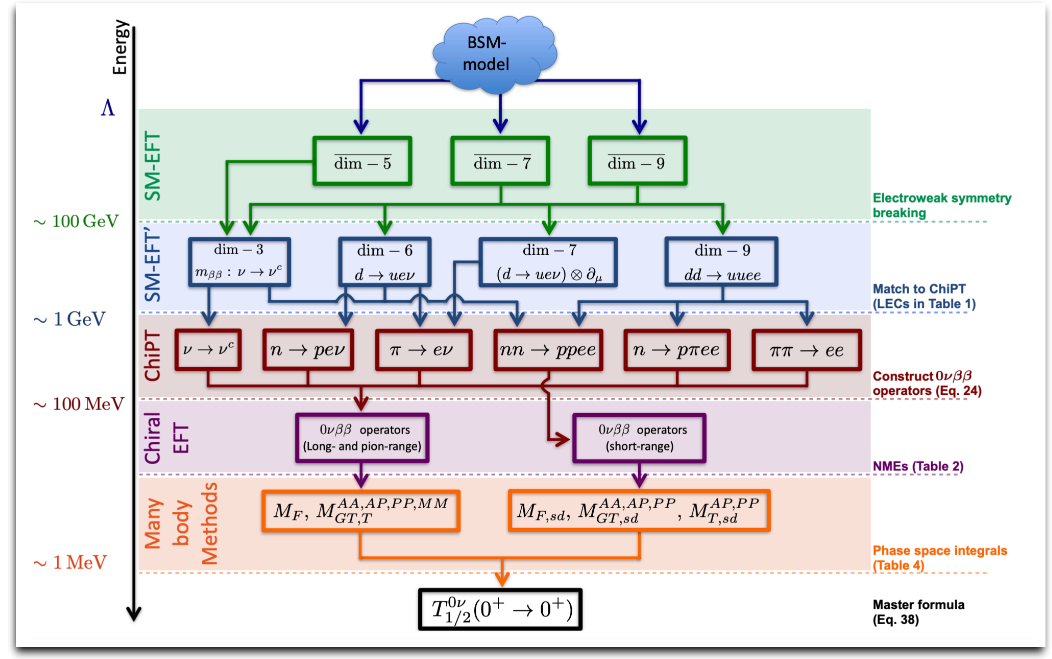
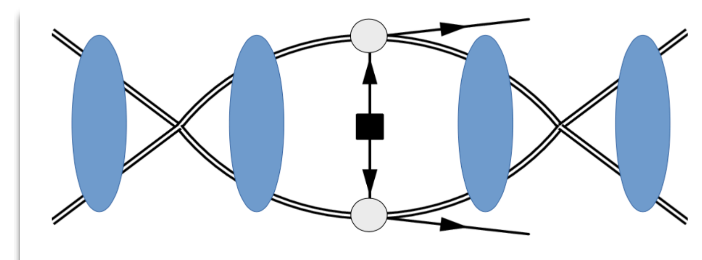
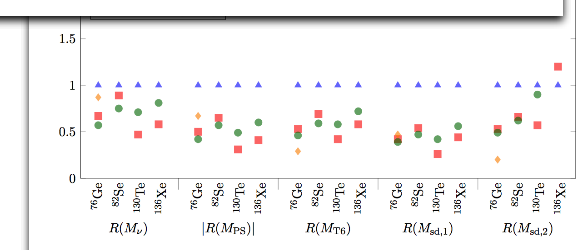



- Matching to chiral EFT involves unknown LECs
  - Renormalization requires terms beyond Weinberg counting
    - Can in principle be determined from LQCD
- Needed Nuclear Matrix Elements determined in literature
  - Effect of 'new' LECs up to ~60% in light nuclei





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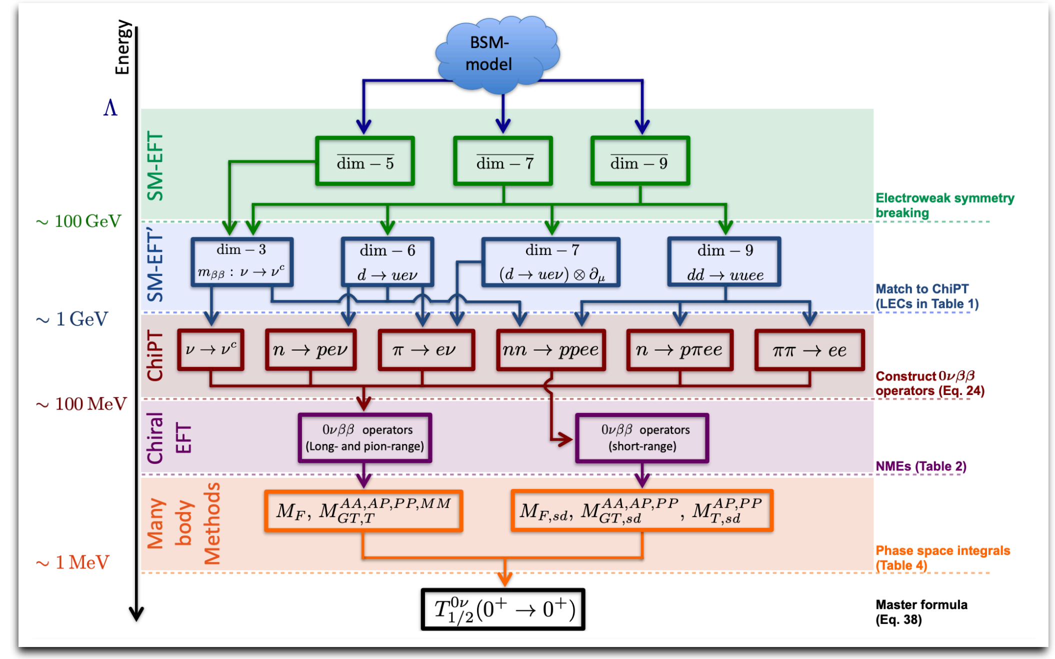


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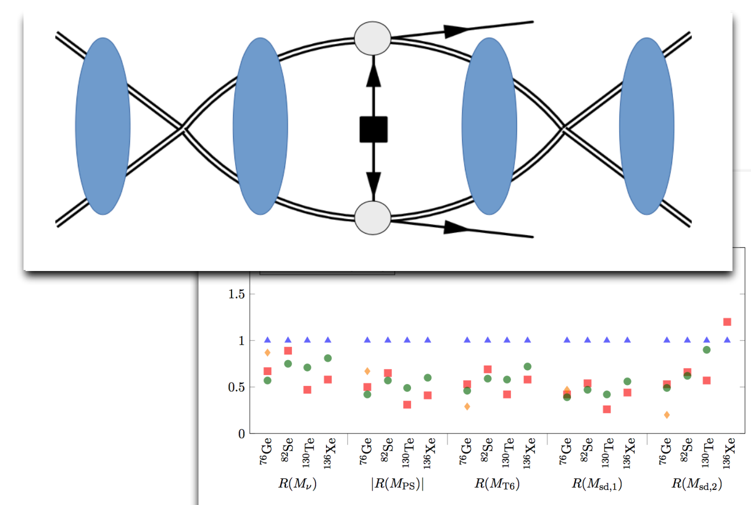
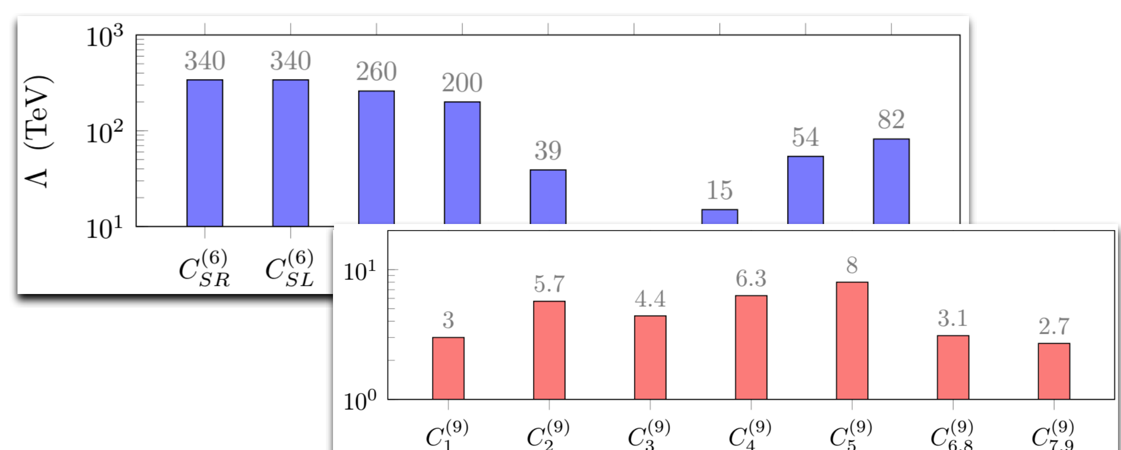



- $0\nu\beta\beta$ can probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
  - O(10) TeV scales for $\nu_R$ interactions




- Order 1 LECs + NMEs uncertainties