Parity Violation: The Standard Model & Beyond

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U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

MITP PV Workshop
Mainz, May 2018

Goals for This Talk

- ***Standard Model physics**: outline two open problems to interpretation of low-energy fundamental symmetry tests:*
    - *EFT in nuclei*
    - *EW boxes w/ nuclei*
- ***BSM physics**: illustrate complementarity of low-energy symmetry tests & energy frontier probes*
    - *Origin of m_ν*
    - *Leptoquark interactions*
- *Tie together workshop topics, show preliminary results & invite discussion*

Four Components

Hadronic Parity Violation *Effective field theory: applicable in nuclei ?*	*EW boxes:* *Interpretation of precision tests w/ nuclei*
$0\nu\beta\beta$ decay searches: *Nature of neutrino, Lepton number violation, origin of matter, origin of m_ν*	*PV electron scattering & β decay* *Indirect BSM probes & LHC complementarity*

Four Components

EFT in nuclei ?

Hadronic Parity Violation

Effective field theory: applicable in nuclei ?

EW boxes:

Interpretation of precision tests w/ nuclei

$0\nu\beta\beta$ decay searches:

Nature of neutrino, Lepton number violation, origin of matter, origin of m_ν

PV electron scattering & β decay

Indirect BSM probes & LHC complementarity

Four Components

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EW boxes in nuclei

Four Components

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Four Components

Hadronic Parity Violation *Effective field theory: applicable in nuclei ?*	*EW boxes:* *Interpretation of precision tests w/ nuclei*
$0\nu\beta\beta$ *decay searches:* *Nature of neutrino, Lepton number violation, origin of matter, origin of* m_ν	*PV electron scattering &* β *decay* *Indirect BSM probes & LHC complementarity*

Leptoquarks: weak decays, EDMs LHC

Outline

I. Hadronic PV & $0\nu\beta\beta$ decay: EFT in nuclei

II. EW boxes

III. PVES & m_ν

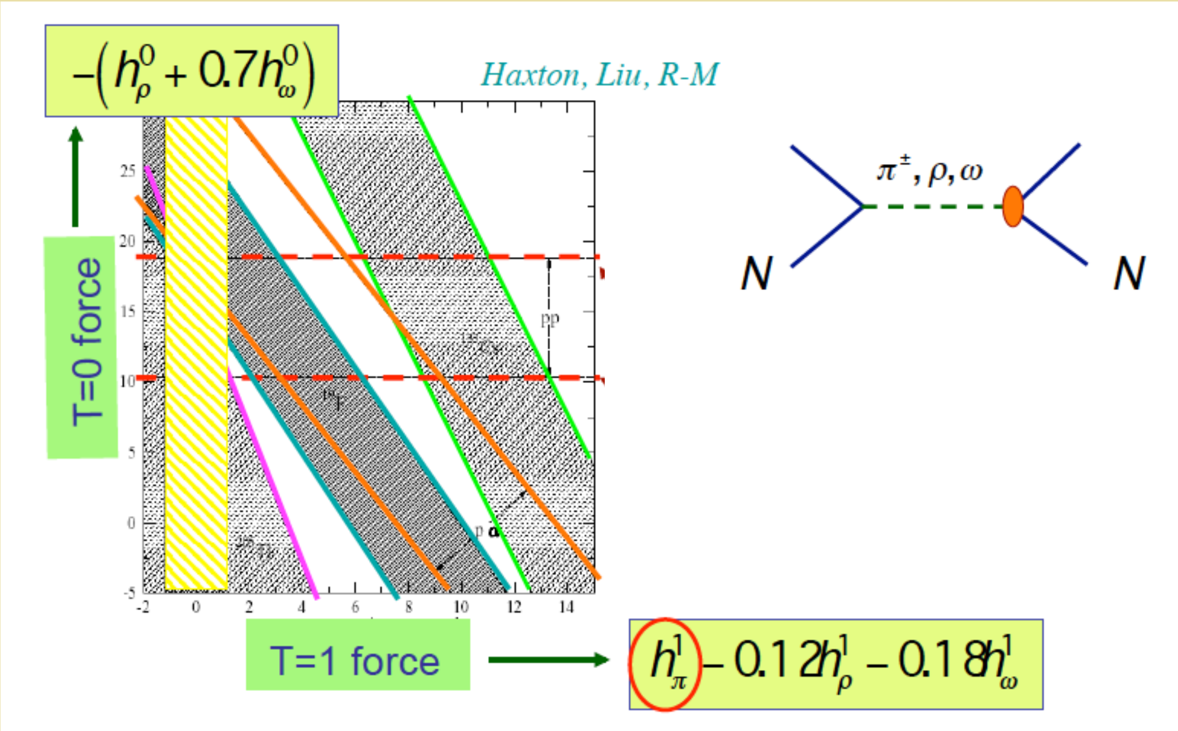
IV. Leptoquarks

V. Outlook

I. SM Interpretation: HWI in Nuclei

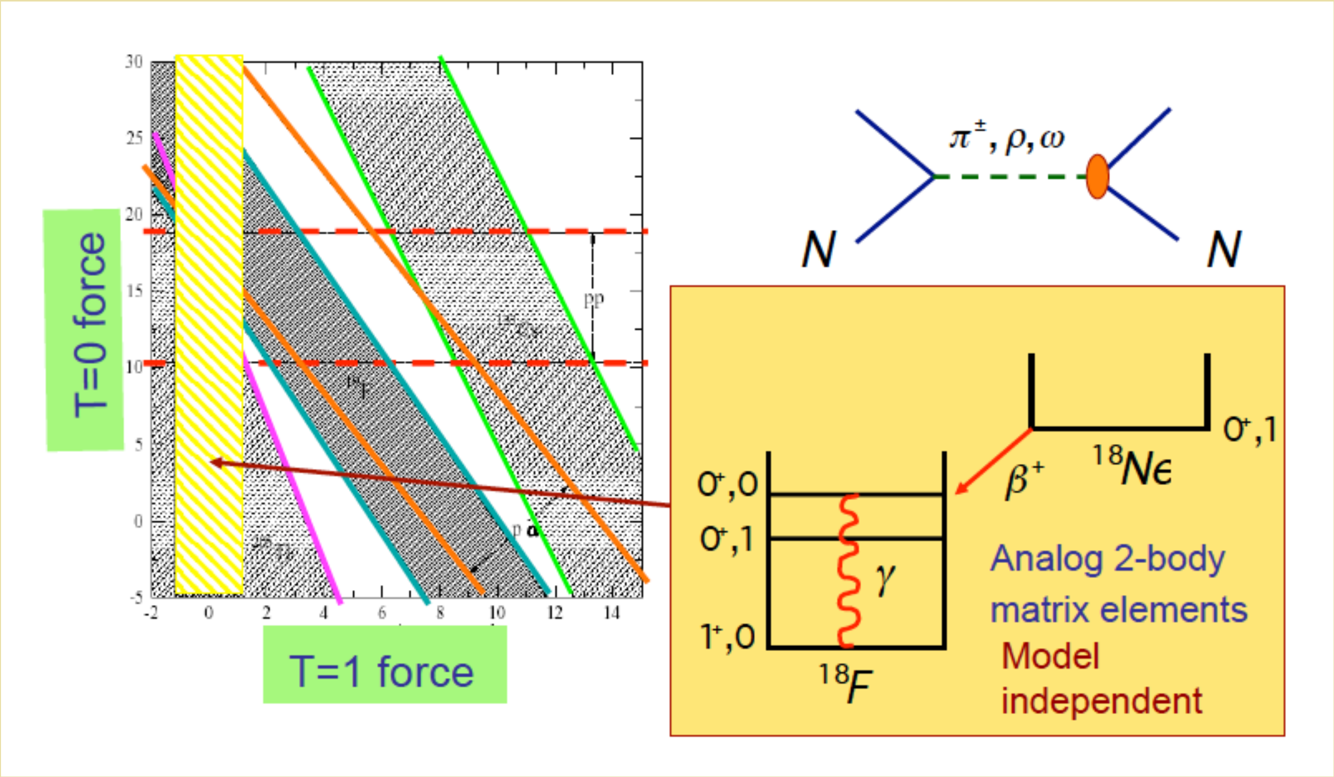
T. Peng, G. Prezeau, MRM,
P. Vogel, P. Winslow

Hadronic PV



$-\left(h_\rho^0 + 0.7h_\omega^0\right)$
Haxton, Liu, R-M
T=0 force
T=1 force
$h_\pi^1 - 0.12h_\rho^1 - 0.18h_\omega^1$
$\pi^\pm, \rho, \omega$
N
N
pp

Hadronic PV


T=0 force
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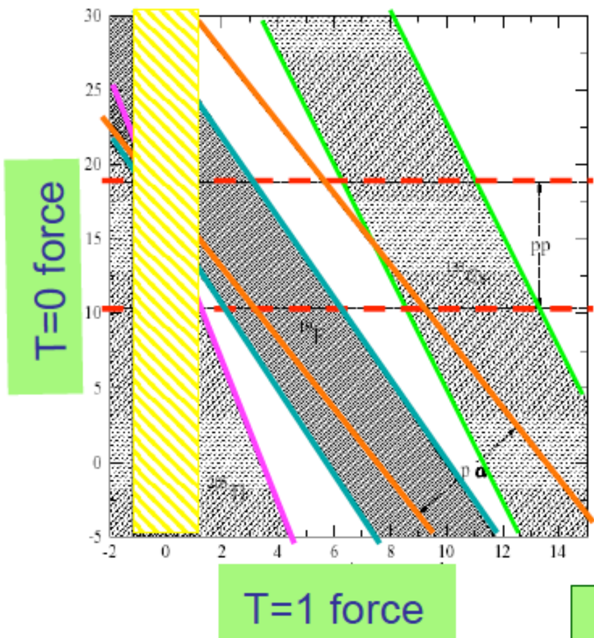
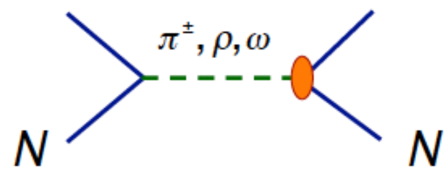
$\pi^{\pm}, \rho, \omega$
N
N
0+,1
^{18}Ne
β^+
0+,0
0+,1
γ
1+,0
^{18}F
Analog 2-body
matrix elements
Model
independent

Hadronic PV





- Problem with expt' s
- Problem with nuc th' y
- Problem with model
- No problem (1σ)

EFT

Hadronic PV

$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0} \sim N_c$$

$$\Lambda_2^{^1S_0-^3P_0} \sim N_c,$$

$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0} \sim 1/N_c$$

$$\Lambda_1^{^1S_0-^3P_0} \sim \sin^2\theta_w$$

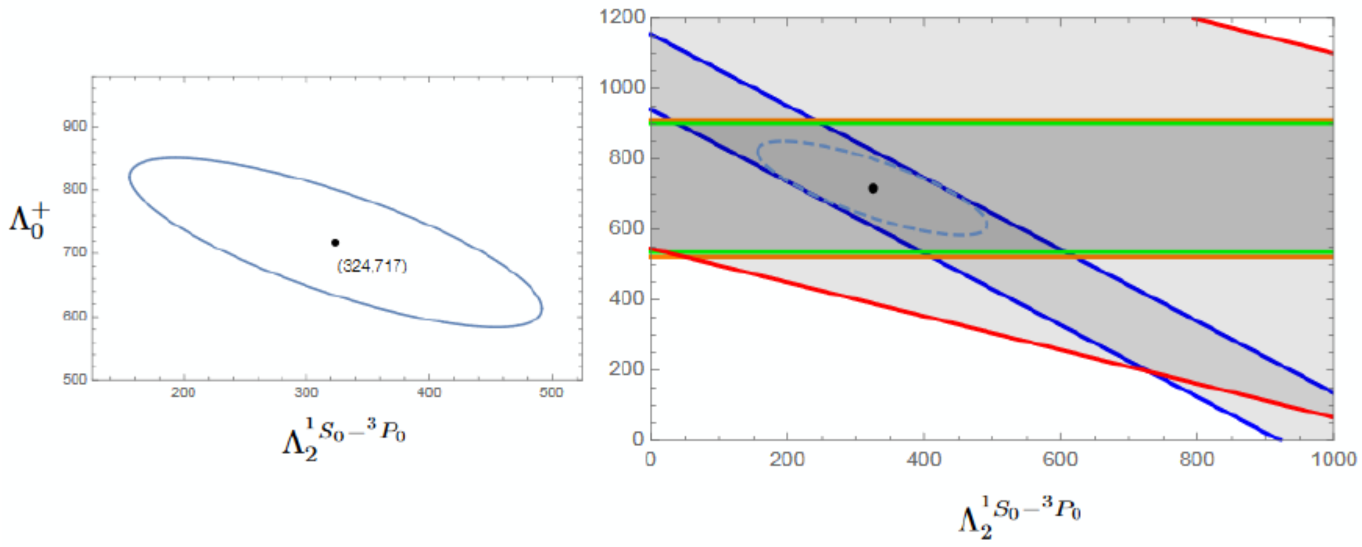
$$\Lambda_1^{^3S_1-^3P_1} \sim \sin^2\theta_w.$$

- *B. Holstein, this workshop*
- *Gardner, Haxton, Holstein '17*

$$\begin{aligned}
\frac{2}{5}\Lambda_0^+ + \frac{1}{\sqrt{6}}\Lambda_2^{^1S_0-^3P_0} + \left[-\frac{6}{5}\Lambda_0^- + \Lambda_1^{^1S_0-^3P_0}\right] &= 419 \pm 43 && A_L(\vec{\mathrm{p}}\mathrm{p}) \\
1.3\Lambda_0^+ + \left[-0.9\Lambda_0^- + 0.89\Lambda_1^{^1S_0-^3P_0} + 0.32\Lambda_1^{^3S_1-^3P_1}\right] &= 930 \pm 253 && A_L(\vec{\mathrm{p}}\alpha) \\
\left[|2.42\Lambda_1^{^1S_0-^3P_0} + \Lambda_1^{^3S_1-^3P_1}|\right] &< 340 && P_\gamma(^{18}\mathrm{F}) \\
0.92\Lambda_0^+ + \left[-1.03\Lambda_0^- + 0.67\Lambda_1^{^1S_0-^3P_0} + 0.29\Lambda_1^{^3S_1-^3P_1}\right] &= 661 \pm 169 && A_\gamma(^{19}\mathrm{F})
\end{aligned}$$

Hadronic PV

New and "improved" plot:



Hadronic PV: Few vs. Many-Body

Complete determination of PV NN & γNN interactions through $\mathcal{O}$(p)

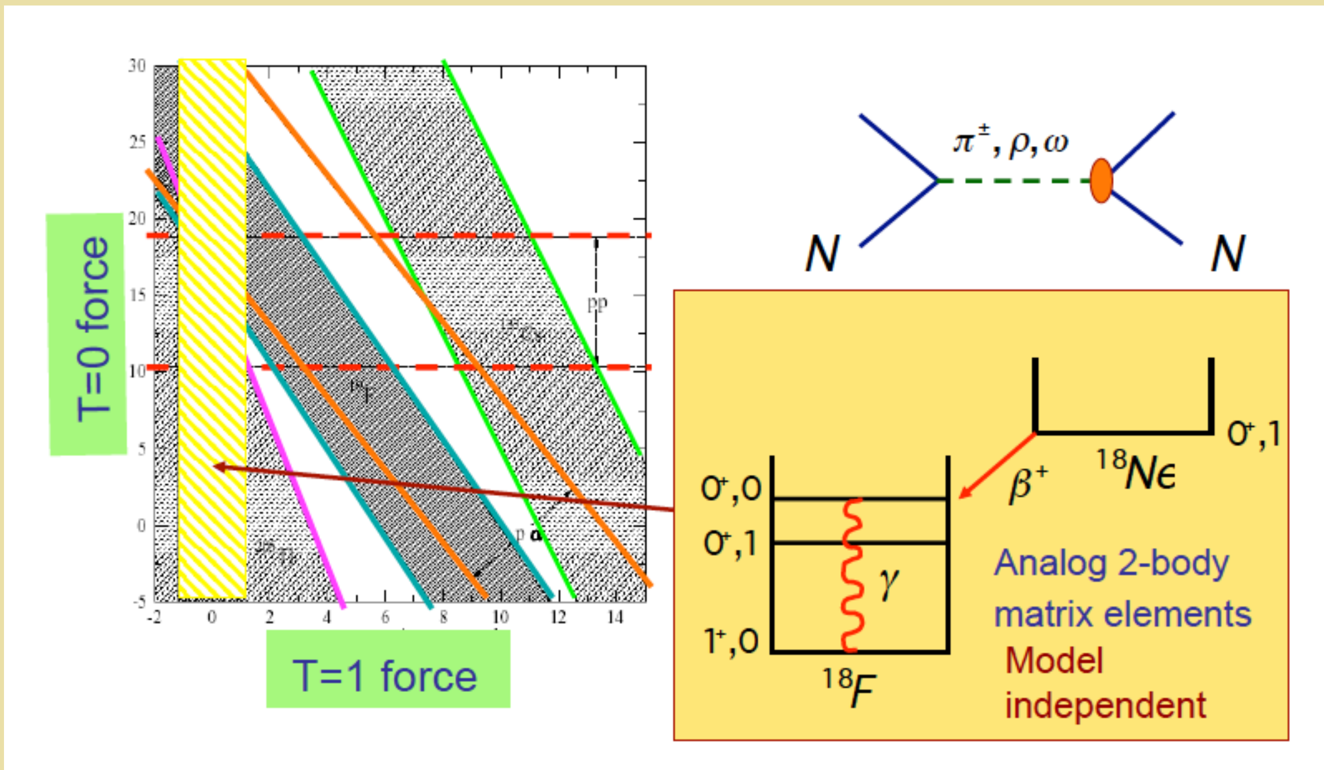
Attempt to understand the λ^i, h_π *etc.* from QCD

Attempt to understand *nuclear* PV observables systematically

Are the PV LEC's "natural"?

Does EFT power counting work in nuclei ?

Hadronic PV



T=0 force
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π±, ρ, ω
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18F
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Analog 2-body
matrix elements
Model
independent

EFT in Nuclei: HPV

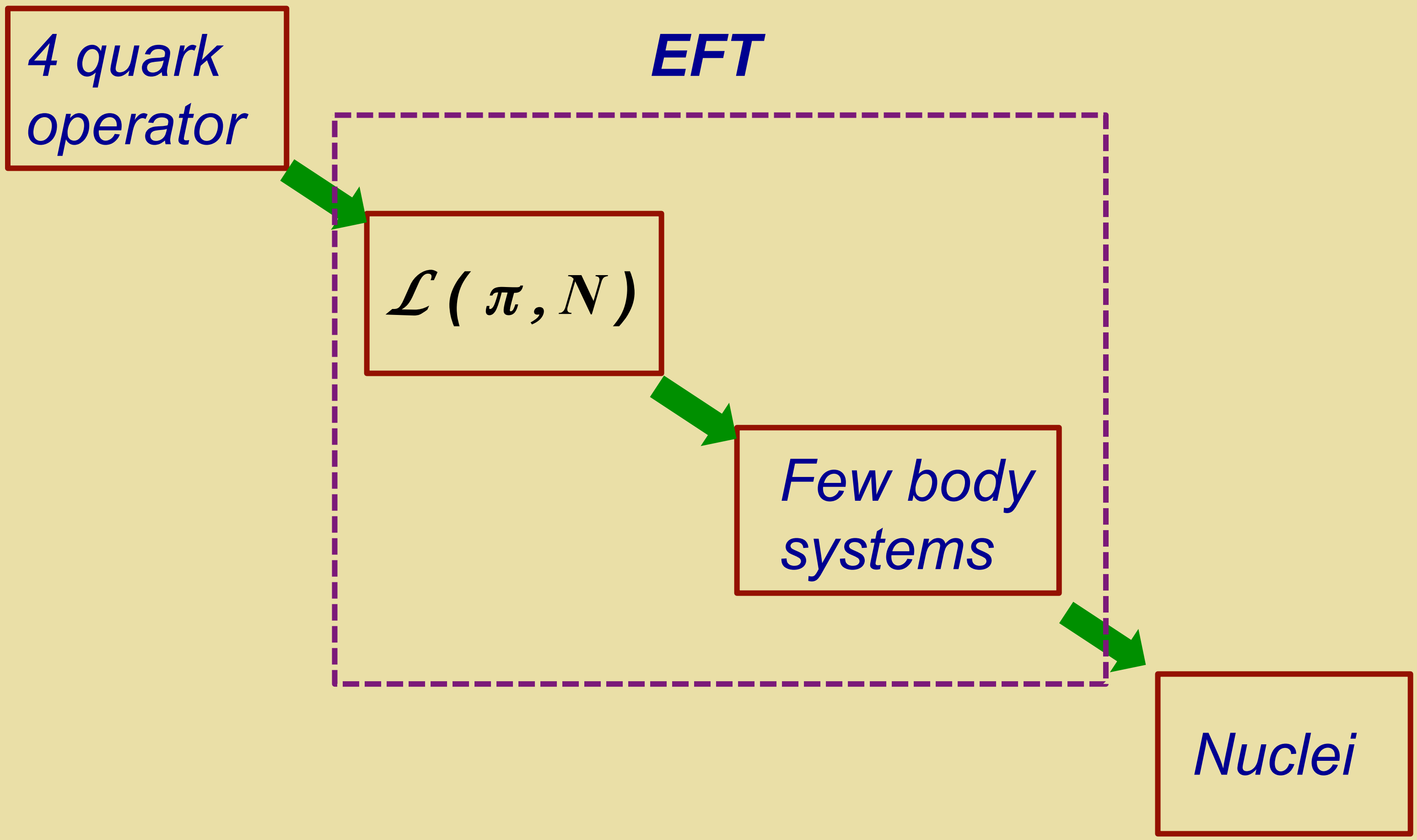
4 quark operator

$\mathcal{L}(\pi, N)$

Few body systems

Nuclei

EFT in Nuclei: HPV



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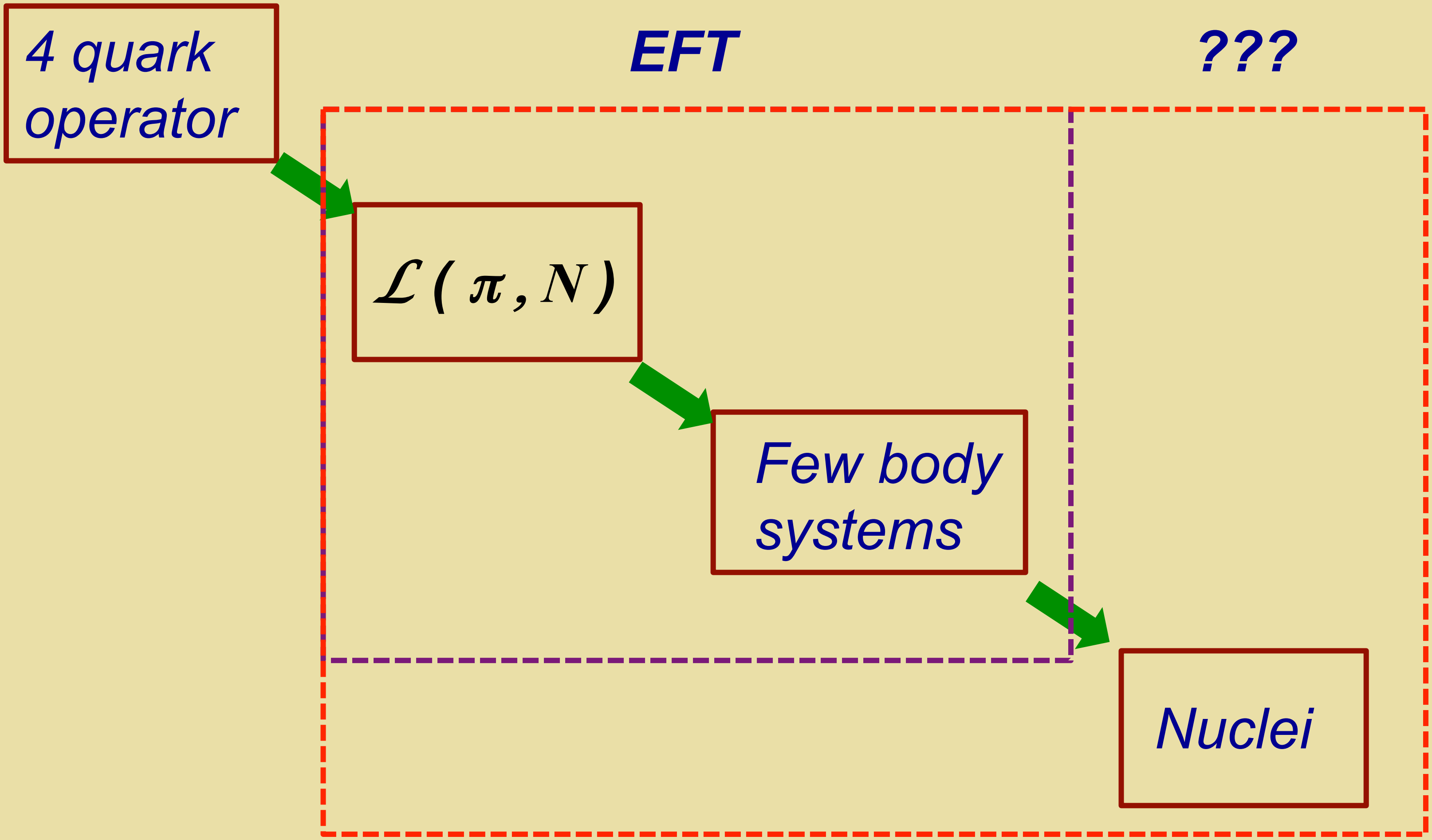
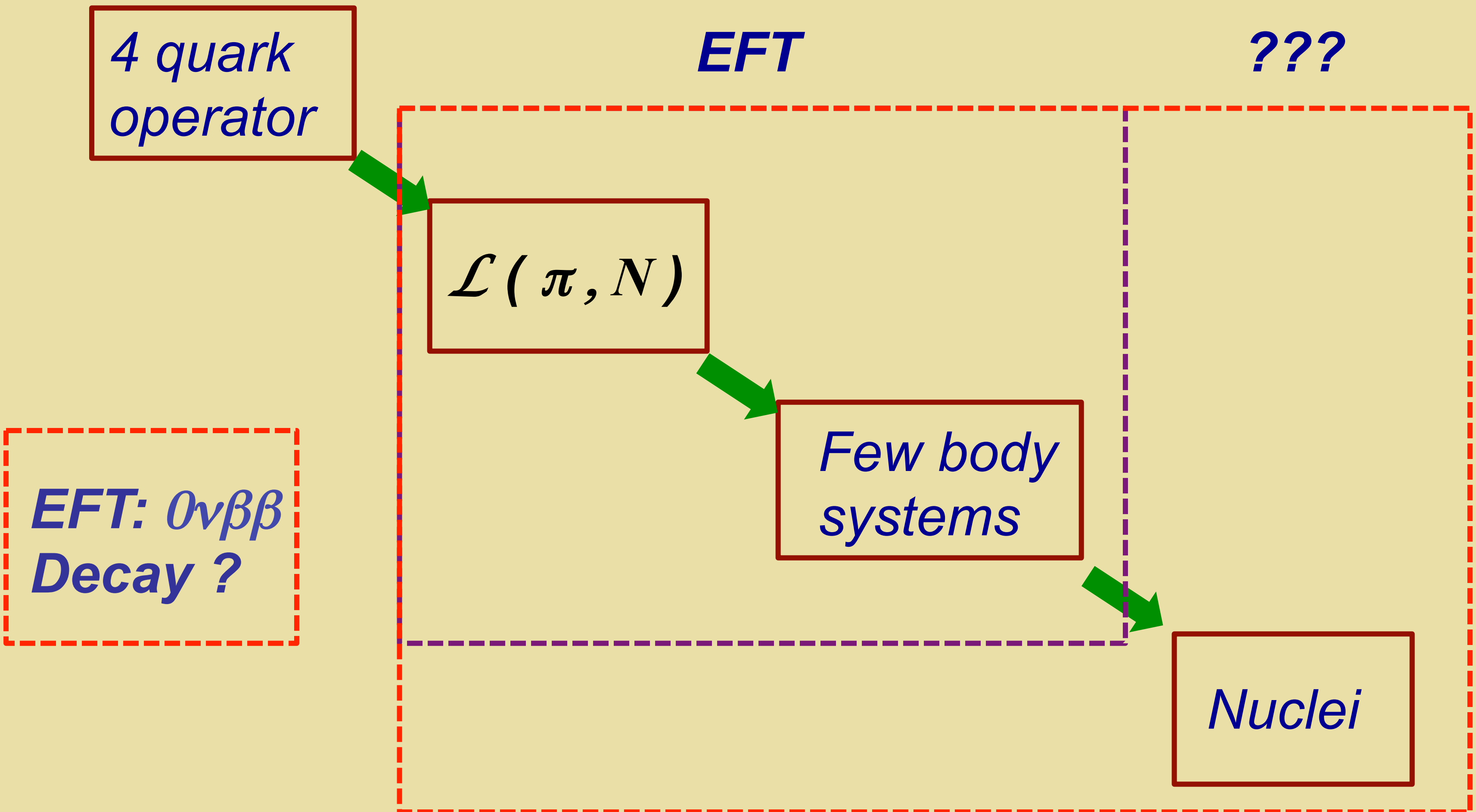


EFT in Nuclei: HPV & $0\nu\beta\beta$ Decay



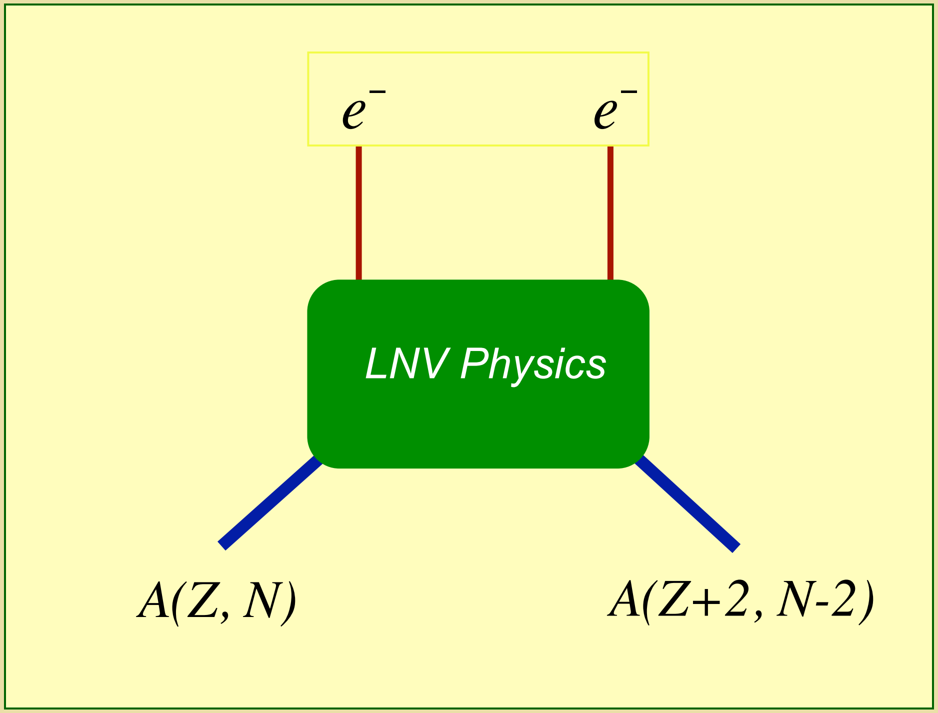
$0\nu\beta\beta$-Decay: LNV? Mass Term?

$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ \text{h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

Majorana



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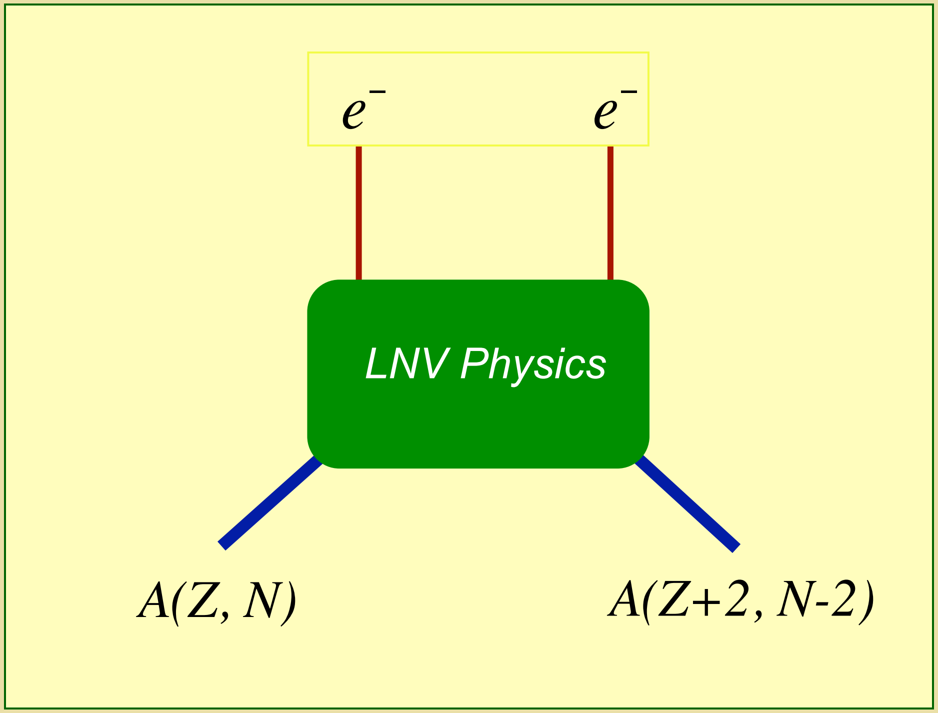
Majorana

Impact of observation

- *Total lepton number not conserved at classical level*
- *New mass scale in nature, Λ*
- *Key ingredient for standard baryogenesis via leptogenesis*



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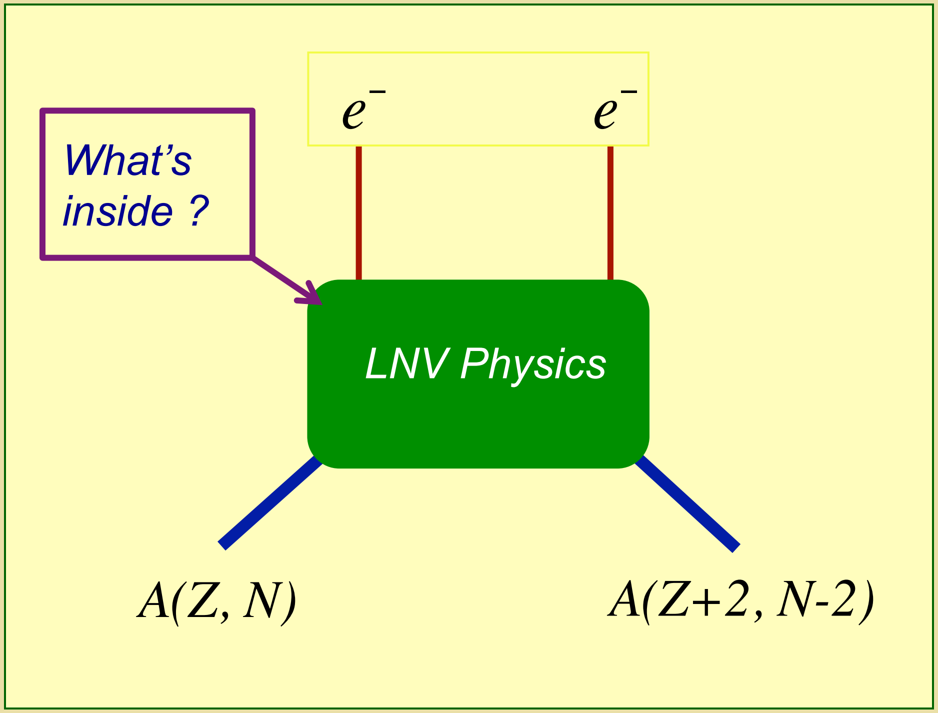
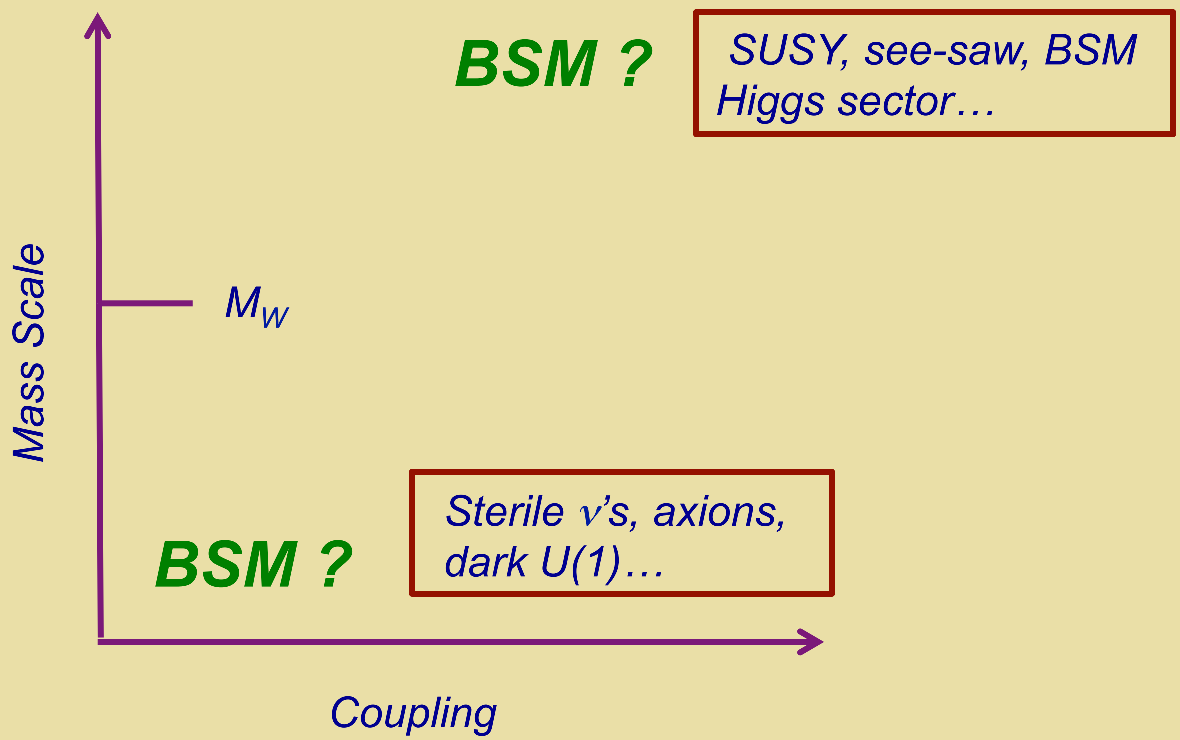


BSM Physics: Where Does it Live ?



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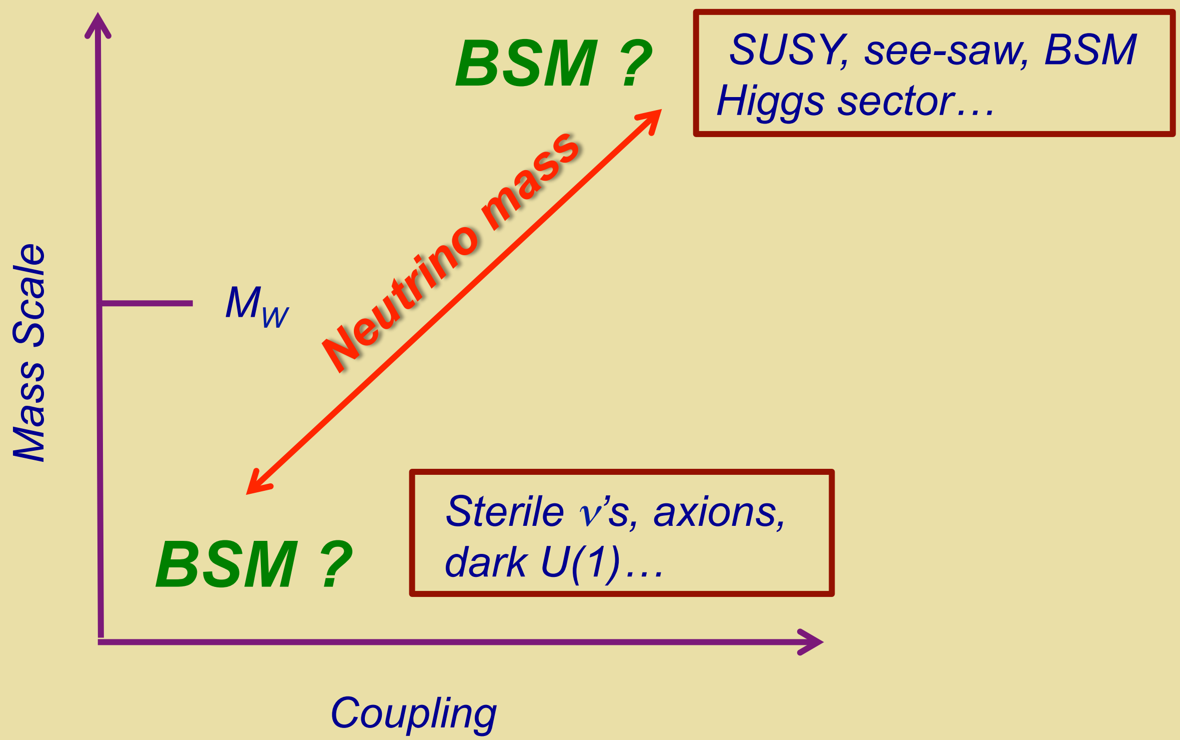

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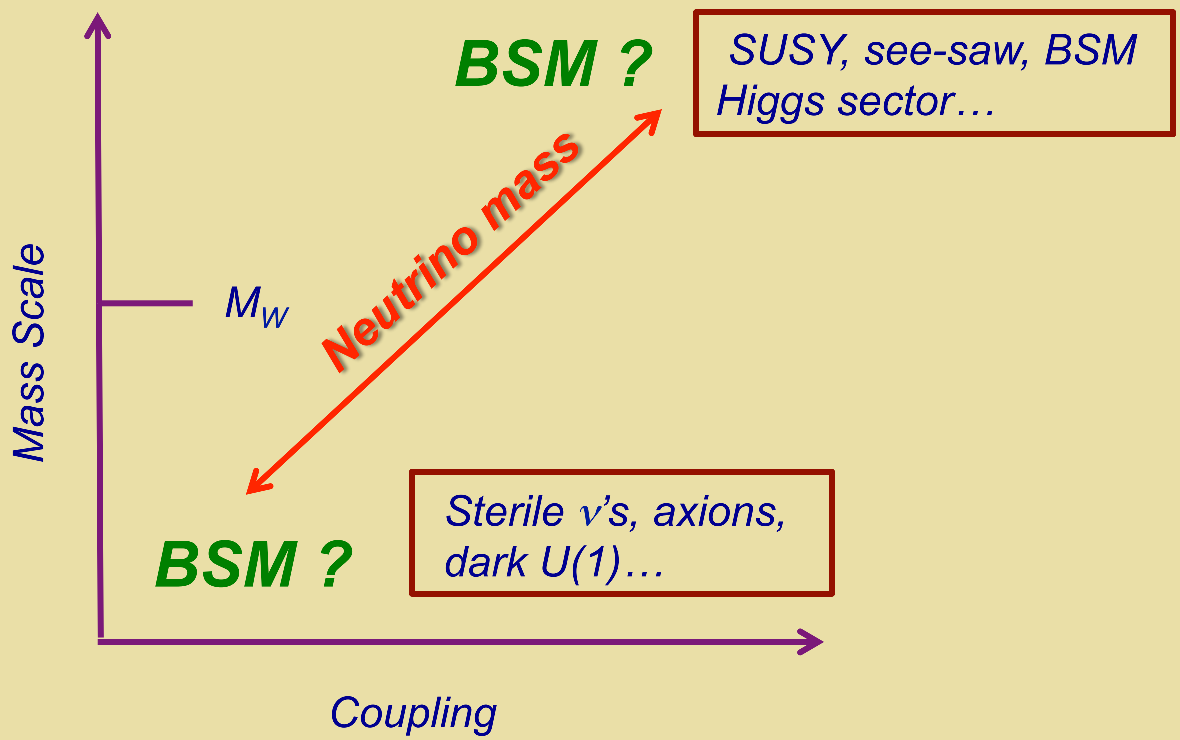

Is the mass scale associated with m_ν far above M_W? Near M_W? Well below M_W?

LNV Mass Scale & $0\nu\beta\beta$-Decay

$A(Z,N) \rightarrow$ **Underlying Physics** $\rightarrow A(Z+2, N-2) + e^- e^-$

- *3 light neutrinos only: source of neutrino mass at the very high see-saw scale*
- *3 light neutrinos with TeV scale source of neutrino mass*
- *> 3 light neutrinos*

LNV Mass Scale & 0νββ-Decay

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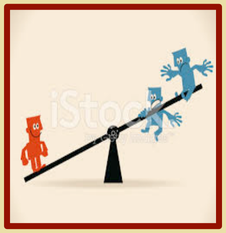

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Dirac

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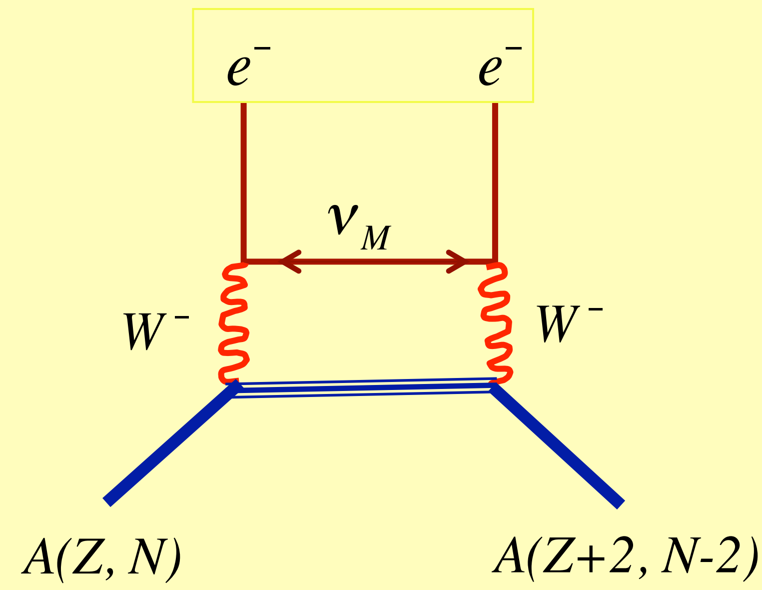
Majorana

"Standard" Mechanism

- *Light Majorana mass generated at the conventional see-saw scale: $\Lambda \sim 10^{12} - 10^{15}$ GeV*
- *3 light Majorana neutrinos mediate decay process*



LNV Mass Scale & $0\nu\beta\beta$-Decay

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Two parameters: Effective coupling & effective heavy particle mass

$0\nu\beta\beta$-Decay: LNV? Mass Term?

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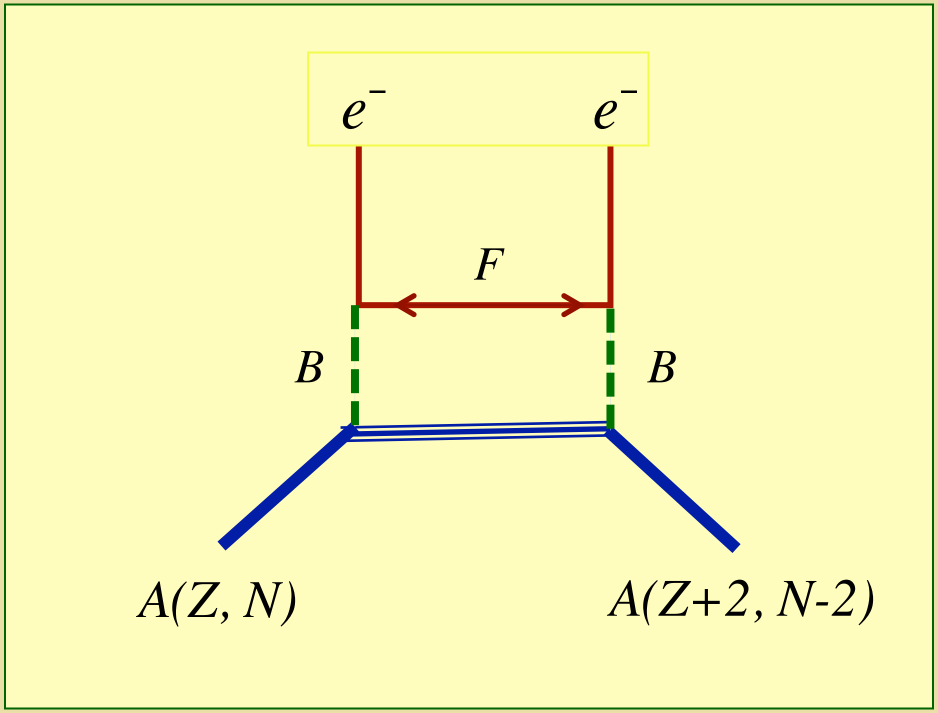
Majorana

TeV LNV Mechanism

- *Majorana mass generated at the TeV scale*
  - *Low-scale see-saw*
  - *Radiative m_ν*
- *m_{MIN} << 0.01 eV but $0\nu\beta\beta$-signal accessible with tonne-scale exp'ts due to heavy Majorana particle exchange*



$0\nu\beta\beta$-Decay: TeV Scale LNV

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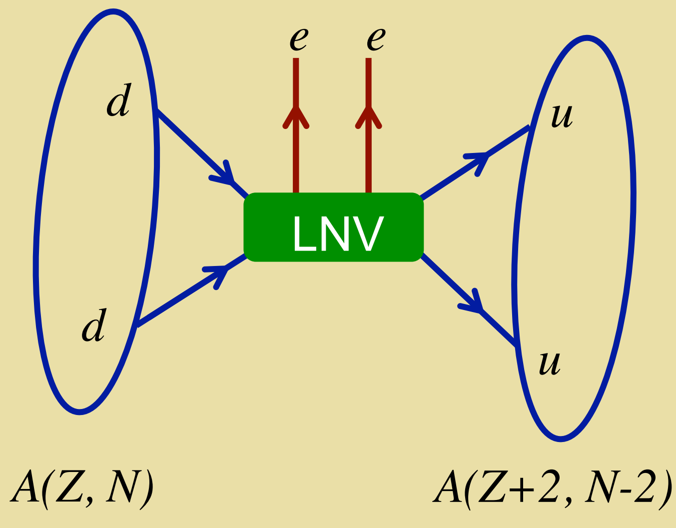
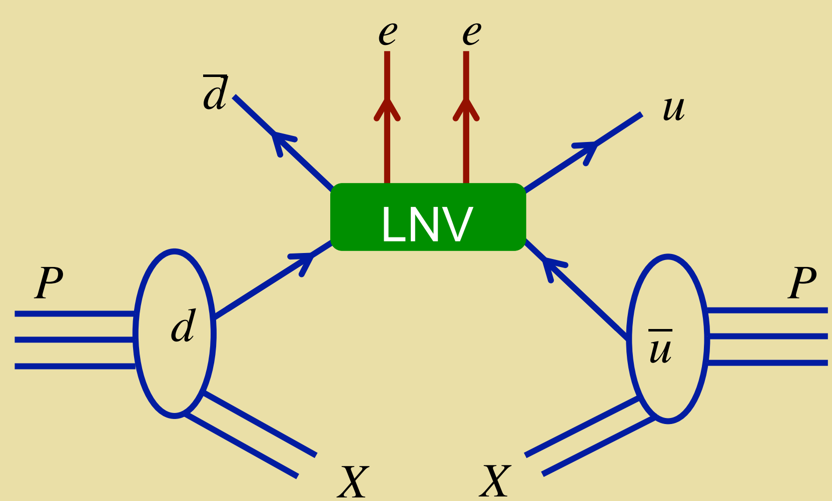
$0\nu\beta\beta$-Decay



pp Collisions



$0\nu\beta\beta$-Decay: TeV Scale LNV

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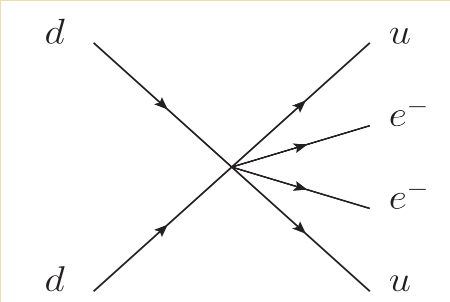
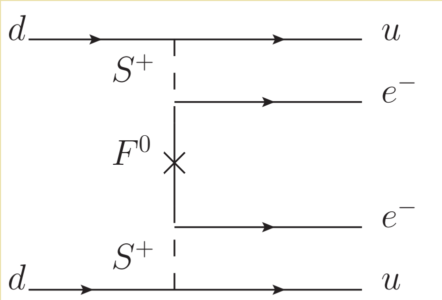
Majorana

TeV Scale LNV

$0\nu\beta\beta$ - decay



LHC: pp $\rightarrow$ jj $e^- e^-$



*Can it be discovered with combination of **$0\nu\beta\beta$** & LHC searches ?*

Simplified models

$0\nu\beta\beta$-Decay: TeV Scale LNV

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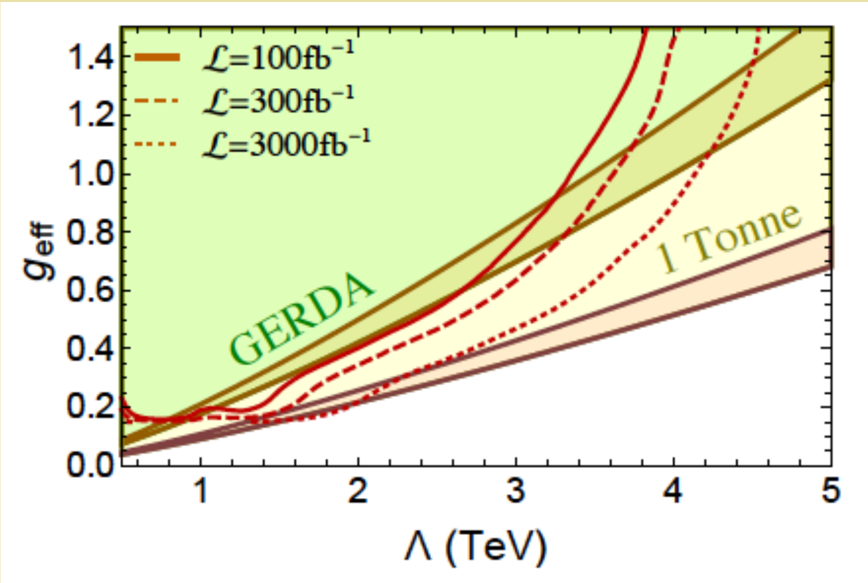
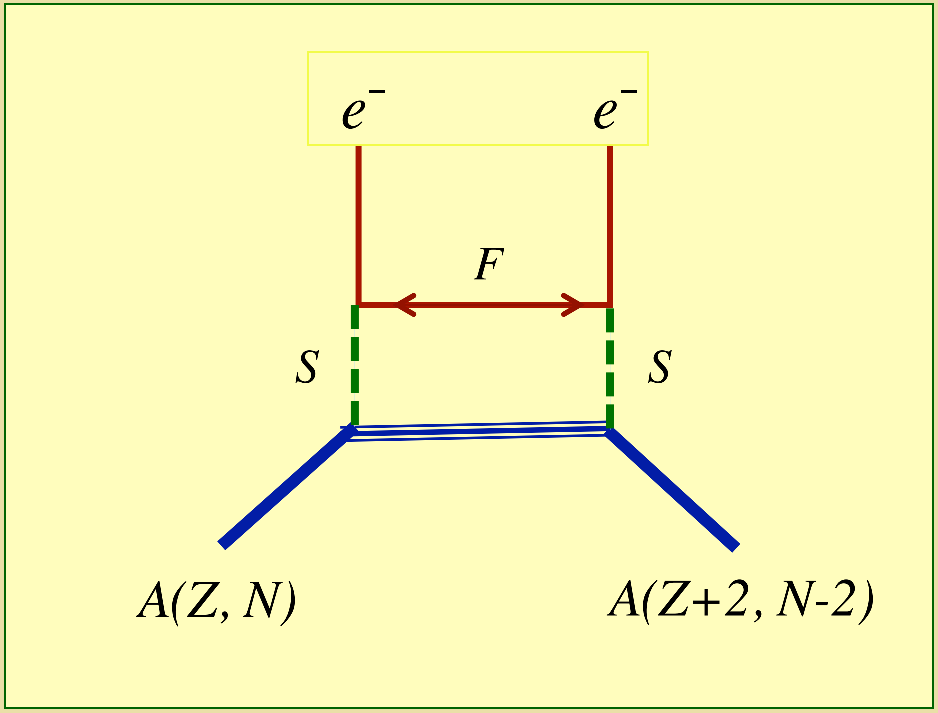
Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



0νββ-Decay: TeV Scale LNV

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Majorana

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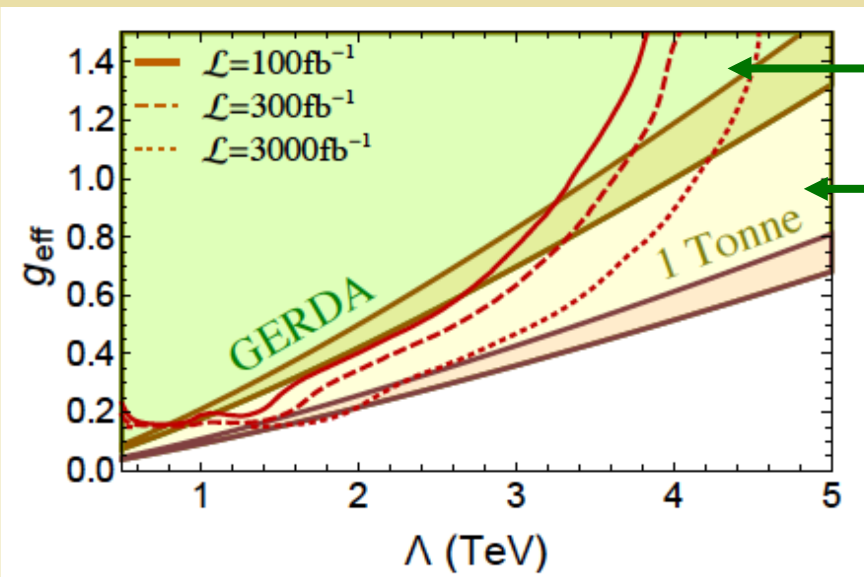

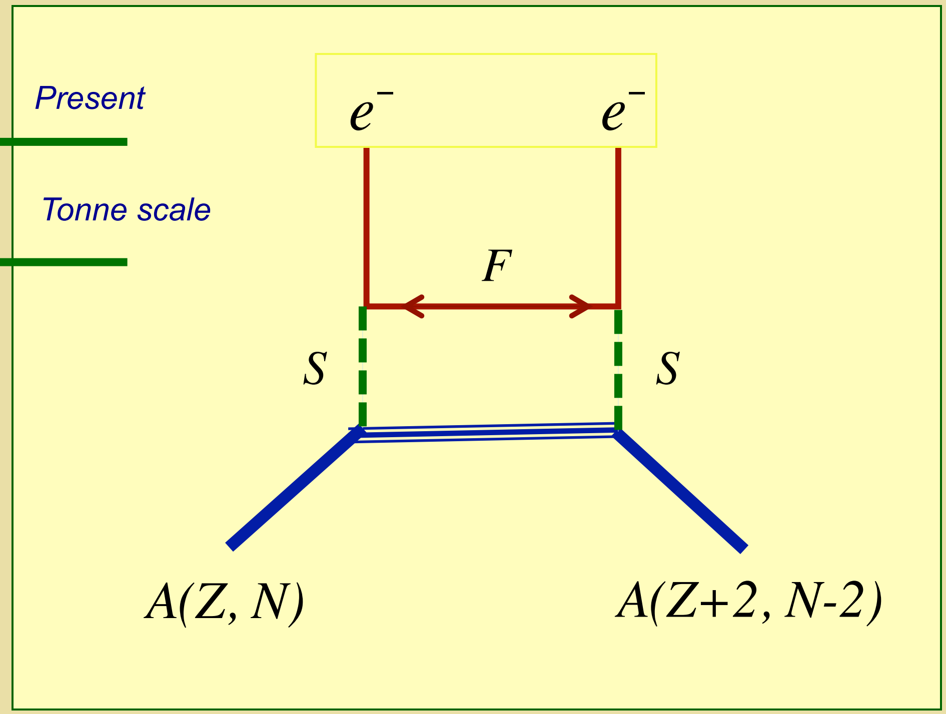

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$0\nu\beta\beta$-Decay: TeV Scale LNV

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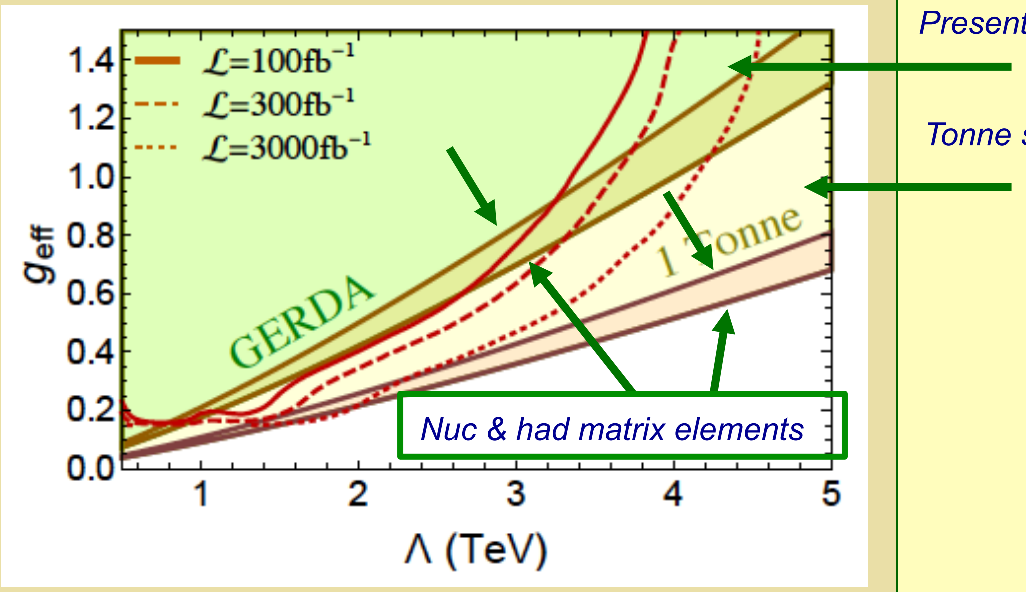

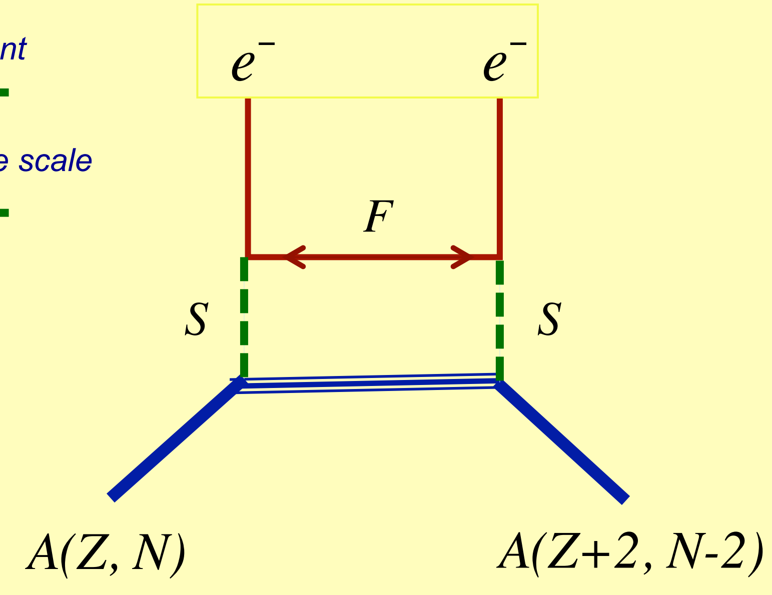

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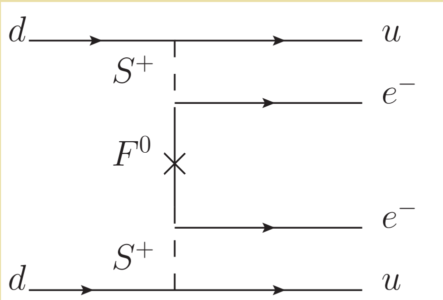
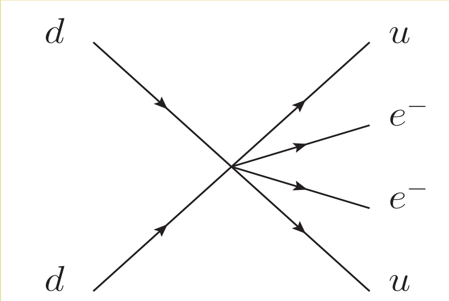
Majorana

Low energy: Matching



Match onto O_{eff} at Λ_{BSM}



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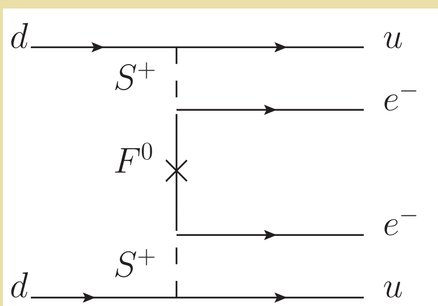
Majorana

Low energy: *Matching*



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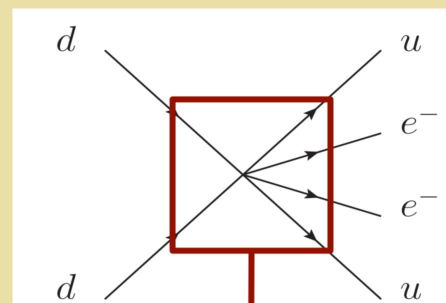

4 quark operator (like HWI)

Match onto O_{had} at Λ_{had}

$\mathcal{L}(\pi, N)$

0νββ-Decay: TeV Scale LNV

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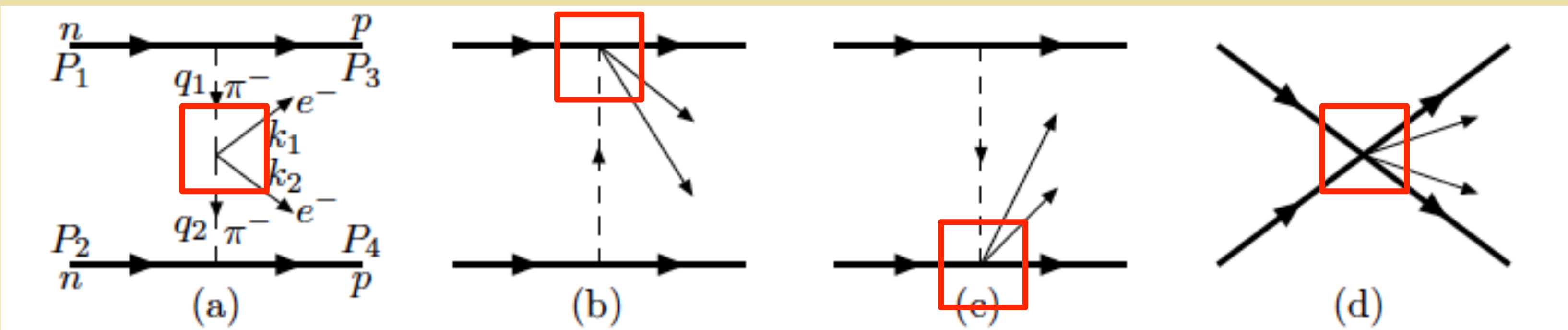
$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ \text{h.c.}$$

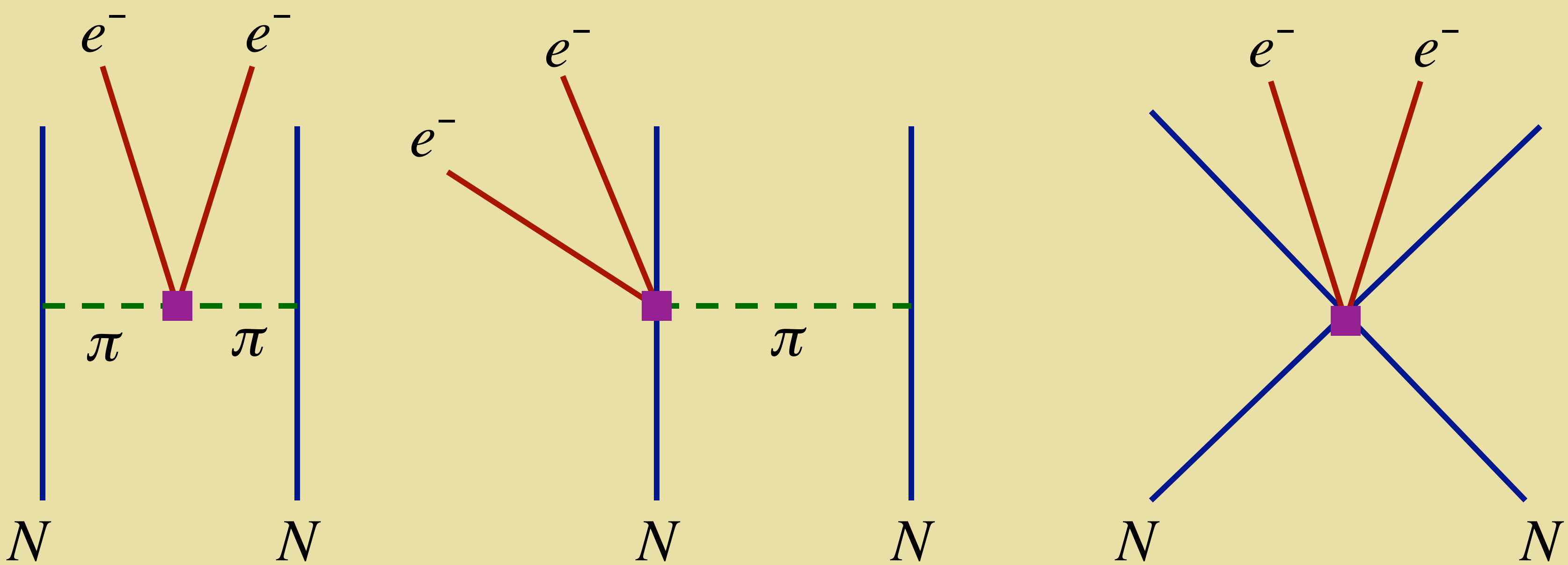
Majorana

Low energy: *Nuclear Matrix Elements: Long Range Effects*



Exploit Chiral Symmetry & EFT ideas

$0\nu\ \beta\beta$ - decay in effective field theory

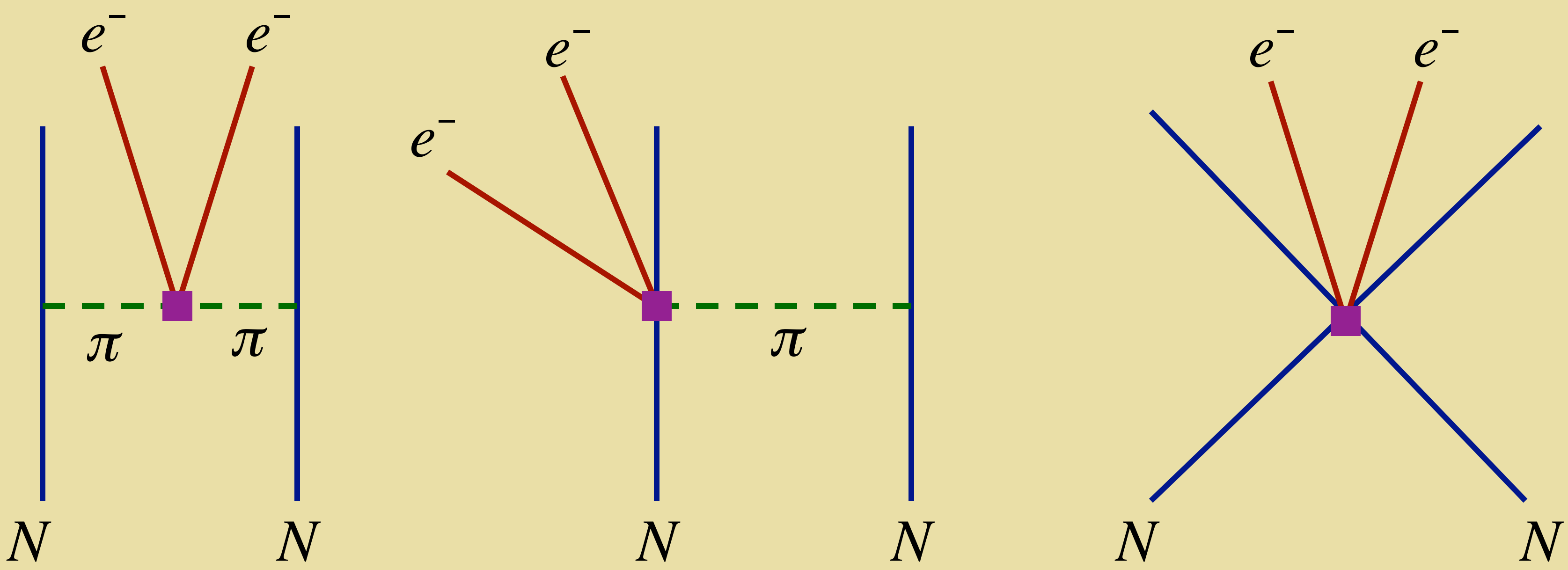


Tractable nuclear operators

Systematic operator classification

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

$0\nu\ \beta\beta$ - decay in effective field theory



$K_{\pi\pi}\ p^{-2}$

$K_{\pi NN}\ p^{-1}$

$K_{NNNN}\ p^{0}$

$0\nu\ \beta\beta$ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\mathcal{L}(q,e) = \frac{G_F^2}{\Lambda_{\beta\beta}} \sum_{j=1}^{14} C_j(\mu)\, \hat{O}_j^{++}\, \bar{e}\,\Gamma_j e^c \quad + \quad h.c.$$

Example (not our case):

$$\hat{O}_{1+}^{ab} = \bar{q}_L \gamma^\mu \tau^a q_L\ \bar{q}_R \gamma_\mu \tau^b q_R$$

$0\nu\ \beta\beta$ - decay: *$a = b = +$*

Prezeau, MJRM, Vogel
PRD 68 (2003) 034016

$0\nu\ \beta\beta$ - decay in effective field theory

Operator classification

$$\mu = M_{WEAK}$$

$$\hat{O}^{ab}_{1+} = \bar{q}_L \gamma^\mu \boldsymbol{\tau}^a q_L \ \bar{q}_R \gamma_\mu \boldsymbol{\tau}^b q_R$$

Chiral transformations: $SU(2)_L \times SU(2)_R$

$$\begin{aligned} q_L &\to L q_L \\ q_R &\to R q_R \end{aligned} \qquad \begin{matrix} L \\ R \end{matrix} = \exp\left(i \vec{\theta}_{\substack{L \\ R}} \cdot \frac{\vec{\tau}}{2} P_{\substack{L \\ R}} \right)$$

$$\hat{O}^{ab}_{1+} \in (3_L, 3_R)$$

Parity transformations: $q_L \leftrightarrow q_R$

$0\nu\ \beta\beta$ - decay: ***a* = *b* = +**

$$\hat{O}^{++}_{1+} \leftrightarrow \hat{O}^{++}_{1+}$$

$0\nu\ \beta\beta$ - decay in effective field theory

Hadronic basis

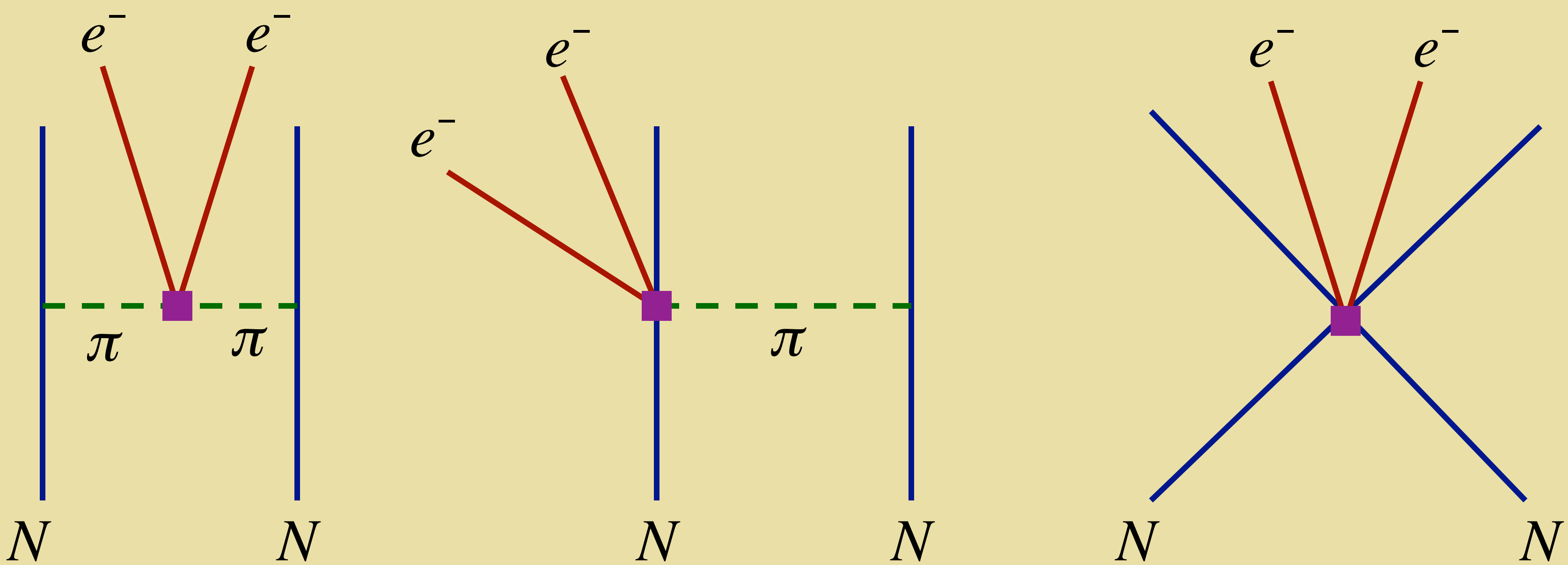
$$X_R^a = \xi \, \tau^a \, \xi^+ , \quad X_L^a = \xi^+ \, \tau^a \, \xi \, , \quad \xi = \exp\left(i\vec{\tau} \cdot \vec{\pi}/2 \right)$$

Chiral transformations

$$\hat{O}_{1+}^{++} \sim Tr\left(X_R^+ \, X_L^+ \right) \sim \frac{2}{F_\pi^2} \, \pi^- \, \pi^- + \cdots$$

No derivatives → $K_{\pi\pi} \sim \mathcal{O}\,(p^0)$

$0\nu\ \beta\beta$ - decay in effective field theory



$K_{\pi\pi}\ p^{-2}$ $K_{\pi NN}\ p^{-1}$ $K_{NNNN}\ p^{0}$

$\mathcal{O}(p^{-2})$ for $\hat{O}_{1+}^{++}$ $\mathcal{O}(p^{0})$ for $\hat{O}_{3+}^{++}$

$0\nu\beta\beta$-Decay: TeV Scale LNV

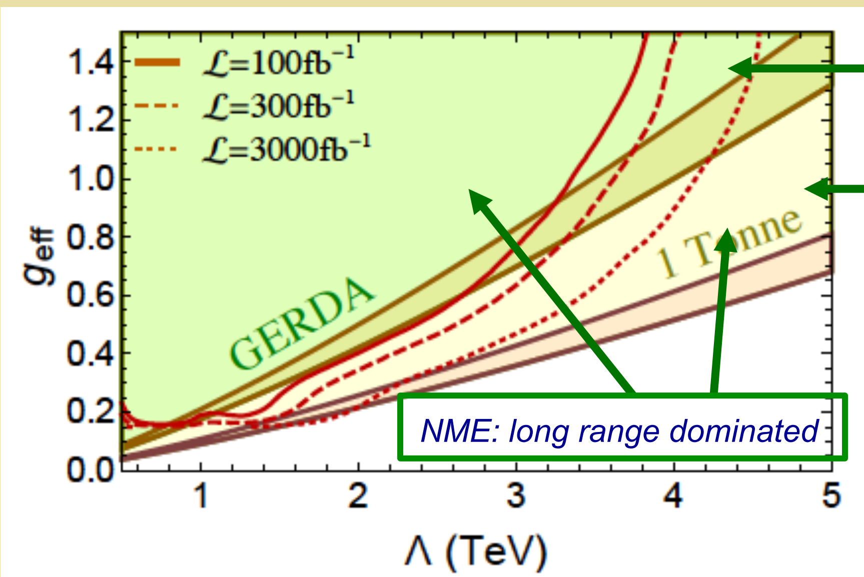
$$\mathcal{L}_{\rm mass} = y\bar{L}\tilde{H}\nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda}\bar{L}^c H H^T L \ + \ {\rm h.c.}$$

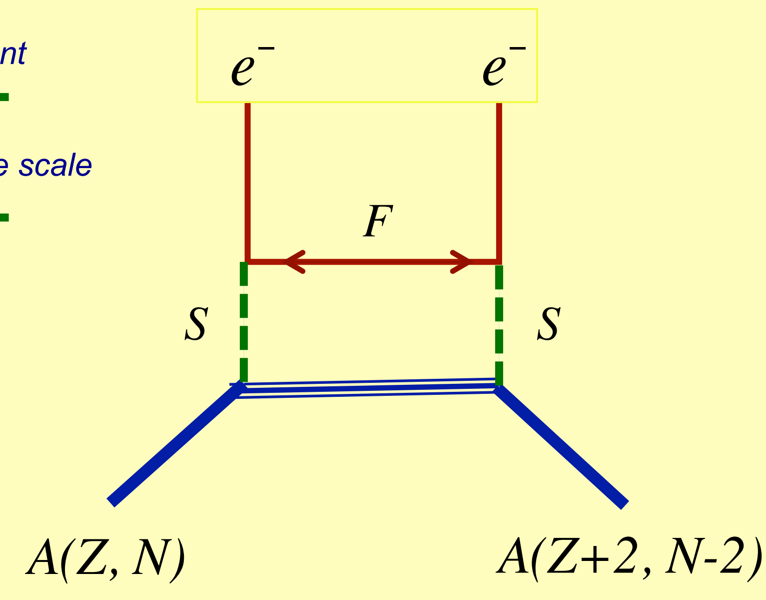
Majorana

Benchmark Sensitivity: TeV LNV



Present

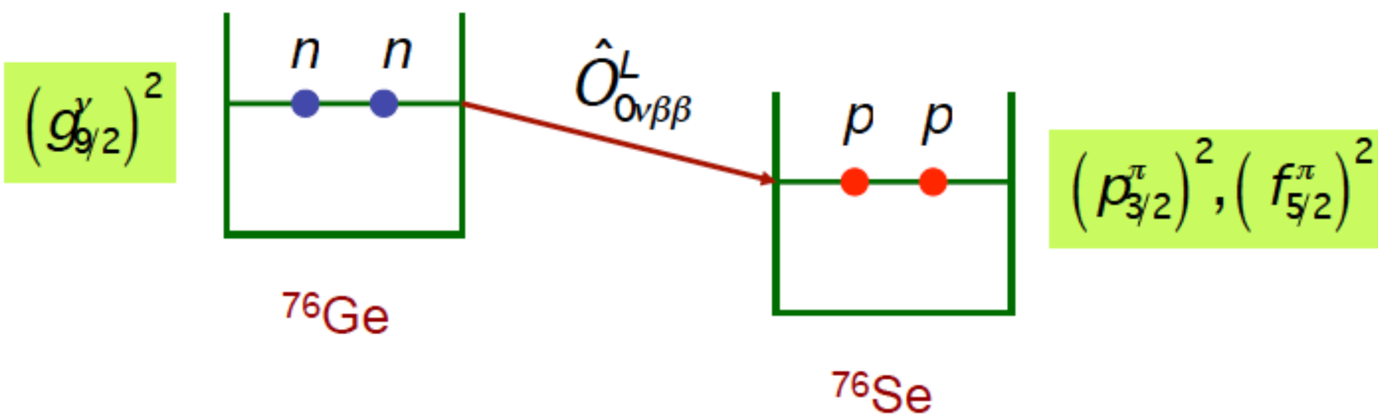
Tonne scale



T. Peng, MRM, P. Winslow 1508.04444

An Open Question

Is the power counting of operators sufficient to understand weak matrix elements in nuclei ?



$\ell = 0, \ldots, 9$ $\qquad$ $\ell' = 0, \ldots, 5$

An Open Question

Is the power counting of operators sufficient to understand weak matrix elements in nuclei ?

$\ell = 0,\ldots,9$ $\qquad \hat{O}^{L}_{0\nu\beta\beta}$ $\qquad \ell' = 0,\ldots,5$

e.g.

M_{fi}	$\sim$	p^0	$\ell = \ell' = 0$	$\hat{O}^{L=0}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^0	$\ell = 2, \ell' = 0$	$\hat{O}^{L=2}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^4	$\ell = 0, \ell' = 2$	$\hat{O}^{L=2}_{0\nu\beta\beta}$
M_{fi}	$\sim$	p^0	$\ell = 4, \ell' = 0$	$\hat{O}^{L=4}_{0\nu\beta\beta}$

etc.

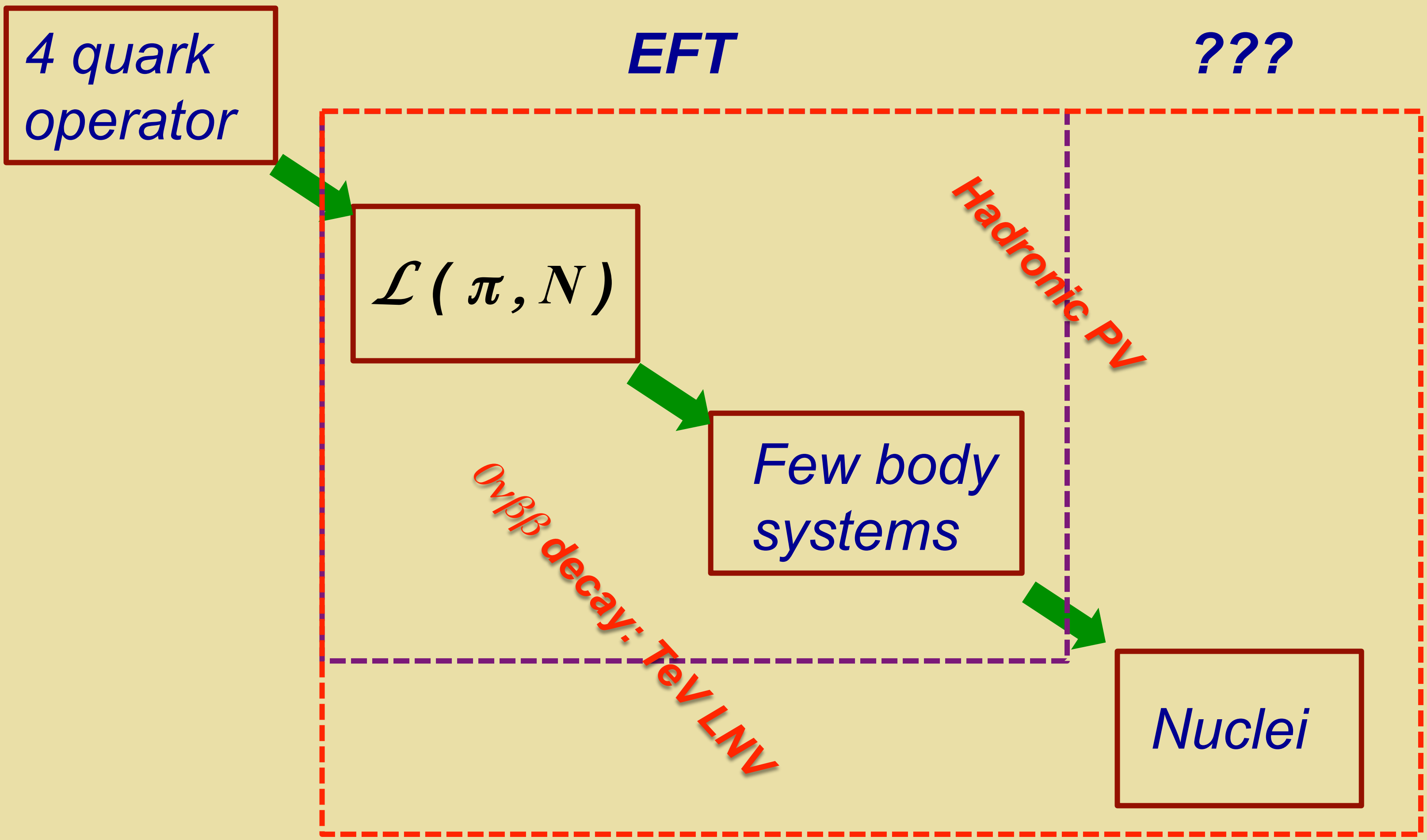
An Open Question

Additional complications:

- Bound state wavefunctions (*e.g., h.o.)* don't obey simple power counting
- Configuration mixing is important in heavy nuclei

- More theoretical study required
- Hadronic PV may provide an empirical test

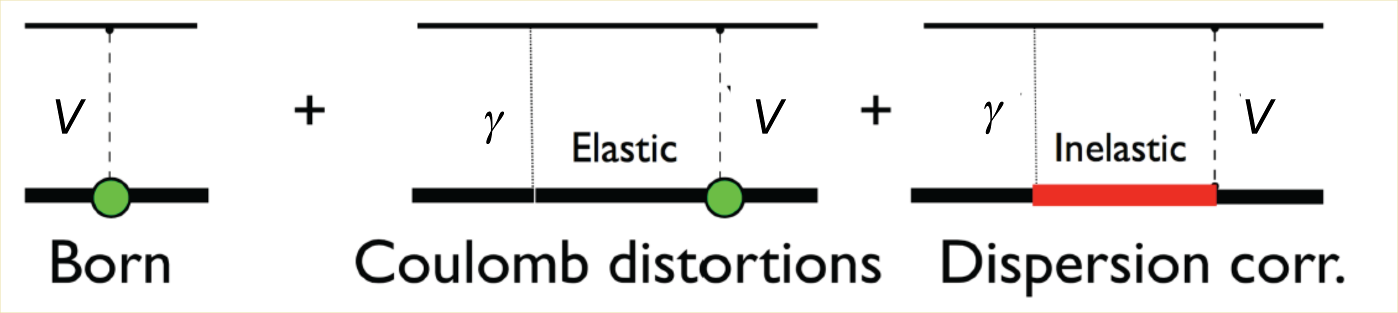
EFT in Nuclei: HPV & $0\nu\beta\beta$ Decay



II. SM Interpretation: EW Box

Discussions: T.W. Donnelly, J. Engel, J. Hardy, C. Horowitz...

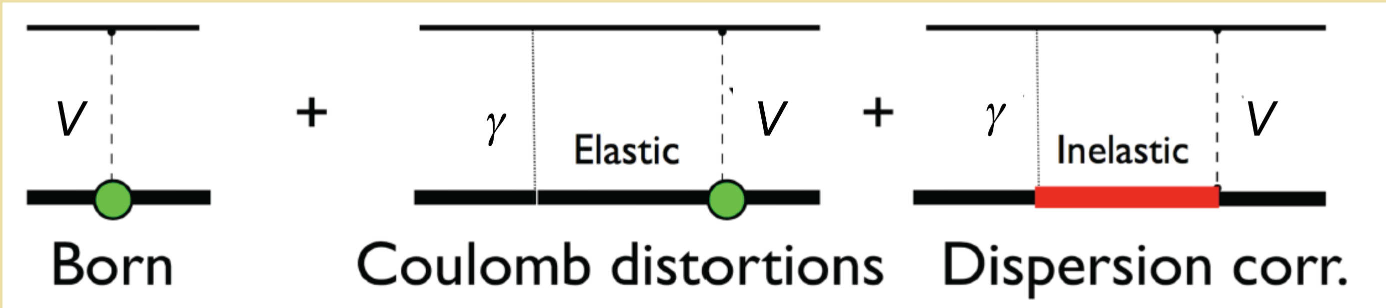
Two EW Boson Exchange



V = Z^0, *W*, γ

Thanks: C. Horowitz

Two EW Boson Exchange

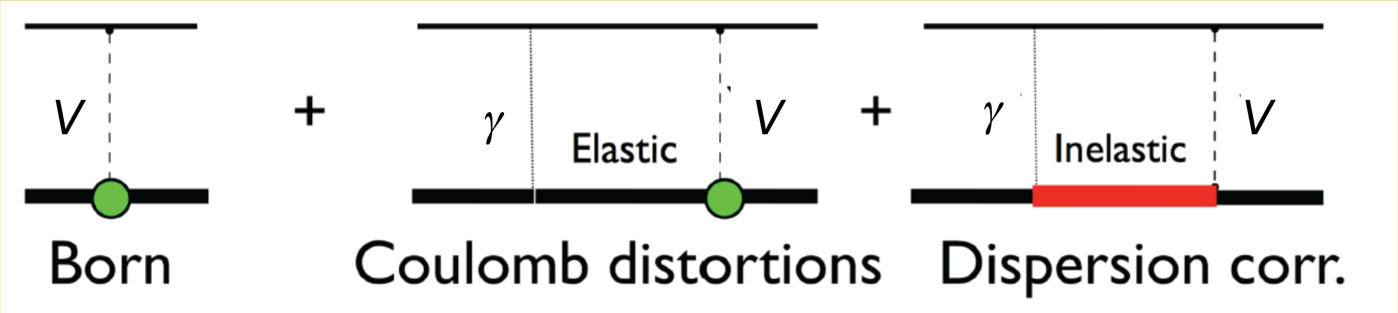


$V = Z^0, W, \gamma$

- *QED ($\gamma\gamma$) in semileptonic interactions is still a puzzle !*
- *No direct probes of EW boxes (γZ, γW) available, but reliable SM computations needed. Can we trust the quoted theoretical uncertainties ? Can we reduce them further ?*

Dispersion Corrections

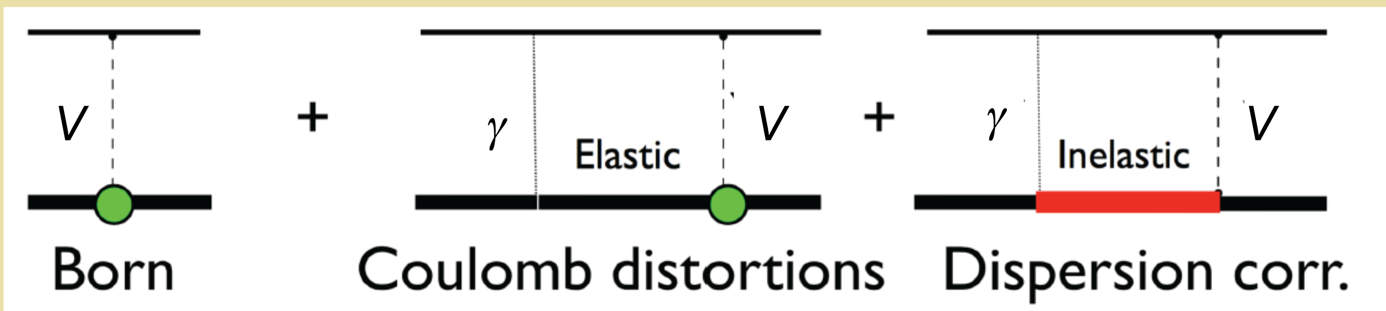
Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests



$V = Z^0, W, \gamma$

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests

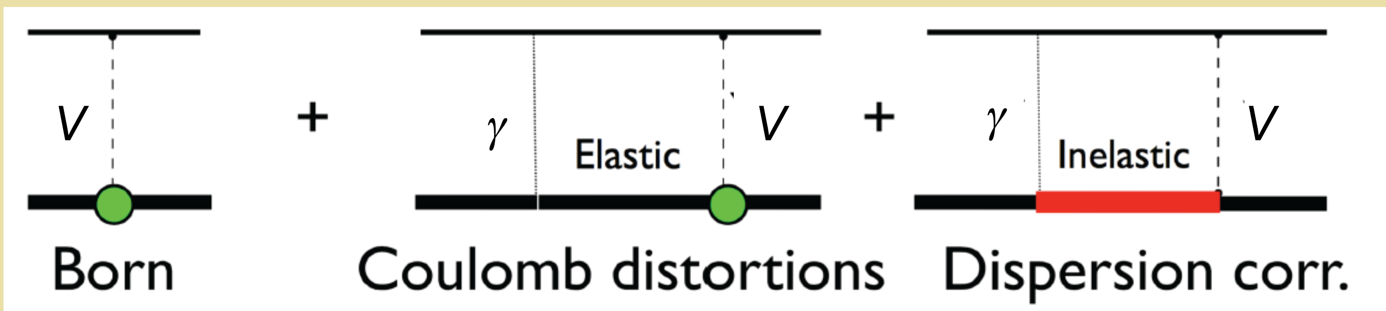


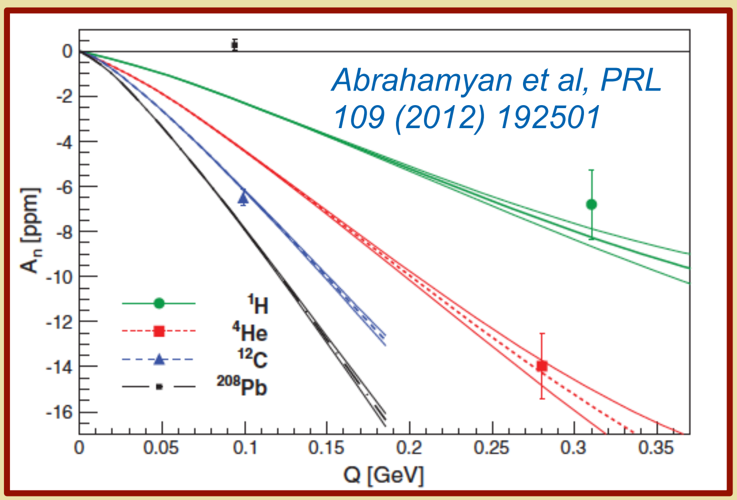
$V = Z^0, W, \gamma$

$V = \gamma$ ***Beam normal asymmetry***

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry, Olympus… provide tests

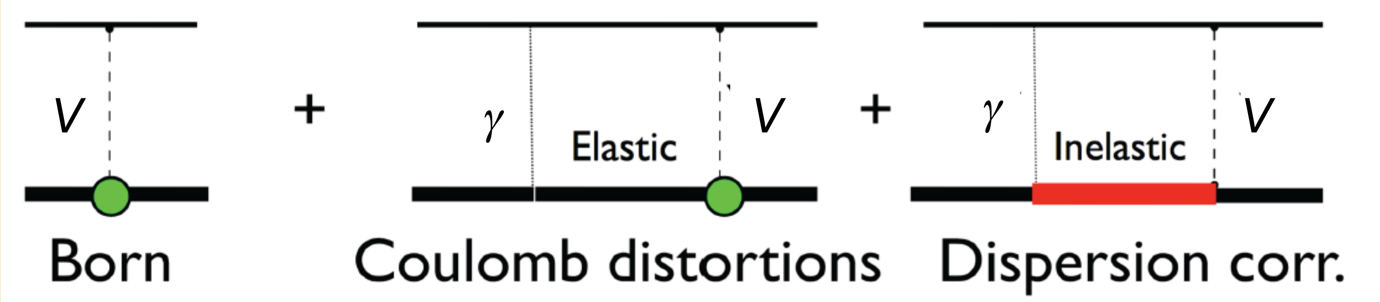




$V = \gamma$ ***Beam normal asymmetry***

- *J Lab Hall A*
- *Future: Mainz, J Lab*

Two EW Boson Exchange

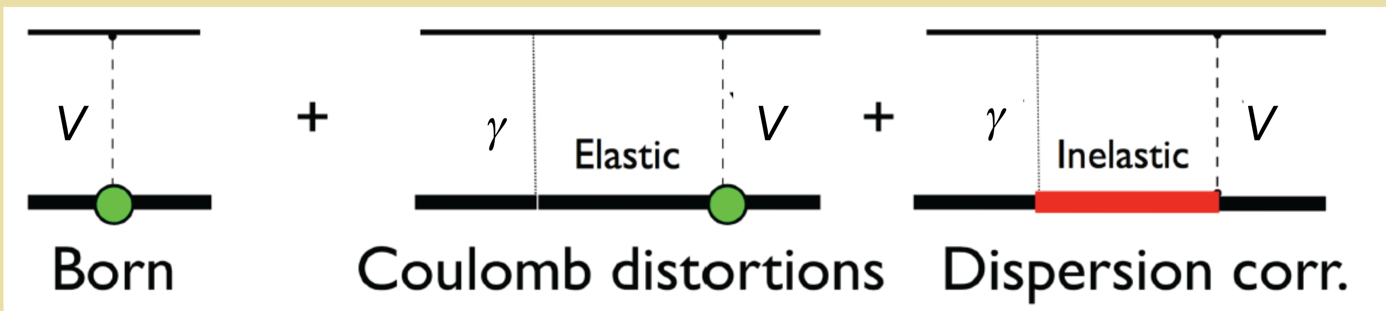


$V = Z^0, W, \gamma$

	$d\sigma$	A_n	A_{PV}	$ft_{1/2}$	$a, A\ldots$	$\delta(E)$	d_A
$\gamma\gamma$	✔	✔	✔	✖	✖	✖	✔
γZ	✖	✖	✔	✖	✖	✖	✖
γW	✖	✖	✖	✔	✔	✔	✖

Dispersion Corrections

Two-boson exchange in semileptonic processes: important for elastic PV eN & eA scattering (^{12}C) & nuclear β-decay; beam normal asymmetry provides, Olympus… provide tests



$V = Z^0, W, \gamma$

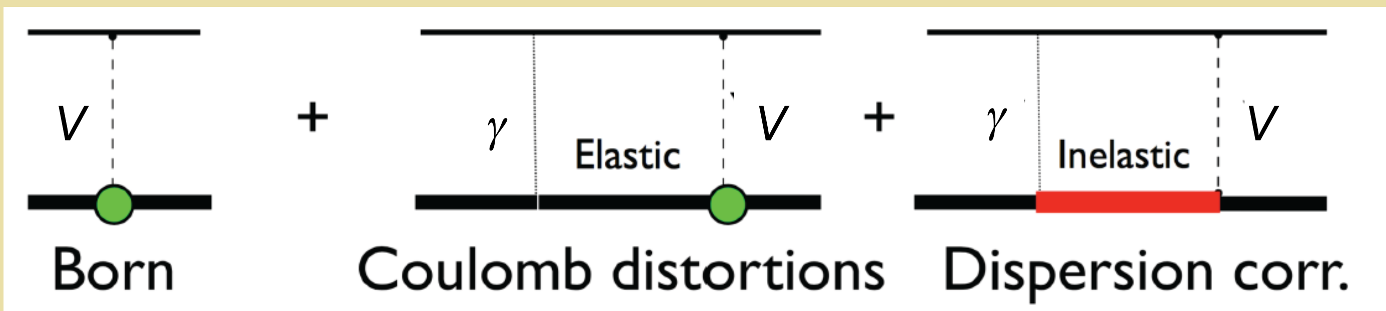
$V = \gamma$ ***Beam normal asymmetry***

$V = Z^0, W$ ***Nucleus-dependent QED & EW corrections***

Important for $\mathcal{O}$ (0.1%) probes of PV $^{12}C(e,e')$ & superallowed β-decay

Dispersion Corrections

Proposal: (1) carry out a consistent set of computations for A_n , PV asymmetry, & δ_{NS} using different methods (2) develop a program of A_n measurements to test computations



$V = Z^0, W, \gamma$

$V = \gamma$ ***Beam normal asymmetry***

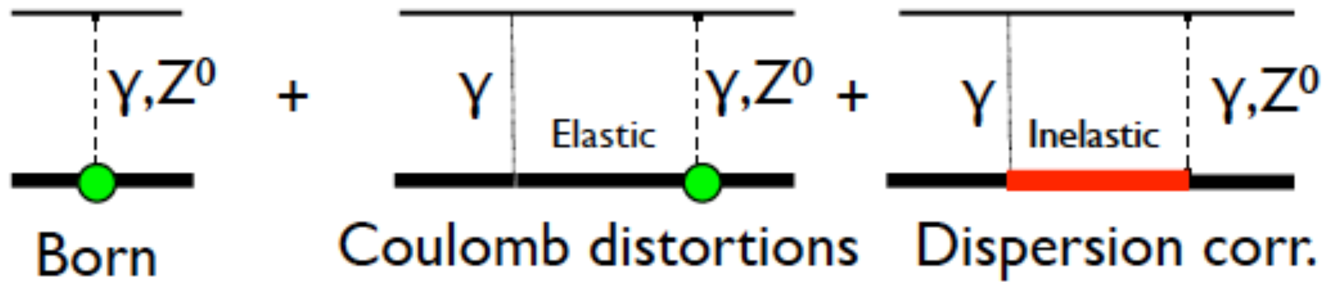
$V = Z^0, W$ ***Nucleus-dependent QED & EW corrections***

Important for $\mathcal{O}$ (0.1%) probes of PV ^{12}C(e,e') & superallowed β-decay

Beam Normal Asymmetry

- Increasingly important for many precision measurements.
- Can isolate some radiative corrections with only polarized electrons (no need for positrons).
- PREX, CREX provide unique data sets on high Z targets. Comparing these to low Z data allows "Rosenbluth like" separations of different coulomb distortion, dispersion ... contributions vs Z. Instead of long / transverse vs angle, have coulomb distortion / dispersion contributions vs Z.
- Analyzing high Z and low Z data together can provide important additional insight even if only interested in low Z experiments.

Beam Normal Asymmetry

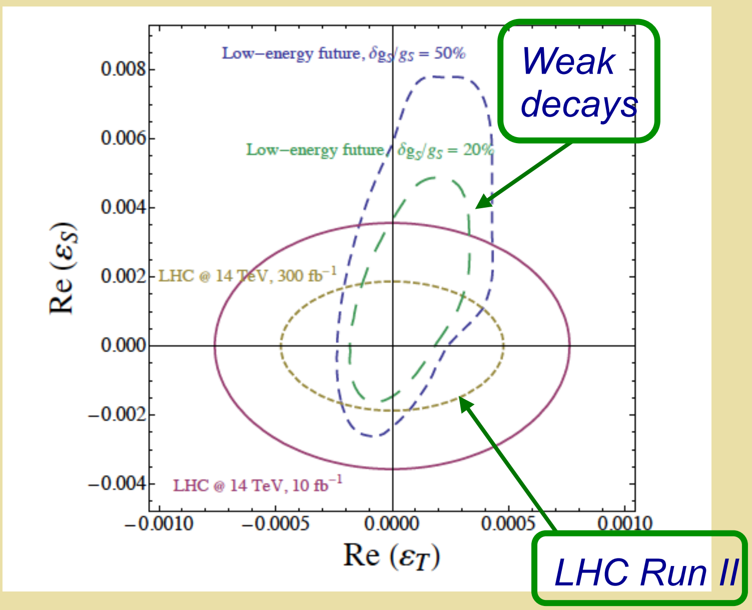


- Coulomb distortions are coherent, order $Z\alpha$. Important for PREX (Pb has Z=82).
- Dispersion corrections order α (not $Z\alpha$). Important for QWEAK because correction is order $\alpha/Q_w \sim 10\%$ relative to small Born term (Q_w). --- M. Gorshteyn
- Both Coulomb distortion and dispersion cor. can be important for Transverse Beam Asymmetry A_n for ^{208}Pb. Note Born term gives zero by time reversal symmetry.

C. Horowitz

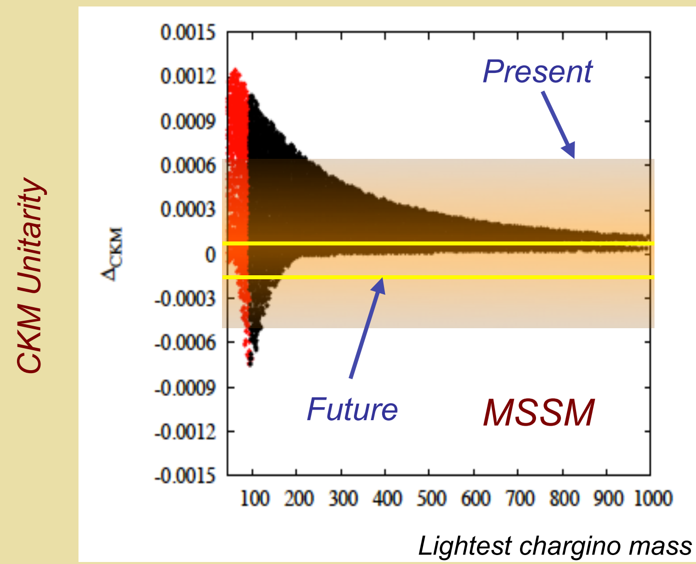
Weak Decays: BSM Implications

Decay Correlations: Scalar & Tensor Currents



Bhattacharya et al '12

SUSY Corrections to CKM Unitarity



Bauman et al '12

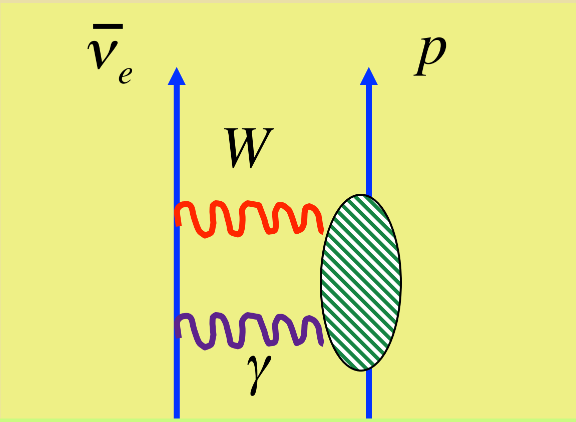
Neutron & Nuclear β–decay: $0^+ \to 0^+$, Nab, ^{6}He…

$\boxed{\textbf{Goal:} \quad \varepsilon \sim \mathcal{O}(10^{-4})}$

Weak decays

$$\frac{G_F^\beta}{G_F^\mu} = |V_{ud}|\left(1 + \Delta r_\beta - \Delta r_\mu\right)$$

SM theory input



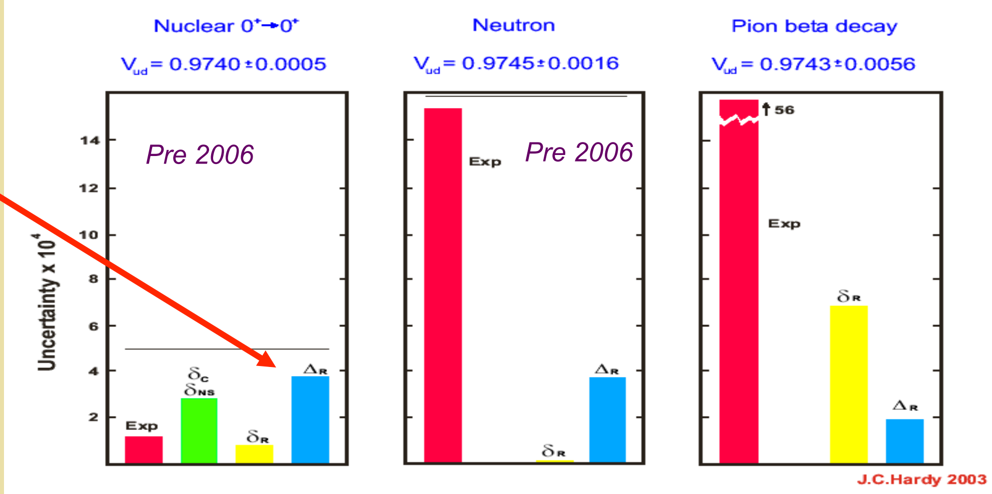
Marciano & Sirlin 2006

β-decay

$$n \to p\, e^-\, \bar{\nu}_e$$

$$A(Z,N) \to A(Z-1,N+1)\, e^+\, \nu_e$$

$$\pi^+ \to \pi^0\, e^+\, \nu_e$$

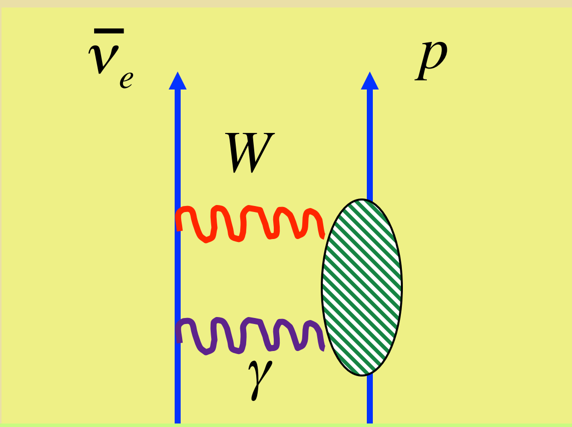


$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{8\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

Weak decays

$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}|\left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)$$

SM theory input



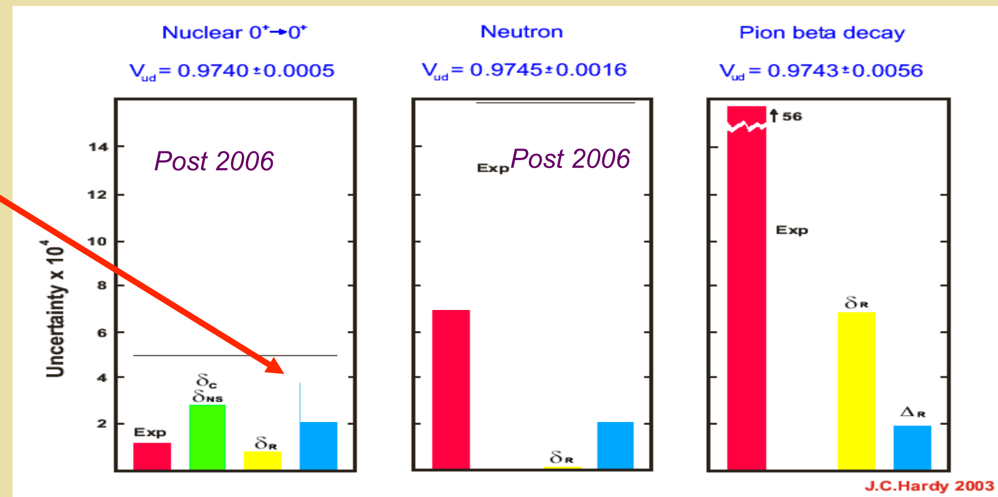
Recent Marciano & Sirlin

β-decay

$$n \rightarrow p\, e^{-}\, \bar{\nu}_e$$

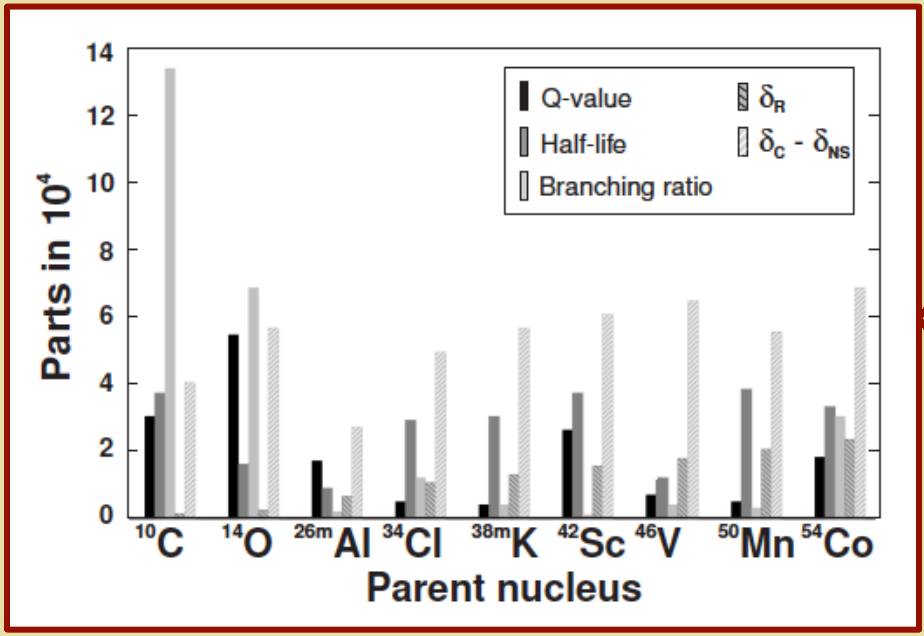
$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^{+}\, \nu_e$$

$$\pi^{+} \rightarrow \pi^{0}\, e^{+}\, \nu_e$$



$$M_{W\gamma} = \frac{G_F}{\sqrt{2}}\frac{\alpha}{8\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}

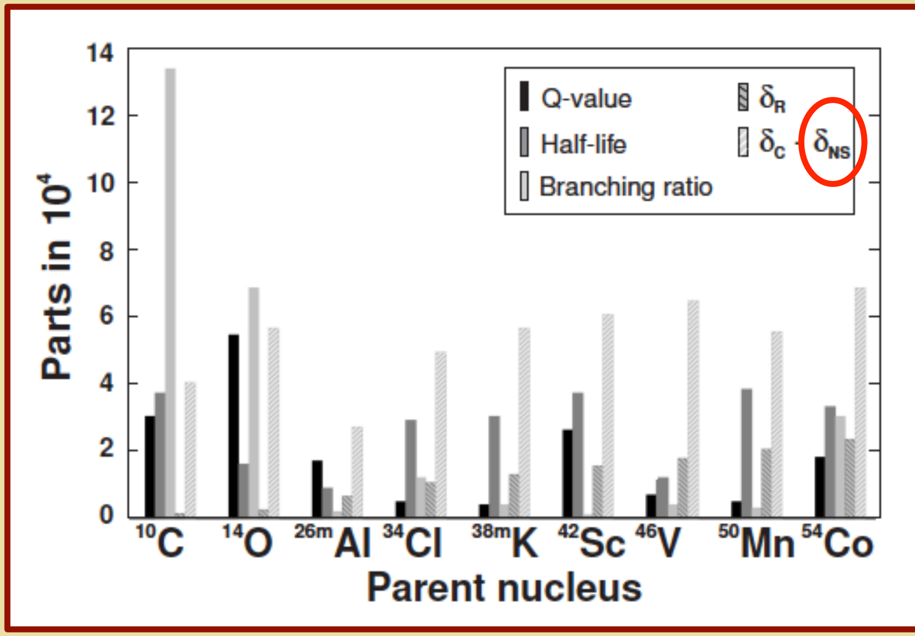


b_F : scalar currents

Input for V_{ud} & CKM unitarity test

Towner & Hardy, PRC 91 (2015) 2, 025501

$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}

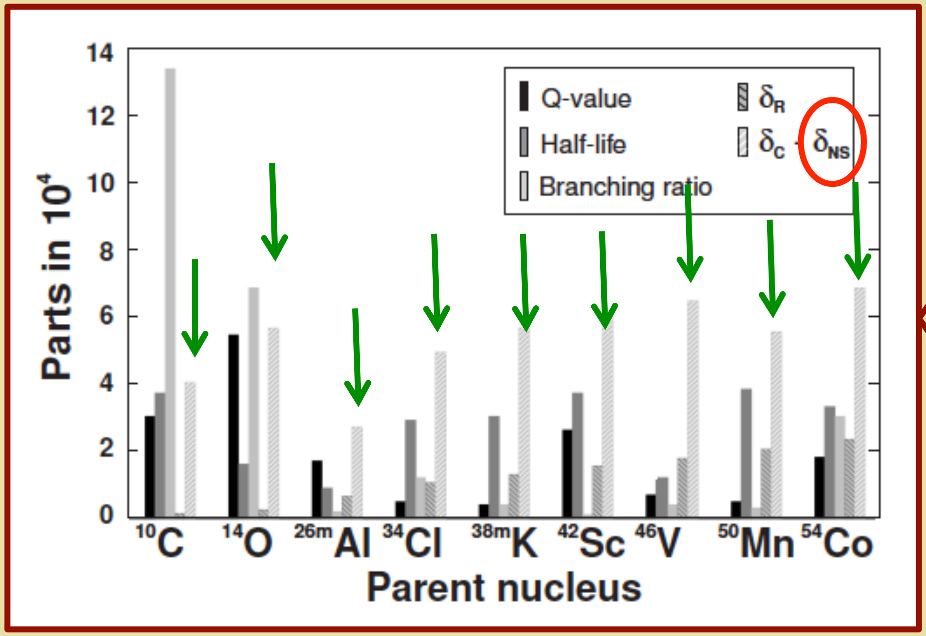


Towner & Hardy, PRC 91 (2015) 2, 025501

b_F : scalar currents

Input for V_{ud} & CKM unitarity test

$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}



b_F : scalar currents

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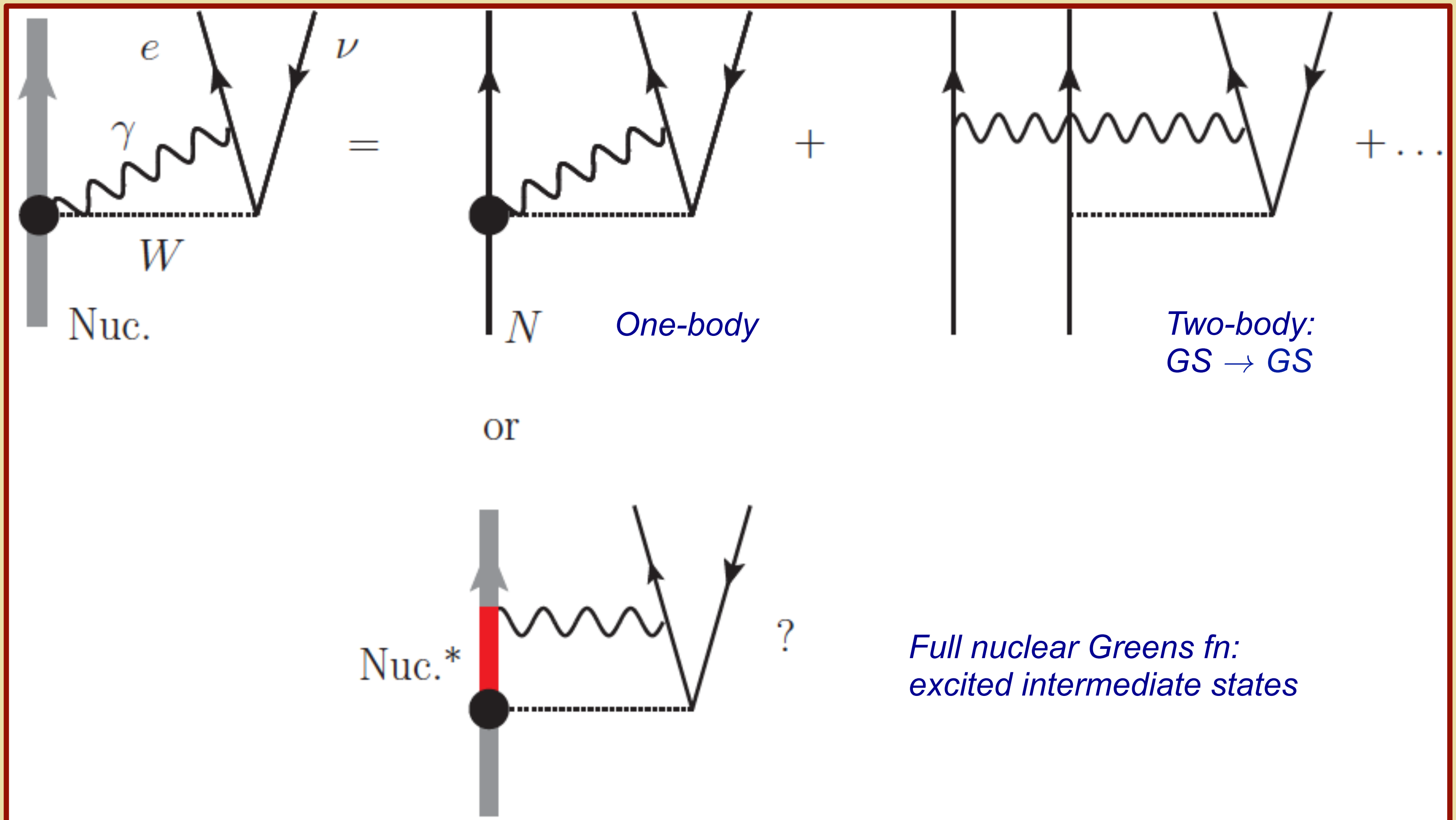
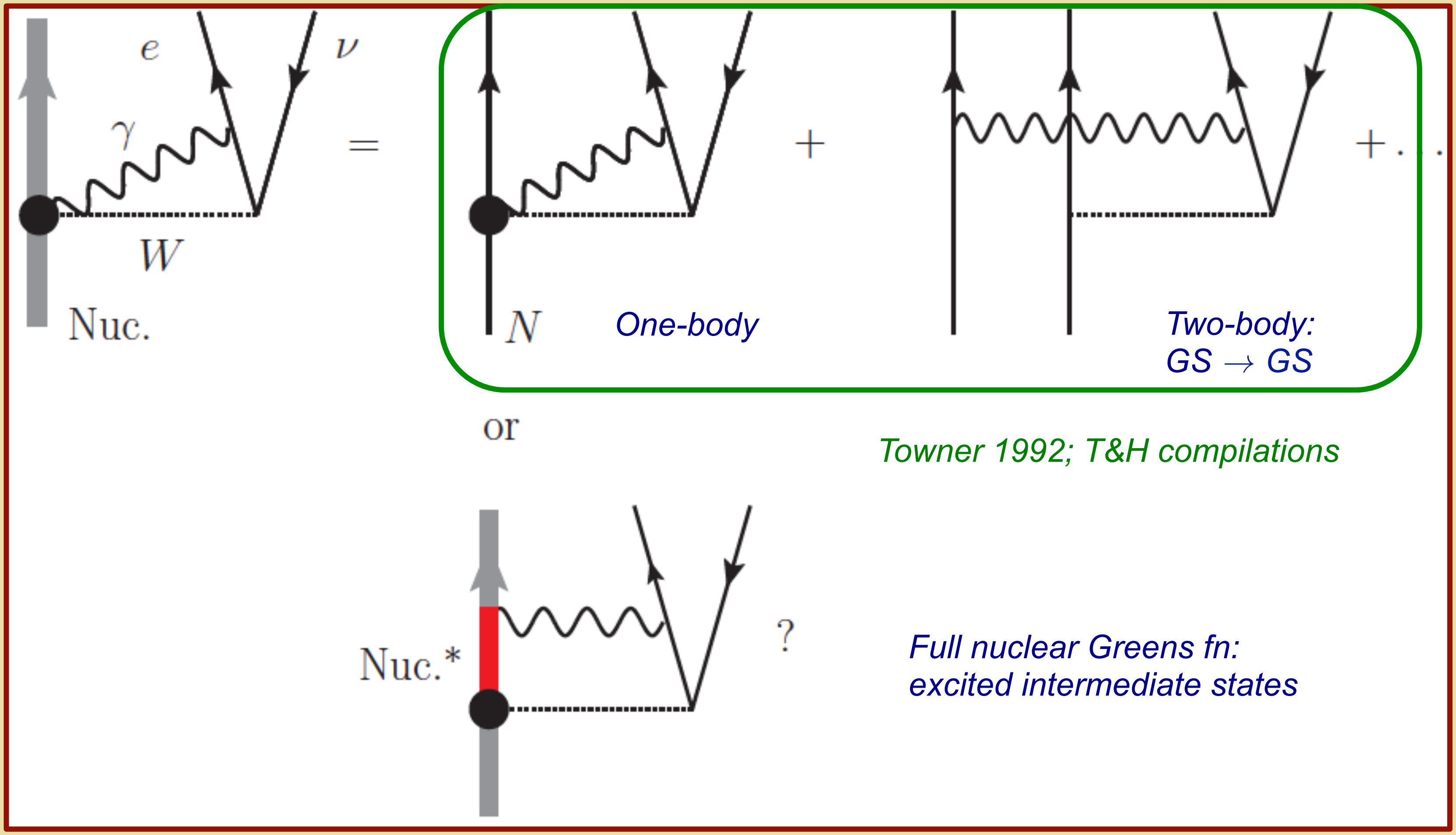
Towner & Hardy, PRC 91 (2015) 2, 025501

$0^+ \rightarrow 0^+$ Decay: δ_{NS}



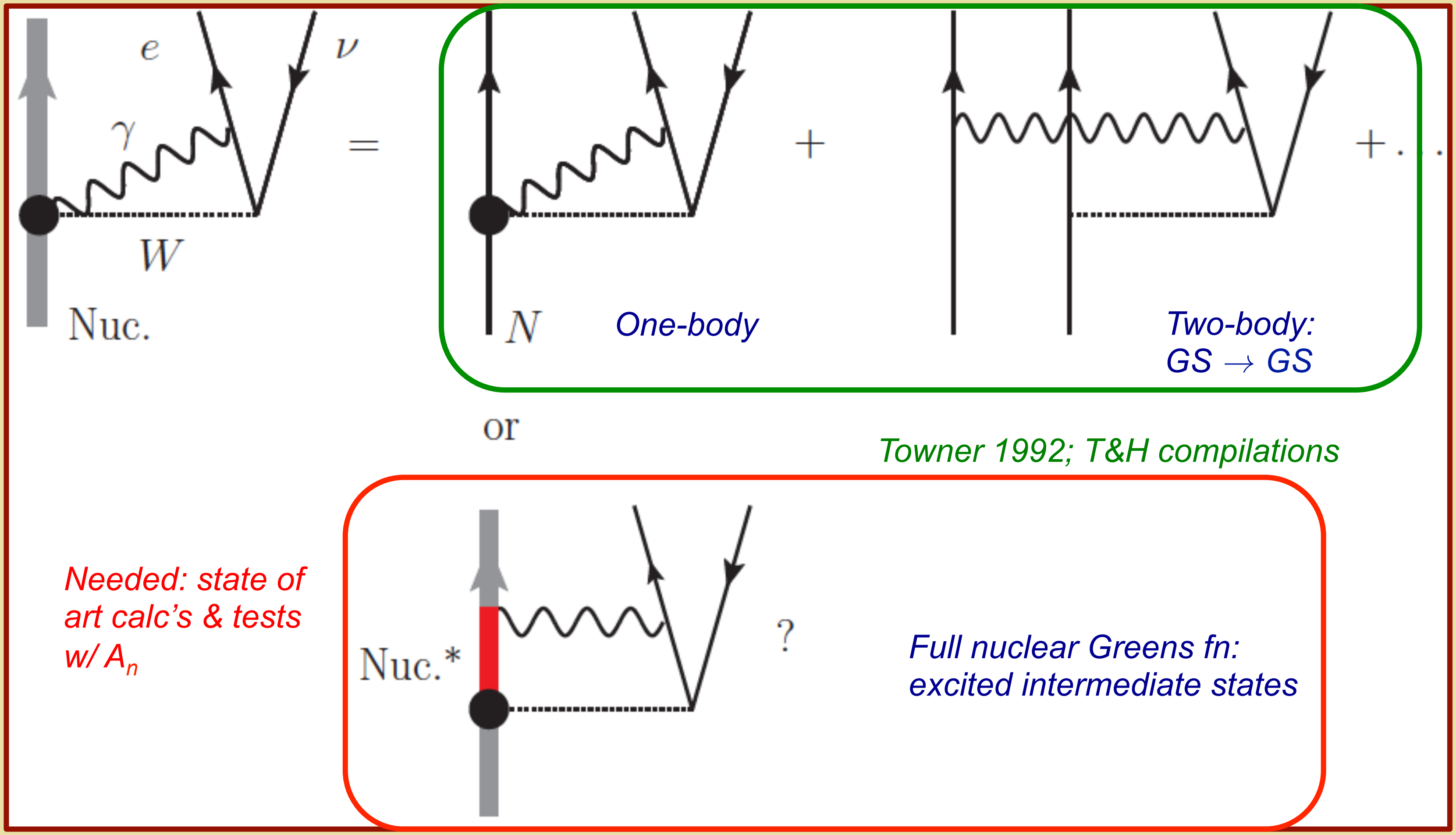
J. Engel

$0^+ \to 0^+$ Decay: δ_{NS}

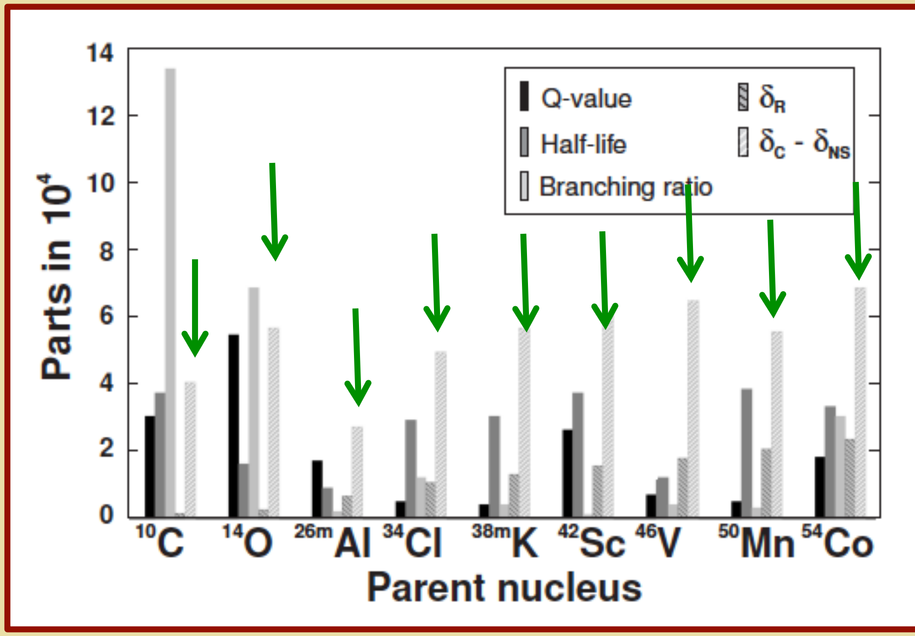


J. Engel

$0^+ \to 0^+$ Decay: δ_{NS}



$0^+ \rightarrow 0^+$ Dispersion Corrections: δ_{NS}



b_F : scalar currents

Input for V_{ud} & CKM unitarity test

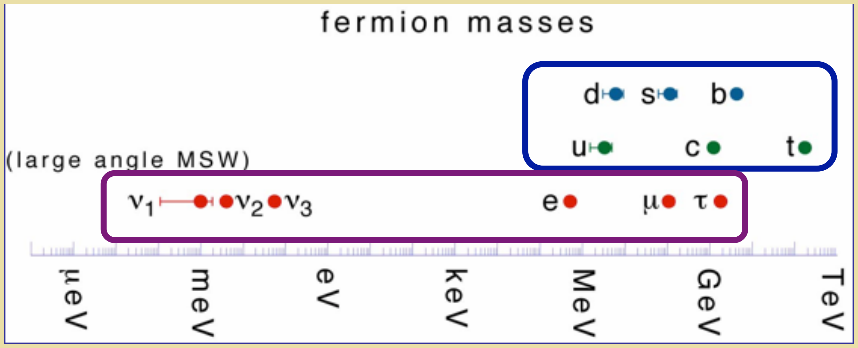
Towner & Hardy, PRC 91 (2015) 2, 025501

- *Re-compute with state-of-the-art many-body methods*
- *Test w/ A_n predictions & expt for ^{10}B, ^{14}N, ^{26}Mg, ^{34}S, ^{38}Ar, ^{42}Ca, ^{46}Ti, ^{50}Cr, ^{54}Fe*
- *Investigate strategy for obtaining reduced error bars*

III. PVES & m_ν

B. Dev, MRM, Y. Zhang in prog

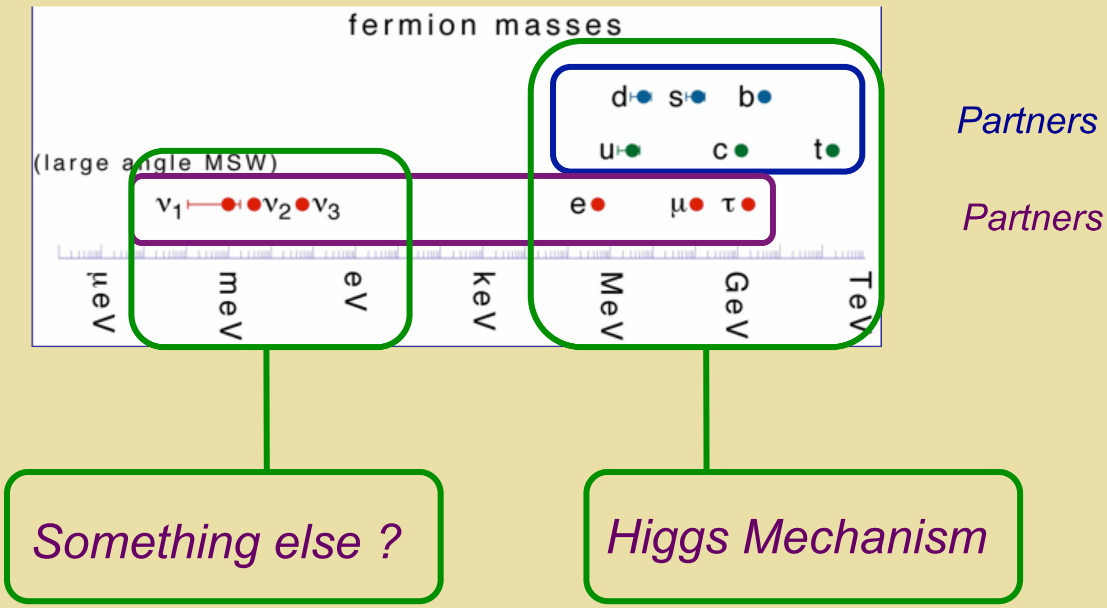
Neutrino Masses



Partners

Partners

Neutrino Masses



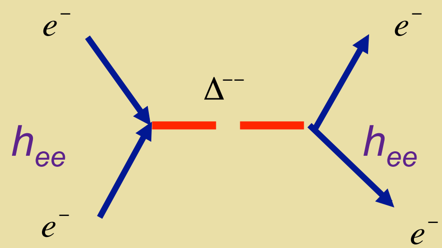
PV Moller: Type I, II See-Saw

PV Moller: Type I, II See-Saw

Left-Right Symmetric Model

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \mathrm{h.c.}$$

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix},$$



$$\mathcal{L}_\delta = \frac{g^2}{4} h_{ij} h^*_{km} \left[\frac{1}{M^2_{\delta^{++}_R}} (\bar{l}^c_{iR} l_{jR})(\bar{l}_{kR} l^c_{mR}) + (L \leftrightarrow R) \right].$$

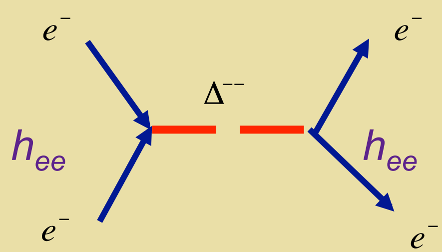
$$\boxed{\left| \frac{\Delta Q^e_W}{Q^e_W} \right| = 0.14 \, \frac{|h_{ee}|^2}{(M_\Delta / 1 \ \mathrm{TeV})^2}}$$

PV Moller: Type II See-Saw

Minimal type II See Saw

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] - \qquad + \text{h.c.}$$

$$\Delta_L = \begin{pmatrix} \Delta^+ \sqrt{2} & \Delta^+ \\ \Delta^0 & -\Delta^+ \sqrt{2} \end{pmatrix}$$



$$\mathcal{L}_{\delta} = \frac{g^2}{4} h_{ij} h^*_{km} \left[\frac{1}{M^2_{\delta_R^{++}}} (\bar{l}^c_{iR} l_{jR})(\bar{l}_{kR} l^c_{mR}) + (L \leftrightarrow R) \right].$$

$$\boxed{\left| \frac{\Delta Q_W^e}{Q_W^e} \right| = 0.14 \, \frac{|h_{ee}|^2}{(M_\Delta / 1 \text{ TeV})^2}}$$

0νββ-Decay: Type II See-Saw

$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \ + \ {\rm h.c.}$$

Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \ + \ {\rm h.c.}$$

Majorana

Introduce "Complex Triplet": Δ_L ~ (1, 3, 2)

$$\Delta_L = \begin{pmatrix} \Delta^+\sqrt{2} & \Delta^+ \\ \Delta^0 & -\Delta^+\sqrt{2} \end{pmatrix}$$

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + {\rm h.c.}$$

0νββ-Decay: Type II See-Saw

$$\mathcal{L}_{\text{mass}} = y\bar{L}\tilde{H}\nu_R \; + \; \text{h.c.}$$

Dirac

$$\mathcal{L}_{\text{mass}} = \frac{y}{\Lambda}\bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Introduce "Complex Triplet": Δ_L ~ (1, 3, 2)

$$\Delta_L = \begin{pmatrix} \Delta^+\sqrt{2} & \Delta^+ \\ \Delta^0 & -\Delta^+\sqrt{2} \end{pmatrix}$$

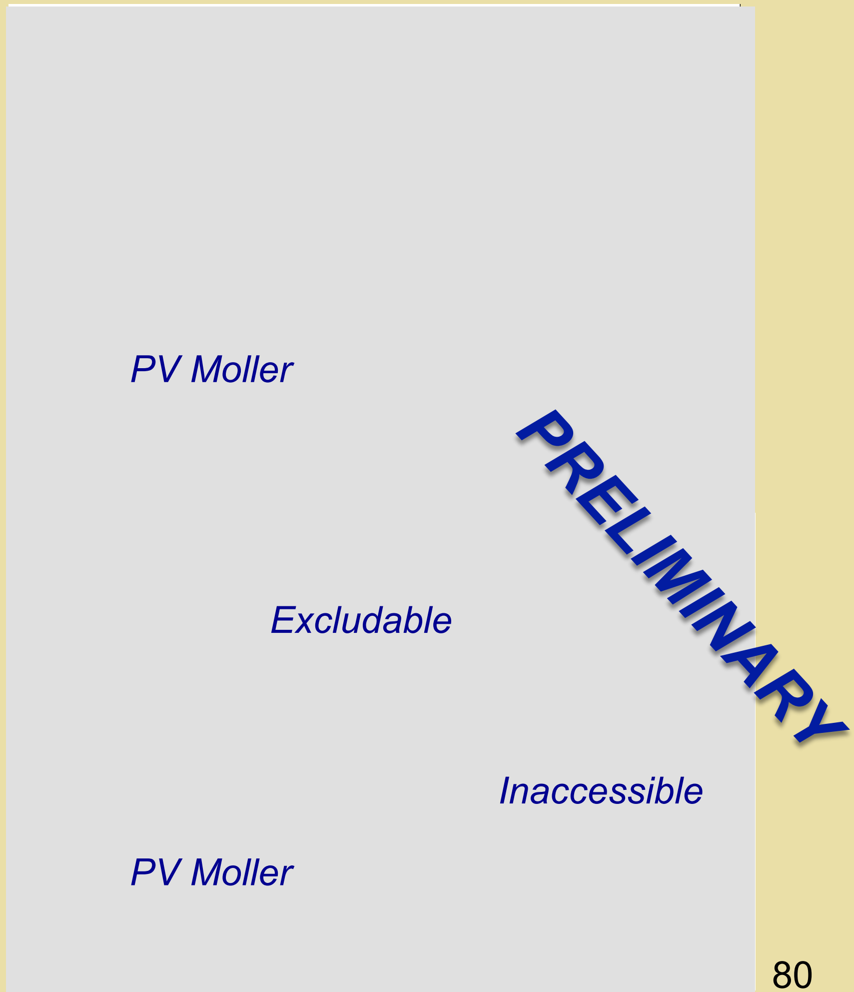
$$\boxed{(m_\nu)_{ij} \propto g h_{ij} \langle \Delta_L^0 \rangle}$$

$$\boxed{\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + \text{h.c.}}$$

h_{ee} linked to neutrino & CLFV pheno

PV Moller & Type II See-Saw

parameters	NH	IH
Δm^2_{21} [eV^2]	$(7.53 \pm 0.18) \times 10^{-5}$	$(7.53 \pm 0.18) \times 10^{-5}$
$\lvert\Delta m^2_{32}\rvert$ [eV^2]	$(2.45 \pm 0.05) \times 10^{-3}$	$(2.52 \pm 0.05) \times 10^{-3}$
$\sin^2\theta_{12}$	0.307 ± 0.013	0.307 ± 0.013
$\sin^2\theta_{23}$	0.51 ± 0.04	0.50 ± 0.04
$\sin^2\theta_{12}$	0.021 ± 0.0011	0.021 ± 0.0011
δ_{CP}	$[0,\ 2\pi]$	$[0,\ 2\pi]$
α	$[0,\ 2\pi]$	$[0,\ 2\pi]$
β	$[0,\ 2\pi]$	$[0,\ 2\pi]$



Neutrino phenomenology

B. Dev, MJRM, Yongchao Zhang in preparation

PV Moller & Type II See-Saw

process	current data	constraints $\left[\left(\frac{M^2_{\pm\pm}}{100\,\mathrm{GeV}}\right)^2\right]$	constraints on $\left(\frac{v_\Delta}{\mathrm{eV}}\right)\left(\frac{M_L^{\pm\pm}}{100\,\mathrm{GeV}}\right)$ NH $m_1 = 0$ ($m_1 = 0.05$ eV)	IH $m_3 = 0$ ($m_3 = 0.05$ eV)
$\mu^- \to e^- e^+ e^-$	$< 1.0 \times 10^{-12}$	$\lvert f^\dagger_{ee} f_{e\mu}\rvert < 2.3 \times 10^{-7}$	4.6 (36)	23 (43)
$\tau^- \to e^- e^+ e^-$	$< 2.7 \times 10^{-8}$	$\lvert f^\dagger_{ee} f_{e\tau}\rvert < 9.1 \times 10^{-5}$	0.23 (1.8)	1.2 (2.2)
$\tau^- \to e^- \mu^+ \mu^-$	$< 2.7 \times 10^{-8}$	$\lvert f^\dagger_{e\mu} f_{\mu\tau}\rvert < 5.2 \times 10^{-5}$	1.1 (1.0)	1.1 (1.2)
$\tau^- \to \mu^- e^+ \mu^-$	$< 1.7 \times 10^{-8}$	$\lvert f^\dagger_{e\tau} f_{\mu\mu}\rvert < 6.8 \times 10^{-5}$	1.1 (2.4)	0.97 (2.4)
$\tau^- \to \mu^- e^+ e^-$	$< 1.8 \times 10^{-8}$	$\lvert f^\dagger_{e\mu} f_{e\tau}\rvert < 6.4 \times 10^{-5}$	0.55 (1.1)	0.47 (1.1)
$\tau^- \to e^- \mu^+ e^-$	$< 1.5 \times 10^{-8}$	$\lvert f^\dagger_{ee} f_{\mu\tau}\rvert < 7.4 \times 10^{-5}$	0.47 (1.6)	2.9 (2.3)
$\tau^- \to \mu^- \mu^+ \mu^-$	$< 2.1 \times 10^{-8}$	$\lvert f^\dagger_{\mu\mu} f_{\mu\tau}\rvert < 6.8 \times 10^{-5}$	2.0 (1.9)	2.1 (2.2)
$\mu^- \to e^- \gamma$	$< 4.2 \times 10^{-13}$	$\lvert\sum_k f^\dagger_{ek} f_{\mu k}\rvert < 0.027$	6.9 (6.9)	6.9 (6.9)
$\tau^- \to e^- \gamma$	$< 3.3 \times 10^{-8}$	$\lvert\sum_k f^\dagger_{ek} f_{\tau k}\rvert < 0.0018$	0.27 (0.27)	0.27 (0.27)
$\tau^- \to \mu^- \gamma$	$< 4.4 \times 10^{-8}$	$\lvert\sum_k f^\dagger_{\mu k} f_{\tau k}\rvert < 0.0021$	0.52 (0.52)	0.54 (0.54)
electron $g-2$	$< 5.2 \times 10^{-13}$	$\sum_k \lvert f_{ek}\rvert^2 < 1.2$	0.0058 (0.033)	0.032 (0.045)
muon $g-2$	$< 4.0 \times 10^{-9}$	$\sum_k \lvert f_{\mu k}\rvert^2 < 0.17$	0.06 (0.1)	0.061 (0.11)
muonium oscillation	$< 8.2 \times 10^{-11}$	$\lvert f^\dagger_{ee} f_{\mu\mu}\rvert < 0.0012$	0.13 (1.1)	0.7 (1.3)
$ee \to ee$	$\Lambda_{\mathrm{eff}} > 5.2$ TeV	$\lvert f_{ee}\rvert^2 < 0.0012$	0.033 (0.98)	1.0 (1.4)
$ee \to \mu\mu$	$\Lambda_{\mathrm{eff}} > 7.0$ TeV	$\lvert f_{e\mu}\rvert^2 < 6.4 \times 10^{-4}$	0.17 (0.36)	0.15 (0.36)
$ee \to \tau\tau$	$\Lambda_{\mathrm{eff}} > 7.6$ TeV	$\lvert f_{e\tau}\rvert^2 < 5.4 \times 10^{-4}$	0.19 (0.39)	0.16 (0.39)

CLFV & other probes

PRELIMINARY

PV Moller

B. Dev, MJRM, Yongchao Zhang in preparation

PV Moller & Types I & II See-Saw: LRSM

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$

Type I see-saw *Type II see-saw*

$$\mathcal{L}_{\text{mass}} = \boxed{\begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}} + \boxed{m_L \bar{\nu}_L^C \nu_L}$$

$$m_N \sim g h_R \langle \Delta_R^0 \rangle \qquad m_L \sim g h_L \langle \Delta_L^0 \rangle$$

PV Moller & Types I & II See-Saw: LRSM

Two sources of m_ν :

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.}$$

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$$m_N \sim g h_R \left\langle \Delta_R^0 \right\rangle$$

$$m_L \sim g h_L \left\langle \Delta_L^0 \right\rangle$$

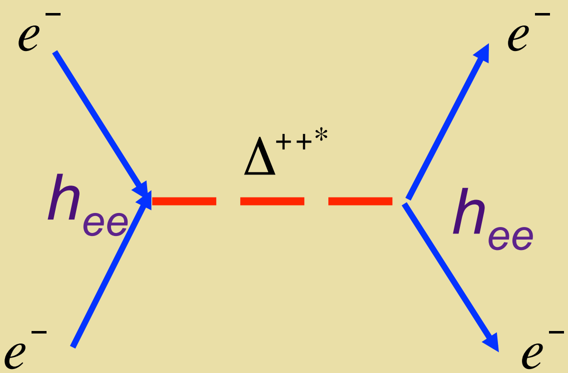
h_{ee}^R not tightly linked to neutrino & CLFV pheno

Moller & LNV: Phenomenology

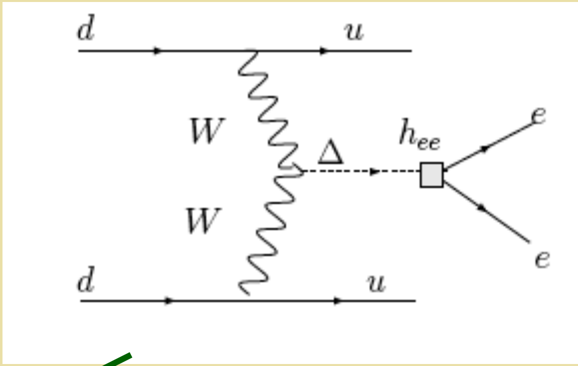
Left-Right Symmetric Model

$$\mathcal{L} = \frac{g}{2} h_{ij} \left[\bar{L}^{C_i} \varepsilon \Delta_L L^j \right] + (L \leftrightarrow R) + \text{h.c.} \qquad \Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix},$$

PV Moller



0νββ Decay



$$h^R_{ee} < 10^{-7} \times (M_{W_R}/100 \text{ GeV})^3 (M_\Delta/100 \text{ GeV})^2$$

PV Moller & Type II See-Saw: LRSM

PRELIMINARY

$0\nu\beta\beta$ decay constraints

B. Dev, MJRM, Yongchao Zhang in preparation

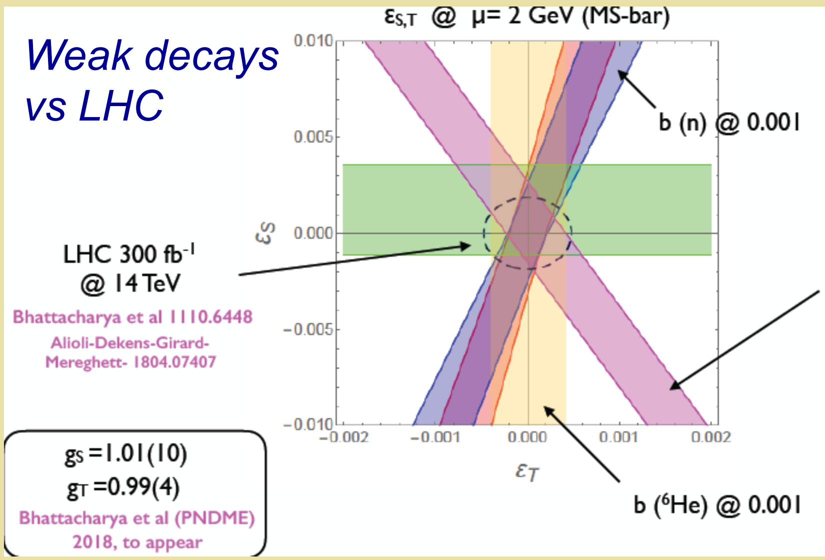
PV Moller & Type II See-Saw: LRSM

PRELIMINARY

B. Dev, MJRM, Yongchao Zhang in preparation

IV. Leptoquarks

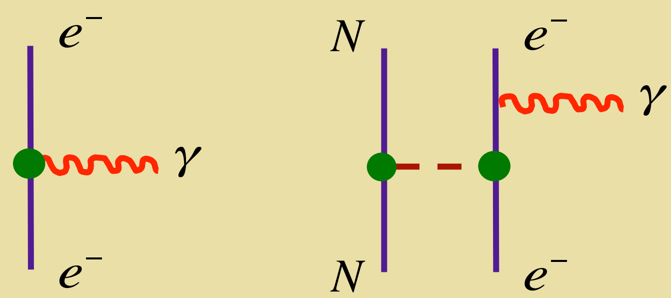
V. Cirigliano, MJRM, T. Shen in prog



- *To what extent does use of EFT operator adequately represent LHC reach ?*

K. Fuyuto, MJRM, T. Shen

Time reversal tests: Paramagnetic Systems



- *Does the electron EDM always dominate ?*

Leptoquarks: β-Decay & the LHC

General Classification: Buchmuller, Ruckl, Wyler

$$
\begin{aligned}
\mathcal{L}_{F=0} \quad &= (h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R l_L \tilde{R}_2 \\
&+(h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} \\
&+\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L\vec{U}_{3\mu} + c.c.
\end{aligned}
$$

Leptoquarks: β-Decay & the LHC

General Classification: Buchmuller, Ruckl, Wyler

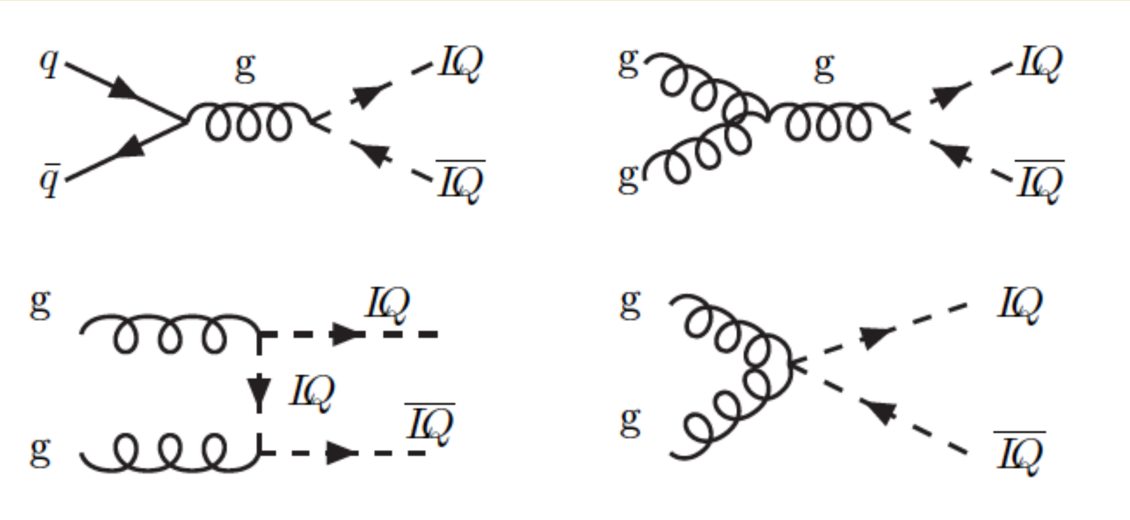
$$\begin{aligned}\mathcal{L}_{F=0} \quad &= \boxed{(h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2} + \tilde{h}_{2L}\bar{d}_R l_L \tilde{R}_2 \\ &+(h_{1L}\bar{q}_L\gamma^\mu l_L + h_{1R}\bar{d}_R\gamma^\mu e_R)U_{1\mu} \\ &+\tilde{h}_{1R}\bar{u}_R\gamma^\mu e_R\tilde{U}_{1\mu} + h_{3L}\bar{q}_L\vec{\tau}\gamma^\mu l_L\vec{U}_{3\mu} + c.c.\end{aligned}$$

Scalar & Tensor Interactions

$$\begin{aligned}&-\frac{1}{2}\frac{h_{2L}h_{2R}^*}{M_{R_2}^2}\epsilon^{ij}\left(\overline{u}_R q_L^j\right)\left(\overline{e}_R \ell_L^i\right) \\ &-\frac{1}{8}\frac{h_{2L}h_{2R}^*}{M_{R_2}^2}\epsilon^{ij}\left(\overline{u}_R\sigma^{\mu\nu}q_L^j\right)\left(\overline{e}_R\sigma_{\mu\nu}\ell_L^i\right)\end{aligned}$$

Leptoquarks: LHC production

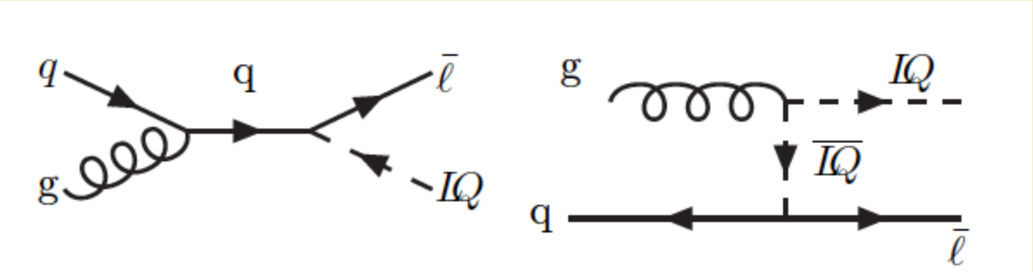
Pair production



Decays: final states

- $\ell\ell jj$
- $\ell\nu jj$

Single LQ production



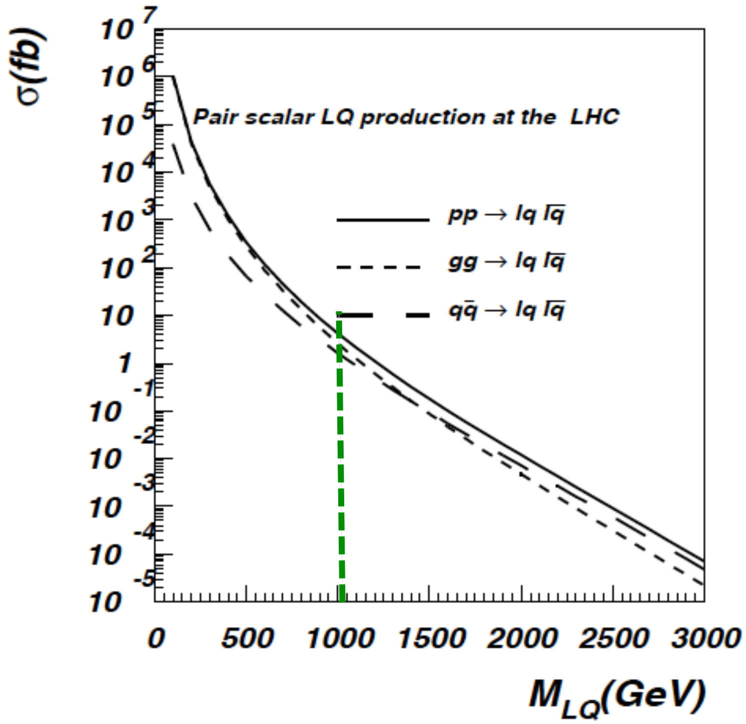
- $\ell\ell j$
- $\ell\nu j$

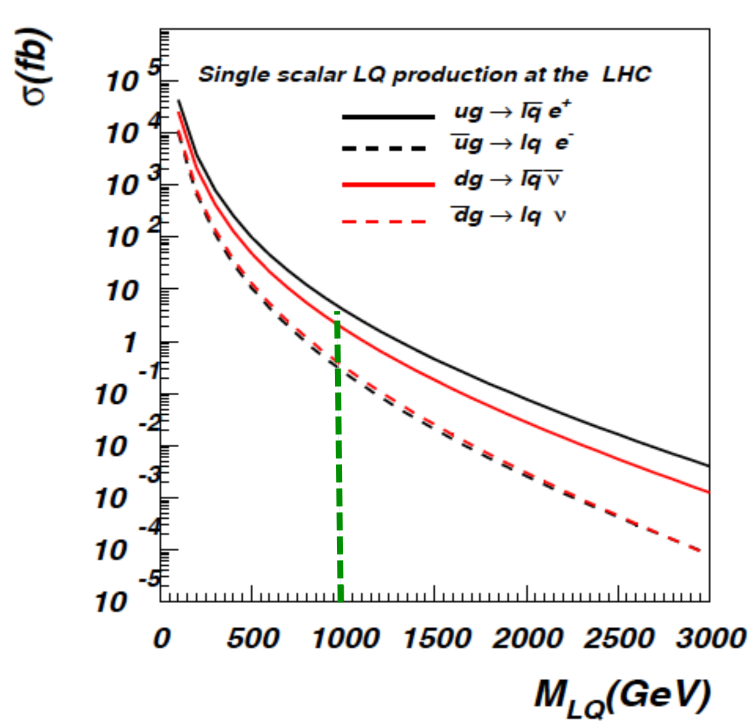
Belyaev et al '05

Leptoquarks: LHC production

Pair production

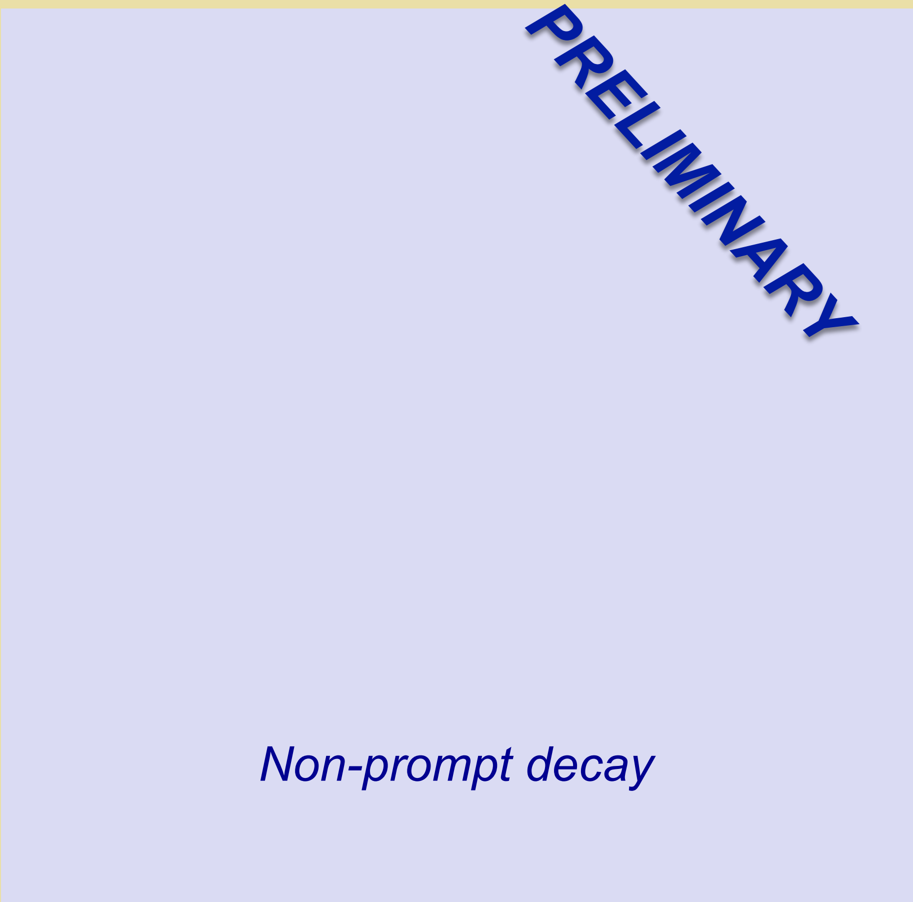
Single LQ production





Belyaev et al '05

Leptoquarks: β-Decay & the LHC



- Exclusion from eej channel at $\mathcal{L}$=300fb^{-1}
- Exclusion from eej channel at $\mathcal{L}$=100fb^{-1}
- Exclusion from eejj channel at $\mathcal{L}$=300fb^{-1}
- Exclusion from eejj channel at $\mathcal{L}$=100fb^{-1}
- Exclusion from eνjj channel at $\mathcal{L}$=300fb^{-1}
- Exclusion from eνjj channel at $\mathcal{L}$=100fb^{-1}
- Exclusion from **weak decays**

V. Cirigliano, MJRM, T. Shen in prog

Detailed Monte Carlo sim; validate w/ 8 TeV data; Boosted decision tree

Leptoquarks: β-Decay & the LHC

- Exclusion from eej channel at $\mathcal{L}$=300fb^{-1}
- Exclusion from eej channel at $\mathcal{L}$=100fb^{-1}
- Exclusion from eejj channel at $\mathcal{L}$=300fb^{-1}
- Exclusion from eejj channel at $\mathcal{L}$=100fb^{-1}
- Exclusion from eνjj channel at $\mathcal{L}$=300fb^{-1}
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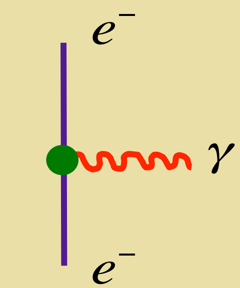
V. Cirigliano, MJRM, T. Shen in prog

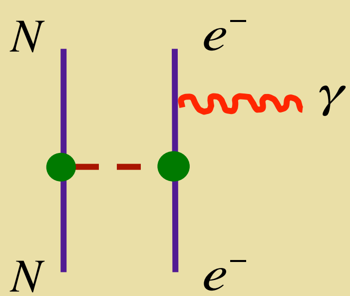
Detailed Monte Carlo sim; validate w/ 8 TeV data; Boosted decision tree

Paramagnetic EDMs: Two Sources

Electron EDM



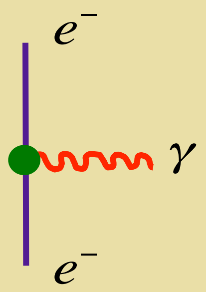
(Scalar q) x (PS e⁻)

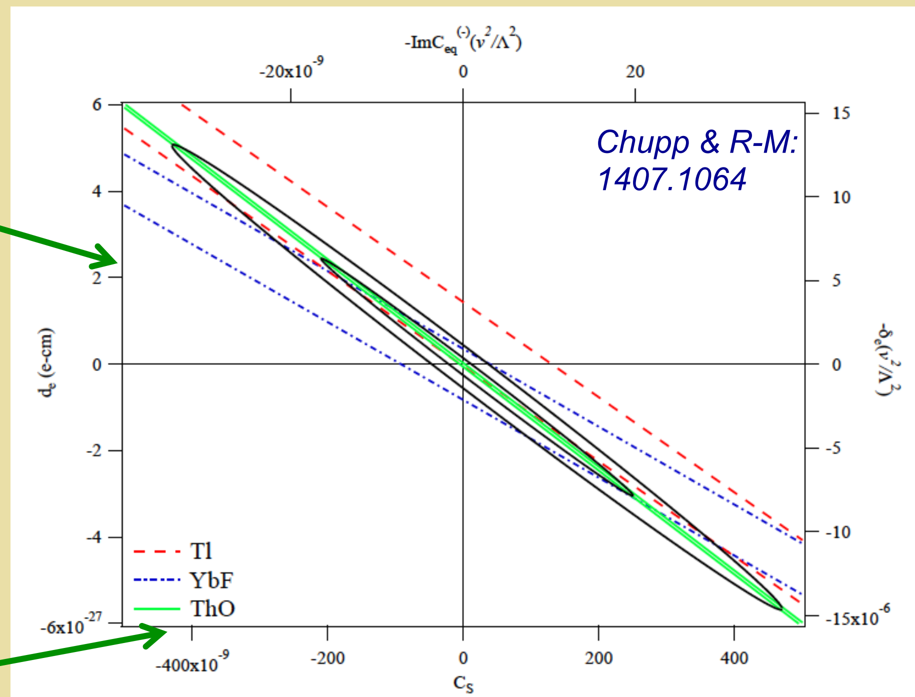


Tl, YbF, ThO…

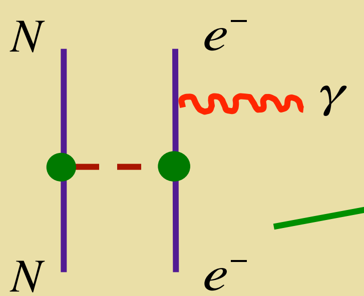
Paramagnetic EDMs: Two Sources

Electron EDM





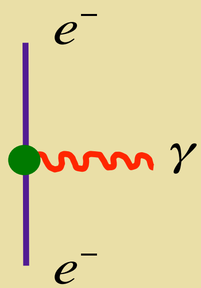
(Scalar q)
x (PS e$^-$)

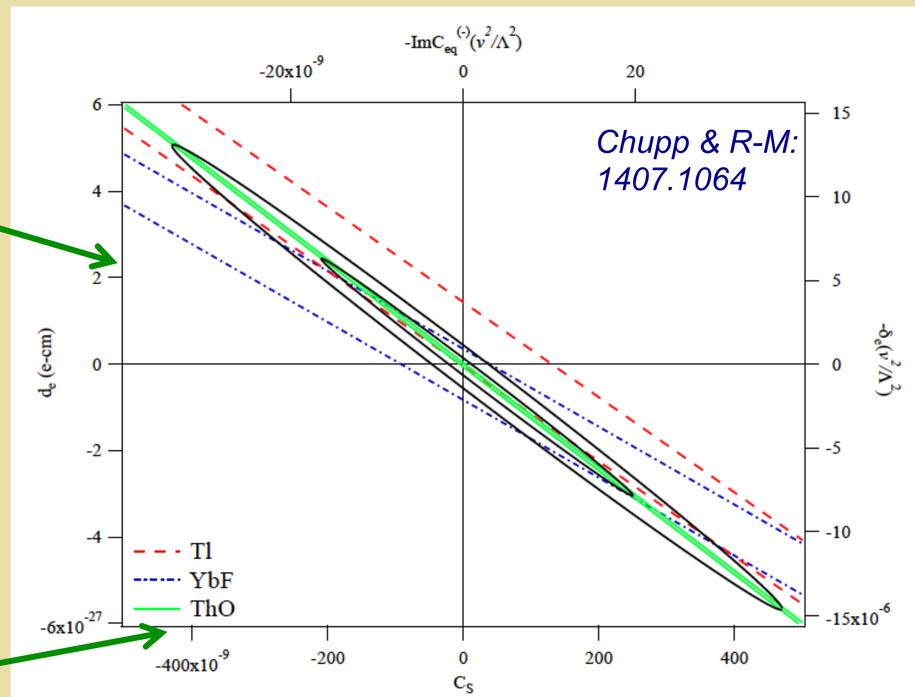


Tl, YbF, ThO…

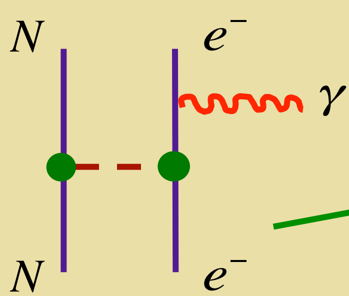
Paramagnetic EDMs: Two Sources

Electron EDM





(Scalar q) x (PS e-)

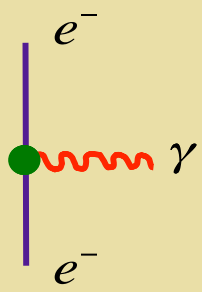


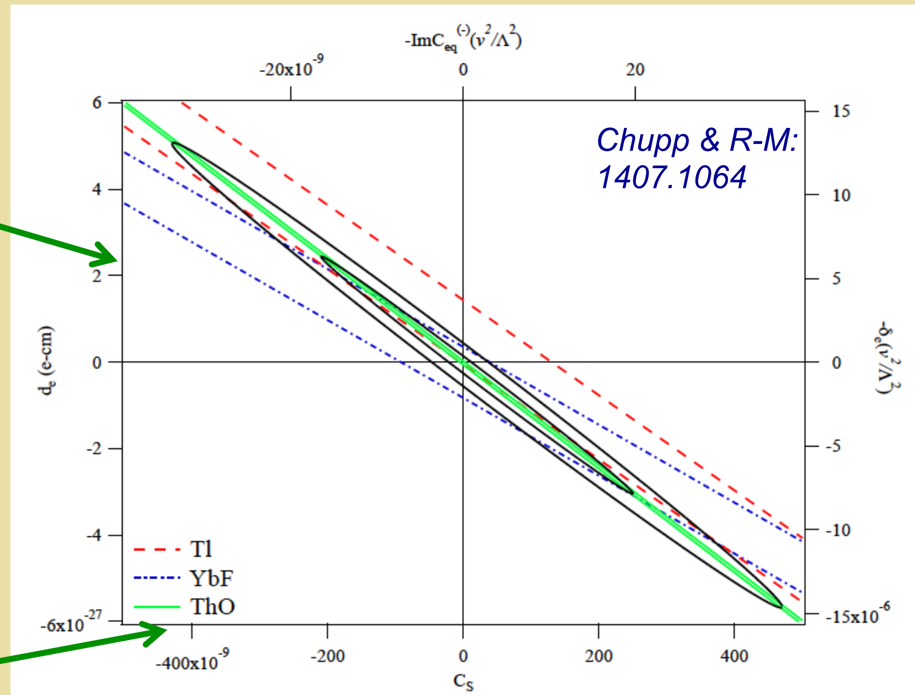
$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	C_S (global)

Tl, YbF, ThO…

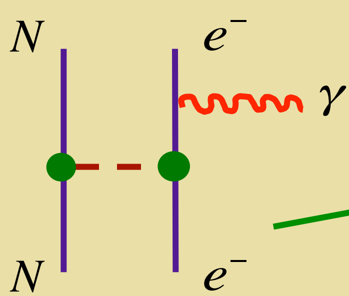
Paramagnetic EDMs: Two Sources

Electron EDM





(Scalar q) x (PS e-)



$\Lambda \gtrsim (1.5\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	Electron EDM (global)
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$	C_S (global)

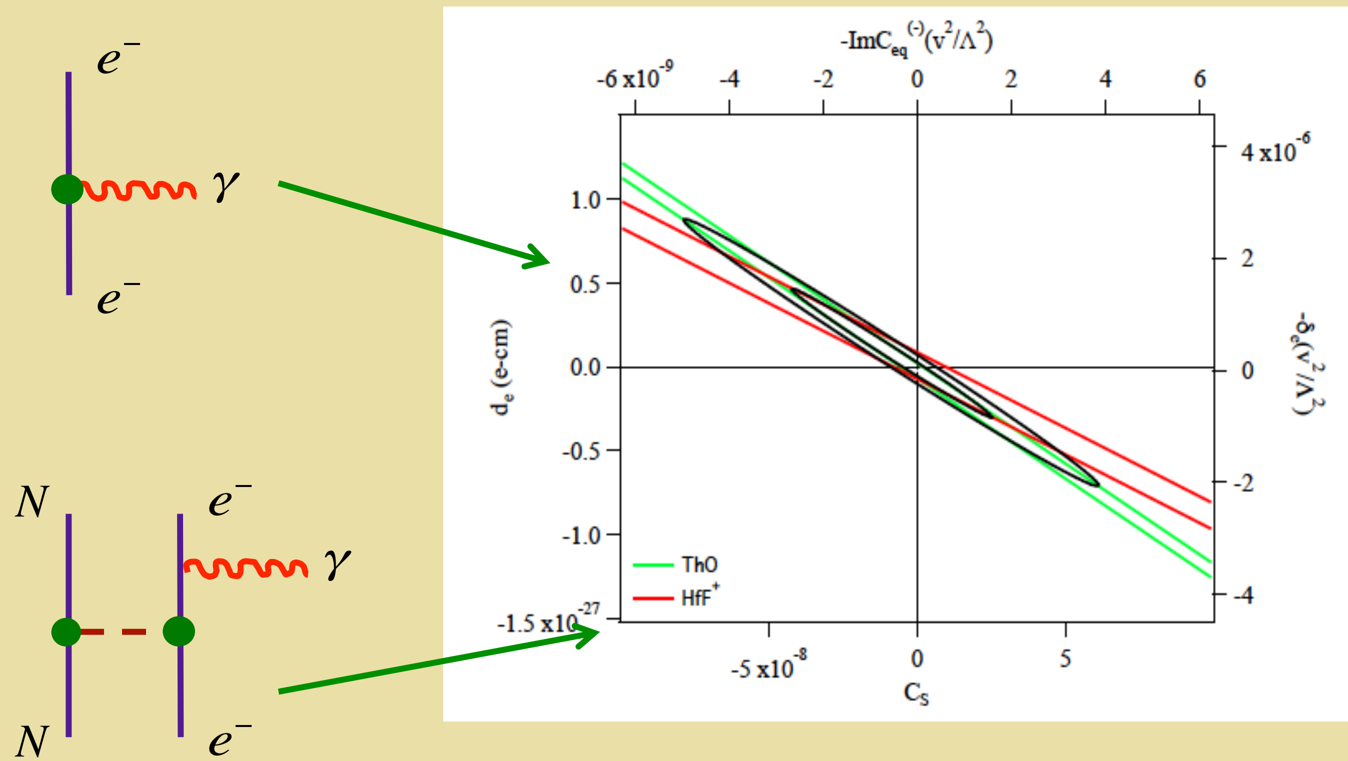
LHC inaccessible

Tl, YbF, ThO…

Paramagnetic EDMs: Two Sources

Electron EDM

(Scalar q) x (PS e^-)



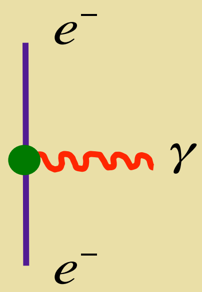
Chupp, Fierlinger, R-M, Singh 1710.02504; Fleig & Jung 1802.02171

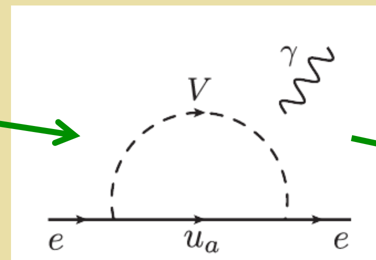
Inclusion of HfF+ : ~ 6 times stronger bounds on d_e & $C_S \rightarrow$ 2.5 higher on Λ

Tl, YbF, ThO, HfF+

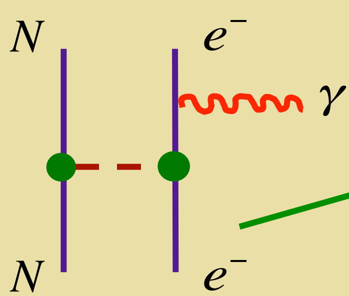
Illustrative Example: Leptoquark Model

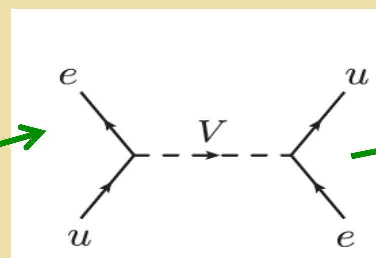
Electron EDM

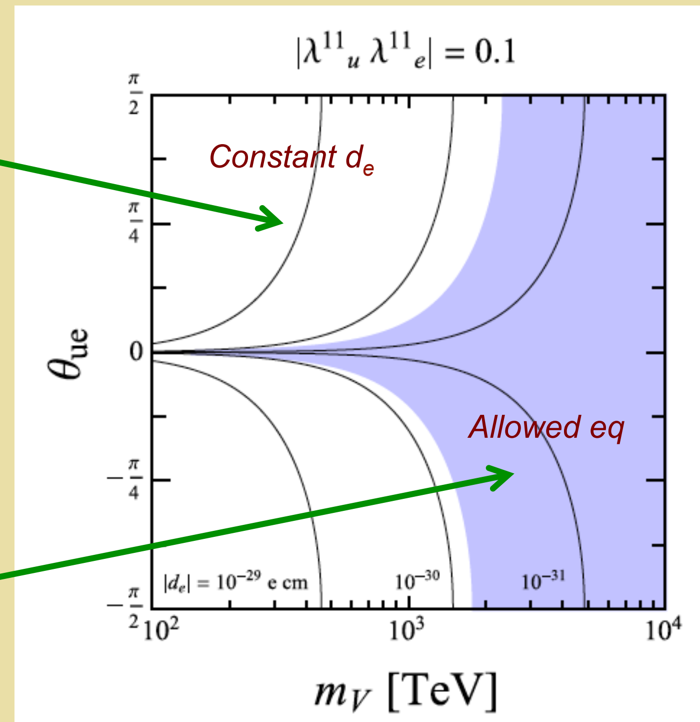




(Scalar q)
x (PS e⁻)







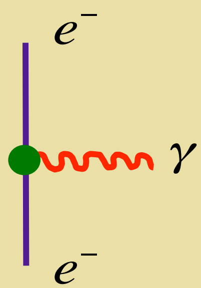
Fuyuto, R-M, Shen 1804.01137

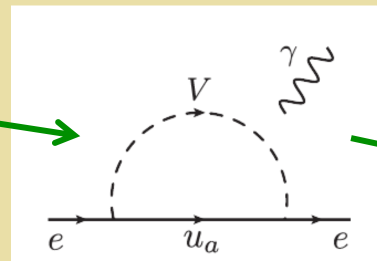
(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

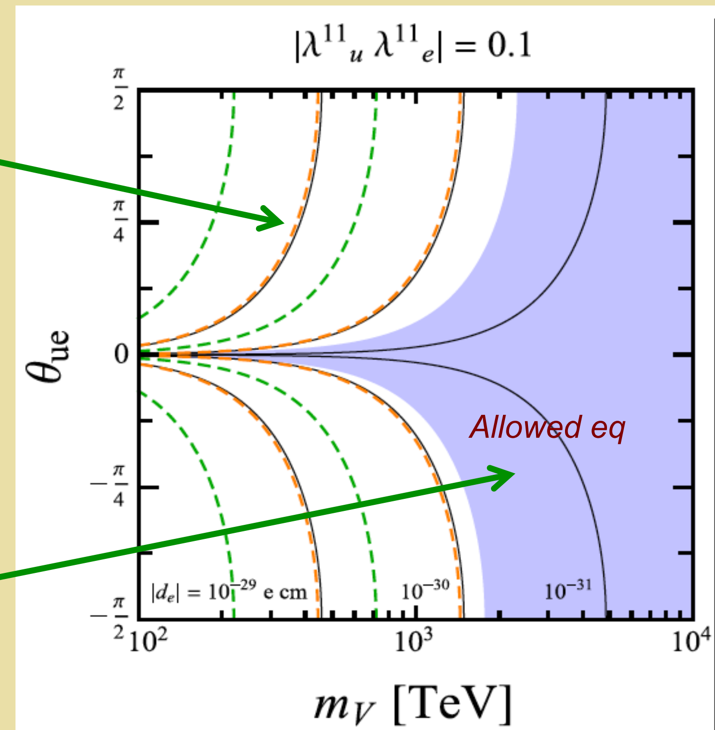
Illustrative Example: Leptoquark Model

Electron EDM

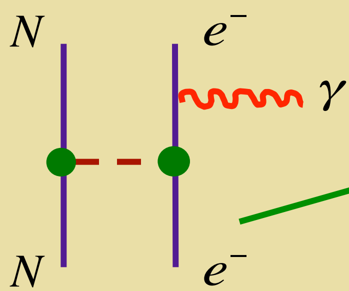


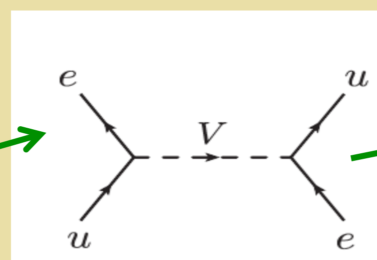


Orange: $|d_p|$ = 10^{-30} , 10^{-31} e cm
Green: $|d_n|$ = 10^{-30} , 10^{-31} e cm



(Scalar q) x (PS e$^-$)





Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

$$\mathcal{L} \ni -\lambda_u^{ab} \bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab} \bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

V. Outlook

- *Studies of parity violation continue to provide unique probes of both Standard Model & beyond Standard Model physics*
- *Obtaining a more robust description of weak interactions in nuclei is a "next frontier" for PV & Standard Model physics, with important implications for the interpretation of $0\nu\beta\beta$ decay, CKM unitarity tests, nuclear Schiff moments…*
- *Interplay of PV studies with other low-energy symmetry tests (CLFV, $0\nu\beta\beta$ decay, EDMs), neutrino pheno, & energy frontier probes will yield important insights into key open BSM questions: origin of m_ν, Λ_{BSM}, …*

Thanks UMass Amherst & MITP Mainz !