BSM Physics: Nuclei as Laboratories

M.J. Ramsey-Musolf

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

My pronouns: he/him/his

Nuclei as BSM Laboratories
ECT* April 2019

Key Theme for This Talk

- *Fundamental questions motivate the search for physics beyond the Standard Model*
- *Tests of fundamental symmetries at low-energy are poised to*
  - *discover the BSM physics that answers several of these questions*
  - *determine its character*
- *Robust hadronic & nuclear computations plus high sensitivity experiments are essential*

Goals For This Talk

- *Put nuclear tests of fundamental symmetries & neutrino property studies in broader BSM context*
- *Highlight a few areas of inter-frontier implications*
- *Emphasize new directions for theoretical work*

Outline

I. The BSM Context — **Origin of Matter**

II. Lepton Number

III. CP (Flavor Conserving)

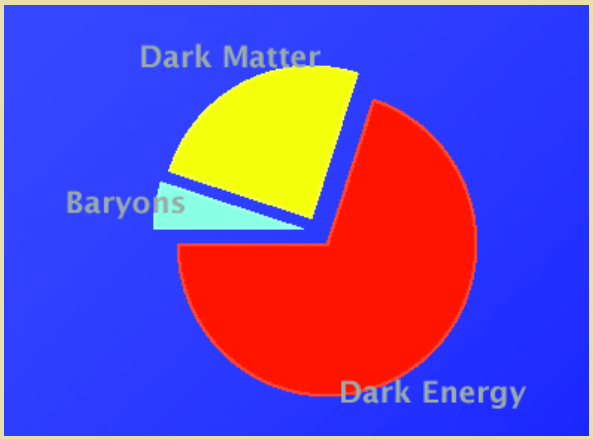
IV. Precision Tests: β-Decay Highlight

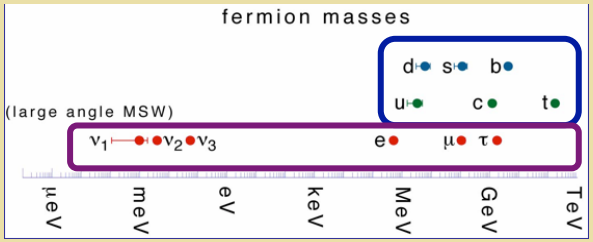
V. Outlook — **BSM Mass Scale**

I. The BSM Context

Fundamental Questions

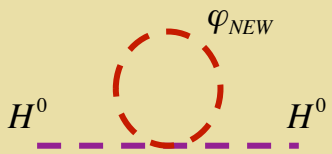
***MUST** answer*





Origin of m_ν

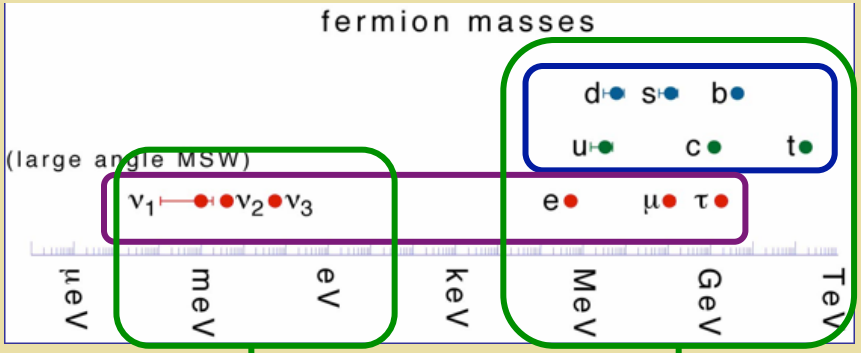
***SHOULD** answer*



$\Delta m^2 \sim \lambda \Lambda^2$

Λ *Cosmological*

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

BSM Physics: Where Does it Live ?

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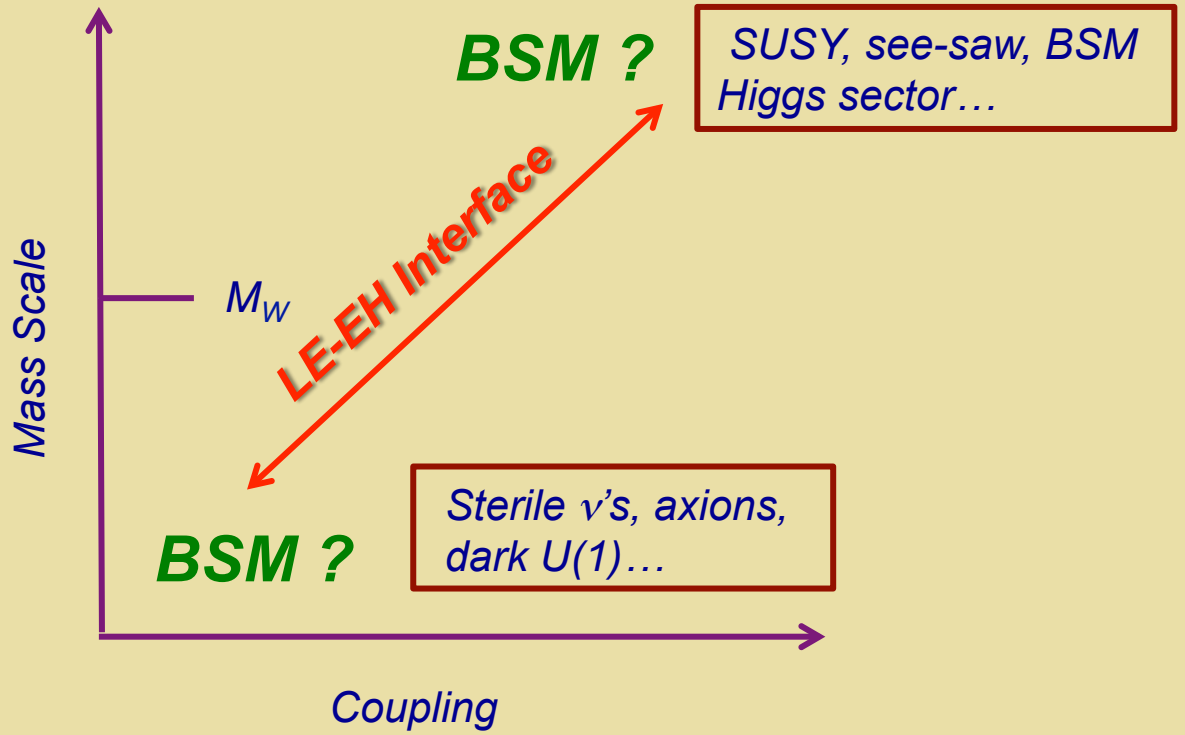
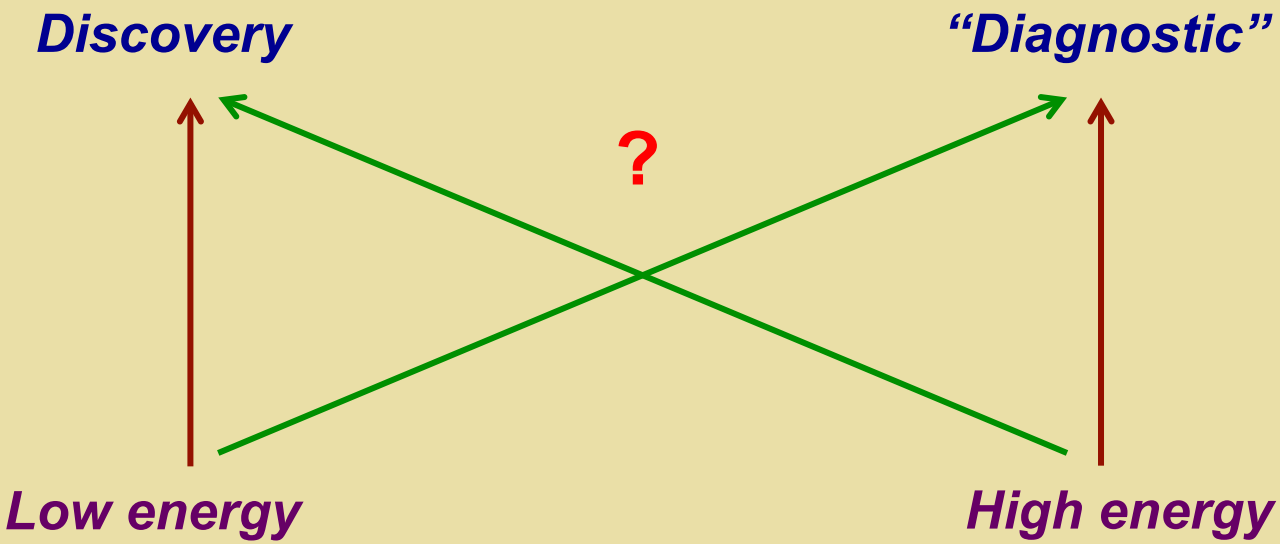


Low-Energy / High-Energy Interplay



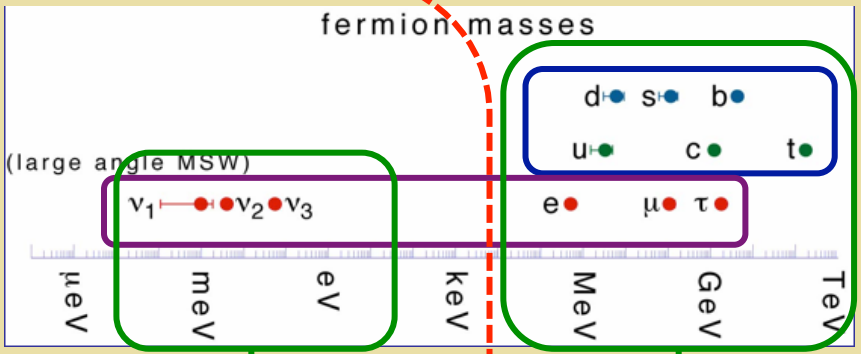
II. Lepton Number

Highlight: TeV LNV

Collaborators: T. Peng, P. Winslow; J. Harz, S. Quirroga, S. Shen

PRD 93 (2016) 093002

Fermion Masses & Baryon Asymmetry



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LNV & ν studies

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

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

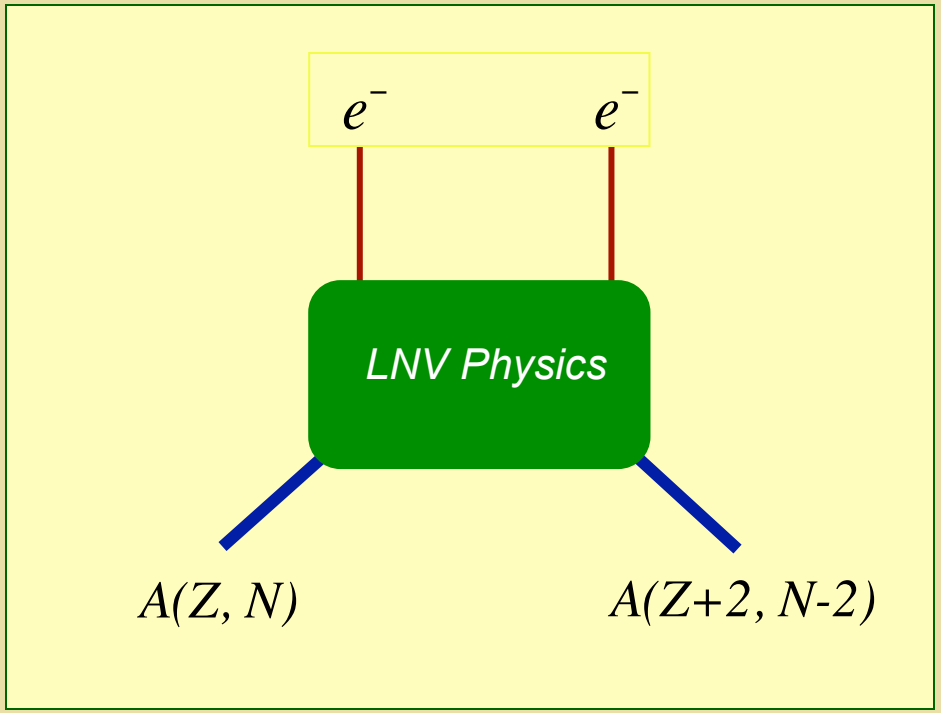
Dirac

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

Majorana

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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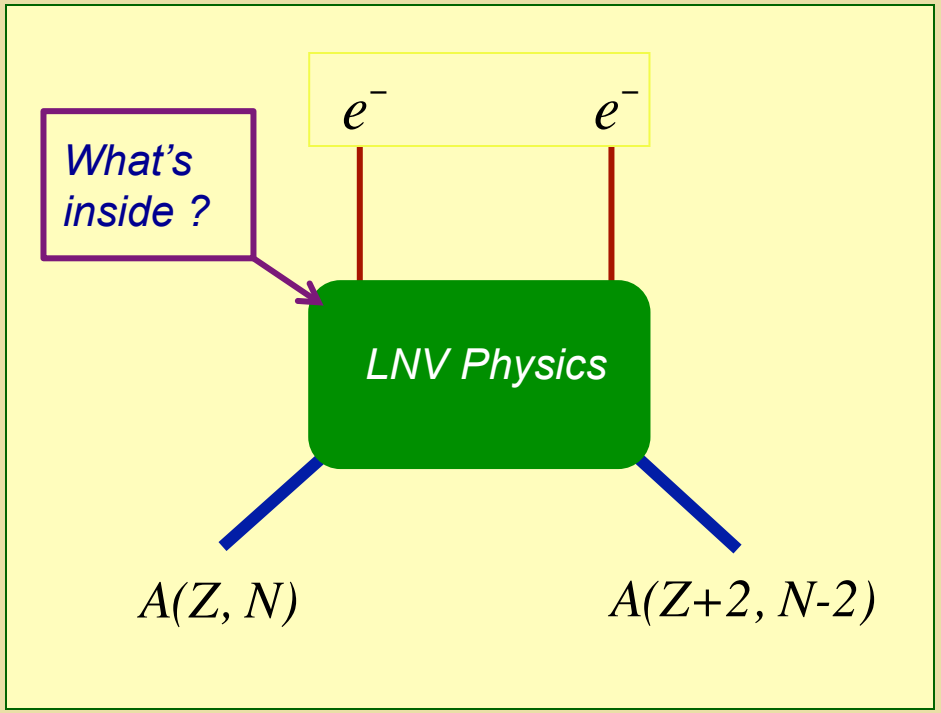
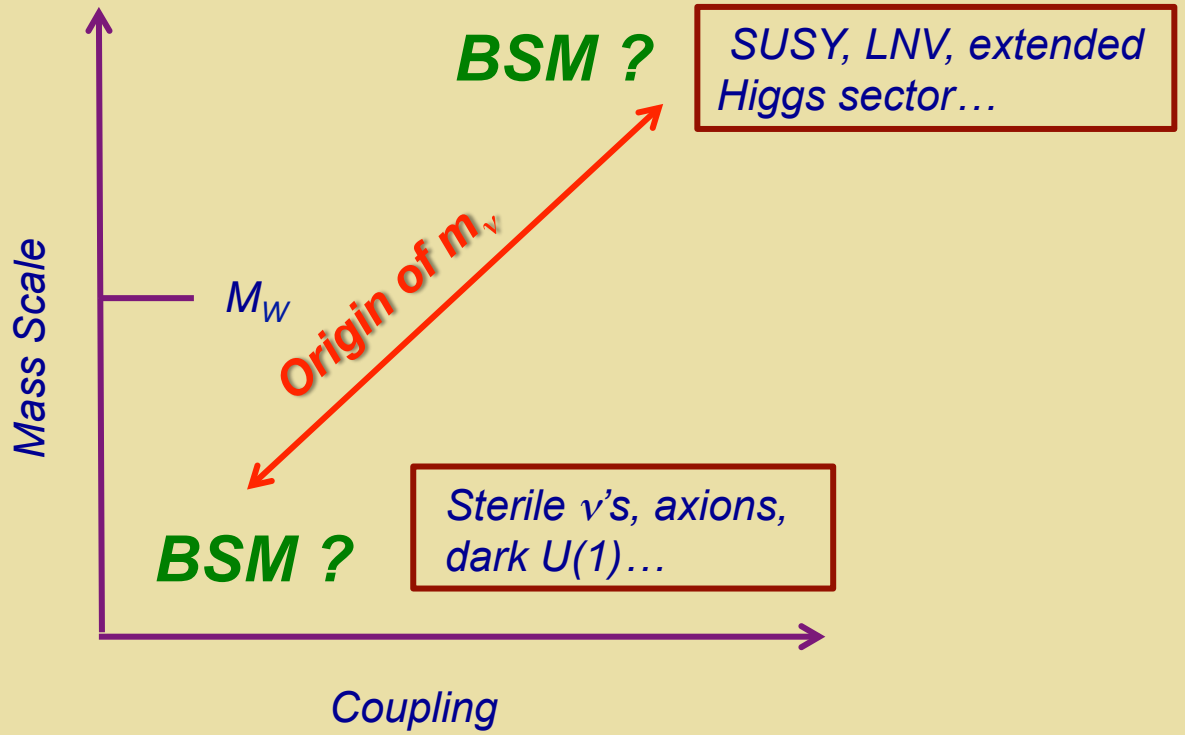


BSM Physics: Where Does it Live ?



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*

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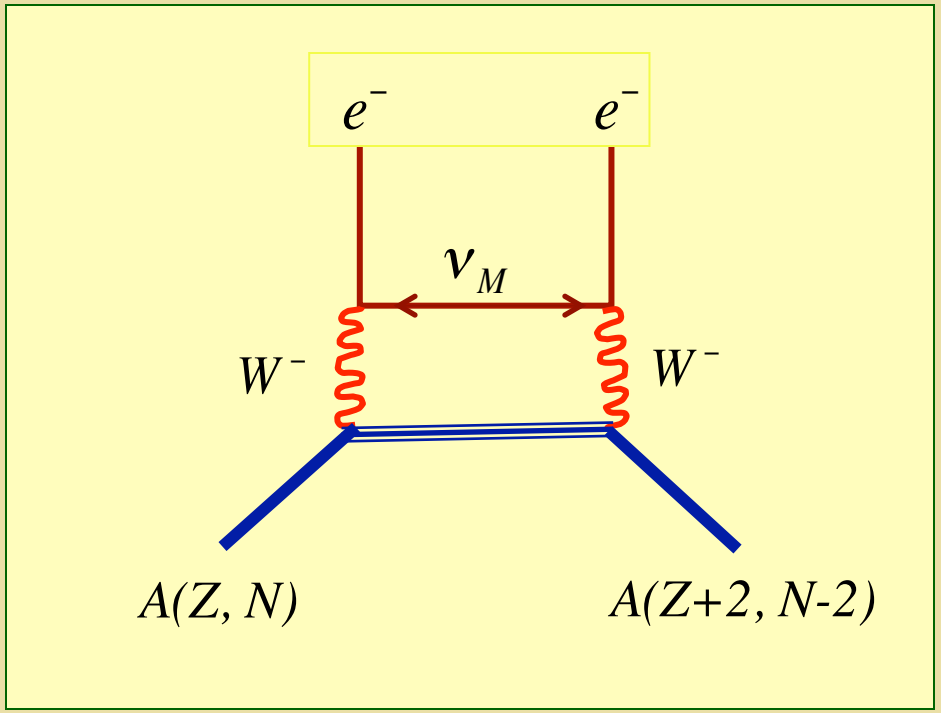
Majorana

"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*



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Two parameters: Effective coupling & effective heavy particle mass

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

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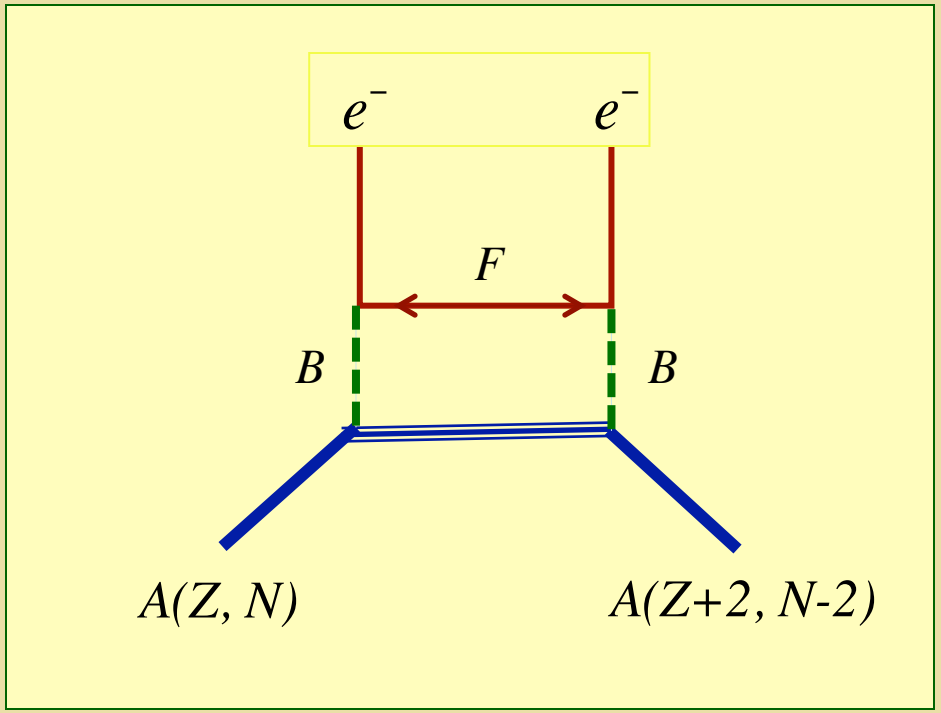
Majorana

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*



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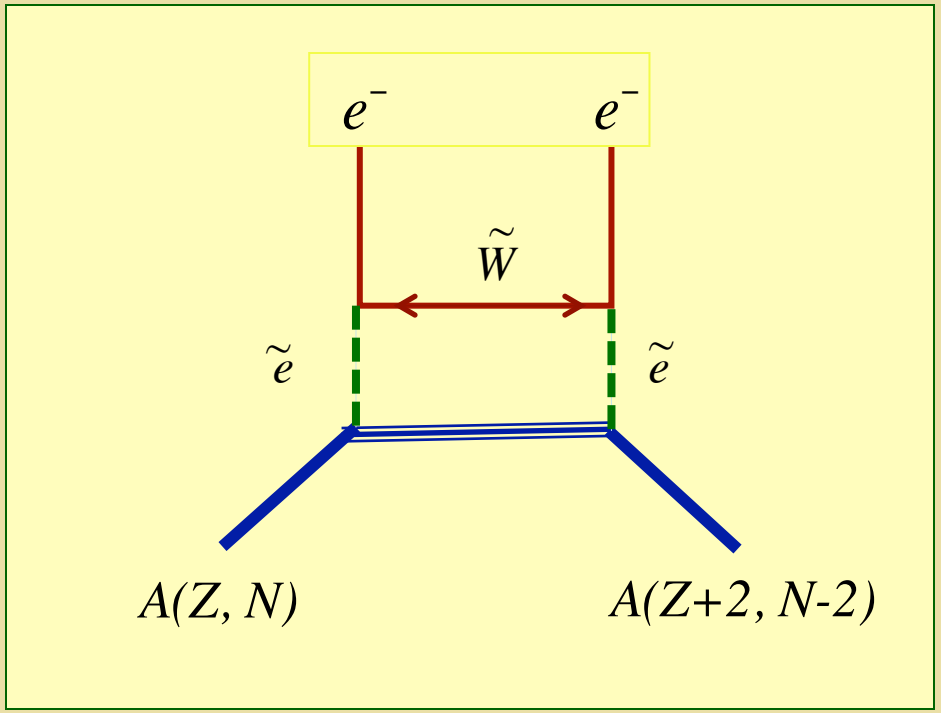

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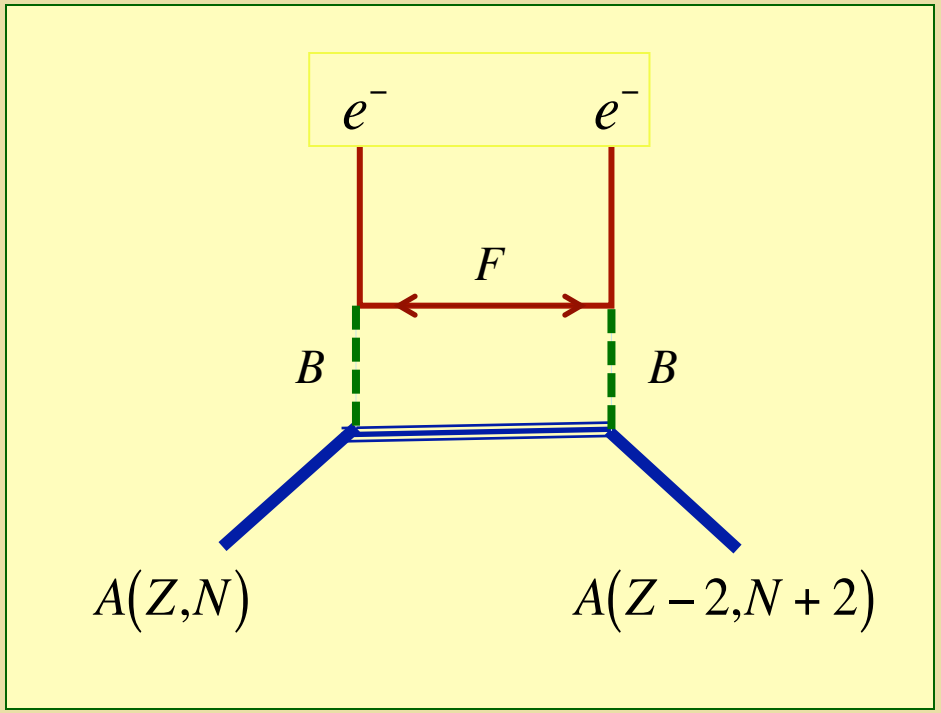
Majorana

TeV LNV Mechanism

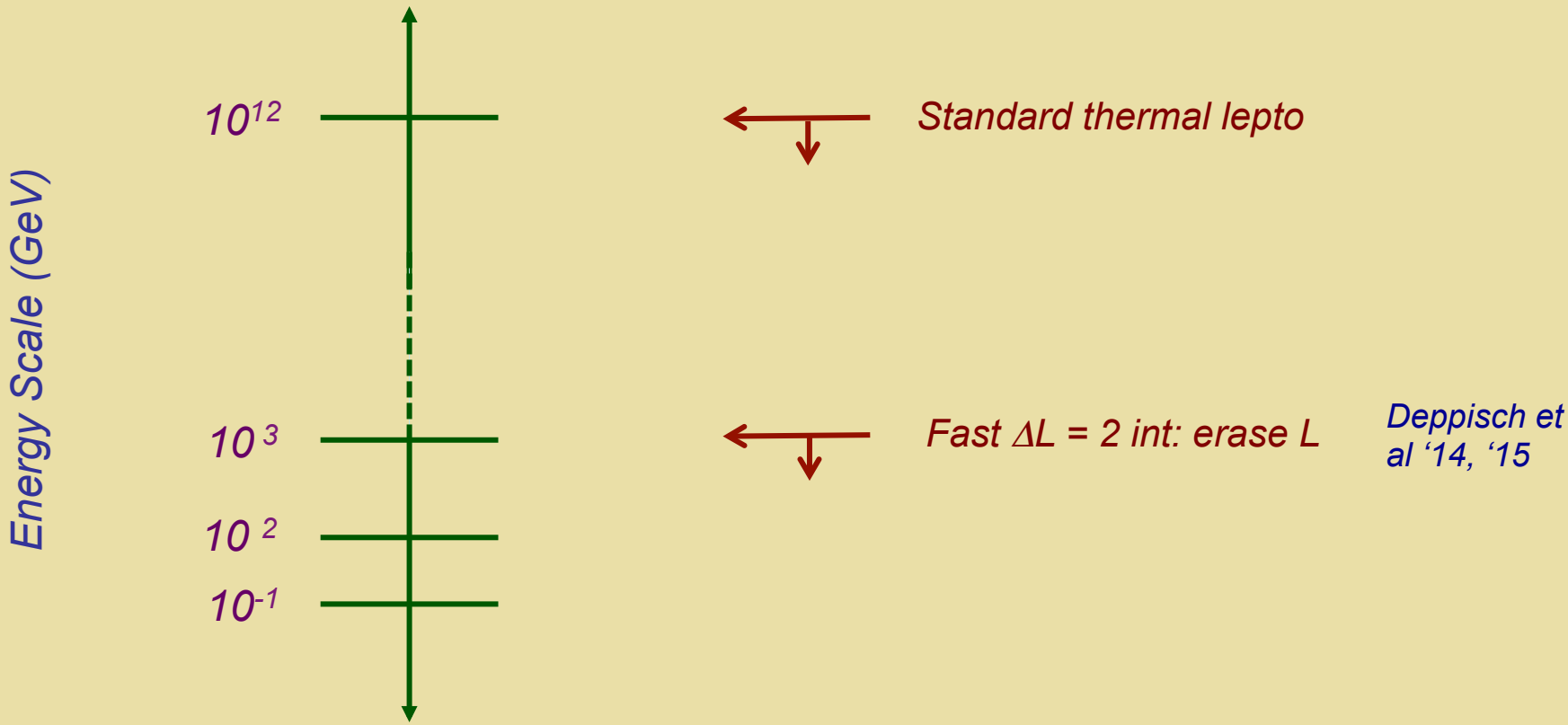
$$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$$

O(1) for $\Lambda \sim 1$ TeV

Implications



TeV LNV & Leptogenesis



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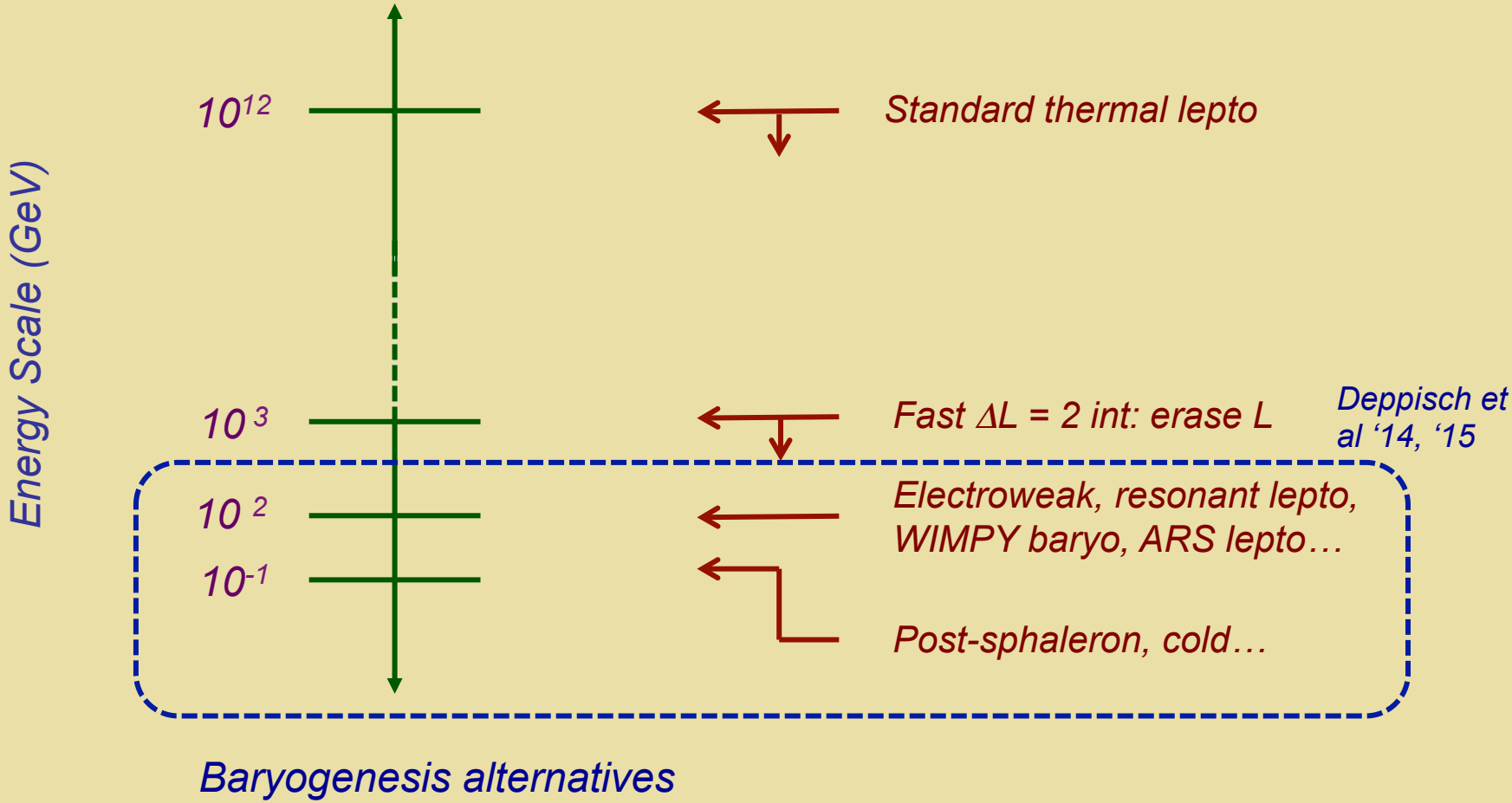

$0\nu\beta\beta$-Decay: TeV Scale LNV

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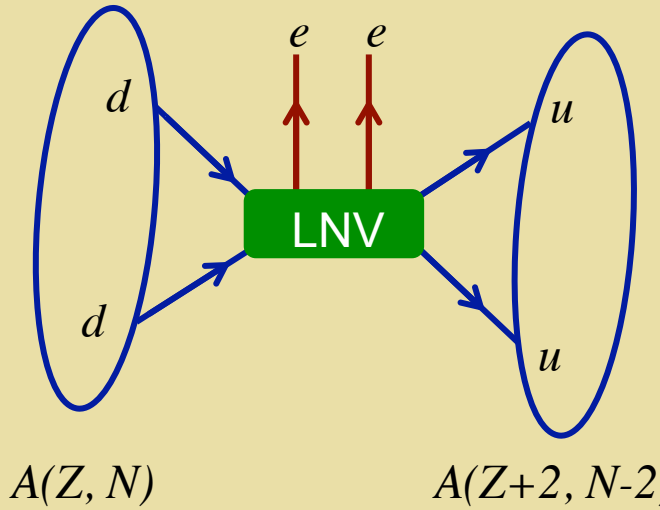
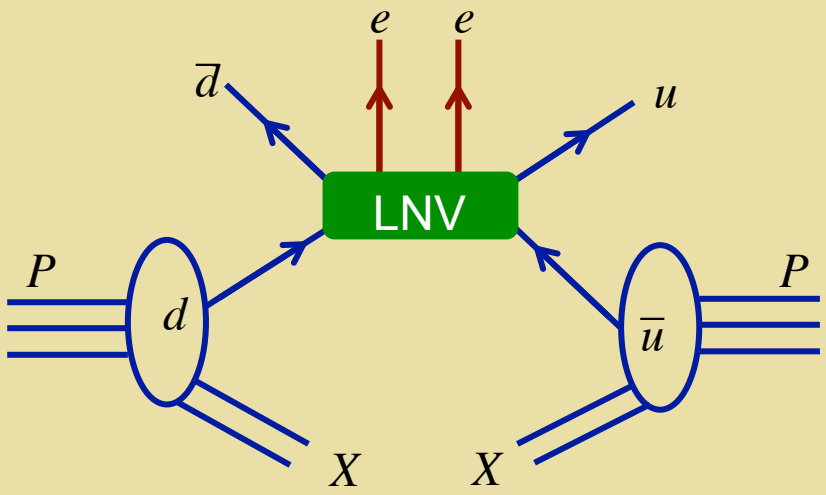
Majorana

LHC: SS Dilepton + Dijet

$0\nu\beta\beta$-Decay



pp Collisions



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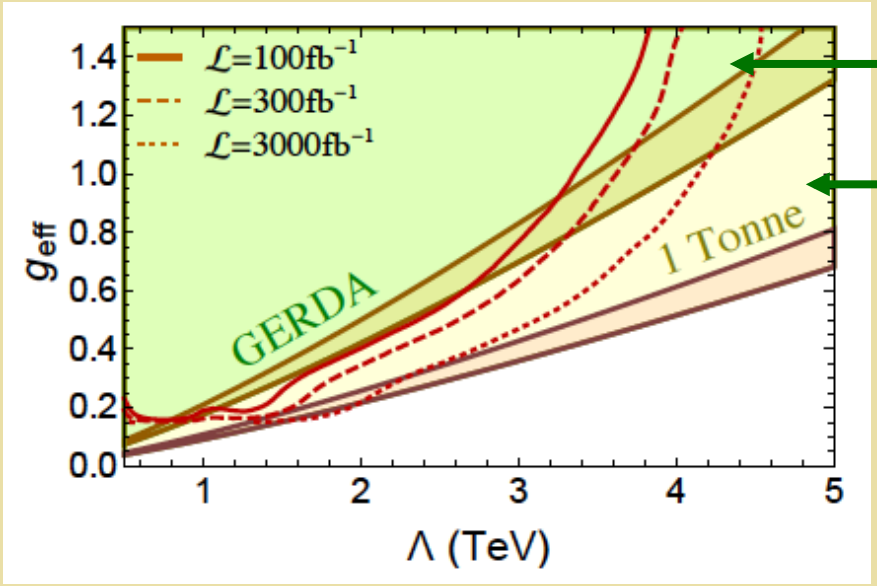
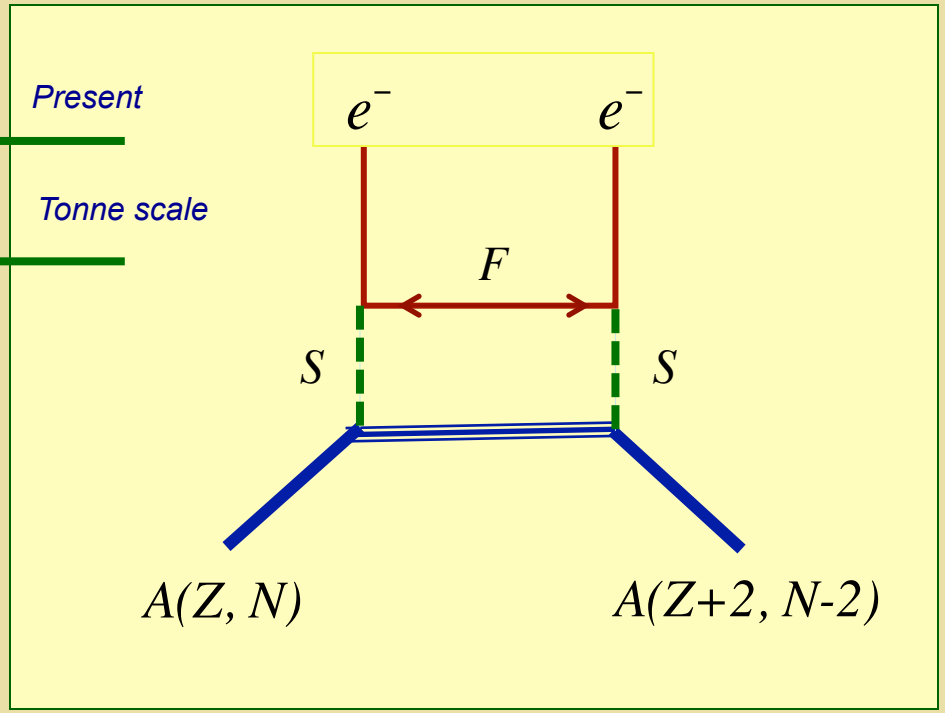
Majorana

Benchmark Sensitivity: TeV LNV



T. Peng, MRM, P. Winslow 1508.04444



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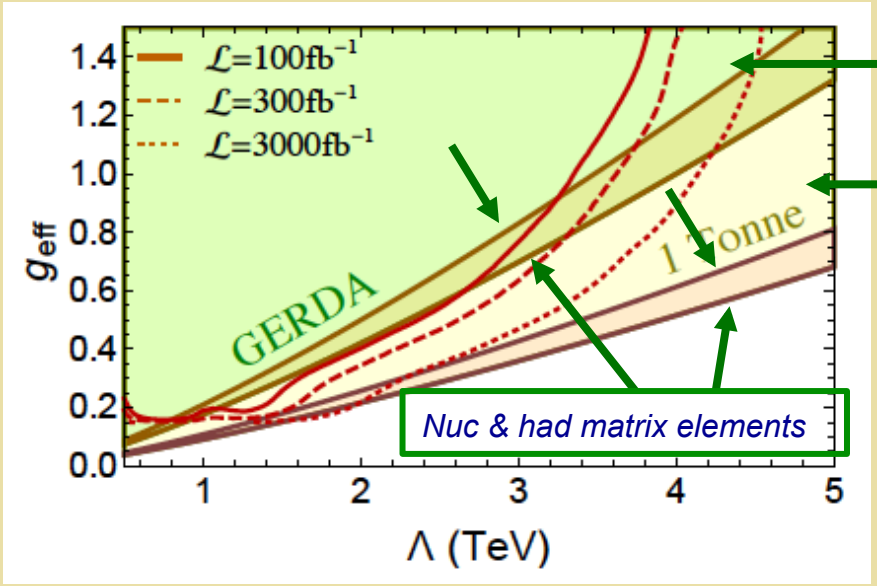

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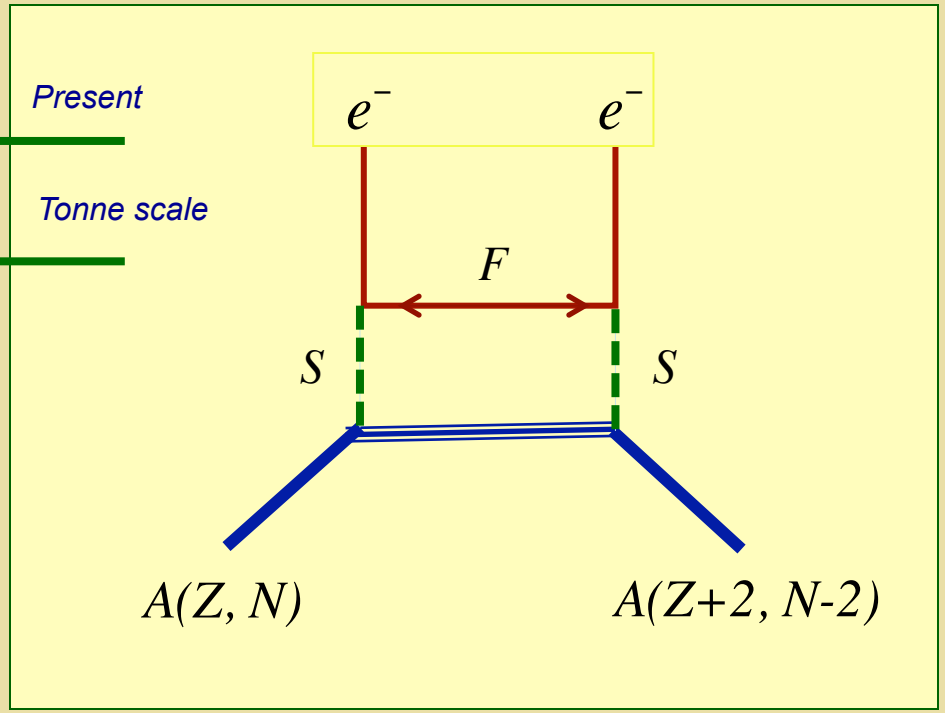

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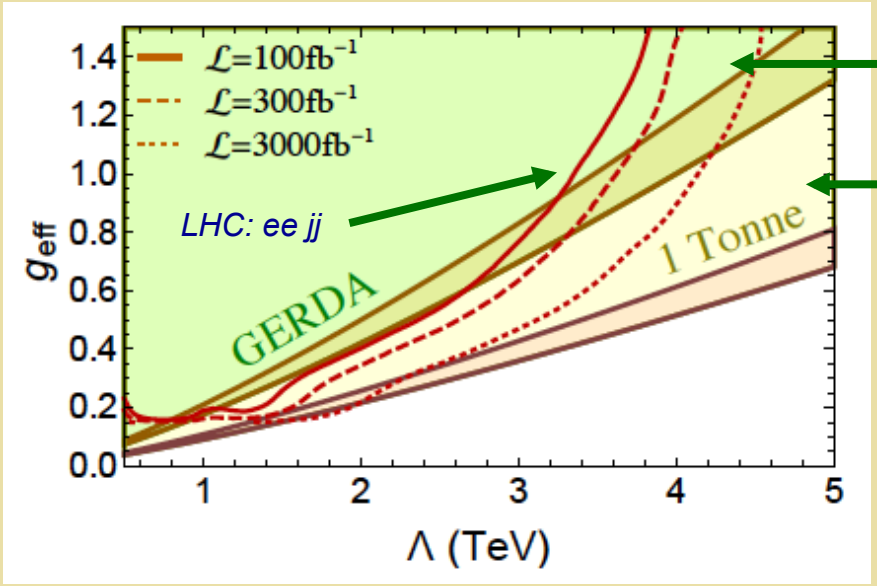

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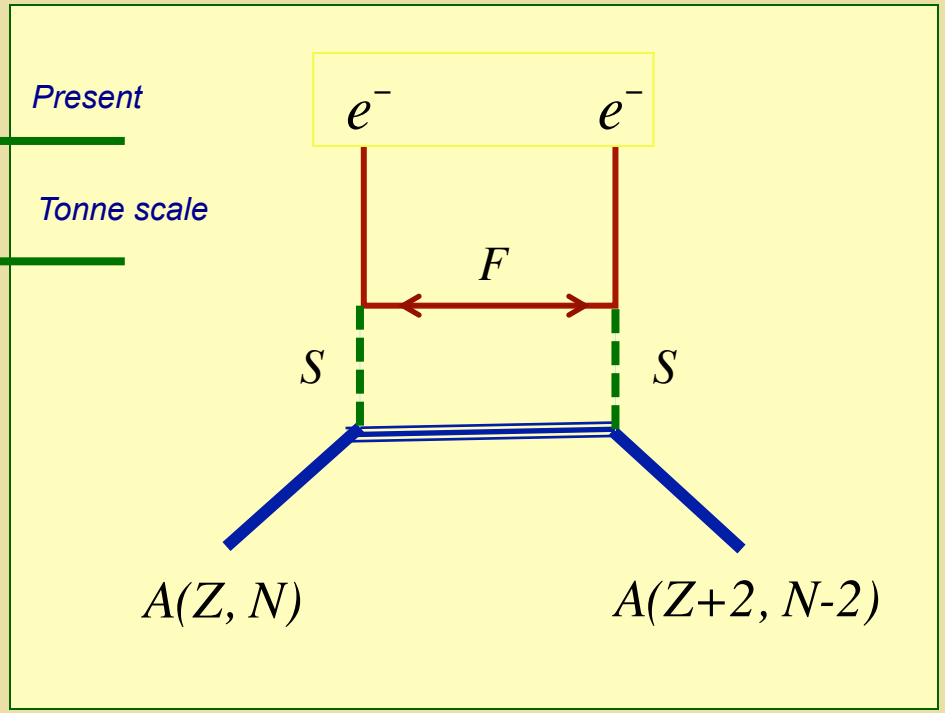

$0\nu\beta\beta$-Decay: TeV Scale LNV & m_ν

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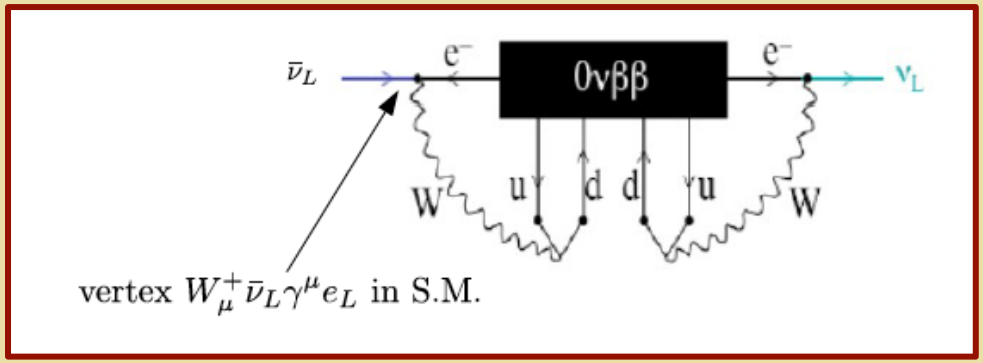
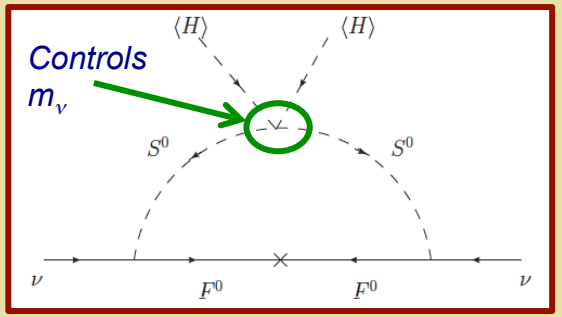
Majorana

Implications for m_ν:





Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

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

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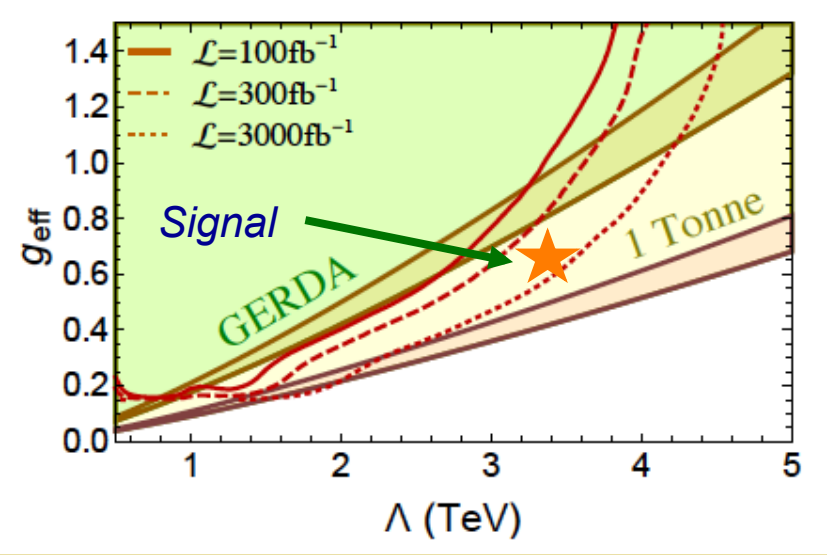

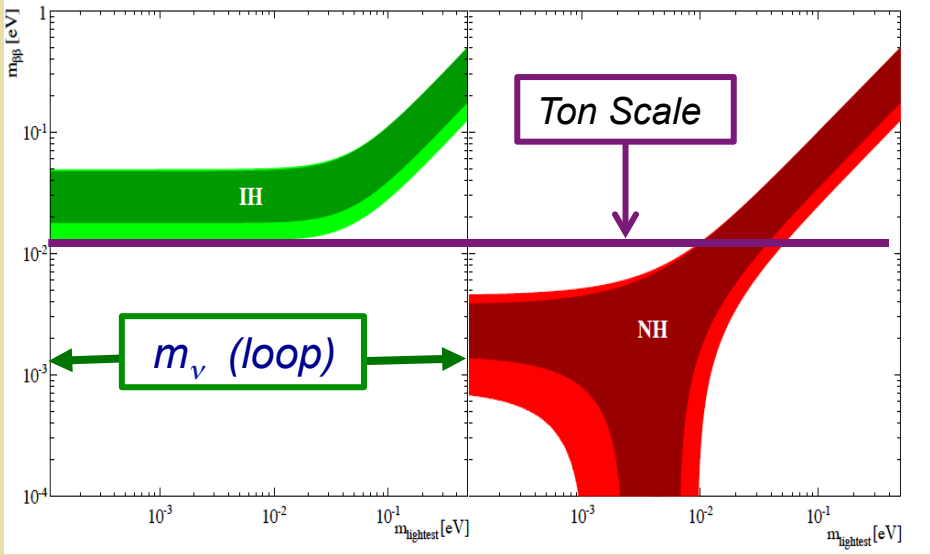

A hypothetical scenario

$0\nu\beta\beta$ / LHC Interplay: Matrix Elements

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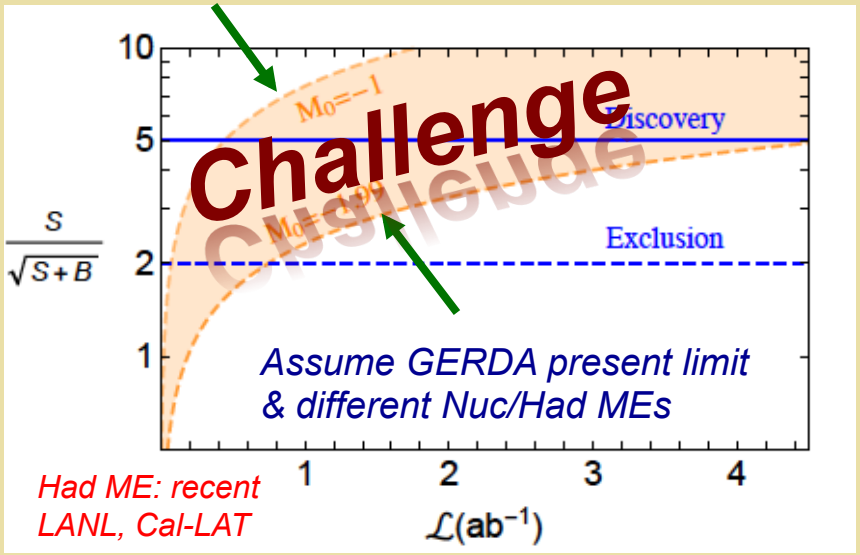
Majorana

Benchmark Sensitivity: TeV LNV



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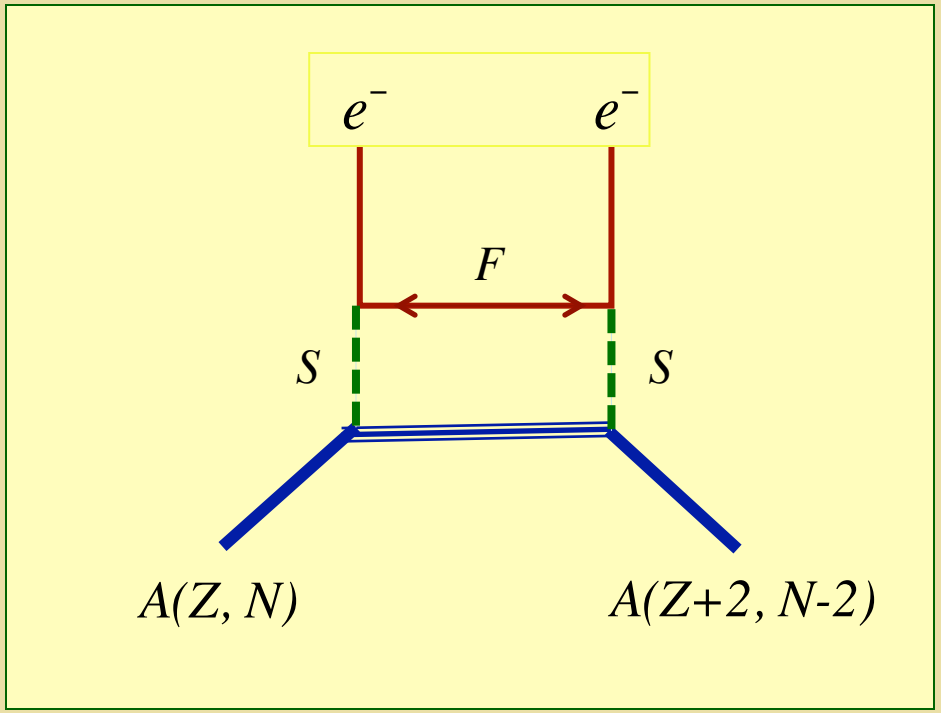
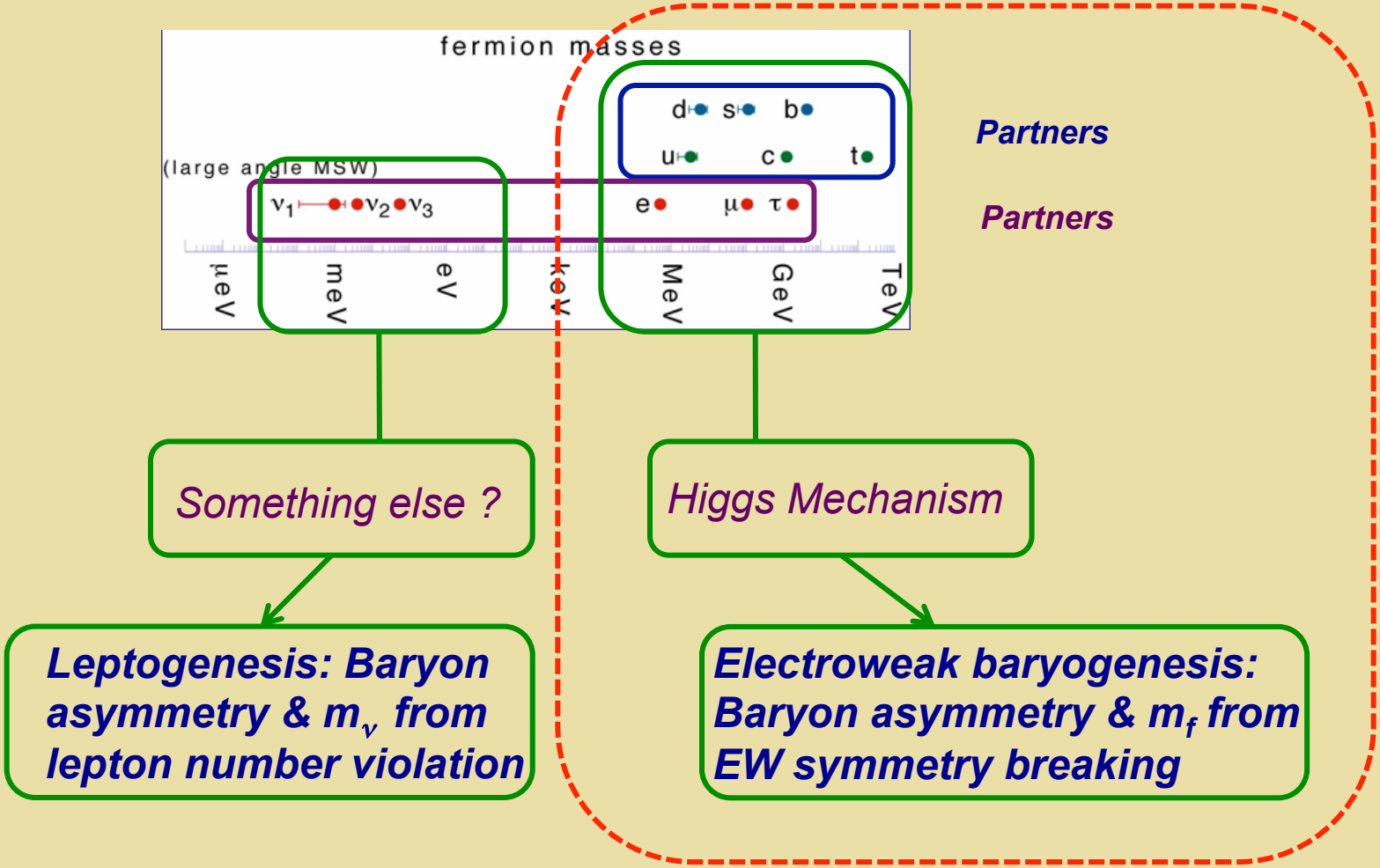


III. CP (Flavor Conserving)

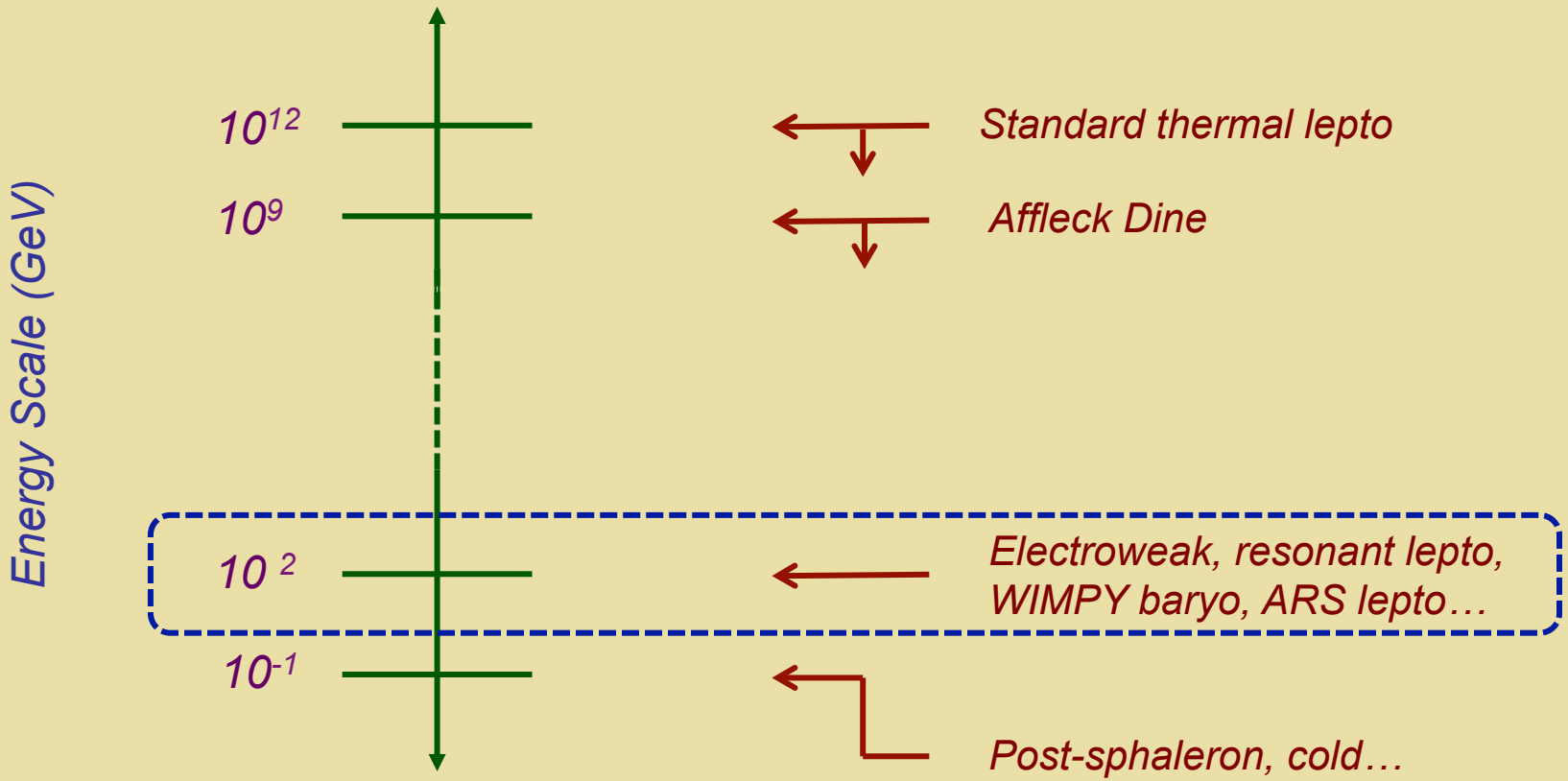
Highlight: EW Baryogenesis, Dark Z

Collaborators: T. Chupp, K. Fuyuto, X.-G. He, S. Inoue, G. Li, Y. Li, G. Ovanesyan, S. Profumo, S. Shen

Fermion Masses & Baryon Asymmetry



Baryogenesis Scenarios

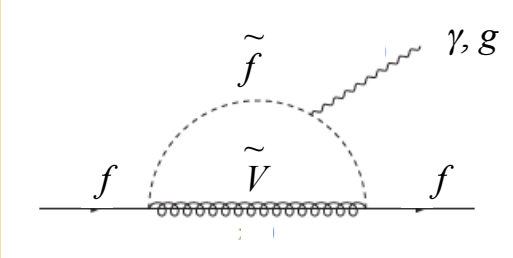


Era of EWSB: t_{univ} ~ 10 ps

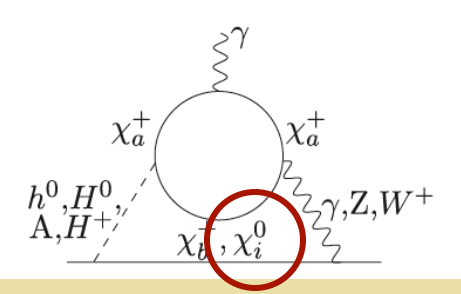
Electroweak Baryogenesis

- *Was Y_B generated in conjunction with electroweak symmetry-breaking?*
- *To what extent can EDM searches test this scenario?*

EDMs & EWBG: MSSM & Beyond

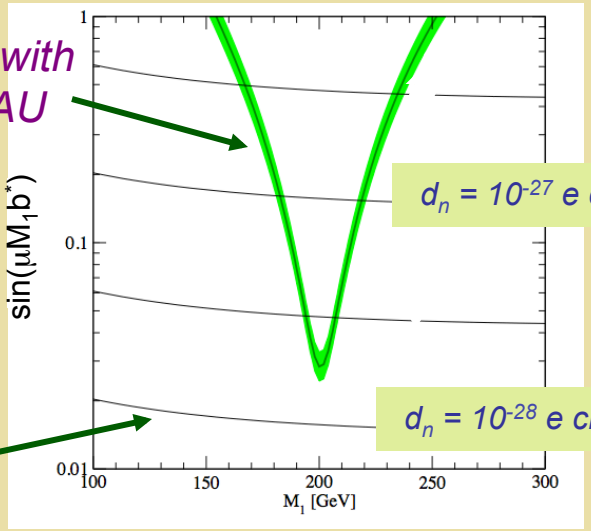


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



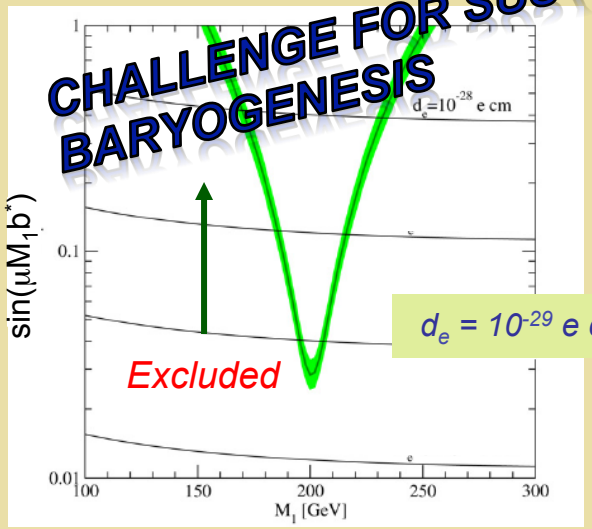
Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



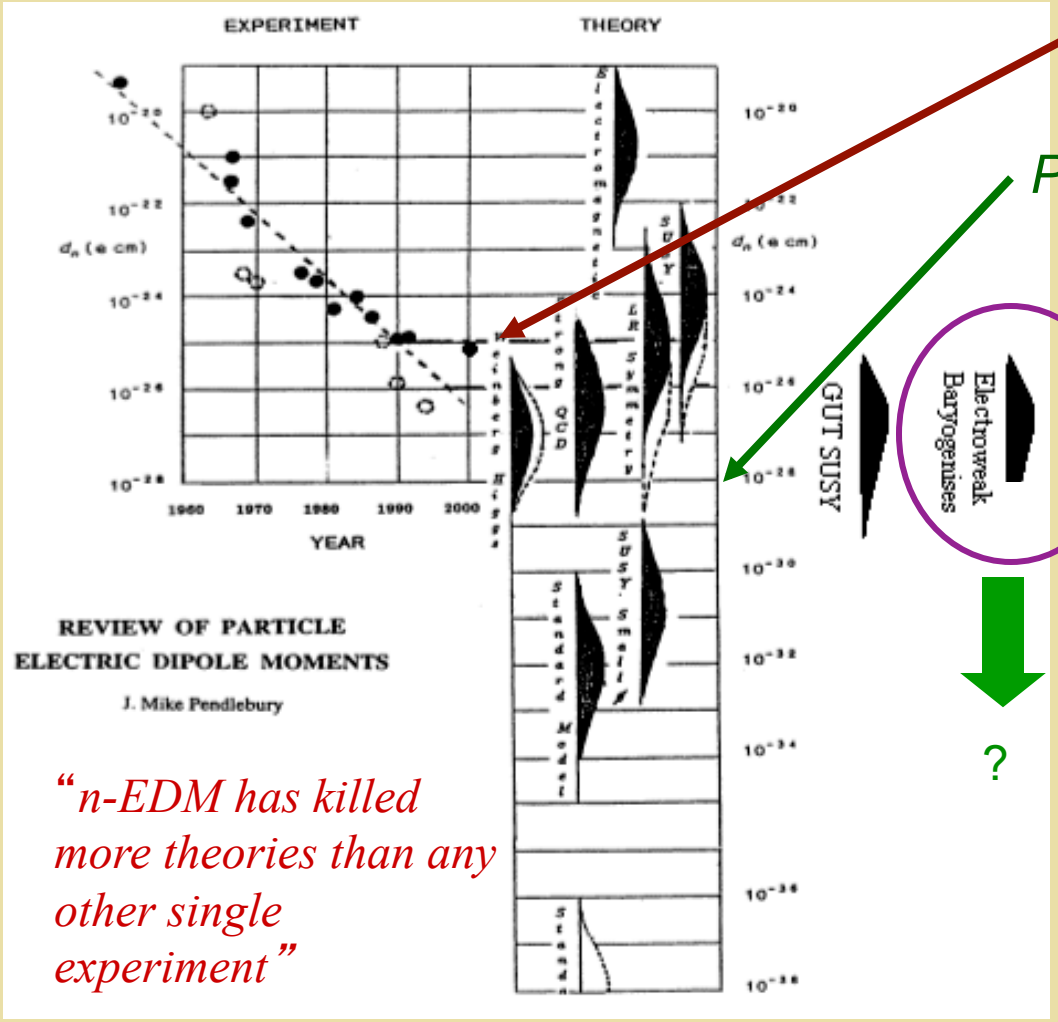
Next gen d_n

Li, Profumo, RM '09-'10



ACME: ThO

EDMs: What We May Learn



"n-EDM has killed more theories than any other single experiment"

Present n-EDM limit

Proposed n-EDM limit

GUT SUSY

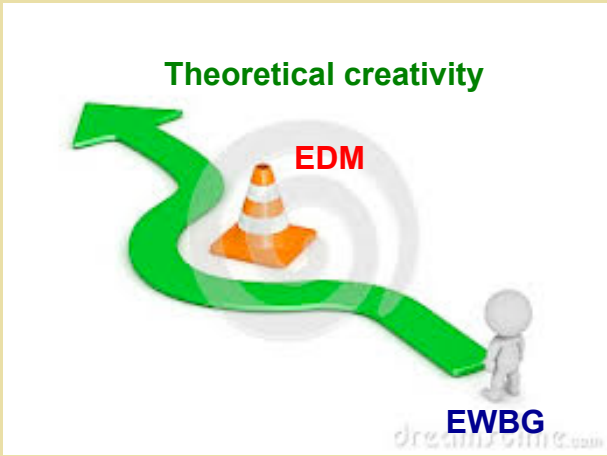
Electroweak Baryogenises

?

Matter-Antimatter Asymmetry in the Universe: ***MSSM***

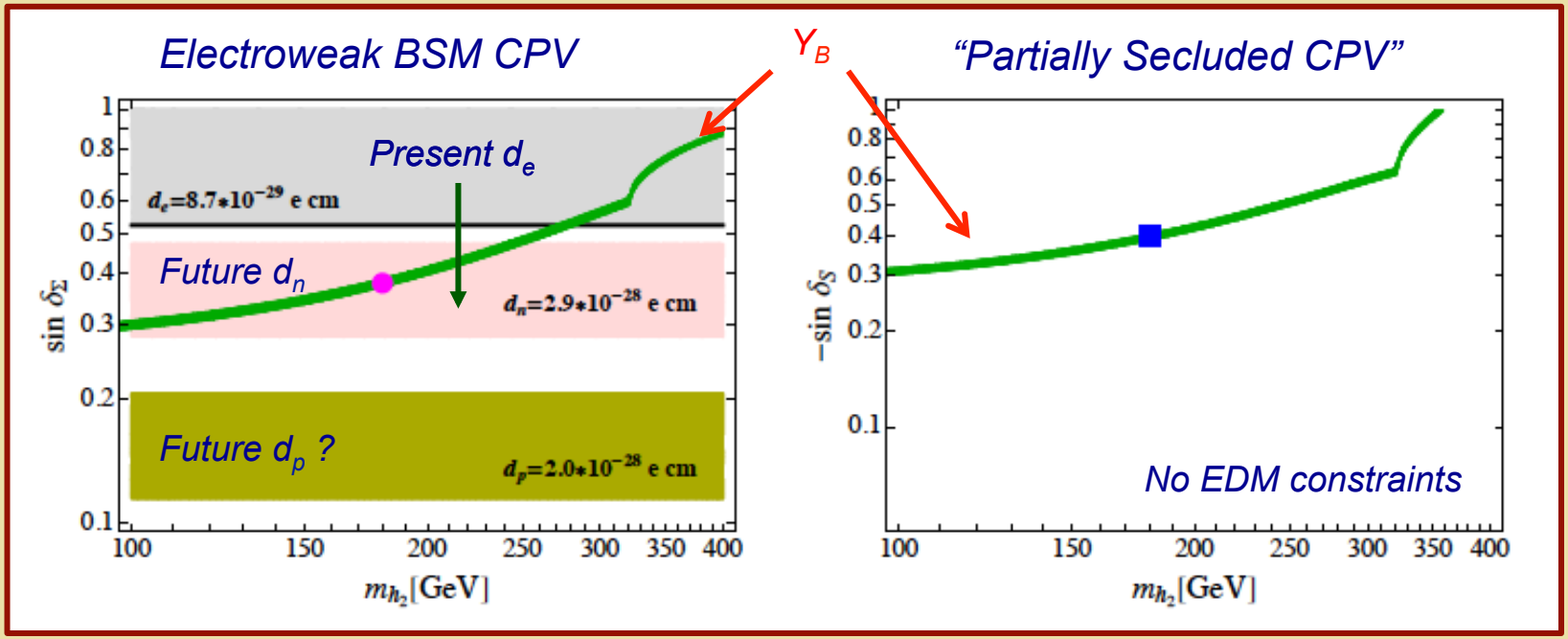
Theory: How robust ? Can EDMs kill EW baryogenesis ?

CPV for EWBG



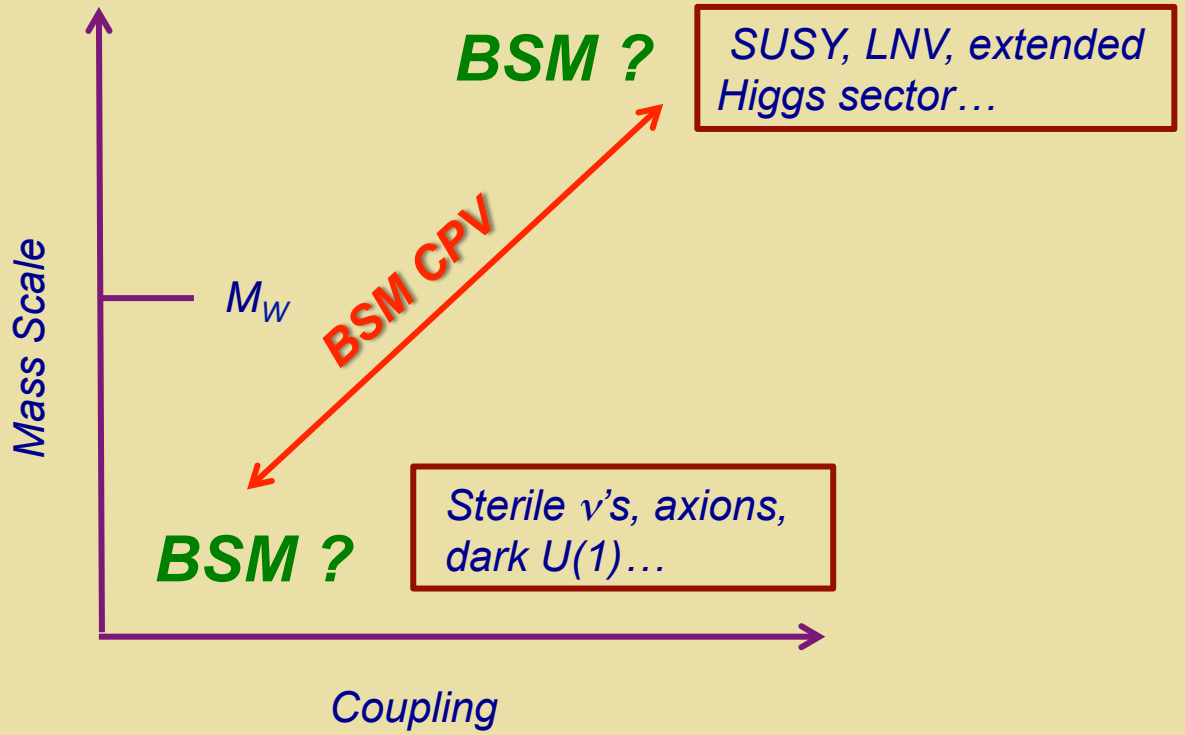
"Two-Step EW Baryogenesis"

Two CPV sources for baryon asymmetry



Inoue, Ovanesyan, R-M: 1508.05404

BSM Physics: Where Does it Live ?



BSM Physics: T (CP) Invariant ?

Dark Photon Portal

Standard Model ↔ ***Hidden Sector***

New CPV ?

Dark Photon Portal

SM	Mediator	Dark
SU(2) Triplet	X	Sector

Thanks: K. Fuyuto

CPV Dark Photon

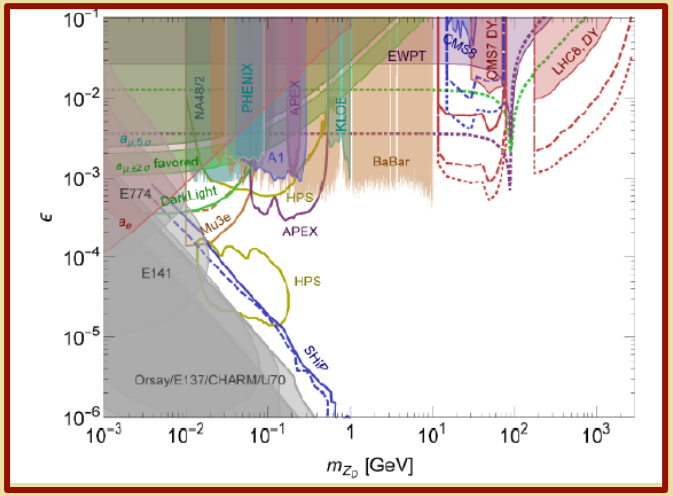
$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

CP-conserving

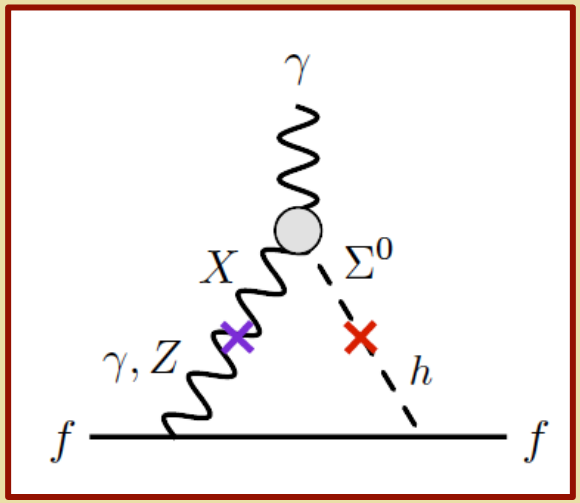
CP-violating

Thanks: K. Fuyuto

$X-\gamma$ Mixing



EDM



CPV Dark Photon

$$\mathcal{L}^{(d=5)} = -\frac{\beta}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]X^{\mu\nu} - \frac{\tilde{\beta}}{\Lambda}\mathrm{Tr}[W_{\mu\nu}\Sigma]\tilde{X}^{\mu\nu}$$

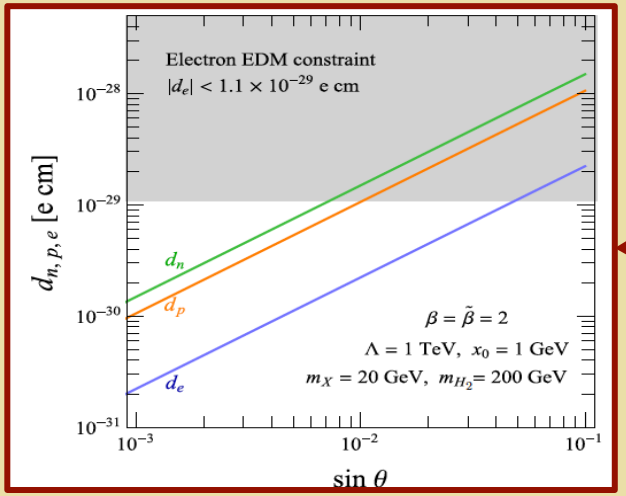
CP-conserving

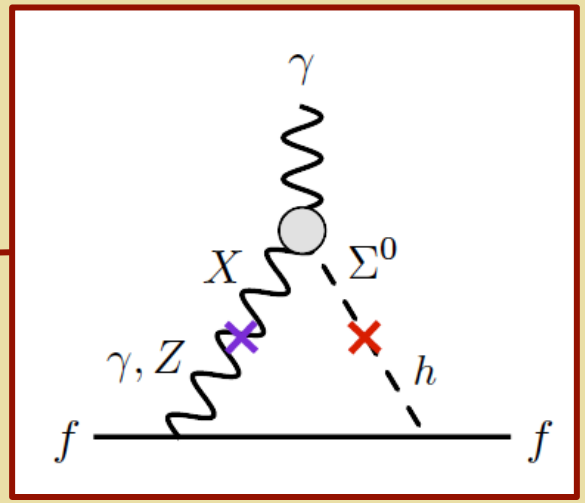
CP-violating

Thanks: K. Fuyuto

X − γ Mixing

EDM

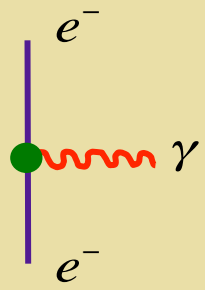




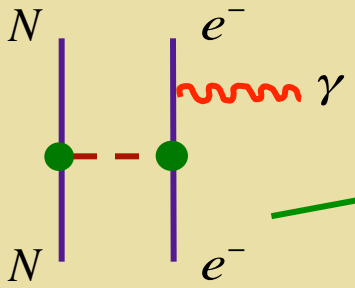
EDM Complementarity

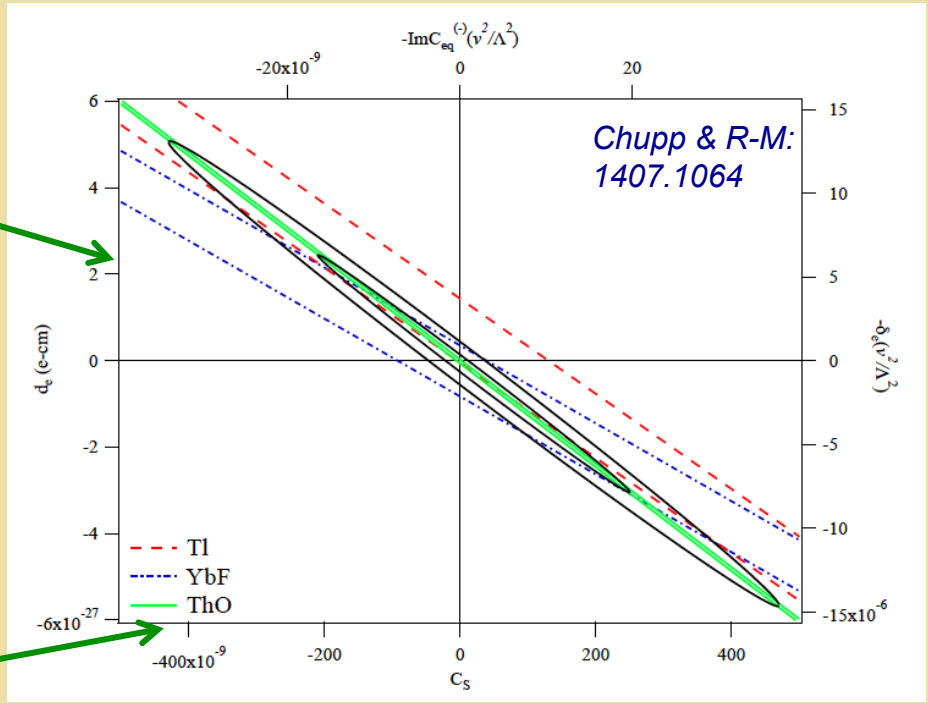
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





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

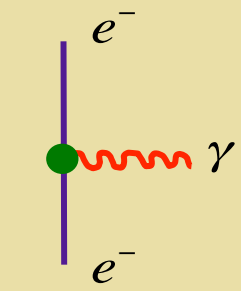
$\Lambda \gtrsim (1300\ \mathrm{TeV}) \times \sqrt{\sin\phi_{\mathrm{CPV}}}$ C_S (global)

Tl, YbF, ThO…

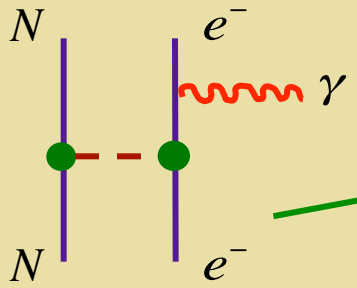
LHC inaccessible

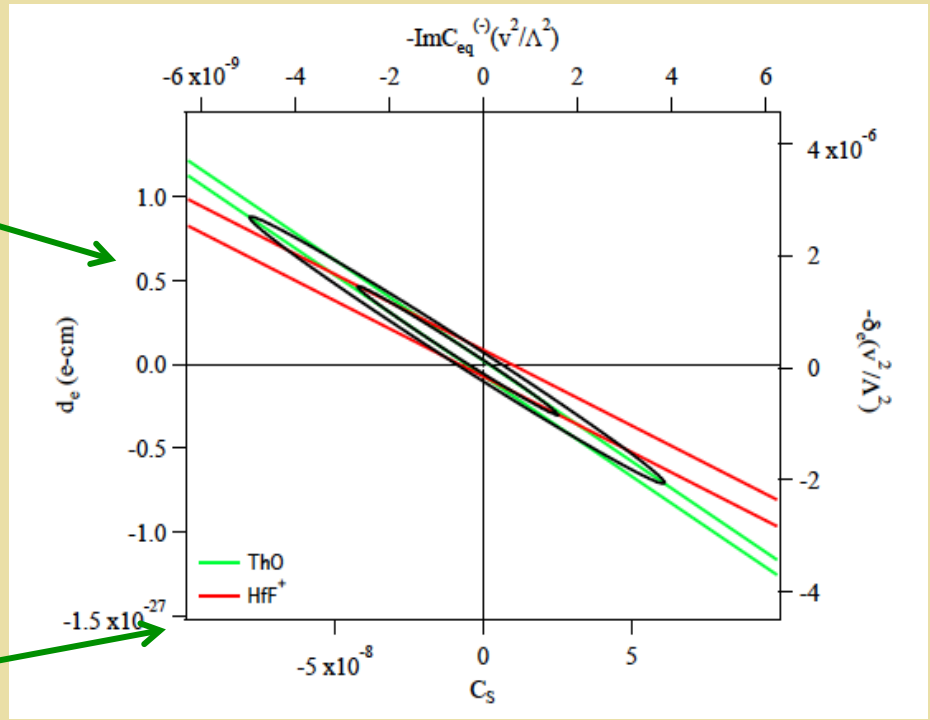
Paramagnetic Systems: Two Sources

Electron EDM



(Scalar q) x (PS e^-)





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

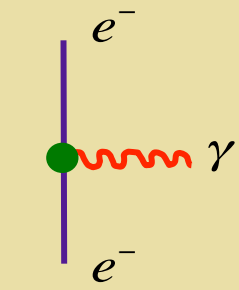
Inclusion of HfF+ : ~ 6 times stronger bounds on d_e & C_S → 2.5 higher on Λ

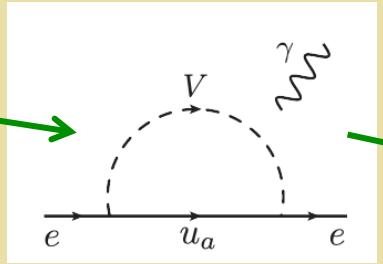
New ThO → even stronger !

Tl, YbF, ThO, HfF+

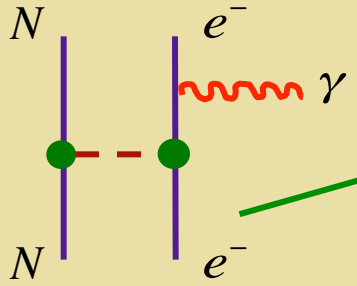
Illustrative Example: Leptoquark Model

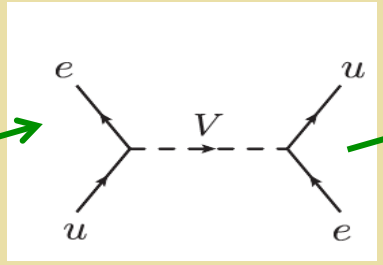
Electron EDM

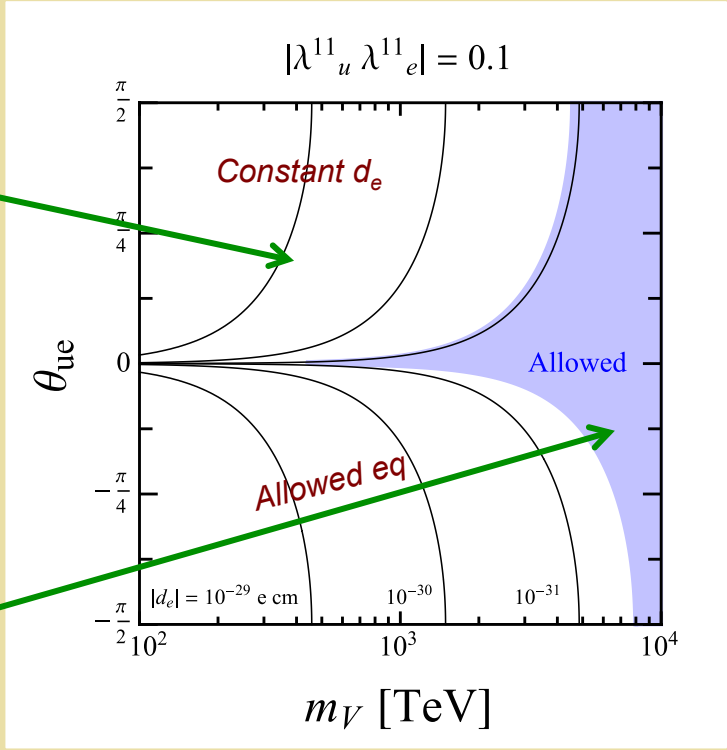




(Scalar q) x (PS e^-)







Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

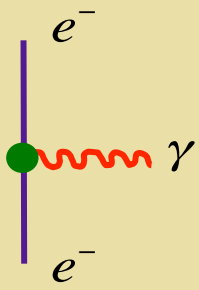
$$\mathcal{L} \ni -\lambda_u^{ab}\bar{u}_R^a X^T \epsilon L^b - \lambda_e^{ab}\bar{e}_R^a X^\dagger Q^b + \text{h.c.}$$

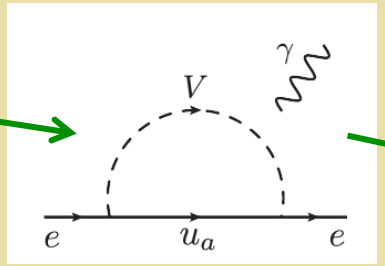
Illustrative Example: Leptoquark Model

Orange: $|d_p| = 10^{-30}$, 10^{-31} , 10^{-32} e cm

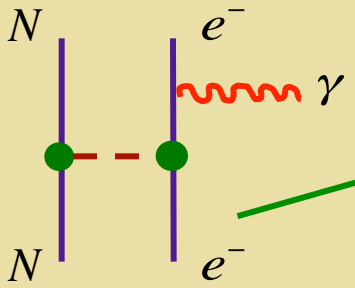
Green: $|d_n| = 10^{-30}$, 10^{-31} , 10^{-32} e cm

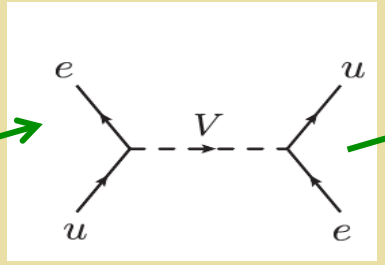
Electron EDM

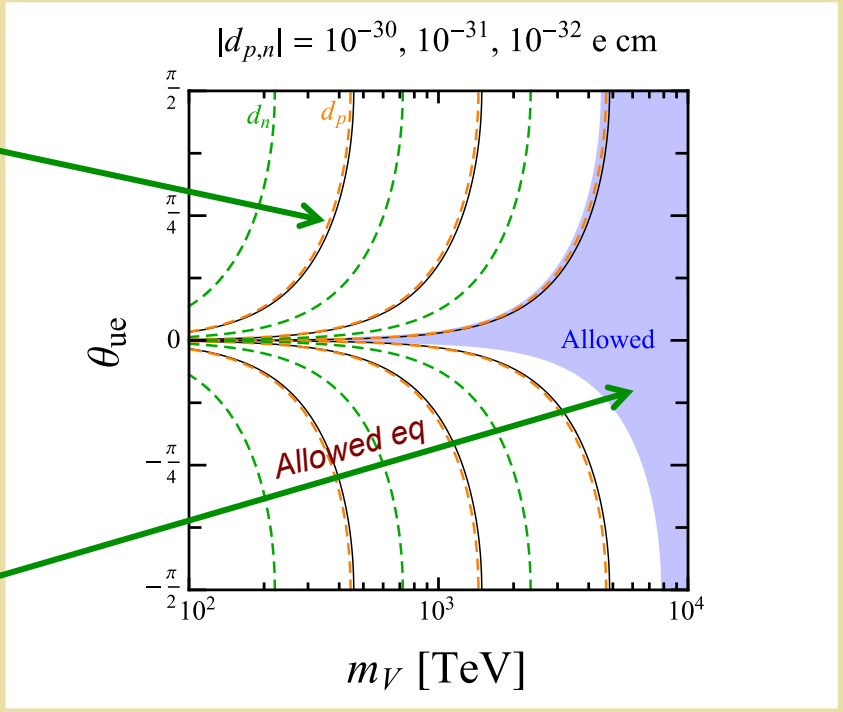




(Scalar q) x (PS e^-)







Fuyuto, R-M, Shen 1804.01137

(3, 2, 7/6)

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

IV. Precision Tests

Highlight: β-decay

Collaborators: M. Gorchtein, H. Patel, C. Seng

PRL 121 (2018) 241804 [1807.10197], 1812.03352

Precision ~ BSM Mass Scale

$$\Delta_{SM} = (O_{EXP} - O_{SM}) / O_{SM}$$

Precision Goal: *

$$\delta \Delta_{SM} \sim O(10^{-4})$$

Heavy BSM Physics:

$$\Delta_{SM} \sim C \ (v/\Lambda)^2$$

$\Lambda \sim 10$ TeV (tree)

$\Lambda < 1$ TeV (loop)

* Can be ~ 10^{-3} or larger if O_{SM} suppressed

Weak Decays: CKM Unitarity

$$d \to u\, e^-\, \bar{\nu}_e$$

$$s \to u\, e^-\, \bar{\nu}_e$$

$$b \to u\, e^-\, \bar{\nu}_e$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\Delta_{\rm CKM} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\rm exp} - 1$$

0.94906 ± 0.00041 $\quad$ 0.05031 ± 0.00022 $\quad$ 0.00002

$$\Delta_{\rm CKM} = -0.0006 \pm 0.0005$$

Precision ~ BSM Mass Scale

Precision Goal:

$$\delta \Delta_{CKM} \sim O(10^{-4})$$

Heavy BSM Physics:

$$\Delta_{CKM} \sim C \ (v/\Lambda)^2$$

$\Lambda \sim 10$ TeV (tree)

$\Lambda < 1$ TeV (loop)

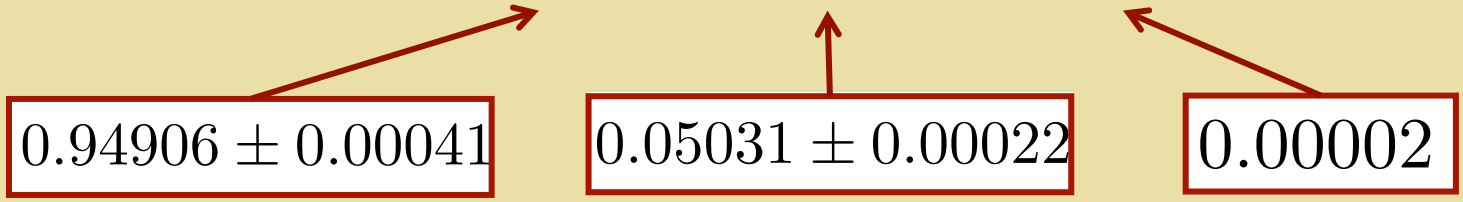
Ultralight BSM Physics:

$$\Delta_{CKM} \sim \varepsilon^2 \ (\alpha /4\pi)$$

$\varepsilon < 1$ (loop)

Error Budget

$$\Delta_{\mathrm{CKM}} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\mathrm{exp}} - 1$$



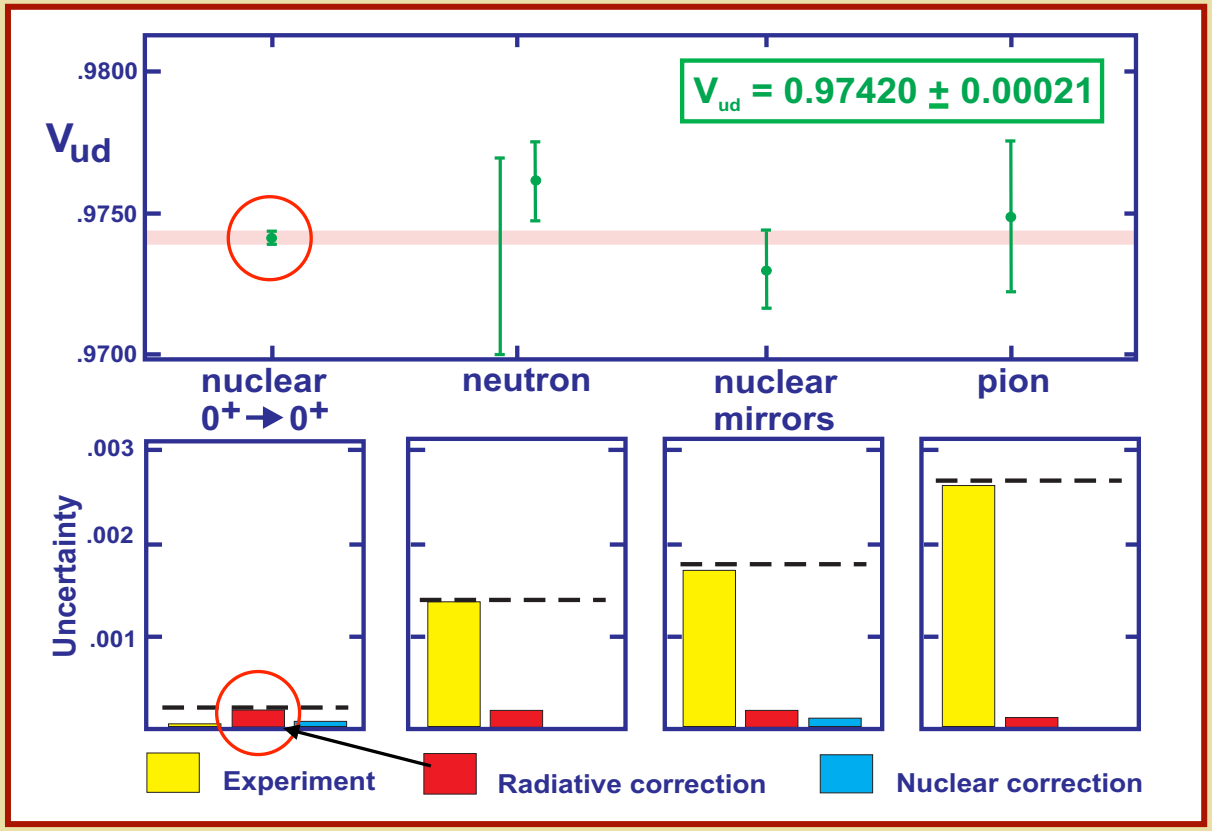
Error Budget

$$\Delta_{\mathrm{CKM}} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\mathrm{exp}} - 1$$

0.94906 ± 0.00041

Radiative Correction

Factor of 2 reduction using disp relations



Thanks: J. Hardy

Error Budget

$$\Delta_{\mathrm{CKM}} = (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)_{\mathrm{exp}} - 1$$

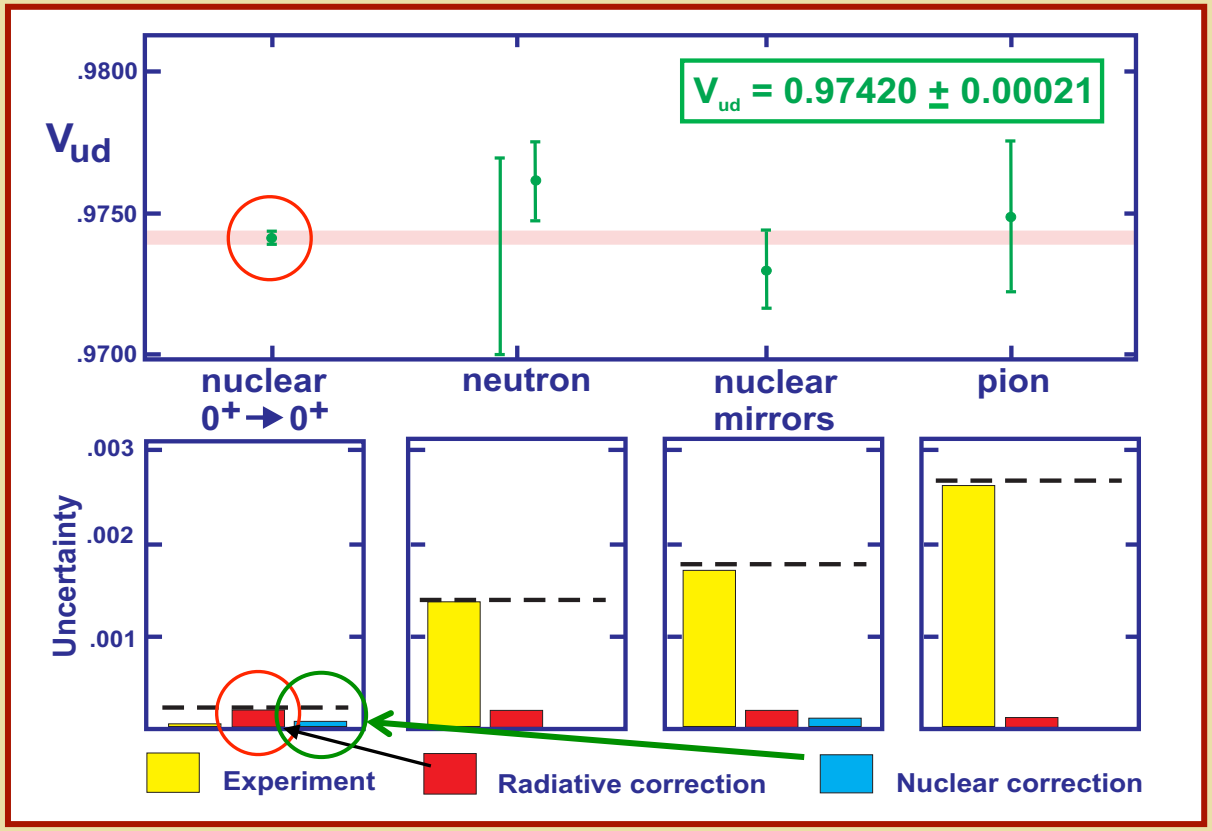
0.94906 ± 0.00041

Radiative Correction

Factor of 2 reduction using disp relations

Nuclear Correction

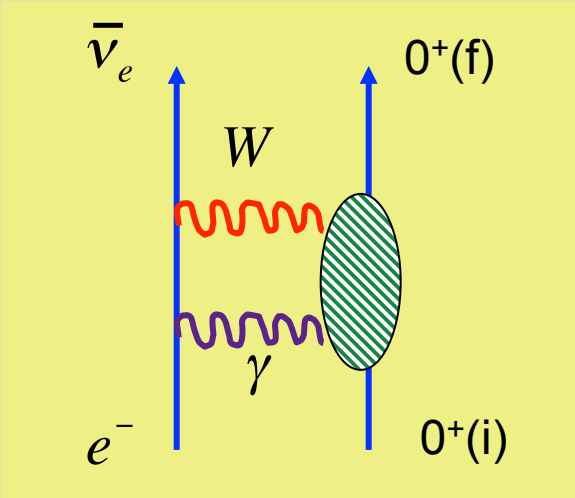
Increase due to previously omitted contributions



Thanks: J. Hardy

Radiative Corrections

Dominant source of uncertainty:



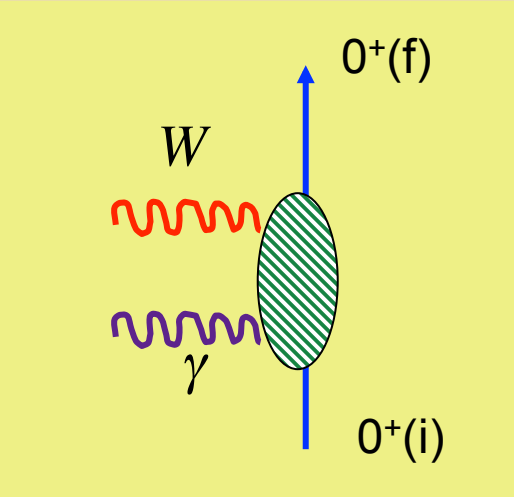
$$M_{\gamma W} = \frac{G_F V_{ud}}{\sqrt{2}} \frac{\alpha}{8\pi} \left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda) \right]$$

Short distance ***Long distance***

Long distance

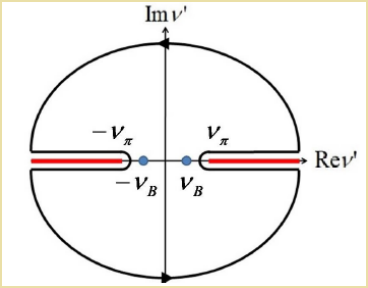
Sensitive to hadronic & nuclear dynamics

Dispersion Relations



Dispersion relation:

Write T_3 as integral over discontinuity along cut



$$T_3^{(I)}(\nu, Q^2) = \frac{2}{i}\int_0^\infty d\nu' \left[\frac{1}{\nu' - \nu} + \frac{\xi^I}{\nu' + \nu}\right] F_3^{(I)}(\nu', Q^2)$$

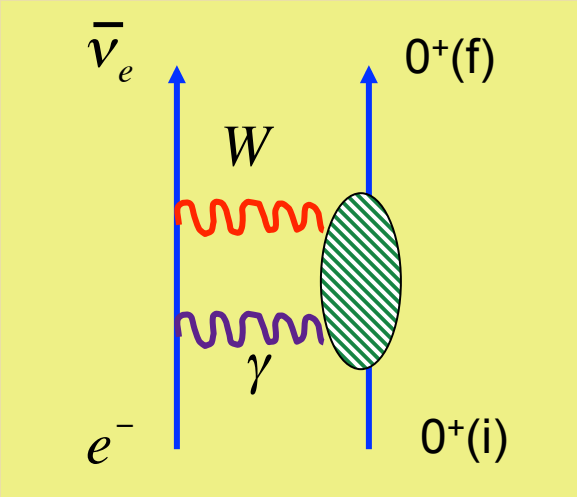
Electroproduction structure functions:

$$W_{\gamma W}^{(I)\mu\nu} = \frac{1}{8\pi}\sum_X (2\pi)^4 \delta^4(p + q - p_X) \langle p| J_{em}^{(I)\mu} |X\rangle \langle X| J_W^\nu |n\rangle$$

$$= \left[-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right] F_1^{(I)} + \frac{\hat{p}^\mu \hat{p}^\nu}{(p\cdot q)} F_2^{(I)} + \frac{i\epsilon^{\mu\nu\alpha\beta} p_\alpha q_\beta}{2(p\cdot q)} F_3^{(I)}$$

$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

Dispersion Relations



Radiative Correction:

$$\Box_{\gamma W}^{VA\,(0)} = \frac{\alpha}{\pi M}\int_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}\int_0^\infty d\nu \frac{(\nu+2q)}{\nu(\nu+q)^2}F_3^{(0)}(\nu,Q^2)$$

$$= \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2 M_W^2}{Q^2[M_W^2+Q^2]} M_3^{(0)}(1,Q^2)$$

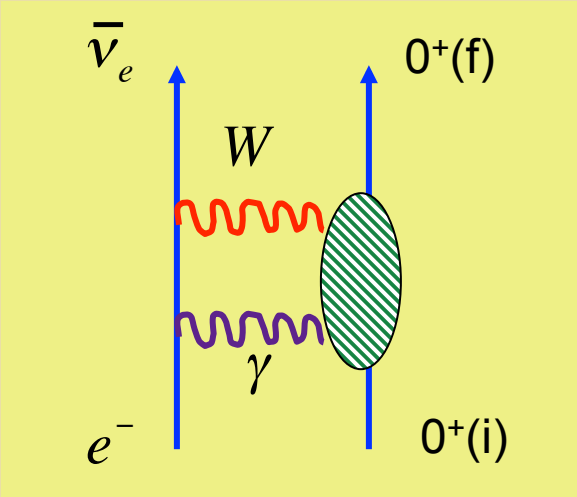
Nachtmann Moments:

$$M_3^{(0)}(N,Q^2) = \frac{N+1}{N+2}\int_0^1 \frac{dx\xi^N}{x^2}\left[2x - \frac{N\xi}{N+1}\right]F_3^{(0)}$$

$$d\sigma \propto L_{\mu\nu}W^{\mu\nu}$$

$$\xi = 2x\left(1+\frac{4M^2x^2}{Q^2}\right)^{-1}$$

Dispersion Relations



Radiative Correction:

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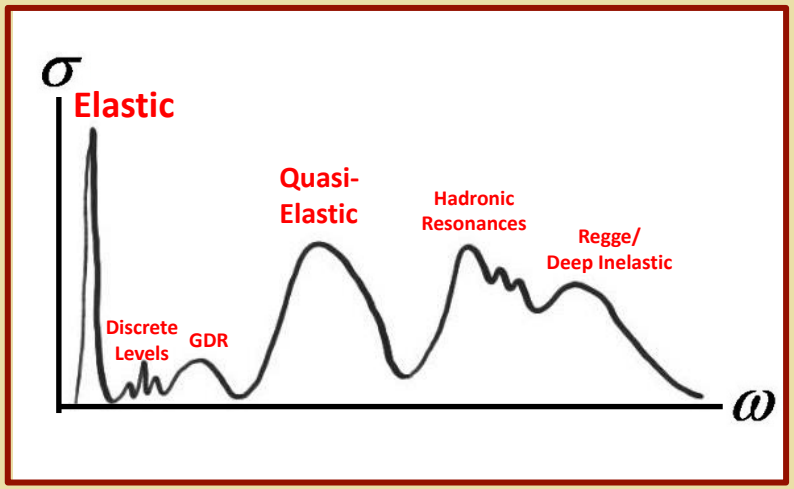
$$= \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2 M_W^2}{Q^2[M_W^2+Q^2]}M_3^{(0)}(1,Q^2)$$

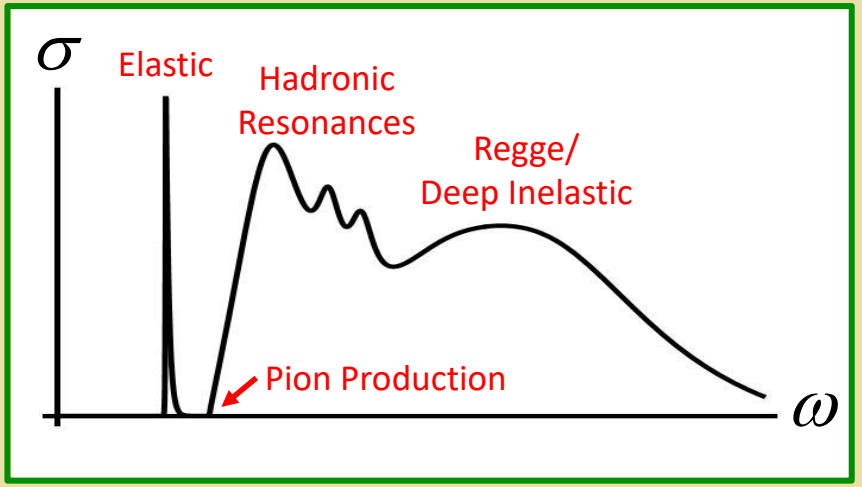
- ***Relate $F_3^{(0)}$ and $M_3^{(0)}$ to data and/or***
- ***Compute $F_3^{(0)}$ and $M_3^{(0)}$ using same methods used to describe semi-leptonic scattering processes with nucleon & nuclear targets***

Leptoproduction: Had & Nuc Response

Nuclei

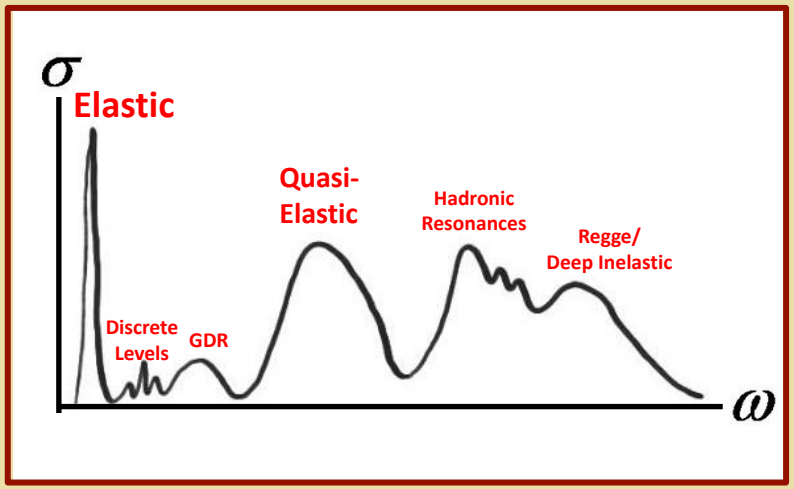


Free nucleons

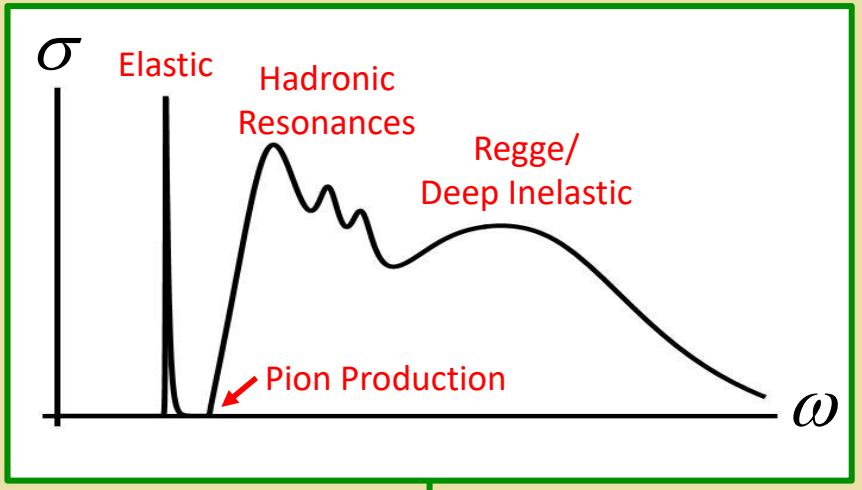


Leptoproduction: Had & Nuc Response

Nuclei



Free nucleons



Single nucleon: PRL 121 (2008) 241804

$\Delta_R^V = 0.02361(38) \rightarrow 0.02467\ (22)$

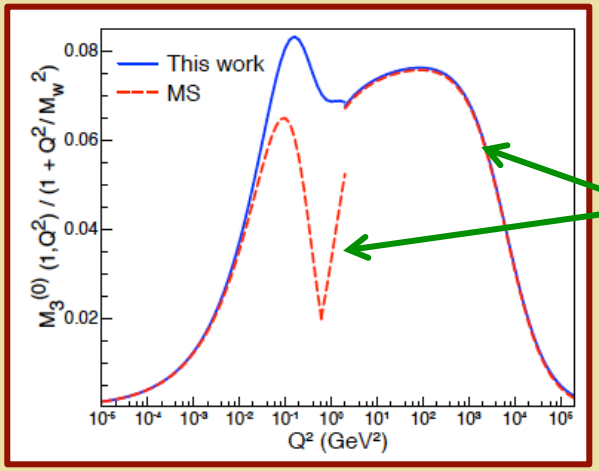
Wγ Box: Update from 2006

$$\Box_{\gamma W}^{VA} = \frac{\alpha}{2\pi}[C_{DIS} + C_B + C^{Regge} + C^{\pi N} + C^{Res}]$$

$$C_{DIS}^{MS} = 1.84 \;\rightarrow\; C_{DIS}^{new} = 1.87$$

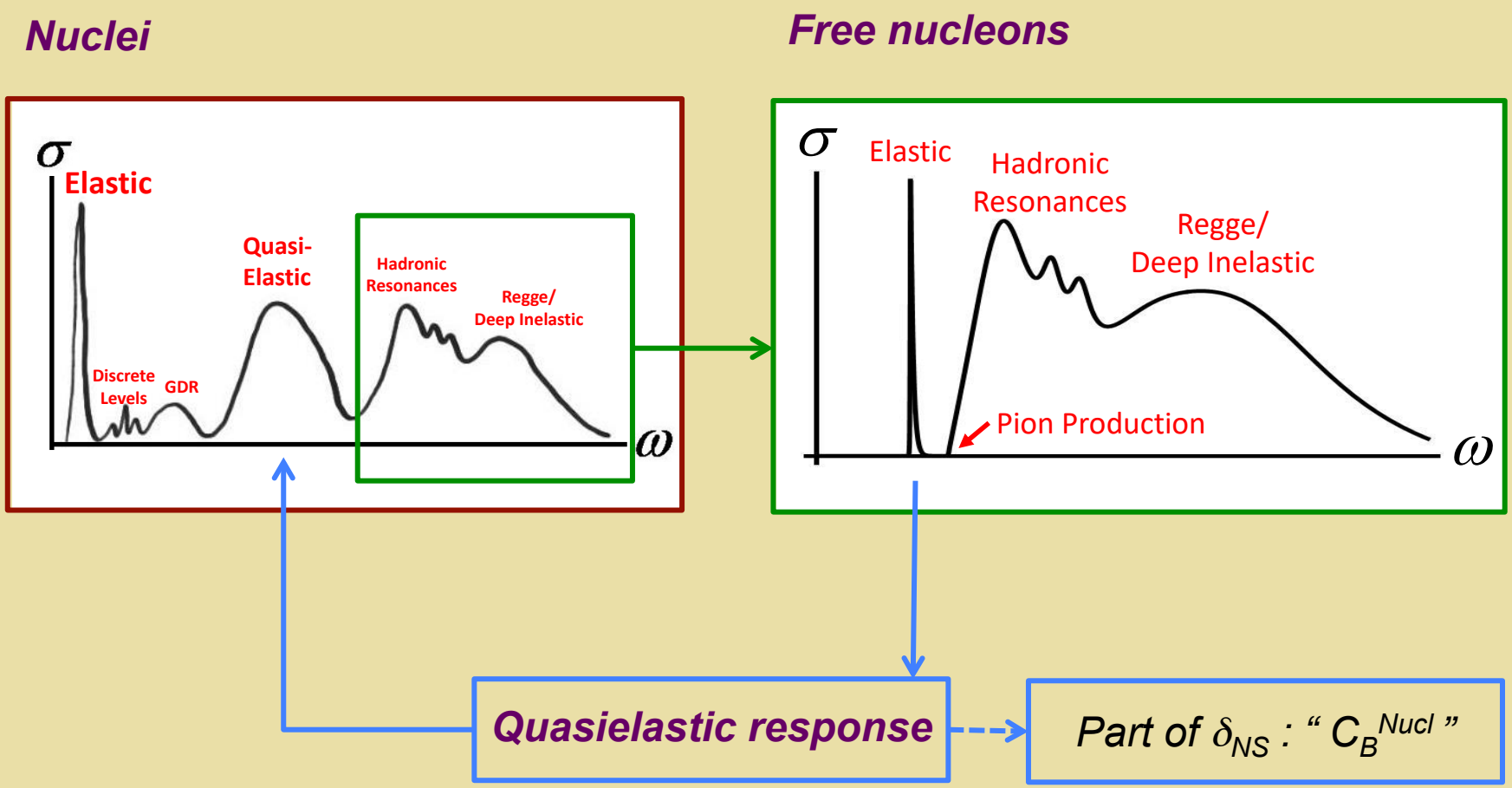
$$C_B^{MS} = 0.829(83) \;\rightarrow\; C_B^{new} = 0.91(5)$$

$$C_{INT}^{MS} = 0.14(14) \;\rightarrow\; C^{Regge} + C^{\pi N} + C^{Res} = 0.48(7)$$

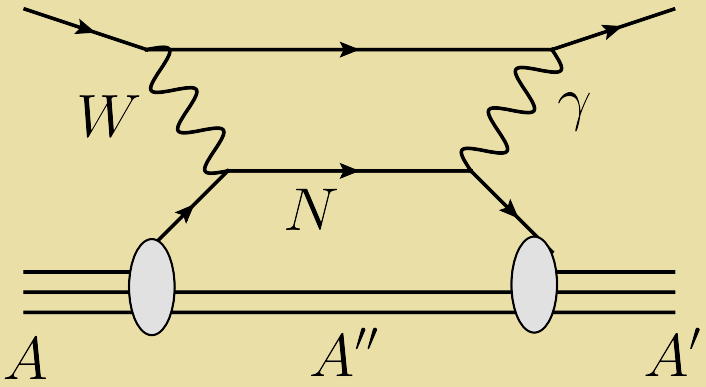


$$F_{\rm MS}(Q^2) = \frac{12}{Q^2} M_3^{(0)}(1, Q^2)$$

Leptoproduction: Had & Nuc Response



Impact on δ_{NS}



$$\Delta\,\delta_{NS} = \frac{\alpha}{\pi}\left(C_{QE} - q_S^{(0)} q_A C_B\right) = -(4.6 \pm 0.9) \times 10^{-4}$$

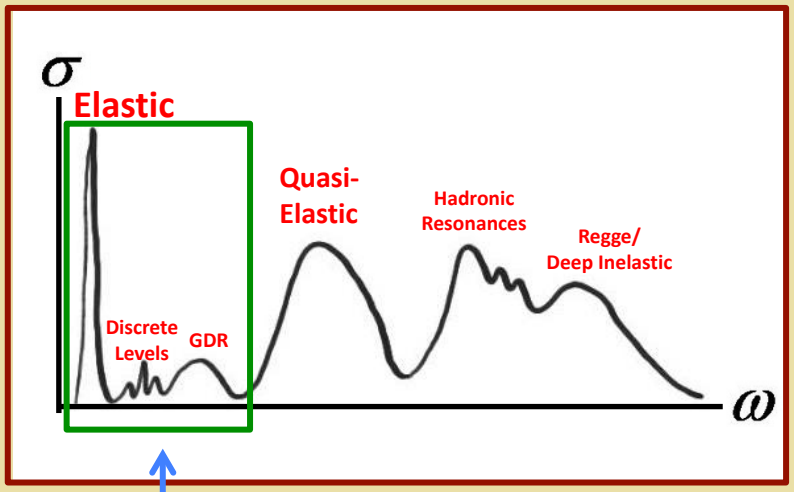
Our new work: QE response

Towner & Hardy

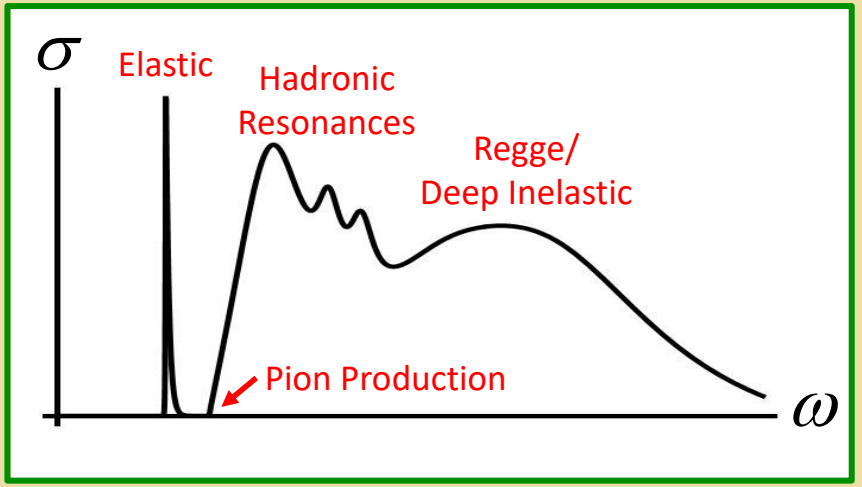
Features:
- Few x 10^-4
- Error bar ?
- Refinements ?

Other Nuclear Corrections

Nuclei



Free nucleons



Low-lying transitions → *Part of* δ_{NS}

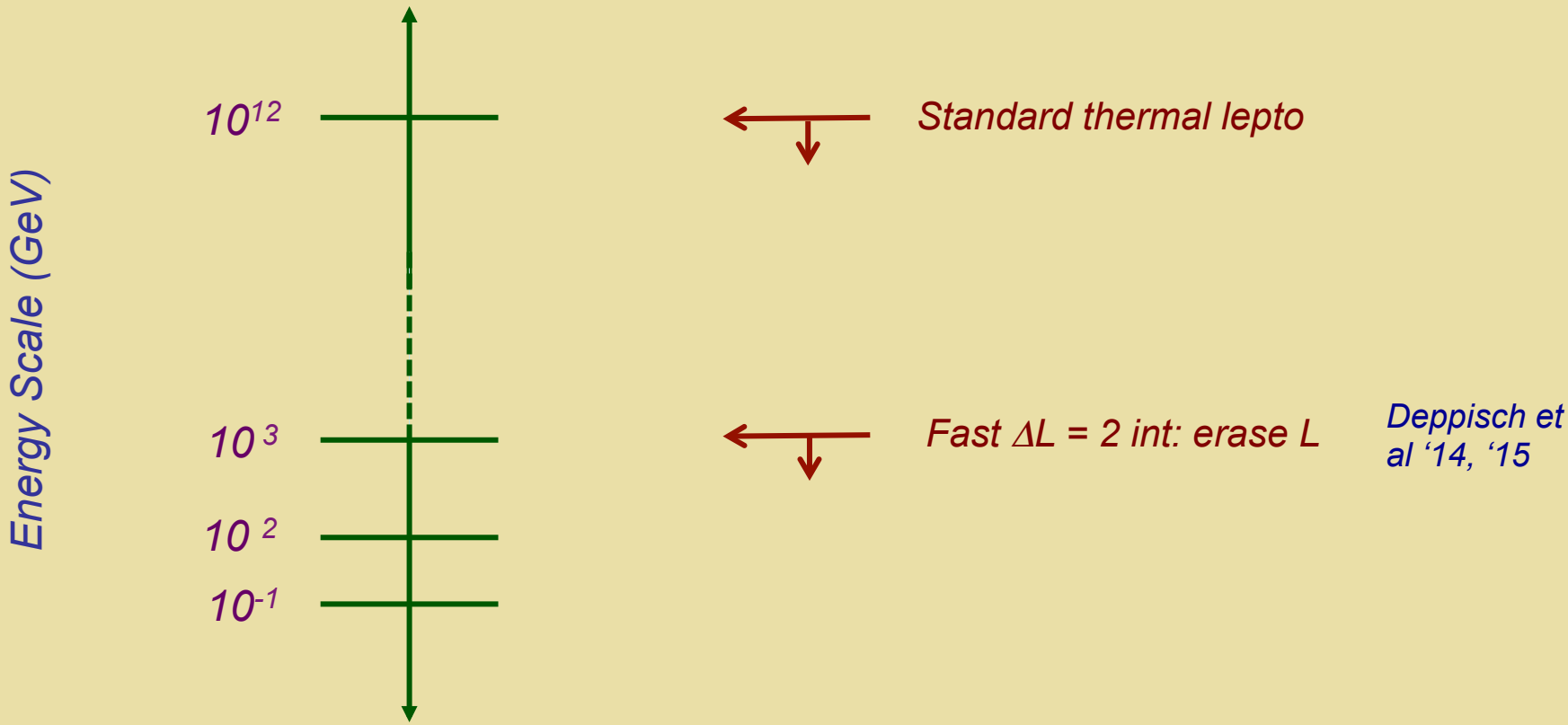
Challenges & opportunities for nuclear th'y

Outlook

- *Fundamental questions motivate the search for physics beyond the Standard Model*
- *Tests of fundamental symmetries at low-energy are poised to*
  - *discover the BSM physics that answers several of these questions*
  - *determine its character*
- *Robust hadronic & nuclear computations plus high sensitivity experiments are essential*

Back Up Slides

TeV LNV & Leptogenesis

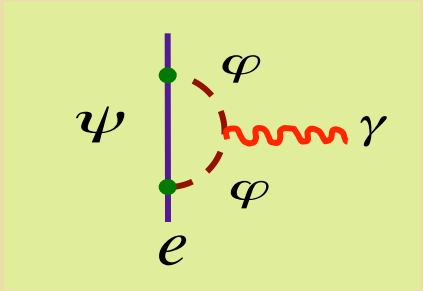


EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
ThO	8.7×10^{-29} **	10^{-38}	10^{-29}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent *New ACME: < 1.1 x 10^{-29}*

Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow$ $\sin\phi_{CP} < 10^{-2}$

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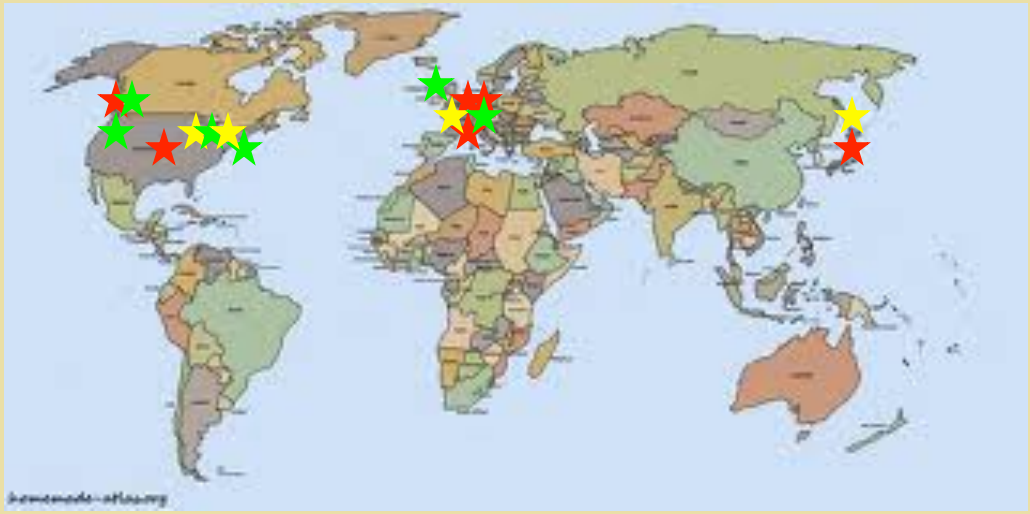


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

Future Tests

- *Lattice computation of $M_3^{(0)}$ (Q^2)*
- *PV electron scattering*

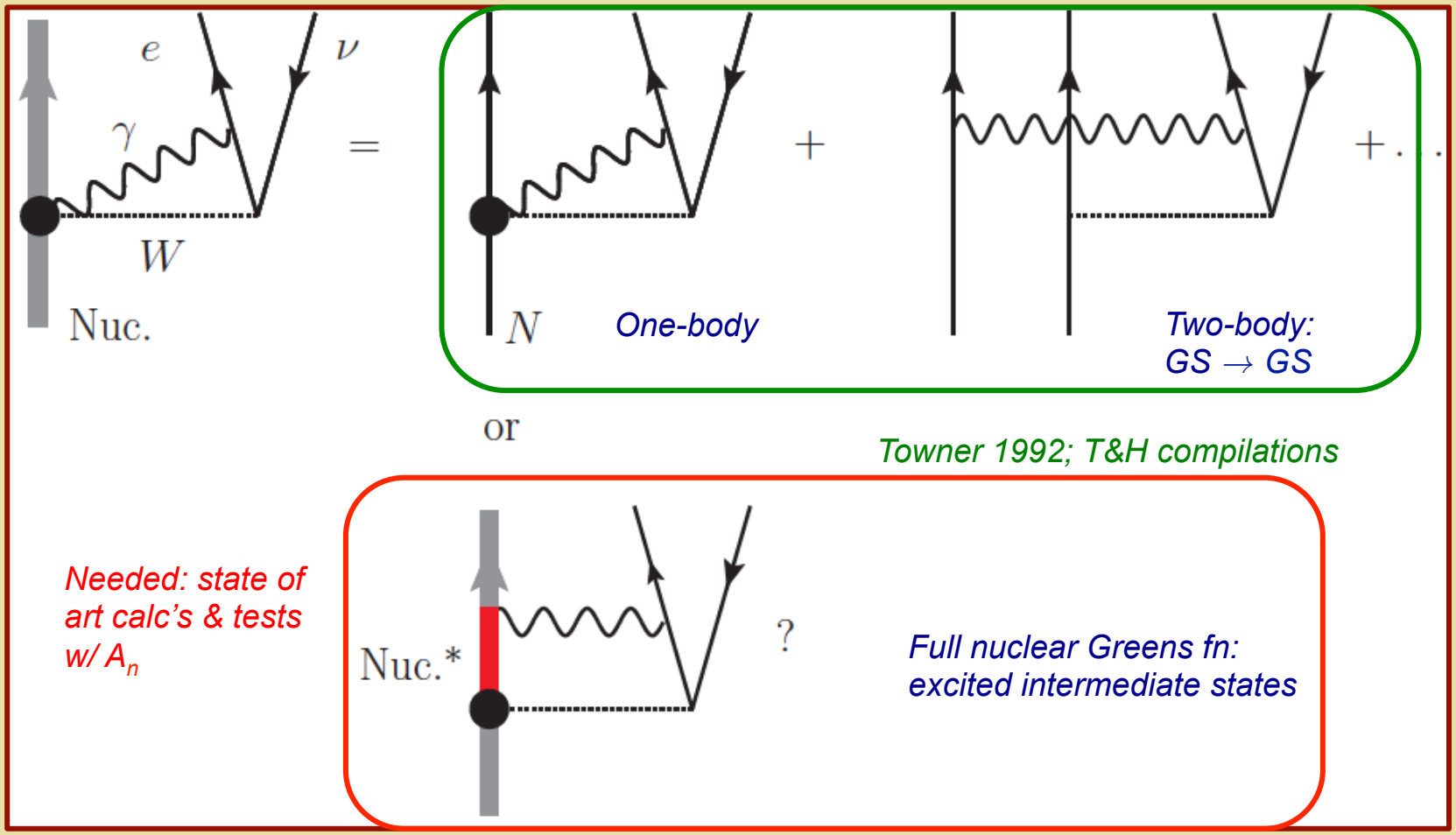
Isospin relation

$$4F_3^{(0)} = F_{3,\gamma Z}^p - F_{3,\gamma Z}^n$$

- *SoLID ?*
- *EIC ?*

- *More neutrino data for $M_3^{(0)}$ (Q^2)*

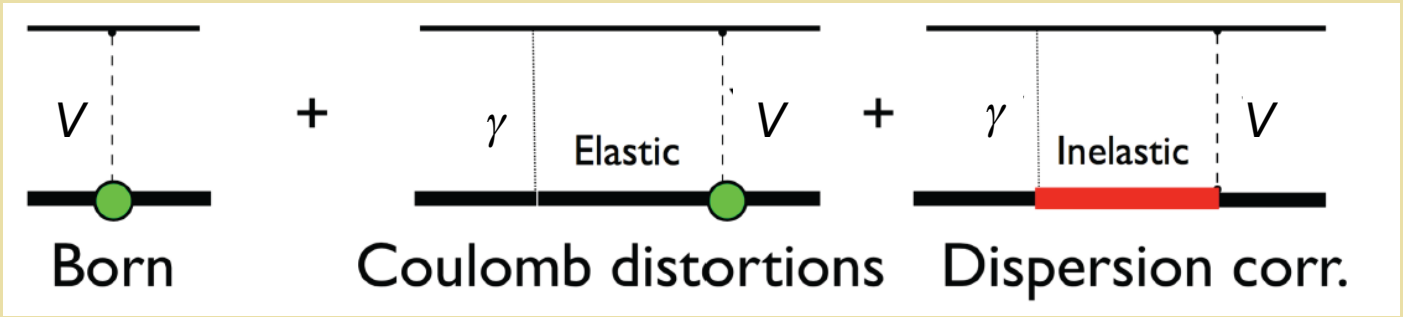
$0^+ \rightarrow 0^+$ Decay: δ_{NS}

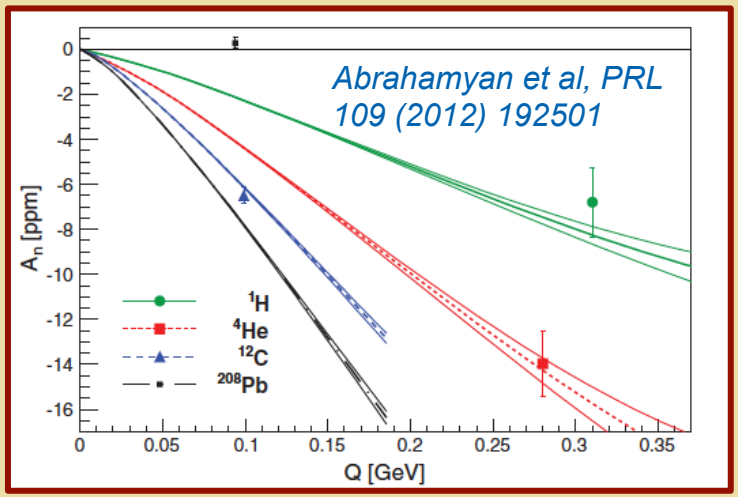


J. Engel

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



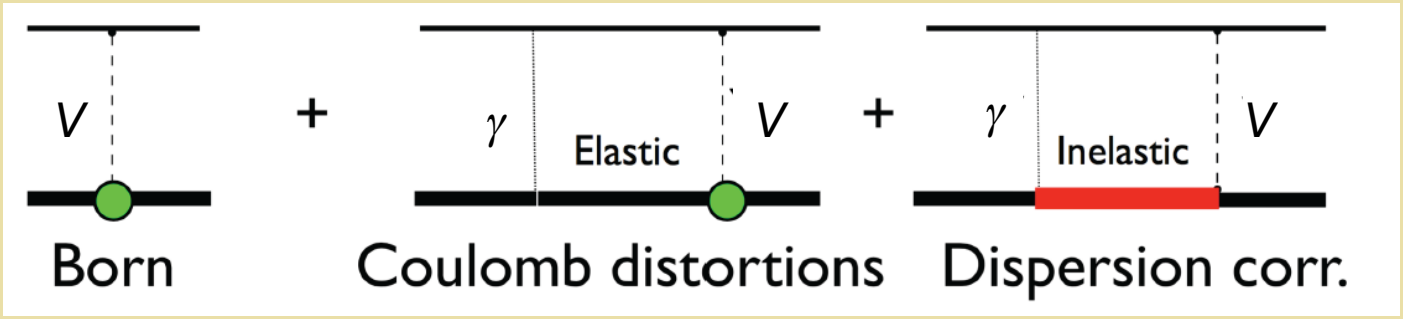


$V = \gamma$ ***Beam normal asymmetry***

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

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***

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

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

Radiative Corrections & Ft Values

Corrected ft values:

$$\mathcal{F}t = ft\,(1+\delta'_R)\,(1+\delta_{NS}-\delta_C)\,\left(1+\Delta_E^{NS}\right)$$

Outer correction

Nuclear struct part of $M_{\gamma W}$

E-independent

Nucl wavef'n

Not a RC

Nuclear struct part of $M_{\gamma W}$

E-dependent

Radiative Corrections & V_{ud}

Superallowed

$$|V_{ud}|^2 = \frac{2984.43s}{\mathcal{F}t(1+\Delta_R^V)}$$

Hadronic & short distance part of $M_{\gamma W}$

Neutron

$$|V_{ud}|^2 = \frac{5099.34s}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

$(g_A / g_v)^2$

Contains Δ_R^V