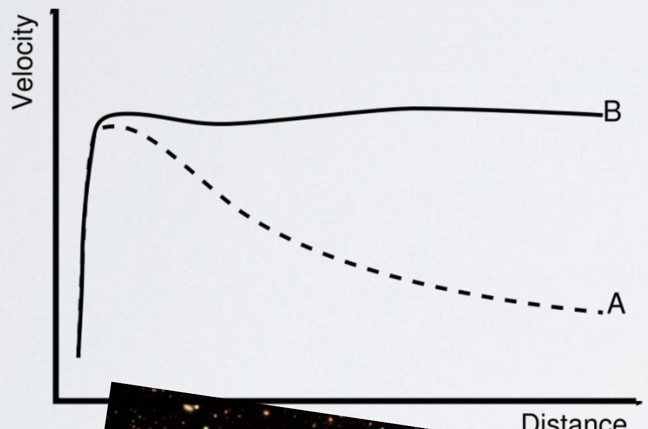
BEYOND-THE-STANDARD-MODEL PHYSICS WITH HADRONS AND NUCLEI

Jordy de Vries
University of Amsterdam & Nikhef

The search for something non-Standard...

13.6 billion years



Theoretical puzzles

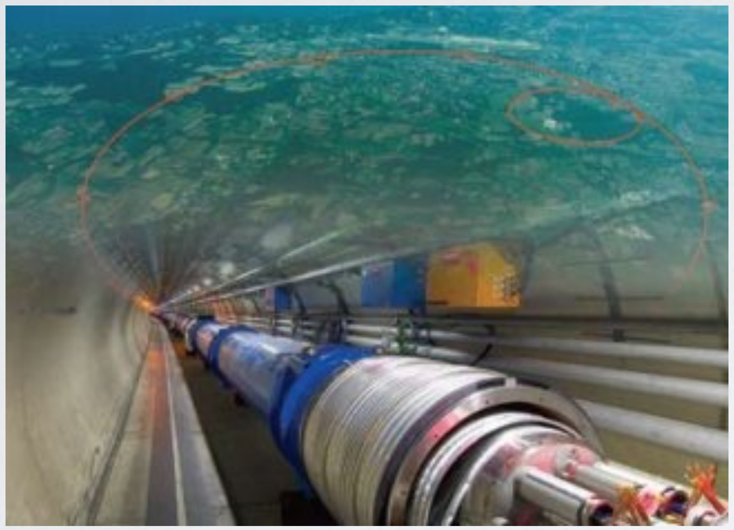
$$\frac{m_{\text{Higgs}}}{m_{\text{Planck}}} \sim 10^{-16}$$

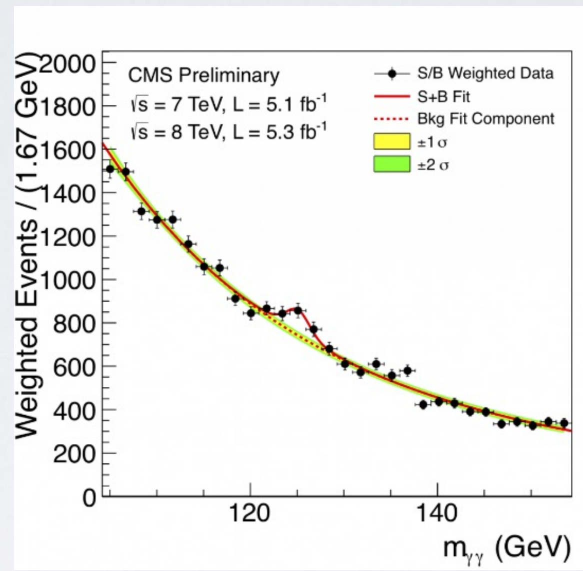
$$\frac{m_e}{m_t} \sim 10^{-6}$$

$$\bar{\theta}_{CP} < 10^{-10}$$

The search for something non-Standard…

Energy





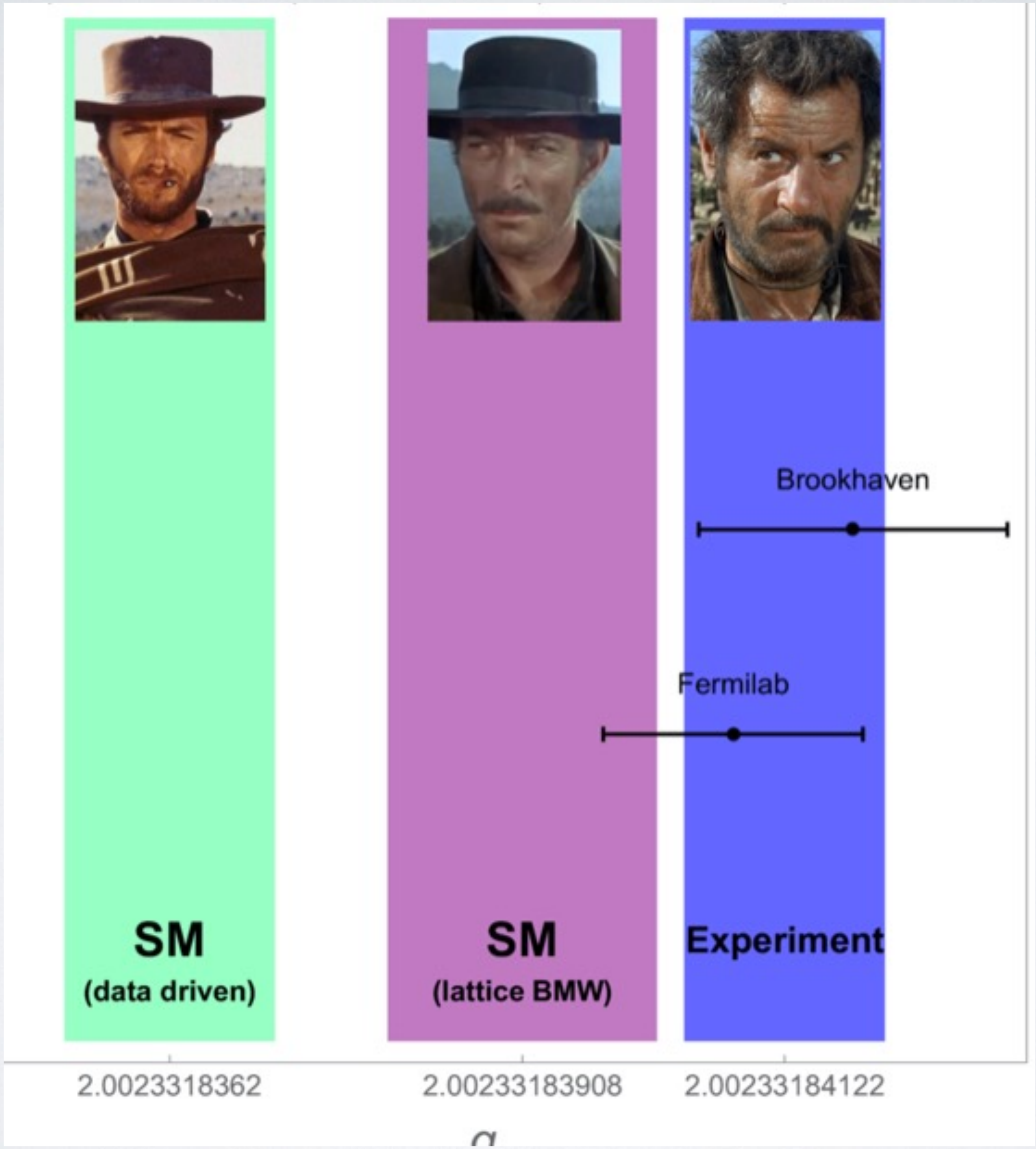
Reach ~ Collider Energy
LHC, FCC, CEPC, ….

Probe indirect BSM effects with known (sometimes no) SM background

Examples: Flavor, g-2, EDMs, $0\upsilon\beta\beta$, proton decay
Also: colliders if BSM scale too high!

Reach ~ experimental and theoretical accuracy

Case in Point

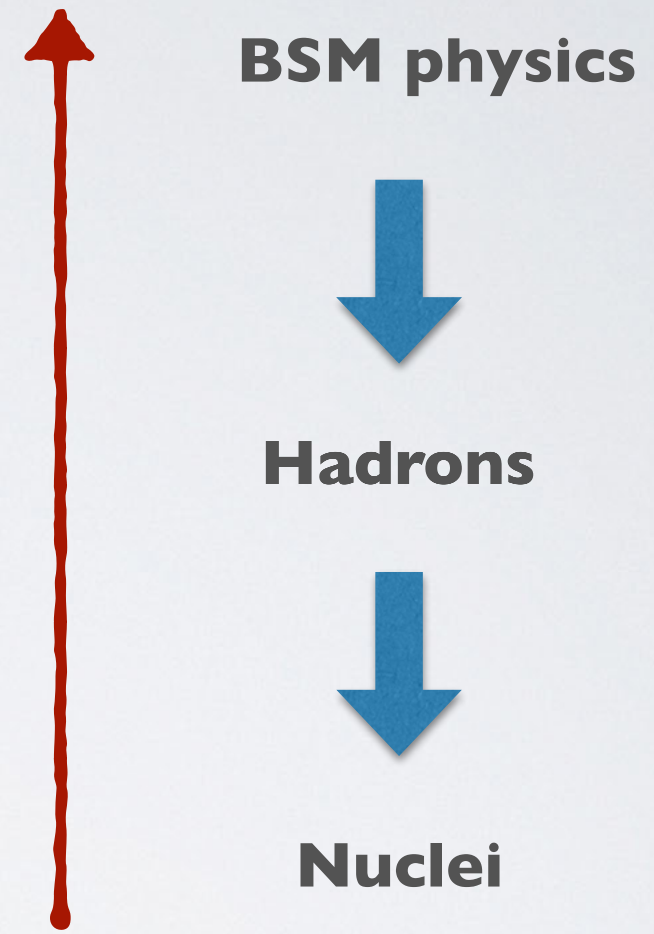


From resonaances.blogspot.com

Theoretical precision often involves QCD

Many examples

- Proton decay & n-nbar oscillations
- Neutrinoless double beta decay
- Mu-to-e conversion
- Dark Matter direct detection
- Axion searches
- Electric dipole moments
- Parity-violating e-p scattering (Qweak)
- Precision beta-decay experiments
- Muon g - 2
- Lepton-flavor universality in B decays
- ……………….



How to interpret and compare experiments in search for BSM physics ?

How can hadronic and nuclear community contribute here ?

Theoretical precision often involves QCD

Many examples

- Proton decay & n-nbar oscillations
- **Neutrinoless double beta decay**
- Mu-to-e conversion
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- ……………….

BSM physics

Hadrons

Nuclei

How to interpret and compare experiments in search for BSM physics ?

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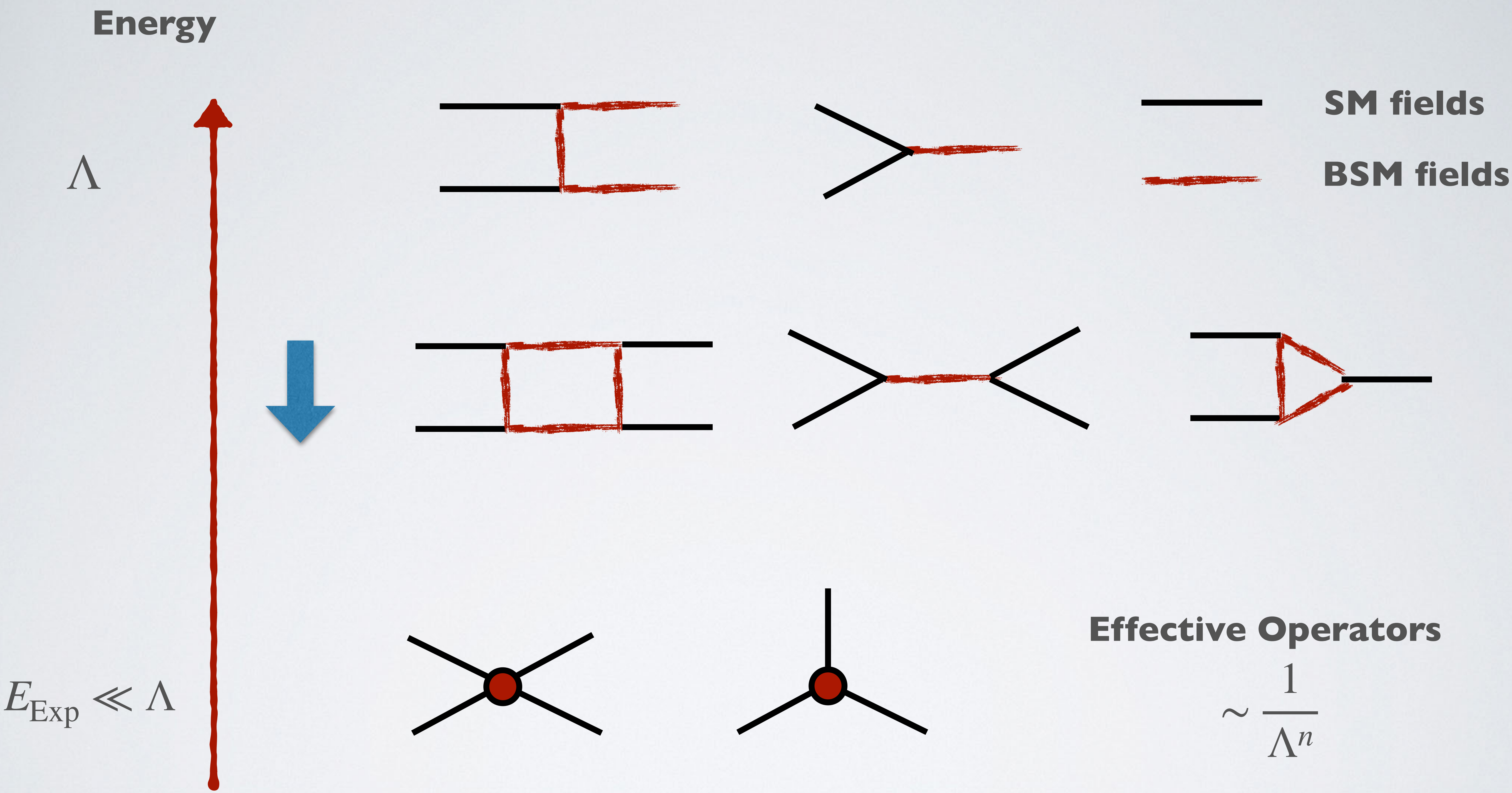
2 examples with a lot of overlap

A general Standard-Model-EFT framework



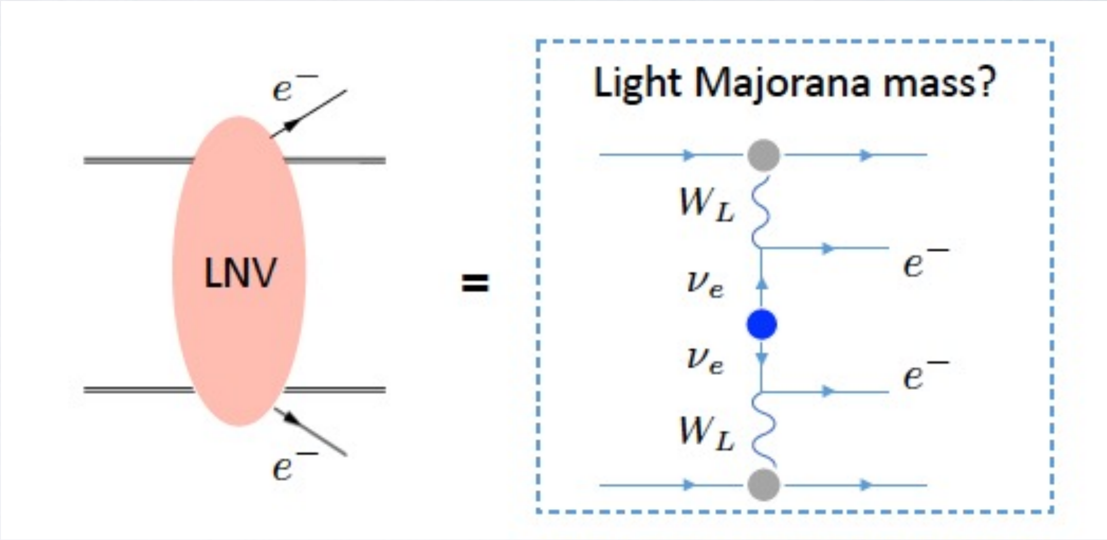
Effects of heavy BSM fields capture by local effective operators

Most relevant SMEFT operators at dimension five (n=1) and six (n=2)

Two low-energy searches for BSM physics

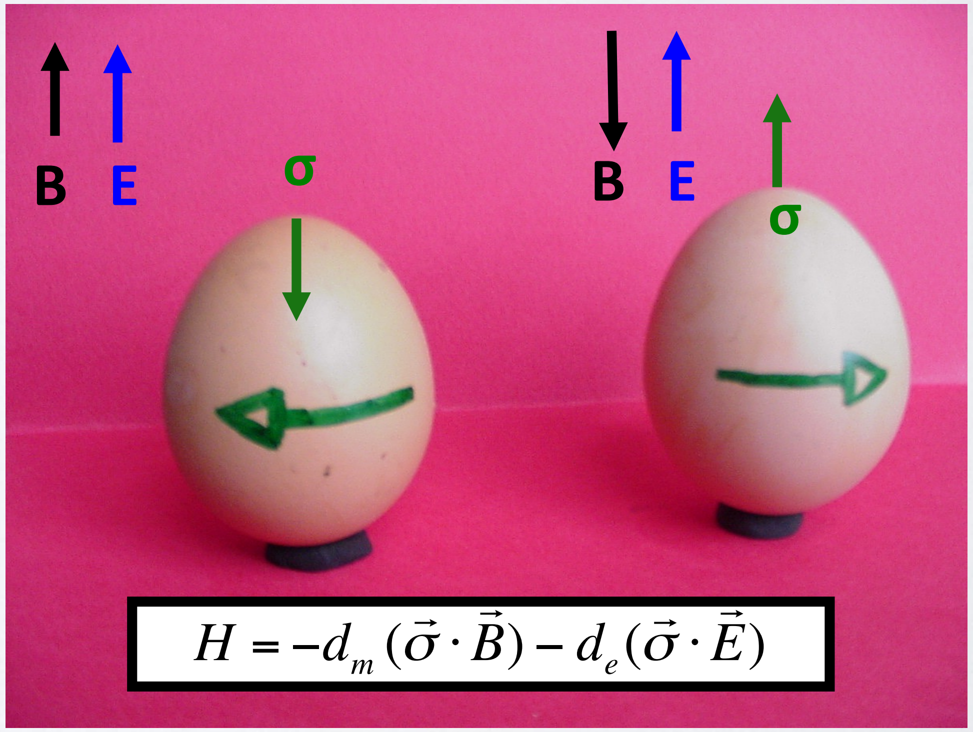
I) Neutrinoless double beta decay

Dim-5



II) Electric dipole moments

Dim-6

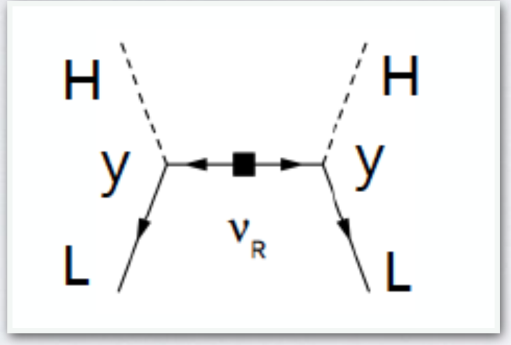


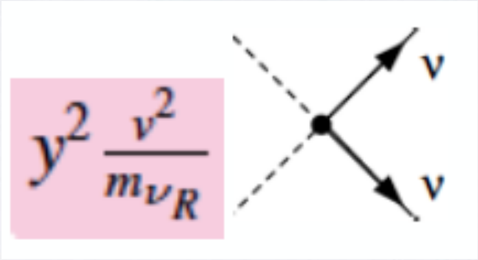
Neutrino masses in SM-EFT

- Neutrinos are formally massless in the SM → but neutrino oscillations ….
- Easy fix: Insert gauge-singlet right-handed neutrino υ_R

$$\mathscr{L} = -\, y_\nu\, \bar{L}\tilde{H}\nu_R - M_R\, \nu_R^T C \nu_R$$

- Integrate out heavy right-handed neutrinos





- Obtain the single dimension-5 SMEFT operator

Neutrino Majorana mass

$$\mathscr{L}_5 = \frac{c_5}{\Lambda}\left(L^T C \tilde{H}\right)(\tilde{H}^T L) \longrightarrow \mathscr{L}_5 = c_5 \frac{v^2}{\Lambda} \nu^T C \nu$$

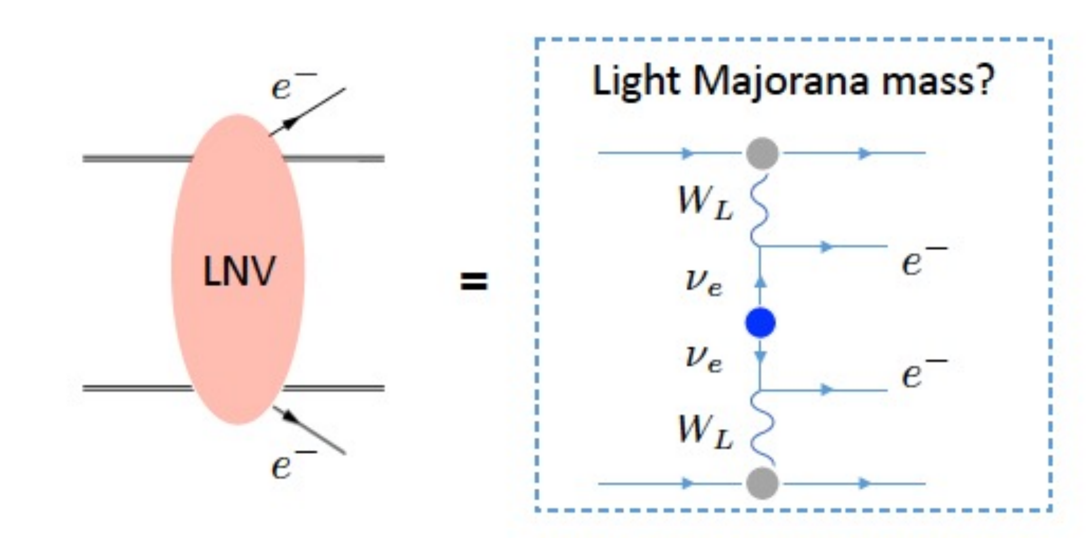
Weinberg '79

- **Violates an accidental SM symmetry: Lepton Number**
- **Implies neutrino are Majorana states → connection to leptogenesis**

Low-energy probes of LNV

- How to determine that neutrinos are Majorana states ?
- Most promising way: look at `neutrinoless' processes

$$K^- \to \pi^+ + e^- + e^- \qquad pp \to e^+ + e^+ + \text{jets}$$



$$X(Z,N) \to Y(Z+2,N-2) + e^- + e^-$$

- Most sensitive probe right now $\qquad \tau(^{136}\text{Xe}) > 1.1 \cdot 10^{26}$ year

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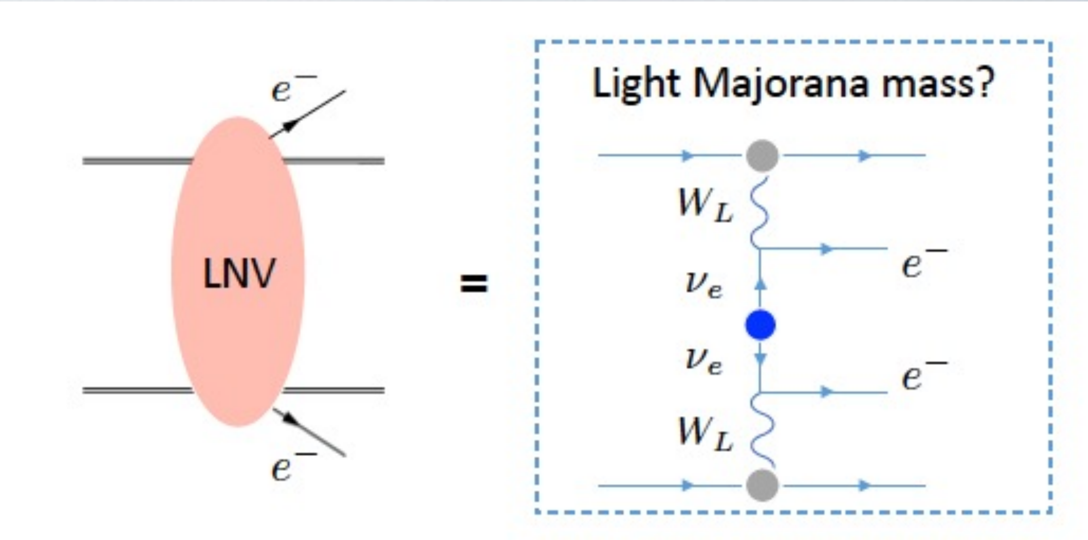
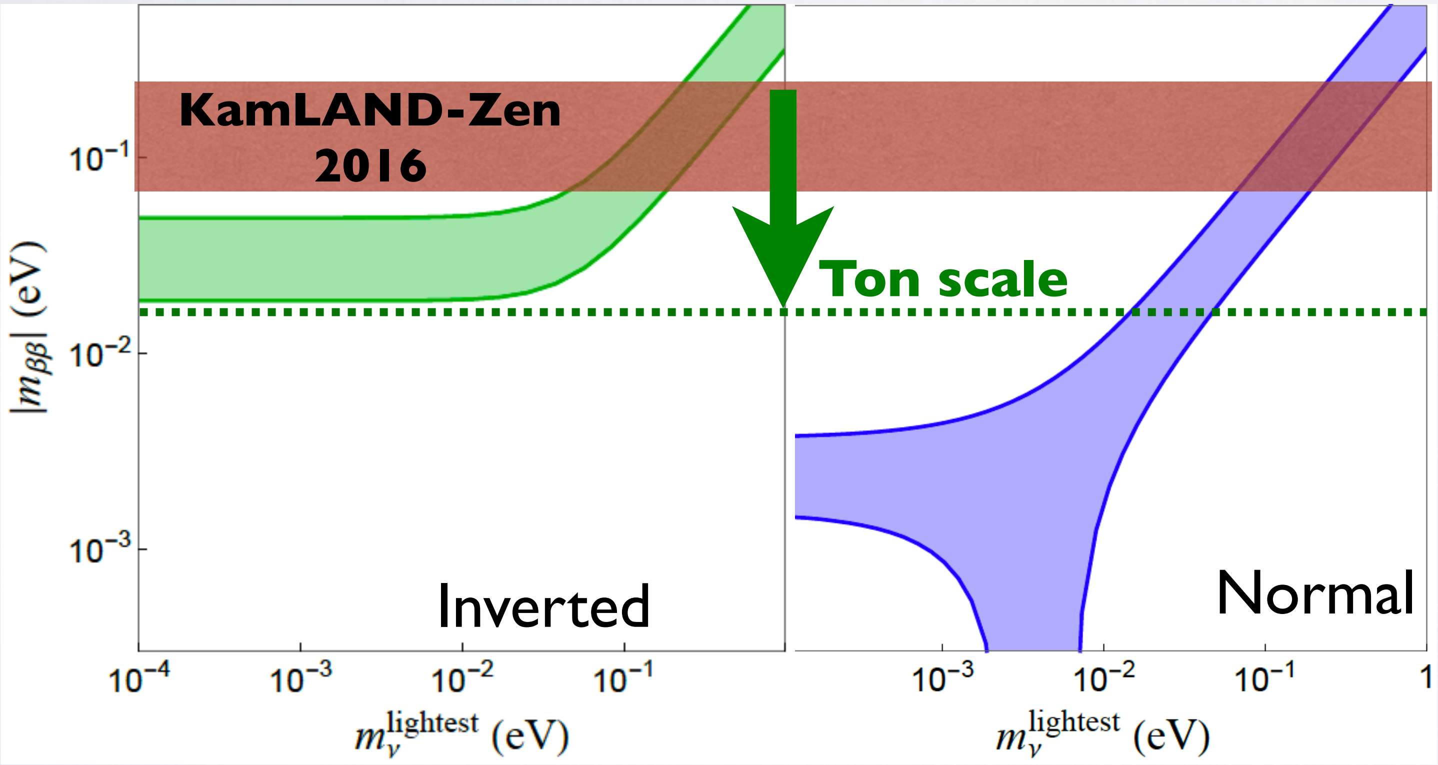


- Most sensitive probe right now $\tau(^{136}\mathrm{Xe}) > 1.1 \cdot 10^{26}$ year
- Exchange of light Majorana Neutrinos: $\Gamma \sim 1/\tau \sim |M_{0\nu}|^2 m_{\beta\beta}^2$ $\qquad m_{\beta\beta} = \sum_i U_{ei}^2 m_i$



'Band' due to hadronic/nuclear uncertainties

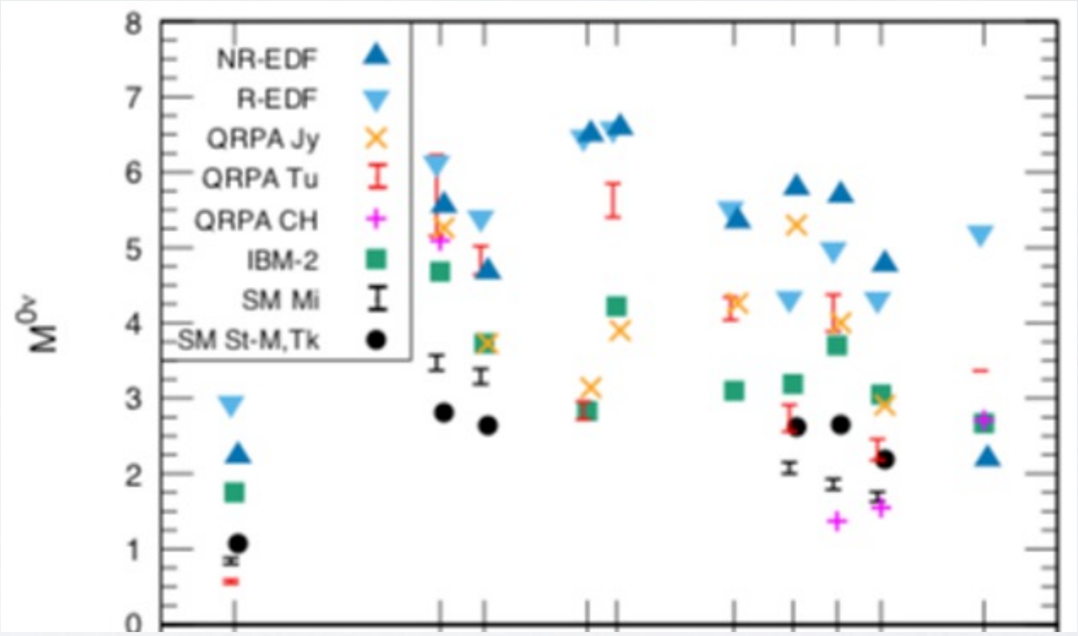
Next-generation discovery possible if inverted hierarchy or m_{lightest} >0.05 eV

Or if there is a different LNV mechanism !

Towards reliable theoretical predictions

- Assuming ‘standard’ mechanism: uncertainties from **hadronic & nuclear theory**

$\Gamma \sim |M_{0\nu}|^2 (m_{\beta\beta})^2$



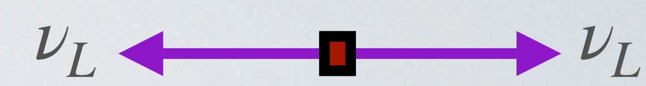
Engel-Menendez ‘16

- Goals: reduce uncertainty using **chiral EFT + lattice + ab initio calculations**

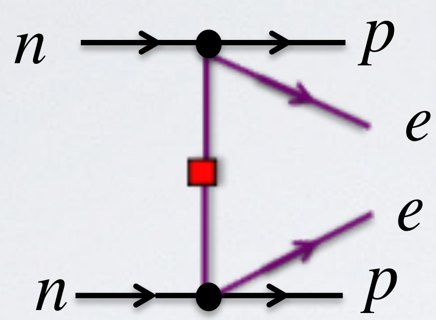
1. **Chiral EFT:** strong nuclear force and electroweak currents
2. **Lattice:** Compute low-energy constants (hadronic matrix elements)
3. **Ab initio:** Nuclear structure and nuclear transition amplitudes

Leading-order transition currents

- Neutrinos are still degrees of freedom in low-energy chiral EFT



- Leads to 'long-range' nn → pp + ee



$$V_\nu \sim \frac{m_{\beta\beta}}{\mathbf{q}^2}$$

$$\mathbf{q} \sim k_F \sim m_\pi$$

$$V_\nu = (2G_F^2 m_{\beta\beta})\tau_1^+\tau_2^+ \frac{1}{\mathbf{q}^2}\left[(1+2g_A^2) + \frac{g_A^2 m_\pi^4}{(\mathbf{q}^2+m_\pi^2)}\right] \otimes \bar{e}_L e_L^c$$

- No unknown hadronic input ! Only unknown is $m_{\beta\beta}$

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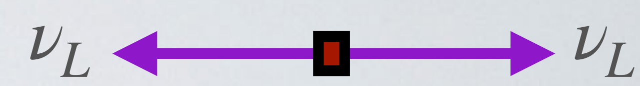

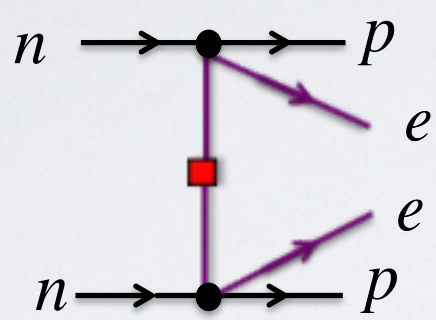

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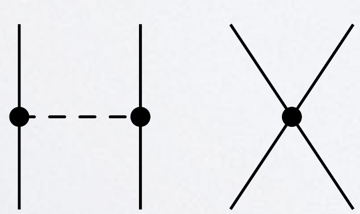
- **Story changes once we consider initial- and final-state interactions**
- Nucleon-nucleon scattering states generated from leading-order potential

LO 

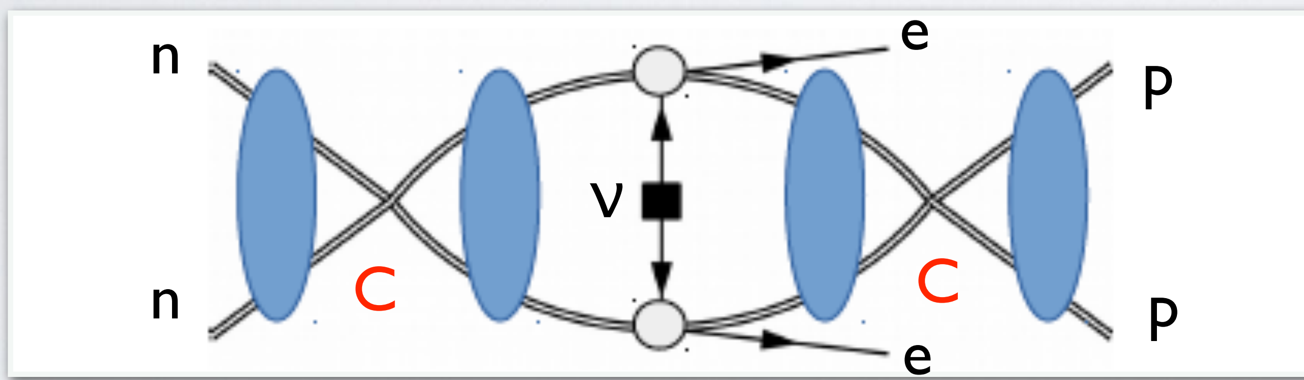
$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2+m_\pi^2}$$

Leading-order transition currents

- Iterate strong potential to all orders to get wave function
- Integrals lead to divergences that are absorbed into C_0
- Nucleon-nucleon phase shifts are renormalized (**regulator independent**)

$$V_{\text{strong}} = C_0 - \frac{g_A^2}{4f_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

- Insert long-distance neutrino exchange into scattering states



$$\sim (1+2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL '18

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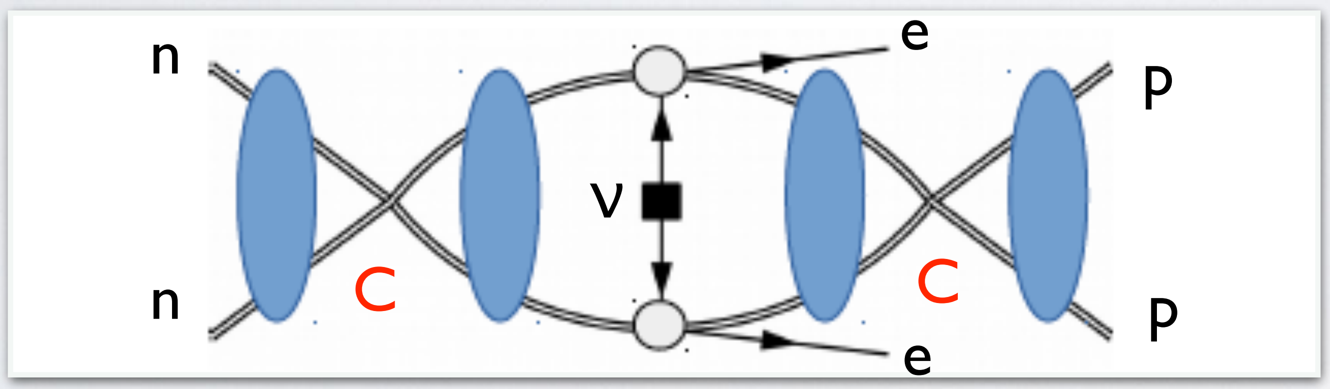
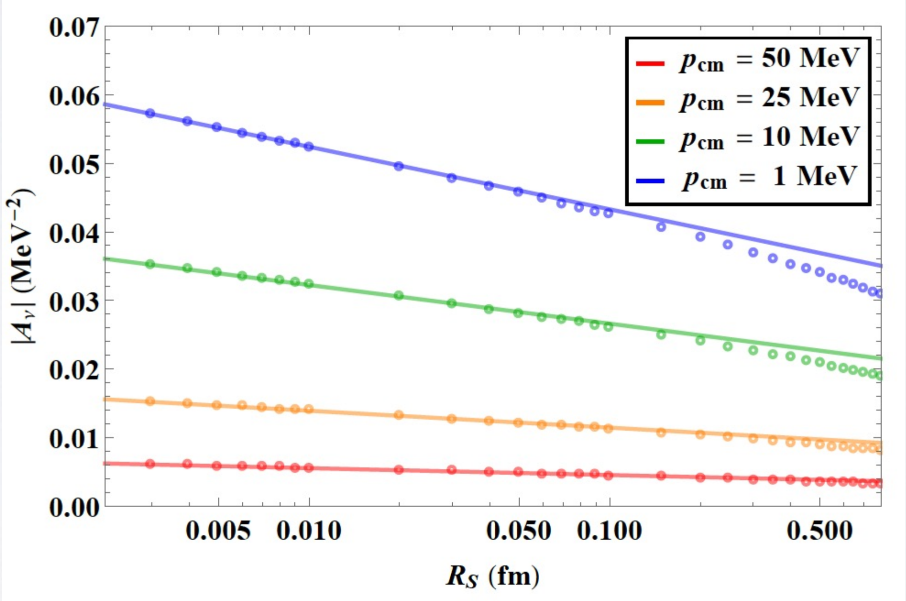




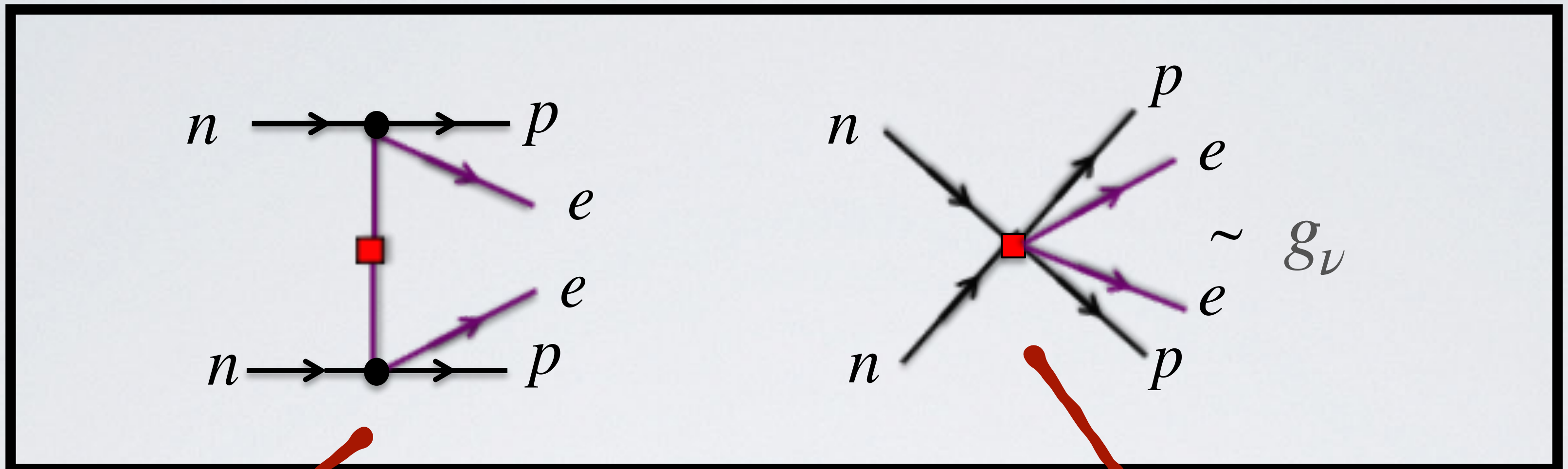
$$\sim (1 + 2g_A^2)\left(\frac{m_N C_0}{4\pi}\right)^2\left(\frac{1}{\epsilon} + \log\frac{\mu^2}{p^2}\right)$$

New divergences

- **Logarithmic regulator dependence !**
- **Requires a counter term: a short-range nn → pp + ee operator**

Cirigliano, Dekens, JdV, Graesser, Mereghetti, Pastore, van Kolck PRL '18

A new leading-order contribution



‘Long-range’ neutrino-exchange
included in all calculations

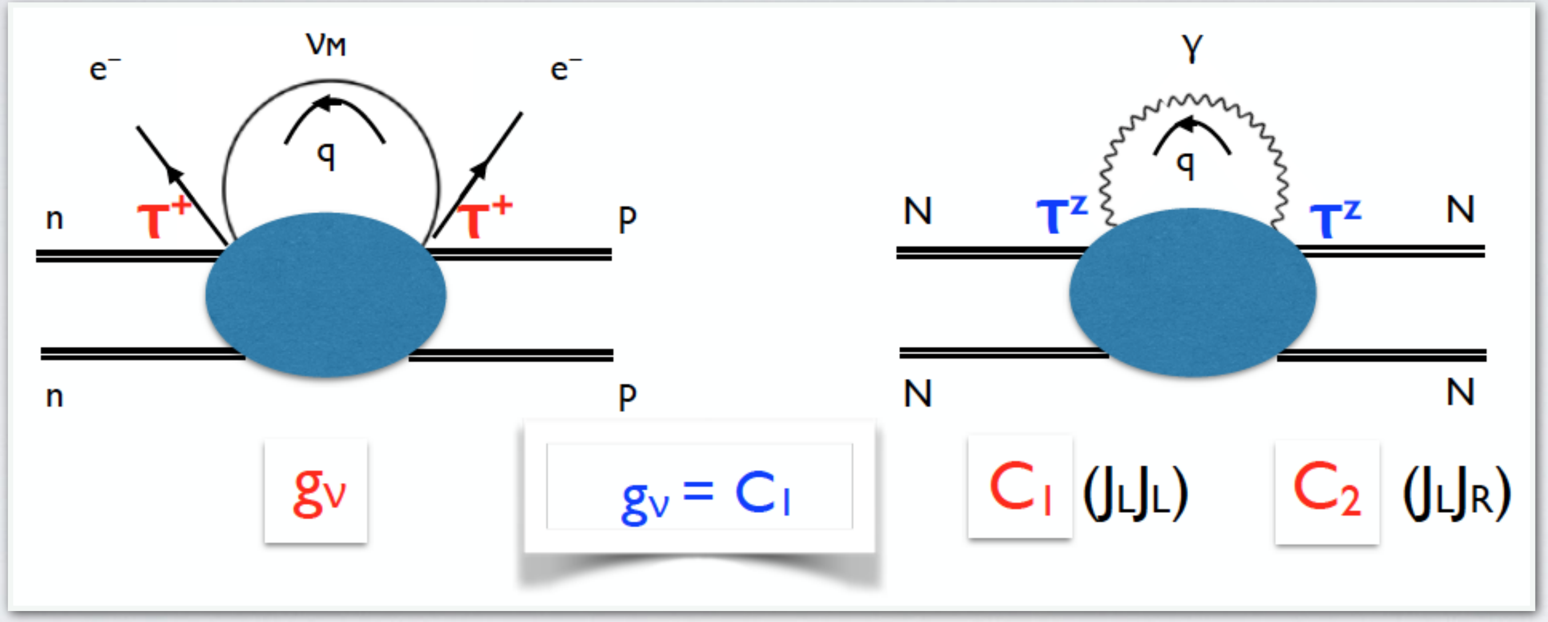
‘Short-distance’ neutrino exchange
required by renormalization of amplitude

- **Short-distance piece depends on unknown QCD matrix element** g_ν
- Crucial input for nuclear calculations of neutrinoless double beta decay

- How to determine the value of this matrix element ?

A connection to electromagnetism

- A neutrino-exchange process looks like a photon-exchange process



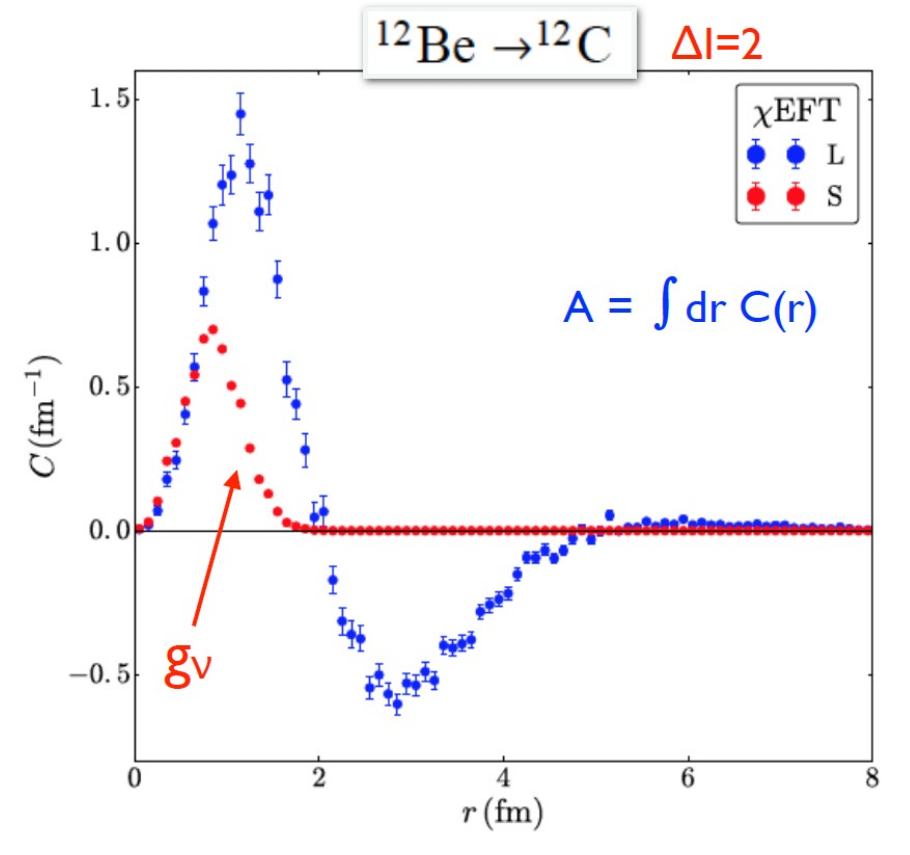
- Isospin-breaking nucleon-nucleon scattering data determines C_1+C_2
- Electromagnetism conserves parity (L + R) coupling and $g_\nu \sim C_1$ only
- Large-Nc arguments indicates $C_1 + C_2 \gg C_1 - C_2$ Richardson, Schindler, Pastore, Springer '21

- **We assume $g_\nu \sim (C_1+C_2)/2$, what happens to neutrinoless double beta decay ?**

Impact on nuclear matrix elements

Cirigliano, Dekens, JdV, et al PRC '19

- Use chiral potentials to generate wave functions
- Extract $g_\nu \sim (C_1+C_2)/2$ from same potential



Nuclear matrix elements	Long Range	Short Range
$^{12}\mathrm{Be} \to {}^{12}\mathrm{C} + e^- + e^-$	0.7	0.5

- Short-distance effects are sizable and change matrix elements by O(1)

- **Caveat-1** Based on $g_\nu \sim (C_1+C_2)/2$ relation
- **Caveat-2** No calculations yet for heavier nuclei

Ab Initio Treatment of Collective Correlations and the Neutrinoless Double Beta Decay of $^{48}\mathrm{Ca}$

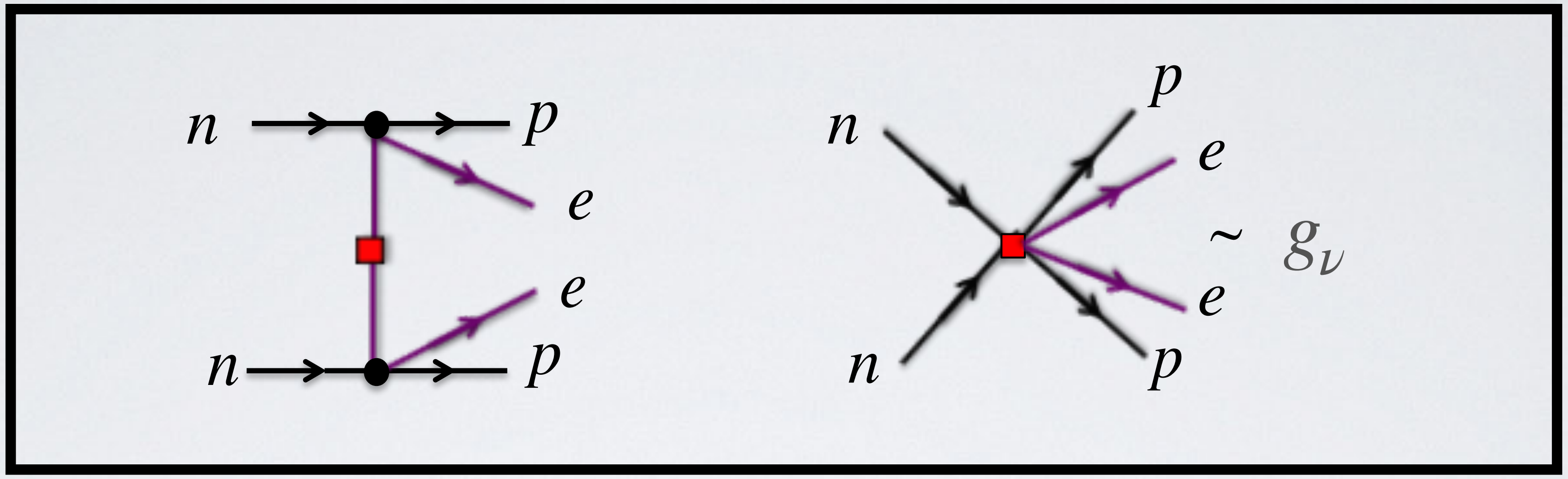
J. M. Yao, B. Bally, J. Engel, R. Wirth, T. R. Rodríguez, and H. Hergert
Phys. Rev. Lett. **124**, 232501 – Published 11 June 2020

Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for $^{48}\mathrm{Ca}$, $^{76}\mathrm{Ge}$, and $^{82}\mathrm{Se}$

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt
Phys. Rev. Lett. **126**, 042502 – Published 29 January 2021

Can we help with Caveat 1 ?

- Input for nuclear calculations is the effective neutrino potential



- The value of g_ν can be obtained from the **total nn → pp amplitude**

Ideally lattice QCD

Tuo et al. '19; Detmold, Murphy '20

Tremendous progress for the 'toy-problem' $\pi^- + \pi^- \rightarrow e^- + e^-$

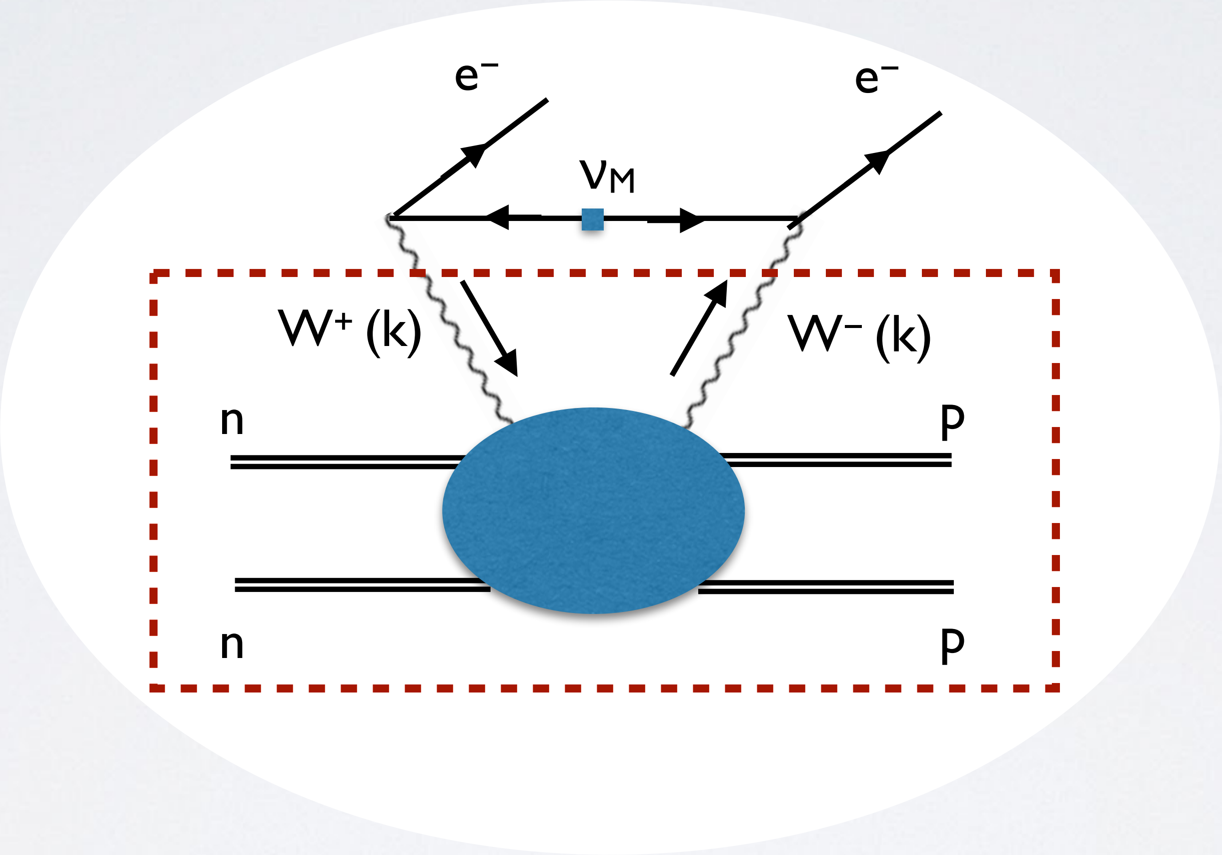
Formalism for lattice calculations being developed Davoudi, Kadam PRL '21 Briceno et al '19 '20

An analytic approach

- The nn → pp + ee amplitude can be represented as an integral expression

$$A_\nu \sim G_F^2 \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2} \boxed{\int d^4x e^{ik\cdot x}\langle pp\,|\,T\{J_W^\mu(x)J_W^\nu(0)\}\,|\,nn\rangle}$$

J_W^μ = weak current (V-A)



- Can represent the `red box' in regions of the virtual neutrino momentum k

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL '21

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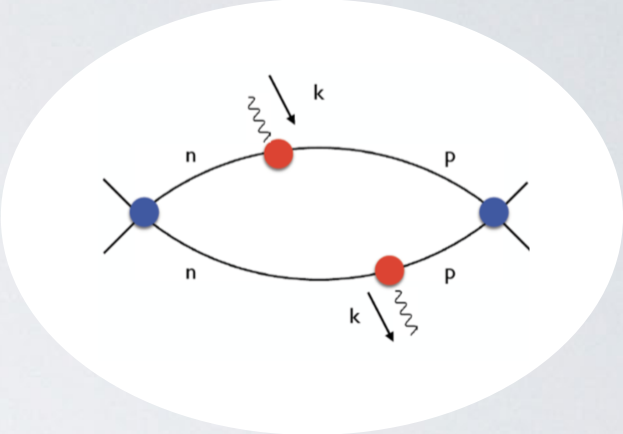
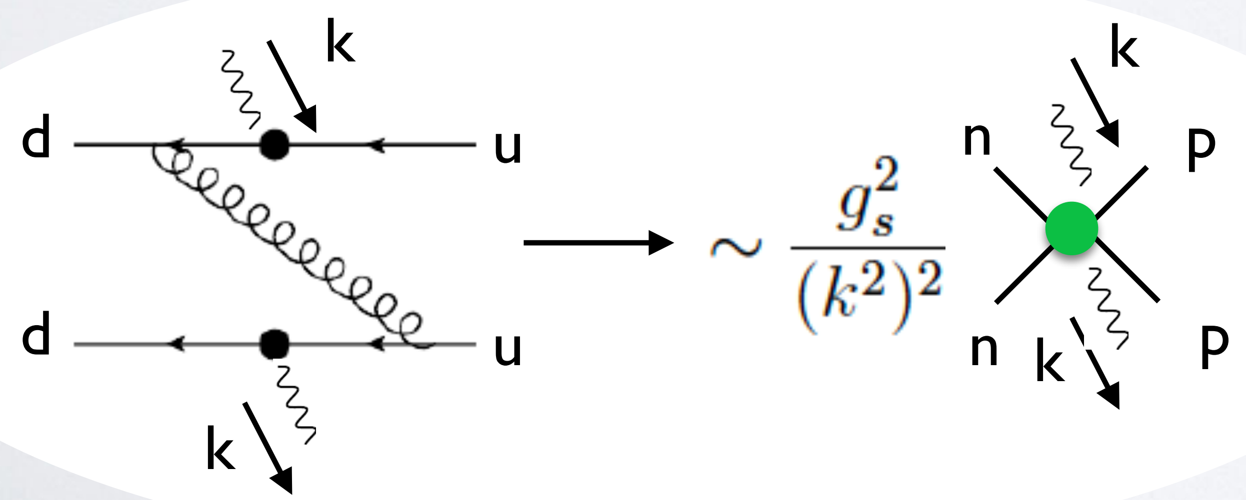


- At small virtual momentum: NLO chiral EFT

- Intermediate momentum: (**model-dependent**) resonance contributions to nucleon form factors and to NN scattering

- Large momentum: Perturbative QCD + Operator Product Expansion



Small dependence on local 4-quark matrix elements

The total amplitude

- The result of this exercise is an expression for total nn →pp + ee amplitude
- Ab initio nuclear calculations can fit the short-distance g_ν in their regulator scheme

$$|A_\nu(|\mathbf{p}|, |\mathbf{p}'|)| = -\,0.019(1)\,\mathrm{MeV}^{-2}$$

$$|\mathbf{p}| = 25\,\mathrm{MeV}$$

$$|\mathbf{p}'| = 30\,\mathrm{MeV}$$

- Example: in dimensional regularization in MS-bar scheme

$$g_\nu(\mu = m_\pi) = (1.3 \pm 0.1 \pm 0.2 \pm 0.5)$$

- This matching can be done for **any scheme** suitable for nuclear calculations

- Same strategy was used to 'predict' EM corrections to nucleon-nucleon scattering

$$a_{CIB} = \frac{a_{nn} + a_{pp} - 2a_{np}}{2} = (15 \pm 5)\,\mathrm{fm}$$

$$a_{CIB}^{\mathrm{data}} = (10.4 \pm 0.2)\,\mathrm{fm}$$

Cirigliano, Dekens, JdV, Hoferichter, Mereghetti PRL '21

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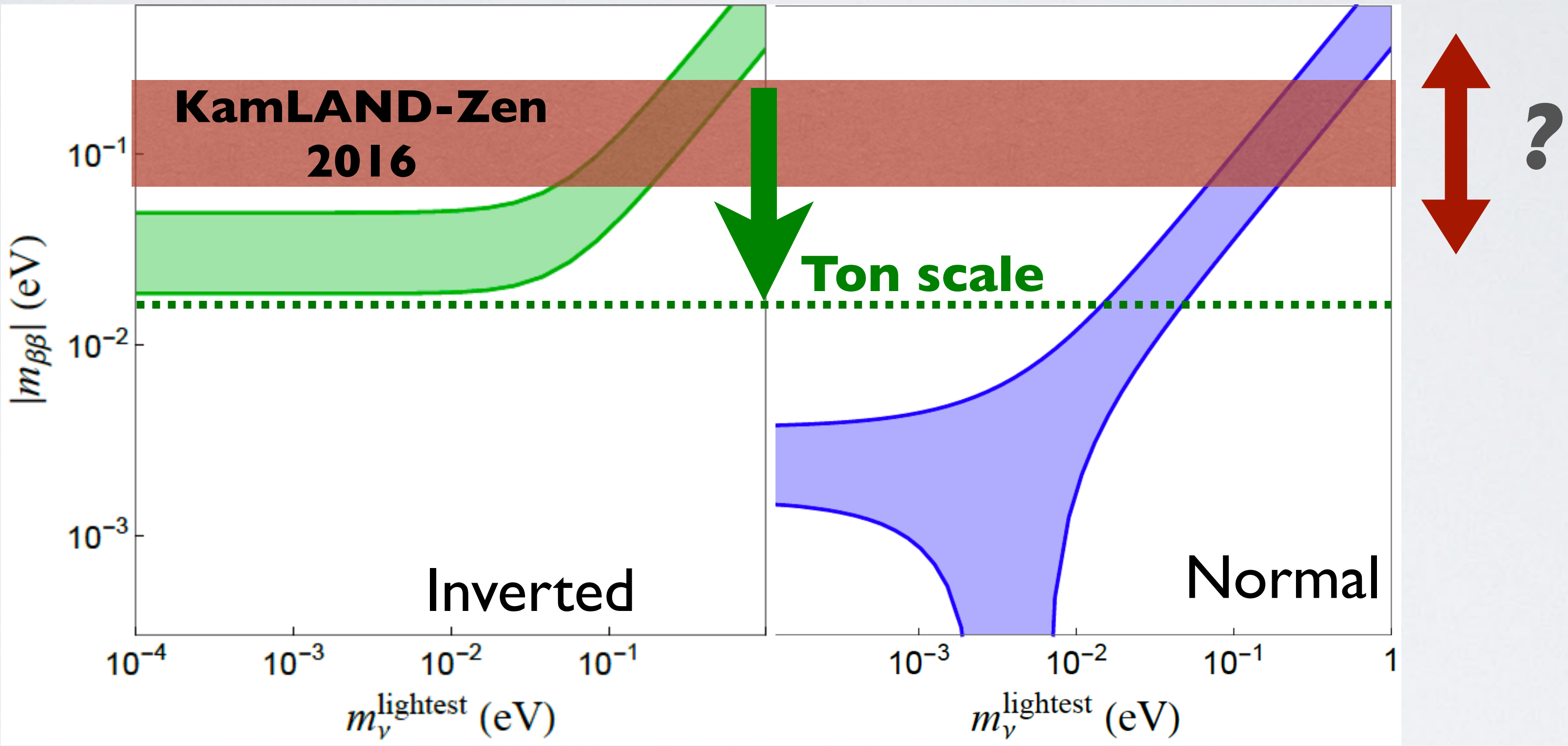


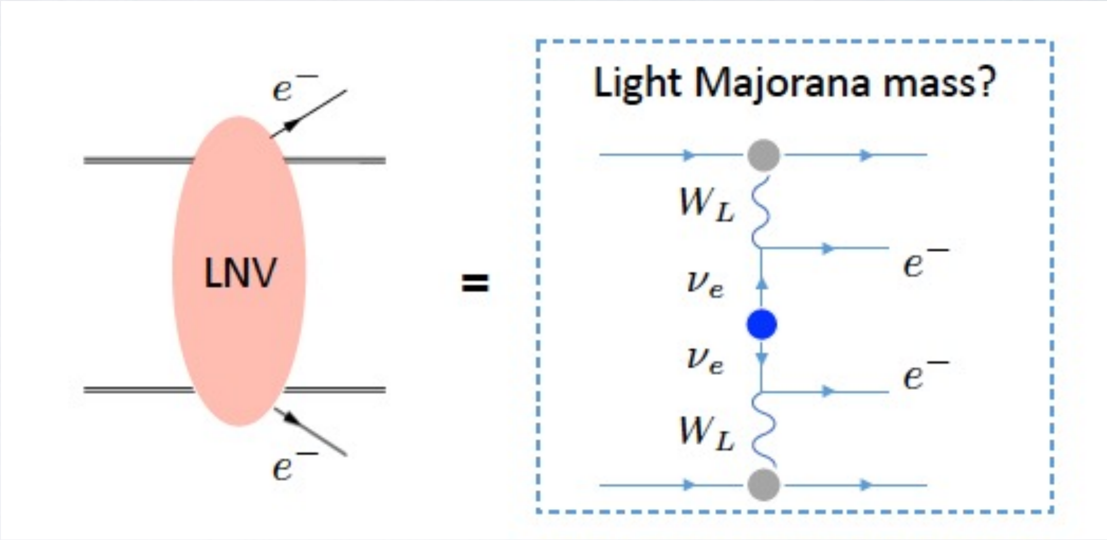
- To be done: determine impact on heavier nuclei

e.g. Wirth, Hergert, Yao

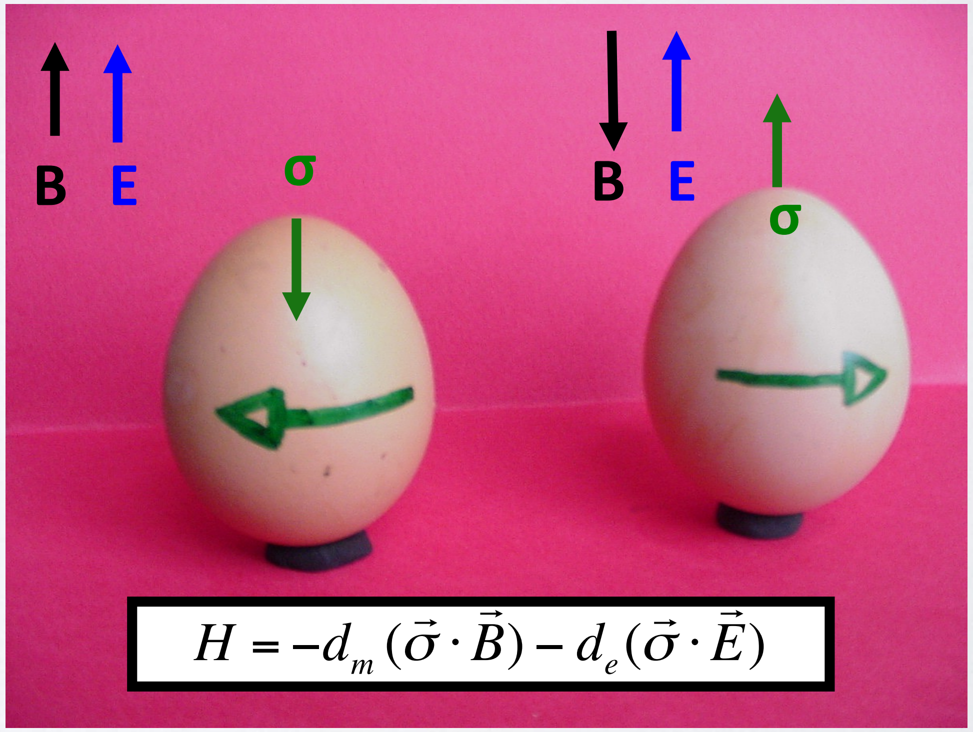
- Ab initio nuclear community is implementing short-distance contribution
- **Unclear yet wether it will increase or decrease the total nuclear matrix element !**

Two low-energy searches for BSM physics

I) Neutrinoless double beta decay

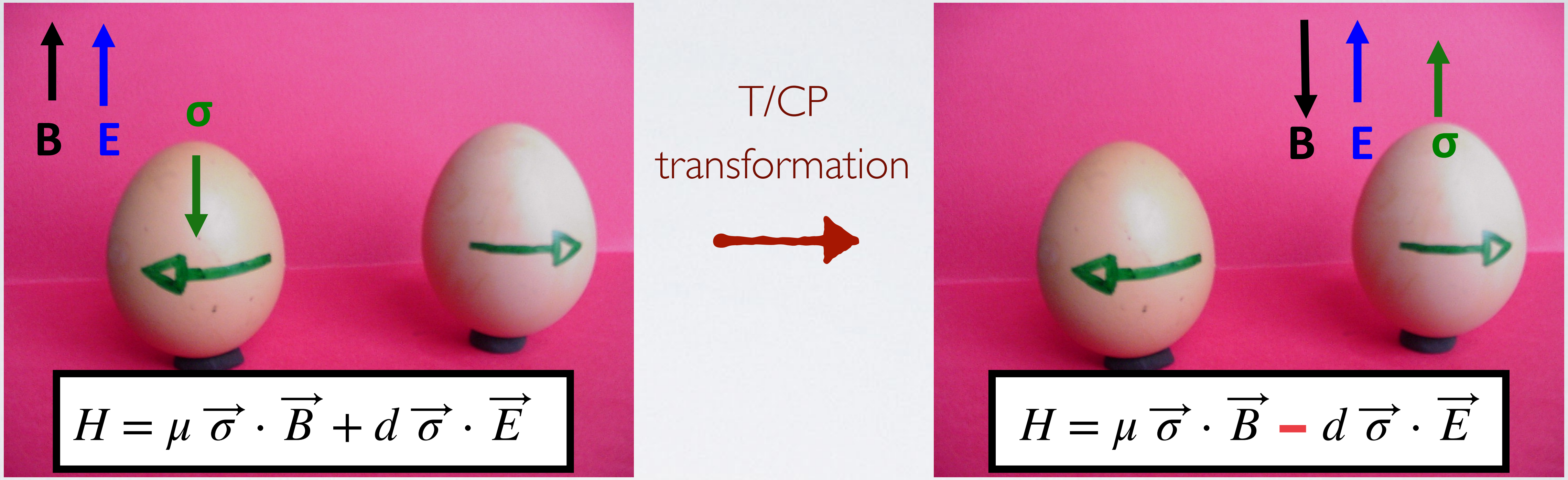


II) Electric dipole moments



A brief intro to EDMs

- Electric Dipole Moments (EDMs) are probes of CP violation



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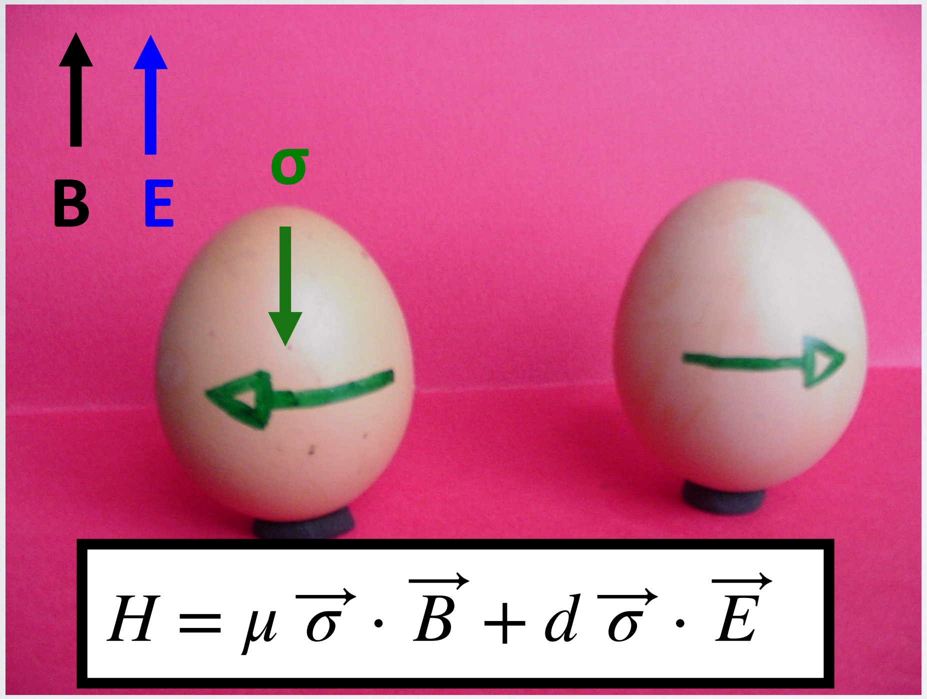
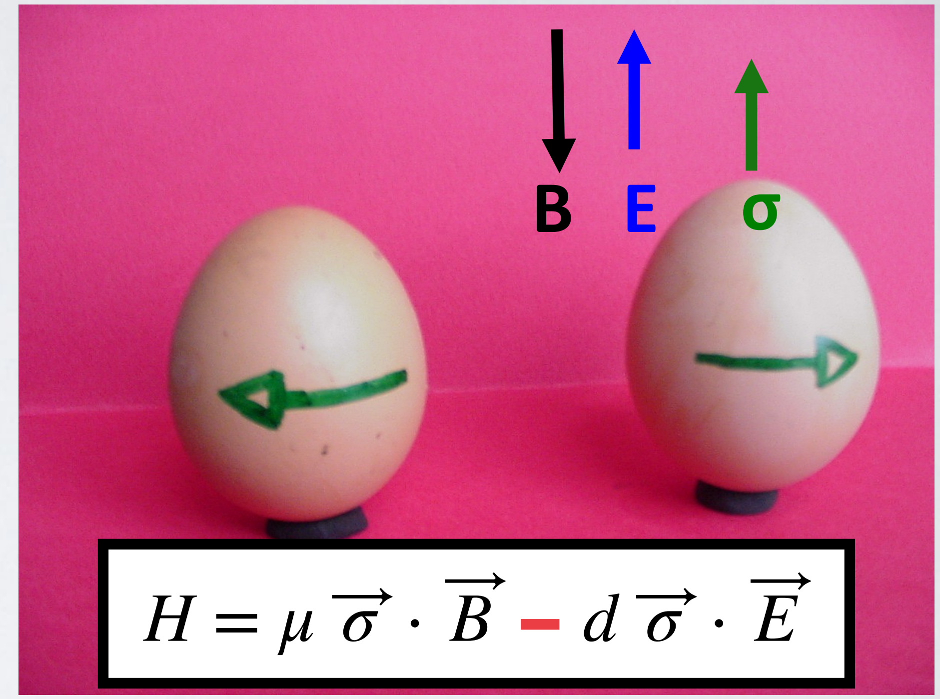
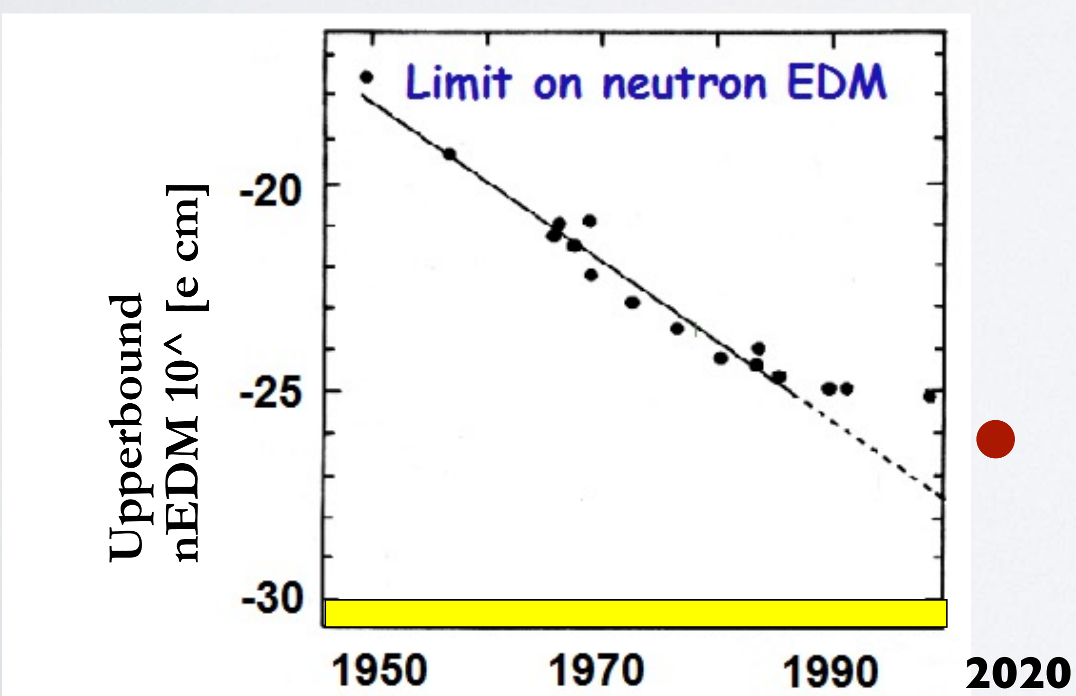


T/CP
transformation



- EDMs are induced by the SM weak interaction only at 3 loop-level (electron EDM at 4-loop)



- SM prediction essentially out of reach right now

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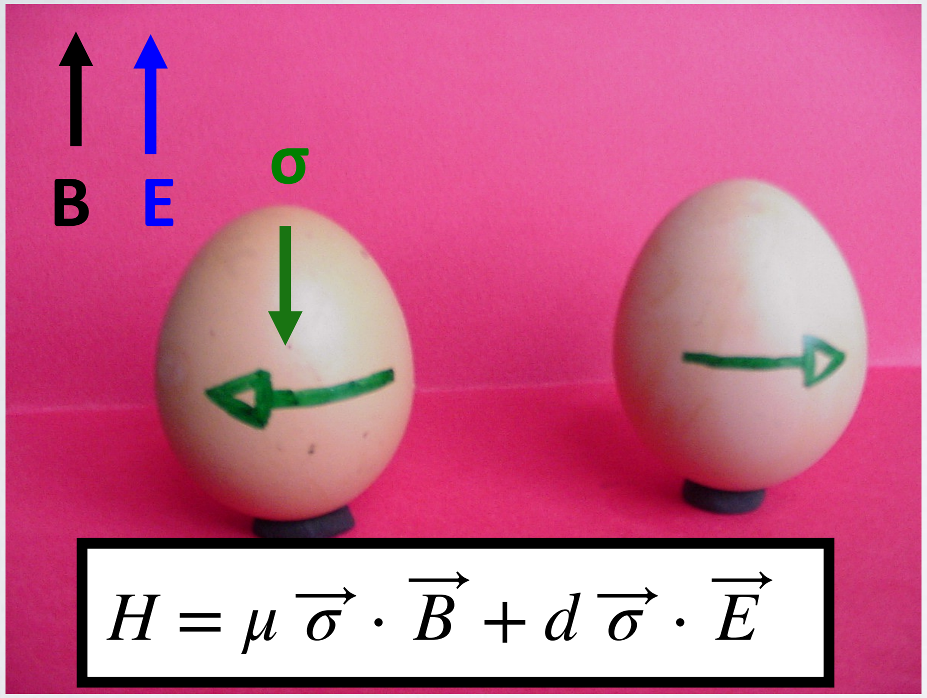

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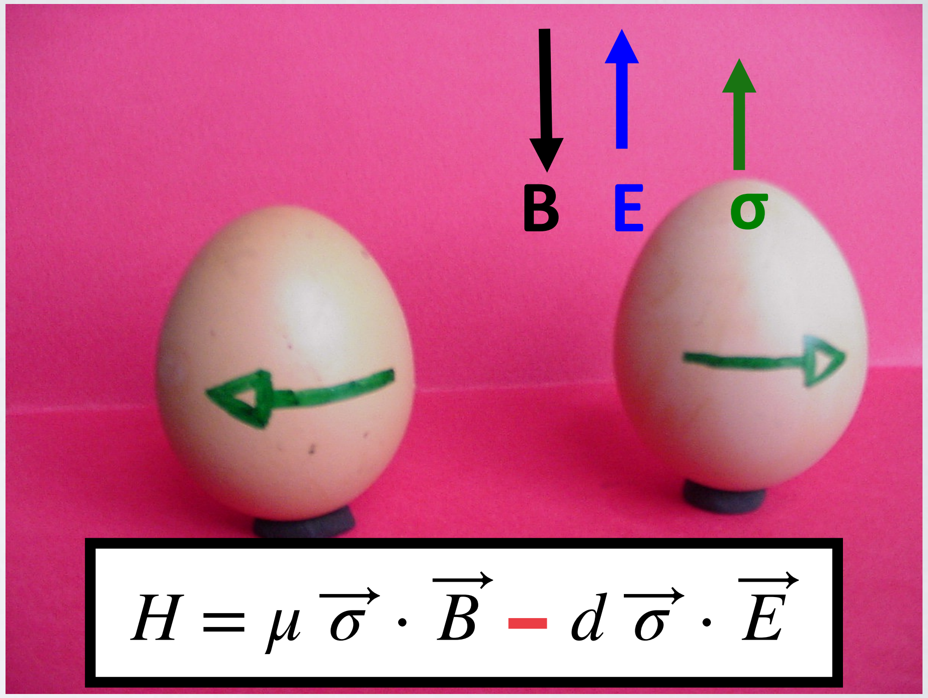

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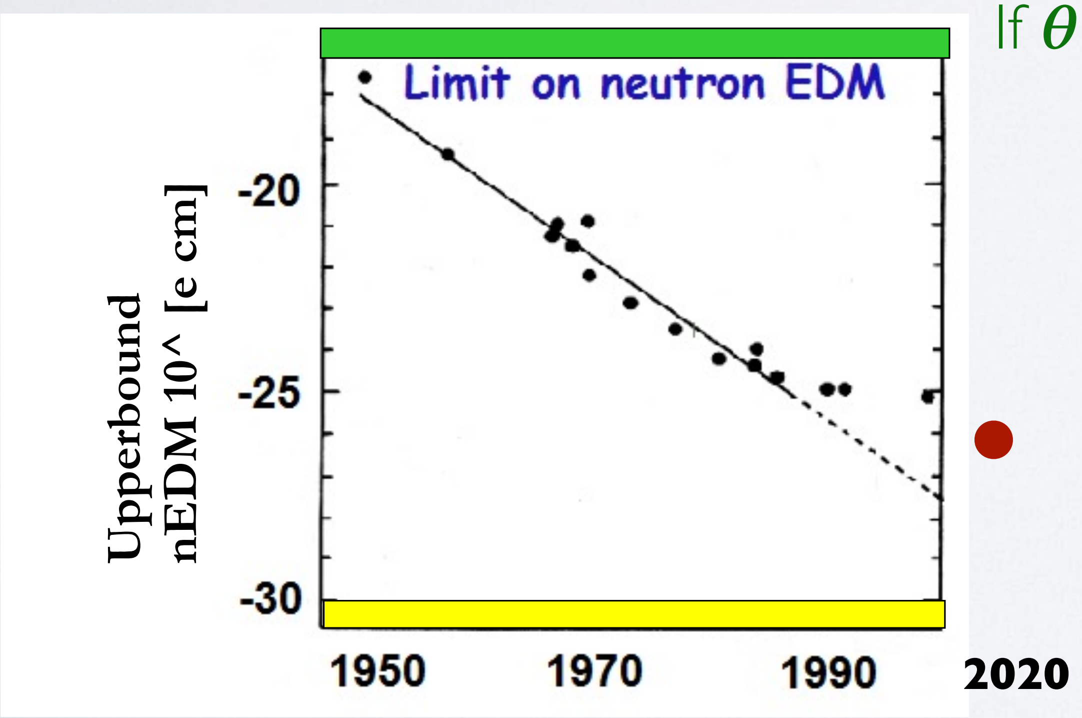


If $\boldsymbol{\theta} \sim 1$

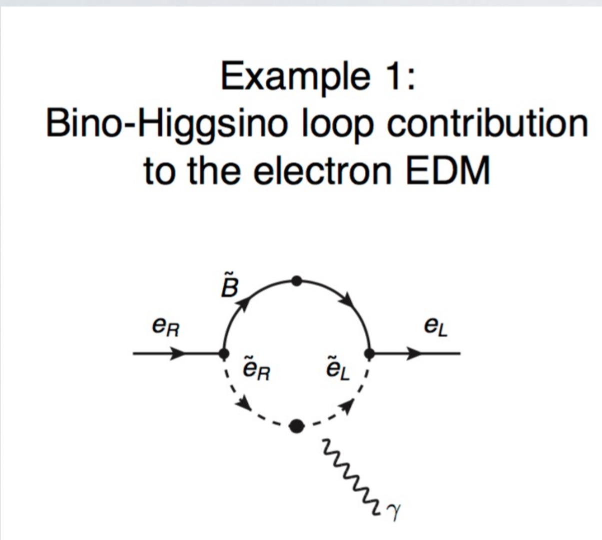
- SM prediction essentially out of reach right now
- EDMs can still arise from the QCD theta term

$$\mathcal{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$

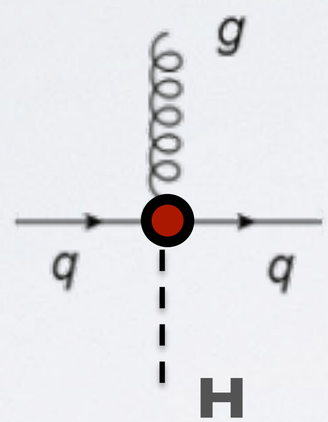
- Strong CP problem: $\boldsymbol{\theta} < 0.0000000001$

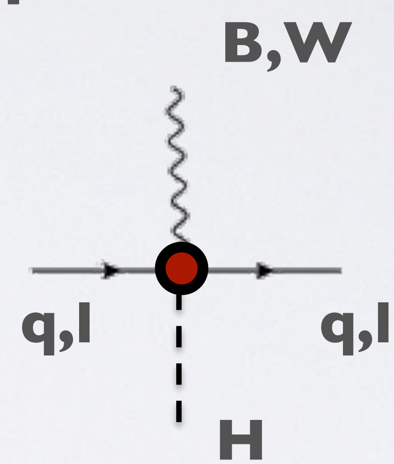
CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- Many BSM models induce new CP violation



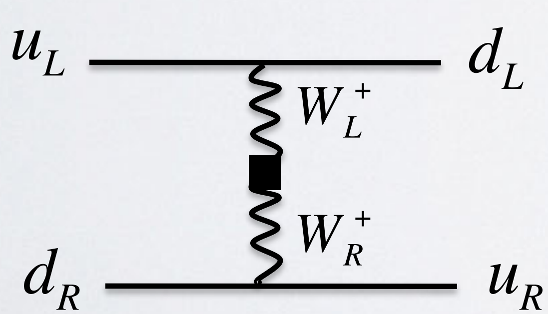
CP-odd dipoles

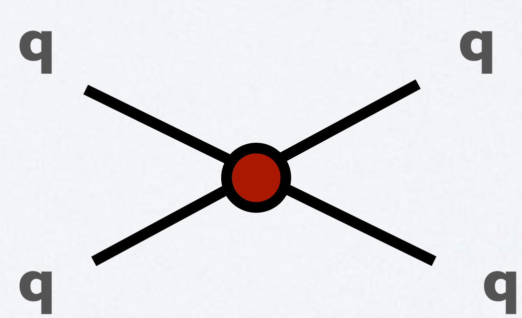




$$\sim \frac{1}{\Lambda^2}\frac{\alpha_{em}}{\pi}\sin\phi_{CP}$$

left-right symmetric models



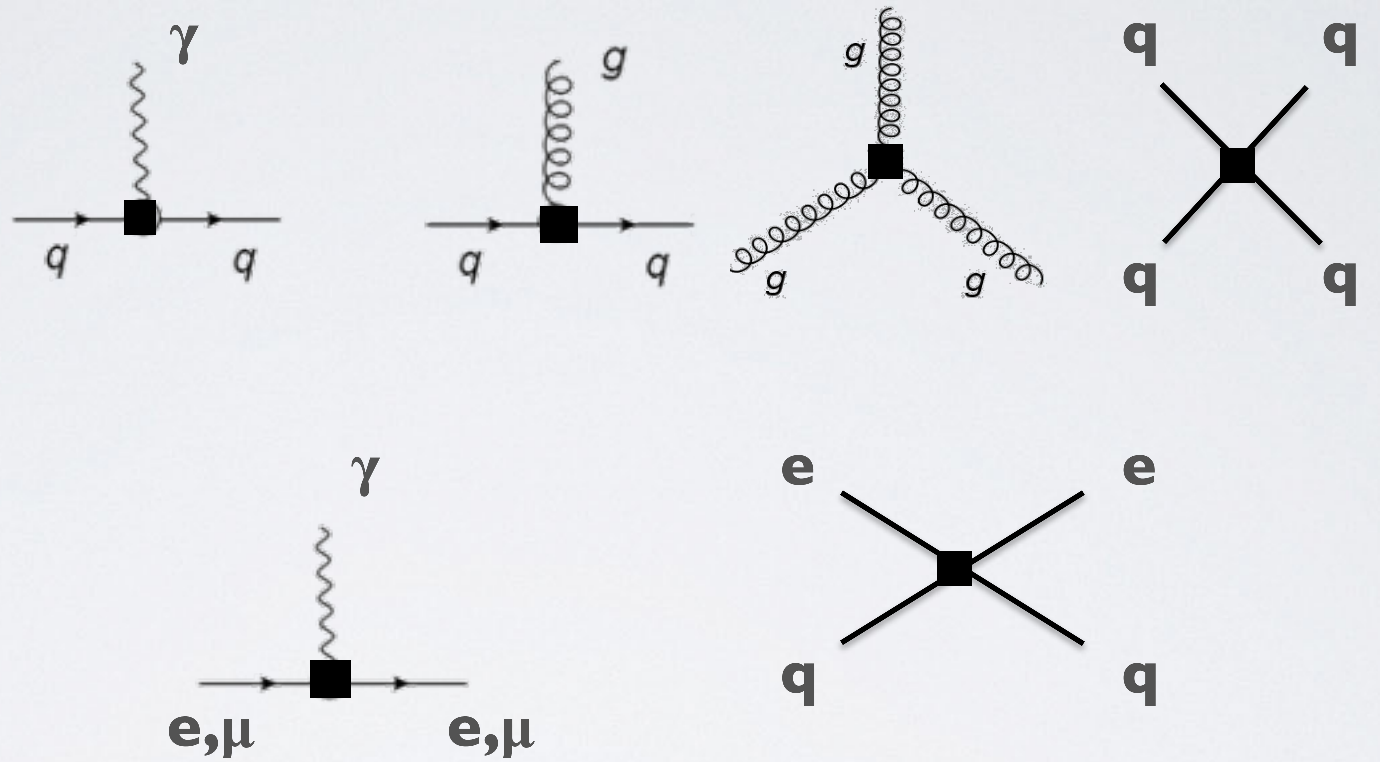


$$\sim \frac{1}{\Lambda^2}\sin\phi_{CP}$$

CP violation in SM-EFT

- Large number of **CP-odd** and **flavor-diagonal** dim-6 operators (unlike Standard Model)
- At energies around a few GeV: handful of operators left

$$\mathscr{L}_\theta \sim \bar{\theta}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$



- **Induce electric dipole moments of leptons, hadrons, nuclei, atoms, molecules**

CP violation in SM-EFT

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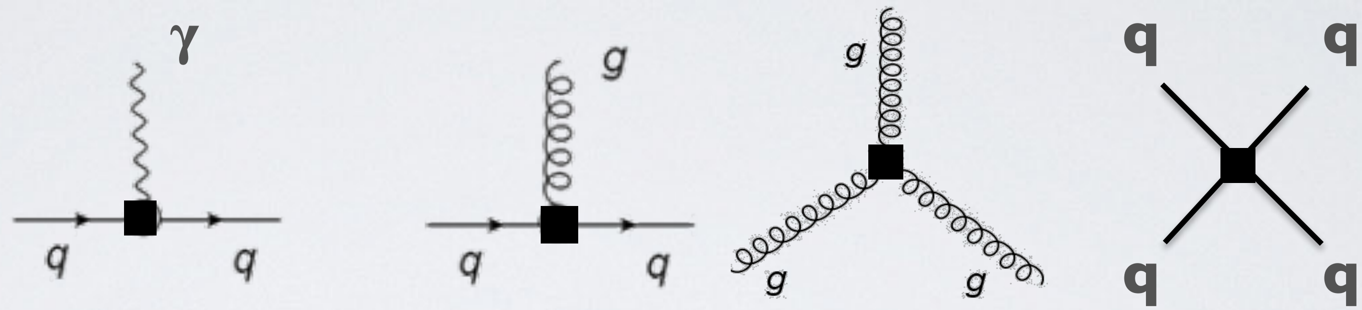
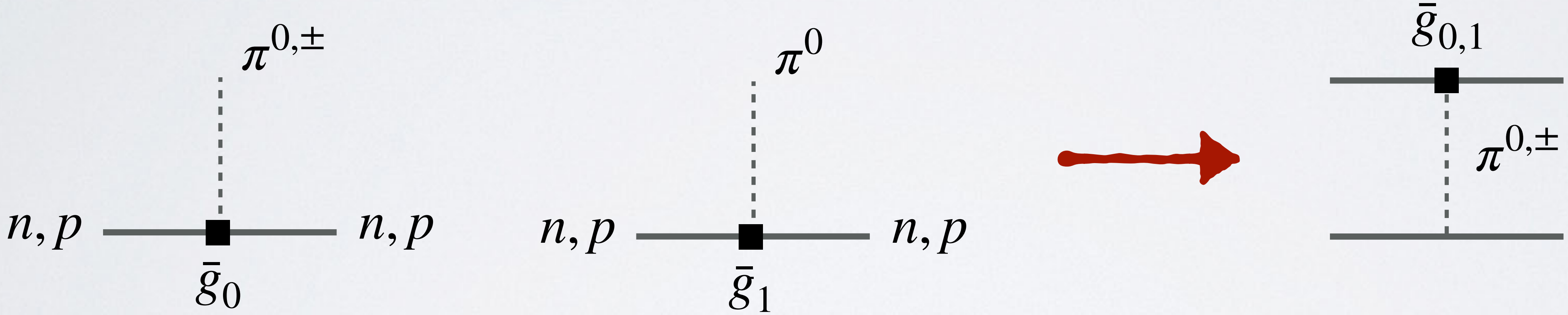


- Use chiral perturbation theory to obtain CP-violating hadronic Lagrangian

JdV et al '12
Bsaisou et al '14



CP-odd nuclear force

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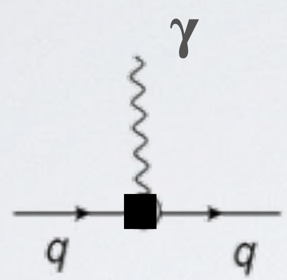

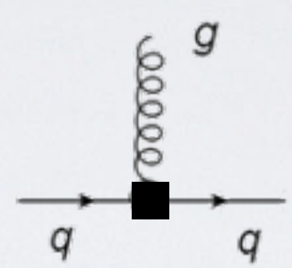

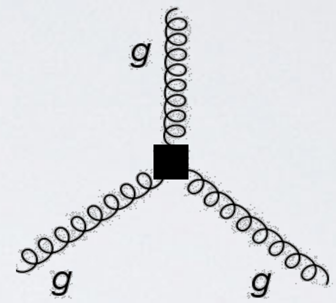

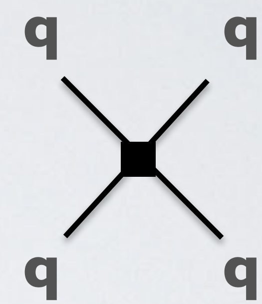

- Use chiral perturbation theory to obtain CP-violating hadronic Lagrangian

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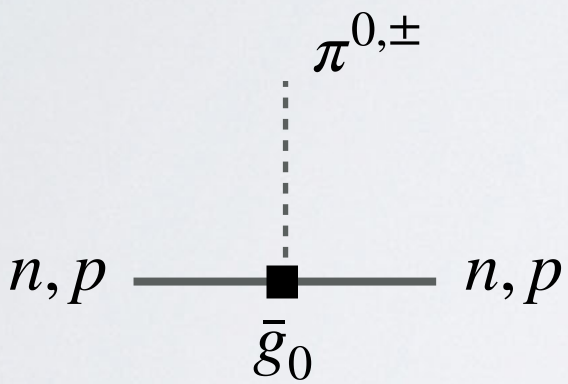
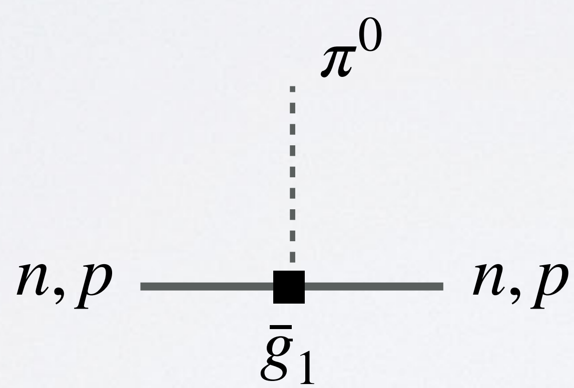
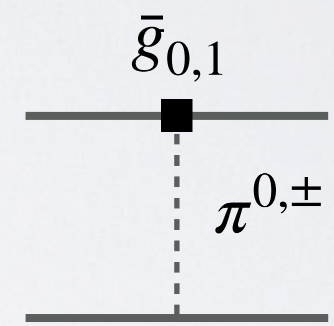
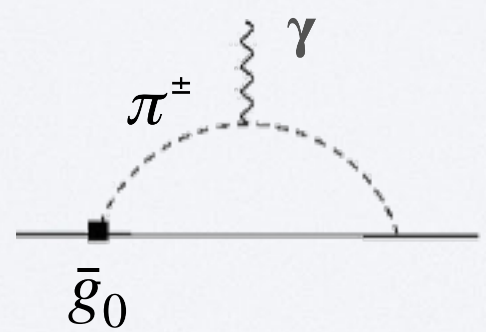


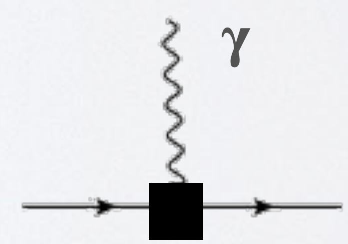




CP-odd nuclear force

- Nucleon EDMs $d_{n,p}$

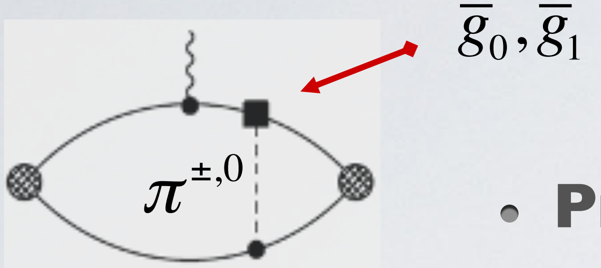




2 counter terms to absorb loop divergence

- Loop suppression: nuclear EDMs **dominated by CP-odd nuclear force** (exceptions exist)

Nuclear CP violation



Nuclear EDM

- **Problem I:** Calculate nuclear EDMs in terms of CP-odd interactions

- Easiest example: the **deuteron** $d_D = d_n + d_p + (0.18 \pm 0.02)\bar{g}_1\, e\,\mathrm{fm}$

JdV et al' PRL '11
Bsaisou et al '14

EDMs of light ions measureable in storage-ring experiments

Farley et al PRL '04

$$\vec{\Omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{v^2} - a\right)\vec{v}\times\vec{E}\right] + 2d\left(\vec{E} + v\times\vec{B})\right)$$

Magnetic dipole moment

Electric dipole moment

- Similar expressions for heavier nuclei, but **sizeable nuclear uncertainties**
- Effort from nuclear structure community to improve this. E.g. Engel et al' PRL 18

Example: QCD theta term

Crewther et al '79

- **Problem II:** Calculate CP-odd LECs $\bar{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

SU$_A$(2) rotation

$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \qquad + m_\star \bar{\theta}\bar{q}i\gamma^5 q \qquad m_\star = \frac{m_u m_d}{m_u + m_d}$$

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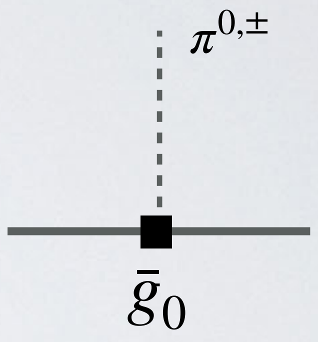
$$\mathcal{L}_{\chi+m} = \mathcal{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad + \bar{g}_0 \bar{N}\tau\cdot\pi N$$



CP-odd matrix elements

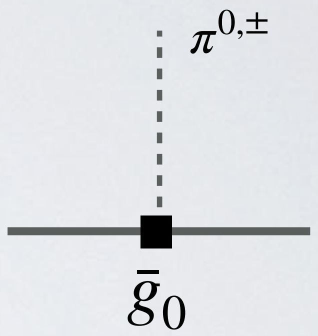
Crewther et al '79

- **Problem II:** Calculate CP-odd LECs $\bar{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

SU$_A$(2) rotation

$$\mathscr{L}_{QCD} = \mathscr{L}_{kin} - \bar{m}\bar{q}q - \varepsilon\bar{m}\bar{q}\tau^3 q \quad \longleftrightarrow \quad +m_\star\bar{\theta}\bar{q}i\gamma^5 q \qquad m_\star = \frac{m_u m_d}{m_u + m_d}$$

$$\mathscr{L}_{\chi+m} = \mathscr{L}_\chi - \frac{m_\pi^2}{2}\pi^2 - \delta m_N \bar{N}\tau^3 N \qquad +\bar{g}_0\bar{N}\tau\cdot\pi N$$



Nucleon mass splitting (strong part, no EM) ⟷ **CP-odd pion-nucleon**

$$\bar{g}_0 = -\frac{\delta m_N}{2f_\pi}\frac{1-\varepsilon^2}{2\varepsilon}\,\bar{\theta} = (15.5 \pm 2.5)\cdot 10^{-3}\,\bar{\theta}$$

JdV et al '15

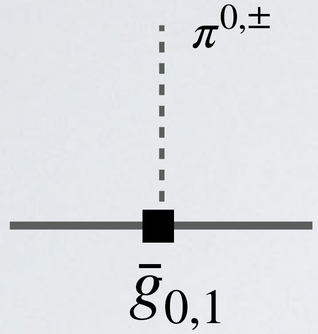
δm_N from lattice-QCD

e.g. Borsanyi et al '14

Higher-dimensional operators

- **Problem II:** Calculate CP-odd LECs $\bar{g}_{0,1}$ and $d_{n,p}$ in terms of quark operators

$$\mathcal{L}_{CEDM} = \tilde{d}_q\, \bar{q}\sigma^{\mu\nu} i\gamma^5 \lambda^a q\, G^a_{\mu\nu}$$



$$\bar{g}_0 \bar{N}\tau \cdot \pi N + \bar{g}_1 \bar{N}N\,\pi^0$$

Pospelov '02

- Values CP-odd pion-nucleon couplings not well understood $\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1}$

Higher-dimensional operators

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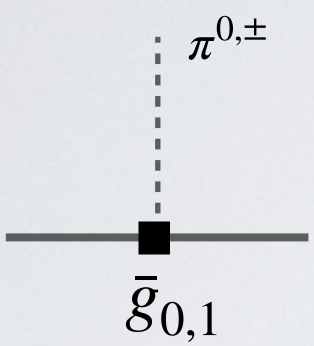
$$\mathcal{L}_{CEDM} = \tilde{d}_q \, \bar{q}\sigma^{\mu\nu} i\gamma^5 \lambda^a q \, G^a_{\mu\nu} \qquad \mathcal{L}_{CMDM} = \tilde{c}_q \, \bar{q}\sigma^{\mu\nu}\tau^3 \lambda^a q \, G^a_{\mu\nu}$$



$$\bar{g}_0 \bar{N}\tau\cdot\pi N + \bar{g}_1 \bar{N} N \pi^0$$

Corrections to hadron masses

Pospelov '02

- Values CP-odd pion-nucleon couplings not well understood

$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1}$$

$$\bar{g}_0 = \frac{\tilde{d}_u + \tilde{d}_d}{2}\left(\sigma^3_C + \ldots\right) \qquad \sigma^3_C = \frac{-1}{2m_N}\langle N|\,\bar{q}\sigma^{\mu\nu}\tau^3\lambda^a q G^a_{\mu\nu}\,|N\rangle$$

JdV, Mereghetti, Seng, Walker-Loud '16

- **CPV couplings related to corrections to hadronic spectrum**
- Relations valid up to next-to-next-to-leading-order chiral corrections
- Original motivation: study modified sigma terms on the lattice

A connection to spin physics

Editors' Suggestion | Open Access

Relating Hadronic CP Violation to Higher-Twist Distributions

Chien-Yeah Seng

Phys. Rev. Lett. **122**, 072001 – Published 22 February 2019

Jaffe, Ji PRL '91

- Generalization of connection between nucleon tensor charge and transversity distribution

$$\bar{g}_0 = \frac{\tilde{d}_u + \tilde{d}_d}{2}\left(\sigma_C^3 + \ldots\right) \qquad \sigma_C^3 = \frac{-1}{2m_N}\langle N|\bar{q}\sigma^{\mu\nu}\tau^3\lambda^a q G^a_{\mu\nu}|N\rangle$$

- Connection twist-3 distribution functions: $e^q(x) \sim \int d\lambda e^{i\lambda x}\langle P|\bar{q}(0)[0,\lambda n]q(\lambda n)|P\rangle$

$$\sigma_C^3 = -6m_N^2(e_2^u - e_2^d) + \ldots$$

Modified sigma term linked to third Mellin moment of e^q distribution

- At time of paper, little experimental input on $e^q(x)$. SIDIS @ CLAS (ep $\rightarrow e\pi^+X$)
- Can this be improved at the EIC ? **Could be very beneficial for EDM studies !**
- Further developments in Hatta '20, '21 and Weiss '21 for Weinberg operator and nucleon EDMs

Concluding remarks

- **Very rich experimental program exploring BSM physics at low energies**
- **Low-energy searches very complementary and competitive with HEP experiments**
- **Interpretation of experiments involves hadronic and nuclear physics**
- **Interplay between EFTs, lattice-QCD, nuclear structure, spin physics**