Fundamental Symmetries in Nuclear Physics: Theoretical Overview

Outline:

- Standard Model: surviving all attempts to replace it by anything ”Beyond”
  - nothing seen at LHC
  - muon g-2 discrepancy seems to have dramatically decreased
  - proton radius puzzle seems to have been solved
- Symmetry-violation searches : may be the best chance to find New Physics
  - P: neutral currents;
  - CP: electric dipole moments: electron; neutron;
  - Beta decays
- Conclusions

CAP Congress 2023 Fredericton

Andrzej Czarnecki  University of Alberta

June 20, 2023

From an LHC talk by Andre Sopczak, last month:

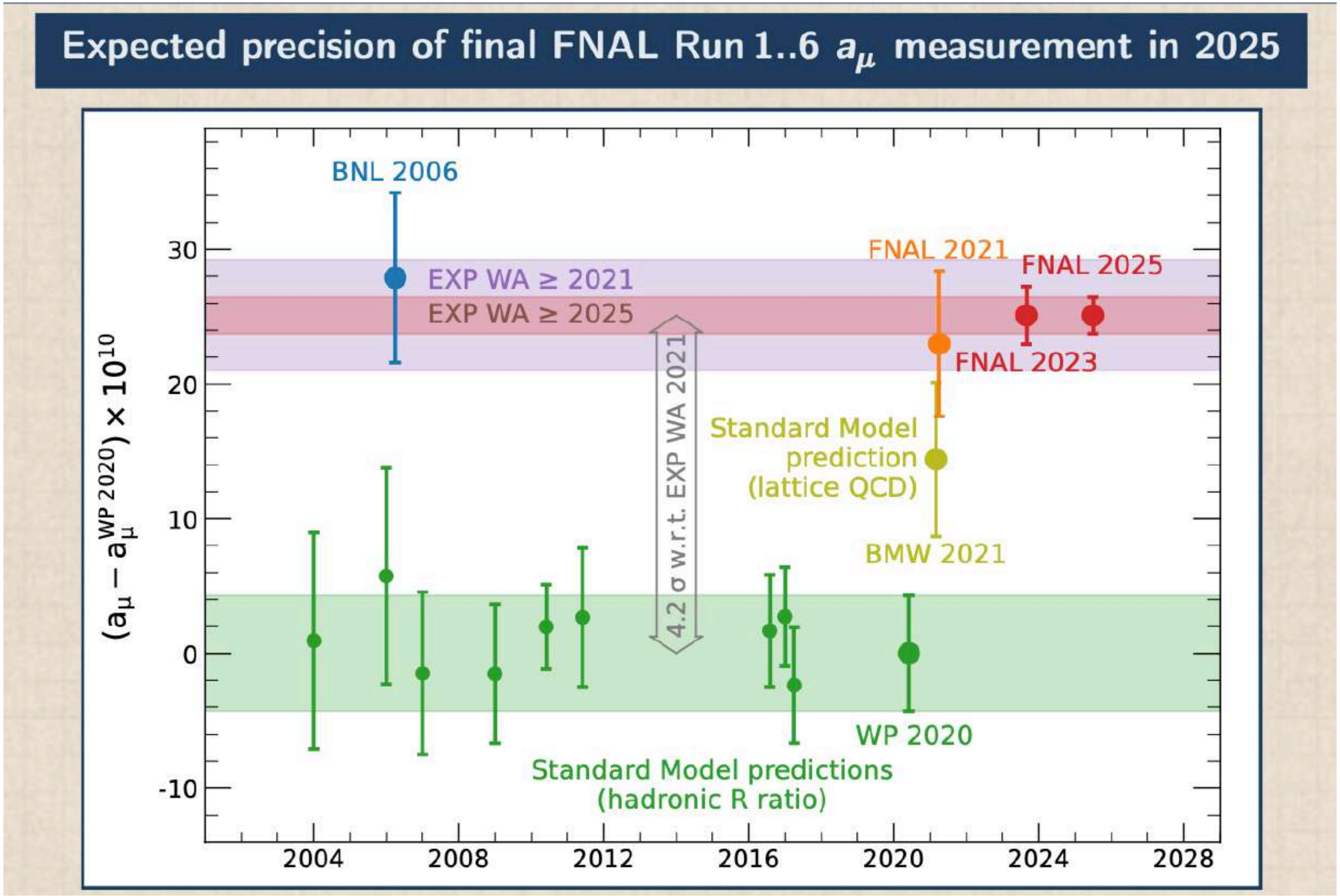
Conclusions – Highlights of Higgs physics Beyond the SM

- Very successful **LHC Run-2 operation, over 160 fb^{-1} (Run-1 and Run-2)**
- Precision measurements of
  - **Higgs boson decay branching fractions and total width**
  - **Relation of coupling to mass**
  - **CP-invariance**
  - **rare decays, LFV, dark photons, exotics (searches)**
- No indication for BSM physics: enhanced production modes
  - **Associated production of single top and Higgs**
  - **Self-coupling HHH, di-Higgs production**
- Limits on new Higgs bosons and unexpected decays
  - **Additional Higgs bosons decaying to taus, and photons**
  - **Heavy Higgs bosons in VHH and ttH/A**
  - **Single and doubly charged Higgs bosons**

Outlook

- **Combinations of ATLAS and CMS results** to double statistics
- LHC **Run-3 started** anticipated to add 300 fb^{-1} (2022 to 2025), HL-LHC approved for 3000 fb^{-1} (2029 -): **new era of measurement precision**
- **Strong and approved LHC programme for new discoveries**

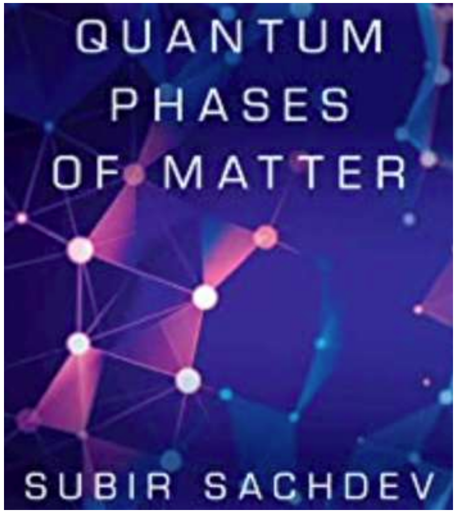
Muon g-2 after BMW and CMD3



Alberto Lusiani for the Muon g-2 Collaboration

BMW = Budapest-Wuppertal-Marseille CMD = Cryogenic Magnetic Detector

New in 2023: role of General Relativity in low/medium-energy physics



Jun 15, 2023
Charged black holes used as intuitive models.

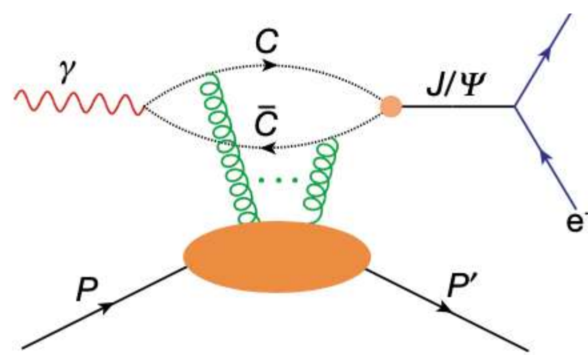
2306.05389

Towards distinguishing Dirac from Majorana neutrino mass with gravitational waves

Stephen F. King,[a] Danny Marfatia,[b] and Moinul Hossain Rahat[a]

Determining the gluonic gravitational form factors of the proton

Nature | Vol 615 | 30 March 2023 | **813**



Beta-decays

isospin; new charged gauge bosons; dark matter; CKM unitarity, …

TITAN
Anna Kwiatkowski

TRIUMF's neutral atom trap
John Behr neutrino helicity, T-violation

Nab
Nick Macsai

Parity violation

new neutral gauge bosons, leptoquarks, …

MOLLER
Dustin McNulty
Brynne Blaikie

0.1% θ_W

francium
Timothy Hucko
Anima Sharma

CP, T violation

Pear-Shaped Nuclei in the FRIB Era
Jaideep Singh

EDM
radioactive molecules

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neutron EDM
World's highest-density ultracold neutron (UCN) source

Radioactive molecules
Ivana Belosevic

198Hg(d, d')
Sally Valbuena nuclear Schiff moments

Lepton number violation

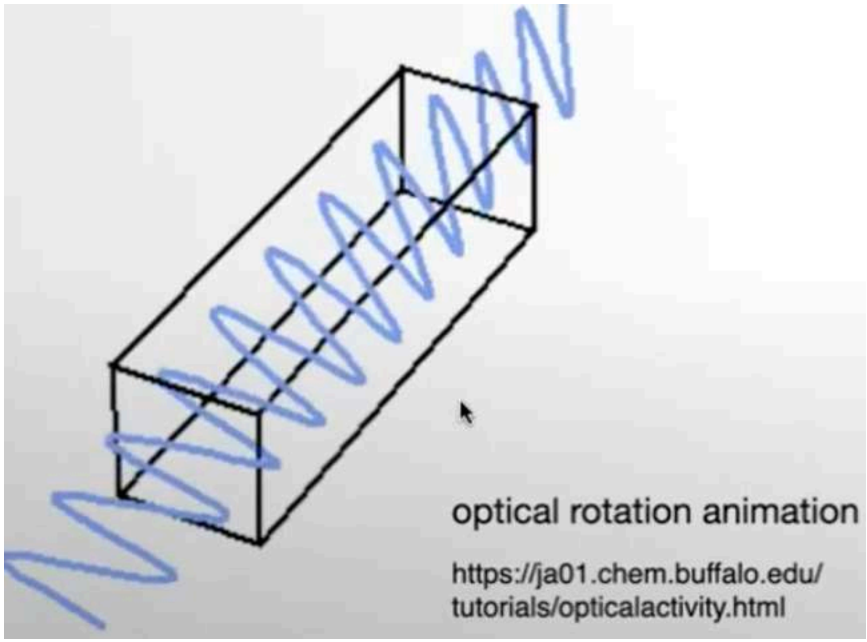
nEXO
Soud Al Kharusi

CPT, matter-antimatter

ALPHA-g

free-fall of antihydrogen
Tim Friesen
Pooja Woosaree

Neutral currents and parity violation



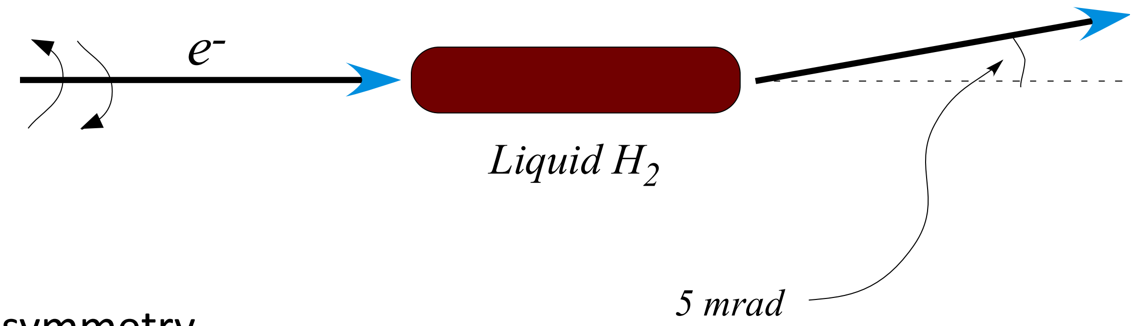
See talks later today:

MOLLER
Dustin McNulty
Brynne Blaikie

francium
Timothy Hucko
Anima Sharma

Neutral currents: PV in Moller scattering

Last measured at E158, SLAC

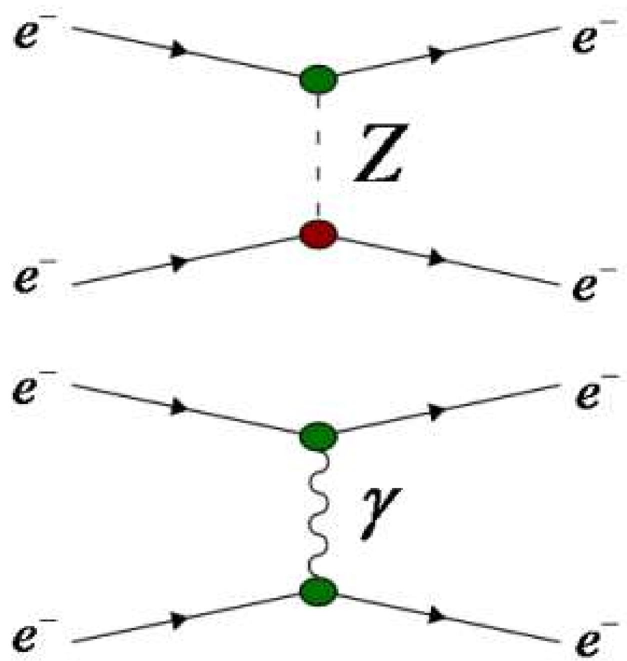


Very small asymmetry,

$$A_{LR} \sim 1 - 4\sin^2\theta_W$$

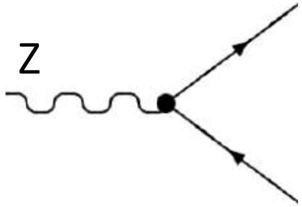
Suppressed vector coupling of Z to leptons and the proton.
The same factor in ep: Qweak

Opportunity for effects of new gauge bosons Z';
interference with dark photons.



Neutral currents and APV: the weak charge Q_W

Q_W characterizes Z-boson's vector coupling; simplifies at $s^2 = 1/4$:



$$2cg_V = e\left(2I^3 - Q\right) \qquad \frac{2cg_V}{e} = \begin{cases} 1-\frac{2}{3} = \frac{1}{3} & u \\ -1+\frac{1}{3} = -\frac{2}{3} & d \\ 1 & \nu \\ -1+1=0 & e^- \end{cases}$$

$$p: \quad 2u + d \to \frac{2}{3} - \frac{2}{3} = 0,$$
$$n: \quad u + 2d \to \frac{1}{3} - \frac{4}{3} = -1.$$

To a good approximation, Q_W of a nucleus = - number of neutrons

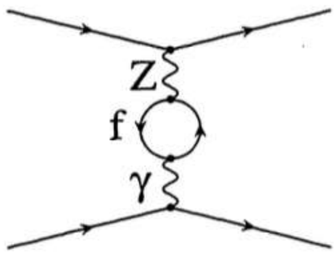
$$\text{Weak charge:} \qquad Q_W = \rho\left[-N + Z\left(1 - 4\sin^2\theta_W\right)\right]$$

$$^{133}\text{Cs: Standard Model: } Q_W^{\text{SM}} = -73.19(13) \qquad \text{Marciano \& Rosner}$$

$$\text{Boulder measurement: } Q_W^{\text{exp}} = -72.74(29)_{\text{exp}}(36)_{\text{th}}$$

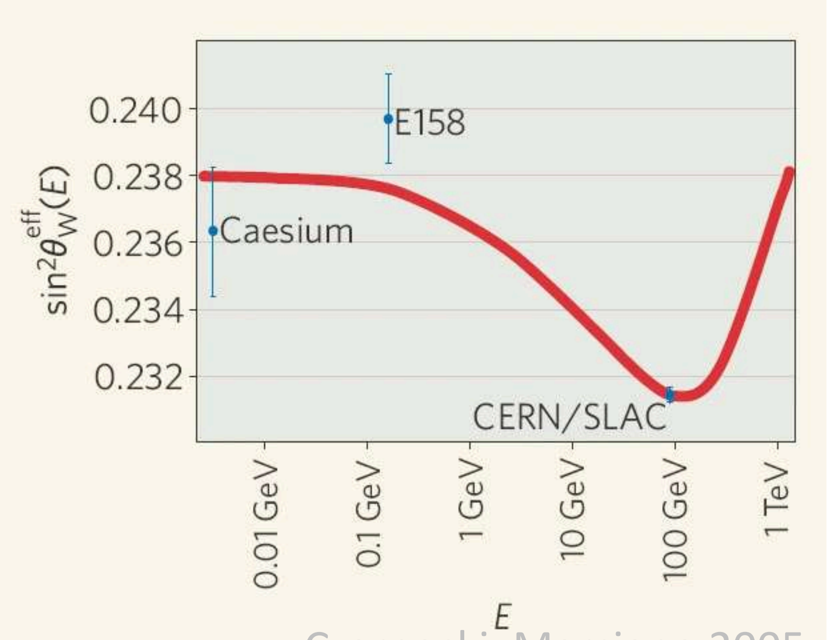
Running of the weak mixing angle

Large, 40% corrections to asymmetry A_{LR}, dominated by mixing,

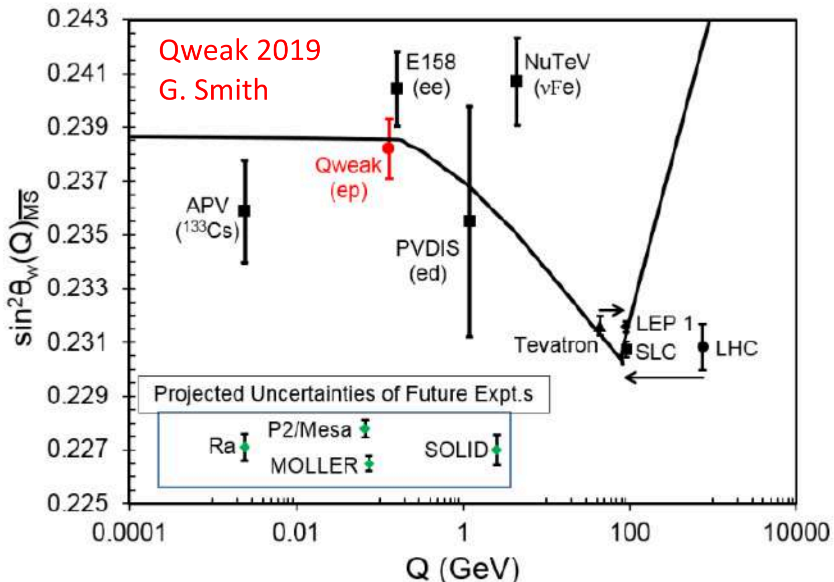


Energy-dependent → running.

Tend to decrease the SM asymmetry.

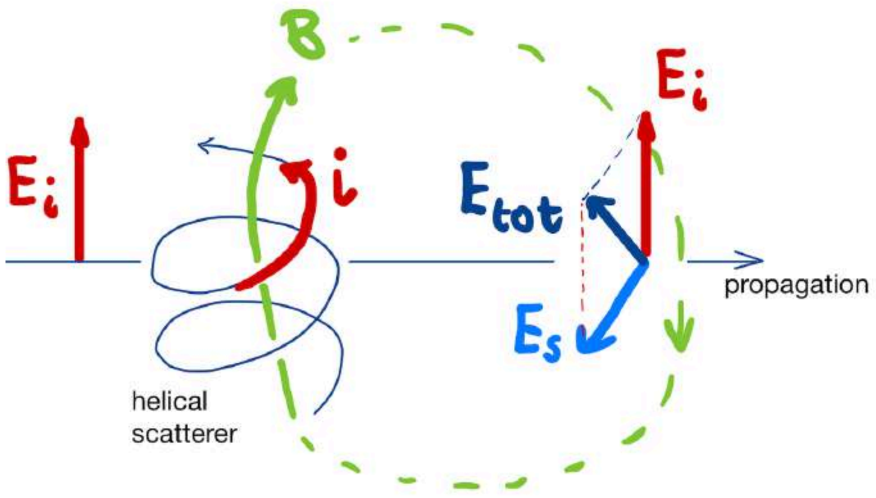


Czarnecki, Marciano 2005



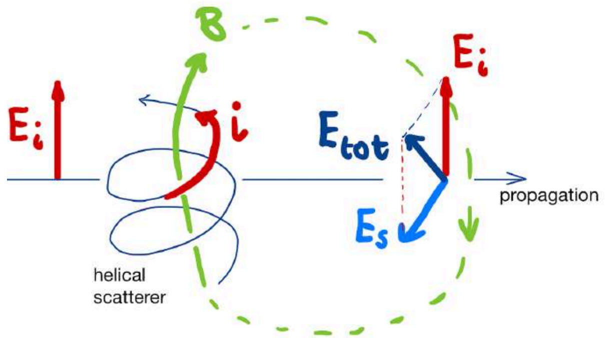
An aside: atomic parity in politics

Optical activity: rotation of the polarization



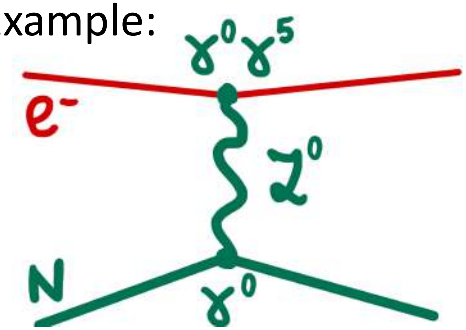
Equivalent point of view: birefringence:
different speed of right- and left-handed photons.

Optical activity: rotation of the polarization



Z-boson exchange generates a helical structure in an atom   Khriplovich

Example:



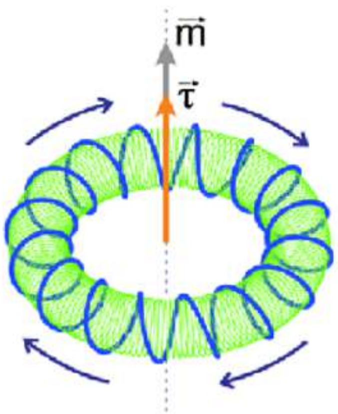
$$u_e \sim \begin{pmatrix} \phi \\ \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{2m}\phi \end{pmatrix} \qquad \bar{u}_e\gamma^0\gamma^5 u_e \sim \phi^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{p}\phi$$

$$\Delta H \sim \frac{G_F}{m}\delta^3(\boldsymbol{r})\,\boldsymbol{\sigma}\cdot\boldsymbol{p}$$

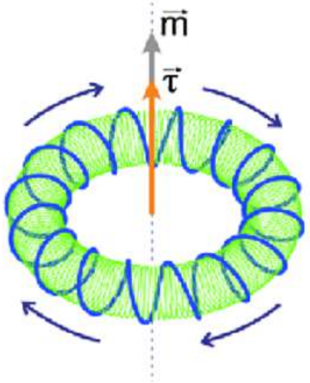
→ $p_{1/2}$ admixture in the ground state.

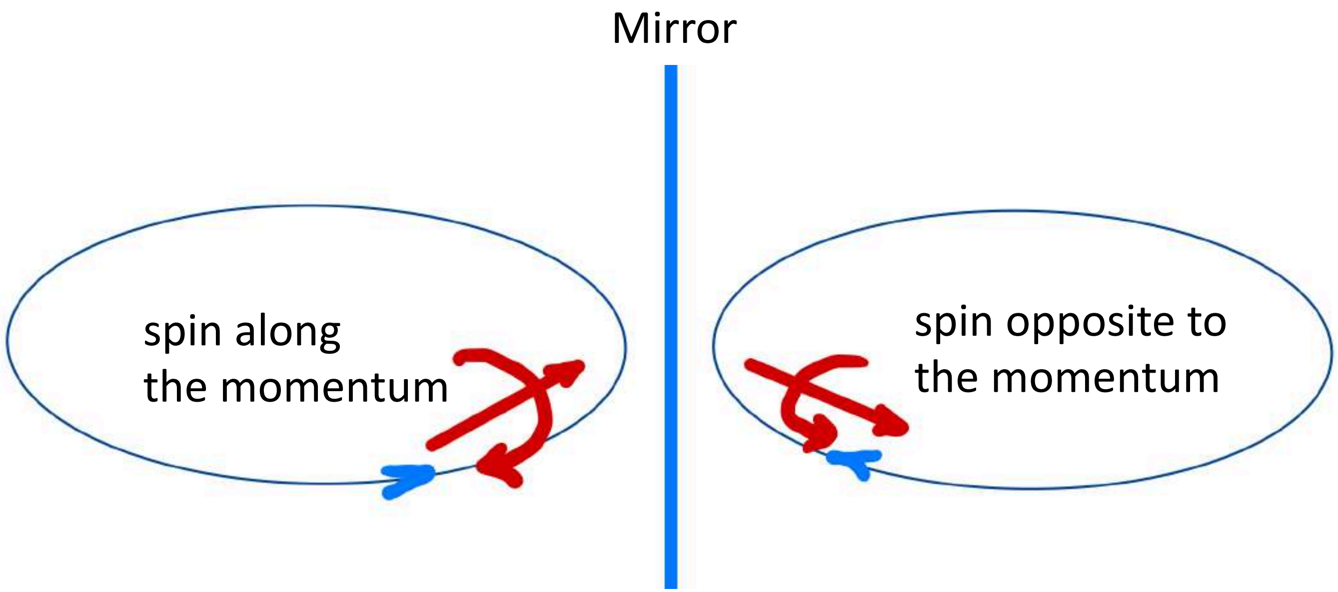
$$\begin{pmatrix} -\frac{1}{\sqrt{3}}Y_{10} \\ \sqrt{\frac{2}{3}}Y_{11} \end{pmatrix} = -\frac{\boldsymbol{\sigma}\cdot\boldsymbol{n}}{\sqrt{4\pi}}\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

this creates an anapole moment



Anapole moment violates P

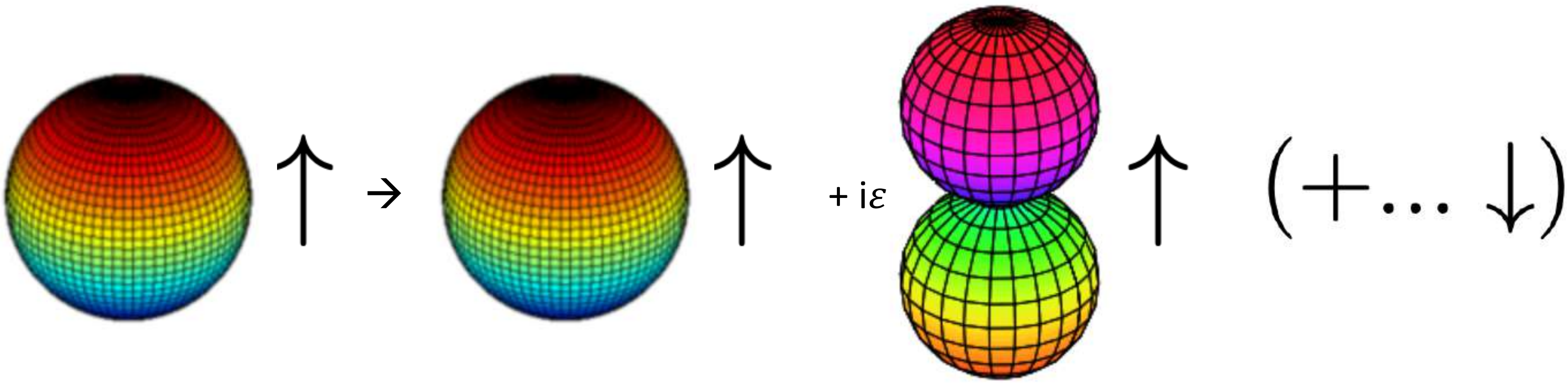




Note: anapole moment preserves T-symmetry:
both the momentum and the spin reverse.

P violation but not CP violation

The P-violating correction to the wave function we found is ~ P-wave



Since the correction has an imaginary coefficient, the resulting density is symmetric up-down,

$$\langle \boldsymbol{r}|\psi\rangle = \langle \boldsymbol{r}|1s_{1/2}\rangle + ic\,\langle \boldsymbol{r}|2p_{1/2}\rangle$$

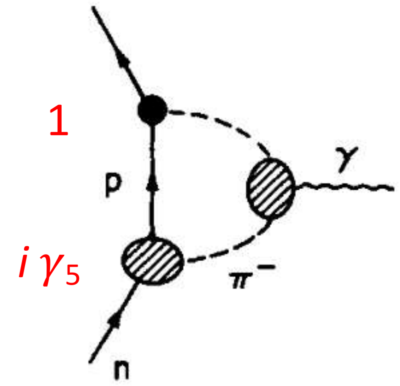
$$\langle \boldsymbol{r}|2p_{1/2}\rangle = \frac{1}{2\sqrt{6a^3}}\frac{r}{a}e^{-r/2a}\left(\sqrt{\frac{2}{3}}Y_{11}\phi^- - \frac{1}{\sqrt{3}}Y_{10}\phi^+\right)$$

$$|\langle \boldsymbol{r}|\psi\rangle|^2 = a^2 Y_{00}^2 + d^2 Y_{11}^\star Y_{11}.$$

No EDM results.

CP-violating effects: EDM

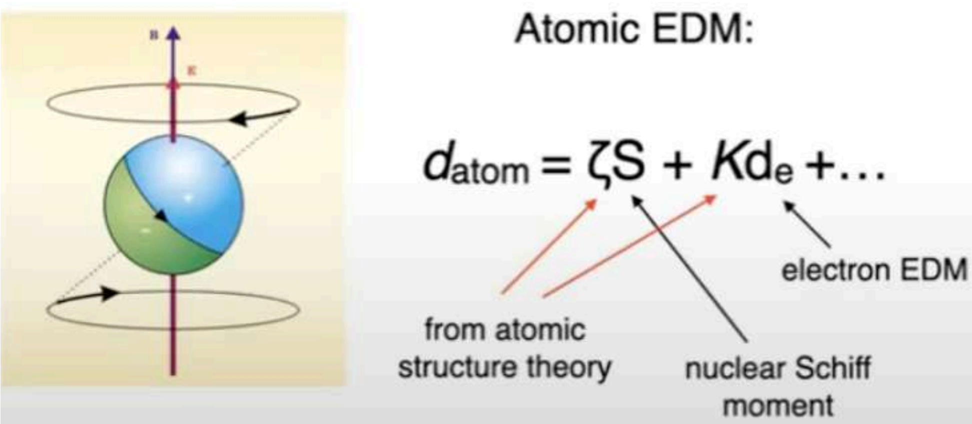
Example:



$$\mathcal{L}_{\pi NN} = \boldsymbol{\pi} \cdot \bar{N} \boldsymbol{\tau} (i\gamma_5 g_{\pi NN} + \bar{g}_{\pi NN}) N$$

Crewther, Di Vecchia, Veneziano, Witten

Electric dipole moments (EDM)



Jacinda Ginges

Dedicated talks:

Pear-Shaped Nuclei in the FRIB Era
Jaideep Singh

EDM
radioactive molecules

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neutron EDM
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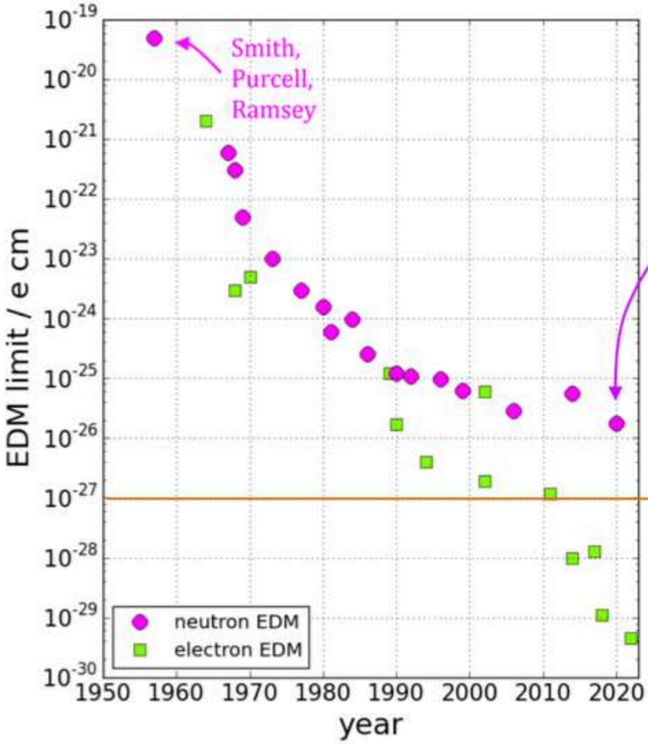
198Hg(d, d')
Sally Valbuena

nuclear Schiff moments

Neutron EDM



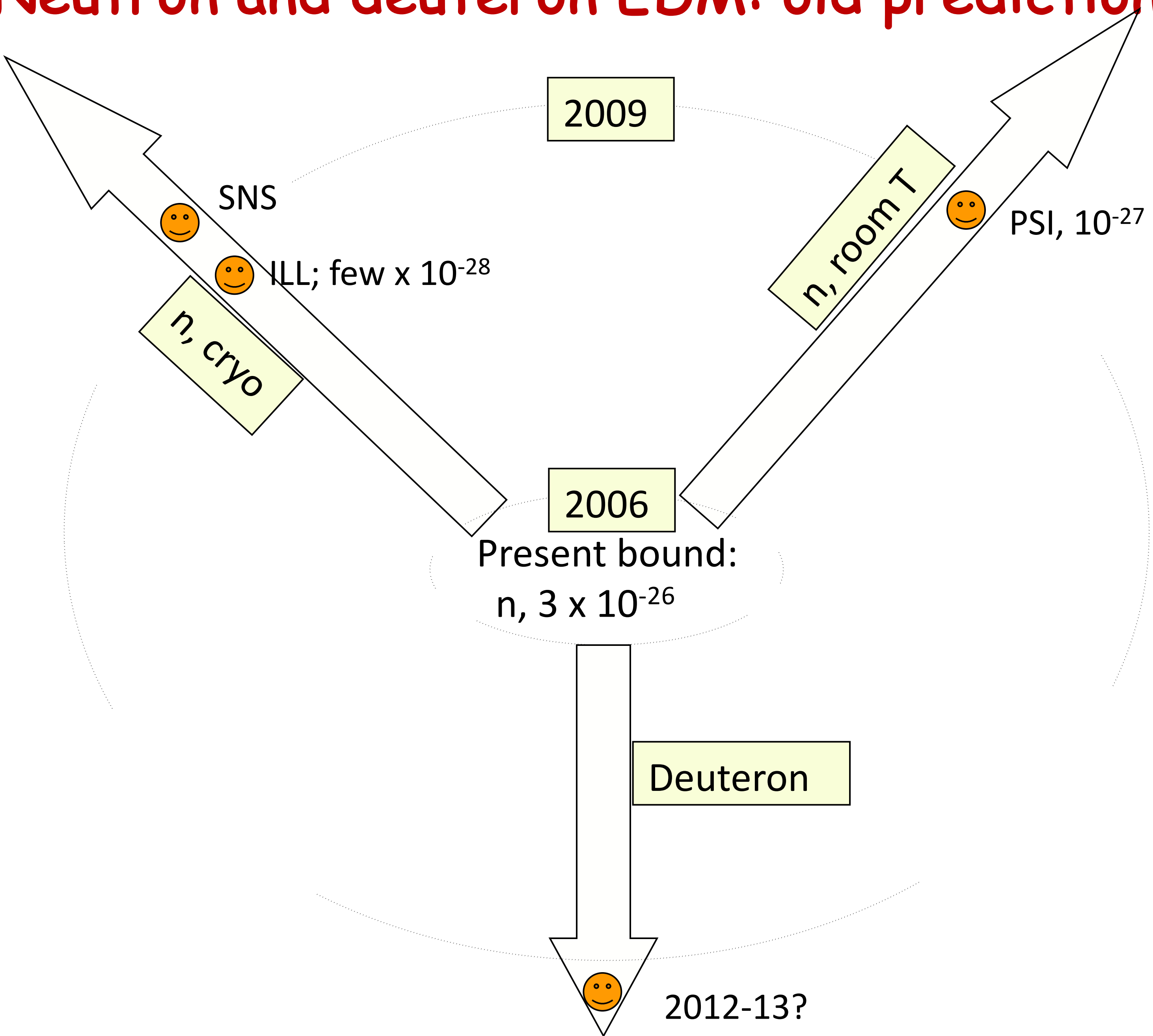
Neutron EDM measured by the nEDM collaboration (2020):

$$d_{\mathrm{n}} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\, e\,\mathrm{cm}$$

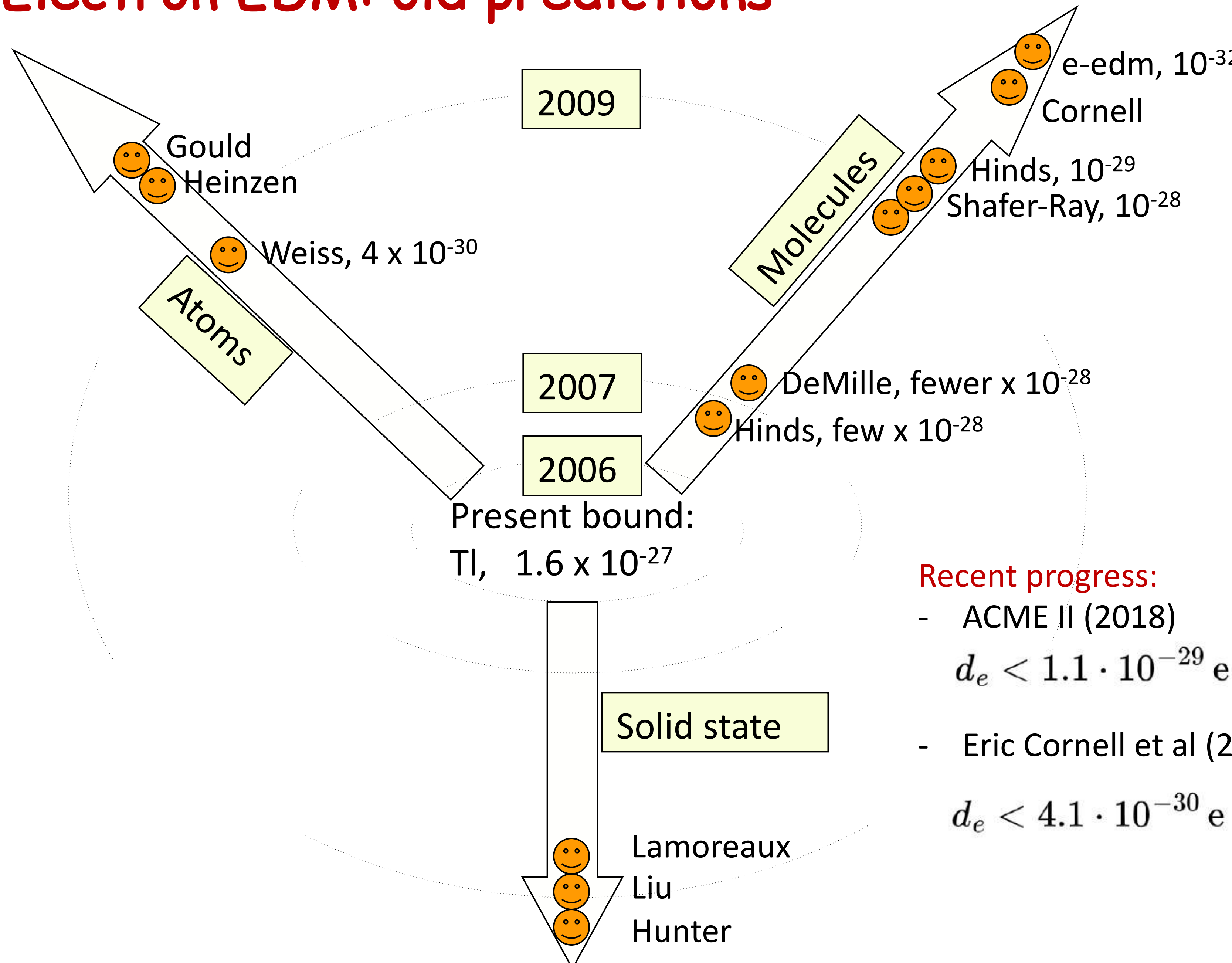
C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

← The next goal: n2EDM

Neutron and deuteron EDM: old predictions



Electron EDM: old predictions



Recent progress:

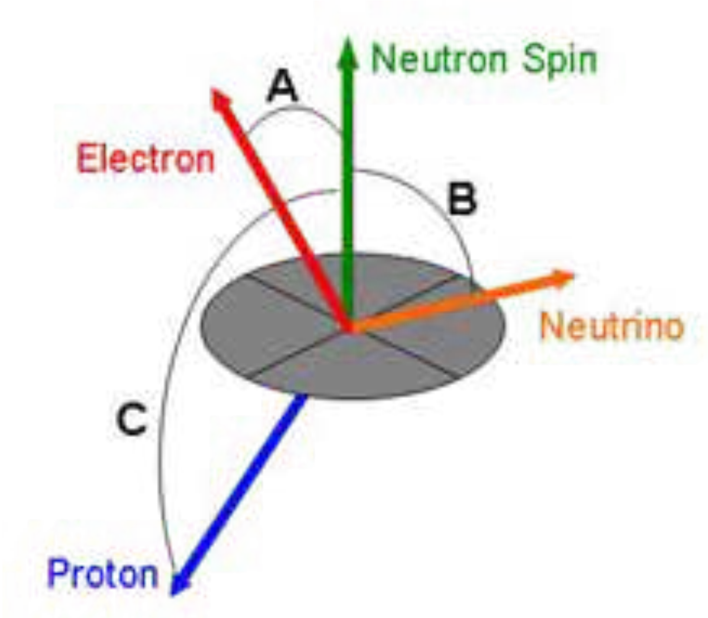
- ACME II (2018)

$$d_e < 1.1 \cdot 10^{-29}\,\mathrm{e \cdot cm}$$

- Eric Cornell et al (2022)

$$d_e < 4.1 \cdot 10^{-30}\,\mathrm{e \cdot cm}$$

Charged currents: beta decay



For details, see these talks:

TITAN
Anna Kwiatkowski

TRIUMF's neutral atom trap
John Behr neutrino helicity, T-violation

Nab
Nick Macsai

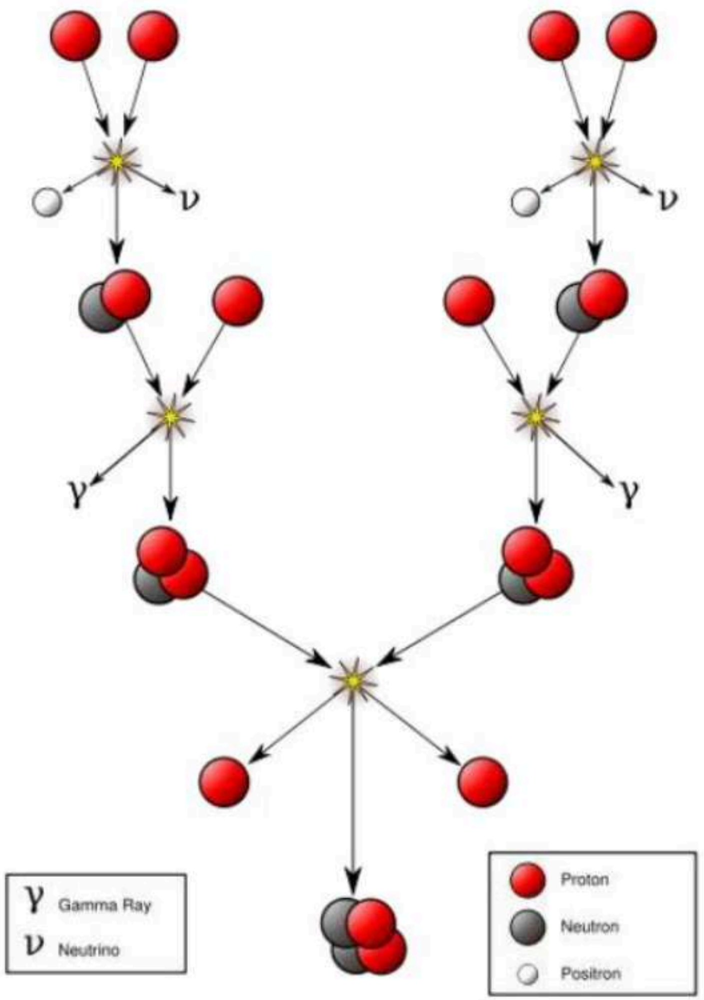
g_A from neutron decay: crucial for solar physics

Recent determinations: from correlations of electron or neutrino momenta with the neutron spin.

Nab experiment: different observable: electron-neutrino momenta correlation.

Example of impact:

Precise knowledge of g_A is important for understanding sun-like stars.

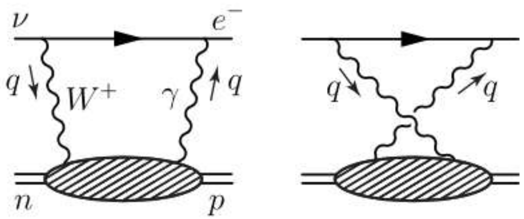


Recent progress in Radiative Corrections

Dispersion relation analysis of the radiative corrections to g_A in the neutron β-decay

Mikhail Gorchtein[1] and Chien-Yeah Seng[2]

2106.09185



Precision better than 10^{-4}. Matches anticipated precision of Nab.

Summary

- Collider experiments have not found New Physics yet

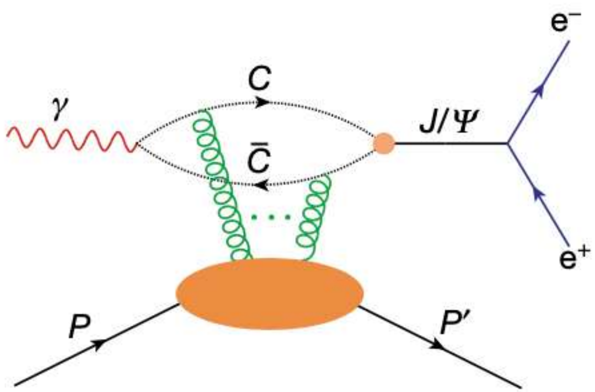
- Precision tests of fundamental symmetries are likely our best hope

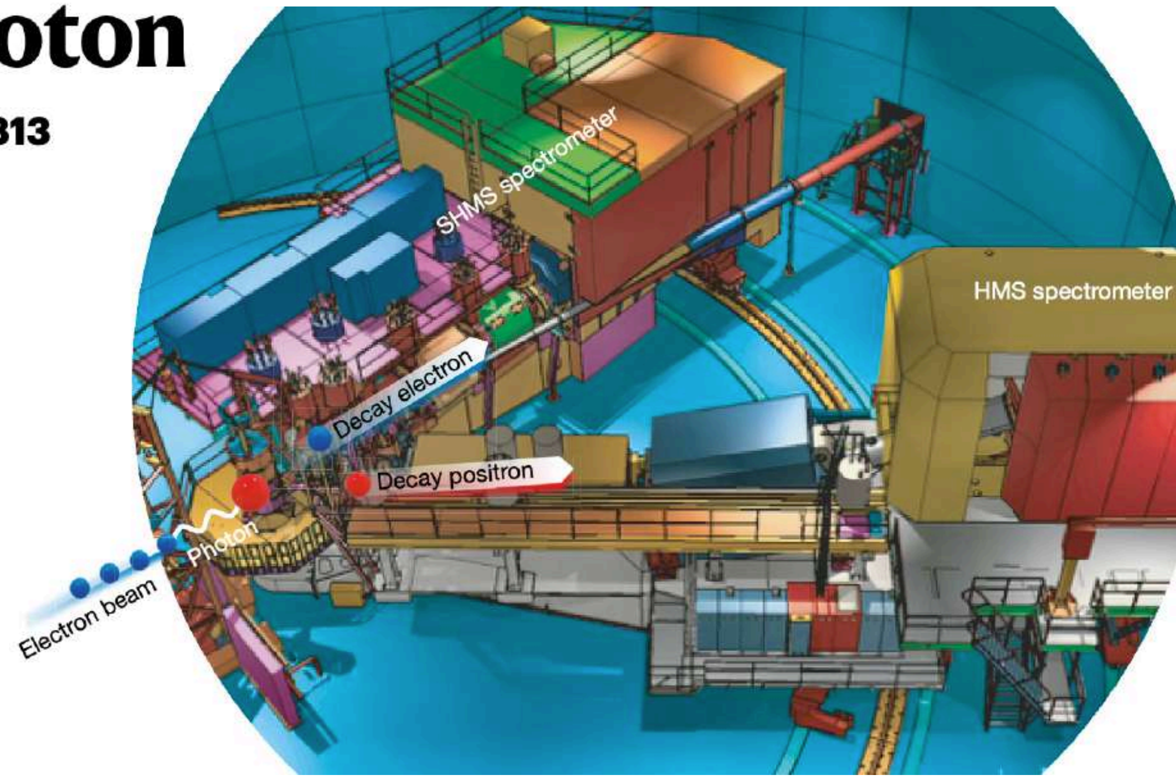
- Canada has a vigorous and multifaceted program in precision measurements (and theory)

- EDMs exist and Lepton Flavors are not conserved
  even in the Standard Model;
  its extensions greatly enhance them;
  let’s find them!

Determining the gluonic gravitational form factors of the proton

Nature | Vol 615 | 30 March 2023 | **813**





- Beyond earlier studies of the charge and spin distributions in the proton;
- New parameter: proton mass radius 0.52(3) fm.

What does the muon g-2 tell us about the new physics and the EDM?

$$a_\mu^{\rm NP} \frac{e}{2m} \bar{\mu}\sigma \cdot F \mu \;\; \to \;\; d^{\rm CP} \frac{e}{2m} \bar{\mu}\gamma_5\sigma \cdot F \mu$$

$$a_\mu^{\rm NP} \sim 10^{-9} \to d^{\rm CP} \frac{e}{2m} \sim a_\mu^{\rm NP} \frac{e}{2m} \sim 10^{-9} \frac{e}{1\,\rm fm} = 10^{-22} e \cdot \rm cm$$

Similar encouragement for lepton flavor violation.