Precision tests of fundamental symmetries

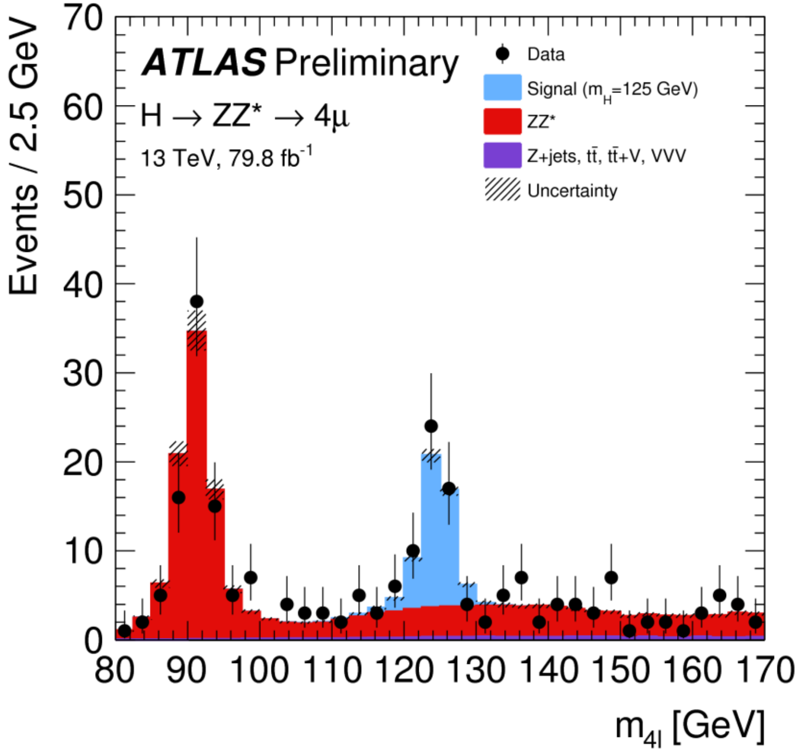
Journée des deux infinis, 30-31/09/2023

Guillaume Pignol, LPSC Grenoble

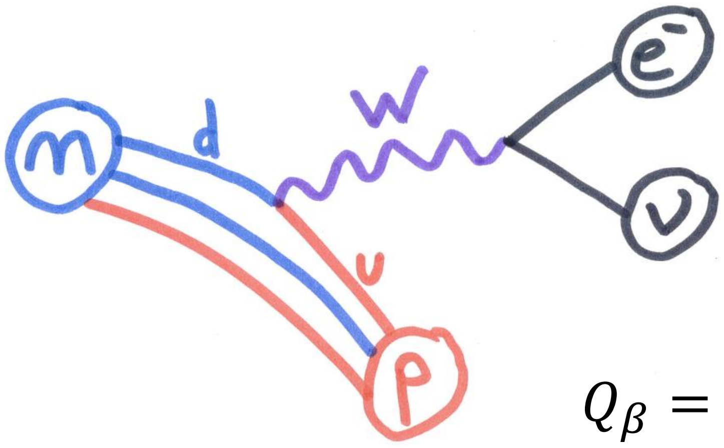
Two frontiers of particle physics

Energy frontier (LHC):
producing heavy unstable particles at colliders, e.g.

- W boson, $m_W = 80$ GeV
- Higgs boson, $m_H = 125$ GeV
- Dark matter particle?

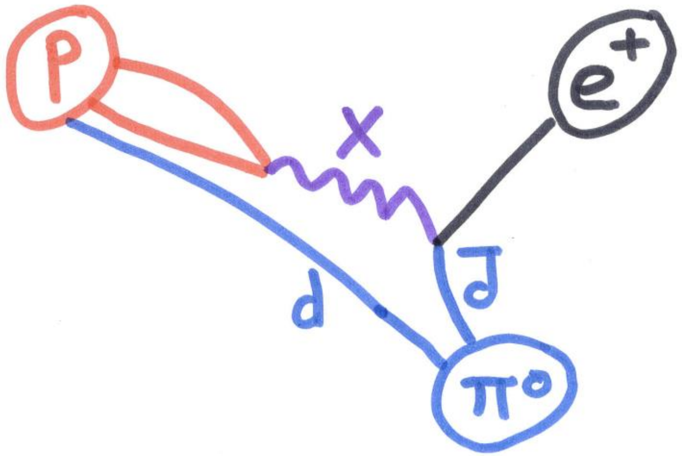


Precision/Intensity frontier:
detecting the effect of virtual particles.
The neutron beta decay, lifetime of 15 minutes, proceeds via the exchange of the virtual W.
Fundamental structure of the Standard Model inferred from properties of the decay (e.g. parity violation).

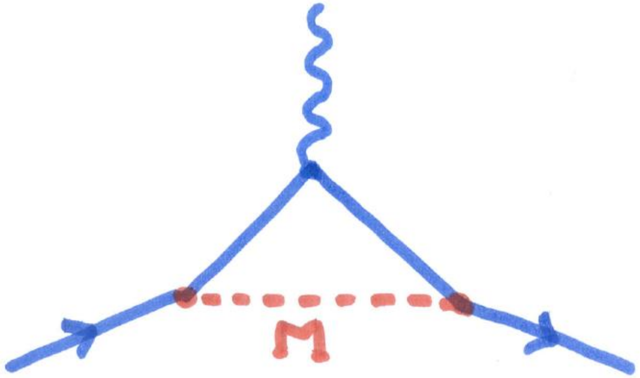


$Q_\beta = 0.8$ MeV

New physics at the precision frontier



New particles could induce **super-rare decays**.
Example:
A new boson with could induce the proton decay.
It would **violate the conservation of B** (baryon number) and L (lepton number).



New particles could induce exotic couplings.
An **electric dipole moment** (EDM) is an interaction of the spin of a particle with the electric field.
This coupling **violates time reversal symmetry**, and is connected with the matter-antimatter asymmetry of the Universe.

Outline of the course

30/10 Lecture 1

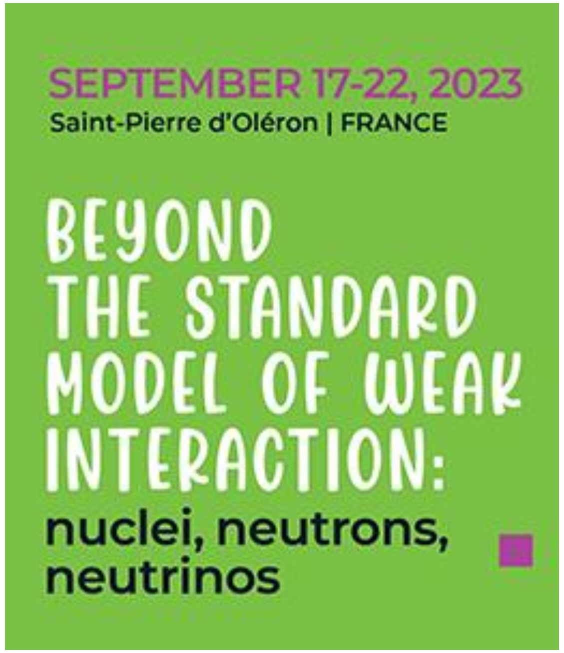
Forbidden processes = Formidable probes of new physics

1. Effective Field Theories, SMEFT
2. Lepton flavor violation $\mu \to e$
3. Time reversal symmetry and the neutron EDM

31/10 Lecture 2

More on the search for neutron EDM

Useful references



https://ejc2023.sciencesconf.org/

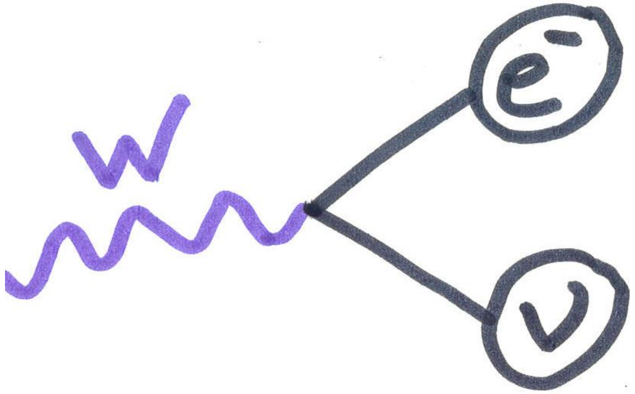
Lectures slides (Th. and Exp.):

- ***The Weak Interaction*** - M. González-Alonso
- ***Beta decay in the SM and beyond*** **-** A. Falkowski
- ***Nuclear beta decay*** - N. Severijns
- ***Neutrons*** - G. Pignol and T. Soldner
- ***Neutrinos*** - A. Zolotarova and M. Fallot

Pedagogical review papers:

- Y. Kuno and G. Pignol, ***Precision experiments with neutrons and muons*** (2020)
- A. Falkowski, ***Lectures on SMEFT*** EPJC (2023)

Effective Field Theories: QFT



In your Quantum Field Theory lecture:
Properties and interactions of particles are encoded in the Lagrange density, a polynomial function of the fields and their derivatives

$$\mathcal{L} = g\, W^{\mu}\ \bar{e}\, \gamma_{\mu}\, \nu_L + \cdots$$

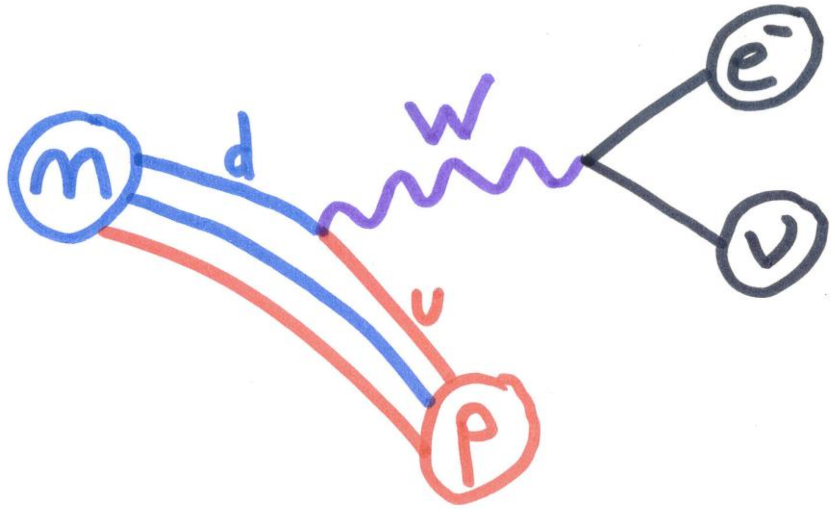
Field of the W boson

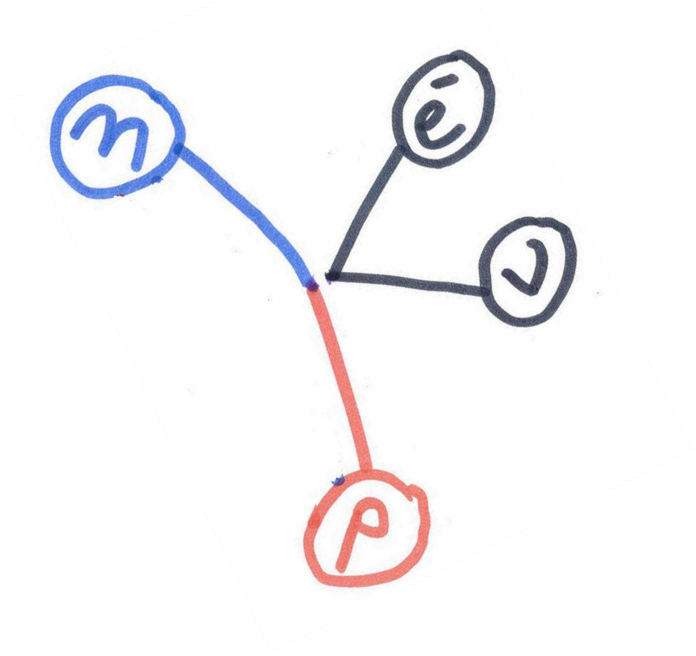
Field of the electron

Field of the neutrino

From which you can calculate mass, decay rates, cross sections…

Effective Field Theories: top => down





Calculate a given low energy process in the "high energy" theory

Energy $\ll m_W$

Match to a QFT with only light particles, here

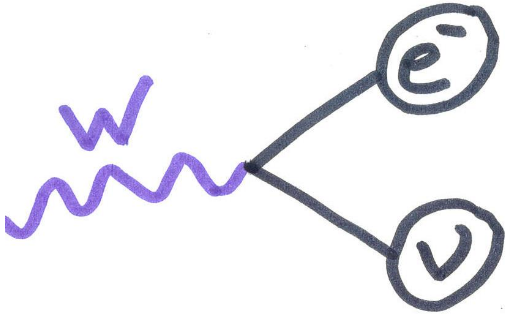
$$\mathcal{L} = G_F\, \bar{p}\, \Gamma^\mu n\, \bar{e}\, \gamma_\mu \nu_L + \cdots$$

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

Dimensional Analysis (or power counting)

$\mathcal{L}$ is mass dimension 4 ($\mathcal{L} \sim E^4$) , because $S = \int \mathcal{L}\, d^4x$ is dimensionless

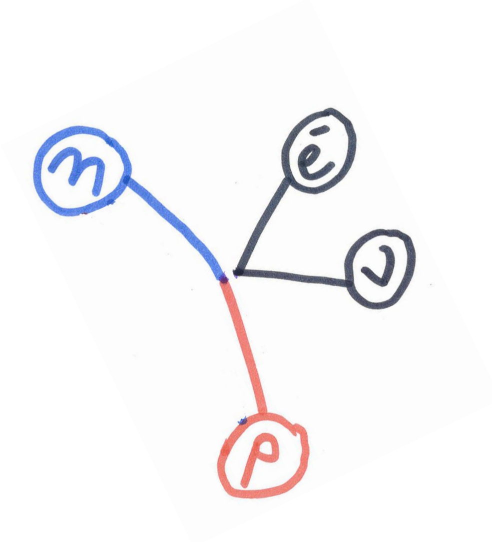
Boson fields are dimension 1, Fermion fields are dimension 3/2



Dimension 4 operator

$g \; \boxed{W^\mu \, \bar{e} \, \gamma_\mu \, \nu_L}$

dimensionless coupling constant



Dimension 6 operator

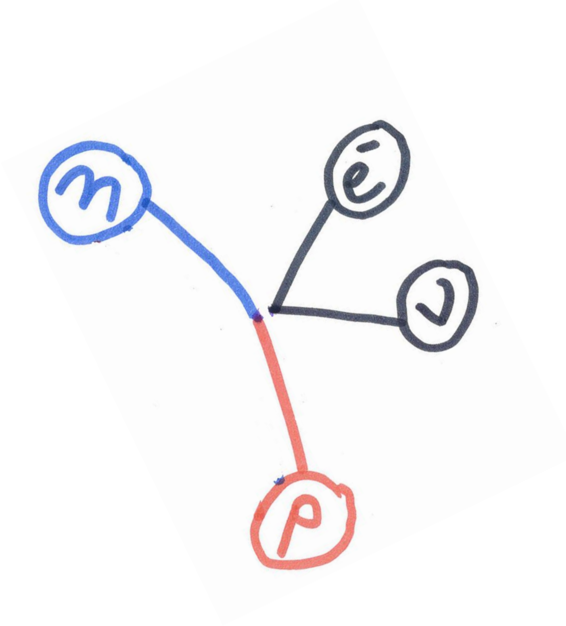
$G_F \; \boxed{\bar{p} \, \Gamma^\mu n \, \bar{e} \, \gamma_\mu \nu_L}$

coupling constant of dimension -2

Effective Field Theories: bottom => up

Question: what is the most general form of the low energy interaction (i.e. the EFT) between n, p, e, ν_L, compatible with Lorentz invariance and electric charge conservation?

Answer: Lee-Yang Lagrangian (1956) – which generalizes Fermi β theory (1933) – with 10 independent coefficients, each of mass dimension -2.



$$
\begin{aligned}
H_{\text{int}} = &(\psi_p^\dagger\gamma_4\psi_n)(C_S\psi_e^\dagger\gamma_4\psi_\nu + C_S'\psi_e^\dagger\gamma_4\gamma_5\psi_\nu) \\
&+(\psi_p^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V'\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu) \\
&+\tfrac{1}{2}(\psi_p^\dagger\gamma_4\sigma_{\lambda\mu}\psi_n)(C_T\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\psi_\nu \\
&+C_T'\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\gamma_5\psi_\nu) + (\psi_p^\dagger\gamma_4\gamma_\mu\gamma_5\psi_n) \\
&\times(-C_A\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu - C_A'\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu) \\
&+(\psi_p^\dagger\gamma_4\gamma_5\psi_n)(C_P\psi_e^\dagger\gamma_4\gamma_5\psi_\nu + C_P'\psi_e^\dagger\gamma_4\psi_\nu),
\end{aligned}
$$

Standard Model Effective Field Theory

Fields = quarks + leptons + gauge bosons (g, W, Z, γ) + Higgs, **no new particles**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

Standard Model,
operators of dimension $\mathrm{D} \leq 4$

Accounts for neutrino
masses and oscillations

New interactions = dimension 6 operators

$$\mathcal{L}_{\mathrm{D=6}} = \sum_{a=1}^{3045} \frac{c_a}{\Lambda^2} O_a^{(6)}$$

imprints of new BSM particles of mass $\gg m_W$

$\Lambda \sim$ masses of new particles, if $c_a \approx 1$.

Λ = energy scale of new physics

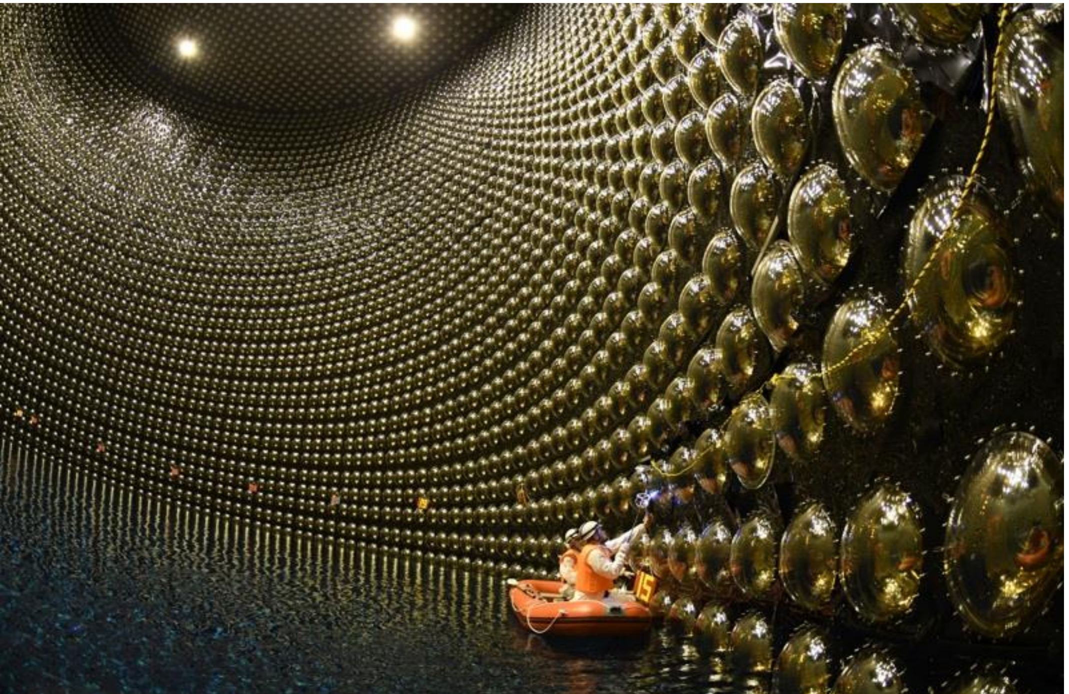
SMEFT and symmetries

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

In the SM,
B is conserved*
(*perturbatively...)
The proton is stable

Contains $\not{B}$ and $\not{L}$ interactions $\mathcal{L}_{\mathrm{D=6}} \supset C_{duu}(du)(ue)$

Protons decay: $\Gamma(p \to e^+\pi_0) \approx m_p^5 |C_{duu}|^2/16\pi$



Limit from Super-Kamiokande experiment in Japan

$\Gamma(p \to e^+\pi_0) < (2.4 \times 10^{34}\ \mathrm{years})^{-1}$

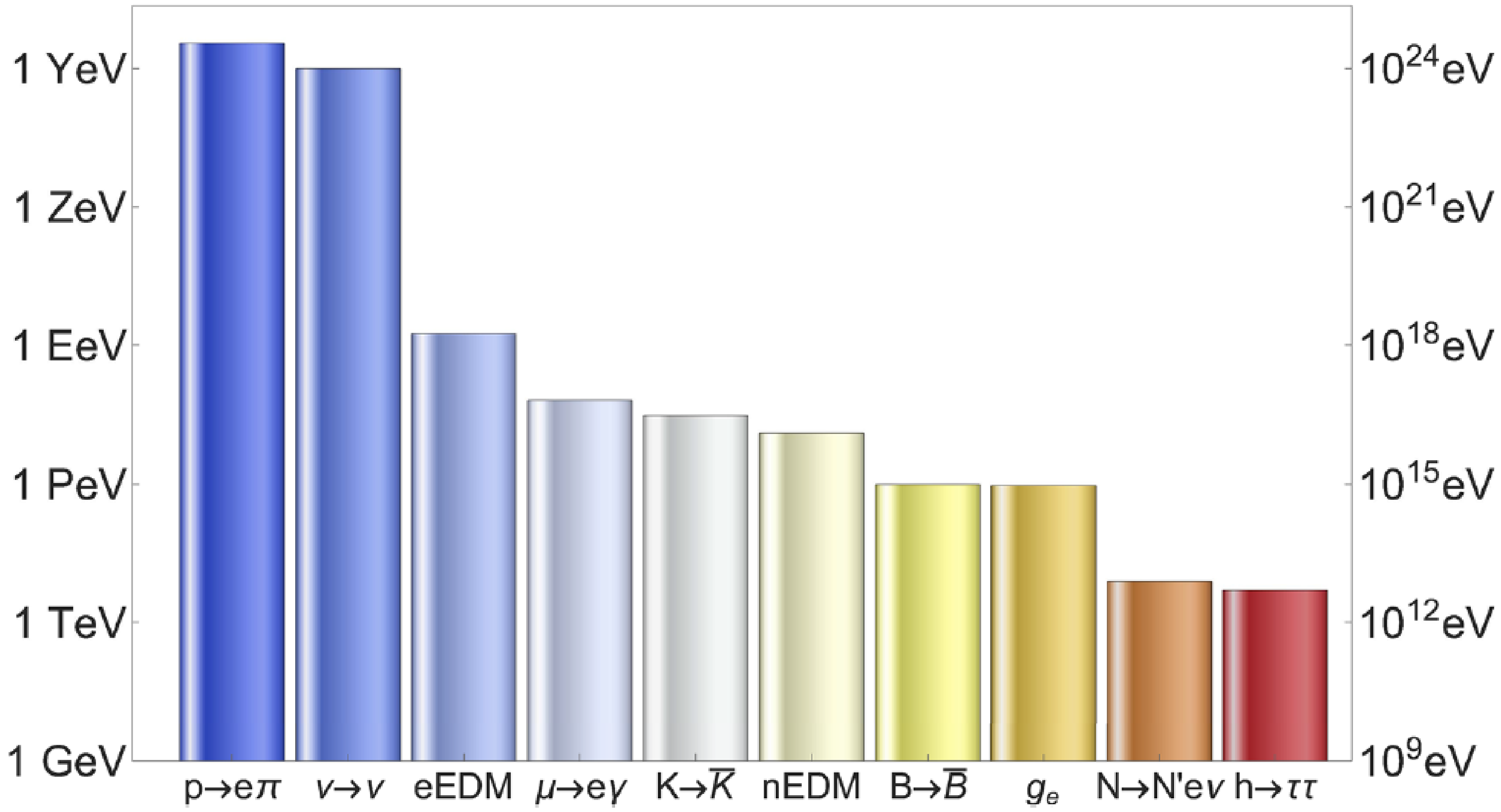
$\to |C_{duu}| < (3 \times 10^{15}\ \mathrm{GeV})^{-2}$

$\to$ The search for proton decay is probing
$\Lambda = 3 \times 10^{15}$ GeV

Probes of high scale new physics

Figure from A. Falkowski, ***Lectures on SMEFT*** EPJC (2023)

Fig. 3 The scale suppressing higher-dimensional SMEFT operators probed by selected observables. From left to right: proton decay, neutrino oscillations, electron EDM, $\mu \to e\gamma$, kaon mixing, neutron EDM, B-meson mixing, electron anomalous magnetic moment, beta decay, Higgs decay to tau leptons



Outline of the course

30/10, Lecture 1

Forbidden processes = Formidable probes of new physics

1. Effective Field Theories, SMEFT
2. **Lepton flavor violation $\mu \to e$**
3. T violation and the neutron EDM

31/10, Lecture 2

More on the search for neutron EDM

SMEFT and Lepton number

Meet the Leptons: $\begin{pmatrix} \nu_e \\ e_L \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau_L \end{pmatrix}$

e_R μ_R τ_R

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{D=5}} + \mathcal{L}_{\text{D=6}} + \cdots$$

In the SM,
Lepton number is conserved separately for each flavour.
e.g. muon decay

$$\mu \to e\, \bar{\nu}_e\, \nu_\mu$$

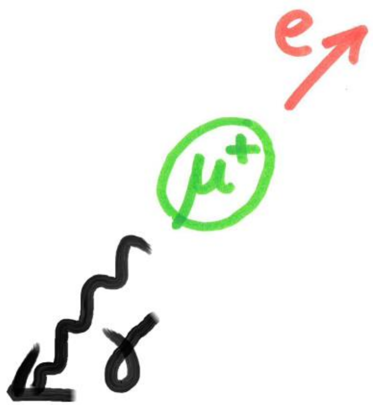
Accounts for neutrino oscillation

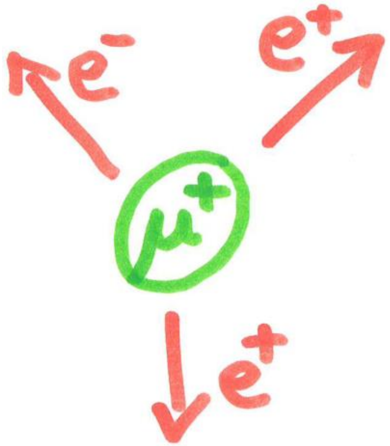
$$\nu_\mu \to \nu_e$$

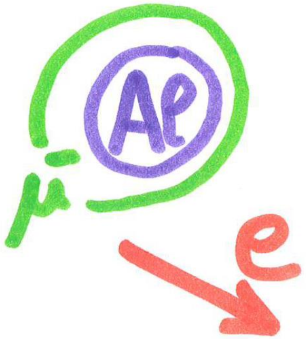
Can induce CLFV
Charged Lepton Flavor Violation, e.g.

$$\mu \to e\, \gamma$$

Three golden channels for CLFV







Best limit
$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4 \times 10^{-13}$
From MEG (2016)

Probing
$\Lambda = 7 \times 10^8$ GeV

Best limit
$\mathrm{BR}(\mu^+ \to e^+e^-e^+) < 1 \times 10^{-12}$
From SINDRUM (1988)

Probing
$\Lambda = 1 \times 10^8$ GeV

Best limit
$\mathrm{CR}(\mu - e, \mathrm{Au}) < 7 \times 10^{-13}$
From SINDRUM II (2006)

Probing
$\Lambda = 1 \times 10^8$ GeV

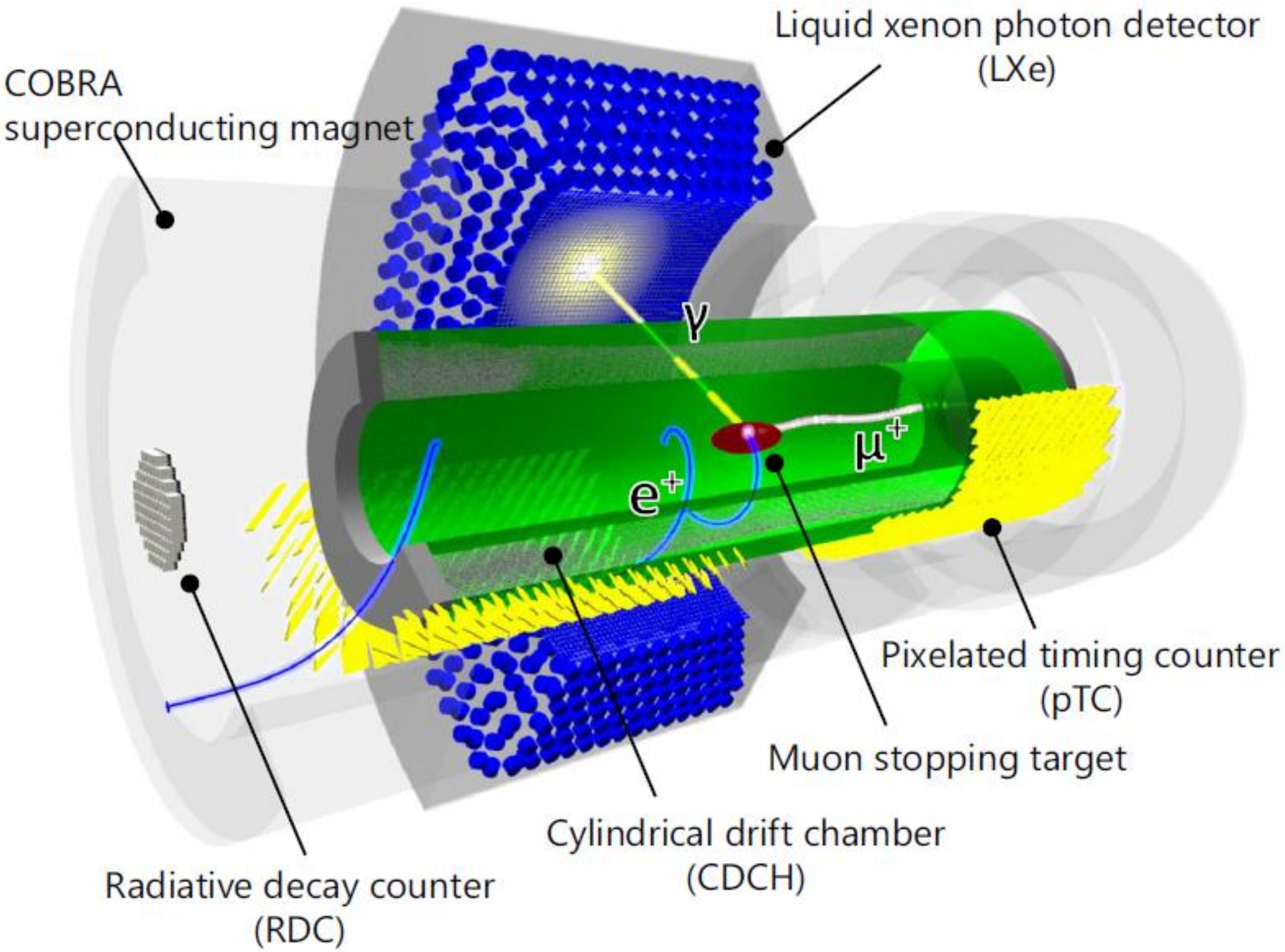
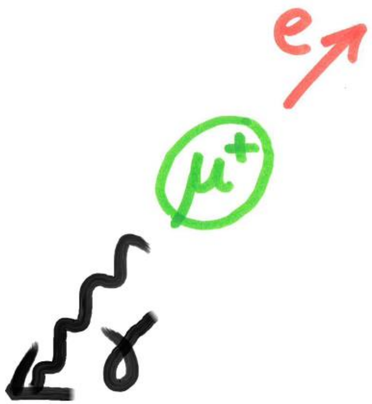


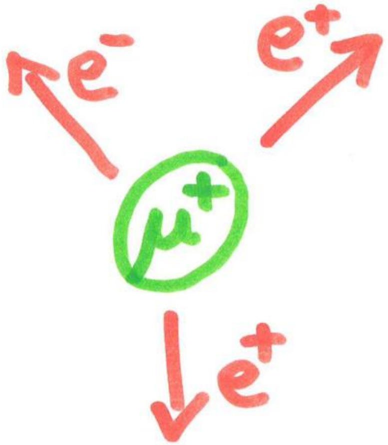
Figure from ***The design of the MEG II experiment*** (2018)



Upgrade MEG II in preparation,
Aims at improving by factor 10

Signature of the event:

- 1 positon and 1 photon in time coincidence
- emitted back to back
- Positon momentum $\frac{m_\mu}{2}$
- Photon energy $\frac{m_\mu}{2}$



Project **Mu3e** in preparation at PSI, to reach 10^{-16} sensitivity

The concept combines:

- Pixel sensors for **precise tracking of e+ and e- in B-field**
- Scintillating fibers and tiles for **precise timing**

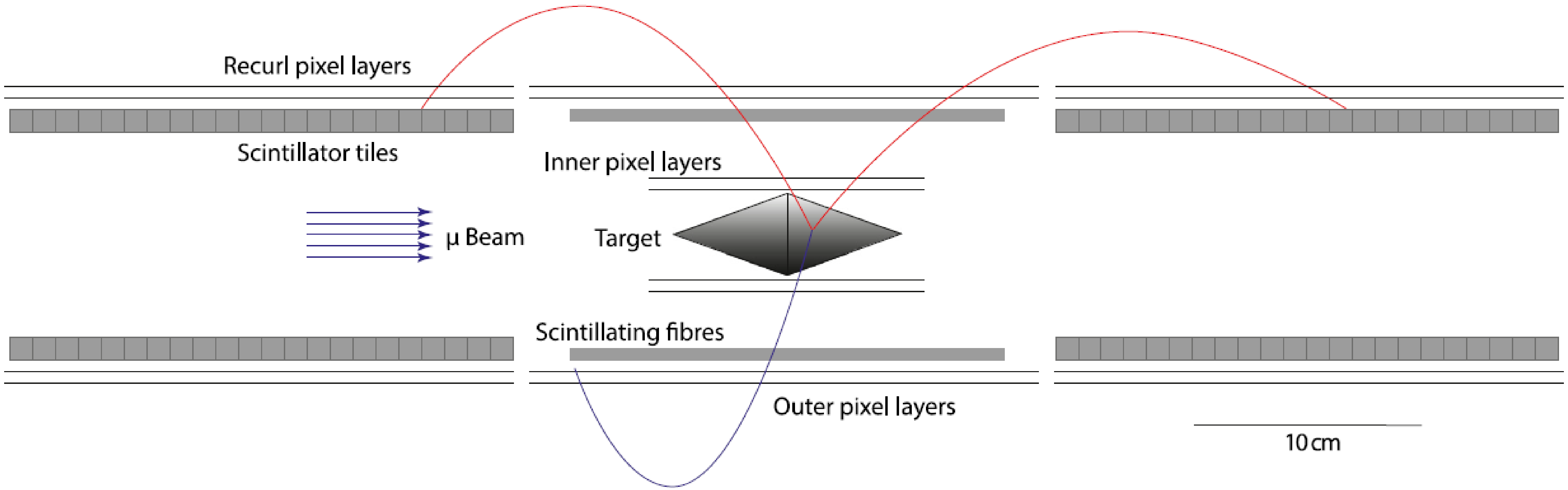
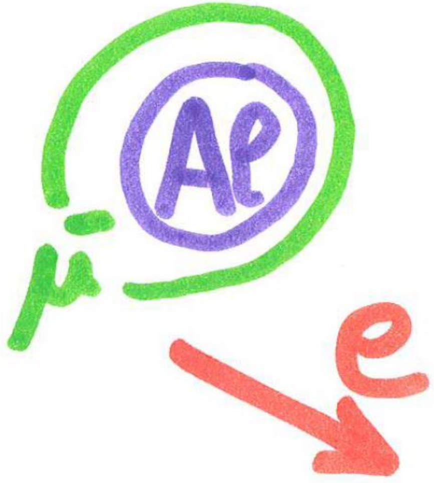


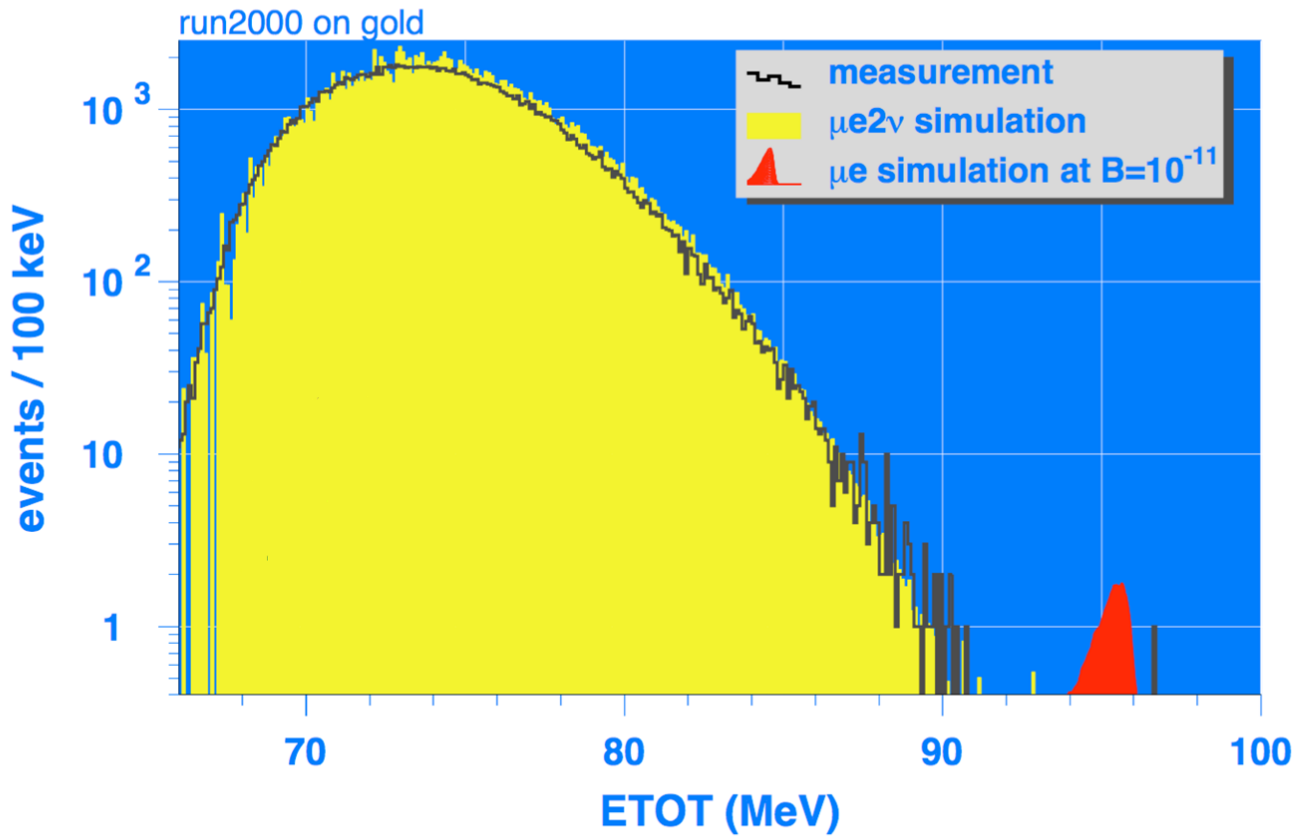
Figure from the paper ***Technical design of the phase I Mu3e experiment*** (2021)

$\mu^- \rightarrow e^-$ conversion in nuclei



Signature: **mono-energetic electron** at the endpoint of the "Decay In Orbit" spectrum

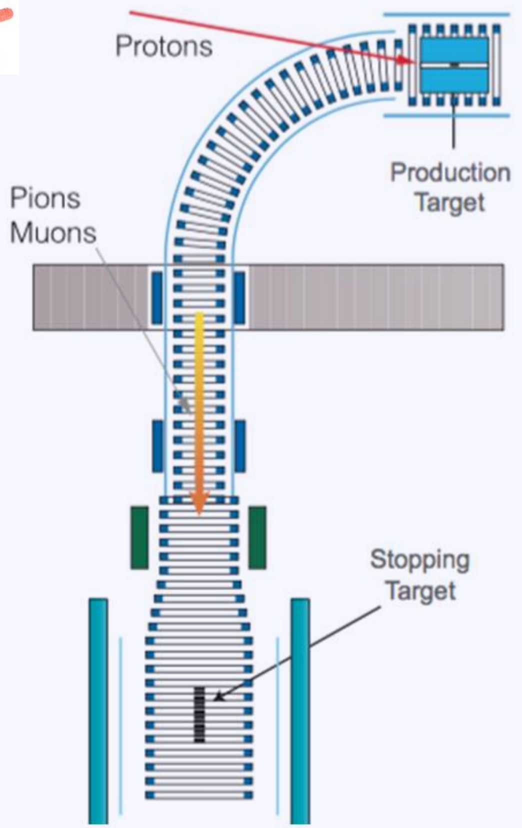
Best bound SINDRUMII (@PSI)
$CR(\mu^- Au \rightarrow e^- \, Au) < 7 \times 10^{-13}$
with 4×10^{-13} stopped muons



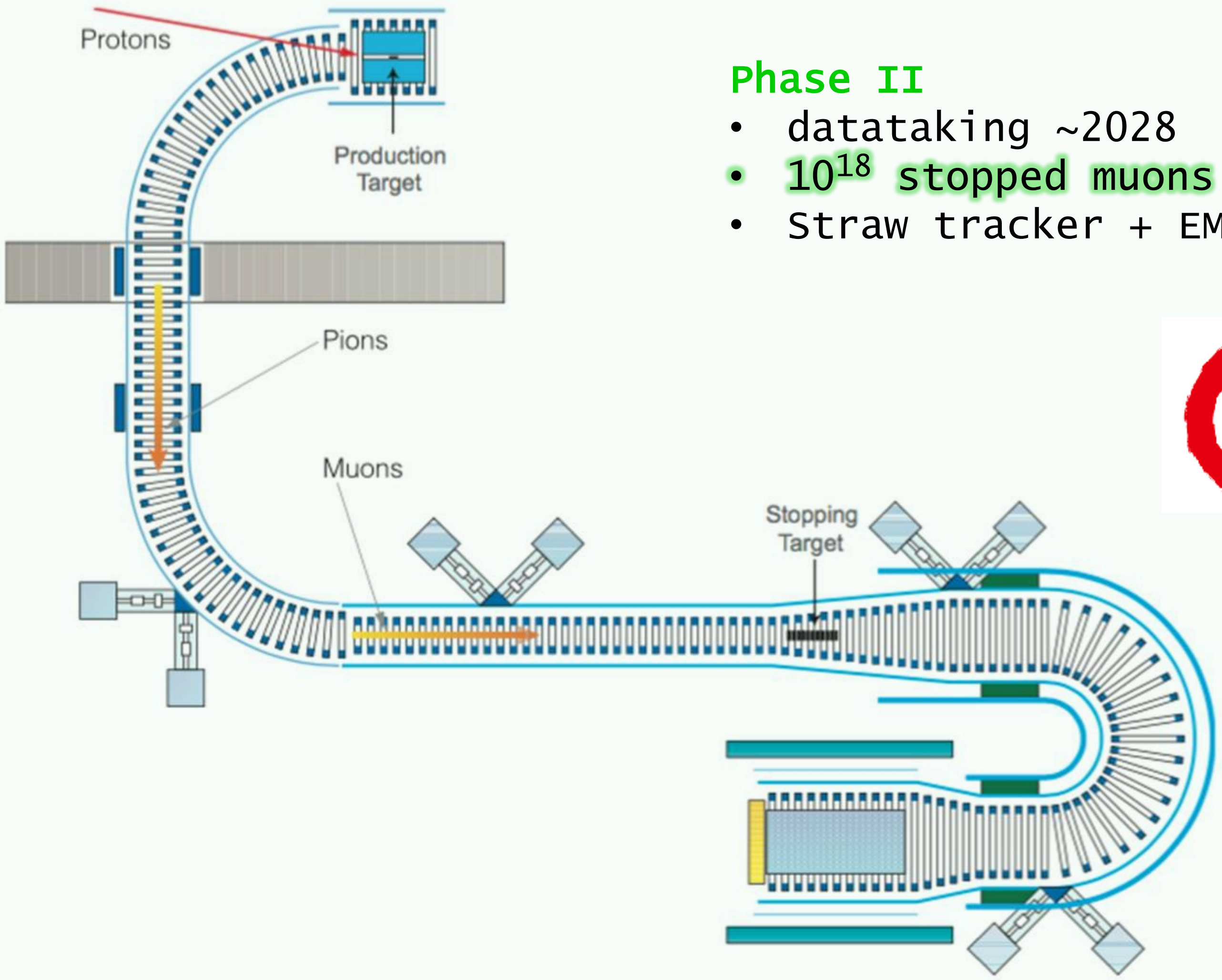
Future projects:

- Mu2e @Fermilab aiming at $CR(\mu^- Al \rightarrow e^- \, Al) < 8 \times 10^{-17}$
- COMET @ JPARC aiming at $CR(\mu^- Al \rightarrow e^- \, Al) < 6 \times 10^{-17}$

COMET, a 2-stage experiment



Phase I
- In preparation
- 10^{16} stopped muons
- Cylindrical Drift Chamber + Cherenkov Hodoscope



Phase II
- datataking ~2028
- 10^{18} stopped muons
- Straw tracker + EMCal

Outline of the course

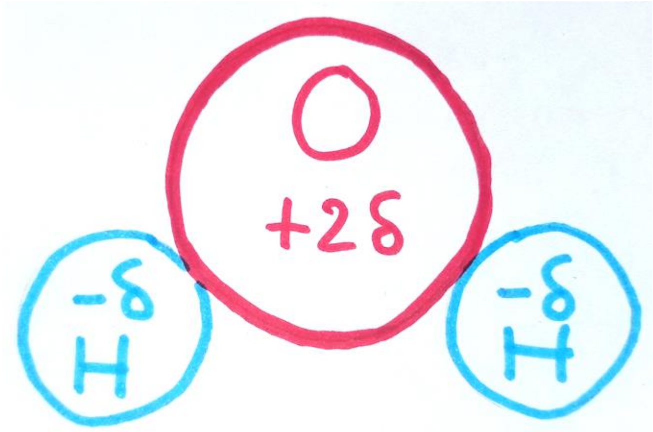
30/10, Lecture 1

Forbidden processes = Formidable probes of new physics

1. Effective Field Theories, SMEFT
2. Lepton flavor violation $\mu \to e$
3. T violation and the neutron EDM
   - What is it?
   - Why?
   - How? => ultracold neutrons

31/10, Lecture 2, More on the search for neutron EDM

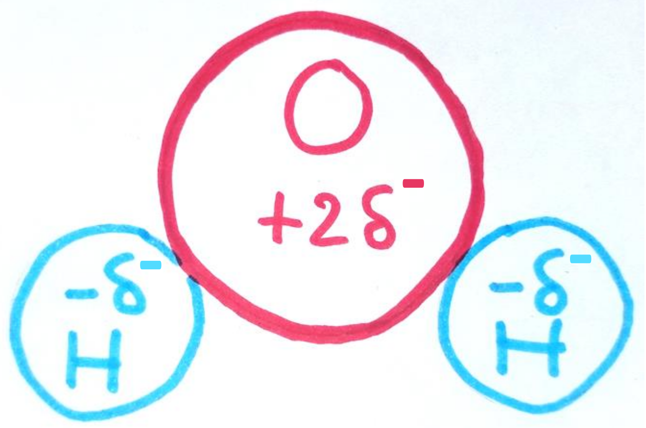
What is an Electric Dipole Moment (EDM) ?



$\vec{d}$ ↓ Electric Dipole Moment

Classical EDM: separation between positive and negative electric charges.
e.g. water molecule d = 0.4 e Å

What is an Electric Dipole Moment (EDM) ?



$\vec{d}\downarrow$ Electric Dipole Moment

Classical EDM: separation between positive and negative electric charges.
e.g. water molecule d = 0.4 e Å

Energy for a "localized" classical charge distribution $\rho(r)$

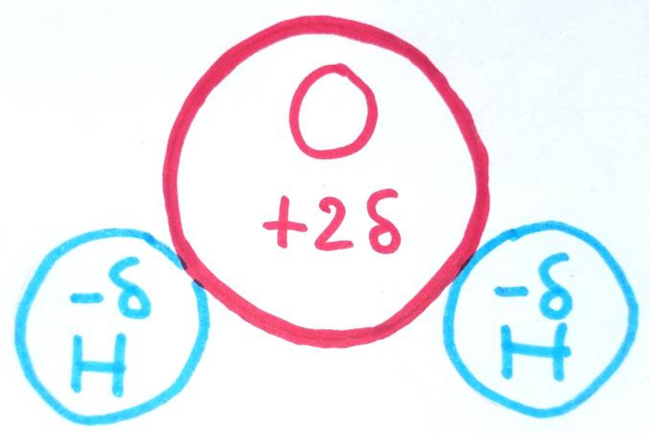
Multipole expansion

exposed to a "weak" electrostatic potential $V(r) = V + r_i \partial_i V + \frac{1}{2} r_i r_j \partial_i \partial_j V + \cdots$

$$W = \int \rho(r) V(r) dr = \left(\int \rho(r) dr\right) V + \left(\int r_i \rho(r) dr\right) \partial_i V + \left(\int \frac{1}{2} r_i r_j \rho(r) dr\right) \partial_i \partial_j V + \cdots$$

Electric charge (scalar) | EDM (vector) | Electric Quadrupole Moment (tensor)

What is an Electric Dipole Moment (EDM) ?



$\vec{d}$ ↓ Electric Dipole Moment

General definition of $q, \vec{d}, \vec{\vec{Q}}$, for systems not necessarily described by a classical charge distribution, like elementary particles:

Energy W in an external electric field $\vec{E} = -\vec{\nabla} V$

$$W = qV - \vec{d} \cdot \vec{E} - \vec{\vec{Q}} \cdot \vec{\nabla}\vec{E} + \cdots$$

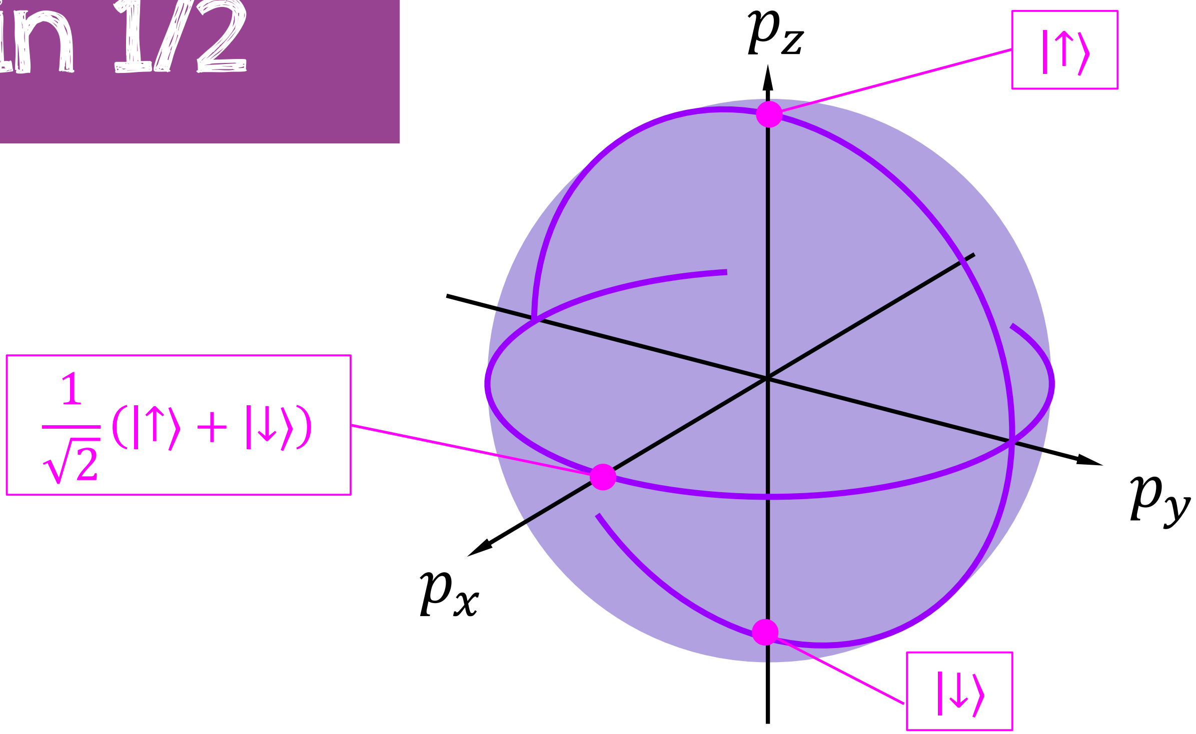
For a quantum system, $\vec{d}$ is a vector operator

What? - Basics of spin 1/2

Internal quantum state of a neutron

$$|\psi\rangle = a\,|\uparrow\rangle + b\,|\downarrow\rangle := \begin{pmatrix} a \\ b \end{pmatrix}$$

$(|a|^2 + |b^2| = 1)$



Spin observable $\vec{\hat{S}} = \hbar/2\ \vec{\sigma}$

$\vec{\sigma}$ are the Pauli matrices

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

The polarization vector $\vec{p} = \langle\psi|\vec{\sigma}|\psi\rangle$

- describes completely the state $|\psi\rangle$

  * up to an irrelevant phase factor ** valid for spin ½ only

- belongs to the **Bloch sphere** $|\vec{p}| = 1$

  * for a pure state, spin 1/2. For a neutron ensemble $|\vec{p}| \leq 1$

What? - Interaction with E & B fields

MDM and EDM are vector operators, they must be proportional to $\vec{\sigma}$ (Wigner-Eckart theorem for spin 1/2)

$$\hat{H} = -\mu\,\vec{\sigma}\cdot\vec{B} - d\,\vec{\sigma}\cdot\vec{E}$$

Spin dynamics
given by Schrödinger equation

$$i\hbar\frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle$$

$$\frac{d}{dt}\begin{pmatrix}a\\b\end{pmatrix} = \left(\frac{i\mu}{\hbar}\,\vec{\sigma}\cdot\vec{B} + \frac{id}{\hbar}\,\vec{\sigma}\cdot\vec{E}\right)\begin{pmatrix}a\\b\end{pmatrix}$$

Or equivalently by the Bloch equation

$$\frac{d\vec{p}}{dt} = \vec{p}\times\left(\frac{2\mu}{\hbar}\vec{B} + \frac{2d}{\hbar}\vec{E}\right)$$

What? - Larmor precession

Case $\vec{B} = B_0 \vec{e}_z$ static, $\vec{E} = \vec{0}$

Initial condition $|\psi(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

$\gamma = \frac{2\mu}{\hbar}$ =: gyromagnetic ratio

$\omega_0 = \gamma B_0$ =: Larmor angular frequency

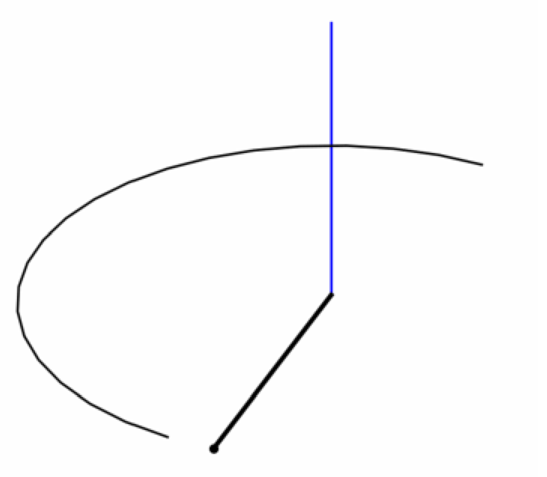
Schrödinger equation:

$$\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \frac{i}{2}\omega_0\, \sigma_z \begin{pmatrix} a \\ b \end{pmatrix}$$

Solution: $\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} e^{i\frac{\omega_0}{2}t} \\ e^{-i\frac{\omega_0}{2}t} \end{pmatrix}$

Bloch equation: $\frac{d\vec{p}}{dt} = \gamma\, \vec{p} \times \vec{B} = \omega_0 \begin{pmatrix} p_y \\ -p_x \\ 0 \end{pmatrix}$

Solution: $\vec{p}(t) = \begin{pmatrix} \sin \omega_0 t \\ \cos \omega_0 t \\ 0 \end{pmatrix}$



Precession at angular frequency $\omega_0 = \gamma B_0$

What are the measured MDM and EDM for the neutron?

$$\hat{H} = -\mu\, \vec{\sigma} \cdot \vec{B} - d\, \vec{\sigma} \cdot \vec{E}$$

$$\mu = -1.913\,042\,7(5)\, \mu_N$$

Nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_N}$$

$$d = (0 \pm 1) \times 10^{-26}\, e\ \mathrm{cm}$$

$$= (0 \pm 1) \times 10^{-12} \times \mu_N / c$$

$$\frac{\mu_N}{c} \approx 0.1\ \mathrm{e\ fm}$$

Why is it so small?

Outline of the course

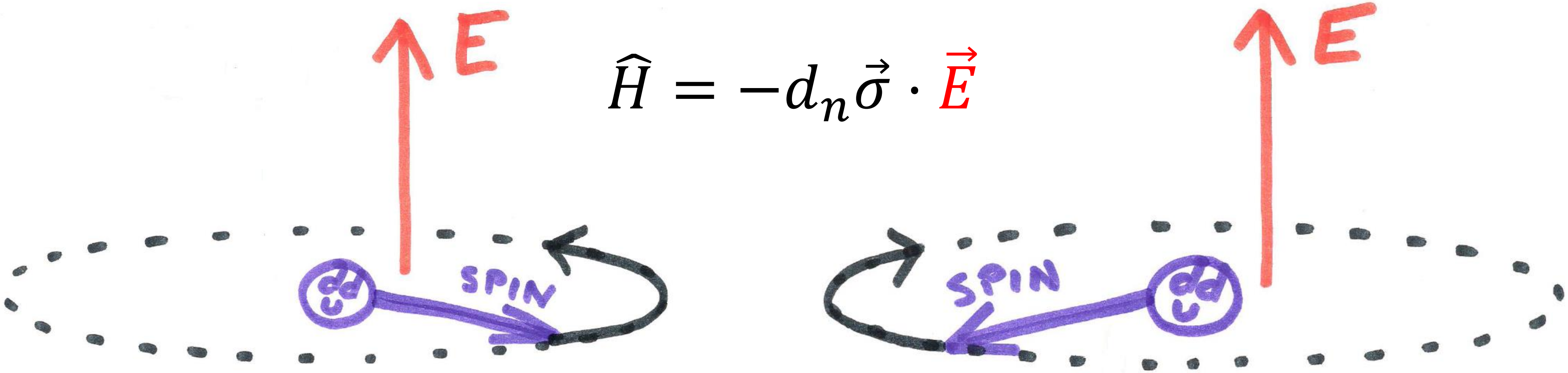
30/10, Lecture 1

Forbidden processes = Formidable probes of new physics

1. Effective Field Theories, SMEFT
2. Lepton flavor violation $\mu \to e$
3. **T violation and the neutron EDM**
   - What is it?
   - **Why?**
   - How? => ultracold neutrons

31/10, Lecture 2, More on the search for neutron EDM

Why tiny? Because of T-symmetry



$$\hat{H} = -d_n \vec{\sigma} \cdot \vec{E}$$

>> PLAY >>

<< REWIND <<

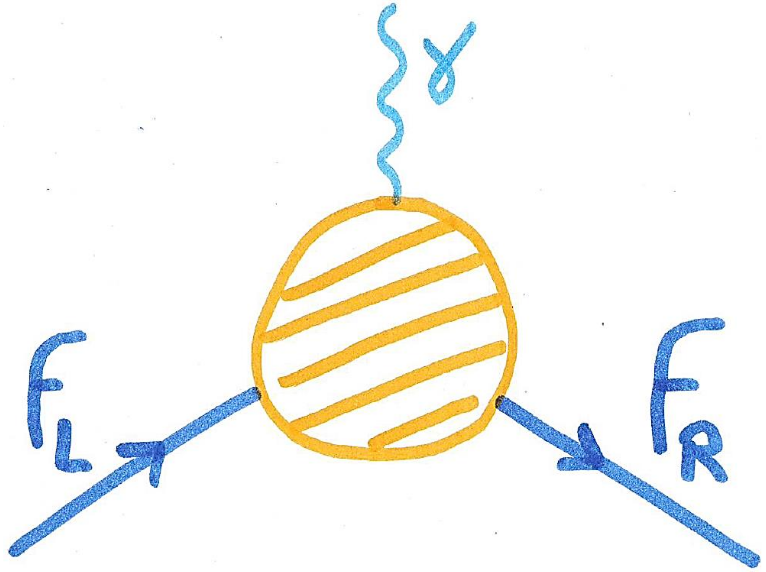
If $d_n \neq 0$ the process and its time reversed version are different.

Violation of T

Violation of CP

CPT theorem

the EDM from the point of view of a high energy theorist



Fermion-photon coupling

$$\mathcal{L} = \frac{1}{2}(\boldsymbol{\delta\mu} + i\boldsymbol{d})\bar{f}_L \sigma_{\mu\nu} f_R \, F^{\mu\nu} + h.c.$$

Real part = anomalous magnetic moment

Imaginary part = electric dipole moment

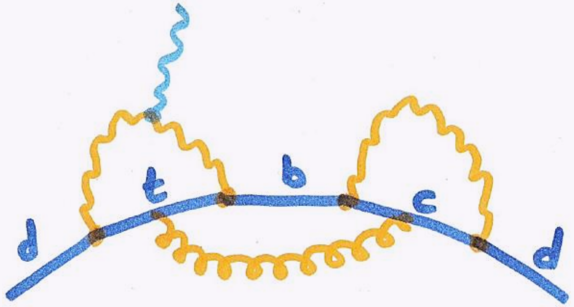
Non-relativistic limit: $\hat{H} = -\boldsymbol{\mu}\sigma B - \boldsymbol{d}\sigma E$

The neutron EDM is quasi-forbidden

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{D=5}} + \mathcal{L}_{\mathrm{D=6}} + \cdots$$

Contribution of weak interaction

Leading order
for quark EDMs at 3 loops!
Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-18}\, \mu_N/c$

* The "long distance" contribution dominates over quark EDMs, still super-small.

The neutron EDM is quasi-forbidden
For known reason (CKM)
And unknown reason (strong CP)

The SM QCD theta term $\frac{\alpha_s}{8\pi}\bar{\theta}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$

generates a potentially enormous neutron EDM : $d_n \sim -0.02 \times \bar{\theta}\, \mu_N/c$

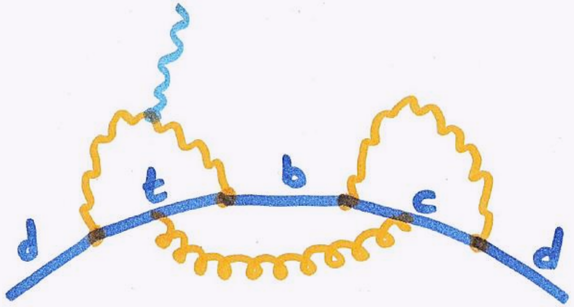
$\rightarrow |\bar{\theta}| < 10^{-10} \rightarrow$ « Strong CP problem »

CP violation and EDM in the SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{D=5}} + \mathcal{L}_{\text{D=6}} + \cdots$$

Contribution of weak interaction

Leading order
for quark EDMs at 3 loops!
Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-18}\ \mu_N/c$

* The "long distance" contribution dominates over quark EDMs, still super-small.

New physics at high scale would generate these new interactions, many of which are CP-violating and contribute to create EDMs.

Neutron EDM probe the energy scale
$\Lambda = 10^7$ GeV

The SM QCD theta term $\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$

generates a potentially enormous neutron EDM : $d_n \sim -0.02 \times \bar{\theta}\ \mu_N/c$

$\rightarrow |\bar{\theta}| < 10^{-10} \rightarrow$ « Strong CP problem »

Summary on What and Why.

What is the neutron EDM?

- For elementary spin ½ particles such as the neutron or the electron, the EDM is really the magnitude of the coupling between spin and E field (don't think of a distribution of charges, it's useless).
- Experimental limit: less than 10^{-12} of the natural size μ_N/c.

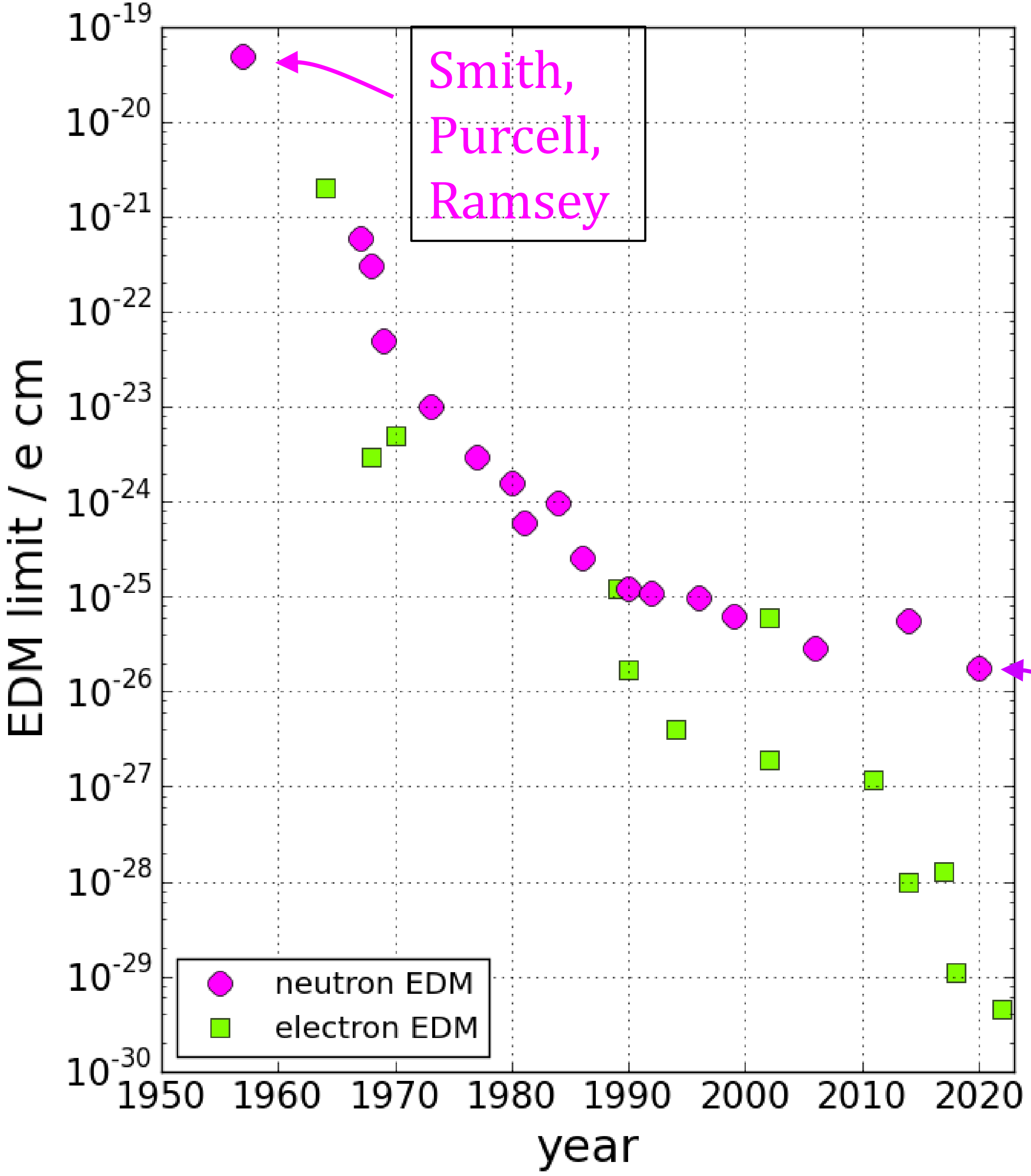
Why is it so small?

- Nonzero EDM violates P and T symmetries, therefore also CP symmetry.
- In the standard model of weak interaction, CP violation needs three generations of quarks. => Super small EDM predicted by CKM

Why do we continue the search?

- Sensitive probe of CP violation beyond the Standard Model.

Since when?



On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. PURCELL AND N. F. RAMSEY
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

IT is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

Limit from the nEDM experiment @PSI

$$|d_n| < 1.8 \times 10^{-26}\ e$$

Abel et al, PRL (2020)

Outline of the course

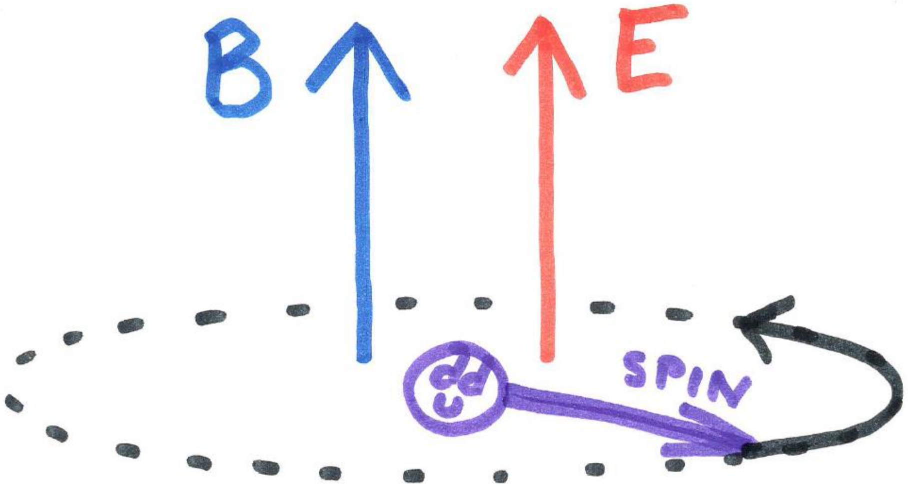
Lecture 1 30/10:

Forbidden processes = Formidable probes of new physics

1. Effective Field Theories, SMEFT
2. Lepton flavor violation $\mu \to e$
3. **T violation and the neutron EDM**
   - What is it?
   - Why?
   - **How?** => ultracold neutrons

Lecture 2 31/10: More on the search for neutron EDM

How? basics of nEDM measurement



Larmor frequency

~ 30 Hz @ $B = 1\ \mu\text{T}$

$$2\pi f = \frac{2\mu_n}{\hbar} B \pm \frac{2d_n}{\hbar} |E|$$

If $d_n \sim 10^{-26}\ e$ cm and $E \sim 10$ kV/cm

duration of one full turn ~ 1 year

To detect such a minuscule coupling

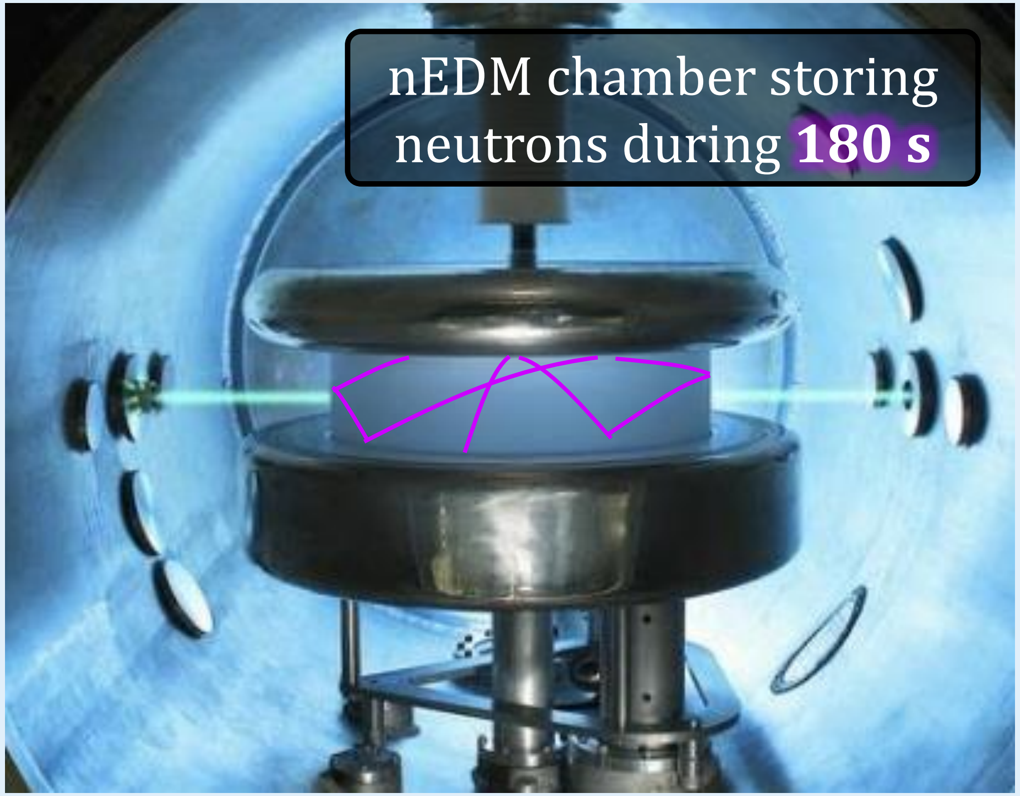
- Long interaction time
- High intensity/statistics
- Control the magnetic field

- Long interaction time
- High intensity/statistics
- Control the magnetic field

Use big magnetic shielding

Use Ultracold neutrons

Neutrons with velocity <5m/s can undergo total reflection and be stored in material "bottles"



+ Use quantum magnetometry

With mercury and cesium atoms

Abel et al, PRL (2020)

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}\, ecm$$

Limited by the number of UCNs (~500 million counts)

Uniformity of the B-field