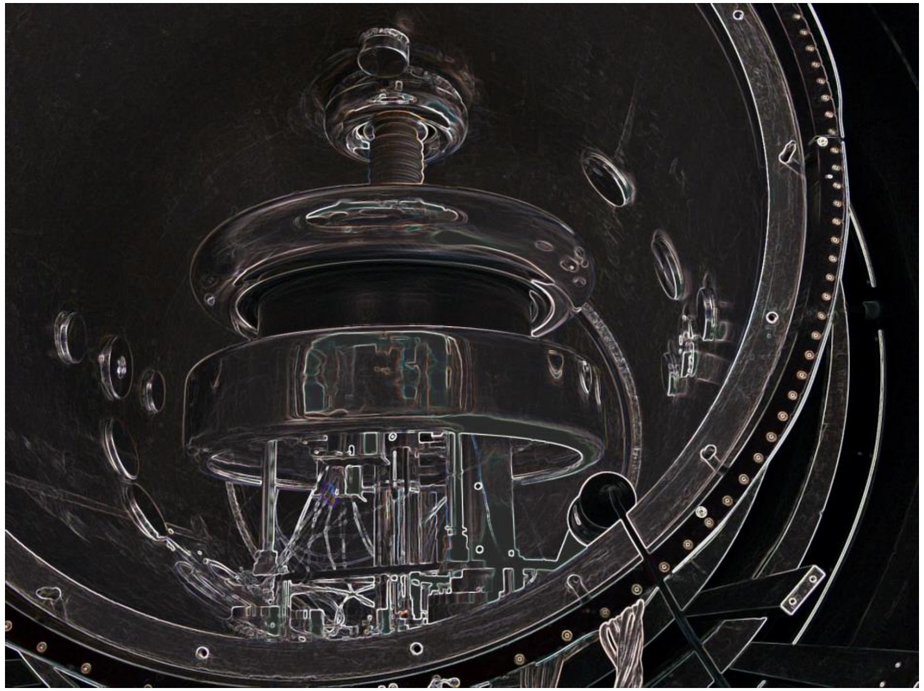
Higgs constraints from low-energy measurements



Université Grenoble Alpes

S. Roccia

Higgs Hunting 2023

Outlook

What is an EDM?
The neutron EDM in the standard model and beyond
.... And how we searched for it at PSI!

Other low energy probes

What is an EDM?

Probe of P, T (CP) symmetries

$$H = -\vec{\mu}_n.\vec{B} - \vec{d}_n.\vec{E} = \frac{hf_n}{2}$$

30 Hz in 1µT

58 nHz in 12 KV/cm

$d_n = (\; 0.0 \pm 1.1_{\,stat} \pm 0.2_{\,syst}) \; 10^{-26} e.\text{cm}$ → 10 years, 34 PhD thesis, 55 persons at a given time

RAL/SUSSEX/ILL result, Phys. Rev. D 92 092003 (2015) based on data taken 1998-2002

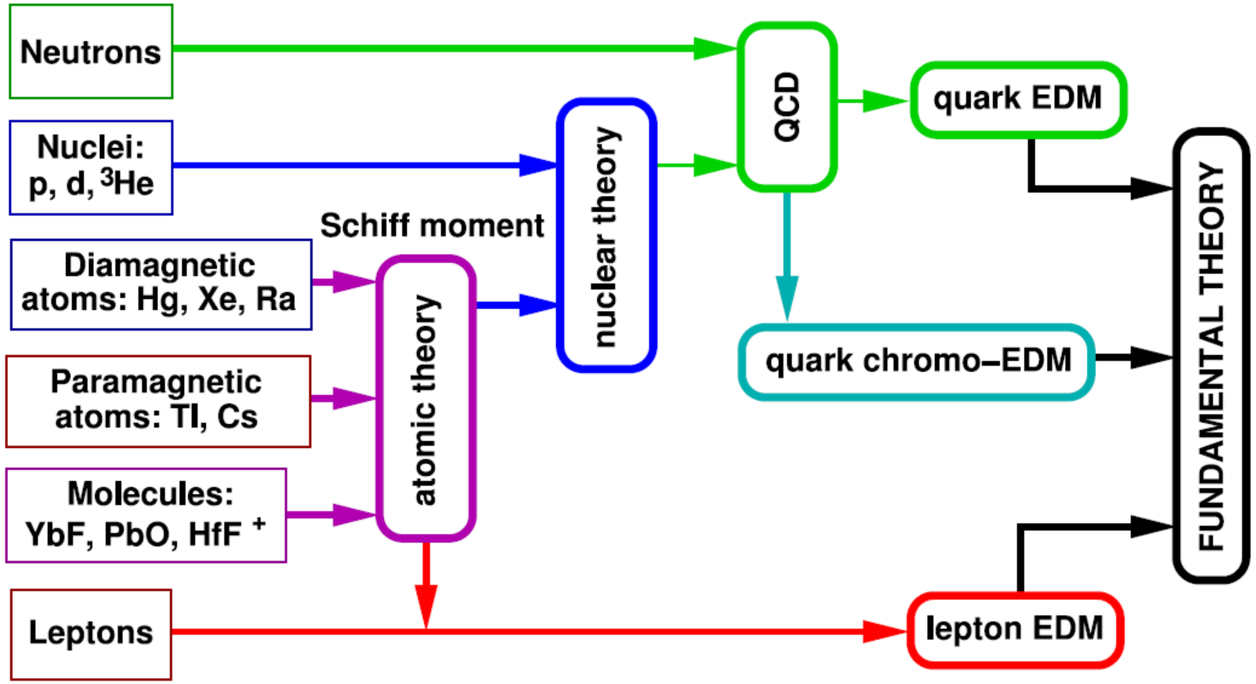
$d_n = (-0.2 \pm 1.5_{\,stat} \pm 1.0_{\,syst}) \; 10^{-26} e.\text{cm}$

nEDM and CP violation

$$d_n = (-0.204 \pm 0.015) d_u + (0.784 \pm 0.040) d_d + (-0.0027 \pm 0.0016) d_s$$
$$+ (1.1 \pm 0.55)(e\tilde{d}_d + 0.5 e\tilde{d}_u) \pm (25 \pm 12) ew (\mathrm{MeV})$$

← Contribution from quark EDM

← The so called "long distance" effects also referred to as Chromo-Electric Dipole Moments from quarks and gluons



C. R. Physique 13 168 (2012)

nEDM and CP violation

d_n^{CKM} d_n^{θ}

$$d_n = 10^{-32} e.cm + 10^{-16}\, e.cm\,(\theta)$$

$$L_{eff} = L_{QCD} + \theta \frac{\alpha_S}{8\,\pi}\, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.00152(71)\theta\; e.fm$

Experimental upper limit: $|d_n| \leq\; 2.10^{-13}\;\; e.fm$ ⇒ $\theta \leq 10^{-10}$

J. Dragos et al., Phys. Rev. C 103, 015202 (2021)

nEDM and CP violation

The chances to find new physics can be quantified in an **effective field theory approach**: the new physics is parameterized by a single energy scale representing the mass of the new force mediators **Λ**, and a large set of dimensionless coefficients

$$\mathscr{L}_{SMEFT} = \sum_{D=2}^{\infty} \sum_{i} O_{i,D} \frac{c_{i,D}}{\Lambda^{D-4}}$$

Wilson coefficients

D is the dimension of the operators $O_{i,D}$
D ≤ 4 describes the Standard Model
D=5 impacts on the neutrino sector
D=6 our playground

$$d_n \approx d_q \approx \hbar c e q_q \sin\delta_{CPV} \left(\frac{g^2}{16\pi^2}\right)^l \varepsilon_{FV} \frac{m_q}{\Lambda^2}$$

A discovery tool

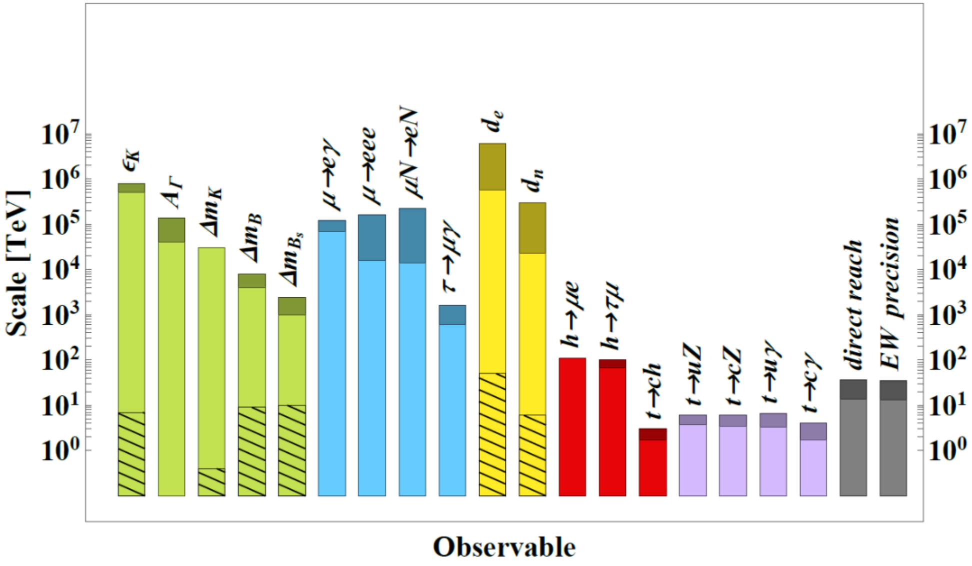


Fig. : Physics Briefing Book of the European Strategy for Particle Physics

R. Alarcon et al., Contribution to Snowmass 2021, arXiv:2203.08103 (2022)

nEDM and CP violation

d_n^{CKM} d_n^{θ} d_n^{NP}

$$d_n = 10^{-32} e.cm + 10^{-16}\, e.cm\,(\theta) + \, 10^{-24}\, e.cm \left(\frac{200\ GeV}{M}\right)^2 \sin(\varphi_{CP})$$

$$L_{eff} = L_{QCD} + \theta\, \frac{\alpha_S}{8\,\pi}\, \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

From lattice calculations: $d_n = -0.0039(2)(9)\theta\ e.fm*$

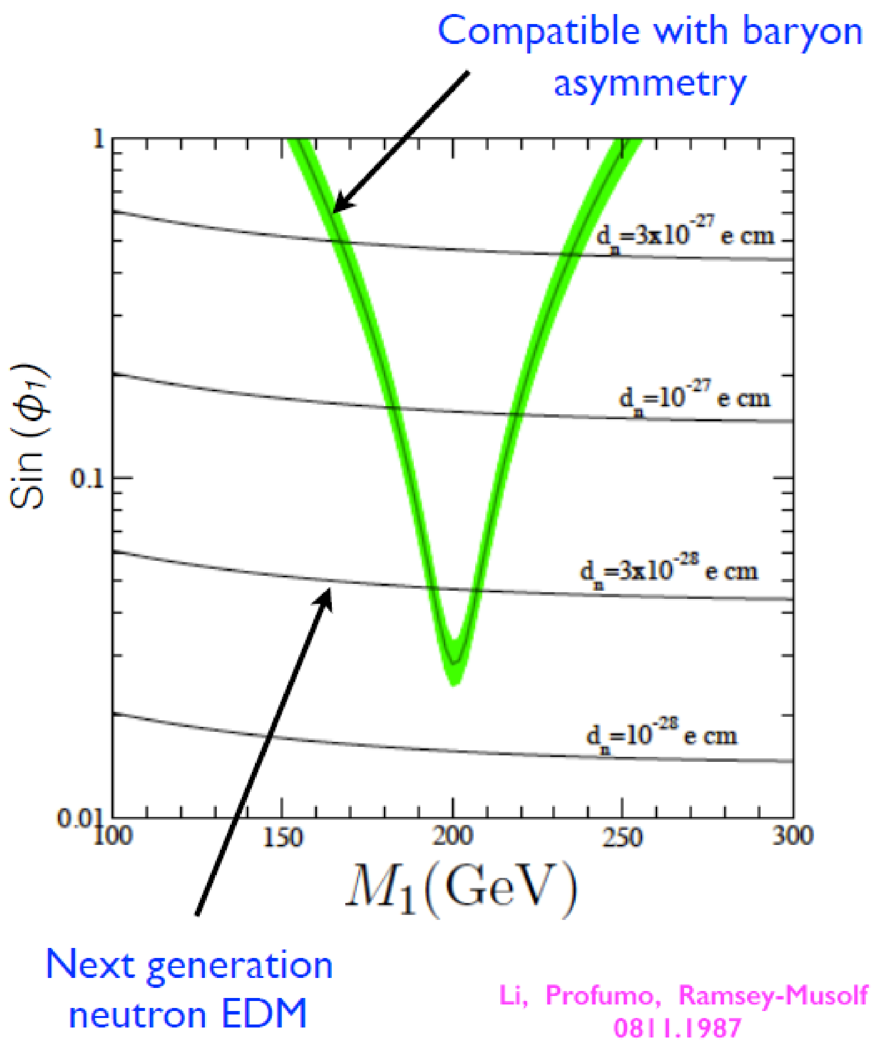
Experimental upper limit: $|d_n| \leq \ 2.10^{-13}\ \ e.fm$ → $\theta \leq 10^{-10}$

New CP violating phases contributes to

* baryonic asymmetry of the universe
* neutron EDM

The nEDM is the probably most stringent test of electroweak baryogenesis

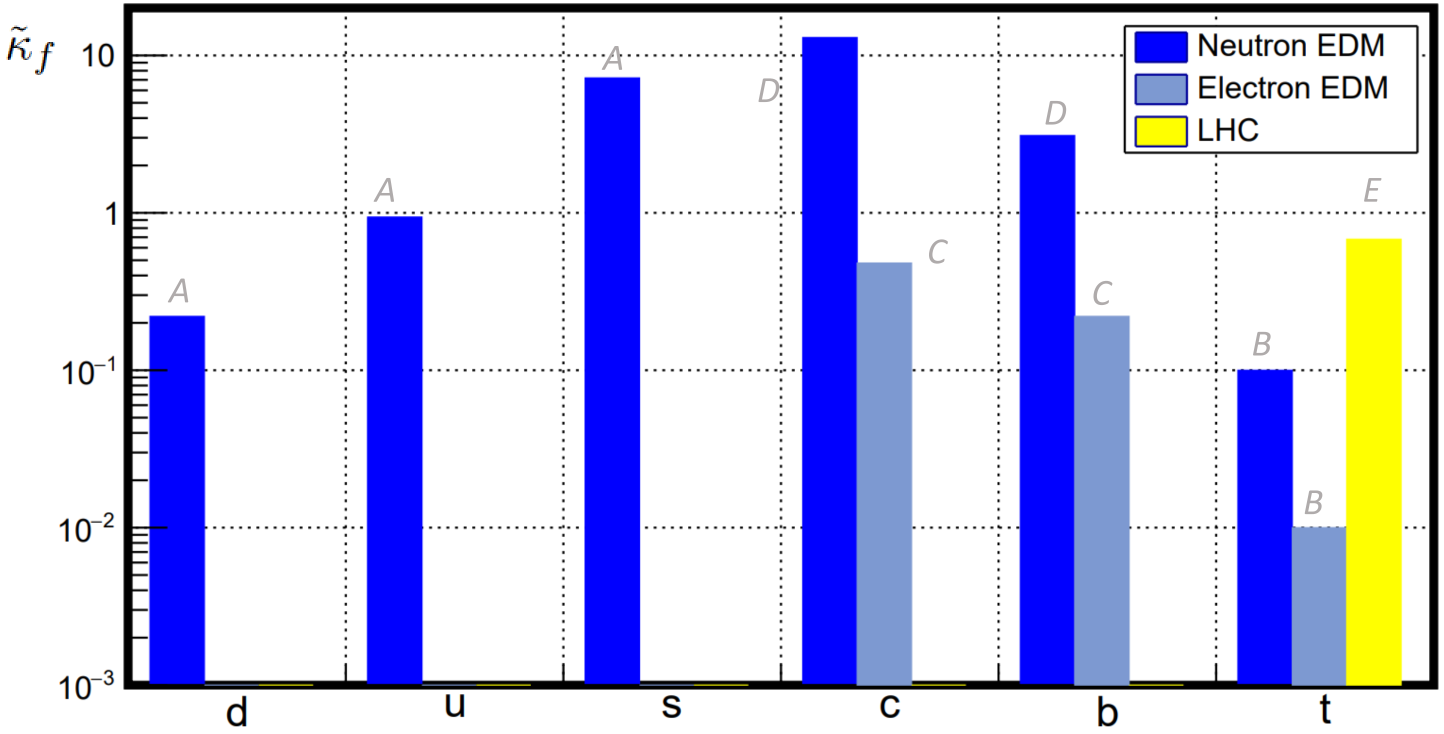
Another possibility is the leptogenesis



Picture by V. Cirigliano

Higgs hunting

Higgs coupling to light fermions: $\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$ SM: $\kappa_f = 1 \text{ and } \tilde{\kappa}_f = 0$



Allowed values for $\tilde{\kappa}_f$

A: Brod et al., J. High Energ. Phys. 2019, 233 (2019)
B: Brod et al., J. High Energ. Phys. 2013, 180 (2013)
C: Brod et al., https://doi.org/10.48550/arXiv.2306.12478
D: Brod et al. , J. High Energ. Phys. 2021, 80 (2021)
E: G. Aad et al. (ATLAS Collaboration) Phys. Rev. Lett. 125, 061802 (2020)

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$$
\begin{aligned}
d_n = & (-0.204 \pm 0.015) d_u + (0.784 \pm 0.040) d_d + (-0.0027 \pm 0.0016) d_s \\
& + (1.1 \pm 0.55)(e\tilde{d}_d + 0.5 e\tilde{d}_u) \pm (25 \pm 12) ew (\text{MeV})
\end{aligned}
$$

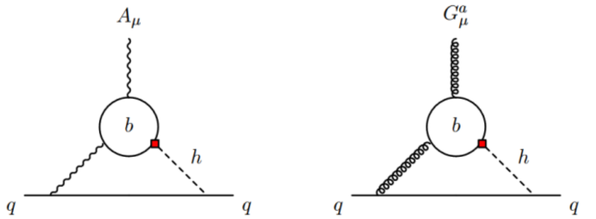
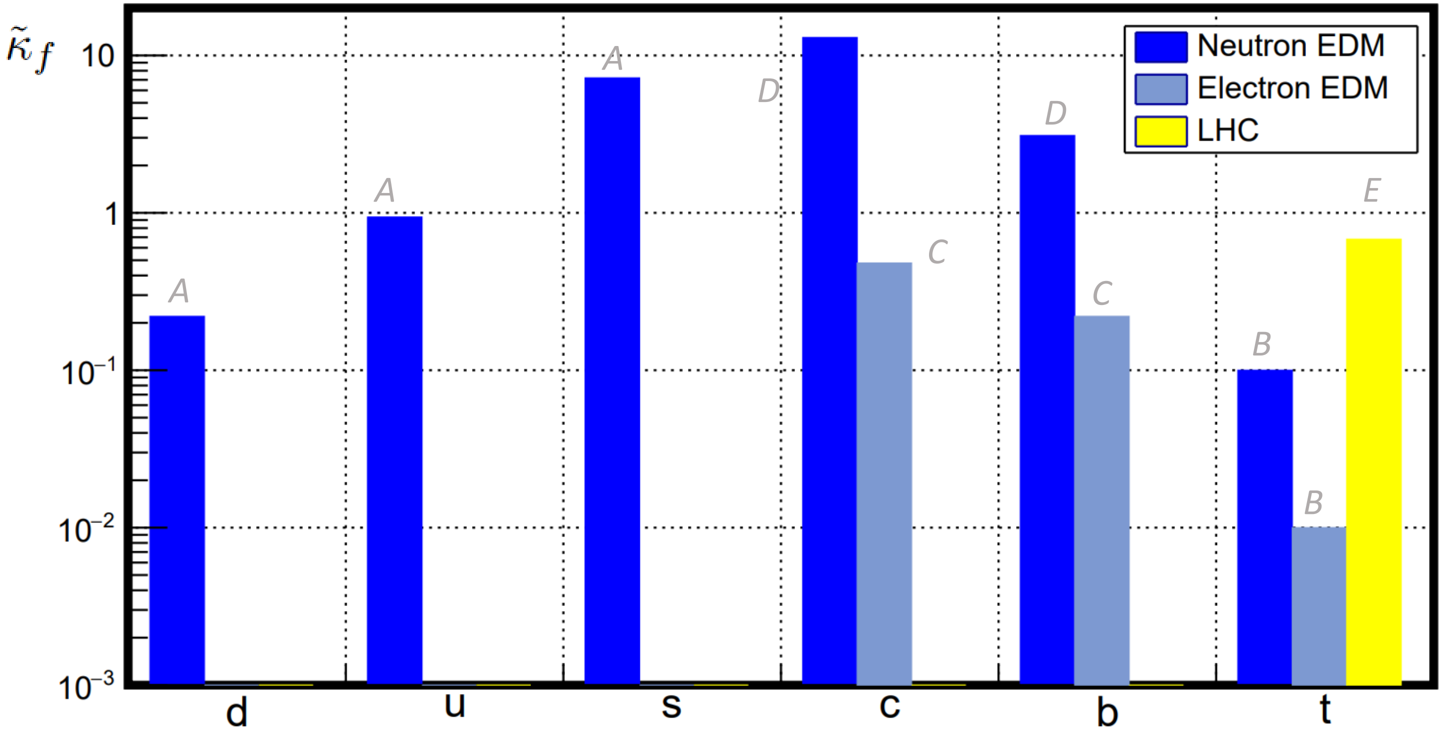


Figure 1. Photonic and gluonic "Barr-Zee" diagrams with modified bottom-Yukawa coupling that induce an EDM of the light quark q. See text for details.

From Ref D



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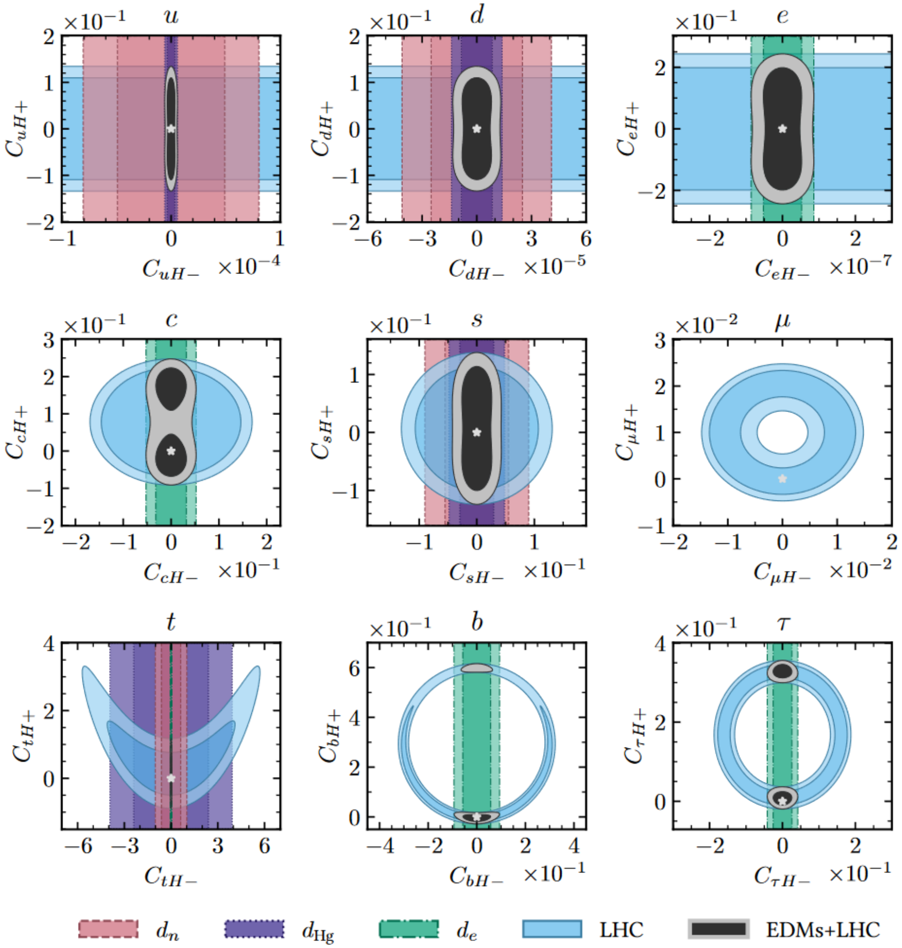
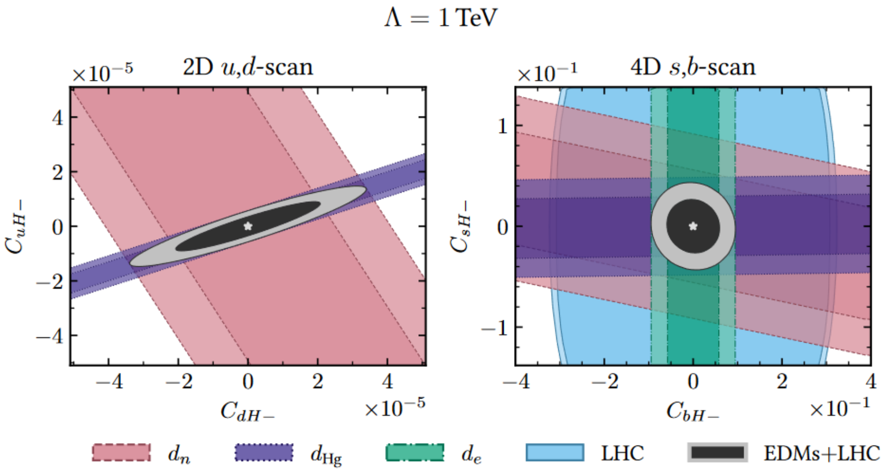
Higgs hunting

Higgs coupling to light fermions: $\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$ SM: $\kappa_f = 1 \text{ and } \tilde{\kappa}_f = 0$

Global analysis!

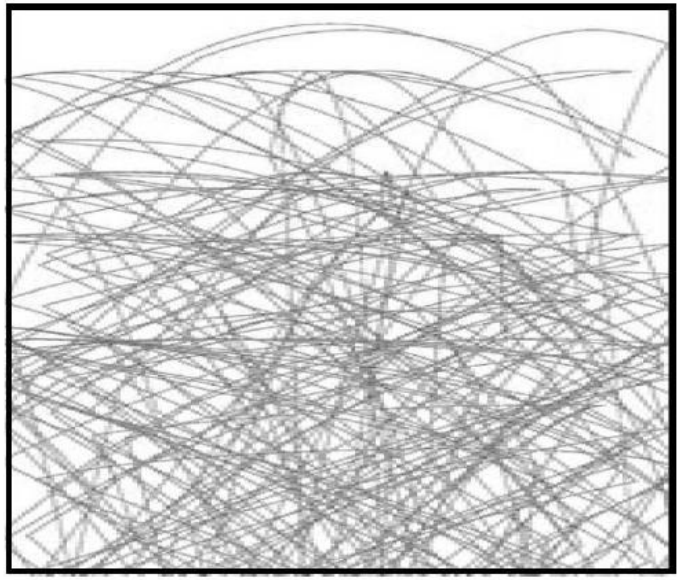




J. Brod, JHEP08 (2022) 294

The search for the neutron EDM

Neutrons reflected for all incidence angles: UCNs

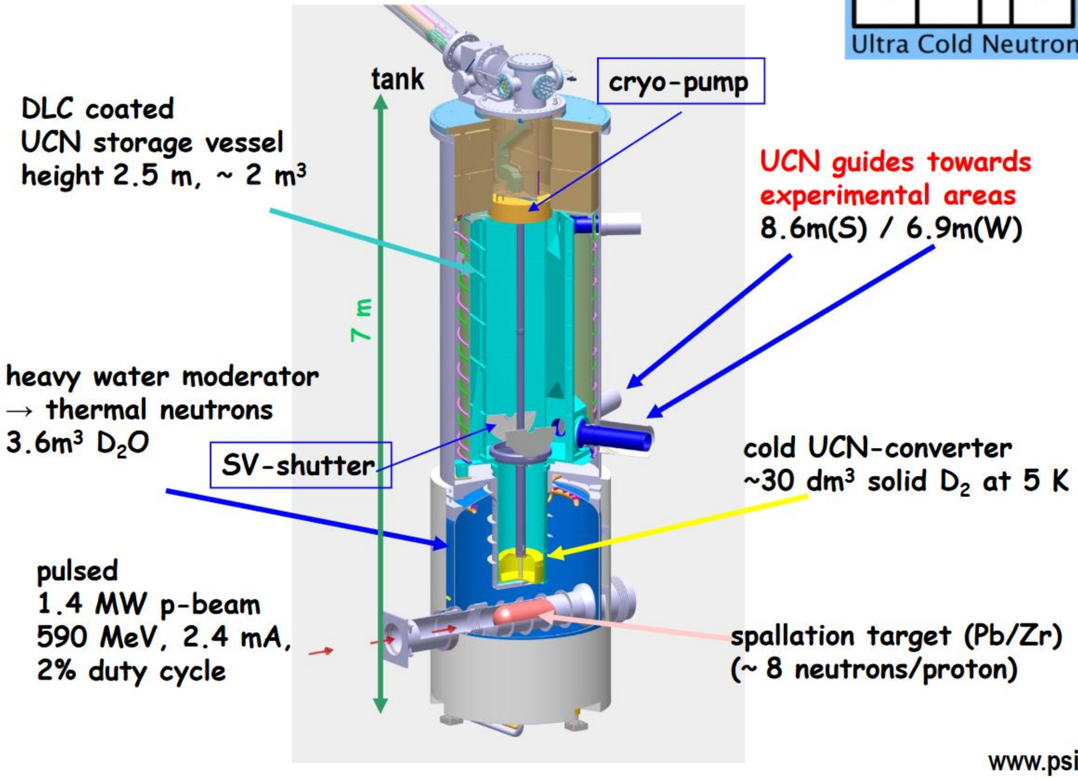


$\lambda_n \approx 800$ Å;

$v_n \approx 5$ m/s;

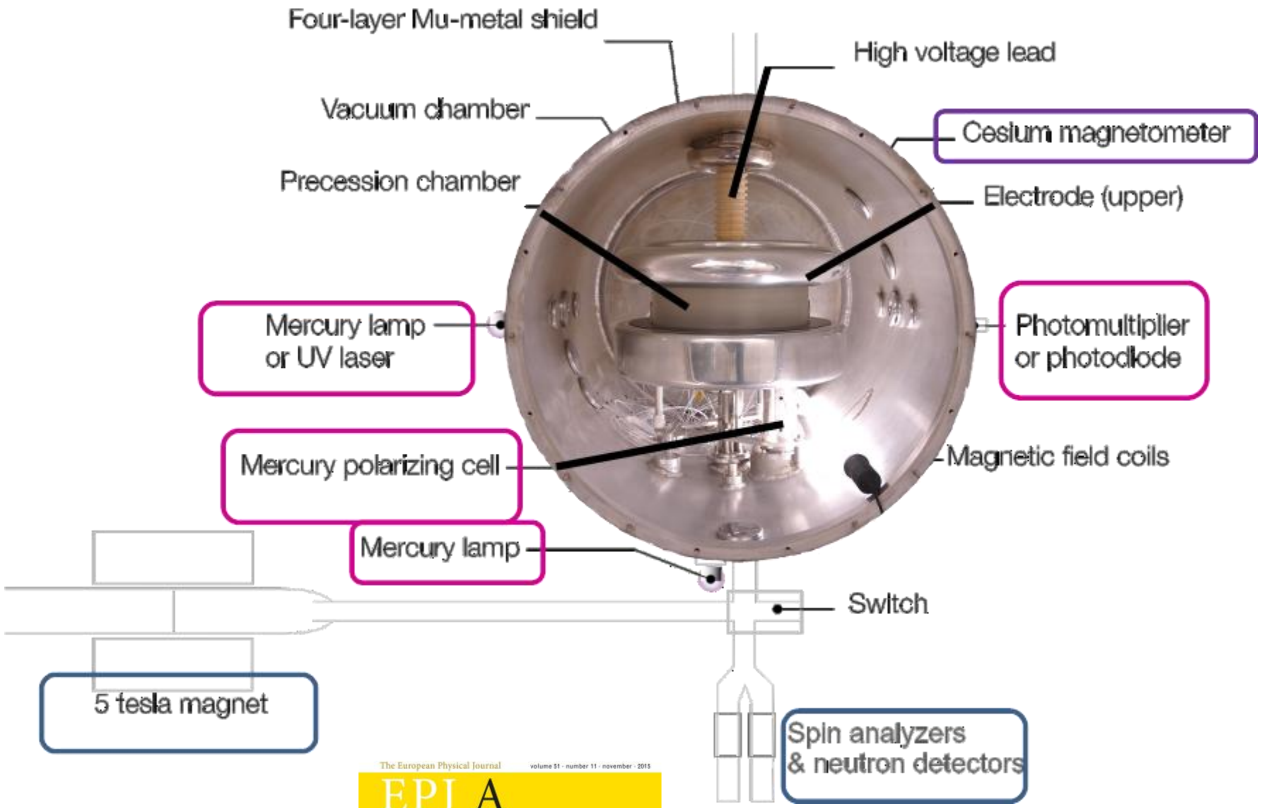
$T_n \approx 2$ mK ;

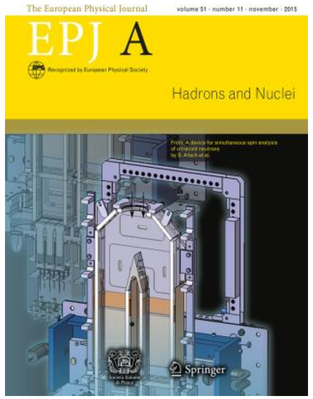
$E_n \approx 130$ neV



www.psi.ch/ucn/

The search for the neutron EDM

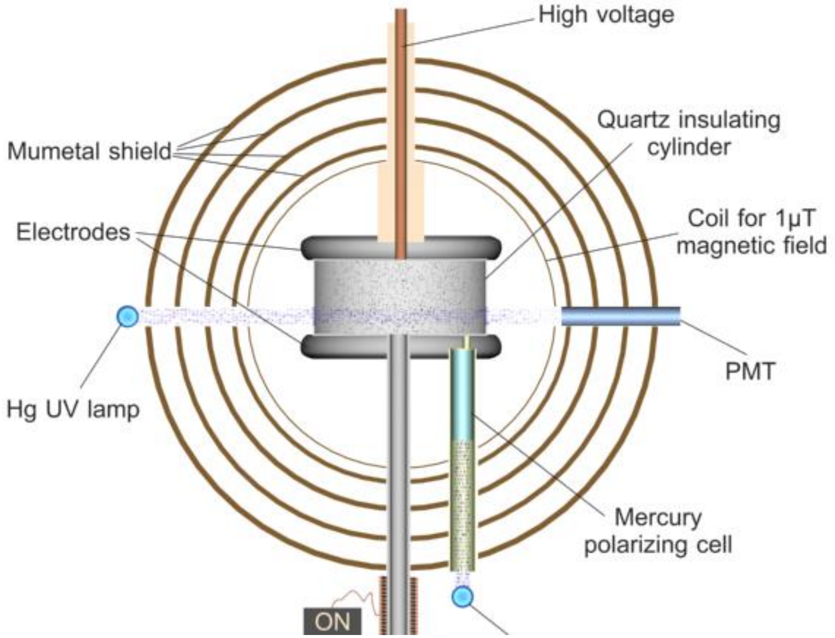




The search for the neutron EDM

First limitation ….. Magnetic field fluctuations

$$
\begin{array}{lcccc}
\mathrm{h}\ f_n\ (\uparrow\uparrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) & + & 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\
\mathrm{h}\ f_n\ (\uparrow\downarrow) & = & 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) & - & 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\
\hline
\mathrm{h}(f_n\ (\uparrow\uparrow)\text{-}\ f_n\ (\uparrow\downarrow)) & = & 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow)-\vec{B}(\uparrow\downarrow)) & - & 2\vec{d}_n.(\vec{E}(\uparrow\uparrow)+\vec{E}(\uparrow\downarrow))
\end{array}
$$

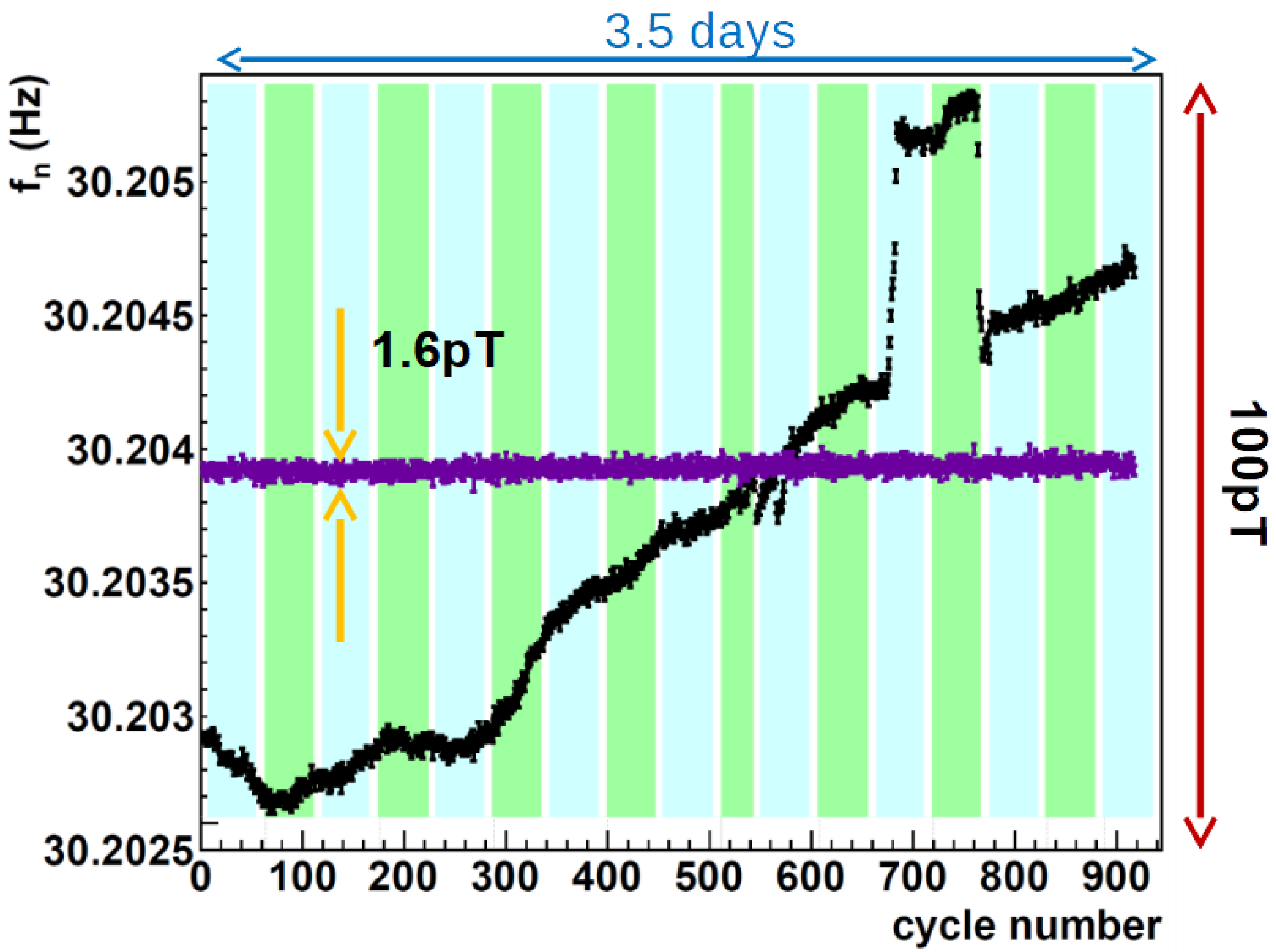


Mercury co-magnetometer (1998)

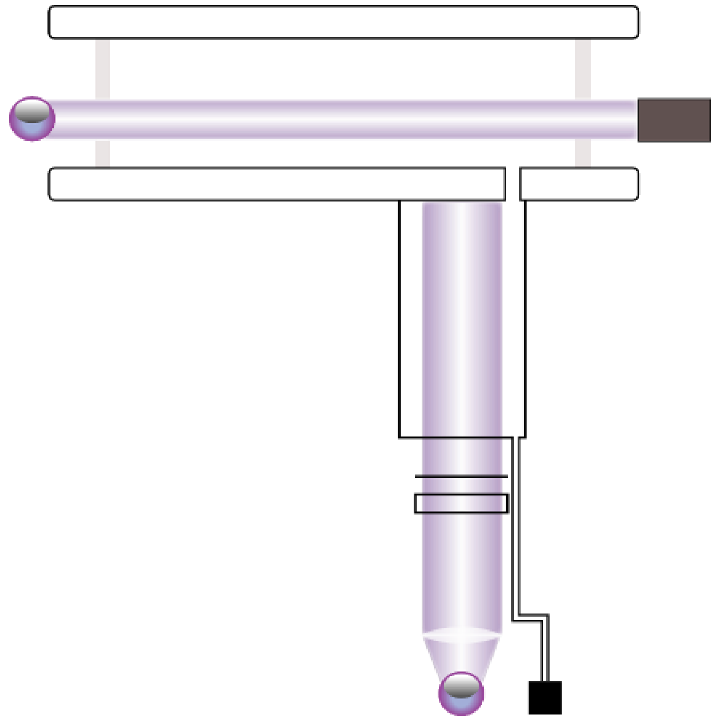
$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

Cesium magnetometer array (2009)

The search for the neutron EDM



The Hg co-magnetometer



The search for the neutron EDM

TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error	
Error on $\langle z \rangle$	...	7	(0 ± 68)
Higher-order gradients $\hat{G}$	69	10	
Transverse field correction $\langle B_T^2 \rangle$	0	5	(33 ± 14)
Hg EDM [8]	−0.1	0.1	
Local dipole fields	...	4	(-71 ± 81)
$v \times E$ UCN net motion	...	2	
Quadratic $v \times E$	...	0.1	
Uncompensated G drift	...	7.5	
Mercury light shift	...	0.4	
Inc. scattering ^{199}Hg	...	7	
TOTAL	69	18	(-38 ± 99)

Systematic error budget:

- Divided by a factor of 5
- Dominated by “new” effects
- Opens the door to a new generation of experiments

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}\ e.\text{cm}.$$

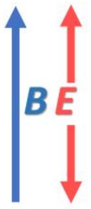
The search for the neutron EDM

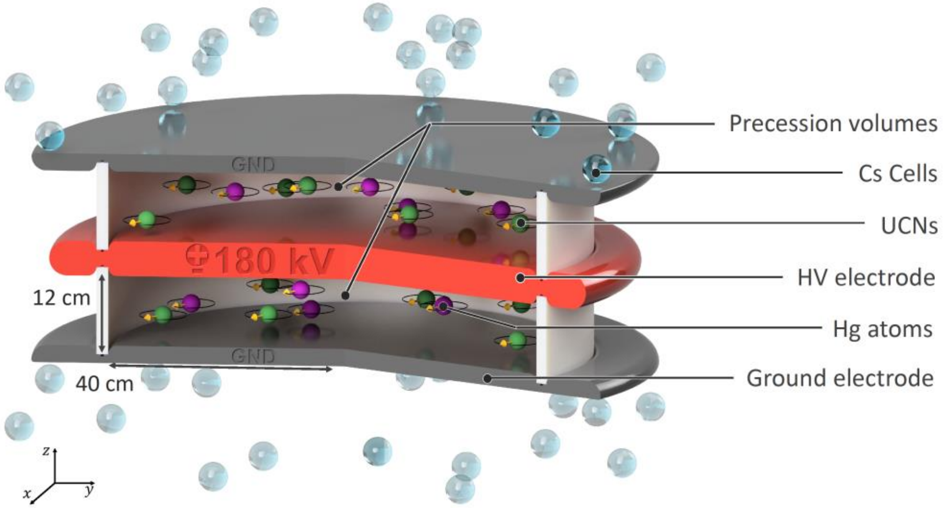
First limitation ….. Magnetic field fluctuations

$$
\begin{aligned}
h\ f_n\ (\uparrow\uparrow) &= 2\ \vec{\mu}_n.\vec{B}(\uparrow\uparrow) + 2\ \vec{d}_n.\vec{E}(\uparrow\uparrow) \\
h\ f_n\ (\uparrow\downarrow) &= 2\ \vec{\mu}_n.\vec{B}(\uparrow\downarrow) - 2\ \vec{d}_n.\vec{E}(\uparrow\downarrow) \\
\hline
h(f_n\ (\uparrow\uparrow) - f_n\ (\uparrow\downarrow)) &= 2\vec{\mu}_n.(\vec{B}(\uparrow\uparrow) - \vec{B}(\uparrow\downarrow)) - 2\vec{d}_n.(\vec{E}(\uparrow\uparrow) + \vec{E}(\uparrow\downarrow))
\end{aligned}
$$

n2EDM

Goal: $1*10^{-27}$ e.cm





$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n B_n}{\gamma_{Hg} B_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}$$

$$d_n = \frac{\pi h f_{Hg}}{4|E|}\left(\mathcal{R}^T_{\uparrow\downarrow} - \mathcal{R}^T_{\uparrow\uparrow} + \mathcal{R}^B_{\uparrow\downarrow} - \mathcal{R}^B_{\uparrow\uparrow}\right)$$

Merci

* Probe the Electroweak baryogenesis
* Probe physics beyond the standard model at the multi-TeV scale

* Different EDMs will probe the source of CP violation

One might stop measuring zero!

* A first measurement at PSI
* A new era is beginning

$$d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}\ e.\text{cm}.$$