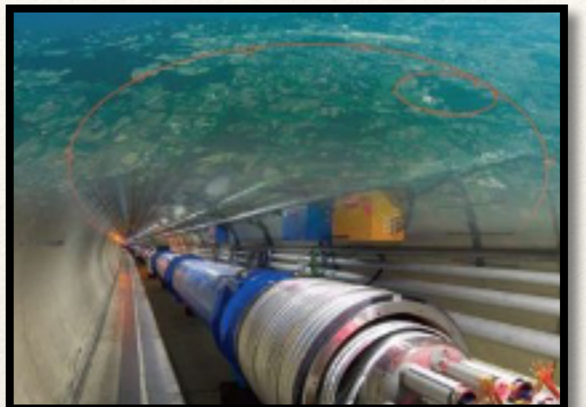
# Low-energy precision searches (eEDM et al.)

Jordy: Physics context
Steven: Strategy for Nikhef and CERN
Rick: Related experiments at the VU

# The search for something non-standard

Energy



**Energy frontier: produce new states on-shell**

**Precision frontier: measure effects from virtual new states (quantum effects)**

Both frontiers have played a key role in the development of the Standard Model

# Experiments with stable matter

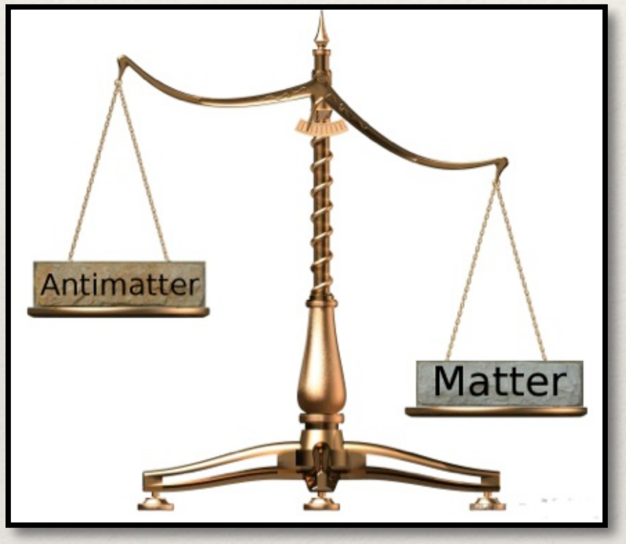
- Certain precision tests of the SM are best done with (semi-)stable, neutral systems: mesons, neutrons, atoms, molecules
- **Easier to collect large numbers and long measurement times**

1. Baryon-number violation (proton decay)
2. Lepton-number violation (neutrinoless double beta decay)
3. ***Flavor-diagonal CP violation (electric dipole moments)***
4. CKM parameters from nuclear and mesonic decays
5. …….

- **Big questions: neutrino masses, matter/antimatter asymmetry, dark matter, CKM unitarity ……….**

# Why EDMs ?

- Why look for Electric Dipole Moments ?

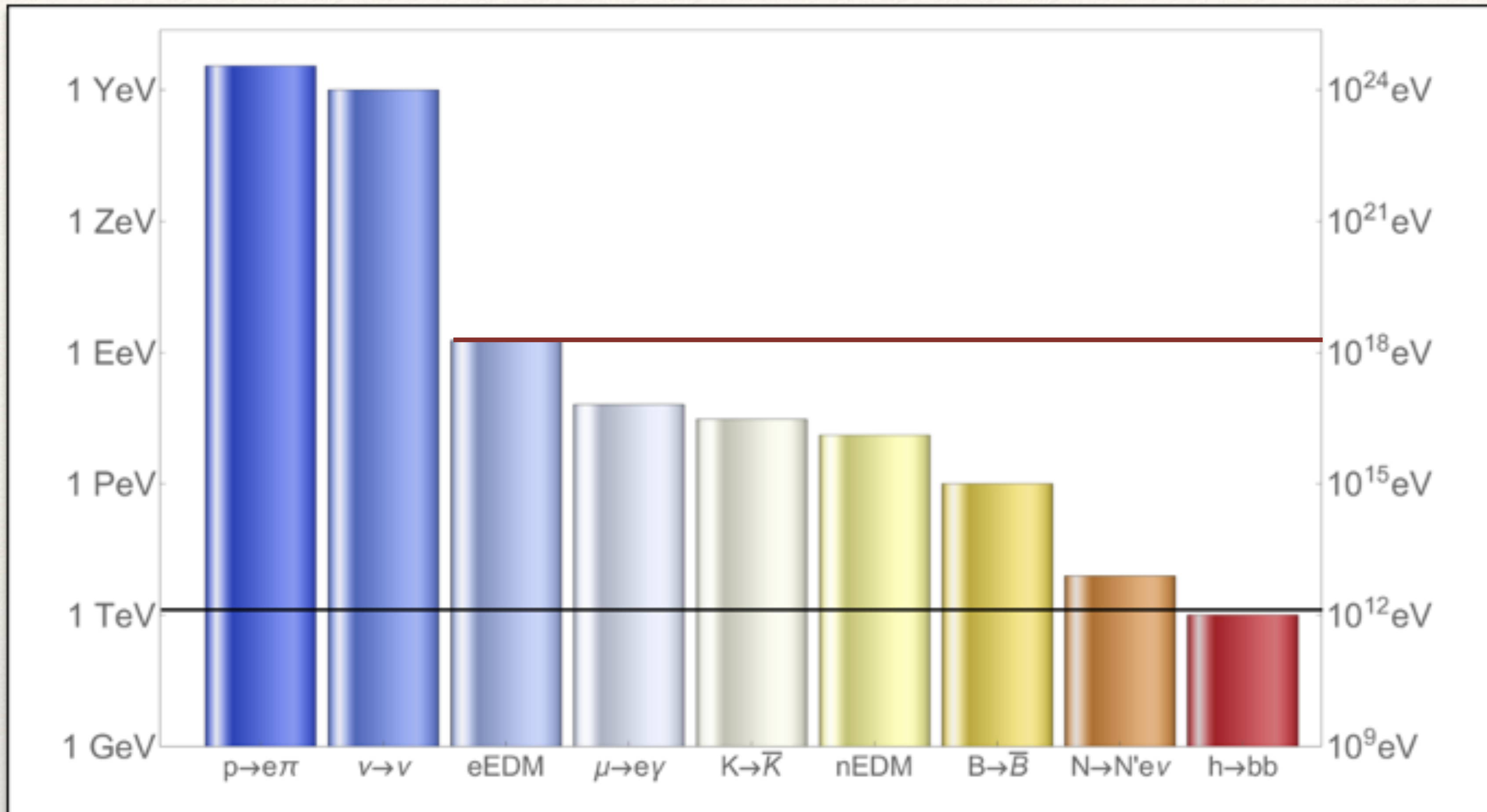



$$10^{-10} > \sin\bar{\theta} > 0$$

**Strong CP problem**


- **Standard Model CP violation not sufficient**
- **CP violation is a broken symmetry**
- **~1/2 of SMEFT operators break CP**

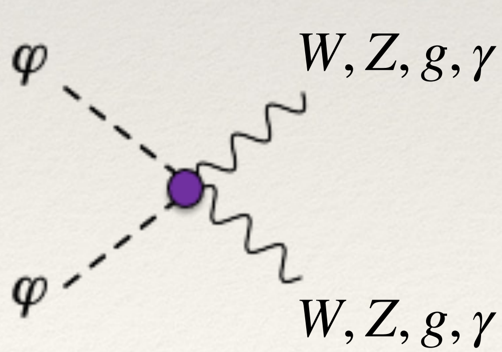
# Tremendous reach




- Low-energy precision searches probe very high energy scales

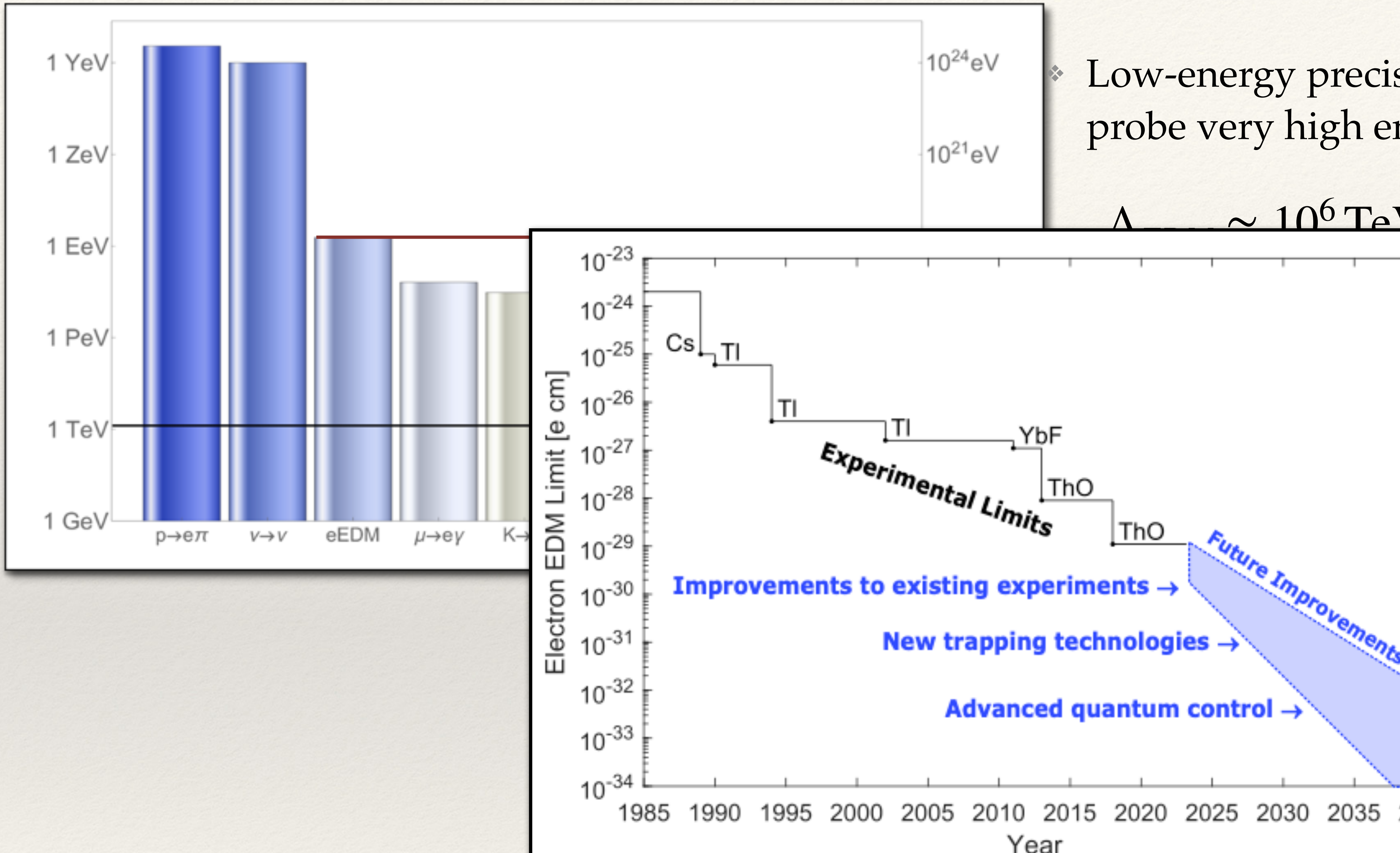
$$\Lambda_{EDM} \simeq 10^6\,\text{TeV}$$

- Example: EDMs provide stringent limits on CP-violating Higgs couplings $\text{Im}\, y_t < 0.1\ \%$




| | | |
|---|---|---|
| $v^2\, C_{\varphi\tilde{B}}$ | $[-5.1, 5.1] \cdot 10^{-6}$ | $[-28, 10]$ |
| $v^2\, C_{\varphi\tilde{W}}$ | $[-4.7, 4.7] \cdot 10^{-6}$ | $[-2.3, 0.43]$ |
| $v^2\, C_{\varphi\tilde{W}B}$ | $[-2.2, 2.2] \cdot 10^{-6}$ | $[-0.57, 0.57]$ |
| $v^2\, C_{\varphi\tilde{G}}$ | $[-5.3, 5.3] \cdot 10^{-5}$ | $[-1.3, 8.1] \cdot 10^{-3}$ |

# Tremendous reach



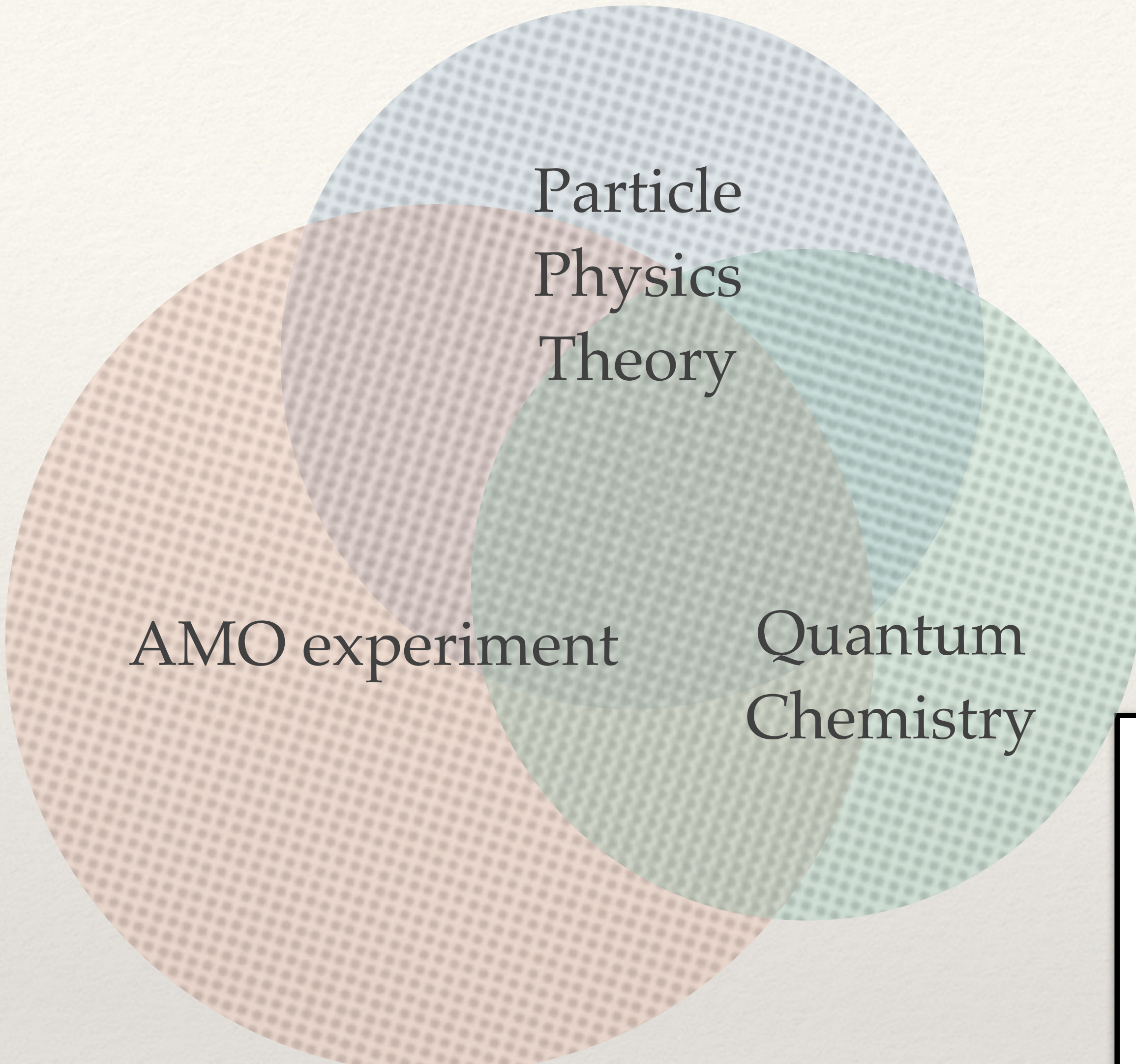

- Low-energy precision searches probe very high energy scales

$\Lambda \sim 10^6$ TeV

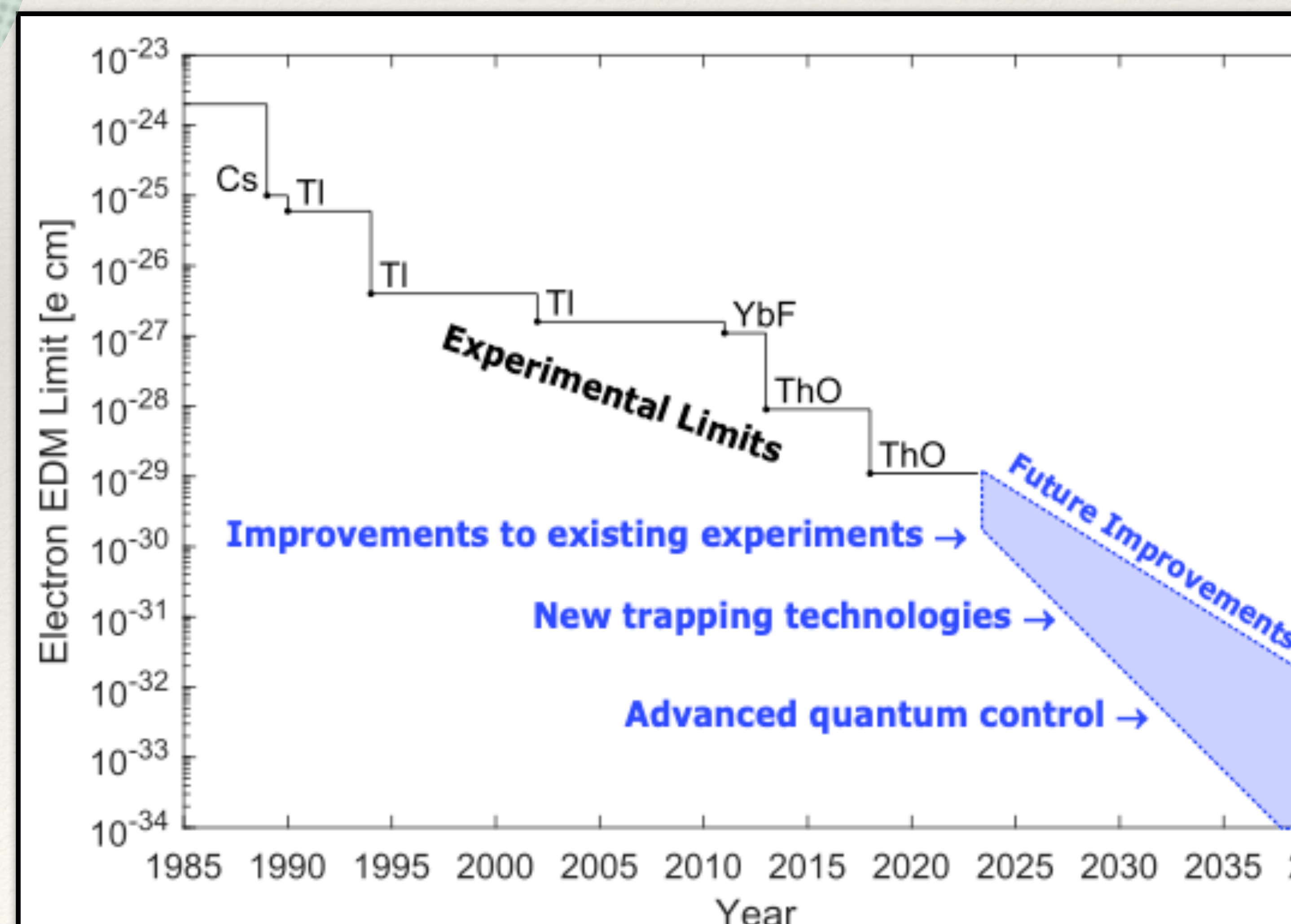
- **'plenty of room at the bottom'** to make further improvements with relatively low costs. Connection to axion searches and quantum technology (quantum sensing)

# Our approach

Connect observables
to underlying theory

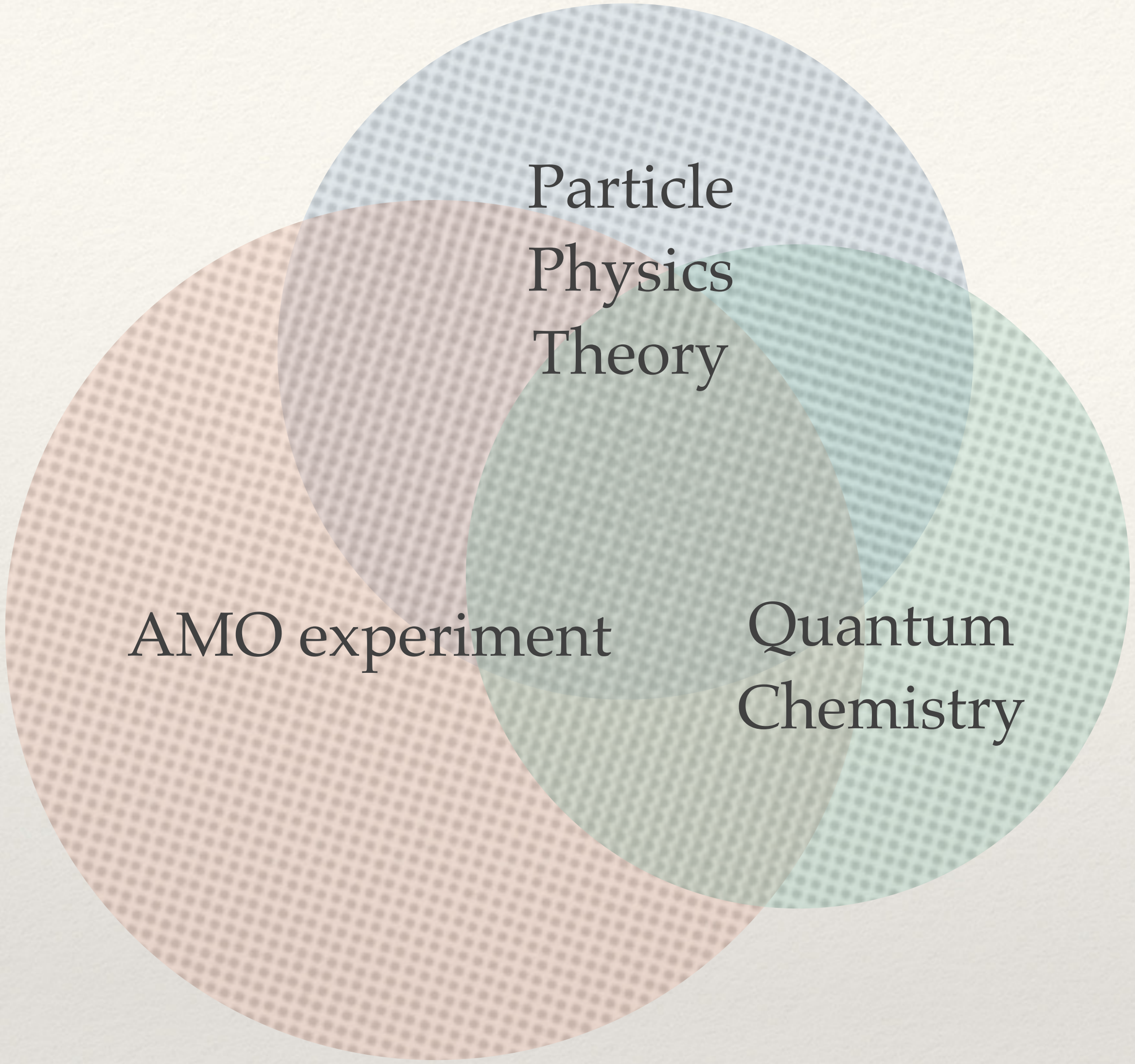



Predict, interpret and propose best
molecular quantum systems




Develop and implement
best experimental strategies,
with maximum statistics
and minimum systematics

# Our strategy

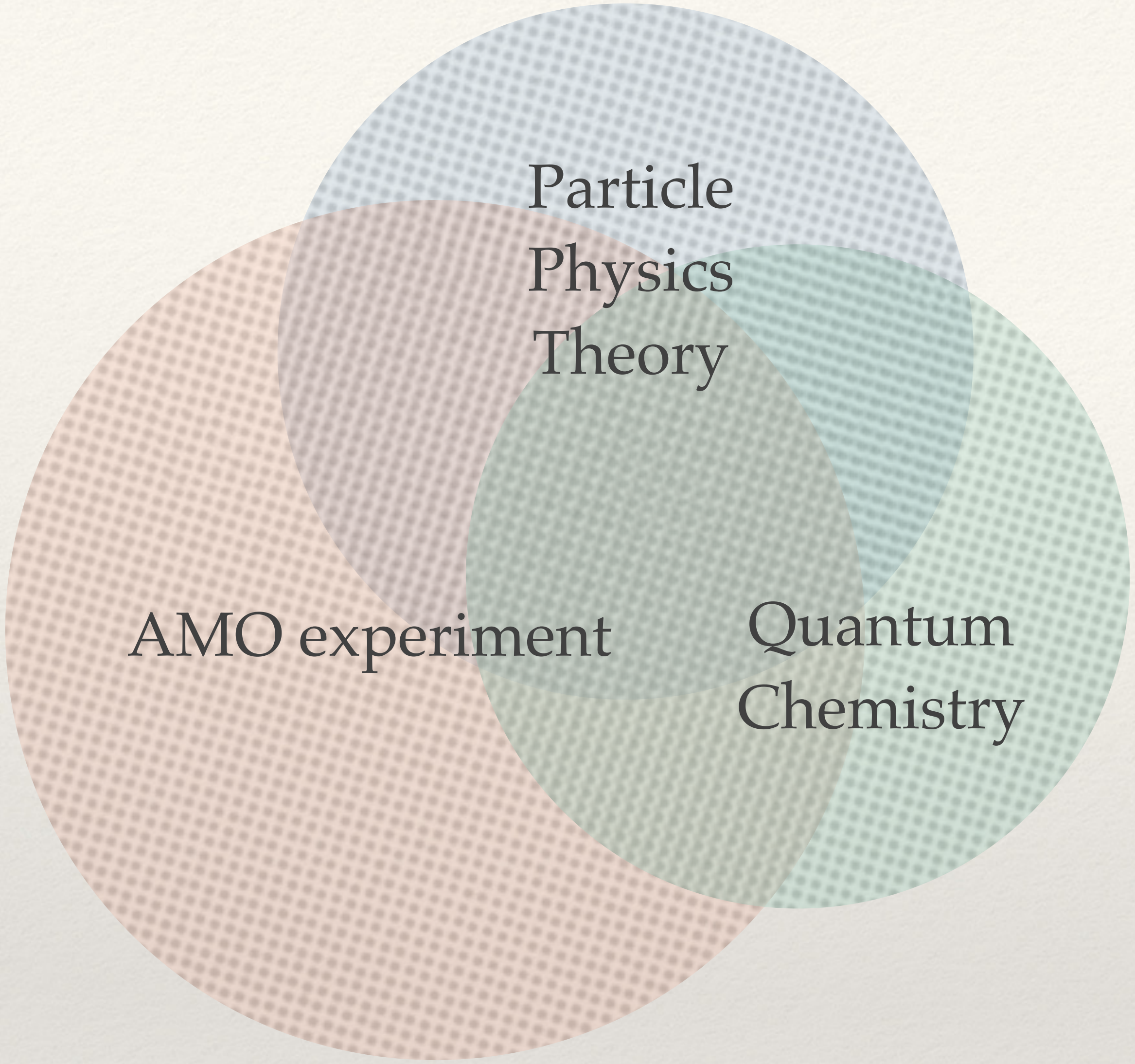



Each of the main areas needs critical mass, focus and support

Progress happens in the region of overlap: so we need to create optimal conditions for collaboration

(inter)national coordination and network is crucial to unite potentially fragmented effort

# Our strategy




Each of the main areas needs critical mass, focus and support

**Nikhef**

Progress happens in the region of overlap: so we need to create optimal conditions for collaboration

**CERN**

(inter)national coordination and network is crucial to unite potentially fragmented effort

# Statements

1. Low-energy precision experiments - like the eEDM experiment - are powerful probes of physics beyond the Standard Model, complementary to high-energy experiments. These experiments require long-term funding and technical support. They are a key part of the Nikhef portfolio, and should be an explicit part of the European Strategy for Particle Physics.

2. CERN is in a great position to coordinate and unite low-energy precision experiments through the Quantum Sensing and Emerging Technologies R&D program (ECFA DRD5). At Nikhef we aim to connect a number of research programs through a dedicated Quantum Sensing R&D effort.

3. The rapidly developing forefront of the eEDM research field is focussing on trapped systems, providing long interaction times. We should strengthen our focus on the development and application of quantum control techniques. We are in a great position given the unique combination of experimental and theoretical expertise which we have in the Netherlands.

extra

# Community input to the European Strategy on particle physics: Searches for Permanent Electric Dipole Moments

edited by M. Athanasakis-Kaklamanakis, M. Au, R. Berger, S. Degenkolb, J. Devries, S. Hoekstra, A. Keshavarzi, D. Ries, P. Schmidt-Wellenburg, and M. Tarbutt,

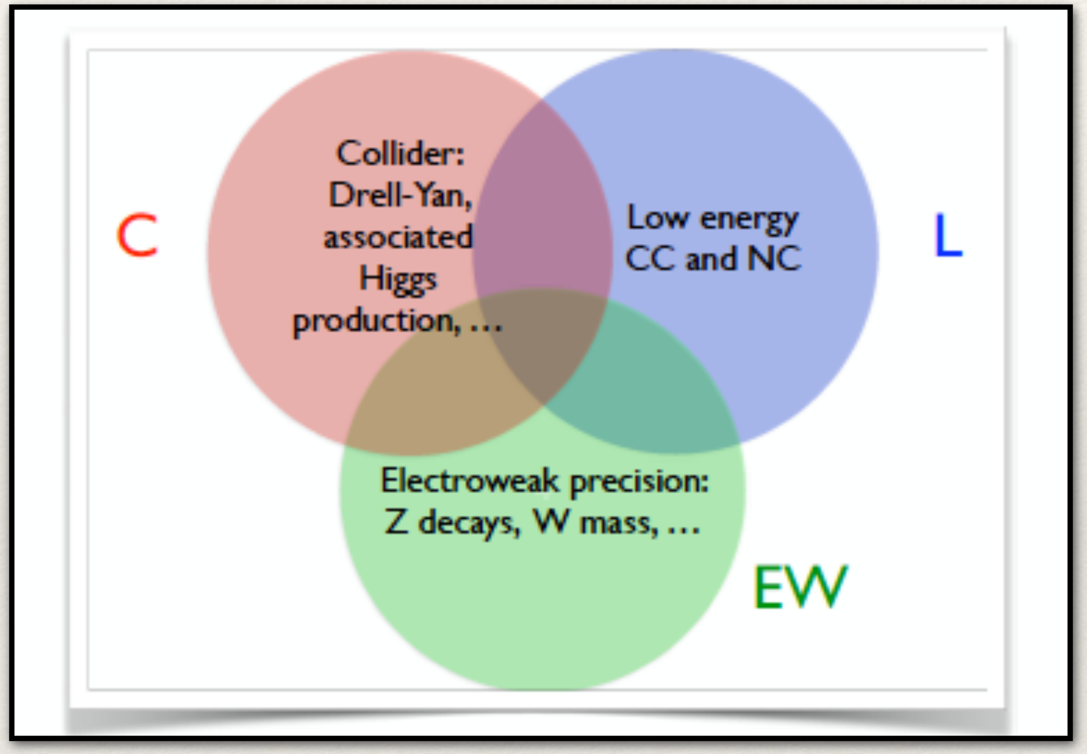
and endorsed by the
European EDM projects and collaborations:

| Name | Species | Method | $\lvert E_{\text{eff}}\rvert$ (GV/cm) | $T$ (ms) | $N$ (approx.) | Status | 90% CL ($10^{-29}$ $e$ cm) | Ref |
|---|---|---|---|---|---|---|---|---|
| Imperial I | YbF ($^2\Sigma$) | Beam | 14.5 | 0.64 | $10^{11}$ | Complete | 105 | [48] |
| ACME I | ThO ($^3\Delta_1$) | Beam | 78 | 1.1 | $4 \times 10^{10}$ | Complete | 9.4 | [49] |
| ACME II | ThO ($^3\Delta_1$) | Beam | 78 | 1.1 | $10^{13}$ | Complete | 1.1 | [4] |
| JILA I | $HfF^+$ ($^3\Delta_1$) | Ion trap | 23 | 700 | $3 \times 10^6$ | Complete | 13 | [50] |
| JILA II | $HfF^+$ ($^3\Delta_1$) | Ion trap | 23 | 3000 | $10^8$ | Complete | 0.41 | [5] |
| ACME III | ThO ($^3\Delta_1$) | Beam | 78 | 5 | $8 \times 10^{14}$ | Commissioning | | [51] |
| JILA III | $ThF^+$ ($^3\Delta_1$) | Ion trap | 36 | 20000 | $10^7$ | Commissioning | | [52] |
| Imperial II | YbF ($^2\Sigma$) | $\mu$K beam | 18 | 20 | $10^{13}$ | Commissioning | | [53] |
| Imperial III | YbF ($^2\Sigma$) | Lattice | 18 | 3000 | $10^{10}$ | Construction | | [53] |
| NL-eEDM I | BaF ($^2\Sigma$) | Slow beam | 5 | 15 | $10^{13}$ | Commissioning | | [54] |
| NL-eEDM II | BaOH ($^2\Sigma$) | Lattice | 5 | 1000 | $10^{10}$ | Construction | | [55] |
| PolyEDM | SrOH ($^2\Sigma$) | Lattice | 2.2 | 1000 | $10^{10}$ | Construction | | [56] |
| EDM$^3$ | BaF ($^2\Sigma$) | Matrix | 6 | 100 | $10^{20}$ | Construction | | [57] |
| PHYDES | BaF ($^2\Sigma$) | Matrix | 6 | 100 | $10^{20}$ | Construction | | [58] |

TABLE II: Electron EDM measurements, completed and planned. For planned experiments, most parameters are projections.

# A combined perspective

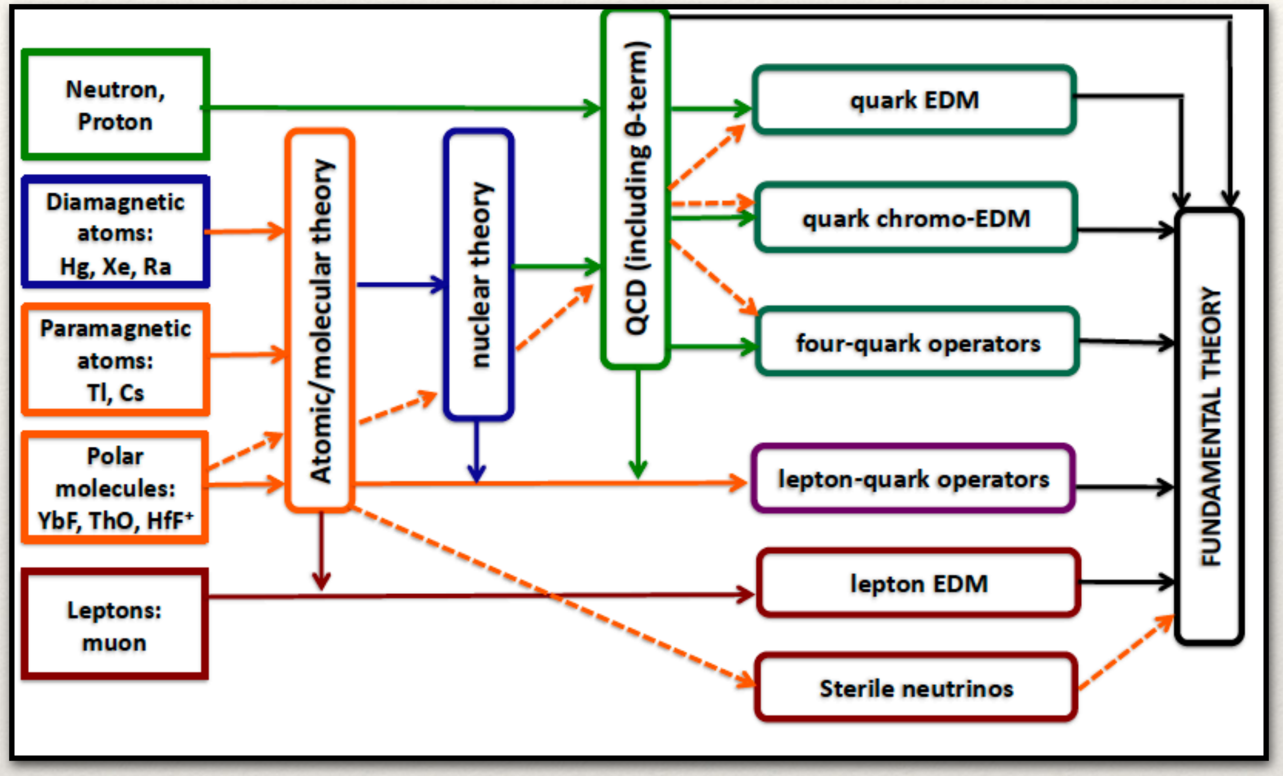
- If we use SM-EFT at the LHC then the LHC is a 'low-energy precision experiment'
- Effective Field Theory techniques to combine collider + low-energy experiments




- The open questions in particle physics are no longer pointing to a specific energy scale
- Precision experiments can provide the missing clue

# Role of theory

- Experiments such as neutrinoless double beta decay, EDMs, Dark Matter searches involve particle, hadronic, nuclear, molecular physics




- Requires collaboration with nuclear, AMO, condensed matter theorists and experimentalists