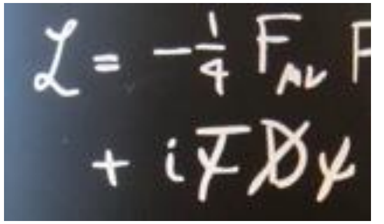
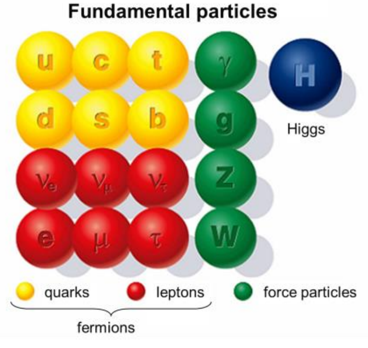
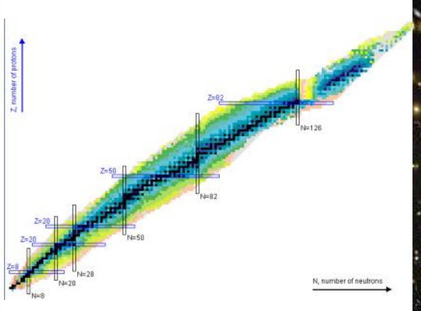
Experimental tests* of fundamental symmetries and conservation laws

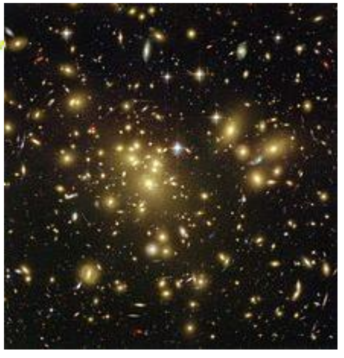
*here: concentrate on low-energy, accelerator based experiments

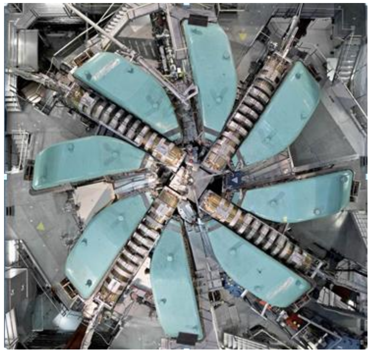


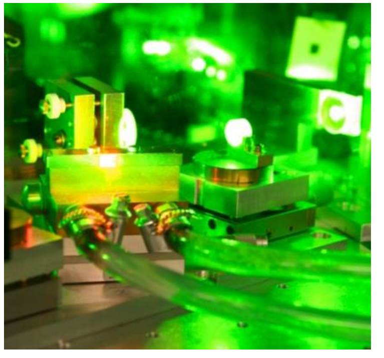
K.Kirch, ETH Zurich – PSI Villigen, Switzerland







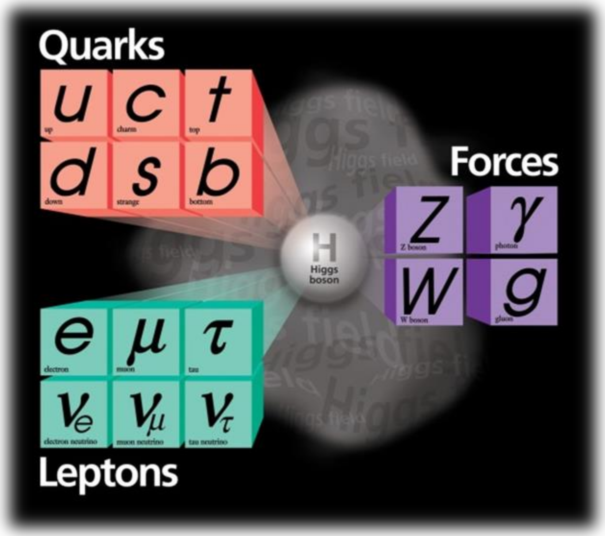




The Standard Model and beyond

See talk by Vincenzo Cirigliano

- The Standard Model of Particle Physics SM: a (the?) most successful theory to date
  - ~consistent with all laboratory results, some tensions**, theory & application to cosmology and astro suggest beyond SM physics (**arguably all pointing to effects in flavor physics)



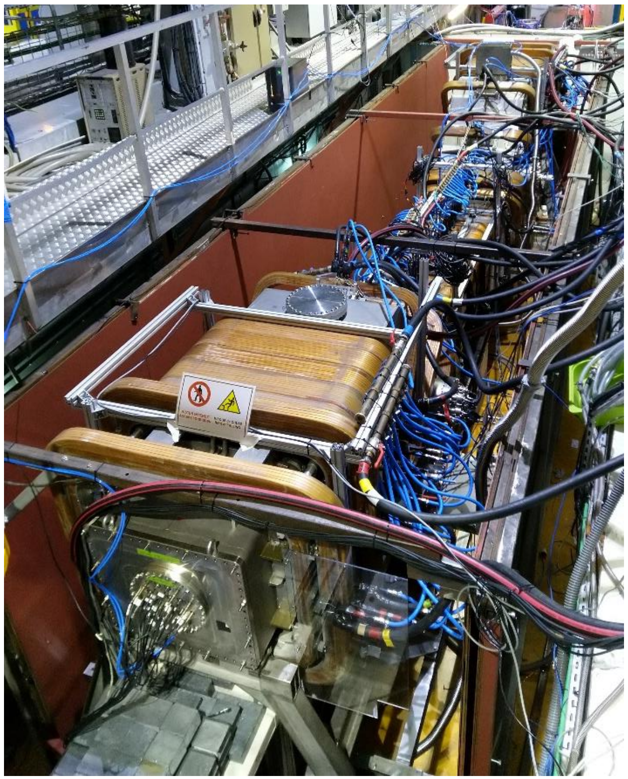
- Laboratory experiments
  - Precision measurements of SM input parameters
    - 19 (26+) param., masses, couplings, mixings, CP phases, θ_{QCD}, Higgs vev
  - Searches for deviations & inconsistencies
    - Dark Matter, BAU, CPV, cLFV, B, L, Lorentz, Gravity, Dark Energy…
    - Often with tests of symmetries and conservation laws

LOOKING UNDER THE LAMPPOST

https://sketchplanations.com/looking-under-the-lamppost

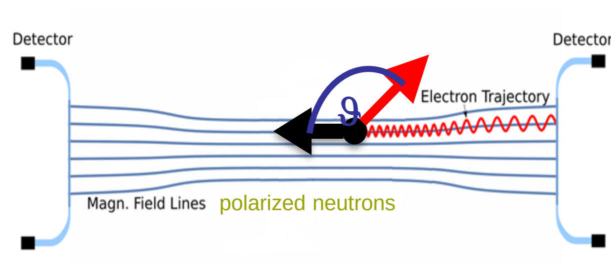
https://www.thetlcgroup.com/recent-trends-in-storytelling/

PERKEO III: Beta Asymmetry in Neutron Beta Decay



PERKEO III installed temporarily
at PF1b / ILL in 2019/20

Measurement of the P-violating **Beta Asymmetry *A*** using a polarized *pulsed* cold neutron beam; provides **nucleon axial-coupling λ**



$$A_{\mathrm{exp}} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P A$$

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

$$A = -0.11985(17)_{\mathrm{stat}}(12)_{\mathrm{sys}} = -0.11985(21).$$

$$\lambda = -1.27641(45)_{\mathrm{stat}}(33)_{\mathrm{sys}} = -1.27641(56)$$

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

Märkisch, *et al.,* PRL 122, 222503 (2019)

CKM matrix element V_{ud} from neutron data only, i.e. without nuclear effects, using world-averages of λ ($S = 2.2$), neutron lifetime τ_n ($S = 1.6$) and recently updated common radiative corrections Δ_R (Seng, et al. PRD 100:013001 (2019)

$$V_{ud} = \sqrt{\frac{5099.34\ \mathrm{s}}{\tau_n(1 + 3\lambda^2)(1 + \Delta_R)}} = 0.97377(11)_{\Delta_R}(33)_{\tau_n}(70)_{\lambda}$$

Dubbers and Märkisch, Ann. Rev. Nucl. Part. Sci. 71 (2021)

courtesy B. Märkisch

BRAND – Search for BSM physics in the decay of polarized neutrons by exploring the transverse electron polarization

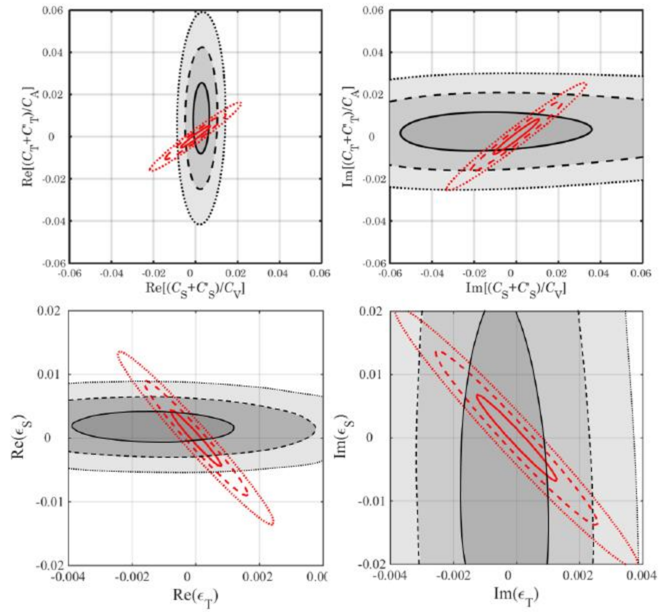
K. Bodek, G. Gupta, K. Lojek, D. Rozpedzik, J. Zejma
A. Kozela, K. Dhanmeher, K. Pysz
N. Severijns, L. De Keukeleere
T. Soldner
A. R. Young, J. Choi
D. Ries, M. Engler, N. Yazdandoost

KU LEUVEN
JG|U
NC STATE UNIVERSITY

$$\omega(E_e,\Omega_e,\Omega_{\bar\nu}) \propto 1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + D\frac{\mathbf{p}_e\times\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}}\right] +$$

$$\boldsymbol{\sigma}_\perp\cdot\left[H\frac{\mathbf{p}_{\bar\nu}}{E_{\bar\nu}} + L\frac{\mathbf{p}_e\times\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + N\frac{\langle\mathbf{J}\rangle}{J} + R\frac{\langle\mathbf{J}\rangle\times\mathbf{p}_e}{J\,E_e} + S\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar\nu}}{E_eE_{\bar\nu}} + U\,\mathbf{p}_{\bar\nu}\frac{\langle\mathbf{J}\rangle\cdot\mathbf{p}_e}{J\,E_eE_{\bar\nu}} + V\frac{\mathbf{p}_{\bar\nu}\times\langle\mathbf{J}\rangle}{J\,E_{\bar\nu}}\right],$$

	SM (λ)	FSI (λ)	c(Re$\mathcal{S}$)	c(Re$\mathcal{T}$)	c(Im$\mathcal{S}$)	c(Im$\mathcal{T}$)
H	+0.0609	0	-0.1714	+0.2762	0	0
L	0	-0.0004	0	0	+0.1714	-0.2762
N	+0.0681	0	-0.2176	+0.3348	0	0
R	0	+0.0005	0	0	-0.2176	+0.3348
S	0	-0.0018	+0.2176	-0.2176	0	0
U	0	0	-0.2176	+0.2176	0	0
V	0	0	0	0	-0.2176	+0.2172

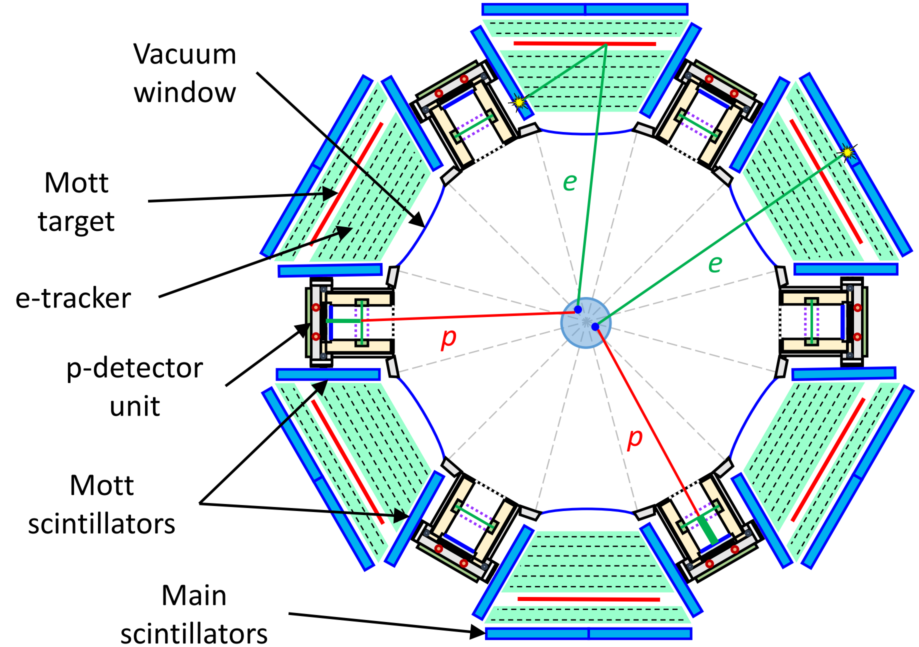


Experimental bounds on the scalar vs. tensor couplings (upper panels) and translated to EFT parametrization. The grey areas represent the information deduced from available experiments while the red lines represent the limits resulting from the coefficients H, L, N, R, S, U and V measured with the anticipated accuracy of 5×10^{-4}.

courtesy K. Bodek

BRAND – methods, expected performance, strategy

- **Experimental methods:**
  - Measure decay electrons and *e-p* coincidences
  - Electron tracking in hexagonal, low *Z*, low pressure MWDC
  - *p-e* conversion followed by *e* detection in scintillator (ToF, position)
  - Decay vertex reconstruction
  - Electron spin analysis by Mott scattering (vertex reconstruction)



- **BRAND is based on experimentally proven methods (nTRV@PSI)**
- **Gradual improvement of exp. accuracy (systematic uncertainty):**

4×10^{-3} → 2×10^{-3} → 1×10^{-3} → 5×10^{-4}

nTRV (PSI) — **BRAND I (ILL)** — **BRAND II (ILL)** — **BRAND III (ESS)**

- **Demonstration tests at ILL - ongoing**

courtesy K. Bodek

See posters by Karishma Dhanmeher and Dagmara Rozpedzik

nEDM at PSI

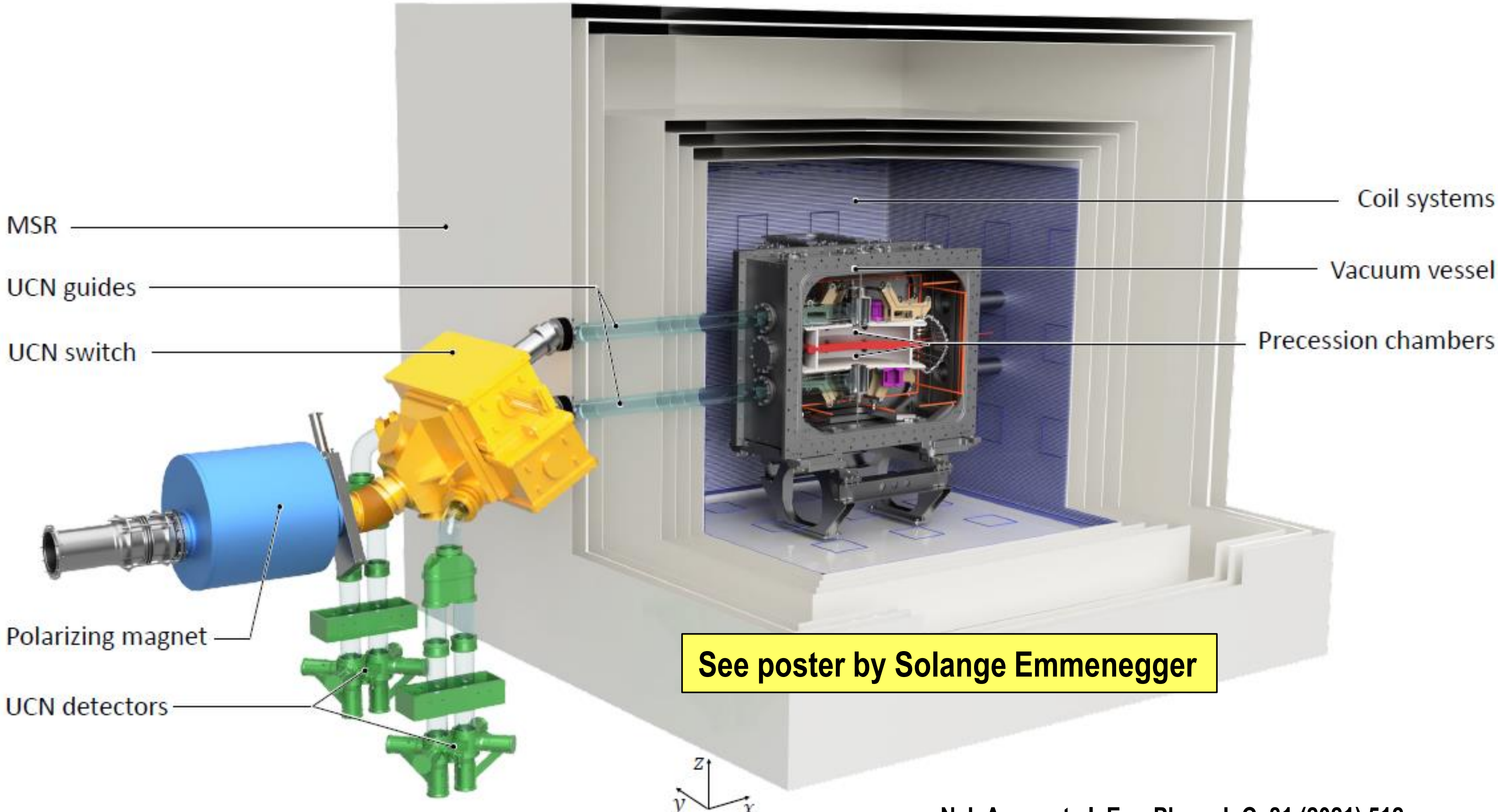
See talk by Geza Zsigmond

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}$ ecm $< 1.8 \times 10^{-26}$ ecm (90% CL)

C. Abel et al., PRL124(2020)081803

n2EDM

baseline sensitivity: 1 x 10^{-27} ecm



See poster by Solange Emmenegger

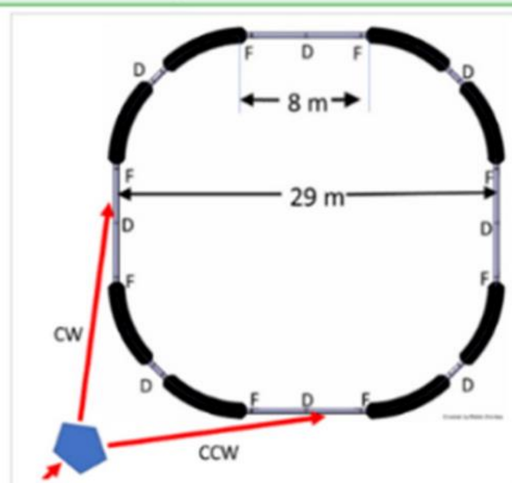
N.J. Ayres et al. Eur. Phys. J. C 81 (2021) 512

Storage ring EDMs

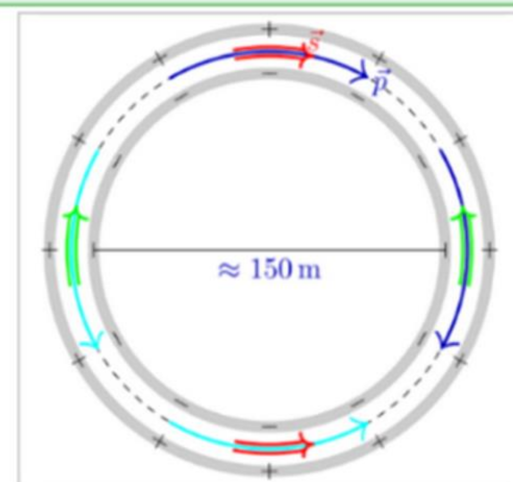
See contributions by Swathi Karanth and Achim Andres

1 Precursor Experiment	2 Prototype Ring	3 All-electric Ring
dEDM proof-of-capability (orbit and polarization control; first dEDM measurement)	**pEDM proof-of-principle** (key technologies, first direct pEDM measurement)	**pEDM precision experiment** (sensitivity goal: 10^{-29} e cm)

present



5-10 years

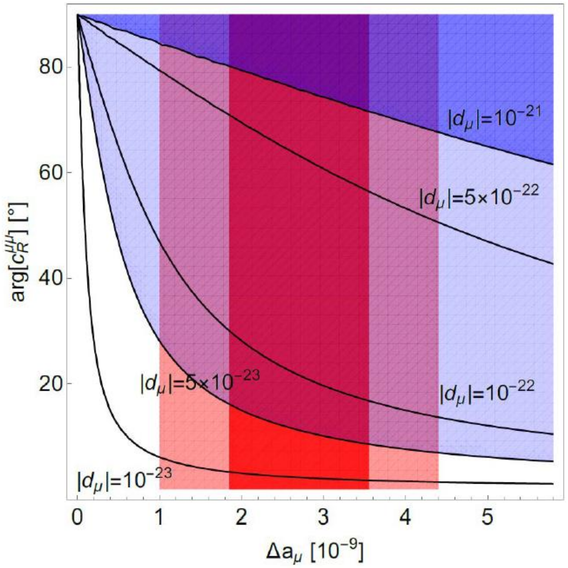


10-15 years

Carli, Lenisa, Pretz, Rathmann, Ströher, Nucl. Phys. News Vol. 31, No. 2 (2021) 27

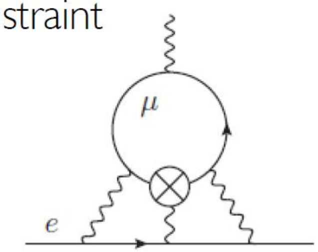
Search for a muon EDM

Limits on μEDM in lepton flavor violating models



A.Crivellin, M. Hoferichter, PSW PRD 98(2018) 113002

- EFT phase of Wilson parameter $c_R^{\mu\mu}$ hardly constraint

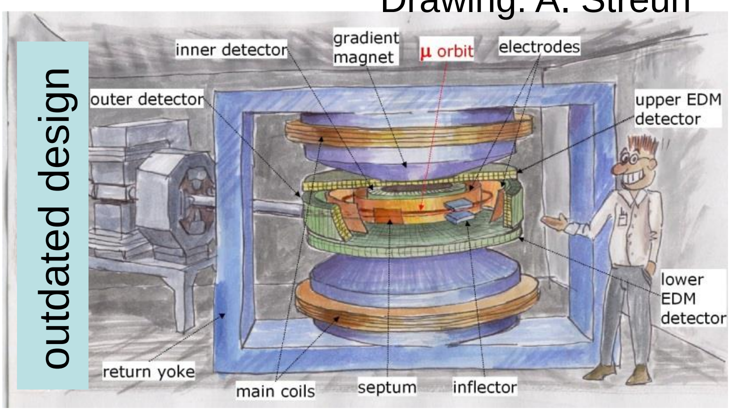


- μEDM contribution in electron EDM allows for large value: $d_\mu \leq 7.5 \times 10^{-19}\, ecm$

Philipp Schmidt-Wellenburg (PSI) | PSI – BVR52 | 27.01.2021

- best experimental limit from muon g-2@BNL
  Bennet et al., PRD80(2008)052008: $d_\mu < 1.8 \times 10^{-19}$ ecm
- recently, indirect limit from ThO-EDM experiment:
  Ema, Gao, Pospelov, arxiv:2108.05398: $d_\mu < 1.9 \times 10^{-20}$ ecm
- reach of muon g-2@FNAL ~10^{-21} e cm
- reach of dedicated search at PSI, Letter of Intent
  A. Adelmann et al., **arxiv:2102.08838**: 6×10^{-23} ecm

Drawing: A. Streun



Adelmann et al., JPG37(2010)085001

Search for Baryon Number Violation with Neutron Oscillations

NNbar Collaboration at European Spallation Source (ESS)

- BN is an "accidental" global symmetry at perturbative level
  - BNV is present in SM non-perturbatively (e.g. instantons = sphalerons)
  - B−L is conserved, not B, L separately
- In cosmology BNV needed by inflation model and for baryogenesis
- BNV generic feature of SM extensions (e.g. GUT, SUSY, extra dimensions..)
- Important to probe possible BNV channels
- HIBEAM@ESS will search for $n \to n'$ to sterile state n' (|ΔB|=1) and
- NNBAR@ESS will search for $n \to \bar{n}$ (|ΔB|= 2 and (B−L)≠0)
  Anticipated sensitivity increase ≥10^3 compared to previous experiments

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source A Addazi *et al, J. Phys. G* 48 (2021) 7, 070501

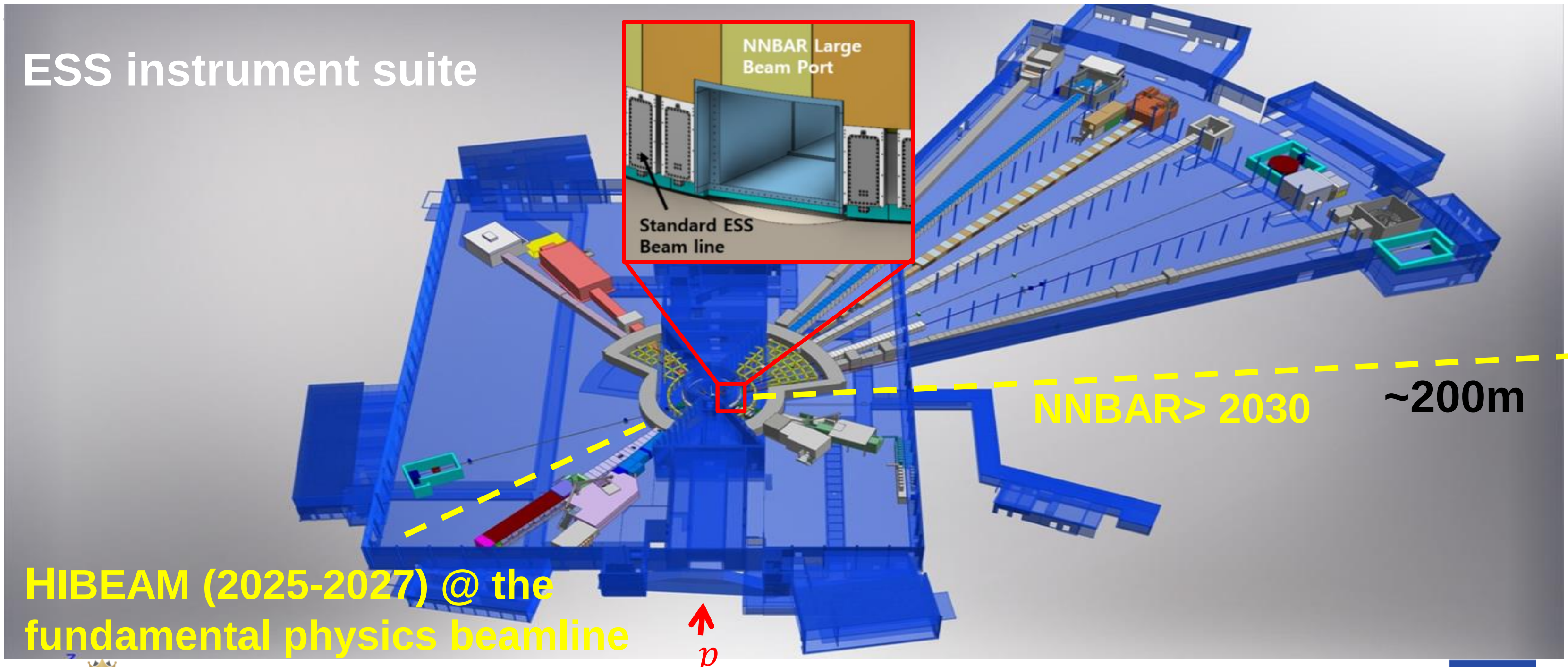
courtesy Y. Kamyshkov

See poster by 'Billy' Sze-Chun Yiu

Future Free Neutron Oscillations Searches at the ESS

Two stage experiment:

- HIBEAM (≳2025) : smaller program of complementary experiments (with focus on sterile neutron searches)
- NNBAR (>2030) : search for $n \rightarrow \bar{n}$ oscillations



HighNESS project at ESS for the development of high intensity cold moderator for applications including $n \rightarrow \bar{n}$. HighNESS is funded by the European Union Framework Program for Research and Innovation Horizon 2020, under grant agreement 951782

courtesy Y. Kamyshkov

Searches for charged lepton flavor violation

The present best limits on cLFV with muons

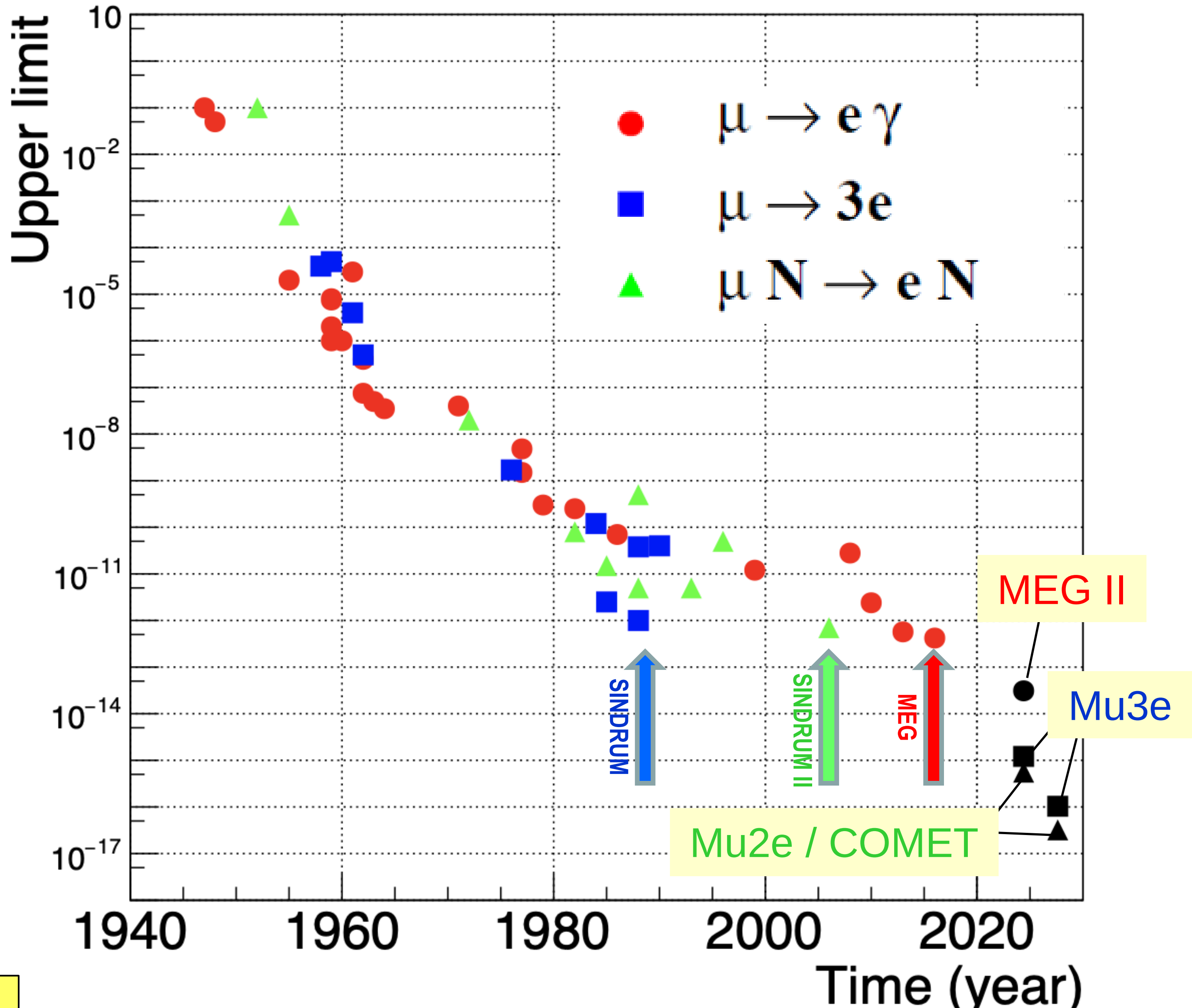
$\mu^+ \rightarrow e^+ e^+ e^-$
BR < 1 x 10^{-12}
SINDRUM 1988

$\mu^- + Au \rightarrow e^- + Au$
BR < 7 x 10^{-13}
SINDRUM II 2006

$\mu^+ \rightarrow e^+ + \gamma$
BR < 4.2 x 10^{-13}
MEG 2013, 2016

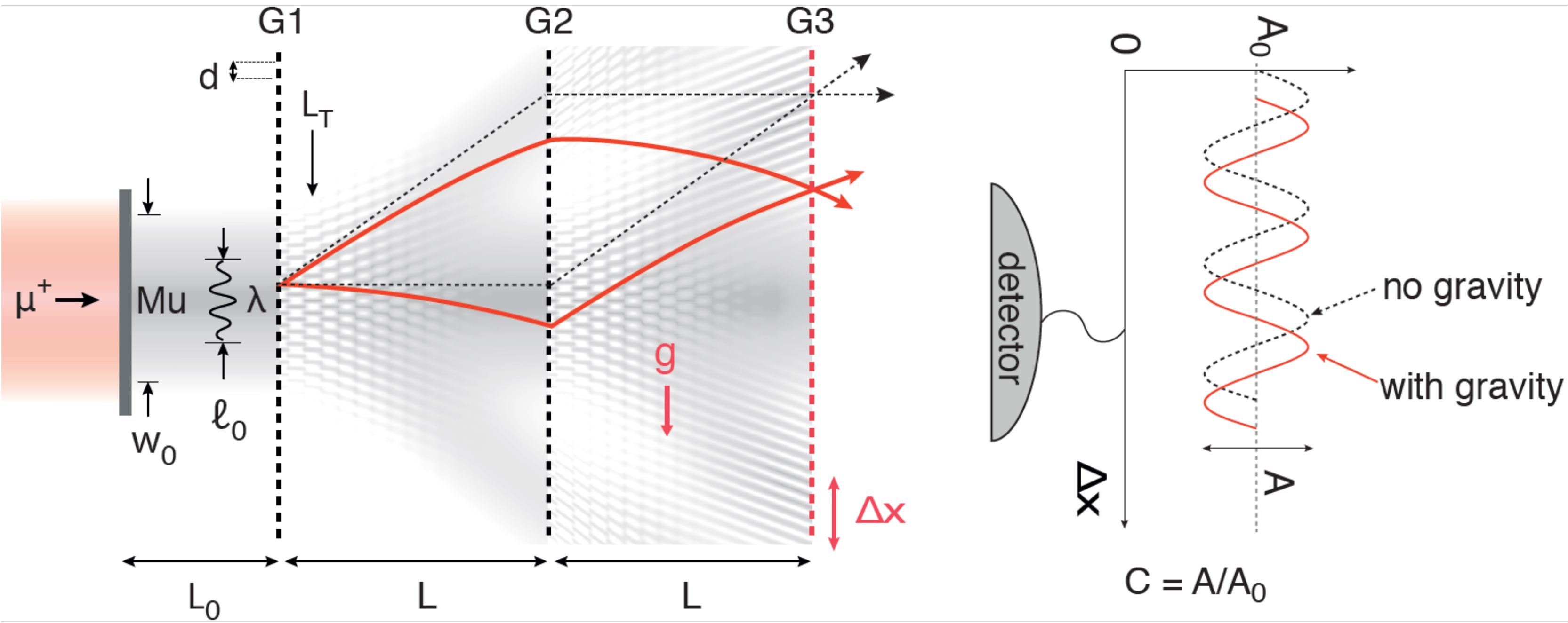
[90 % C.L.]

See 7 contributions on Mu2e



Muonium Antimatter Gravity Experiment

- M beam based on muCool beam and M production of SF-He
- Measure gravitational phase shift in atom interferometer
- Determine sign of $\overline{g}$ in one day
- Measure $\overline{g}$ to few percent within a year

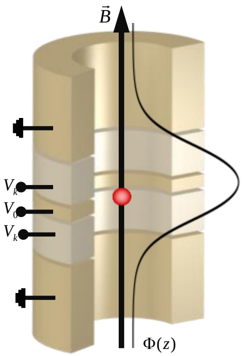


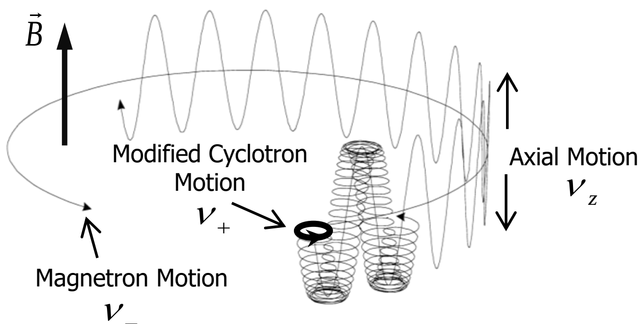
Anna Soter et al.

See also: Atoms 6(2018)17 and arXiv:physics/0702143

BASE Collaboration

- Precision measurements of the fundamental properties of protons and antiprotons based on frequency measurements in advanced Penning trap systems



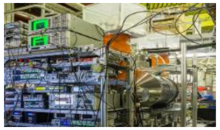


Q/M ratios

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

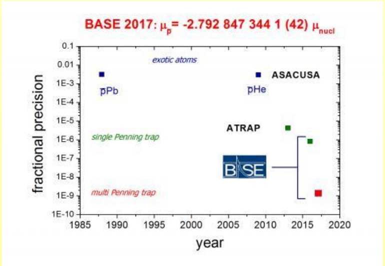
Magnetic Moments

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$



Most precise antiproton/proton magnetic moment measurments

G. Schneider et al., Science **358**, 1081 (2017).
C. Smorra *et al.*, Nature **550**, 371 (2017)



Proton:

g/2 = 2.792 847 344 62 (82)

30-fold improvement compared to previous measurement

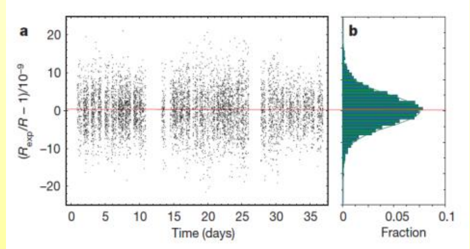
Antiproton:

g/2 = 2.792 847 344 1 (42)

3000-fold improvement compared to previous best measurement

Most stringent CPT test with baryons

S. Ulmer, et al., **Nature 524, 196 (2015)**



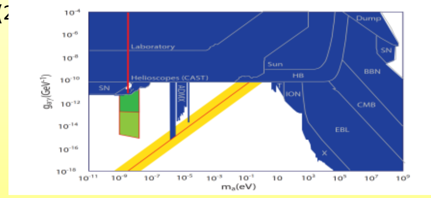
$$1 + \frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = 1(69) \times 10^{-12}$$

$R_{exp,c}$ = 1.001 089 218 755 (64) (26)

CPT consistent

FIP detection

J. Devlin *et al.*, Phys. Rev. Lett. **126**, 041301 (2…



Single particle detection systems to search for Dark Matter

See talk by Barbara Maria Latacz

courtesy S. Ulmer

1S/2S Spectroscopy of Antihydrogen

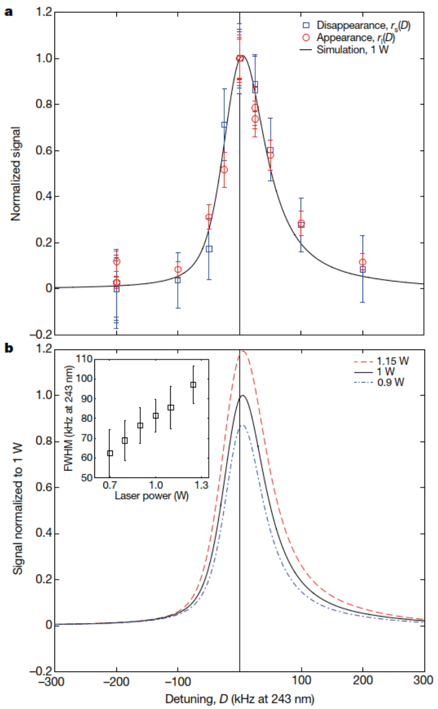
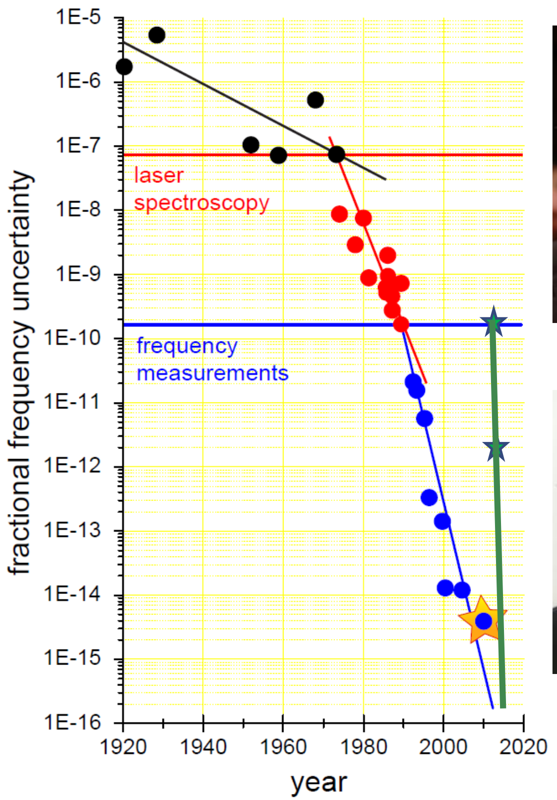


Table 1 | Antihydrogen atom counts

	Laser detuning, D (kHz)	Number of trials	Atoms lost during laser exposure, L	Atoms lost during microwave exposure, M	Surviving atoms, S	Initially trapped atoms, N_i
Set 1	−200	21	7±7	383±23	504±25	894±35
	−100	21	22±9	415±24	494±24	931±35
	0	21	264±24	423±24	217±16	904±38
	+100	21	75±14	411±23	424±23	910±35
Set 2	−200	21	26±9	394±23	466±24	886±34
	−25	21	113±16	423±24	326±20	862±35
	0	21	219±22	390±23	269±18	878±37
	+25	21	173±20	438±24	296±19	907±37
Set 3	−200	23	8±7	354±22	479±24	841±33
	0	23	303±26	454±25	248±17	1,005±40
	+50	23	176±20	390±23	339±20	905±37
	+200	23	36±11	446±24	459±23	941±35
Set 4	−200	21	7±7	525±26	541±25	1,073±37
	−50	21	86±15	475±25	495±24	1,056±38
	0	21	274±25	480±25	275±18	1,029±40
	+25	21	202±21	516±26	305±19	1,023±38
Total		344	1,991	6,917	6,137	15,045

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\,\text{kHz}$$



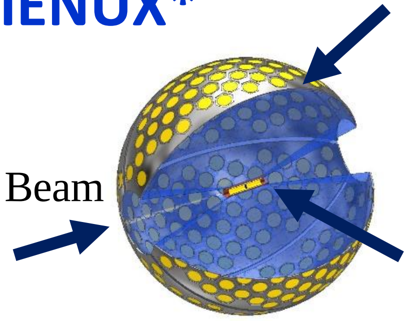
Tests hydrogen/antihydrogen CPT invariance with a fractional precision of 2 p.p.t.

Future perspective: Laser cooling of antihydrogen just demonstrated

courtesy S. Ulmer

ALPHA collaboration, Nature 592, 35 (2021)

Next Generation Rare Pion Decay Experiment: PIENUX*



Goals:

- Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$: $O(\pm 0.01\%)$

  Improve the best test of universality g_e / g_μ by 10 x

- Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.05\%)$

  Provide a new high precision measurement of V_{ud} comparable to β-decay.

- Improve search sensitivities for sterile neutrinos by an order of magnitude

  e.g. $\pi \to e\nu_H, \pi \to \mu\nu_H, \pi \to (e/\mu)\nu\nu\bar{\nu}, \pi \to (e/\mu)\nu X$

* Interim name

courtesy D. Bryman

https://meetings.triumf.ca/event/230/contributions/1418/attachments/954/1087/S2127LOI_PIENUX_Presentation.pdf

P T CP B LF CPT …

… neutron decay nEDM other EDM

nnbar muonic cLFV M pbar mag-mom

spectroscopy pion decay …

Chris Burden, *Urban Light* (2008), on March 21, 2020. Photo by AaronP/Bauer-Griffin/GC Images.

Thank you!

Chris Burden, *Urban Light* (2008), on March 21, 2020. Photo by AaronP/Bauer-Griffin/GC Images.