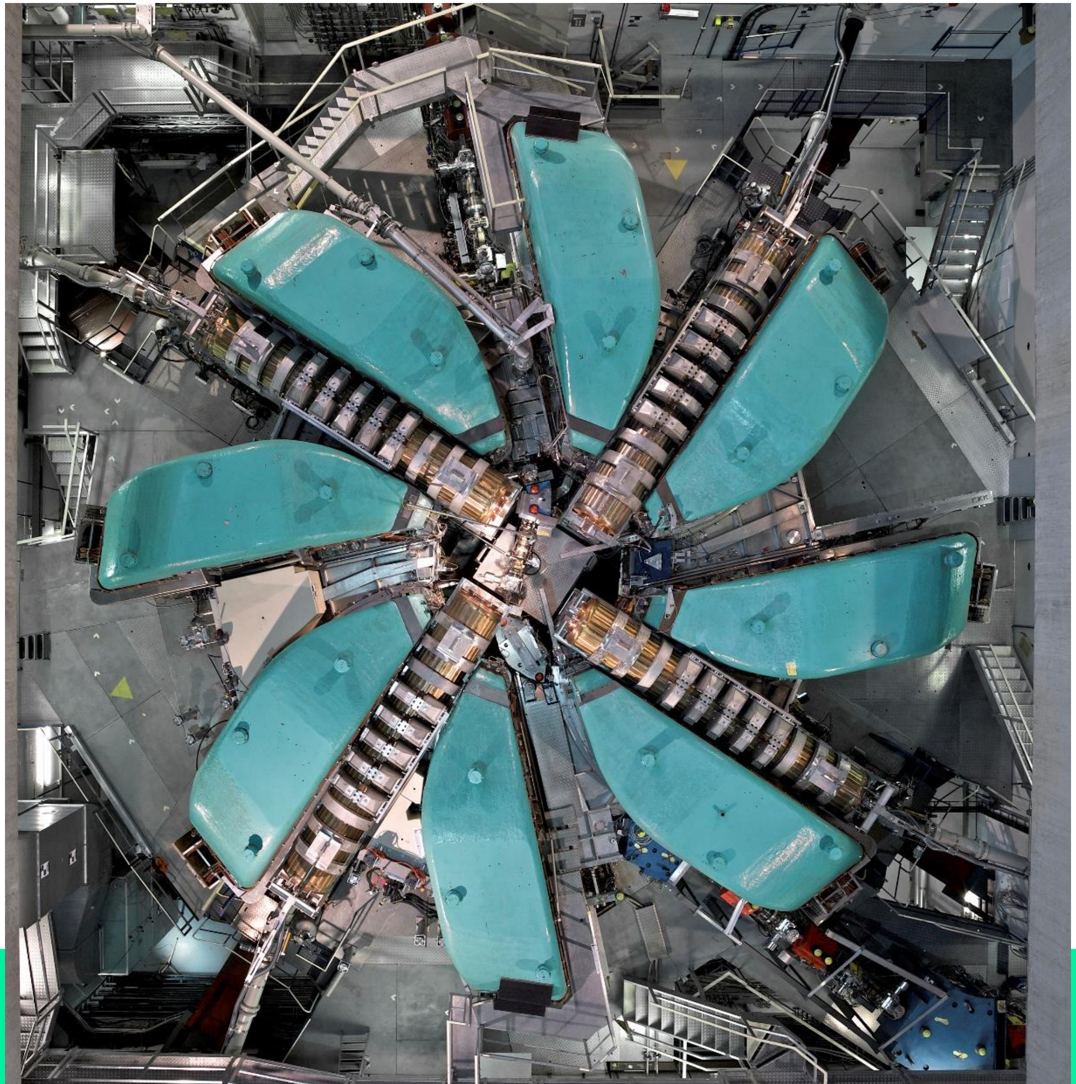
PSI Center for Neutron and Muon Sciences

ETH

Low-energy precision experiments with neutrons, pions and muons

20 Years of Stefan Meyer Institute

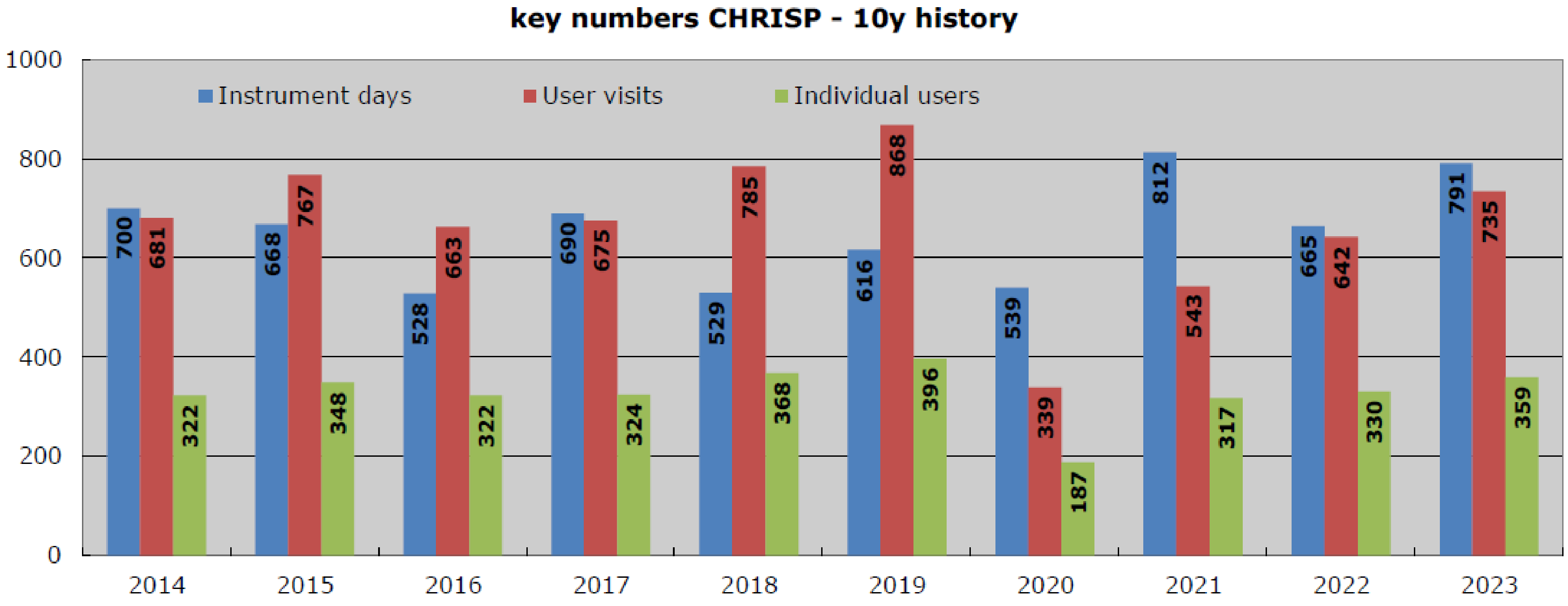


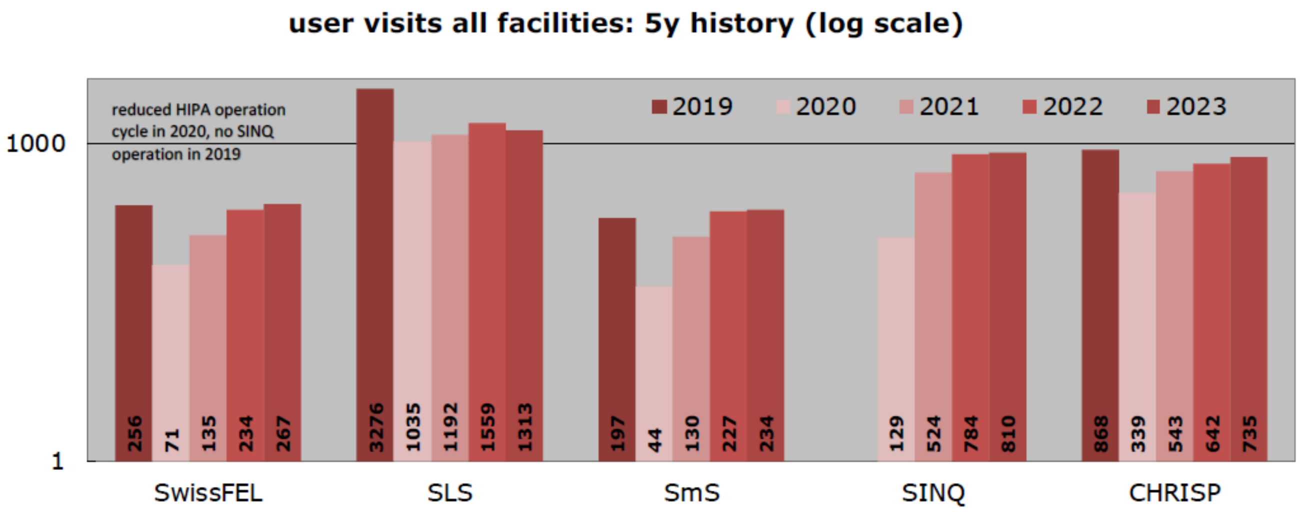
HIPA Ring cyclotron at PSI, image: PSI

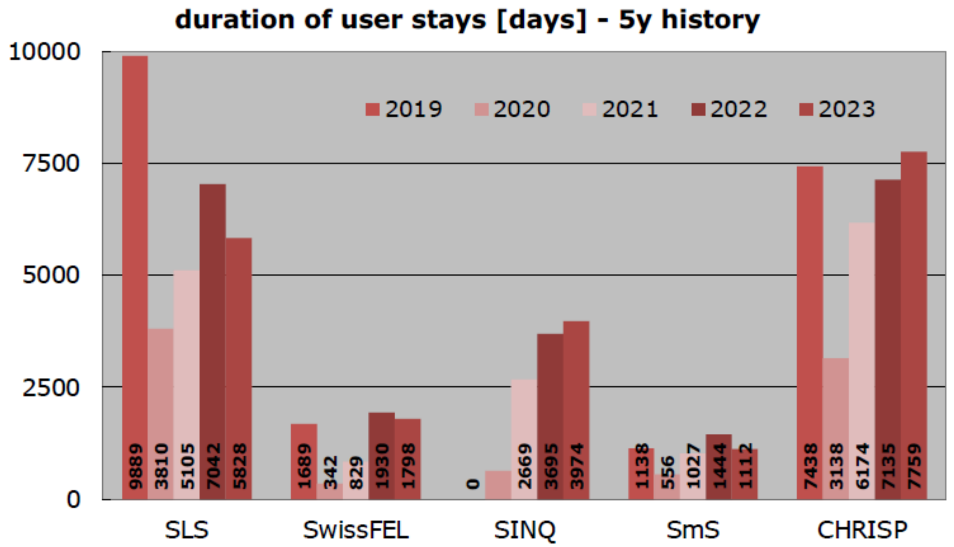
Klaus Kirch, ETH Zurich and Paul Scherrer Institute
Vienna, 11 November 2024


FRANCE
PSI
GERMANY
Schaffhausen
Lake Constance
Basel
Winterthur
Sankt Gallen
Zürich
LIECHTENSTEIN
AUSTRIA
Biel
Luzern
Kriens
BERN
Lausanne
Lac Léman
CERN
Genève (Geneva)
ITALY
Lake Como
Lugano
Lake Maggiore
ITALY
FRANCE
Milan

Users at CHRISP (CH Research InfraStructure for Particle physics)





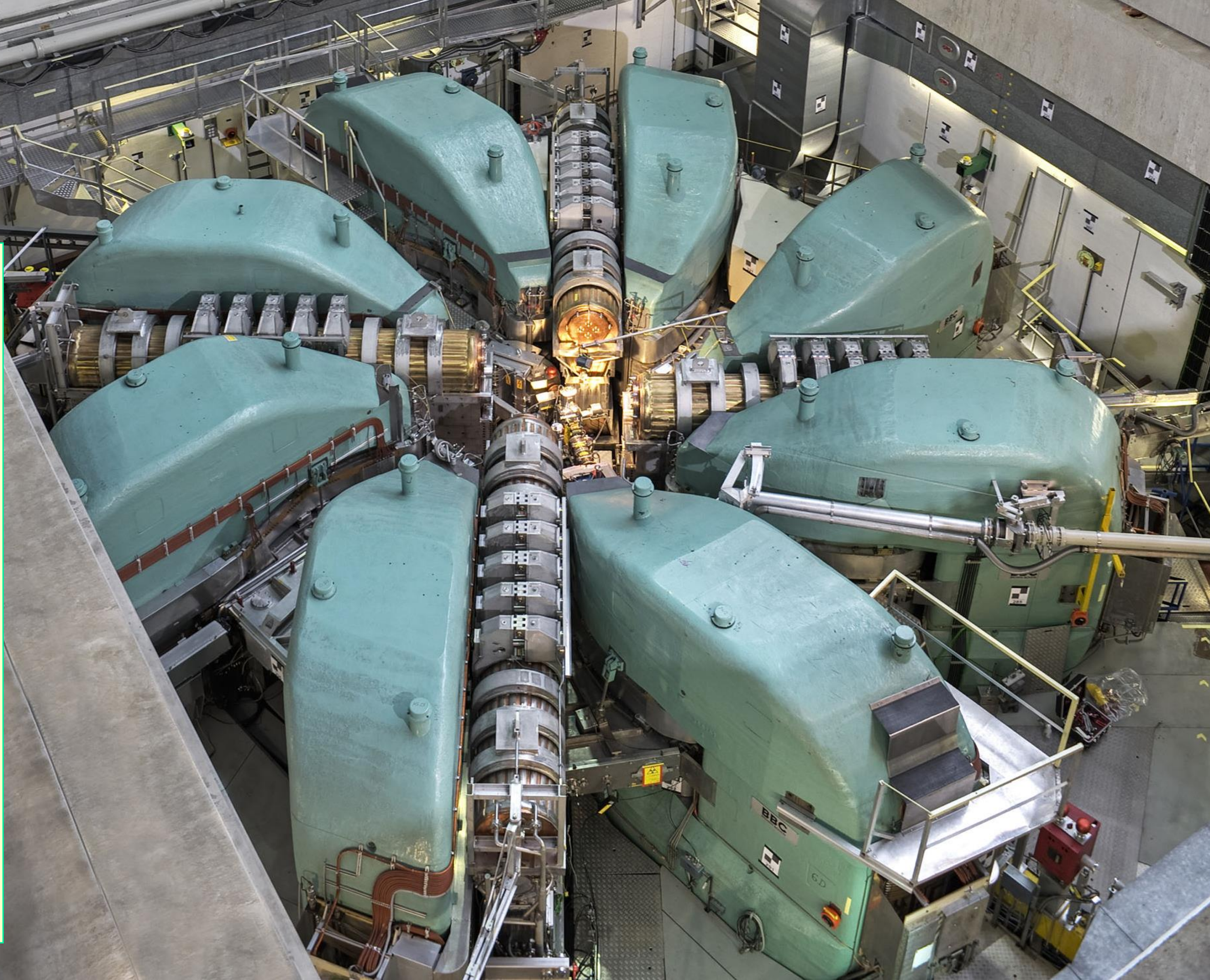


PSI HIPA
Ring cyclotron

- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), $\varnothing$ 15m
- losses at extraction $\leq$ 200W
- reducing losses by increasing RF voltage was main upgrade path

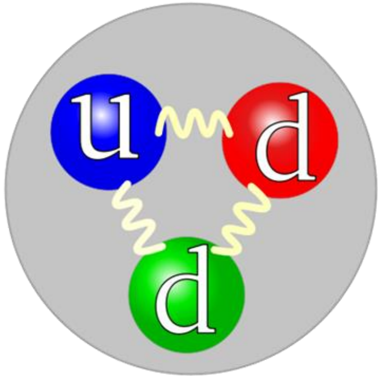
[losses $\propto$ (turn number)^3, W.Joho]

- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW



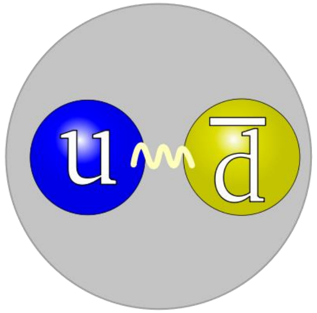
The lightest unstable particles of their kind

Neutron



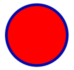
Baryon

Pion

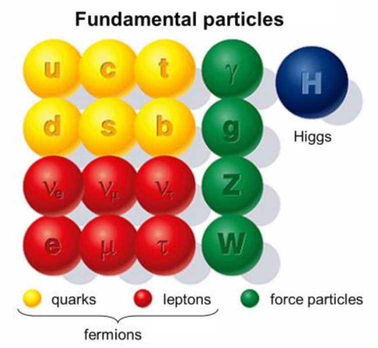


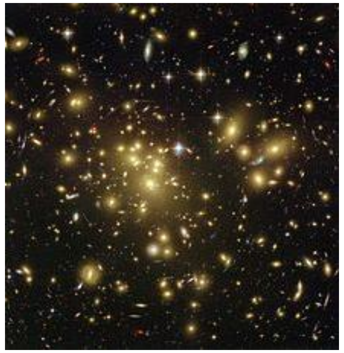
Meson

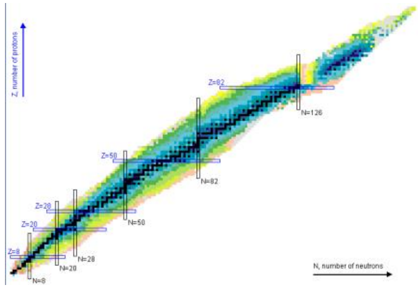
Muon

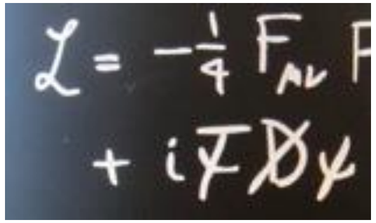


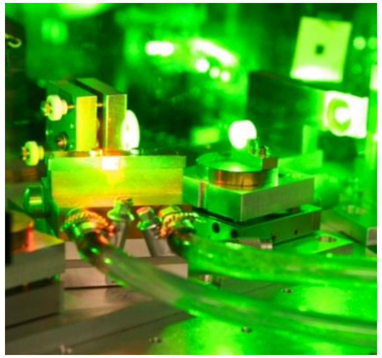
Lepton











Highest intensities enable highest precision for

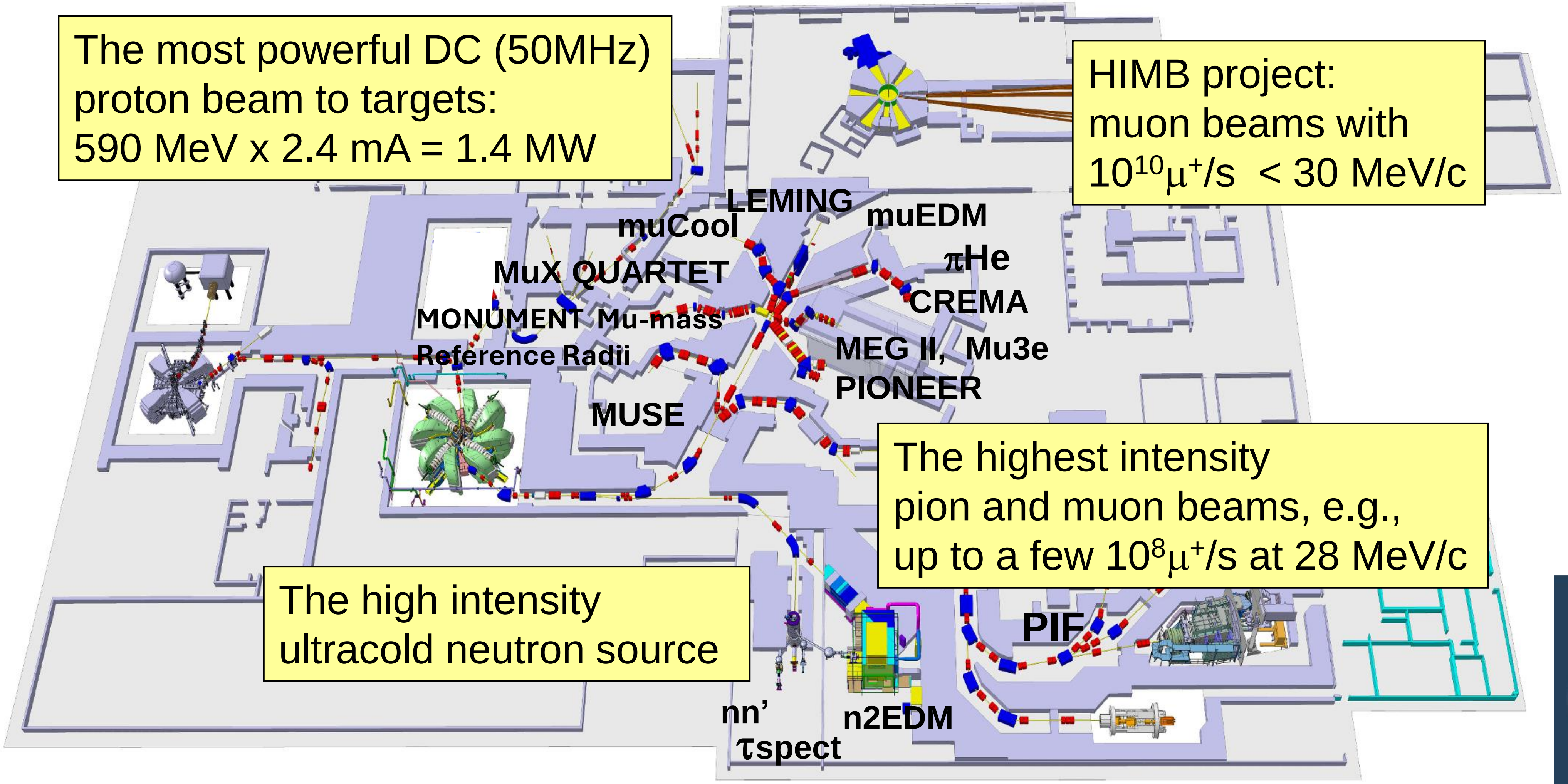
- Measurements of properties of particle, atoms and nuclei
- Studies of all known interactions
- Searches for unknown effects

The intensity frontier at PSI: π, μ, UCN

Precision experiments with **the lightest unstable particles** of their kind

The most powerful DC (50MHz) proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW

HIMB project:
muon beams with
$10^{10}\mu^+$/s < 30 MeV/c



The highest intensity
pion and muon beams, e.g.,
up to a few $10^8\mu^+$/s at 28 MeV/c

The high intensity
ultracold neutron source

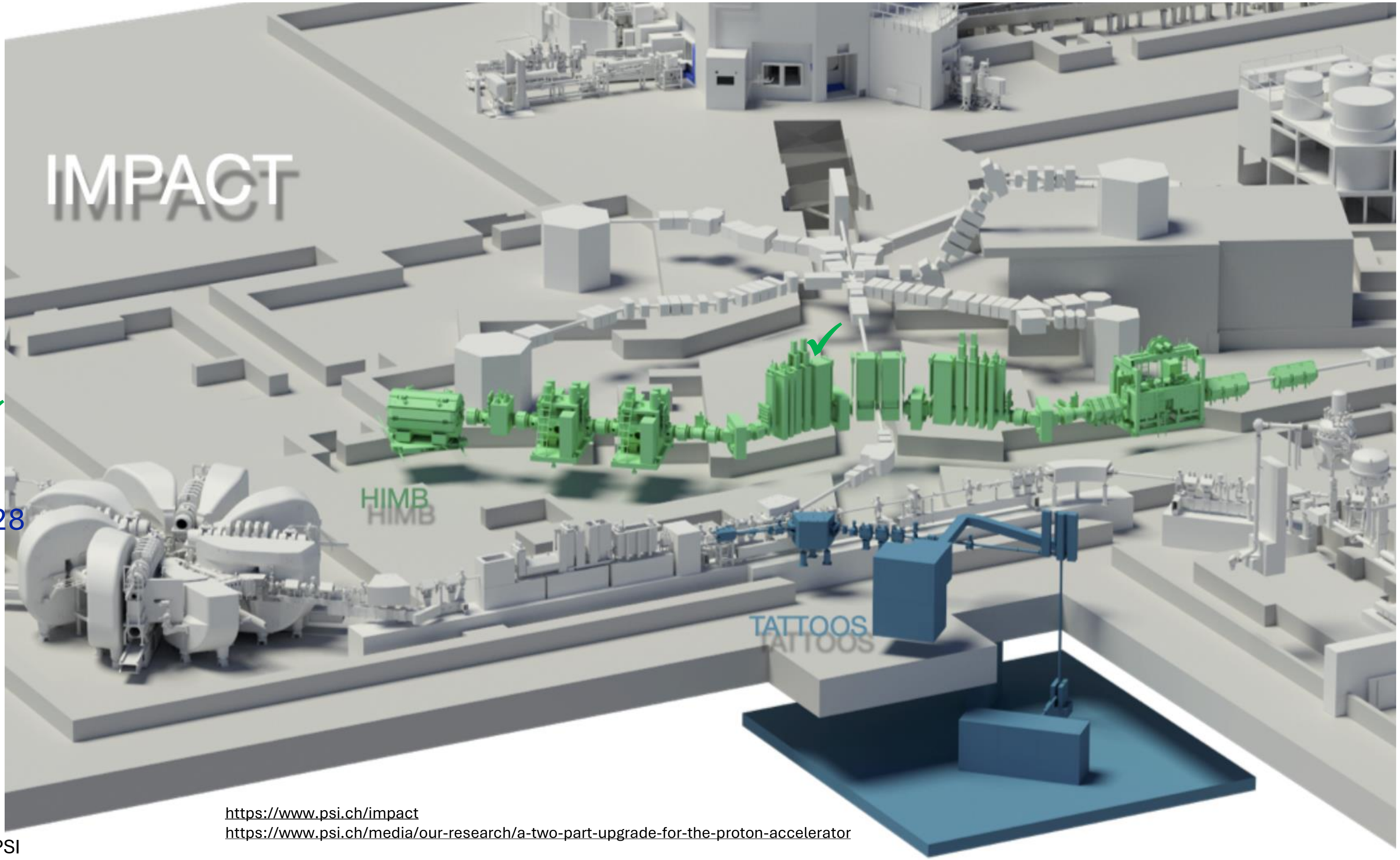
Swiss national laboratory with <u>strong international collaborations</u>

See recent Particle Physics at PSI, https://scipost.org/SciPostPhysProc.5.001

IMPACT – Isotopes and Muon Production using Advanced Cyclotron and Target technologies

PSI

- 01/22 CDR published ✓
- 07/22 Scientific Review ✓
- 12/22 ETH Board: IMPACT for Swiss Roadmap of RIs 2023 ✓
- 2022-24 PSI funds pre-project ✓
- 12/24 Swiss parliament decision about funding 2025-28
- 08/28 start HIMB
- 08/30 start TATTOOS



https://www.psi.ch/impact
https://www.psi.ch/media/our-research/a-two-part-upgrade-for-the-proton-accelerator

Low-energy precision (PSI) particle physics ...

in 8 examples, relevant to

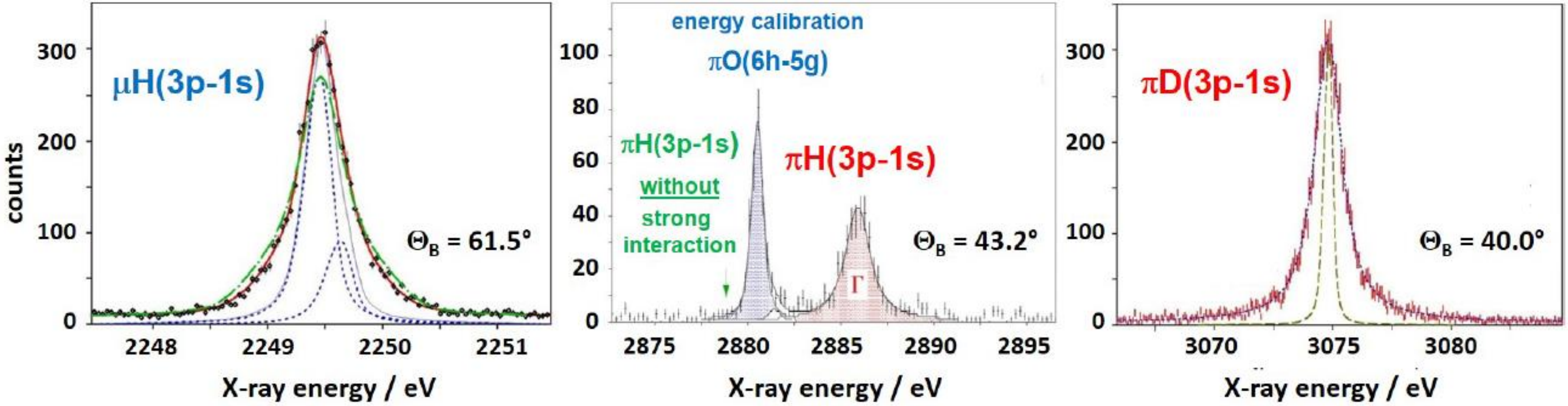
QCD, Weak Interactions, QED, cLF, DM, Gravity

Example 1: Pion nucleon interaction

PSI

Precision spectroscopy of pionic hydrogen and deuterium

D. Gotta and L.M. Simons, SciPost Phys. Proc. 5, 014 (2021)



Strong interaction shifts and widths in pionic hydrogen and pionic deuterium

$\epsilon_{1s}^{\pi H}$	$\Gamma_{1s}^{\pi H}$	$\epsilon_{1s}^{\pi D}$	$\Gamma_{1s}^{\pi D}$
7085.8 ± 9.6 [10]	856 ± 27 [11]	-2356 ± 31 [7]	1171^{+23}_{-49} [7]

[7] EPJA47(2011)88, [10] EPJA40(2014)190, [11] EPJA57(2021)70

Precision spectroscopy of pionic hydrogen and deuterium

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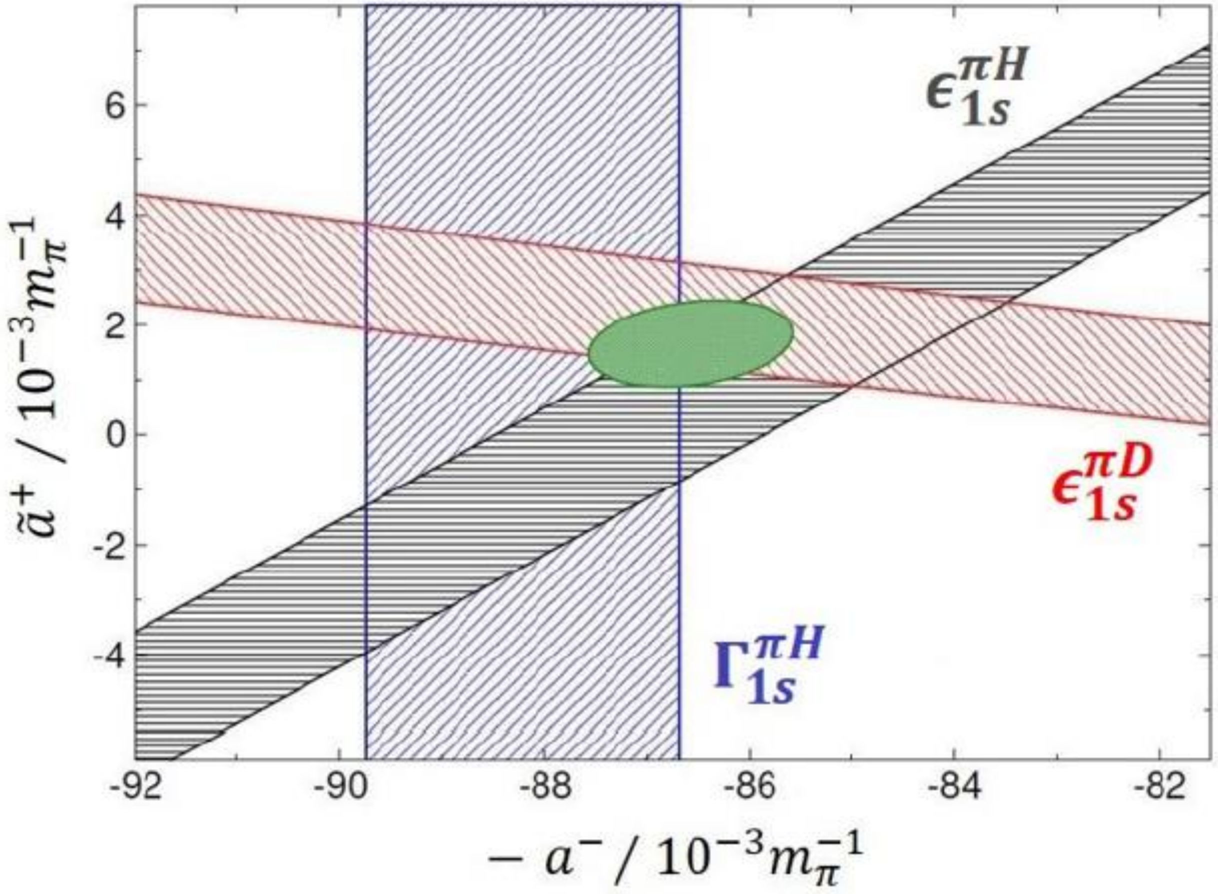
Figure 14.4: Constraints (bands) and combined result (ellipspe) for the isoscalar and isovector πN scattering lengths $\tilde{a}^+$ and a^- as derived from $\epsilon_{1s}^{\pi H}$, $\epsilon_{1s}^{\pi D}$, and $\Gamma_{1s}^{\pi H}$ [11].



SciPost Phys. Proc. 5, 014 (2021)

$\tilde{a}^+$	a^-	α
$(1.7 \pm 0.8) \cdot 10^{-3}\, m_\pi^{-1}$ [11]	$(86.6 \pm 1.0) \cdot 10^{-3}\, m_\pi^{-1}$ [11]	$(251\,^{+5}_{-11})$ mb [7]

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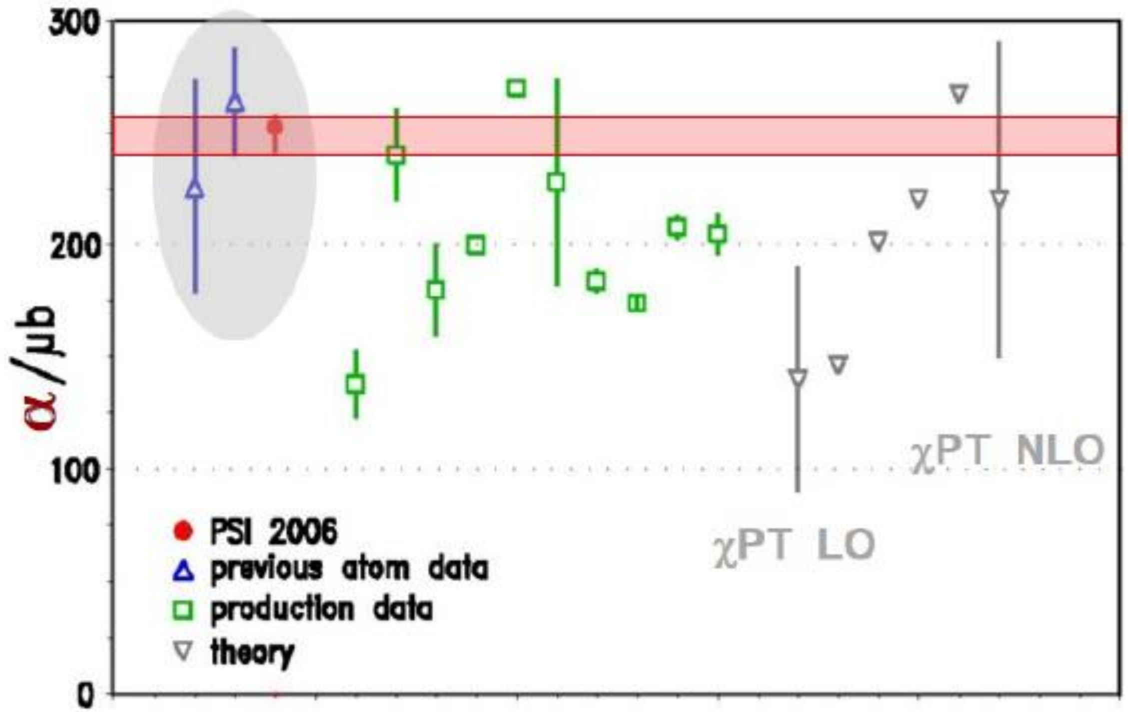
Figure 14.5: Comparison of results for pion-production strength α at threshold on isoscalar NN pairs. The horizontal band represents the precision of the most recent result for $\Gamma_{1s}^{\pi D}$ [7].



SciPost Phys. Proc. 5, 014 (2021)

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[7] EPJA47(2011)88, [10] EPJA40(2014)190, [11] EPJA57(2021)70

Example 2: The neutron electric dipole moment

Explanations of the Baryon Asymmetry
of the Universe require additional CP violation

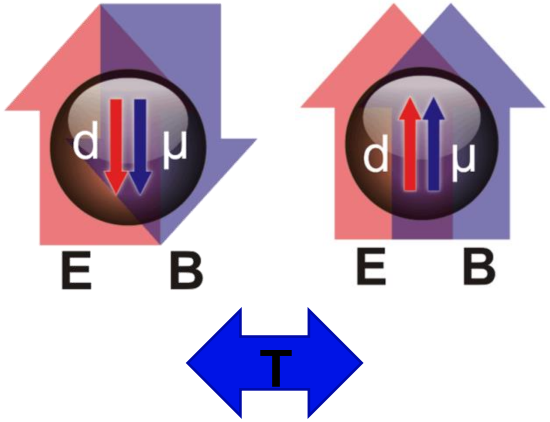
Permanent EDM of fundamental spin systems such as the neutron are the most sensitive probes for BSM CPV

The neutron EDM also measures $\theta_{QCD} \approx 10^{16} \times d_n$ / ecm

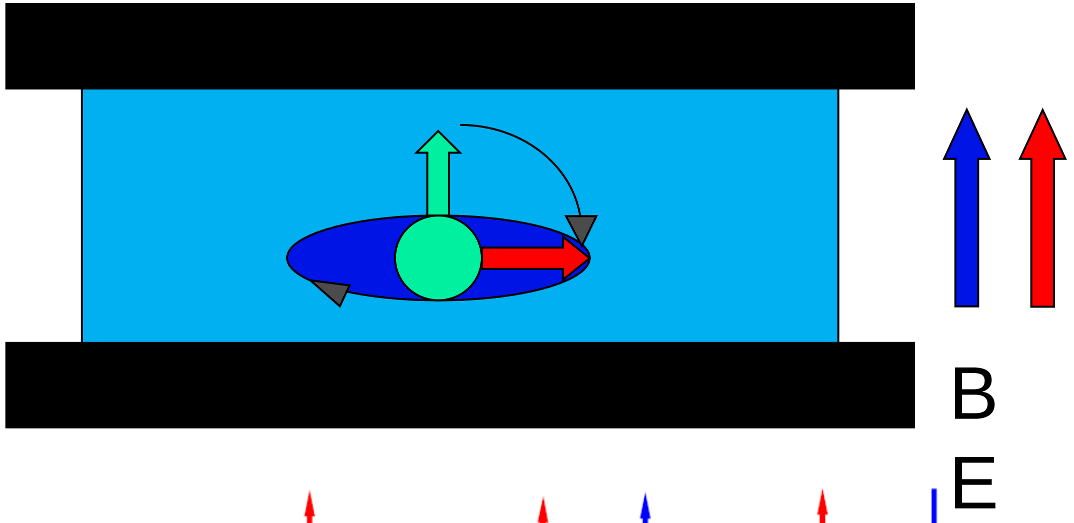
Observed:
$(n_B - n_{\bar{B}})/n_\gamma = 6 \times 10^{-10}$

SM expectation:
$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett.5(1967)24

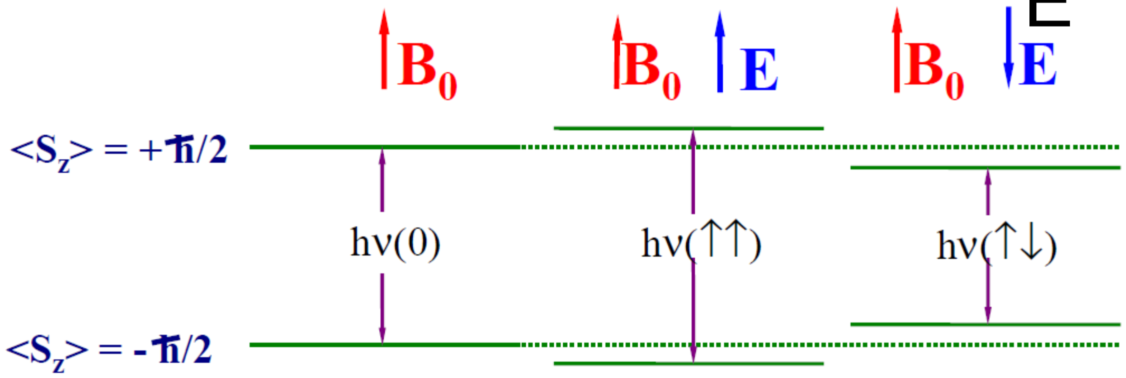


How to measure the neutron (or other) electric dipole moment ?



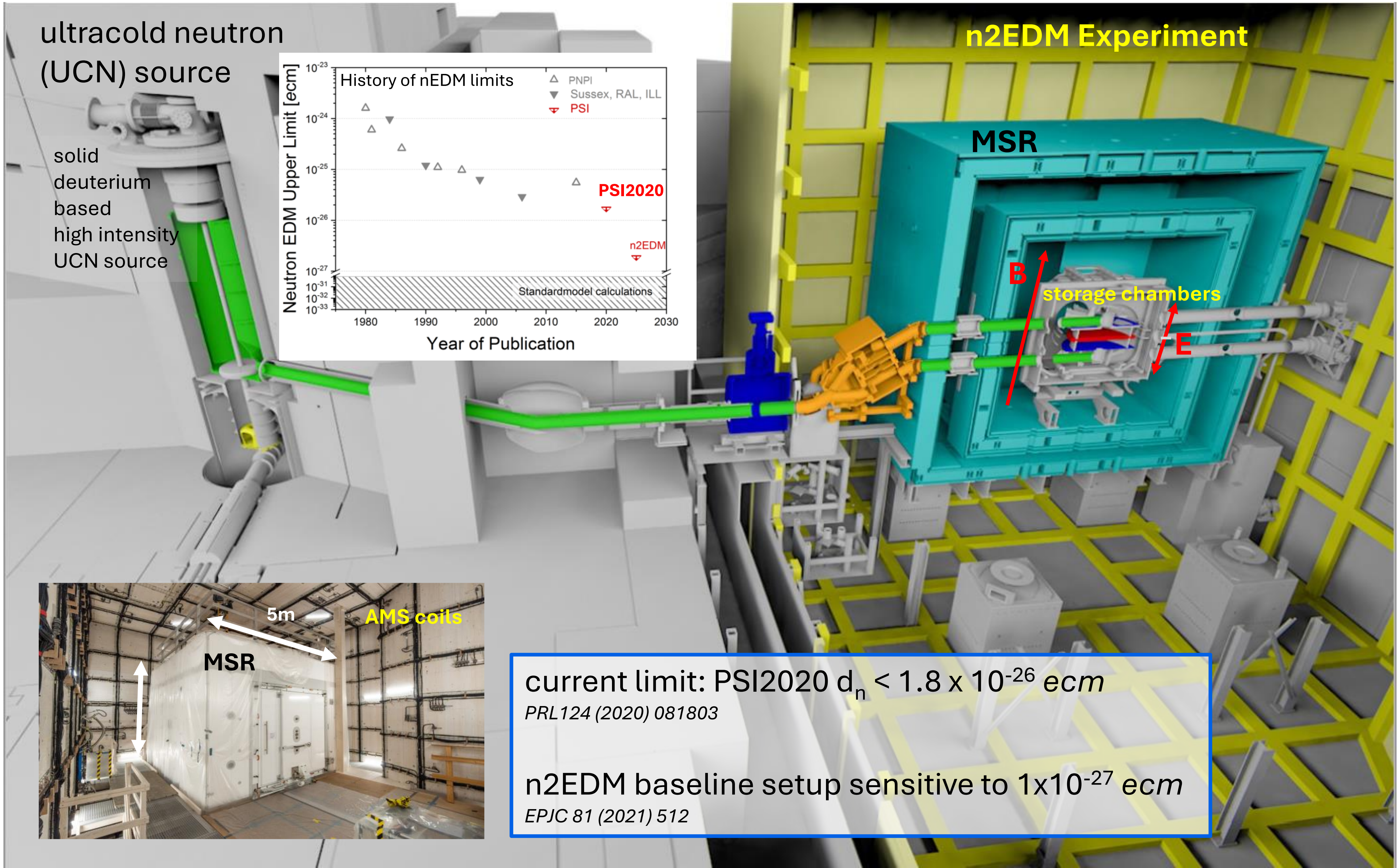
$$hf_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$hf_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

$$h\Delta f = 4\, d_n E$$



$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Search for the neutron electric dipole moment: n2EDM



current limit: PSI2020 $d_n < 1.8 \times 10^{-26}$ *ecm*

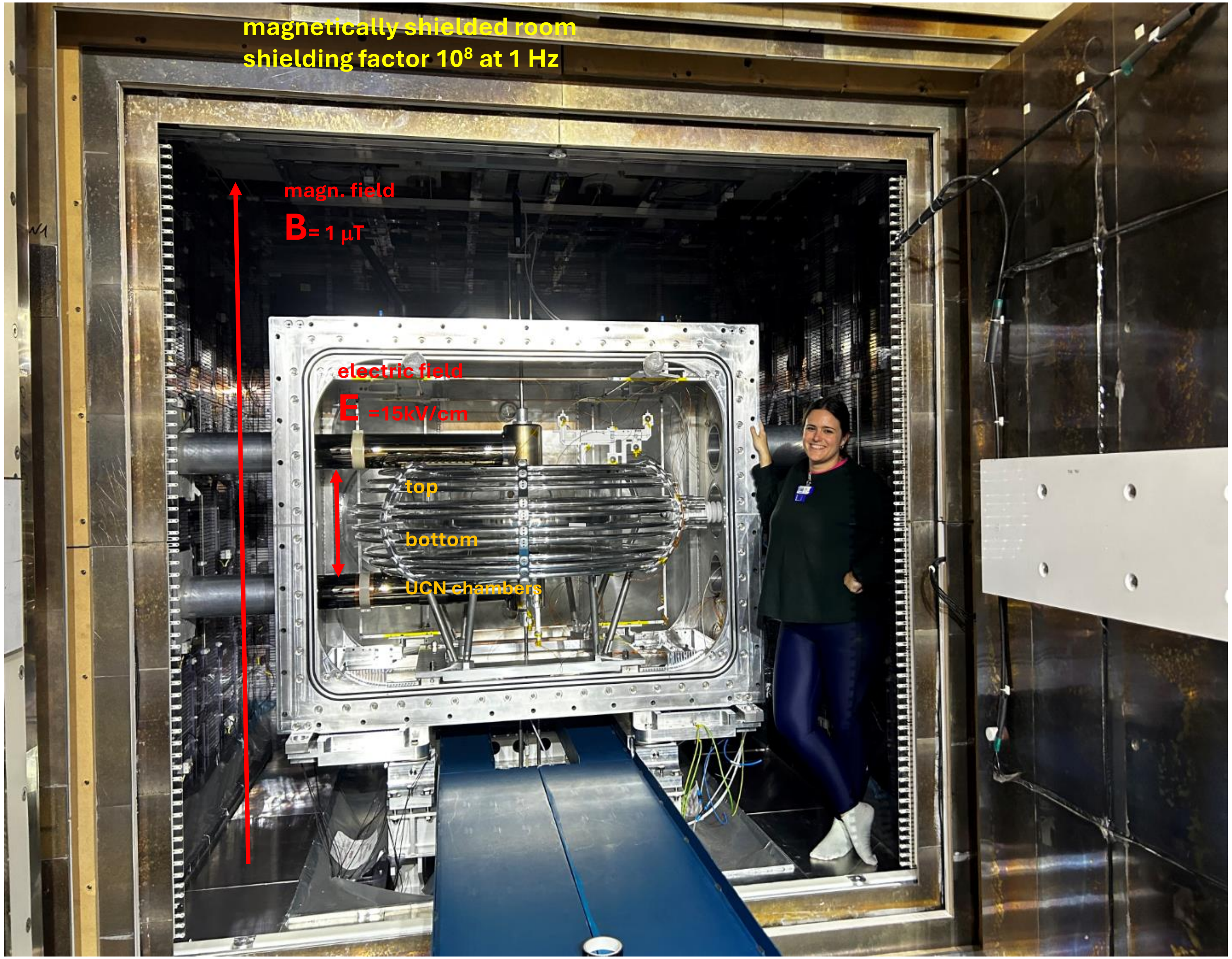
PRL124 (2020) 081803

n2EDM baseline setup sensitive to 1×10^{-27} *ecm*

EPJC 81 (2021) 512

The n2EDM experiment

PSI



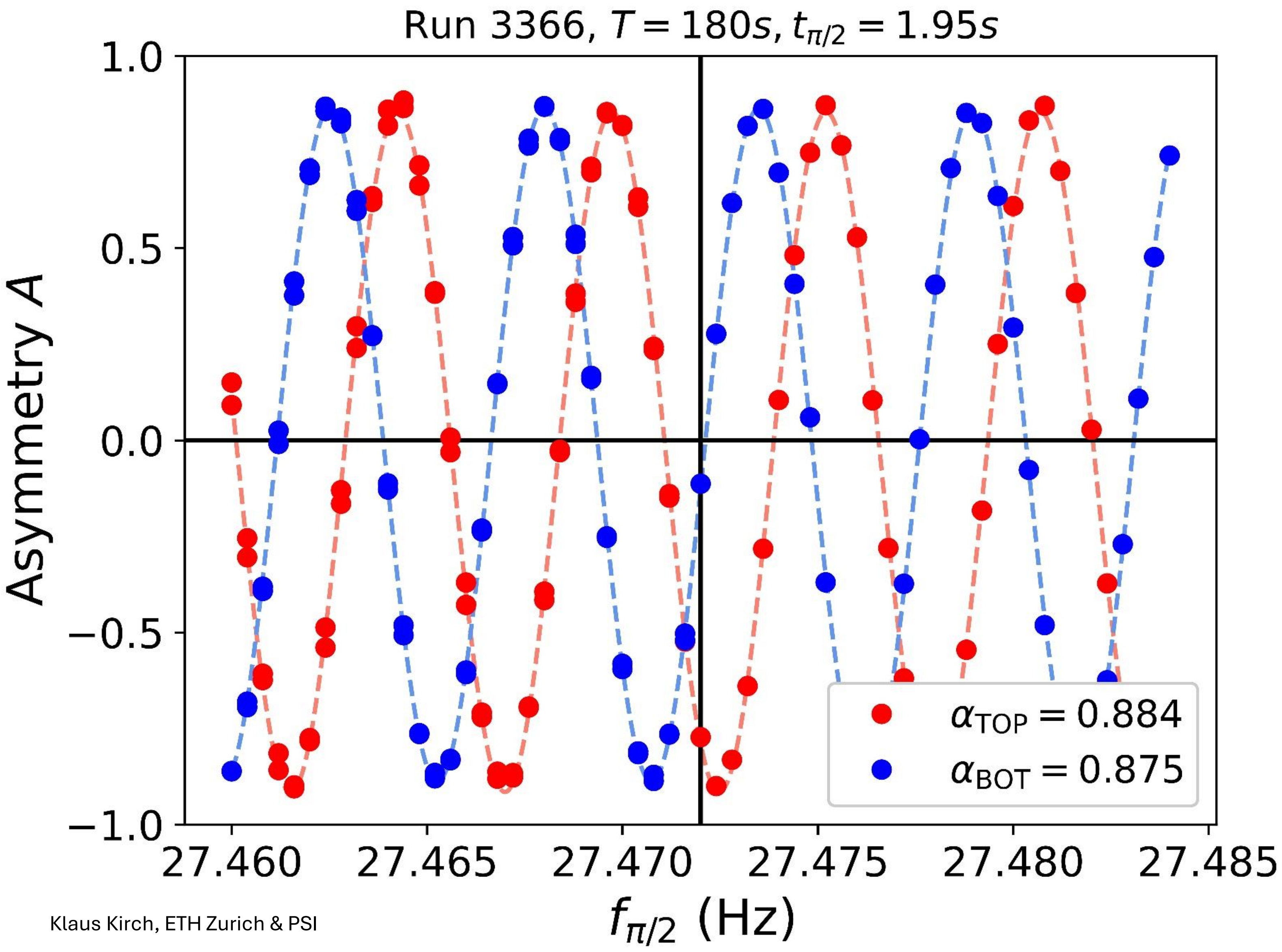
n2EDM is being commissioned and prepared for high-quality data to be taken in 2025/26.

End of 2026 to middle of 2028 we will have a HIPA shutdown to install IMPACT.

End of 2028, n2EDM wants to be back with the magic field option.

Unprecedented magnetic environment: RSI93(2022)095105, EPJC83(2023)1061, EPJC84(2024)18, arXiv:2410.07914

A Ramsey curve with n2EDM

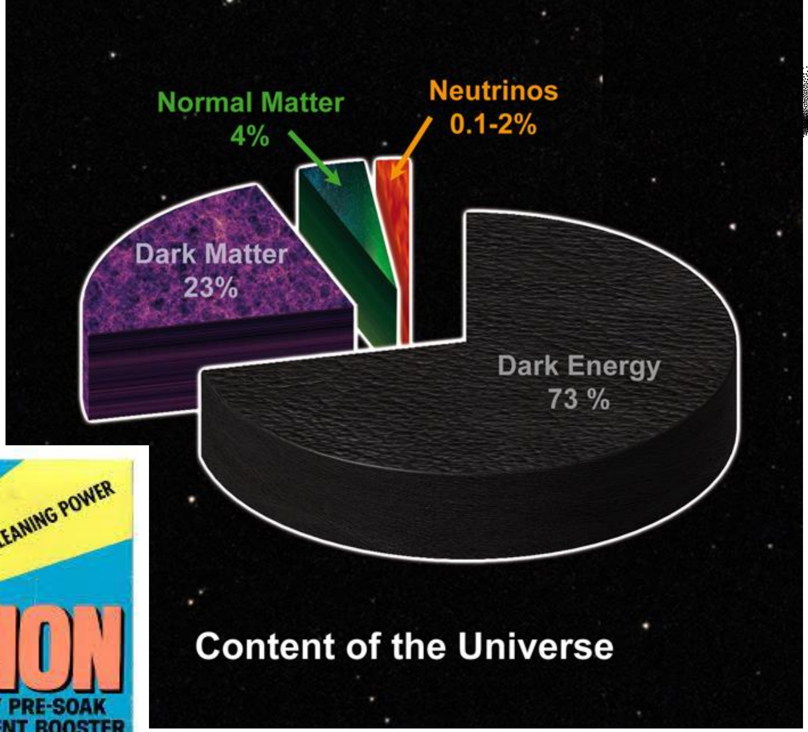


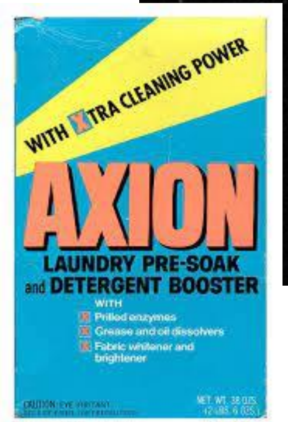
Example 3: Axion-like particles

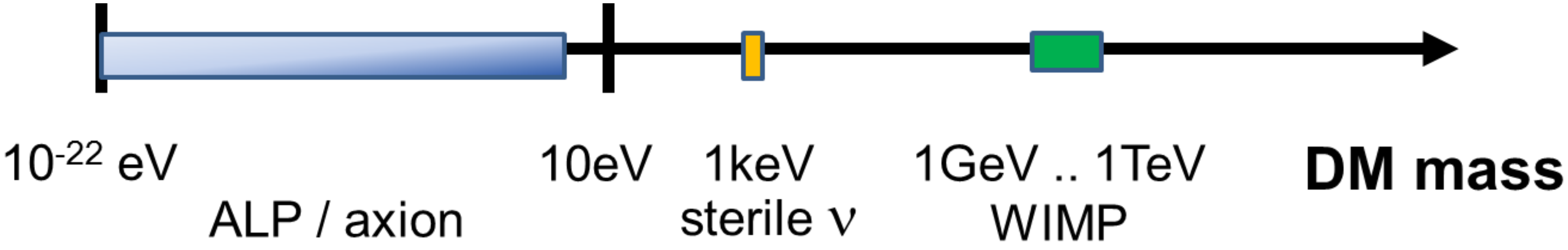
The smallness of θ_{QCD} can be explained invoking axions

Axions and ALPs are viable candidates for Dark Matter

The neutron EDM is sensitive to axions and ALPs, which could produce oscillating EDM values







nEDM search for ultra-light axion dark matter

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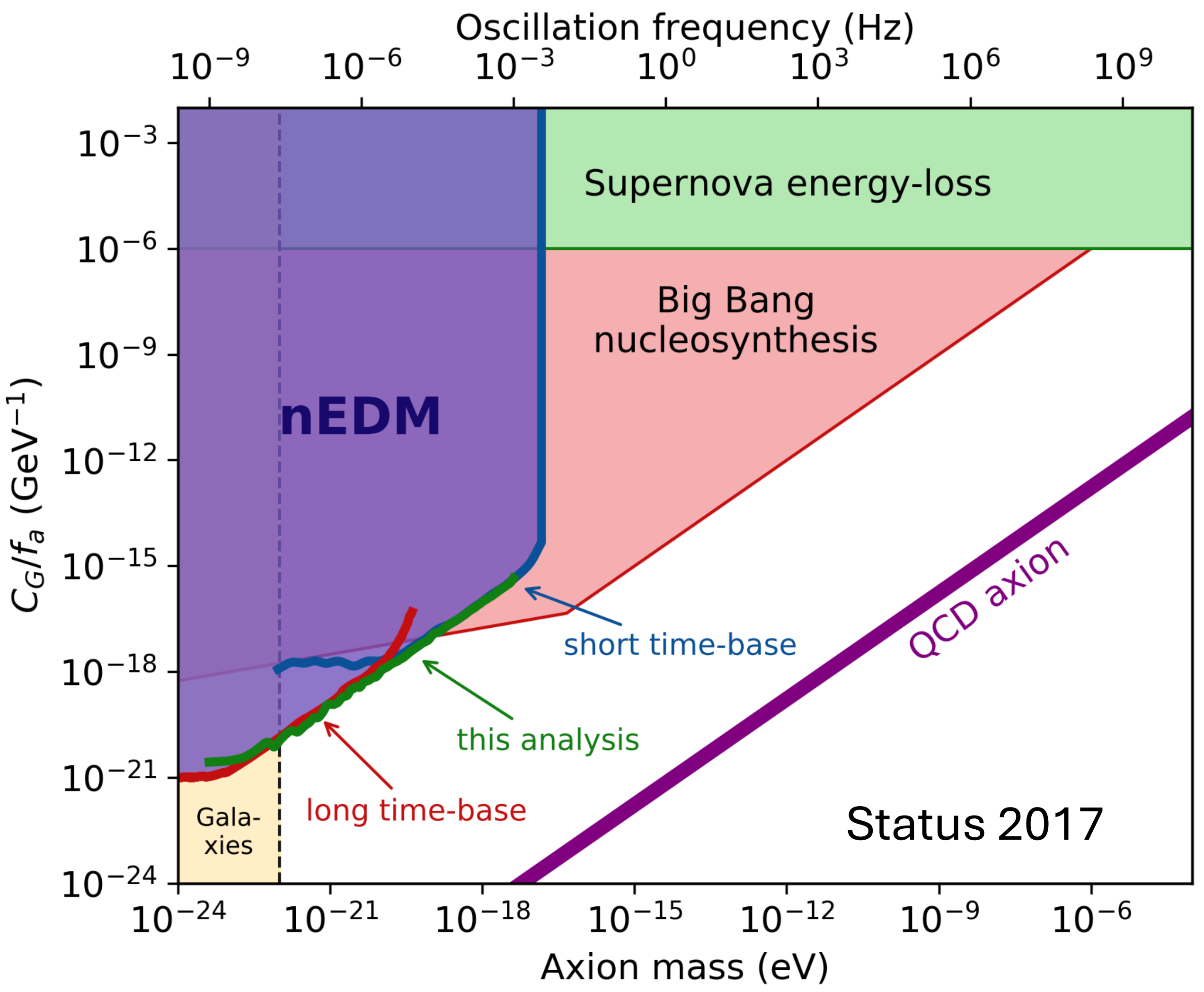


With theorists Flambaum, Stadnik, Fairbairn, Marsh

See:
Graham, Rajendran, PRD88(2013)035023
Budker et al., PRX4(2013)1
Stadnik, Flambaum, PRD89(2014)043522
Kim, Marsh, PRD90(2016)025027

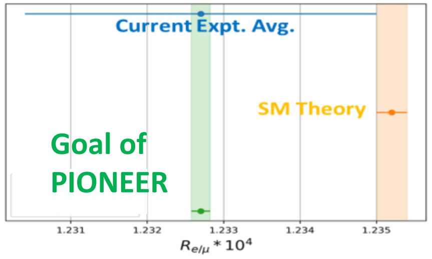
Abel et al., PRX7(2017)041034
update: ETH-Diss. 27846
Solange Emmenegger (2021)

Oscillating nEDM data could come from the interaction of **ultralight axions** which could be the **Dark Matter in the Universe**.

nEDM places the first laboratory limits. on **axion – gluon** couplings

Example 4: Weak interaction and lepton flavor in pion decay

PIONEER at PSI
Next Generation Rare Pion Decay Experiment



PIONEER Goal: Improve precise SM tests by an order of magnitude.

- Phase I: Provide the best test of Lepton Flavor Universality; $\frac{g_e}{g_\mu} \sim \pm 0.005\%$

  * 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 exotic decay search sensitivities by an order of magnitude

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

- Phase II $\to$ III: Provide the cleanest measure of V_{ud} and new input for $\frac{V_{us}}{V_{ud}}$

  * Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.2\% \to \pm 0.05\%)$

Courtesy: Doug Bryman

PIONEER Proposal: $\pi^+ \rightarrow e^+ \nu$

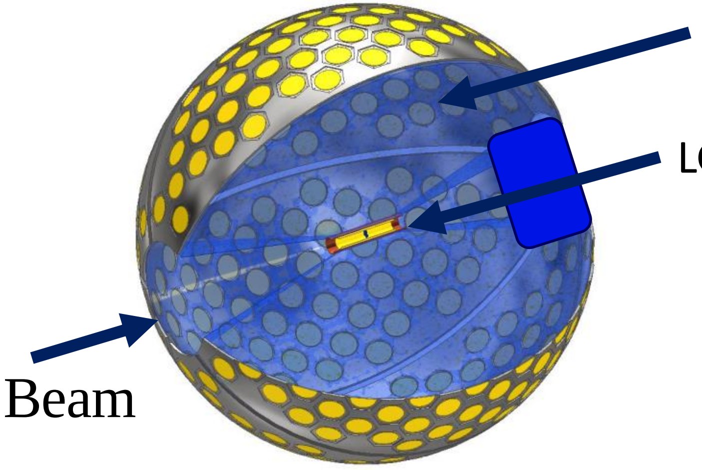
Approved at PSI 2022
Beam tests 2022,23

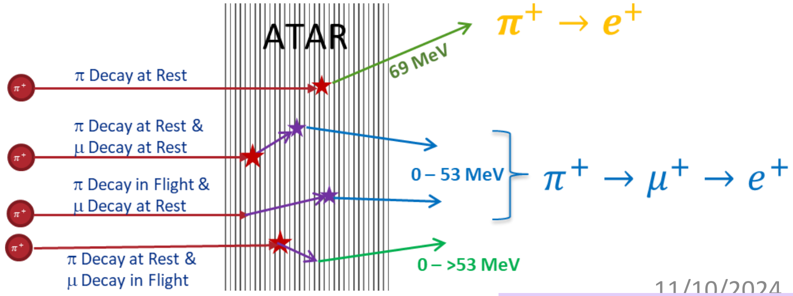
- PSI cyclotron, πE5 beamline
- LXe scintillation calorimeter (LYSO also under consideration)

  Fast, bright scintillation response
- Active Tracking Target "ATAR" (LGAD) Control of systematic uncertainties

  Fast timing and pulse shape;allow $\pi \rightarrow \mu \rightarrow$ e decay chain observations
- Fast electronics and pipeline DAQ $\rightarrow$ Improve efficiency

Learn more about PIONEER:
Doug Bryman: doug@triumf.ca
David Hertzog: hertzog@uw.edu
Anna Soter: anna.soter@psi.ch





Courtesy: Doug Bryman

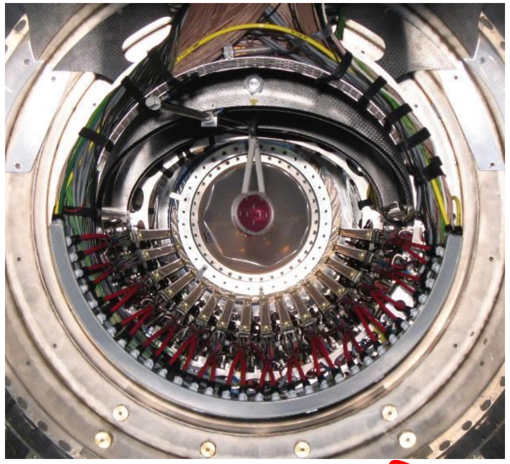
Example 5: Charged lepton flavor in muon decay

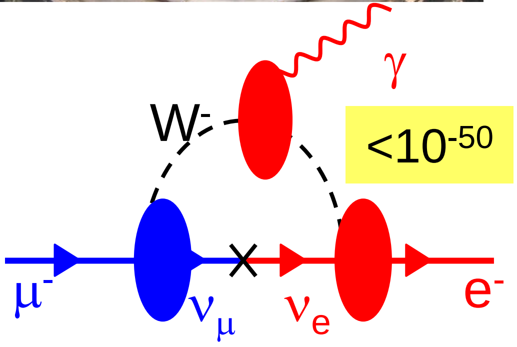
The decay of a positive muon into a positron and a photon (or $e^+ e^-$ pair) violates charged lepton flavor

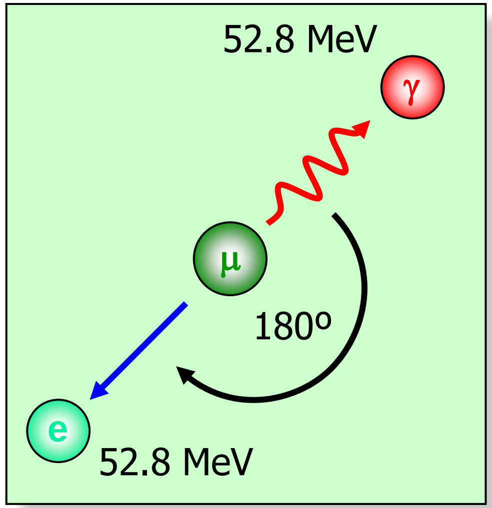
Neutral leptons violate lepton family number

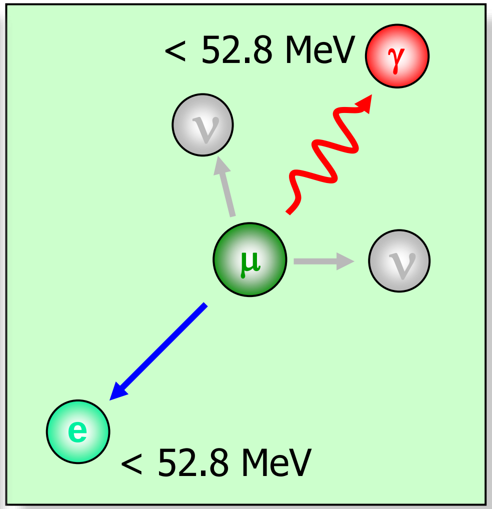
Charged lepton flavor may also be violated and many BSM models predict substantial cLFV

Muons are extremely sensitive probes for cLFV in decays like $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$, and $\mu^- \to e^-$ conversion









Searches for charged lepton flavor violation

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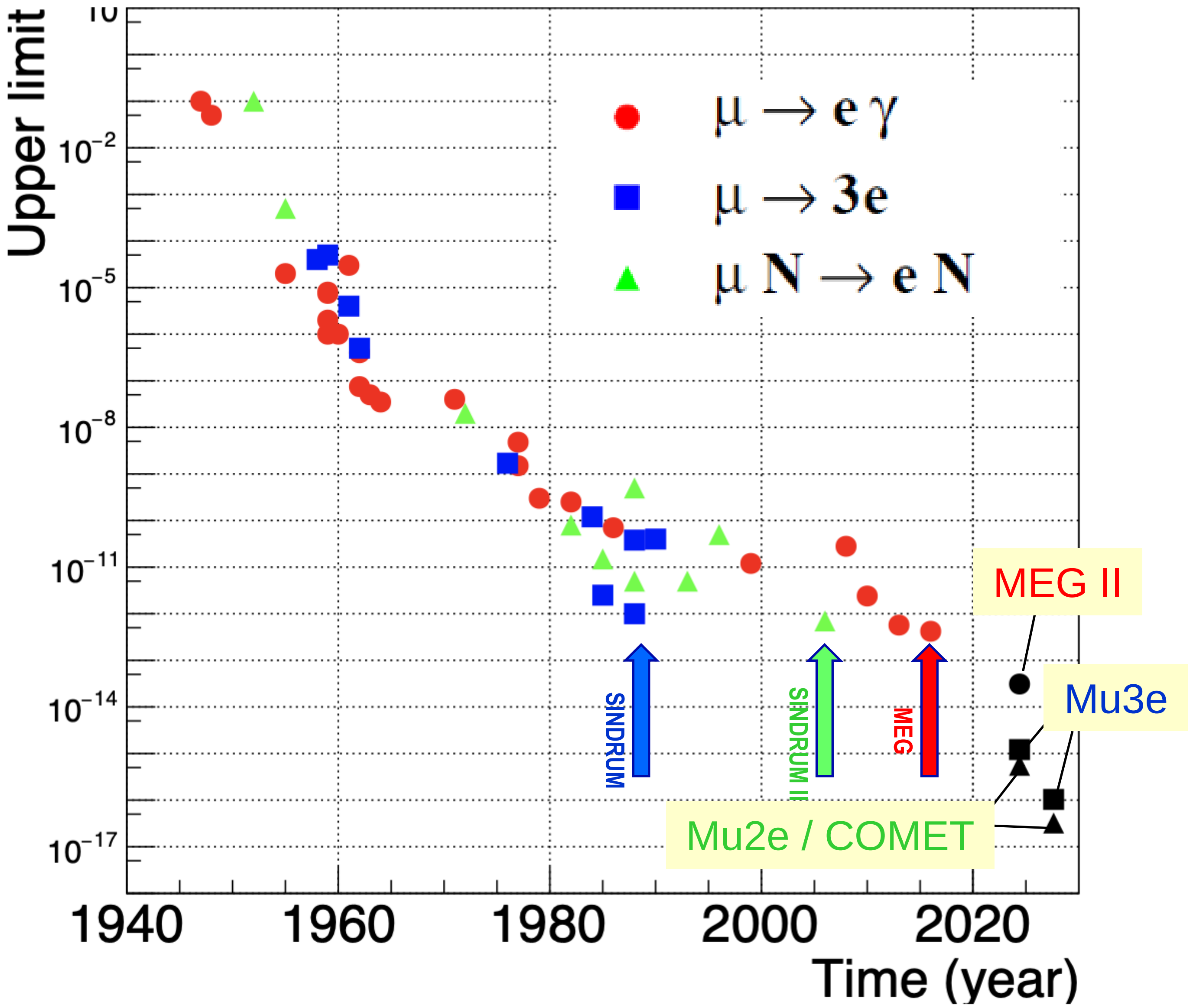
The present best limits on cLFV with muons

$\mu^+ \rightarrow e^+ e^+ e^-$
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 < 3.1 x 10^{-13}
MEG 2013, 2016,
MEG II 2023

[90 % C.L.]



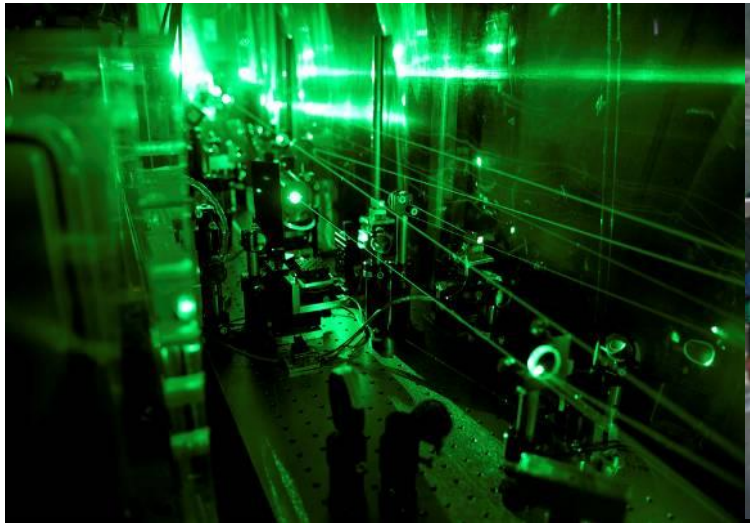
See: Review of Particle Physics at PSI, SciPost Phys. Proc. 5 (2021), https://scipost.org/SciPostPhysProc.5

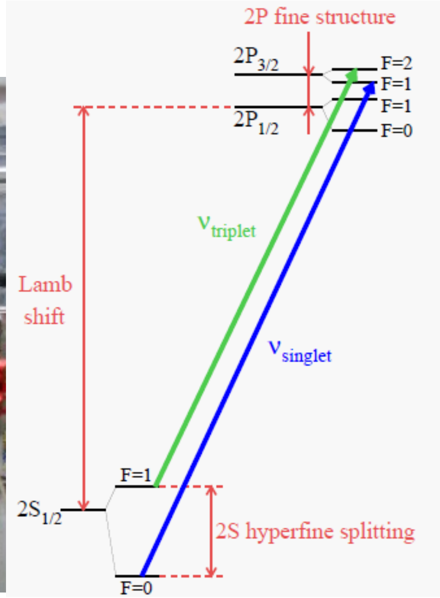
Example 6: Light nuclear charge radii for QED and nuclear theory

The 1S-2S transition in H is known to 4×10^{-15}.
Experiments on He^{+} at high precision are under way.

Comparison with QED at a level of 10^{-12} is limited by the knowledge of the proton and alpha charge radii

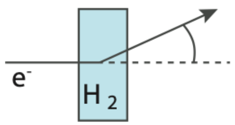
The Lambshift 2S-2P in muonic atoms is highly sensitive to nuclear charge radii and has been successfully performed for the stable H and He isotopes.



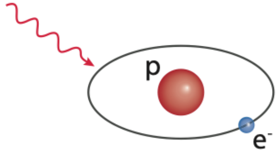


The proton radius puzzle from 2010 on

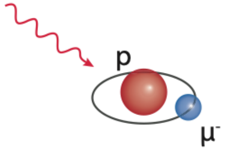
PSI



e⁻-p scattering

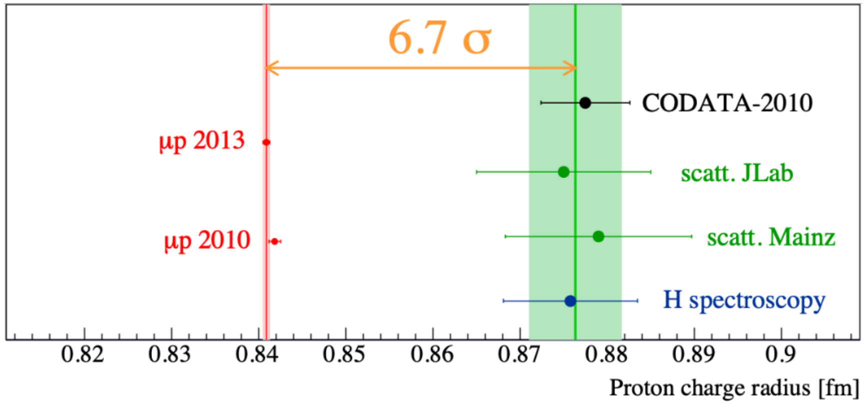


H spectroscopy



μp spectroscopy

2010

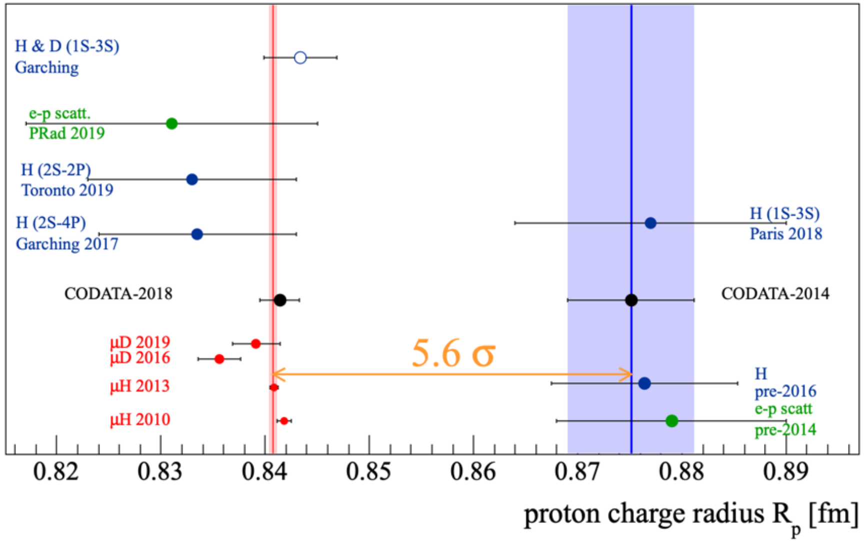


Numerous theoretical investigations of BSM physics and proton structure were performed but no solution for this tension was found

More than 1000 citations

re-analyses of e-p scattering data gives inconsistent results (not shown in plots)

2021

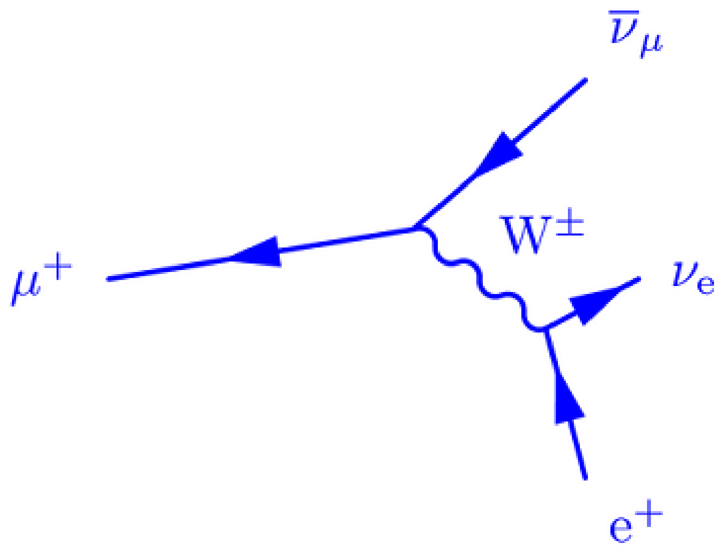


Four (out of five) of the new experiments confirm the small proton radius from muonic hydrogen

A. Antognini, R. Pohl et al.

Example 7

The measured value of the muon lifetime determines the Fermi coupling constant G_F



$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

The Weak coupling constant G_F

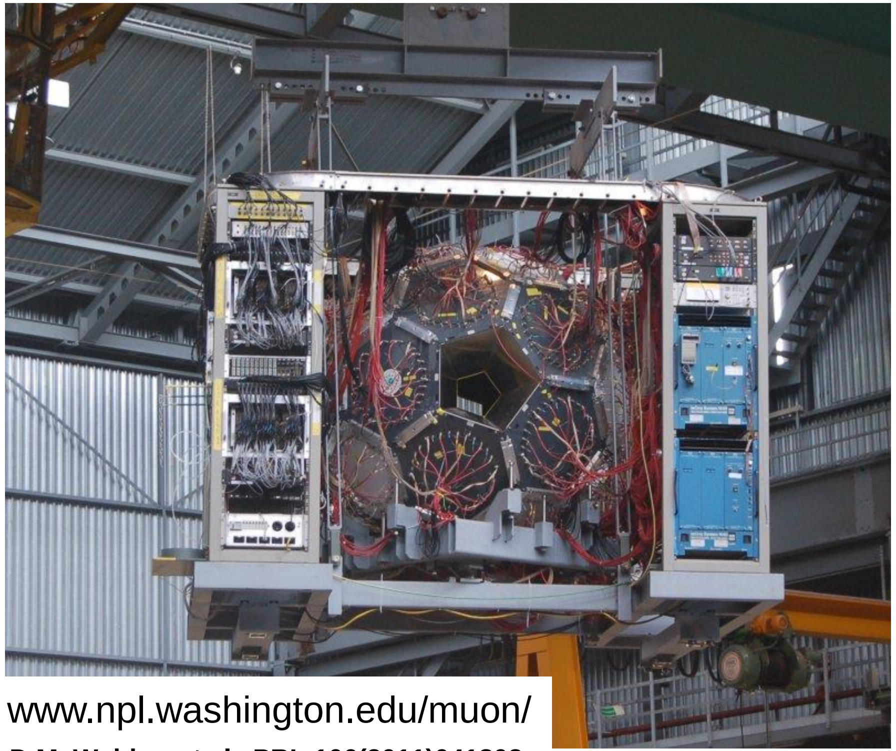
Fundamental electro-weak parameters of the Standard Model

α	G_F	m_Z
0.00015ppm	4.1 → 0.5 ppm	23ppm

MuLan: The most precise measurement of any lifetime:

MuLan: Illinois, Kentucky, Boston, J.Madison, Regis, Wesleyan, PSI,KVI

$G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}\ (0.5\ \text{ppm})$

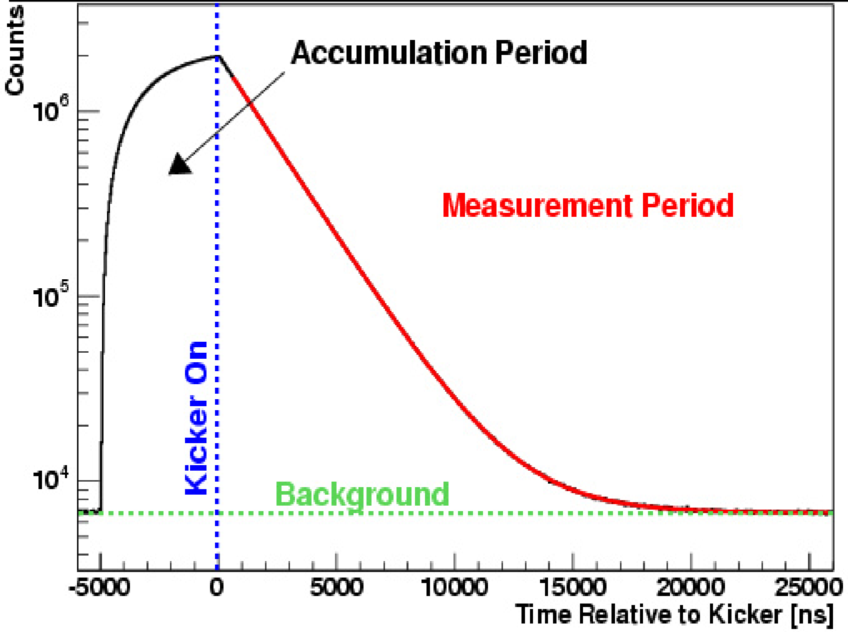


www.npl.washington.edu/muon/

D.M. Webber et al., PRL 106(2011)041803

V. Tishchenko et al., PRD 87(2013)052003

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)



$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

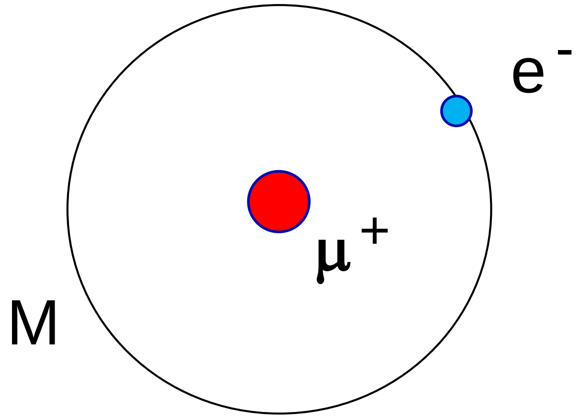
(Last) Example 8

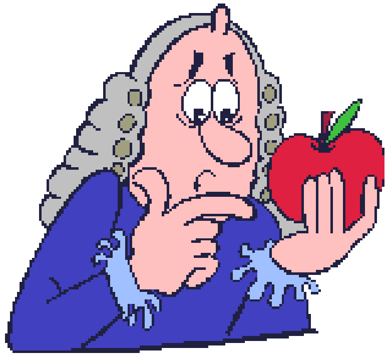
We do not yet know how an ultimate quantum theory of gravity will look like

General Relativity is extremely well tested - but only involving matter (and light, and binding energy)

No direct measurement of antimatter falling in the Earth gravitational field has been done at an interesting level of precision yet (here: leptonic, 2. gen.)

Even the concept of ‘antigravity’ is still around and calls for a direct measurement





Muonium Antimatter Gravity Experiment

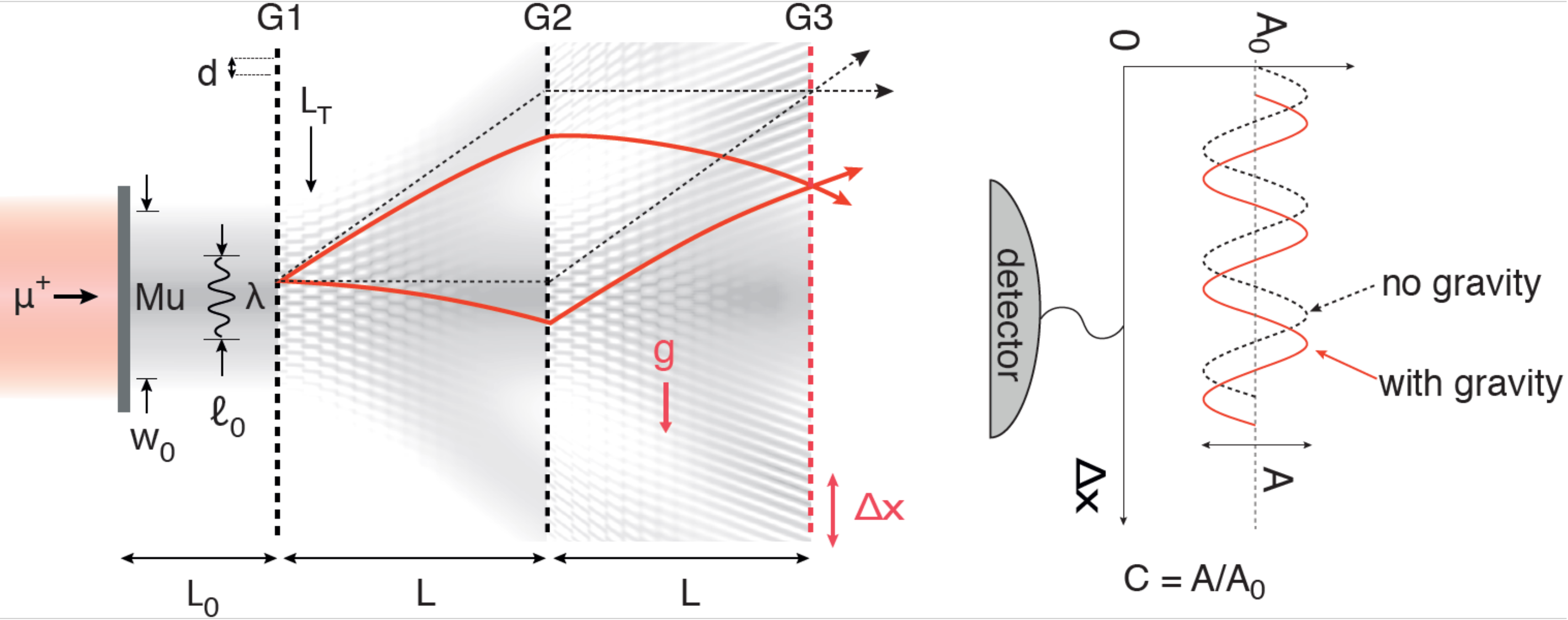
PSI

M beam based on muCool beam and M production of SF-He

Measure gravitational phase shift in atom interferometer

Determine sign of $\bar{g}$ in one day

Measure $\bar{g}$ to few percent within a year



Anna Soter et al.

arXiv:physics/0702143, Atoms 6(2018)17, SciPost Phys Proc 5(2021)030 & 031

Happy Birthday SMI!