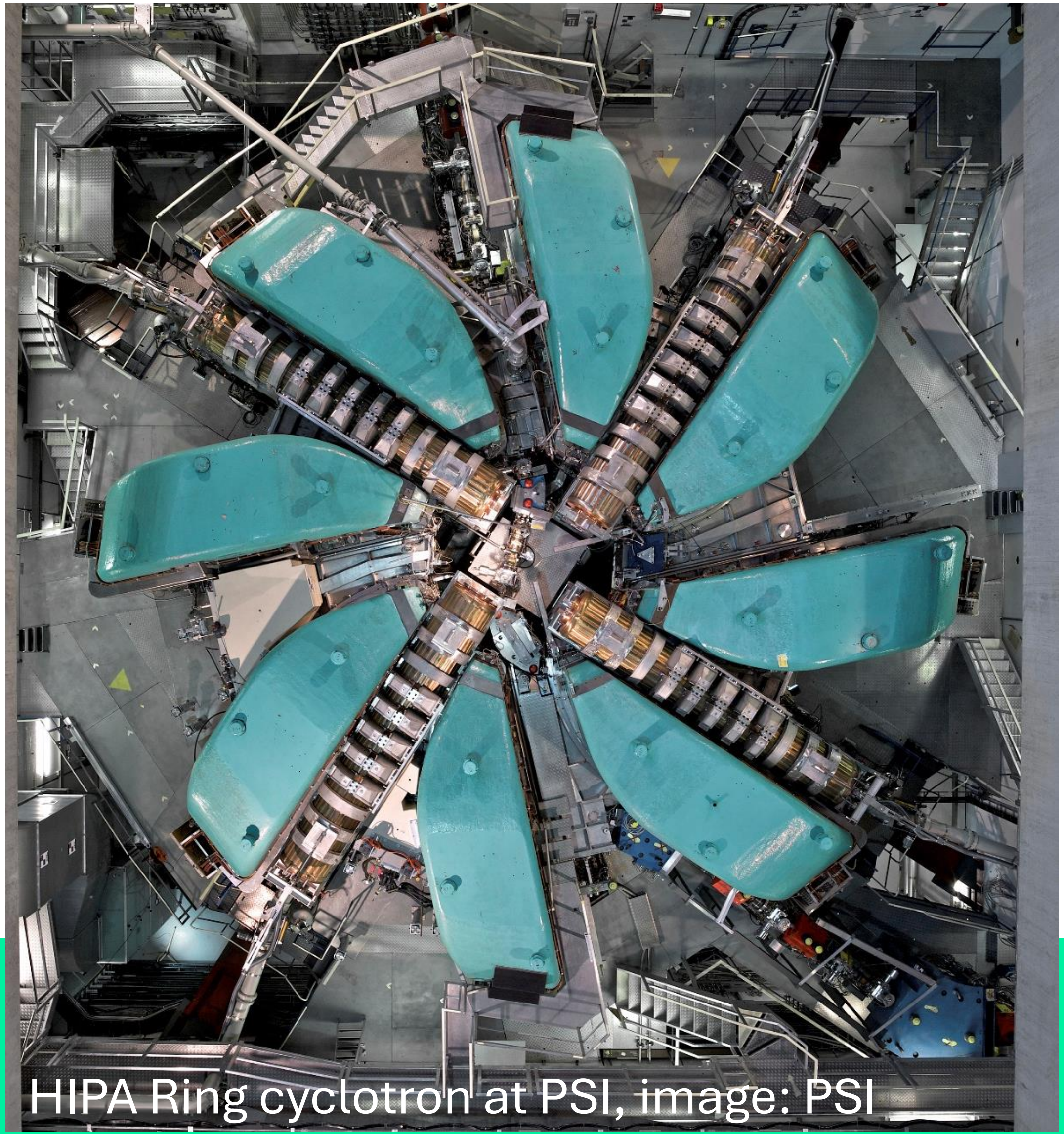
PSI Center for Neutron and Muon Sciences

ETH

Muon physics infrastructure and program at PSI

BDX & Beyond Workshop
Jefferson Lab, Sep 4-5, 2025



HIPA Ring cyclotron at PSI, image: PSI

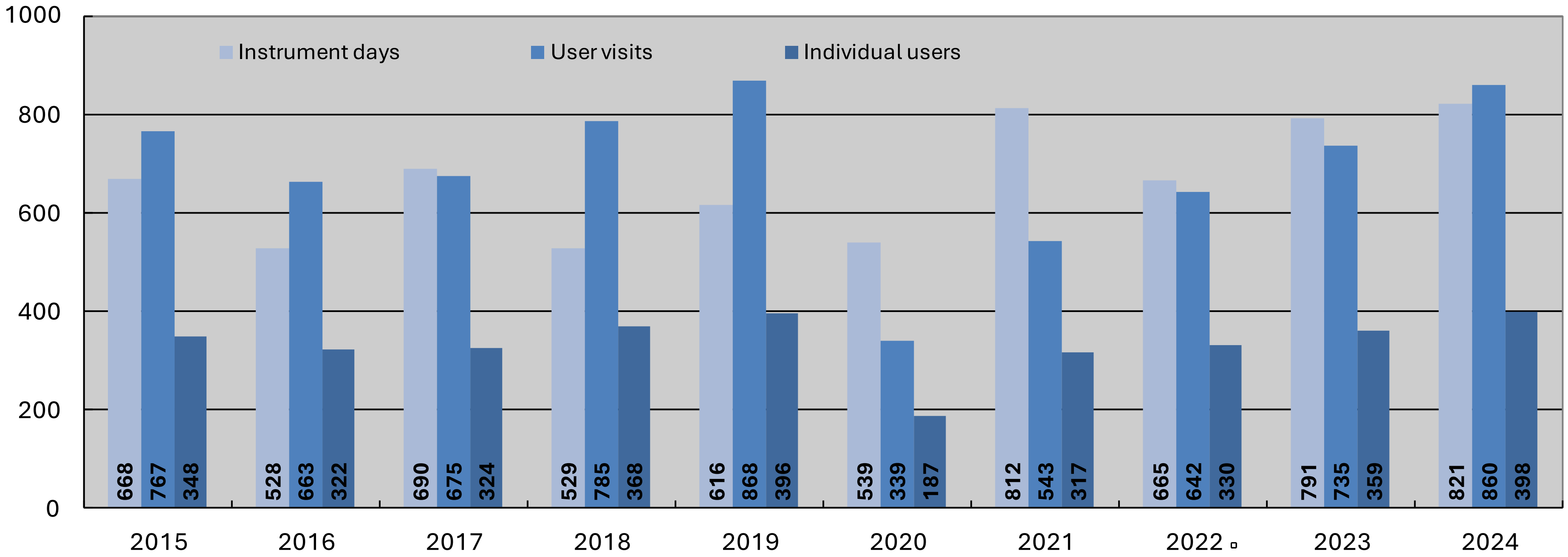
Klaus Kirch, ETH Zurich and Paul Scherrer Institute
05 September 2025


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

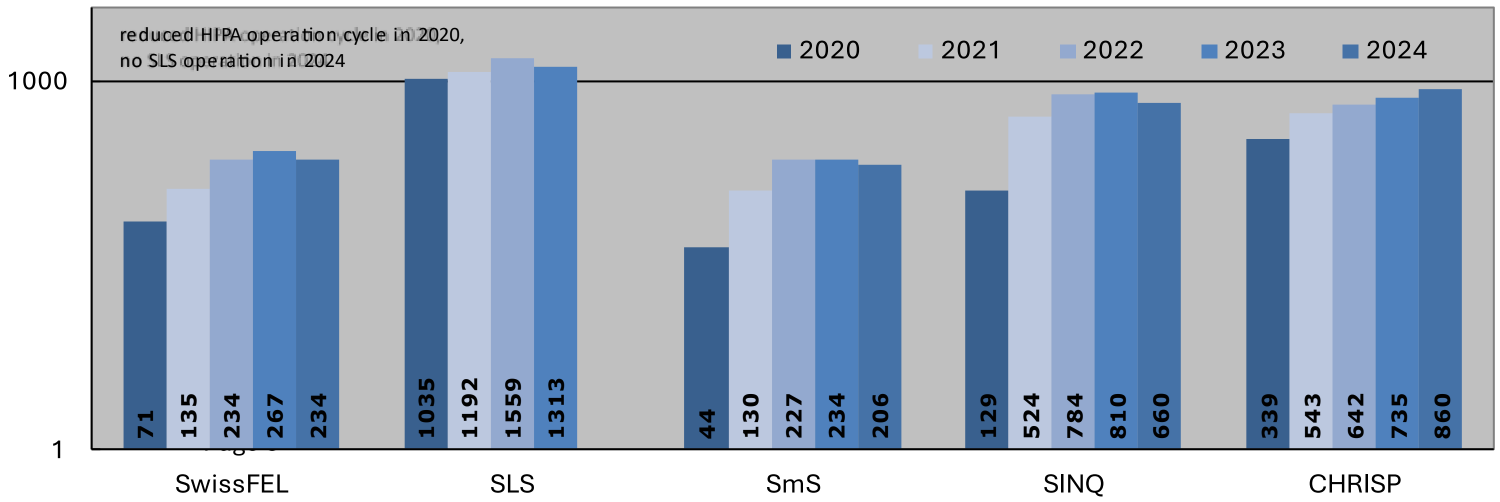
Users at CHRISP (CH Research InfraStructure for Particle physics)

PSI

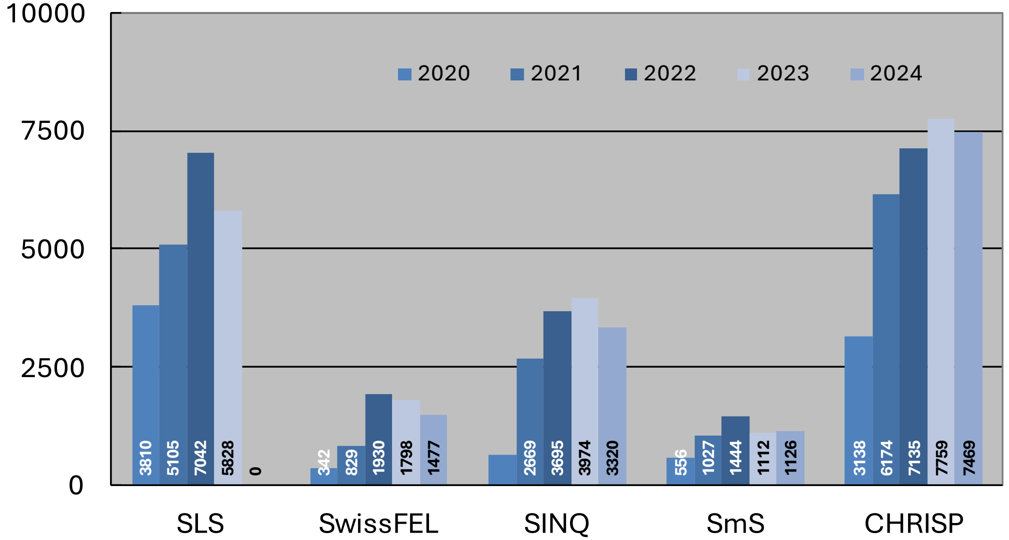
key numbers CHRISP - 10y history



user visits all facilities: 5y history (log scale)



duration of user stays [days] - 5y history

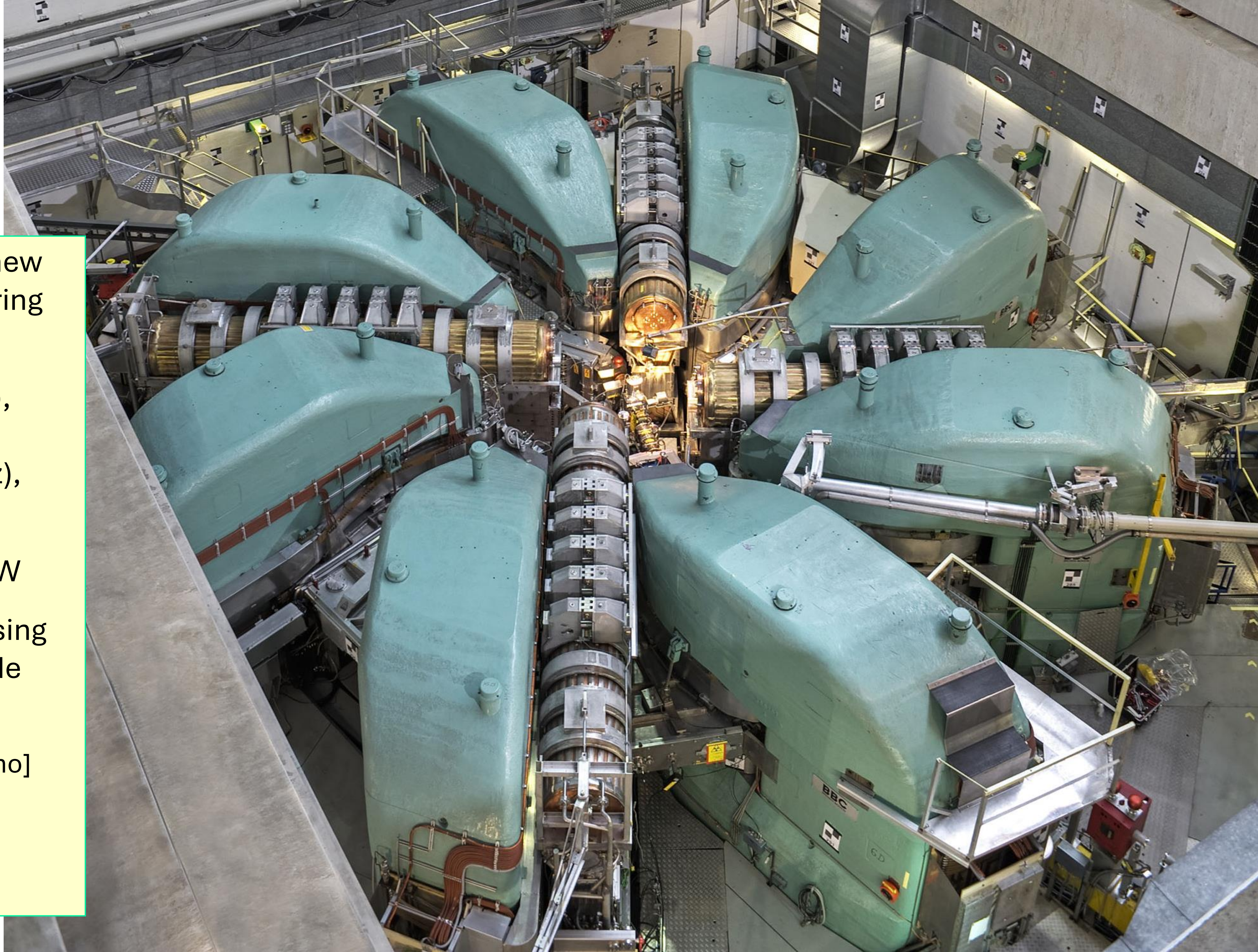


PSI HIPA
Ring cyclotron

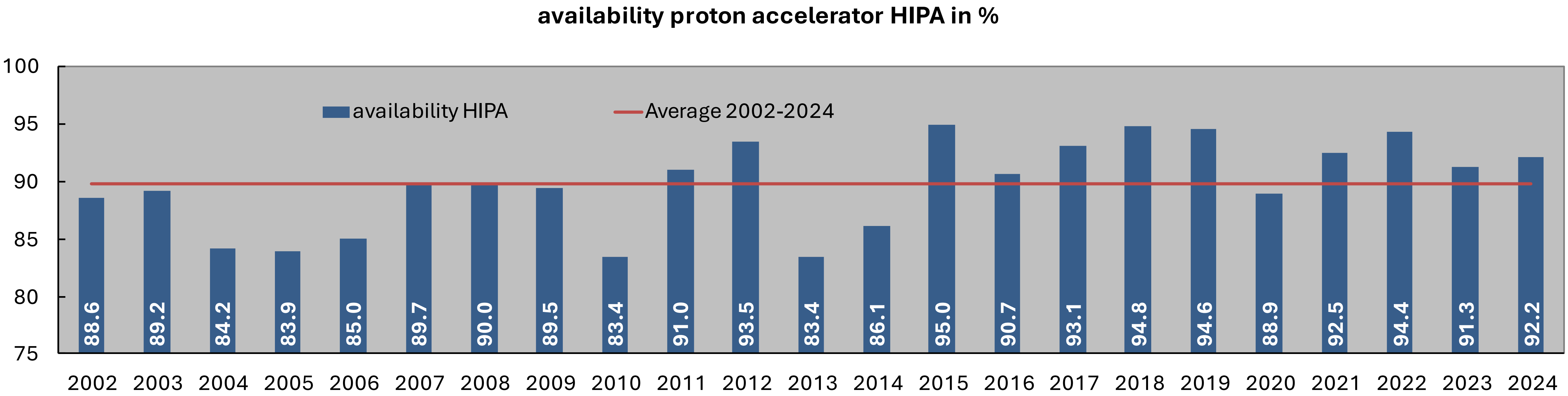
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

[losses ∝ (turn number)^3, W.Joho]

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

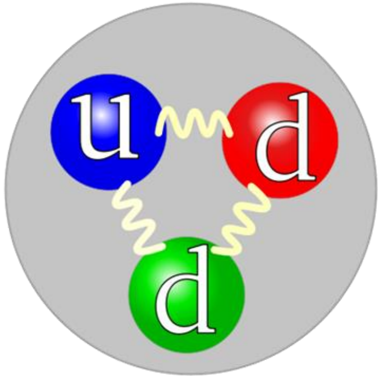


Proton beam availability



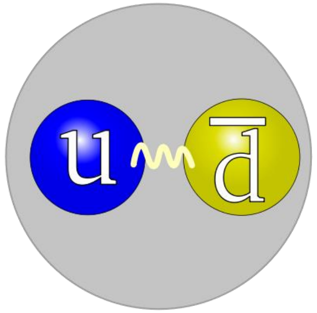
The lightest unstable particles of their kind

Neutron



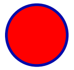
Baryon

Pion

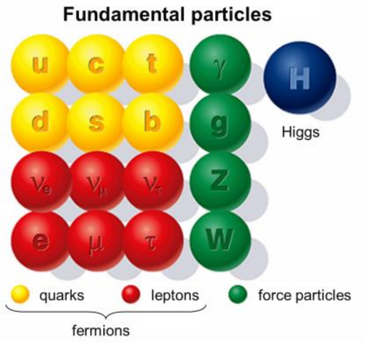


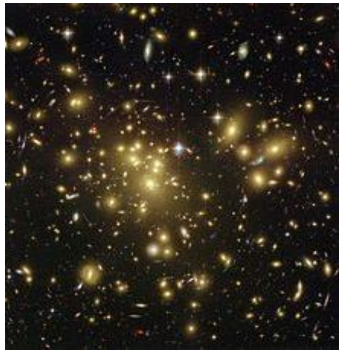
Meson

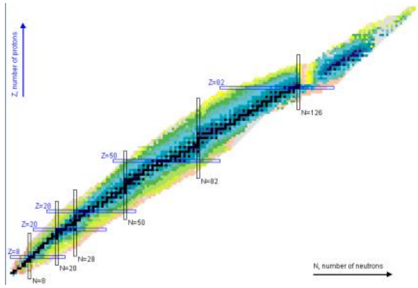
Muon

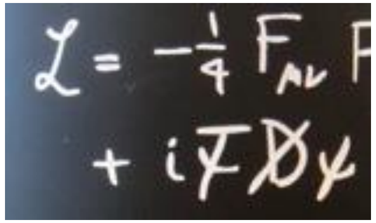


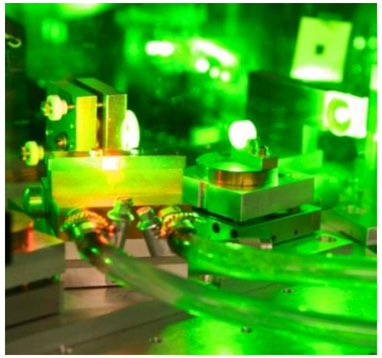
Lepton









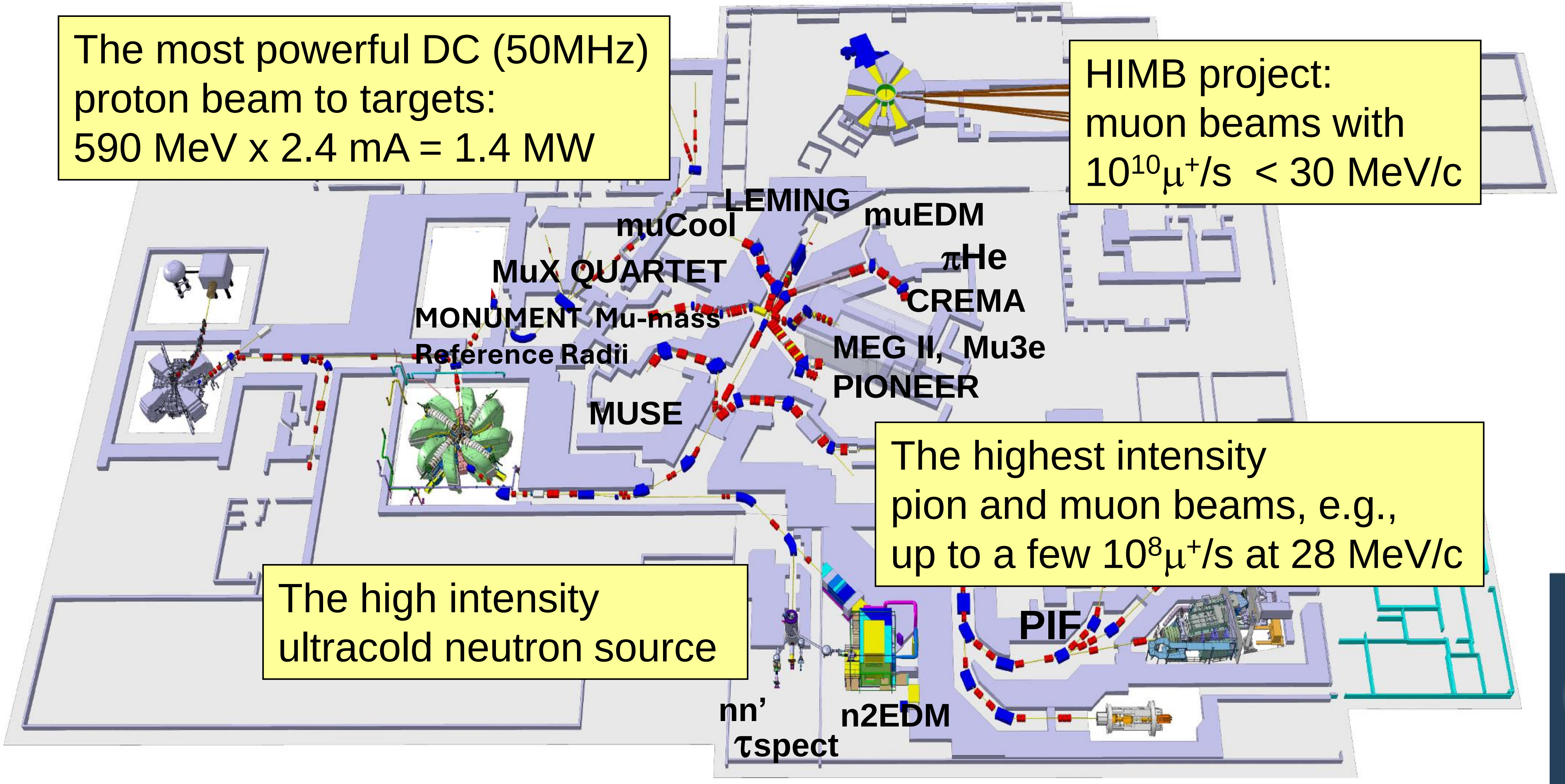


Highest intensities enable highest precision for

- 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

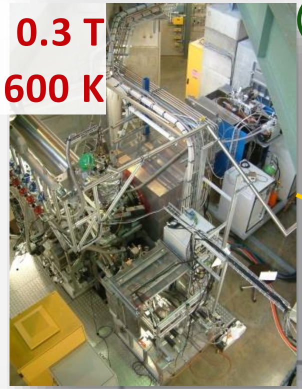
The highest intensity pion and muon beams, e.g., up to a few $10^8\mu^+$/s at 28 MeV/c

The high intensity ultracold neutron source

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

Instruments at the SμS (Swiss Muon Source)

PSI



0.3 T
2.5 - 600 K

LEM

Thin films, devices

Low Energy Muon Facility

Muon Energy: **1-30 keV** (μ^+)

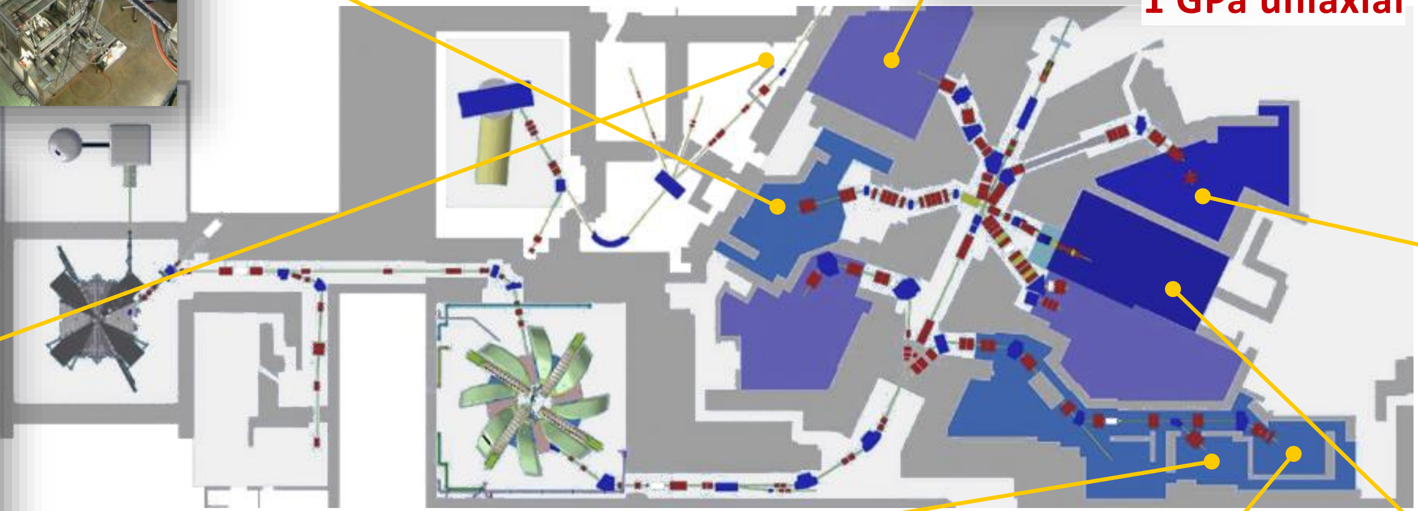
DOLLY/VMS

Uniaxial pressure, 1 GPa

Muon Energy: **4 MeV** (μ^+)

πE1 beam line shared with LTP, in operation 50% of the year

0.8 T
0.25 - 300 K
1 GPa uniaxial



GIANT

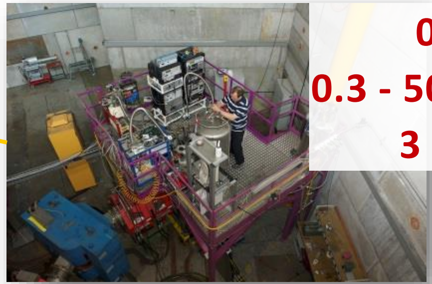
MIXE, 1 – 15 MeV (μ-)
elemental analysis
3 weeks per year

GPD

Hydrostatic pressure, 3 GPa

General Purpose Decay Channel Instrument (for Pressure Studies)

Muon Energy: **5-60 MeV** (μ^+/ μ^-)



0.6 T
0.3 - 500 K
3 GPa

HAL-9500

9.5 T, 10 mK

High Field and Low Temperature

Muon Energy: **4 MeV** (μ^+)

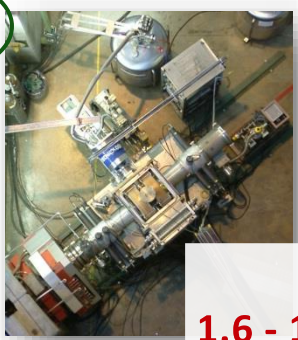
9.5 T
0.01 – 300 K
Δt ~ 60 ps

GPS

General Purpose Surface Muon Instrument

Very fast
MORE

Shared Surface Muon Beam
Muon on Request (MORE)
Muon Energy: **4 MeV** (μ^+)



0.8 T
1.6 - 1000 K

FLAME

***FL**exible **A**dvanced **M**uSR **E**nvironment*

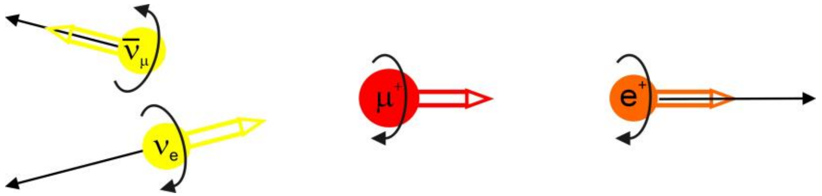
Muon Energy:
4 MeV (μ^+)

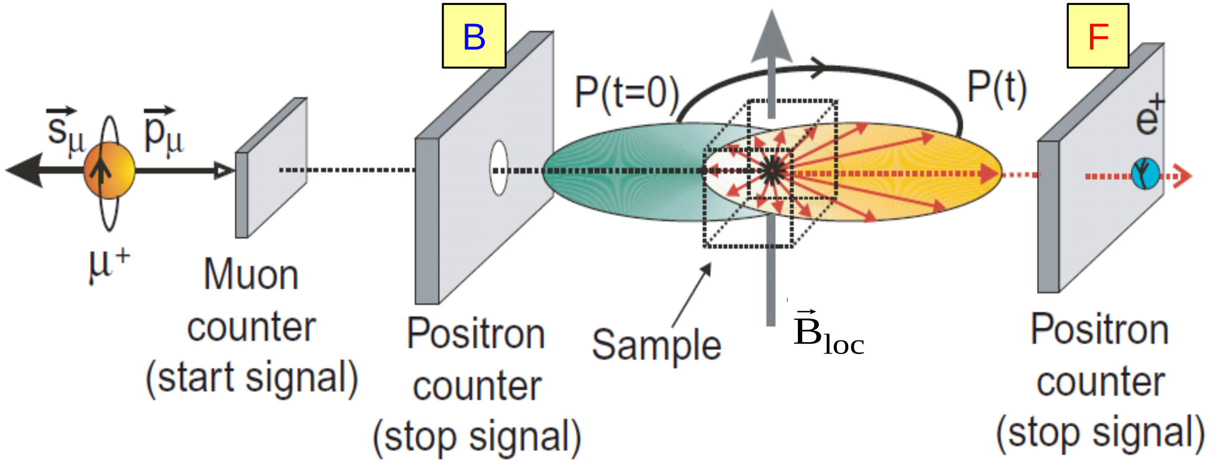
Veto at mK
multi-sample
MORE

3.5 T
0.02 - 310 K

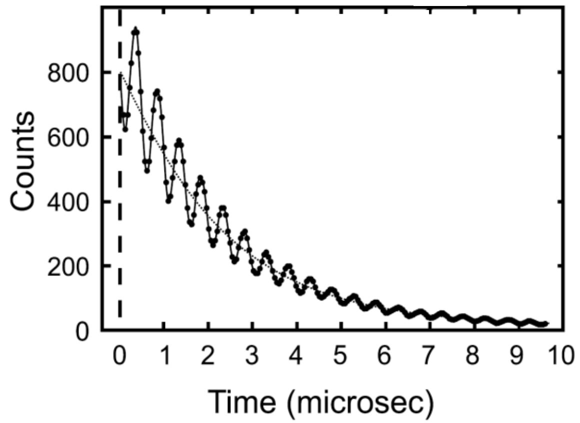
Courtesy: Thomas Prokscha

Principle of a μSR experiment

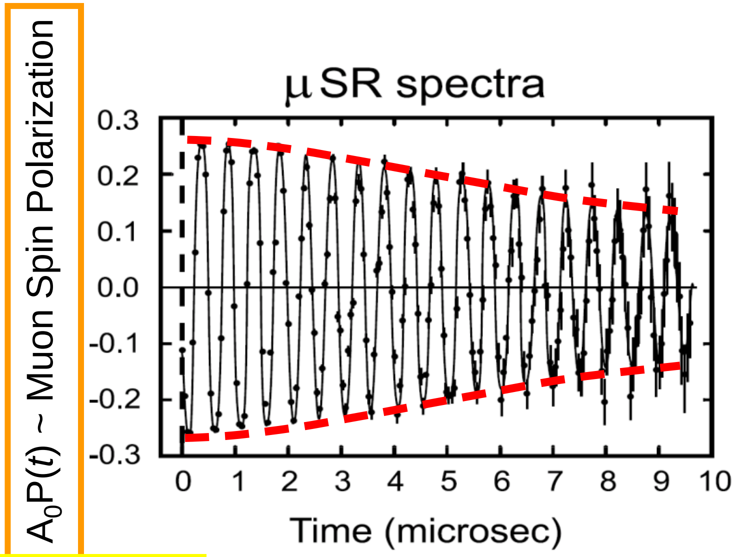




Positron emitted preferentially in the direction of the muon spin:
allows to measure evolution of polarization P(t) of muon ensemble



$$N_{e^+}(t) = B_G + N_0 \exp(-t/\tau_\mu)\ [1 + A_0P(t)]$$



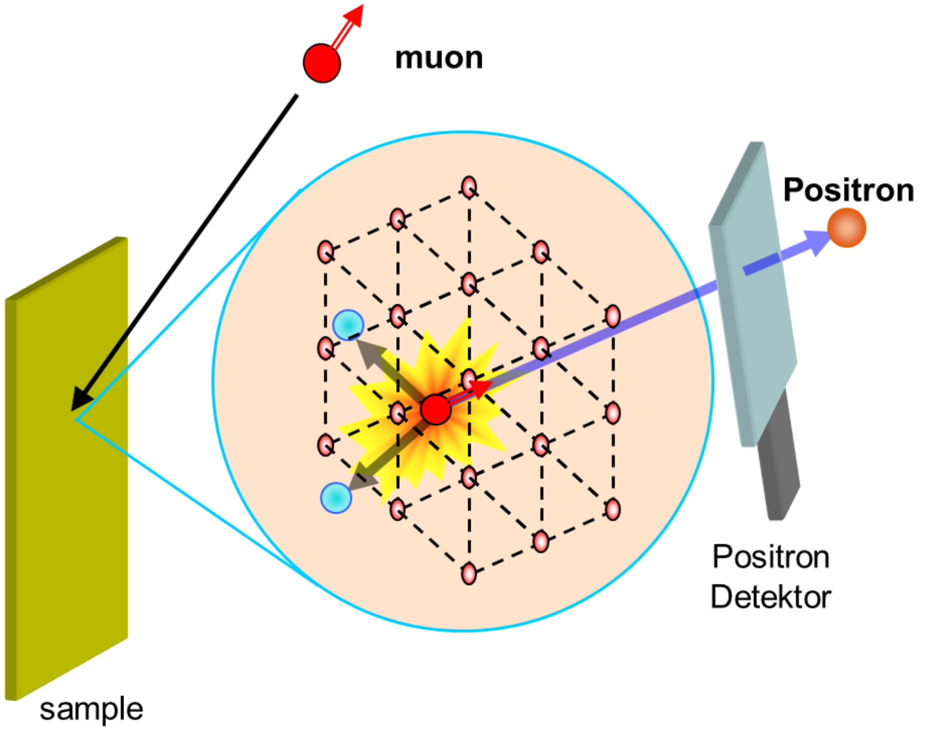
$A_0P(t)$ contains the physics:

frequency: $\omega_L = \gamma_\mu B_{loc}$ value of field at muon site
damping: width of field distribution, fluctuations
amplitude: magnetic/non-magnetic volume fraction, or muonium fraction

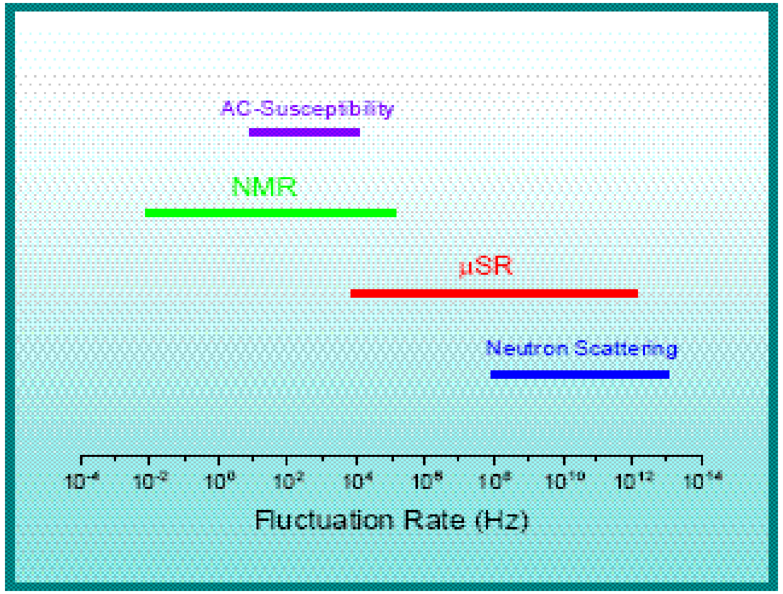
$A_0P(t) = [F(t) - B(t)] / [F(t) + B(t)]$

Courtesy: Thomas Prokscha

The muon as a «local» magnetic micro-probe



$\tau_\mu = 2.2\ \mu s$



The μSR technique has a unique time window for the study of magnetic fluctuations in materials that is complementary to other experimental techniques.

From "μSR brochure" by J.E. Sonier, Simon-Fraser-University, Canada, 2002. http://musr.org/intro/musr/muSRBrochure.pdf

Static and dynamic properties of fields
very sensitive magnetic/spin probe: $10^{-3} - 10^{-4}\ \mu_B$

time window for fluctuations: $10^{-4} - 10^{-11}$ sec

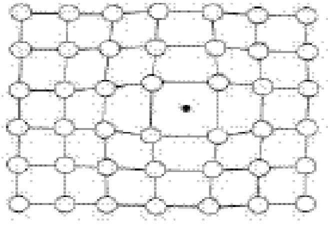
Courtesy: Thomas Prokscha

μSR applications

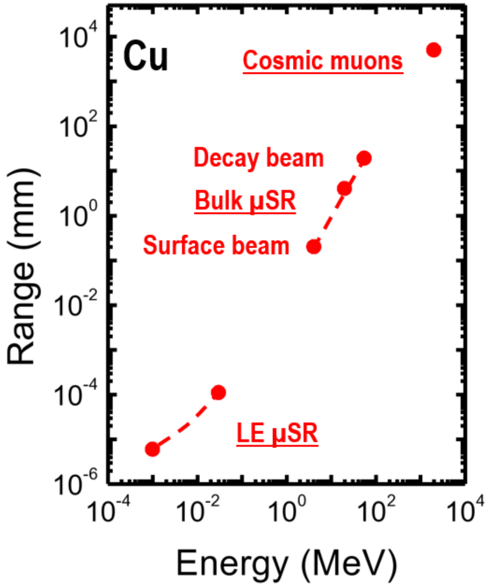
Solid State Physics (mainly positive muons):

μ^+ as a local spin-½ probe **to study internal magnetic fields**, magnetic fluctuations, phase transitions (anti-ferromagnet/ferromagnet/spin-glass/superconductor…) and coexistence of phases, magnetic penetration depths in superconductors…

μ^+ as a prototype of a light interstitial →



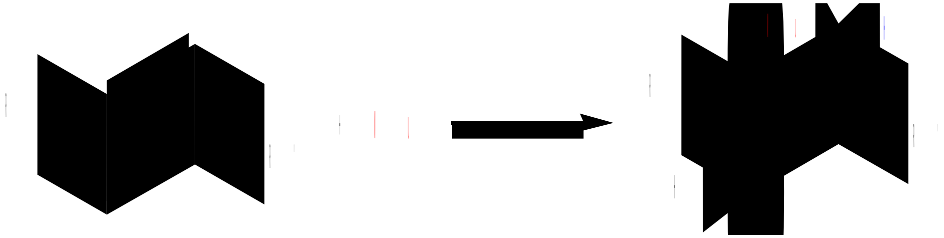
hydrogen-like states (**muonium**) in semiconductors



Chemistry, "Soft Matter", positive muons only:

μ^+ „is a light proton", $m_\mu = 1/9\ m_p$, study of kinetic and dynamic isotope effects, reaction kinetics

formation of ~100% polarised spin label by Mu (μ^+e^- bound state) addition to an unsaturated chemical bond:



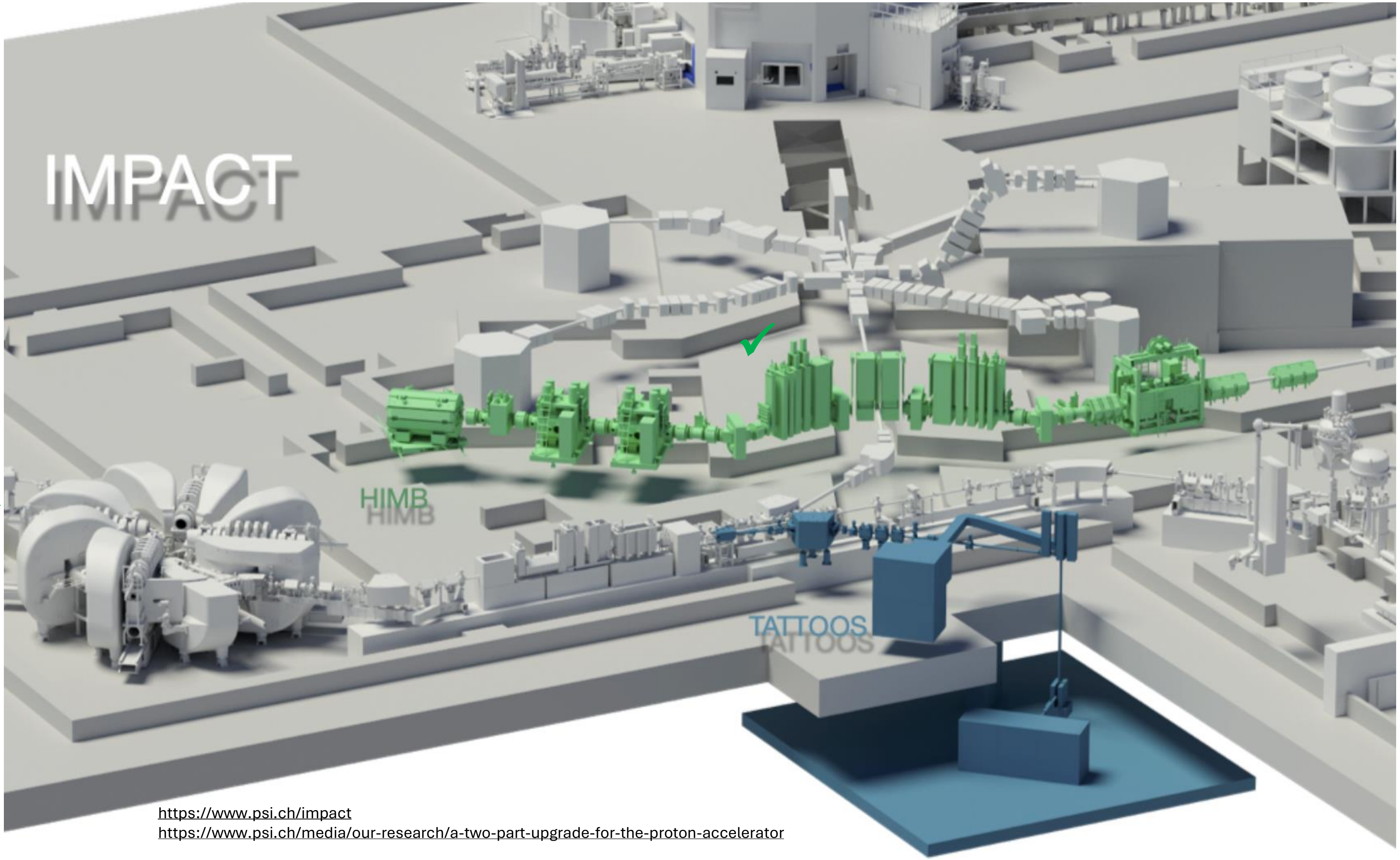
study of organic molecule/polymer dynamics, study of local environment of organic molecules

Courtesy: Thomas Prokscha

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

PSI

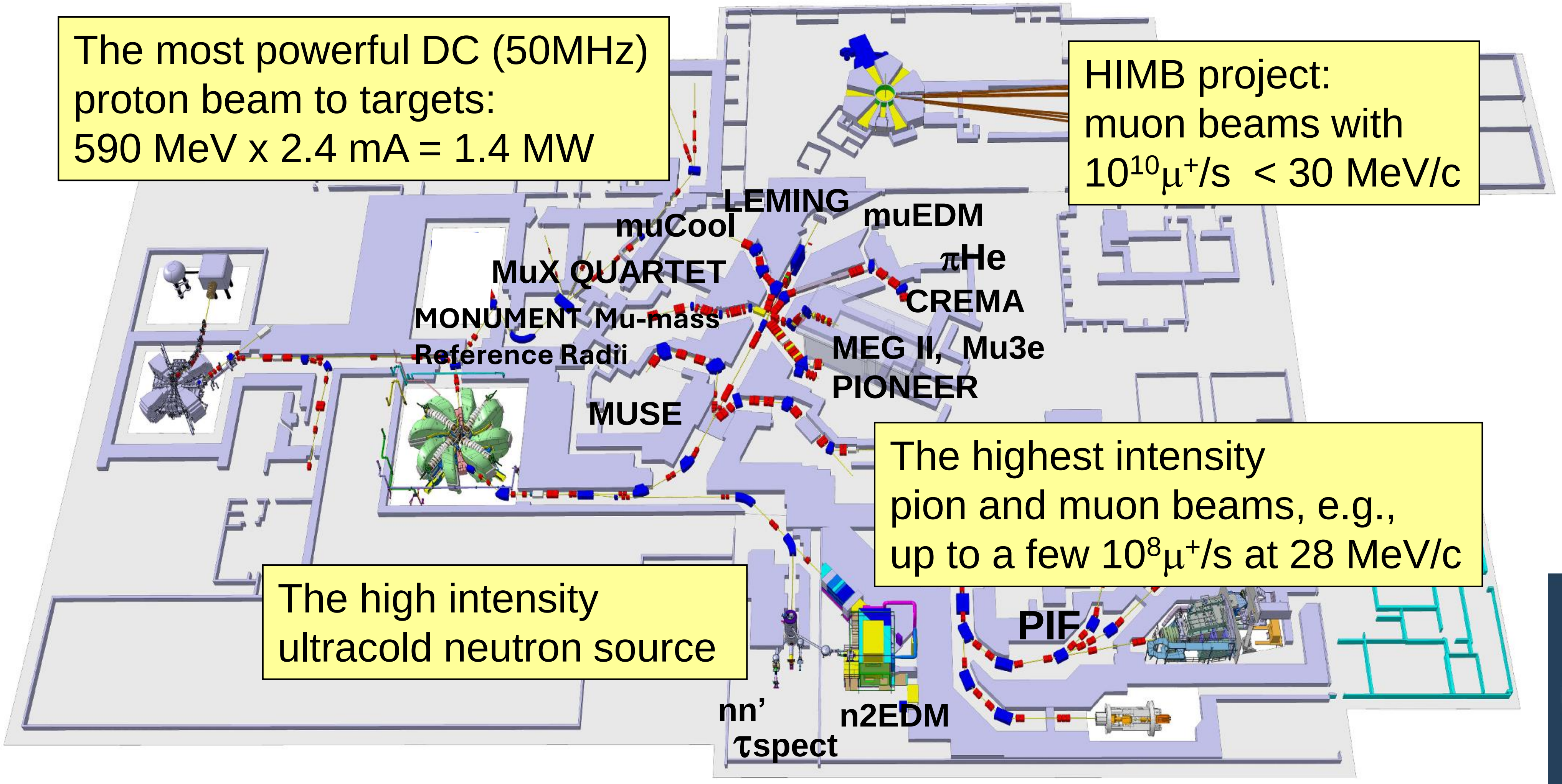
- 01/22 CDR published ✓
- 07/22 Scientific Review ✓
- 12/22 ETH Board: IMPACT for Swiss Roadmap of RIs 2023 ✓
- 2022-24 PSI funds pre-project ✓
- 12/24 Swiss parliament decision about funding 2025-28 ✓
- 08/28 start HIMB
- 08/30 start TATTOOS



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

The intensity frontier at PSI: π, μ, UCN

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



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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

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

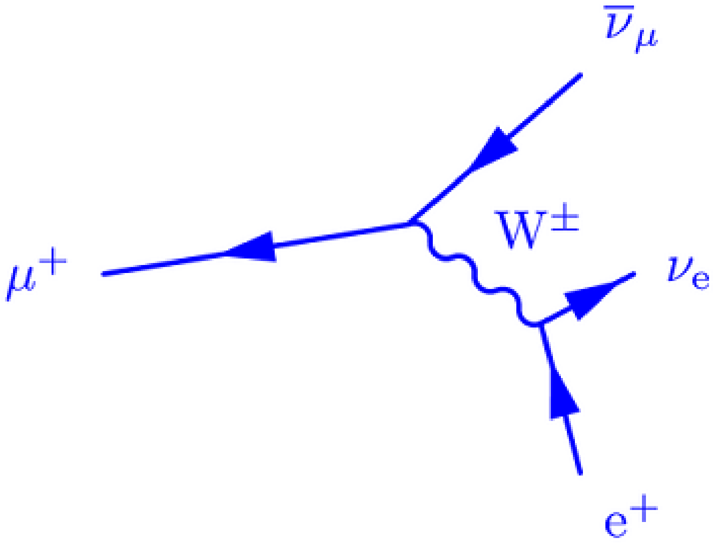
Low-energy precision (PSI) particle physics …

in 5 examples, relevant to

Weak Interactions, QED, QCD, cLF, gravity, (…)

Example 1

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



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

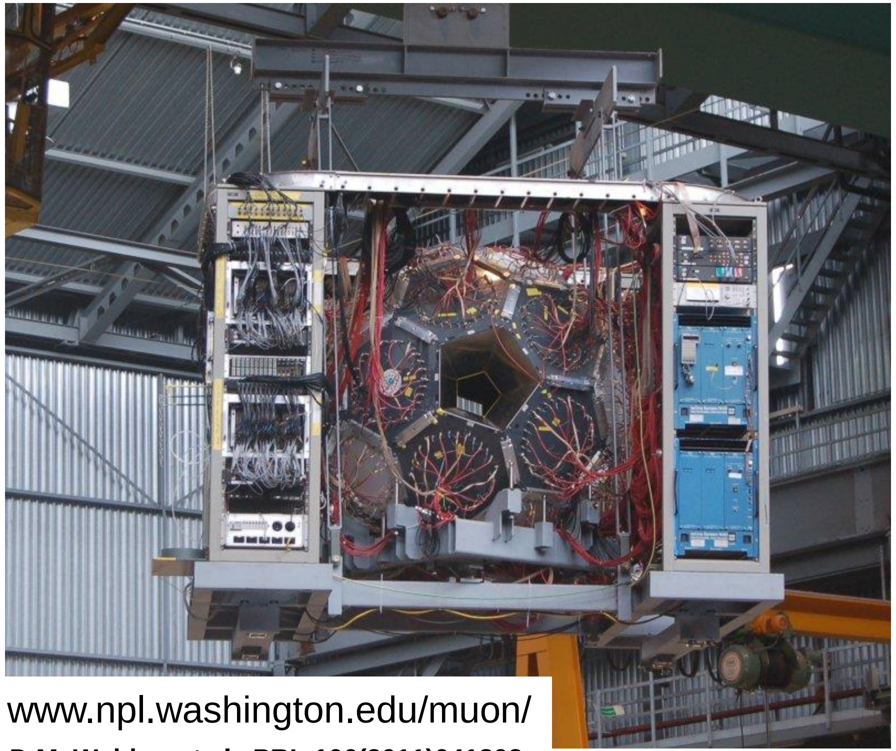
The Weak coupling constant G_F

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:

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

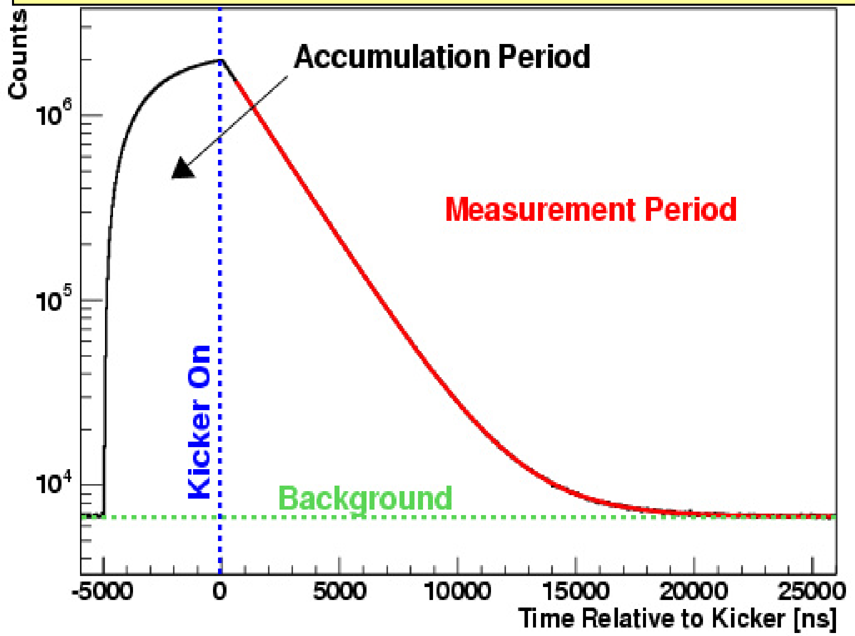


www.npl.washington.edu/muon/

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)



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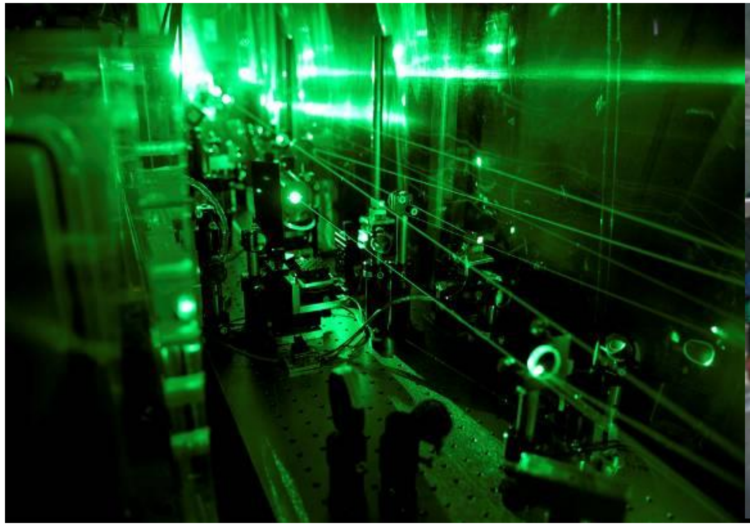
MuLan: Illinois, Kentucky, Boston, J.Madison, Regis, Wesleyan, PSI,KVI

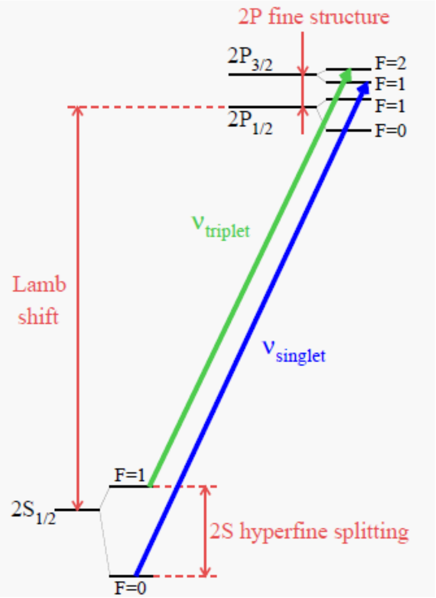
Example 2: Light nuclear charge radii for QED and nuclear theory

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

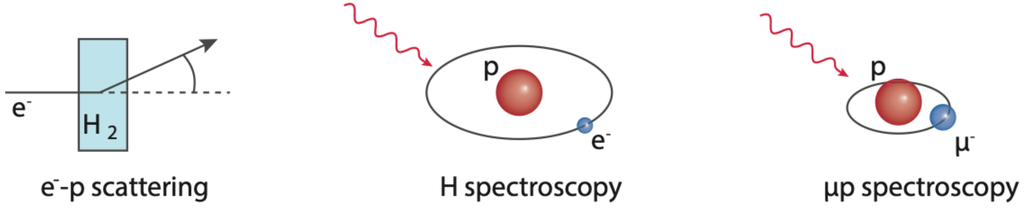
Comparison with QED at a level of 10^{-12} is limited by the knowledge of the proton and alpha charge radii

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.

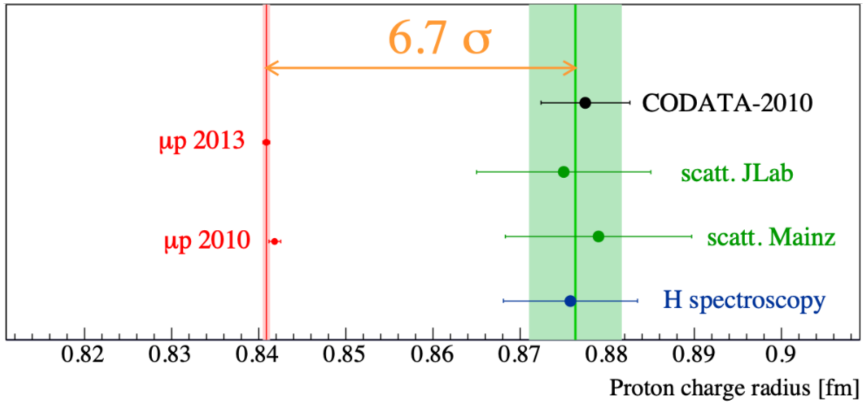




The proton radius puzzle from 2010 on



2010

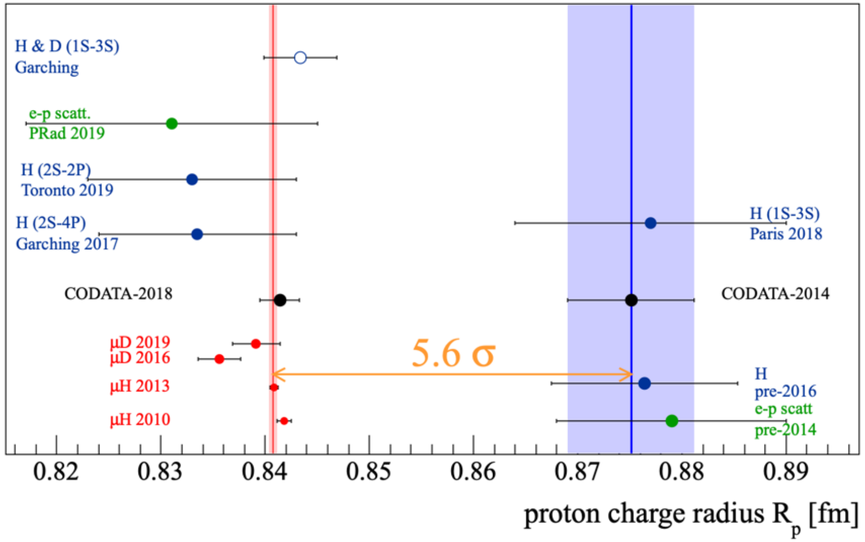


Numerous theoretical investigations of BSM physics and proton structure were performed but no solution for this tension was found

More than 1000 citations

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

2021



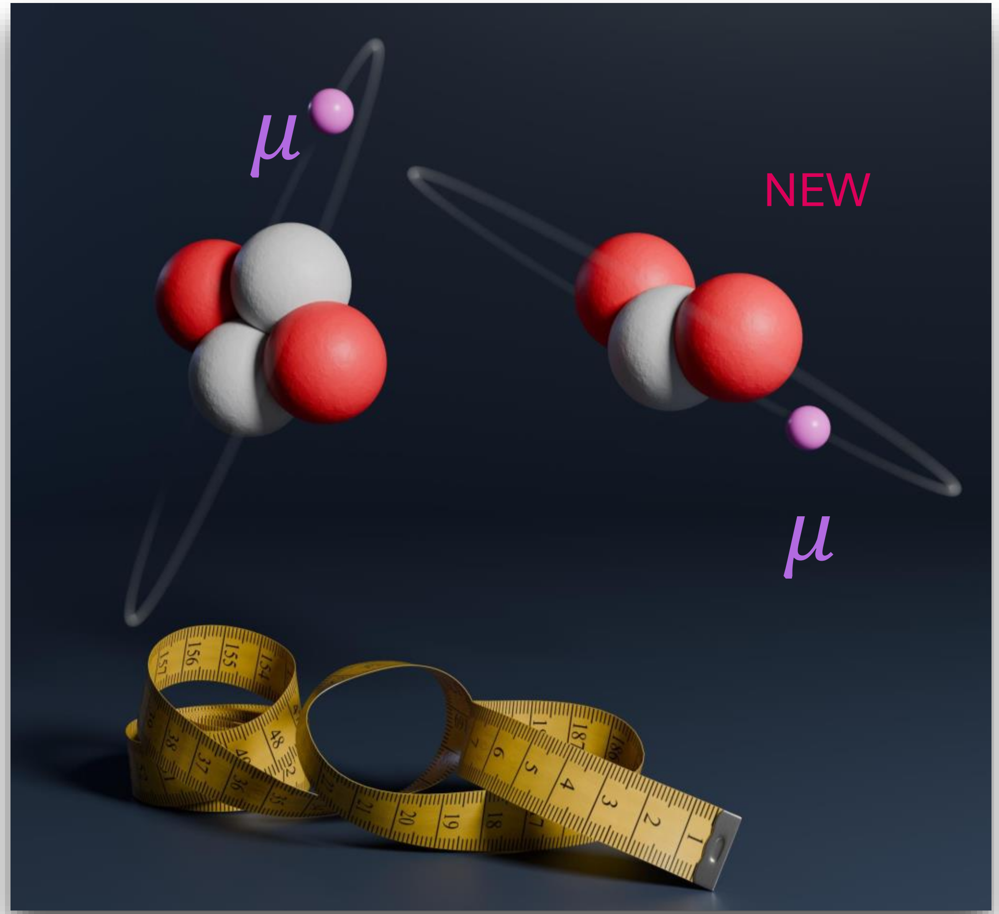
Four (out of five) of the new experiments confirm the small proton radius from muonic hydrogen

A. Antognini, R. Pohl et al.

The helion charge radius from laser spectroscopy of $\mu^3\mathrm{He}^+$

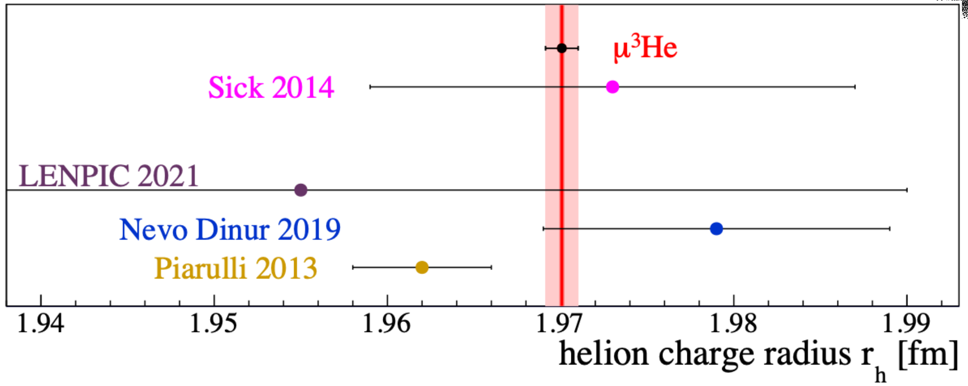
PSI

The **CREMA** collaboration
arXiv:2305.11679
Science 388(2025)854

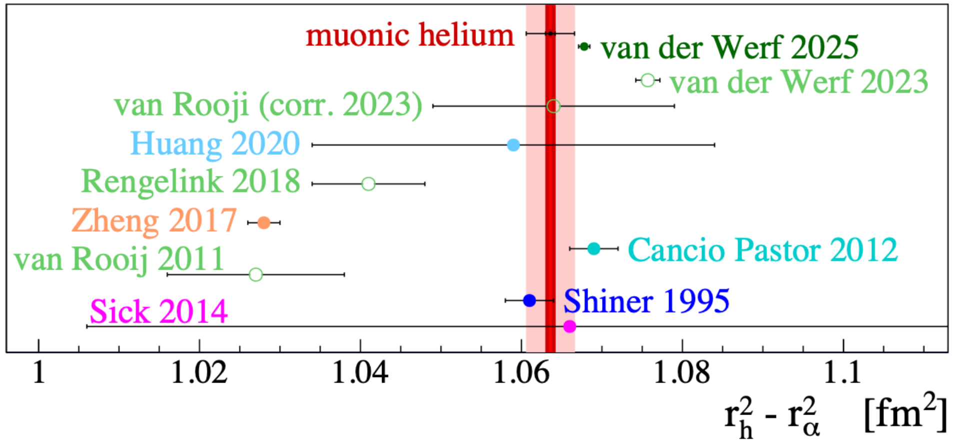


Courtesy: Aldo Antognini, ETHZ&PSI

https://www.psi.ch/en/news/media-releases/new-standards-in-nuclear-physics



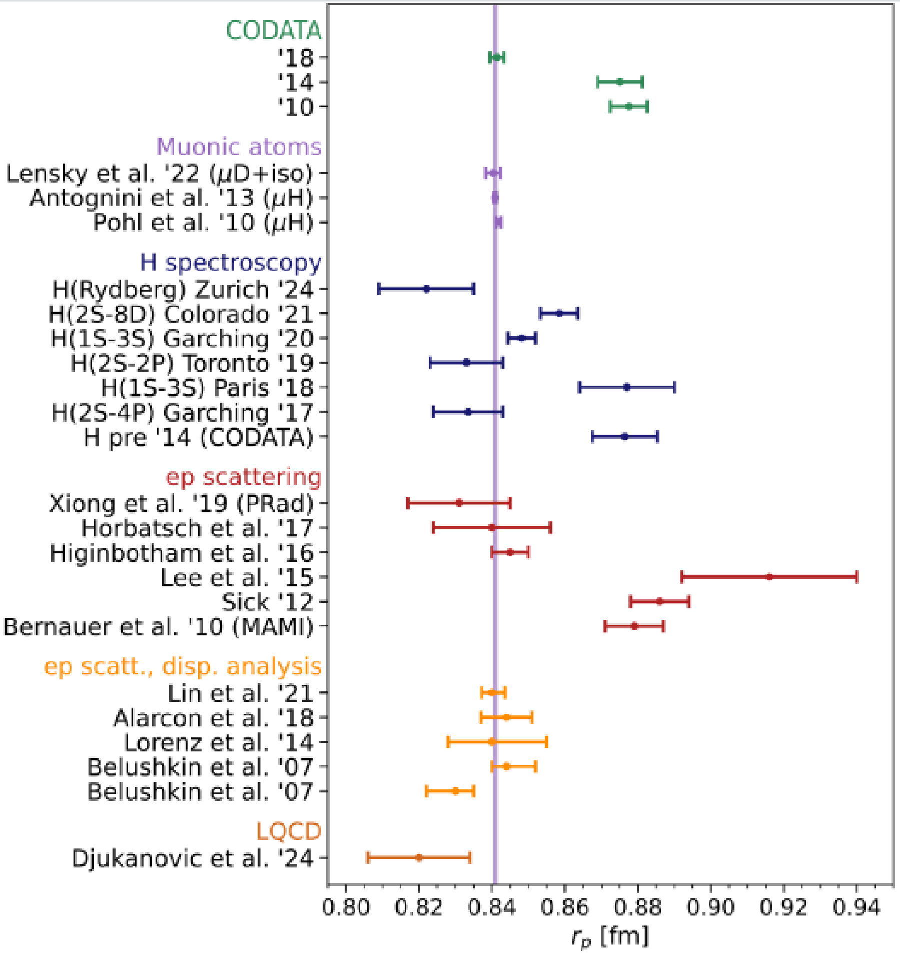
- Benchmarks for nuclear ab initio theories and the systematic development of nuclear potentials
- Two-body QED test when combined with upcoming He^+ measurements



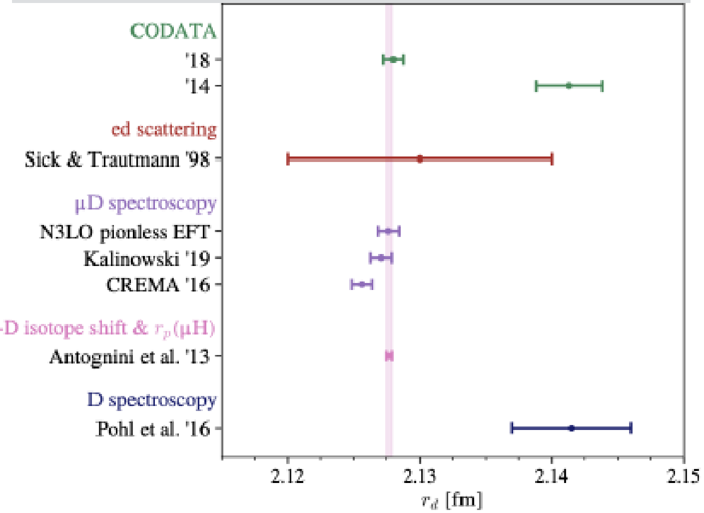
- The resulting isotopic shift plays a pivotal role in understanding the currently intriguing 9σ discrepancies in He ionization energies, which challenge three-body QED calculations

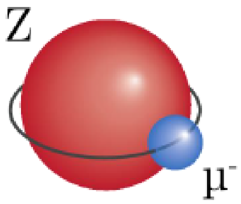
PSI CREMA collaboration

Proton radius (2010, 2013)

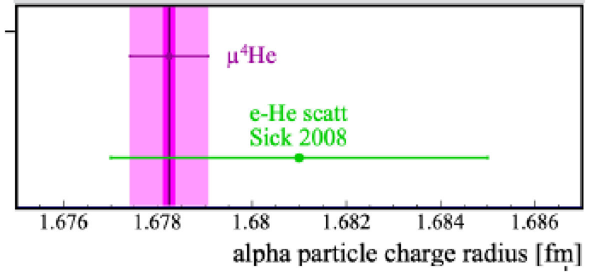


Deuteron radius (2016)

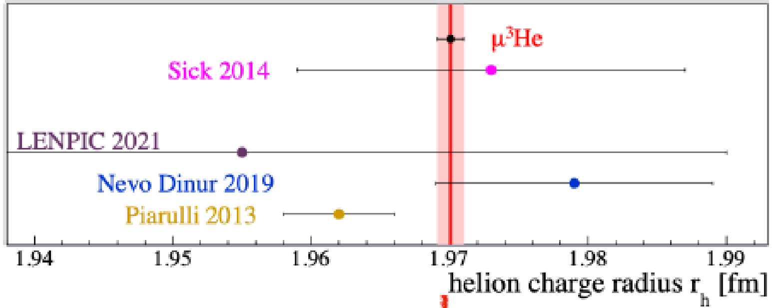


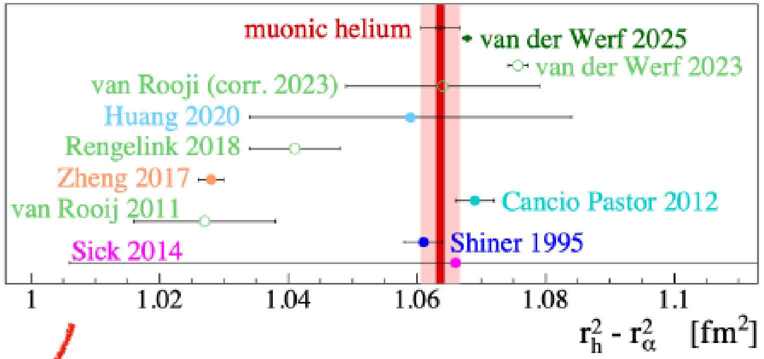


^{4}He radius (2021)

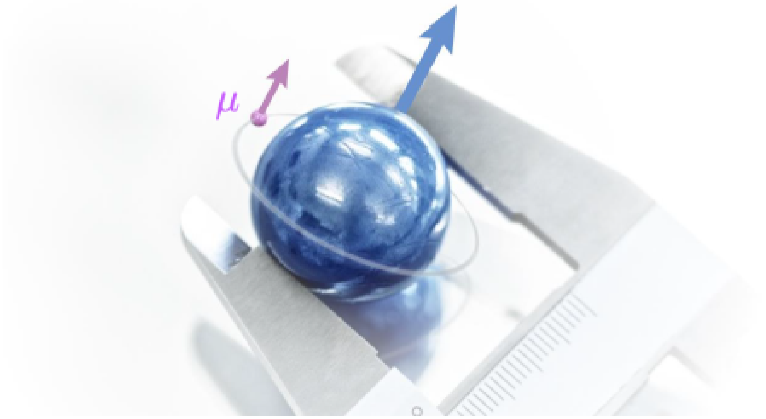


^{3}He radius (2024)





1S-HFS (2026)



2030

Aldo Antognini

Example 3

Measurement of the charged pion mass (or perhaps a test of QED?)

M. Trassinelli et al. / Physics Letters B 759 (2016) 583–588

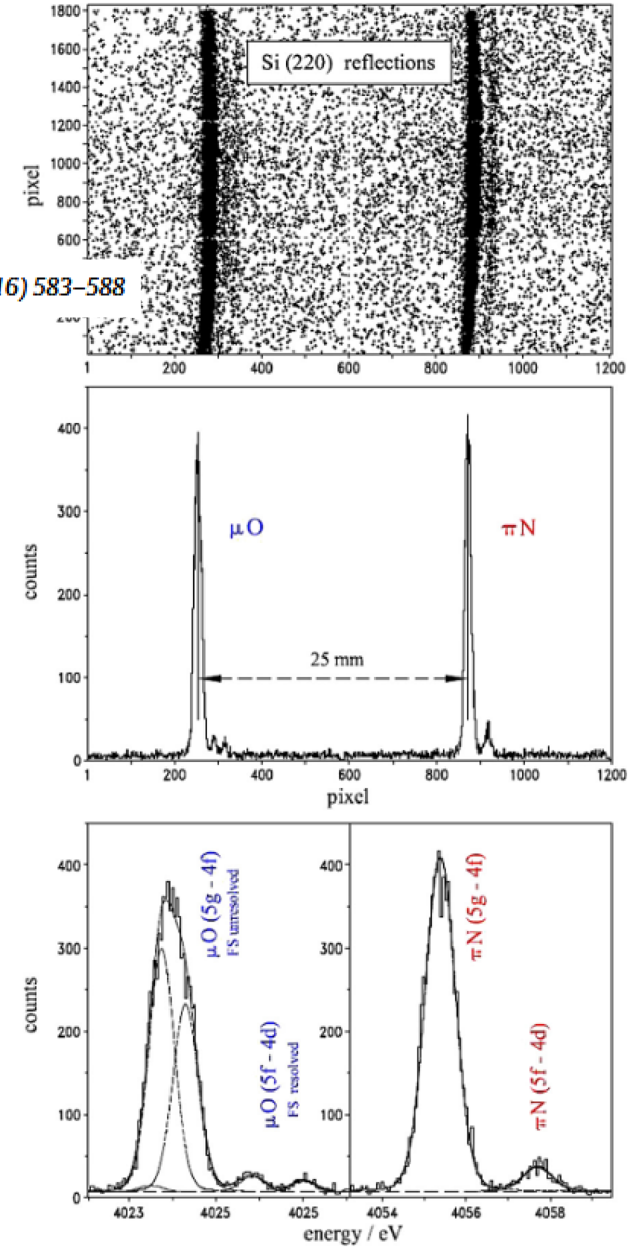


Fig. 1. Simultaneously measured $(5g-4f)$ transitions in muonic oxygen (calibration) and pionic nitrogen. Top: Distribution of the Bragg reflections on the surface of the 2×3 CCD array. The binning corresponds to the pixel size of the CCDs (note the different scales vertically and horizontally). Straight dashed lines indicate CCD boundaries. Middle: Projection on the axis of dispersion after correction for curvature (see text). Bottom: Details of the fit to line patterns.

PHYSICAL REVIEW LETTERS **130,** 173001 (2023)

Proof-of-Principle Experiment for Testing Strong-Field Quantum Electrodynamics with Exotic Atoms: High Precision X-Ray Spectroscopy of Muonic Neon

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Precision measurements of pionic x rays with gas targets employing a cyclotron trap and a crystal spectrometer have been carried out at relatively high pressures around 1 atm [23]. In the updated experiment by Trassinelli *et al.* [24], the pionic x rays from πN were measured together with the muonic x rays from μO, which were located close to the target pionic line and used as a reference for energy calibration under the assumption that the calculated BSQED contribution was correct. They could, in principle, achieve a QED test with a 1%-level accuracy by calibrating the μO lines against the Cu $K\alpha$ line, which was measured simultaneously as a stability monitor, although they did not discuss this aspect.

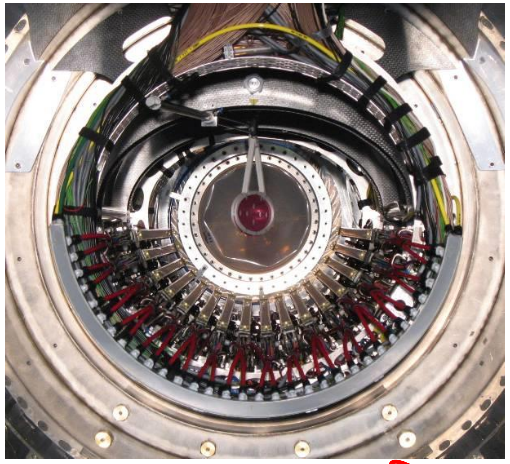
Example 4: Charged lepton flavor in muon decay

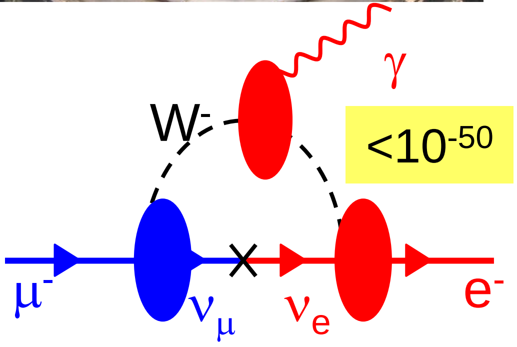
The decay of a positive muon into a positron and a photon (or $e^+ e^-$ pair) violates charged lepton flavor

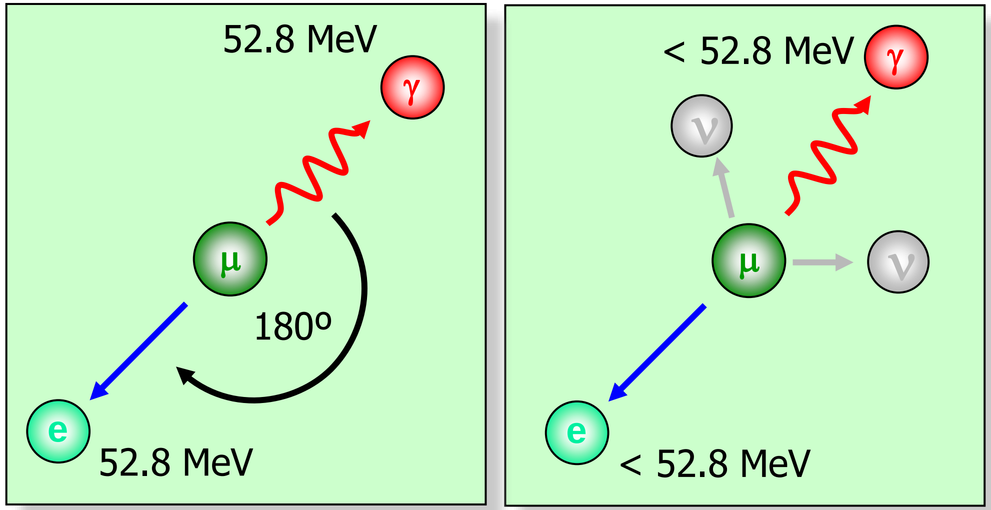
Neutral leptons violate lepton family number

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

PSI

The present best limits on cLFV with muons

$\mu^+ \rightarrow e^+ e^+ e^-$

BR < 1 x 10^{-12}
SINDRUM 1988

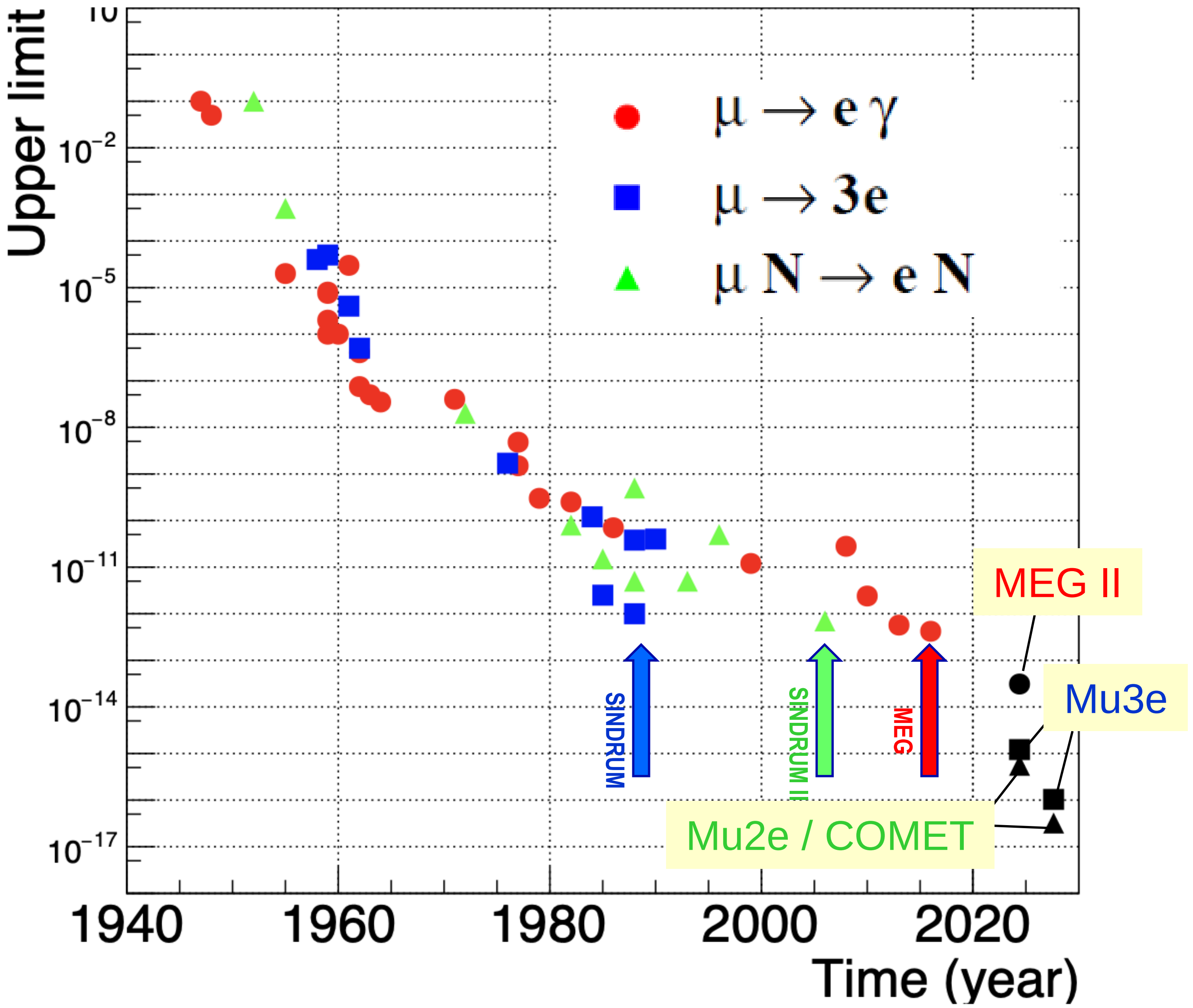
$\mu^- + Au \rightarrow e^- + Au$

BR < 7 x 10^{-13}
SINDRUM II 2006

$\mu^+ \rightarrow e^+ + \gamma$

BR < 1.5 x 10^{-13}
MEG 2013, 2016,
MEG II 2023, 2025

[90 % C.L.]



See: Review of Particle Physics at PSI, SciPost Phys. Proc. 5 (2021), https://scipost.org/SciPostPhysProc.5; https://arxiv.org/abs/2504.15711

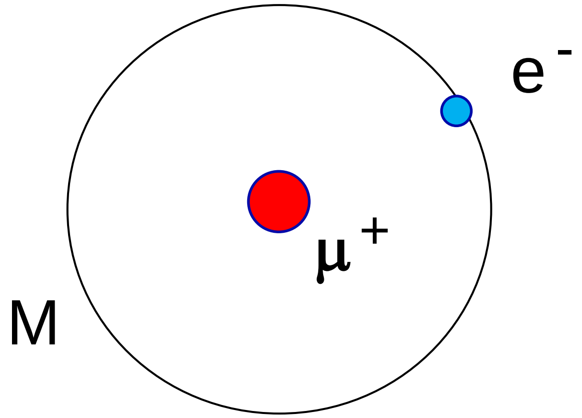
(Last) Example 5

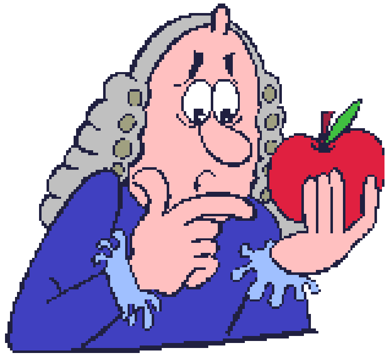
We do not yet know how an ultimate quantum theory of gravity will look like

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

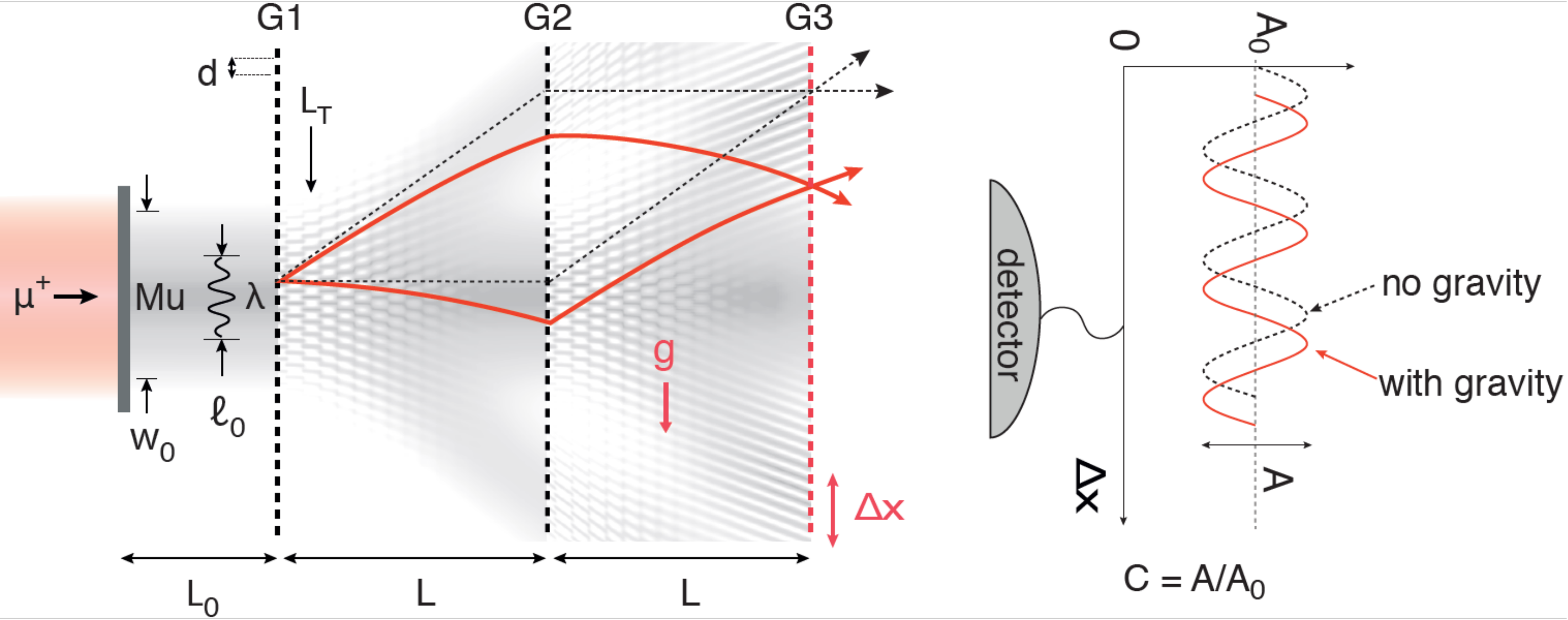
PSI

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

Thank you!

- At PSI, we provide highest intensities of low-momentum muon beams
- We operate seven muon beams simultaneously for a diverse program in particle physics and materials
- The beams at low momenta are continuous, at higher momenta one can use the 50MHz RF structure
- We are preparing for a 1.5 year long shutdown to replace a target station and implement two high-intensity muon beams