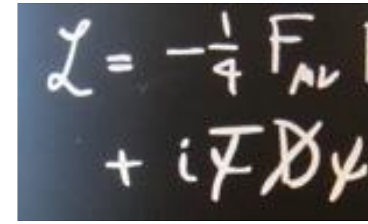
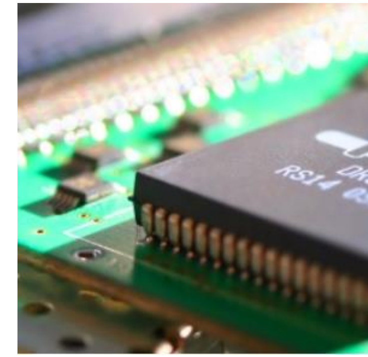
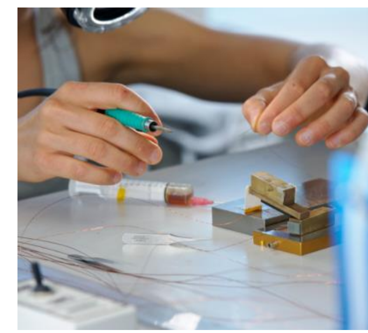
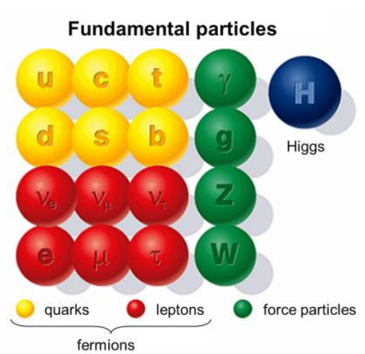


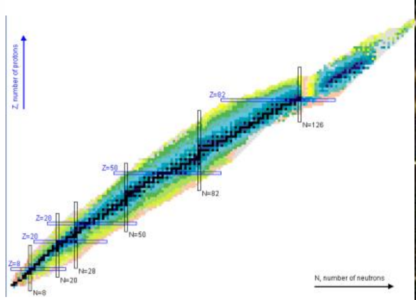


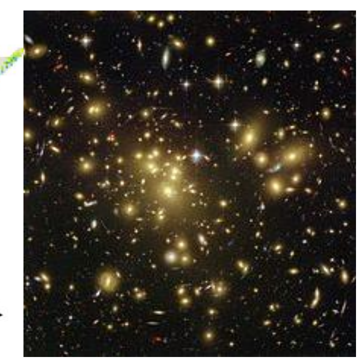
Overview of particle physics at PSI

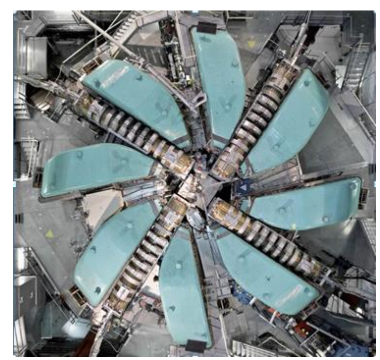


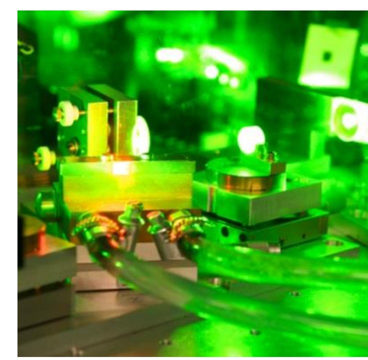
K.Kirch, ETH Zurich – PSI Villigen, Switzerland











PSI Laboratory for Particle Physics

LTP-Groups

- Theory
- High Energy Physics
- Muon Physics
- Ultacold Neutrons
- Electronics for Measuring Systems
- Detectors, Irradiation and Applied Particle Physics
- Electronics vocational training

Academic links to universities: common professorships and teaching

Discovery Physics at high and low energies

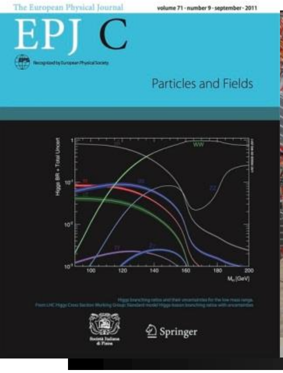
- **Precision measurements** (MuLan, CREMA, MuCap, MuSun, MUSE ..) **and searches for new physics** (MEG II, Mu3e, n2EDM, ...) **at PSI**
- **At LHC: Participation and key contributions to CMS** (Si-pixel and data analysis, e.g. B-$\mu\mu$ at PSI)
- **Particle phenomenology**

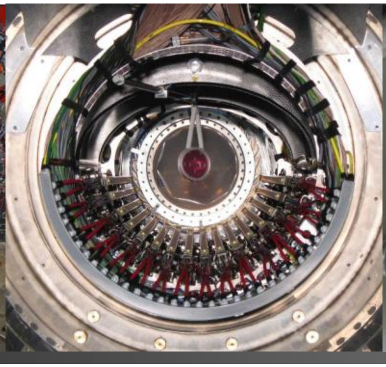
Collaborations with

- all Swiss universities
- many universities and institutions world-wide

Outreach and Spin-off

- Detectors (pixel, gas and scintillation) for particle physics; n, μSR, x-rays
- Chip design, electronics and software for PSI and world-wide, e.g. DRS-4, elog, Midas, ...
- Irradiation using p, π, μ, e
- Zuoz schools (2020: 25th!)
- PSI20xy workshop: PSI2021



PAUL SCHERRER INSTITUT

Zuoz Summer School 9-15 August 2020

Nicolas Berger (Annecy)
Statistics
Jamie Boyd (CERN)
From raw data to physics
Vincenzo Cirigliano (Los Alamos)
EFT and low-energy probes of new physics
Barbara Jäger (Tübingen)
Perturbative (QCD) calculations
Angela Papa (Pisa/PSI)
Low-energy experiments
Renato Renner (ETH)
Foundations of quantum mechanics
Andrea Wulzer (Padova)
The big questions

Vision and Precision

https://www.psi.ch/particle-zuoz-school

Registration open!

Program Committee:
A.Bay, G.Dissertori, G.Iacobucci, G.Isidori, K.Kirch, U.Langenegger, R.Rattazzi, N.Serra, A.Sfyrla, A.Signer, M.Spira, R.Wallny, M.Weber

Adrian Signer, Michael Spira, Anita van Loon-Govaerts, **zuoz2020@psi.ch**

CHiPP Swiss Institute of Particle Physics

sc|nat Swiss Academy of Sciences
Akademie der Naturwissenschaften
Accademia di scienze naturali
Académie des sciences naturelles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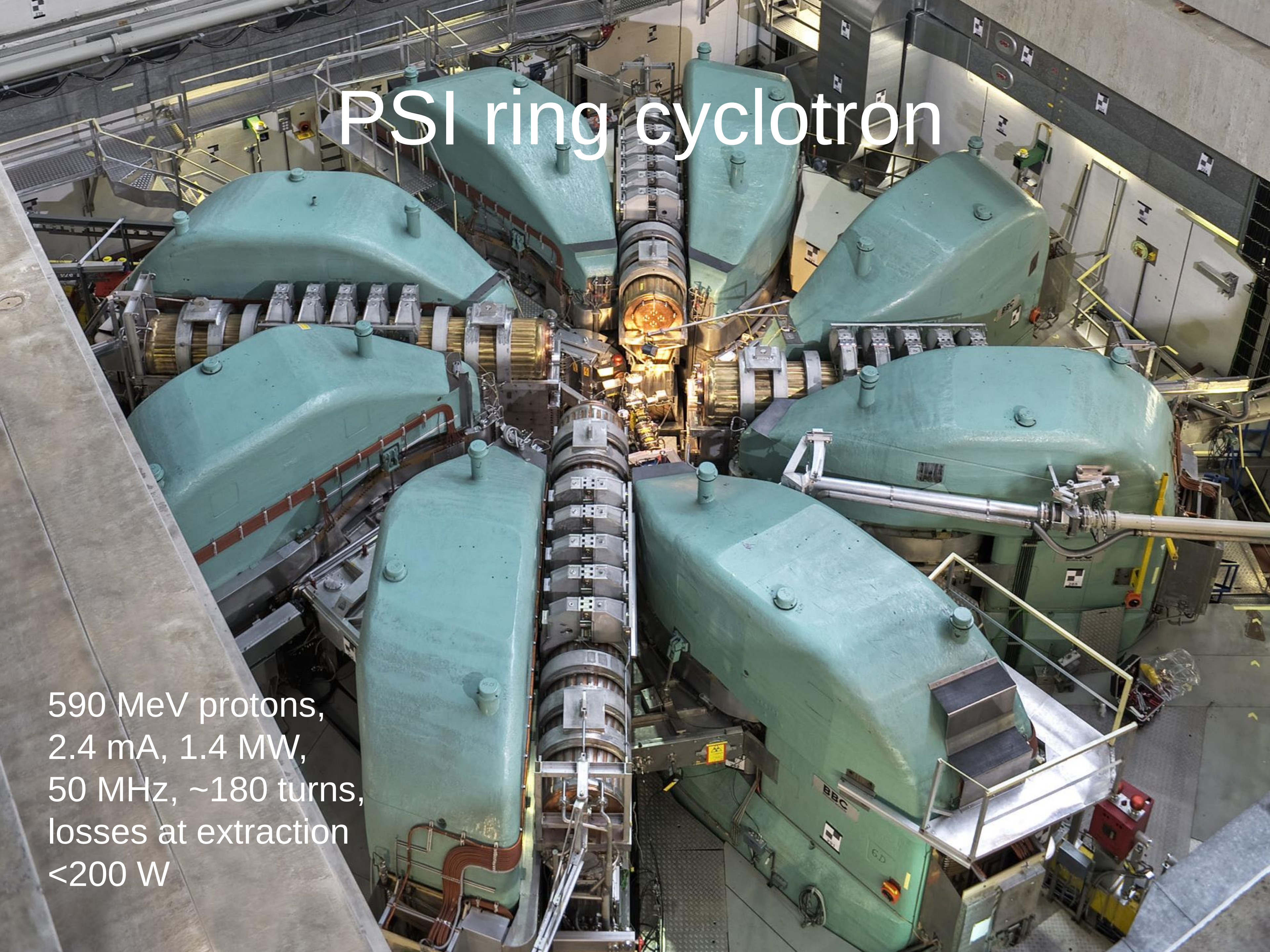
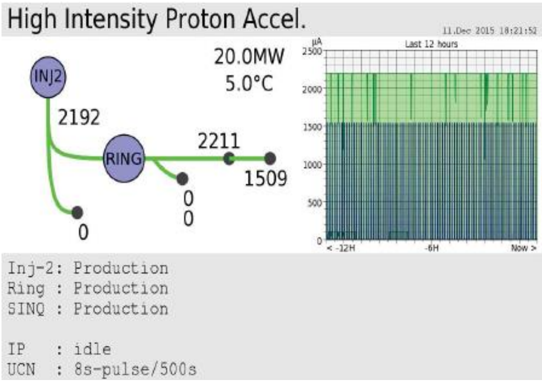
CERN
Genève (Geneva)
ITALY
Lugano
Lake Como
Lake Maggiore
ITALY
FRANCE
Milan

PSI ring cyclotron

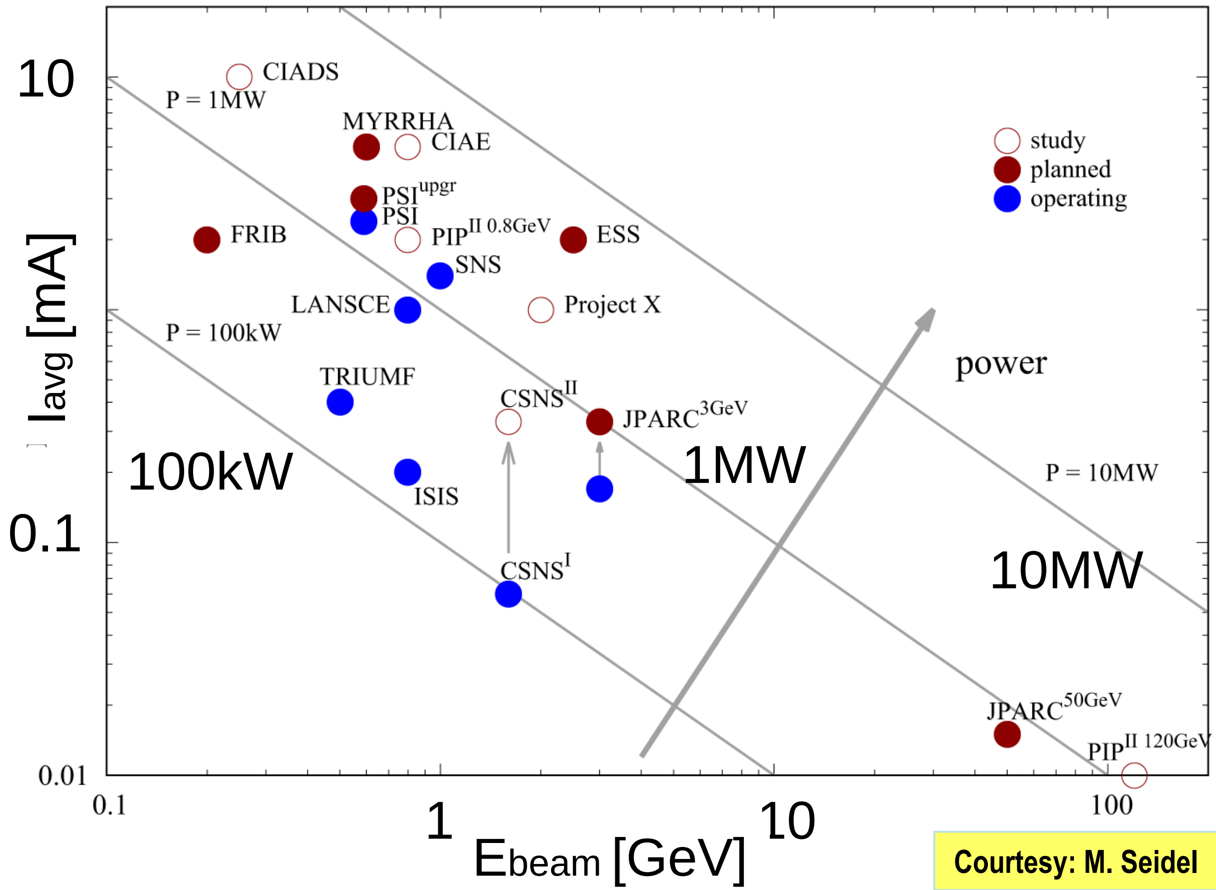


590 MeV protons,
2.4 mA, 1.4 MW,
50 MHz, ~180 turns,
losses at extraction
<200 W

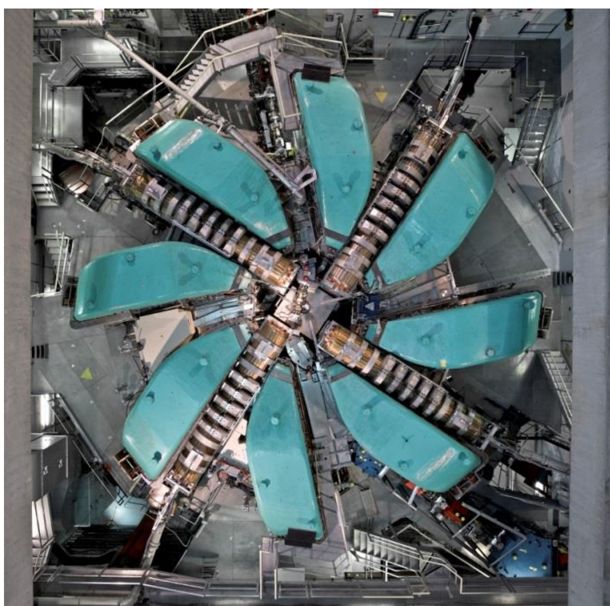
PSI ring cyclotron



The most powerful
proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW



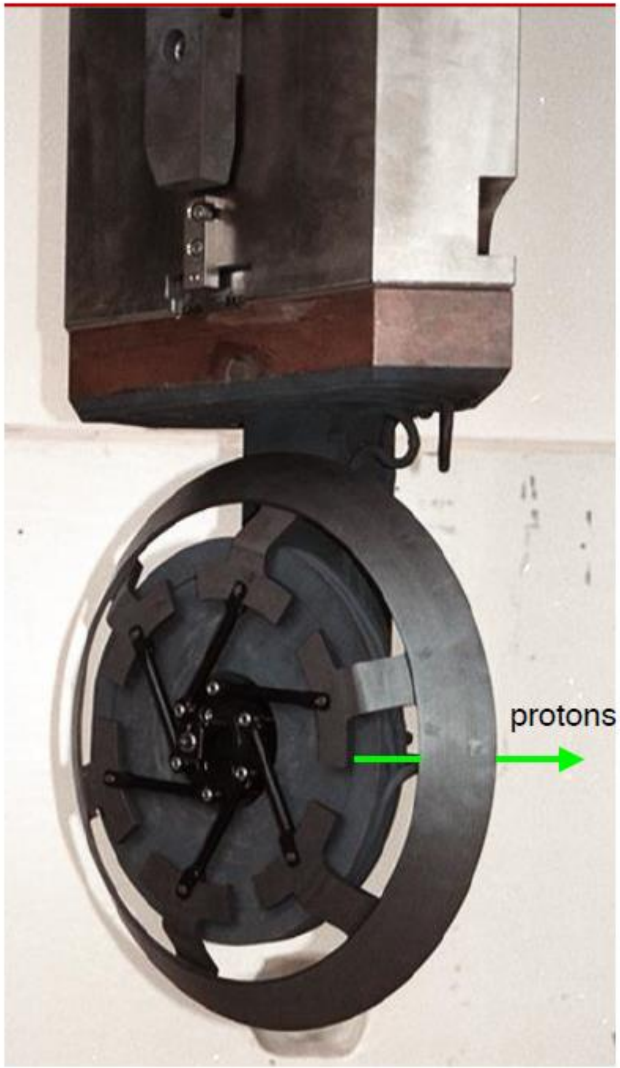
Courtesy: M. Seidel



HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions at low momenta and of ultracold neutrons.

Muon Production Target TgE

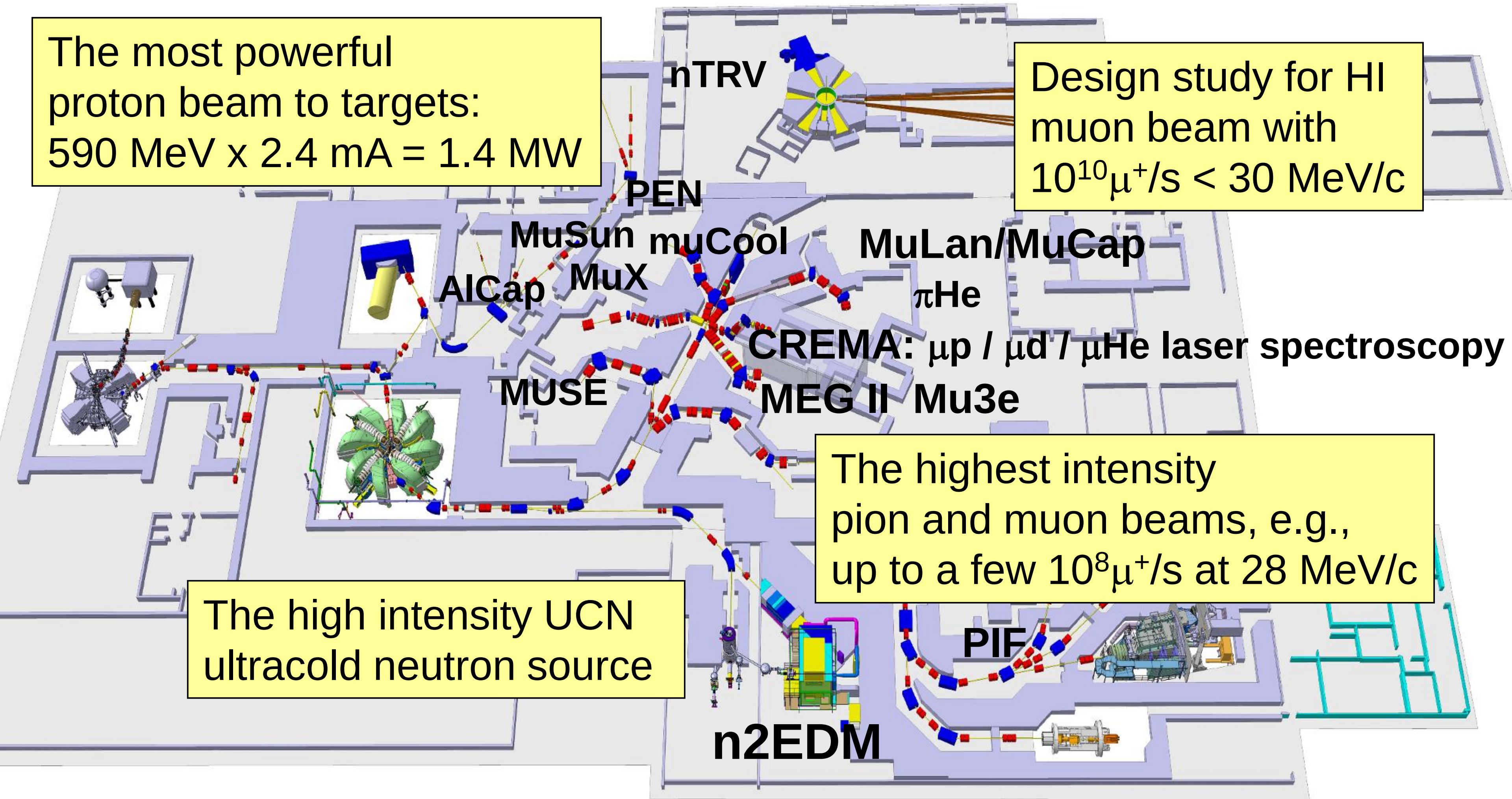
- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiation cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)



⇨ Up to 5×10^8 μ^+/s (depending on beam line)

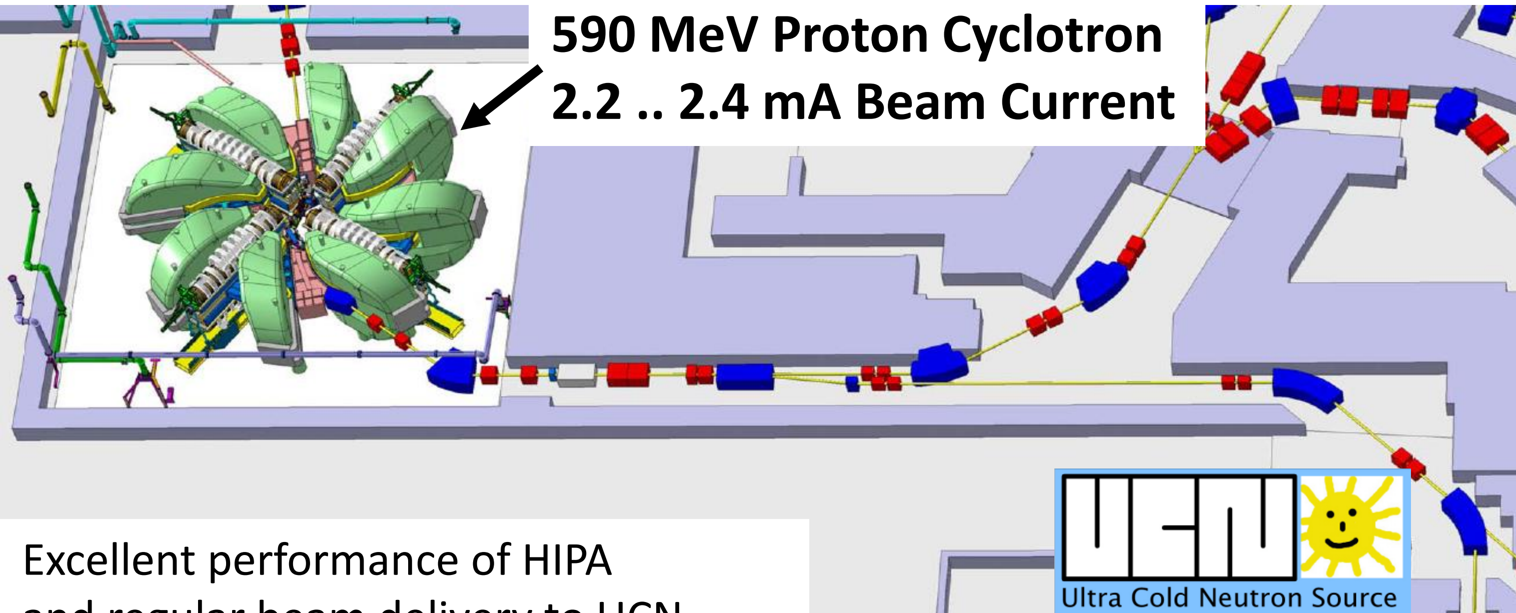
The intensity frontier at PSI: π, μ, UCN

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

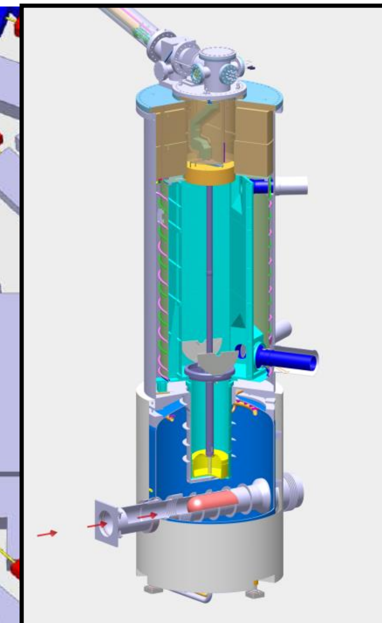


Swiss national laboratory with strong international collaborations

Ultracold Neutron Source & Facility

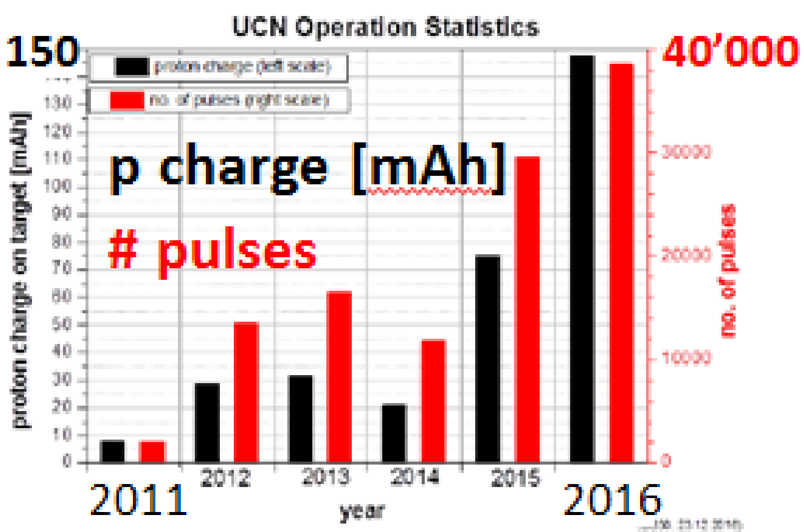


590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current



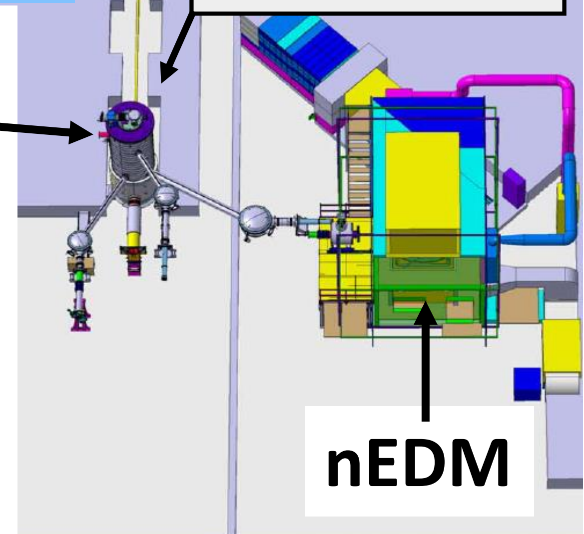
Ultra Cold Neutron Source

Excellent performance of HIPA
and regular beam delivery to UCN



UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
- UCN to nEDM 2012-17
  -> intensity 90x over 2010
- Increased duty factor 2015+:
  20 → 60 μA average
- Setting up n2EDM

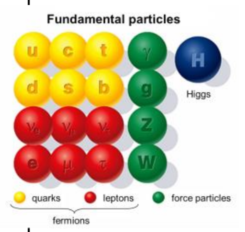


nEDM

The weak coupling constant G_F

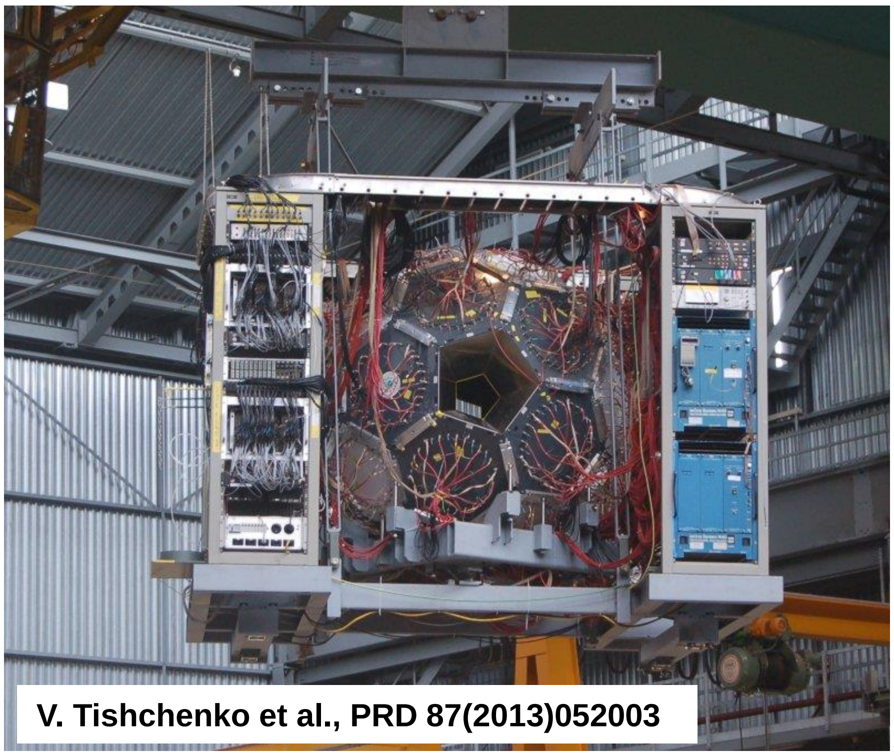
Fundamental electro-weak parameters of the Standard Model

α	G_F	m_Z
0.00037ppm	4.1 → 0.5 ppm	23ppm



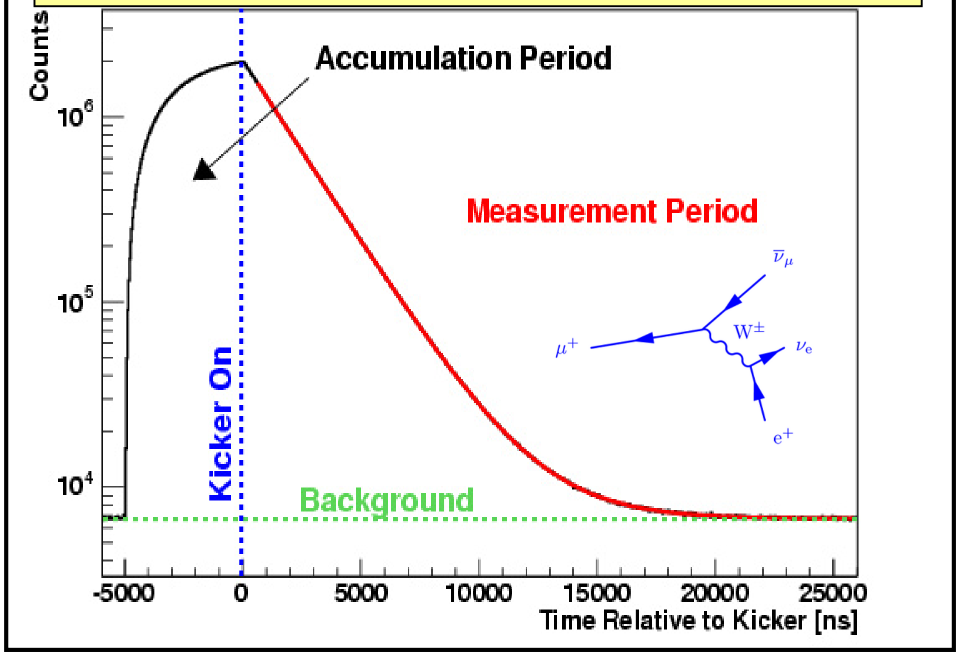
MuLan: The most precise measurement of any lifetime:

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



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

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

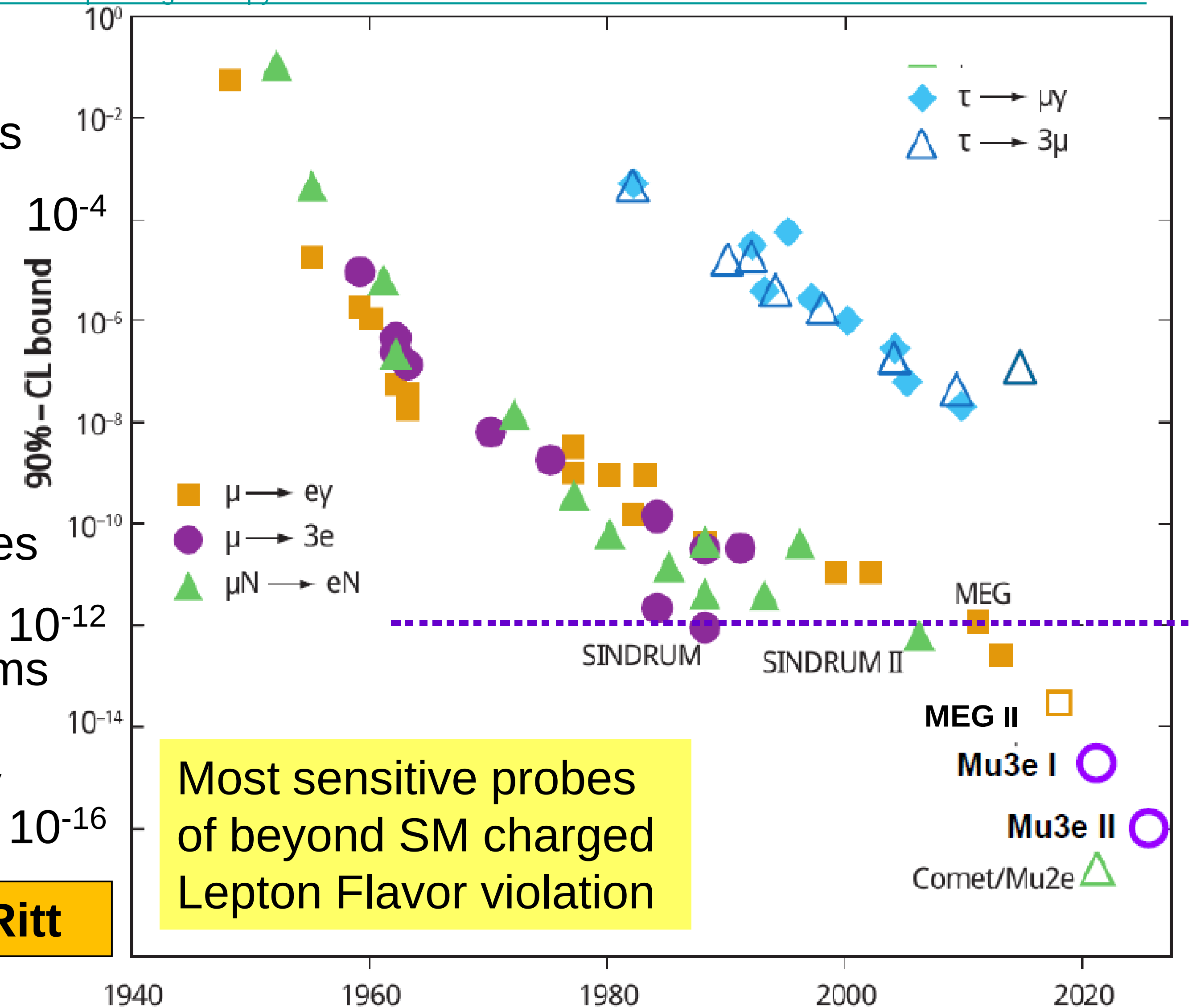


$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

Search for cLFV

Mu3e R-12-03, see A.Schöning http://indico.psi.ch/getFile.py/access?contribId=5&sessionId=2&resId=0&materialId=slides&confId=5459
MEG II, R-99-05, see T.Mori http://indico.psi.ch/getFile.py/access?contribId=7&sessionId=2&resId=0&materialId=slides&confId=5459

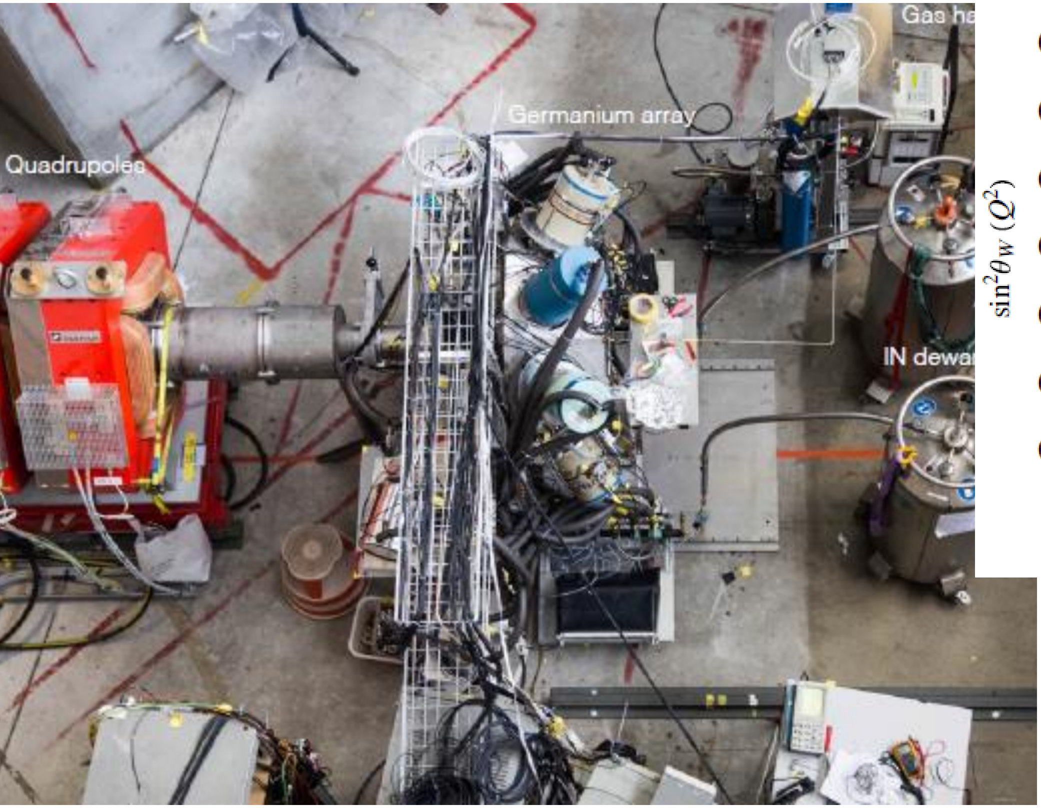
- Present best bounds from experiments at PSI
- New efforts at PSI, FNAL, JPARC aiming at 10-10’000 x improved sensitivities
- Need highest intensity muon beams and unprecedented detector technology

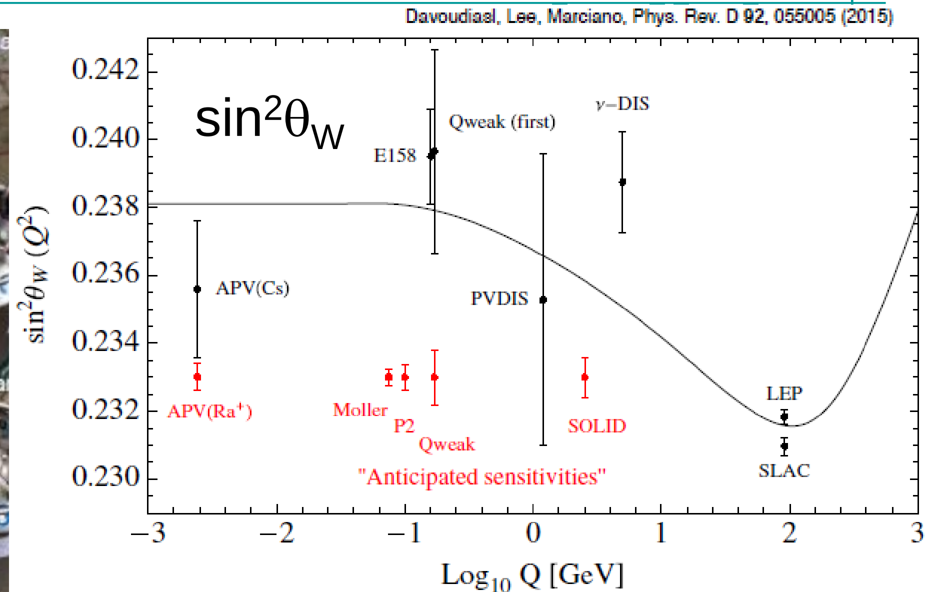


See talk by Stefan Ritt

MuX: charge radius of ^{226}Ra

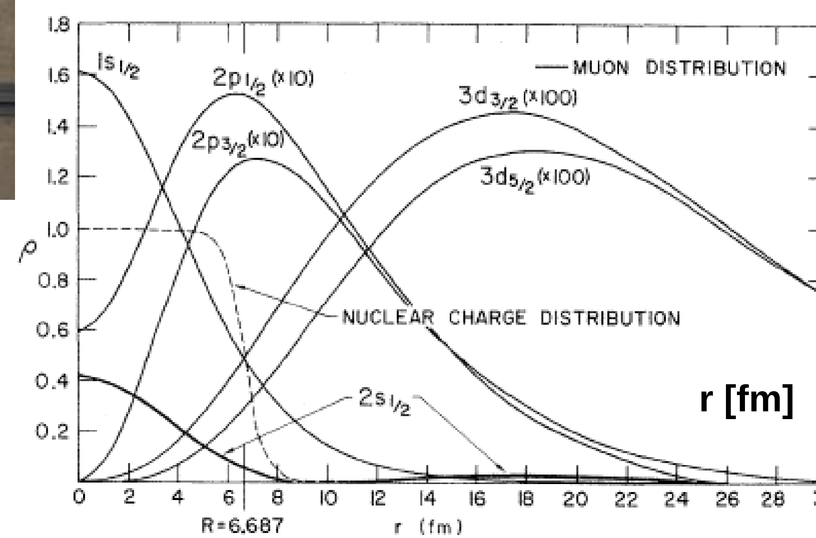
PSI R-16-01, see A.Knecht https://indico.psi.ch/event/6381/contributions/15942/attachments/13549/17502/Andreas_Knecht_-_muX_BVR50.pdf





Lead Z=82

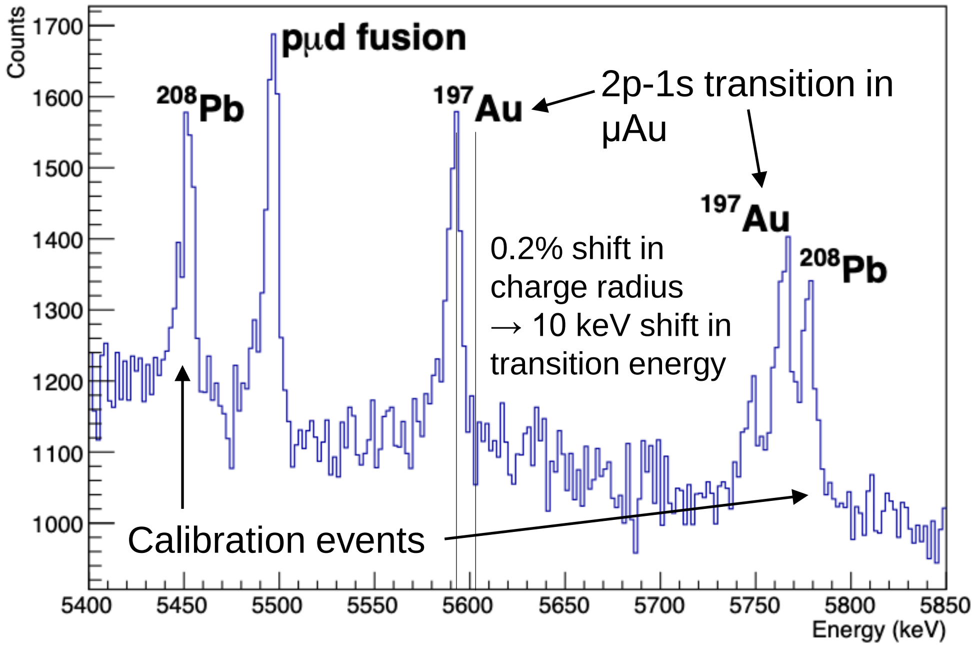
Kessler et al., PRC 11, 1719 (1975)

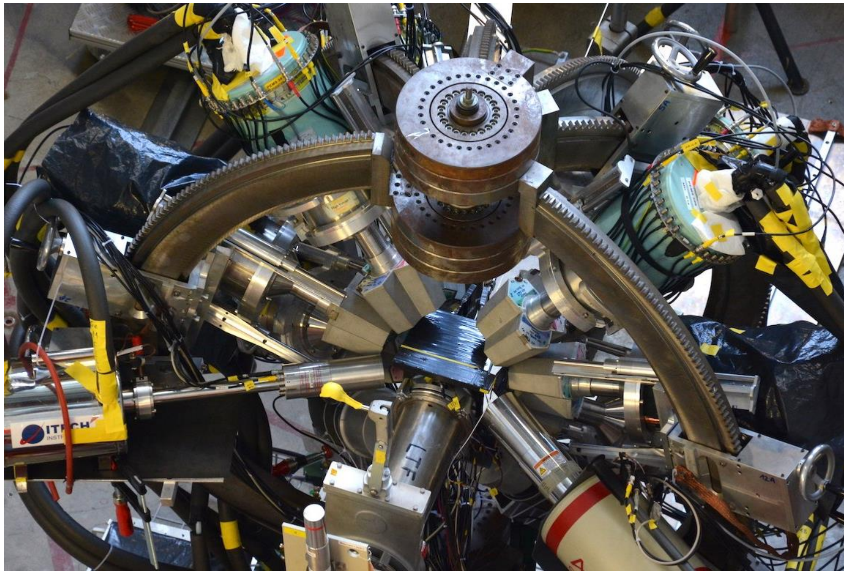


A measurement of the rms charge radius of ^{226}Ra to <0.2% using 5μg target mass.

μ^- stop in 100bar H2, transfer to D admixture and finally to the heavy nucleus, then cascade and emit Xrays up to 6 MeV.

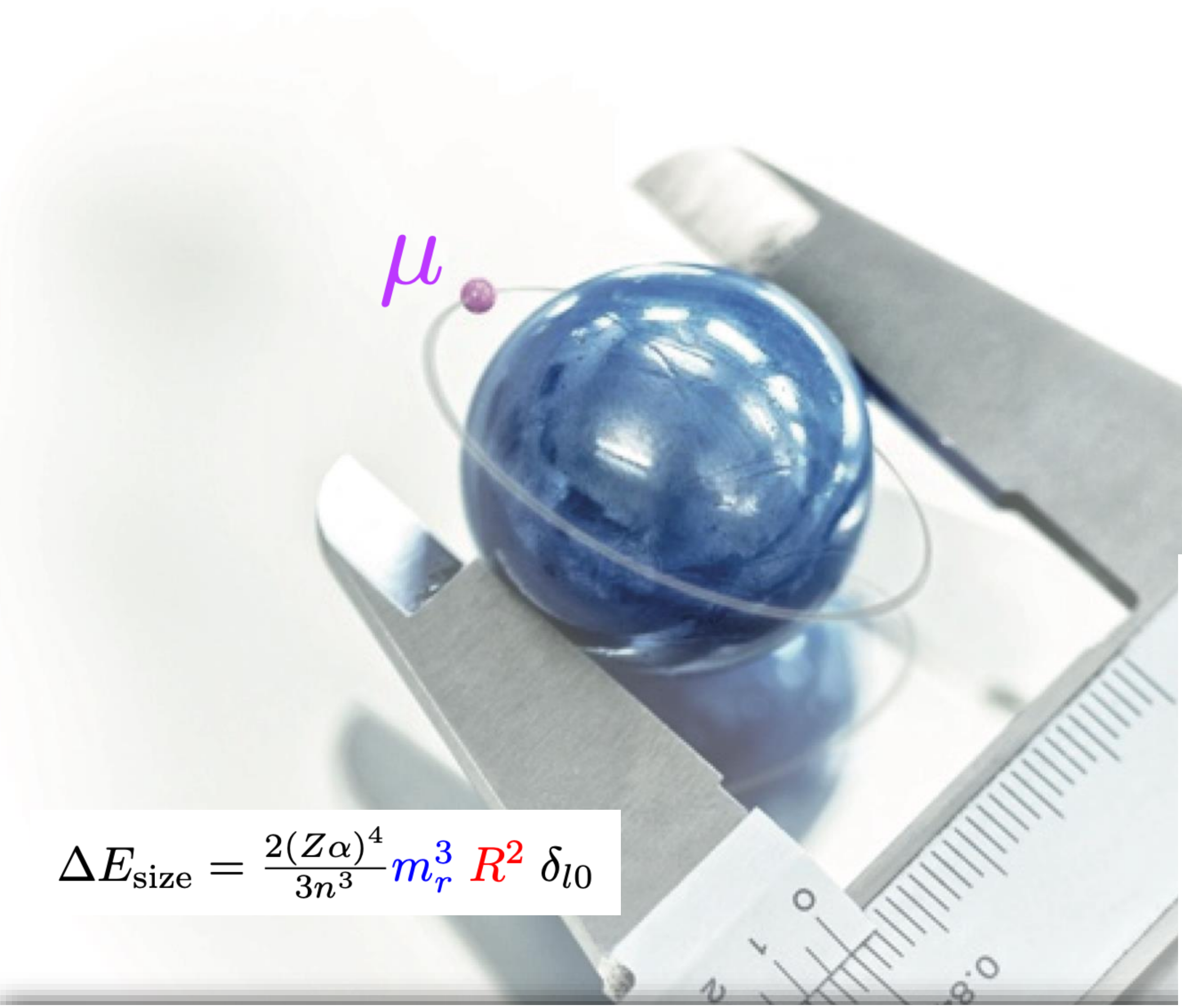
muX Experiment



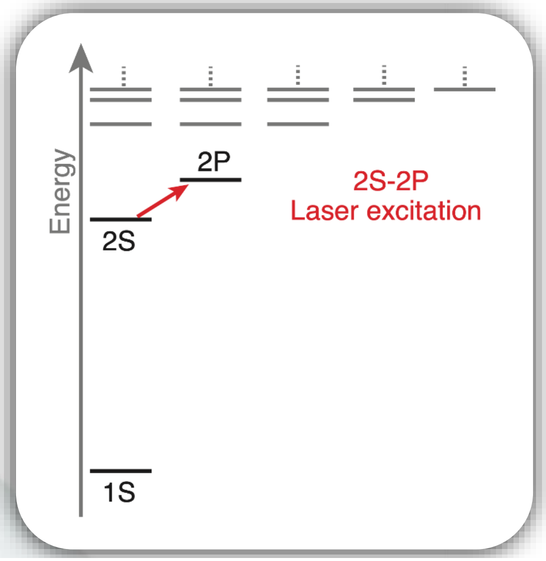


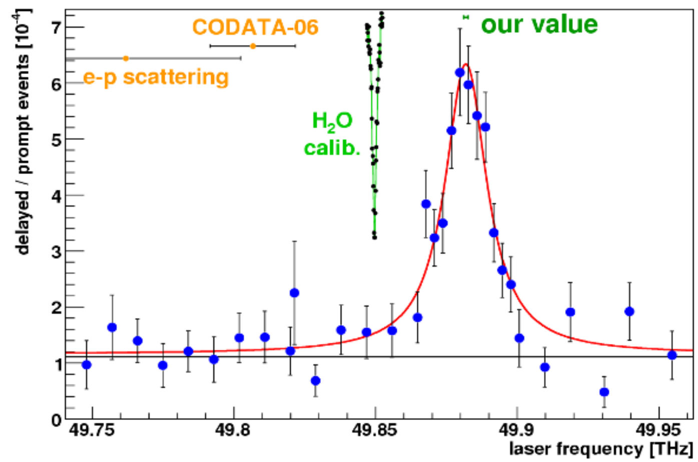
- Method developed using French/UK loan pool germanium detectors
- Proof-of-principle measurement with **5 μg** gold target
- Miniball detector array at PSI in 2019:
  - Measurements of charge radii of ^{248}Cm and ^{226}Ra (relevant for atomic parity violation (APV))
  - Muon capture rate measurements relevant for neutrinoless double beta decay
  - Test of muonic APV measurement by detecting 2s-1s transition
  - Exploring elemental analysis using muons

Laser spectroscopy of light muonic atoms



$$\Delta E_{\text{size}} = \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, R^2 \, \delta_{l0}$$





Measured:
ten 2S-2P transitions in μp, μd, μ^3He^+, μ^4He^+
with 10 ppm accuracy

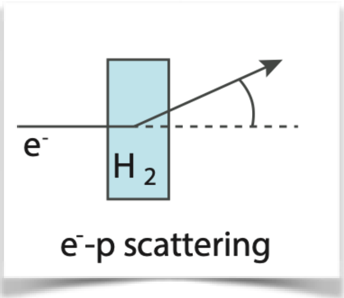
\+

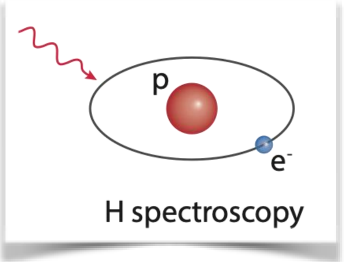
Theoretical predictions:
QED + Nuclear structure

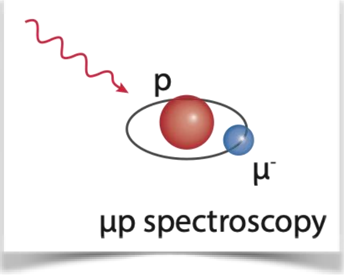
⇨

p, d, ^{3}He, ^{4}He
charge radii
with 10^{-3} red. acc.

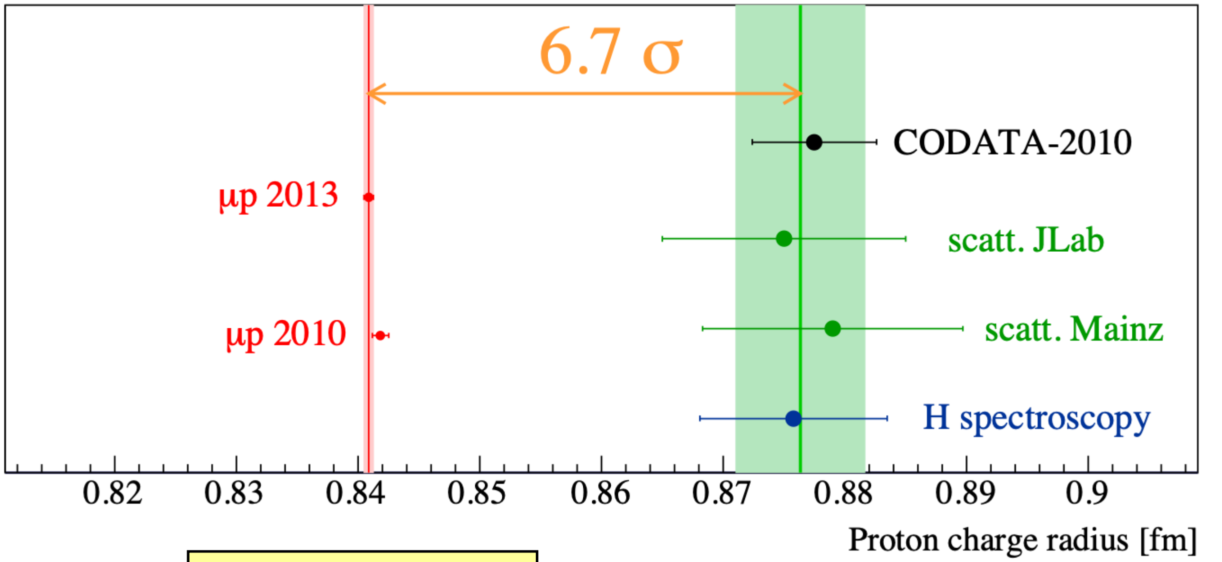
The proton radius puzzle







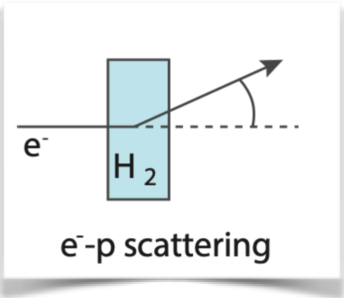
2010

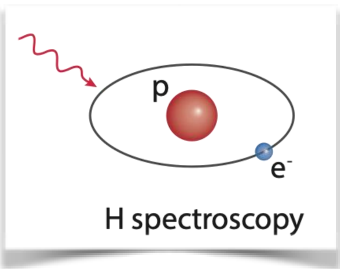


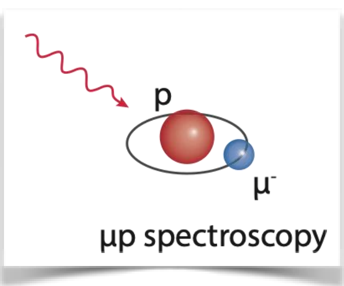
r_p=0.84087(39) fm

Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

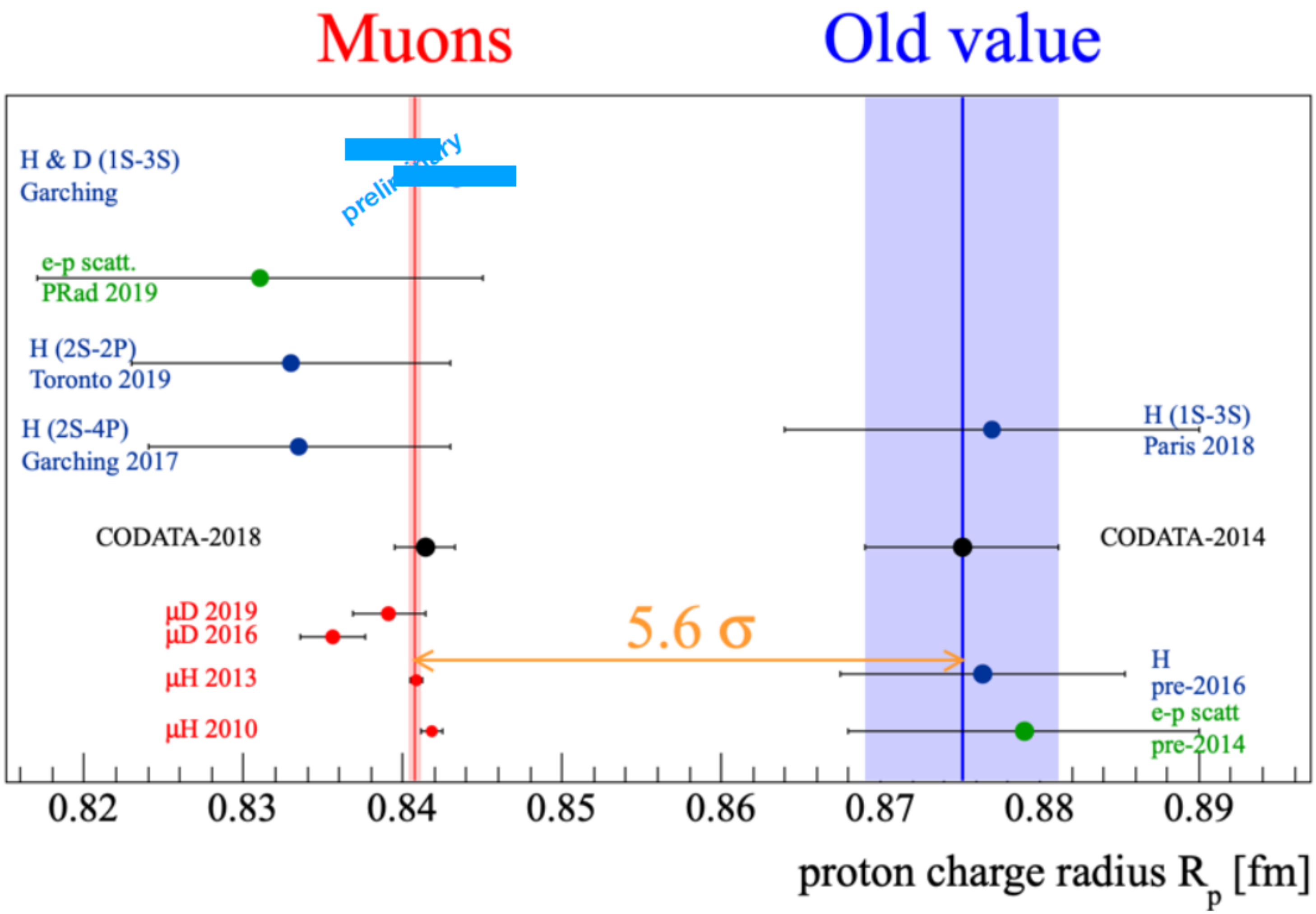
The proton radius puzzle







2019

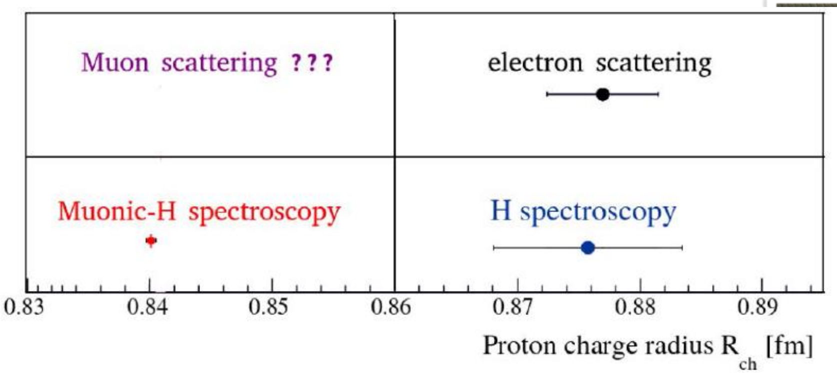


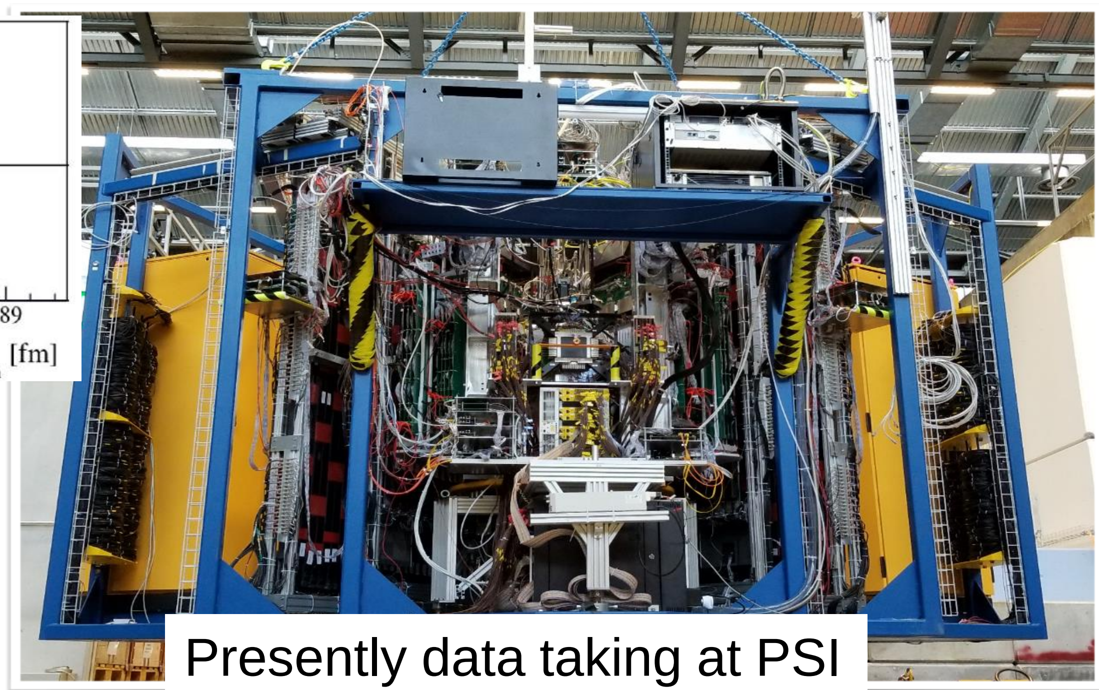
MUSE

R. Gilman et al., arXiv:1709.09753

PSI R-12-01, see E.Downie http://indico.psi.ch/getFile.py/access?contribId=6&sessionId=2&resId=0&materialId=slides&confId=5459

- Scattering of μ^+, e^+, μ^-, e^- at low Q^2 on hydrogen to compare cross sections and charge radii, determine two-photon contributions and test μ-e universality
  - 115, 153, 210 MeV/c beam momenta, 20º-100º scattering angles, tracking incoming and outgoing particles
  - Production data taking planned for 2019/20



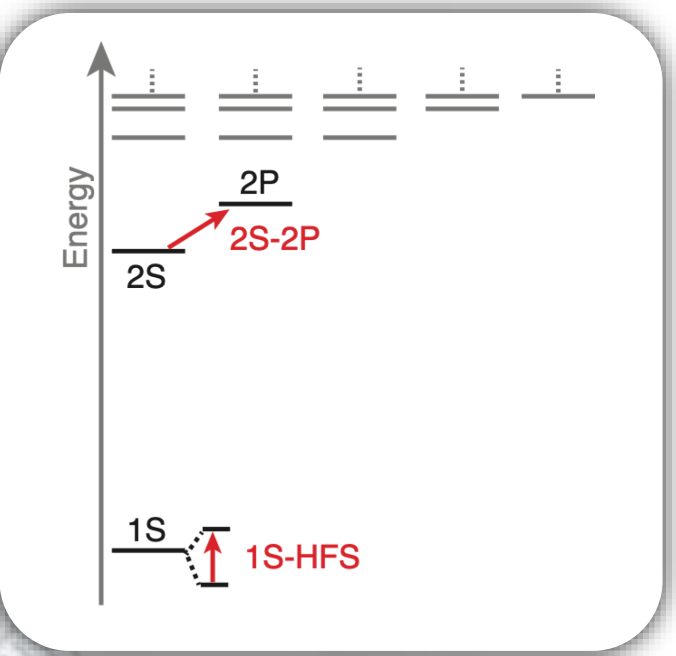


Presently data taking at PSI

Courtesy: E. Downie

HyperMu Experiment

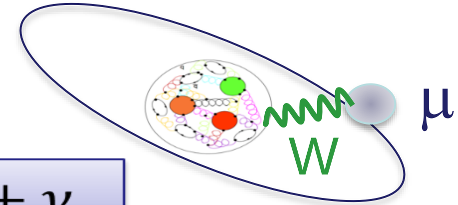
PSI R-16-02, see A. Antognini:
https://indico.psi.ch/event/6381/contributions/15944/attachments/13545/17498/talk_antognini_BVR2019_HyperMu.pdf



- From 2S-2P
  → charge radii
- From HFS
  → magnetic (Zemach) radii

- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^{3}He, μ^{4}He
- 1S-HFS μp

Muon capture on protons

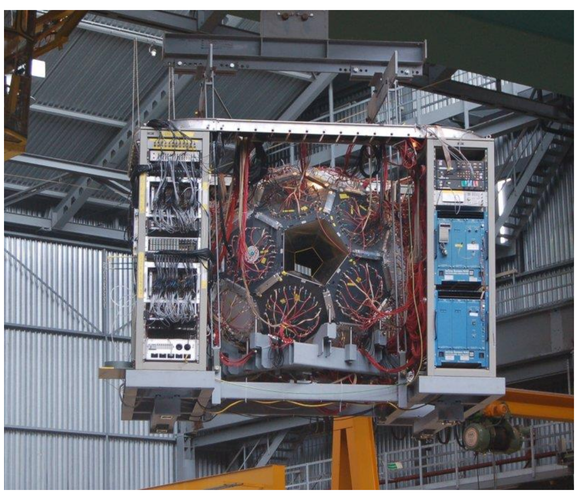


$$\mu + p \rightarrow n + \nu$$

Positive muon lifetime: MuLan

The most precise measurement of any lifetime: **MuLan**´s μ^+ and a 0.6 ppm determination of the **Fermi coupling constant**

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)



www.npl.washington.edu/muon/

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

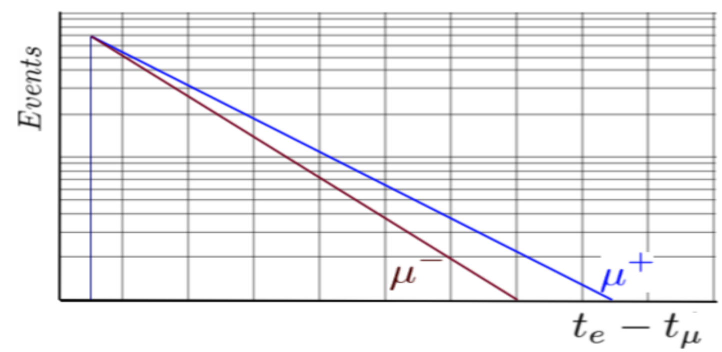
V.A.Andreev et al., PRL 110(2013)012504

Negative muon lifetime: MuCAP

The most precise measurement (10ppm) of the μ^- lifetime in pure hydrogen yields **MuCap**´s 1% determination of the μ^-p capture rate resolving the longstanding issue with the **Pseudoscalar coupling g_p**

capture rate, only 0.16% of $\mu \rightarrow e\nu\nu$

Lifetime method



$\Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$

measure lifetime to 10ppm !!

New perspective on the nucleon axial form factor

See NuMu2019: https://indico.psi.ch/event/7709/timetable/#20191025

$$g_A(q^2) = g_A(0)(1 + \frac{1}{6} r_A^2 q^2 + \dots)$$

Nucleon axial radius and muonic hydrogen - a new analysis and review

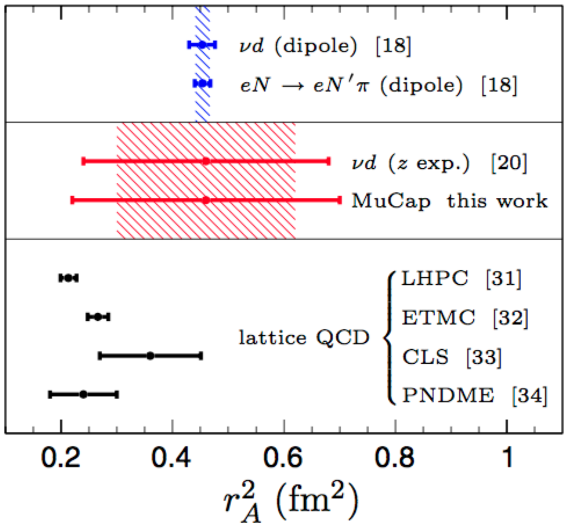
R J Hill , P Kammel, W J Marciano and A Sirlin

Rep. Prog. Phys. **81** (2018) 096301

- Nucleon axial radius r_A has surprisingly large uncertainty

$$r_A^2(z\ \text{exp.}) = 0.46 \pm 0.22\ \text{fm}^2 \qquad \nu_\mu d \to \mu^- pp$$

Phys.Rev. D93 113015, (2016)



  - basic nucleon property
  - doubles uncertainty in CCQE $\nu n \rightarrow p\mu$ cross section prediction (for DUNE, HyperK, ..)
- Future 3x improved MuCap could reduce
  - r_A^2 uncertainty 0.22 → 0.09 fm^2
  - CCQE $\sigma(\nu n)$ uncertainty almost 2 times

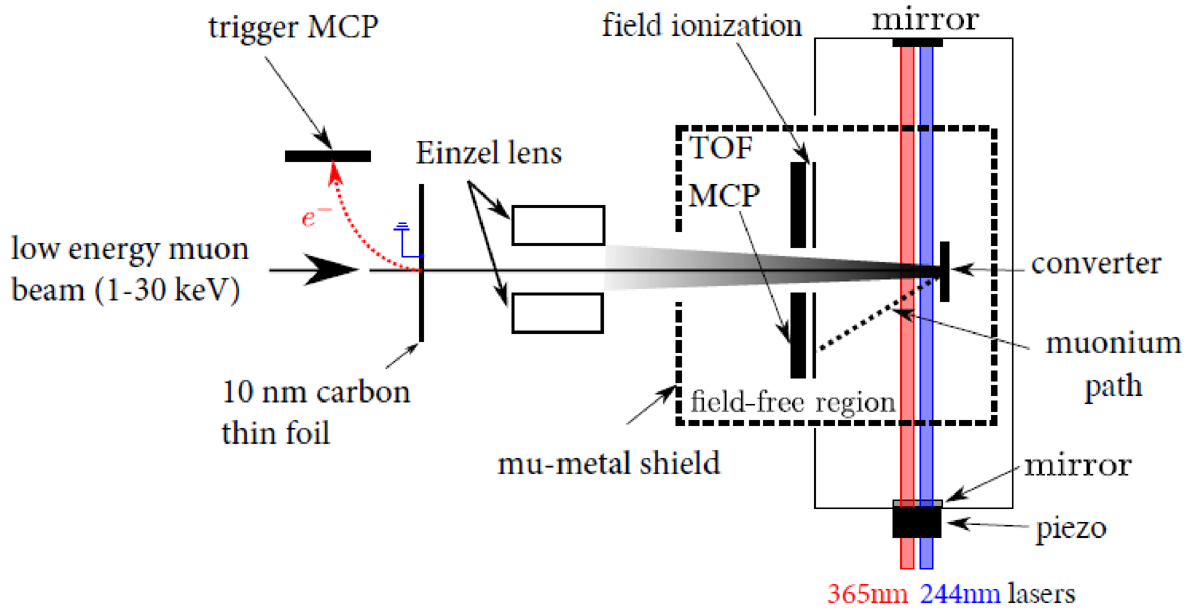
Mu-MASS: Measure **1S-2S transition** with Doppler free laser spectroscopy

GOAL: improve by 3 orders of magnitude (10 kHz, 4 ppt)

Crivelli, P. Hyperfine Interact (2018) 239: 49

See PSI-R-19-01, P. Crivelli https://indico.psi.ch/event/6381/contributions/15940/attachments/13527/17491/PSIBV50_Crivelli.pdf

- Low energy μ^+ beam
- Muonium production
- Muonium 2S excitation
- Muonium 20P excitation
- Muonium field ionisation μ^+ detection



OUTPUT

→ **Muon mass @ 1 ppb**

→ Ratio of q_e/q_μ @ 1 ppt

→ Test of Standard Model Extension

→ **Rydberg constant @ ppt level**

→ **Test of bound state QED (1×10^{-9})**

→ New determination of α @ 1 ppb

STATUS AND PLANS:

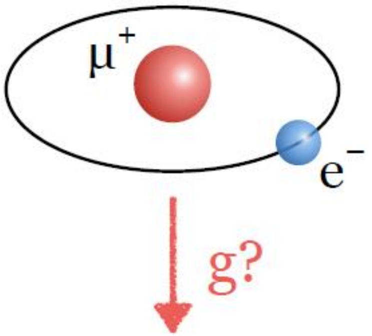
- laser system and detectors being prepared
- test at the PSI low energy muon beam line, Dec19
- Data taking starting end of 2020

Courtesy: P. Crivelli

Exotic gravity experiment using muonium

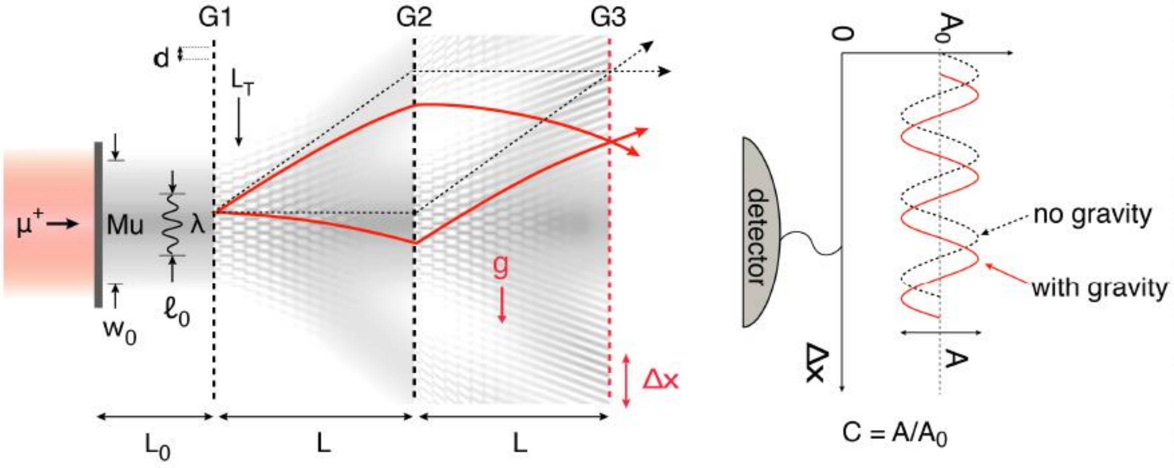
See A. Soter: https://indico.psi.ch/event/6381/contributions/15952/attachments/13547/17500/soter_mu_BVR_compressed.pdf

Muonium: exotic atom with elementary antimatter



Test of the weak equivalence principle using second generation leptonic antimatter

Method: atomic interferometer



Sensitivity: $$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N}}$$

Small grating period (d~100 nm) to measure sub-nm shifts

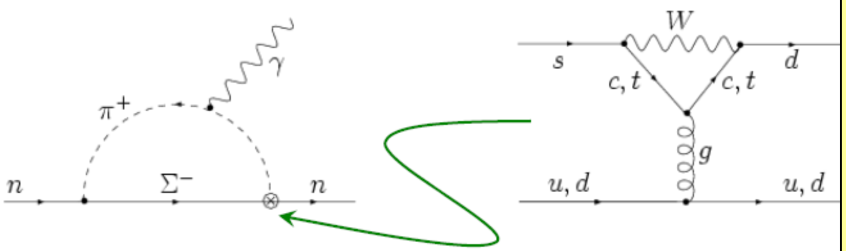
Interaction time with gravity~ few μs !

Large contrast (C~0.3)
Many atoms (N_0~10^4/s)

Courtesy: A. Soter

Electric Dipole Moments tiny in SM

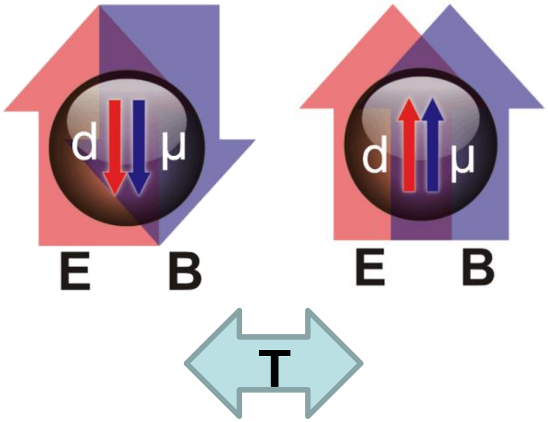
- Neutron, Proton, ..



$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky '86]

Expect from SM:
$d_n < 10^{-30}$ e•cm
Experimentally:
$< 3.0 \times 10^{-26}$ e•cm
Pendlebury et al., PRD92(2015)092003



Most sensitive probe of BSM CP violation

- Leptons: 4th order EW

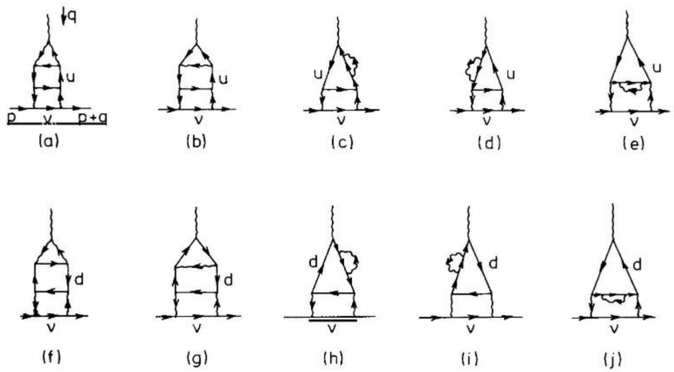


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[Hoogeveen '90, Pospelov, Ritz 2014]

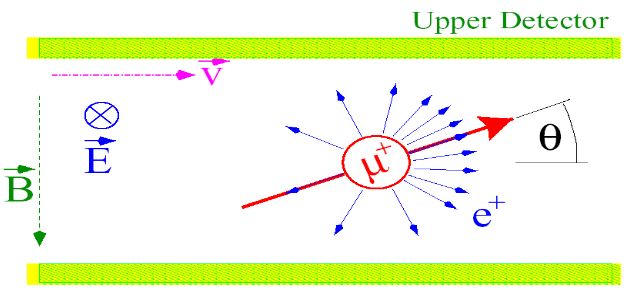
Expect from SM:
$d_e \leq 10^{-44}$ e•cm
$d_\mu \leq 10^{-42}$ e•cm
$d_\tau \leq 10^{-41}$ e•cm
Experimentally:
$d_e < 2 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

ThO molecule
Andreev et al., Nature562(2018)355

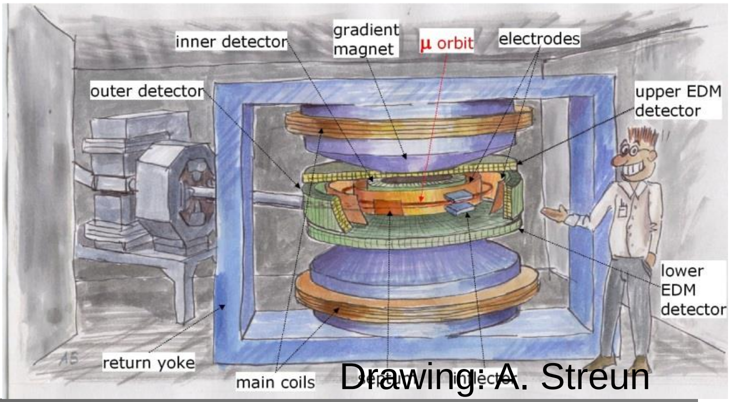
muon g-2 storage ring
Bennett et al., PRD80(2009)052008

Possibility for a large Muon EDM?

- In a model independent approach, d_μ uniquely constrains some couplings (M. Pruna arXiv:1710.08311), d_μ is not limited by small d_e but only by the direct experimental limit $d_\mu < 1.8 \times 10^{-19}$ecm (Bennett et al., PRD80(2009)052008)
- If NP in a_μ → d_μ could naturally be of same order, $\sim 10^{-22}$ecm (Feng, Matchev, Shadmi, NPB613(2001)366)
- If NP in a_μ and a_e (with the sign of the slight tension in a_e)
  → muon and electron sectors would be decoupled
  → large d_μ possible (Crivellin, Hoferichter, Schmidt-Wellenburg, arXiv:1807.11484)
- Present g-2 experiment will improve sensitivity to $d_\mu \sim 10^{-20..21}$ecm
- Dedicated small storage ring could reach $d_\mu \sim 10^{-22..23}$ecm at PSI (Adelmann et al., JPG37(2010)085001)

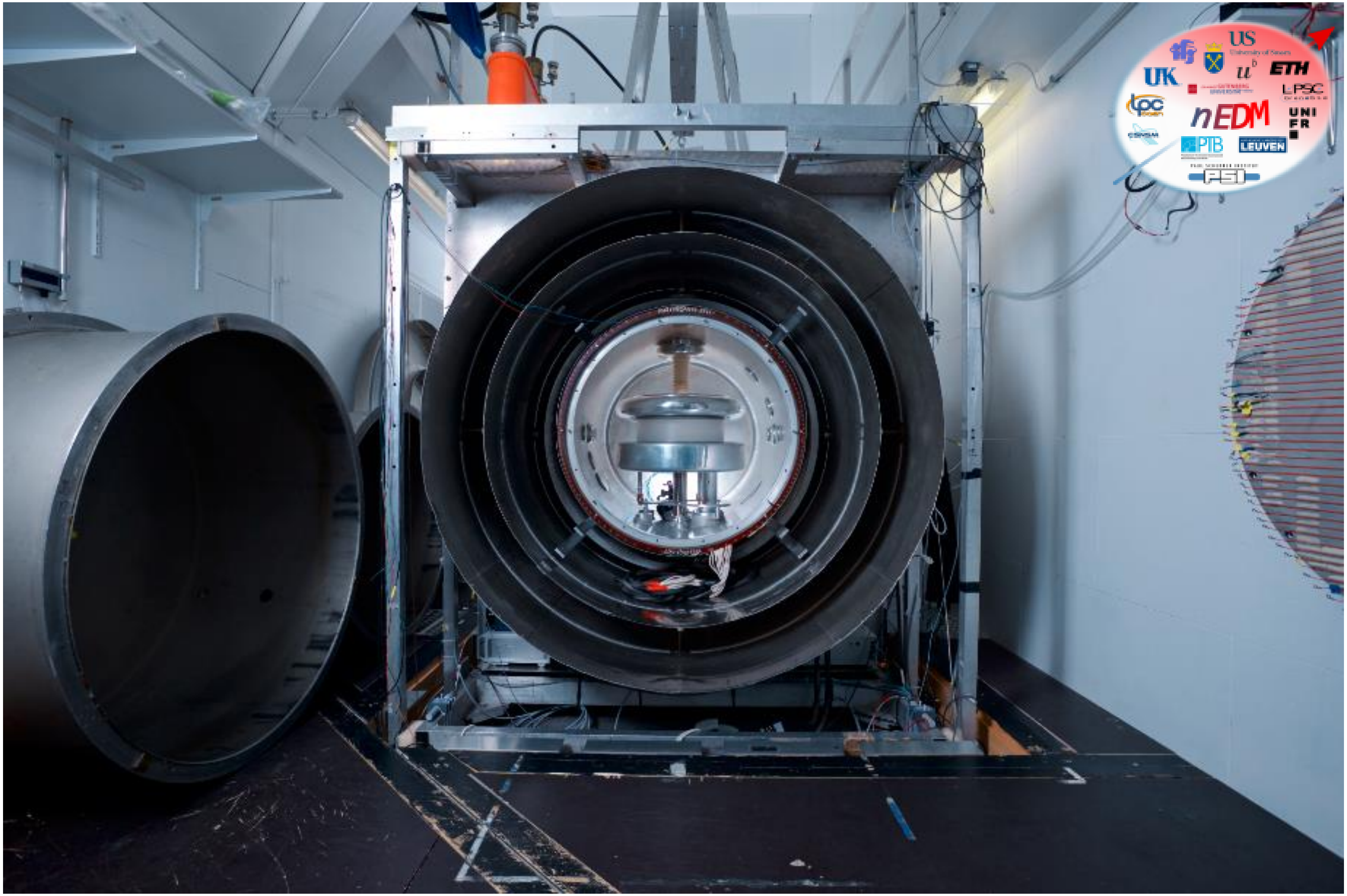


See talk by Kim Siang Khaw



Drawing: A. Streun

nEDM at PSI

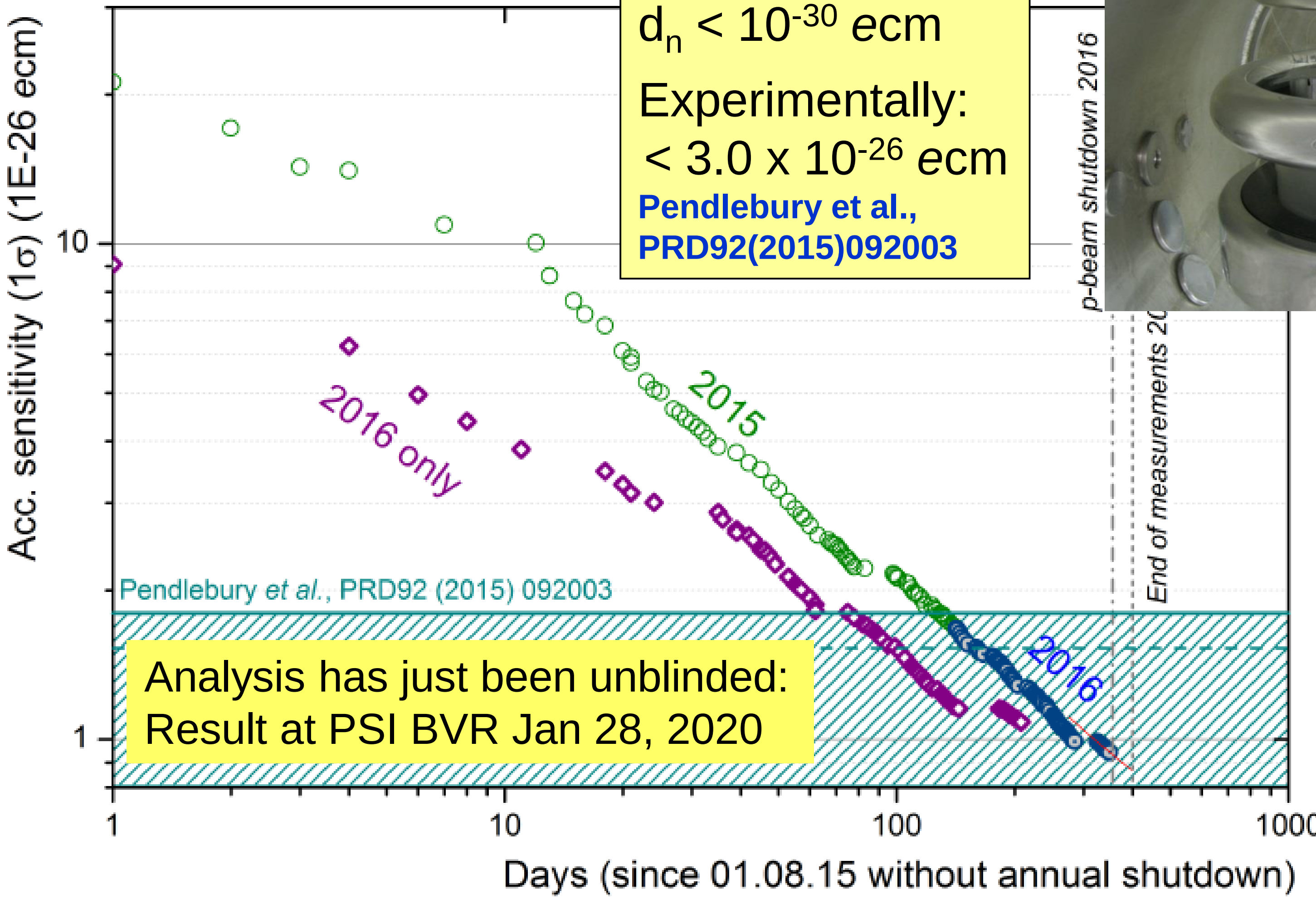


The neutron EDM statistics

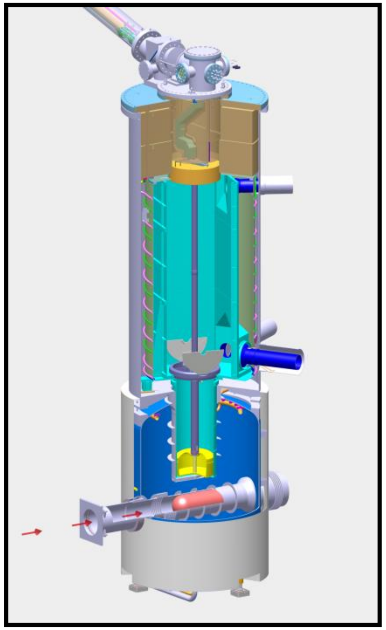
Expect from SM:
$d_n < 10^{-30}$ ecm

Experimentally:
$< 3.0 \times 10^{-26}$ ecm

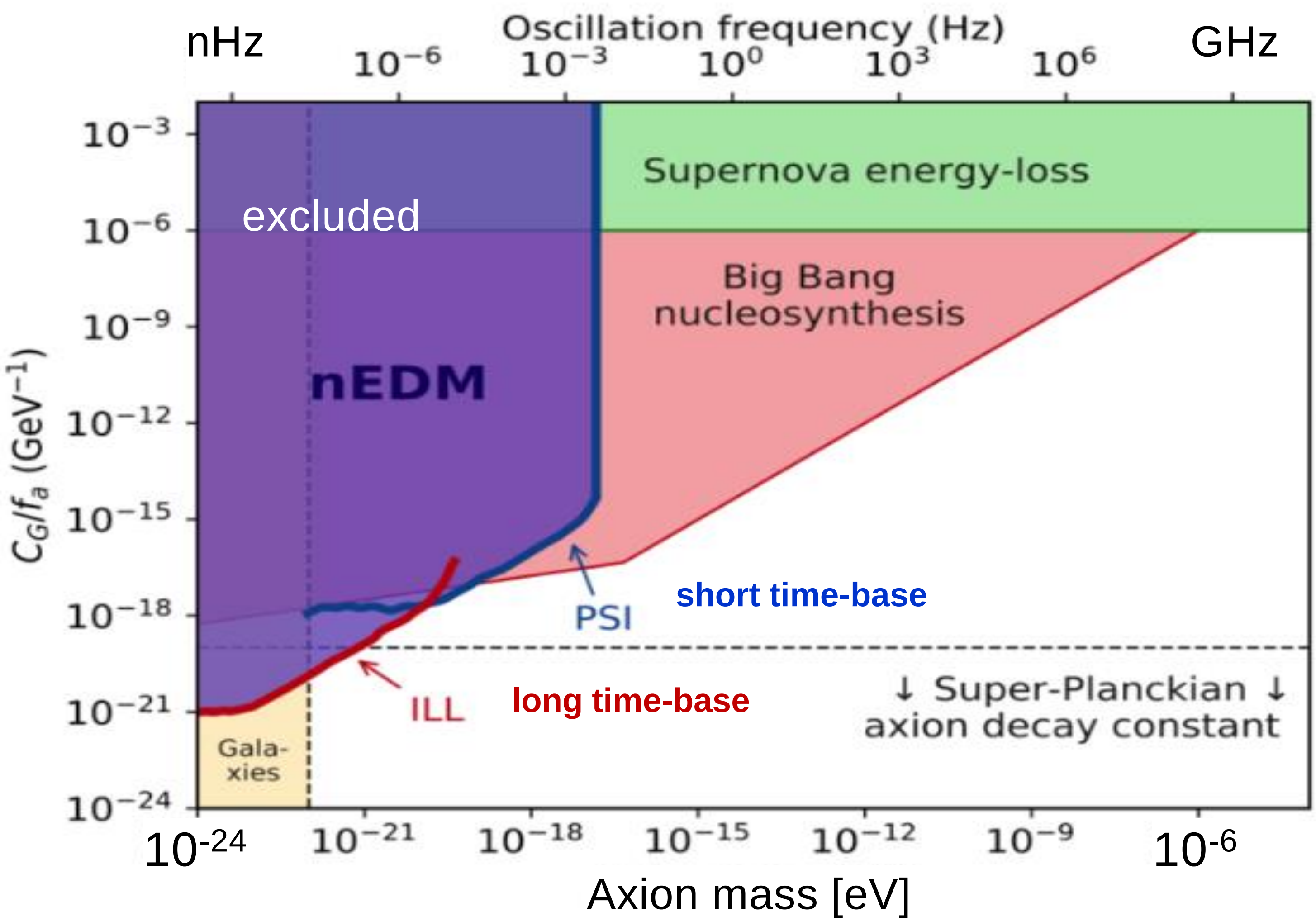
Pendlebury et al., PRD92(2015)092003

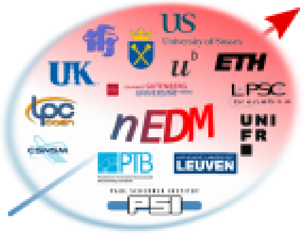


Analysis has just been unblinded:
Result at PSI BVR Jan 28, 2020



nEDM search for ultra-light axion dark matter





With theorists Flambaum, Stadnik, Fairbairn, Marsh

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

Abel et al., PRX7(2017)041034

2018: n2EDM at PSI

2019: n2EDM at PSI

n2EDM baseline:
$\sigma(d_n)$~1E-27*e*cm in 500 days
Commissioning 2020/21


Thank you!