PSI Center for Neutron and Muon Sciences

Particle Physics

Summer Student Program 2024

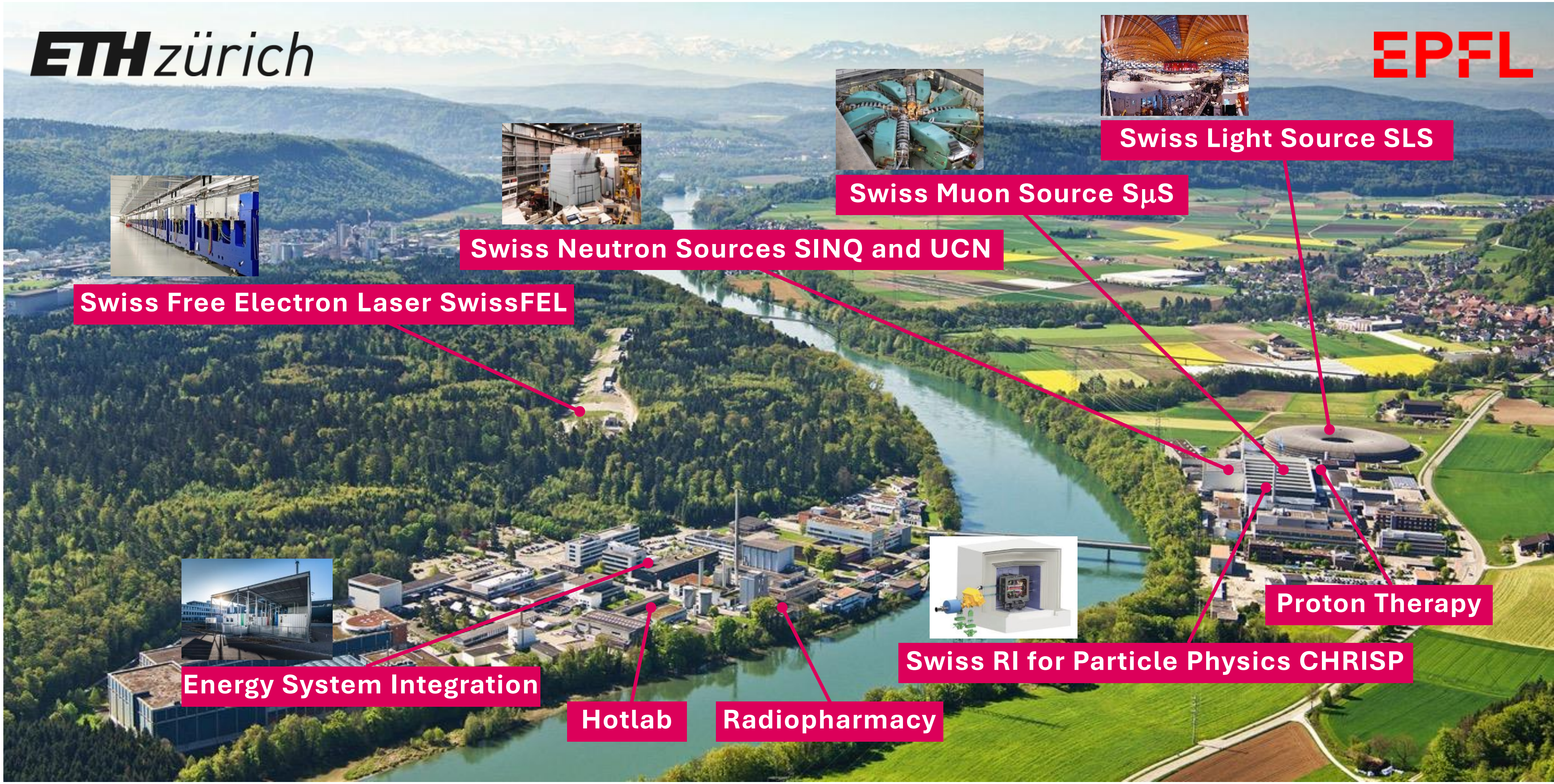
Klaus Kirch, PSI & ETH Zürich
July 17, 2024

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

PSI

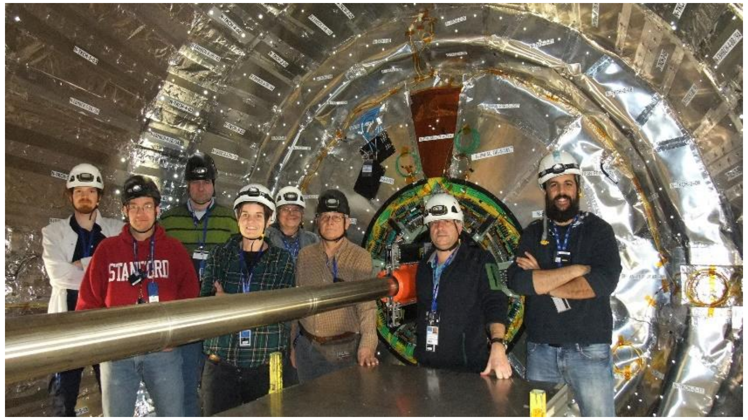
Paul Scherrer Institute – ETH Domain

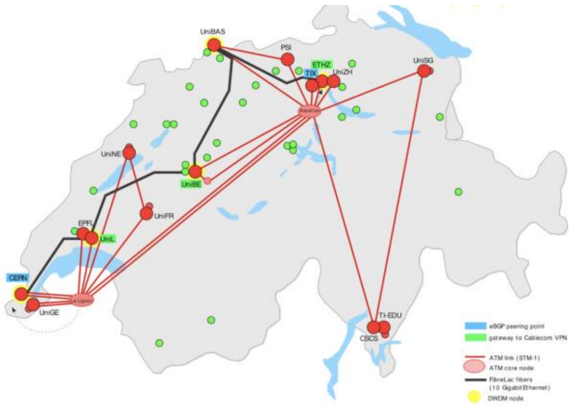
PSI

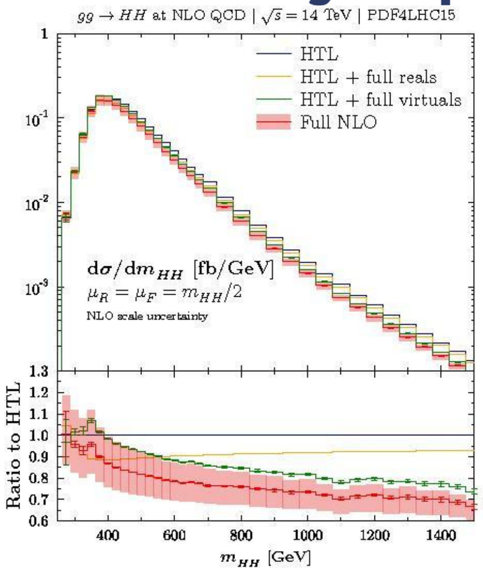


PSI groups at LHC

- High-energy physics group in CMS
  - 16 CMS members (including senior scientists, postdocs, PhD students, technicians and emeriti)
  - Leading contributions to detector development, physics analysis and ORD
  - Holding key positions within collaboration: Trigger Coordinator (M. Missiroli), Common Analysis Tools Coordination (C. Lange), TEPX Upgrade Coordinator (W. Erdmann), Secretary of CMS Management Board (Q. Ingram)
- High-performance computing and emerging technologies
  - Tier3 computing centre at PSI and Tier2 computing centre at CSCS
- LTP theory group
  - Phenomenology of physics at the LHC (Higgs, SM, SUSY, Exotica)
  - Coordination within LHC Higgs cross section working group (M. Spira)

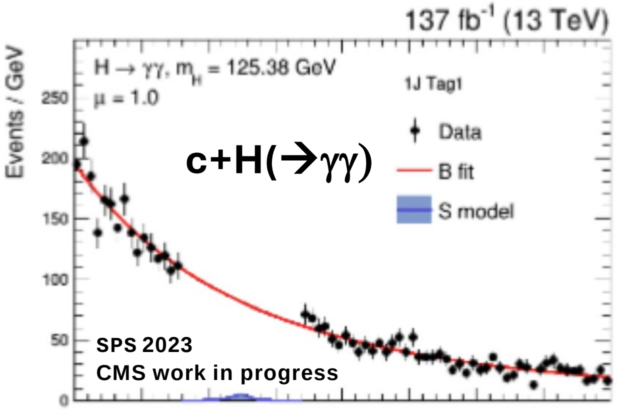


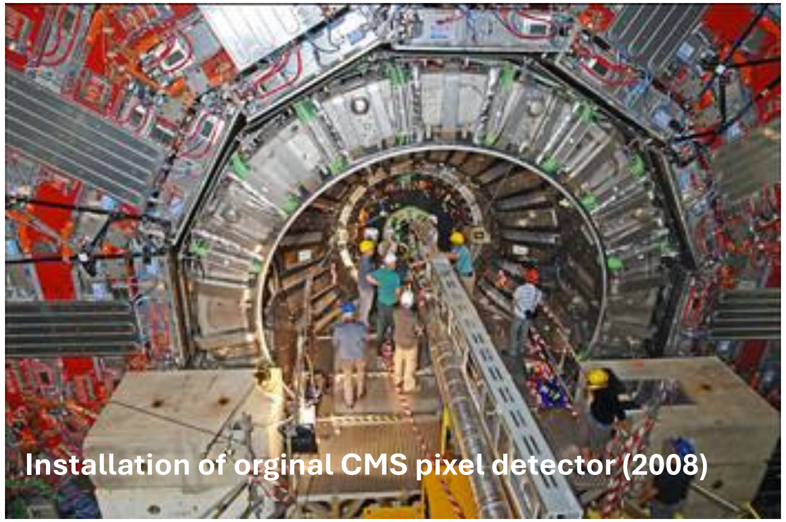


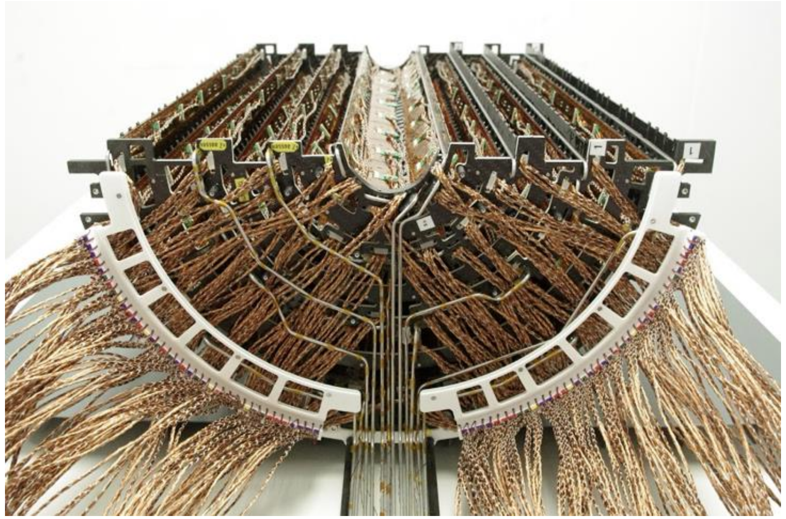


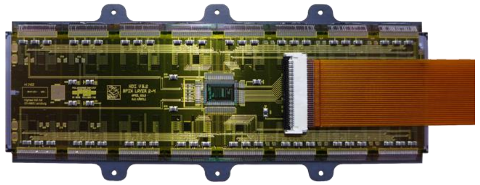
PSI activities in CMS

- CH consortium (PSI, ETH,UZH) led design, construction, integration, commissioning of original and Phase-1 CMS pixel detector
  - Major parts built at Swiss institutes with components from local industry
- Key contributions to pixel detector operation, calibration, performance monitoring, local reconstruction, tracking and vertexing
- Active in physics analysis, in particular Standard Model, B and Higgs physics

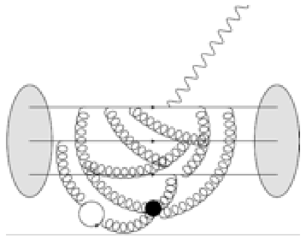



Installation of orginal CMS pixel detector (2008)




CMS Phase-1 pixel detector (2017)

PSI Laboratory for Particle Physics



Particle Physics (LTP)
Prof. Dr. K. Kirch (ETHZ)
3200

Particle Physics Theory
Dr. M. Spira
3201

High Energy Particle Physics
Prof. Dr. L. Caminada
3202

Muon Physics
Dr. S. Ritt
3203

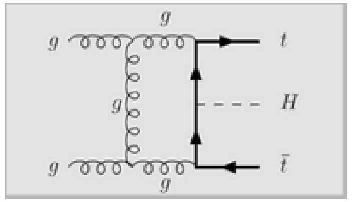
UCN Physics
Dr. B. Lauss
3204

Electronics for Measuring Systems
U. Greuter
3205

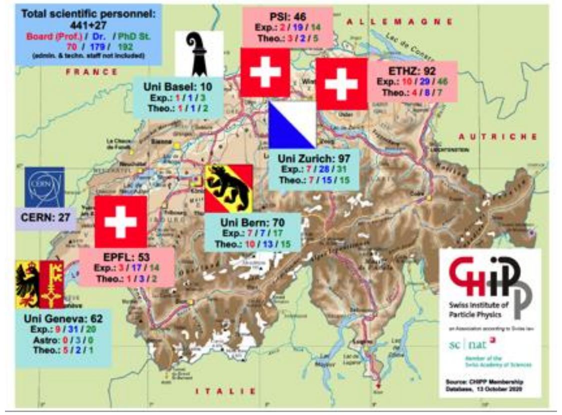
Detectors, Irradiation, Applied Particle Physics
Dr. M. Hildebrandt
3206

Electronics Vocational Training and Service Pool
C. Kämpf
3208

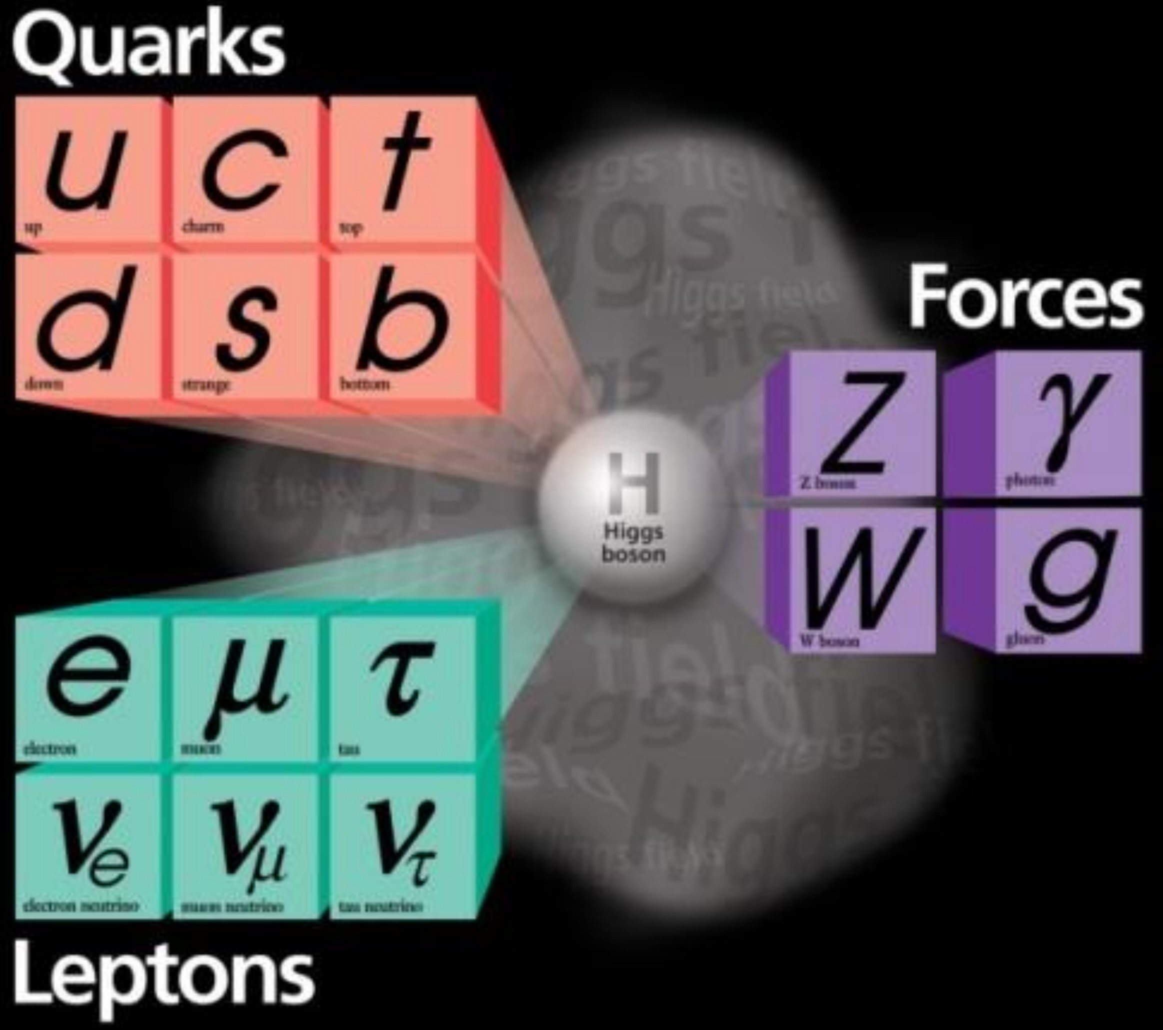
- Pursue leading research in experimental and theoretical, accelerator-based particle physics at PSI and at CERN.
- Develop, apply and make available cutting-edge technologies.
- Organize and support user activities at CHRISP.
- Work together closely with CHIPP, universities and international collaborations.
- Train next generation of physicists and electronicians at PSI and at universities.
- Inform and educate the broader public.



Swiss Particle Physics Landscape 2023

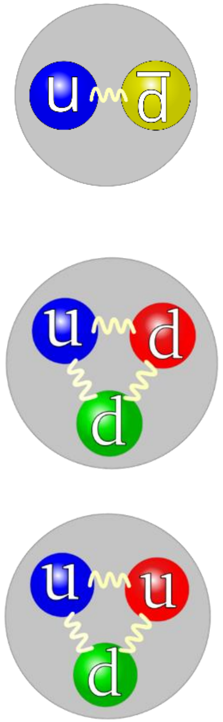


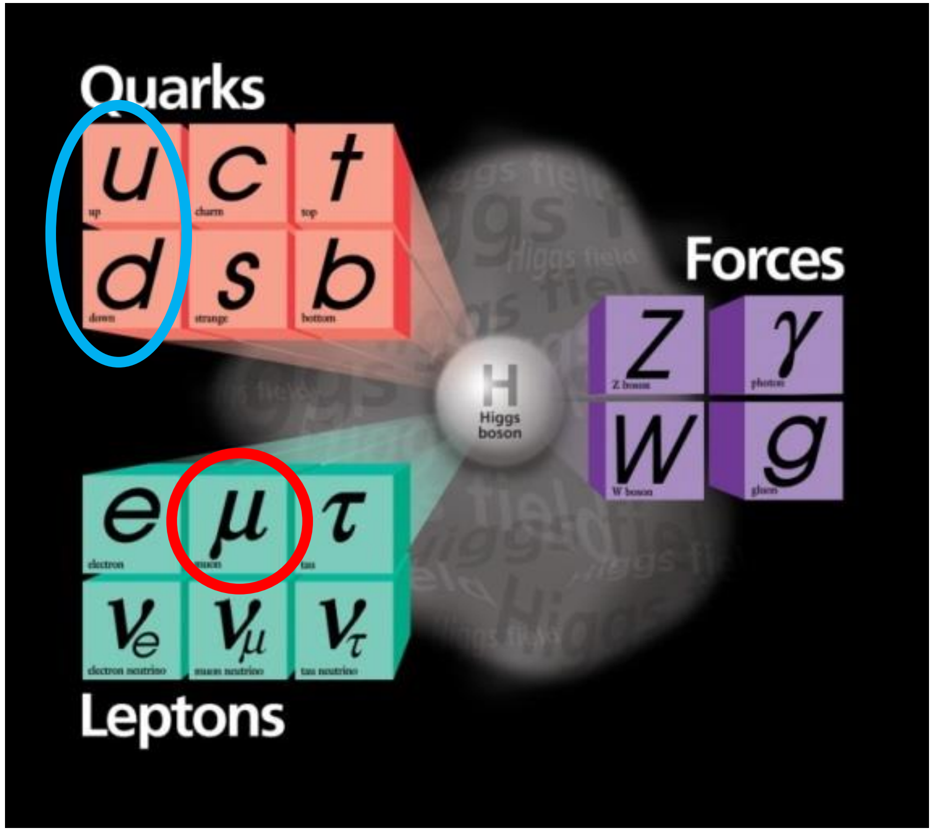
The known particles

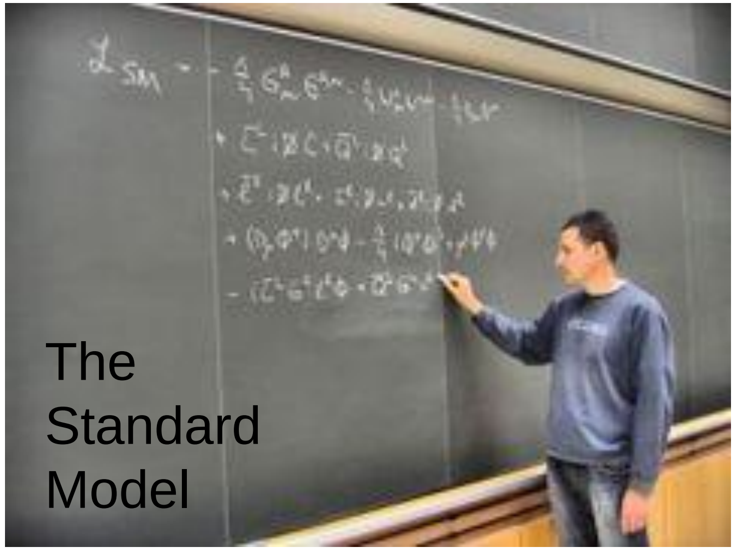


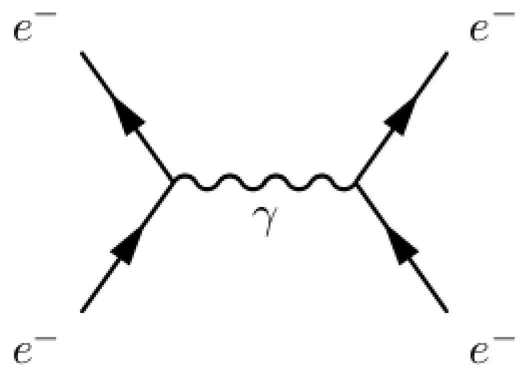
Source: Fermi National Accelerator Laboratory

Pions, Muons, Neutrons, Protons

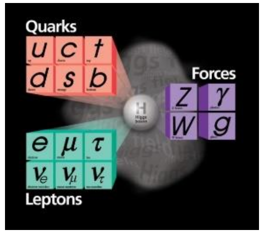




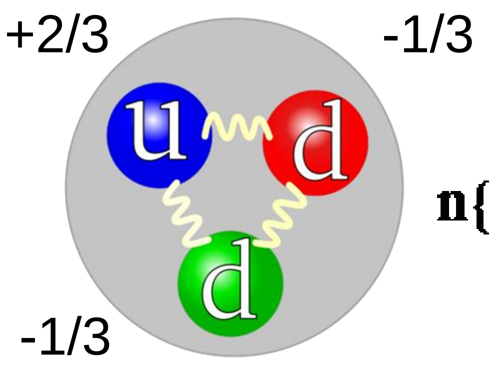




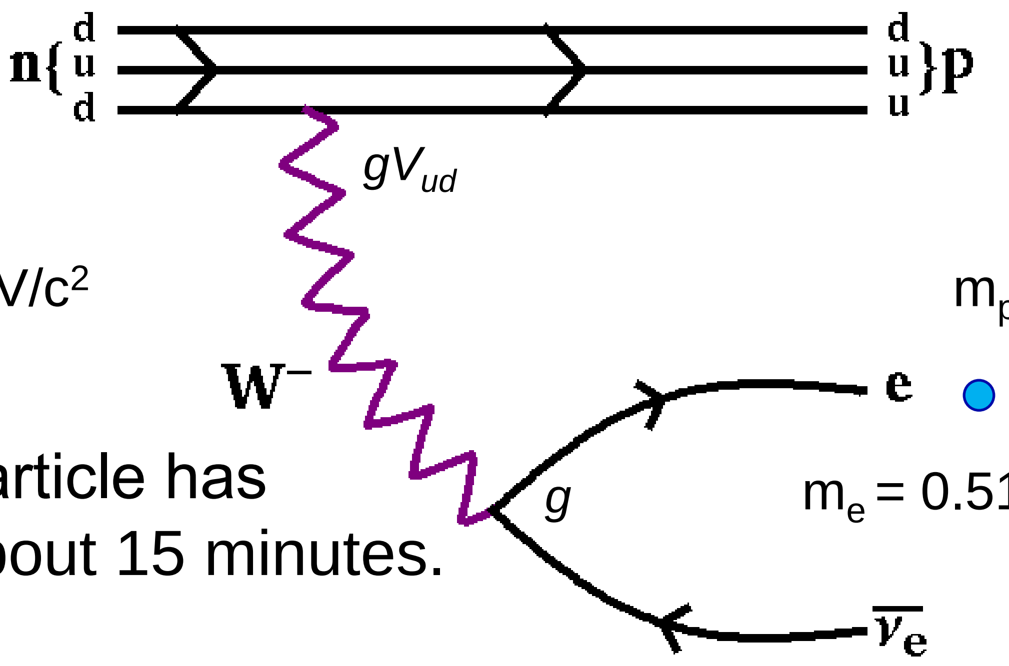
Composite system: The neutron

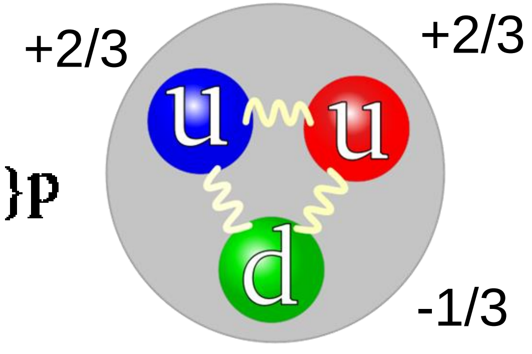


Spin 1/2



$m_n = 939.57\ \mathrm{MeV}/c^2$



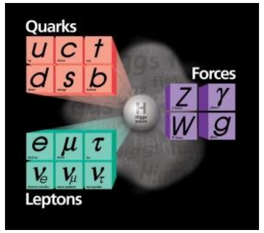


$m_p = 938.27\ \mathrm{MeV}/c^2$

$m_e = 0.511\ \mathrm{MeV}/c^2$

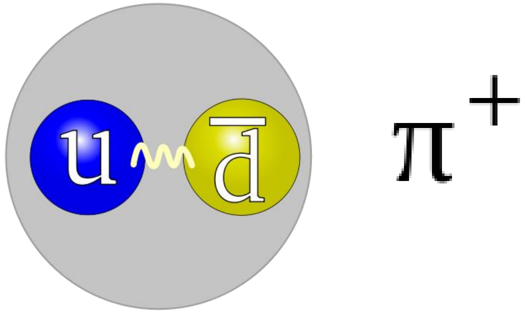
$m_\nu < 10^{-6}\ \mathrm{MeV}/c^2$

… as a free particle has
a lifetime of about 15 minutes.

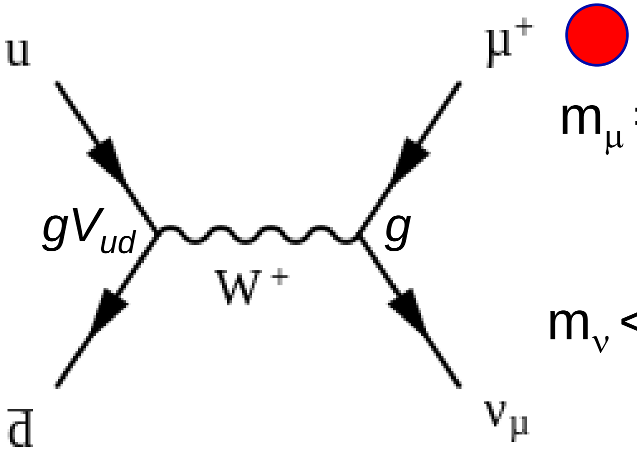


Composite system: The pion

Spin 0



$m_\pi = 139.57$ MeV/c^2



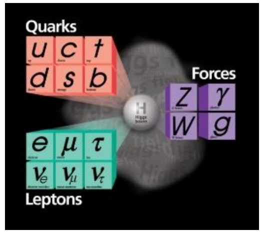
Spin 1/2

$m_\mu = 105.66$ MeV/c^2

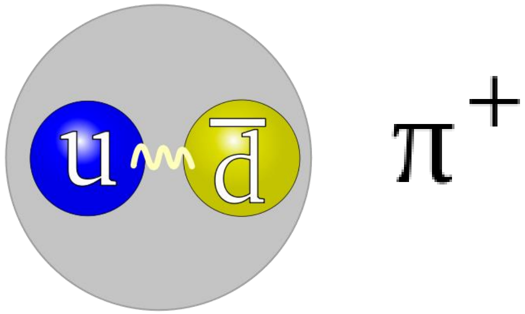
$m_\nu < 10^{-6}$ MeV/c^2

Spin 1/2

Composite system: The pion

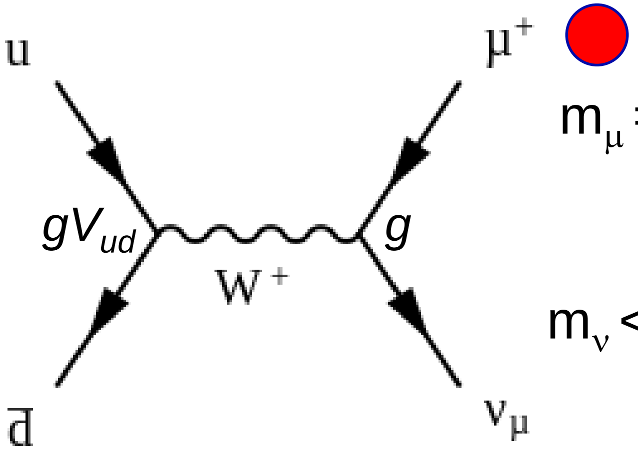


Spin 0



$m_\pi = 139.57$ MeV/c^2

Spin 1/2

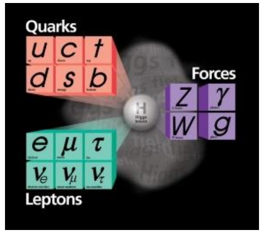


$m_\mu = 105.66$ MeV/c^2

$m_\nu < 10^{-6}$ MeV/c^2

Spin 1/2

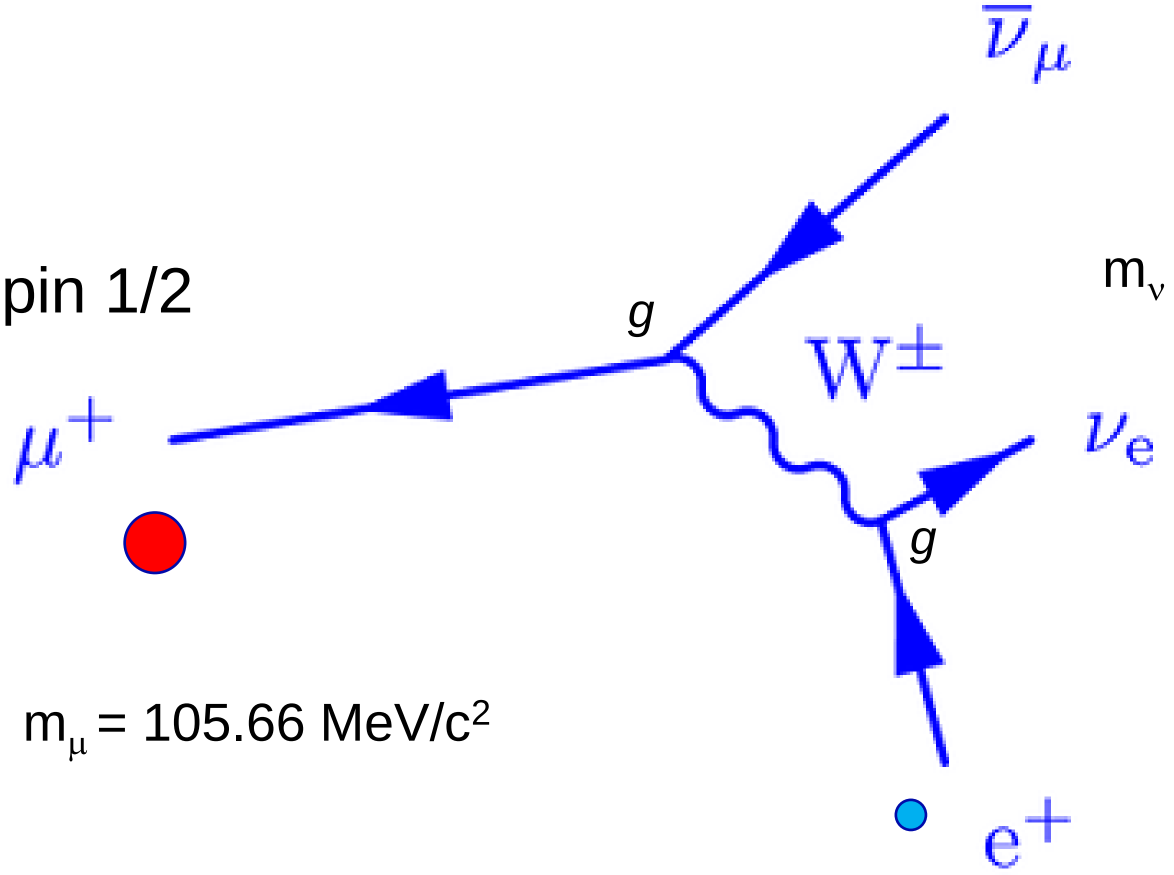
... and a source of muons



Fundamental particle: The muon

Spin 1/2

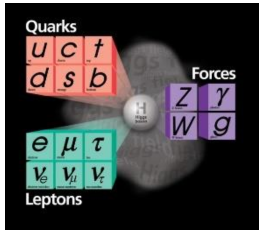
$m_\nu < 10^{-6}$ MeV/c^2



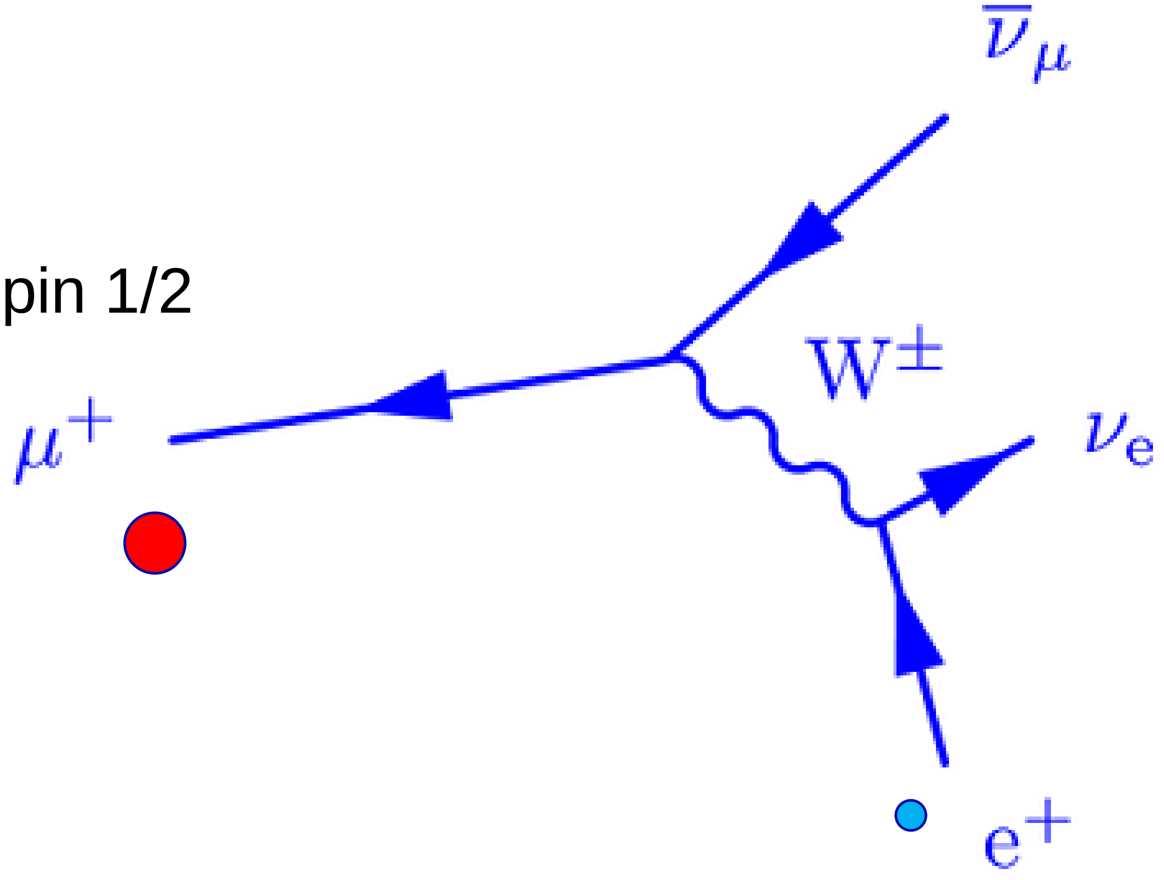
$m_\mu = 105.66$ MeV/c^2

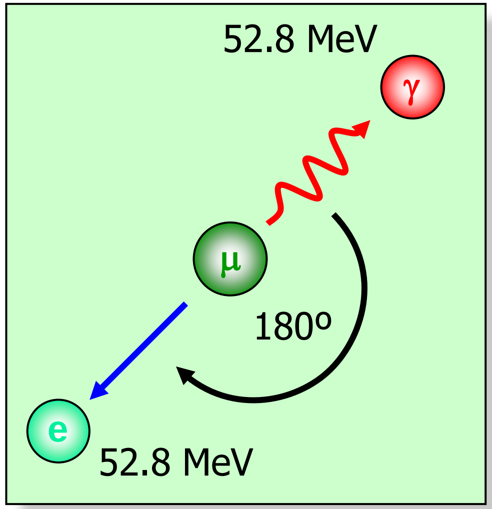
$m_e = 0.511$ MeV/c^2

Fundamental particle: The muon

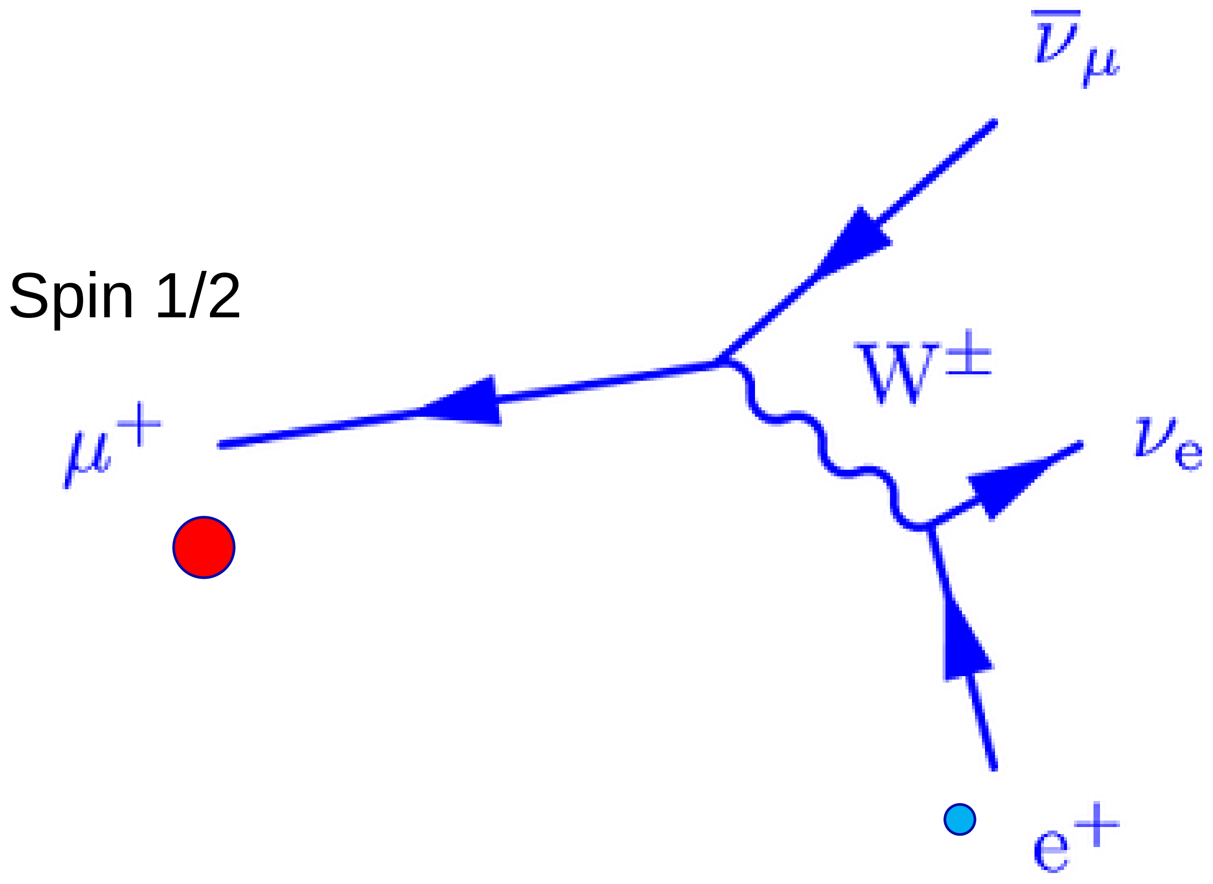


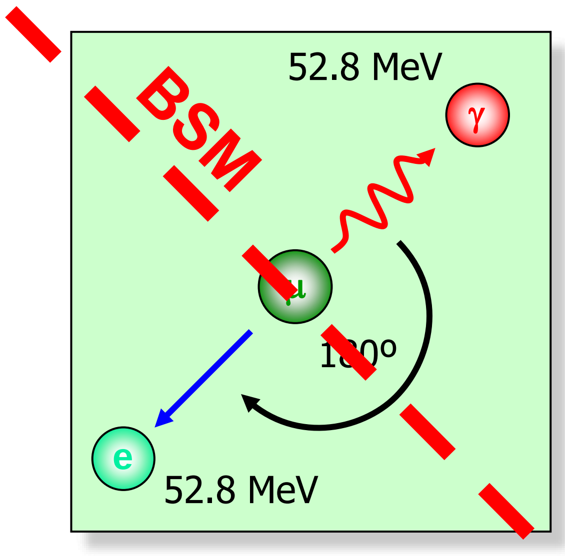
Spin 1/2

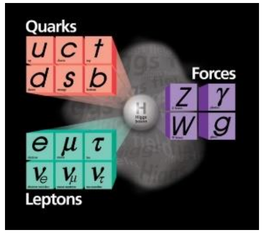




Fundamental particle: The muon



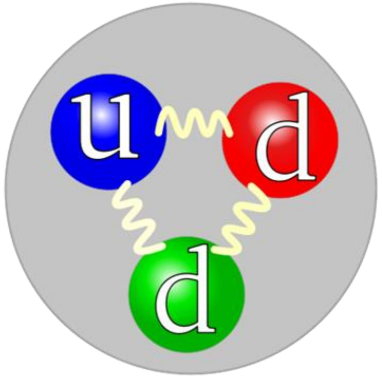




PSI

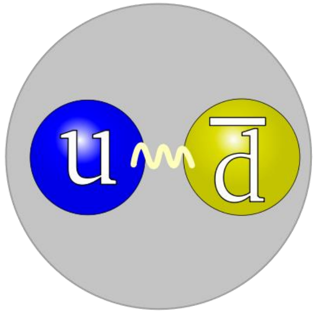
The lightest unstable particles of their kind

Neutron



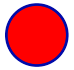
Baryon

Pion



Meson

Muon



Lepton

HIPA and ring cyclotron

produces
the world-wide highest intensities
of these particles at low momenta:

Mesons:

Pions,

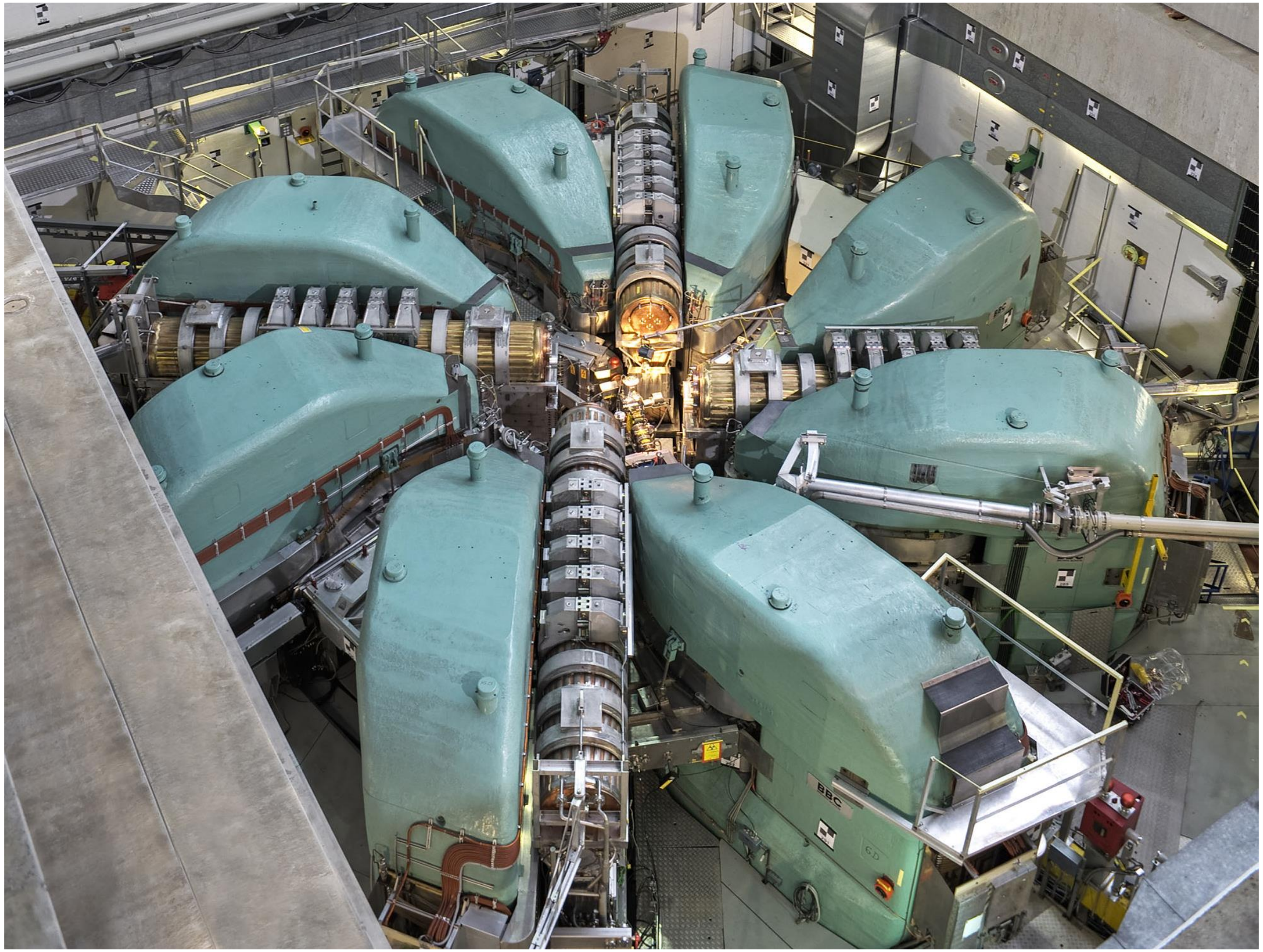
π^+, π^-, π^0

Leptons:

Muons, μ^+, μ^-

Baryons:

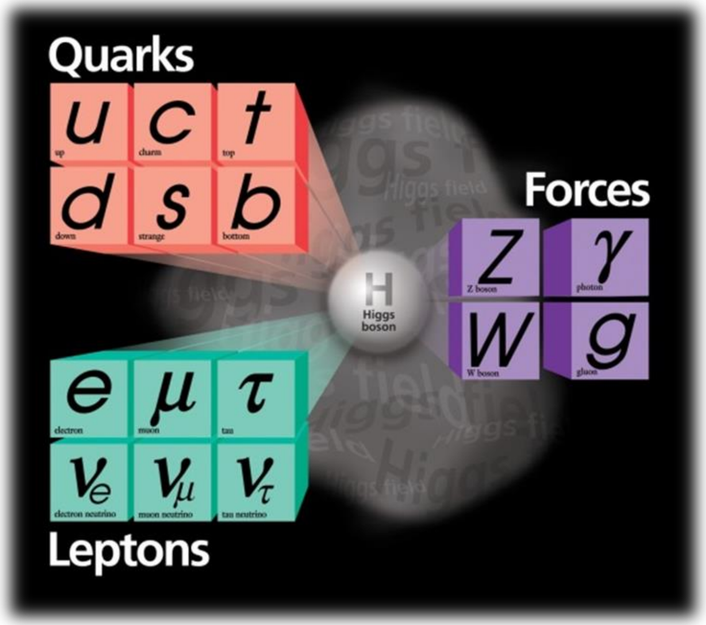
UCN, n



The Standard Model and beyond

A (the?) most successful theory

- **~consistent with all laboratory results,** some tensions, theory & application to cosmology and astro suggest beyond SM physics



Laboratory experiments

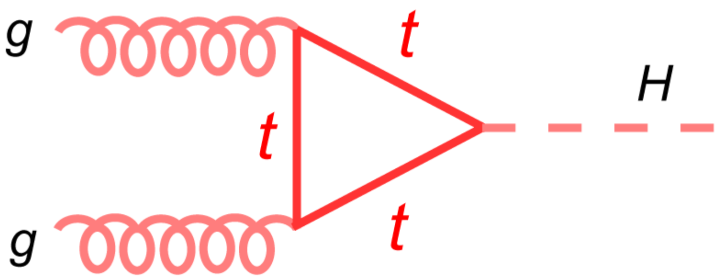
- Precision measurements of SM input parameters
  - 19 (26+) param., masses, couplings, mixings, CP phases, θ_{QCD}, Higgs vev
- Searches for deviations & inconsistencies
  - Dark Matter, BAU, CPV, cLFV, B, L, Lorentz, Gravity, Dark Energy…
  - Often with tests of symmetries and conservation laws

Search for ‘new’ physics

PSI

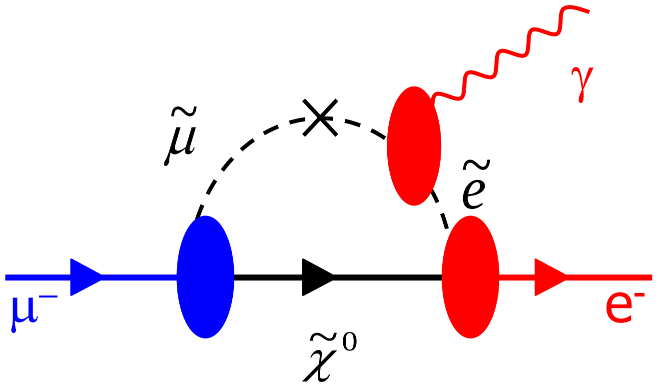
High Energy

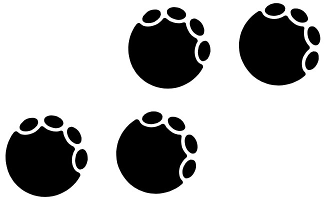
direct production of new particle



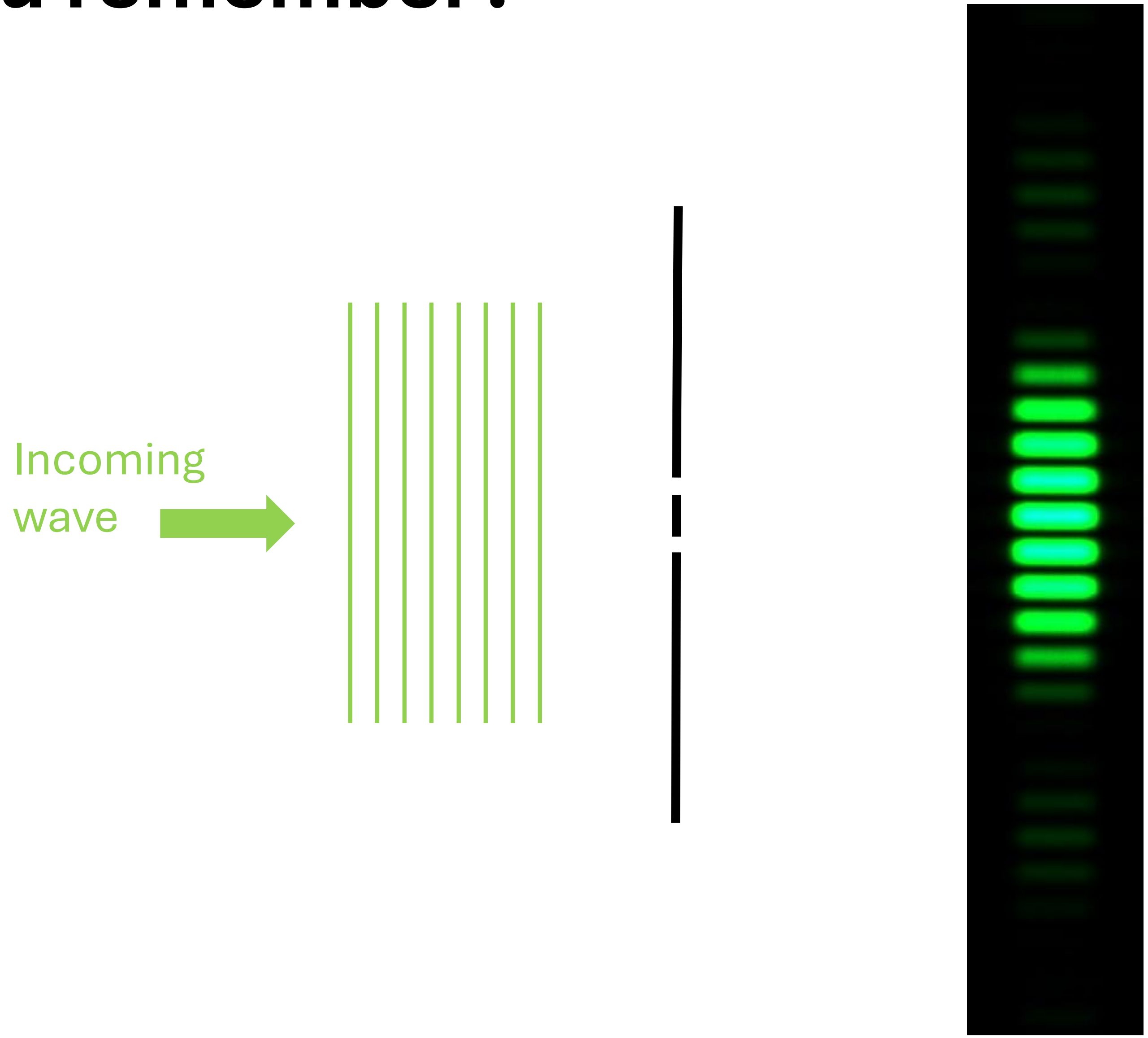
High Intensity

For example:
Search for $\mu \rightarrow e\gamma$

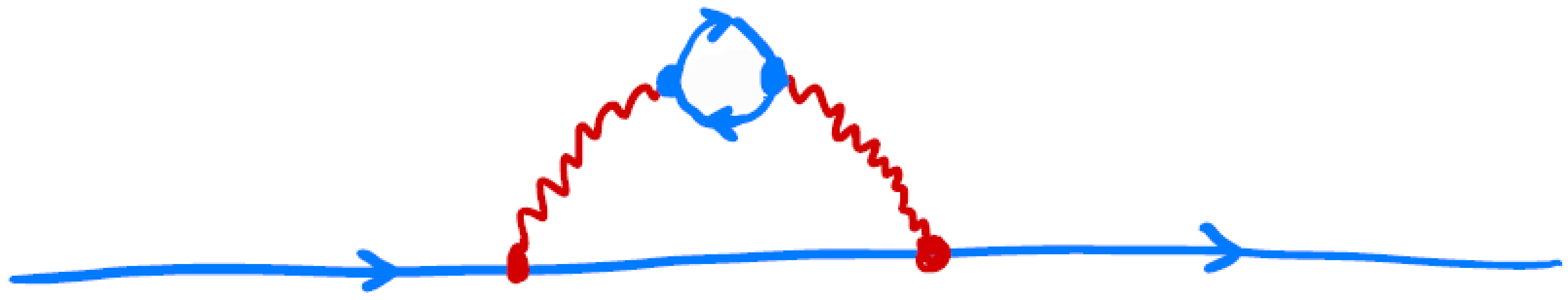




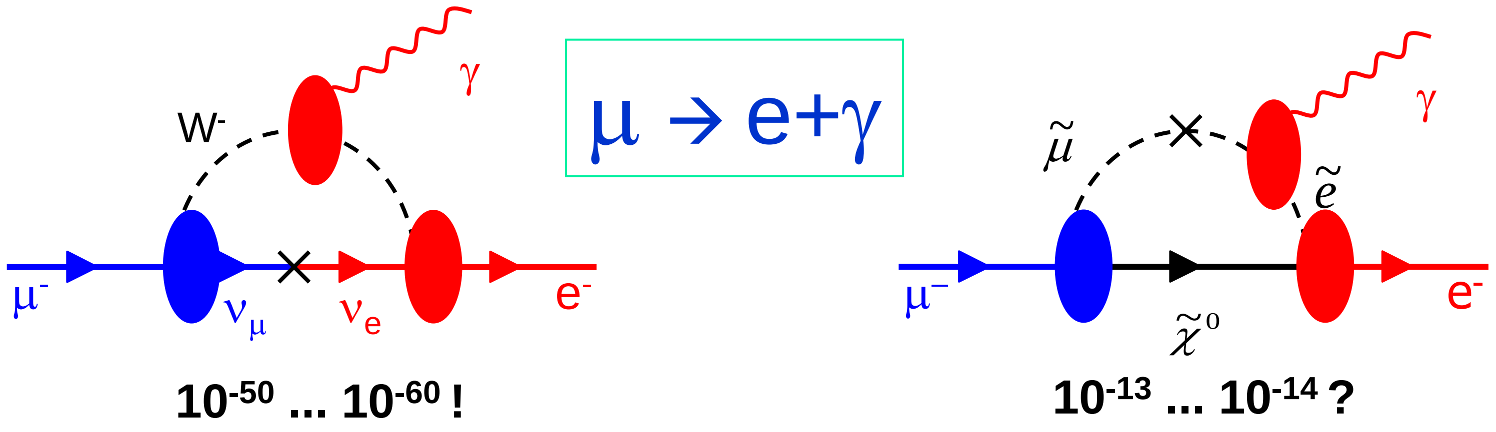
Do you remember?



Effects of particles in ‘Loops’



Effects of ‘new’ particles in ‘loops’

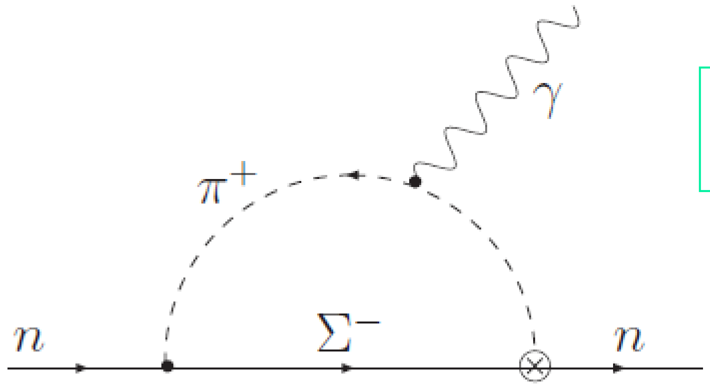


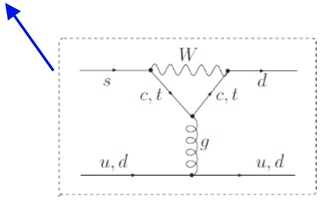
… excellent sensitivity when standard effects negligible.

Effects of ‘new’ particles in ‘loops’

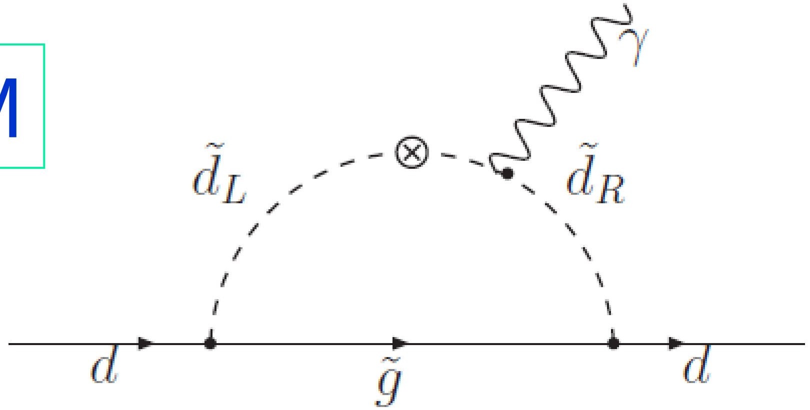
PSI

nEDM





~10^{-32} ecm



< 2 10^{-26} ecm

… excellent sensitivity when standard effects negligible.

Searches for charged lepton flavor violation

PSI

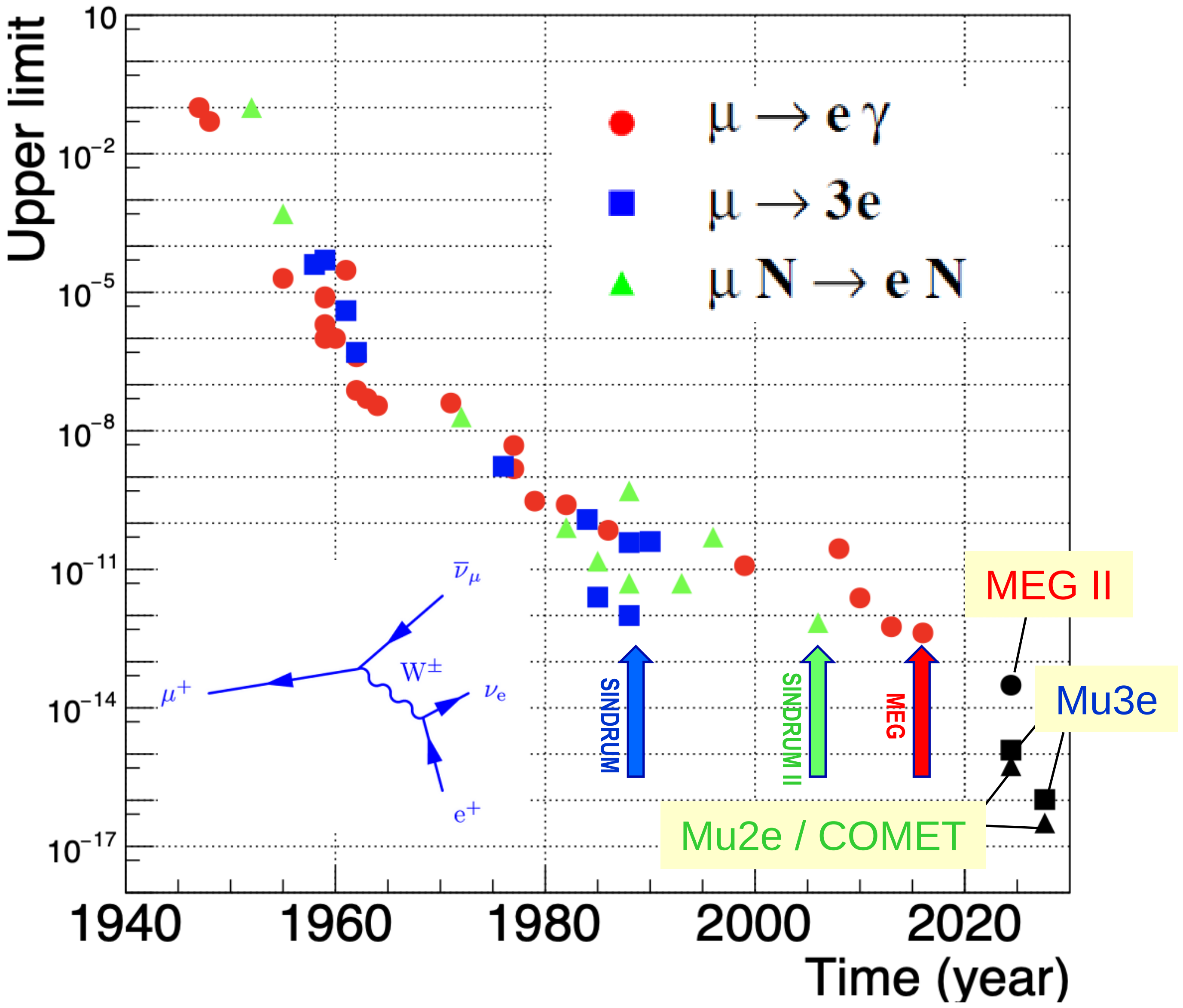
The present best limits on cLFV with muons

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

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

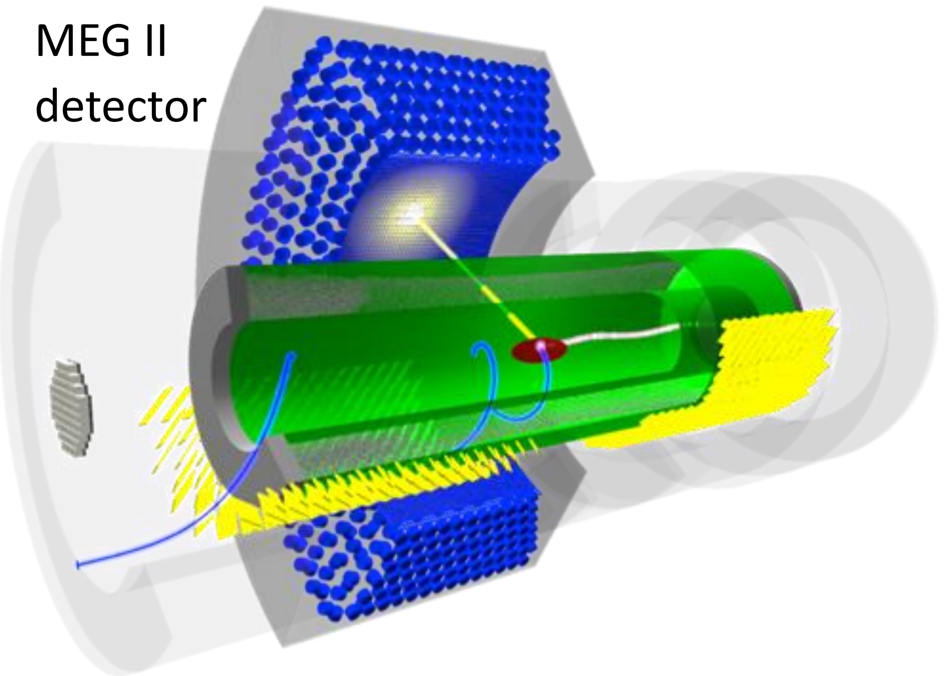
$\mu^+ \to e^+ + \gamma$
BR < 3.1 x 10^{-13}
MEG 2023

[90 % C.L.]

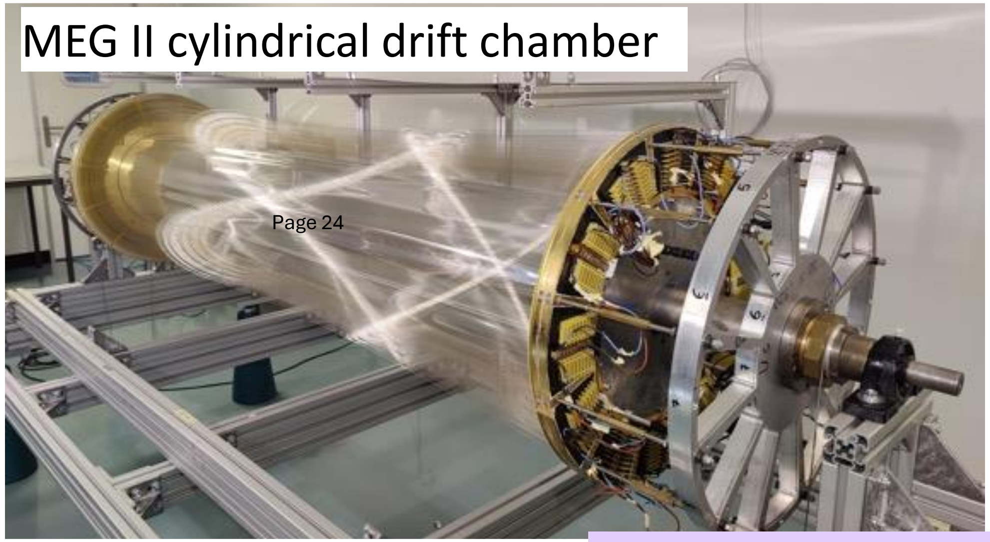


The MEG II Experiment

MEG II detector



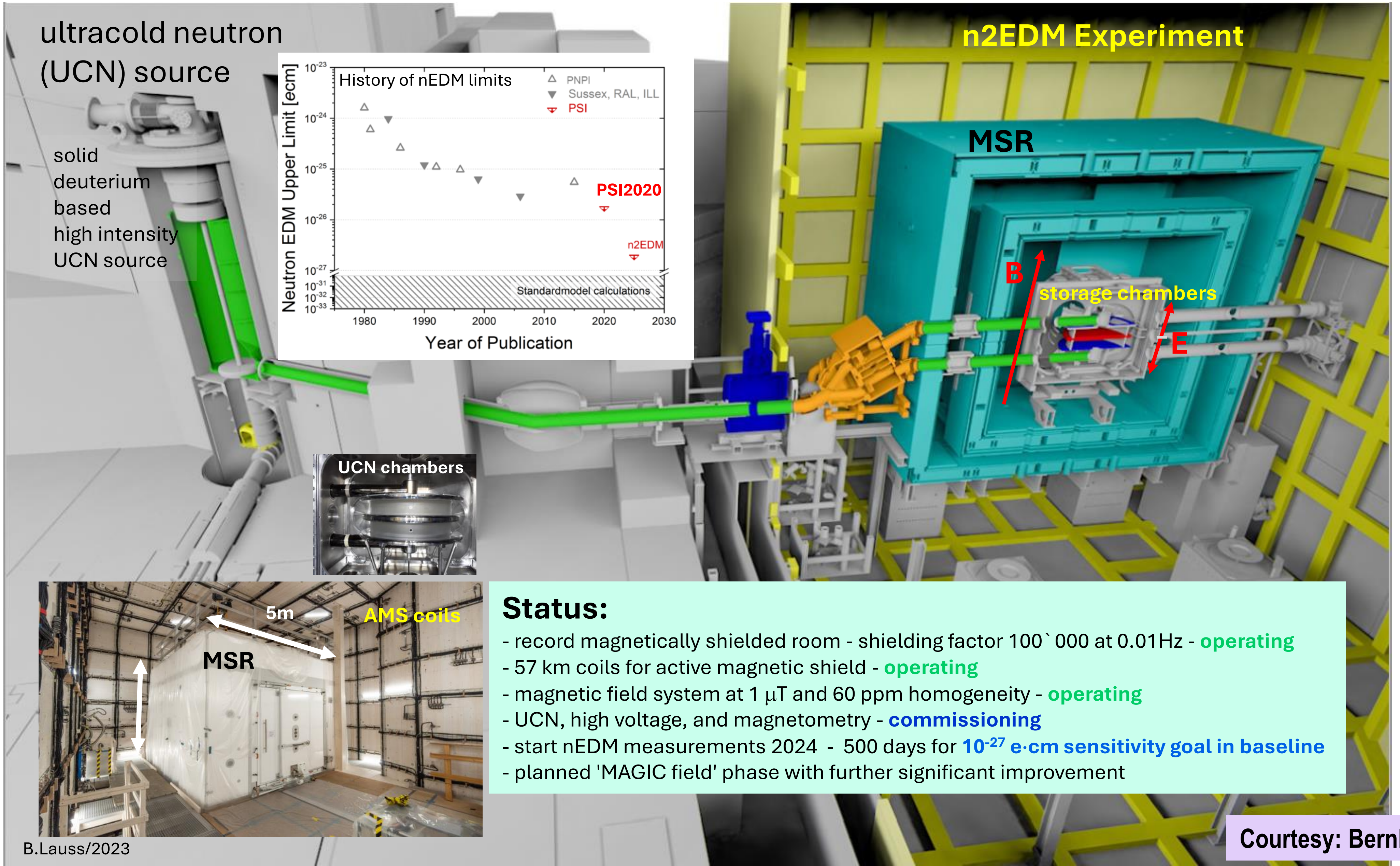
- MEG II experiment searching for $\mu \to e\,\gamma$ aiming at $B(\mu \to e\,\gamma) < 6 \times 10^{-14}$ @90%CL
- MEG result 2016: $B(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$ more than 28x improvement
  Eur. Phys. J. C (2016) 76:434
- MEG II data taking 2021-26
- 2021 data analysis has recently been released,
  arxiv.org/abs/2310.12614
  alone: $B(\mu \to e\,\gamma) < 7.5 \times 10^{-13}$
  combined with MEG: $B(\mu \to e\,\gamma) < 3.1 \times 10^{-13}$
- 2022&2023 → already ~5 times MEG data set



Courtesy: Angela Papa

n2EDM - Search for a permanent neutron EDM

PSI



Status:

- record magnetically shielded room - shielding factor 100`000 at 0.01Hz - **operating**
- 57 km coils for active magnetic shield - **operating**
- magnetic field system at 1 µT and 60 ppm homogeneity - **operating**
- UCN, high voltage, and magnetometry - **commissioning**
- start nEDM measurements 2024 - 500 days for **10^{-27} e·cm sensitivity goal in baseline**
- planned 'MAGIC field' phase with further significant improvement

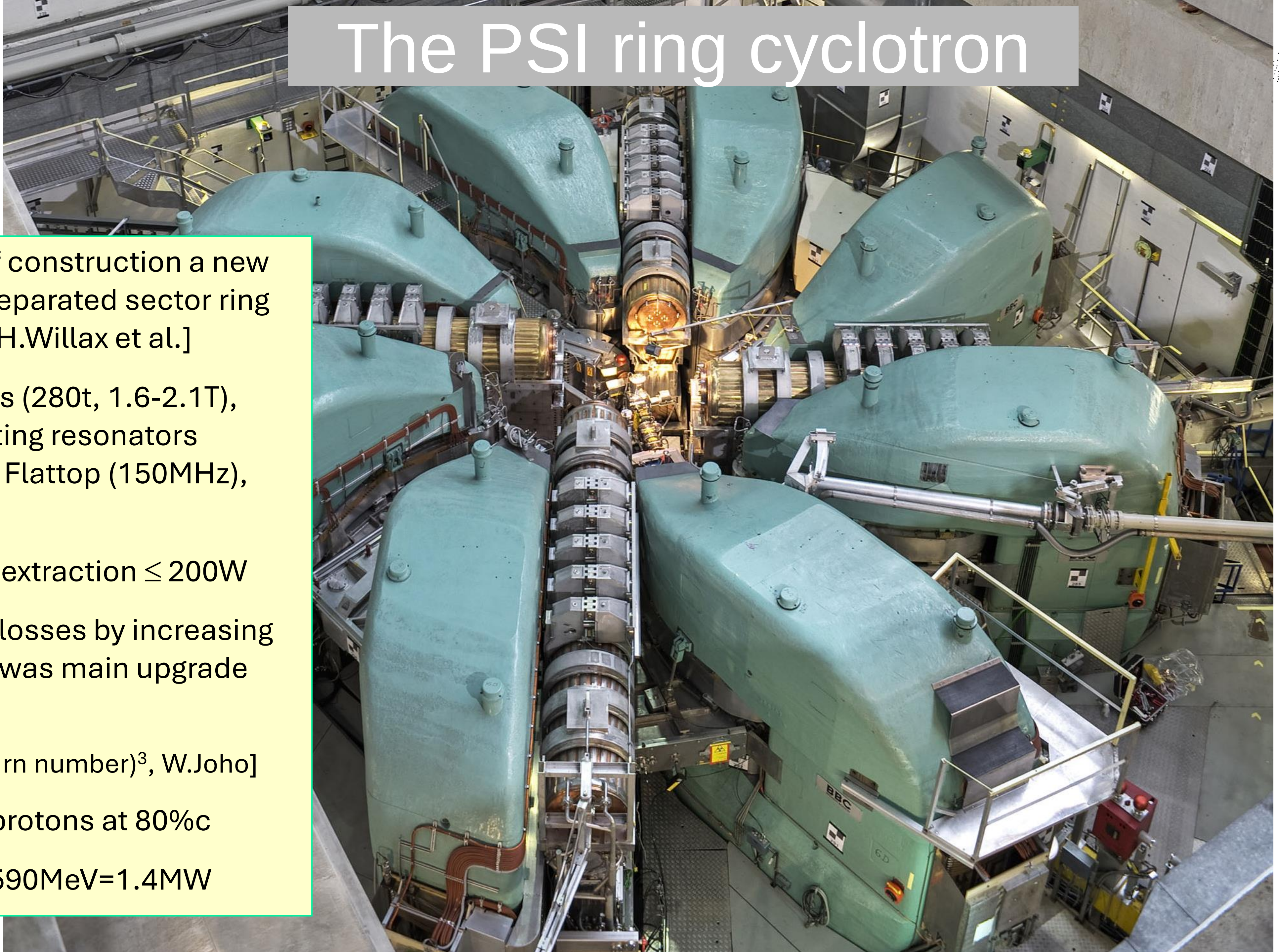
B.Lauss/2023

Courtesy: Bernhard Lauss

The PSI ring cyclotron

The PSI ring cyclotron

PSI



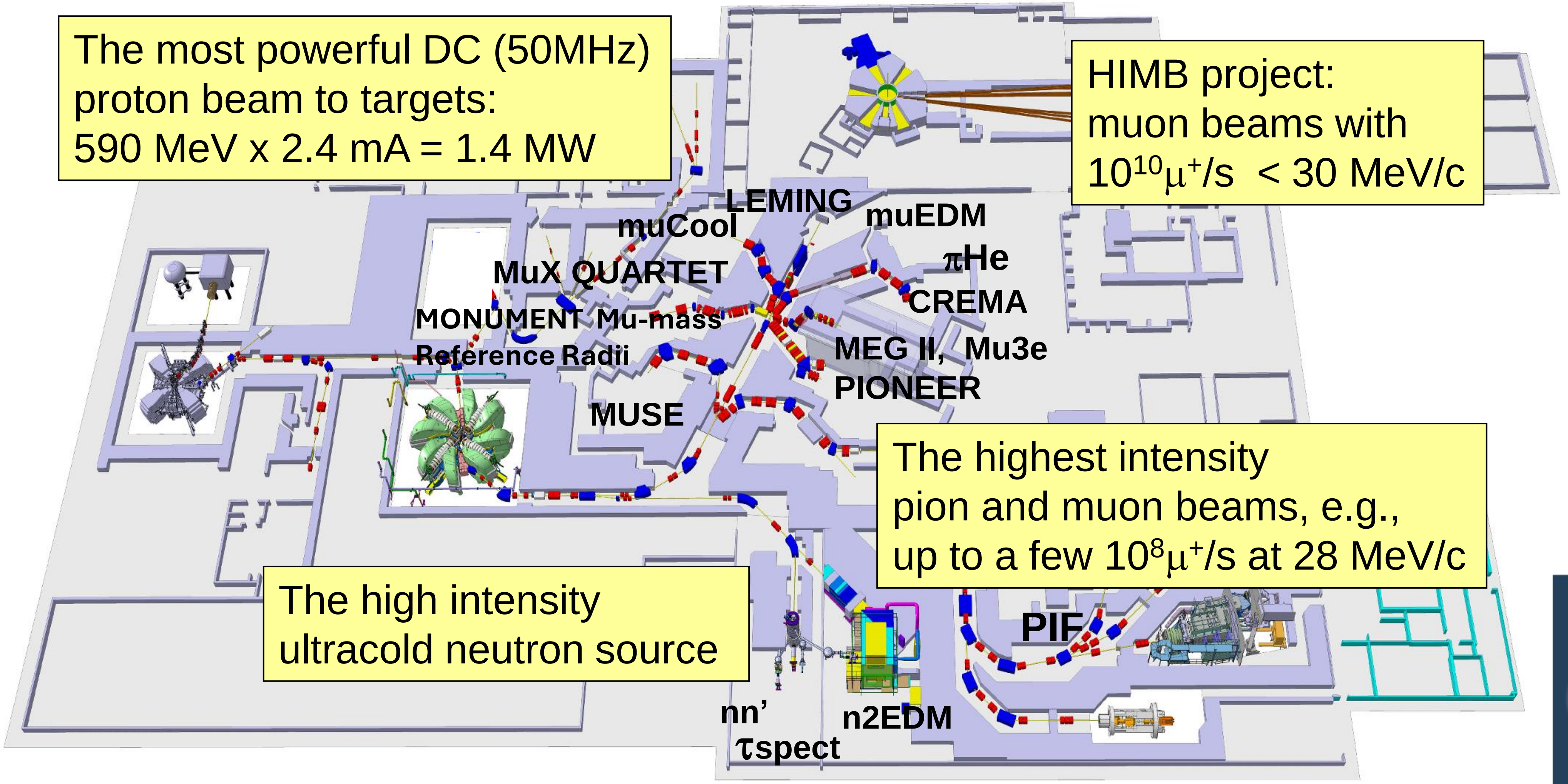
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

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

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

The intensity frontier at PSI: π, μ, UCN

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

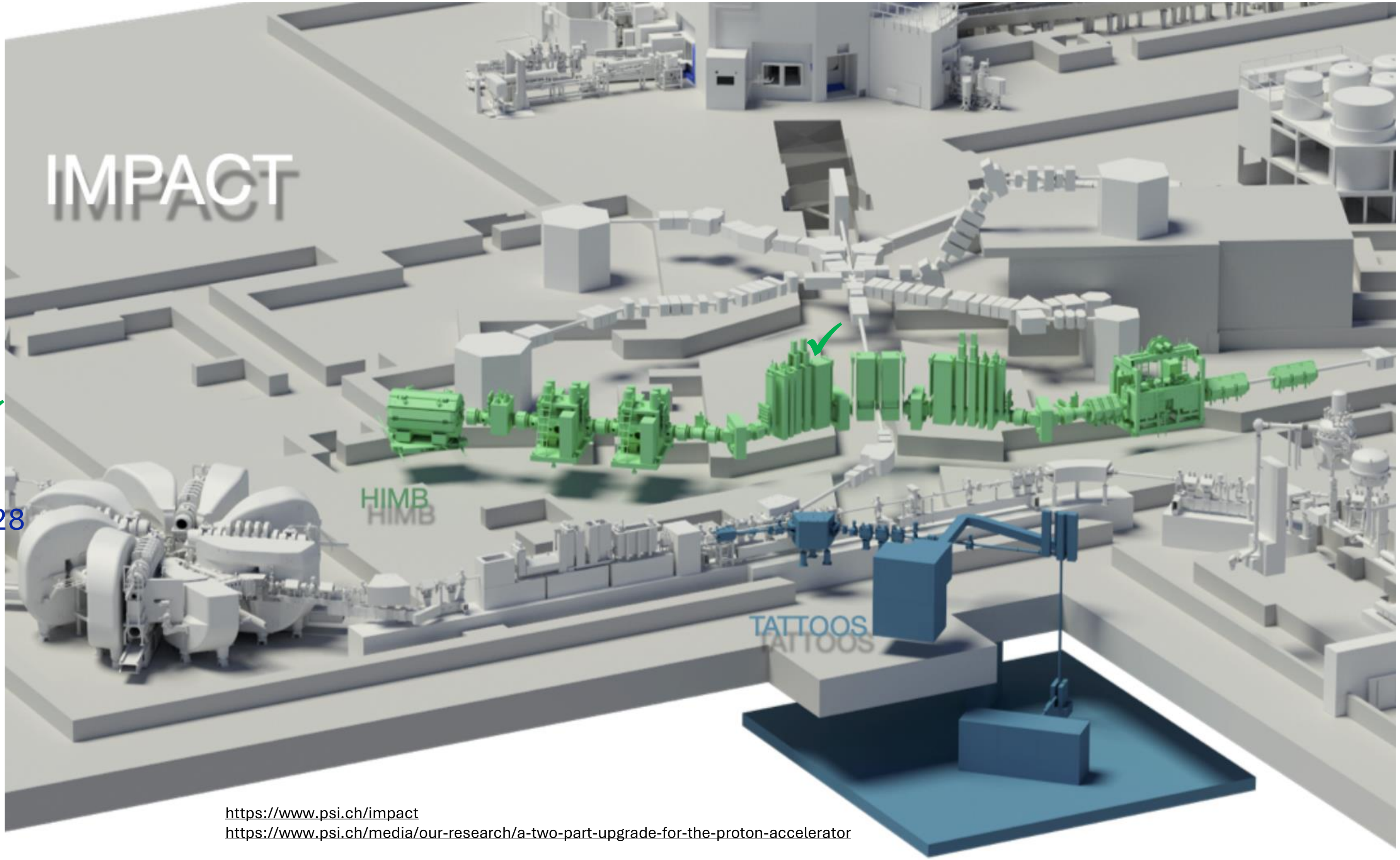


Swiss national laboratory with <u>strong international collaborations</u>

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

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

- 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
- Full implementation
- 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 momentum pion and muon beams

User facilities for particle physics

- **PSI** provides the world’s highest intensity continuous beams and the largest integrated intensities
- **J-PARC** provides the world’s highest intensity pulsed beams

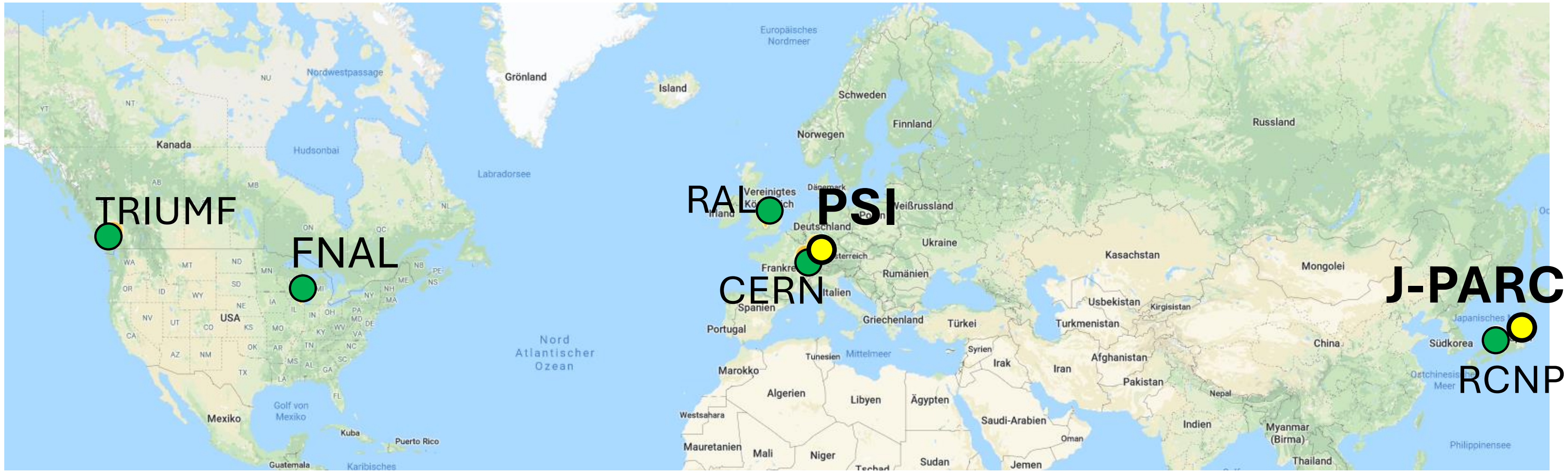
At lower intensities, for other applications or at high momenta, muons are also available at:

CERN, FNAL, RAL, TRIUMF, RCNP

Discussions/plans for new low momentum muon facilities: CSNS, RAON, FNAL

Future pulsed beams at FNAL and J-PARC will provide up to 10^{11}/s pulsed μ^- to dedicated exps.

HiMB at PSI should provide 10^{10}/s low momentum positive muons for general purpose



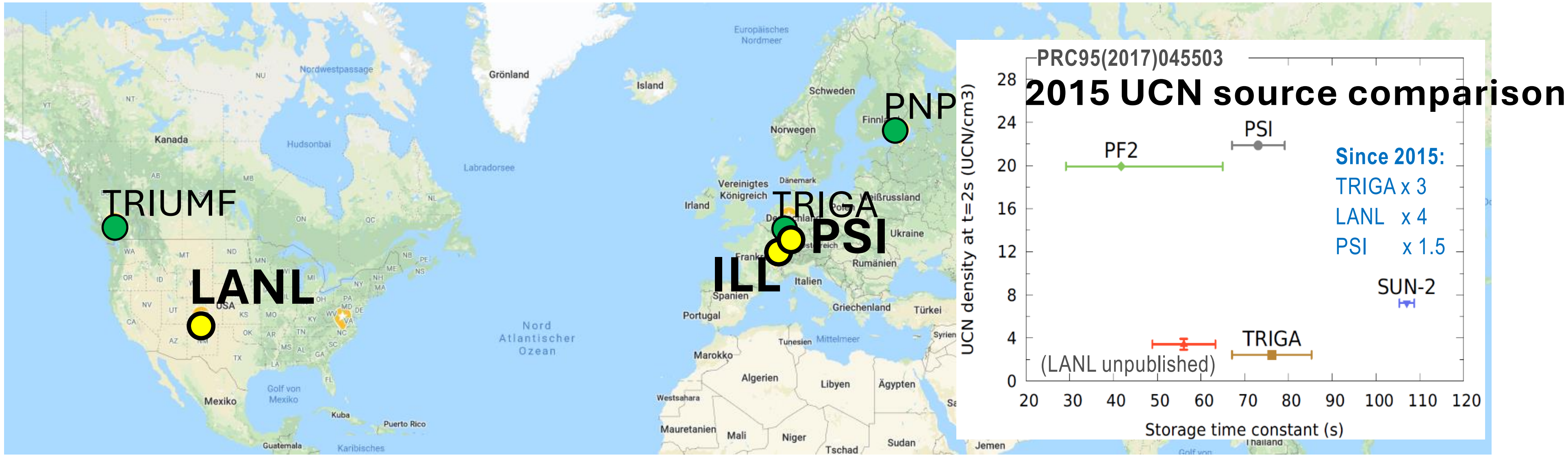
Ultracold neutrons

User facilities for particle physics with UCN

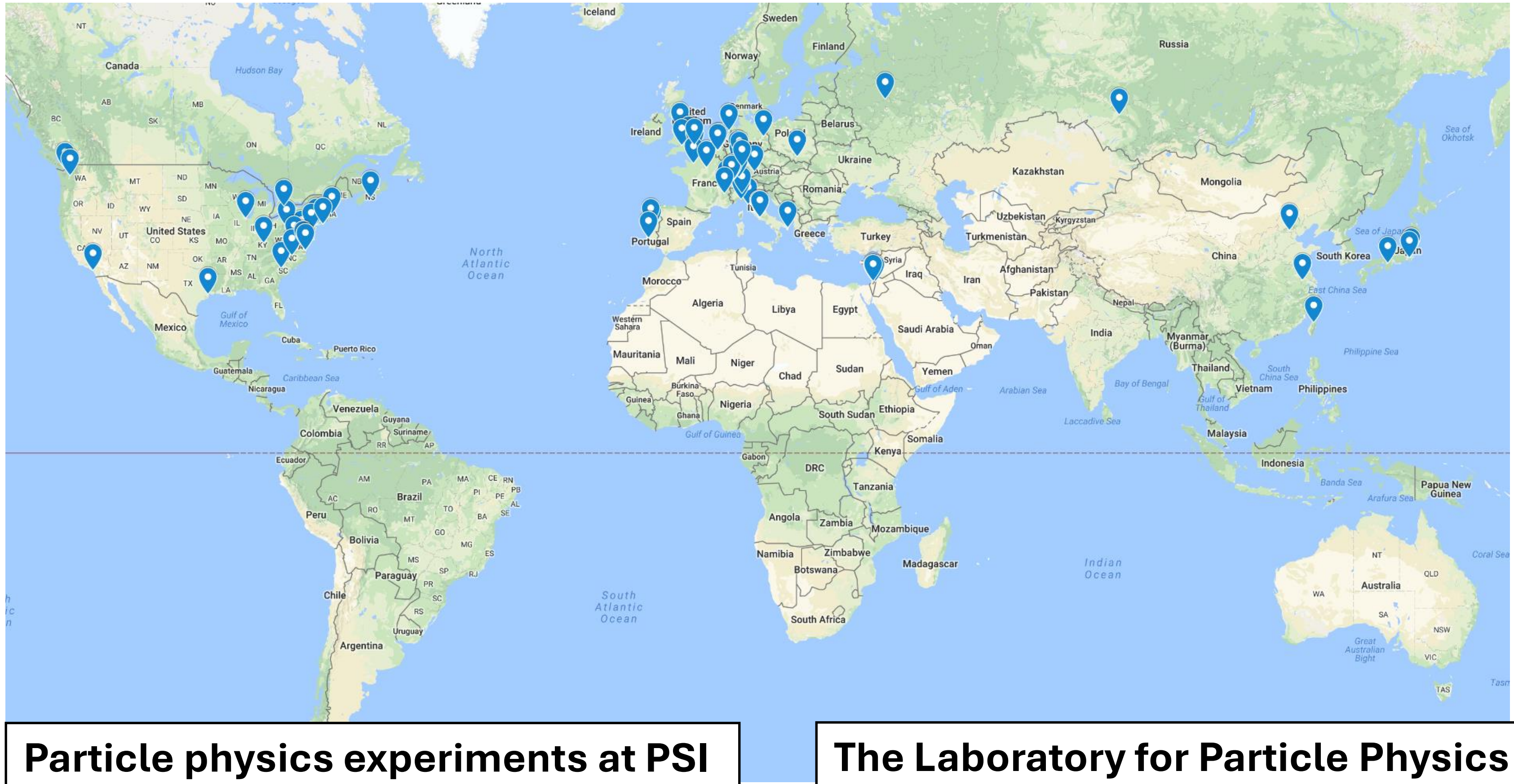
- **PSI** is world-leading with the **neutron electric dipole moment** experiment and serving other exps.
- **ILL** PF-2 has been the world's UCN hub for more than 30 years and produced a plethora of results
- **LANL** is world-leading with the **neutron lifetime** experiment and serving also other experiments
- **TRIGA** Mainz is a smaller scale UCN source with neutron lifetime exp. and limited user program
- Others are not yet running experiments

Planned future installations and upgrades:

ILL (SuperSUNS, add. PF-2), TRIUMF-KEK (under construction), NCSU Pulstar, PNPI, FRM II,
SNS (to produce UCN in one dedicated experiment); UCN2.0 at PSI to stay ahead of competition



Institutions active in particle physics at PSI



Particle physics experiments at PSI

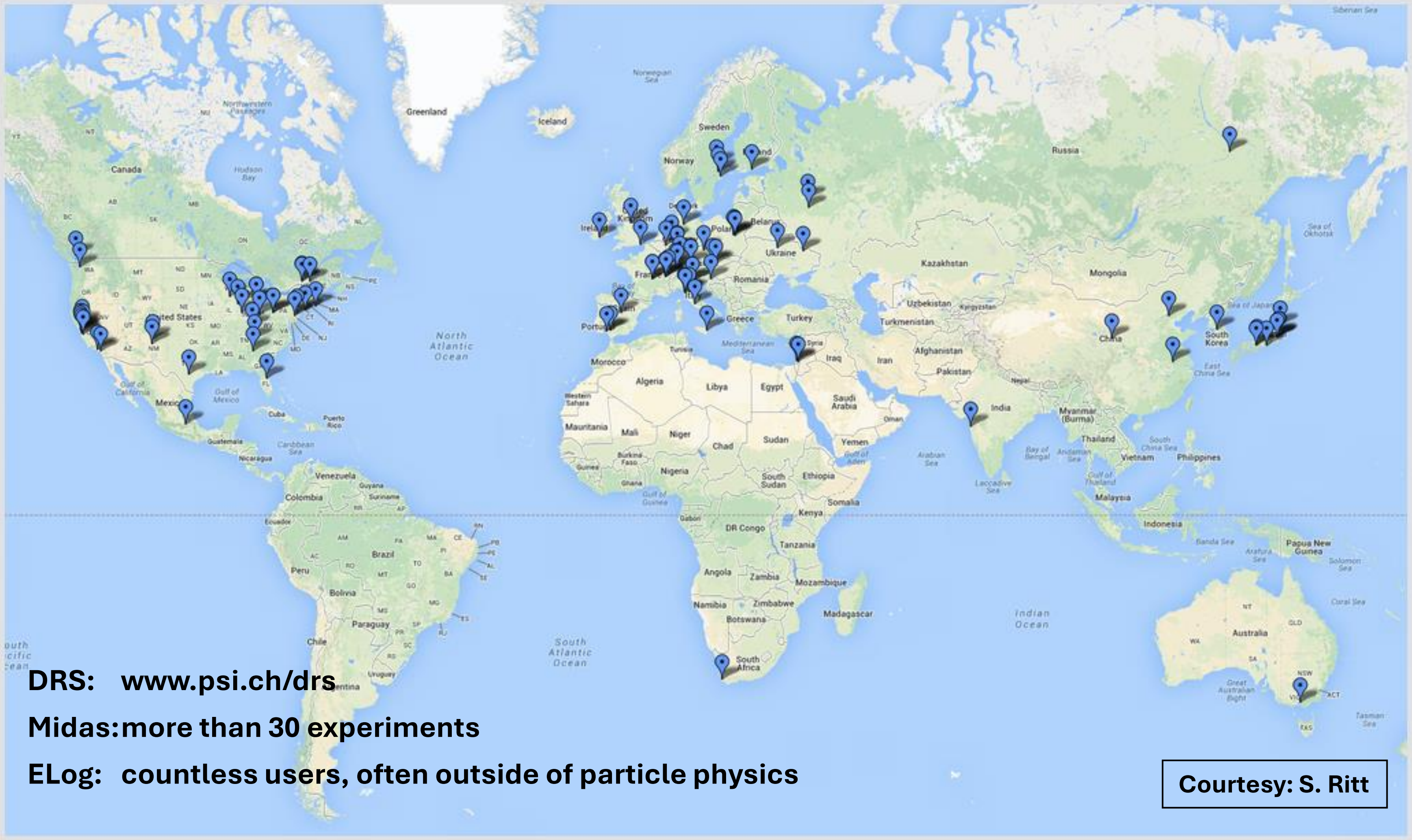
- ~70 institutions world-wide participating
- ~350 individuals / ~700 visits per year
- 8'000-10'000 user days per year (1/3 of all at PSI)

The Laboratory for Particle Physics

- ~10 MCHF/year, incl. ~30% 3rd party funds
- ~60 FTE, incl. tenured and tenure track scientists, electronics engineers, technicians, postdocs, PhD students

Some PSI particle physics technologies

PSI´s DRS-4 Chip in use around the world:
more than 19’000 chips in about 200 experiments



DRS: www.psi.ch/drs

Midas: more than 30 experiments

ELog: countless users, often outside of particle physics

Courtesy: S. Ritt

Tour of HIPA and its user facilities