# Precision physics with muons at PSI

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MITP Topical Workshop 2022

Mainz – 15/11/2022

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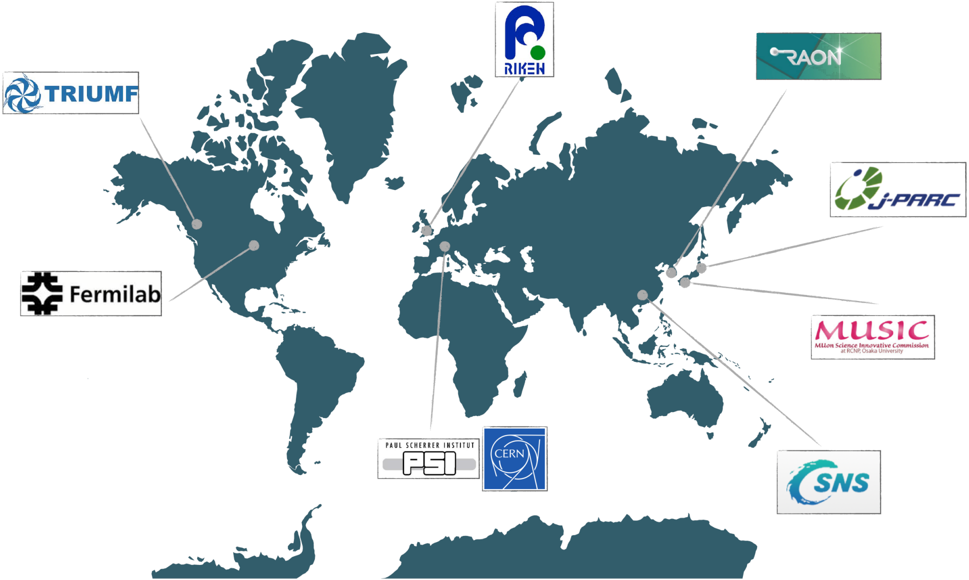
# Muon facilities around the world



# The Paul Scherrer Institut

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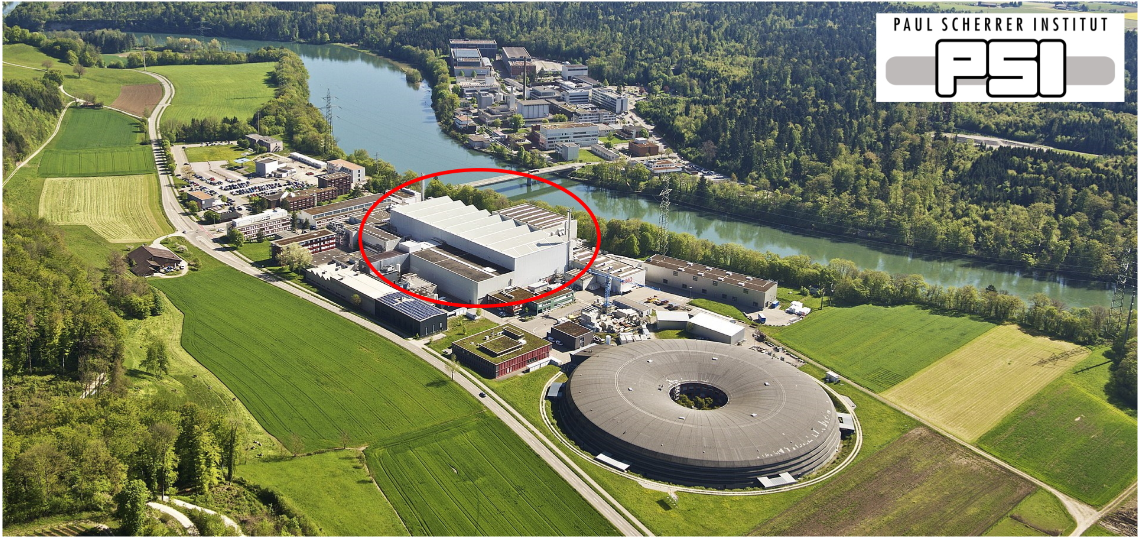
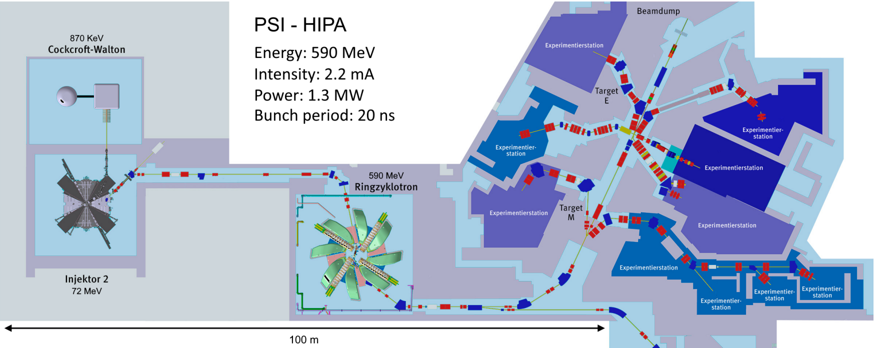
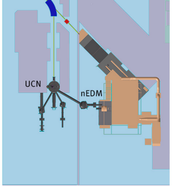


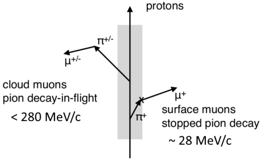
# The High Intensity Proton Beam facility



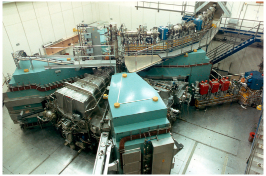
## PSI - HIPA

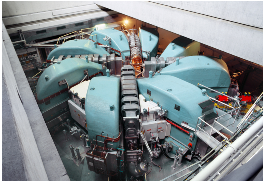
Energy: 590 MeV
Intensity: 2.2 mA
Power: 1.3 MW
Bunch period: 20 ns




$$p\,p \rightarrow p\,n\,\pi^+ \qquad \pi^+ \rightarrow \mu^+\,\nu_\mu$$
$$p\,n \rightarrow n\,n\,\pi^+ \qquad \pi^- \rightarrow \mu^-\,\bar{\nu}_\mu$$
$$p\,p \rightarrow n\,n\,\pi^+\,\pi^+$$
$$p\,n \rightarrow p\,n\,\pi^+\,\pi^-$$

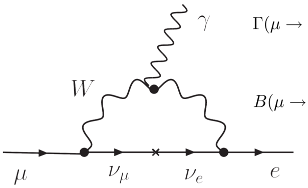
$5 \cdot 10^8\ \mu^+/s$





# Search for charged Lepton Flavour Violation

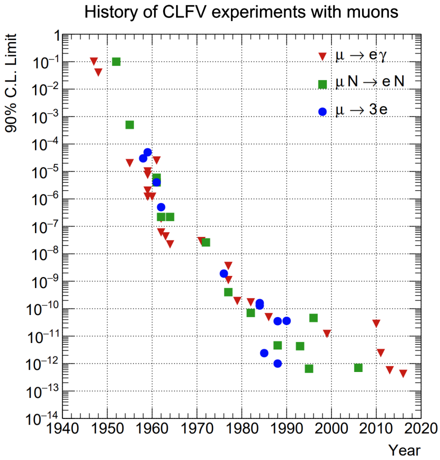
- The discovery of neutrino oscillation showed that lepton family number is **not** a sacred symmetry of Nature.
- No hints of **charged Lepton Flavour Violation** so far.
- A promising way: low-energy processes involving **muons**, e.g. $\mu \to e\gamma$, $\mu \to eee$ and $\mu N \to eN$.
- Any observation would be a clear signal beyond the SM.




$$\Gamma(\mu \to e\gamma) = \frac{G_F^2 m_\mu^5}{192\pi^3}\frac{3\alpha}{32\pi}\left|\sum_i (V^*_{PMNS})_i (V_{PMNS})_i \frac{m^2_{\nu_i}}{m_W^2}\right|^2$$

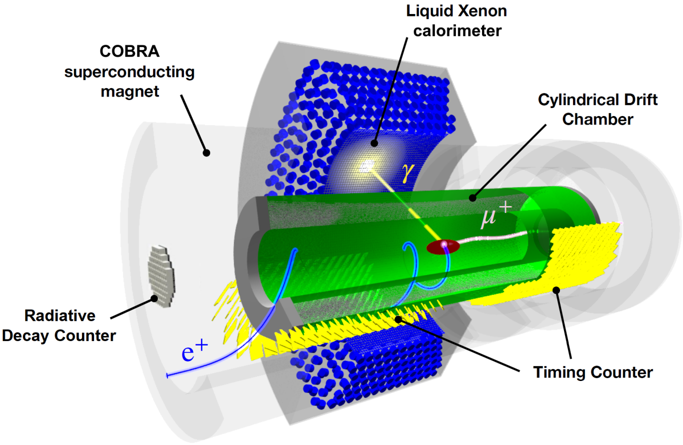
$$B(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\overline{\nu})} \approx \frac{\alpha}{2\pi}\sin^2 2\theta \left(\Delta m^2 / m_W^2\right)^2$$

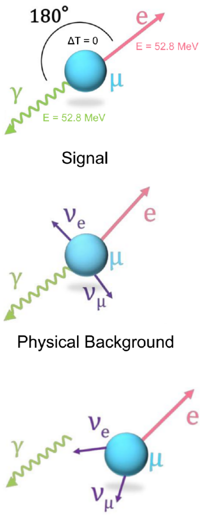
$$\approx \frac{1}{2 \times 137 \times \pi}\left(\frac{7 \times 10^{-5}\, eV^2}{80\, GeV^2}\right)^2 \approx 10^{-55}$$




[1] L. Calibbi and G. Signorelli, *Charged Lepton Flavour Violation: An Experimental and Theoretical Introduction* (2017) [1709.00294]

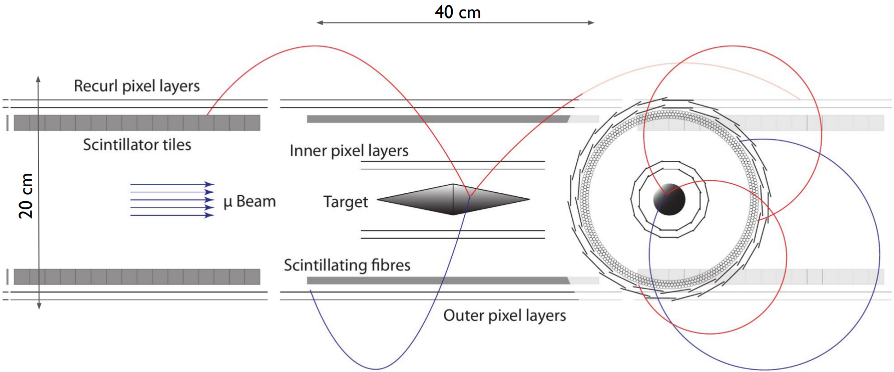
**MEG**: $\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \cdot 10^{-13}$ at 90% CL $\longrightarrow$ **MEG II**: $6 \cdot 10^{-14}$ at 90% CL




[1] A. M. Baldini et al., *The design of the MEG II experiment* (2018) [1801.04688]

**SINDRUM**: $\mathrm{BR}(\mu^+ \to e^+e^+e^-) < 1 \cdot 10^{-12}$ at 90% CL $\longrightarrow$ **Mu3e**: $2 \cdot 10^{-15}$ at 90% CL




[1] K. Arndt at al., *Technical design of the Mu3e experiment* (2021) [2009.11690]

# Other (future) projects

- **MUSE**: a forthcoming experiment to measure the proton radius via $\mu p$ scattering ($\Delta r \approx 0.006 - 0.01$ fm).
- **muEDM**: a proposed experiment to measure the muon EDM with a sensitivity of $6 \cdot 10^{-23} e{\cdot}\text{cm}$.
- **PIONEER**: a new experiment to study rare pion decays to test lepton flavour universality at low energy:

$$R_{e/\mu} = \Gamma(\pi^+ \to e^+\nu_e) \,/\, \Gamma(\pi^+ \to \mu^+\nu_\mu) = 1.23524(15) \cdot 10^{-4} \quad + \quad \text{BR}(\pi^+ \to \pi^0 e^+ \nu_e) \approx 10^{-8}$$

- **muCool**: a new cooling system based on stopping muons inside a helium gas target and focusing the beam ($\Delta E < 1$ eV, $\Delta x < 1$ mm) with a combination of e.m. fields $\longrightarrow$ muon collider injector?
- Several experiments based on **muonic atoms** spectroscopy.


[1] W. Altmannshofer et al., *Studying the Proton "Radius" Puzzle with $\mu p$ Elastic Scattering* (2013) [1303.2160]

[2] M. Sakurai et al., *muEDM: Towards a search for the muon electric dipole moment at PSI* (2022) [2201.06561]

[3] W. Altmannshofer et al., *PIONEER: Studies of Rare Pion Decays* (2022) [2203.01981]

[4] I. Belosevic et al., *muCool: A novel low-energy muon beam for future precision experiments* (2019) [1901.04886]

# Looking for the ~~needle~~ muon in the haystack: $\mu \to e\,X$

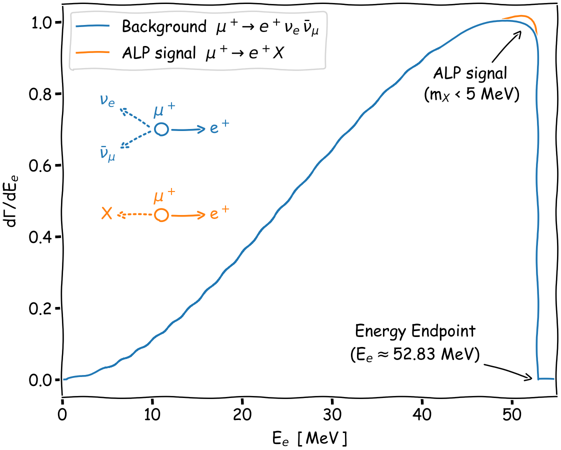
- MEG II and Mu3e are competitive also for muon decays involving an invisible **axion-like particle** $X$.
- Here focus on $\boldsymbol{\mu^+ \to e^+ X}$ (simple but elusive!)
- The signature is a **monochromatic** $\boldsymbol{e^+}$ close to the **energy endpoint** of the $\boldsymbol{\mu^+ \to e^+ \nu_e \bar{\nu}_\mu}$ background:

$$E_e^{max} = \frac{m_\mu}{2}\left[1 + \left(\frac{m_e}{m_\mu}\right)^2\right] \approx 52.83 \text{ MeV}$$

- The higher-order QED corrections for $E_e \to E_e^{max}$ are enhanced by the emission of **real photons**.

  $\hookrightarrow$ Large theoretical error hiding low signals!

- The experimental search requires extremely accurate theoretical predictions for simulations and analysis.




Signal energy: $E_e^X(m_X) = \dfrac{m_\mu^2 + m_e^2 - m_X^2}{2m_\mu}$

# We need a Mule to do the hard work

- The new generation of precision experiments with leptons needs extremely accurate SM predictions, usually at the **next-to-next-leading order** (NNLO).
  $\hookrightarrow$ McMule $\longrightarrow$ **M**onte **C**arlo for **MU**ons and other **LE**ptons.
- A unified framework for the numerical computation of **QED corrections** for decay and scattering processes involving leptons, mainly at low energies.
- For an implemented process the output is the differential distribution w.r.t. *any* user-defined IR-safe observable that can be constrained with *any* cut.
  $\hookrightarrow$ Can reproduce detector acceptances, analysis cuts, trigger selections etc.
- Avaiable at `https://mule-tools.gitlab.io`
- See Yannick, Tim and Marco's talks tomorrow morning for more details.

[1] P. Banerjee et al., *QED at NNLO with McMule* (2020) [2007.01654].

McMule

| **Process** | **Precision** |
|---|---|
| $\mu \to e\,\nu\,\bar\nu$ | NNLO † |
| $\mu \to e\,\nu\,\bar\nu\,\gamma$ | NLO † |
| $\mu \to e\nu\bar\nu ee$ | NLO † |
| $e\,e \to e\,e$ | NNLO |
| $e\,e \to \nu\,\bar\nu$ | NNLO |
| $e\,e \to \gamma\,\gamma$ | NNLO ⋆ |
| $e\,e \to \mu\,\mu$ | NNLO ⋆ |
| $e\,p \to e\,p$ | NNLO |
| $\mu\,p \to \mu\,p$ | NNLO |
| $\mu\,e \to \mu\,e$ | NNLO ⋆ |

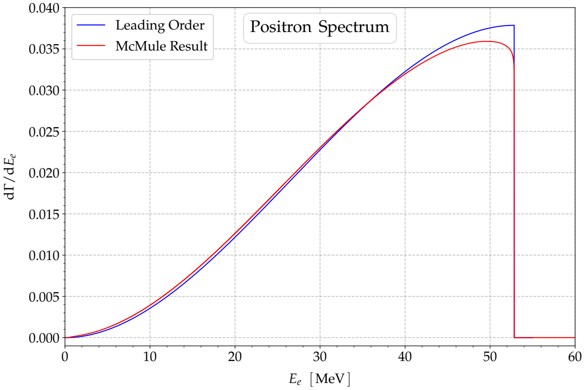
† $\tau$ decays as well

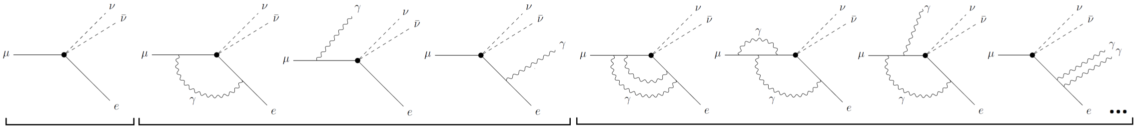
⋆ Work in progress

# A new state-of-the-art computation of $\mu \to e\,\nu\,\bar{\nu}$

- Full **QED corrections at NNLO** with $m_e \neq 0$.
- The **collinear** logarithmic terms $\log(m_e/m_\mu)$ included up to N$^4$LO with NLL accuracy
- The **soft** logarithms $\log(1 + m_e^2/m_\mu^2 - 2E_e/m_\mu)$ are analytically resummed with NNLL accuracy.
- (Hadronic) Vacuum Polarisation effects at $\alpha^2$.
- Theory error on positron spectrum $\sim 5 \cdot 10^{-6}$.

[1] P. Banerjee et al., *High-precision muon decay predictions for ALP searches* (2022) [2211.01040].



# Conclusions

- Muon physics is one of the main research field at PSI with several outgoing or forthcoming experiments.

  [1] A. Signer et al., *Review of Particle Physics at PSI* (2021)

- The HIMB project will increase the muon rate up to $10^{10}\ \mu^+/\text{s}$, providing totally new experimental opportunities.

  [2] M. Aiba et al., *Science Case for the new High-Intensity Muon Beams HIMB at PSI* (2021) [2111.05788]

- Theorists are ready to lock themselves in offices and do more calculations to match the improved experimental precision.