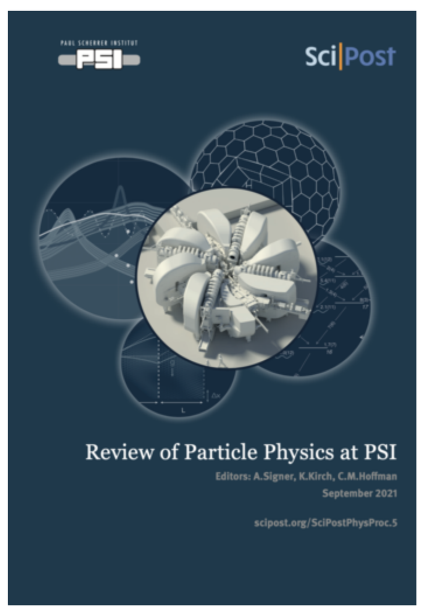
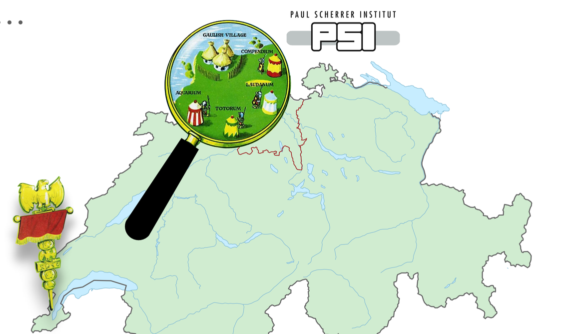
PARTICLE PHYSICS IN THE WILD WEST

Theory Group, Laboratory for Particle Physics, Paul Scherrer Institute

WANTED! (DEAD OR ALIVE) BACHELOR, MASTER, AND PHD STUDENTS

The year is 2021. Particle Physics in Switzerland is entirely occupied by the LHC troops. Well, not entirely. The indomitable Gauls in the small village Villigen in Züri West still stand out …





Join us at **PSI** — the largest research institute for natural and engineering sciences in Switzerland — for **low-energy particle physics at the precision frontier!**

McMule (Monte Carlo for Muons and other leptons)

- Low-energy precision experiments with leptons require a precise knowledge of the Standard Model background:
  - Lepton-lepton scattering @ MUonE $\mu e \to \mu e$ or PRAD ($e^-e^- \to e^-e^-$) or PADME ($e^+e^- \to \gamma\gamma$)
  - Lepton-proton scattering @ P2 and PRAD ($ep \to ep$) or MUSE ($\mu p \to \mu p$ and $ep \to ep$)
  - Charged lepton flavour violating decays @ MEG ($\mu \to e\gamma$) or Mu3e ($\mu \to 3e$)
- McMule: Monte Carlo framework for fully-differential higher-order QED
- NNLO corrections in massive QED, e.g., for $\mu e \to \mu e$, $\ell p \to \ell p$, and $\mu \to e\nu\nu$
- simple FKS$^\ell$ subtraction scheme for numerical phase-space integration
- some obstacles: multi-scale loop integrals, divergent phase-space, numerical instabilities, …

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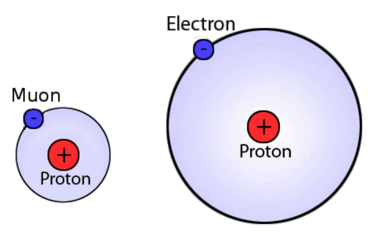
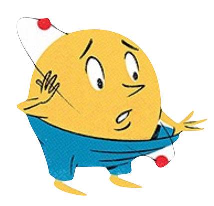
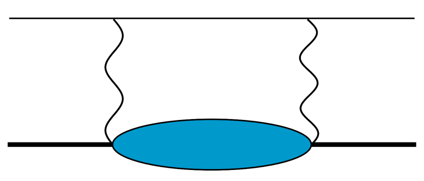
Muonic atoms



- Spectroscopy of muonic atoms (μH, μD, μHe) by CREMA Collaboration @ PSI allows for unprecedentedly precise nuclear charge radius extractions:
  - Proton charge radius: $\langle r^2 \rangle_E = 0.84087(12)_{\text{sys}}(23)_{\text{stat}}(25)_{\text{TPE}}(15)_{\text{QED}}$
- Heavy muons have a better "view" on the nucleus
- Measurement of the ground state hyperfine splitting in μH
  - Pin down magnetic properties of the proton
  - Extract proton Zemach radius R_Z



- Theory uncertainty limited by two-photon exchange (TPE):
  - Muonic hydrogen: $E_{\text{HFS}} = \left[183.810(12) - 1.2968(80)\, R_Z + \Delta E^{\text{pol.}}_{\text{TPE}}\right]$ meV
- Disagreement between chiral perturbation theory prediction of the TPE polarizability effect and dispersive evaluation based on empirical proton structure functions
  - Further studies needed on both sides …



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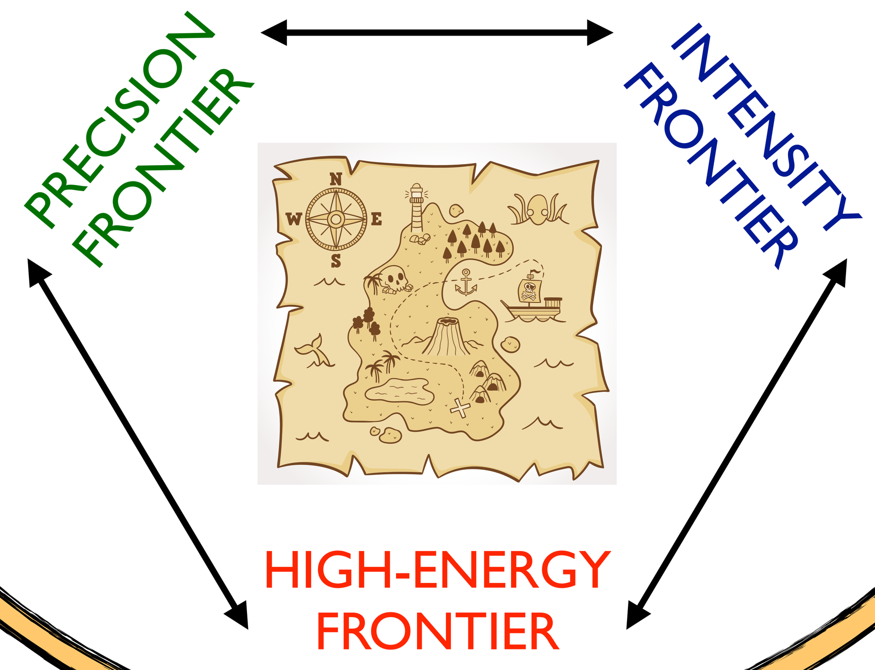
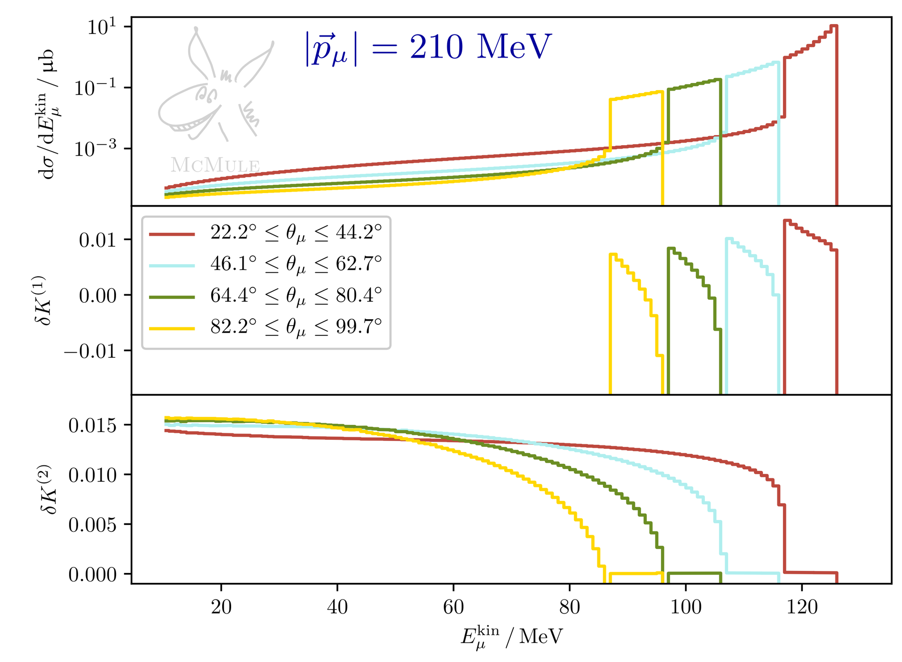
New Physics Searches

- Many indications for **physics beyond the Standard Model**, aka "**New Physics**" from astrophysical observations (baryon asymmetry, dark matter, dark energy, …)
- Lab searches for New Physics proceed along 3 frontiers:



MUSE (MUon proton Scattering Experiment)

- Muon & electron scattering off the proton @ PSI



- Four-momentum-transfer $Q^2 \in [0.002, 0.08]$ GeV
- ℓ^- & ℓ^+ beams
- Measure electric Sachs form factor $G_E(Q^2)$ of the proton
  - Fourier transforms of charge distributions:

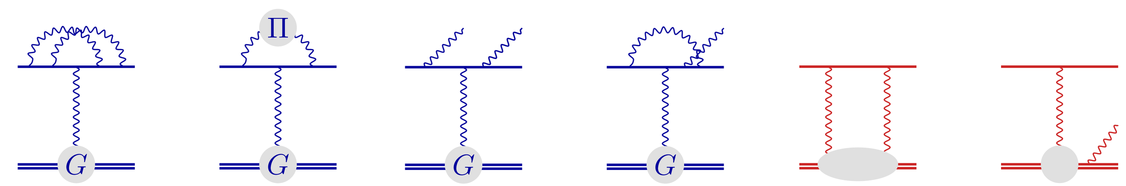
$$\rho_E(\mathbf{r}) = \int \frac{\mathrm{d}\mathbf{q}}{(2\pi)^3}\, G_E(\mathbf{q}^2)\, e^{-i\mathbf{q}\mathbf{r}}$$

- Determine proton charge radius:

$$\langle r^2 \rangle_E = \int \mathrm{d}r\, \rho_E(r) = -6\, \frac{\mathrm{d}}{\mathrm{d}Q^2}\, G_E(Q^2)|_{Q^2=0}$$

- Measure and calculate elastic and inelastic two-photon exchange

Example:
QED radiative, vacuum polarization and hadronic corrections (to be) implemented in **McMule**



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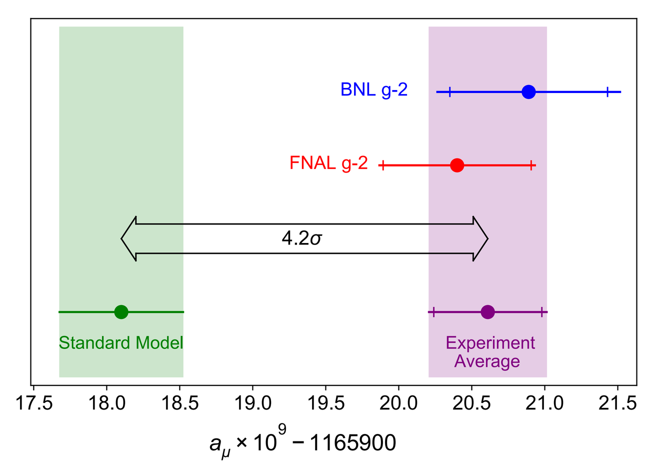
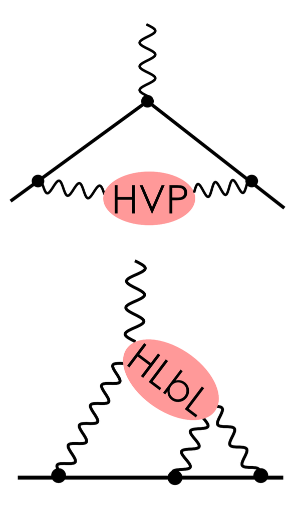
Muon anomalous magnetic moment (g-2)$_\mu$

- 4.2σ discrepancy between Standard Model (SM) prediction and experimental value → New Physics or misinterpretation of the SM?
- Uncertainty of SM theory dominated by hadronic vacuum polarization (HVP) & light-by-light scattering (HLbL)

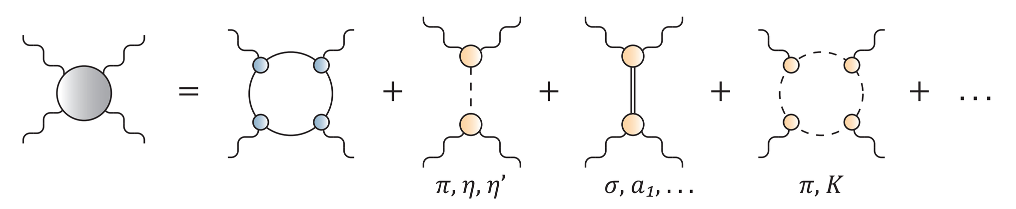


	$(g\text{-}2)_\mu \times 10^{14}$	$\Delta(g\text{-}2)_\mu \times 10^{14}$
Experiment	116 592 061 000	41 000
SM	116 591 810 000	43 000
QED	116 584 718 931	104
HVP	6 845 000	40 000
Electroweak	153 600	1 000
HLbL	92 000	18 000

- Hadronic corrections are challenging to calculate because QCD is non-perturbative at low energies
- Discrepancy between data-driven evaluation of HVP from $\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$ and lattice QCD prediction by BMW Collaboration



- HLbL topology notoriously difficult to calculate
  - Pseudoscalar-poles and meson-boxes make up 2/3 of HLbL contribution
  - Uncertainty dominated by scalar, tensor, axial-vector and short-distance contributions



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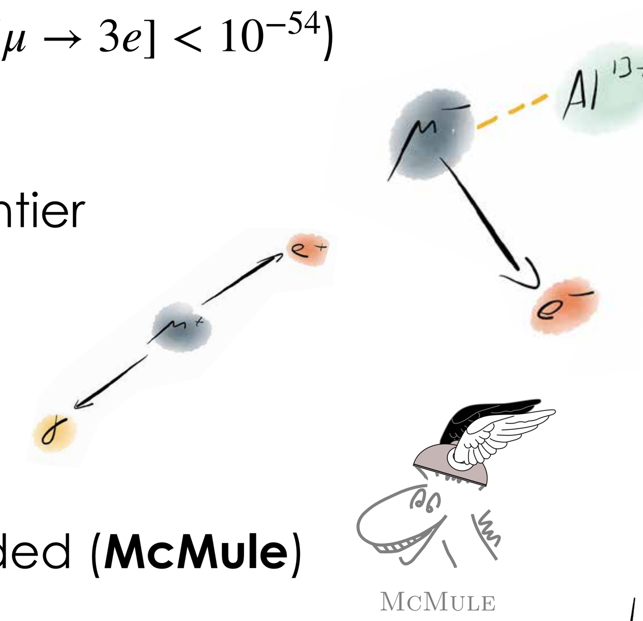
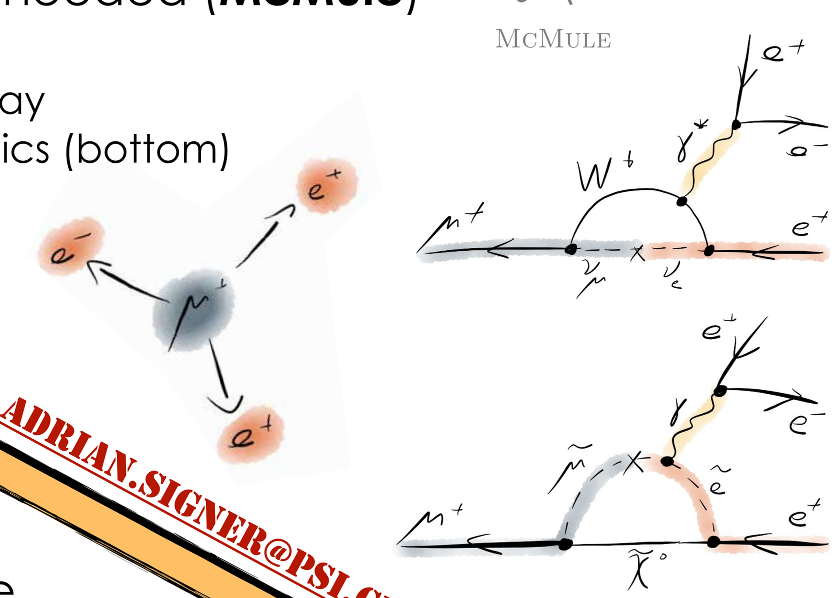
Charged lepton flavour violating (CLFV) decays

- CLFV decays are suppressed in the Standard Model (e.g., $\text{Br}[\mu \to 3e] < 10^{-54}$) → observation is a clear sign for New Physics
- PSI experiments at the intersection of precision & intensity frontier
  - SINDRUM: $\text{Br}[\mu \to 3e] < 10^{-12}$ and Mu3e aims for $\text{Br}[\mu \to 3e] < 10^{-16}$
  - SINDUM-II: $\text{Br}[\mu^-\text{Au} \to e^-\text{Au}] < 7 \times 10^{-13}$
  - MEG: $\text{Br}[\mu \to e\gamma] < 4.2 \times 10^{-13}$ and MEG-II aims for $\text{Br}[\mu \to e\gamma] < 10^{-14}$
- Precise knowledge of the Standard Model background needed (**McMule**)



Example: $\mu \to 3e$ decay
SM (top) & New Physics (bottom)



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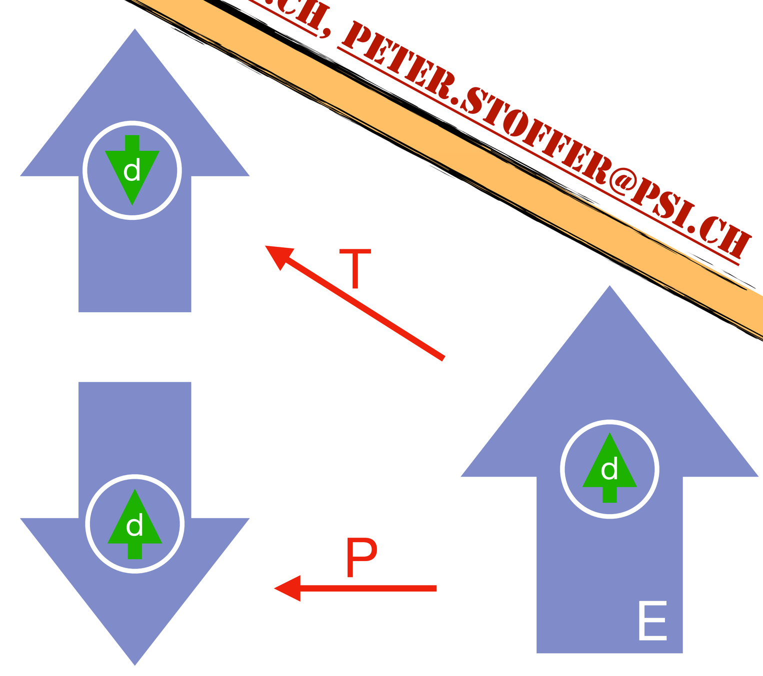
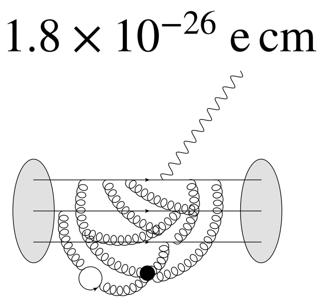
Neutron electric dipole moment (EDM)

- Combined charge (C), parity (P), and time-reversal (T) symmetry = CPT symmetry holds by CPT theorem for all physical phenomena
- Permanent EDM of a fundamental or composite particle violates P and T symmetry → CP violation
- CP violation in the SM due to CKM matrix is tiny
- Baryon asymmetry of universe requires more CP violation → New Physics
- Current bound on neutron EDM: $|d_n| < 1.8 \times 10^{-26}$ e cm @ PSI
- Best constraints on New Physics require control over non-perturbative hadronic matrix elements





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