Precision particle physics at PSI

K.Kirch, ETH Zurich – PSI Villigen, Switzerland

Using highest intensities of pions, muons and UCN for

- **Precision measurements** of Standard Model parameters
- **Searches** for physics beyond the Standard Model
The Standard Model of Particle Physics

is extremely successful …
(with some issues concerning neutrino masses, muon g-2, B-decays, …)

… but does not explain

- Gravity, Dark matter
- Dark energy
- 3 families
- QCD theta term
- Values of particle masses and couplings
- Baryon Asymmetry of the Universe
- Conservation of baryon and charged lepton number

…
LTP-Groups

- Theory
- High Energy Physics
- Muon Physics
- Ultacold Neutrons
- Electronics and Measurement Systems
- Detectors
- Applied Particle Physics and Irradiations

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, nEDM, Mu3e, n2EDM, ...) at PSI
- At LHC: Participation and key contributions to CMS (Si-pixel R&D and data analysis, e.g. B-μμ 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 (2016: 23rd!)
- PSI20xy workshop: PSI2016
The Heart of HIPA: The Ring Cyclotron

- at time of construction a new concept: separated sector Ring cyclotron [H. Willax et al.]
- 8 magnets (280t), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), $\Phi$ 15m
- losses at extraction $\leq$ 200W
- red. losses by increasing RF voltage was main upgrade path

[losses $\propto$ (turn number)$^3$, W. Joho]
History of maximum beam power

milestones:
- new injector cyclotron (‘84)
- upgrading Ring RF power
- replacing Ring cavities
- new ECR source

Originally planned: ≈100µA
today: 2.400µA
[routine: 2.200µA]

Courtesy: M. Seidel
High Intensity Proton Accelerator – the international context

PSI HIPA serves three communities

Courtesy: M. Seidel
The intensity frontier at PSI: $\pi$, $\mu$, UCN

Precision experiments with the lightest unstable particles of their kind

The most powerful proton beam to targets: $590 \text{ MeV} \times 2.4 \text{ mA} = 1.4 \text{ MW}$

Feasibility study for HI muon beam with $10^{10}\mu^+/s$ below $30 \text{ MeV/c}$

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

The new high intensity ultracold neutron source

Swiss national laboratory with strong international collaborations
Precision physics I: Ordinary muon decay
The Weak coupling constant $G_F$

# Fundamental electro-weak parameters of the Standard Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.00037 ppm</td>
</tr>
<tr>
<td>$G_F$</td>
<td>4.1 → 0.5 ppm</td>
</tr>
<tr>
<td>$m_Z$</td>
<td>23 ppm</td>
</tr>
</tbody>
</table>

**MuLan**: The most precise measurement of any lifetime:

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

$$\tau = 2\ 196\ 980.3 \pm 2.2 \text{ ps} \ (1.0 \text{ ppm})$$

www.npl.washington.edu/muon/
D.M. Webber et al., PRL 106(2011)041803
V. Tishchenko et al., PRD 87(2013)052003
Bound state QED
The most precise value of the proton charge radius via a measurement of the Lambshift in muonic hydrogen

$r_p = 0.84087(39) \text{ fm}$

www.psi.ch/muonic-atoms

R. Pohl et al., Nature 466 (2010) 213
A. Antognini et al., Science 339 (2013) 417
Charge radii of the proton and the deuteron extracted from precision measurement of the muonic atom 2S-2P Lambshift. Also measured: muonic He-3, He-4.

Next spectroscopy:
- muonic p, He-3 HFS
- muonic radium
- Muonium 1S-2S
The $\mu$ p 2S-2P Lambshift experiment
Search for new physics

High Energy

direct production of new particle

High Intensity

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

\[ \mu^- \rightarrow \bar{\mu} \bar{\varepsilon} \gamma \]

$\bar{\varepsilon} \rightarrow e^-\gamma$

$\gamma$
Charged Lepton Flavor Violation is small in the Standard Model

- Only known LFV so far: neutrino mixing
- cLFV suppressed by $(\delta m_\nu/m_W)^4$ and thus smaller than $10^{-50}$
  - SM not observable
  - accidentally small !?
- Plenty of room for new physics

Expect from SM:
$BR(\mu-e\gamma) < 10^{-50}$

Experimentally so far:
$< 5.7 \times 10^{-13}$

PRL110(2013)201801
The present best limits on LFV are from muon experiments at PSI

\[ \mu^+ \rightarrow e^+ e^- \]
BR < \(1 \times 10^{-12}\)
SINDRUM 1988

\[ \mu^- + \text{Au} \rightarrow e^- + \text{Au} \]
BR < \(7 \times 10^{-13}\)
SINDRUM II 2006

\[ \mu^+ \rightarrow e^+ + \gamma \]
BR < \(5.7 \times 10^{-13}\)
MEG 2013

[90 % C.L.]

Most sensitive LFV search

**dLFV Searches: Current Situation**

Marciano, Mori, Roney
The present best limits on LFV come from PSI muon experiments

\[ \mu^+ \rightarrow e^+ee \]
BR < $1 \times 10^{-12}$
SINDRUM 1988

\[ \mu^- + Au \rightarrow e^- + Au \]
BR < $7 \times 10^{-13}$
SINDRUM II 2006

\[ \mu^+ \rightarrow e^+ + \gamma \]
BR < $5.7 \times 10^{-13}$
MEG 2013

Next steps at PSI: MEG-II $\rightarrow$ $4 \times 10^{-14}$
Mu3e $\rightarrow$ $10^{-15}$ (\(\pi E5\)) $\rightarrow$ $10^{-16}$ (HiMB)
MEG analysis

Issues and Improvements in the $\mu \to e\gamma$ analysis

- Alignment of Muon Stopping Target
- Alignment of LXe Detector
- Analysis of Annihilation-of-Flight (AIF) Gamma Rays
- Recovery of Missing First Turns

Expect publication soon:
sensitivity [2009-13] $\sim 5 \times 10^{-13}$

Half data published
sensitivity [2009-11] $\sim 8 \times 10^{-13}$

Improved analysis applied to all data

2.8 x $10^{-11}$
2.4 x $10^{-12}$
5.7 x $10^{-13}$
MEGII Status

Key elements:
- Higher beam intensity
- Higher detector efficiency and resolution
- Improved calibration methods
- New DAQ system

Sensitivity [2017-20] $\sim 4 \times 10^{-14}$

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>MEGII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ (mm)</td>
<td>5</td>
<td>2.4</td>
</tr>
<tr>
<td>$v$ (mm)</td>
<td>5</td>
<td>2.2</td>
</tr>
<tr>
<td>$w$ (mm)</td>
<td>6</td>
<td>3.1</td>
</tr>
<tr>
<td>$\Delta E/E$ ($w&lt;2\text{cm}$)</td>
<td>2.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>$\Delta E/E$ ($w&gt;2\text{cm}$)</td>
<td>1.7%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$t$ (ps)</td>
<td>67</td>
<td>&lt;50</td>
</tr>
<tr>
<td>$\varepsilon$ (%)</td>
<td>65</td>
<td>&gt;70</td>
</tr>
<tr>
<td>$p$ (keV)</td>
<td>306</td>
<td>130</td>
</tr>
<tr>
<td>$\theta$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\varphi$ (mrad)</td>
<td>8.7</td>
<td>4.8</td>
</tr>
<tr>
<td>$t$ (ps)</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>$\varepsilon$ (%)</td>
<td>40</td>
<td>88</td>
</tr>
</tbody>
</table>
MEGII Status

Key elements:
- Higher beam intensity
- Higher detector efficiency and resolution
- Improved calibration methods
- New DAQ system

Sensitivity [2017-20] ~ 4 x 10^{-14}

Better uniformity w/ 12x12 VUV SiPM

35 ps resolution w/ multiple hits
Mu3e Status

Key elements:

- Staged approach (here only phase I up to $10^8$ muons/s)
- Impressive momentum resolutions
- Good timing also with minimal amount of material

2013-5 | 2015-7 | 2017 | 2018-20
---|---|---|---
Design | Construction | Eng Run | Run

Sensitivity phase I [2018-20] $\sim 10^{-15}$

(Final Sensitivity phase II [202x] $\sim 10^{-16}$)

Superconducting solenoid Magnet
Homogeneous field 1T

Mupix detector
Tracking, integrate sensor and readout in the same device: 50 um thick 1 layer: $\sim 0.1\%X_0$

Tile detector
70 ps resolution w/ single hit

Fibre hodoscope
$\sim 500$ ps resolution w/ double hits thickness: $< 0.3\%X_0$
HiMB Status

Feasibility studies ongoing

- HIMB@SINQ: $3 \times 10^{10}$ muon/s at 1.7 mA(SINQ) prior to capture. Impractical as it would require removing beam-pipe constraints.

- HIMB@EH: a new solenoidal beamline coupled with a new 20 mm slanted graphite target. Very promising: $O(10^{10}$ muon/s) seems feasible
MEG and Mu3e complementarity

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O} \left( \frac{1}{\Lambda^3} \right) \]

\[ [C] = \text{GeV}^{-2} \]

New Physics at scale $\Lambda \gg M_Z$

See:
G.M. Pruna and A. Signer JHEP 1410, 014, (2014)
Search for new physics

High Energy

direct production of new particle

g\rightarrow t \rightarrow g

g\rightarrow t \rightarrow g

High Intensity

Search for $\mu \rightarrow e\gamma$

$\tilde{\mu} \rightarrow \tilde{e} \rightarrow e^{-}$
Search for new physics

High Energy

direct production of new particle

High Intensity

Search for nEDM
Search for new physics

High Energy

direct production of new particle

Mass reach: few TeV

High Intensity

Search for nEDM

Mass reach: 1 - 1000 TeV
Electric Dipole Moments are small in the Standard Model

Leptons: 4th order electro-weak

Expect from SM, approximately:
\[ d_e \leq 10^{-38} \text{ e}\cdot\text{cm} \]
\[ d_\mu \leq 10^{-36} \text{ e}\cdot\text{cm} \]
\[ d_\tau \leq 10^{-35} \text{ e}\cdot\text{cm} \]

Experimentally so far:
\[ d_e < 9 \times 10^{-29} \text{ e}\cdot\text{cm} \]
\[ d_\mu < 2 \times 10^{-19} \text{ e}\cdot\text{cm} \]
\[ d_\tau < 3 \times 10^{-17} \text{ e}\cdot\text{cm} \]
Electric Dipole Moments are small in the Standard Model

Neutron, Proton, ...

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

[Khriplovich & Zhitnitsky ‘86]

Expect from SM:
$d_n < 10^{-30} \text{e cm}$

Experimentally so far:
$< 2.9 \times 10^{-26} \text{e cm}$
Caveat:

The strong CP problem

\[ L_{QCD} \approx L_{QCD}^{0} + g^{2}/(32\pi^{2}) \theta_{QCD} G \bar{G} \]

\[ d_{n} \approx 10^{-16} \text{ e cm} \cdot \theta_{QCD} \]

\[ \theta_{QCD} \lesssim 10^{-10} \]

Why is \( \theta_{QCD} \) so small?

\( \rightarrow \) accidentally small!?
The SUSY CP problem
(for neutron and electron!)

\[ d_n \approx 10^{-23} \text{ e cm} \left( \frac{300 \text{ GeV/c}^2}{M_{\text{SUSY}}} \right)^2 \sin \phi_{\text{SUSY}} \]

Why is \( \phi_{\text{SUSY}} \) so small?

(this is testing \( M \) already to 10TeV and you may also ask: why are the masses so huge?)


for \( M_{\text{SUSY}} = 500 \text{ GeV}, \tan \beta = 3 \)
The SUSY CP problem
(for neutron and electron!)

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A. Ritz, update 2013
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Why is $\phi_{\text{SUSY}}$ so small?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)

A. Ritz, update 2016
The BAU CP Problem
Nature has probably violated CP when generating the Baryon asymmetry !?

\begin{align*}
\text{Observed}^*: \\
\frac{n_B - n_{\bar{B}}}{n_\gamma} &= 6 \times 10^{-10} \\
\text{SM expectation:} \\
\frac{n_B - n_{\bar{B}}}{n_\gamma} &\sim 10^{-18}
\end{align*}

Sakharov 1967:
B-violation \\
C & CP-violation \\
non-equilibrium

\text{[JETP Lett. 5 (1967) 24]}

* WMAP + COBE, 2003
\frac{n_B}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}
UCN sources

[Operating:
- ILL PF-2 (turbine)
- LANL (sD2)
- PSI (sD2)
- TRIGA Mainz (sD2)
- RCNP (SF-He)
- ILL SUN2 (SF-He)
- ILL: Sun1 GRANIT
- [NIST: lifetime]]

[R&D and construction:
- ILL SuperSUN
- TRIUMF/RCNP
- PNPI WWR-M
- NCSU PULSTAR
- FRM-2
- SNS-EDM

[Possible projects:
- J-PARC
- PIK
- ESS]
Neutron EDM projects

(essentially all of them aiming at 1-2 orders of magnitude improvement)

**Operating:**
- PNPI, ILL@ILL
  - (result 2013/14, upgrading)
- nEDM@PSI
  - (2018 upgrade to n2EDM)

**R&D and construction**
- @RCNP/TRIUMF
- @FRM-2
- @SNS
- @PNPI
- @LANL

**Possible future projects**
- @J-PARC
- @PIK
- @ESS
All nEDM competitive today use ultracold neutrons – UCN

UCN: similar to ideal gas with **temperatures of milli-Kelvin**
(very dilute and not in thermal equilibrium with walls)
move with **velocities of few m/s**
have kinetic **energies of order 100 neV**

<table>
<thead>
<tr>
<th>Strong</th>
<th>Magnetic</th>
<th>Gravitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermi potential $V_F$</td>
<td>$V_m = -\mu B$</td>
<td>$V_g = m_n g h$</td>
</tr>
<tr>
<td>300 neV</td>
<td>60 neV T$^{-1}$</td>
<td>100 neV m$^{-1}$</td>
</tr>
</tbody>
</table>

$E_n < 300 \text{ neV}$

$5 \text{ T field} \rightarrow 300 \text{ neV}$

$3 \text{ m up} \rightarrow 300 \text{ neV}$
How to measure the neutron (or other) electric dipole moment?

\[ \hbar \nu_{\uparrow\uparrow} = 2 (\mu B + d_n E) \]

\[ \hbar \nu_{\downarrow\downarrow} = 2 (\mu B - d_n E) \]

\[ \hbar \Delta \nu = 4 d_n E \]

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET \sqrt{N}} \]
Ramsey’s method with UCN

\[ \sigma(f_n) = \frac{\Delta \nu}{\alpha \sqrt{N \pi}} \]

Polarized UCN

External clock

\[ B_1 \]

\[ B_0 \]

Spin counts

\[ \Delta \nu \]

\[ f_{rf} \]
Ultracold Neutron Source & Facility

590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current

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 since 2012
- Increased duty factor 2015: 20 → 40 μA average
- 2016: towards 60μA
The PSI UCN source

DLC coated UCN storage vessel
height 2.5 m, ~ 2 m³

heavy water moderator → thermal neutrons
3.6 m³ D₂O

pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% duty cycle

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

cold UCN-converter
~30 dm³ solid D₂ at 5 K

UCN guides towards experimental areas
8.6m(S) / 6.9m(W)

SV-shutter
cryo-pump
tank

7 m

DLC coated UCN storage vessel
height 2.5 m, ~ 2 m³

heavy water moderator → thermal neutrons
3.6 m³ D₂O

pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% duty cycle

spallation target (Pb/Zr)
(~ 8 neutrons/proton)
The PSI UCN source
Getting routine with operation

40 $\mu$A average beam current can result in max. 1 mAh / day

nEDM operates with approx. 250 pulses per day

1 typical pulse ~ few seconds, 5E16 p on target, 4E17 spallation n, 1E9 UCN
Continuous improvement under way: UCN per proton pulse

2s Normkicks

- Dec.22 2010: 0.03 Mill
- Nov11-2011: 2.0 Mill
- Sep21-2012: 2.6 Mill
- June 27 - 2013: 3.4 Mill

Standard operating Pulse
Norm Pulse
Continuous improvement under way

2s Normkicks

- Dec.22 2010: - 0.03 Mill
- Nov11-2011: - 2.0 Mill
- Sep21-2012: - 2.6 Mill
- June 27 - 2013: - 3.4 Mill

UCN Counts /s

2013

2012

2011

2010

x10

UCN Counts after storage

Time (s)

storage time (s)

25 liter vessel

Ultra Cold Neutron Source
UCN source – nEDM counts

UCN counts after 180s of storage in the nEDM precession chamber

Main features:
- operation / failsafe
- fast UCN output decrease
- Recovery after conditioning
- Overall positive trend
Installing nEDM at PSI in 2009

Coming from ILL
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801
The nEDM spectrometer

Four-layer Mu-metal shield to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber where neutron precession is induced and measured

Photomultiplier tube to detect the intensity modulation of the mercury light

Mercury polarizing cell where the mercury is polarized

Mercury lamp to polarize the mercury ultraviolet (253.7 nm)

High voltage lead with a 1MΩ resistance

Cesium magnetometer

Electrode (upper) charged up to 150 kV electric field = 10⁵ V/m

Mercury lamp to read out the mercury polarization

Magnetic field coils are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

Switch to distribute the UCNs to different parts of the apparatus

Spin analyzer

Neutron detector

5 tesla magnet to spin polarize the UCNs
The nEDM spectrometer

Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber
where neutron precession is induced and measured

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Neutron detector

5 tesla magnet
to spin polarize the UCNs
Features of nEDM@PSI

- Hg-199 co-magnetometer
  - improved S/N by factor >4
  - laser read-out proven, being implemented

- CsM array
  - 16 scalar sensors in operation (6 HV)
  - vector CsM proven

- B-field
  - homogeneity (T2~1000s)
  - reproducibility (~50pT), after degaussing (~200pT)

- Simultaneous spin analysis
- Known systematics well under control down to ~2 x 10^{-27} ecm
Frequency ratio $R$

\[ R = \frac{\langle f_{\text{UCN}} \rangle}{\langle f_{\text{Hg}} \rangle} = \frac{\nu_n}{\nu_{\text{Hg}}} \left( 1 + \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2 \rangle_\perp}{|B_0|^2} + \delta_{\text{Earth}} + \delta_{\text{Hg-lights}} \right) \]
Magnetic moments

\[
\frac{\gamma_n}{2\pi} = 29.164705(55) \text{ MHz/T} \\
[1.89 \text{ ppm}]
\]

\[
\frac{\gamma_n}{\gamma_{\text{Hg}}} = 3.8424574(30) \\
[0.78 \text{ ppm}]
\]

\[
\frac{\gamma_{\text{Hg}}}{2\pi} = 7.5901152(62) \text{ MHz/T} \\
[0.82 \text{ ppm}]
\]

S. Afach et al., PLB 739 (2014) 128
Spin-dependent exotic interactions

S. Afach et al., PLB 745 (2015) 58
A spin-echo recovers energy dependent dephasing for \( T = 2t_1 \) in a magnetic field with vertical gradient.

S. Afach et al., PRL114(2015)162502
Towards new limits
Neutron EDM search

\[
\sigma(d_N) = \frac{\hbar}{2\alpha E T \sqrt{N}}
\]

<table>
<thead>
<tr>
<th></th>
<th>RAL/Sx/ILL*</th>
<th>PSI 2013</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>best</td>
<td>avg</td>
<td>best</td>
</tr>
<tr>
<td>E-field</td>
<td>10</td>
<td>8.3</td>
<td>12</td>
</tr>
<tr>
<td>Neutrons</td>
<td>18 000</td>
<td>14 300</td>
<td>10 500</td>
</tr>
<tr>
<td>(T_{\text{free}})</td>
<td>130</td>
<td>130</td>
<td>200</td>
</tr>
<tr>
<td>(T_{\text{duty}})</td>
<td>240</td>
<td>240</td>
<td>340</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.6</td>
<td>0.453</td>
<td>0.62</td>
</tr>
<tr>
<td>(\sigma/d) (10^{-25}\text{ecm})</td>
<td>2.3</td>
<td>3.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Once nEDM runs out of steam statistically, it will be replaced by n2EDM (~2018).
Towards new limits
Neutron EDM search

The slope determines the path forward

Towards new limits
Neutron EDM search

The slope determines the path forward

Towards new limits
Neutron EDM search

The slope determines the path forward

Towards new limits
Neutron EDM search

The slope determines the path forward
Exciting times ahead

• Expect new MEG result shortly
• UCN source performance continuously improving
• New nEDM result 2016/17
• Lambshift 2S-2P in $\mu$He being analyzed
• HiMB feasibility study under way
• MEG II and Mu3e progress very promising
• Phase space compression experiment muCool demonstrated milestones …

see you perhaps at PSI2016?
LTP organizes the PSI20xy conferences and the Particle Physics Zuoz school


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Klaus Kirch  Tokyo, Feb 18, 2016
Thank you!