Precision Muon Experiments and the Standard Model.

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Measurements of $e^\pm$ time distributions from $\mu$ decay

- describe recent / ongoing precision measurements of $e^\pm$ time distributions from $\mu \rightarrow e\nu\nu$ decay.
- involve measurements of $10^{11}$-$10^{12}$ decays and mining of petabyte-scale datasets.

encoded in time distribution are muon lifetime and precession signal.
A quick tour of

MuLan @PSI

MuCap @PSI

MuSun @PSI

Muon g-2 @FNAL
A quick tour of

MuLan
Fermi constant and Higgs field.

MuCap
QCD symmetries and hadronic mass.

MuCap
hydrogen burning and solar neutrinos

Muon g-2
new particles and unknown forces
MuLan - lifetime of the positive muon $\tau_{\mu^+}$

a purely-leptonic decay that's amenable to muon decay

\[
\frac{1}{\tau_{\mu}} = \frac{G_F^2 m_\mu^5}{192 \pi^2} \left(1 + \Delta q\right)
\]

$\Delta q$ contains QED, QCD radiative corrections

$\sim 0.1$ ppm uncertainty in $\tau_{\mu} - G_F$ relationship from $\Delta q, m_\mu$
MuLan - accumulating \( \mu^+ \)'s and measuring \( e^+ \)'s
MuLan - accumulating $\mu^+$'s and measuring $e^+$'s
MuLan detector

a tile ....
a house ..
the ball.
\( \tau_{\mu} \) is an “anchor” in tests of weak universality using \( \tau \rightarrow e\nu\nu, \tau \rightarrow \mu\nu\nu \) decays and also studies of muon capture by lifetime techniques.

The Fermi constant, \( G_F \) (MuLan) = \( 1.1663788(7) \times 10^{-5} \) GeV\(^{-2} \) [0.6 ppm], together with the mass of the Higgs particle, determine the Higgs vacuum expectation value, \( v \), and self interaction parameter, \( \lambda \).
MuCap - lifetime of muon hydrogen atom, $\tau_{\mu p}$

- **Muon capture**, $\mu^- p \rightarrow n \nu$
- **Beta decay**, $p \rightarrow n e^+ \nu$

- Proton's weak couplings $g_v, g_a, g_m, g_p$

- The induced pseudoscalar coupling $g_p$ is fundamental quantity in description of proton's weak interaction.

- Relation between couplings $g_p, g_a$ is predicted by QCD symmetries and symmetry breaking arguments that generate the masses of protons, neutrons and other hadrons.
determine the $\mu\cdot p \to \nu n$ capture rate by $\Lambda = 1/\tau_\mu - 1/\tau_{\mu p}$

MuCap - lifetime of muon hydrogen atom, $\tau_{\mu p}$

$\log(\text{counts})$

$\exp(-t/\tau_{\mu p})$  $\exp(-t/\tau_\mu)$

$\sim 10^{-3}$ difference

$time$
MuCap - μ-ρ chemistry, a complication

Different atomic, molecular species, with different μp-spin decompositions and different capture rates.

use ultra-pure (chemically, isotopically) 10 bar H₂ (1% liquid hydrogen density) to prepare near-pure singlet atoms.
MuCap setup

\[ e \]

Tracking in TPC

\(\mu\text{PC}, \mu\text{SC}, \mu\text{SCA}\)

ePC2

ePC1

TPC

eSC
MuCap Result, $\Lambda_s = 715.6 \pm 5.4$ (stat) $\pm 5.1$ (syst) s$^{-1}$

$g_p = 8.06 \pm 0.48$ (expt) $\pm 0.2$ (thry)

- Result for $g_p$ is essentially free of ambiguities associated with $\mu$ chemistry
- Verifies our understanding of chiral symmetry breaking in QCD (origins of neutron, proton masses).
the μ-d capture rate depends on the poorly known two-nucleon weak axial current - the parameter $L_{1A}$ (or $d_R$) in QCD-inspired effective field theories).

knowledge of this current is important for calculation of pp thermonuclear fusion in sun (the main source of solar energy).

also important for precision determination of $^8$B solar neutrino flux from measurements of vd charged / neutral current interaction rates in heavy water.
MuSun - $\mu^{-}d$ chemistry, a complication

Use ultra-pure (chemically, isotopically) 30 Kelvin, 5% liquid density $D_{2}$ gas, to prepare doublet state atoms.

Different atomic, molecular species, with different $\mu d$-spin decompositions and different capture rates.

Muon catalyzed fusion

Muon recycling
$\mu^{-} + ^{3}\text{He} + n$
$\mu^{-} + ^{3}\text{H} + p$

Muon sticking
$\mu^{-}^{3}\text{He} + n$
$\mu^{-}^{3}\text{H} + p$
MuSun - $\mu$-d chemistry, a complication

Molecular formation rates from doublet / quartet states

Population of muonic atom species

Almost no molecule formation by doublet atoms at low temps.
MuSun Cryogenic TPC

Provides identification of muon stops in $D_2$ gas
Goal of ±1.5% measurement of capture rate $\Lambda_d$ – five-fold improvement over prior measurements and commensurate with EFT predictions.


Enables determination of two-body weak axial current $(L_{1A}/d_R)$ in 2N sector with x5 precision. Permits the calibration of basic solar neutrino and astrophysical reactions.

Theses include rates of $\mu$-chemistry, the doublet capture rate, and hyperfine effect in muon capture.
Anomalous moment and g-factor, \( a = (g-2)/2 \).

\[ \vec{\mu} = g \frac{e}{2m} \hat{S} \]

Dirac theory endows the point-like, spin-1/2 particles with a g-factor of exactly 2

For two decades the measurement of the electron's g-factor were in agreement with the Dirac equation.

The Kusch-Foley experiment - using precision measurements of Zeeman splittings - discovered the electron's g-factor was slightly larger than 2, \( g_e = 2.00238(6) \).

Schwinger – within a year - explained the anomaly by means of the electron's self-interaction and vacuum fluctuations.
Muon's anomalous magnetic moment, $a_\mu = (g-2)/2$, in the Standard model.
Muon anomalous magnetic moment, $a_\mu$. 

--- SM prediction ---

<table>
<thead>
<tr>
<th>Theory</th>
<th>Year</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMNT</td>
<td>06</td>
<td>$165.7591802 (49) \times 10^{-11}$ (0.42 ppm)</td>
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<tr>
<td>JN</td>
<td>09</td>
<td></td>
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<tr>
<td>Davier et al, $\tau$</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Davier et al, $e^+e^-$</td>
<td>10</td>
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<tr>
<td>JS</td>
<td>11</td>
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<tr>
<td>HLMNT</td>
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<td></td>
</tr>
<tr>
<td>HLMNT</td>
<td>11</td>
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</table>

--- experiment ---

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Precision</th>
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<tbody>
<tr>
<td>BNL</td>
<td>$165.7592089 (63) \times 10^{-11}$ (0.54 ppm)</td>
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<tr>
<td>BNL (new from shift in $\lambda$)</td>
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</tbody>
</table>
Muon anomalous magnetic moment, $a_\mu$.

- BNL E821 measured $a_{\lambda\mu}$ to a precision of 0.54 ppm and represents a stringent test of Standard Model and constraint on unknown particles / forces.
- Current $\sim 3.5\sigma$ deviation between experiment and SM is arguably the strongest hint of new physics from particle / nuclear experiments.
• Goal of Fermilab g-2 expt is a statistical uncertainty of 100 ppb in $a_\mu$ – requires x21 the number of positrons in BNL821.

• Re-purposed accelerator infrastructure will provide a pure, polarized, 3.1 GeV/c, muon beam with 12 Hz pulse rate and 100 ns pulse length (muons are made via pion production and subsequent decay).
Muons of momentum 3.094 GeV/c are injected and stored in a highly-uniform, vertical magnetic field with electrostatic quadrupoles for vertical confinement.
<table>
<thead>
<tr>
<th>Physical frequency</th>
<th>Variable Expression</th>
<th>Frequency</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomalous precession</td>
<td>( f_a = \frac{e}{2\pi m} a \mu B )</td>
<td>0.23 MHz</td>
<td>4.37 ( \mu )s</td>
</tr>
<tr>
<td>Cyclotron</td>
<td>( f_c = \frac{e}{2\pi q} b )</td>
<td>6.71 MHz</td>
<td>149 ns</td>
</tr>
<tr>
<td>Horizontal betatron</td>
<td>( f_x = \sqrt{1-n f_c} )</td>
<td>6.23 MHz</td>
<td>160 ns</td>
</tr>
<tr>
<td>Vertical betatron</td>
<td>( f_y = \sqrt{n f_c} )</td>
<td>2.48 MHz</td>
<td>402 ns</td>
</tr>
<tr>
<td>Horizontal CBO</td>
<td>( f_{CBO} = f_c - f_x )</td>
<td>0.48 MHz</td>
<td>2.10 ( \mu )s</td>
</tr>
<tr>
<td>Vertical waist</td>
<td>( f_{VW} = f_c - 2f_y )</td>
<td>1.74 MHz</td>
<td>0.57 ( \mu )s</td>
</tr>
</tbody>
</table>

Penning trap
Penning trap for 3.094 GeV/c muons.
Muons of momentum 3.094 GeV/c are stored in highly-uniform, vertical magnetic field with electrostatic quadrupoles for vertical confinement.

\[ \vec{p} \]
\[ \vec{s} \]

---

Anomalous frequency
Cyclotron frequency
Larmor frequency

\[ \vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = - \frac{q}{m} \left[ a_\mu \vec{B} - \left( a_\mu \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] \]

\[ \gamma = 29.3 \]

\[ \sim 0, \text{ at magic momenta} \]
Muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and energy-angle distribution of electrons about $\mu$-polarization.

In $\mu^+$ decay the V-A form of weak interactions favors positron emission opposite the $\mu$-spin direction.

`self-analyzing' muons
Forwarded-emitted electrons have high energies.

- Due to relativistic boost the forward-emitted electrons have high energies and backward-emitted electrons have low energies.

- Time distribution of high-energy electrons (forward-emitted electrons) is therefore modulated by anomalous precession frequency.

\[
\frac{dN}{dt} = N_0 e^{-t/\tau} \left[ 1 + A \cos\left( \omega \tau t + \phi \right) \right]
\]

* not really so simple
\[ \omega_a = -\frac{q}{m} [a_{\mu} B] \] and determination of the muon anomaly, \( a_{\mu} \)

\[
 a_{\mu} = \frac{\omega_a / \omega_p}{\mu_{\mu} / \mu_p - \omega_a / \omega_p}
\]

measured proton Lamor precession frequency
measured muon anomalous precession frequency
known to 26ppb from muonium hyperfine experiment.

proton NMR used to measure the B-field in storage ring.
## Schedule

<table>
<thead>
<tr>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
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</table>

### Construction (Project & Muon Campus):
- g-2 Cryo Plant
- Ring Assembly
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems
- Accelerator Modifications
- **Ring cold ready for operations**
- **Experiment ready for operations**
- **Accelerator ready for operations**

### Operations (Laboratory):
- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up
- **Full Running Intensity**
- Physics Production Running

### Analysis (Collaboration):
- Analysis Tools Development
- Mock Data
- 1st Results
- 2nd Results
- 5-10 x BNL
- 21 x BNL
- Final Results