The Precision Muon Group at UW
arrived Fall 2010, like many of you

- Faculty
  - David Hertzog, Peter Kammel (all projects)
  - Tianchi Zhou and Alejandro Garcia (g-2)
- Postdocs:
  - Peter Winter, Serdar Kizgul → Frederik Wauters
- Graduate Students:
  - Brendan Kiburg, Sara Knaack, Jason Crnkovic, Michael Murray, Andreas Trautner, + 2 RA-supported SLOTS OPEN

- **Mulan**: $G_F$ from $\mu^+$ lifetime
- **MuCap**: $g_p$ from $\mu^-p$ capture
- **MuSun**: $\mu^-d$ capture calibrates basic astrophysics
- **Muon g-2**: anomalous magnetic moment
- **Mu2e**: Charged lepton flavor violation test

David Hertzog: hertzog@uw.edu
http://www.npl.washington.edu/muon/
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http://www.npl.washington.edu/muon/
An unusual subatomic particle

- Mass $\sim 207 \, m_e$: heavy electron
- Lifetime $\sim 2.2 \, \mu s$ is long: beams, probes
- $\mu^-$ can form 1-electron hydrogen-like atoms
  - $\mu^-p$, $\mu^-d$, $\mu^-A$
  - Muonium: $\mu^-e^+$
- Primary decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ (parity violation)
- Easily polarized: $\pi^+ \rightarrow \mu^+\nu_\mu$

\[ \nu \leftrightarrow \pi^+ \leftrightarrow \mu^+ \]

- Typically 42,000 times more sensitive to “new physics” quantum loops compared to electrons $\sim (m_\mu/m_e)^2$
- Lepton number conservation: No “$\mu \rightarrow e$” conversion
Schedules that would affect you …

- **g-2**: Fermilab planning document has …

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- **MuSun**: 1\textsuperscript{st} physics run Summer 2011; Next Summer 2013
Washington Responsibilities in 2 new projects

• **g-2**
  – Hertzog – co-spokesman, calorimeter development
  – Kammel – Beam Team architect; detector specialist
  – Zhou – Detector Physicist
  – Garzia – Precision physics; expert in related experiments

• **MuSun**
  – Kammel – co-spokesman, TPC development, analysis
  – Hertzog – beam development; analysis
Snapshot of careers of some former Ph.D. students from our group

- R. Tayloe (Faculty, Indiana)
- P. Reimer (Sr. Scientist, ANL)
- J. Ritter (I lost track !)
- T. Jones (Tech startups)
- B. Bunker ($$ industry)
- F. Gray (Faculty, Regis)
- C. Polly (Wilson Fellow, FNAL)
- D. Chitwood (Dynetics, Inc.)
- S. Clayton (LANL; APS Dissertation Prize winner)
- D. Webber (PDRA, Wisconsin)
New $G_F$

$$G_F(MuLan) = 1.1663788(7) \times 10^{-5} \text{GeV}^{-2} \ (0.6 \text{ ppm})$$

The most precise particle or nuclear or (we believe) atomic lifetime ever measured
Some recent Press ... 

How strong is the weak force?

New measurement of the muon lifetime – the most precise determination of any lifetime – provides a high-accuracy value for a crucial parameter determining the strength of weak nuclear force. The experiments were performed by an international research team at the accelerator facility of the Paul Scherrer Institute. The results are about to be published in the journal Physical Review Letters.

The weak force is one of the four fundamental forces of nature. Although we hardly encounter processes governed by the weak force in our everyday life, it is still of crucial importance; e.g., being responsible for the processes that make the Sun shine. An international research team led by scientists from the University of Illinois, Boston University and the University of Kentucky performed experiments at the Paul Scherrer Institute (Villigen, Switzerland) that allowed them to determine a parameter crucial for the strength of the weak force with unprecedented accuracy of 0.6 parts per million. This so-called Fermi constant is one of the fundamental natural constants determining the interactions of processes in the world of elementary particles.

Our understanding of the subatomic world in the 1970s was based on the electromagnetic interaction – another of the four fundamental forces of nature. It is called the electroweak force and is determined by three parameters, the Fermi constant being one of them.

For more information please visit:

https://inside science.org/article/117698
MuLan Motivation

- $\tau_{\mu^+}$ determined Fermi Constant to unprecedented precision (actually $G_\mu$)
  
  $G_F$  $\alpha$  $M_Z$
  9 ppm  0.37 ppb  23 ppm

- $\tau_{\mu^+}$ needed for “reference” lifetime for precision muon capture experiments
  - MuCap $\rightarrow g_P$
  - MuSun $\rightarrow L_{1A}$

- Is lifetime in bound muonium the same as the free lifetime?
The precision of \( G_F \) has improved by \(~4\) orders of magnitude over 60 years.

Achieved!
The lifetime difference between $\tau_{\mu^+}$ and $\tau_{\mu^-}$ in hydrogen leads to the singlet capture rate $\Lambda_S$

The singlet capture rate is used to determine $g_P$ and compare with theory

$$\Lambda_S = \Lambda_{\mu^-} - \Lambda_{\mu^+} = (\tau_{\mu^-})^{-1} - (\tau_{\mu^+})^{-1} \Rightarrow g_P$$
The experimental concept...

![Graph](image1)

Accumulation Period, $T_A$

Measurement Period, $T_M$

Kicker Transition

Background Level

- 450 MHz WaveForm Digitization (2006/07)
- MHTDC (2004)

Real data

Kicker On

170 Inner/Outer tile pairs

- 12
- -12.5 K
Probing hadrons with muons

Nucleon level: Relevant degrees of freedom?

$g_P$
First unambiguous determination of $g_P$ in > 30 years. Clearly confirms theory.
MuSun: “Calibrating the Sun”

\[ \mu^- + d \rightarrow \nu + n + n \quad \text{Measure rate < 1.5 %} \]

1. **Simplest weak process in a nucleus**
   where precise QCD based theory & precise experiment feasible

2. **Relation to neutrino/astrophysics**
   - Solar fusion reaction \( p+p \rightarrow de^+\nu \)
   - \( \nu + d \) scattering in SNO
   - Model independent connection to \( \mu d \)
     with single **Low Energy Constant**

Determine this LEC in clean 2N system
Precise experiment needed

- Potential Model + MEC
- pionless, needs $L_1A$
- hybrid EFT
- consistent ChPT

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Graph showing data points for various researchers and theoretical predictions. The x-axis is labeled $\Lambda_d$ (s$^{-1}$) with values ranging from 360 to 500.
Cryo-TPC development

- Cryo-TPC
- Vacuum vessel
- Cold head
- Neon condensor
- Neon heat pipe
- Vibration-free support
Cryo-TPC development

- Aluminum shell
- Rear neon collector
- Front neon collector
- Be window flange
- Be window
- 500 Mhz waveform digitization
MuSun: Recent Milestones

Dec 2009

Assembly
Current status:

• $T = 30 \text{ K}$
• $HV = 80 \text{ kV}$
• Purity excellent
• Improved resolution of TPC
MuSun: Recent Milestones

Oct-Nov 2010

Commissioning and several weeks first data taking

ultrapure D$_2$

$T=32$ K, $p=5$ bar

$V_{\text{drift}} = 80$ kV

Event display

$\mu$ in TPC

$dd\mu \rightarrow p + t + \mu$ fusion
The New Muon g-2 Experiment at Fermilab

APPROVED January 2011

Experiment: 3.6 \times 10^{-11}

Future Goals: Goal: 0.14 ppm

Expected Improvement

Goal: 0.14 ppm

Expected Improvement
\( a_\mu = (g - 2)/2 \) is non-zero because of virtual loops, which can be calculated very precisely.

The "g-2 test": Compare experiment to theory. Is SM complete?

\[
\delta a_\mu^{\text{NewPhysics}} = a_\mu^{\text{Expt.}} - a_\mu^{\text{Theory}}
\]
INT Workshop on
The Hadronic Light-by-Light Contribution to the Muon Anomaly
February 28 - March 4, 2011

And for the rest of the Theory
Here in 2 weeks

The Workshop Plan:

The workshop will bring together both theorists and experimentalists to focus on one of the outstanding theoretical issues in interpreting the muon anomalous magnetic moment:

1. Can agreement be reached on the individual and combined theoretical contributions to the hadronic light-by-light (HLbL) contribution to the muon anomalous magnetic moment, $\alpha_{\mu}$, based on QCD-inspired models?
2. Can the lattice approach lead to a result having sufficient precision to check the models or to independently establish the HLbL value?
3. Which data that can be obtained at Frascati, and at other facilities, are essential to constrain the theoretical calculations and what theoretical developments are required to connect data to model predictions?

We envision summary talks and working sessions on all topics and will produce a Review style article, signed by the contributors. The goal of the group is not to produce "one number" at this time, but to summarize the state of the art and to design the path to a future meeting, that would have a "one number, one uncertainty" goal as its mission.

Motivation:

The muon anomalous magnetic moment can be calculated and measured to very high precision. Comparison of experiment to theory has been, and will continue to be, a very sensitive test of New Physics. The present uncertainty on the Standard Model contribution is $\alpha_{\mu}(\text{SM}) = 49 \times 10^{-11}$. The
Hadronic Vacuum Polarization is determined from data

\[ a_\mu(\text{had}) = \left( \frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left( \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \right) \]
A world-wide effort exists to measure over full range. Our group is also working with Belle data to measure some cross sections here.
Most recent comparisons of Standard Model to Experiment

$$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (296 \pm 81) \times 10^{-11} \Rightarrow 3.6 \sigma$$

What is nature trying to tell us?
What is this telling us?

\[ a_\mu^{exp} - a_\mu^{SM} = (296 \pm 81) \times 10^{-11} \]
\[ \Rightarrow 3.6 \sigma \]

- **Magnitude and sign** most important implications
  - it's not "just sigma"
  - \( \sim +300 \times 10^{-11} \) is relatively large

- **UED models** (1D) typically predict “tiny” effects

- **SUSY models** – many predict contributions as observed
  - I’ll flash this as it is rather well studied

- **The “Uninvented”** – perhaps most importantly, sets a stringent experimental constraint for any new models
SUSY contribution to $a_\mu$:

\[
a_\mu(\text{SUSY}) \simeq (\text{sgn}_\mu) \times 130 \times 10^{-11} \cdot \tan \beta \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^2
\]

difficult to measure at LHC
SUSY and g-2: The power to resolve among models and break LHC degeneracies
Suppose the MSSM point SPS1a is realized and the parameters are determined at LHC-

- $\text{sgn}(\Delta)$ gives $\text{sgn}(\mu)$
- $\text{sgn}(\mu)$ difficult to obtain from the collider
- $\tan \beta$ poorly determined by the collider

Assuming SPS1a; 100 fb\(^{-1}\) at 14 TeV
The Keys to an improved experiment:

- Build on a **proven technique**
- Make use of **unique storage ring**
- **New team built from E821 experts**, augmented by **significant new strengths**
- Obtain more muons
- Control systematic errors

The New \((g - 2)\) Experiment:

**A Proposal to Measure the Muon Anomalous Magnetic Moment to ±0.14 ppm Precision**

New \((g - 2)\) Collaboration:
Ideal muon delivery to storage ring

- Background reduced by x20
- Muon storage x10 per proton
- 20x Events vs BNL in 1 year
Sikorsky S64F 12.5 T hook weight (Outer coil 8T)

- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.
4 Key elements of the g-2 measurement

(1) Polarized muons
   ~97% polarized for forward decays

(2) Precession proportional to \((g-2)\)

(3) \(P_\mu\) magic momentum = 3.094 GeV/c
   \(E\) field doesn’t affect muon spin when \(\gamma = 29.3\)

(4) Parity violation in the decay gives average spin direction
The anomaly is obtained from three well-measured quantities:

\[ \omega_p \]

\[ \omega_a \]

\[ a \mu = \frac{\mu_\mu}{\mu_p} \]

\[ \frac{\mu_\mu}{\mu_p} = 3.183\ 345\ 24(37)\ \text{(120 ppb)} \]

\[ = 3.183\ 345\ 39(10)\ \text{(31 ppb)} \]
The Storage Ring will be moved to FNAL
The Storage Ring components affect muon storage

Superconducting inflector magnet

Fast Kickers

incoming muons

Electrostatic Quadrupoles
The Detectors are a main Washington responsibility.
An “event” is an isolated positron above a threshold.
If you find this interesting ...

- David Hertzog
  - C533
  - hertzog@uw.edu

- Peter Kammel
  - C515
  - pkammel@uw.edu

- And, you can talk to our current students who are here
  - Michael Murray (MuSun: transferred to UW)
  - Andreas Trautner (1st year, exchange; Belle project)
  - Sara Knaack, Jason Crnkovic, Brendan Kiburg (UIUC)