Precision Muon Physics

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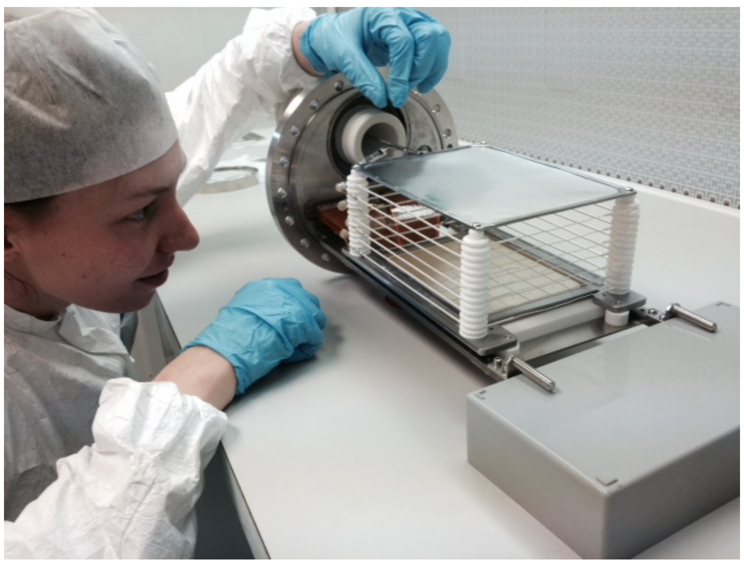


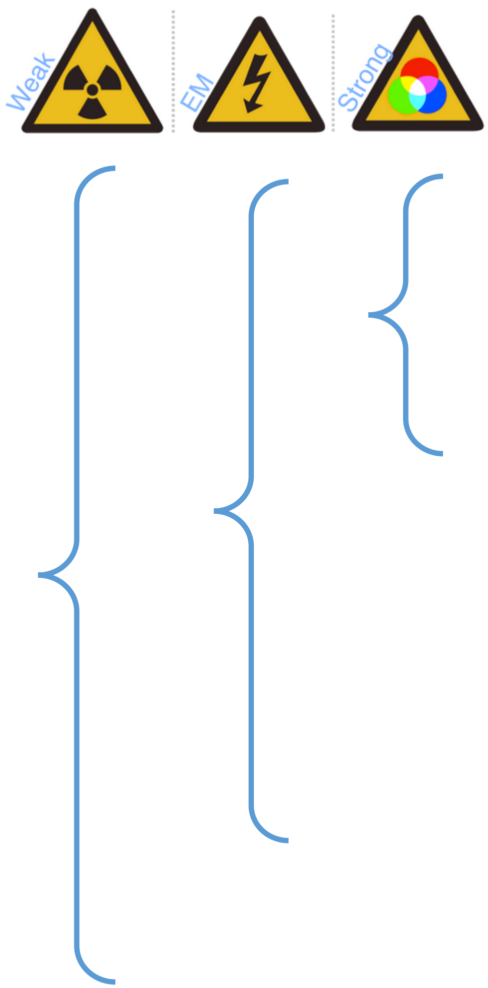
MuSun

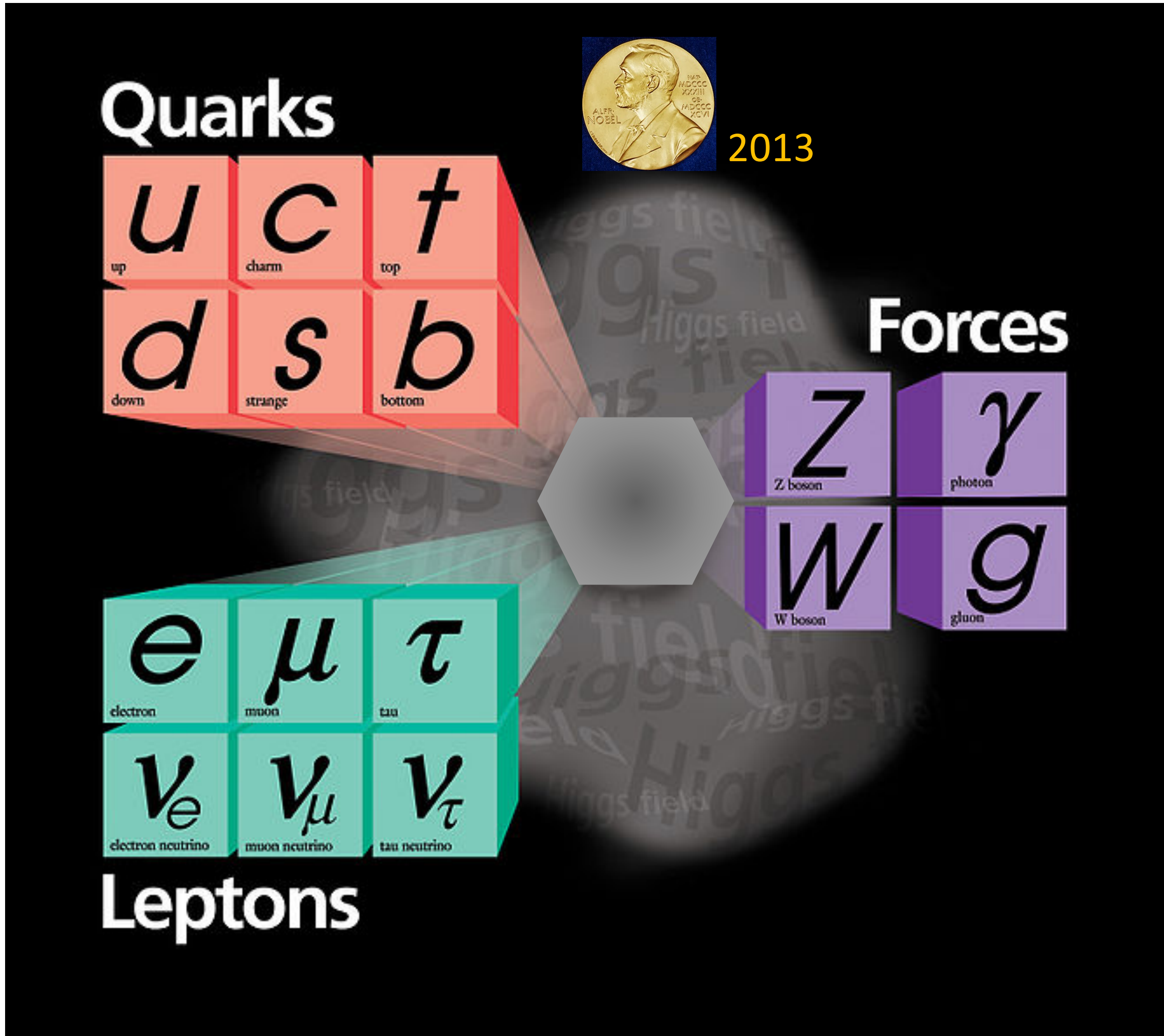
Muon g-2

Outline

- Introduction
- MuSun — Weak few nucleon reactions and astrophysics
- Muon g-2 — Search for New Physics

The Standard Model





Standard Model Equations

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

- Predictions to extremely high precision
- Last 30 years experiments tried to find cracks, to guide deeper understanding
- Strong interaction (Quantum Chromodynamics) still difficult to calculate (Lattice QCD)

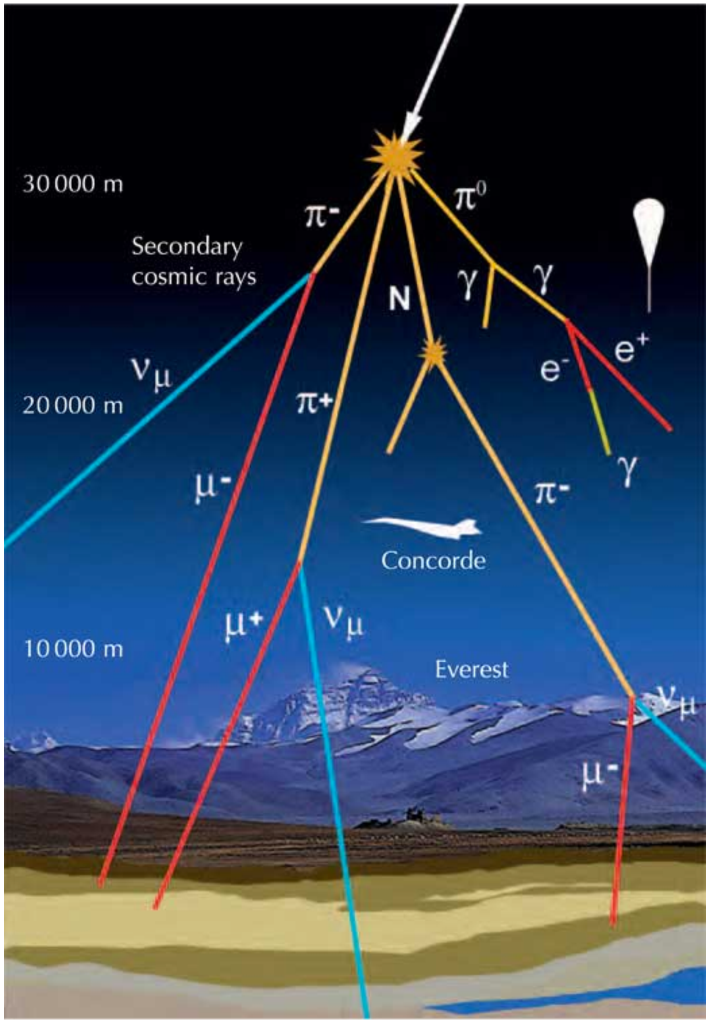
What's special about Muons?

Summary of measured Muon properties and selected decay rates and limits.

Property	Symbol	Value	Precision
Mass	m_μ	105.658 3715(35) MeV	34 ppb
Mean lifetime	τ_μ	$2.196\,9811(22) \times 10^{-6}$ s	1.0 ppm
Anom. mag. moment	a_μ	$116\,592\,091(63) \times 10^{-11}$	0.54 ppm
Elec. dipole moment	d_μ	$<1.9 \times 10^{-19} e \cdot$ cm	95% C.L.
Branching ratios	**PDG average**	**B.R. limits**	**90% C.L.**
$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	≈100%	$\mu^- \to e^- \gamma$	5.7×10^{-13}
$\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma$	1.4(4)%	$\mu^- \to e^- e^+ e^-$	1.0×10^{-12}
$\mu^- \to e^- \bar{\nu}_e \nu_\mu e^+ e^-$	$3.4(4) \times 10^{-5}$	$\mu^- \to e^-$ conversion	7×10^{-13}

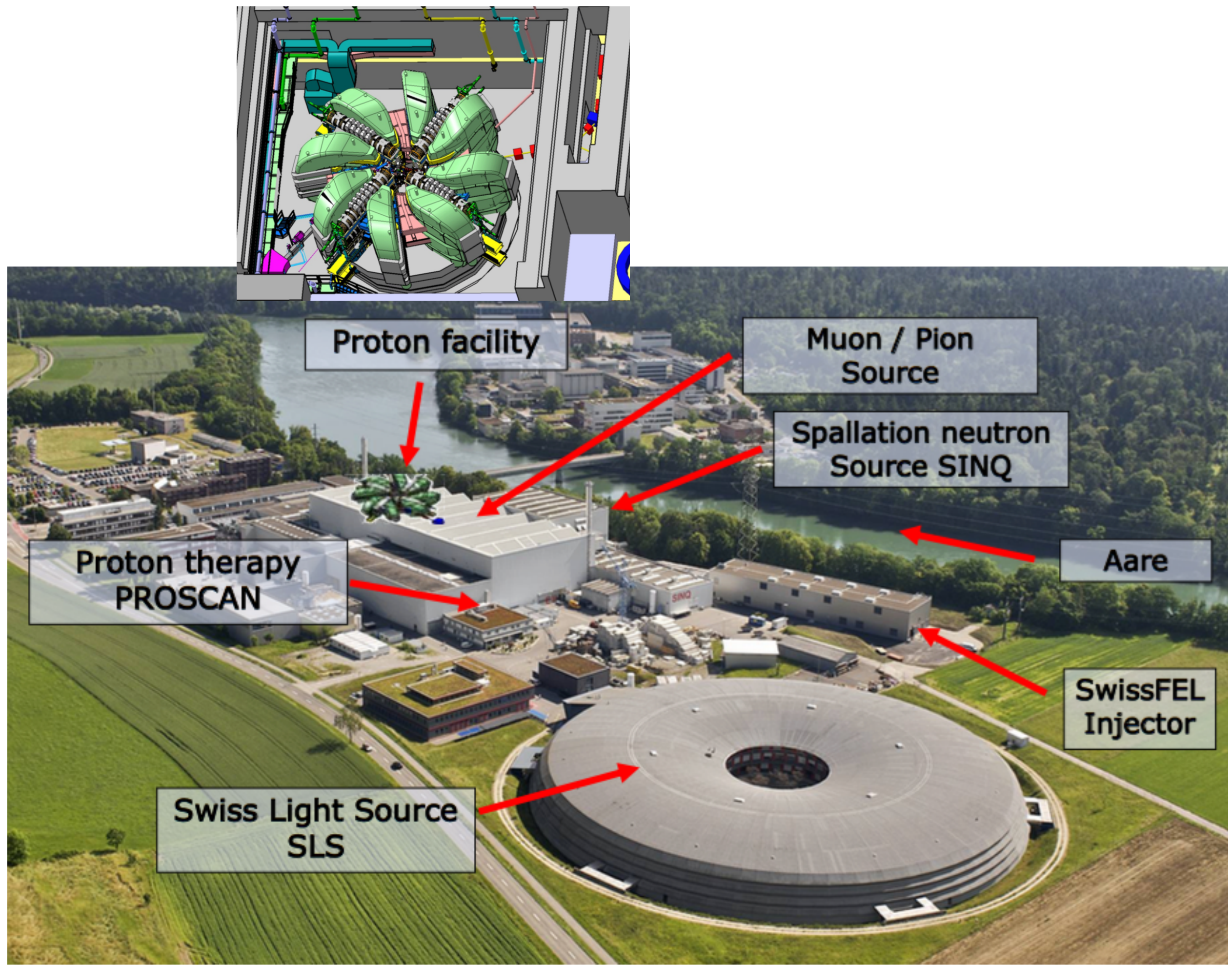
- Precision physics @ Intensity frontier
- Muon decay: basic structure of weak interactions
- Muon capture probes nuclear weak interactions, MuSun
- Quantum loop sensitivity to new physics $(m_\mu/m_e)^2$, Muon g-2
- Charged Lepton Flavor violation
- Muon collider, MSR, etc

How are they generated?

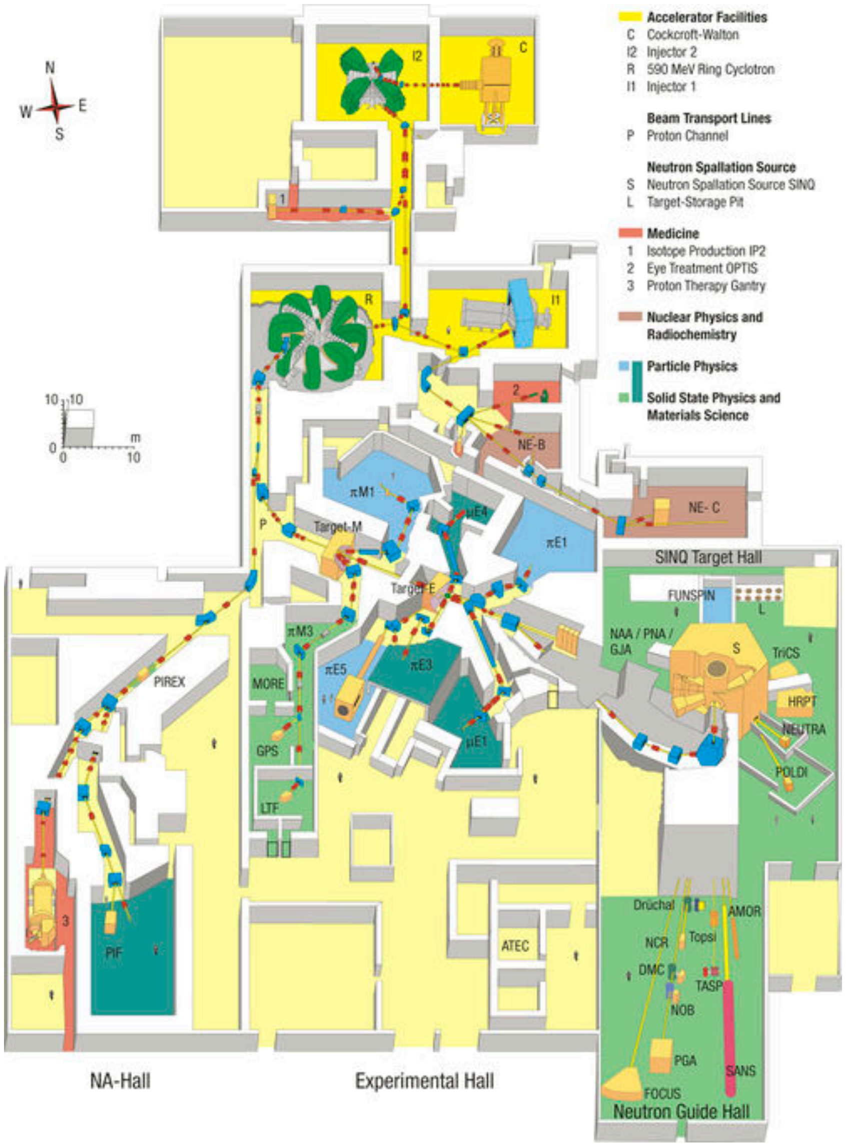


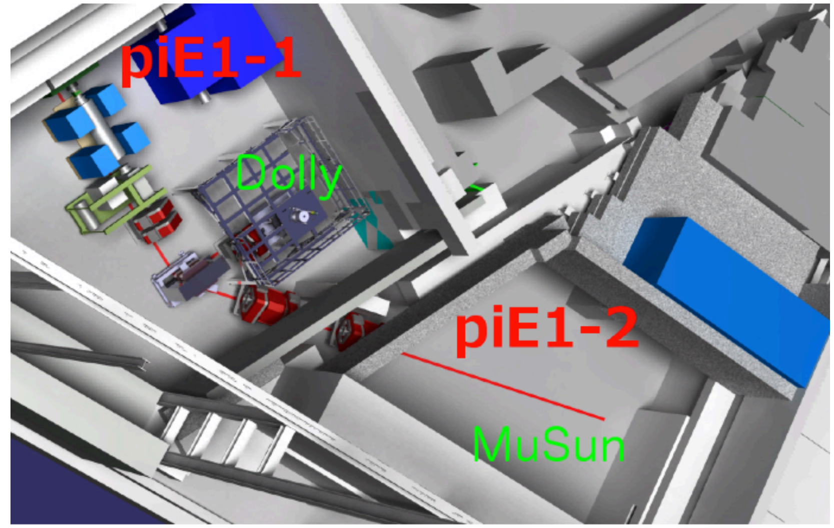
Paul Scherrer Institut

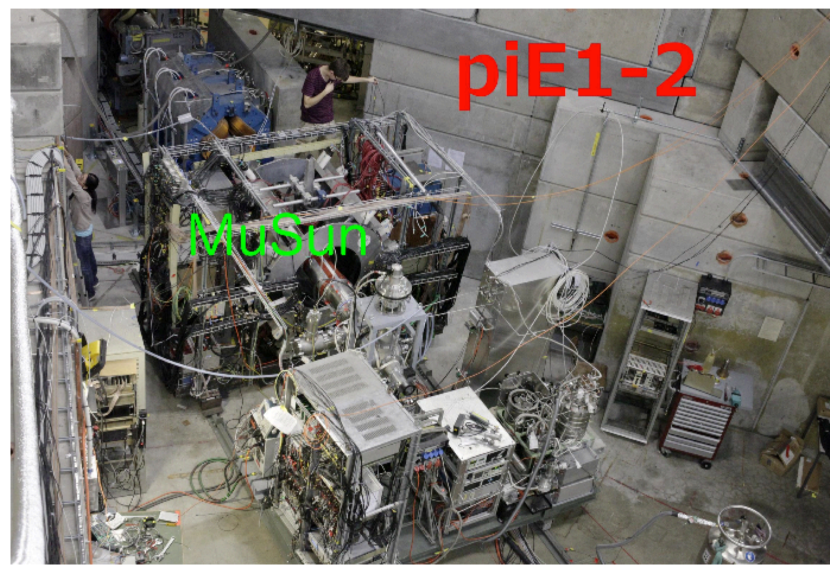
Villigen, Switzerland



PSI and “our” Beamline

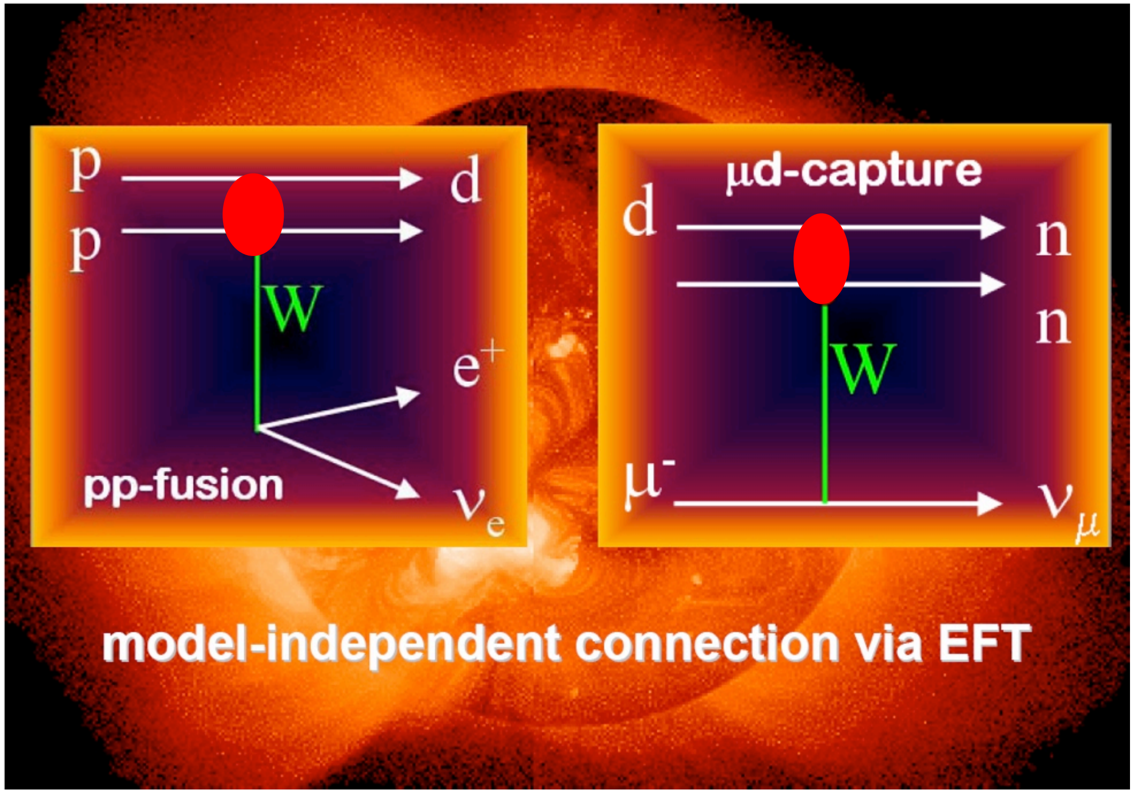






MuSun Experiment

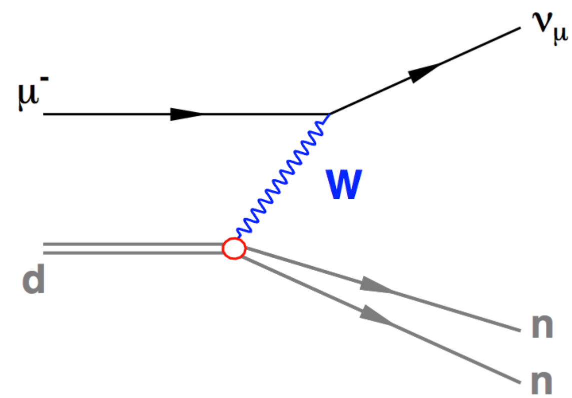
Precision measurement of SM parameters



Muon capture on the deuteron

- Goal: measure capture rate to 1.5 %

$$\mu + d \rightarrow n + n + \nu$$

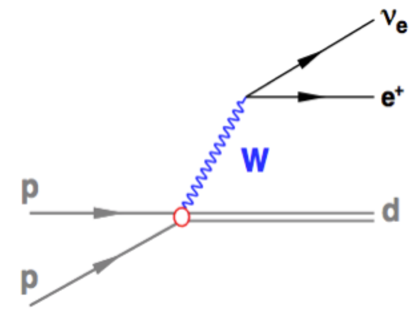


- Motivation:
  - Low energy effective field theory of QCD has been developed. This theory describes protons, neutrons and nuclei consistent with the fundamental QCD.
    Parameters have to be determined from experiment.
  - Prediction for basic astrophysics reactions depend on this knowledge.
    "Calibrate the Sun"

Calibrating the sun and neutrino interactions

The sun in is powered by proton-proton fusion

$$p\,p \rightarrow d\,e^+\,\nu$$

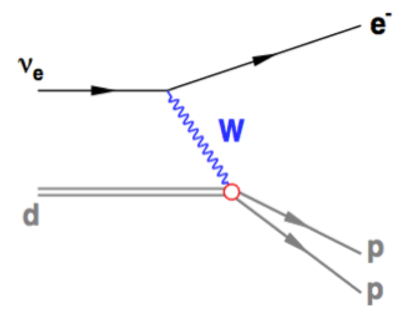


The neutrino deficit from the sun led to
the discovery of neutrino oscillation using

$\nu_e\,d \rightarrow p\,p\,e^-$ (CC)

$\nu_x\,d \rightarrow p\,n\,\nu_x$ (NC)


2015

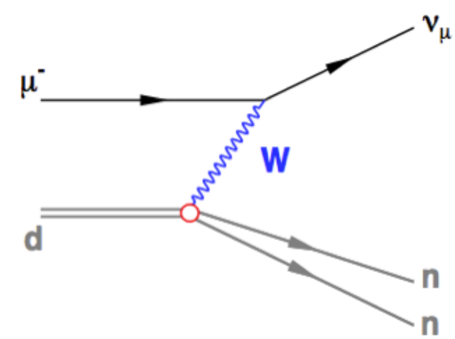


The rates for both reactions cannot be determined at terrestrial conditions. The calculation is challenging.

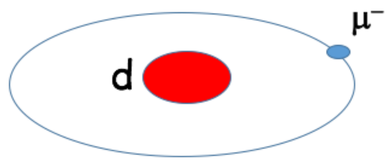
Calibrate via the related ***muonic*** reaction:

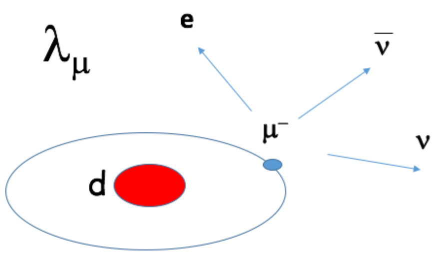
$$\mu\,d \rightarrow n\,n\,\nu$$

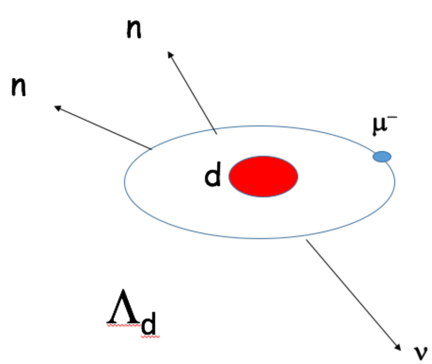
But existing measurements poor !



Experimental technique



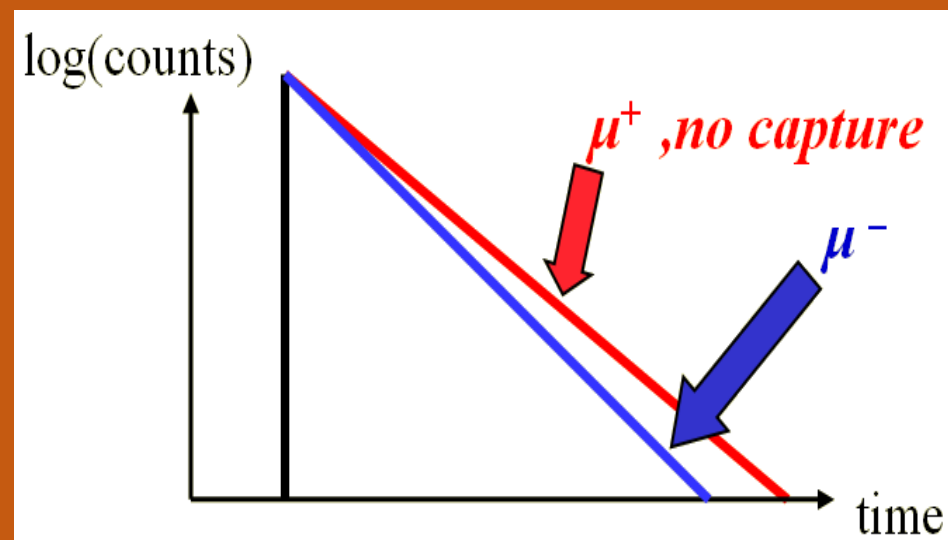




$\Lambda \sim Z^4$!

- $\mu d \rightarrow nn\nu$ rare, only 0.1% of $\mu \rightarrow e\nu\nu$
- neutron detection not precise enough

Lifetime method



$$\Lambda_d = \lambda_- - \lambda_+$$

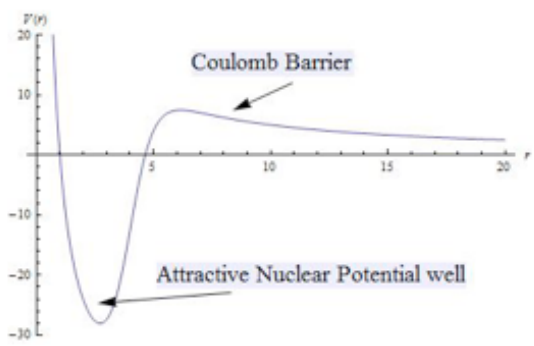
measure λ_- to 10ppm

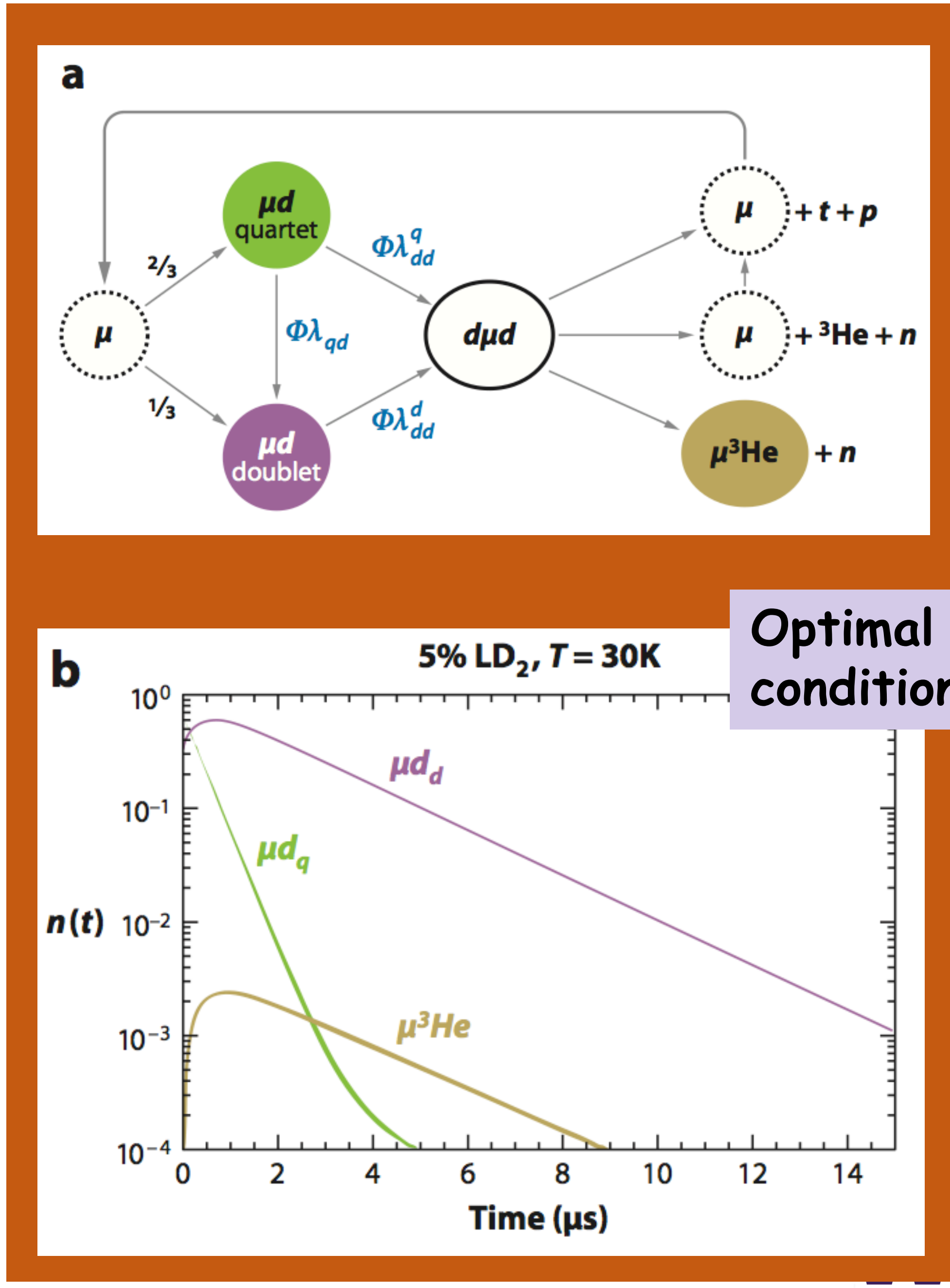
Experimental technique

Muonic atoms **m_e/m_μ** smaller than ordinary atoms

Muon-catalyzed fusion of ddμ molecules

Requires energy to overcome Coulomb repulsion





Optimal conditions

MuSun Experimental Strategy

Precision technique

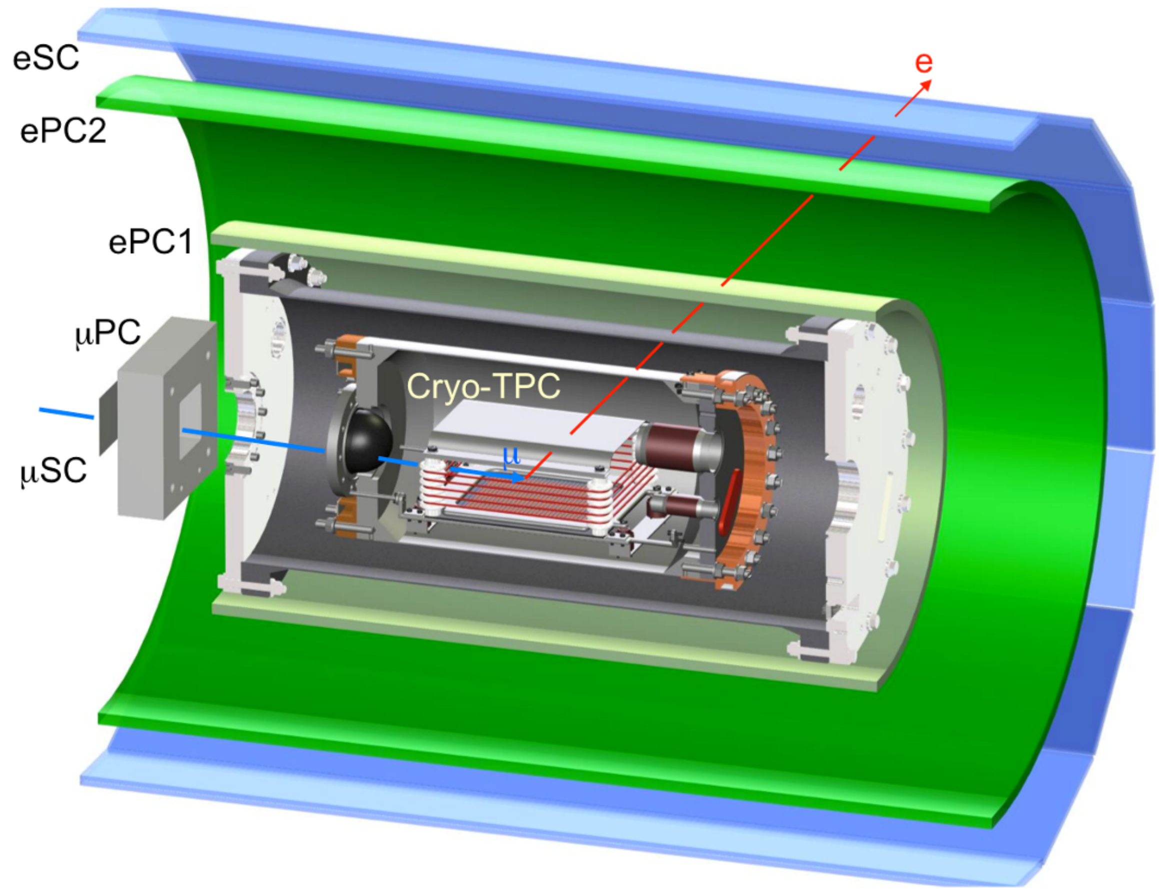
Clear Interpretation

Clean stops in D_2

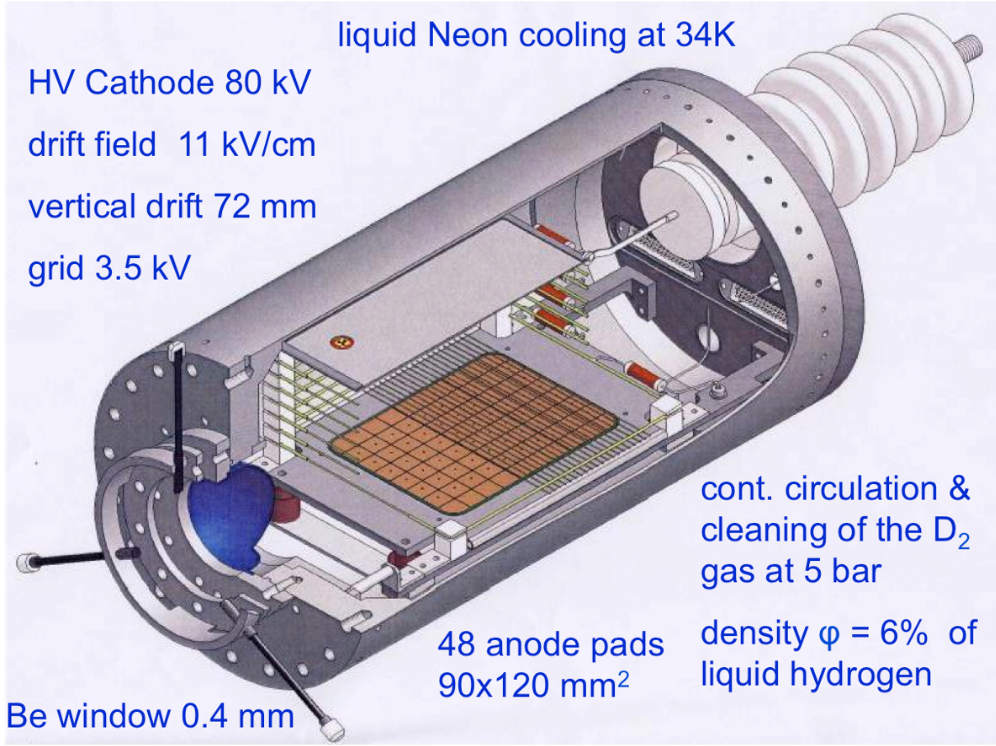
Impurities < 1ppb

H/D < 100 ppm

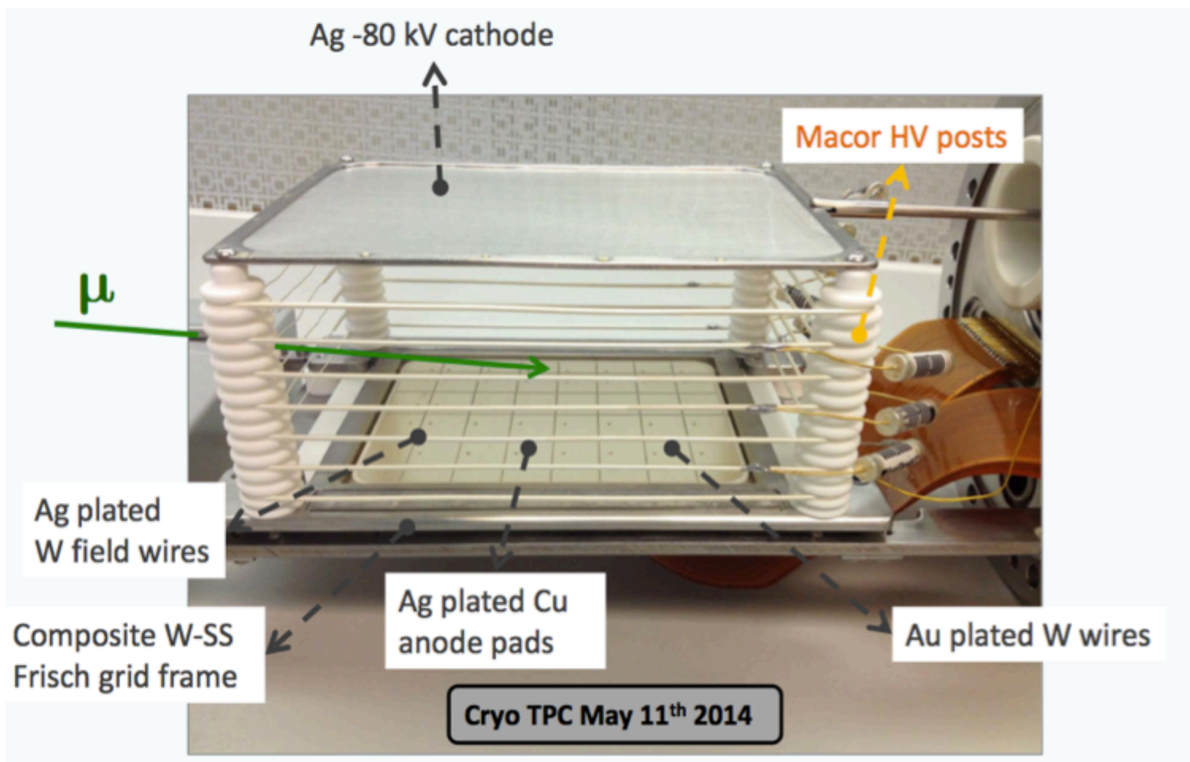
Time projection chamber (TPC)



TPC

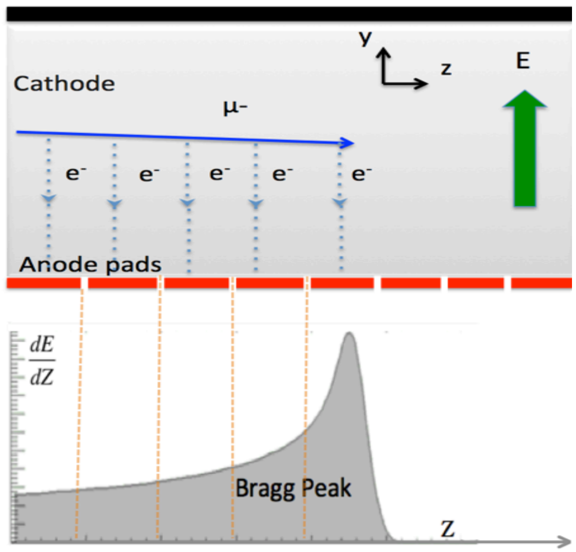


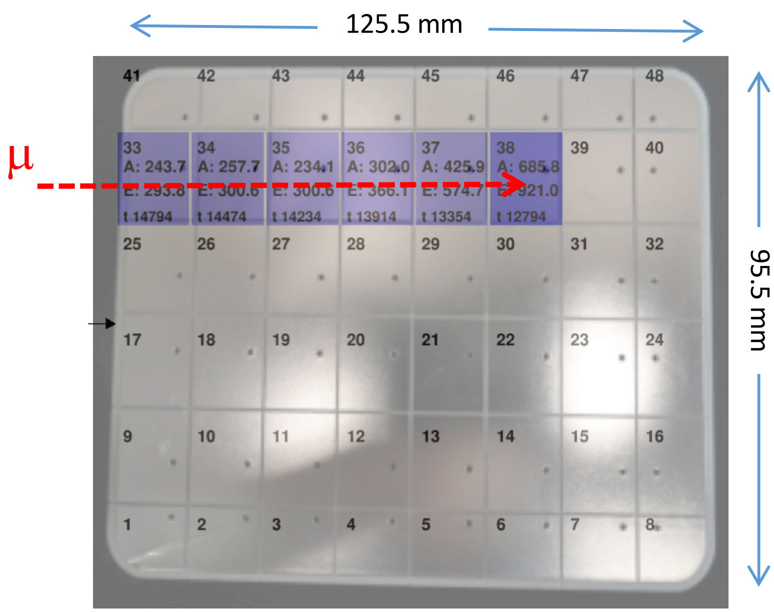
liquid Neon cooling at 34K
HV Cathode 80 kV
drift field 11 kV/cm
vertical drift 72 mm
grid 3.5 kV
cont. circulation & cleaning of the D_2 gas at 5 bar
density φ = 6% of liquid hydrogen
48 anode pads
90x120 mm^2
Be window 0.4 mm



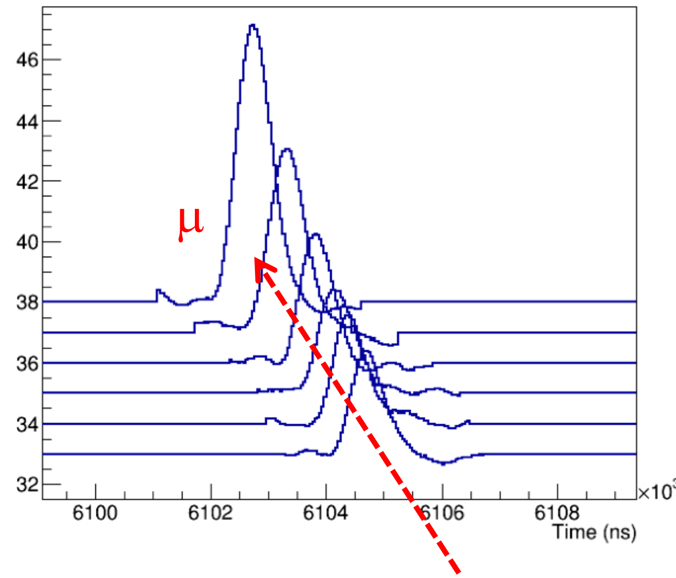
Ag -80 kV cathode
Macor HV posts
μ
Ag plated W field wires
Composite W-SS Frisch grid frame
Ag plated Cu anode pads
Au plated W wires
Cryo TPC May 11th 2014

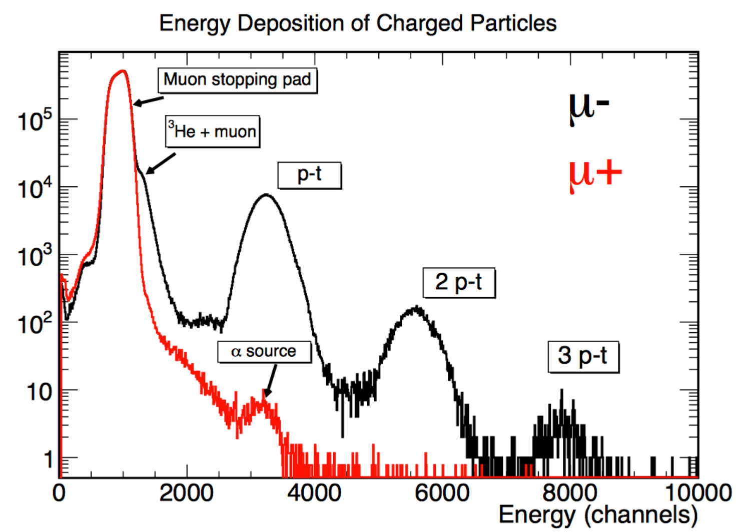
Events in TPC



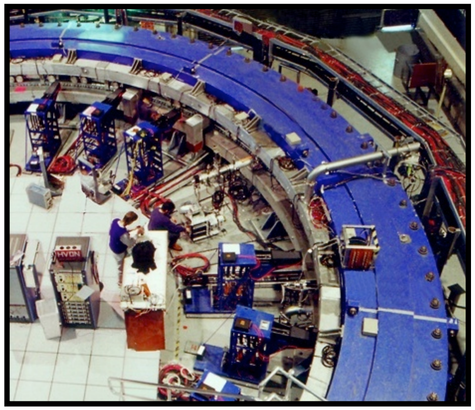


MuSun



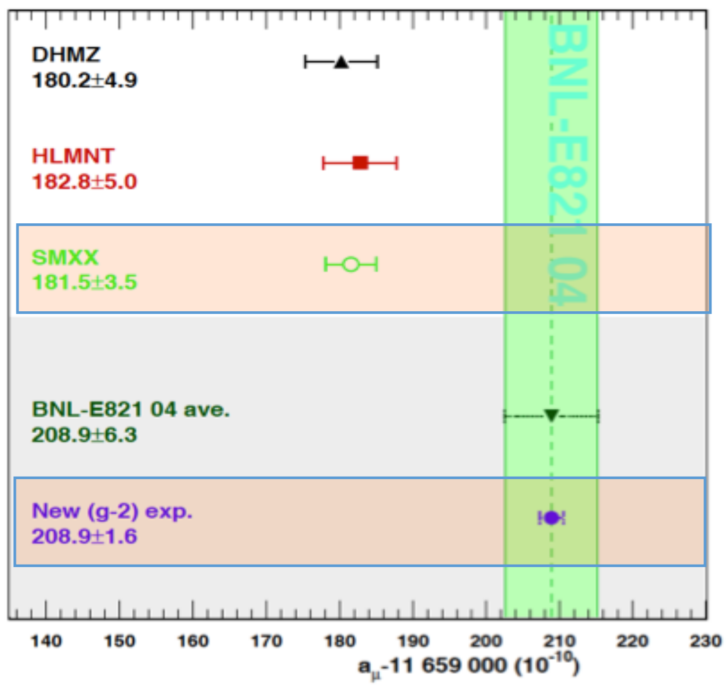


Muon g-2 Experiment at Fermilab
Challenging the Standard Model



future

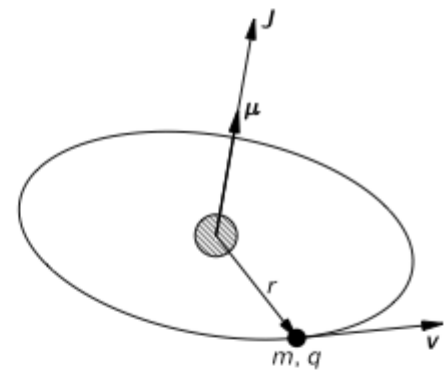
future



Spinning top and Larmor precession

Classical relation for atom

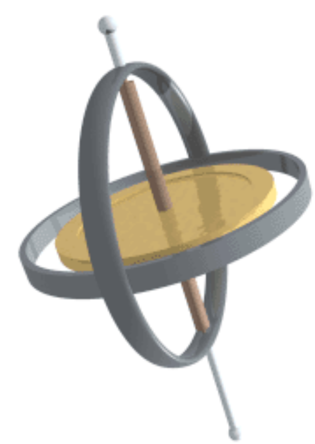
- magnetic moment $$\mu = IA = \frac{qvr}{2}$$
- angular momentum $$L = rmv$$
- g factor $$\mu = g \times \frac{q}{2m} L$$



g=1

Larmor precession in field B

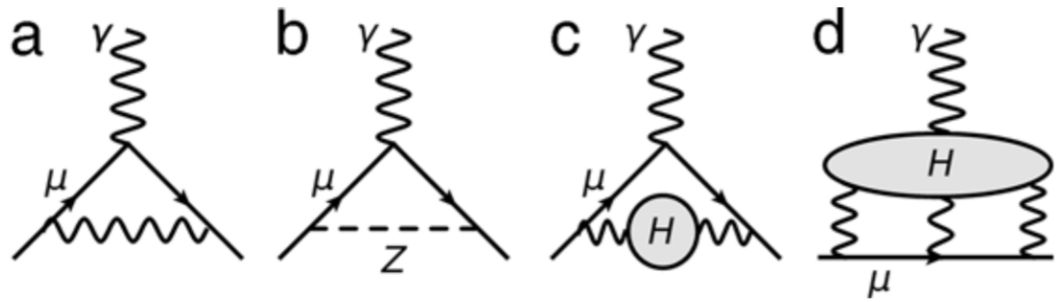
$$\omega = \frac{\mu}{J} B = g \times \frac{qB}{2m}$$



Quantum Mechanics and g-2

Spin ½ particles described by Dirac equation: **g=2**

Higher order QED corrections



$$\vec{\mu} = g\frac{Qe}{2m_{\mu,e}}\vec{s}, \qquad \underbrace{g = 2}_{\text{Dirac}}(1 + a_\mu);$$

$$a_\mu(\mathrm{SM_a}) = 116591802\,(49) \times 10^{-11} \quad (0.42\ \mathrm{ppm})$$

$$a_\mu(\mathrm{SM_b}) = 116591828\,(50) \times 10^{-11} \quad (0.43\ \mathrm{ppm})$$

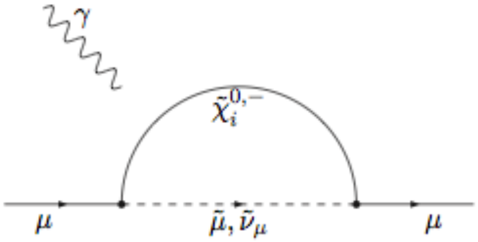
$$a_\mu(\mathrm{Exp}) = 116592091\,(63) \times 10^{-11} \quad (0.54\ \mathrm{ppm})$$

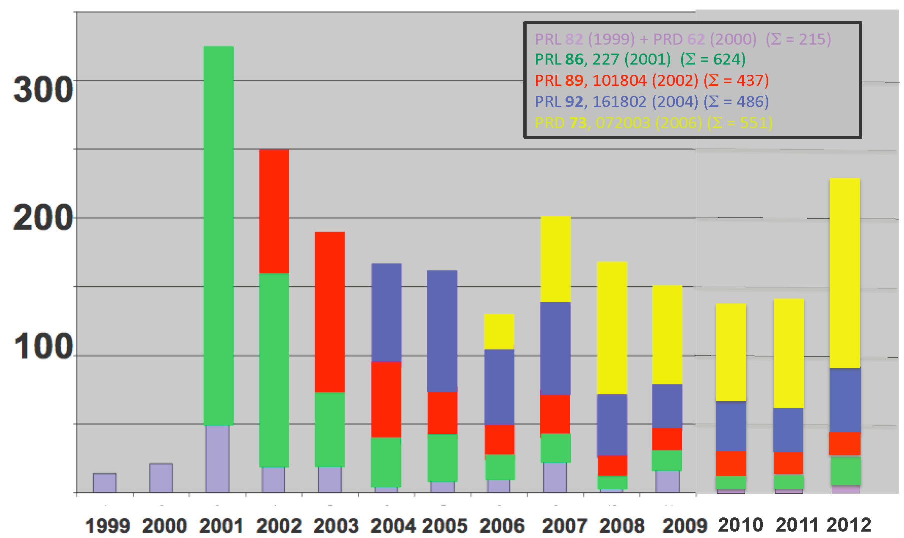
3.4 σ

Beyond Standard Model

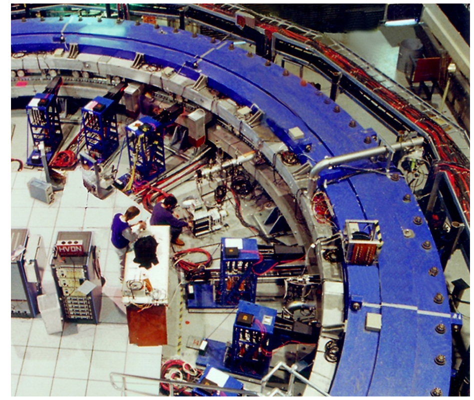
Precise knowledge of a_μ will aid in discrimination between a wide variety of standard model extensions

- Supersymmetric models
- Many others: extra dim, compositeness…
- Dark photon
- The "Un-invented"





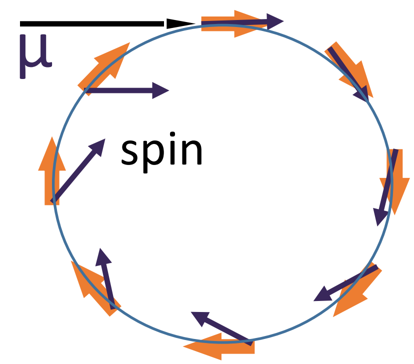
Key elements of g-2 measurement



- Polarized muons

  ~97% polarized for forward decays

- Precession proportional to (*g*-2)

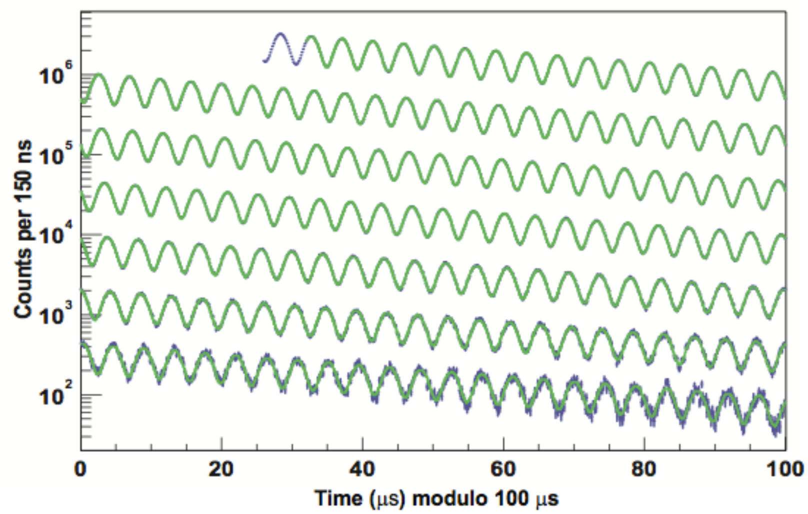


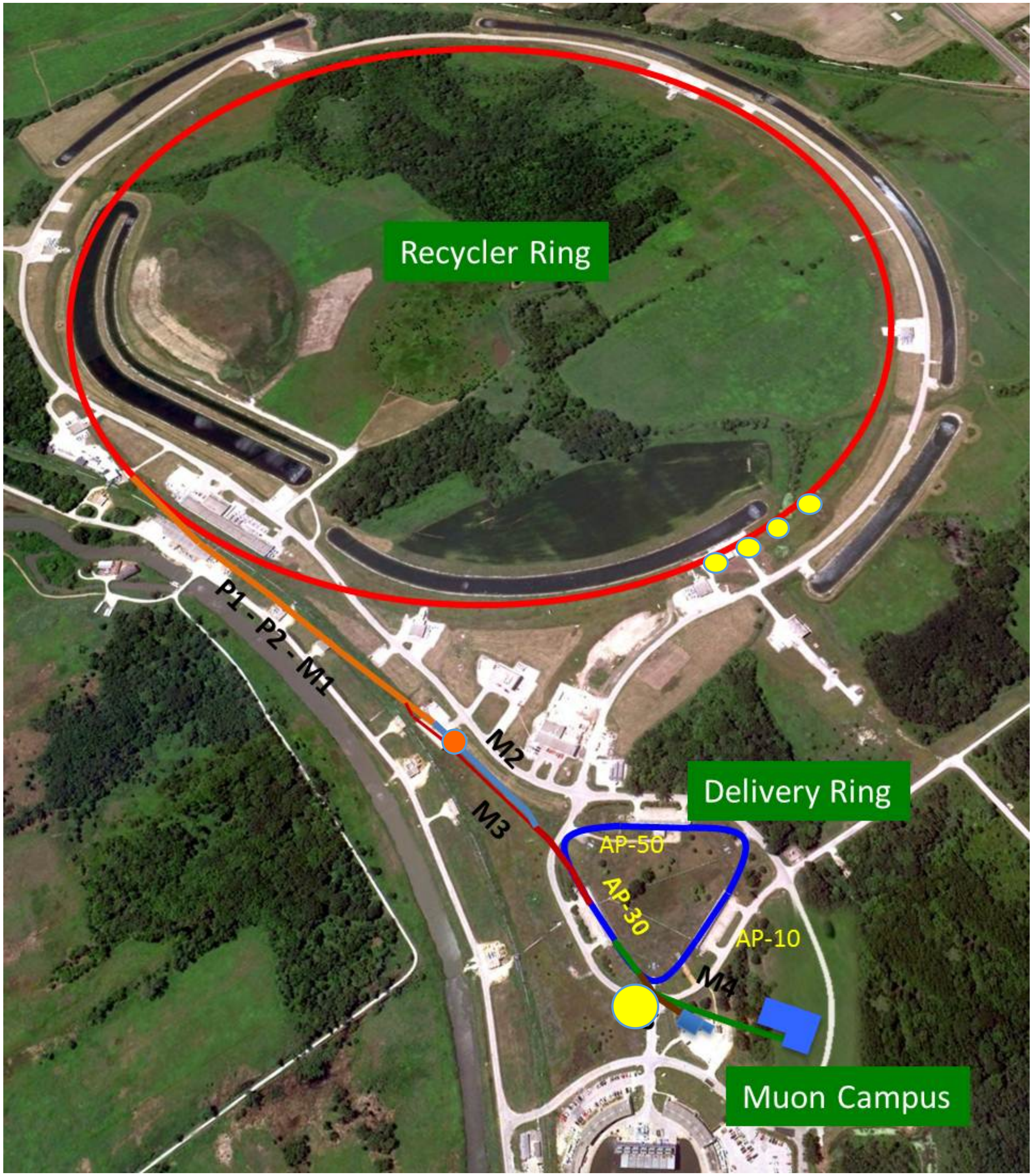
$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

- P_μ magic momentum = 3.094 GeV/c

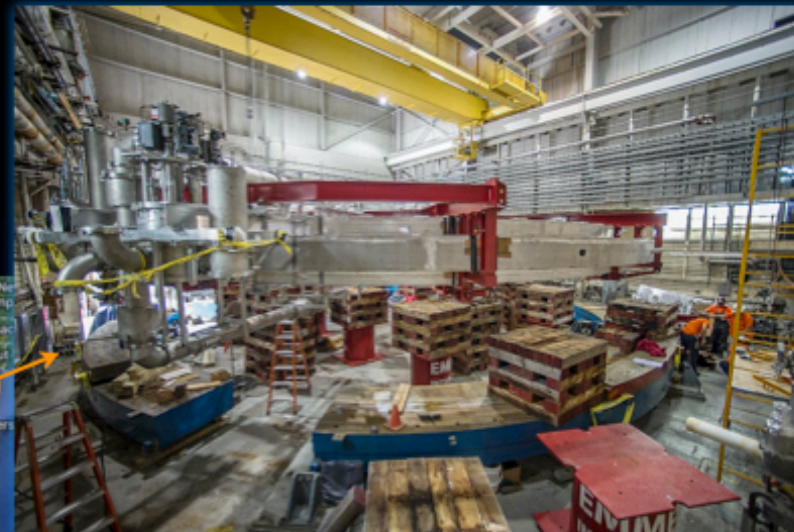
$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

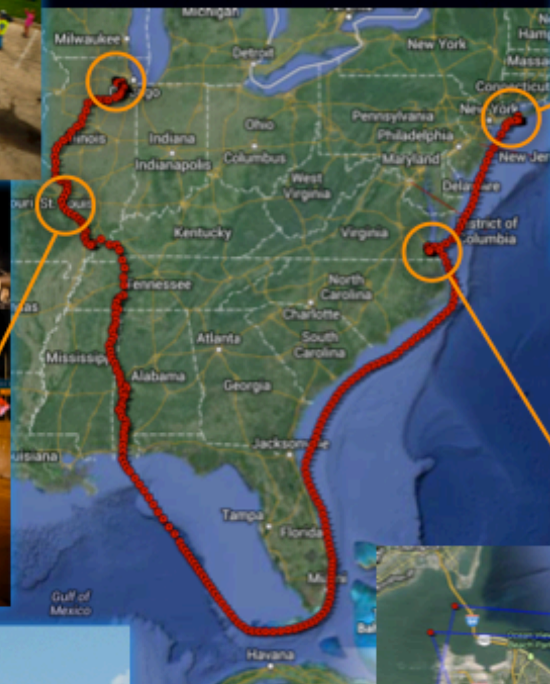
- Parity violation in the decay gives average spin direction

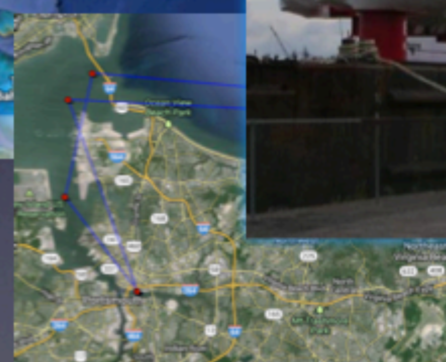



Recycler Ring
P1 - P2 - M1
M2
M3
Delivery Ring
AP-50
AP-30
AP-10
M4
Muon Campus

Taking the ring for a spin

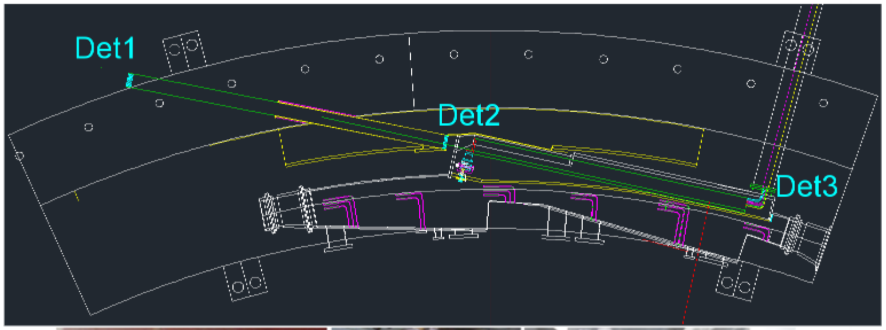


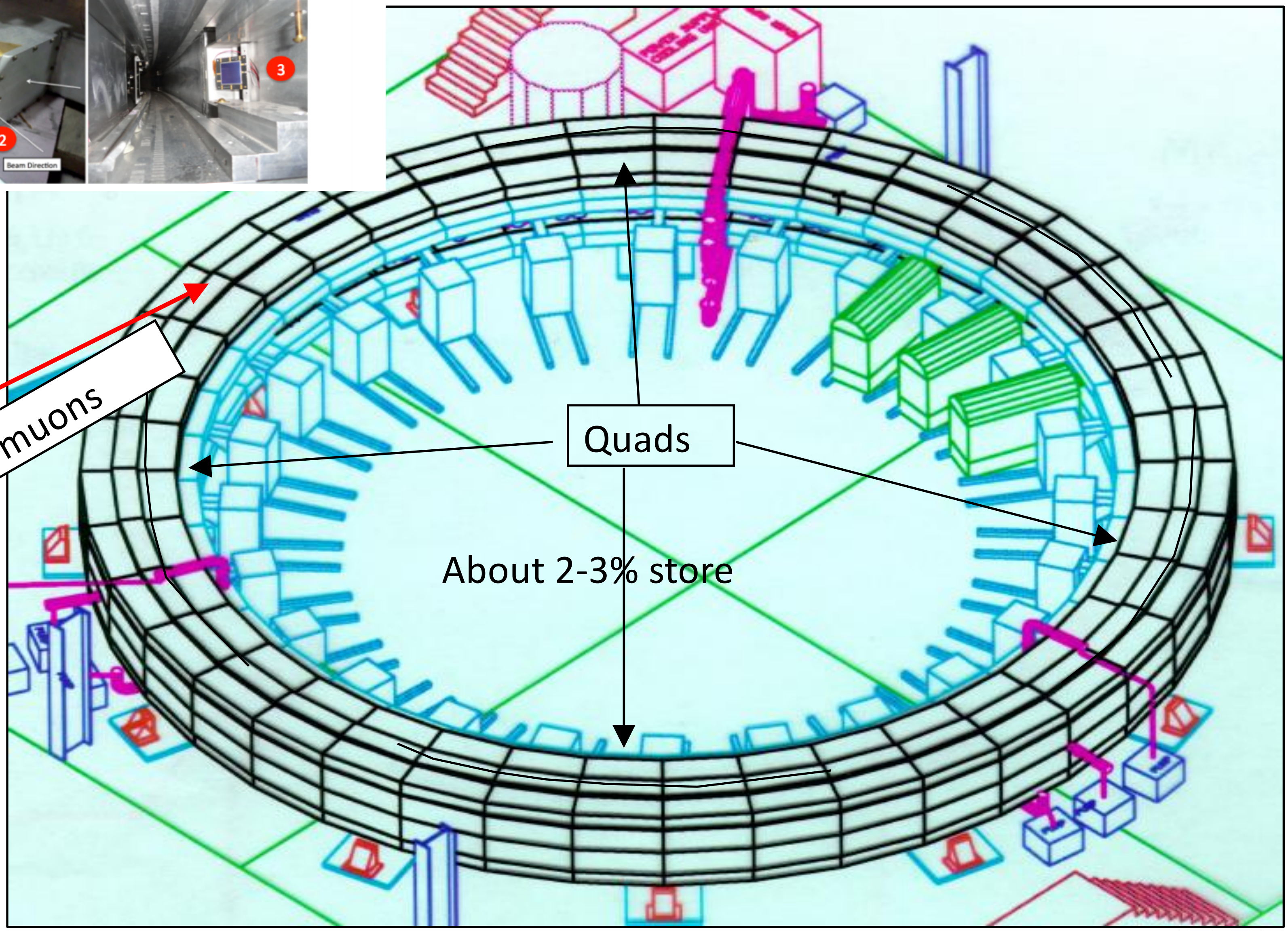




15 m diameter
3 mm flex tolerance

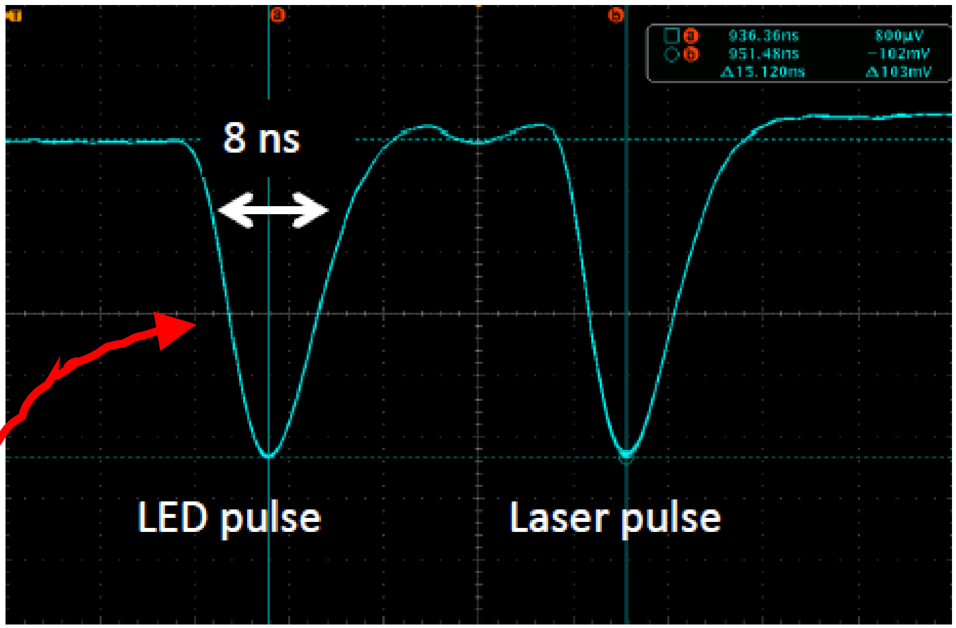
Muon storage ring

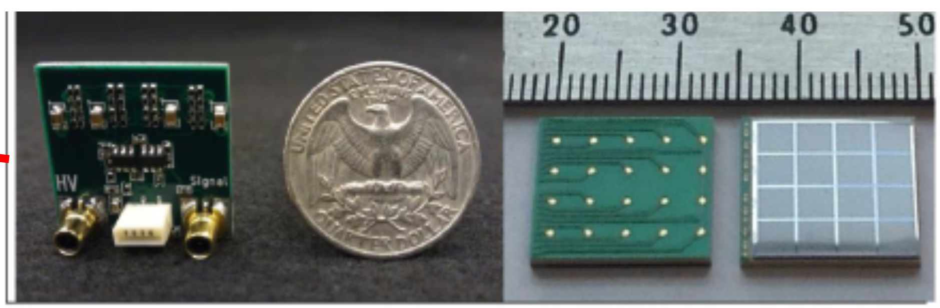


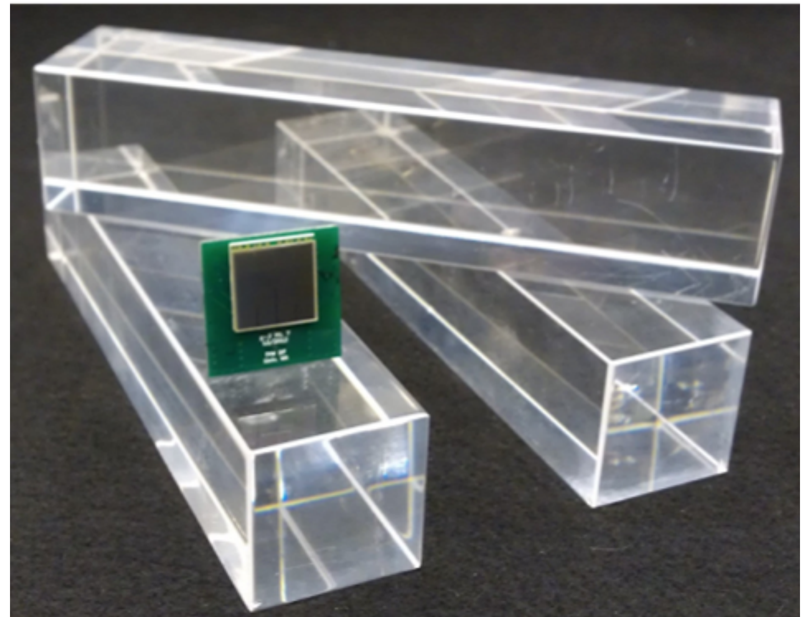


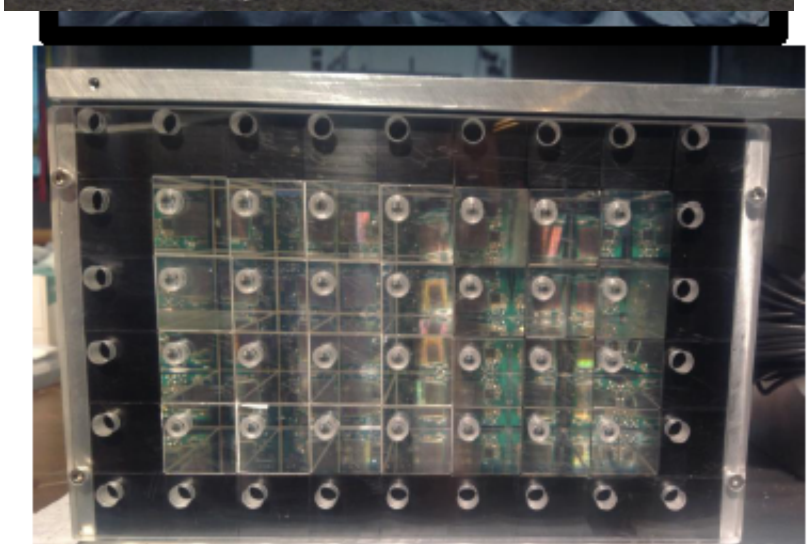
Segmented PbF_2 Calorimeter with SiPM Readout

SiPM boards optimized to produce PMT-like pulses to exploit short pulse duration of Cherenkov crystals (relevant: pileup)









28-channel prototype calorimeter tested at SLAC

Muon (g-2) at Fermilab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Muon g-2 moves on to a new life

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