Muon Physics

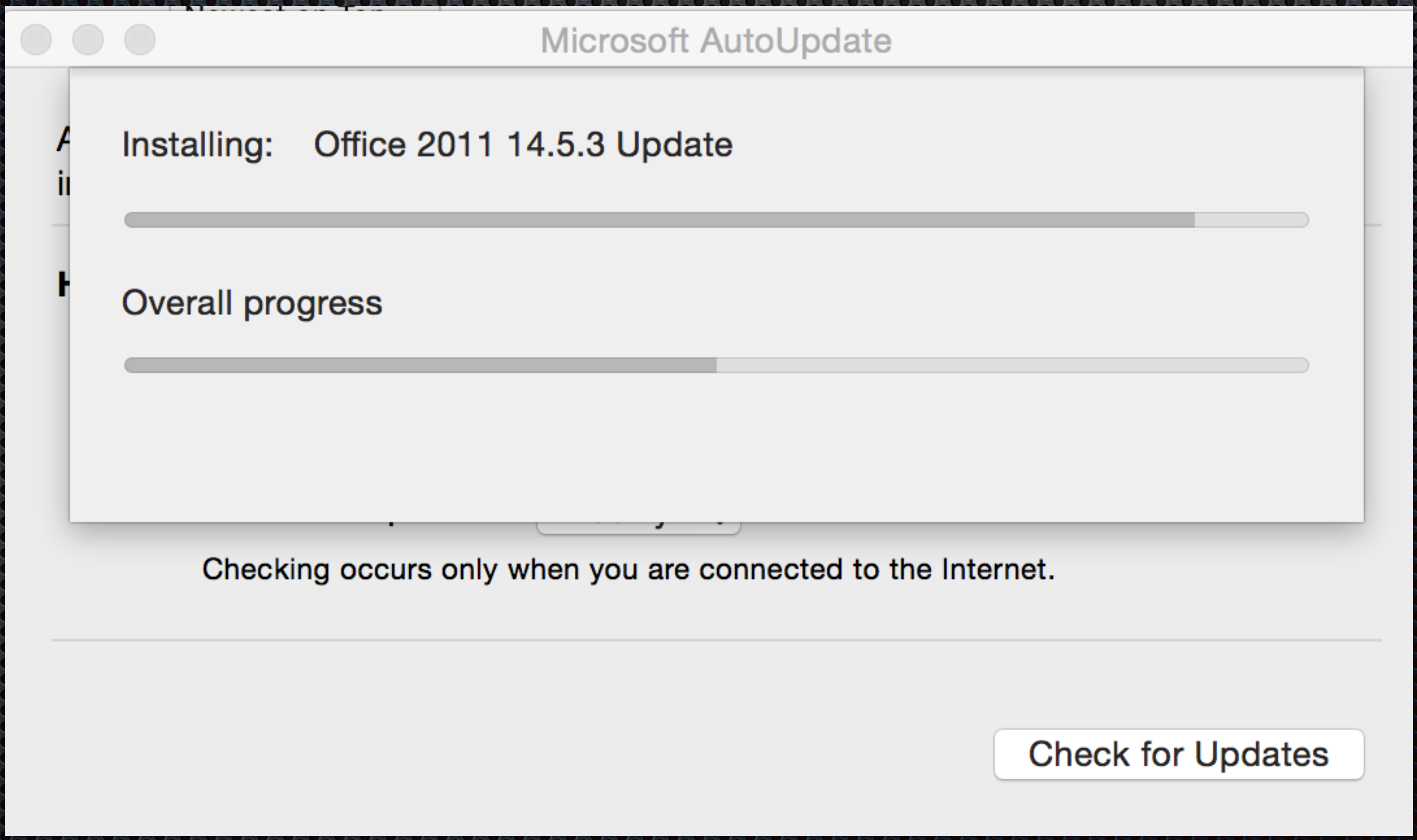
CTEQ 2015
R. Bernstein

thanks to: Alessandro Baldini, Brendan Kliburg, Luca Galli, Tim Gorringe, Dave Hertzog, Peter Kammel, Yoshi Kuno, Andre Schöning, Giovanni Signorelli, Peter Winter, …

also see Gorringe and Hertzog, 1506.01465v1;
RHB and P.S. Cooper, 1307.5787

Checked Before Talk

- I hope no interruptions!



Problem with Review Talks

leave out someone's favorite topic

cover everything

I will do both of these

[redacted] is he?

many of these are dead. Hmm…

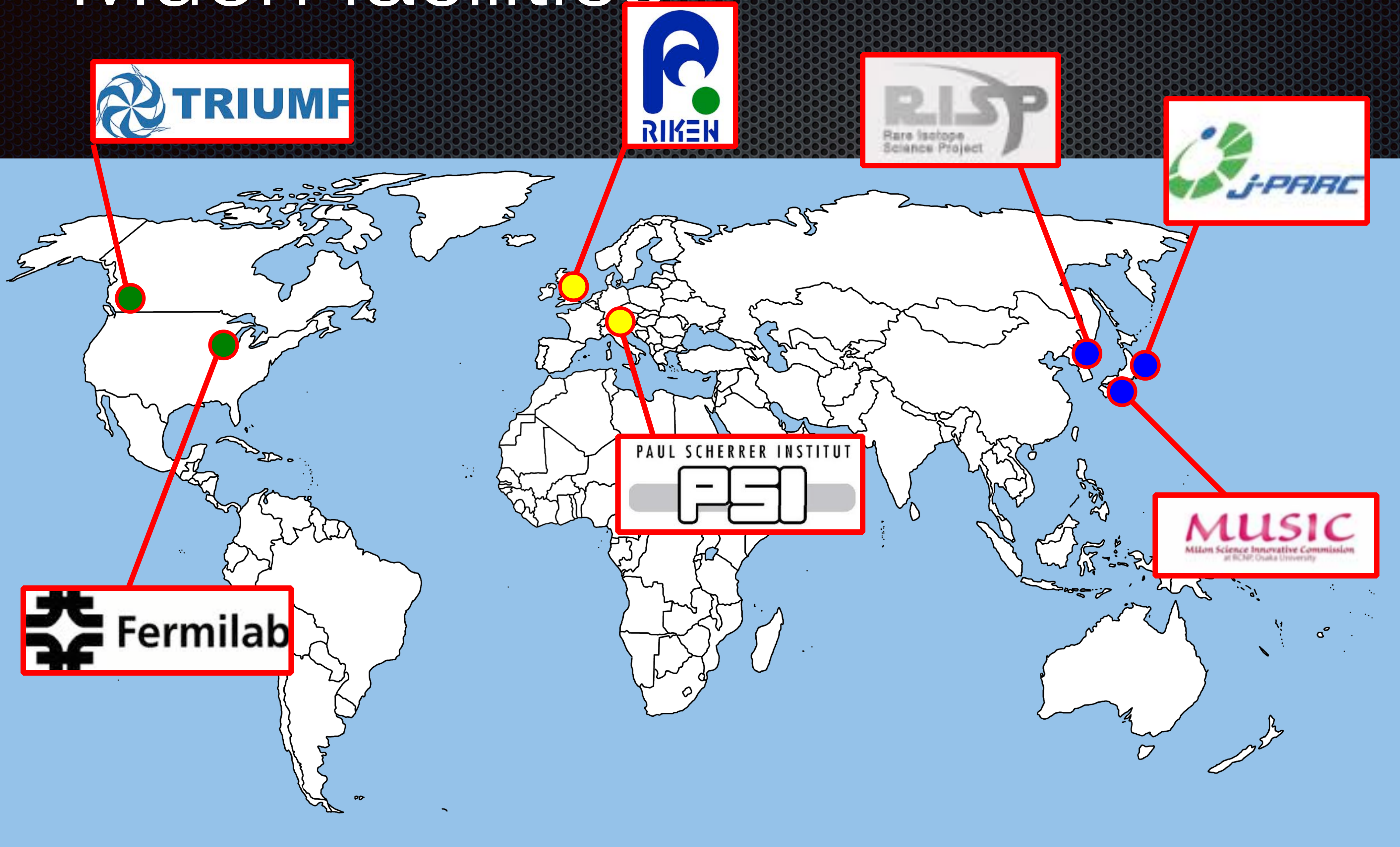
Big Ideas I Want You To Get

- Muon Physics spans a lot of interesting physics
- It's mostly about precision tests, *but not just*
- It can open windows that may be closed to colliders
- Charged Lepton Flavor Violation and g-2 are Nobel-class physics perhaps best studied with muons and you should learn about them.

Today/Tomorrow

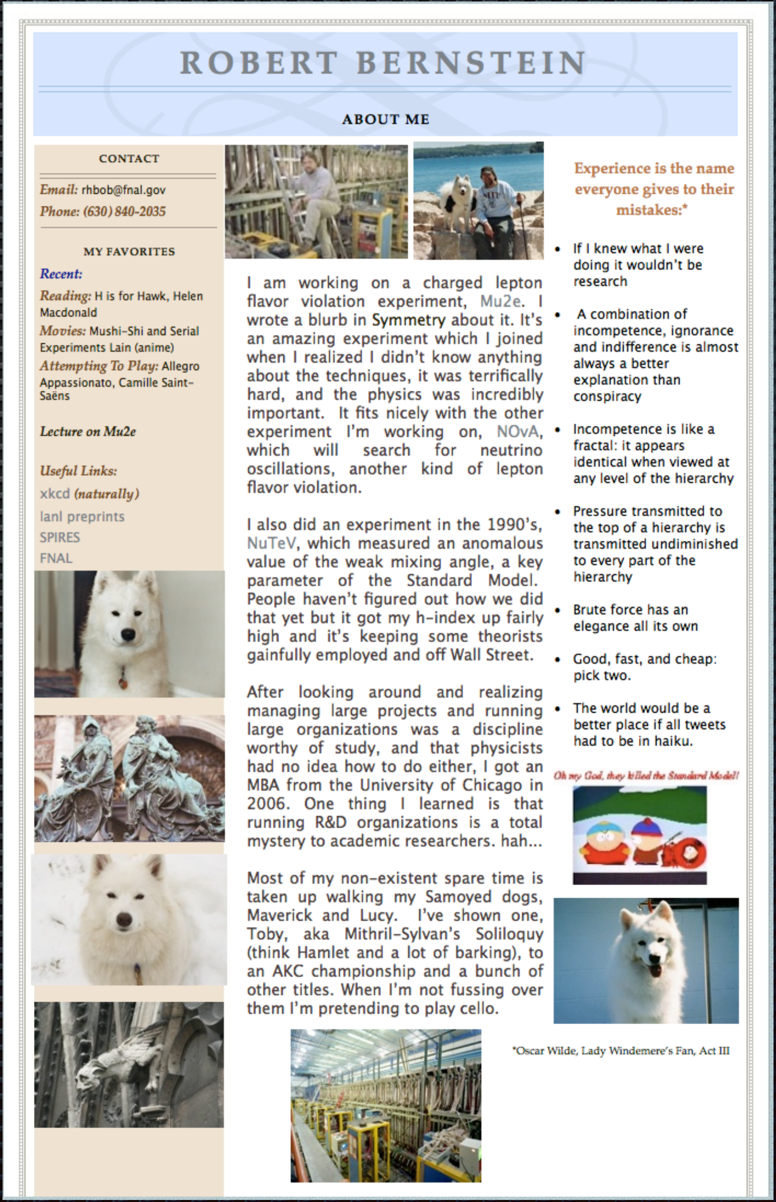
- Today: precision experiments, mostly at PSI
    - muon couplings and properties
    - proton charge radius puzzle
- Tomorrow: precision and searches, at PSI and FNAL
    - g-2, and charged lepton flavor violation

Muon facilities



Why Am *I* Giving This Lecture?

- Good question
- MIT ’76, PhD Chicago ‘84 in search for direct CP-Violation in K_L, Columbia Post-Doc, FNAL
- Deep-Inelastic Scattering in Neutrinos
  - CCFR
  - Designed and Co-Spokesperson of NuTeV
    - famous post-doc Donna Naples of Pitt
- Neutrino Oscillations (MINOS, NOvA)
- Mu2e, muon-to-electron conversion co-spokesperson 2007-2014.



(certainly not for my web page design skills)

OK, you know who I am

What About You?

- Theorists?
- Experimenters?
  - Intensity Frontier?
    - Muon?
      - am I going to discuss your work?
  - Cosmic Frontier?
  - Energy Frontier?
- Students?
- Post-Docs?

Outline

- What is a muon and how does it fit in the Standard Model?
- Properties of the Muon
- Probing the muon and probing with muons
  - muon decay, muon couplings, g-2, charged lepton flavor violation

Historical Note

- Yukawa predicted a particle that bound protons and neutrons in 1935 with a mass ~ 100 MeV/c^2
- Neddermeyer and Anderson (Phys Rev 51, 884 (1937)) see minimum-ionizing particles:

new particle?

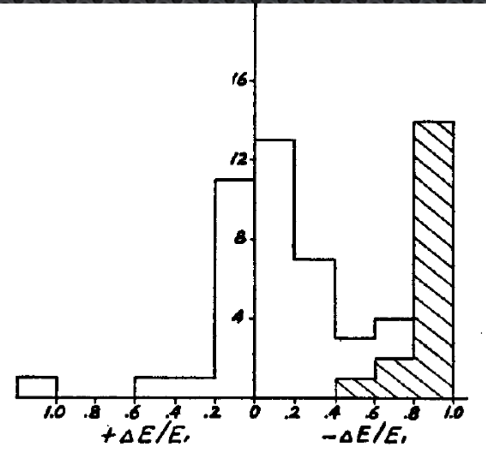


Figure 2: Distribution of fractional losses in 1 cm of platinum.

Remember this is mid-1930s

- Do we believe *dE/dx*?
- Do we believe quantum mechanics?
- This was not a clear, linear process!
  - no theory predicting a new particle and a machine to build it
  - ambiguity at every stage
- How could they cinch it in the days before 5σ?
  - Well, we do believe Maxwell's Equations

Discovery of new Particle

If it is taken that the
ionization density varies
inversely
as the velocity squared, the
rest mass of the particle in
question is found to be
approximately 130 times the
rest
mass of the electron.

±25%

http://journals.aps.org/pr/pdf/10.1103/PhysRev.52.1003

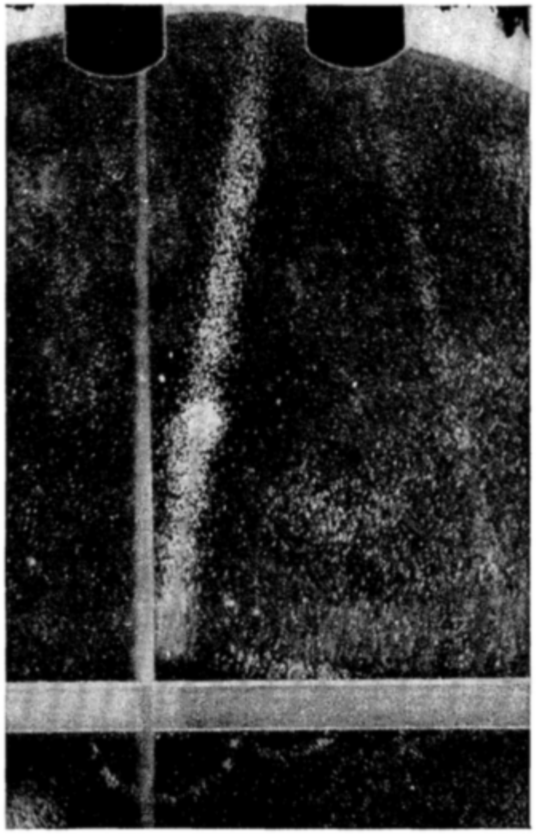


FIG. 2. Track A.

Street and Stevenson, 1937

Experiments We'll Discuss Today

- Muon as Probe:
  - Muon Capture: MuCap
  - Deep Inelastic Scattering and PDF: EMC/E665
  - Proton Charge Radius: muon lamb shift and MuSE at PSI
- Probing the Muon:
  - Lifetime and G_F: MuLan
  - Decay Parameters: TWIST
  - Magnetic/Electric Dipole Moment: g-2 at BNL and FNAL

Tomorrow

- Charged Lepton Flavor Violation
  - Decay: MEG and Mu3e at PSI

    $$\mu^+ \to e^+\gamma, \quad \mu^+ \to 3e \text{ (no neutrinos!)}$$

  - Interaction and Properties:
    Mu2e (FNAL) and COMET (J-PARC)

    $$\mu^- N \to e^- N$$

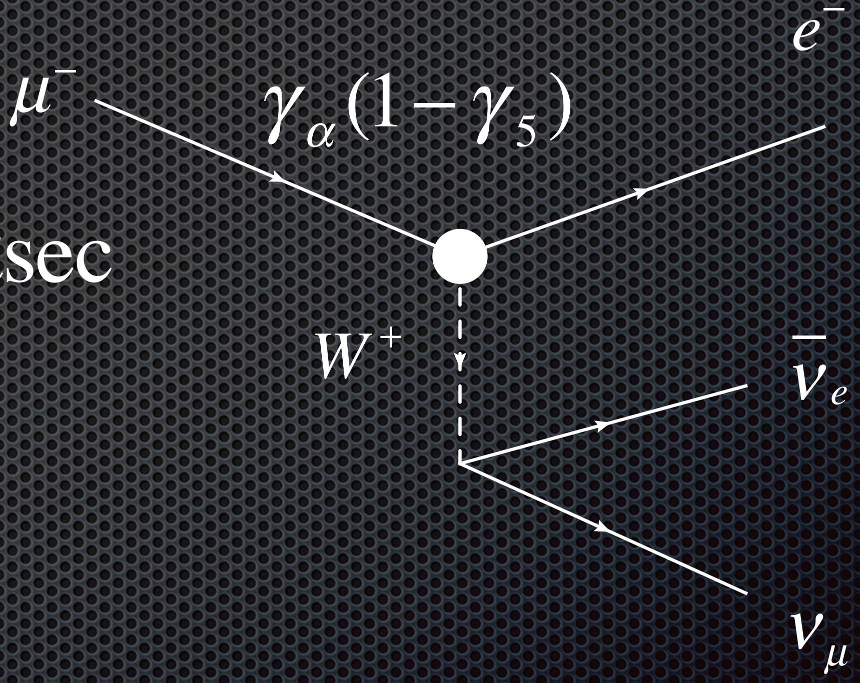
Groundwork

- First we need to establish some basics:
  - decay modes
  - spectra
  - angular distributions

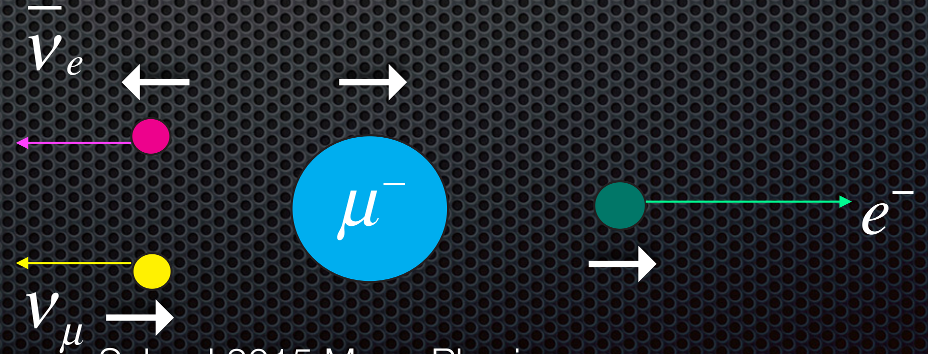
Muon Decay 101

- Main Decay Channel: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

$$\Gamma = \frac{1}{\tau} \approx \frac{G_F^2 m_\mu^5}{192\pi^3} \sim 2.2\mu\text{sec}$$



→ spin

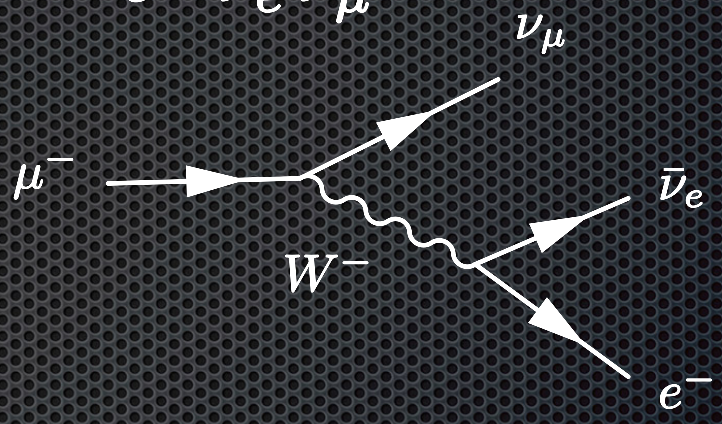


polarization is important

Muon Decay 201:

$$\mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$$

- In the Standard Model,



$$dW = \frac{G_F^2 m_\mu^5}{3\times 2^6 \pi^3}[2\varepsilon^2(3-2\varepsilon)]\times[\text{angular and spin}]d\Omega$$

$$n(\varepsilon) = 2\varepsilon^2(3-2\varepsilon), \int_0^1 n(\varepsilon)\, d\varepsilon = 1$$

$$\varepsilon = \frac{E_e}{E_{e,\max}}$$

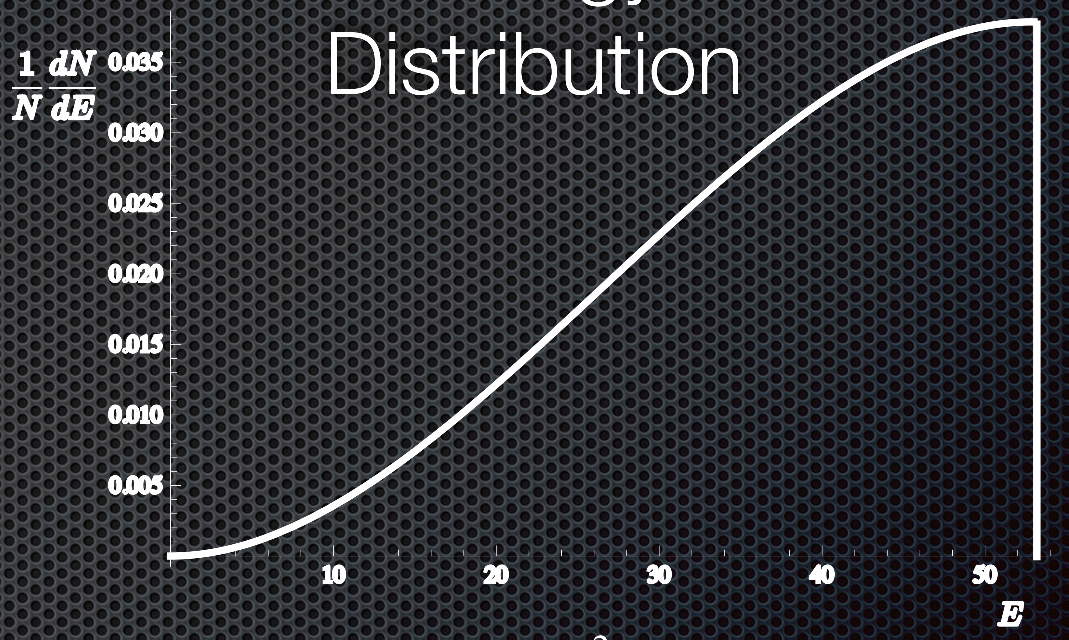
$$E_{e,\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} = 52.8 \text{ MeV}$$

this is really considerably more complicated and we will come back to it with TWIST

A few points to keep in mind

- This is a simple, precise prediction
- Therefore it should be precisely checked, possibly revealing new interactions
- And we will use it extensively, so please keep this in mind

Energy Distribution



$$n(\varepsilon) = 2\varepsilon^2(3-2\varepsilon)$$

Michel Spectrum

L. Michel, Proc. Phys. Soc. London A63,514 (1950)

Muon Decay 301

- Angular Distribution (will need this later)

$$\frac{dP(\varepsilon,\theta)}{d\epsilon\; d\Omega} = \frac{1}{2\pi} n(\epsilon)\left(1 - \alpha(\epsilon)\cos\theta\right)$$

$$\alpha(\epsilon) = q\,\frac{2\epsilon - 1}{3 - 2\epsilon}$$

- Higher momentum electrons tend to be along muon momentum (remember for *g-2*)

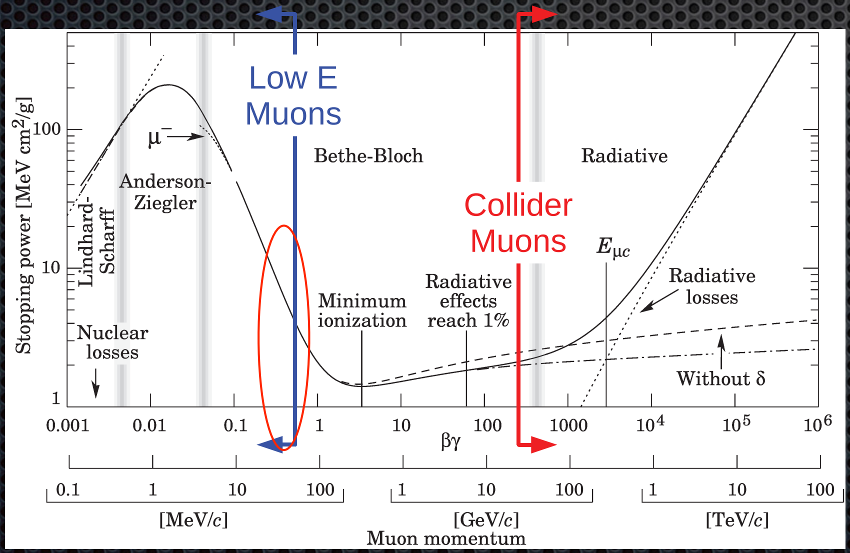
Now Look for Deviations

- Does the muon decay as we expect?
- Before examining experiments (muon detectors) let’s discuss muon beams

Surface Beams

$\pi \to \mu\nu$

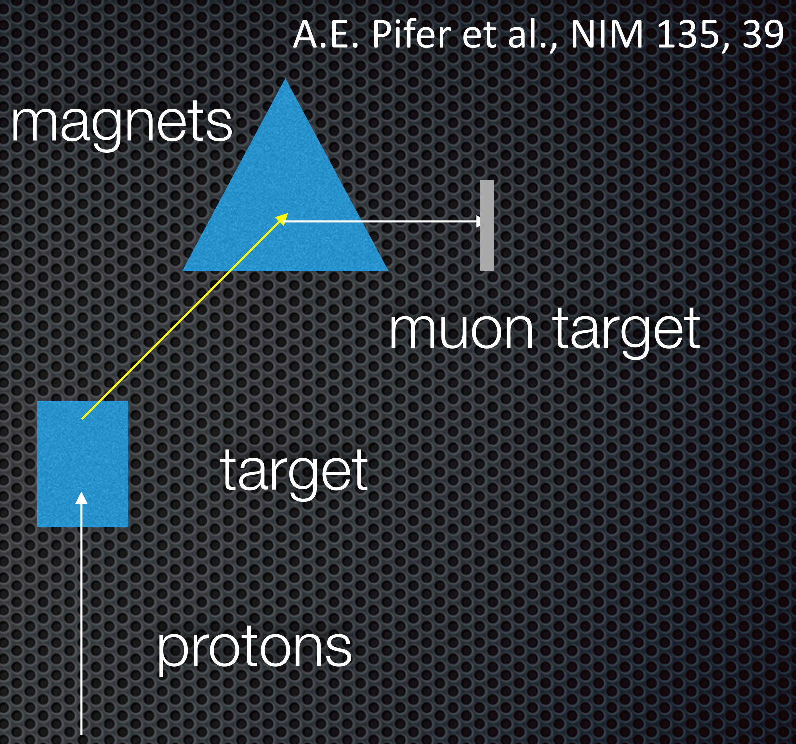
- Surface beams: bring pions to rest; decay kinematics give p_μ= 29.8 MeV/c
  - how much material do you need to stop a 29.8 MeV/c muon?



start at 10-20 MeV cm^2/gm and climb up; few mm of Al

from PDG

Surface Beam Characteristics



- Make target right thickness, pions stop near exit and muons lose very little energy after birth: monochromatic
- Polarization nearly 100% (100% at birth, but some loss as exit material)
- Can range out in very well defined distance since monochromatic: well defined vertex for muon decay

$$R_\mu \propto p^{3.5} \text{ then } \frac{\Delta R}{R} \sim \sqrt{(3.5\frac{\Delta p}{p})^2 + (\Delta R_{\text{straggling}})^2}$$

Cloud Beams

- Pions decay in flight:
  - Pions higher momentum, decay outside of proton target
  - Wide momentum range (good for many things)
- Muons contaminated by pions, electrons
- Thicker stopping target, not well-defined depth
- These can be any energy that is practical

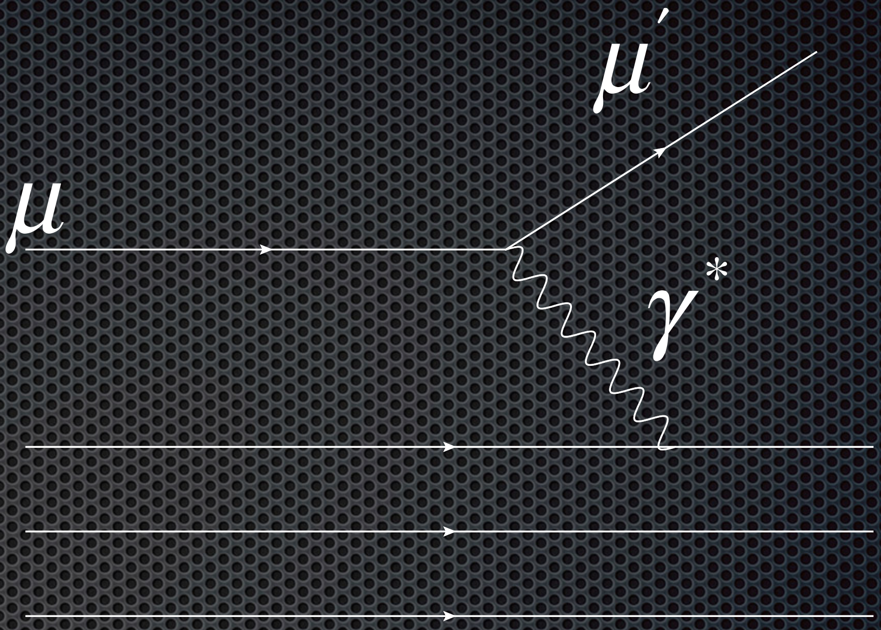
μ^+ and μ^- Beams

- Both μ^+ and μ^- lose energy by *dE/dx*
  - and eventually stop
- μ^- will fall into an atomic orbit
  - μ^- atom, with a 1s state much closer to nucleus than the electron
- μ^+ will not, and will quickly decay

Stopped and Captured

- Surface beams are positive:
  - stop π^+ ; π^- would strongly interact with the nucleus before it could decay
- Surface/Stopped beams are good for muon decay properties
  - collect large numbers, know initial momentum, good polarization
- Captured muon beams are good for studying interactions with nuclei

A few words about PDFs



energy transfer and fractional energy

$$\nu = (E_\mu^{\text{out}} - E_\mu^{\text{in}})$$

$$y = \nu / E_\mu^{\text{in}} = (E_\mu^{\text{out}} - E_\mu^{\text{in}}) / E_\mu^{\text{in}}$$

measure

4-momentum transfer $Q^2 = -q^2 \approx 4 E_\mu^{\text{out}} E_\mu^{\text{in}} \sin^2 \frac{\theta}{2}$

know

$$x = \frac{Q^2}{2M\nu}$$

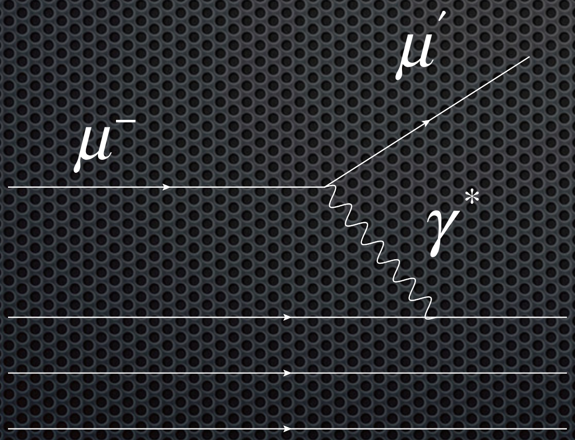
fraction of momentum of nucleon belonging to struck parton

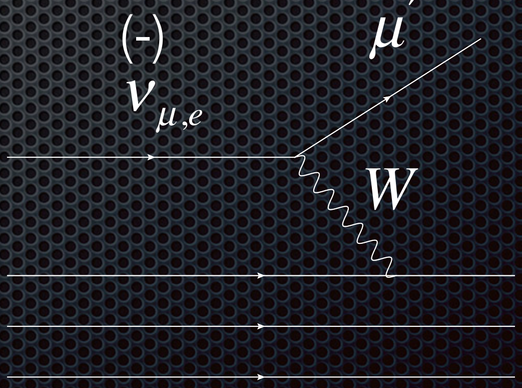
Neutrinos vs. Muons

$$N \propto \int \phi(E)\sigma(E)dE$$

- Muons: measure incoming flux (number, energy) and choose particle/antiparticle

- Neutrinos: don't measure incoming flux; often contaminations of particle/antiparticle and other species*





* could give talk on this but I will spare you

Why Bring This Up?

$$N \propto \int \phi(E)\sigma(E)dE$$

- When measuring neutrino oscillations or neutrino structure functions, you have to know the flux to get the answer
- End up iterating in structure functions since we only know the product, up to much worse neutrino detector resolutions
- Getting *absolute* cross-section (which you need for normalization of structure functions) often requires separate experiment

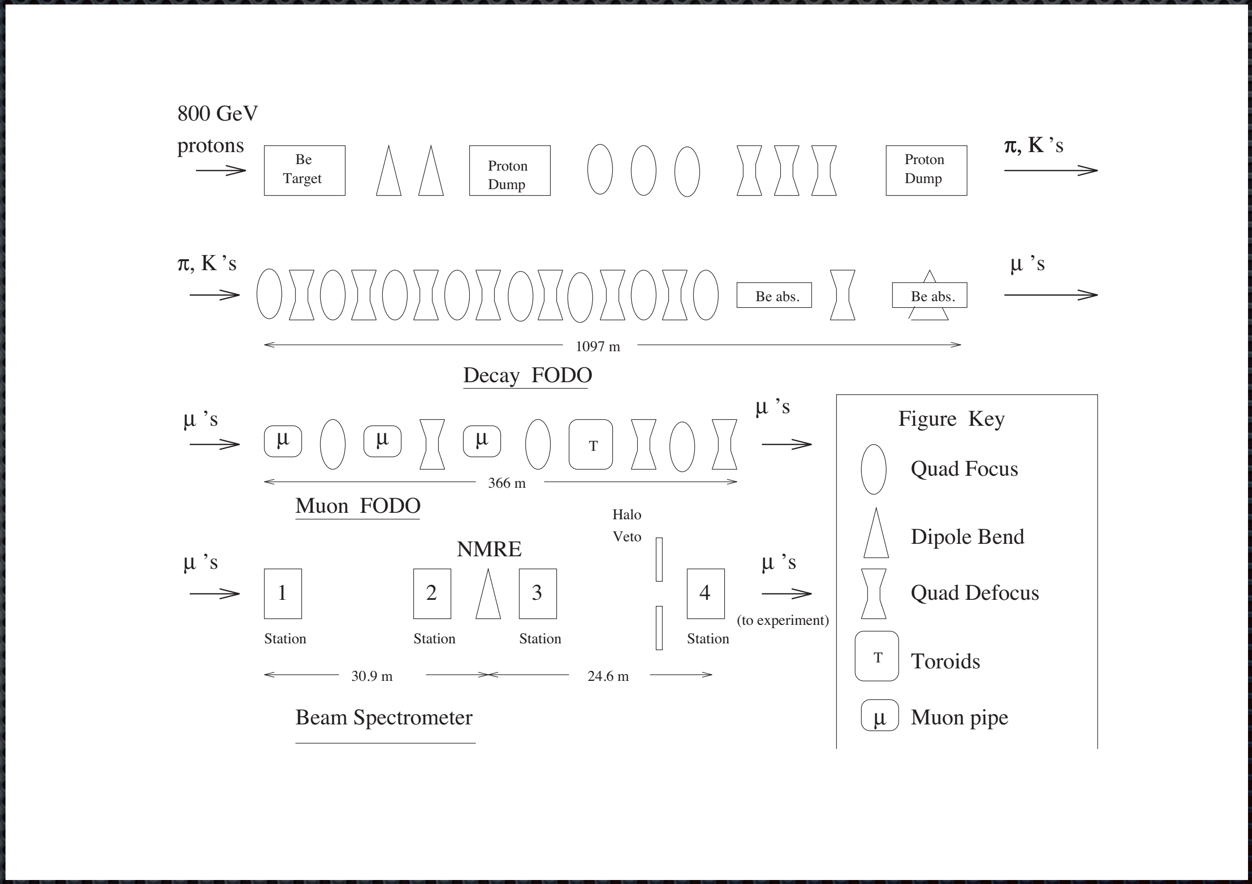
In Oscillation Experiments

$$N \propto \int \phi(E) \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)\sigma(E)dE$$

- can cancel a lot with two-detector oscillation experiments, but single-detector is tough.
- Need an good detector or clean modes
  - neutrino oscillation experiments often use “quasi-elastic” events ($y=0$) where all momentum goes into muon, no nuclear breakup
  - exclusive channels for appearance modes

Actual DIS Muon Beam

- From E665



A.Kotwal,
PhD Thesis

Muon DIS Spectrometers

E665

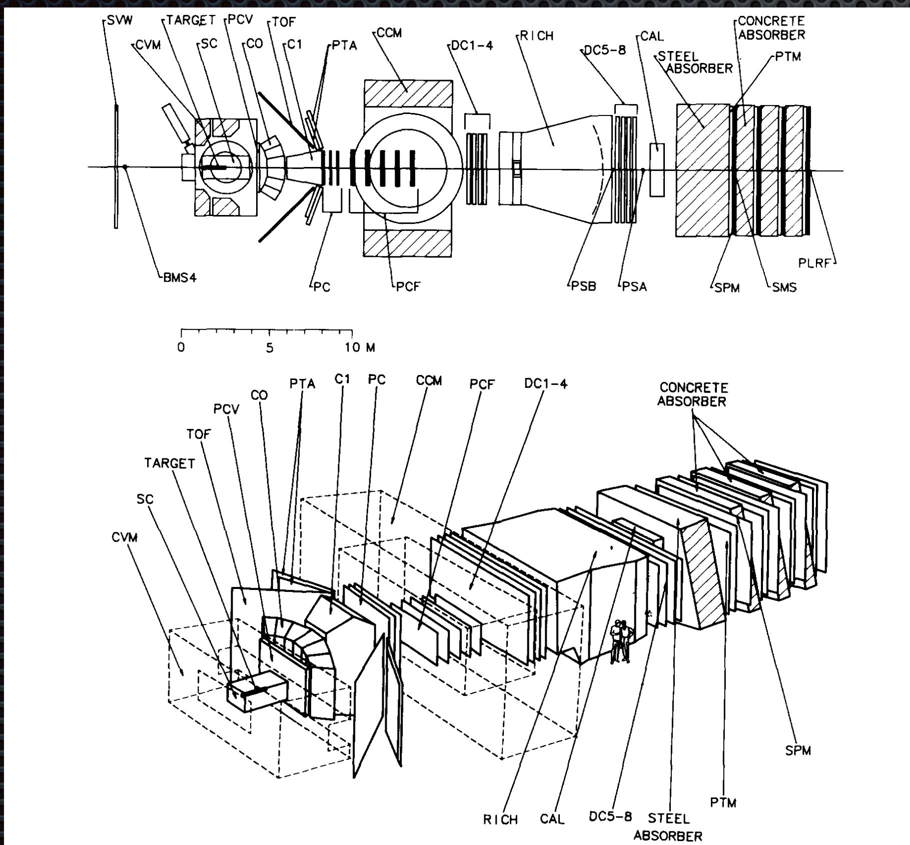
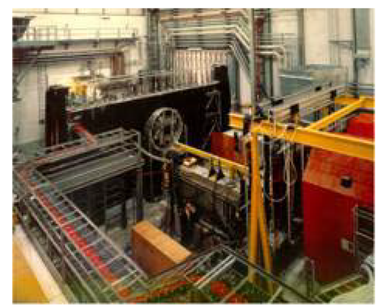
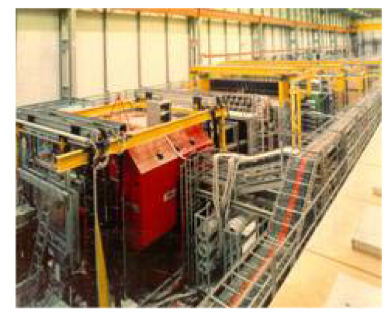


Fig. 2. Plan and perspective views of the E665 spectrometer.



A view of the EMC apparatus looking upstream



A view of the EMC apparatus looking downstream

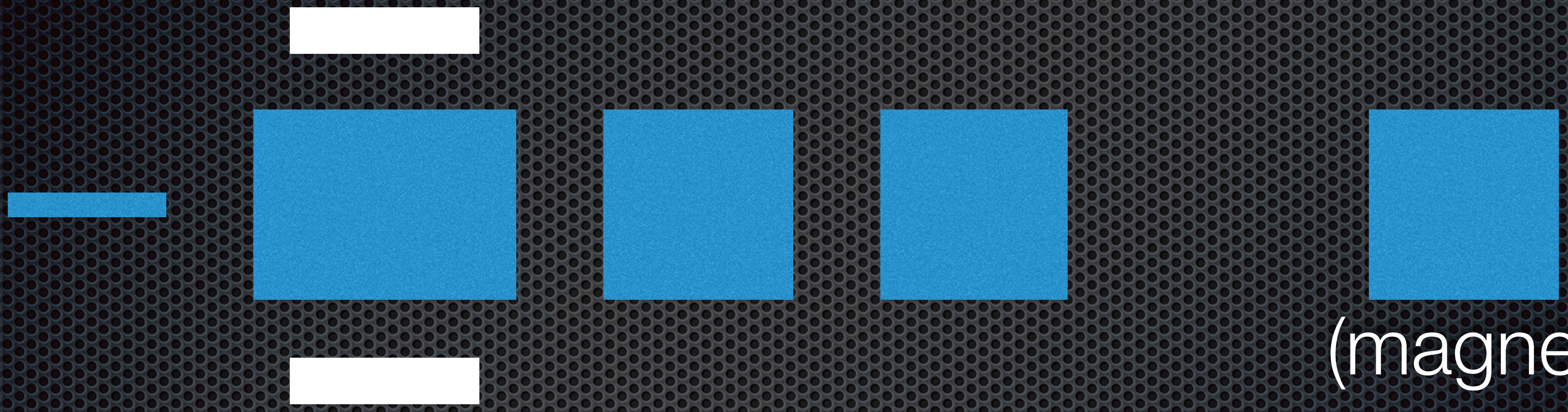
Volume 123B, number 3,4 PHYSICS LETTERS 31 March 1983

EMC

M.R. Adams et al., Nucl.Instrum.Meth. A291 (1990) 533-551

What Are We Looking At?

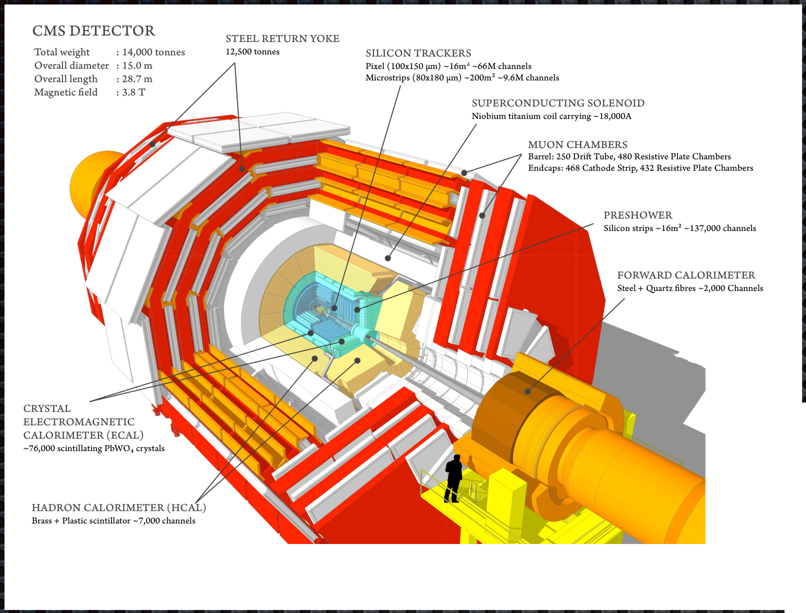
magnetic field

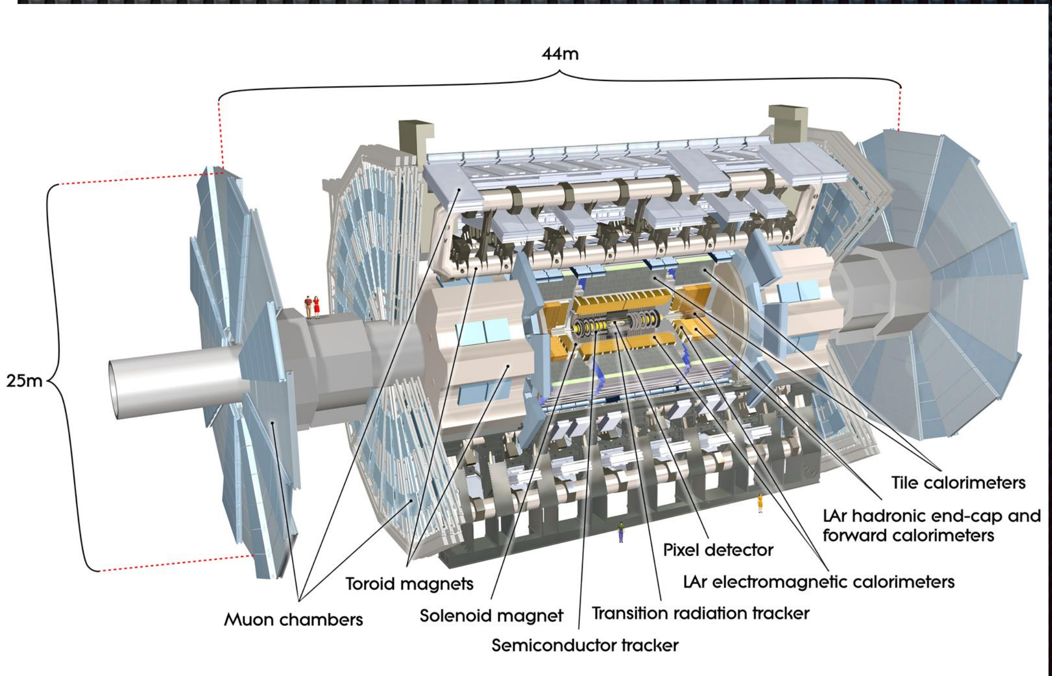


target →tracking →PID →calorimeter →

(magnetized)
material
to range out
everything else
for muon ID

Is this sequence familiar?



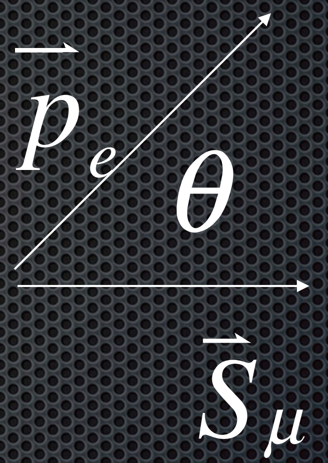


Experiments:

- Decay Parameters
  - *TWIST at TRIUMF*
- Lifetime
  - *MuLan at PSI*
- Interactions:
  - *MuCap and MuSun at PSI*

TWIST: Angular Distributions

- Recast



$$\frac{d^2\Gamma}{\epsilon^2 d\epsilon\, d(\cos\theta)} \propto 1-\epsilon+\frac{2}{9}\rho(4\epsilon-3)$$

$$+\frac{1}{3}P_\mu \xi \cos\theta\left[(1-\epsilon)+\frac{2}{3}\delta(4\epsilon-3)\right]$$

$$+\eta\, O(m_e/m_\mu)+\text{Radiative Corrections}$$

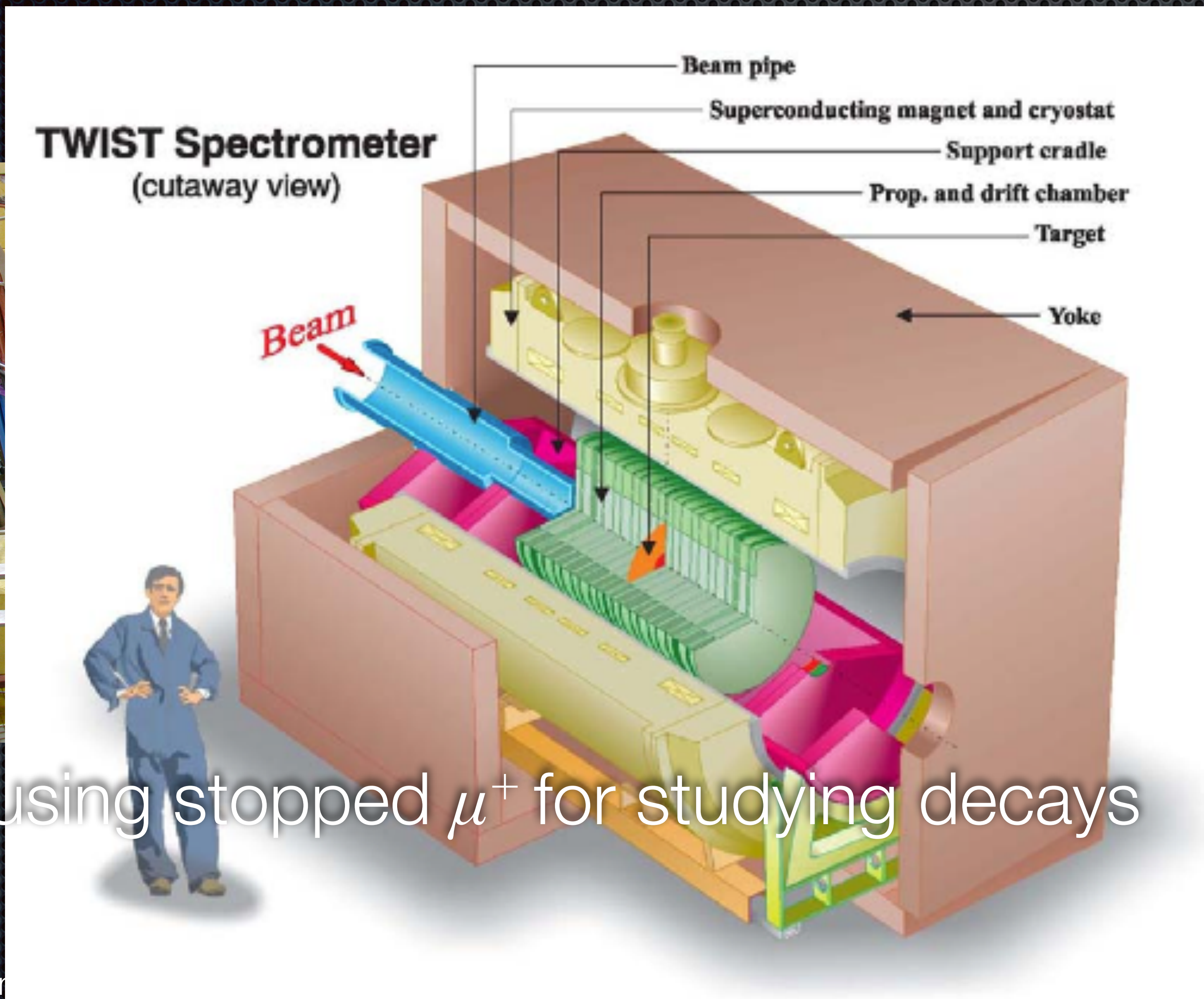
P_μ is the polarization

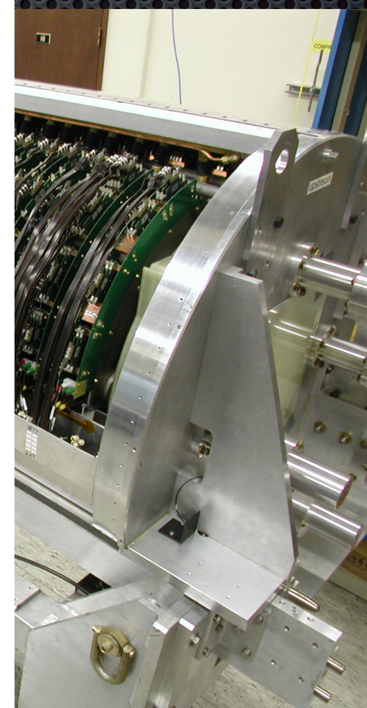
we only measure a term proportional to this product, which is why we separate it out

$$\text{Standard Model: } \rho=\frac{3}{4}, \delta=\frac{3}{4}, \xi=1$$

at TRIUMF

Apparatus





using stopped μ^+ for studying decays at TRIUMF

Results

Andrei Gaponenko,
now Wilson Fellow on Mu2e

everyone's nightmare:
blinding key got lost 😱

Results

$$\rho = 0.74977 \pm 0.00012\ (\text{stat}) \pm 0.00023 (\text{syst})$$

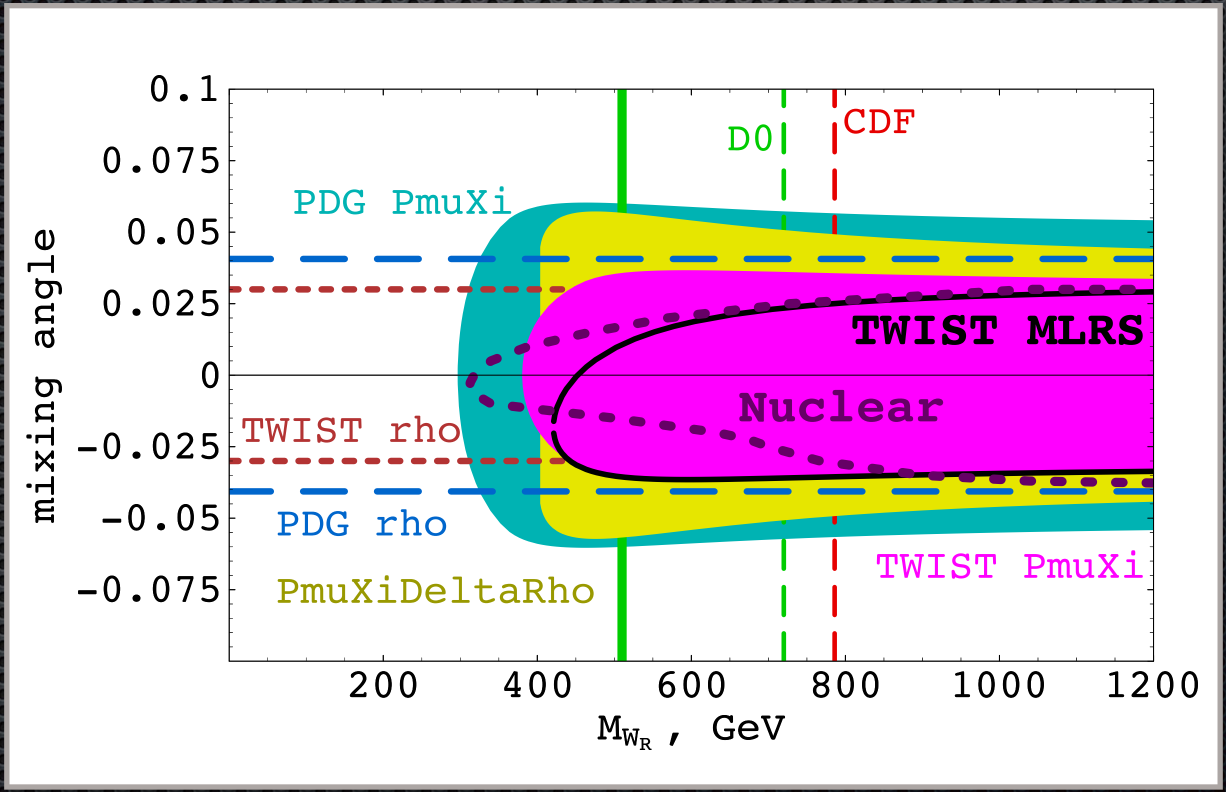
$$\delta = 0.75049 \pm 0.00021 (\text{stat}) \pm 0.00027 (\text{syst})$$

$$P_\mu \zeta = 1.00084 \pm 0.00029 (\text{stat}) \pm^{+0.00165}_{-0.00063} (\text{syst})$$

J.F. Bueno et al., Phys. Rev. D 84, 032005 (2011)

A. Hillairet et al., Phys. Rev. D 85, 092013 (2012)

- sample LR symmetric model



adapted from Bayes et al. 10.1103/PhysRevLett.106.041804

Probing for New Interactions

- We can generically write new physics effects as

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{M_W^2}(1+\Delta r(m_H, M_W, m_t \ldots))$$

where g is the electroweak gauge coupling and Δr is a function of old and new physics (at appropriate q^2)

- Example: we can extract $sin^2\theta_W$

NuTeV (neutrinos, but I did this…)

$$\sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F M_W^2}\left(1+\Delta r(m_H, M_W, m_t, \ldots)\right)$$

and predict m_t and m_H! (way before their discovery)

Use to look for new physics

- Recall:

$$\frac{1}{\tau_\mu} = \frac{G_F m_\mu^5}{192\pi^3}\left(1 + \Delta\Lambda(\text{electron mass}) + \Delta\Lambda(\text{radiative corrections})\right)$$

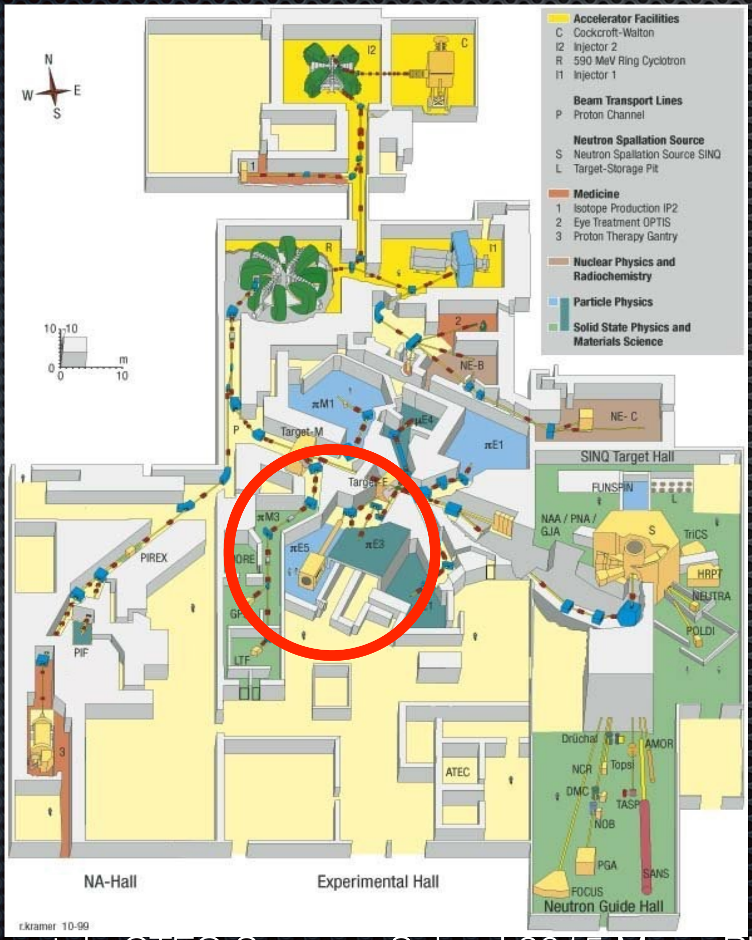
- therefore precise measurements of muon lifetime and G_F let you probe for deviations
- cross-check every way possible: μ^+/μ^-, interactions with other particles….
- next three experiments about this idea

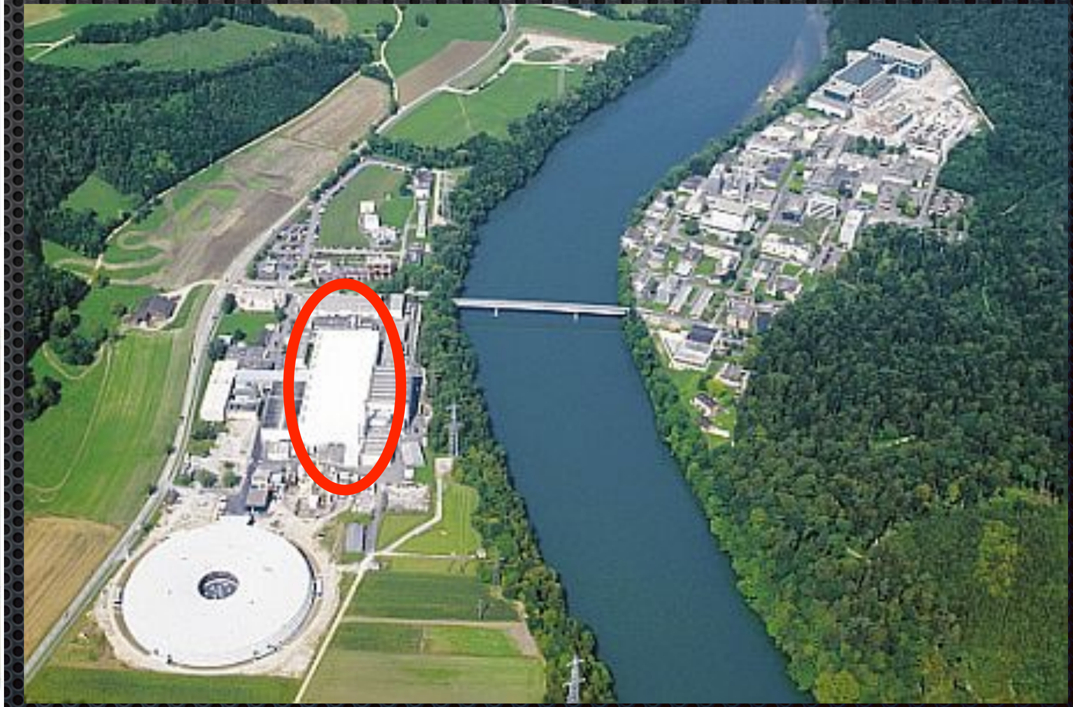
PSI

- New buildings in Switzerland require art

PSI (the other Swiss Lab)

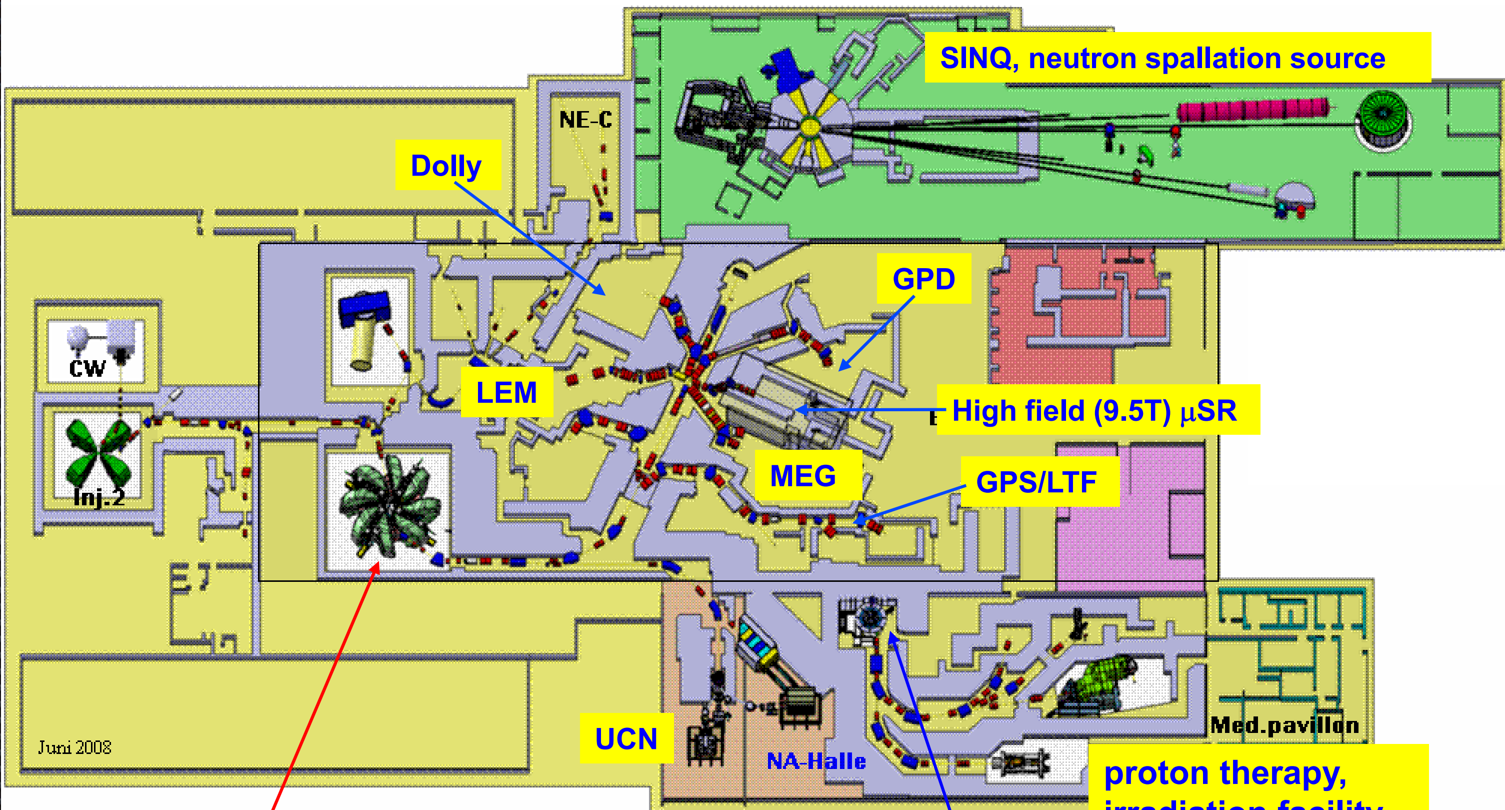
- Home for many of these experiments and currently world's hottest muon beam (but FNAL is working on this!)





More Detail

PSI proton accelerator complex

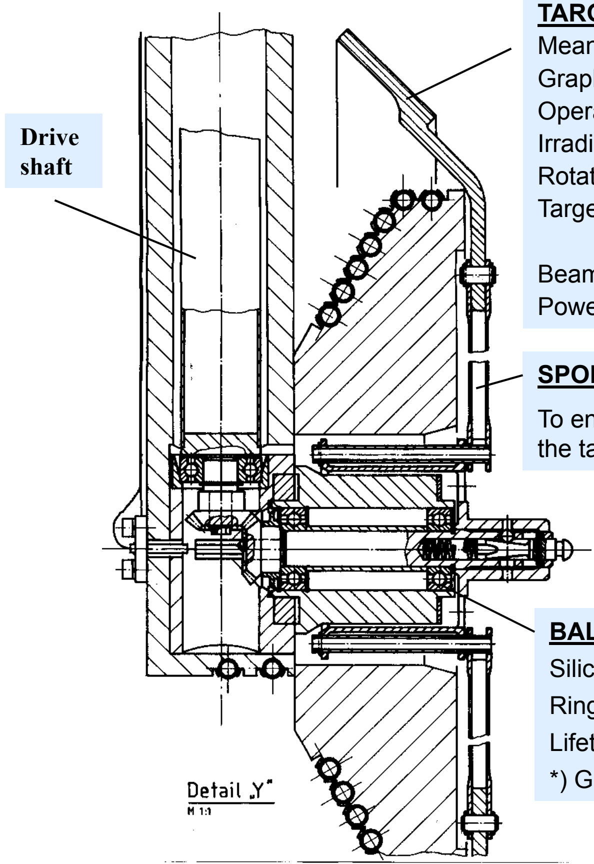


50 MHz proton cyclotron, 2.2 mA, 590 MeV, 1.3 MW beam power (2.4 mA, 1.4 MW test operation)

Comet cyclotron (superconducting), 250 MeV, 500 nA, 72.8 MHz

Rotating Target

Target-E design



TARGET CONE
Mean diameter: 450 mm
Graphite density: 1.8 g/cm^3
Operating Temperature: 1700 K
Irradiation damage rate: 0.1 dpa/Ah
Rotational Speed: 1 Turn/s
Target thickness: 60 / 40 mm
10 / 7 g/cm^2
Beam loss: 18 / 12 %
Power deposition: 30 / 20 kW/mA

SPOKES

To enable the thermal expansion of the target cone

BALL BEARINGS *)

Silicon nitride balls

Rings and cage silver coated

Lifetime 2 y

*) GMN, Nürnberg, Germany

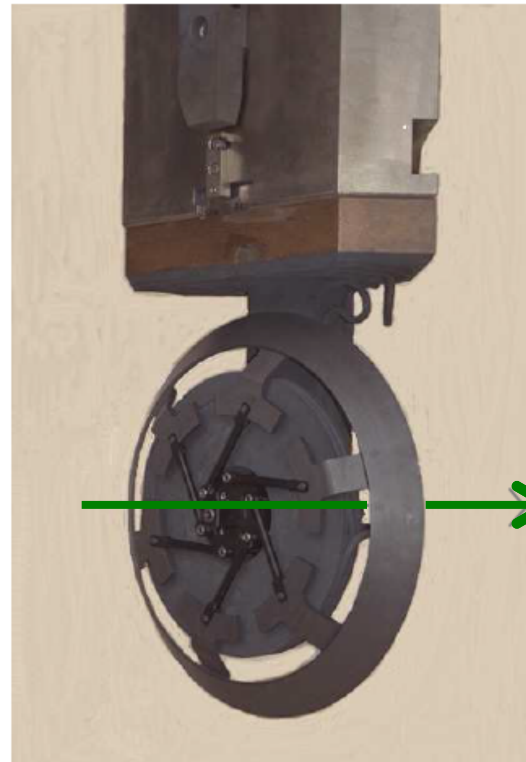


TABLE 1. Some Parameters For The Targets

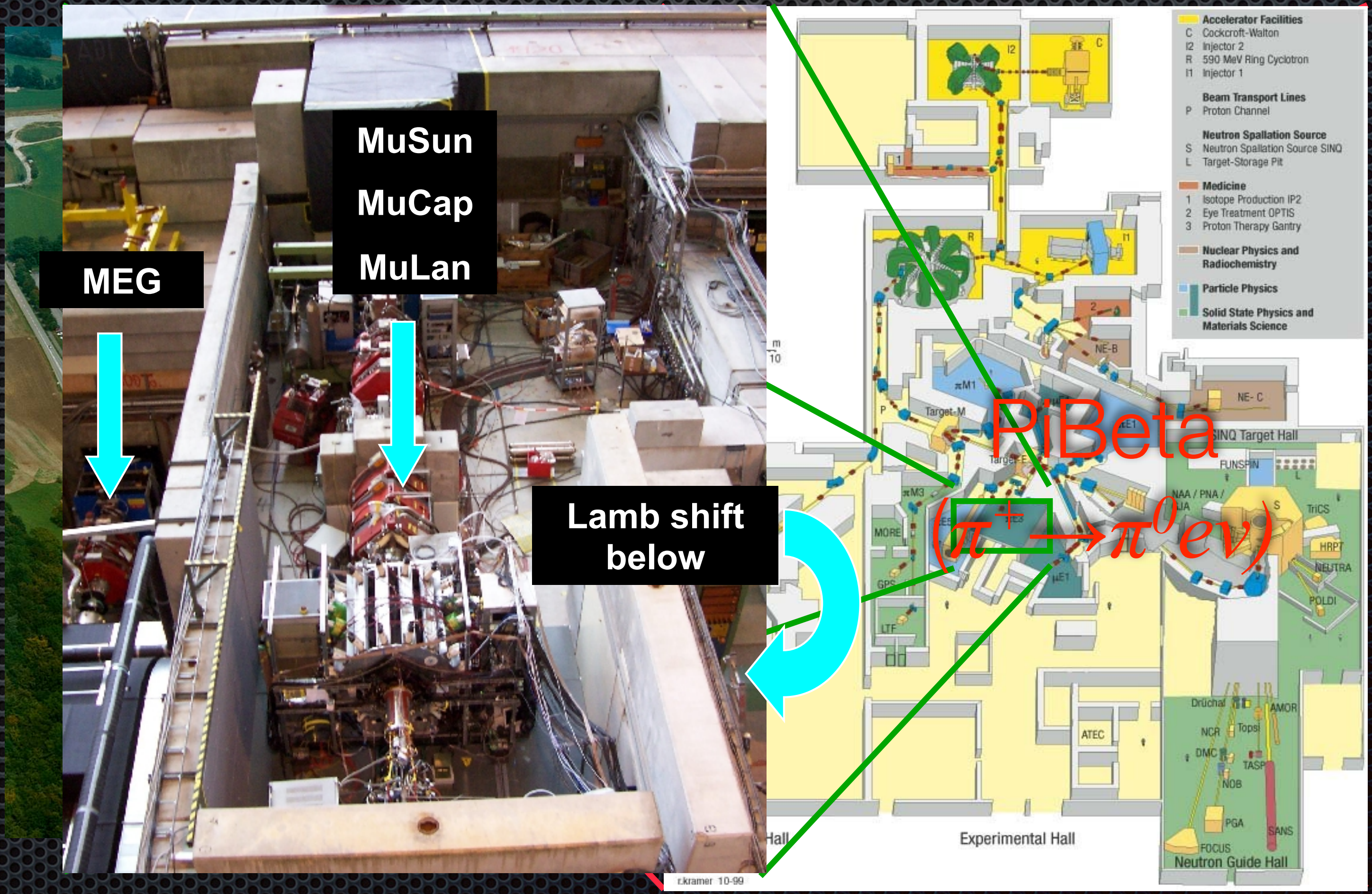
Meson Production Target	M	E
Mean Diameter (mm)	320	450
Target Length (mm)	5.2	60
Target Width (mm)	20	6
Graphite Density (g/cm^3)	1.8	1.8
Proton Beam Losses (%)	1.6	18
Power Deposition (KW/mA)	2.4	30
Irradiation Damage Rate (dpa/Ah)	0.11	0.1
Operating Temperature (K)	1100	1700
Rotational Speed (Turns/s)	1	1

Some Experimental Details

- At PSI: 1.3 MW 590 MeV p, 20 nsec rep rate: 2 μA of μ

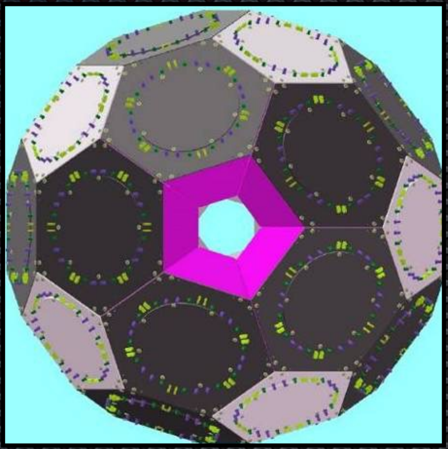
we'll talk about MEG

we'll talk about Lamb shift expt and proton radius

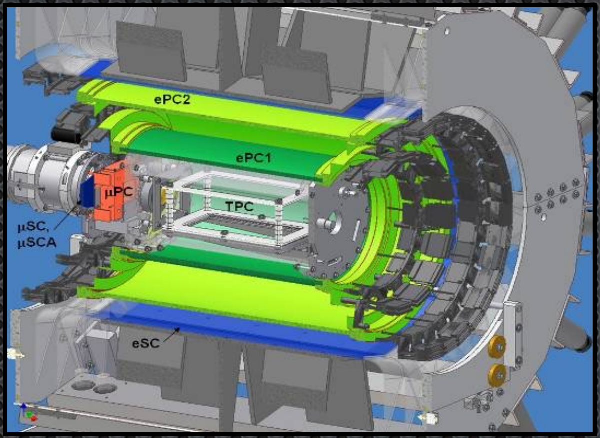


Precision Muon Physics

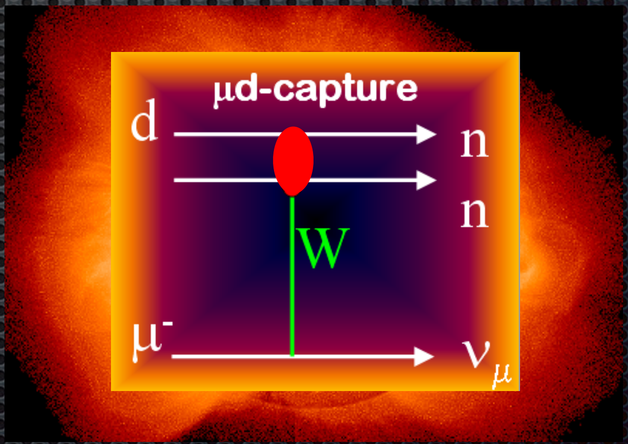
Fermi Constant
MuLan



QCD Symmetries
MuCap



"Calibrating the Sun"
MuSun



much of this section stolen from Hertzog, Kammel, Winter

Relationships:

- MuLan: stopped muon beam measuring μ^+ lifetime
- MuCap: captured muon beam capture on p
  - use precisely measured μ^+ lifetime from MuLan
- MuSun captured muon beam capture on pp

Principle

- Do μ^+ and μ^- have the same lifetime?
  - free muons have to by CPT; but in matter, it matters
  - μ^- can fall into atomic orbit. Then

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{free decay}}} + \frac{1}{\tau_{\text{interaction}}}$$

extract
new physics here:
does the muon
interacts with
nucleus in
unexpected
ways?

we will use this simple idea a lot

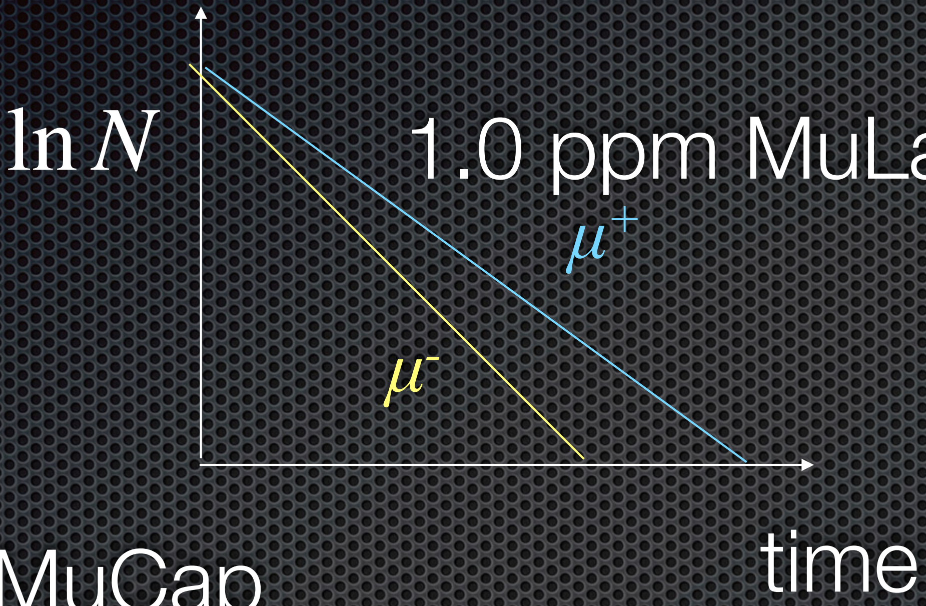
Another difference

- μ^+ can attach to electrons and form "muonium"
  - we can then study muon-electron interaction, long history, and we just don't have time. This is gorgeous physics. (if we have time tomorrow)
  - but they're not captured, and muonium formation is rare, treat μ^+ as free
  - Now use what we learned before: $\frac{1}{\tau_\mu} = \frac{G_F m_\mu^5}{192\pi^3}$

MuLan

not their logo

1.0 ppm MuLan



15 ppm MuCap

$$\mu^- + p \to n + \nu_\mu$$

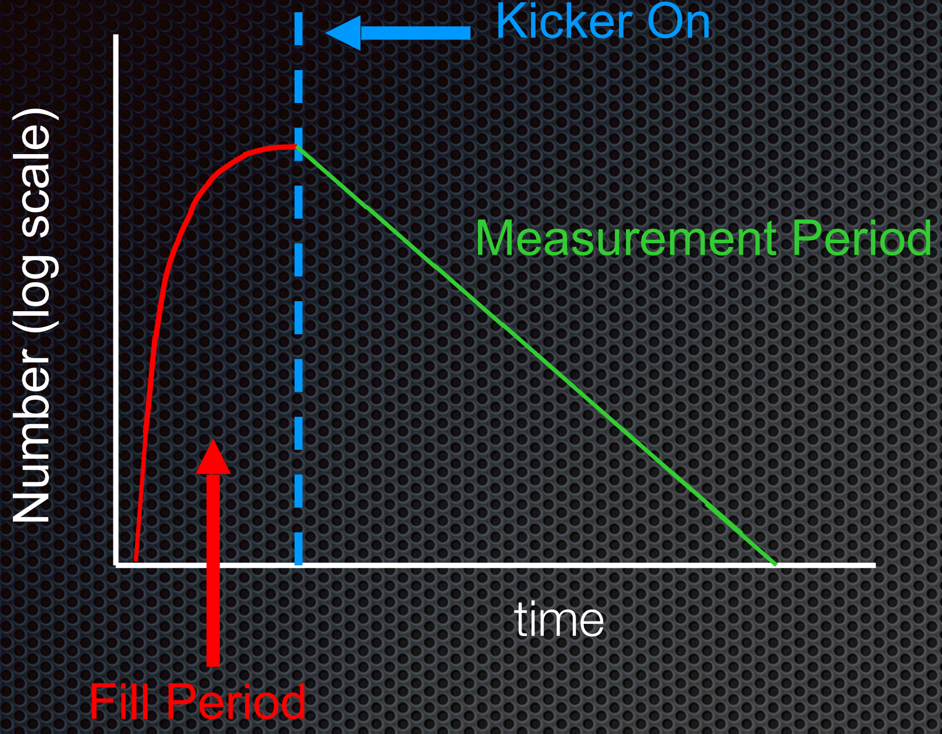
capture rate and properties inferred from difference

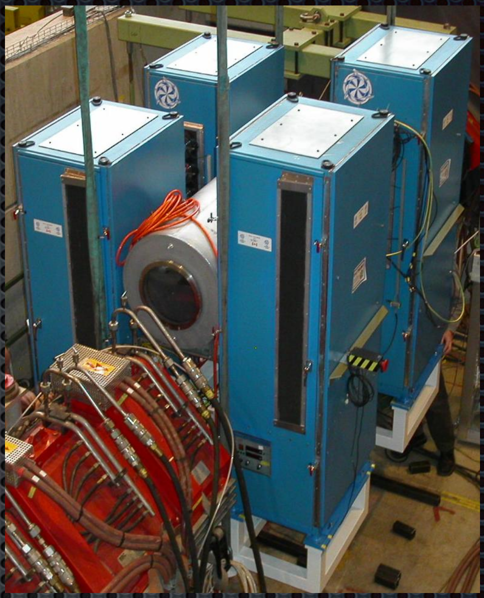
$$\Delta\tau_{\mu^+-\mu^-} \simeq 0.16\%$$

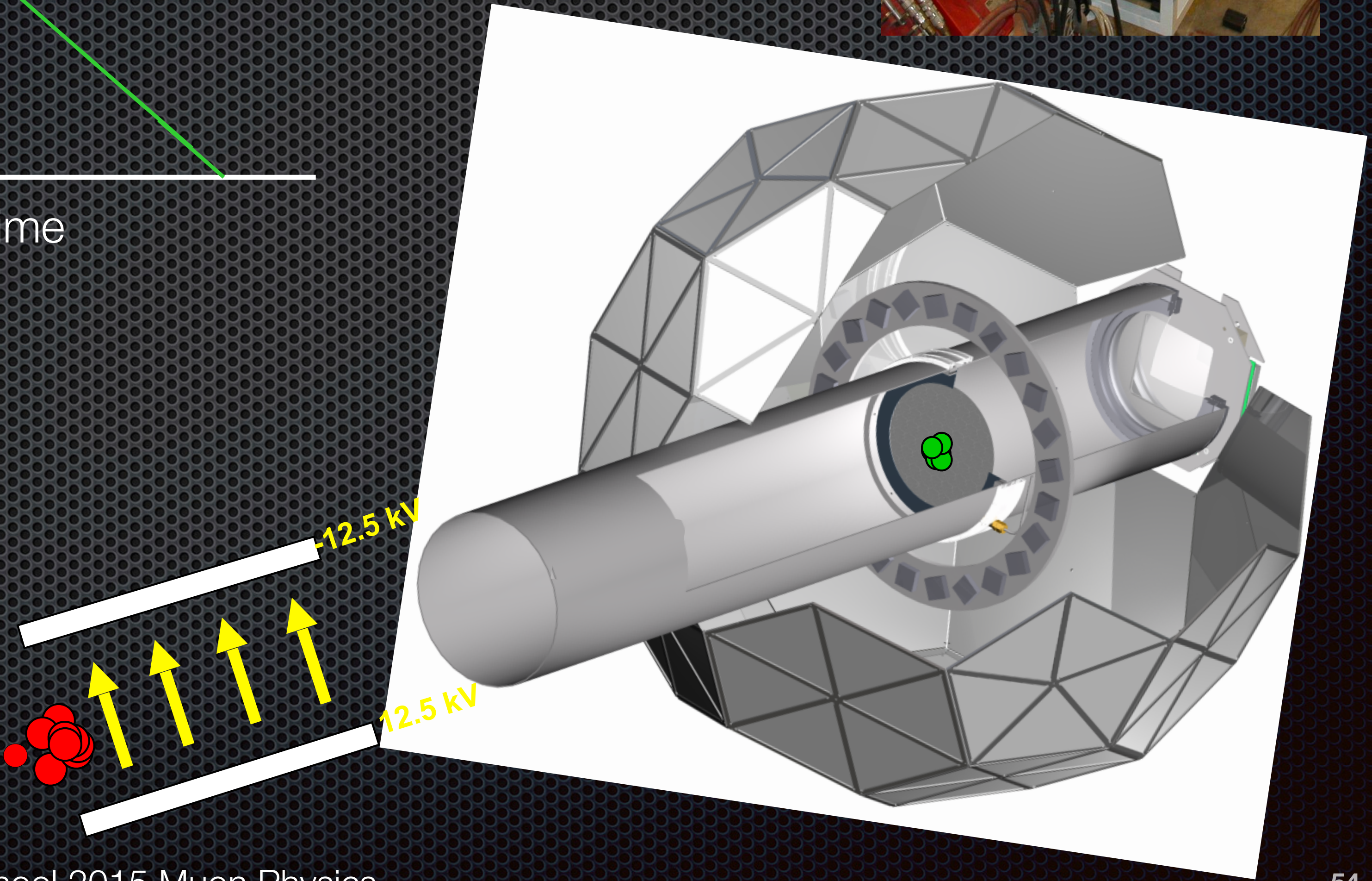
and using lifetime from before, infer capture rate and check $\mu^- p$ interactions:

$$\frac{1}{\tau_{\text{singlet state}}} = \frac{1}{\tau(\mu^-)} - \frac{1}{\tau(\mu^+)};$$ this tells us the pseudoscalar coupling

Experimental Concept

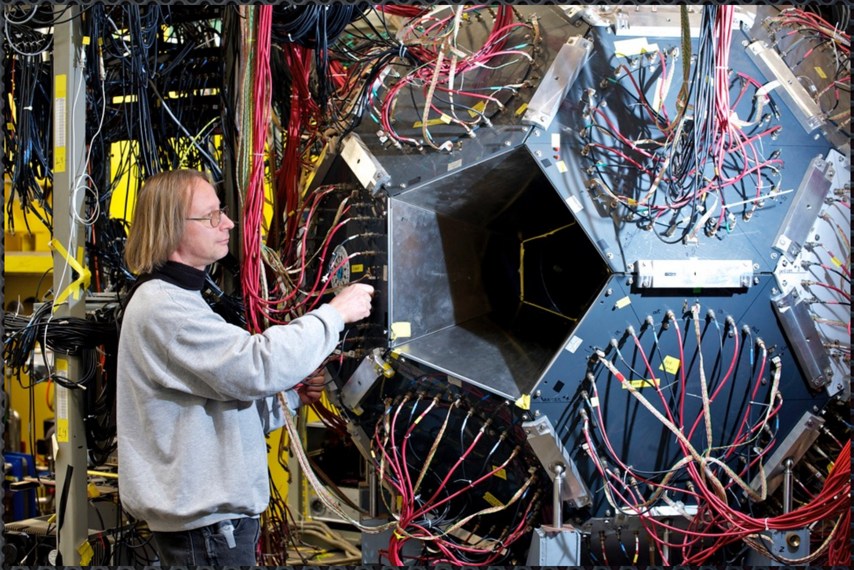


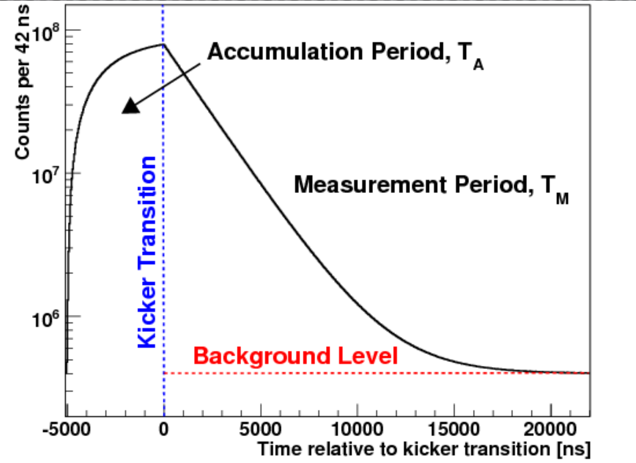


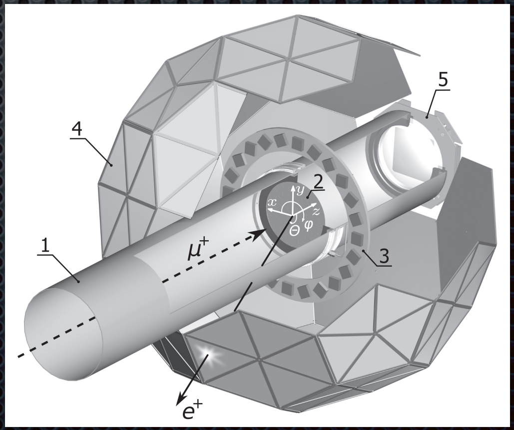


Experimental Considerations

- Gain Stability with time
- Control of pileup: if efficiency varies with intensity, will distort lifetime measurement
- Spin: dephasing will change angular distribution, changing acceptance







Results

PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)

- Skipping over details, for which my friends will get me later

Effect	2006	2007	Comment
Kicker extinction stability	0.20	0.07	Voltage measurements of plates
Upstream muon stops	0.10	0.10	Upper limit from measurements
Overall gain stability:	0.25	0.25	MPV vs time in fill; includes:
Timing stability	0.12	0.12	Laser with external reference ctr.
Pileup correction	0.20	0.20	Extrapolation to zero ADT
Residual polarization	0.10	0.20	Long relax; quartz spin cancelation
Clock stability	0.03	0.03	Calibration and measurement
Total Systematic	**0.42**	**0.42**	**Highly correlated for 2006/2007**
Total Statistical	**1.14**	**1.68**	

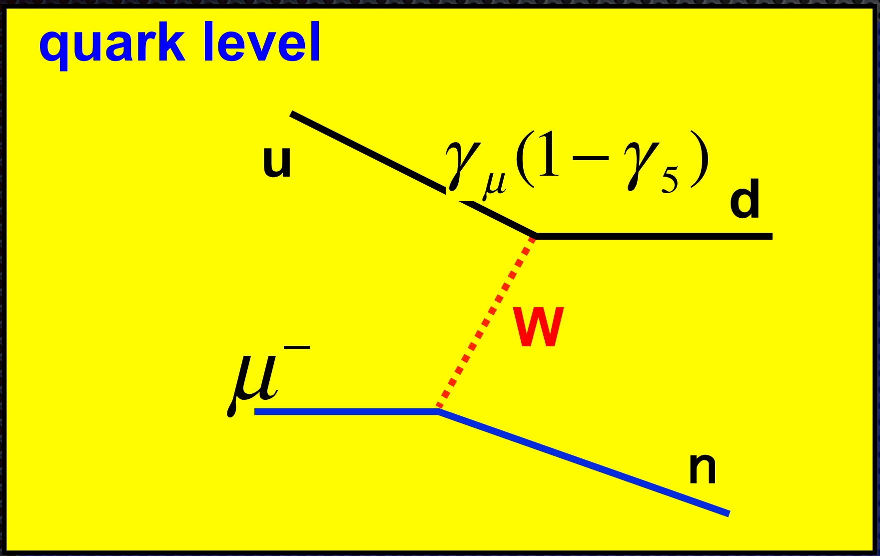
$$G_F = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2}(0.5\mathrm{ppm})$$

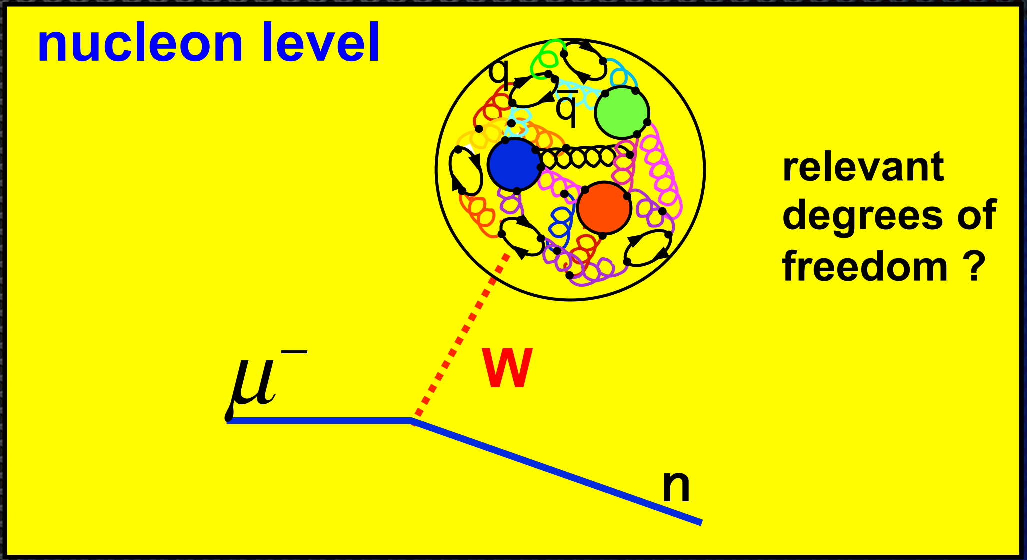
$$\tau = 2196980.3 \pm 2.2\ \mathrm{psec}\ (1.0\ \mathrm{ppm})$$

the most precise nuclear or atomic lifetime ever measured

Muon Capture on the Proton

- MuCap



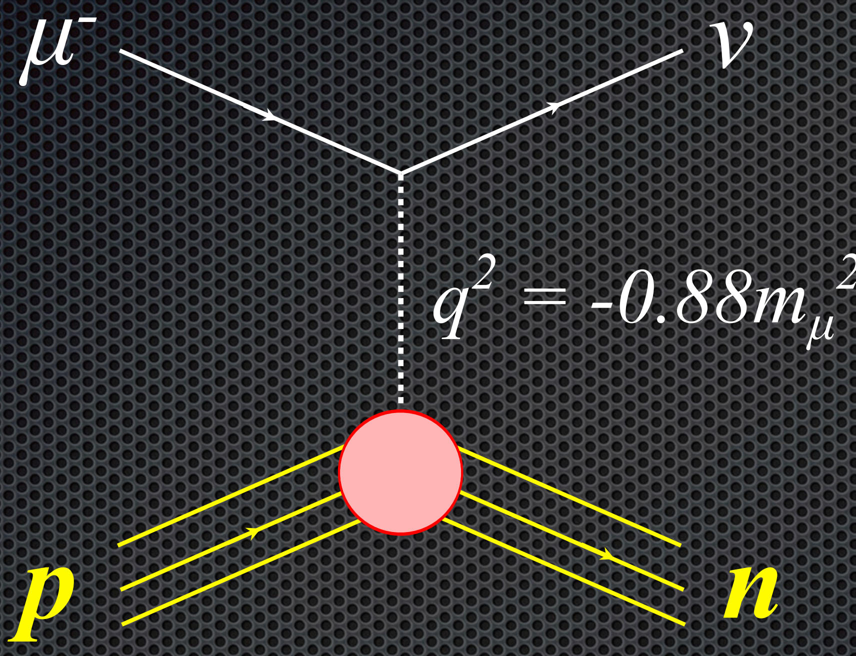


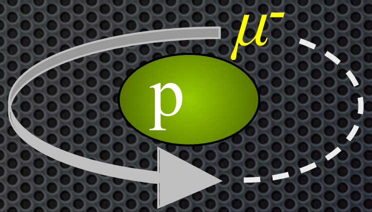
$$\frac{\Delta\Lambda_S}{\Lambda_S} = 1\% \quad \Rightarrow \quad \frac{\Delta g_P}{g_P} \approx 6.1\%$$

singlet capture rate

Nucleon form factors

$$\mu^- + \boldsymbol{p} \rightarrow \boldsymbol{n} + \nu$$





Observable: Singlet capture rate Λ_S

$$M \propto G_F V_{ud} \times \psi_\nu (1-\gamma_5) \psi_\mu \times \psi_n \left(V^\alpha - A^\alpha\right) \psi_p$$

Quarks In Nuclei

- Not just V-A anymore (leaving out a few terms)

$$J^\alpha = \bar{u}_n \left(g_V \gamma^\alpha + \frac{i g_M}{2 m_N} \sigma^{\alpha \nu} q_\nu - \left(g_A \gamma^\alpha \gamma_5 + \frac{g_p}{m_\mu} q^\alpha \gamma_5 \right) \right) u_p$$

$$V \qquad - \qquad A$$

- CVC and PCAC:
  - if $\partial_\alpha A^\alpha$ explicitly broken leads to pion field

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois

(Received February 23, 1960)

2008 Nobel

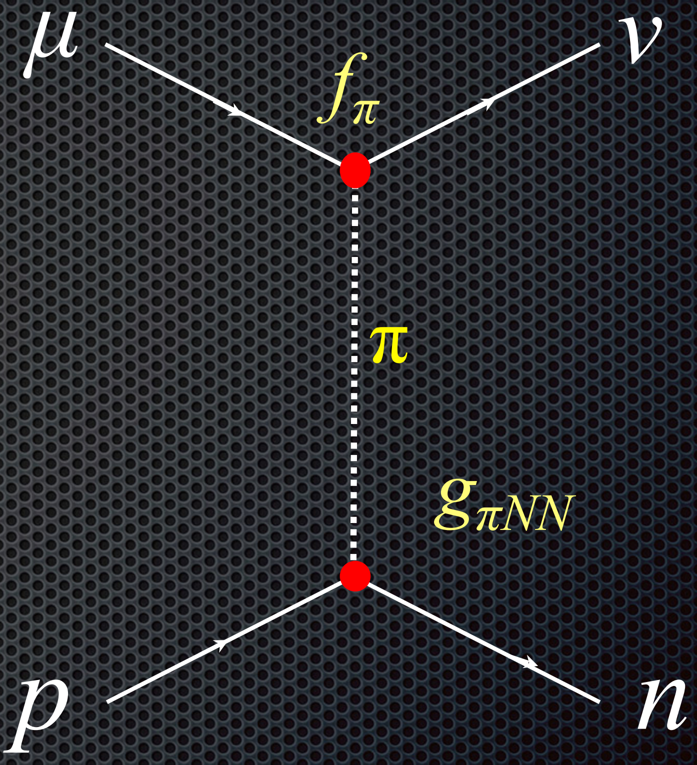
Pseudoscalar form factor g_P

$$g_p(q^2) = -\frac{2m_N m_\mu g_A(q^2=0)}{q^2 - m_\pi^2}$$

PCAC pole term

(Adler, Dothan, Wolfenstein)

$$g_P = 8.26 \pm 0.23$$



NLO (ChPT)

Bernard, Kaiser, Meissner
PR D50, 6899 (1994)

What's Important:

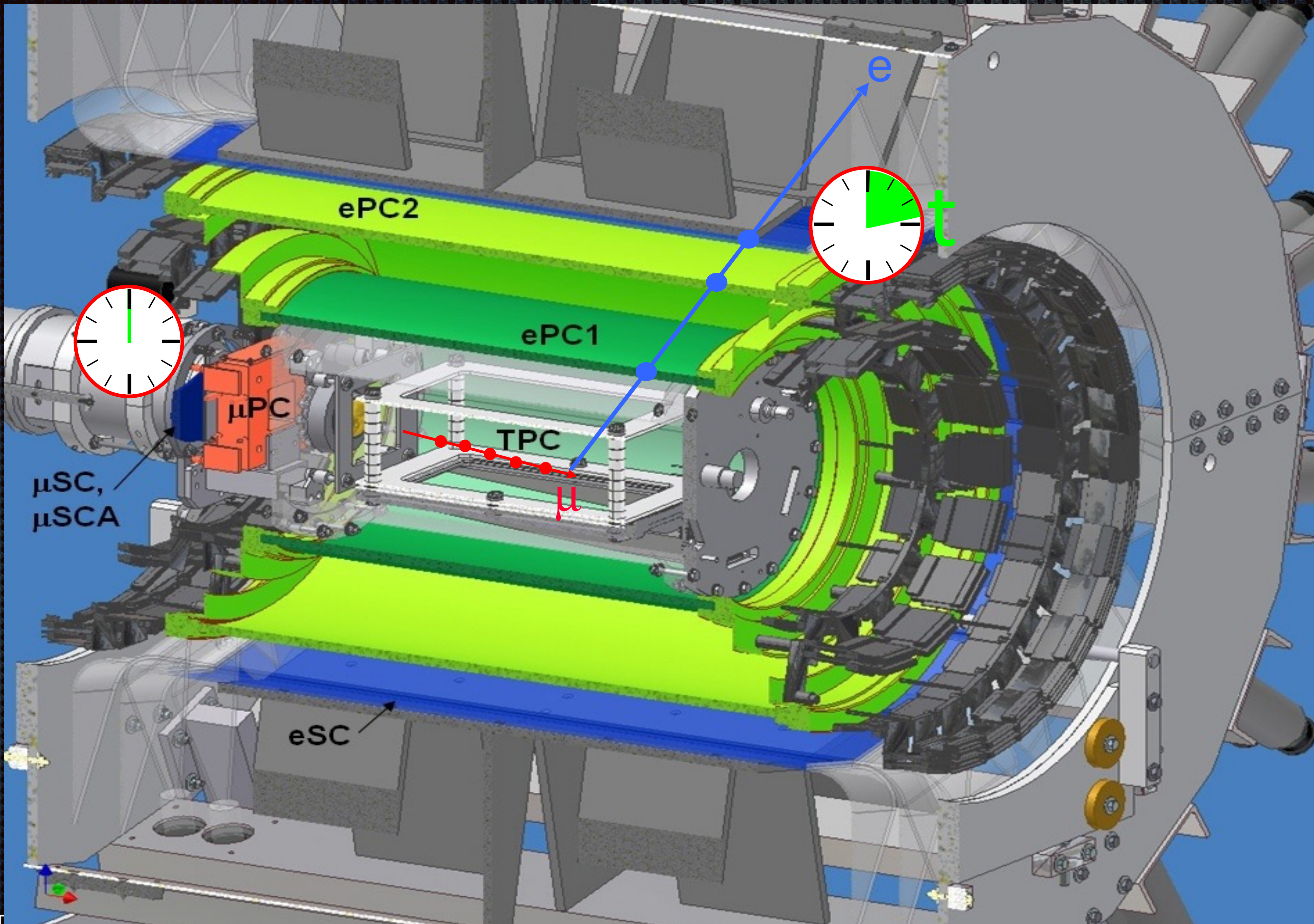
- Modern QCD connects these quark/nucleon views
- solid QCD prediction via ChPT (2-3% level)
- basic test of chiral symmetries and low energy QCD

Recent review: P. Kammel and K. Kubodera, Annu. Rev. Nucl. Part. Sci. 60 (2010), 327

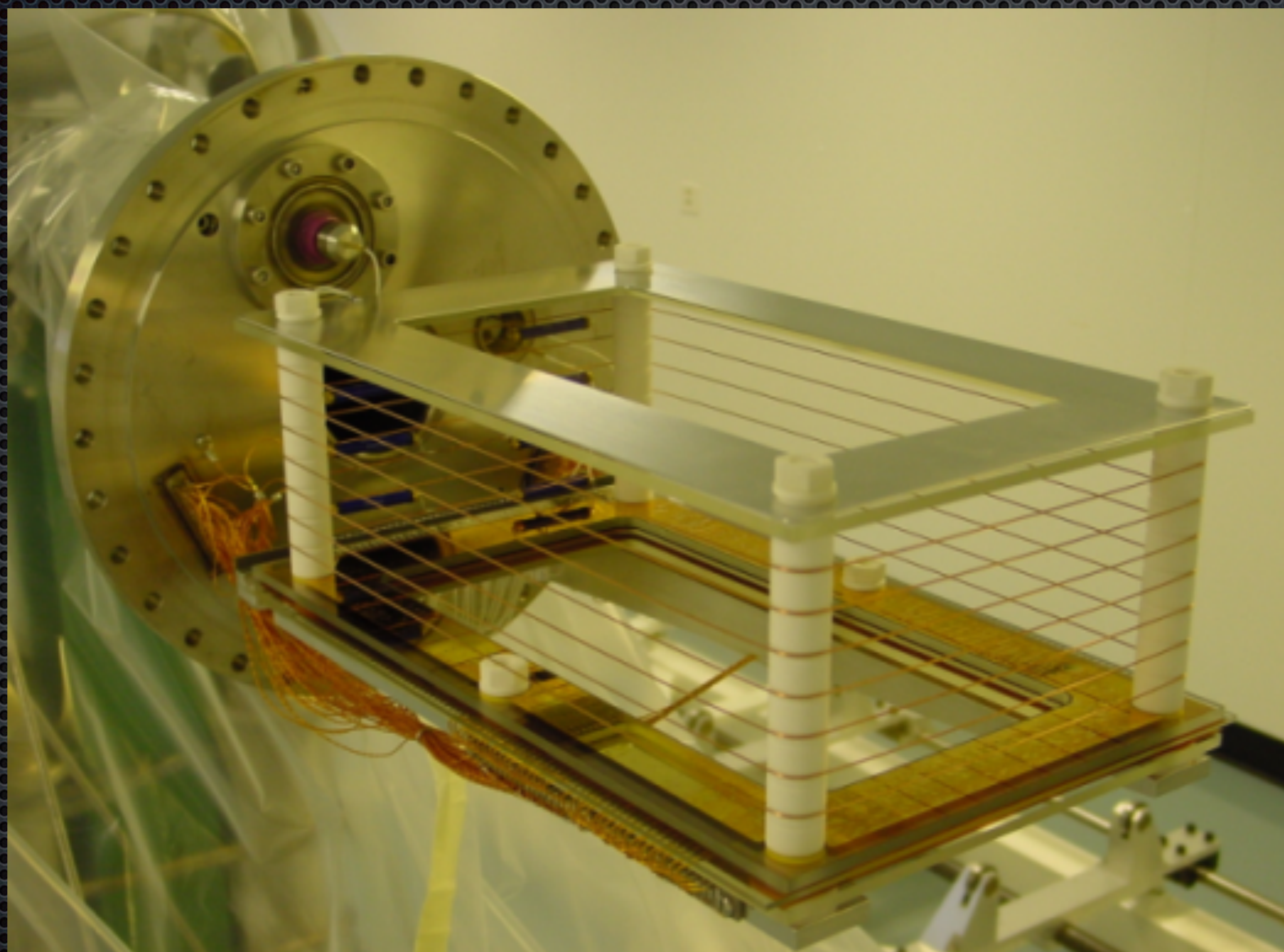
Chiral Symmetries

- Chiral symmetry: left and right-handed parts of Lagrangian transform independently
  - this is $SU(2)_L \times SU(2)_R$
- Gluons spontaneously break this symmetry to isospin, yielding three massless pions (and all baryon masses)
- $SU(2)_L \times SU(2)_R$ is broken anyway because quark masses are not zero
  - pions have mass (pseudo-Goldstone bosons)

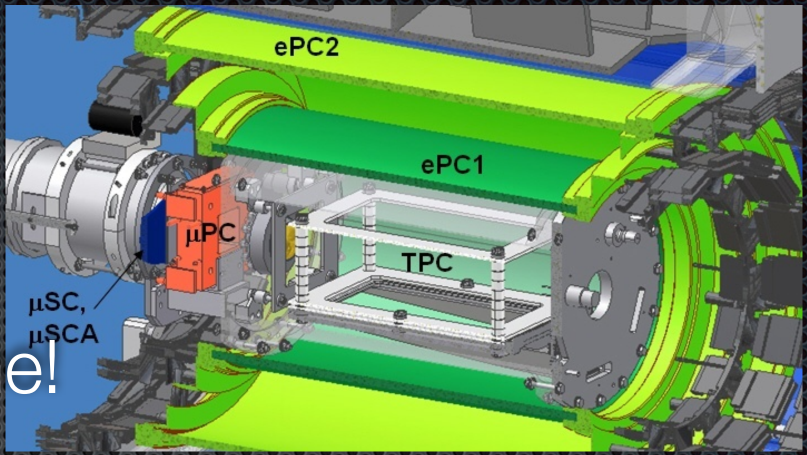
MuCap (at PSI)



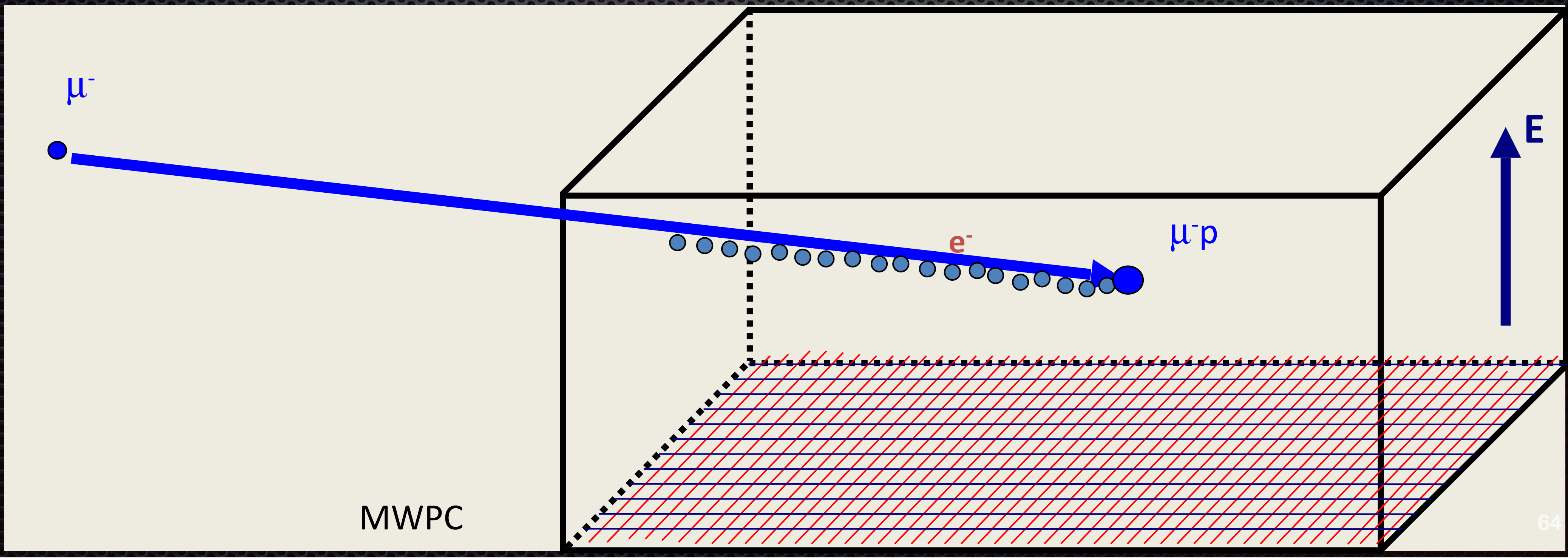
TPC



Experiment



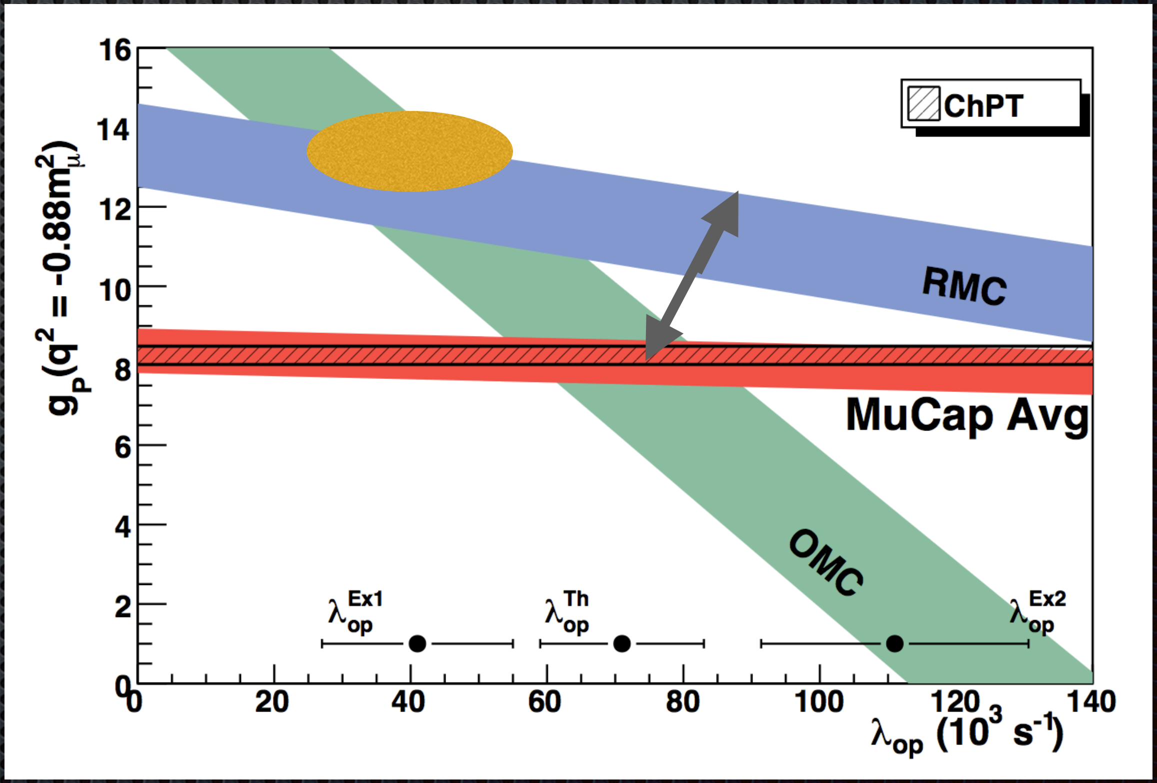
- Stop in pure H_2 gas
  - $pp\mu$ molecules can distort lifetime!
  - impurities < 10 ppb
  - isotopic impurities < 6 ppb
- Image muons stop with TPC
- Measure electrons vs. time (infer lifetime)



Result

- Issues about previous experiments resolved

$$g_p(\mathrm{MuCap}) = 8.06 \pm 0.55$$
$$g_p(\mathrm{theory}) = 8.26 \pm 0.23$$



Compare Lifetimes

- Do We Get Same Lifetime from MuLan, MuCap?
  - make bound state corrections
  - corrections for impurities
  - assume chiral perturbation theory right
    - can check either *CPT* or χ*PT*

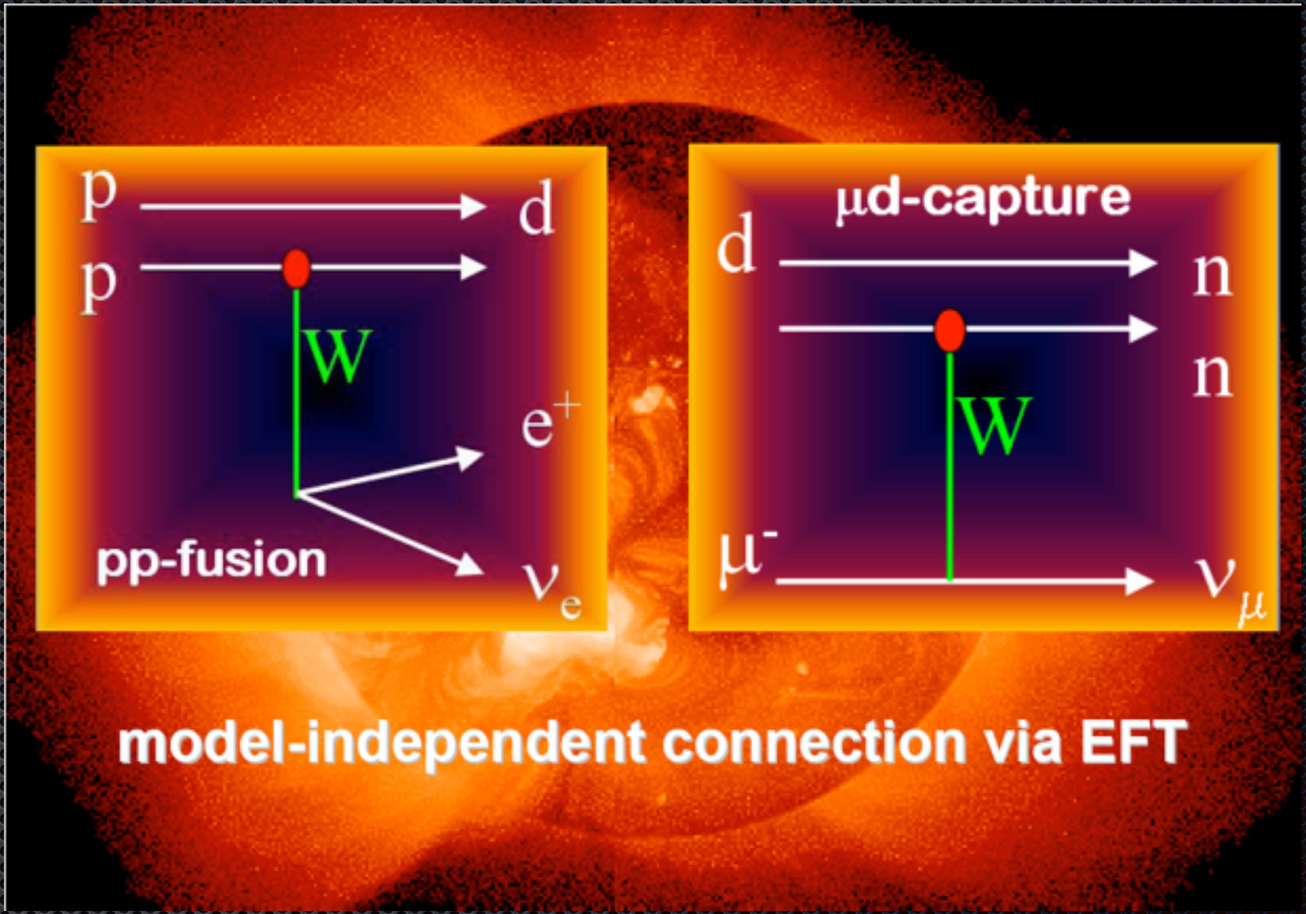
$$\tau(\text{free } \mu^{+}, \text{MuLan}) = 2196980.3 \pm 2.2 \text{ psec}$$

$$\tau(\text{effective } \mu^{-}, \text{MuCap}) = 2196963 \pm 42 \text{ psec}$$

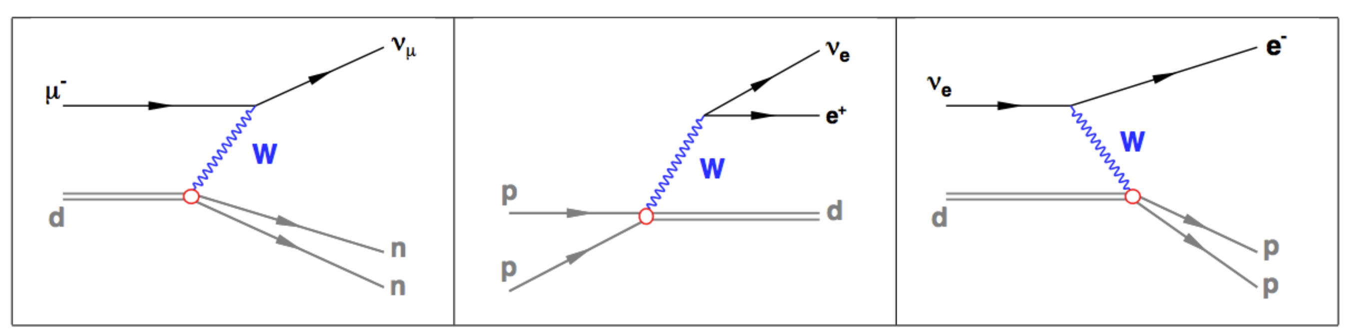
$$\frac{\tau^{+} - \tau^{-}}{\tau_{\text{average}}} = 7 \pm 19 \text{ ppm}$$

MuSun

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



Motivation



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

measure rate Λ_d in $\mu d(\uparrow\downarrow)$ atom to <1.5%

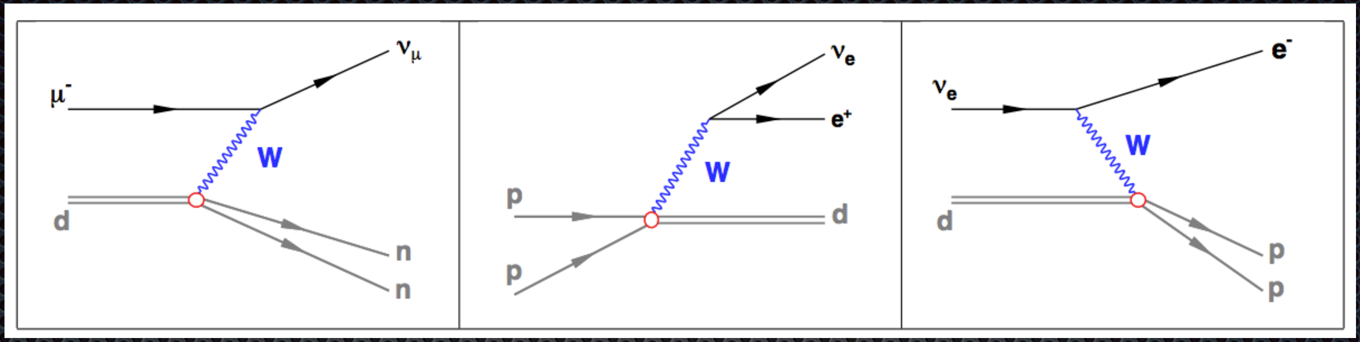
- simplest nuclear weak interaction process with precise theory & experiment
- g_P from MuCap, rigorous QCD based calculations: effective field theory
- MuCap tested one-nucleon amplitudes; MuSun tests two-nucleon.

Λ_d is the capture rate from doublet hyperfine;

$\Lambda_d \approx \lambda_- - \lambda_+$

λ_+ *(like $1/\tau$)* from MuCap

Motivation



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

- close relation to neutrino/astrophysics

solar fusion $\quad pp \rightarrow de\nu_e$

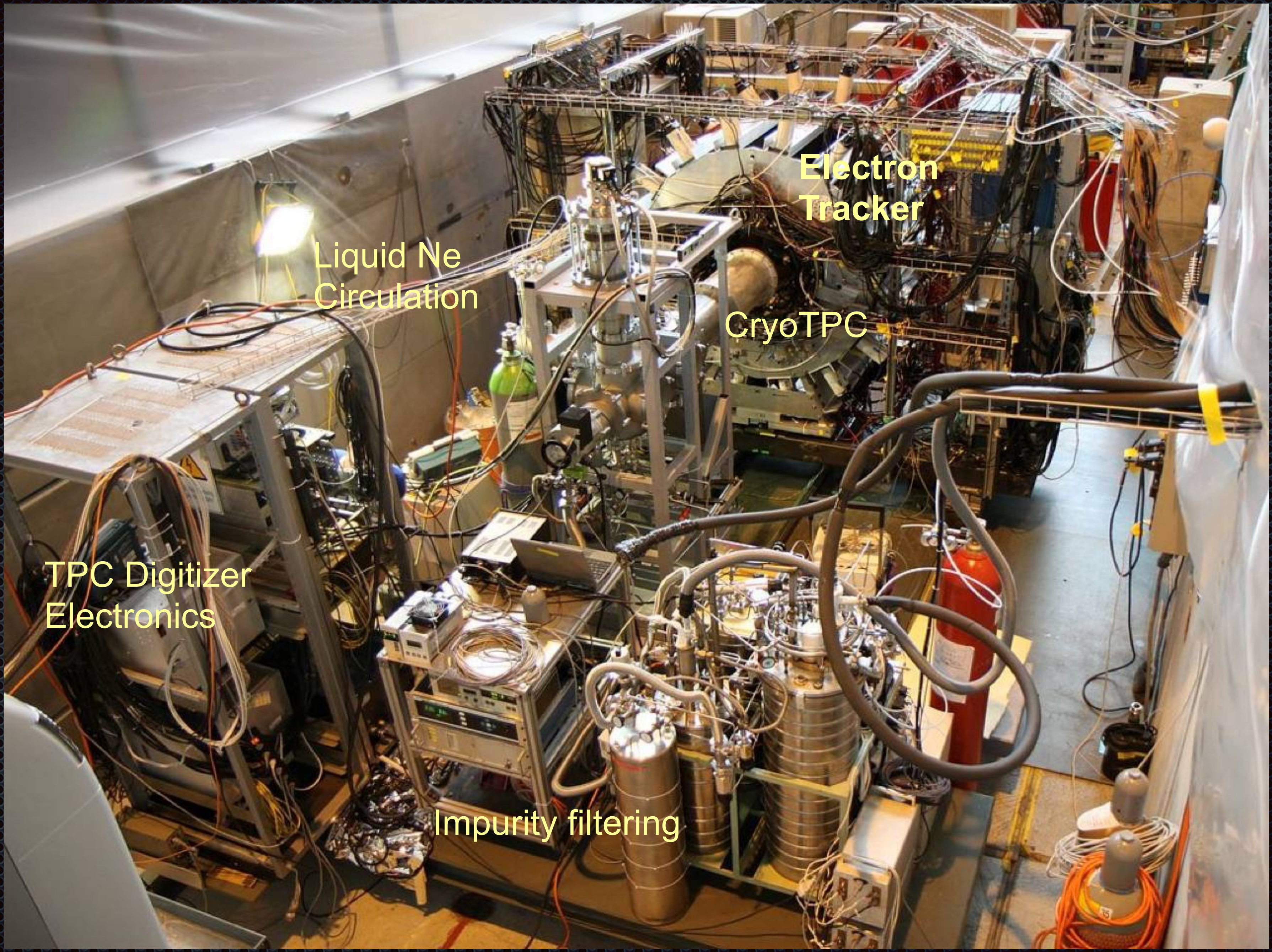
SNO: $\quad \nu_e d \rightarrow p\,p\,e \quad$ (CC)

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

MuCap tested one-nucleon amplitudes; MuSun tests two-nucleon

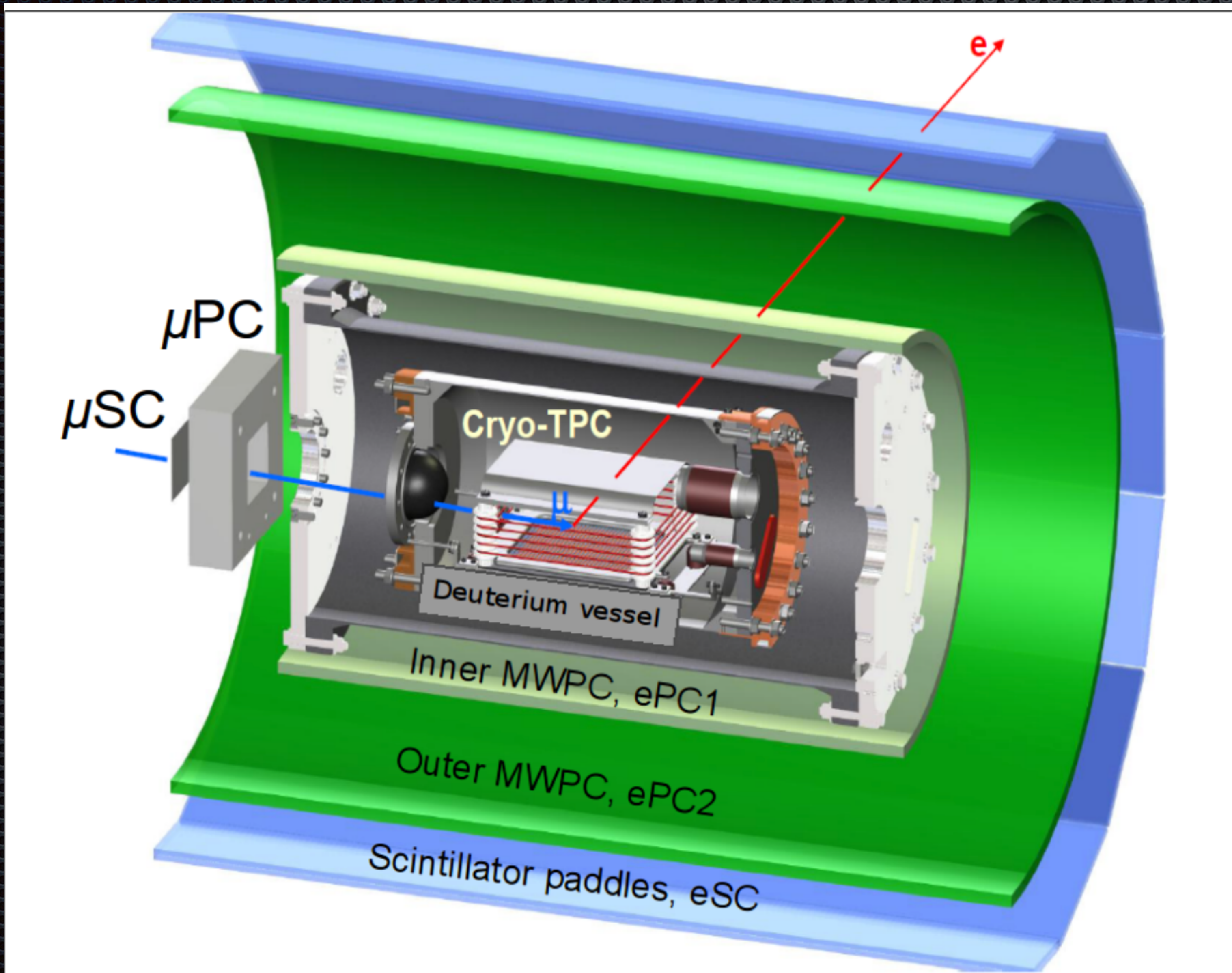
why was SNO NC measurement important?

MuSun Detector System

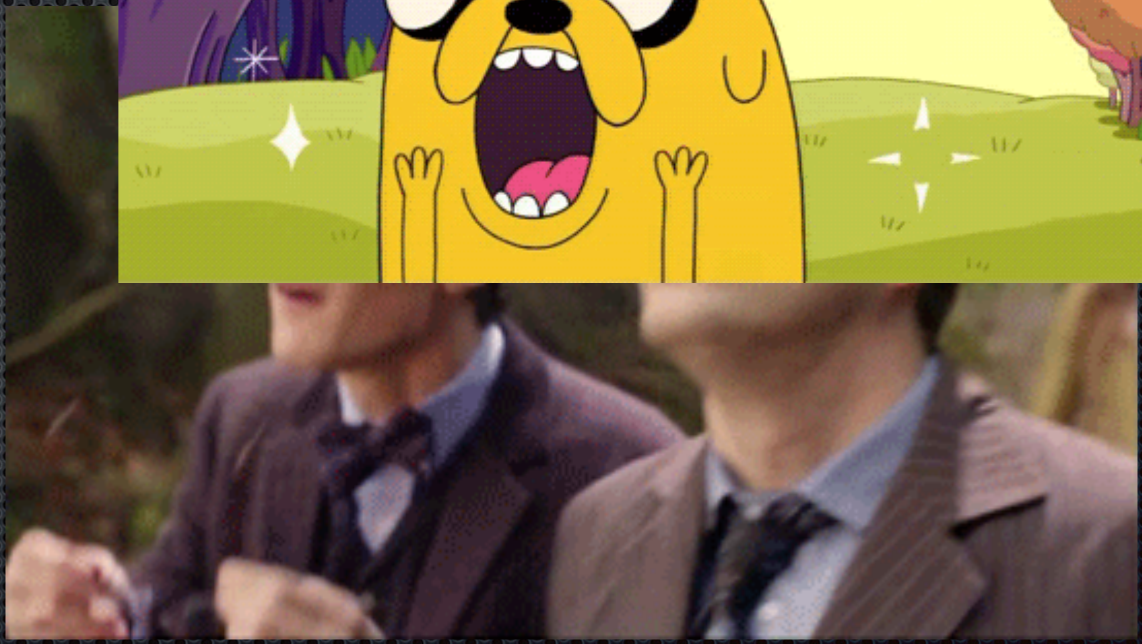


about 40% of data have been taken

In detail:



Begin Long Section Where Things Don't Agree With the Standard Model



when things don't agree
look more closely

Proton Charge Radius

- Many of you saw this in 2010
- What is going on, and what does it have to do with muons?

The Puzzle

- Charge radius of proton: like a “rms” location of charge
  - neutral particles can have a charge radius too, e.g. the K^o made of strange and down quarks. Strange quarks are heavier, hence closer to origin.
- Proton charge radius can be measured:
  - by calculating energy levels
  - by scattering (as for K^o)

Spectroscopy

- Basics: Schrödinger Eqn, 1st year quantum:

$$E_n = -\frac{m_e \alpha^2}{2n^2} \Rightarrow 13.6 \text{ eV aka the Rydberg}$$

- Plus QED corrections (Lamb shift, spin-orbit,…)
- Plus finite size of proton

$$\Delta E_{\text{finite size}} \propto (\text{charge radius} = r_E)^2 / n^3$$

- And we can have both muonic and electronic atoms. Muons are more massive; live closer to nucleus, proton looks $(206)^2$ times “larger”

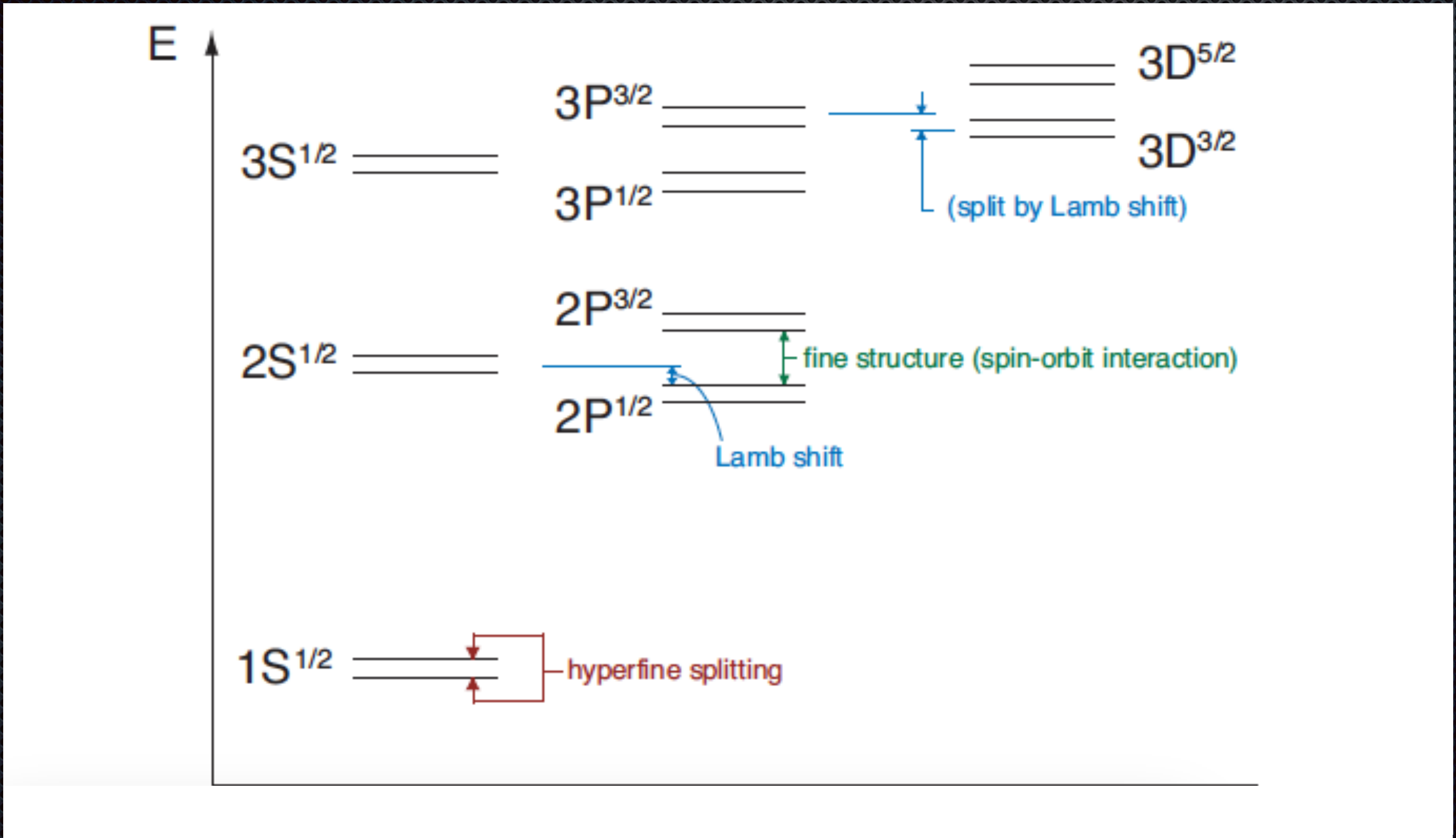
Problem:

Pohl et al., Nature 2010
Antognini et al., Science 2013

- CREMA expt: measured 2s-2p Lamb shift in muonic hydrogen. (Charge Radius Experiment with Muonic Atoms)
- 2s and 2p:
  - Bohr: 2s = 2p, degenerate
  - Dirac: $2s_{1/2} \neq 2p_{3/2}$ but $2s_{1/2} = 2p_{1/2}$
  - One-loop vacuum polarization: $2s_{1/2} \neq 2p_{1/2}$ (Lamb Shift)
- Measured large deviation of Lamb Shift from theory
- Interpret result in terms of proton radius

not to scale

In picture:



http://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-102212-170627

Data

- Beamline at PSI $\pi e5$
- Produces ~600 μ/sec
- KE from 3-6 keV. This is hard because muons are produced in MeV range, and you have to decelerate to keV range within muon lifetime.
- Stop muons in 1mbar H_2 gas in a 20 cm long, 0.5 x 1.5 cm size target (uniform laser illumination)
- Each muon detected separately, with C foils: detect secondary electrons, then TOF
- Trigger pulsed laser on coincidence
- Look for resonance

we'll see this range later

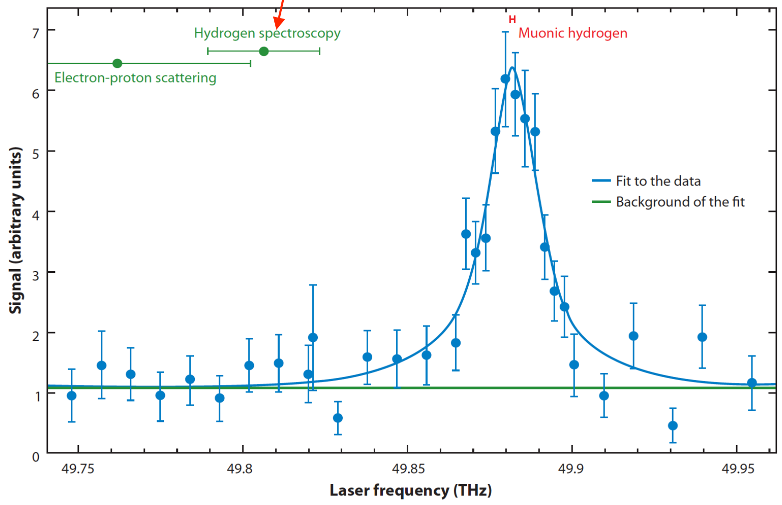


Figure 3

Resonance in muonic hydrogen, together with the positions predicted using the proton radii from elastic electron–proton scattering using pre-2009 world data (15, 17) and the CODATA 2006 value from hydrogen spectroscopy (16).

Beam/ Apparatus

- need to get muons to a few keV
- dE/dx: too much variation (straggling) and angular divergence (scattering)
- 5T solenoid to make small beam (tight gyration radius)
- Solenoid size then puts constraints on laser and stopping volume

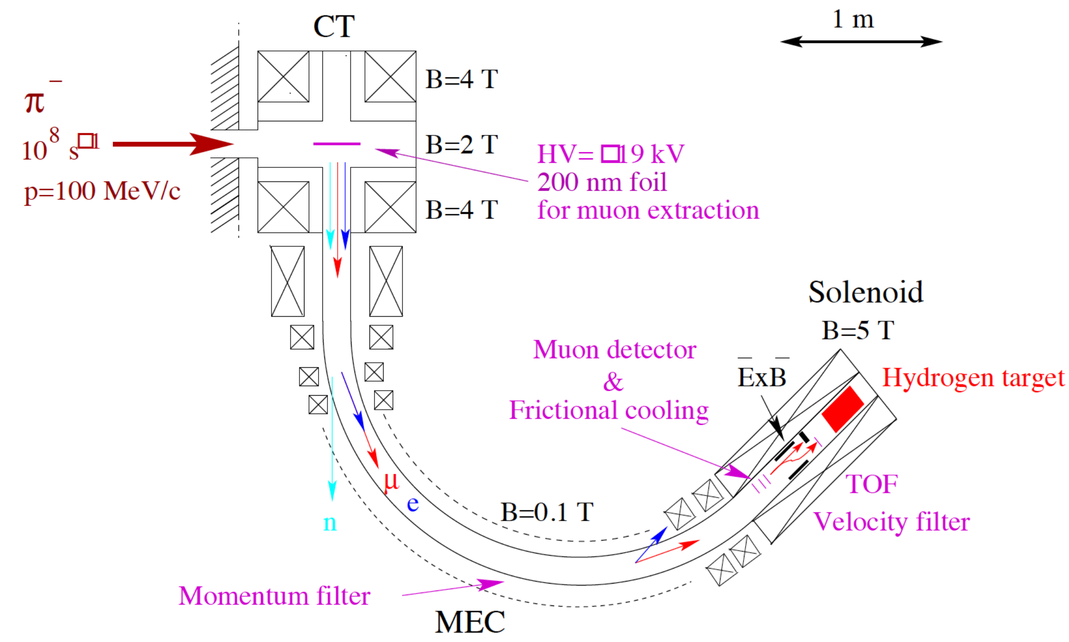
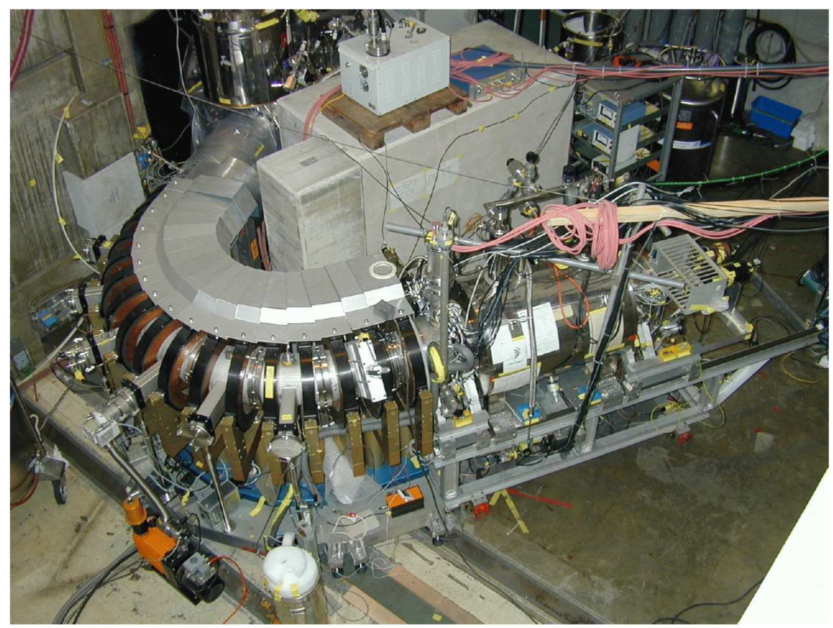


Figure 3.1: Lay–out of the muon beam, with cyclotron trap CT, muon extraction channel MEC and 5 Tesla solenoid.



http://edoc.ub.uni-muenchen.de/5044/1/Antognini_Aldo.pdf

And the result is

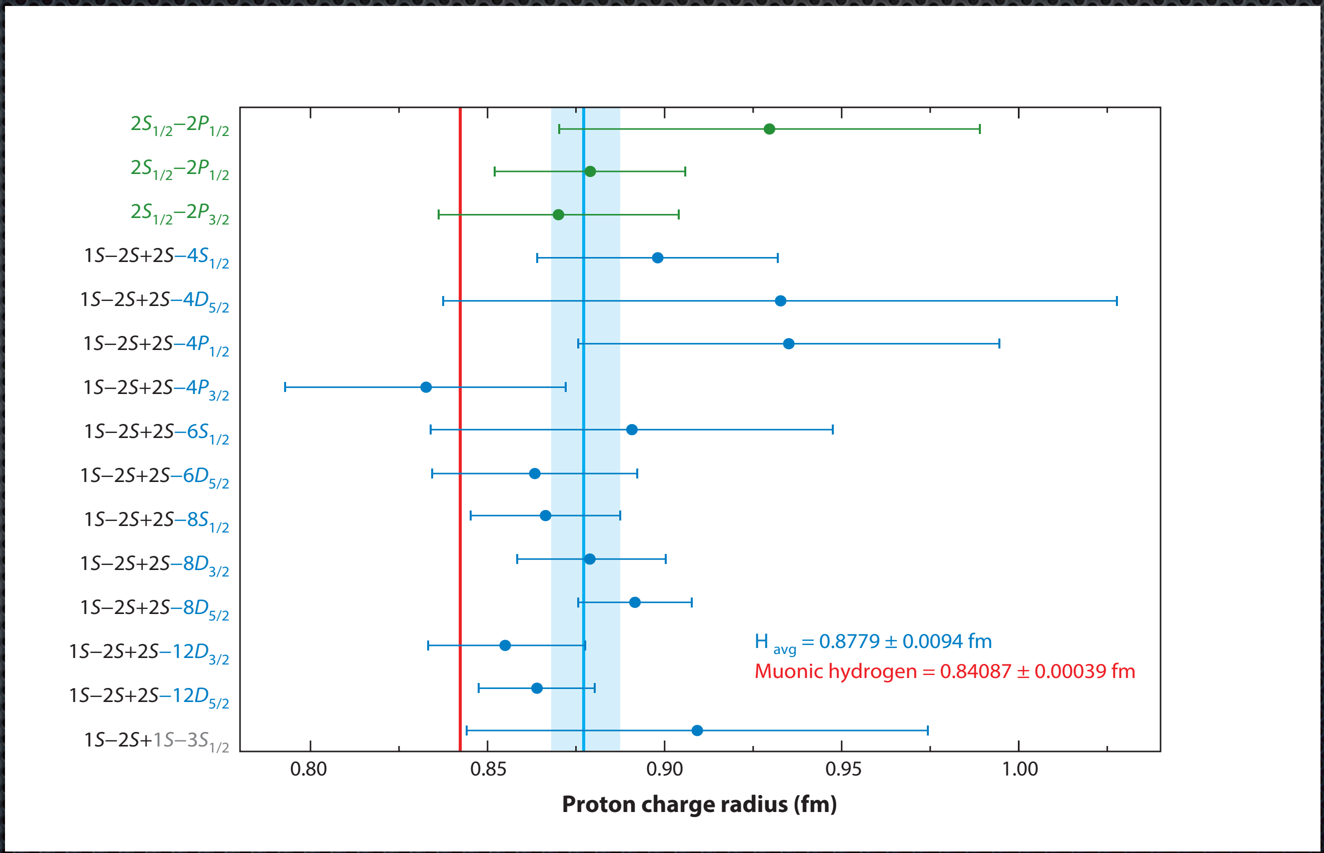
- 7σ discrepancy (people argue about the 7. but not >5)

charge radius	electron	muon
spectroscopy	0.8775(51) fm	0.84087(39) fm

- 7σ discrepancies need independent checks
    - either something is wrong, new physics, or both…

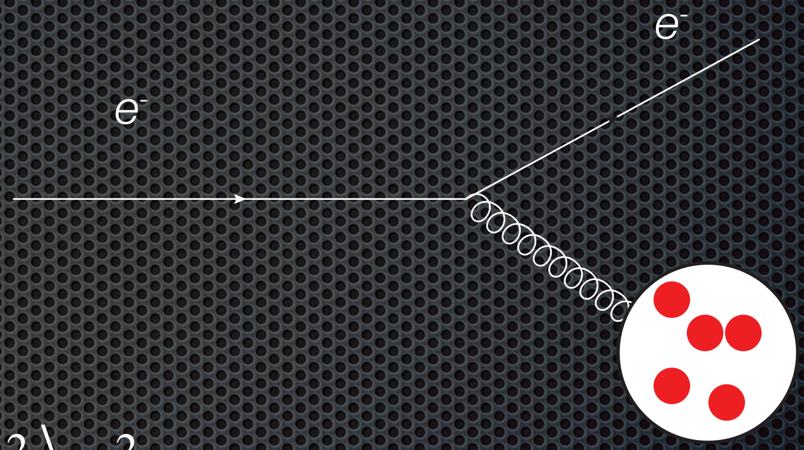
Electron vs. Muon

- Multiple electron measurements, averaged by CODATA
- The 2s-2p values at top are independent of Rydberg



Scattering Method

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{pointlike}} \left|F(q^2)\right|^2$$



$$F(q^2) = \int d^3r\, e^{i\vec{q}\cdot\vec{r}} \rho(r) = 1 - \frac{1}{6}\langle r^2 \rangle q^2 + \ldots$$

- Really define things in terms of J_μ (see Hill at CIPANP2015)

$$r_e^2 \equiv 6 \left.\frac{dG_E(q^2)}{dq^2}\right|_{q^2=0}$$

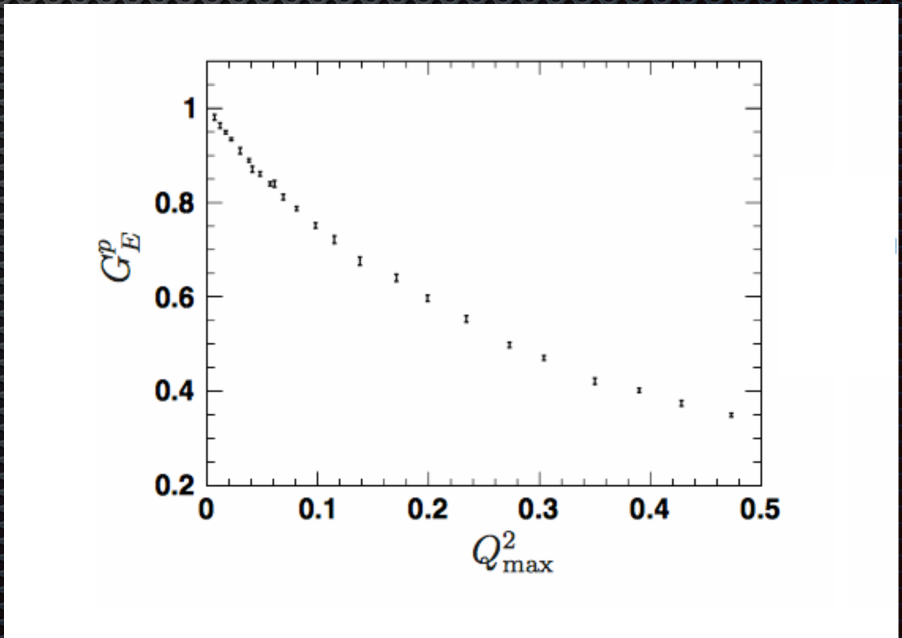
Form Factor Fit to Charge Radius

- Plot is result of integrating up to Q^2_{max}

$$J^{\mu} = \gamma^{\mu} F_1(q^2) + \frac{i}{2m_p}\sigma^{\mu\nu} q_{\nu} F_2(q^2)$$

$$G_E = F_1 + \frac{q^2}{4m_p^2} F_2, \quad G_M = F_1 + F_2$$

$$r_e^2 \equiv 6 \frac{dG_E(q^2)}{dq^2}\bigg|_{q^2=0}$$



Results so far

- Need to measure form factor vs q^2 and extrapolate to q^2=0

charge	electron	muon
spectroscopy	0.8775(51) fm	0.84087(39) fm
scattering	~0.88-0.90 fm	MUSE at PSI; PRad at Jefferson Lab

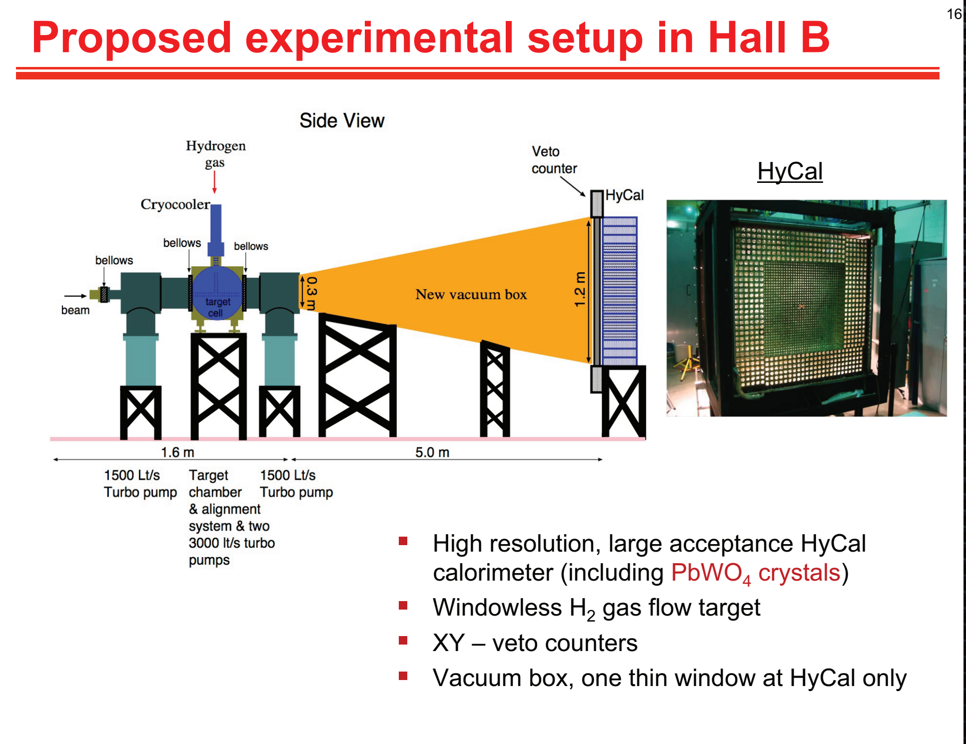
see both Carlson and Hill, CIPANP 2015 for how complicated this really is— but complicated doesn't mean wrong. Stay tuned

Scattering Experiments

- MUSE: simultaneous measurement of μ^+p, μ^-p and e^+p elastic scattering at PSI
  - Q^2 from 0.002 to 0.07 GeV^2
- PRad: elastic e-p cross-sections at Jefferson Lab
  - Q^2 from 0.0002 to 0.02 GeV^2
- Both focusing on low Q^2 where one gets radius

PRad

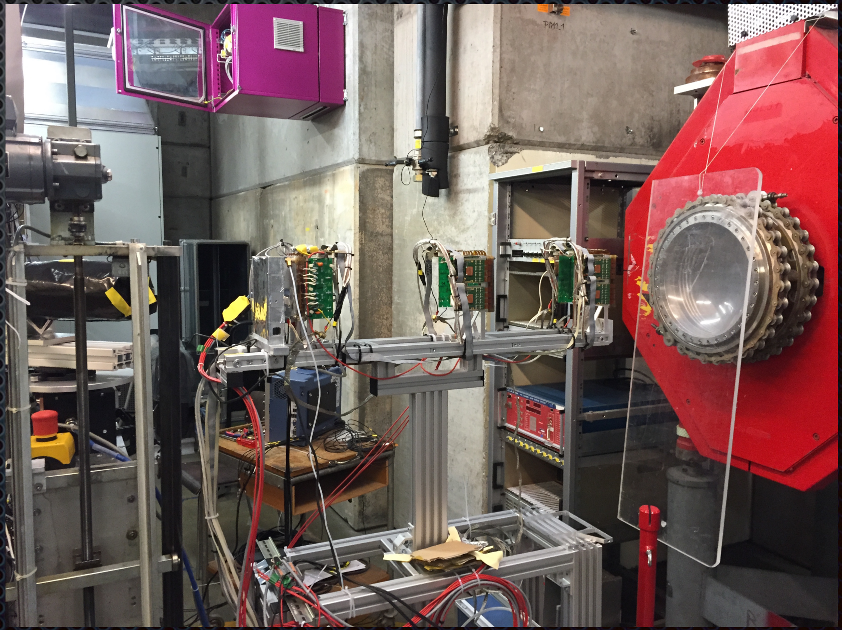
- Get to very low Q^2 with non-magnetic spectrometer, large acceptance; use calorimetry
- Electrons at 1.1 and 2.2 GeV to increase Q^2 range, H_2 target
- Normalize to Møller scattering: $e^- e^- \rightarrow e^- e^-$



(wrt Møller, look up QWeak for parity violation giving WMA)

MUSE at PSI

- More “traditional” scattering experiment, but still ferociously difficult
- 115, 153, 210 MeV mixed π, μ, e beam; timing to reject π events
- 4 cm LH2 target
- Quartz Cerenkov (50 psec for PID)
- Wire Chambers/Scintillators



Possible Resolutions

- Error in scattering experiments:
  - fits, data, uncertainties
- Proton Structure Theory
  - some new effect different between electron, muon
- New Physics
  - lepton non-universality? new force?
    - but lots of constraints

Rydberg and new physics

- Then what is source of experimental mistake in Rydberg determinations?
- New Physics
  - could be related to $g-2$!
  - Rydberg constant is wrong?
  - dark matter
  - ???

Part 2: g-2 and CLFV