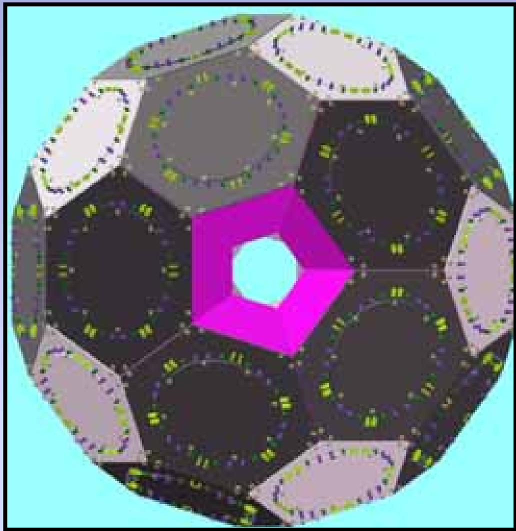
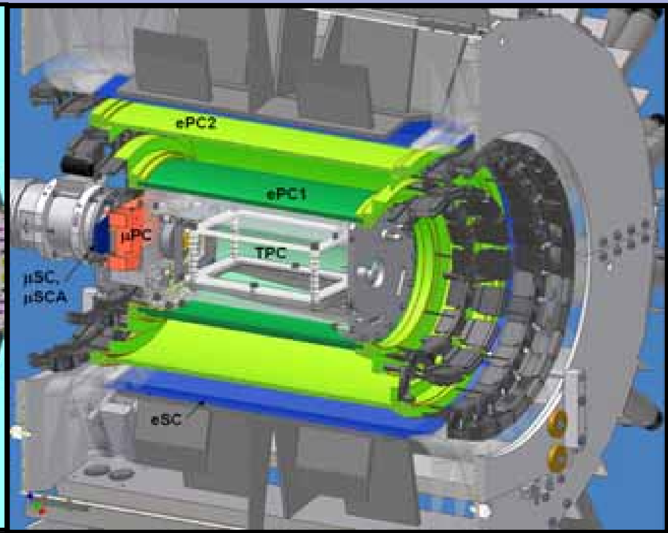
Precision Muon Physics:
New results and a hint at things to come

David Hertzog
University of Illinois at Urbana-Champaign

τ_μ



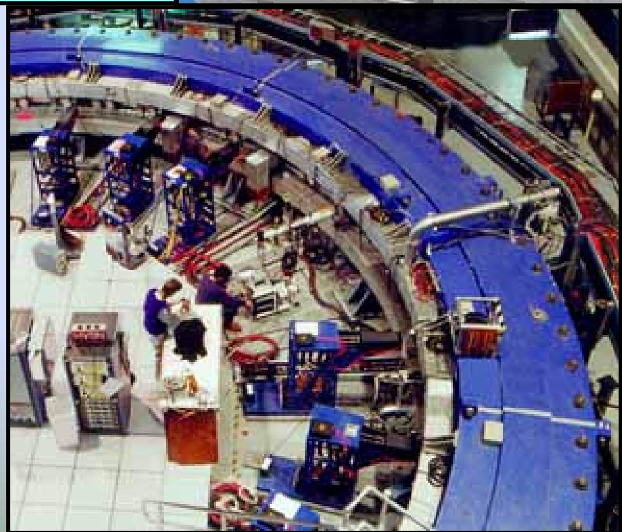
MuLan



MuCap

g_P

a_μ



Muon g-2

Moriond EW 2007

The predictive power of the Standard Model depends on well-measured input parameters

The most precise electroweak parameters…

G_F	α	M_Z
9 ppm	0.0007 ppm	23 ppm

Precision μ^+ lifetime

A connection in technique

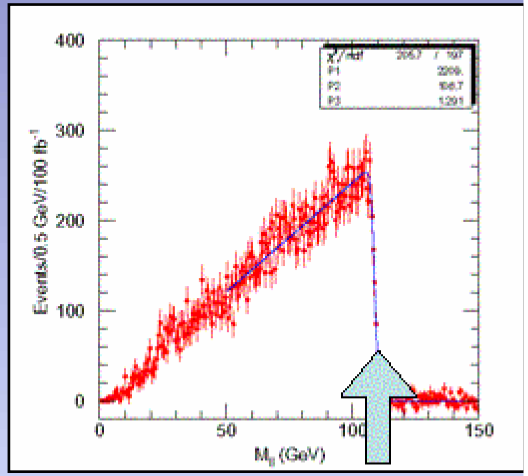
What is the weak-nucleon charged current?

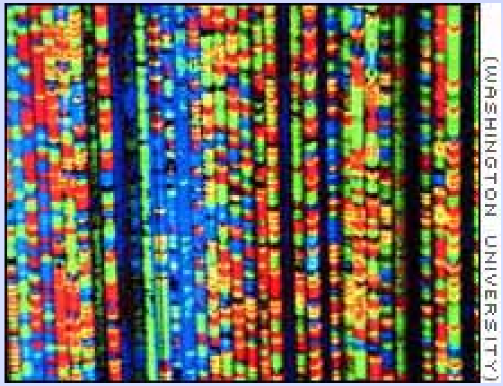
g_p

Precision μ^- lifetime in ultra-pure hydrogen gas (capture)

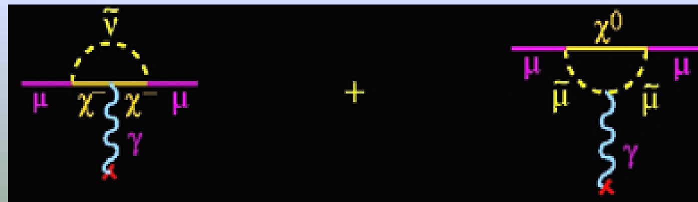
Exploring Physics Beyond the Standard Model

- **At the LHC, many of you will find all sorts of new particles …** (let's hope)
  - **But, what are they ?**
- **The genome mapping of the new physics will require a broad toolset,**
  - **Branching ratios**
  - **Masses**
  - **Precision measurements**
    - Lepton flavor violation (signals or limits)
    - Electric dipole moments (signals or limits)
    - Rare decays
    - Precision measurement vs SM predictions
      - Unitarity tests
      - Muon g-2



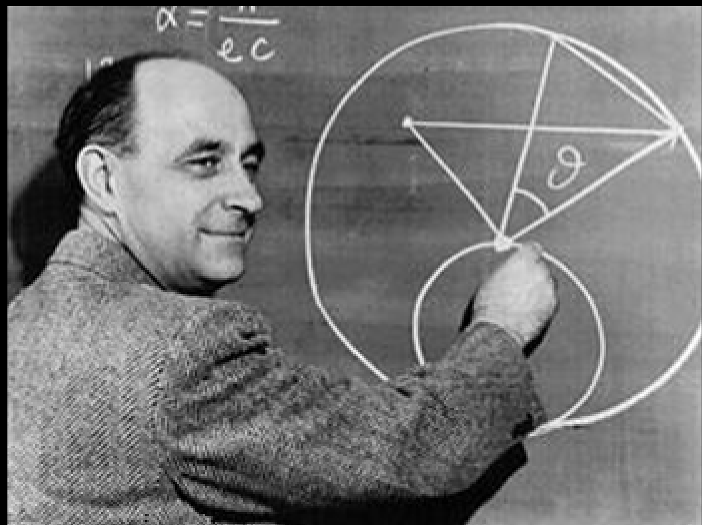


SUSY "sequencing"



MuLan:
Muon Lifetime Analysis

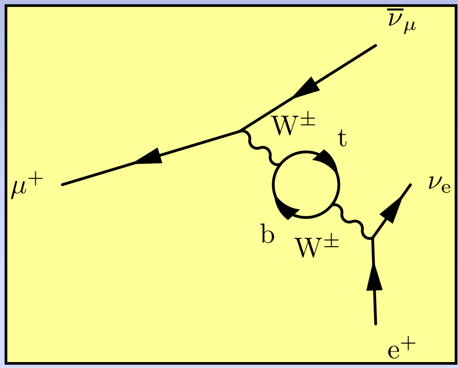
G_F



Muon decay is a pure weak process … determines G_μ, often called G_F

The Fermi constant is related to the electroweak gauge coupling *g* by

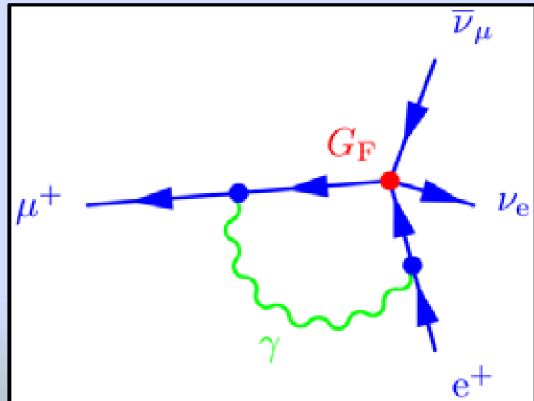
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r(m_t, m_H, \ldots)\right)$$



Contains all weak interaction loop corrections

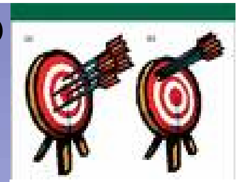
In the Fermi theory, muon decay is a contact interaction

$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}$$



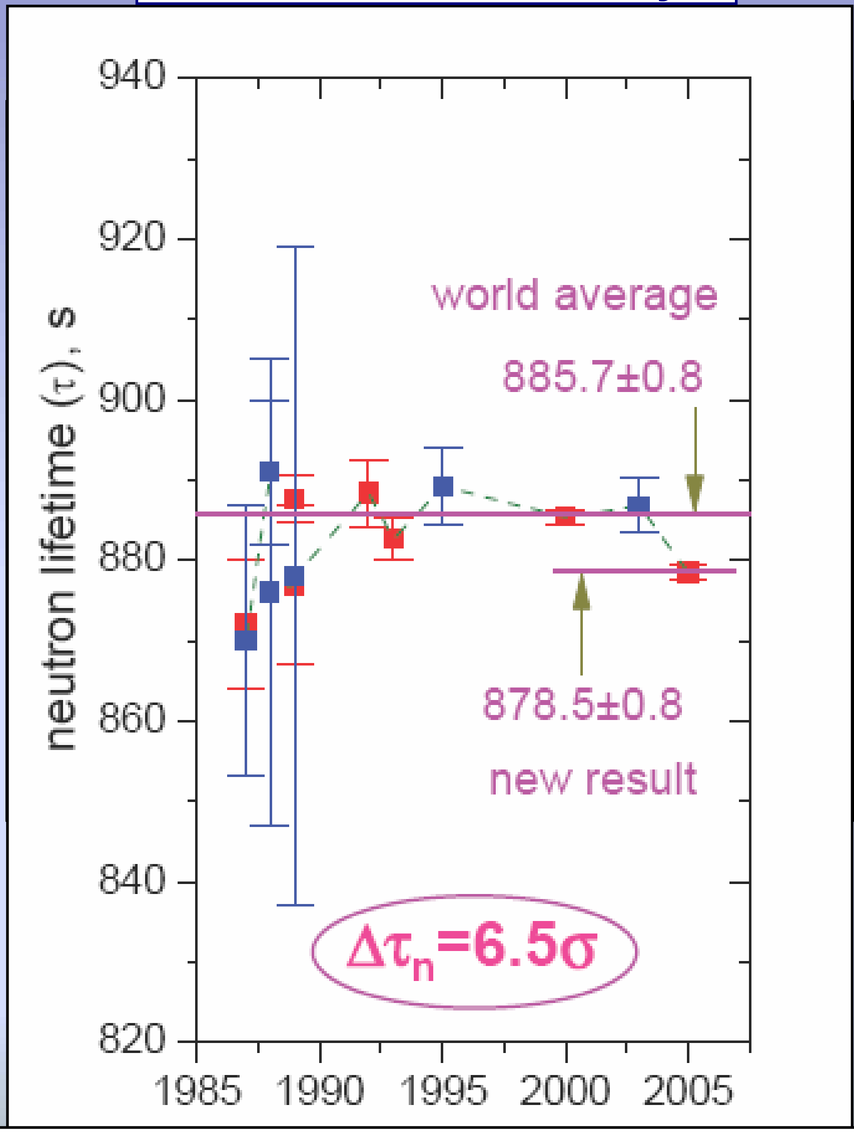
In 1999, van Ritbergen and Stuart completed full 2-loop QED corrections reducing the uncertainty in G_F from theory to < 0.3 ppm (it was the dominant error before)

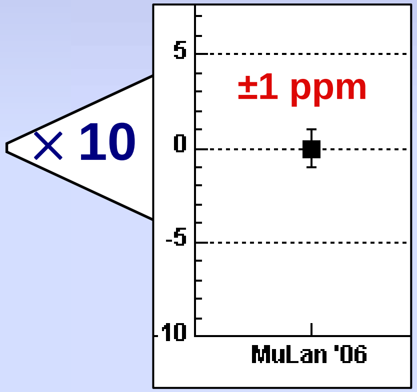
World avg $\delta\tau_\mu/\tau_\mu$ is 18 ppm, but is it right?



Precision vs Accuracy

Lessons from History





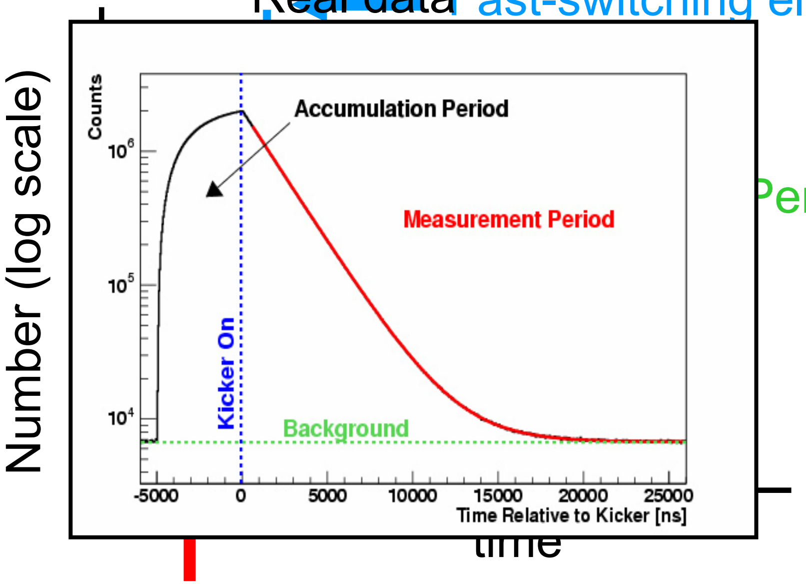
?

Goal of MuLan is 1 ppm. Today I report 11 ppm 1st result

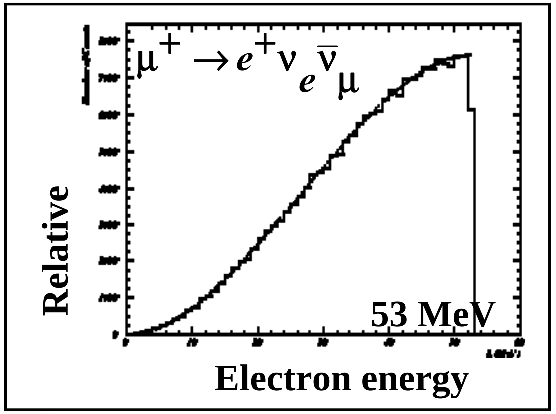
The experimental concept in one animation …

Real data

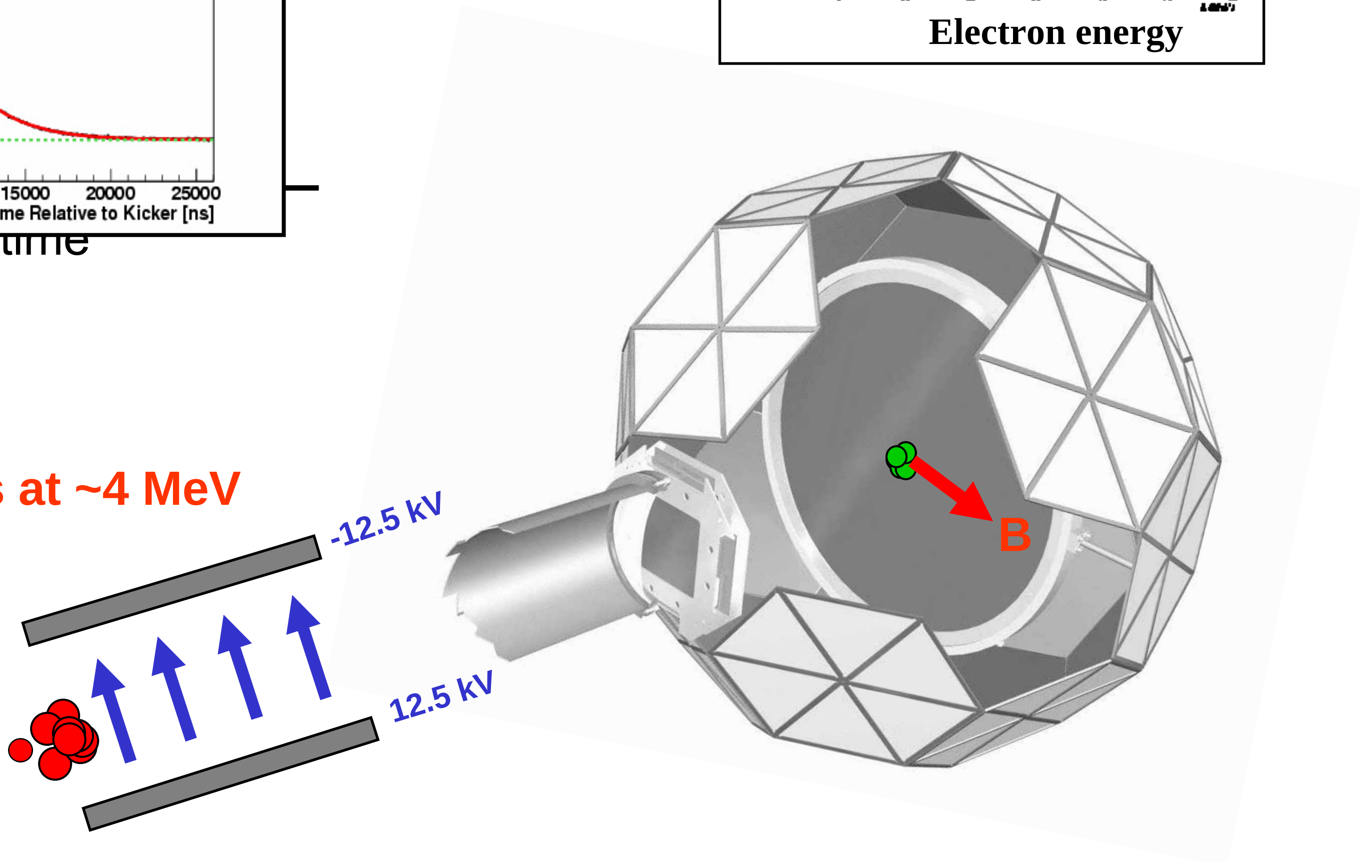
Fast-switching electric kicker on



Fill Period

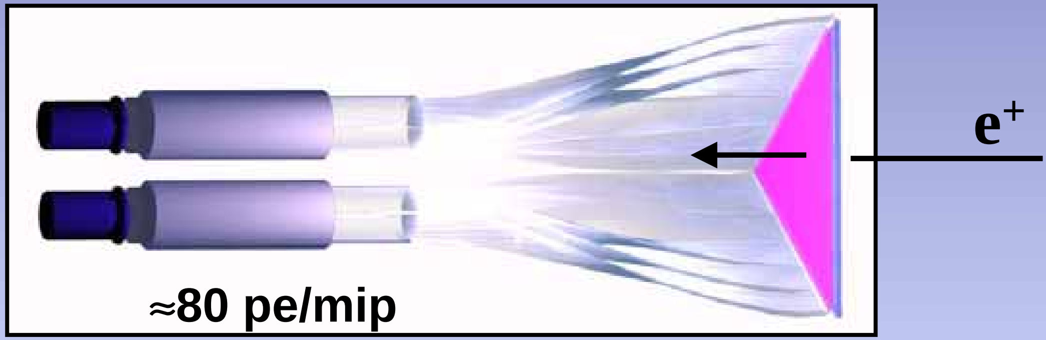


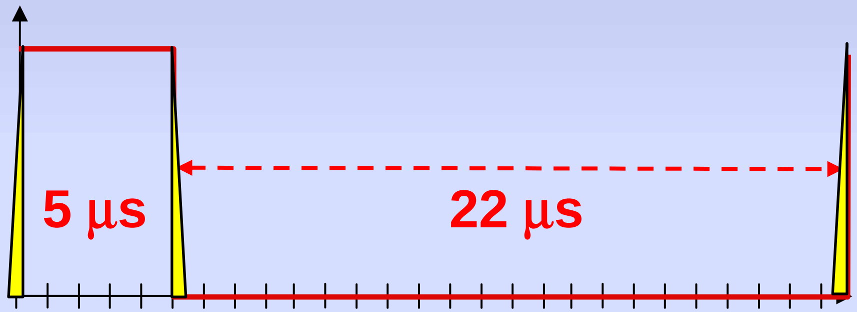
100% polarized muons at ~4 MeV

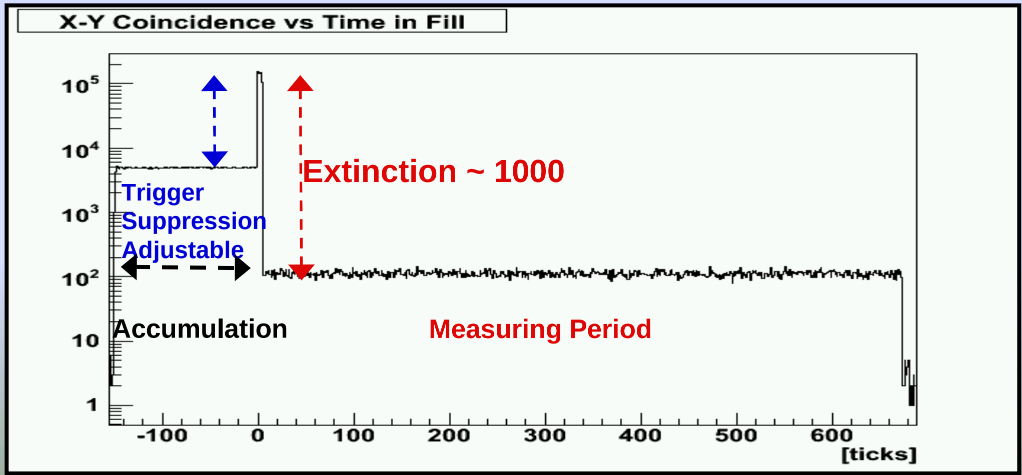


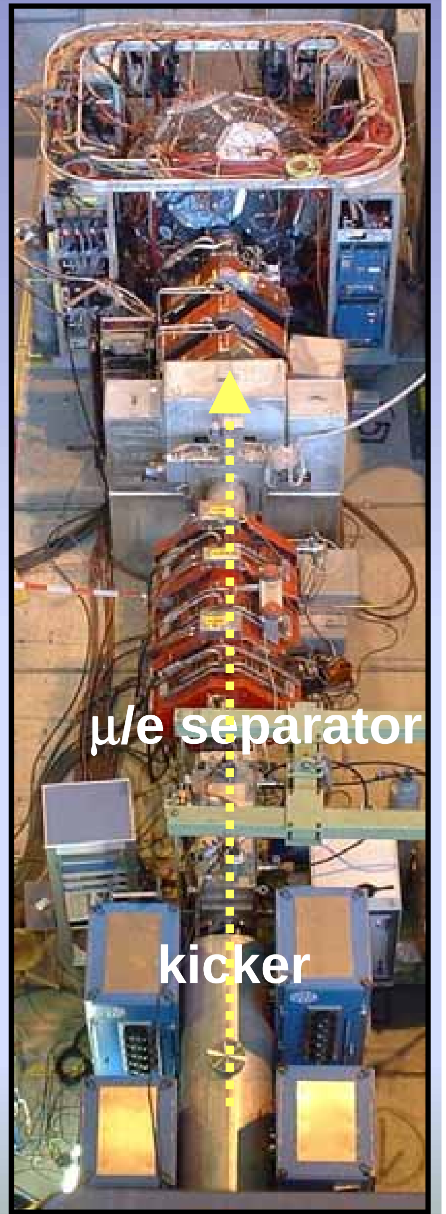
Rapidly precessed here

Create a time-structured "surface" muon beam with flux of roughly 10^7 μ^+/s

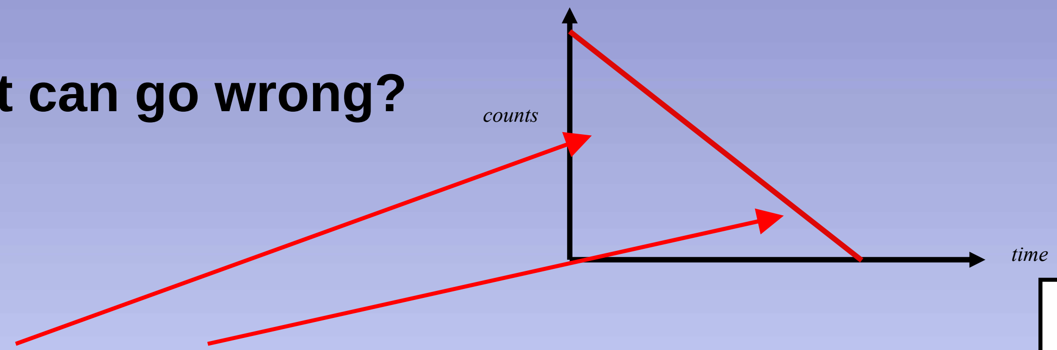






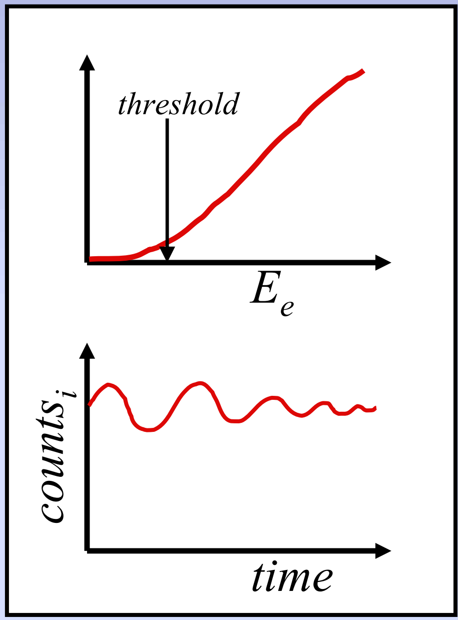


For 10^{12} decays, it's all about the systematic errors

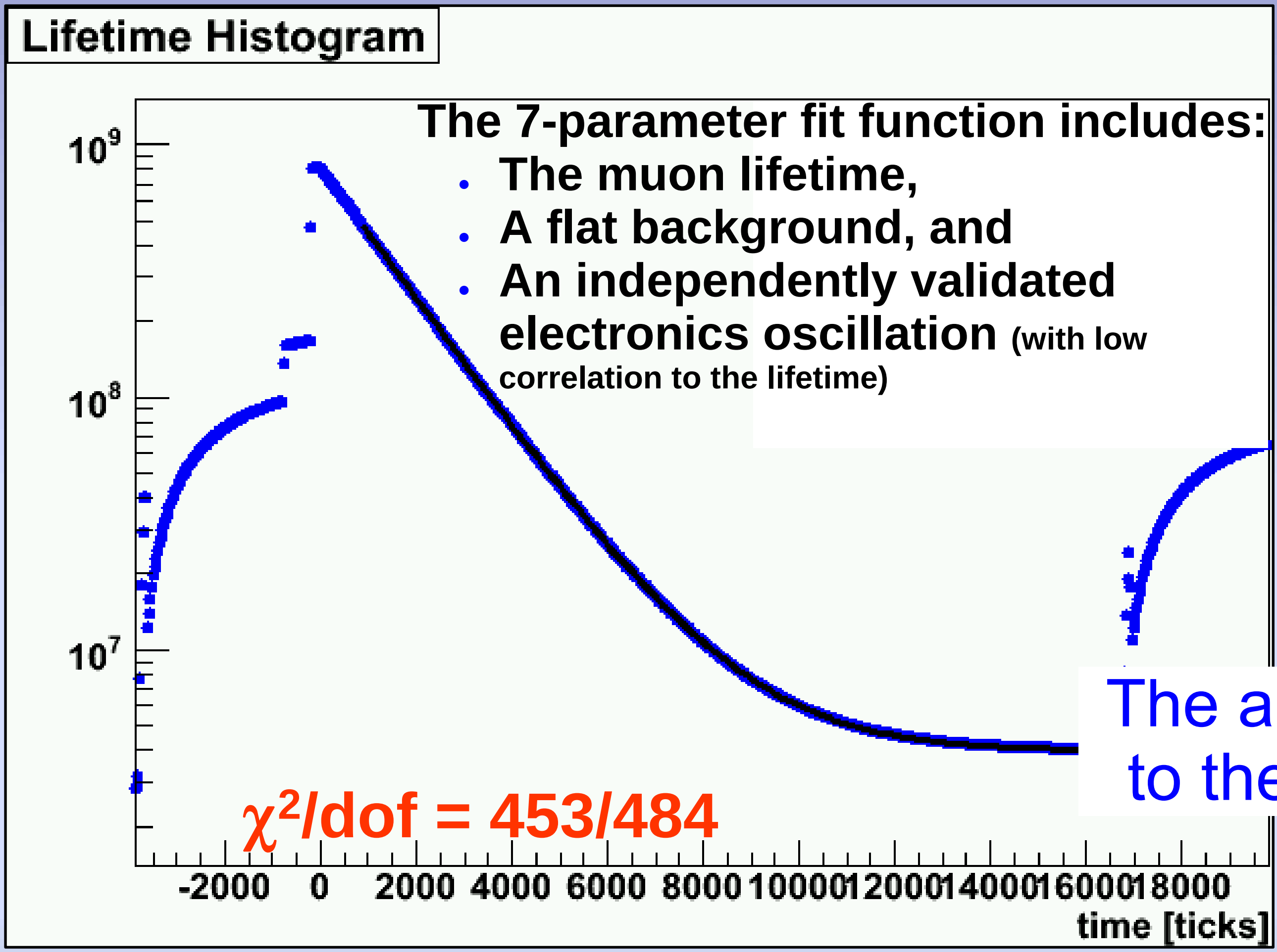


- What can go wrong?

- "Early-to-late" changes
  - Instrumental shifts
    - Gain or threshold
    - Time response
  - Effective acceptance
    - Residual polarization or precession
    - Errant muons
- Pileup
  - Missing events

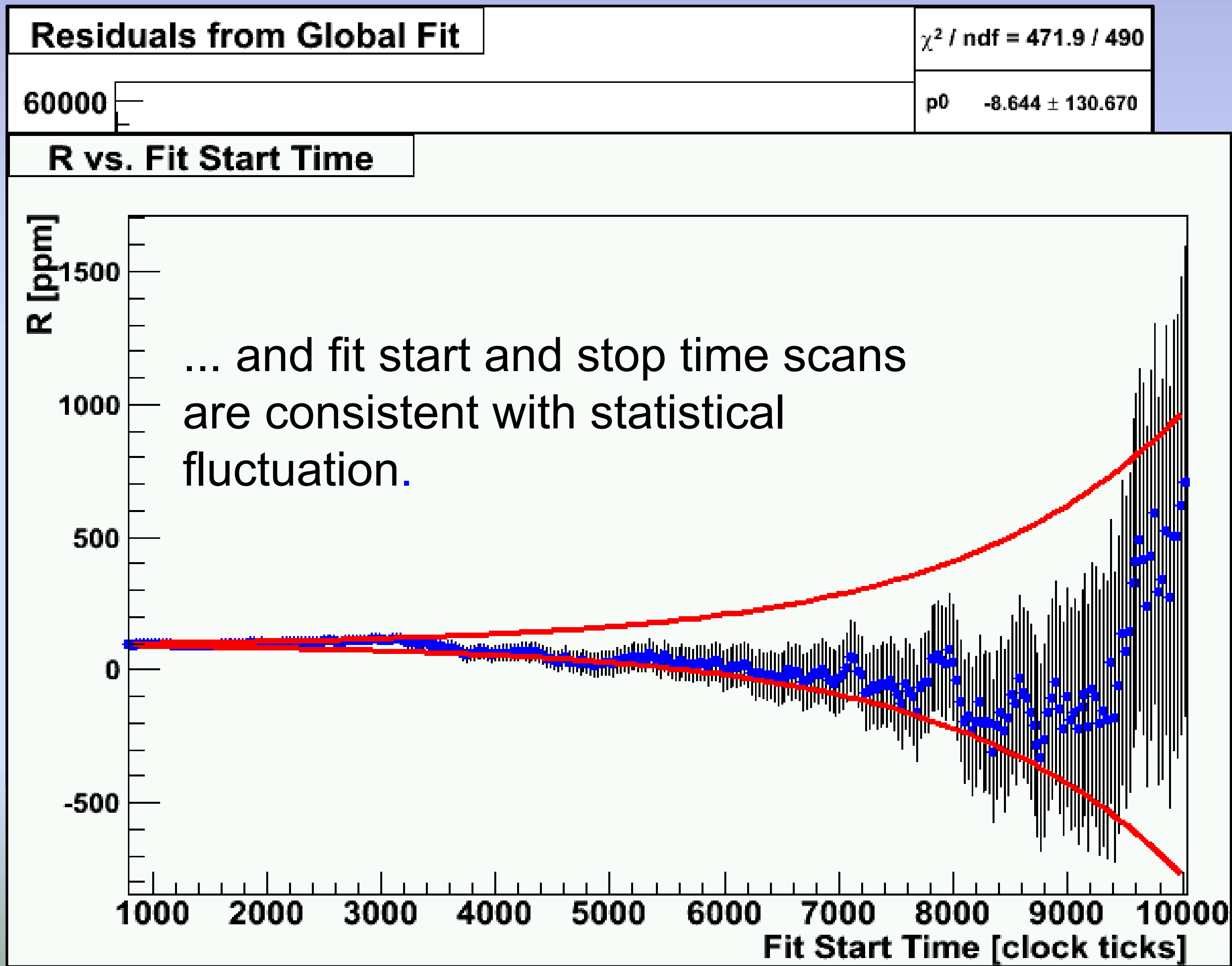


Result from 2004 data taking



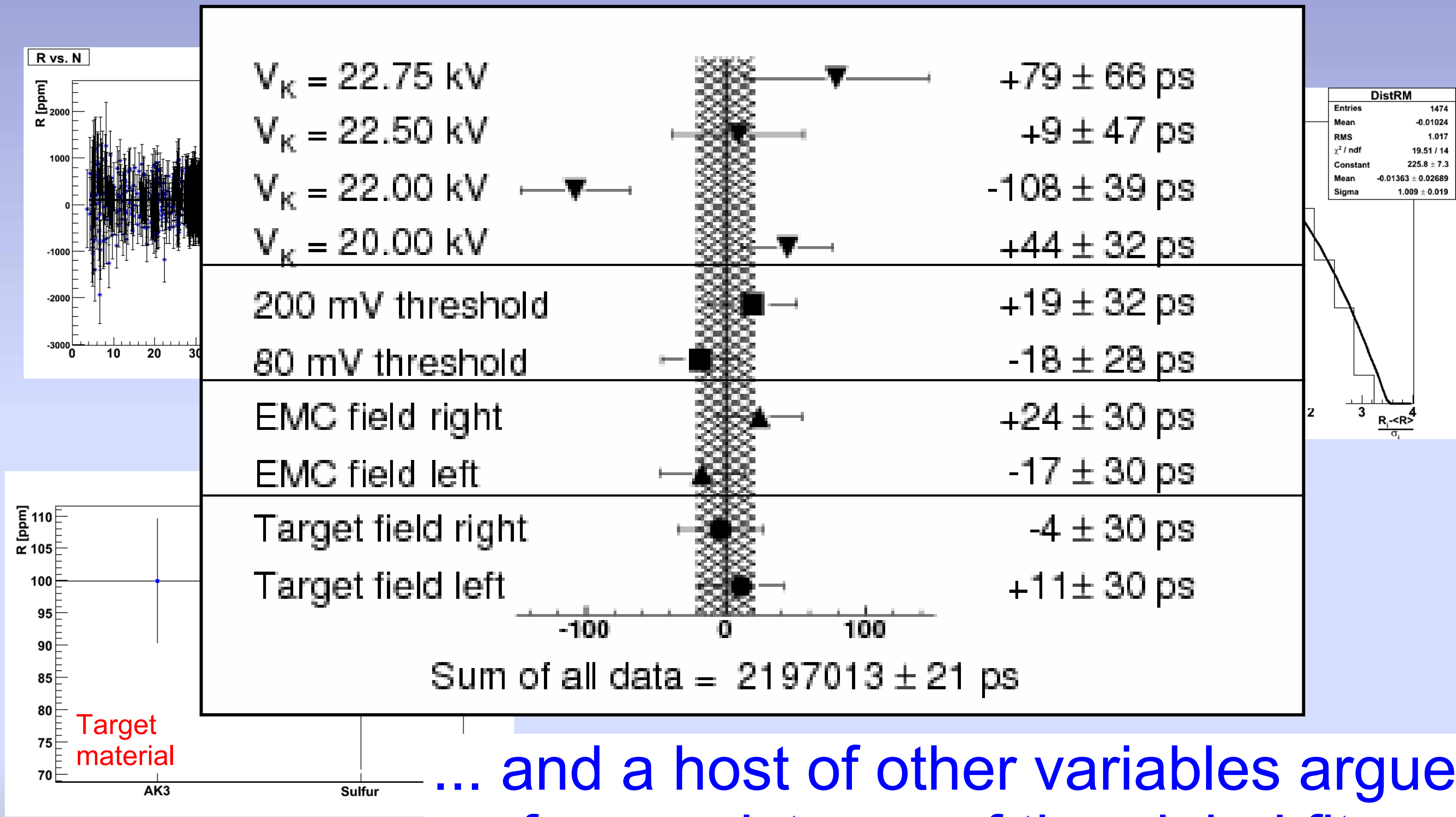
The analyzers are blind to the clock frequency

The fit residuals show no structure...



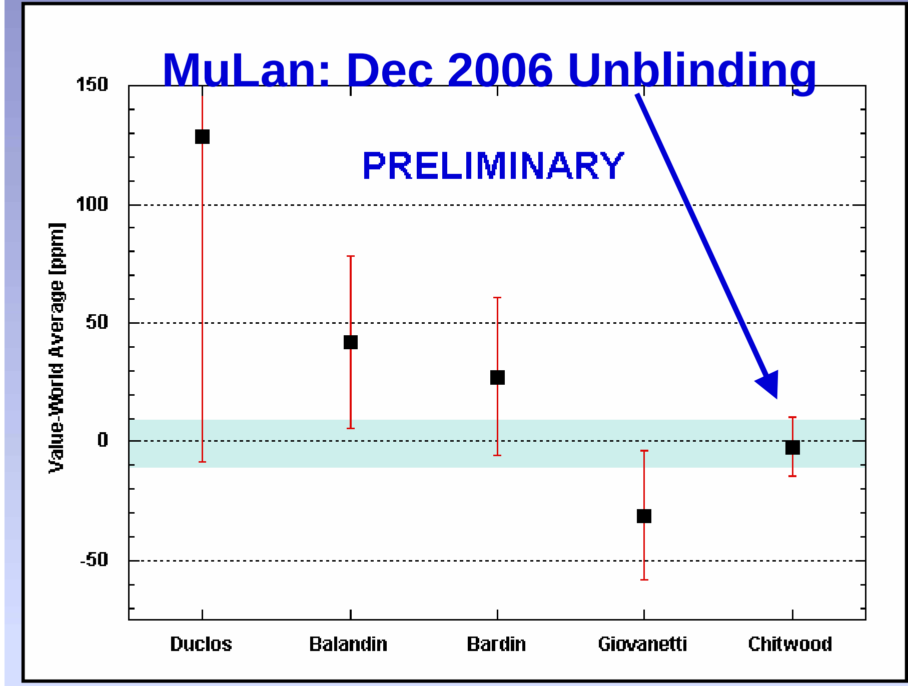
... and fit start and stop time scans are consistent with statistical fluctuation.

More fit consistency



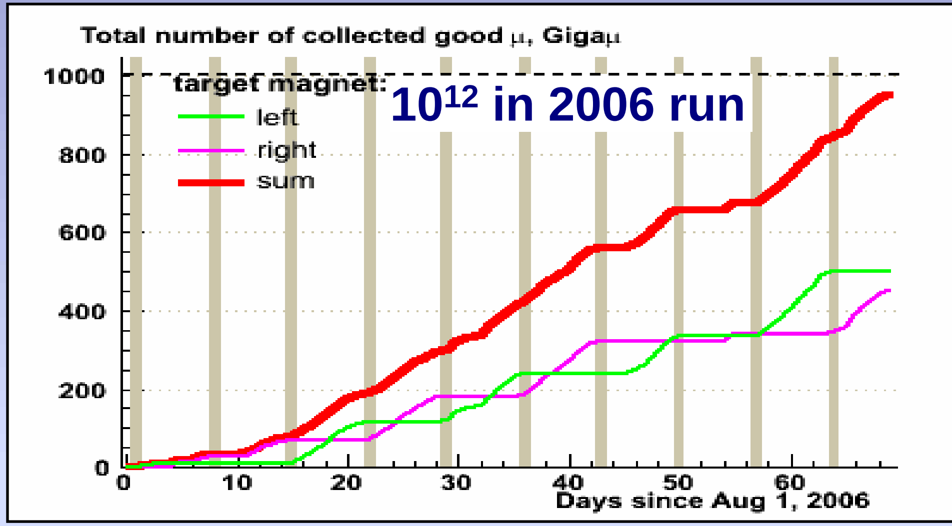
... and a host of other variables argue for consistency of the global fit.

2007: First Physics Result



τ_μ(MuLan) = 2.197 013(24) μs (11 ppm)

G_F = 1.166 372(6) x 10^{-5} GeV^{-2} (5 ppm)



Improved Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant

D.B. Chitwood[3], T. Banks[2], M.J. Barnes[7], S. Battu[5], R.M. Carey[1], S. Cheekatmalla[5], S.M. Clayton[3], J. Crnkovic[3], K.M. Crowe[2], P.T. Debevec[3], S. Dhamija[5], W. Earle[1], A. Gafarov[1], K. Giovanetti[4], T.P. Gorringe[5], F.E. Gray[3,2], M. Hance[1], M.F. Hare[1], D.W. Hertzog[3], P. Kammel[3], B. Kiburg[3], J. Kunkle[3], B. Lauss[2], I. Logashenko[1], K.R. Lynch[1], R. McNabb[3], J.P. Miller[1], F. Mulhauser[3], C.J.G. Onderwater[3,6], C.S. Özben[3], Q. Peng[1], C.C. Polly[3], S. Rath[5], B.L. Roberts[1], V. Tishchenko[5], G.D. Wait[7], J. Wasserman[1], D.M. Webber[3], P. Winter[3]

(MuLan Collaboration – Version 10; Feb 12)

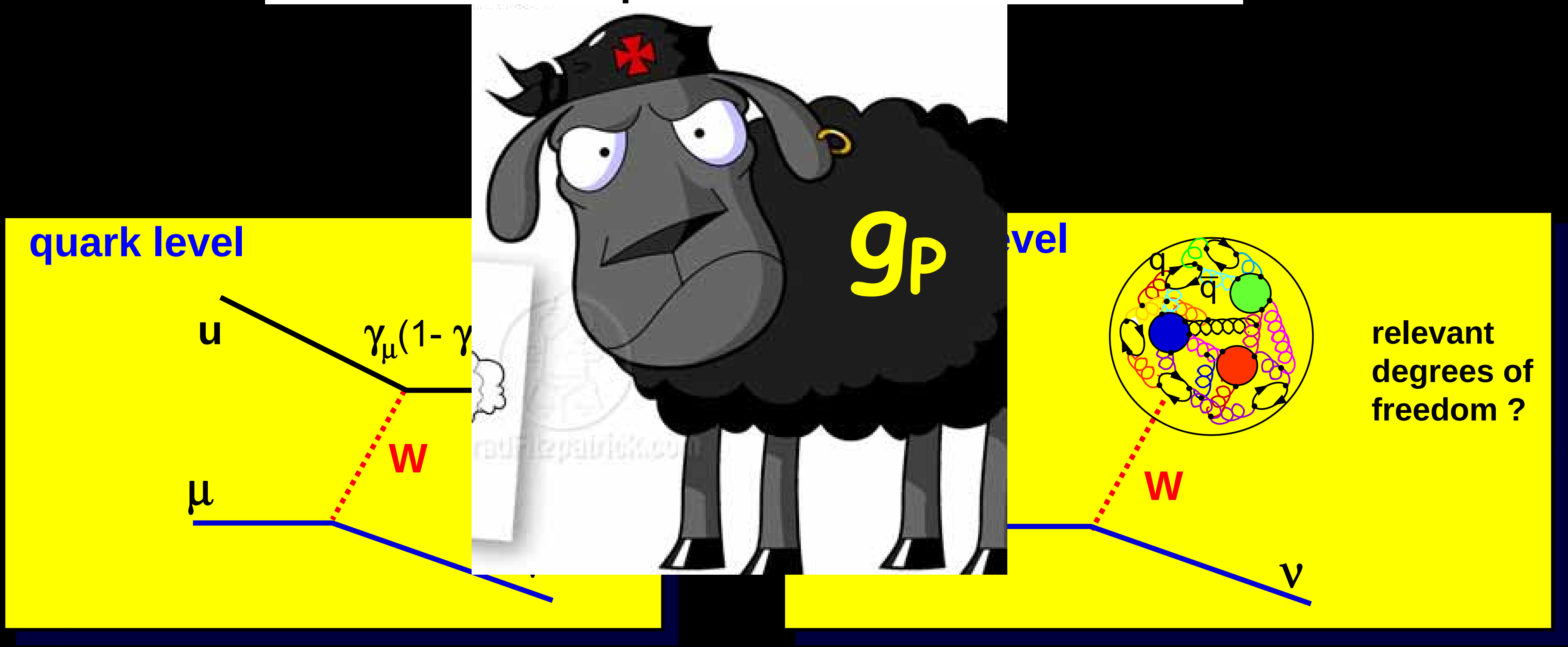
[1] *Department of Physics, Boston University, Boston, Massachusetts 02215*
[2] *Department of Physics, University of California, Berkeley, California 94720*
[3] *Department of Physics, University of Illinois at Urbana-Champaign, Illinois 61801*
[4] *Department of Physics, James Madison University, Harrisonberg, Virginia 22807*
[5] *Department of Physics, University of Kentucky, Lexington, Kentucky 40506*
[6] *Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, NL 9747 AA Groningen, The Netherlands*
[7] *TRIUMF, Vancouver, BC, V6T 2A3, Canada*

To be submitted next week

First Physics from MuCap

(muon capture on *p* to get induced pseudoscalar coupling

The Black Sheep of Form Factors – T. Hemmert



Short story: Muon Capture and Axial Nucleon Structure

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

Capture rate Λ_S

$$\mathcal{M} = \frac{-iG_F V_{ud}}{\sqrt{2}} \overline{u}(p_\nu)\gamma_\alpha(1-\gamma_5)u(p_\mu)\overline{u}(p_f)\tau_- \left[V^\alpha - A^\alpha\right] u(p_i)$$

Lorentz, T invariance gives these possibilities

$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

How does Λ_S depend on precision of the FF s ?

Well known

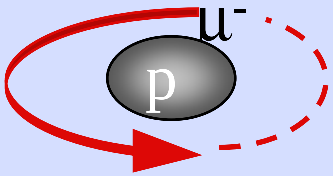
$$\frac{\partial \Lambda_S}{\Lambda_S} = 0.47 \frac{\partial g_V}{g_V} = 0.024\%$$

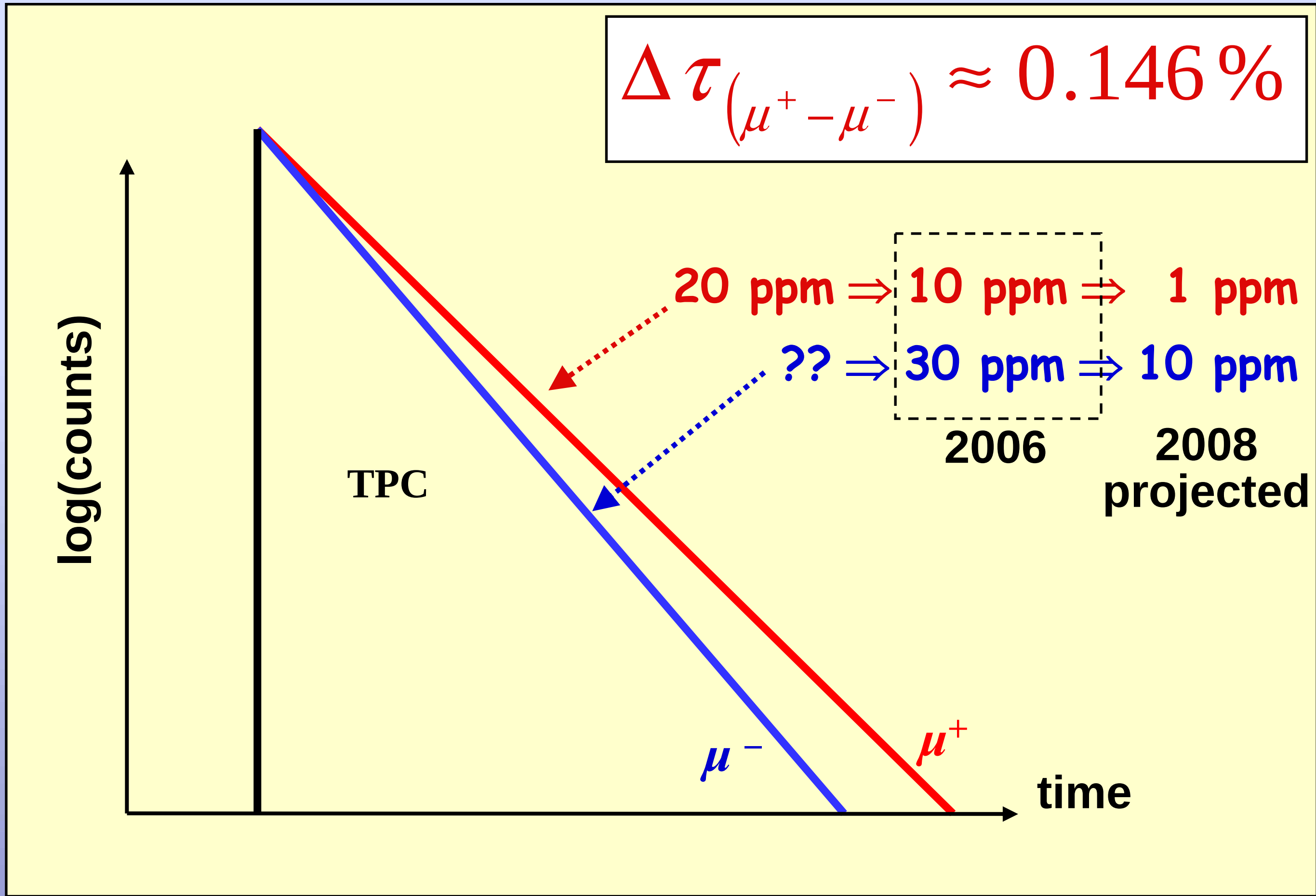
$$\frac{\partial \Lambda_S}{\Lambda_S} = 0.15 \frac{\partial g_M}{g_M} = 0.01\%$$

$$\frac{\partial \Lambda_S}{\Lambda_S} = 1.57 \frac{\partial g_A}{g_A} = 0.38\%$$

$$\frac{\partial \Lambda_S}{\Lambda_S} = 0.18 \frac{\partial g_P}{g_P} \approx 9\%$$

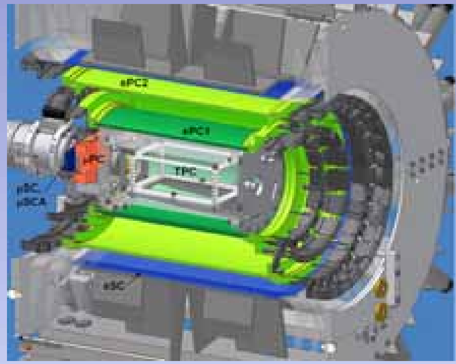
g_p can be determined from a μ^+ / μ^- lifetime difference, which gives the capture rate: $\mu^- + p \rightarrow n + \nu_\mu$

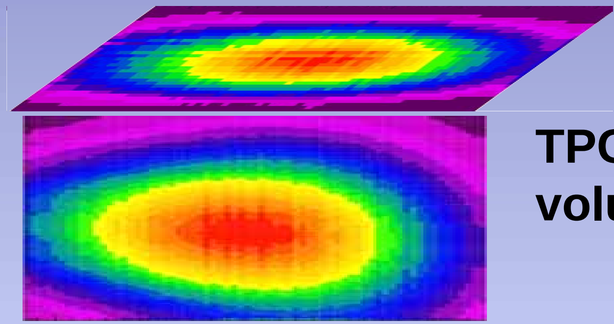




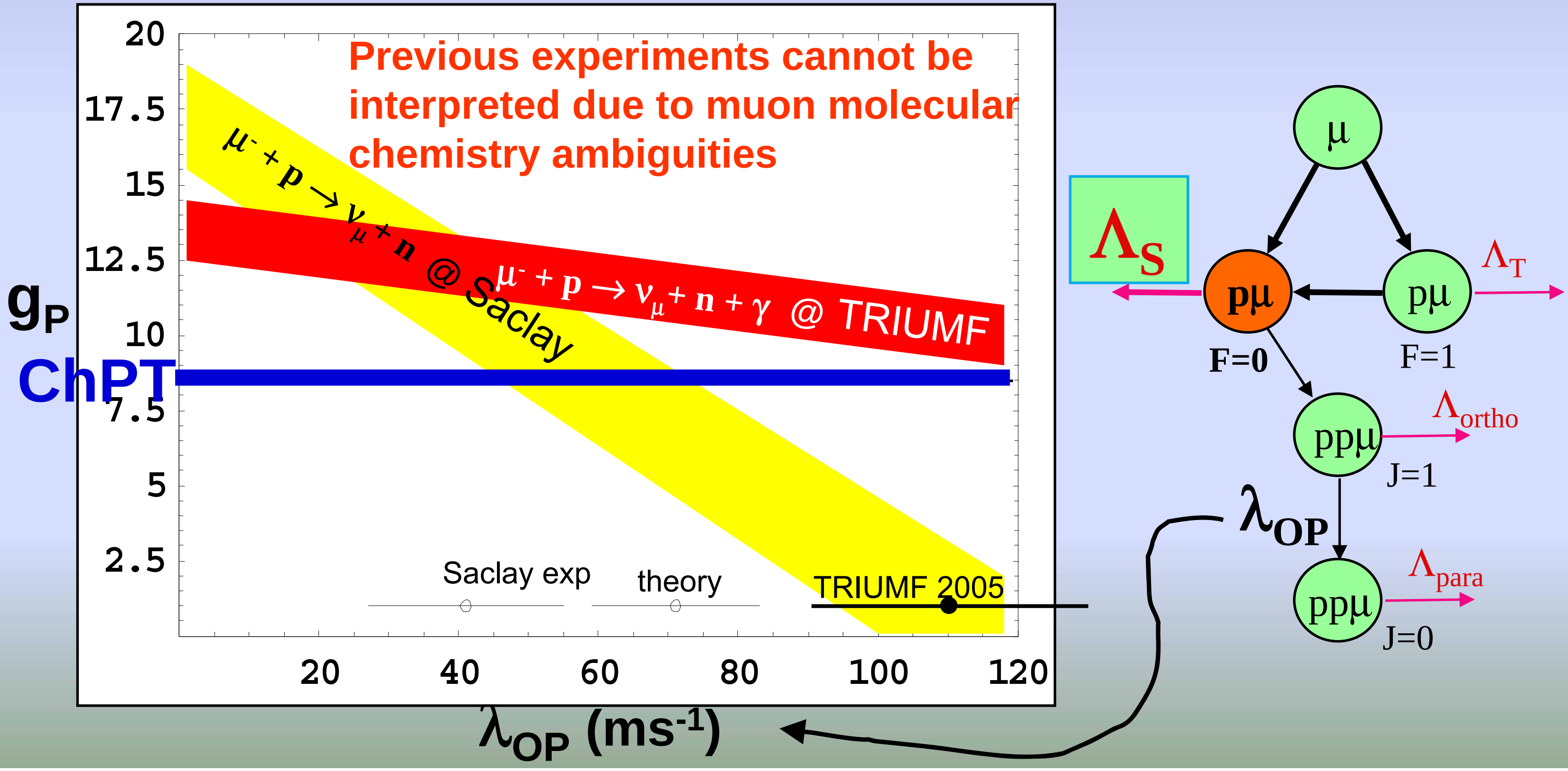
$$\Lambda_S = \Lambda_{(\mu^-)'} - \Lambda_{\mu^+} = \left(\tau_{(\mu^-)'}\right)^{-1} - \left(\tau_{\mu^+}\right)^{-1}$$

Stop μ^- in 10 atm pure hydrogen … and image stop location





TPC stopping volume



Difference in lifetimes leads to first unambiguous results; PRL to be submitted next week

Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton's Pseudoscalar Coupling g_P

T.I. Banks,[1] S.M. Clayton,[2] V.A. Andreev,[3] T.A. Case,[1] D. Chitwood,[2] K.M. Crowe,[1] J. Deutsch,[4] J. Egger,[5] S.J. Freedman,[1] V.A. Ganzha,[3] T. Gorringe,[6] F.E. Gray,[1] D.W. Hertzog,[2] M. Hildebrandt,[5] P. Kammel,[2] B. Kiburg,[2] S. Knaack,[2] P. Kravtsov,[3] A.G. Krivshich,[3] B. Lauss,[1] E.M. Maev,[3] O.E. Maev,[3] F. Mulhauser,[2,5] C.S. Özben,[2] C. Petitjean,[5] G.E. Petrov,[3] R. Prieels,[4] G.N. Schapkin,[3] G.G. Semenchuk,[3] M. Soroka,[3] V. Tishchenko,[6] A. Vasilyev,[3] A.A. Vorobyov,[3] M. Vznuzdaev,[3] and P. Winter[2]

(MuCap Collaboration)

[1] University of California, Berkeley, and LBNL, Berkeley, CA 94720, USA
[2] University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[3] Petersburg Nuclear Physics Institute, Gatchina 188350, Russia
[4] Université Catholique de Louvain, B-1348, Louvain-la-Neuve, Belgium
[5] Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[6] University of Kentucky, Lexington, KY 40506, USA

(Dated: March 13, 2007)

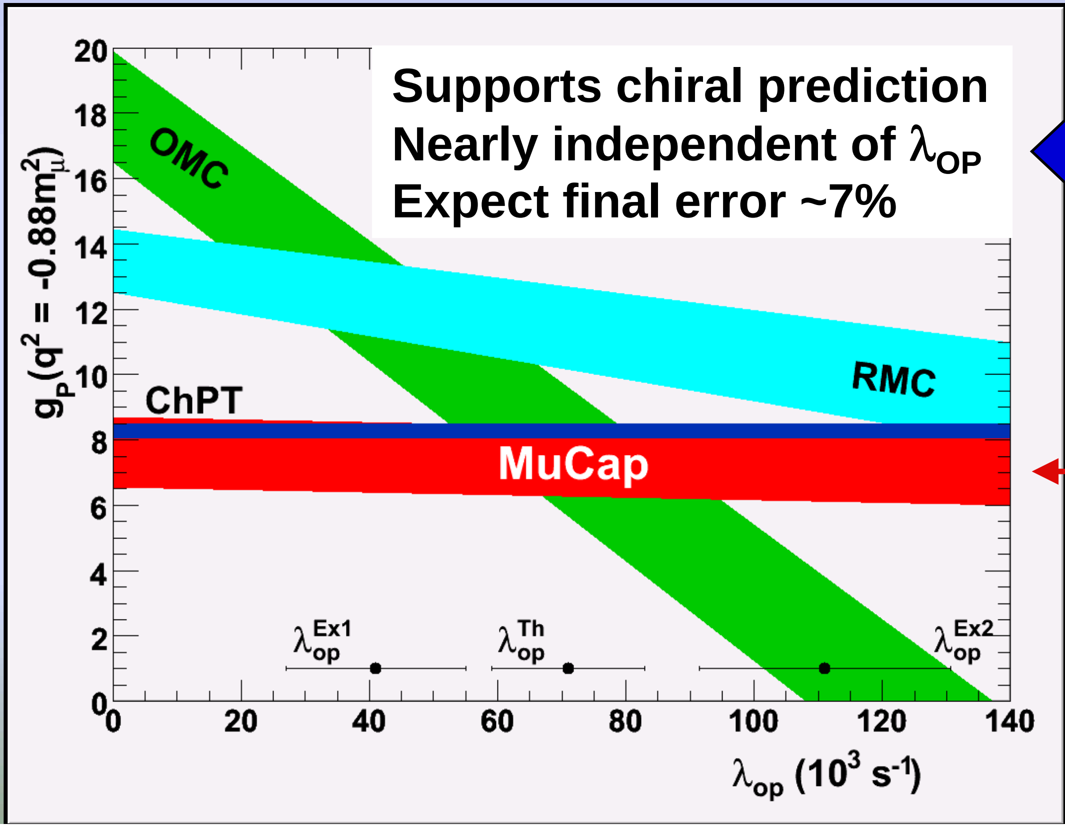
μ^-

μ^+

Delta λ

$\Lambda_S(s^{-1})$

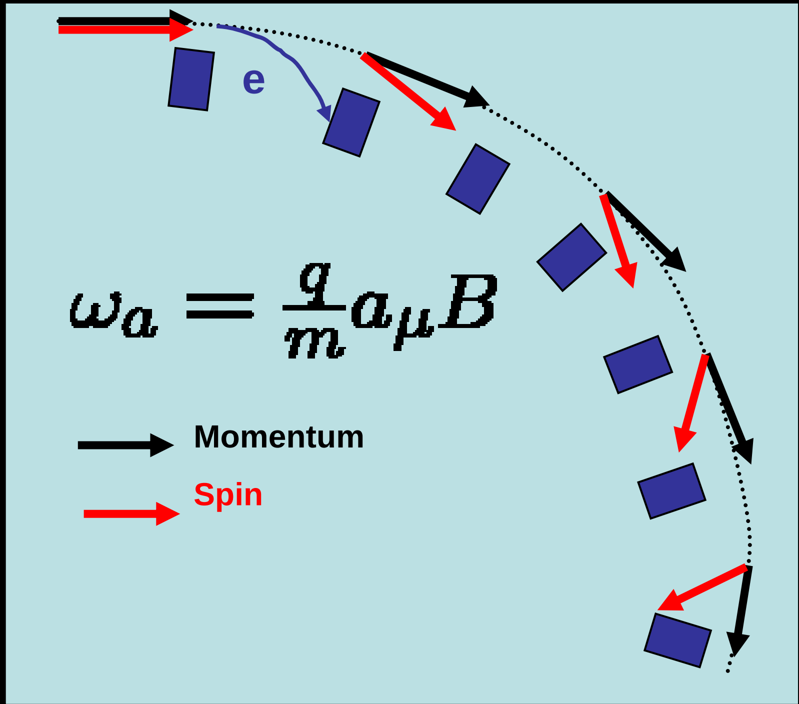
725.1±17.5

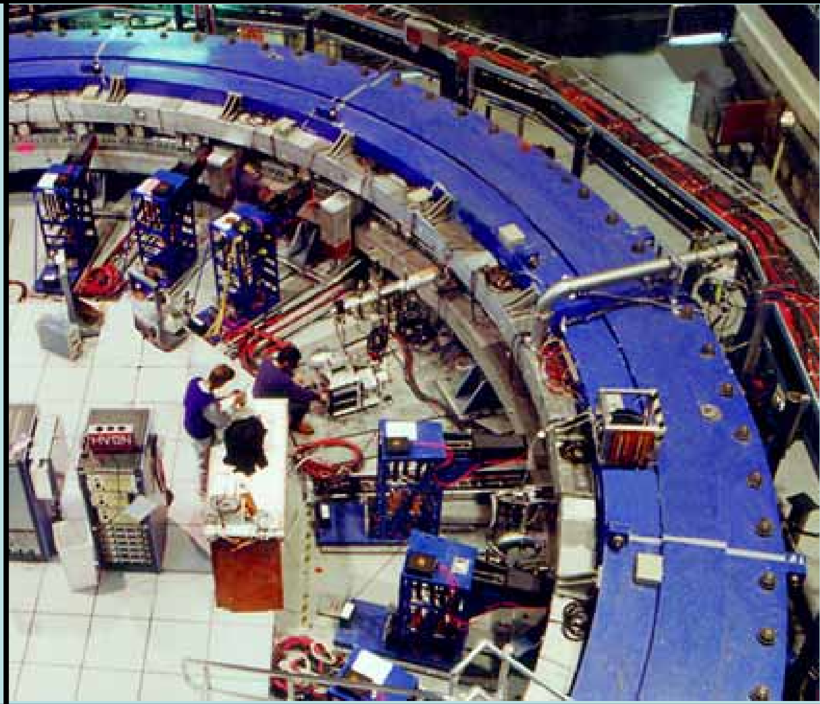


Supports chiral prediction
Nearly independent of λ_{OP}
Expect final error ~7%

$g_P = 7.3 \pm 1.1$

Muon g-2





In the last two years:,

Final report: Bennett et al, PRD <u>73</u>, 072003 (2006)

Future: BNL E969; precision by > factor of 2 increase

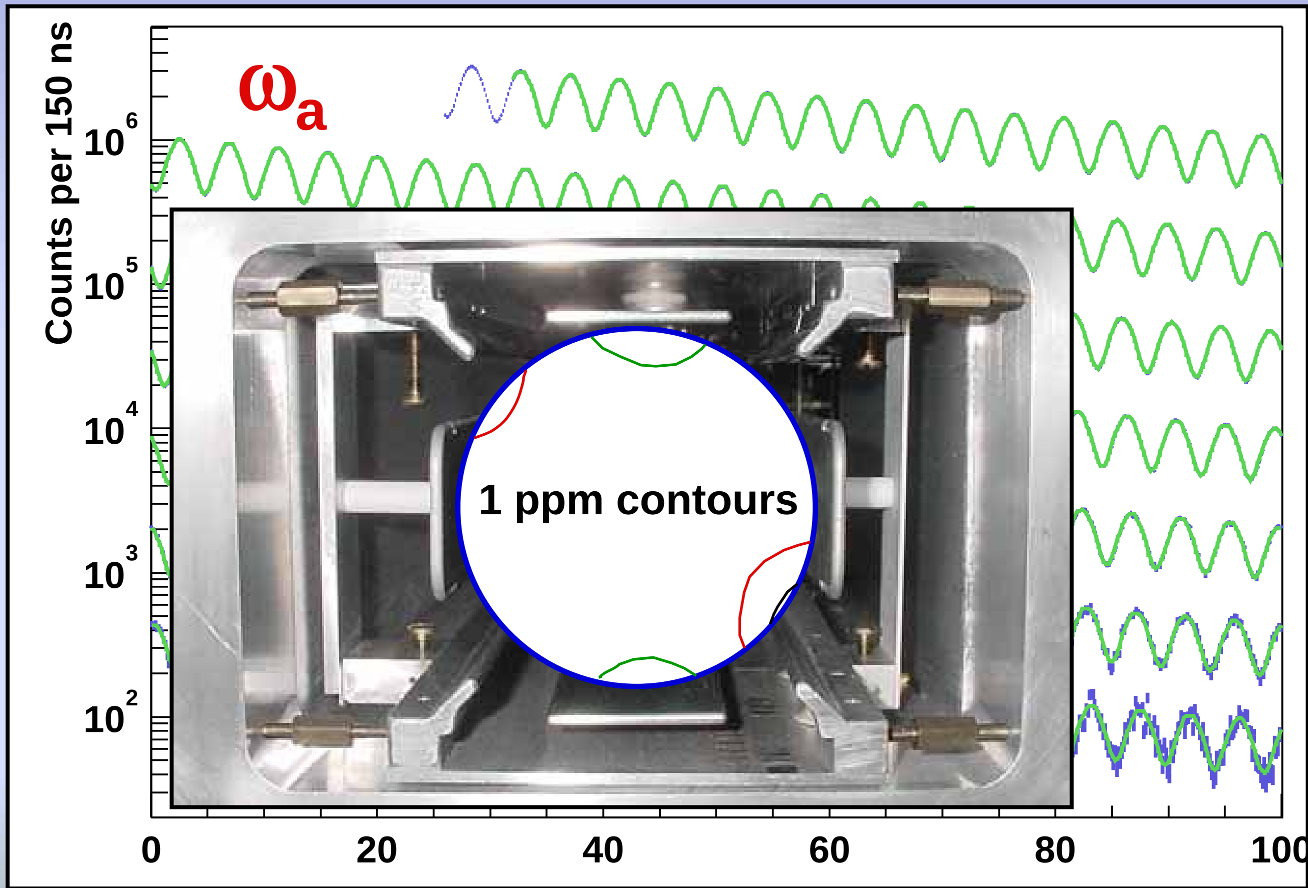
Theory: Reduced uncertainty; Increased consistency

> 1300 citations to the project papers

$$a_\mu(\text{Expt.}) = 11659208.0(6.3)\times 10^{-10} \qquad (0.54\ \text{ppm})$$

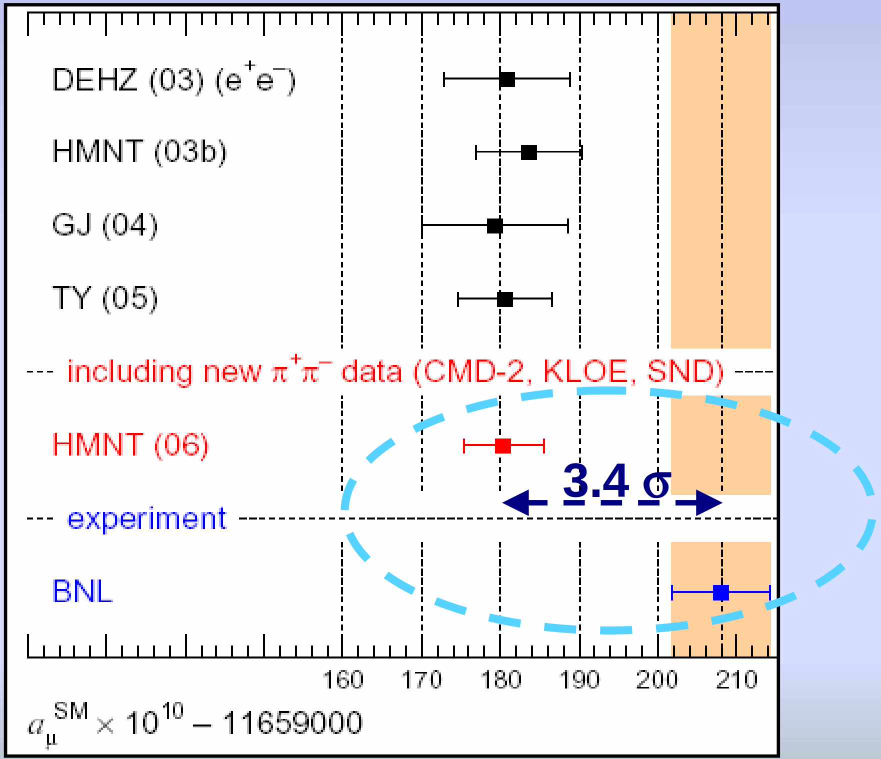
Muon g-2 is determined by a ratio of two precision measurements: ω_a and B

(and some knowledge of the muon orbit)



See Z. Zhang's theory review talk later today

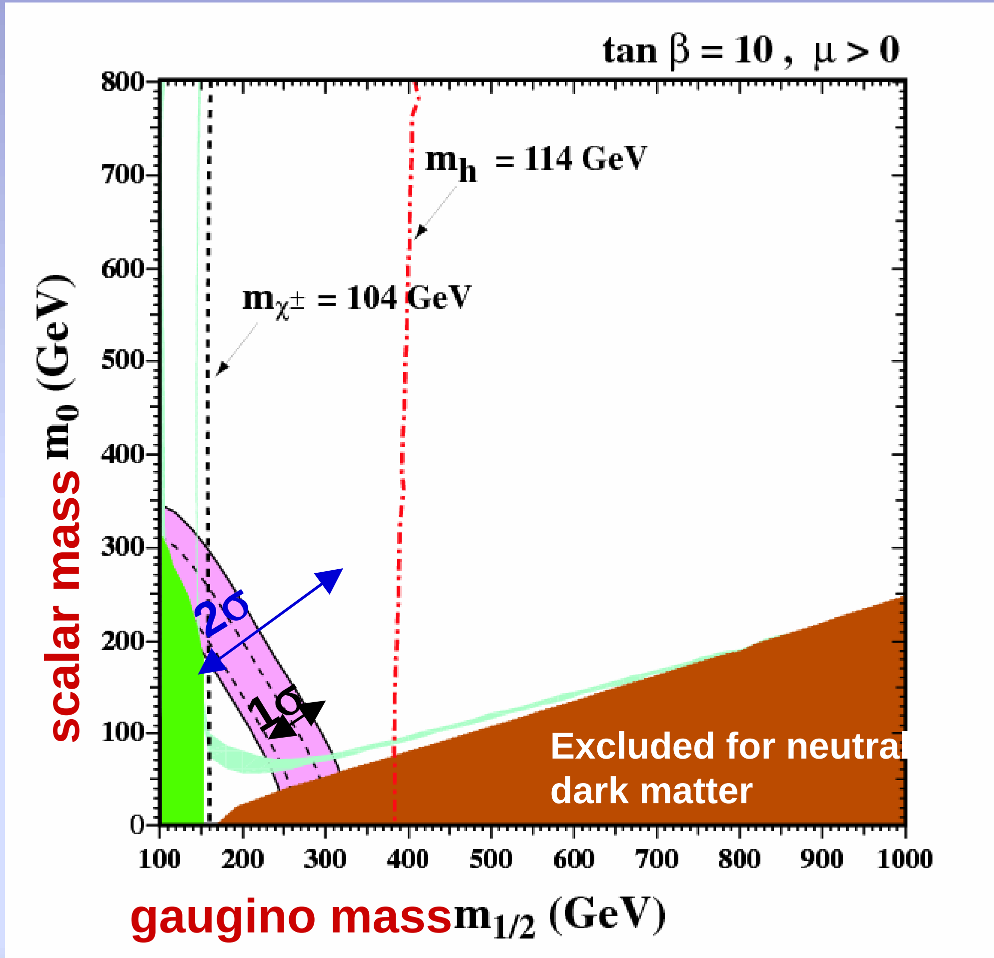
- **Key points:**
  - **Theory: 0.48 ppm**
  - **Experimental 0.54 ppm**
- Δa_μ(expt-thy) = (27.6±8.1) × 10^{-10} (3.4 σ)



K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

Arguably, strongest experimental evidence of Physics Beyond Standard Model

Typical SUSY 2D space showing g-2 effect (note: NOT an exclusion plot)



Future (if E969 funded)
$\Delta a_\mu = 295 \pm 39 \times 10^{-11}$

With new experimental and theoretical precision and same Δa_μ

Topical Review: D. Stöckinger hep-ph/0609168v1

This CMSSM calculation: Ellis, Olive, Santoso, Spanos. Plot update: K. Olive

The goal of E969 at BNL is a 0.22 ppm final total uncertainty, factor of >2 improvement

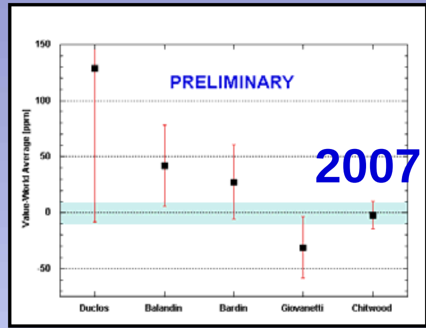
- **More muons** by clever improvements in beamline and other items related to delivery and storage
- **New techniques** to measure higher flux of events
- Across board continued **reduction in systematics**

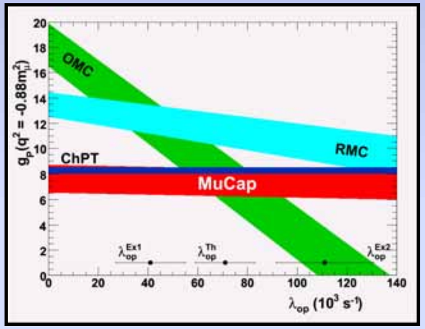
Systematic uncertainty (ppm)	1998	1999	2000	2001	Goal
Magnetic field – ω_p	0.5	0.4	0.24	0.17	0.1
Anomalous precession – ω_a	0.8	0.3	0.3	0.21	0.1

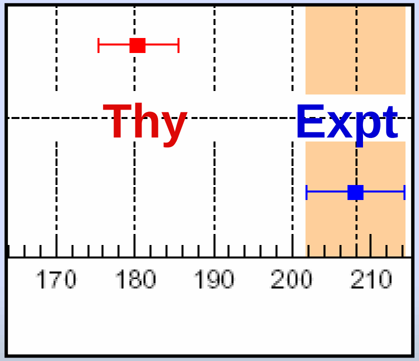
But, how we do all that is another talk for another day…

Summary

- **MuLan:**
  - **First G_F update in > 23 years**
    - τ_μ = 2.197 013(24) μs (11 ppm)
    - G_F = 1.166 372(6) x 10^{-5} GeV^{-2} (5 ppm)
- **MuCap:**
  - **First g_P with non-controversial interpretation**
    - g_P = 7.3 ± 1.0
    - Agrees with χPT expectation
- **g-2**
  - Δa_μ(expt-thy) = (27.6 ± 8.1) x 10^{-10} (3.4 σ)
  - **E969 in future: 2-fold improvement in expt and theory**
    - Awaits funding opportunity





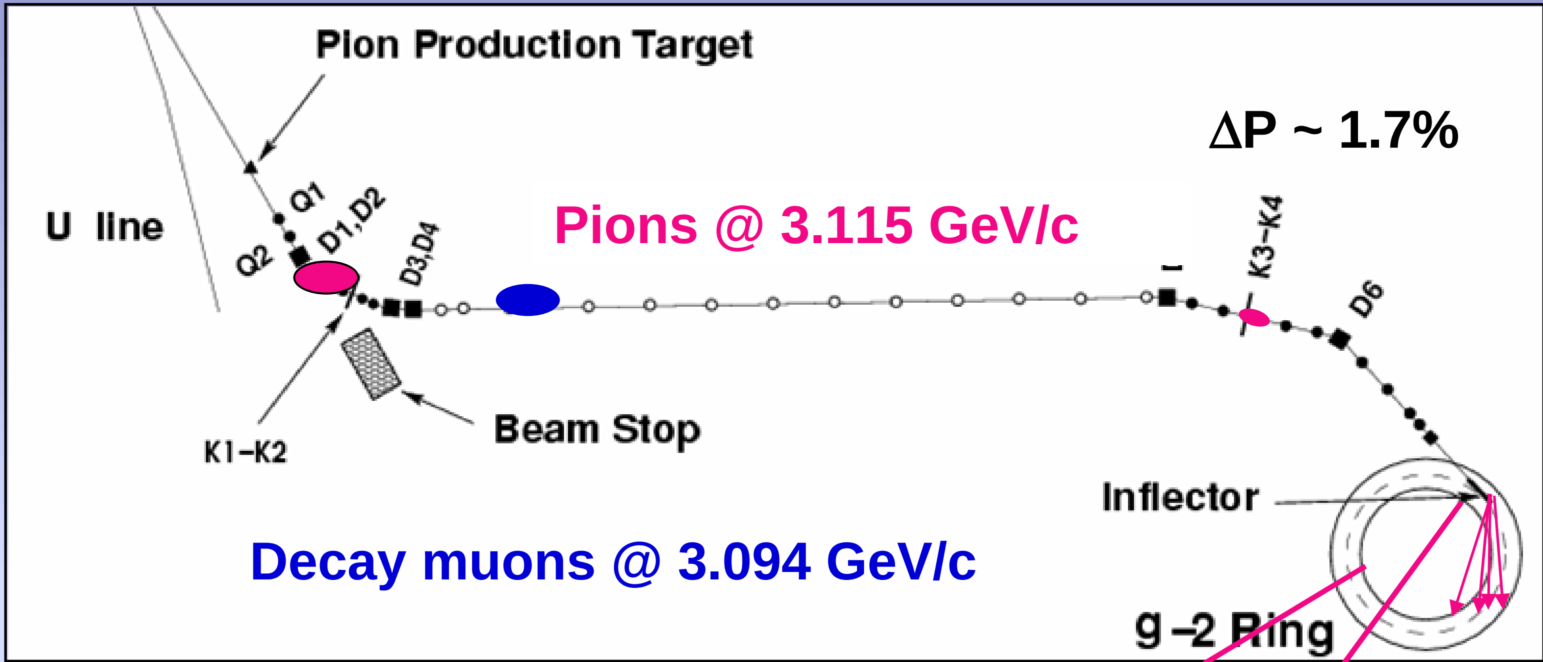


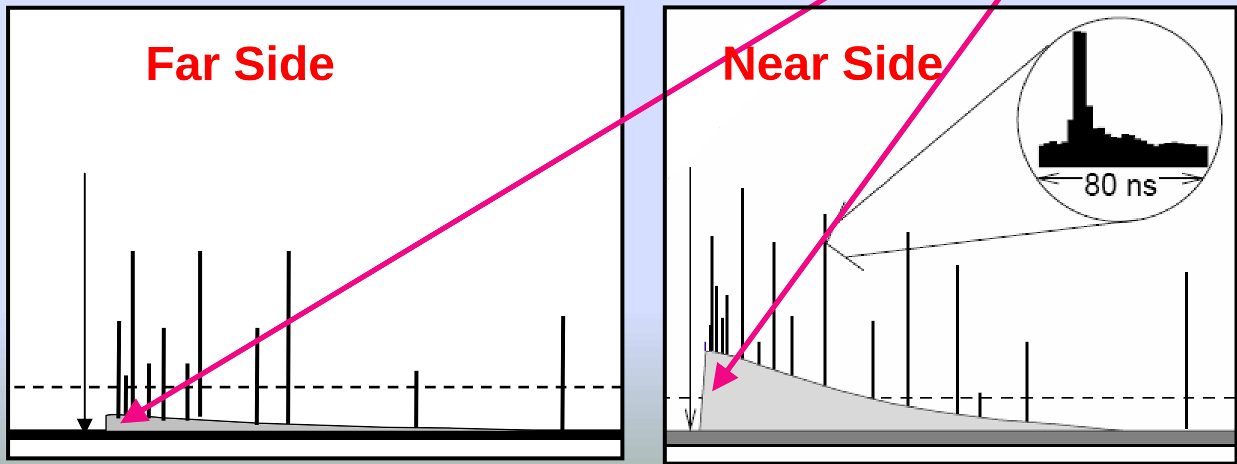
D. Hertzog

Why Hitoshi is no longer "sad"

Extra slides

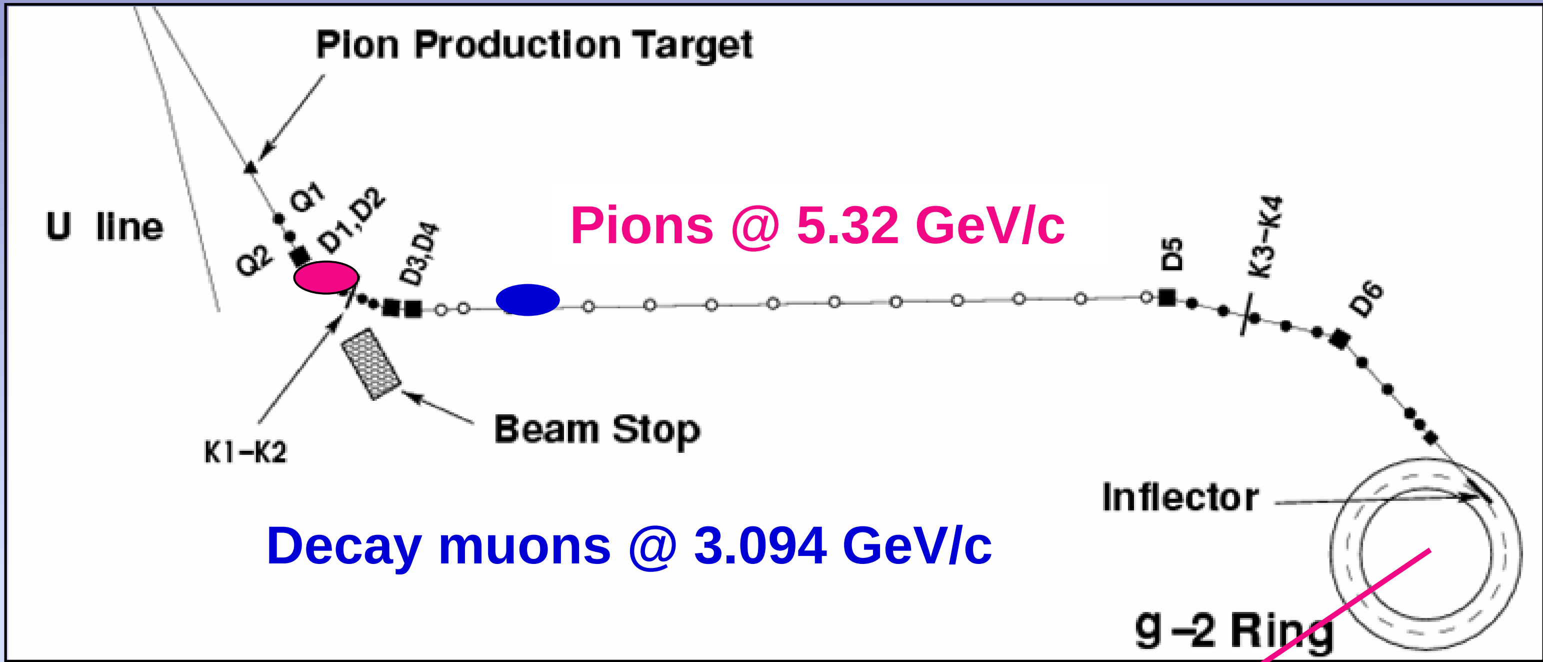
E821 used forward decay beam, which permitted a large π component to enter ring



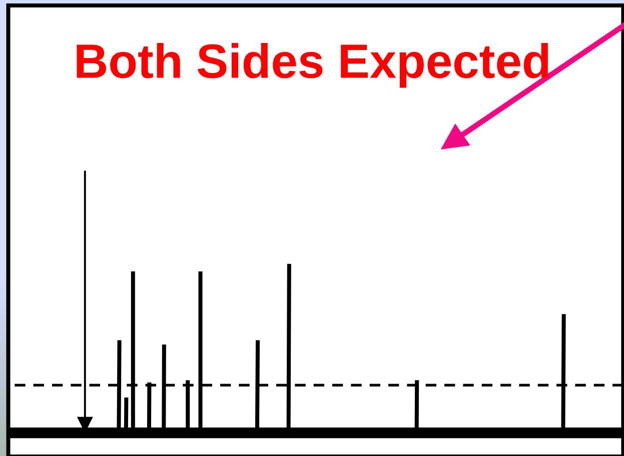


This baseline limits how early we can fit data

"Plan A" for the new experiment uses a backward decay beam with large mismatch in π/μ momentum



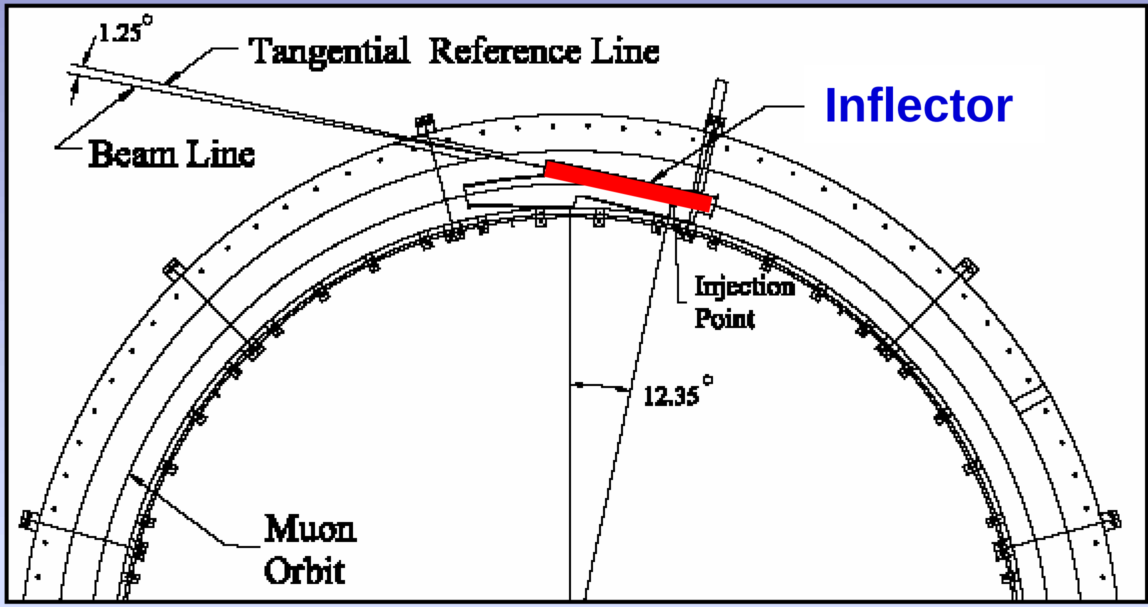
Approximately the same muon flux is realized, but studies continue on this



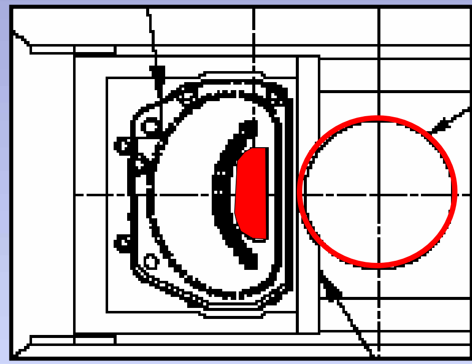
No hadron-induced prompt flash

x 1
more
muons
???

Improved transmission into the ring

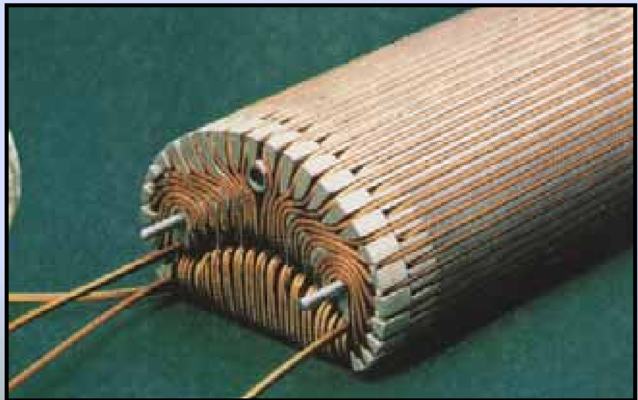


Inflector aperture



Storage ring aperture

E821 Closed End



Outscatters muons

P969 Proposed Open End

x 2 more muons

Presented to P5 Committee March 06

E969 Costs (2006 M$) (full cost review)

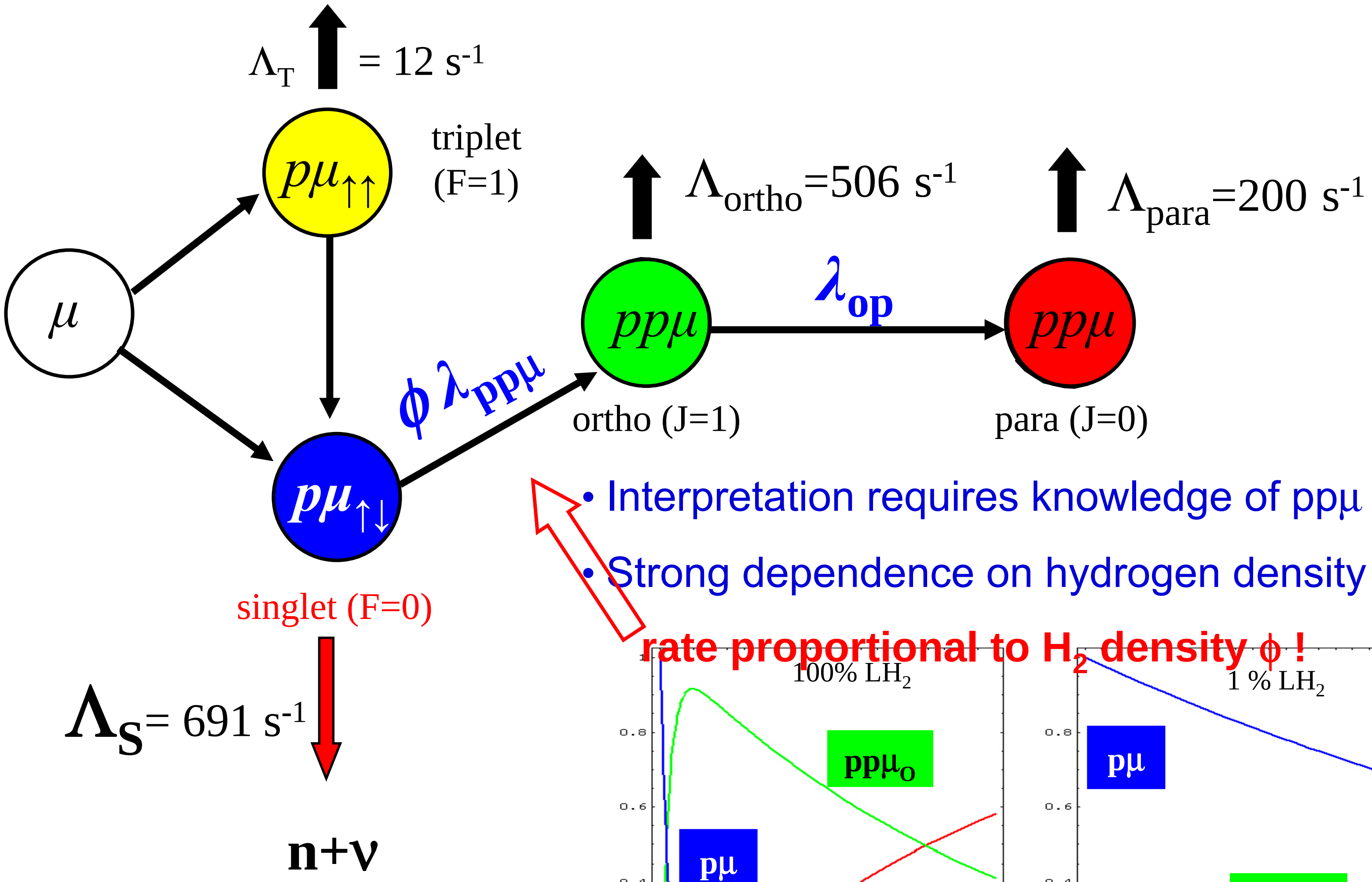
Baselining costs	0.4
AGS/Booster Rehab including ES&H	11.7
Construction (44% contingency)	12.2
Universities (27% contingency)	2.4
Operations (includes FTEs to support cryo and external beam operations)	13.6
Total Costs	40.2

The upgrade construction is ~$15 M including large contingencies

"Lab" costs for machines and running that normally aren't charged to an experiment

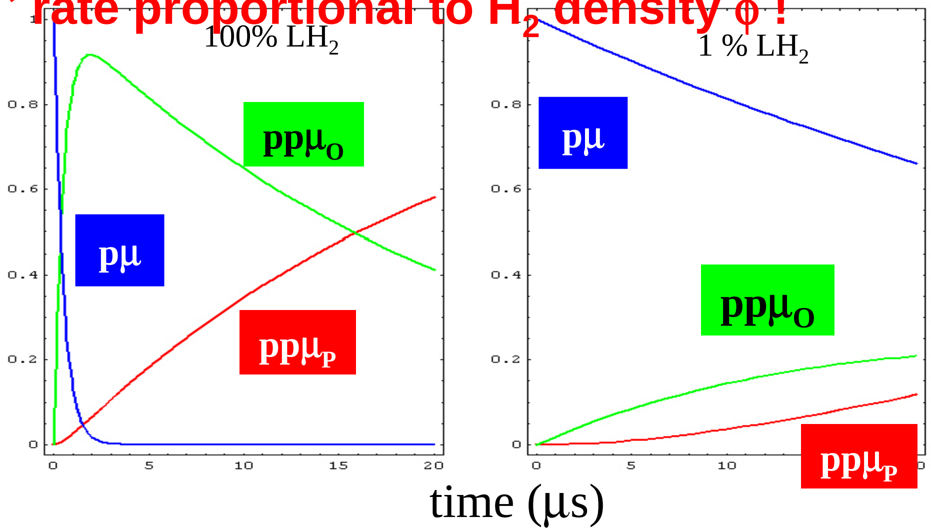
Seek: Partnership with DOE-NP / HEP and NSF

Muon capture and muon molecular processes



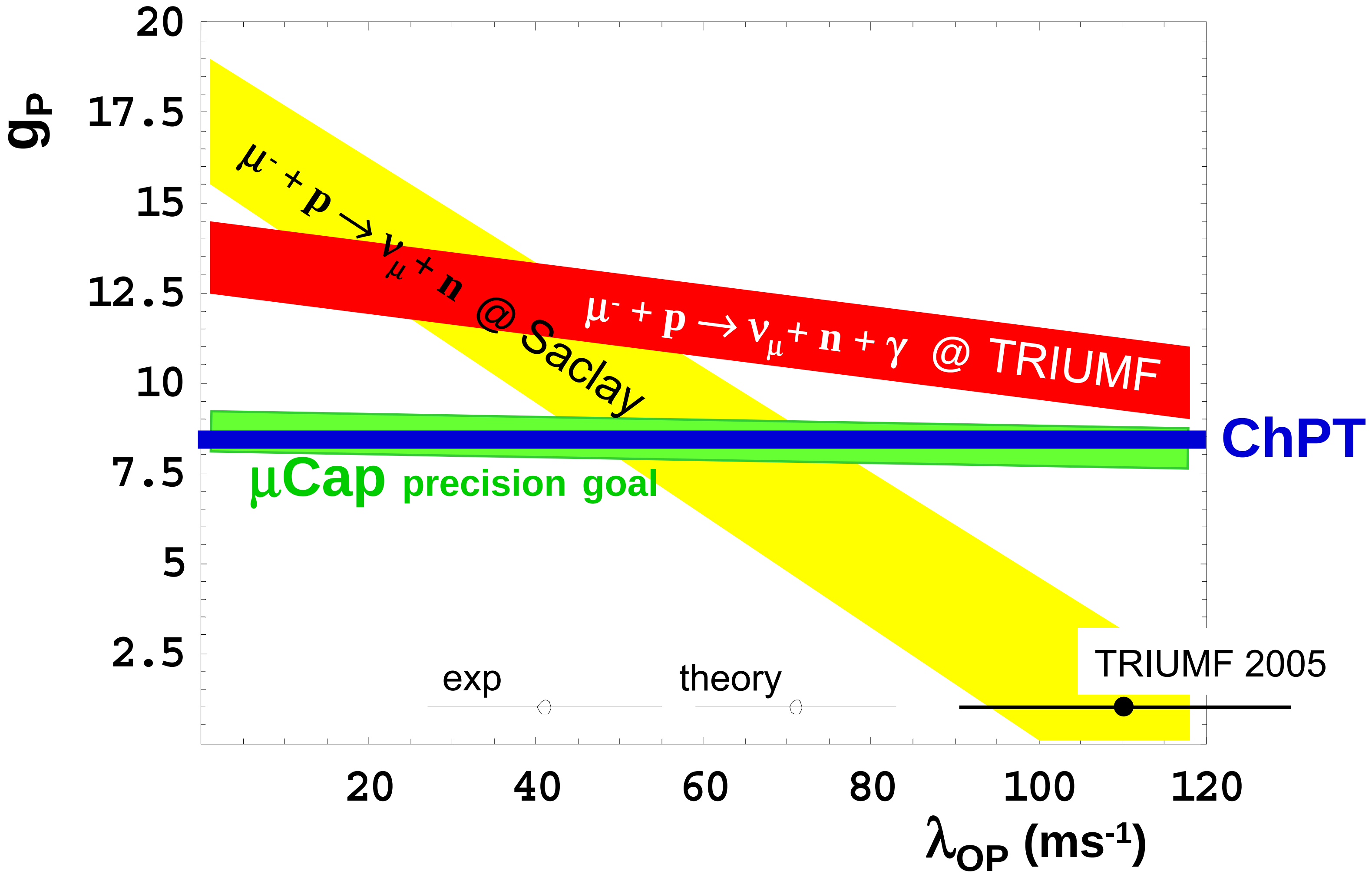
- Interpretation requires knowledge of ppμ population
- Strong dependence on hydrogen density ϕ

rate proportional to H_2 density ϕ !



P Kammel

Precise Theory vs. Controversial Experiments

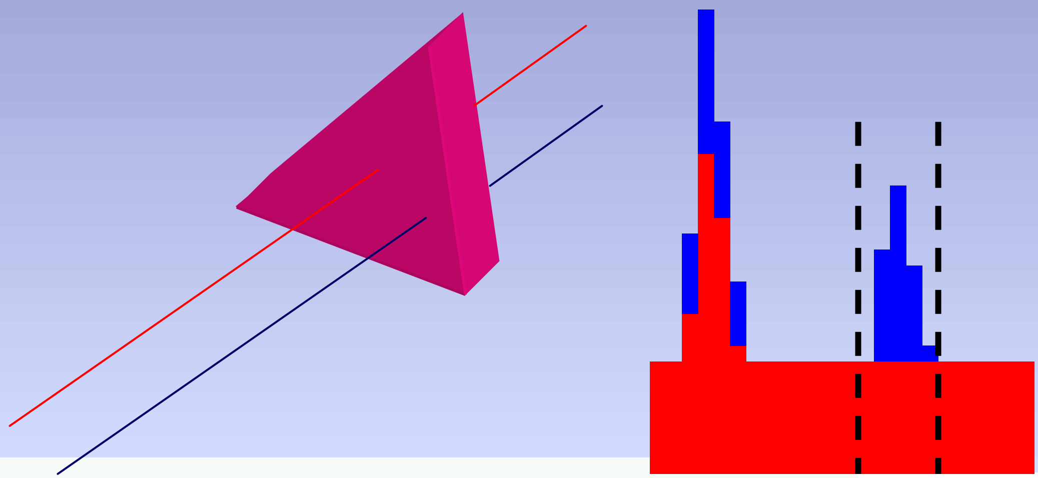


$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2) F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_a(0) m_\mu m_N r_A^2$$

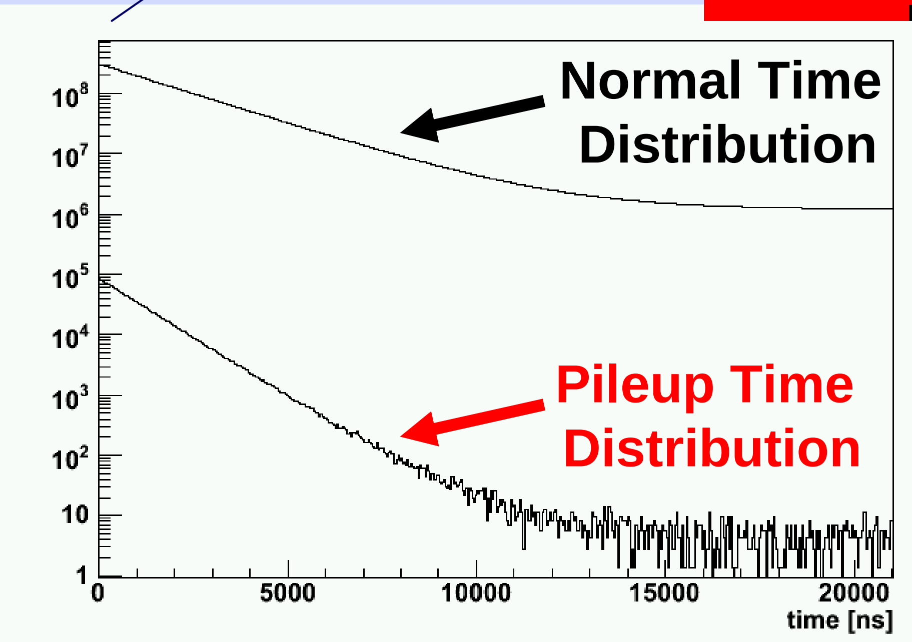
$$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.26 \pm 0.23$$

P Kammel

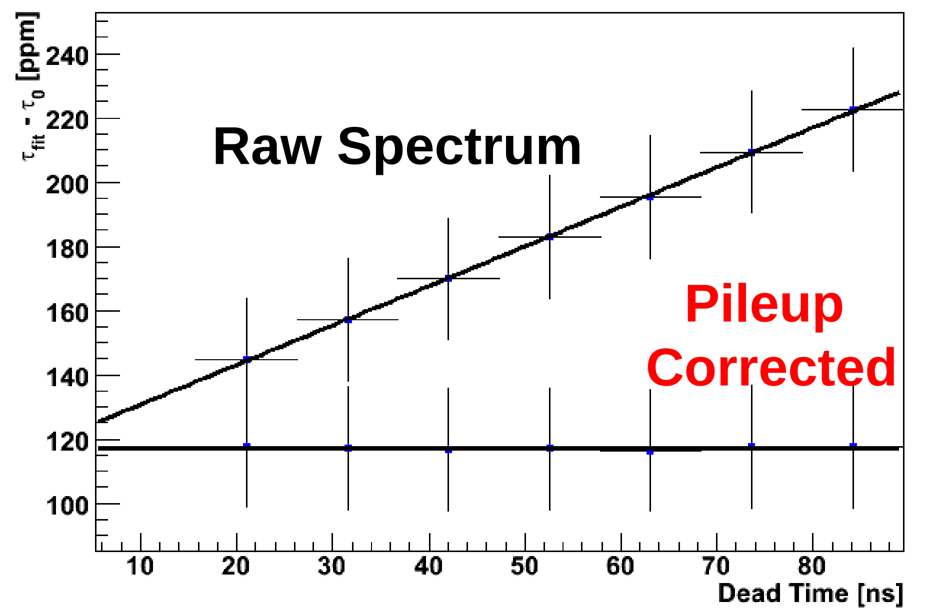
Systematics: Pileup



- Same probability
- Statistically reconstruct pileup time distribution
- Fit corrected distribution



Measured τ vs. Deadtime



Note: Experimental limits on η (non SM) are largest uncertainty of Fermi constant

G_F depends on η

$$G_F \approx G_F^{V-A}\left(1 - 2\eta\frac{m_e}{m_\mu}\right), \quad (7)$$

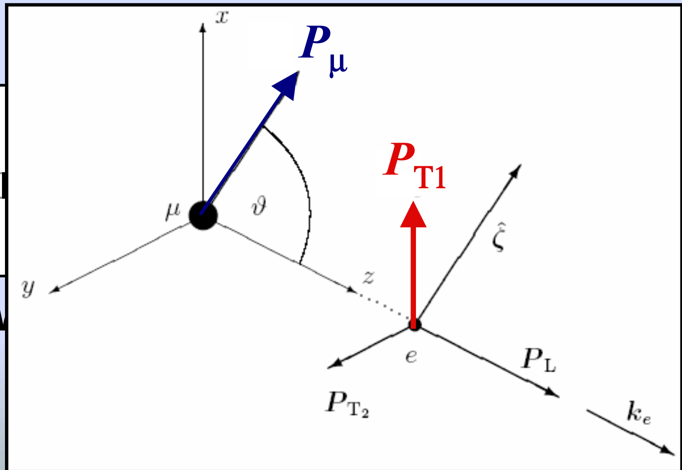
where m_e/m_μ is the mass ratio of electron and muon.

Danneberg et al, PRL 94 021802 (2005)

$$\eta = (-2.1 \pm 7.0 \pm 1.0) \times 10^{-3},$$

70 ppm uncertainty on G_F

Access to η through transverse polarization measurement of outgoing positron



Fetscher expt. PSI

Gl

New … r η