Outline

Constants of the Standard Model

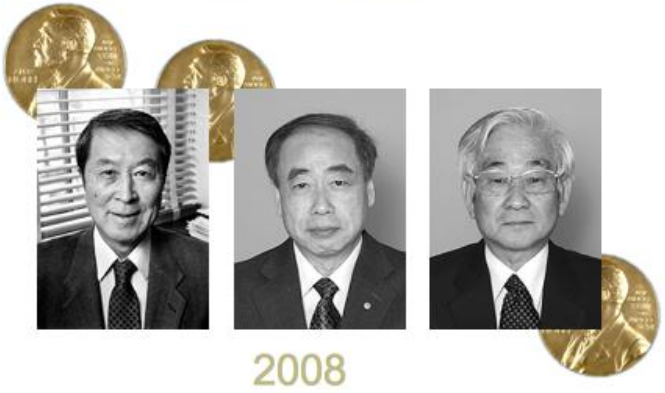
What makes a measurement?

Selected experiments

Conclusion

G
F

QFD has a rich phenomenology



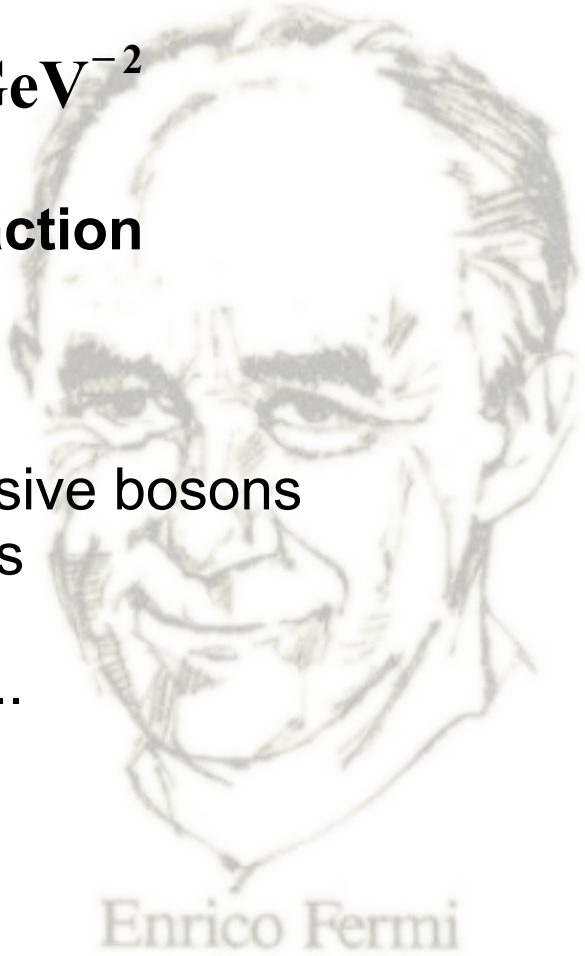
The weak coupling constant is

$$G_F \simeq 1.17 \times 10^{-5}\,\mathrm{GeV}^{-2}$$

WI is the only interaction

- changing flavor
- violating parity
- violating CP
- mediated by massive bosons
- affecting neutrinos

Many *ad hoc* inputs ...



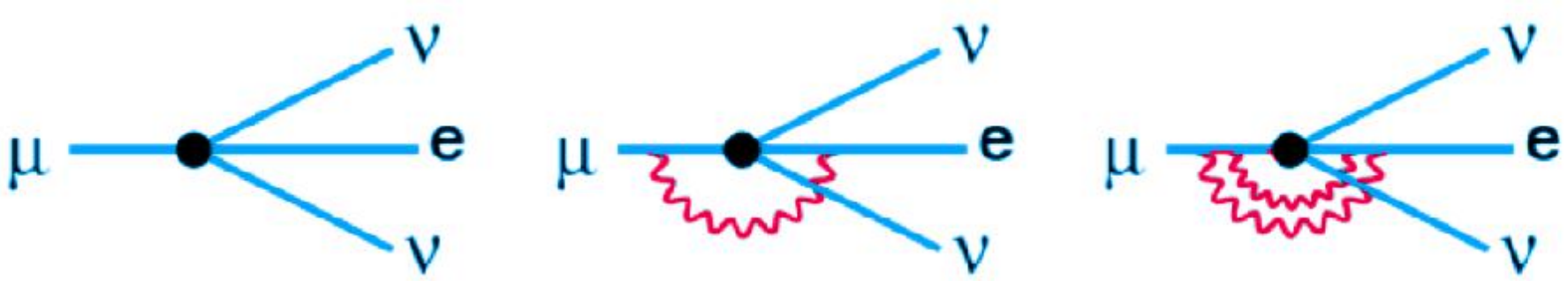
Muon lifetime in the SM

0.13ppm

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

Independent of underlying specifics of WI

$$\sum_{i=0} A_i \alpha^i \qquad \alpha(m_\mu) = 1/135.90$$



$$\Delta q = \Delta q^{(0)} + \Delta q^{(1)} + \Delta q^{(2)}$$

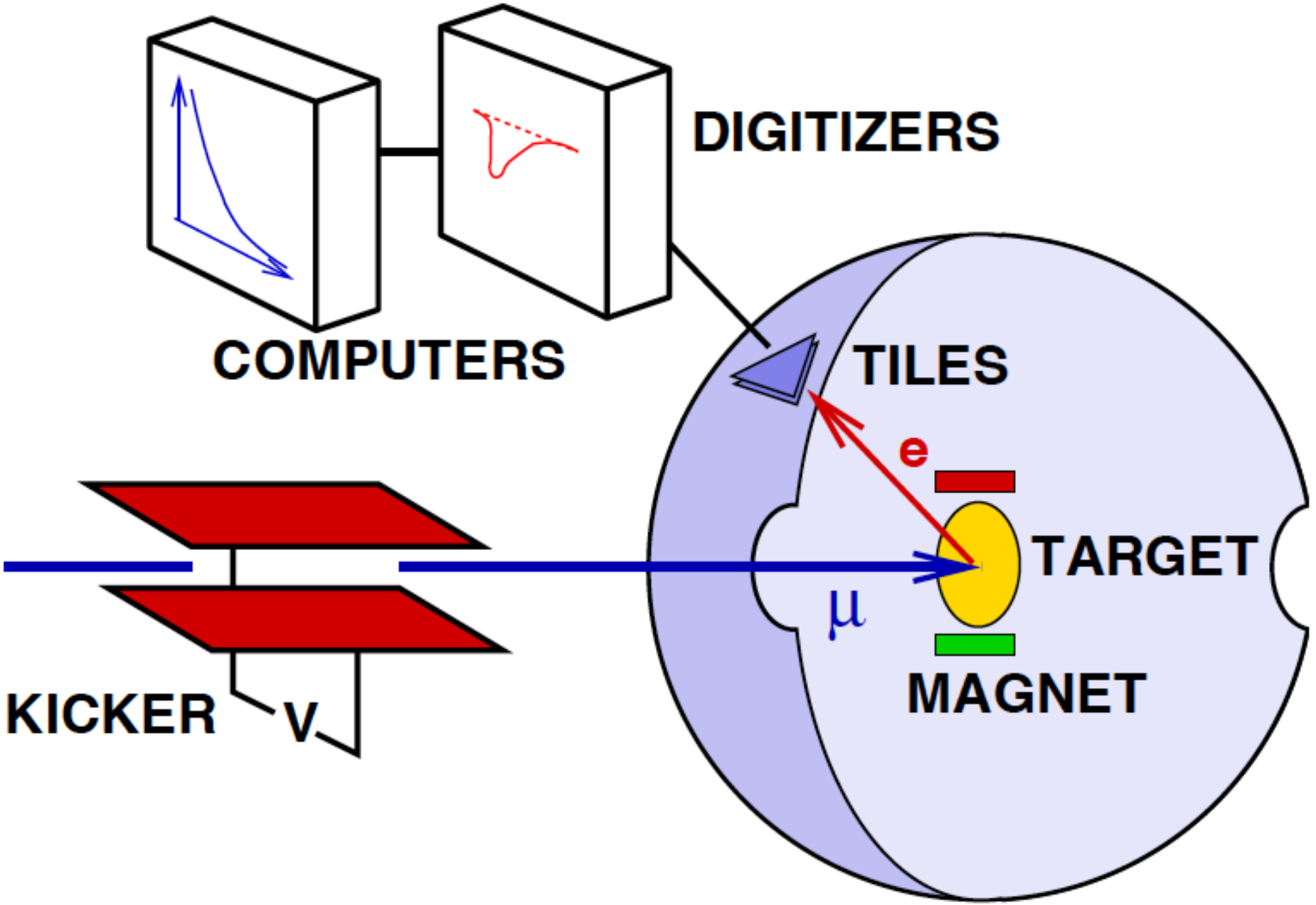
Phase space
10 ppm from $m_{\nu\mu}$
~0 from CMB

-4.1995 x 10^{-3}

+1.5 x 10^{-6}

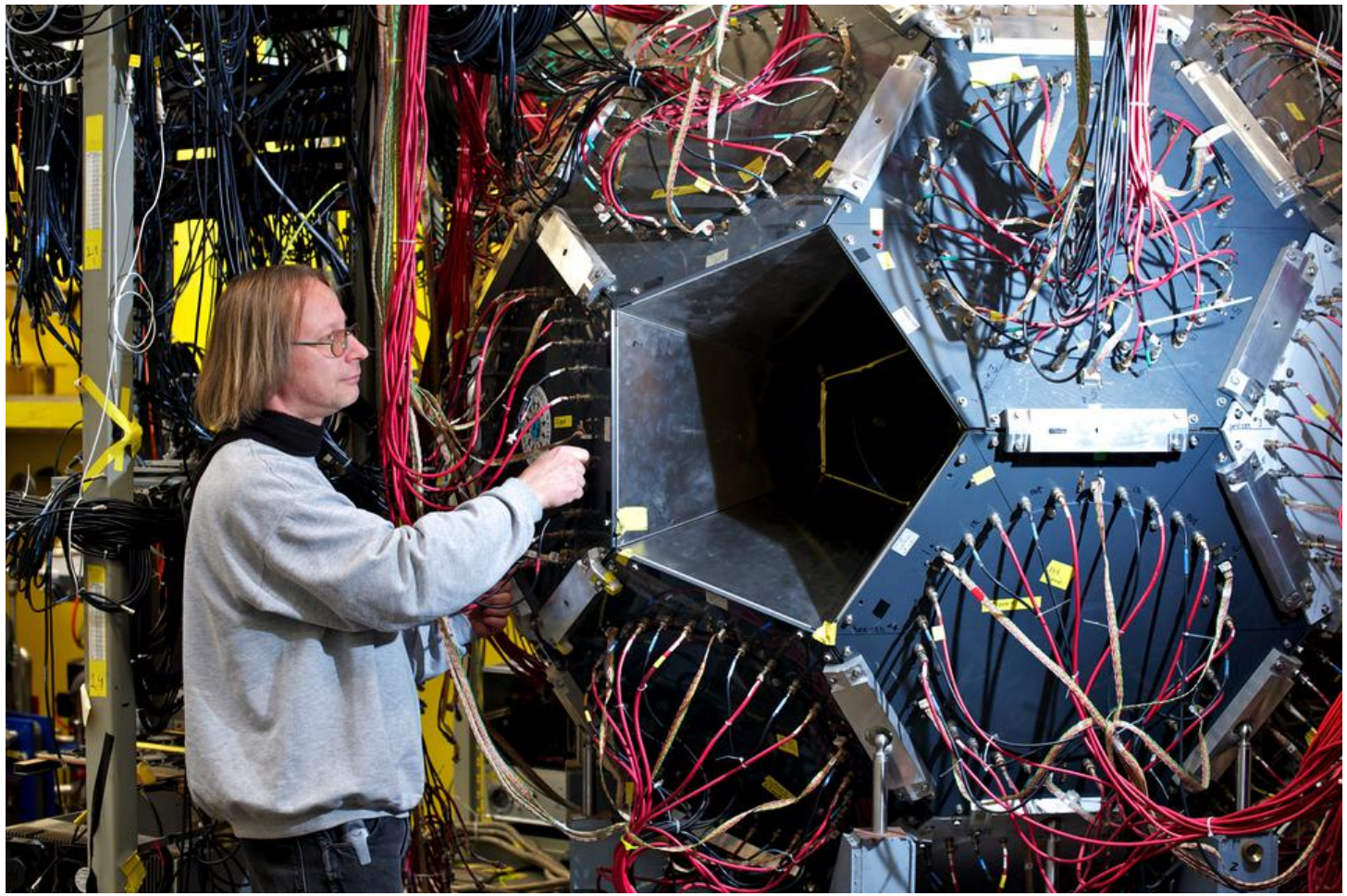
T. van Ritbergen, R.G. Stuart, Nucl.Phys. B564 (2000) 343-390

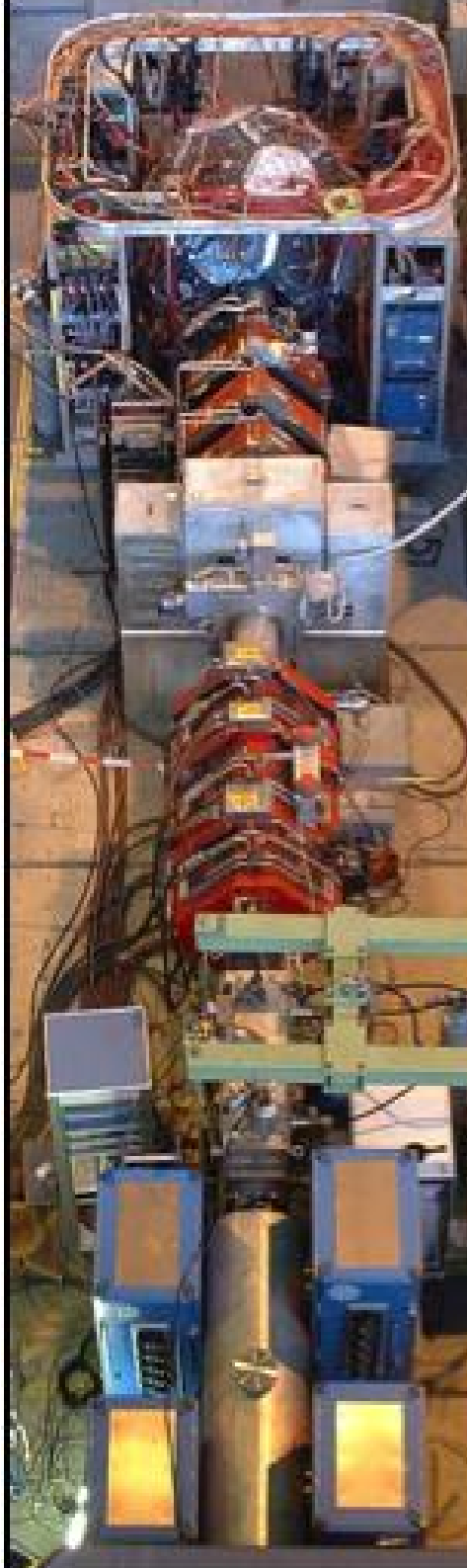
Principle of a lifetime measurement



What to do to get 1 ppm

Record 2×10^{12} muon decay times to <2ps



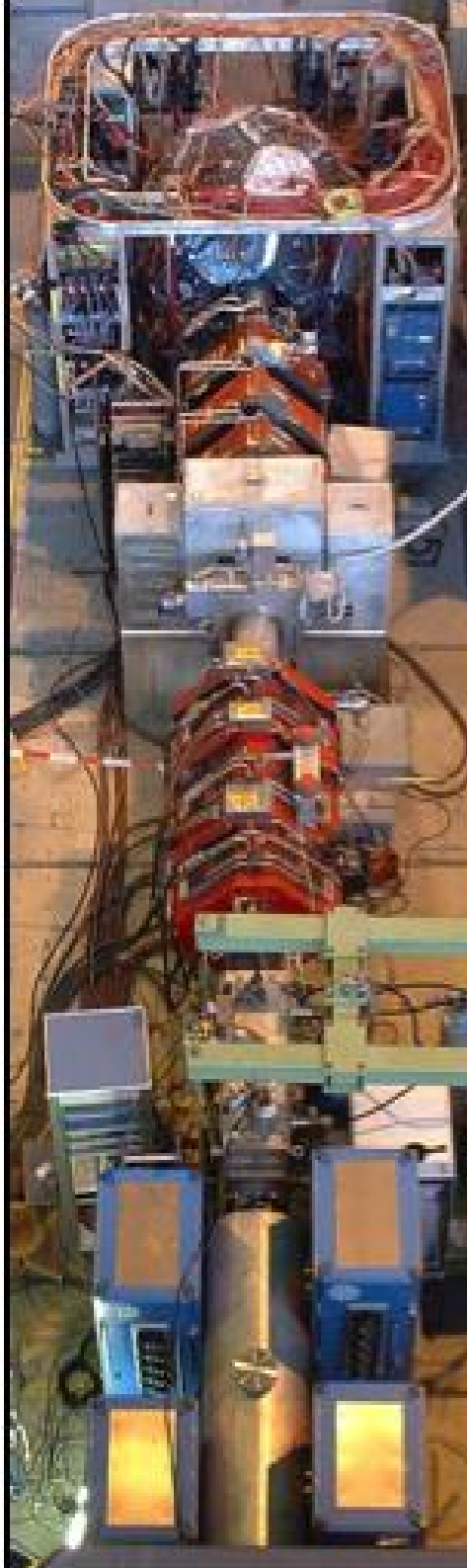


The muLan experiment @ PSI

- most intense muon beam (2MW protons)
- Chop DC beam: 5μs on + 22μs off
- Eliminate muon polarization effects
  - *“on” time = 5 spin cycles*
  - *magnetized stopper target*
  - *symmetric detector (170 elem.)*
- Keep acceptance constant < 10^{-6}/lifetime
- Record 2 x 10^{12} muons → 1 ppm statistics
- Blind analysis

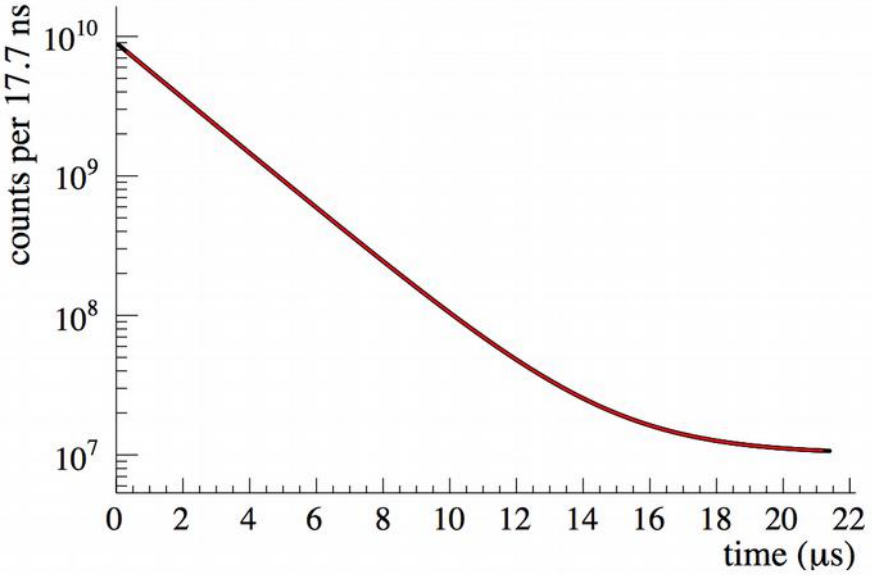
Computational challange

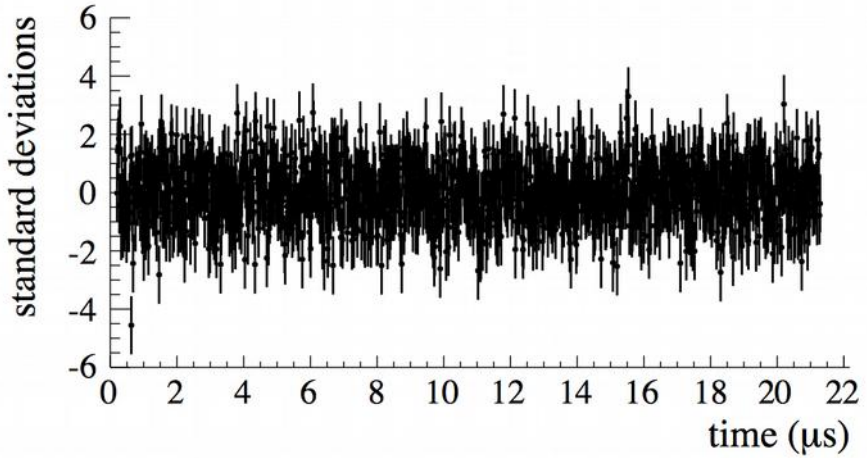
- 0.2 PByte
- 80,000 CPU hours per data pass

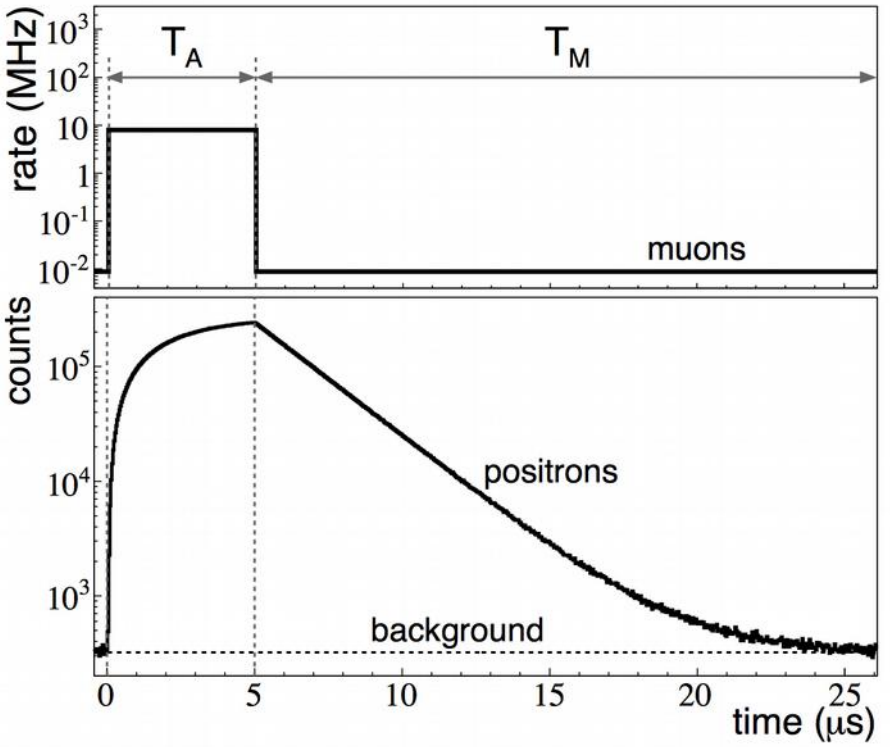


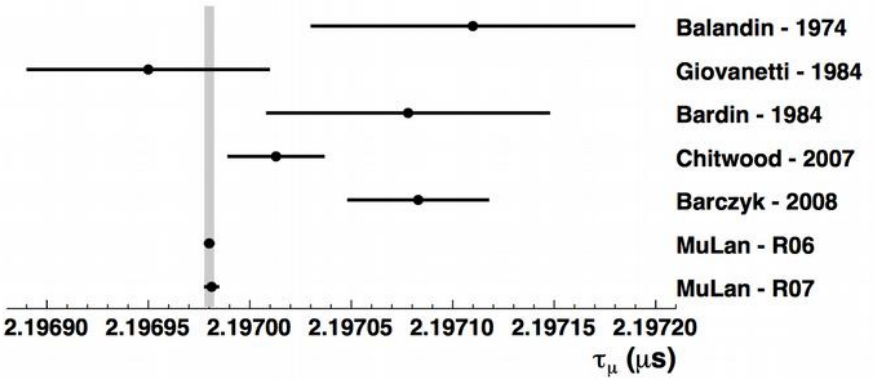
muLan results

χ^2 consistent with 1
for NDF ~ 1200, $\Delta\chi^2$=0.04









Phys. Rev. D 87, 052003 (2013)

Largest challenge : systematics

Effect uncertainty in ppm	R06	R07
Kicker stability	0.20	0.07
Spin precession or relaxation	0.10	0.20
Pileup	0.20	
Gain stability	0.25	
Upstream muon stops	0.10	
Timing stability	0.12	
Clock calibration	0.03	
Total systematic	0.42	0.42
Statistical uncertainty	1.14	1.68

Fermi coupling constant

$$\frac{1}{\tau_\mu^{th}} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q) \quad [\,<0.3\,\text{ppm}\,]$$

$$+$$

$$\tau_\mu^{exp} = 2.196\,9803(22)\,\mu s \quad [1\,\text{ppm}]$$

$$\downarrow$$

$$G_F = 1.166\,378\,8(7)\times 10^{-5}\,\text{GeV}^{-2} \quad [0.6\,\text{ppm}]$$

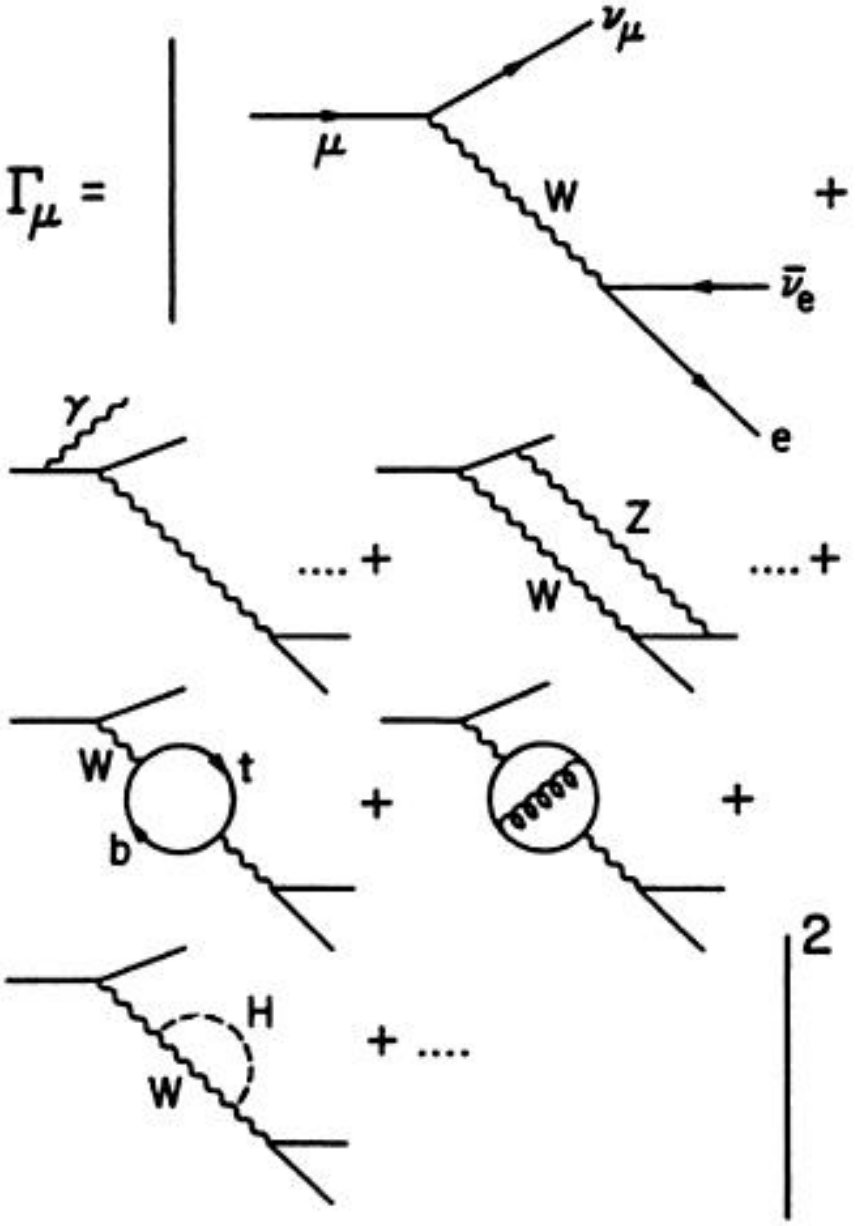
PRL 106, 041803 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011

Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

D. M. Webber,[1] V. Tishchenko,[2] Q. Peng,[3] S. Battu,[2] R. M. Carey,[3] D. B. Chitwood,[1] J. Crnkovic,[1] P. T. Debevec,[1] S. Dhamija,[2] W. Earle,[3] A. Gafarov,[3] K. Giovanetti,[4] T. P. Gorringe,[2] F. E. Gray,[5] Z. Hartwig,[3] D. W. Hertzog,[1] B. Johnson,[6] P. Kammel,[1] B. Kiburg,[1] S. Kizilgul,[1] J. Kunkle,[1] B. Lauss,[7] I. Logashenko,[3] K. R. Lynch,[3] R. McNabb,[1] J. P. Miller,[3] F. Mulhauser,[1,7] C. J. G. Onderwater,[1,8] J. Phillips,[3] S. Rath,[2] B. L. Roberts,[3] P. Winter,[1] and B. Wolfe[1]

(MuLan Collaboration)

Closer look at the radiative corrections



Combining high & low energy

Muon lifetime

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

m_{top} predicted at 179±11 GeV/c^2

CDF : m_{top} = 173.1±1.3 GeV/c^2

m_{top} now in global EW analysis

depend on m_Z, m_{Higgs}, m_t, α including 2nd order weak!

Boson masses (LEP)

$$G_F = \frac{\pi\,\alpha(0)}{\sqrt{2}\, M_W^2\left(1-M_W^2/M_Z^2\right)}\left(1+\Delta_r\right)$$

Other tests: W.J. Marciano, J. Phys. G: Nucl. Part. Phys. 29 (2003) 23–29

QED : most precise QFT available

The EM coupling constant is $\alpha = \frac{e^2}{\hbar c} \simeq \frac{1}{137}$

Smallness of α permits perturbative calculations

Very precise measurements and calculations possible, *e.g.*, hydrogen, muonium, positronium spectra and lepton anomalies

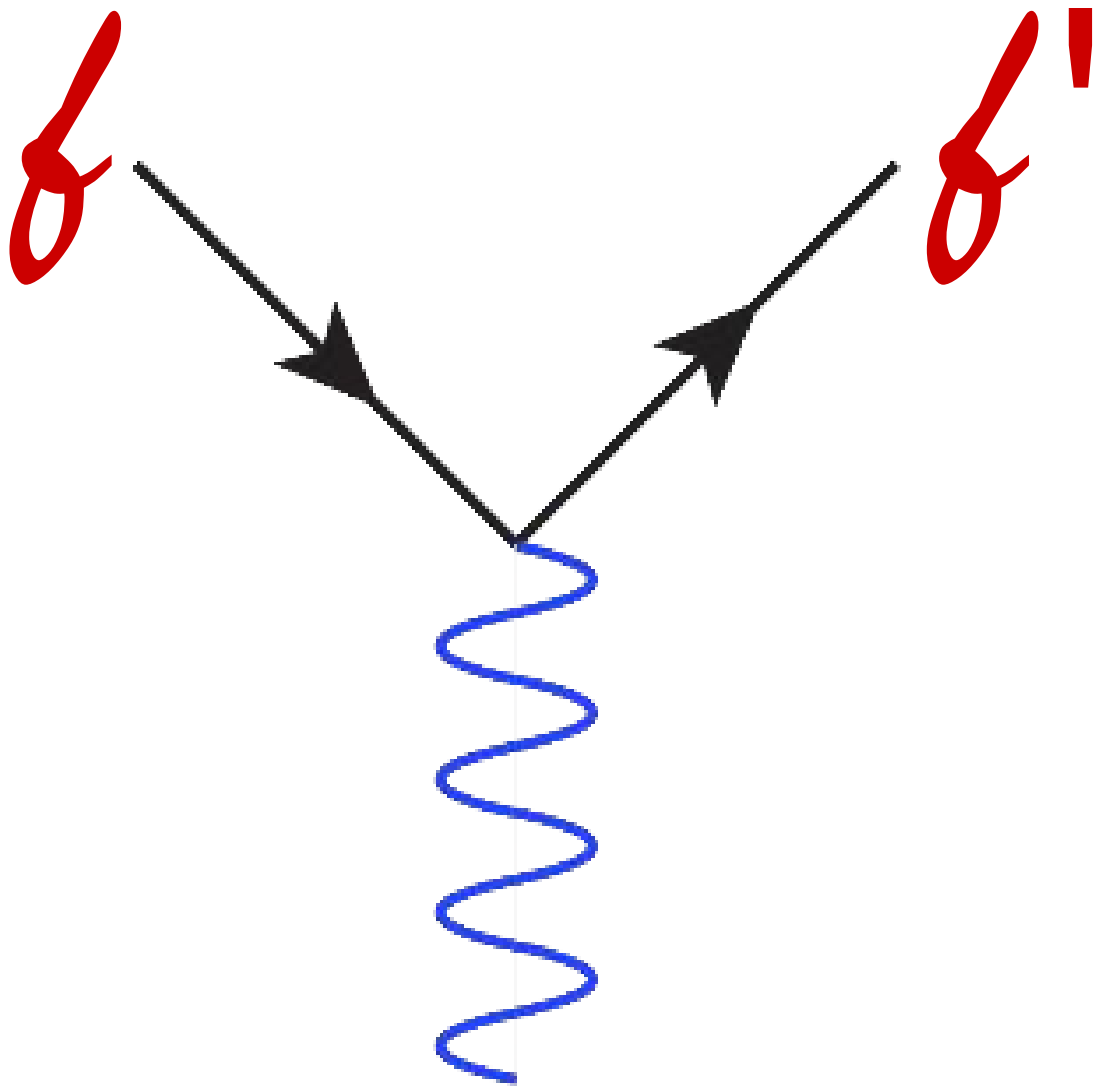
All QED observables of the form

$$A_{QED} = \sum_{n=1} A_i \left(\frac{\alpha}{\pi}\right)^n \qquad \frac{\alpha}{\pi} \simeq 2.3 \times 10^{-3}$$

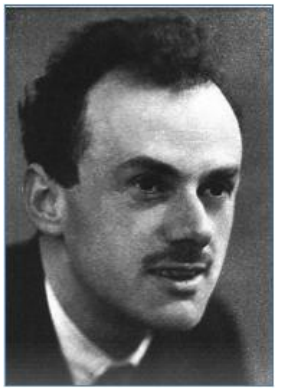
The Nobel Prize in Physics 1965

"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"

EM interaction of a fermion



EM dipole moments



This differs from (1) by the two extra terms

$$\frac{e\hbar}{c}(\sigma, \mathrm{H}) + \frac{ie\hbar}{c}\rho_1(\sigma, \mathrm{E})$$

in F. These two terms, when divided by the factor $2m$, can be regarded as the additional potential energy of the electron due to its new degree of freedom. The electron will therefore behave as though it has a magnetic moment $e\hbar/2mc$. σ

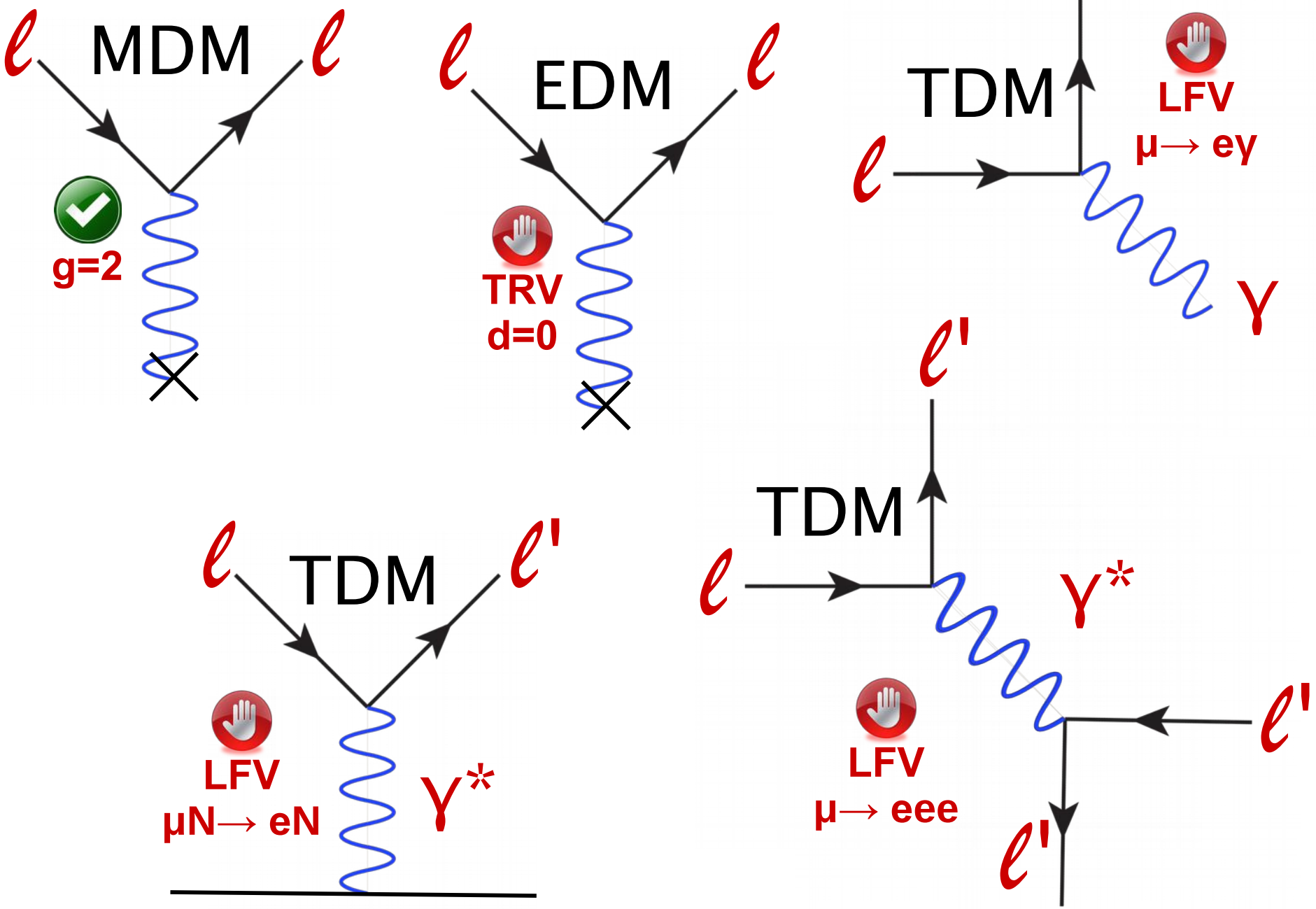
$$\vec{\mu} = g\frac{e\hbar}{2mc}\hat{\sigma} \qquad \vec{d} = \eta\frac{e\hbar}{2mc}\hat{\sigma}$$

$$g = 2(a+1) \qquad \eta = 0$$

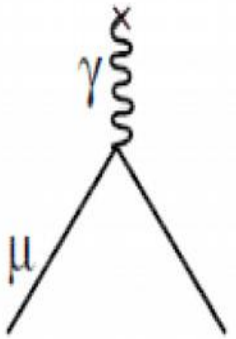
Anomaly — P & T conservation

This is where the physics is!

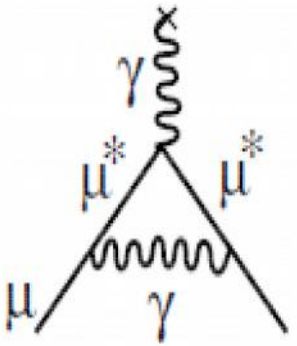
QED vertices



Radiative corrections

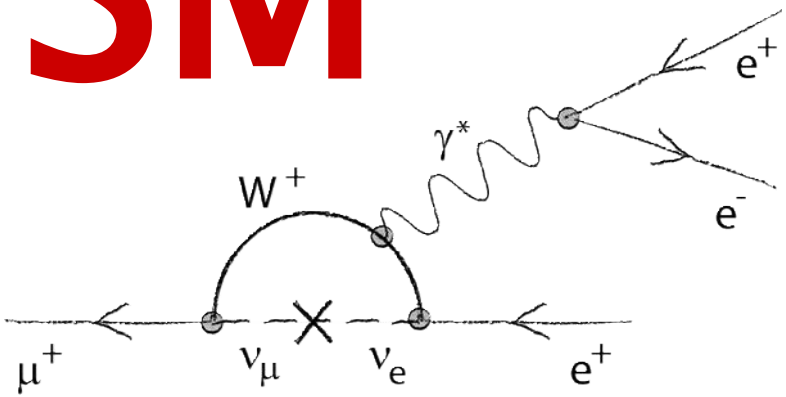


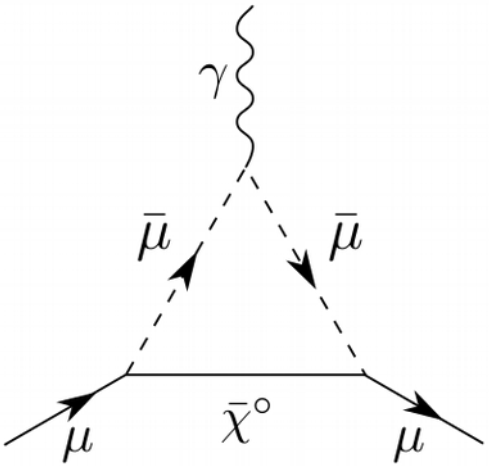
Dirac

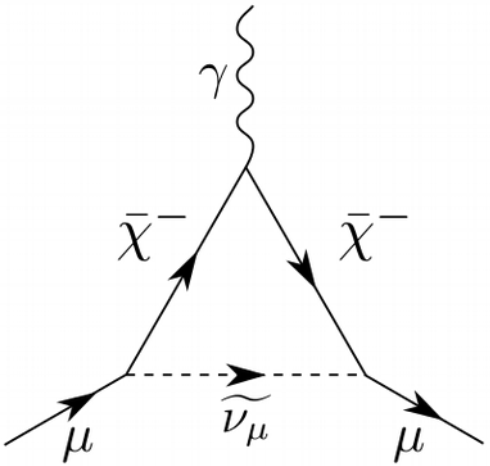


Schwinger

SM







BSM

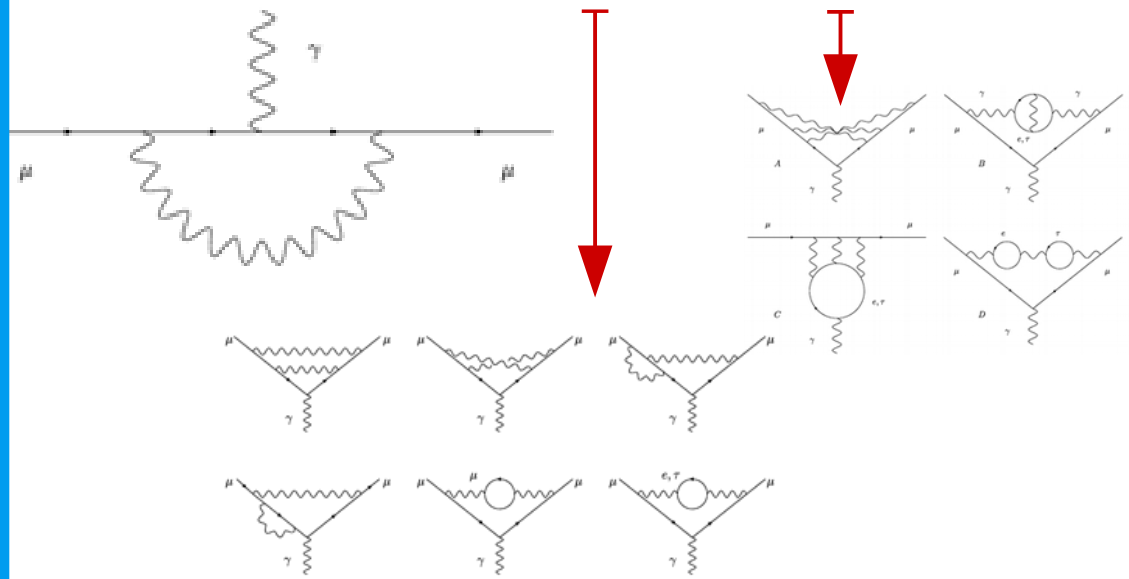
Electron anomaly in the SM

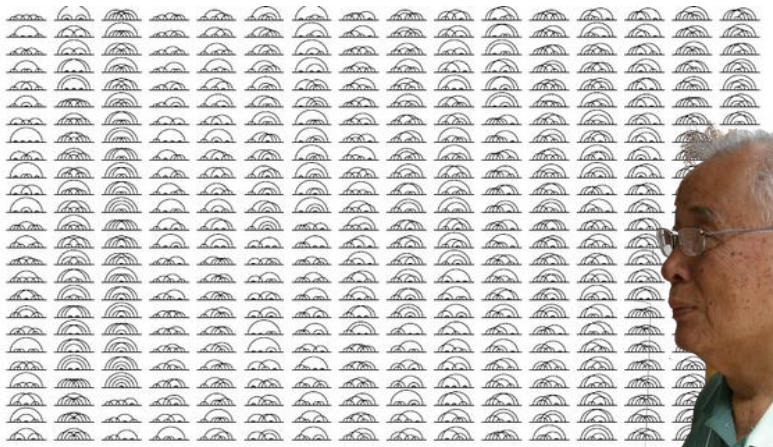
Kinoshita & Feynman

0.5 -0.328 478 444 002 90(60) +1.181 234 016 827 (19) -1.9144 (35) 0.0 (4.6)

$$a_e = a_1\left(\frac{\alpha}{\pi}\right) + a_2\left(\frac{\alpha}{\pi}\right)^2 + a_3\left(\frac{\alpha}{\pi}\right)^3 + a_4\left(\frac{\alpha}{\pi}\right)^4 + a_5\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

#diagrams: 1 7 72 891 12672



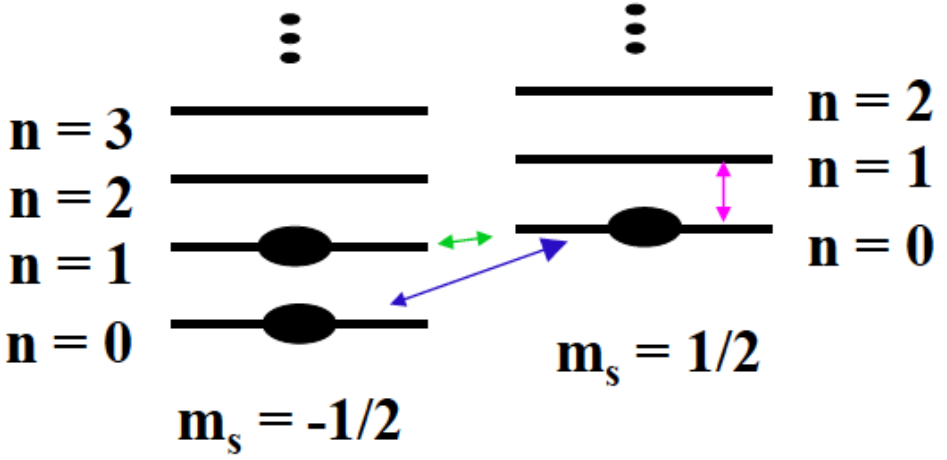


QM101 : "Geonium" atom

$$\vec{\mu} = \frac{e}{2m}\left(g\vec{S} + \vec{L}\right) \qquad H = -\vec{\mu}\cdot\vec{B}$$

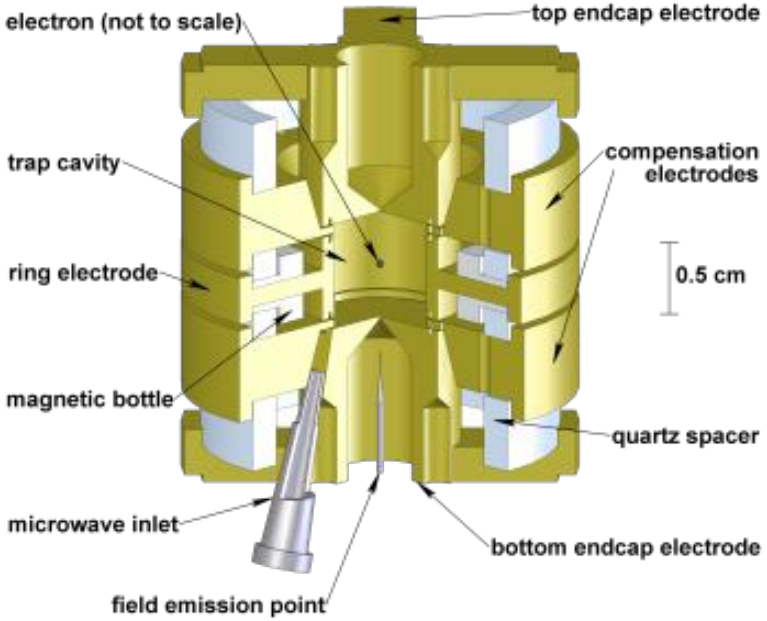
$$\frac{g}{2} = \frac{\omega_s}{\omega_c} = 1 + \frac{\omega_a}{\omega_c}$$

simplified



149GHz ↔ 0.6meV ↔ 7K

One-electron quantum cyclotron



- **Resolve lowest cyclotron and spin states**
- Quantum jump spectroscopy
- Cavity-controlled spontaneous emission
- Radiation field controlled by cylindrical trap cavity
- Cooling away of blackbody photons
- Synchronized electrons probe cavity radiation modes
- Elimination of nuclear paramagnetism
- One-particle self-excited oscillator

g/2 = 1.001 159 652 180 73(28) (0.28ppt)

Fine structure constant

$$a_e^{\exp} = g/2 - 1 = 0.001\,159\,652\,180\,73\,(28)$$

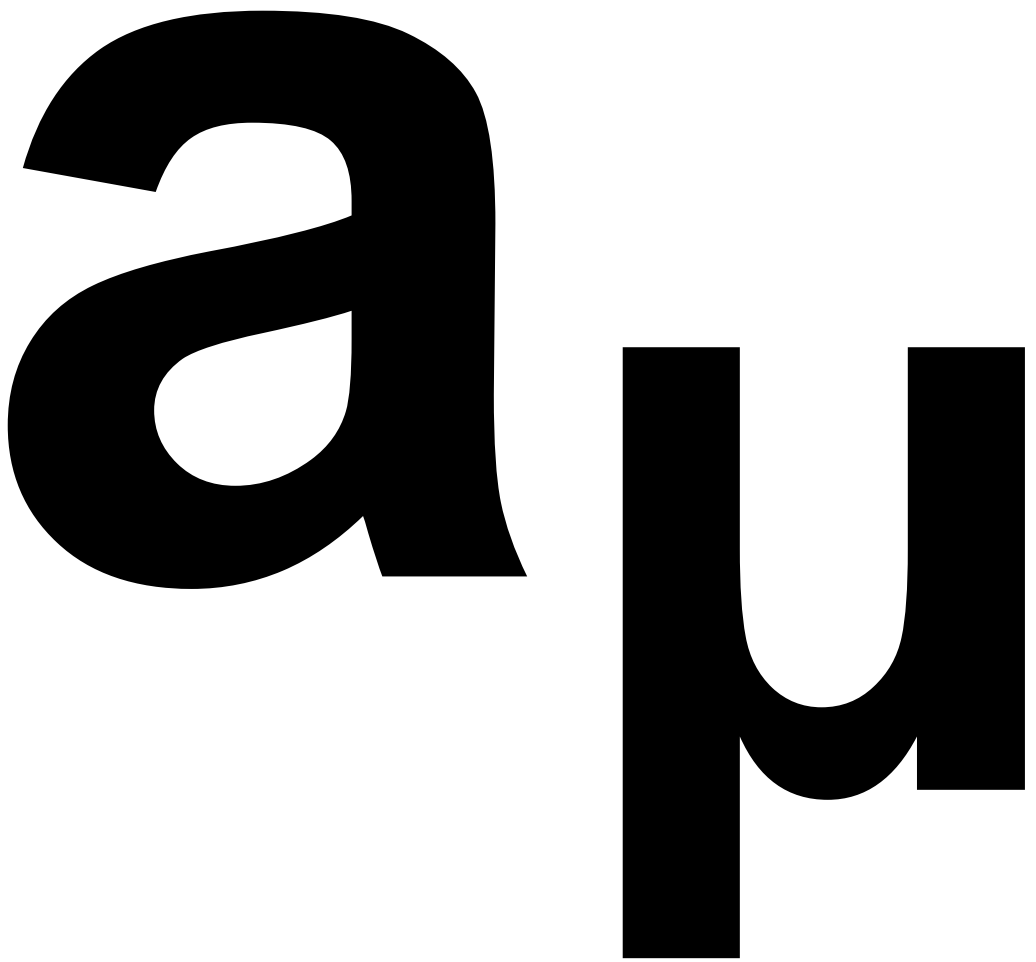
$$+$$

$$a_e = a_1\left(\frac{\alpha}{\pi}\right) + a_2\left(\frac{\alpha}{\pi}\right)^2 + a_3\left(\frac{\alpha}{\pi}\right)^3 + a_4\left(\frac{\alpha}{\pi}\right)^4 + a_5\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

$$\downarrow$$

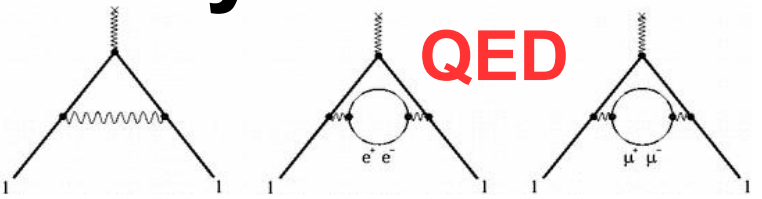
$$\frac{1}{\alpha} = 137.035\,999\,084\,(51)\,[0.37\ ppb]$$

D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. 100, 120801 (2008)

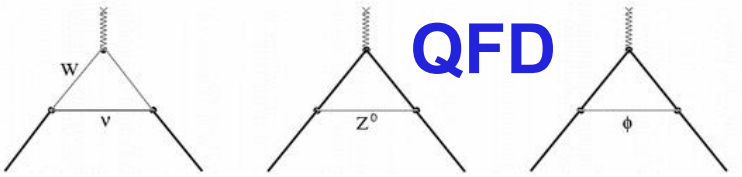

a_μ

Beyond QED : muon anomaly

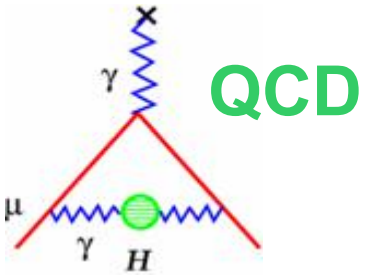
Generated via radiative corrections



$$a_\mu = a_\mu^{QED} + a_\mu^{QCD} + a_\mu^{QFD} + a_\mu^{new}$$

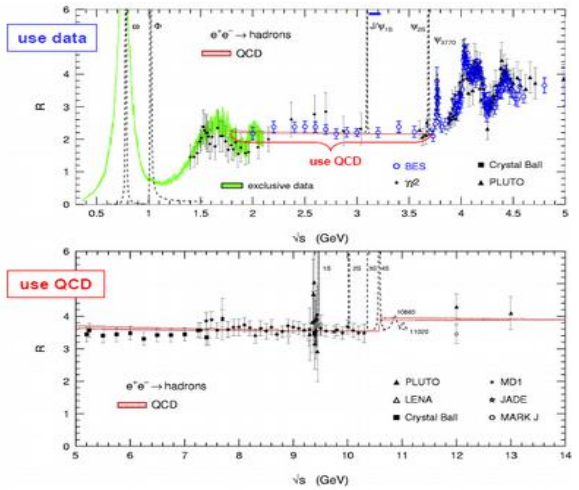


1,000,000 : 60 : 1



a : calibration point for SM (QED+QCD+QFD)
Δa : calibration point for all new theories

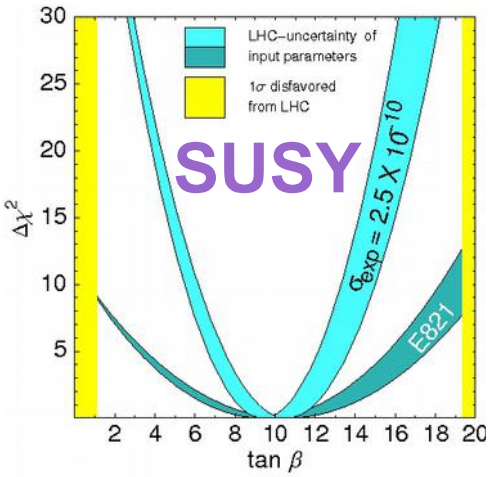
QCD dominates theory uncertainty (~0.5ppm)



$$a_\mu^{\mathrm{had,LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds\, \frac{R(s)\,\hat{K}(s)}{s^2},$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

(arXiv:0705.4617v1)



Larmor precession

Spin precession at rest in a magnetic field

$$\frac{d\vec{s}}{dt} = -\vec{\mu} \times \vec{B} \quad \rightarrow \quad \vec{\Omega} = g \frac{e\hbar}{2mc} \vec{B}$$

Measure B in terms of proton NMR frequency

$$g_\mu = g_p \frac{\Omega_\mu}{\Omega_p} \frac{m_\mu}{m_p}$$

g_p = 5.585 694 713(46)

measure

0.112 609 5261(29)

Precession in a storage ring

$$\frac{d\vec{s}}{dt} = \frac{e}{mc}\vec{s} \times \left[\left(a + \frac{1}{\gamma}\right)\vec{B} + \frac{a\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\vec{\beta}\times\vec{E}\right]$$

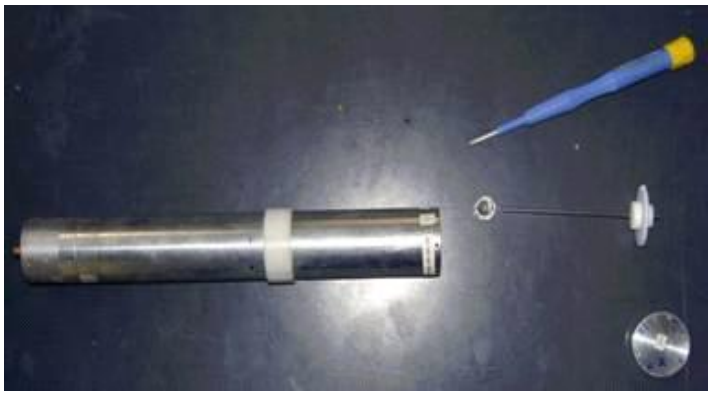
$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma mc}\left[\vec{E} + \vec{\beta}\times\vec{B} - \vec{\beta}(\vec{\beta}\cdot\vec{E})\right]$$

$$\omega_a = \omega_s - \omega_\beta = a\frac{e}{mc}B$$

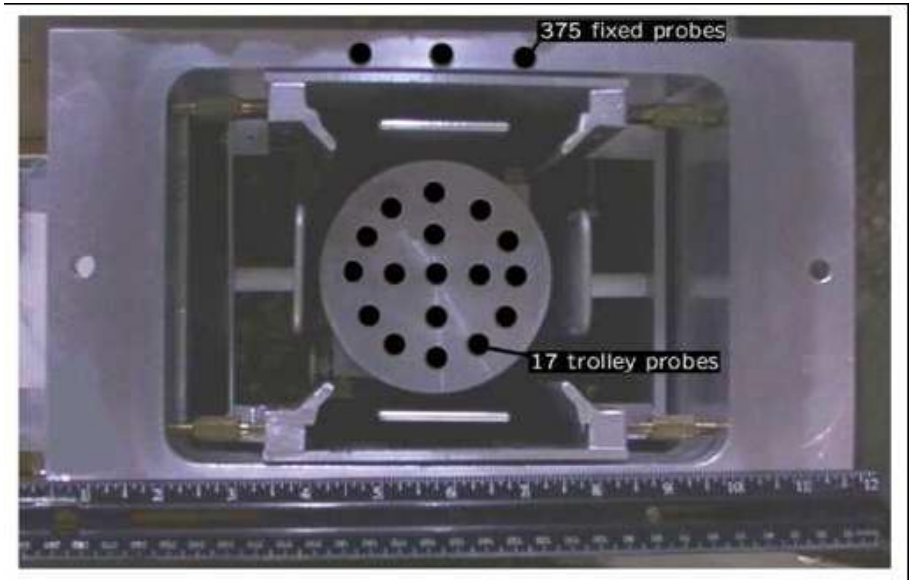
Measure spin precession & magnetic field

Storage ring @ BNL

4D magnetic field tracking

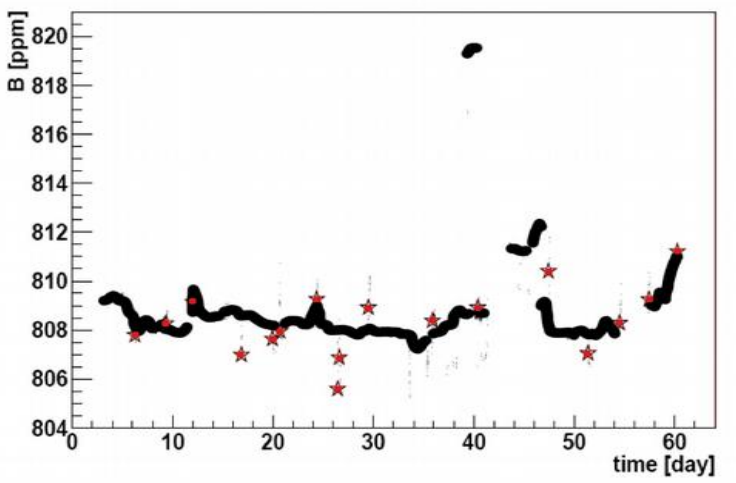


Beam profile weighing &
t interpolation

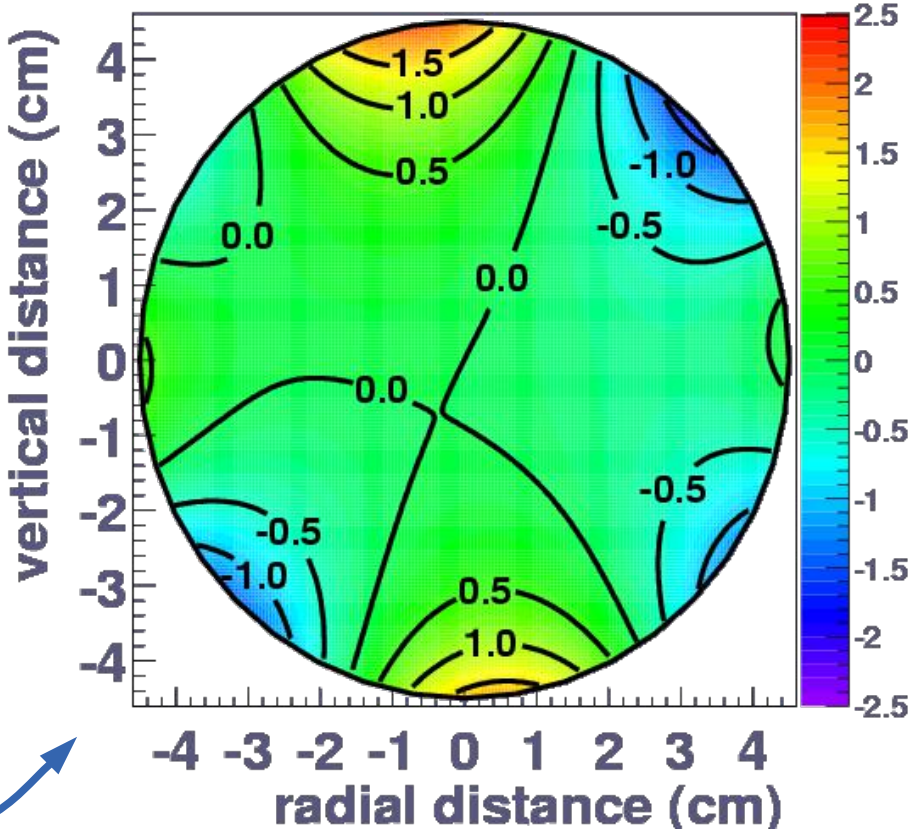


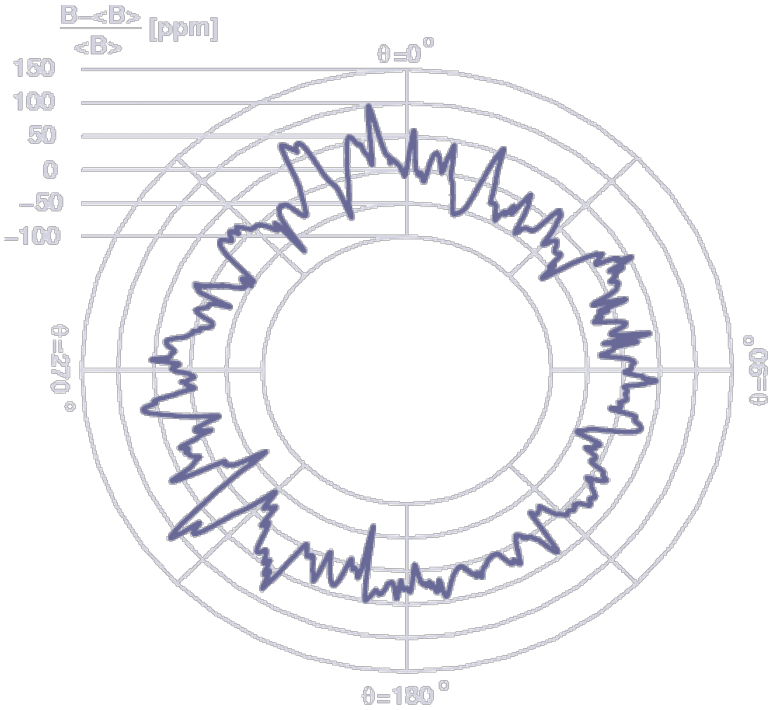
φ averaging &
(x,y) multipole expansion

4D magnetic field tracking



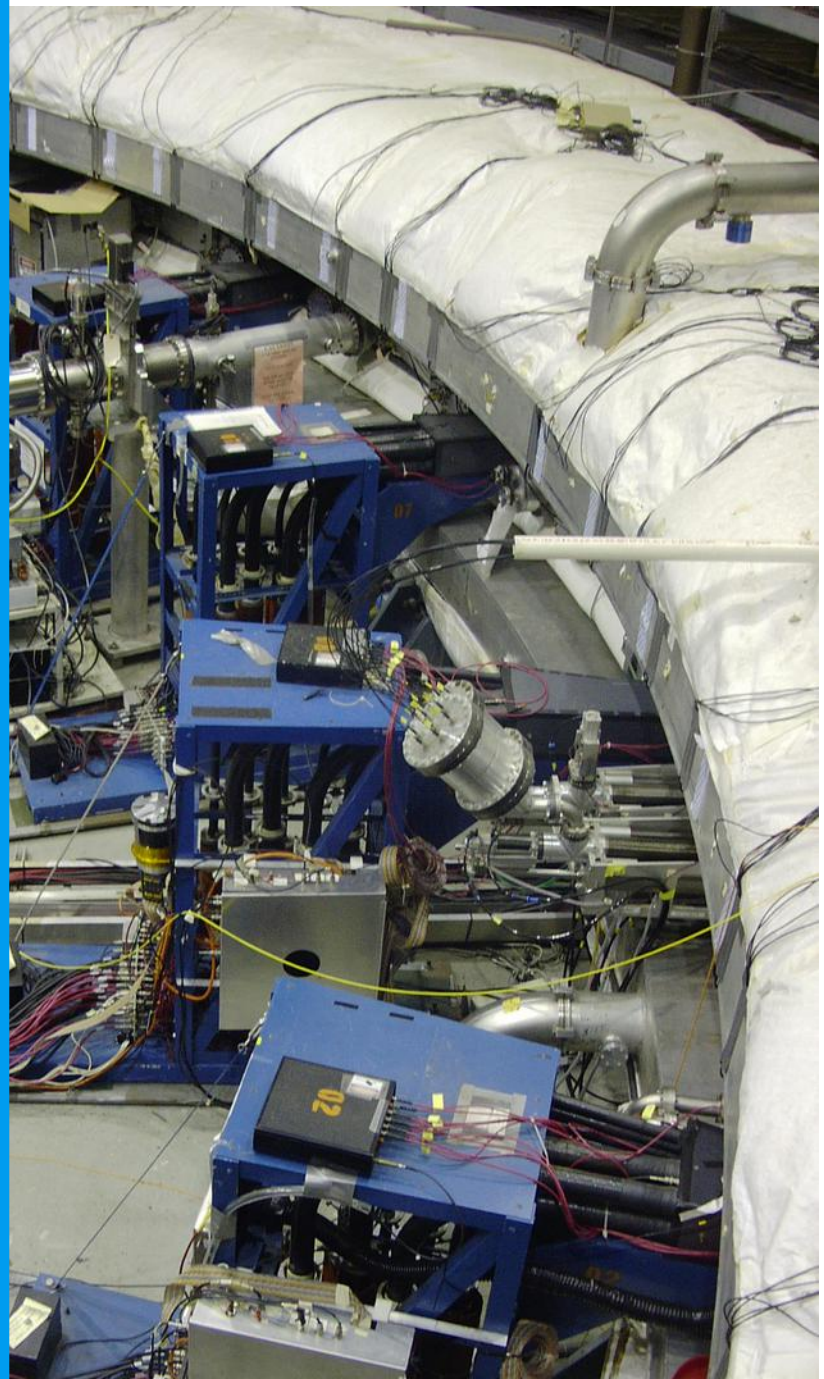
Beam profile weighing &
t interpolation





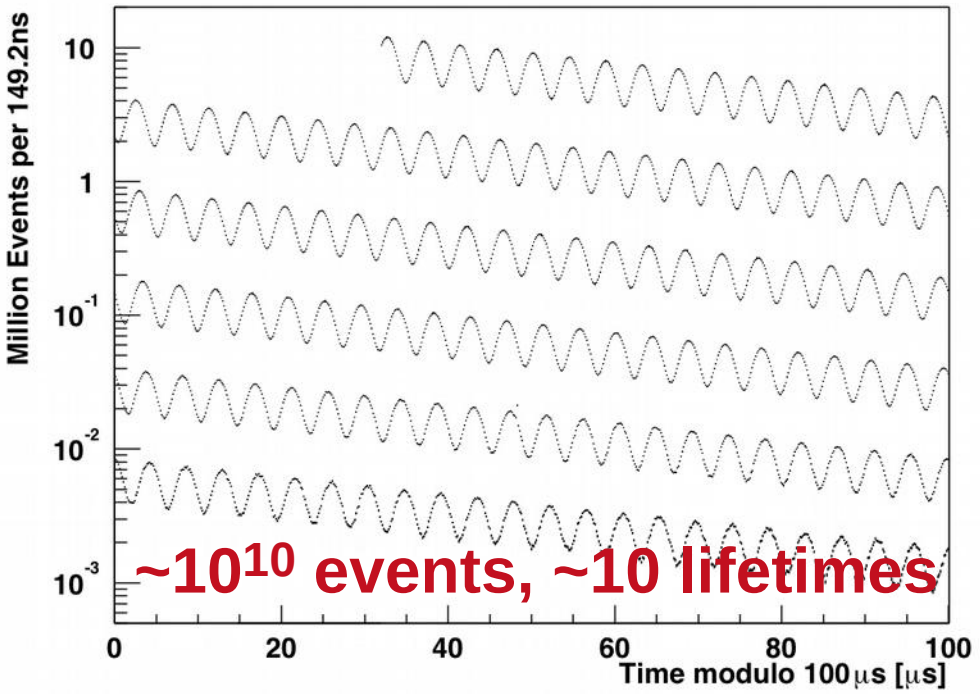
φ averaging &
(x,y) multipole expansion

Muon spin tracking



- $e^{\pm}$ emission correlated to μ spin
- E_{lab} ← boost → θ_{CM}
- detect electron time & energy

- 24 Pb-fiber calos w/ WFD readout
- segmented scint. detectors
- trace back detector
- Fiber harps



Double blind analysis

$$R = \frac{\omega_a}{\omega_p} \qquad a_\mu = \frac{R}{\lambda - R} \qquad \lambda = \frac{\mu_\mu}{\mu_p}$$

- ω_a and ω_p analyzed independently
  ↳ unknown offsets
- ω's analyzed independently by several groups (2-5)
  ↳ unknown offsets
- require internal consistency
  ↳ χ^2, insensitive to irrelevant variations, ...
- require mutual consistency (incl. systematics)
  ↳ ω's equal within (highly correlated) statistics, ...
- obtain all systematics (incl. E-field, pitch, ...)
  ↳ understand differences, ...
- remove offset, do long-division and publish
  ↳ no room for discussion!

Uncertainties

TABLE XI. Systematic errors for the magnetic field for the different run periods.

Source of errors	R99 [ppm]	R00 [ppm]	R01 [ppm]
Absolute calibration of standard probe	0.05	0.05	0.05
Calibration of trolley probes	0.20	0.15	0.09
Trolley measurements of B_0	0.10	0.10	0.05
Interpolation with fixed probes	0.15	0.10	0.07
Uncertainty from muon distribution	0.12	0.03	0.03
Inflector fringe field uncertainty	0.20	—	—
Others[a]	0.15	0.10	0.10
Total systematic error on ω_p	0.4	0.24	0.17
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61791256	61791595	61791400

[a]Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

TABLE XIV. Systematic errors for ω_a in the R99, R00 and R01 data periods.

σ_{syst} ω_a	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	[a]
Lost muons	0.10	0.10	0.09
Timing shifts	0.10	0.02	[a]
E-field and pitch	0.08	0.03	[a]
Fitting/binning	0.07	0.06	[a]
CBO	0.05	0.21	0.07
Gain changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

[a]In R01, the AGS background, timing shifts, E field and vertical oscillations, beam debunching/randomization, binning and fitting procedure together equaled 0.11 ppm.

Storage ring results

QED

QCD

QFD

new?

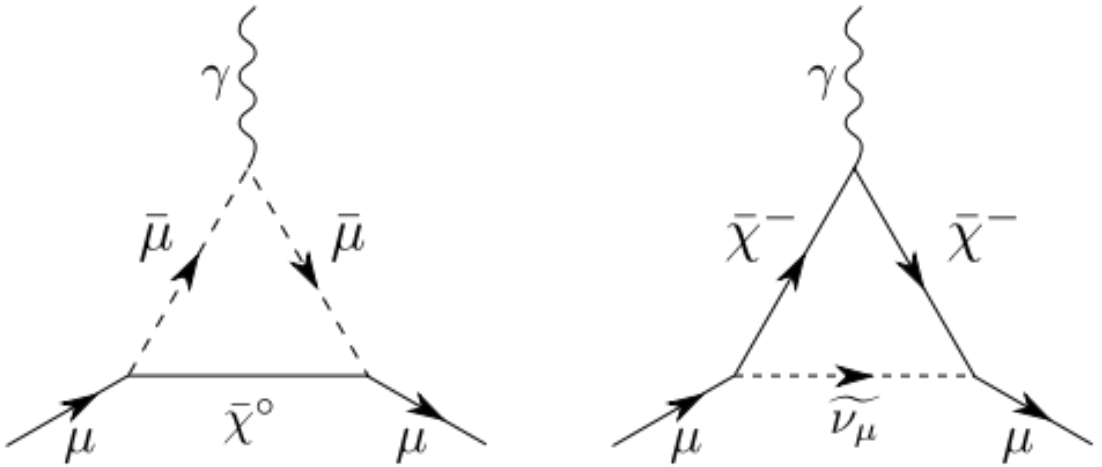
Year	a_μ	σa_μ	Ref.	
1961	0.001145	0.000022	Charpak	CERN
1965	0.001162	0.000005	Charpak	
1966	0.001165	0.000003	Farley	
1969	0.001060	0.000067	Henry	
1972	0.00116616	0.00000031	Bailey	
1975	0.001165895	0.000000027	Bailey	
1979	0.001165910	0.000000012	Bailey	
1979	0.001165936	0.000000012	Bailey	
1999	0.001165925	0.000000015	Carey	BNL
2000	0.0011659191	0.0000000059	Brown	
2001	0.0011659202	0.0000000015	Brown	
2002	0.0011659204	0.0000000009	Bennett	
2004	0.0011659214	0.0000000009	Bennett	

$a_\mu(\text{expt.}) - a_\mu(\text{th}) = (30 \pm 8) \times 10^{-10}$ (3.6σ)

Experiment: $\sigma_a/a = 0.54$ ppm

Theory: $\sigma_a/a = 0.44$ ppm

Sensitivity for new physics

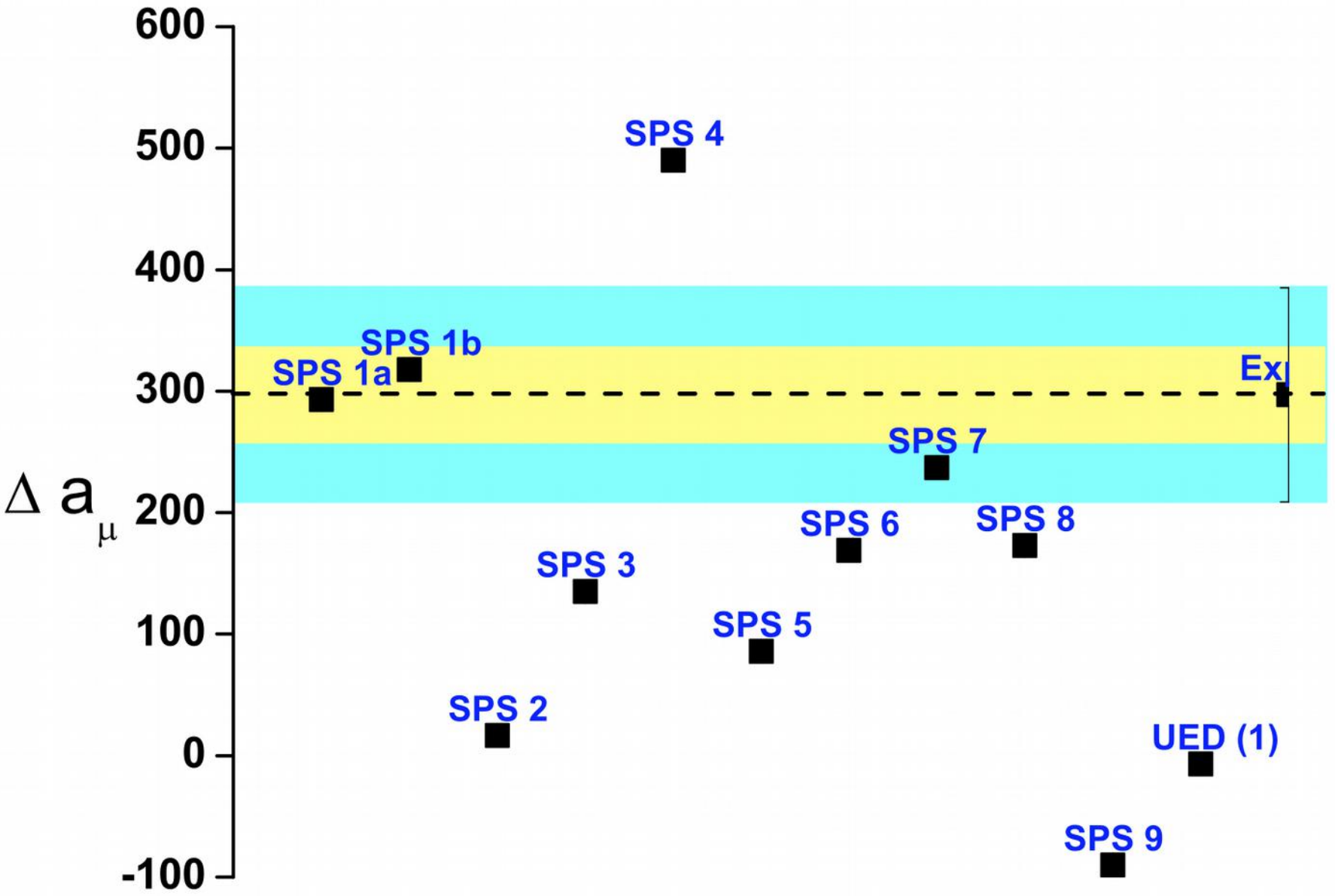


$$a_\mu(\Lambda) \simeq \frac{m_\mu^2}{\Lambda^2} \simeq 1100 \times 10^{-11} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

Current level of precision (10^{-9})

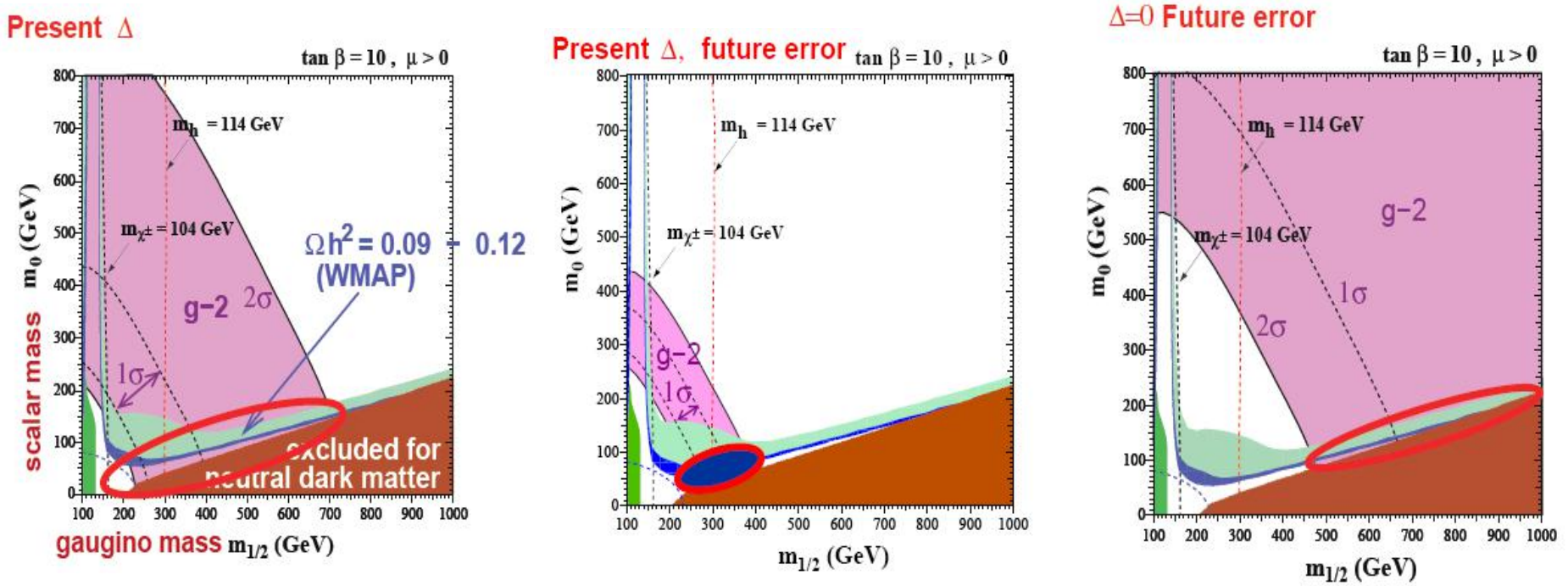
$$a_\mu(\mathrm{SUSY}) \simeq \mathrm{sgn}\,(\mu)\ 130 \times 10^{-11}\ \tan\beta\ \left(\frac{100\ \mathrm{GeV}}{\Lambda}\right)^2$$

Some plausible scenarios (Snowmass)



Reach of g-2

$$\Delta a_{SUSY} \simeq sgn(\mu) 1.3 \times 10^{-9} \tan\beta \left(\frac{100\,GeV}{\tilde{m}}\right)^2$$



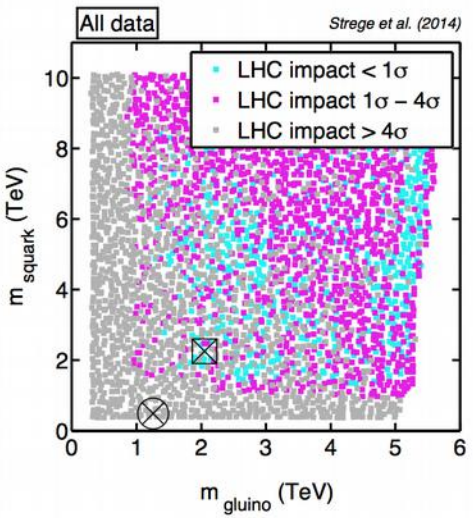
The (g-2) discrepancy is consistent with other constraints on the SUSY LSP being the dark matter candidate.

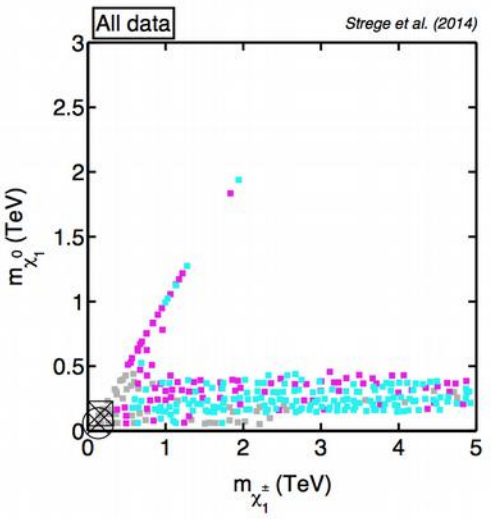
With m_{LSP} known (LHC?), g-2 sensitive to tanβ

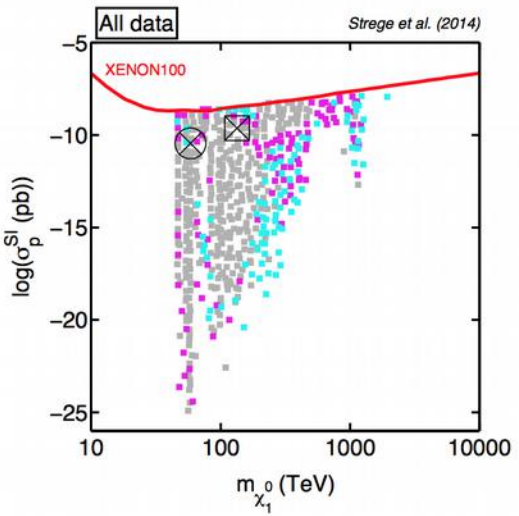
CMSSM calculation Following Ellis, Olive, Santoso, Spanos, from K. Olive

SUSY : g-2 & LHC

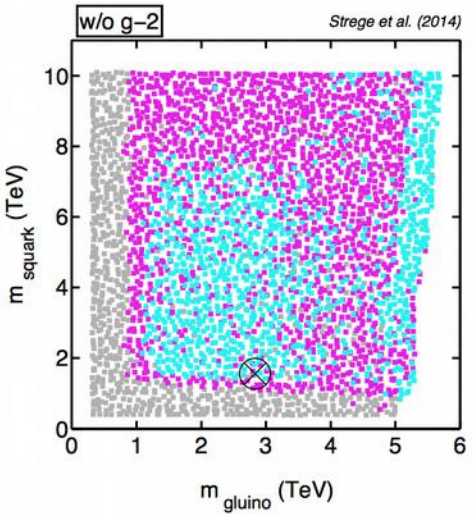
arXiv:1405.0622

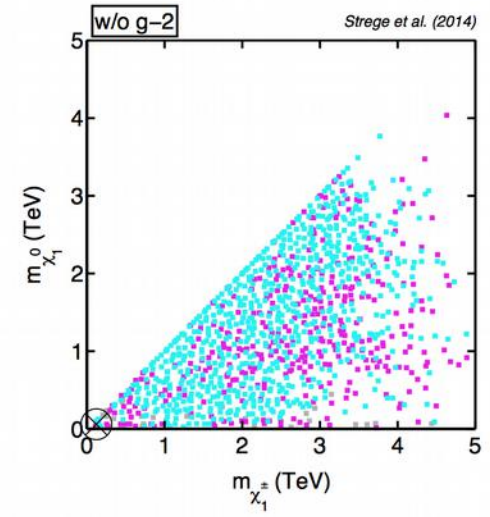


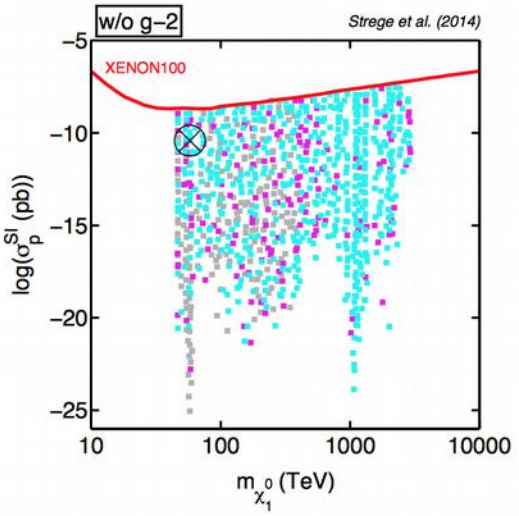




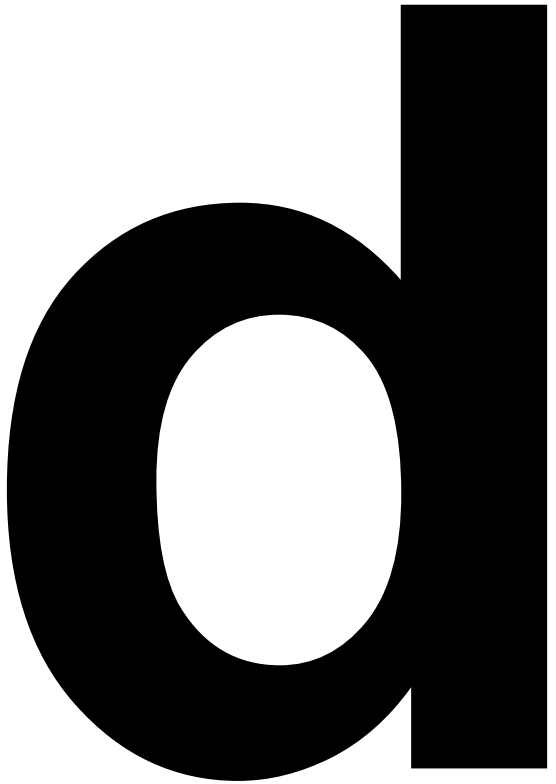
With g-2







Without g-2


d

Permanent EDMs violate T/CP and P

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$= -[\mu\vec{B} + d\vec{E}]\cdot\hat{S}$$

$$\vec{d} = \begin{cases} \kappa\vec{E} & \text{induced} \\ d\hat{S} & \text{permanent} \end{cases}$$

T

P

$$= -[\mu\vec{B} + d(-\vec{E})]\cdot\hat{S}$$

$$= -[\mu(-\vec{B}) + d\vec{E}]\cdot(-\hat{S})$$

d ≠ 0 → **T** & **P** violation → **CP** violation

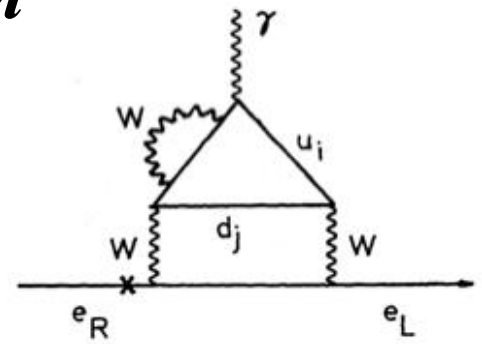
EDMs in the Standard Model : δ_{CP}

All CP-odd effects involve Jarlskog invariant:

$$J_{CP} = \sin^2\theta_{12}\sin\theta_{13}\sin\theta_{23}\sin\delta_{CP} \sim 3\times10^{-5}$$

≠0 because of SM flavor structure (Nobel 2008)

$$d_n(SM) \sim (10^{-7})^2 \cdot J_{CP} \cdot \frac{e}{M_n} \sim 10^{-31}\, e\cdot cm$$



EDMs flavor-conserving → multi-loop (≥3)

SM Predictions:

Quarks	:	$\sim10^{-33\cdots34}\, e\cdot cm$
Neutron	:	$\sim10^{-31\cdots32}\, e\cdot cm$
^{199}Hg	:	$\sim10^{-33\cdots34}\, e\cdot cm$
Electron	:	$<10^{-40}\, e\cdot cm$

Standard Model CKM EDMs are (currently) unmeasurably small

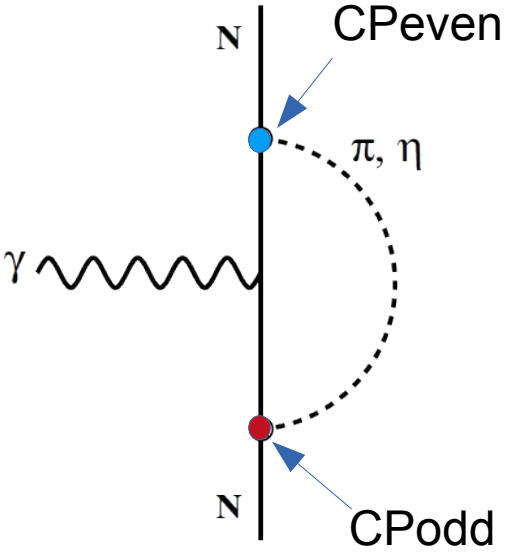
I.B. Khriplovich, S.K. Lamoreaux, *CP Violation Without Strangeness*, Springer, 1997

EDMs in the Standard Model : θ_{QCD}

QCD contains P- and T-odd term:

$$L_\theta = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

$$\bar{g}_{\pi NN} \approx -0.027\,\bar{\theta} \qquad g_{\pi NN} \approx 13$$



Naively, one would expect θ ~ O(1)

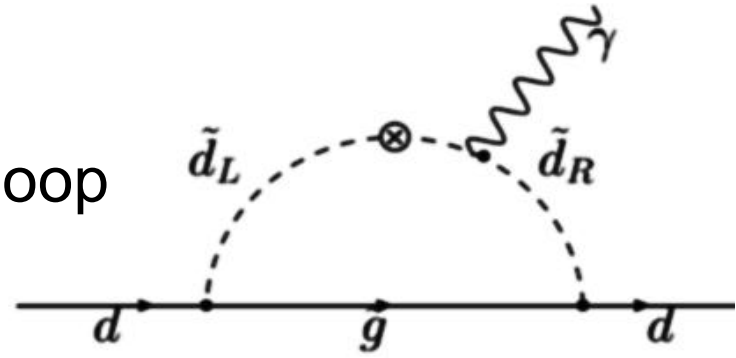
Experimentally, $|\theta| < 10^{-9}$ (from the neutron EDM)

Strong CP problem

e.g. M.E. Pospelov and A. Ritz, NP**B558** (1990) 243

EDMs from New Physics

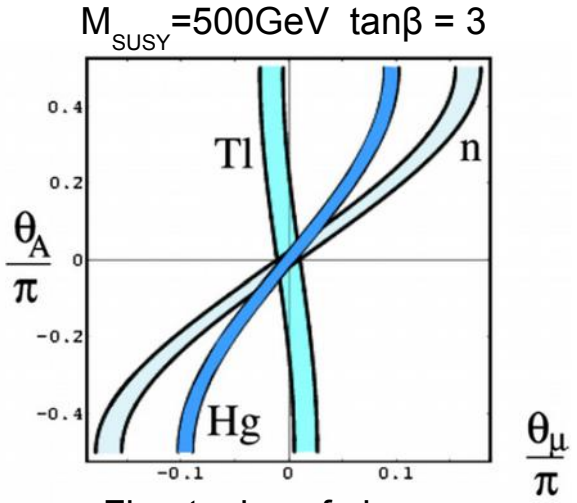
~ all "new physics" : extra CPV, often 1-loop



d(NP) >> d(SM)

e.g. SUSY :

$$d_n(NP) \sim \sin\delta_{CP}\left(\frac{1\ \text{TeV}}{M_{SUSY}}\right)^2 \times 10^{-25}\, e\cdot\text{cm}$$



Fine-tuning of phases

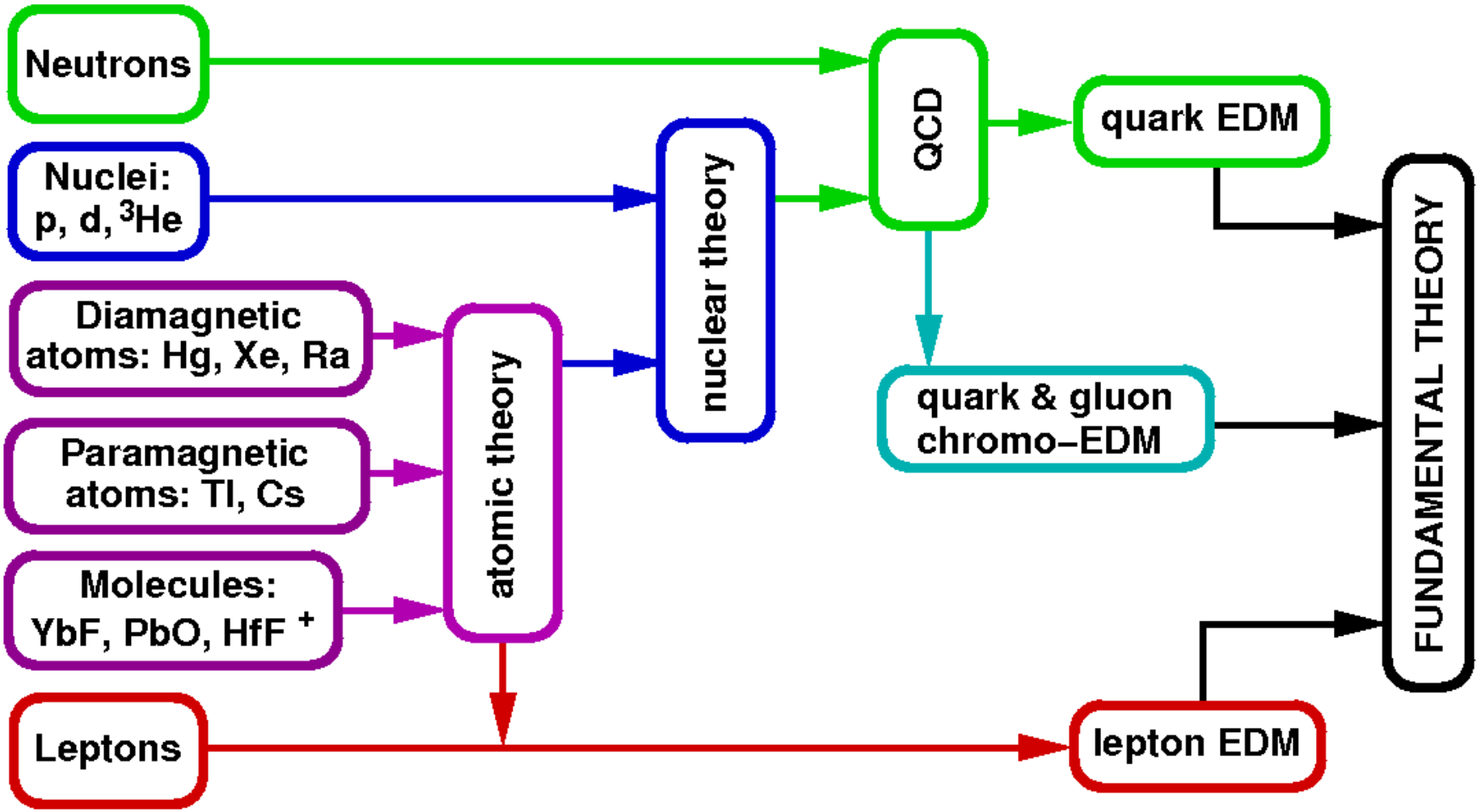
SUSY CP Problem

- New physics expected at TeV scale (LHC!)
- *current* EDM expt[s] sensitive at few TeV scale
- BAU → additional sources of CPV?

Ultra-sensitive New Physics Probe

e.g. M.E. Pospelov and A. Ritz, **AP318** (2005) 119

EDM Genealogy



Need multiple systems to unravel

Hadronic EDMs

In terms of CPV πNN interactions:

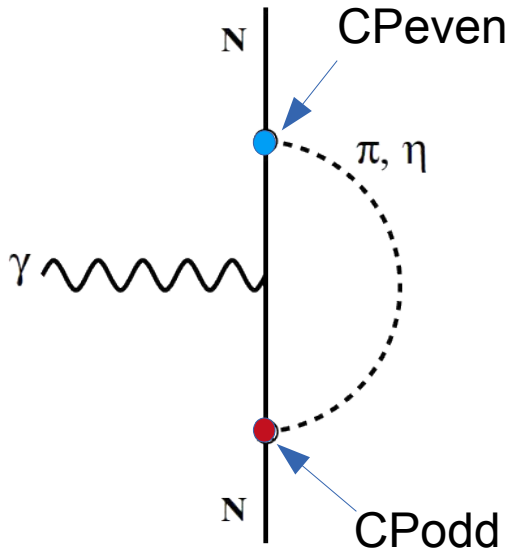
	$g_\pi^{(0)}$	$g_\pi^{(1)}$	$g_\pi^{(2)}$	Limit [e·cm] (95% C.L.)
n	0.14		-0.14	3×10^{-26}
p	-0.05	0.03	0.14	
^{2}H	0.09	0.23		
^{129}Xe	6×10^{-5}	6×10^{-5}	12×10^{-5}	7×10^{-27}
^{199}Hg	0.2×10^{-5}	20×10^{-5}	-3×10^{-5}	3×10^{-29}
^{225}Ra	-0.06	-0.12	0.11	

Needs New Technique

QCD CPV : $g_\pi^{(0)} \approx 0.027\bar{\theta}$

New Physics *e.g.* quark-chromo-EDMs

$$d_D = -4.67\,\tilde{d}_d + 5.22\,\tilde{d}_u$$
$$d_n = -0.01\,\tilde{d}_d + 0.49\,\tilde{d}_u$$



C.-P. Liu, R.G.E. Timmermans, Phys. Rev. C 70, 055501 (2004)

Comparison to existing limits

- **Neutron EDM**

  $|d_n| < 2.9 \times 10^{-26}\ e \cdot \text{cm}$ (90% C.L.)

  C.A. Baker et al., PRL97, 131801 (2006)

- **Proton EDM**

  $|d_p| < 7.9 \times 10^{-25}\ e \cdot \text{cm}$ (95% C.L.)

  from **^{199}Hg EDM** $< 3.1 \times 10^{-29}\ e \cdot \text{cm}$

  W.C. Griffith et al., PRL102, 101601

- **Deuteron EDM**

  No dedicated experiment

  From Deuterium 1S-2S : $|d_D| < 10^{-15}\ e \cdot \text{cm}$

  From $\mathbf{|d_n|, |d_p|, |d_{Hg}|}$ and $\mathbf{g_\pi^{(0)}, g_\pi^{(1)}, g_\pi^{(2)}}$: $|d_D| < 10^{-24}\ e \cdot \text{cm}$

Dedicated experiments on p and D contribute a lot!

EDM-induced spin precession

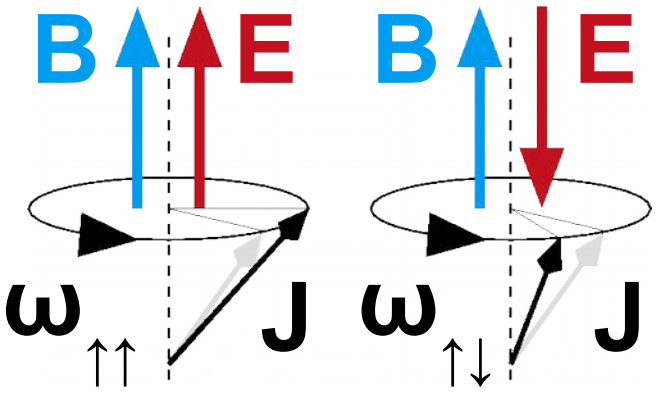
Prepare spin polarized ensemble

Interaction with electric field

Measure spin evolution

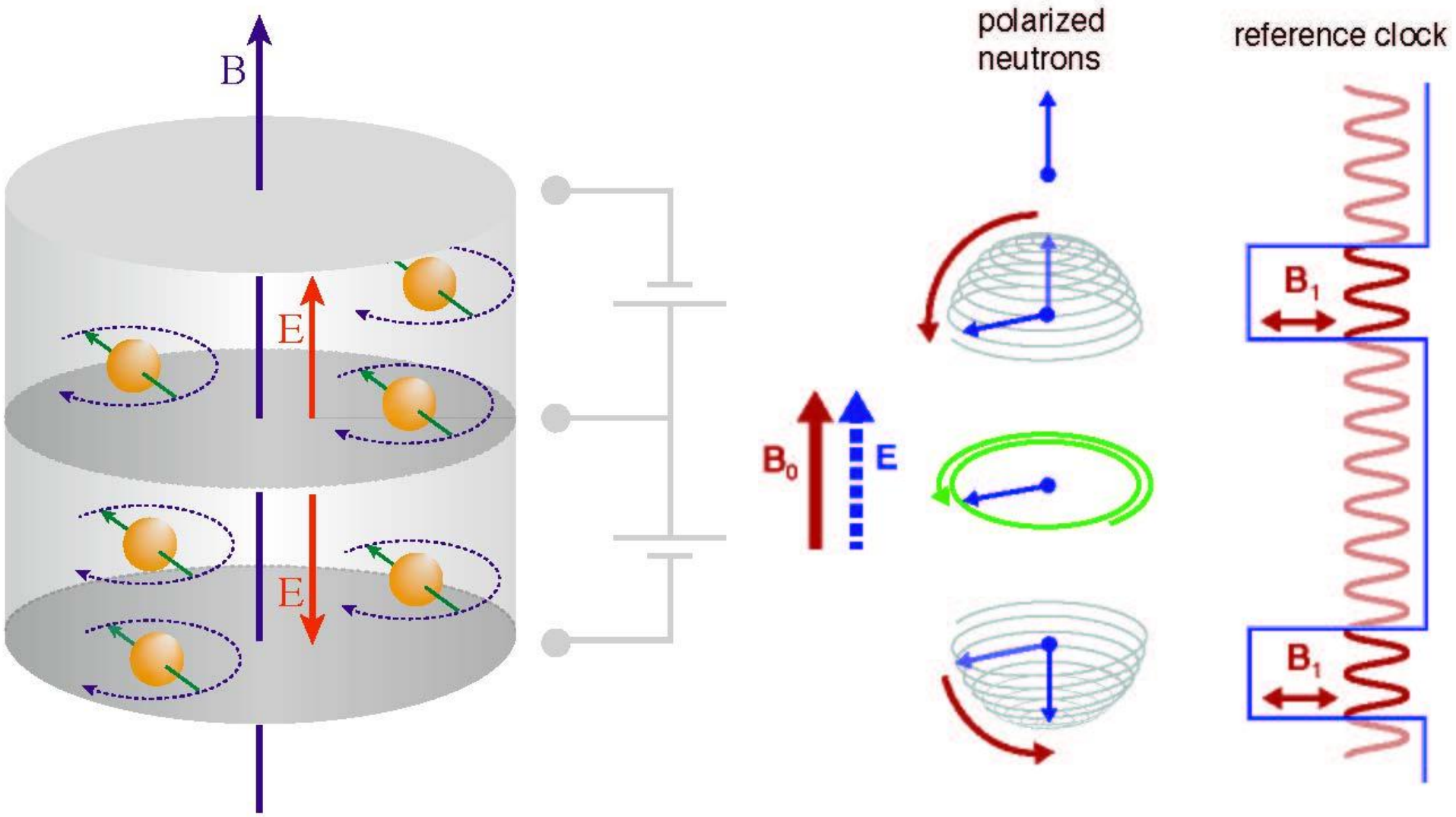
$$\frac{d\langle \vec{J} \rangle}{dt} = (\mu \vec{B} + d \vec{E}) \times \langle \hat{J} \rangle$$

$\vec{\omega}$

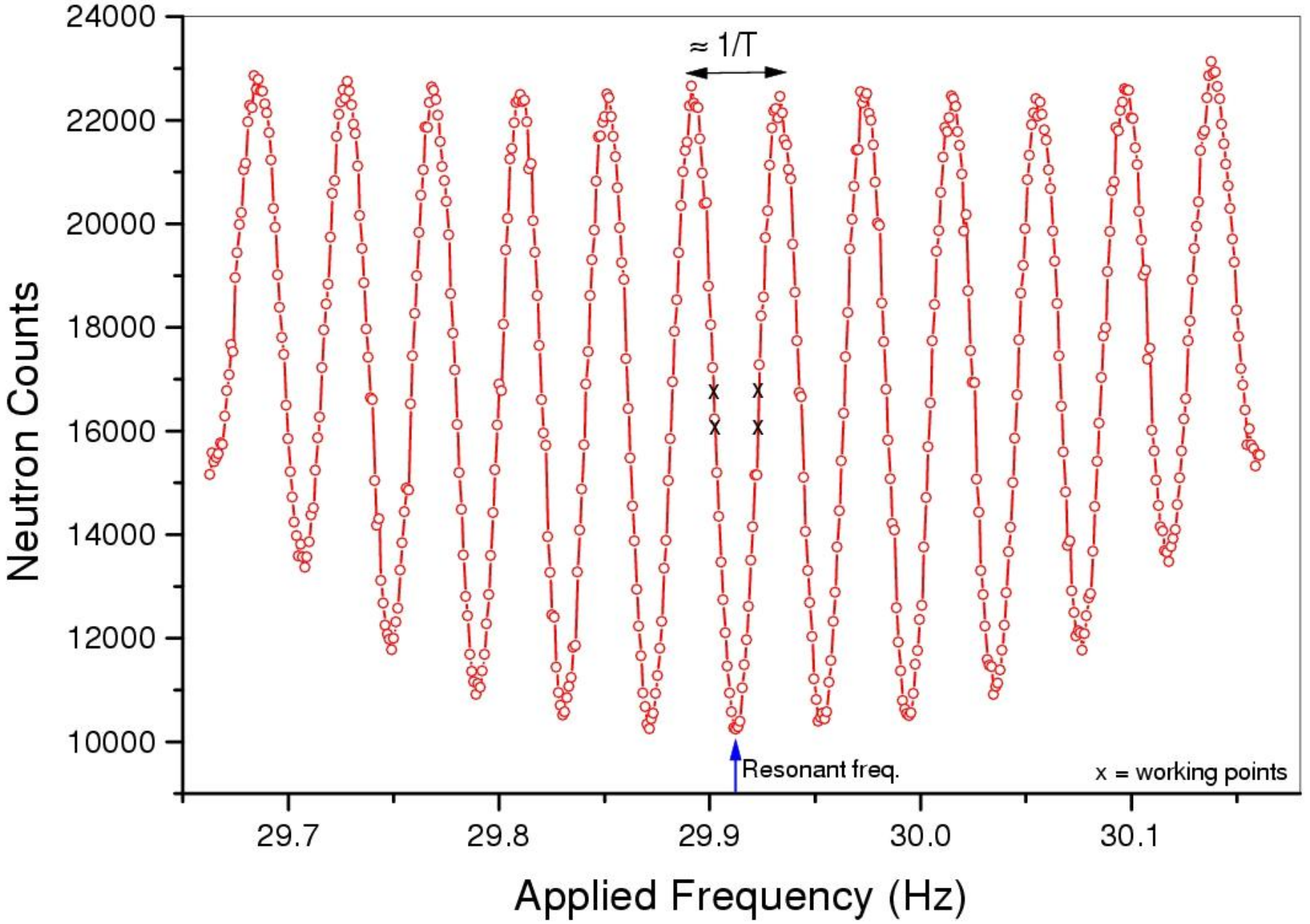


Traditional technique for neutral systems

Ramsey's method w/ multiple cells



Ramsey's fringes



Sensitivity

General expression for the (statistical) uncertainty

$$\sigma_d \propto \frac{1}{P\,E\,\sqrt{N}\,T\,A}$$

N: number of particles in experiment

P: initial polarization of sample

A: analyzing power of polarimeter

E: electric field in particle rest frame

T: characteristic time

Pillars of a sensitive experiment

- Strong source
- High polarization
- Efficient polarimeter
- High electric field strength
- Spin coherence, efficient storage

Equally important: understand systematic effects

^{205}Tl experiment : eliminate systematics

Atomic Beam Sources

256 combinations

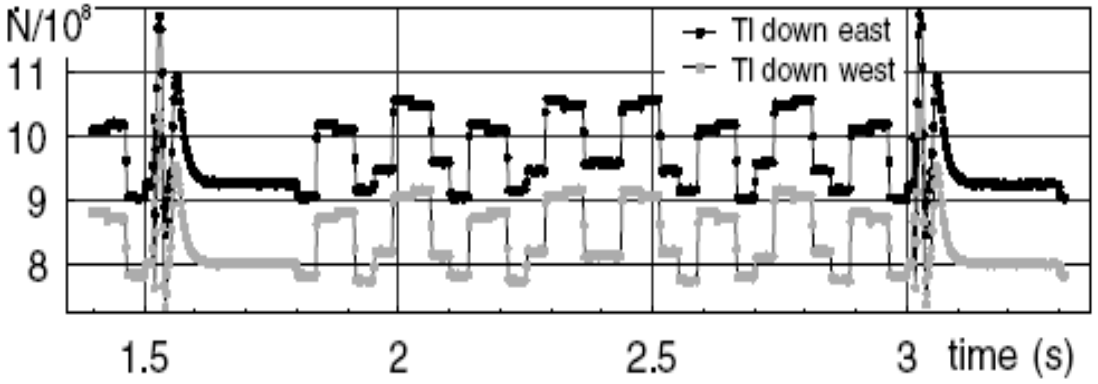
Polarization (pump)/ Polarimetry (fluorescence

1 combination = EDM

RF $\pi/2$ flipper

φ_{RF} : ±(90°±45°±1°)
field : ±E, ±B
beam : up/down/east/west
HV cable : ±polarity

E/B field



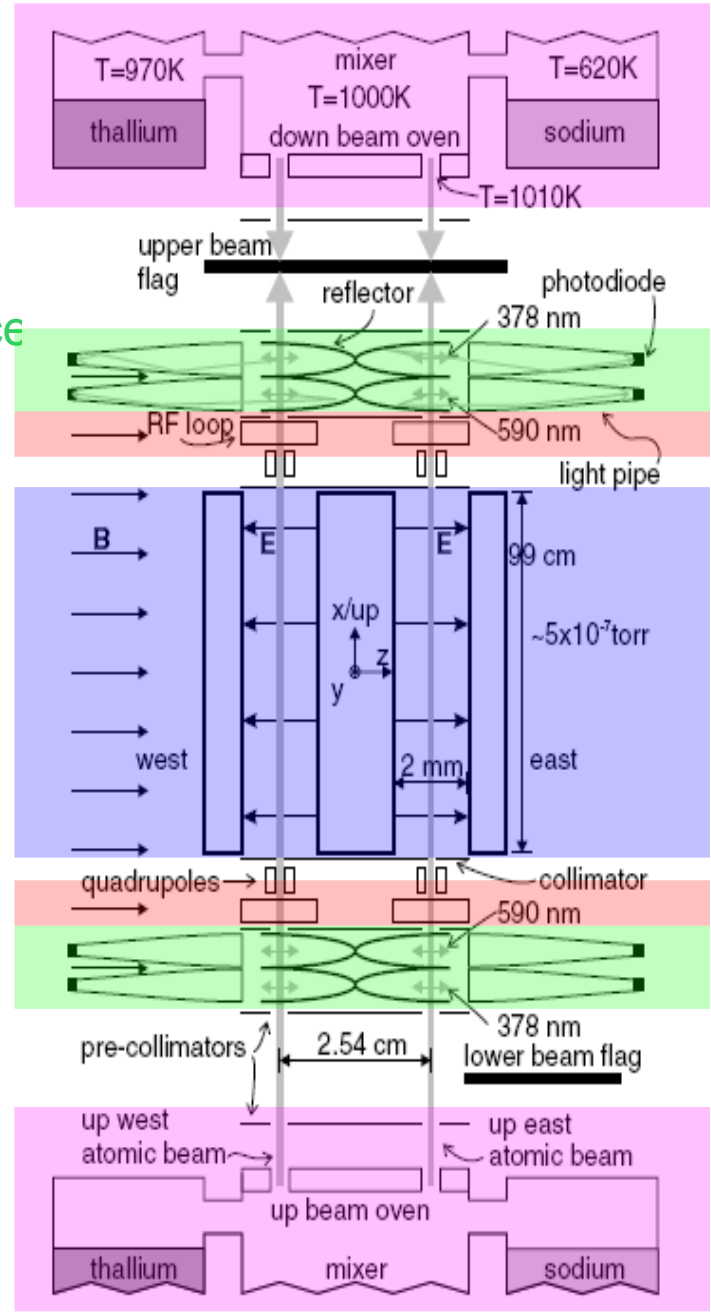
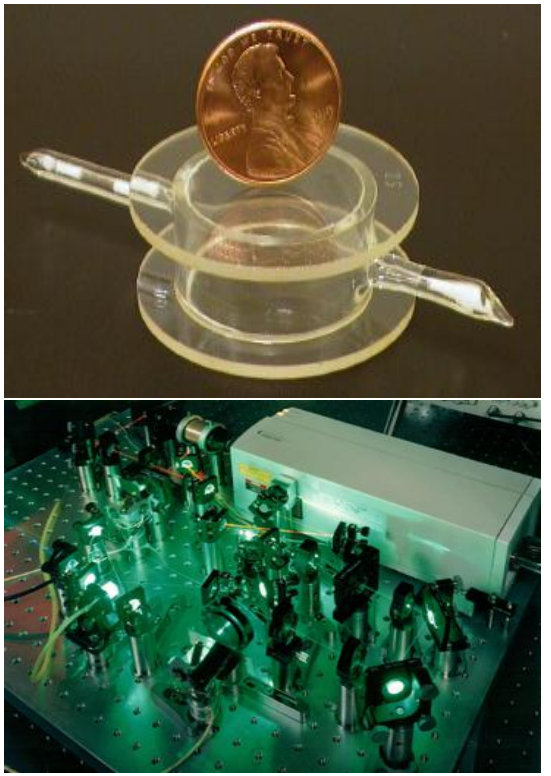


FIG. 1. Schematic diagram of the experiment; not to scale.

Interpretation of ^{199}Hg EDM

$|d_{Hg}| < 3.1 \times 10^{-29}$ e·cm (95% C.L.)

Parameter	^{199}Hg bound
$\tilde{d}_q$ (cm)	6×10^{-27}
d_p (e cm)	7.9×10^{-25}
C_S	5.2×10^{-8}
C_P	5.1×10^{-7}
C_T	1.5×10^{-9}
$\bar{\theta}_{QCD}$	3×10^{-10}
d_n (e cm)	5.8×10^{-26}
d_e (e cm)	3×10^{-27}



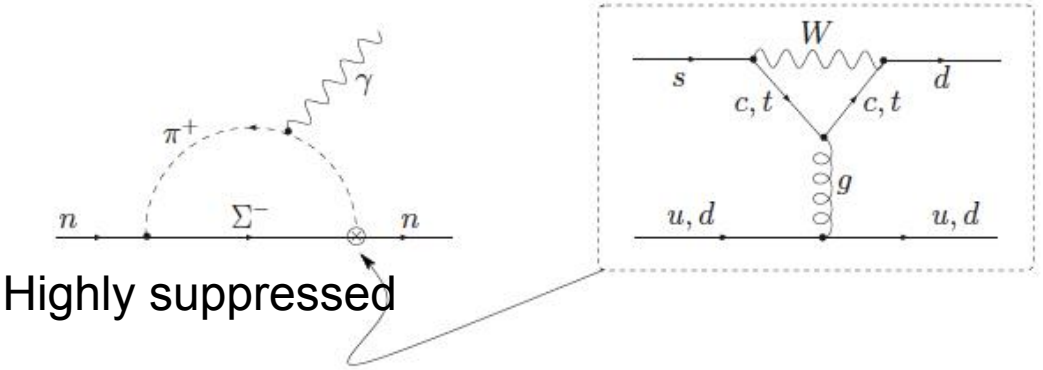
$\delta\nu_{stat}$ = 0.13 nHz (7.5 ppt)

1 cycle per 244 years

W. C. Griffith,et al., Phys. Rev. Lett. 102, 101601 (2009)

BSM reach

arXiv:1201.4252

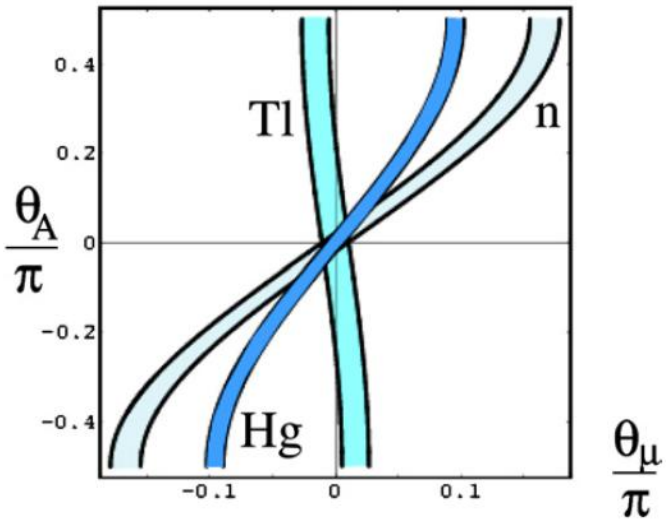


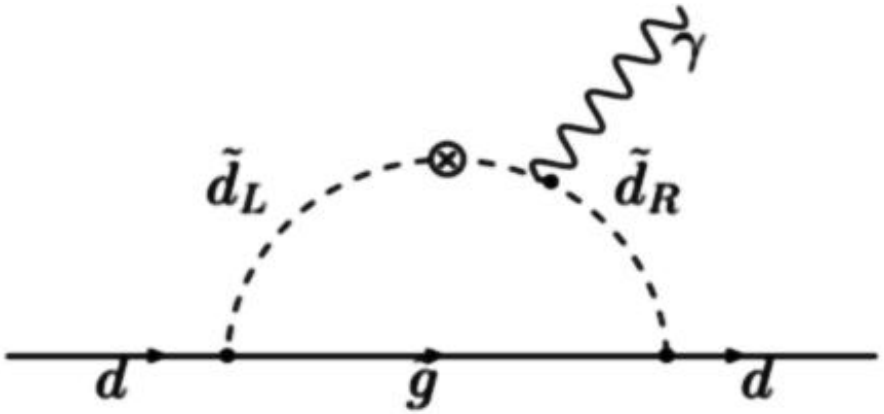
Highly suppressed

Clean(est) tool to find new CPV

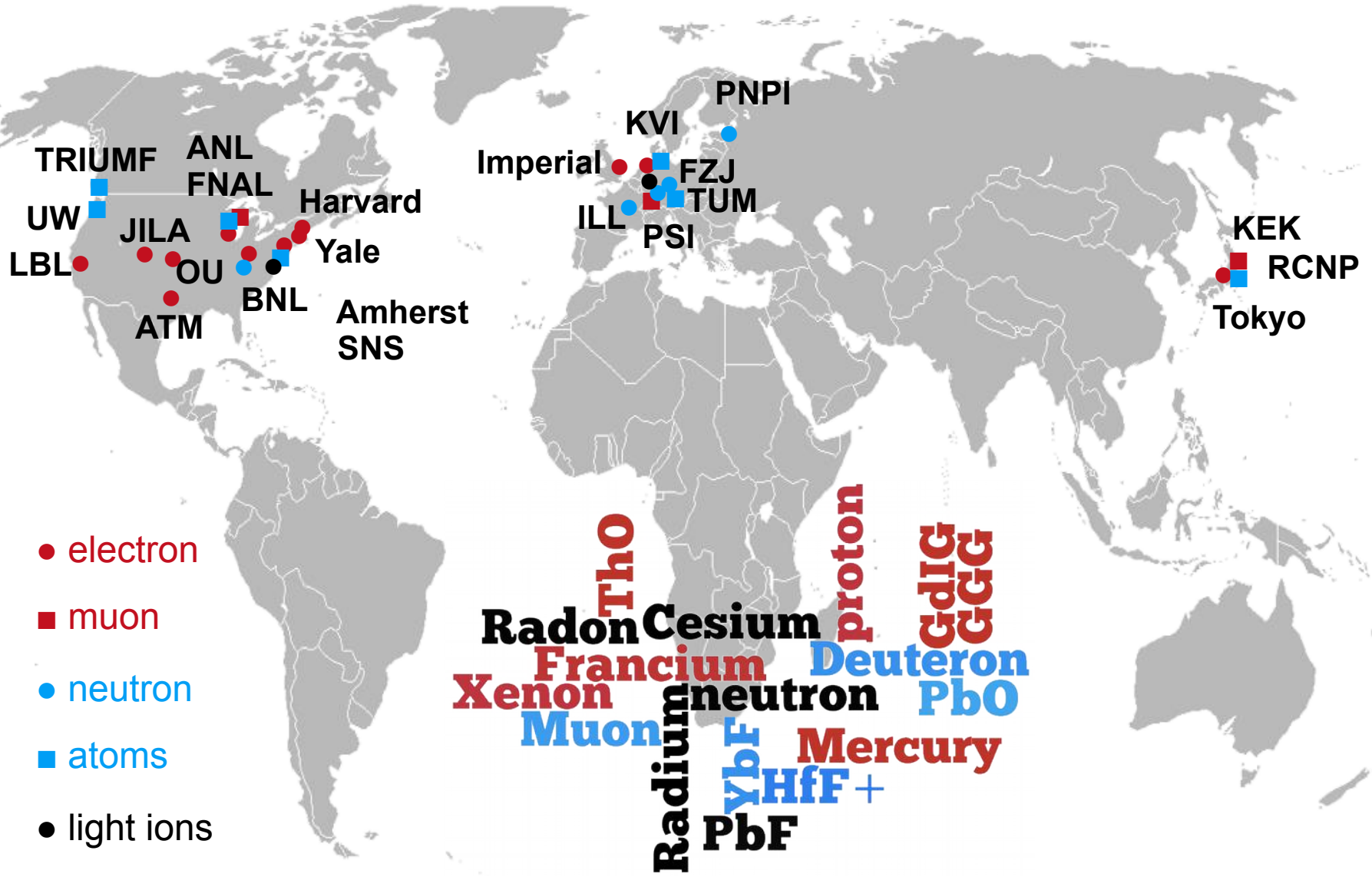
$$d_n(NP) \sim \sin\delta_{CP}\left(\frac{1\ TeV}{M_{SUSY}}\right)^2 \times 10^{-25}\ e\cdot cm$$

SUSY CP Problem





Efforts Worldwide

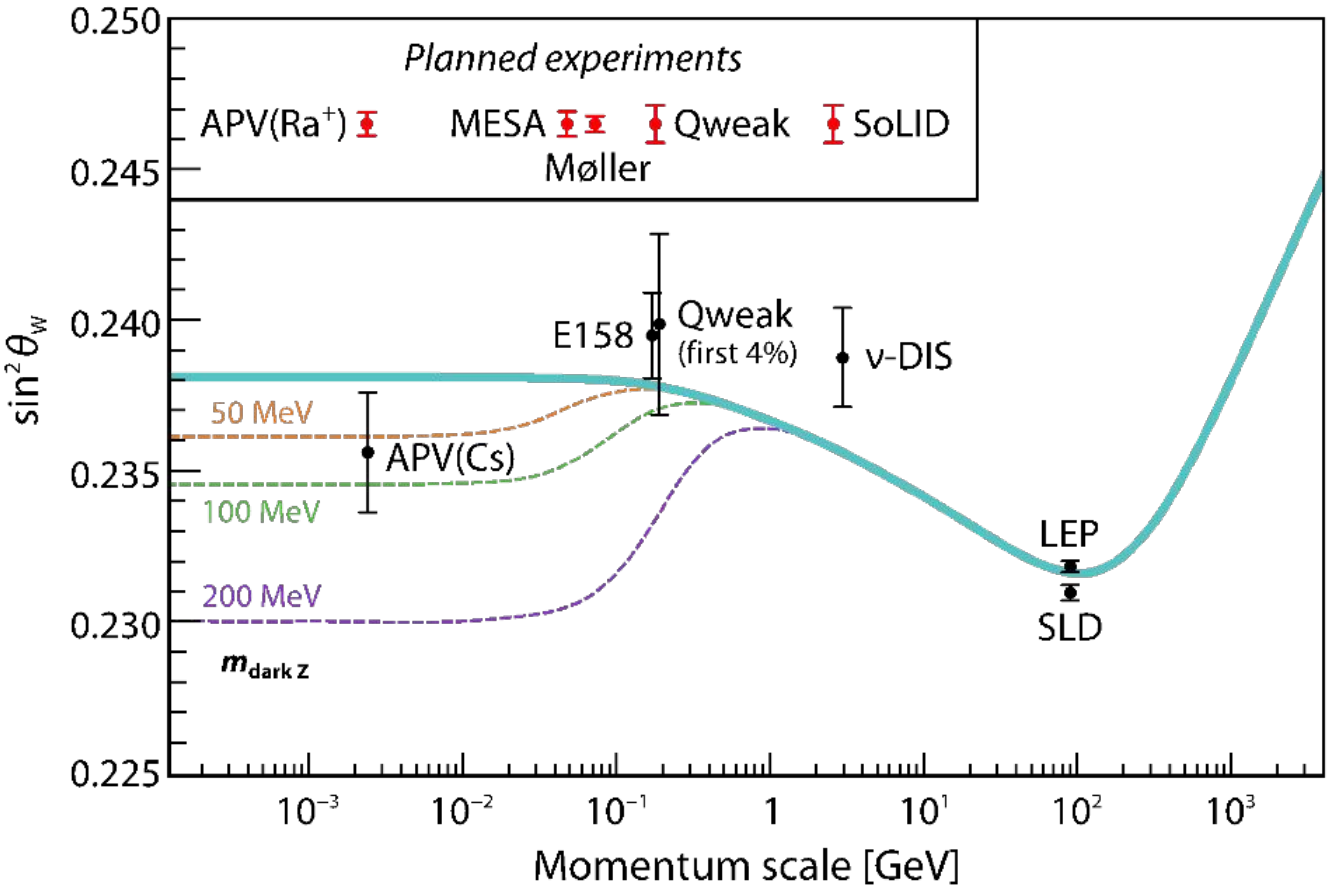


An undoubtedly incomplete list; inspired by Dave DeMille & Rob Timmermans

θW

Electroweak unification

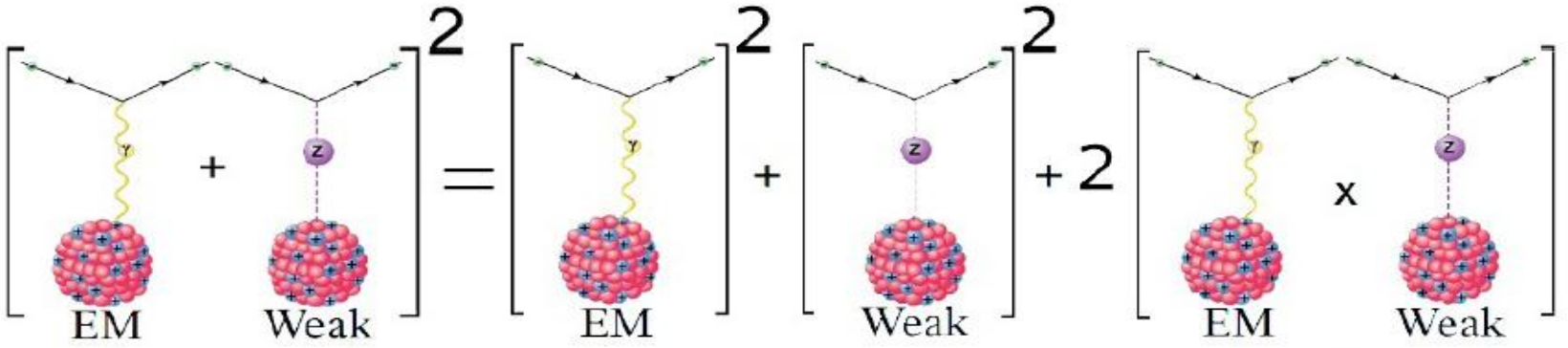
$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \longrightarrow e = g\sin\theta_W \longleftarrow \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W}$$



One of the most poorly tested phenomena of the SM!

S. Kumar, W. Marciano, Annu. Rev. of Nucl. Part. Sci. 63, 237 (2013) H. Davoudiasl, Hye-Sung Lee, W. Marciano, arXiv. 1402.3620 (2014)

Atomic parity violation in the SM



Atomic states acquire tiny admixture of opposite-parity states

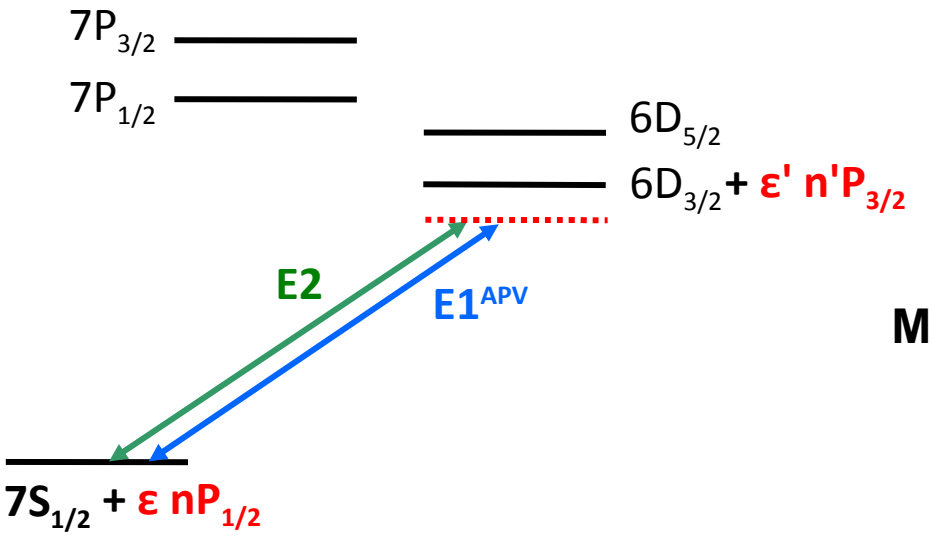
Recent Theory work: (just a few examples)

- Dzuba, Flambaum — Phys. Rev. A83, 052513 (2011) ; Phys. Rev. A85,012515 1-5 (2012)
- Derevianko, Porsev et al. — Phys.Rev. D 82, 036008 (2010) ; Phys. Rev. Lett. 102, 181601 (2009)
- Safronova et al. — Can. Jour. Phys. 89, 371 (2011) ; Phys. Rev. A 79, 062505 (2009)
- Timmermans et al. — Phys. Rev. A79, 052512 (2009) ; Phys. Rev A 78, 050501 (2008)
- Sahoo et al. — Phys. Rev. A 83, 030502 (2011) ; Pram. Jour. Phys. 75, 1041 (2010)
- . . .

Ra^+ atomic parity violation

$$|7S_{1/2}\rangle \rightarrow |7\tilde{S}_{1/2}\rangle = |7S_{1/2}\rangle + \varepsilon\,|nP_{1/2}\rangle$$

Stronger mixing for smaller
$\Delta E = E(7S_{1/2})-E(nP_{1/2})$



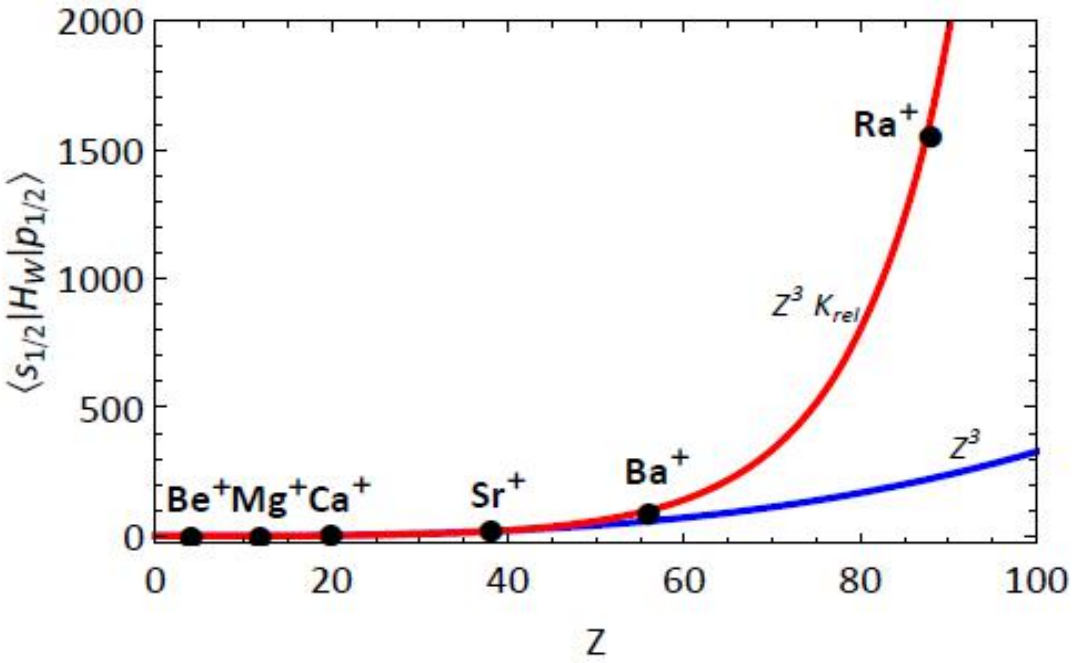
$$E1_{APV} = k\,Q_W$$

Measure — **Infer**

Calculate atomic wavefunction

Intrinsic sensitivity of Ra^+

Bouchiat & Bouchiat (1974): "stronger than Z^3"



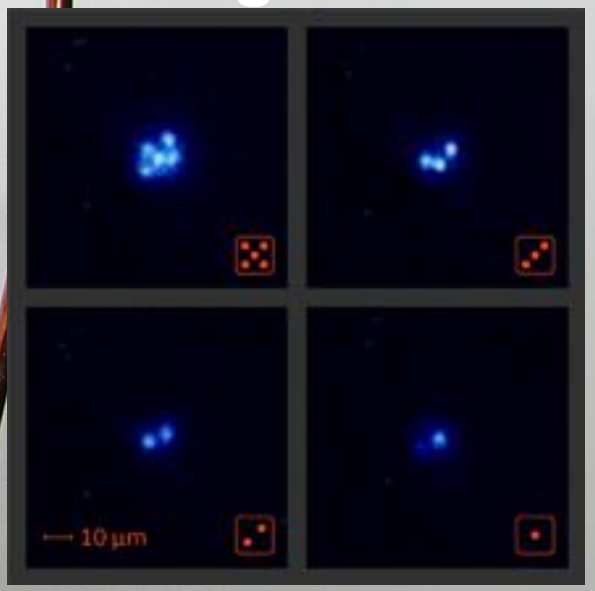
$$E1^{APV} = 46.4(1.4)\times 10^{-11}\, i e a_0 (-Q_W / N)$$

$$Q_W = -N + (1 - 4\sin^2\theta_W) Z + rad.\,corr.\,+ \underline{\text{new physics}}$$

Uncertainty for Ra^+ now ~ 3%. Need <1% for SM test

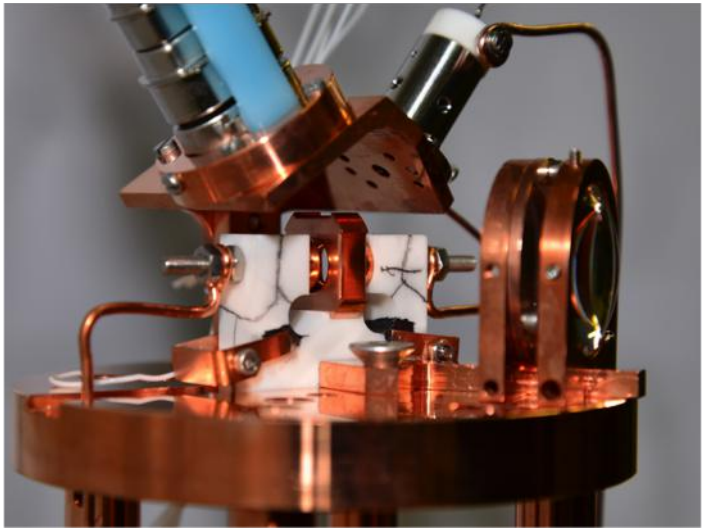
L.W. Wansbeek et al., Phys. Rev. A 78, 050501(R) (2008)

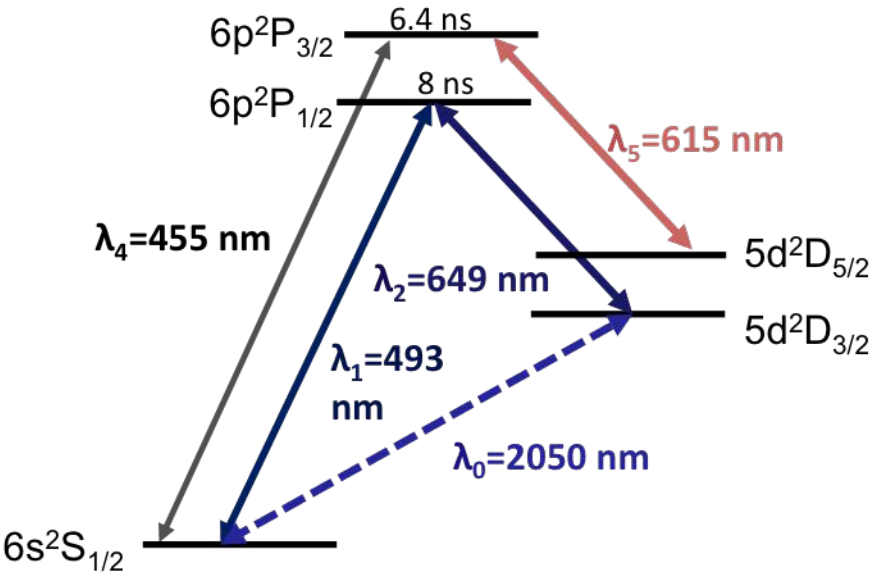
Barium/Radium APV setup

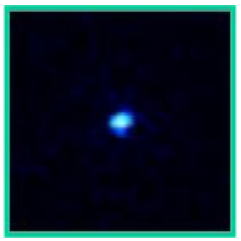


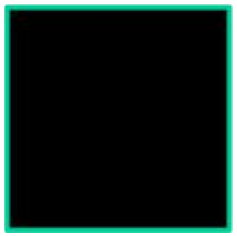
Single ion sufficient
Localize << λ
10 days → 1/5 Cs

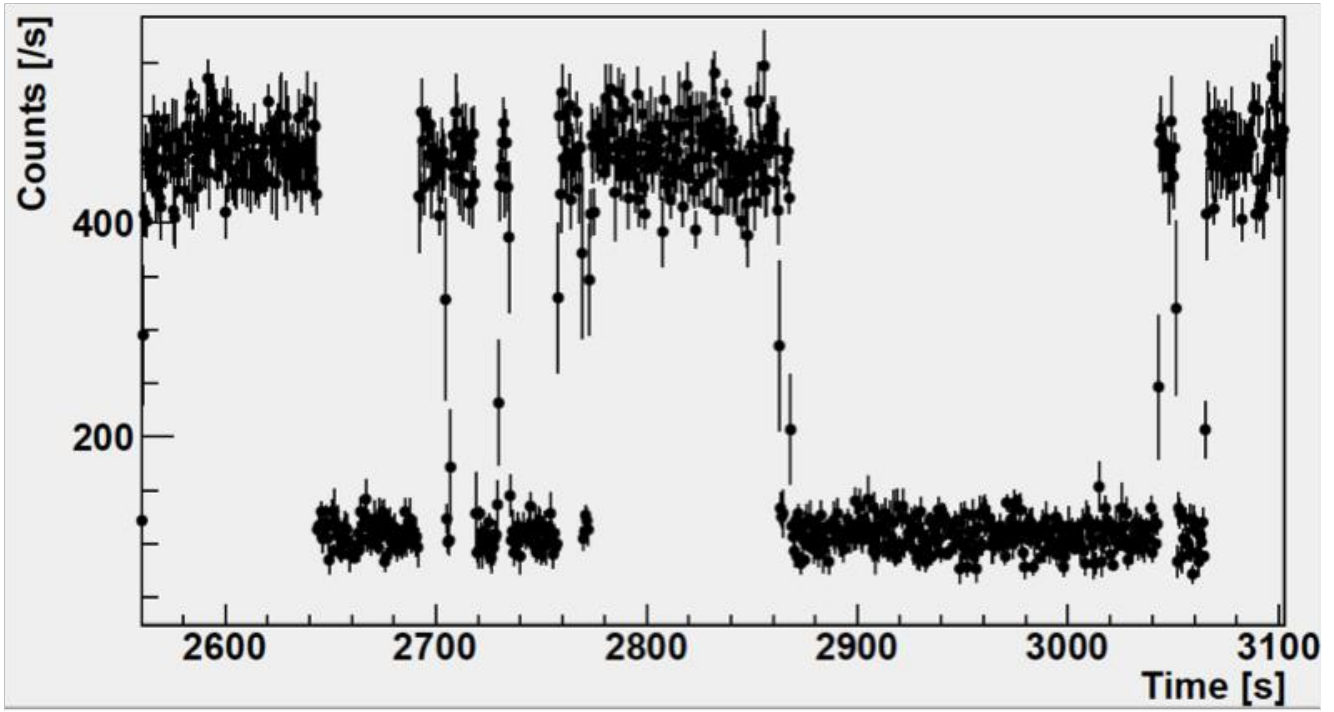
Quantum jump spectroscopy











BSM from APV : an example

Extra Z' boson in SO(10) GUTs

$$\delta Q_W \simeq (2N+Z)\, a'_e(\xi)\, v'_d(\xi) \left(\frac{M_Z^2}{M_{Z'}^2}\right)$$

London & Rosner (1986)
Marciano & Rosner (1990)
Altarelli et al. (1991)

Cesium APV : M(Z') > 1.3TeV
Tevatron : M(Z') > 0.82 TeV
LHC : M(Z') > 4.5 TeV
Radium APV : M(Z') > 5 TeV

arXiv:1111.4566
arXiv:1111.2172
arXiv:1203.1320

Reach of APV

Sensitivity for very large masses

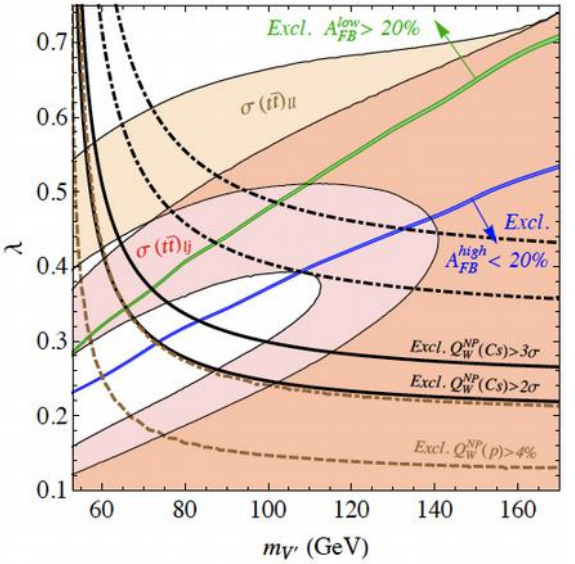
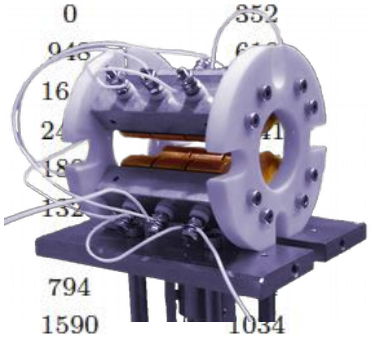


TABLE I: Mass bounds from various APV observables. The second column contain the mass bounds from the actual measurement in Eqn. 1 at 95% CL. The remaining columns contain the masses that future APV experiments will be able to exclude, given a measurement that is in agreement with the SM prediction.

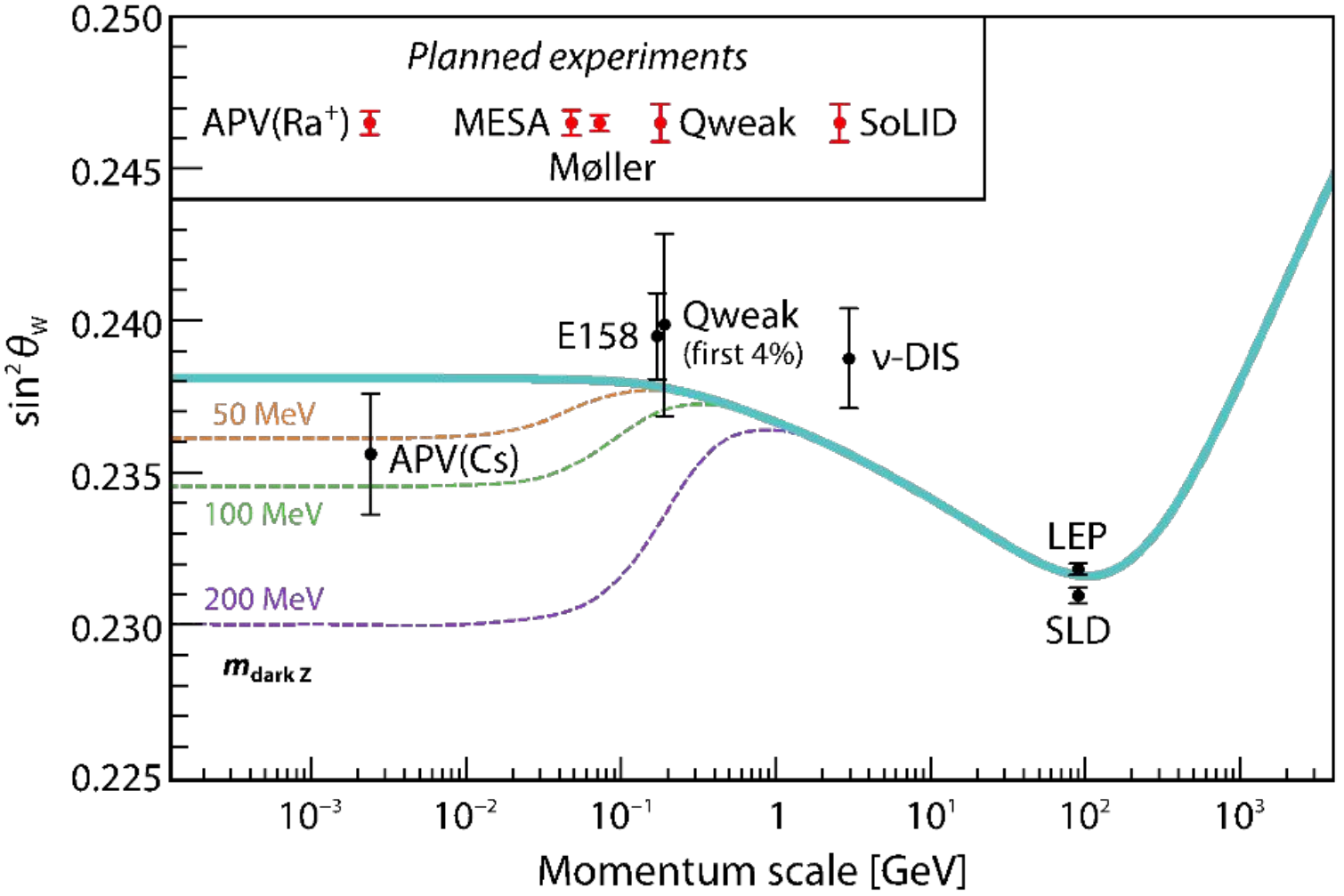
Model	$Q_W(^{133}_{55}\mathrm{Cs})$ 0.48% 95% CL	$Q_W(^{208}_{87}\mathrm{Fr})$ 0.1% 95% CL	$\mathcal{R}_{\mathrm{Fr}}(121,122)$ 0.3%, 95% CL	$\mathcal{R}_{\mathrm{Fr}}(121,122)$ 0.1%, 95% CL	$\mathcal{R}_{\mathrm{Yb}}(98,100)$ 0.3%, 95% CL	$\mathcal{R}_{\mathrm{Yb}}(98,100)$ 0.1%, 95% CL	Q_W^p 4.1% 95% CL
E_6 η	485	997	339	585	337	581	356
E_6 χ	969	1993	679	1170	674	1162	712
E_6 ψ	0	0	0	0	0	0	0
E_6 I	1083	2228	759	1308	754	1299	796
E_6 sq	1110	2283	778	1340	772	1331	815
E_6 N	593	1220	416	716	413	712	436
Left Right (LR)	1033	2117	0	0	0	0	352
Alternate LR (ALR)	741	1527	701	1210	696	1202	772
UUM	505	1012	3	1651	946	1640	1124
SSM	1033	2117		0	0	0	352
TC1	520	1073	552	954	549	94	6
Littlest Higgs (LH)	505	1012	953	1651	946	16	
Simplest LH (SLH)	1589	3274	1409	2433	1400	2	4
Anom. Free LH (AFLH)	1320	2718	1051	1812	1043	18	
331 2U1D	968	1993	770	1329	765	13	
331 1U2D	1589	3274	1409	2433	1400		
ETC	245	490	461	800	458	794	
TC2	872	1800	926	1601	920	1590	1034

GeV/c^2



Reach of APV

Sensitivity for light dark matter



Outline

Constants of the Standard Model

What makes a measurement?

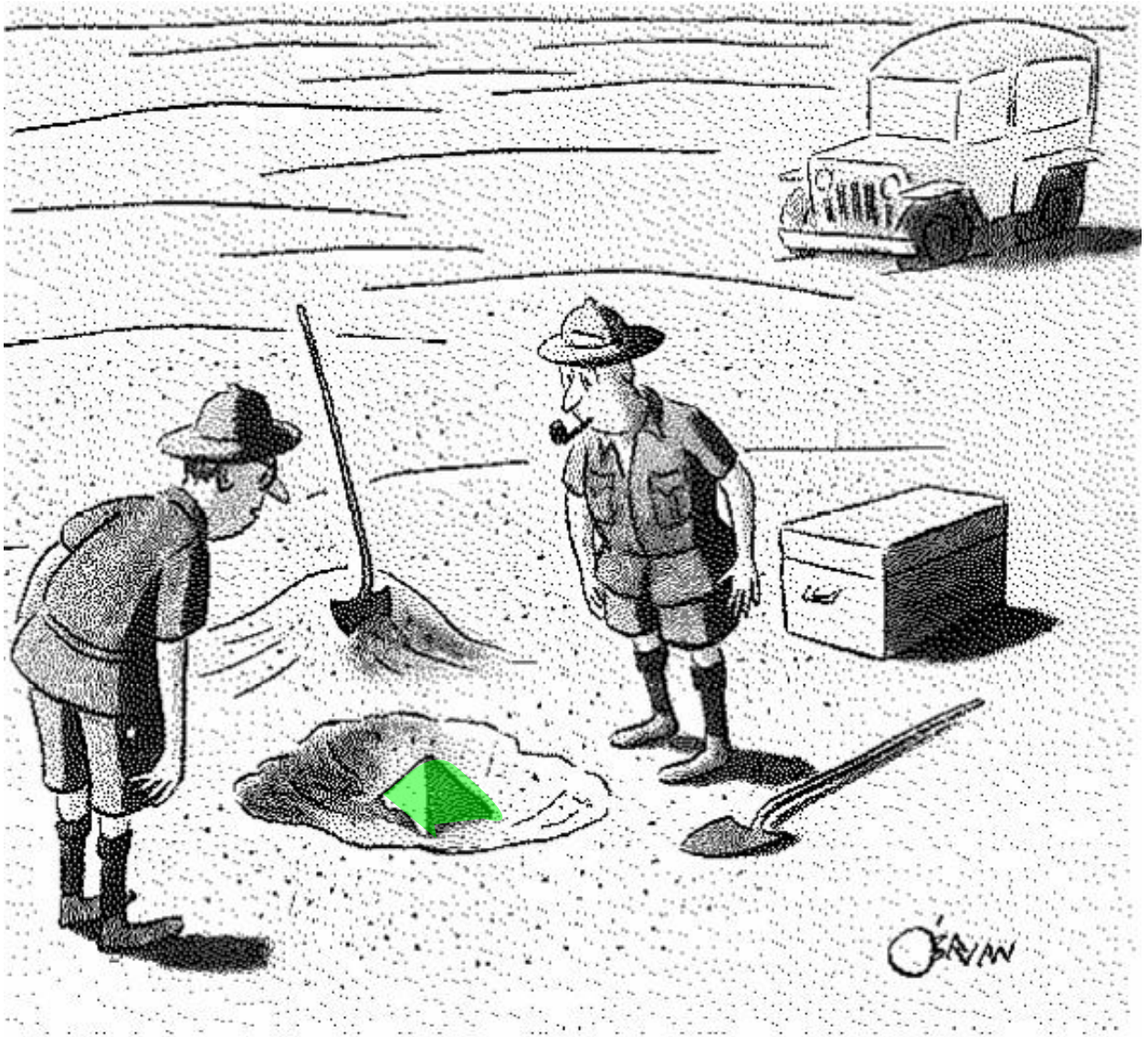
Selected experiments

Conclusion

Finale

- **Sensitive experiments** are needed to find new physics
- **Fundamental phenomena** can be studied
  - directly & selectively in HE experiments (production)
  - indirectly & collectively in LE experiments (radiative correction)
- All **well motivated**, none more justified than others
- **Thorough theoretical understanding** of "obscuring" but known phenomena is indispensable for precision SM tests and sensitive searches for NP
- **Low energy experiments**
  - define the SM — α, G_F
  - confirm SM predictions — $\sin^2\theta_W$, a_μ
  - search for NP — CPV, dark matter
- **Together** with LHC *et al.* a new generation of low energy precision experiments may soon show **proof of new physics**!

Let's keep digging



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Future

Several searches on-going for decades (APV, LFV, EDMs, …)

Timescale : year – decade (mu2e, g-2, …)

Collaboration : 2 – 100's persons

Funding : 0.1 – 100M€

Expect great synergy from high-Intensity machines
(Project-X, J-PARC, …)

Will depend on what is found at LHC

Generic discovery potential far beyond LHC++/LC/μμcollider/...

Complementary to direct searches