university of groningen / faculty of mathematics and natural sciences / van swinderen institute for particle physics and gravity

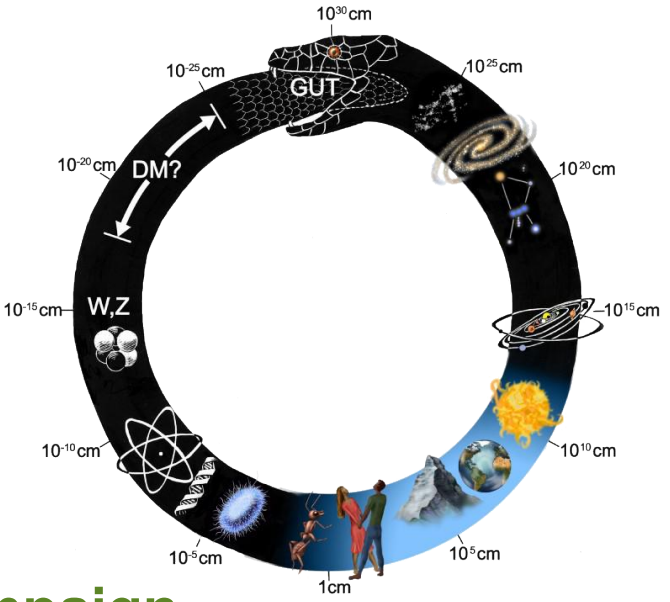
Precision Electroweak Experiments

– at low energies –

Gerco Onderwater

BND School 2017 - Callantsoog

Who am I?



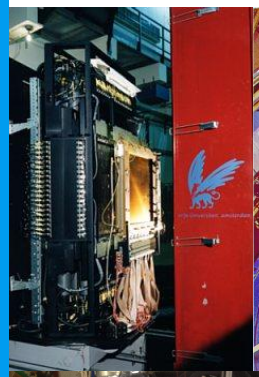
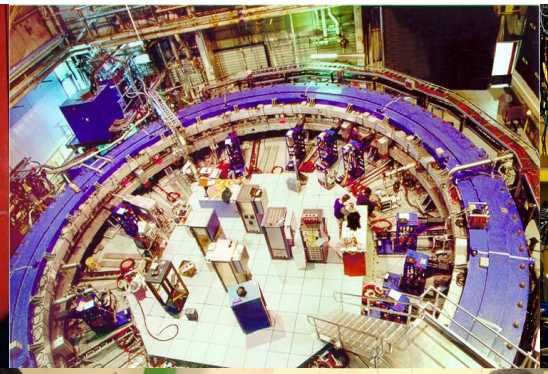
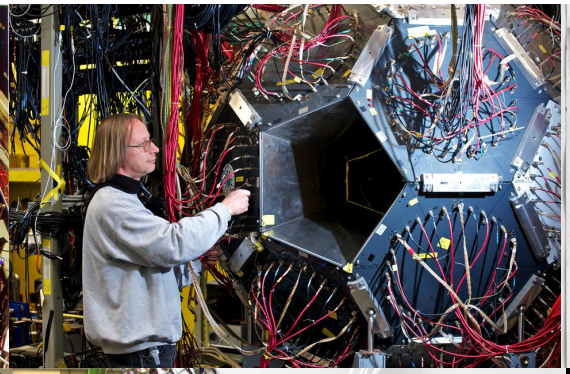
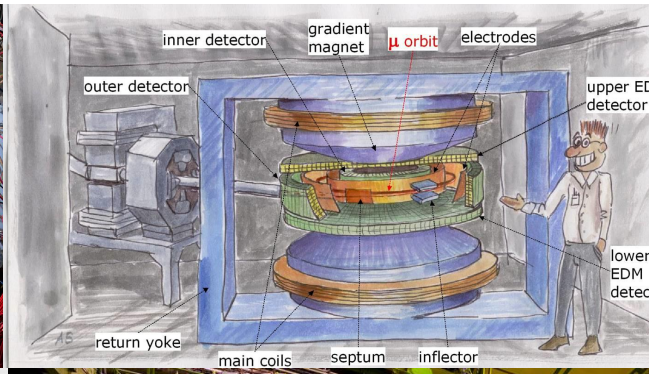
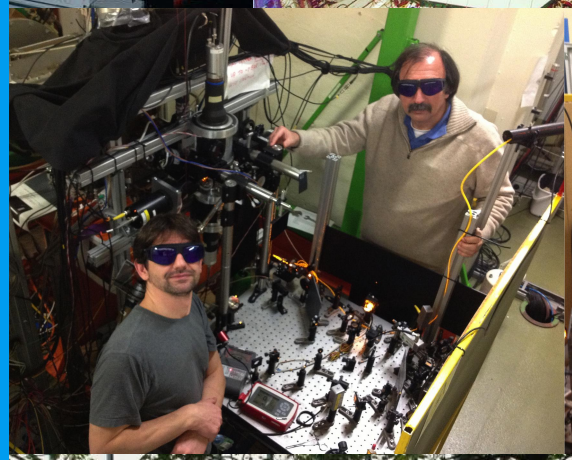
1993-1998 : VU/NIKHEF
Hadron group at the AmPS facility

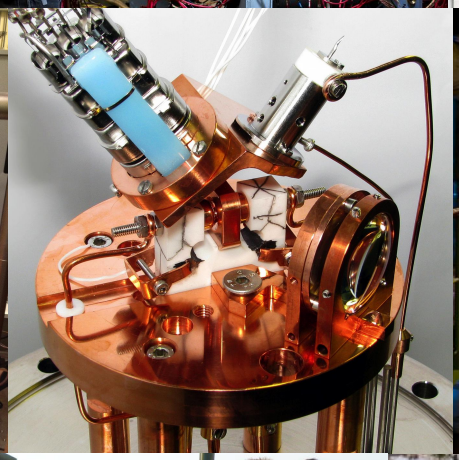
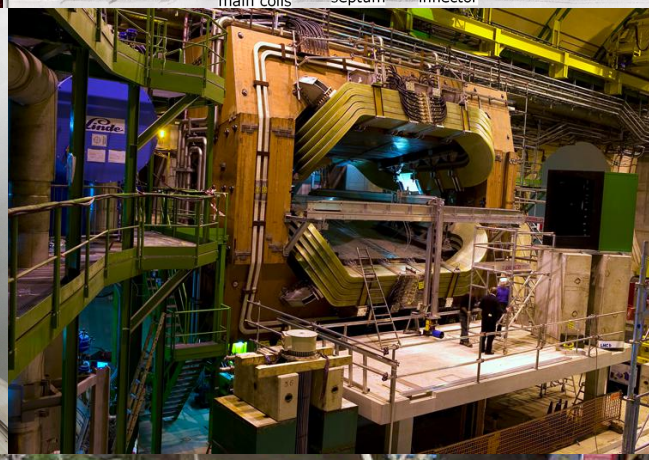
1998-2004 : Univ. of Illinois at Urbana-Champaign
Precision Physics Group
Several low-energy “precision” experiments, incl. muon g-2, EDM & lifetime @ BNL & PSI

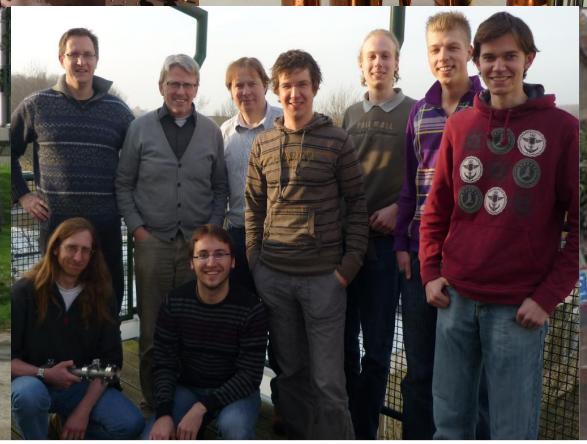
2004-now : Univ. of Groningen
Van Swinderen Institute for Particle Physics & Gravity
Experimental Particle Physics Group

C, P, & T: EDM (μ,p,d,Ra,Xe), Ra^{+}APV, β-decay, SrF
LIV: Na-decay, dα/dt
LFV : LHCb ($B \rightarrow e\mu$)
New muon g-2

My Research





inner detector
gradient magnet
μ orbit
electrodes
outer detector
upper ED detector
lower EDM detec
return yoke
main coils
septum
inflector




Exploring the Quantum Universe

Baryon asymmetry

Dark matter

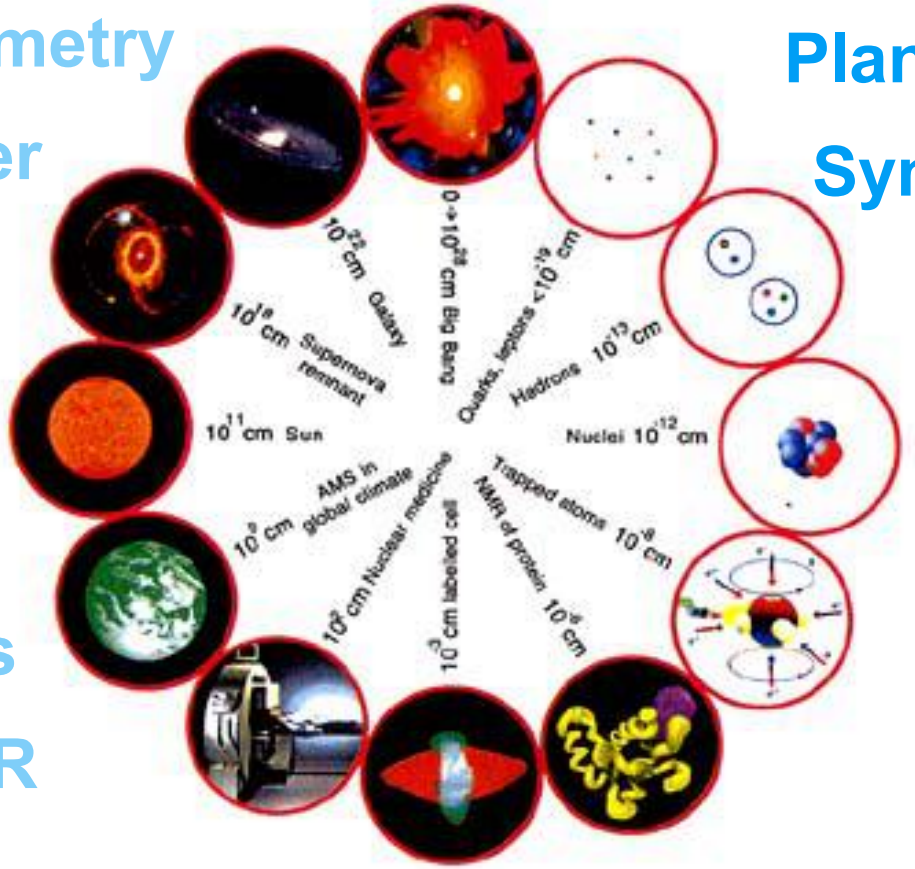
Dark energy

Neutron stars

Baryogenesis

Leptogenesis

UHECR



Planck physics

Symmetry violation

Leptons & Baryons

Mass

Unification

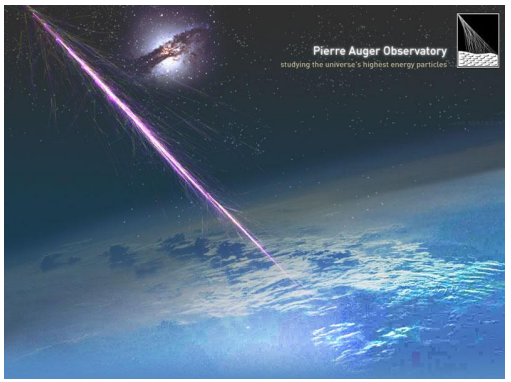
Neutrinos

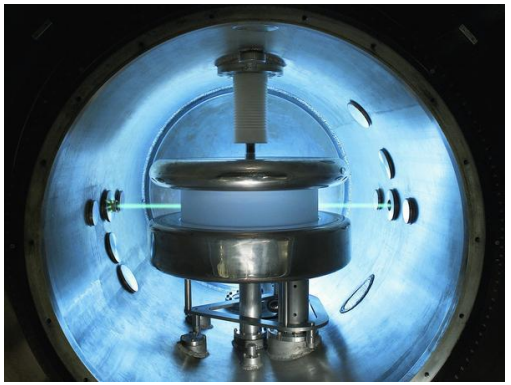
Understand nature at

Extreme scales ↔

Testing of the

Standard Model





Energy frontier

LHC

Space-Time frontier

Cosmology

Intensity frontier

B-factories, ν-factories

Precision frontier

Vigorous research programs at all frontiers needed to understand fundamental physics

Precision Frontier

Extremely precise calculations

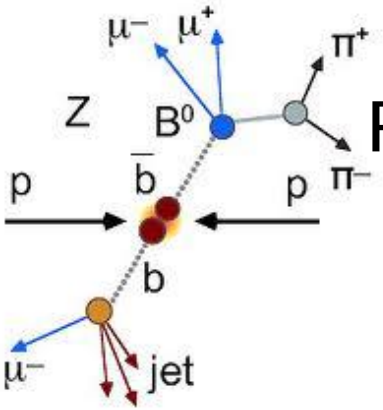
QED/QFD : *from first principles*
QCD : *latQDC, EFT, χPT, ...*

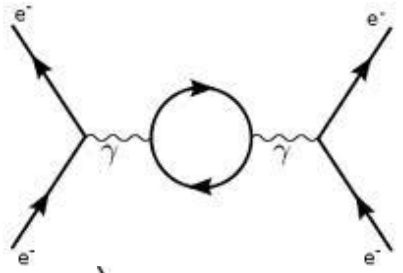
AND

Extremely precise measurements

Atomic, Nuclear, Particle physics techniques
Symmetry violation
Rare processes

What is “low energy”?

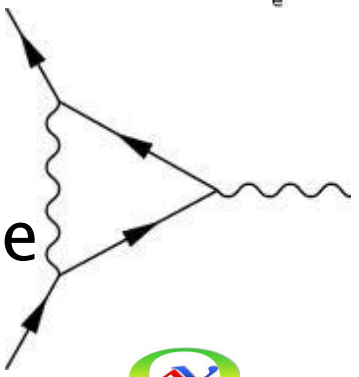




Real particles ↔ Virtual particles

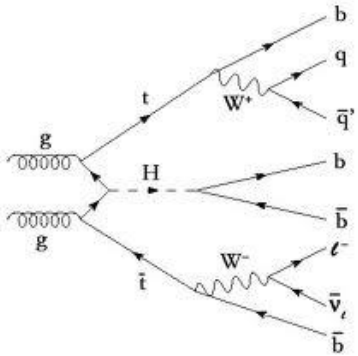
Production ↔ Loops

Exclusive ↔ Inclusive



Generic ↔ Specific Observable

Specific ↔ Generic Sensitivity



Statistics ↔ Systematics

Concentrated ↔ Dispersed

Large Scale ↔ Small Scale

Collider ↔ Table top

What is “low energy”?

Real particles ↔ Virtual particles

Production ↔ Loops

Exclusive ↔ Inclusive

Generic ↔ Specific Observable

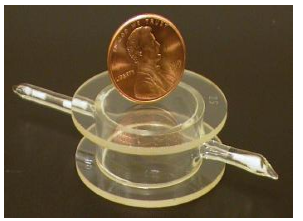
Specific ↔ Generic Sensitivity

Statistics ↔ Systematics

Concentrated ↔ Dispersed

Large Scale ↔ Small Scale

Collider ↔ Table top



Physics : high energy = QCD perturbative

What is “precision”?

precision

/prɪˈsɪʒ(ə)n/

noun

the quality, condition, or fact of being exact and accurate.
"the deal was planned and executed with military precision"
synonyms: exactness, exactitude, accuracy, accurateness, correctness, preciseness, clarity, clearness, distinctness; More

- marked by or adapted for accuracy and exactness.
  modifier noun: **precision**
  "a precision instrument"
- *technical*
  refinement in a measurement, calculation, or specification, especially as represented by the number of digits given.
  plural noun: **precisions**
  "a technique which examines and identifies each character with the highest level of precision"

Translations, word origin, and more definitions

Pushing at the limits of what we can conceptually and techniqually (and financially) accomplish.

Outline

Constants of the Standard Model

What makes a measurement?

Selected experiments

Conclusion

Outline

Constants of the Standard Model

What makes a measurement?

Selected experiments

Conclusion

Based on “Planning the edifice : structure of theories”, Ch. 3, Uzan & Leclercq
G. Cohen-Tannoudji, “Universal constants, standard models and fundamental metrology”, Eur. Phys. J ST, 172, 5 (2009)

What is a “constant”?

Definition of CONSTANT

: something invariable or unchanging: as

a : a number that has a fixed value in a given situation or universally or that is characteristic of some substance or instrument

b : a number that is assumed not to change value in a given mathematical discussion

c : a term in logic with a fixed designation

Definition of “fundamental”?

I.
- a : serving as an original or generating source : PRIMARY <a discovery fundamental to modern computers>
- b : serving as a basis supporting existence or determining essential structure or function : BASIC

II.
- a : of or relating to essential structure, function, or facts : RADICAL <*fundamental* change>; *also* : of or dealing with general principles rather than practical application <*fundamental* science>
- b : adhering to fundamentalism

III. of, relating to, or produced by the lowest component of a complex vibration

IV. of central importance : PRINCIPAL <*fundamental* purpose>

V. belonging to one's innate or ingrained characteristics : DEEP-ROOTED <her *fundamental* good humor>

Practical definition in physics

a “constant”

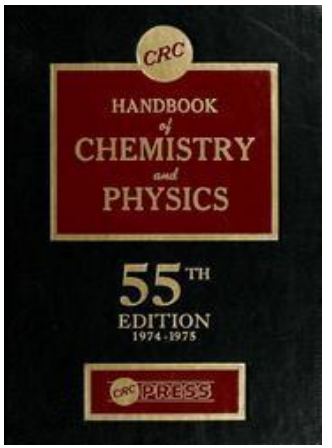
is

any non-determined parameter

in

the definition of a physical law

Time dependence ...



Which constants are necessary
depends on
the theory known at the time

Nineteenth centrury

– lots of constants for thermodynamics & dynamics

e.g. Boltzmann's constant, heat capacity, specific heat, latent heat, ideal gas constant, molar mass, Joule-Thomson coefficient, compressibility, ...

– no need for Planck's constant ħ or fine structure constant α

According to discipline ...

Which constants are necessary
depends on
the theory considered

Mechanics

*e.g gravitational acceleration **g** and gravitational constant **G***

Thermodynamics

*e.g. ideal gas constant **R**, Boltzmann's constant **k***

Electromagnetism

*e.g. speed of light **c**, elementary charge **e***

Quantum mechanics

*e.g. Planck's constant **h**, fine structure constant **α***

According to ease of use ...

List of constants is not absolute

e.g. book on relativistic physics might replace constants with equivalent ones:

$$m_e \rightarrow m_e c^2$$

List depends on intended use

Will we ever know all?

End 19th century : all that seems necessary to describe nature are classical mechanics, thermodynamics and electromagnetism.

Maxwell (1871) : *"... in a few years, all great physical constants will have been approximately estimated, ... and the only occupation which will be left to men of science will be to carry these measurements to another place of decimals."*

What is “fundamental”?

1983 : Steven Weinberg

“Fundamental” constants

cannot be calculated

from other constants

“... not just because the calculation is too complicated (e.g. viscosity of water) but because we do not know of anything more fundamental (*sic!*)”

Closer look at electromagnetism

$$\hbar = \frac{h}{2\pi}$$

$$\alpha = \frac{e^2}{(4\pi\varepsilon_0)\hbar c} = \frac{\mu_0 c e^2}{4\pi\hbar} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\,\frac{e^2}{\hbar c}$$

$$\varepsilon_0 \mu_0 c^2 = 1$$

$$a_e = C_e^{(2)}\left(\frac{\alpha}{\pi}\right) + C_e^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + C_e^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + C_e^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$

$$K_J = \frac{e}{\pi\hbar}$$

$$K_J^2 R_K = \frac{2}{\pi\hbar}$$

$$R_\infty = \frac{\alpha^2 m_e c}{4\pi\hbar} = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c}$$

$$R_K = \frac{\mu_0 c}{2\alpha} = \frac{2\pi\hbar}{e^2}$$

$$R_y = h c R_\infty$$

Which E&M constants fundamental?

ε_0 : electric constant

μ_0 : magnetic constant

c : speed of light

e : electron charge

α : fine structure constant

h : Planck's constant

$\hbar$: Planck's constant / 2π

m_e : electron mass

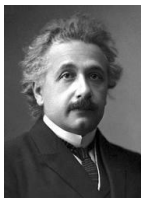
R_∞ : Rydberg constant

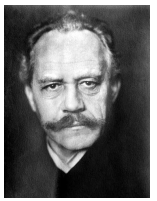
R_y : Rydberg constant (in energy units)

a_e : electron anomalous magnetic moment

K_J : Josephson constant

R_K : von Klitzing constant





Selecting h, c & e as fundamental ...

... then you also need e.g. α and m_e

$$\hbar = \frac{h}{2\pi}$$

$$\varepsilon_0 \mu_0 c^2 = 1$$

$$\alpha = \frac{e^2}{(4\pi\varepsilon_0)\hbar c} = \frac{\mu_0 c e^2}{4\pi\hbar} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{e^2}{\hbar c}$$

$$R_K = \frac{\mu_0 c}{2\alpha} = \frac{2\pi\hbar}{e^2}$$

$$a_e = C_e^{(2)}\left(\frac{\alpha}{\pi}\right) + C_e^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + C_e^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + C_e^{(8)}\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$

$$K_J = \frac{e}{\pi\hbar}$$

$$K_J^2 R_K = \frac{2}{\pi\hbar}$$

$$R_\infty = \frac{\alpha^2 m_e c}{4\pi\hbar} = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c}$$

$$R_y = hc R_\infty$$

How to decide?

Choice of constants depends on

- measurability
- uniformity
- universality
- ease of use
- state of knowledge
- applicability

Hierarchy of constants

Classification by Lévy-Leblond [1979]

A. Properties of particular physical objects

B. Characteristics of classes of phenomena

C. Universal constants

D. Invisible constants

E. Constants indistinguishable from zero

Hierarchy of constants

Examples

A. Particle masses, magnetic moments

B. Coupling constants, mixing angles

C. Speed of light, Planck's constant, Gravitational constant

D. Isotropy of space, equivalence inertial & gravitational mass, #dimensions, #flavors

E. Photon mass, graviton mass, neutrality of matter, (neutrino mass)

Evolution

When introducing new, more unified or more fundamental, theories

i. number of constants may change

ii. hierarchy of fundamental constants time dependent

iii. reflects our knowledge and ignorance

Constants may : emerge, progress, retrogress, transmute, disappear

fundamental theories ↔ fundamental constants

Most fundamental constants

Three “most fundamental” constants: **G**, **c** and **ħ** (class C)

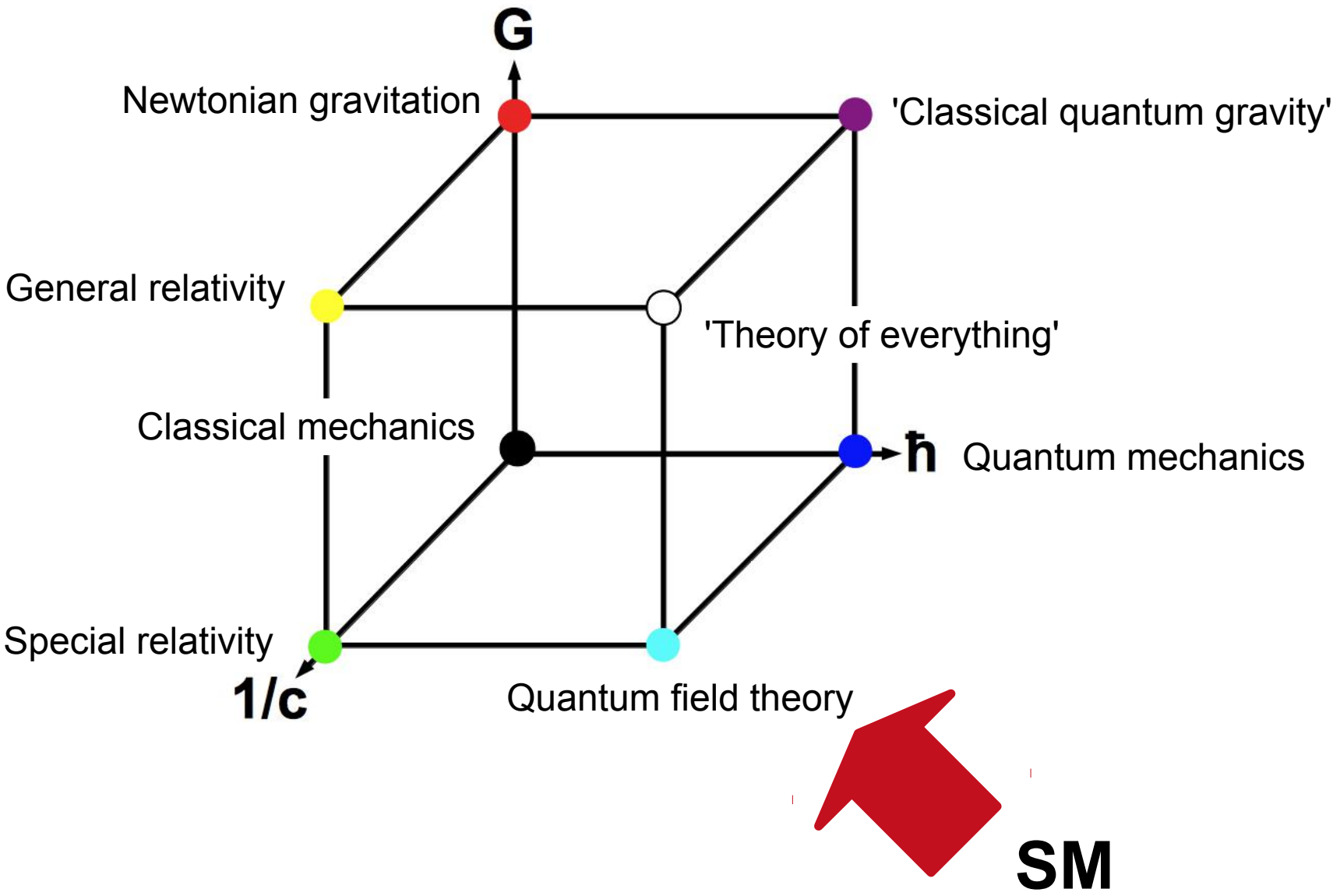
Why? What is their role?

Related to evolution of physics & formulation of new theories

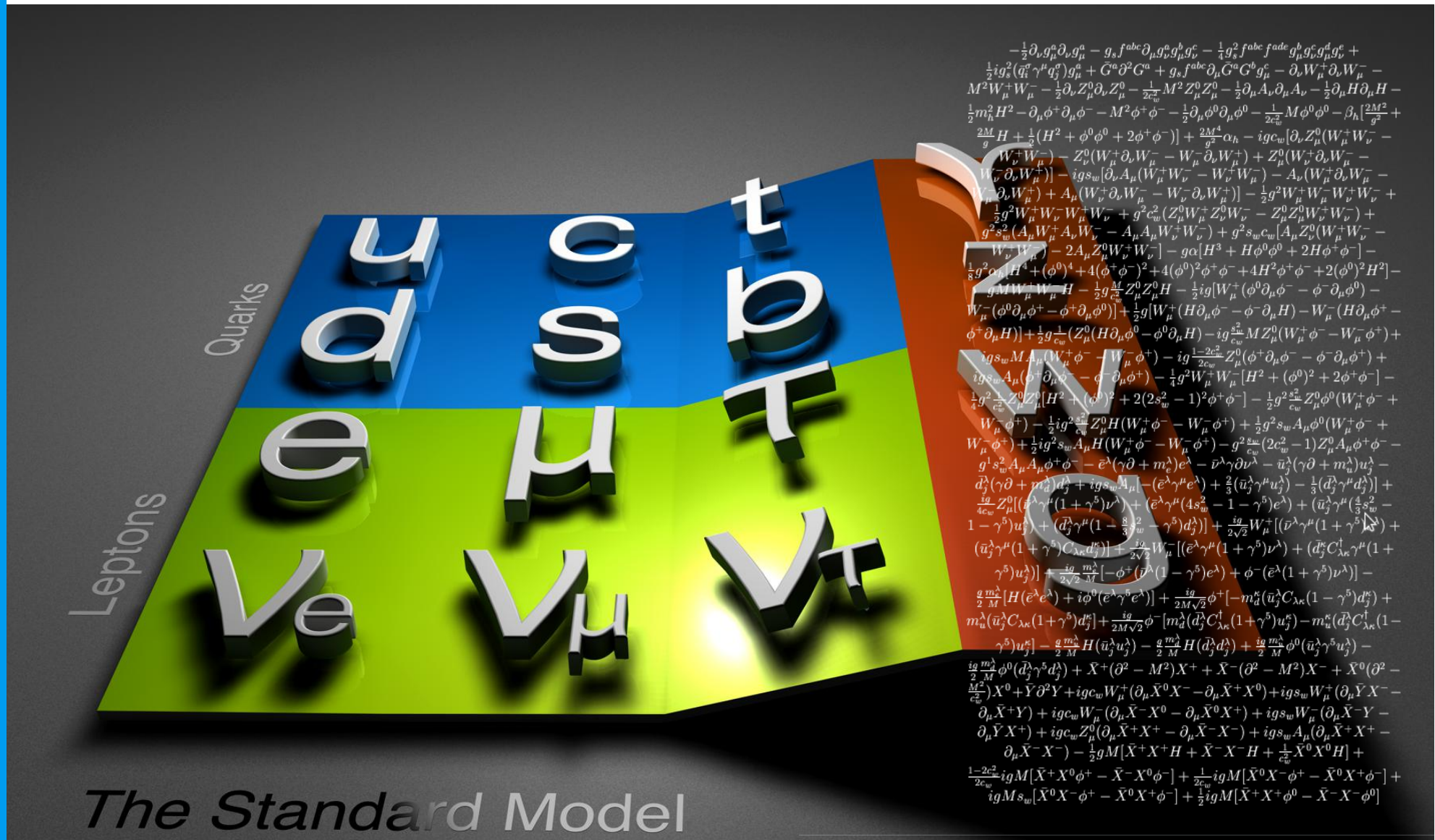
Constants → domain of validity of theories

$v \rightarrow c$: relativistic effects become important
$A \approx \hbar$: quantum effects become important
$G > 0$: gravitation effects become important

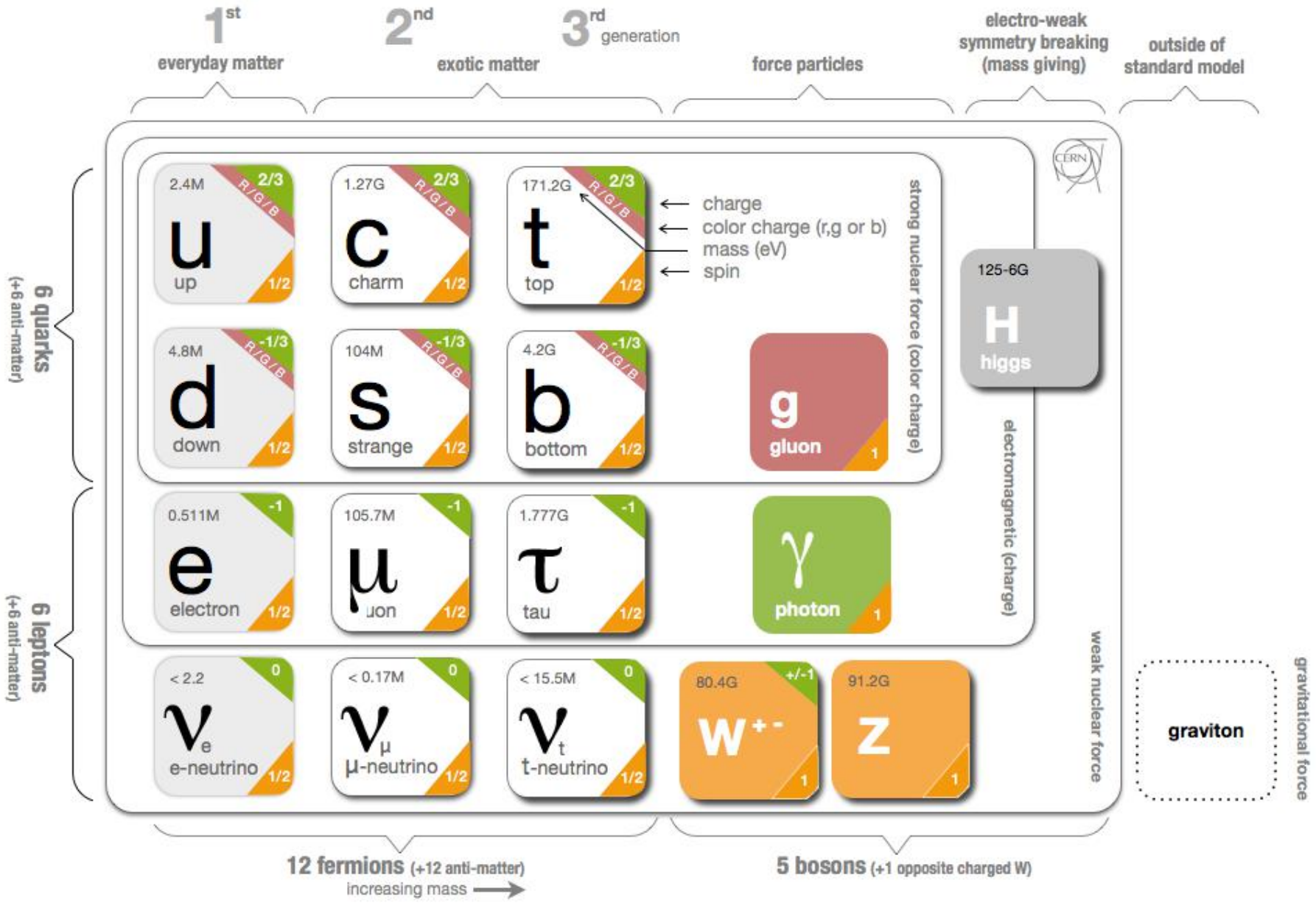
Cube of theories



What about particles?



Standard Model



Which are the fundamental parameters?

Standard Model : physics @ most fundamental level

Parameters cannot be related to more fundamental theory

Dimensions provided by **ħ, c & G**

Many dimensionless fundamental parameters

(these any observer can agree upon, regardless of their unit system)

Some hidden constants ...

SM parameters

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

SM parameters

Fermion masses : m = Gv

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

SM parameters

Coupling constants

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

SM parameters

Flavor mixing

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

SM parameters

CP violation

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

SM parameters

Mass generation via Higgs

Par	Meaning	Value	Par.	Meaning	Value
g	Weak coupling @ m_Z	0.6520(1)	G_e	Electron Yukawa coupl.	2.94×10^{-6}
θ_W	Weinberg angle	0.48290(5)	G_μ	Muon Yukawa coupl.	0.000607
g_s	Strong coupling @ m_Z	1.221(22)	G_τ	Tauon Yukawa coupl.	0.0102156233
μ^2	Quadratic Higgs coef.	$\sim -10^{-33}$	G_{ve}	e-neutrino Yukawa coupl.	$<1.7\times10^{-11}$
λ	Quartic Higgs coef.	~1?	$G_{v\mu}$	μ-neutrino Yukawa coupl.	$<1.1\times10^{-6}$
$\sin\theta_{12}$	Quark CKM angle	0.2243(16)	$G_{v\tau}$	τ-neutrino Yukawa coupl.	<0.10
$\sin\theta_{23}$	Quark CKM angle	0.0413(15)	G_u	u-quark Yukawa coupl.	0.000016(7)
$\sin\theta_{13}$	Quark CKM angle	0.0037(5)	G_d	d-quark Yukawa coupl.	0.00003(2)
δ_{13}	Quark CKM phase	1.05(24)	G_c	c-quark Yukawa coupl.	0.0072(6)
$\sin\theta'_{12}$	Neutrino MNS angle	0.55(6)	G_s	s-quark Yukawa coupl.	0.0006(2)
$\sin\theta'_{23}$	Neutrino MNS angle	≥0.94	G_t	t-quark Yukawa coupl.	1.002(29)
$\sin\theta'_{13}$	Neutrino MNS angle	≤0.22	G_b	b-quark Yukawa coupl.	0.026(3)
δ'_{13}	Neutrino MNS phase	?	θ_{QCD}	CPV QCD vacuum phase	$<10^{-9}$

Tegmark, Aguirre, Rees, Wilczek Phys.Rev. **D73**, 023505 (2006)

Some statistics

Apparently there are 26 (some say 28) dimensionless parameters needed in the Standard Model.

12	*are masses (w.r.t. to Higgs v.e.v.)*
3	*are coupling constants*
6	*are related to flavor mixing*
3	*incorporate CP-violation*
2	*are needed for Higgs physics*
(+2	*if neutrino's are Majorana particles)*

Some take this abundance of parameters as a hint that the Standard Model is only a low-energy limit of some more fundamental theory with (supposedly) fewer parameters.

(For those into SUSY: it has at least twice as many parameters ....)

Ease of use

What is the best set to use depends on what you're upto:

e.g. in gauge & scalar sectors of the SM we find

$$g,\ g',\ \mu^2,\ \&\ h$$ **Easy for calculations**

or

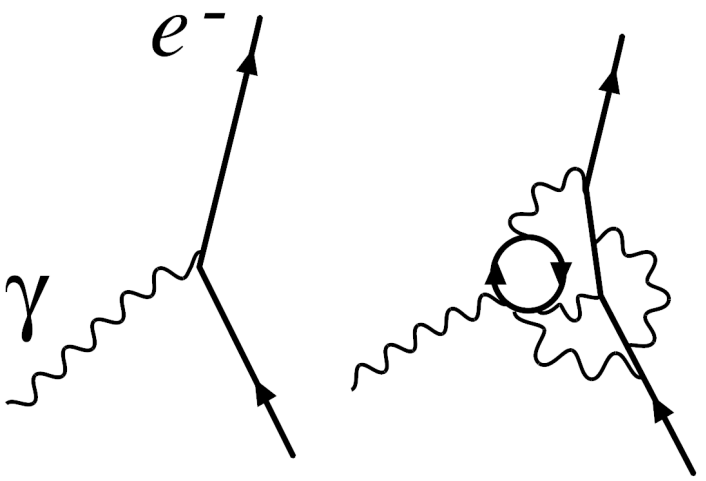
$$\alpha,\ \theta_W,\ M_W,\ \&\ M_H$$

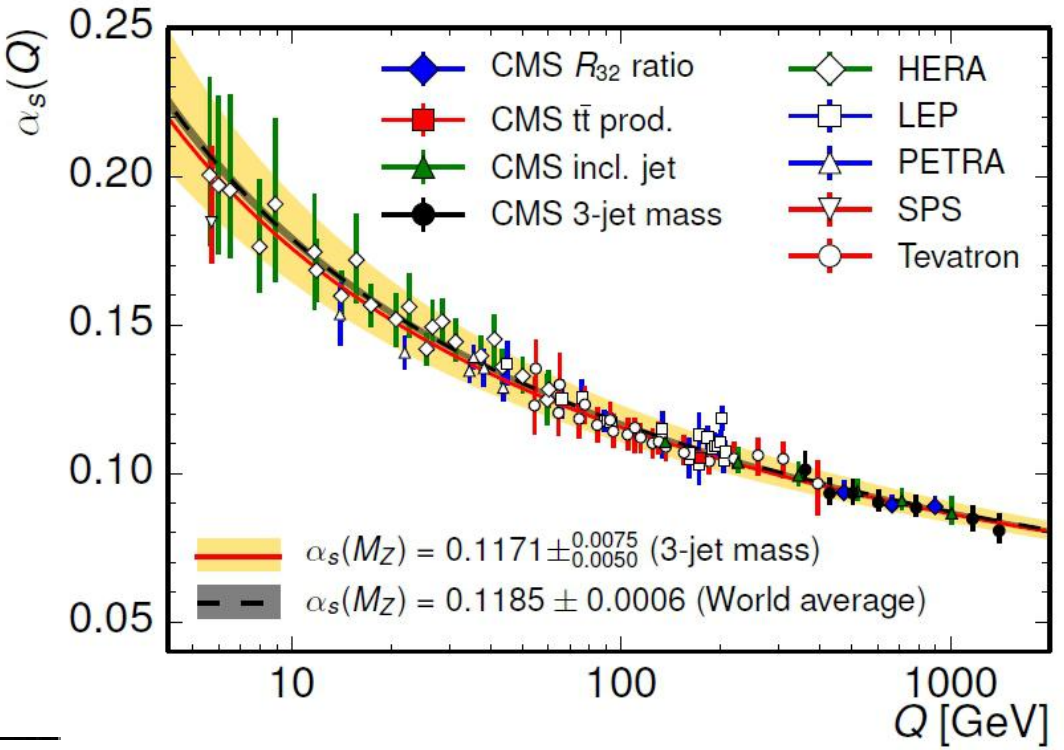
or

$$\alpha,\ G_F,\ M_Z,\ \&\ M_H$$ **Easy to measure**

Loops, running & renormalisation

Energy available in the process, or time/length scale at which you probe affects measured coupling constant

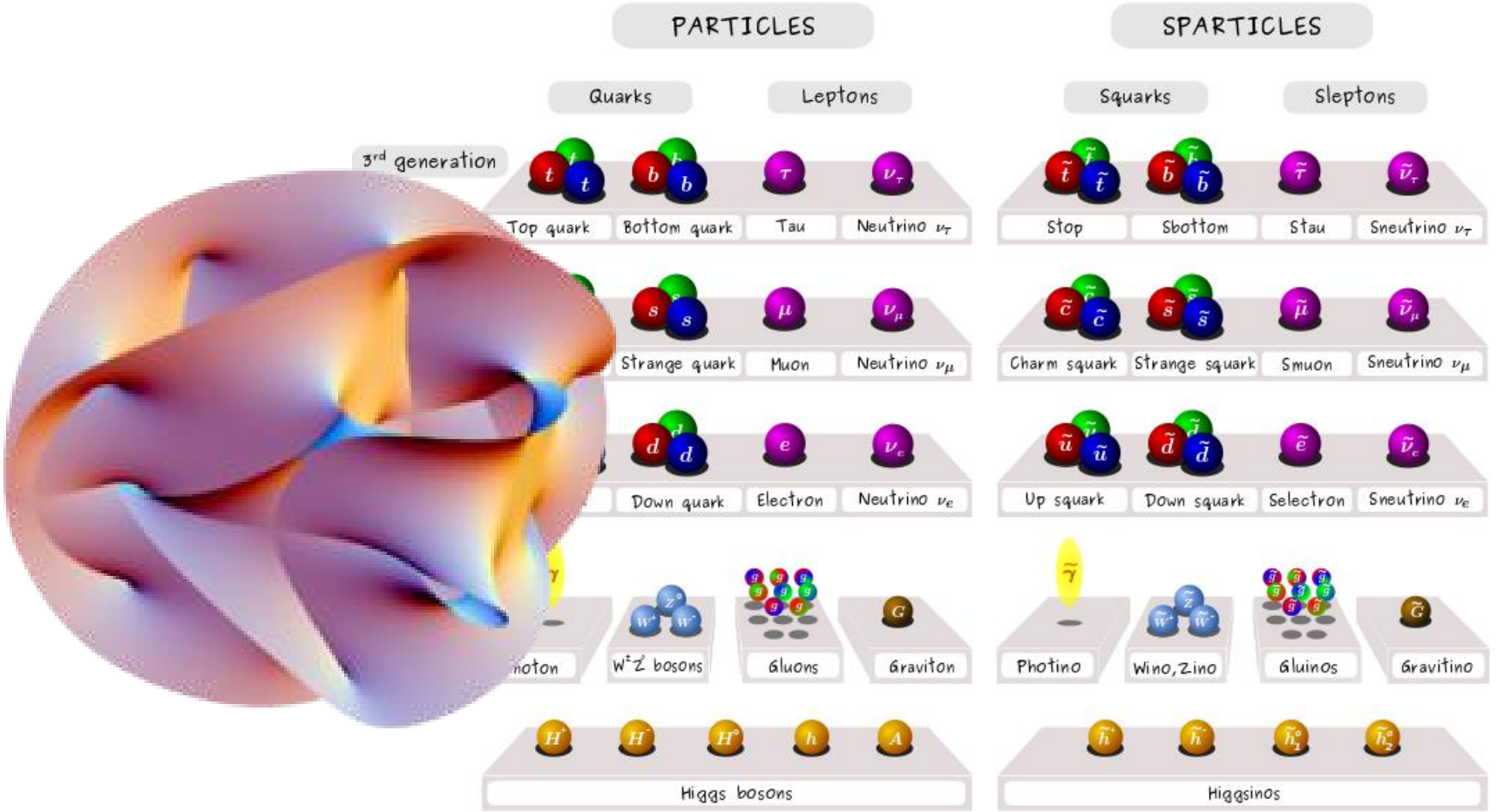




$$\alpha^1(Q^2) = \frac{\alpha(m_e^2)}{1 - \frac{\alpha(m_e^2)}{3\pi} \log \frac{Q^2}{m_e^2}} .$$

And beyond the SM

Potential SM extensions typically come with additional (for now "hidden") parameters



Precision frontier

Extremely precise calculations

QED/QFD : *from first principles*
QCD : *latQDC, EFT, χPT, ...*

AND

Extremely precise measurements

Atomic, Nuclear, Particle physics techniques
Symmetry violation
Rare processes

Outline

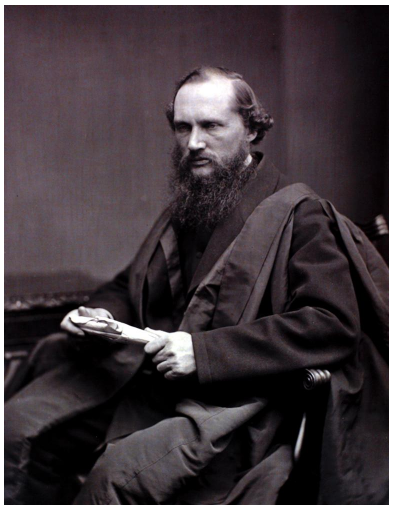
Constants of the Standard Model

What makes a measurement?

Selected experiments

Conclusion

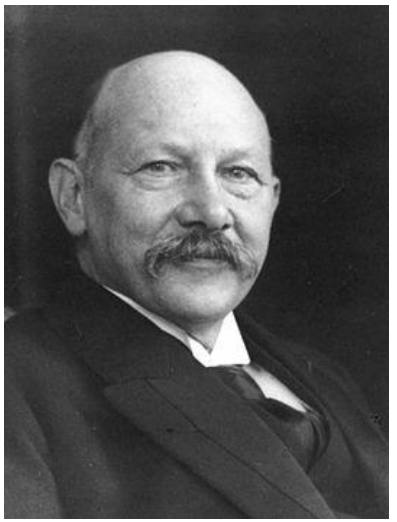
Measurement & knowledge



Lord Kelvin : *"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it in numbers, your knowledge is of a meagre and unsatisfactory kind ..."*

Heike Kamerlingh Onnes : *"Through measurement to knowledge"*

Measurement leads to the expression of characteristics of systems in terms of numbers



Aim of measurement :

give reliable knowledge on objects or concepts

Measurement & knowledge

How is a numerical value obtained?

In practice:

Linked to the set up of methodologies, instruments and reference standards

Aim: achieve reliable comparisons

Express results in terms of identified units

Also linked to developments in mathematics, control and computer science

Physical measurement

Comparison of two physical systems only gives access to *dimensionless numbers*.

“This” is <u>so many</u> of “those”

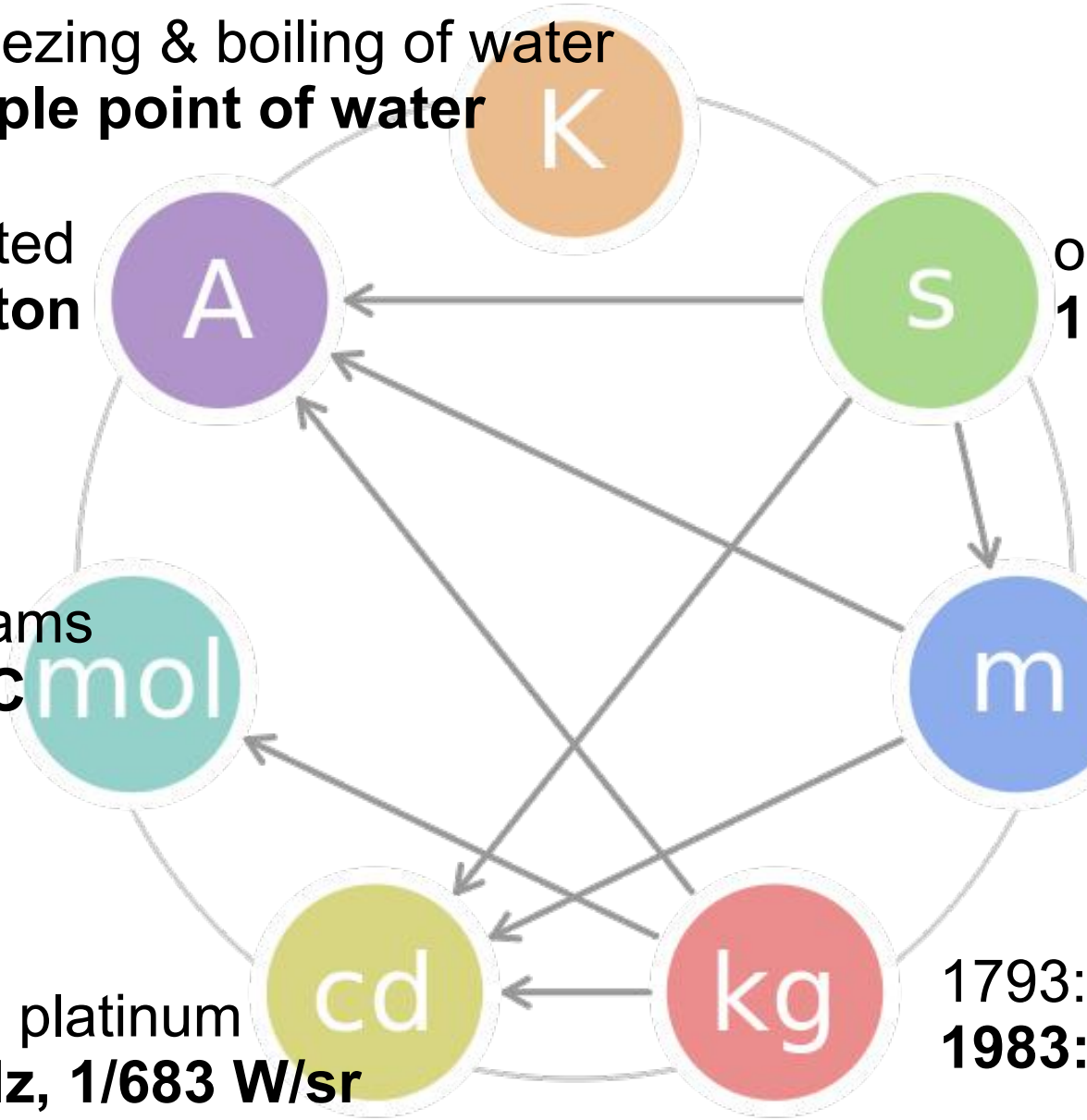
One often used to realize system of units

How many units are needed?

Everything measurable needs (generally) a unit:
Length, time, mass, current, velocity, voltage, temperature, entropy, area, volume, magnetization, resistance, capacitance, radioactivity, frequency, ...

Scientific measurement system

1743: freezing & boiling of water
1946: triple point of water



1881: Oersted
1946: Newton

orig.: day/86400
1967: ^{133}Cs hfs

1900: mass grams
1967: 12mg ^{12}C

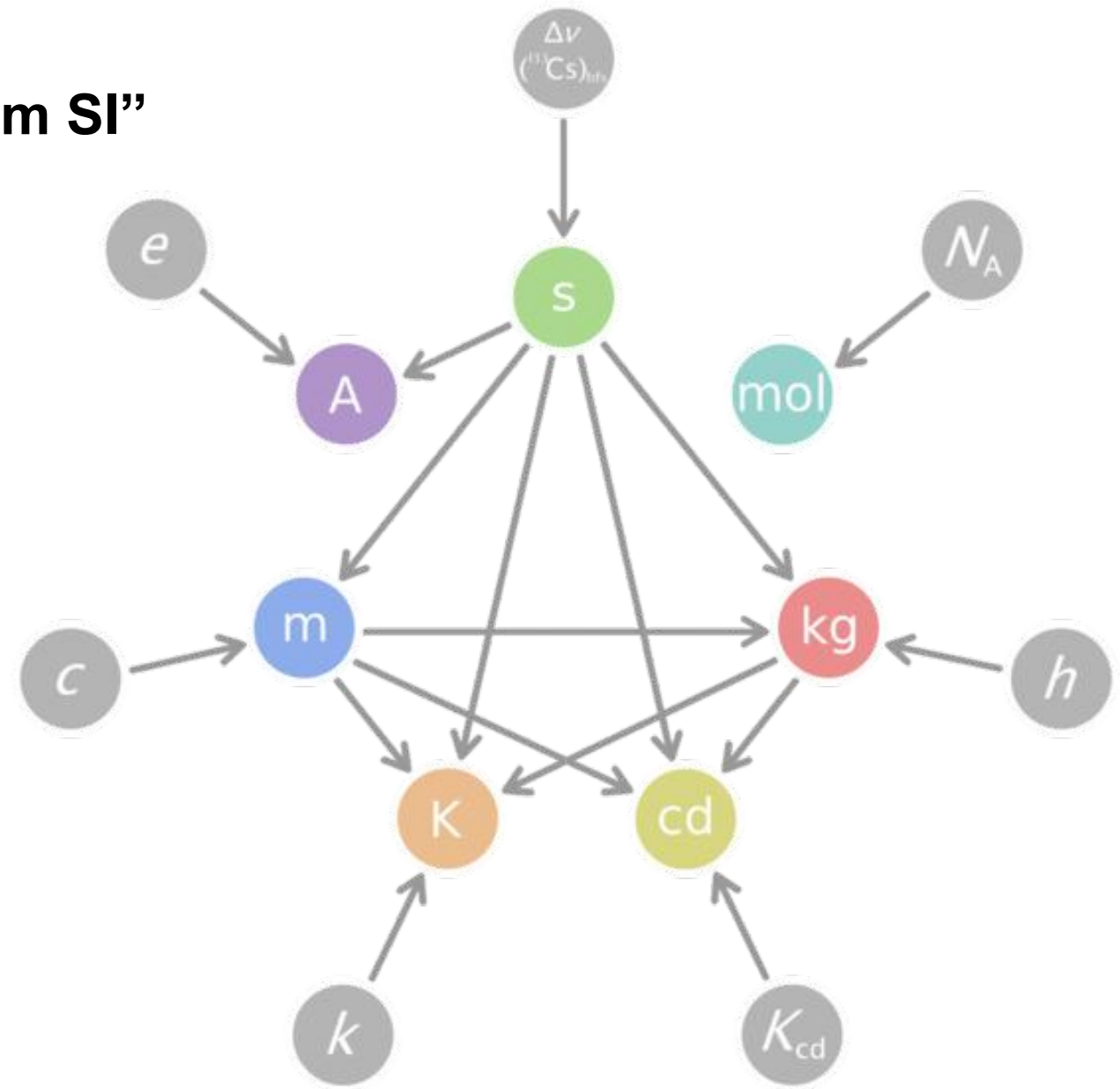
1793: meridian
1983: light

1946: molten platinum
1979: 540THz, 1/683 W/sr

1793: dm³ of water
1983: prototype

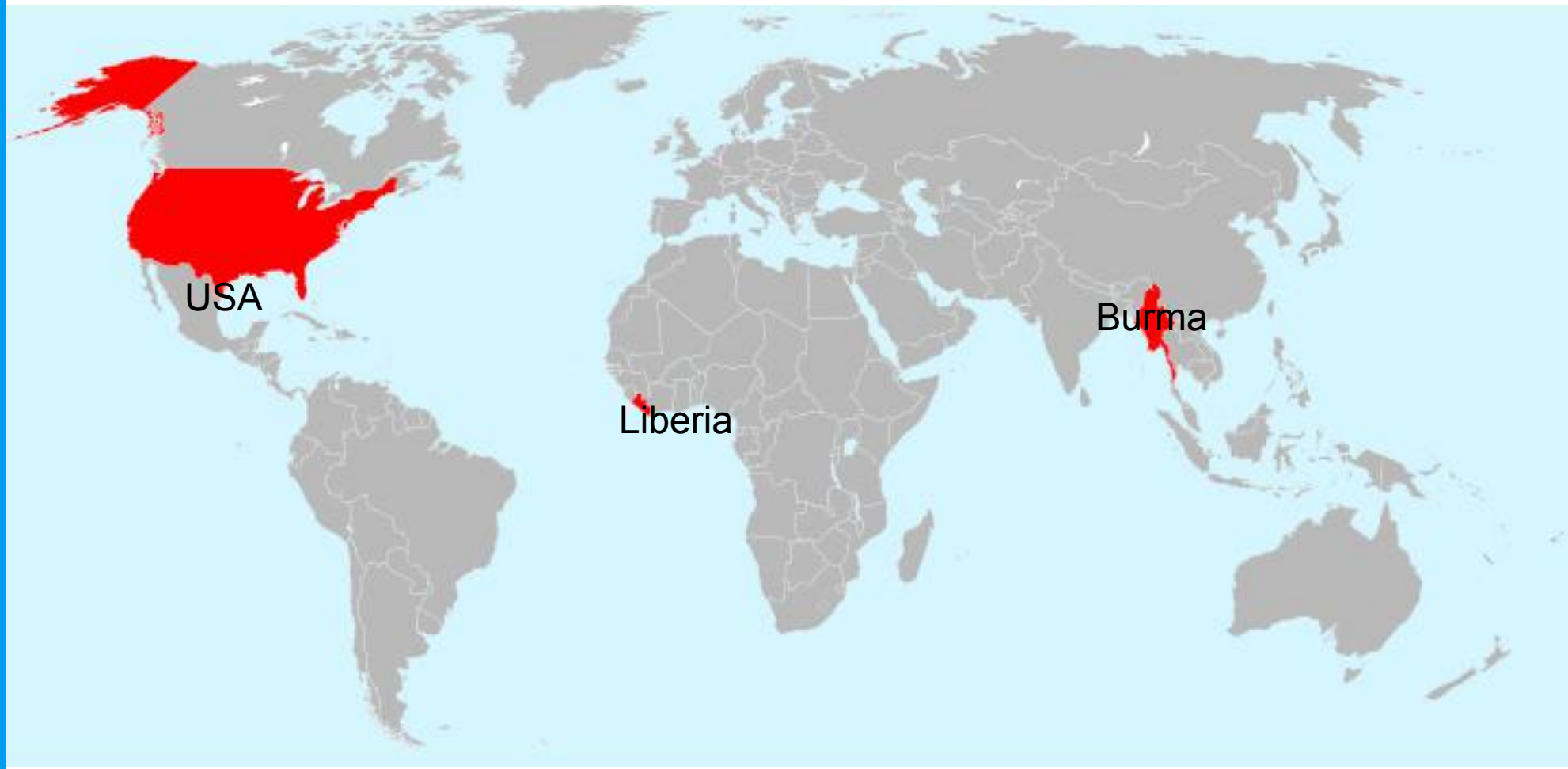
Scientific measurement system

“Quantum SI”



Relies on fundamental constants

SI adopted worldwide (almost ...)



Towards “natural” units

The SI system of units is essentially a practical one in which each unit has a convenient magnitude for use “on the street”, but

overall they do not have a natural basis

Consider communicating your mass and size to someone on a remote planet in a distant galaxy. “Meter” and “kilogram” would not be very useful for this purpose.

There are, however, physical quantities which come rather close to being the natural units of science, and these are termed the

fundamental *physics* constants

here we need to take a closer look at theory

Planck units

Setting the three constants to unity

$$c = \hbar = G = 1$$

Using SI-units

$$c = 299\,792\,458\ m \cdot s^{-1}$$
$$\hbar = 1.054\,571\,628(53) \times 10^{-34}\ J \cdot s$$
$$G = 6.674\,28(67) \times 10^{-11}\ m^3 \cdot kg^{-1} \cdot s^{-2}$$

the “natural” units for length, mass and time appear

$$l_P = \hbar / m_P c = \sqrt{\hbar G / c^3} = 1.6163 \times 10^{-35}\ m$$

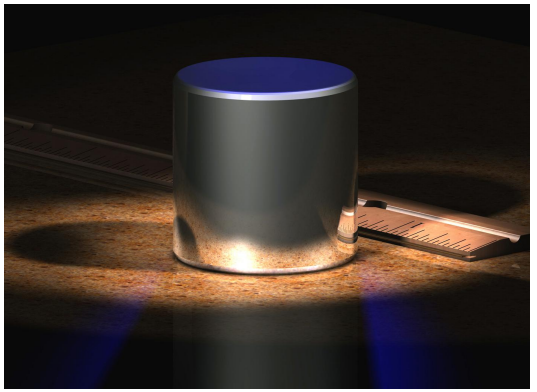
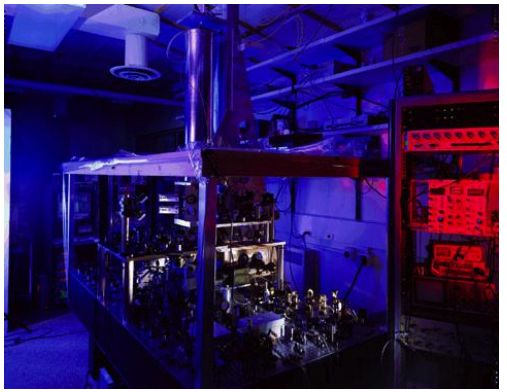
$$m_P = \sqrt{\hbar c / G} = 2.1764 \times 10^{-8}\ kg$$

$$t_P = \sqrt{\hbar G / c^5} = 5.3912 \times 10^{-44}\ s$$

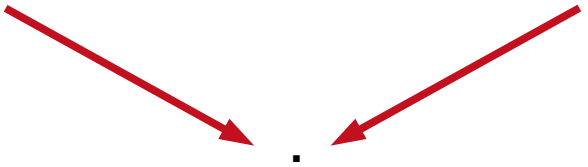
not particularly practical for everyday use ...

Planck rulers

SI "rulers"

Planck "ruler"



black hole with mass such that radius is equal to de Broglie wavelength

Need only ONE for length, mass and time!

Other “natural” units systems

Quantity / symbol	Planck	Stoney	Atomic	QCD
Speed of light in vacuum, **c**	1	1	1/α	1
Electric constant, ε_0	1/4π	1/4π	1/4π	1/4πα
Magnetic constant, $\mu_0=1/\varepsilon_0 c^2$	4π	4π	4πα²	4πα
Impedance of vacuum, $Z_0 = 1/\varepsilon_0 c$	4π	4π	4πα	4πα
Planck's constant, $\hbar=h/2\pi$	1	1/α	1	1
Elementary charge, **e**	√α	1	1	1
Josephson constant, $K_J = e/\pi\hbar$	√α/π	α/π	1/π	1/π
Von Klitzing constant, $R_K = 2\pi\hbar/e^2$	2π/α	2π/α	2π	2π
Gravitational constant, **G**	1	1	α_G	$\mu^2\alpha_G$
Electron mass, m_e	$\sqrt{\alpha_G}$	$\sqrt{\alpha_G}/\alpha$	1	1/μ

α : fine structure constant
α_G : gravitational coupling constant = $(m_e/m_{Planck})^2$
μ : proton-to-electron mass ratio

Mass mystery ...

Units are an (arbitrary) choice, but they still affect a measurement ...

CODATA masses

The NIST Reference on Constants, Units, and Uncertainty

m_p	= 1.672 621 898(21) x 10^{-27} **kg**	(1.2×10^{-8})
m_p	= 1.007 276 466 879(91) **u**	(9.0×10^{-11})
$m_p \cdot c^2$	= 1.503 277 593(18) x 10^{-10} **J**	(1.2×10^{-8})
$m_p \cdot c^2$	= 0.938 272 0813(58) **GeV**	(6.2×10^{-9})
m_e	= 9.109 383 56(11) x 10^{-31} **kg**	(1.2×10^{-8})
m_e	= 5.485 799 090 70(16) **u**	(2.9×10^{-11})
$m_e \cdot c^2$	= 8.187 105 65(10) x 10^{-14} **J**	(1.2×10^{-8})
$m_e \cdot c^2$	= 0.510 998 9461(31) **MeV**	(6.2×10^{-9})
m_μ	= 1.883 531 594(48) x 10^{-28} **kg**	(2.5×10^{-8})
m_μ	= 0.113 428 9257(25) **u**	(2.2×10^{-8})
$m_\mu \cdot c^2$	= 1.692 833 774(43) x 10^{-11} **J**	(2.5×10^{-8})
$m_\mu \cdot c^2$	= 105.658 3745(24) **MeV**	(2.3×10^{-8})

Outline

Constants of the Standard Model

What makes a measurement?

Selected experiments

Conclusion

G
F

QFD has a rich phenomenology

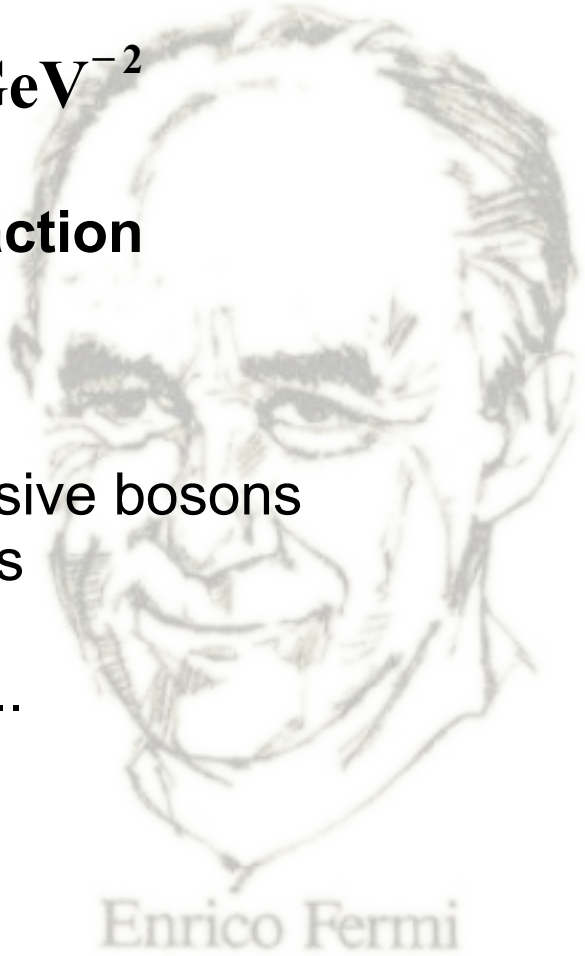
The weak coupling constant is

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

WI is the only interaction

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

Many *ad hoc* inputs ...



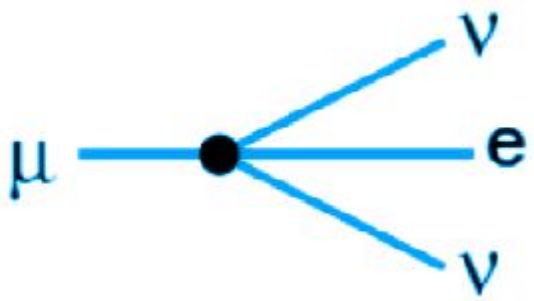
Muon lifetime in the SM

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

0.13ppm

Independent of underlying specifics of WI

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



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

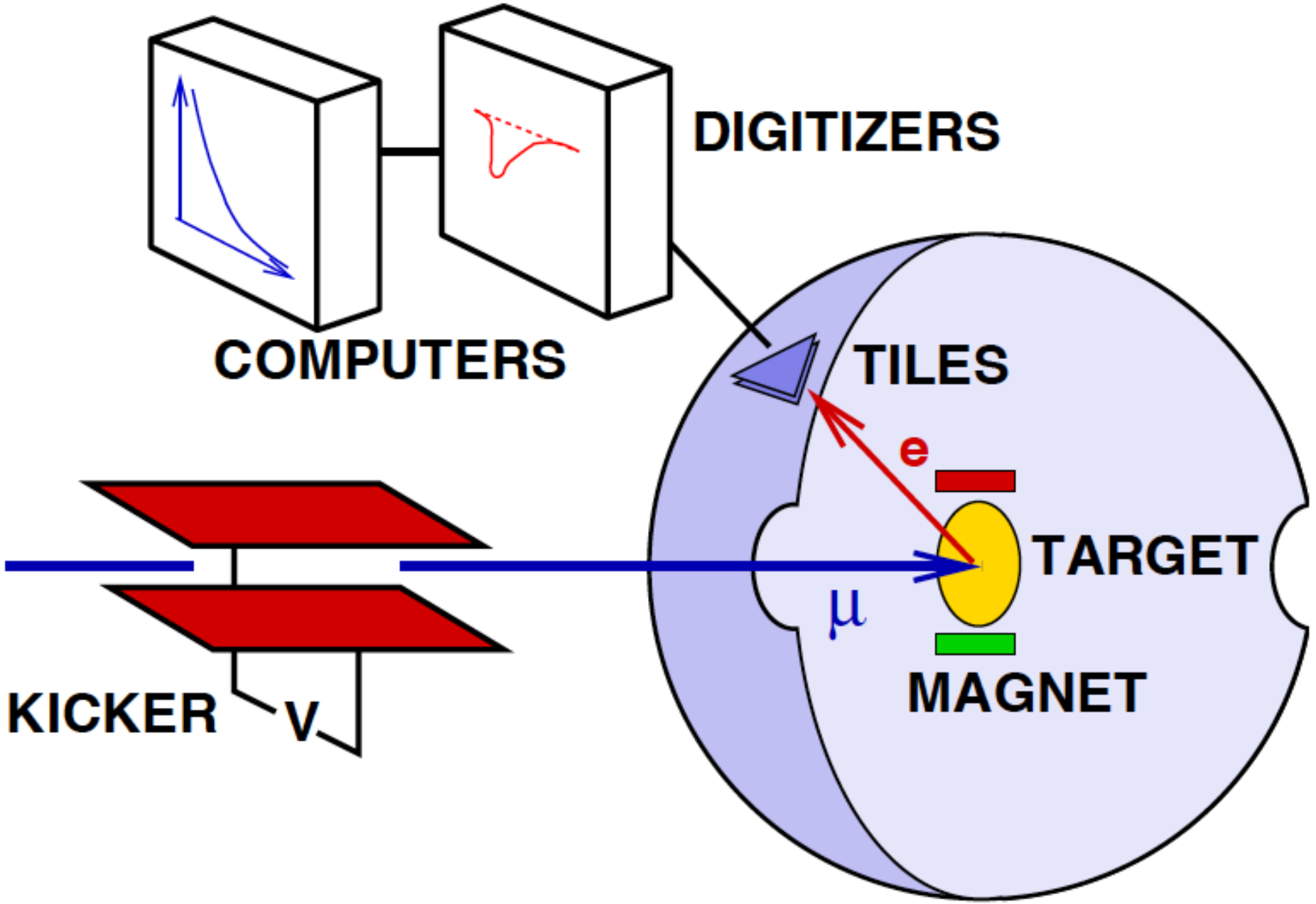
Phase space
10 ppm from $m_{\nu\mu}$
~0 from CMB

-4.1995×10^{-3}

$+1.5 \times 10^{-6}$

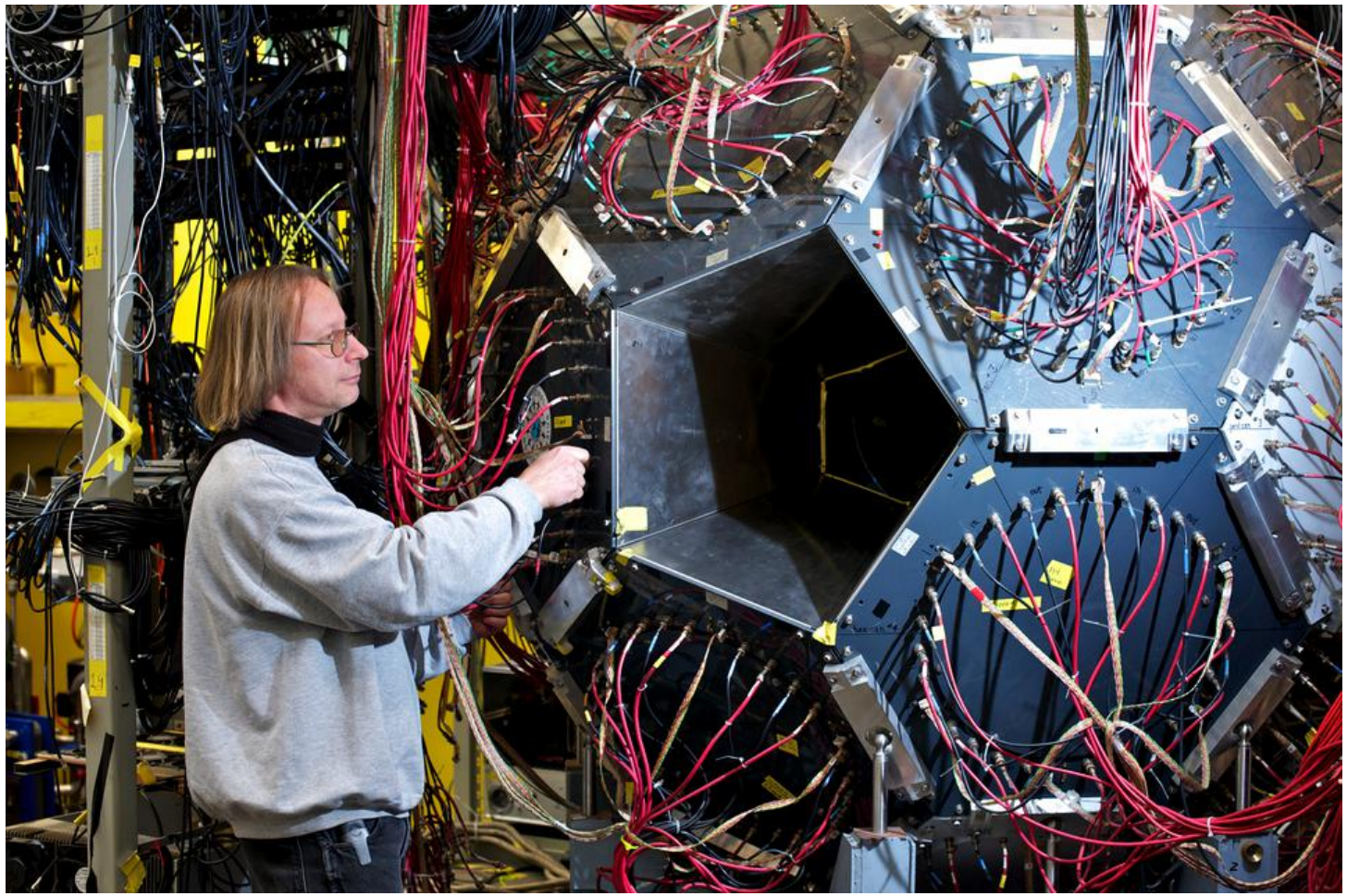
T. van Ritbergen, R.G. Stuart, Nucl.Phys. B564 (2000) 343-390

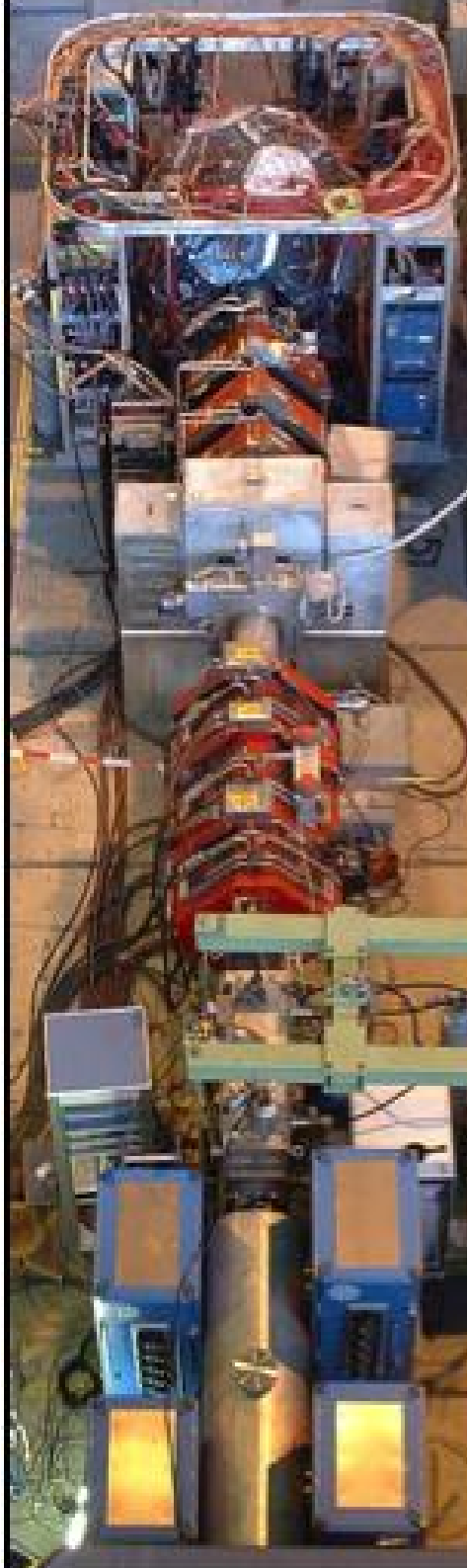
Principle of a lifetime measurement



What to do to get 1 ppm

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



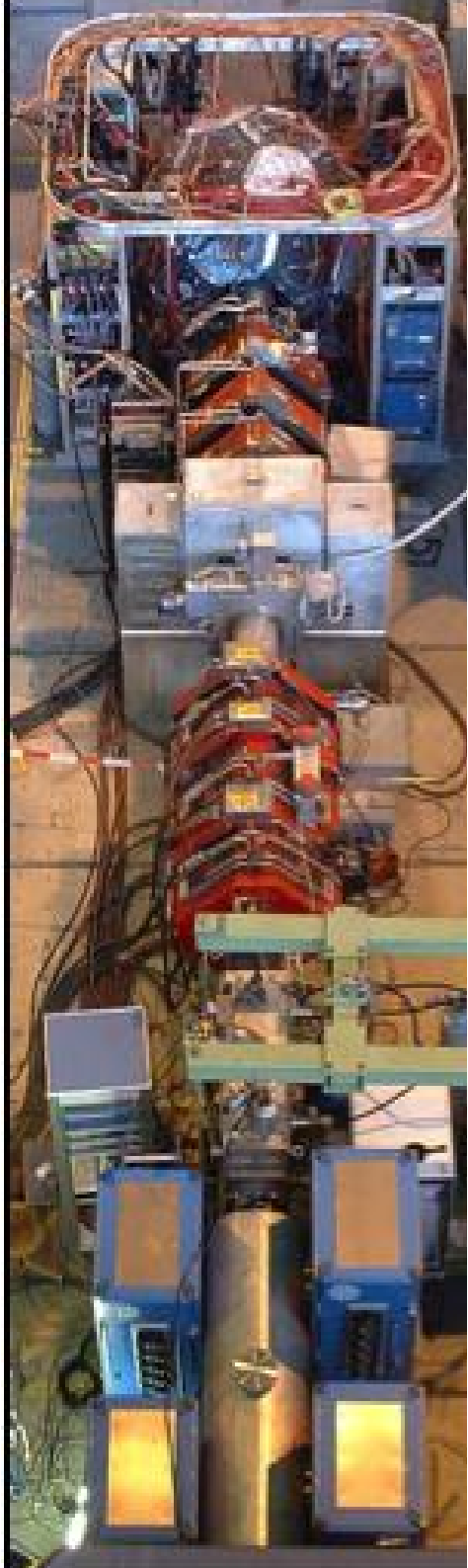


The muLan experiment @ PSI

- 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

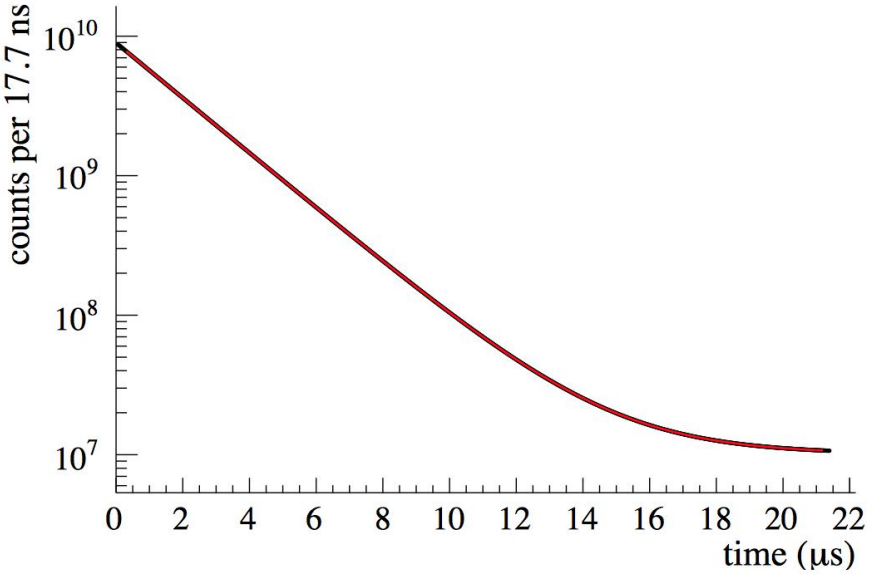
Computational challange

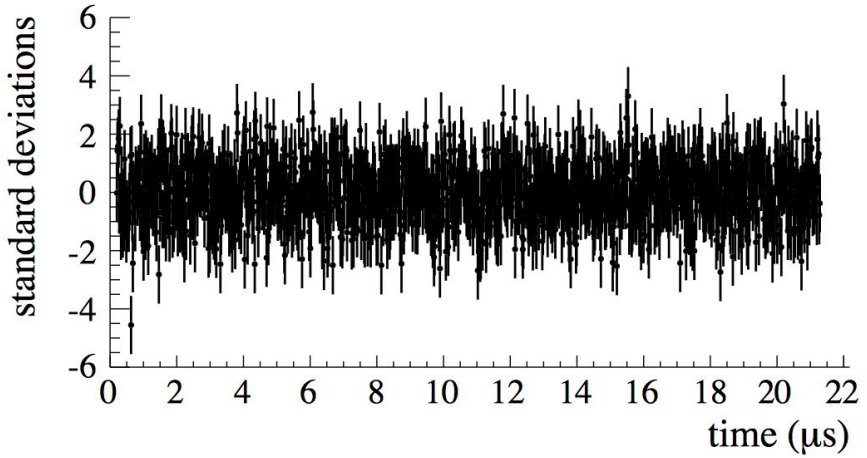
- 0.2 PByte
- 80,000 CPU hours per data pass

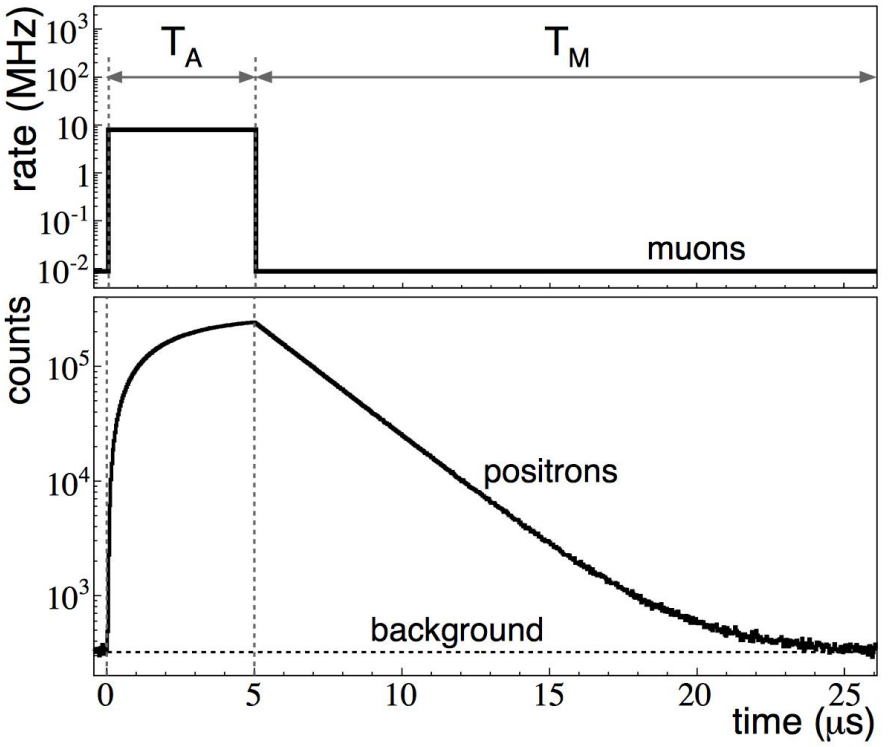


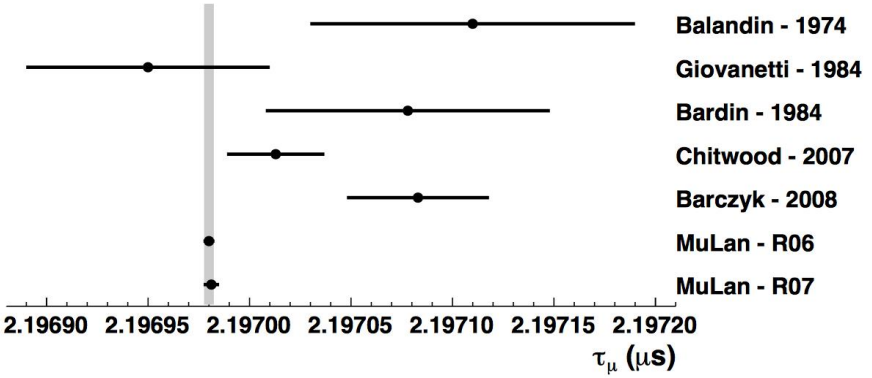
muLan results

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

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

$$+$$

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

$$\downarrow$$

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

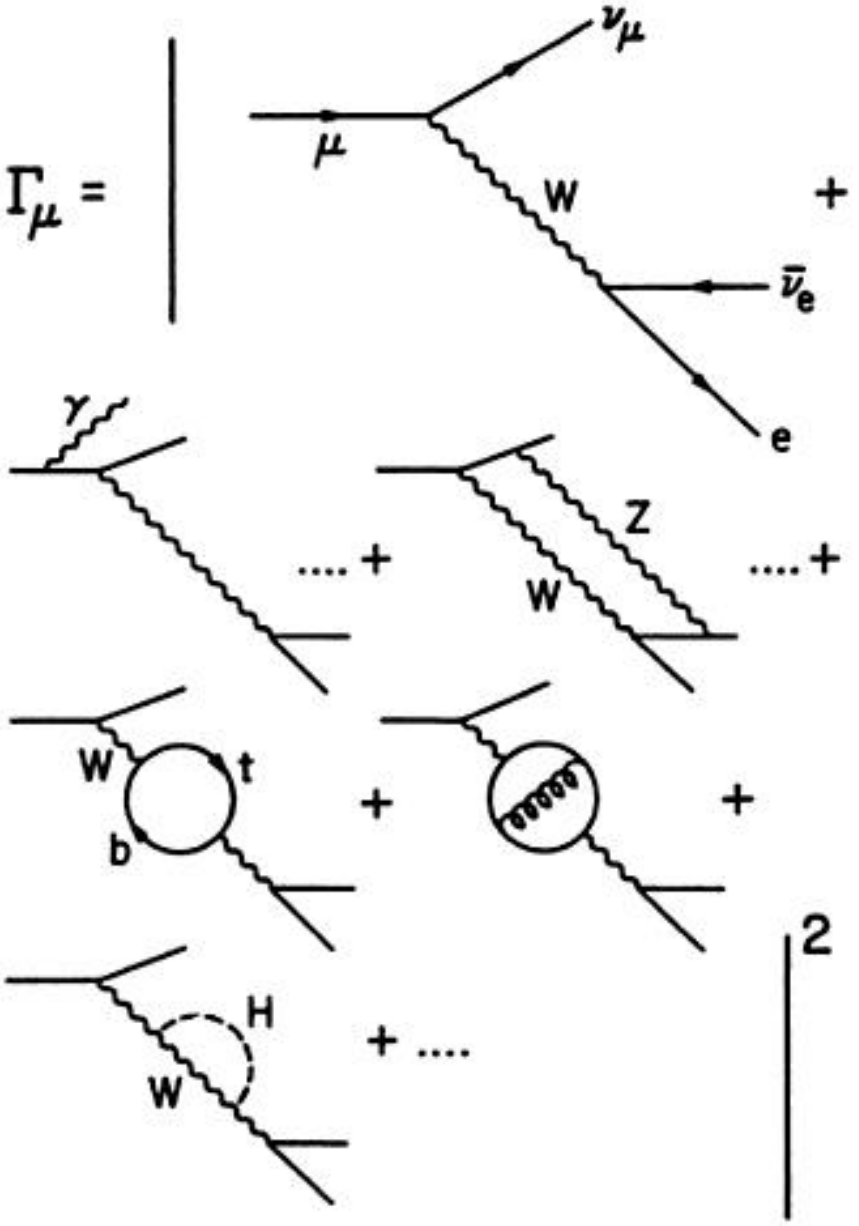
PRL 106, 041803 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011

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

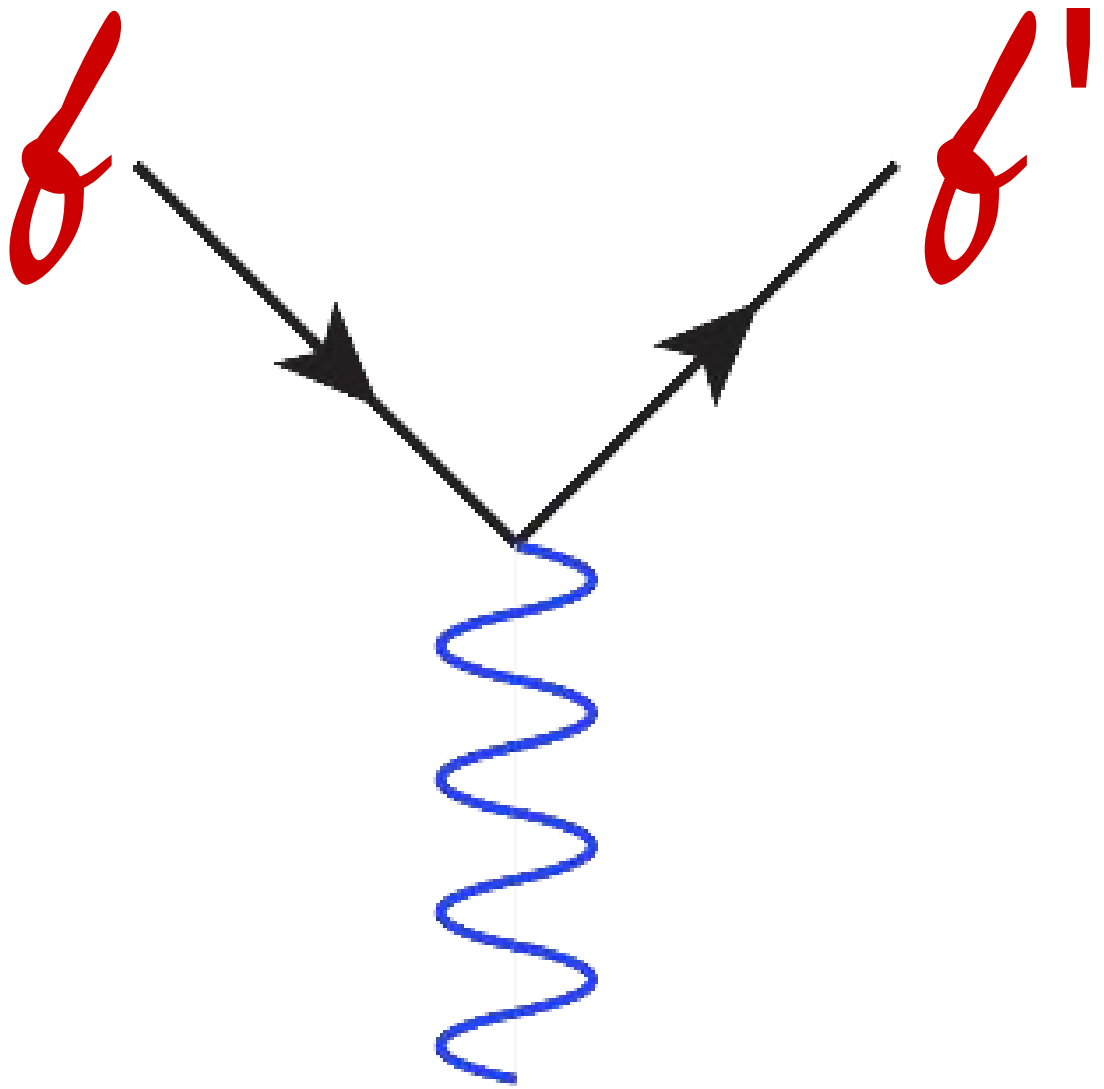
All QED observables of the form

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

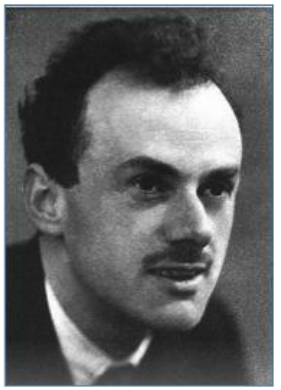
The Nobel Prize in Physics 1965

"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

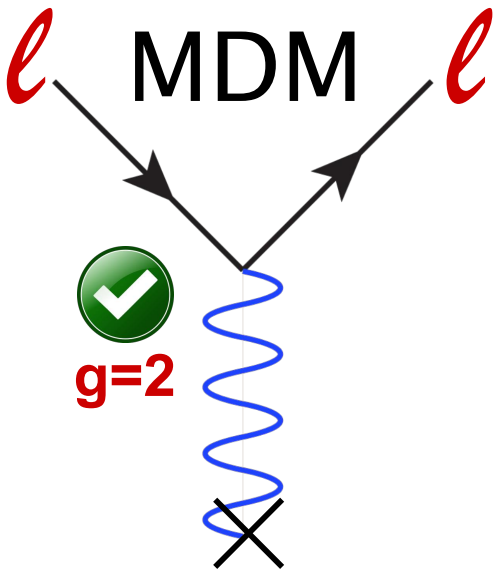
$$\vec{\mu} = g\frac{e\hbar}{2mc}\hat{\sigma} \qquad \vec{d} = \eta\frac{e\hbar}{2mc}\hat{\sigma}$$

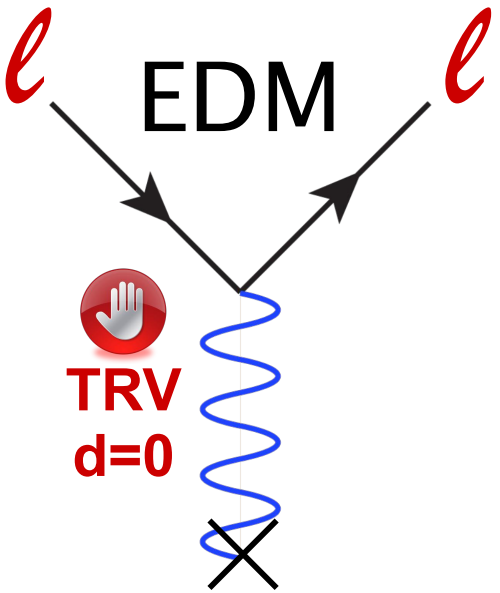
$$g = 2(1+a) \qquad \eta = 0$$

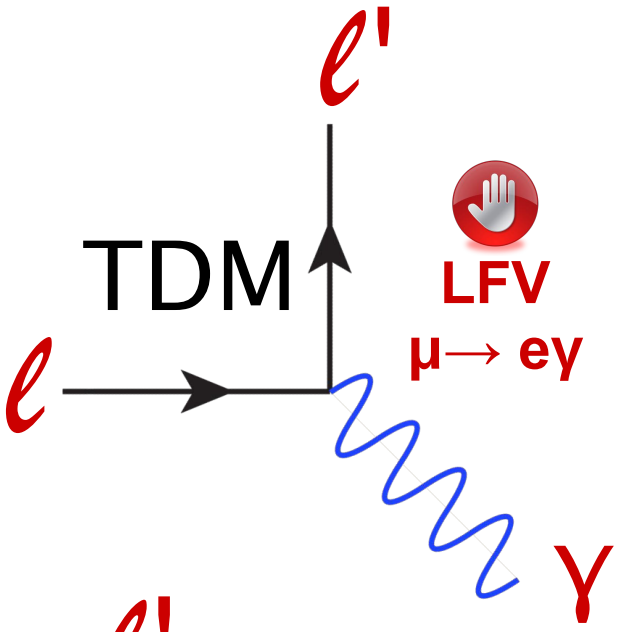
Anomaly — P & T conservation

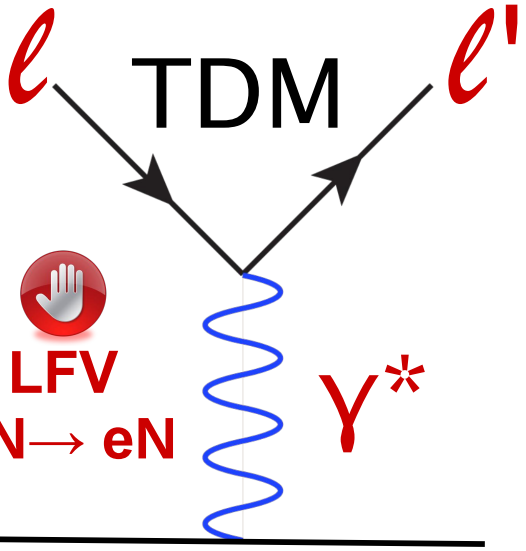
This is where the physics is!

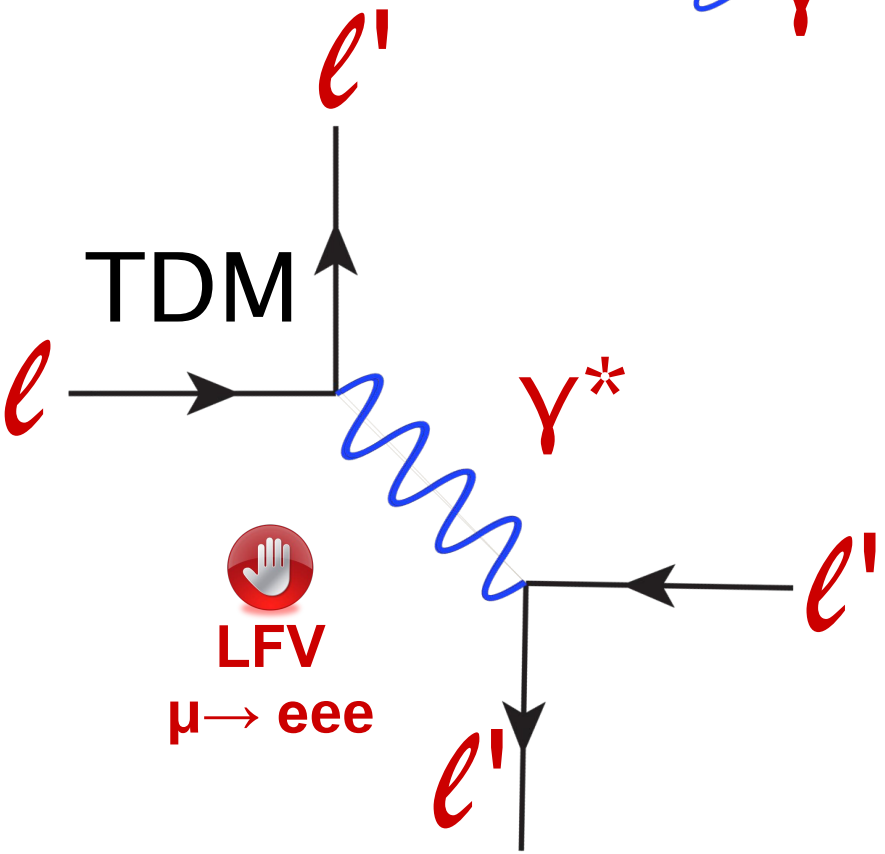
QED vertices



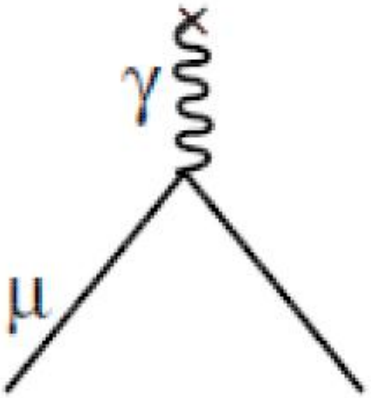


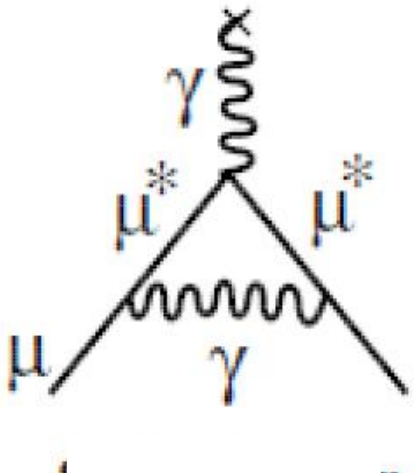




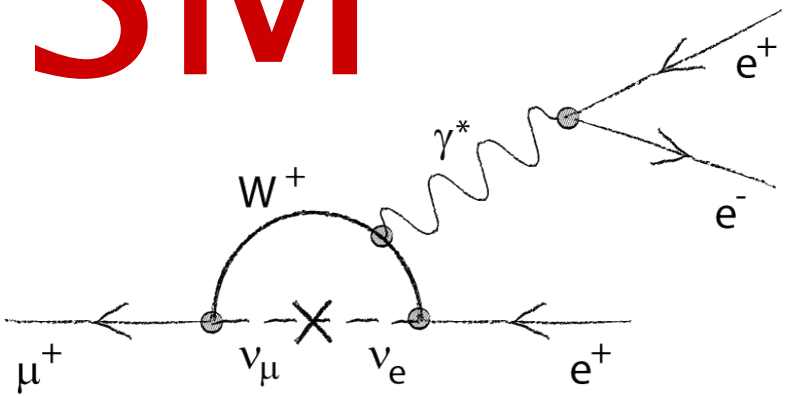


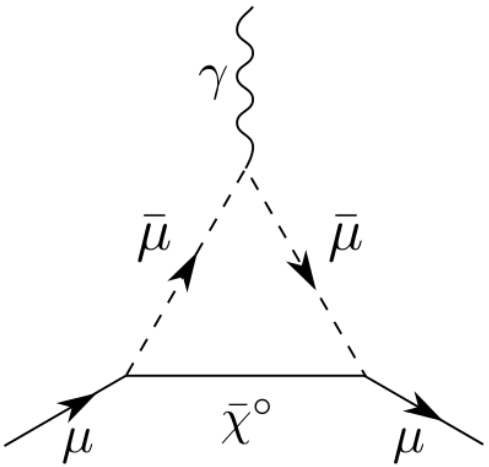
Radiative corrections

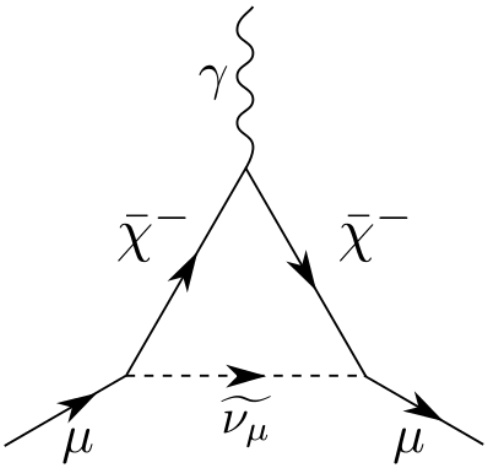




SM







BSM

Electron anomaly in the SM

Kinoshita & Feynman

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

a_1: 0.5

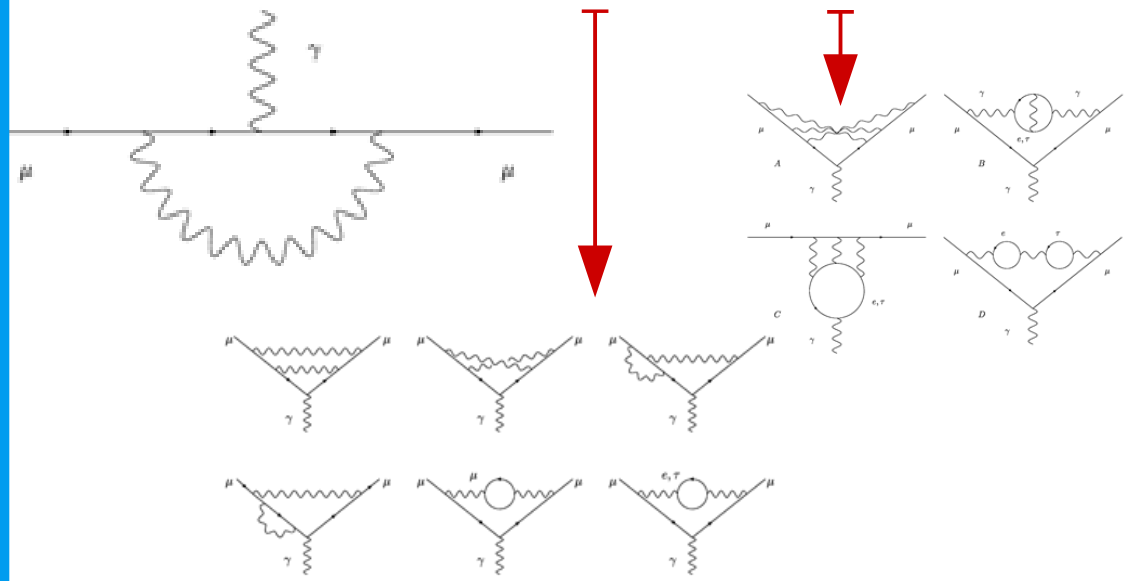
a_2: -0.328 478 444 002 90(60)

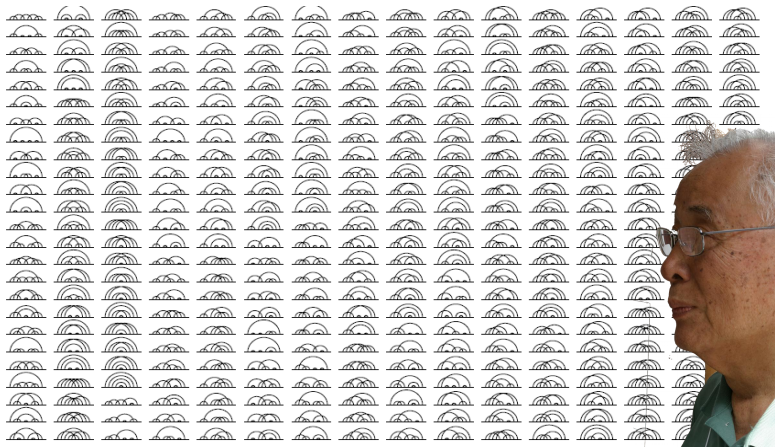
a_3: +1.181 234 016 827 (19)

a_4: -1.9144 (35)

a_5: 0.0 (4.6)

#diagrams: 1 | 7 | 72 | 891 | 12672



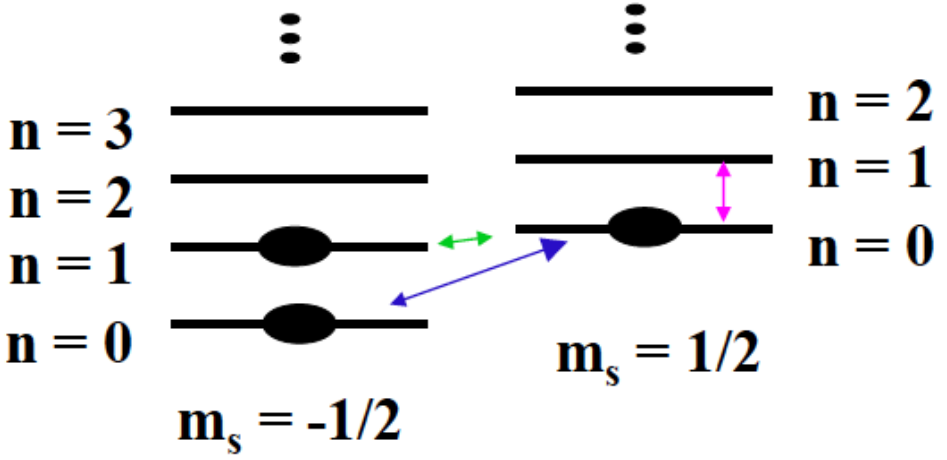


QM101 : "Geonium" atom

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

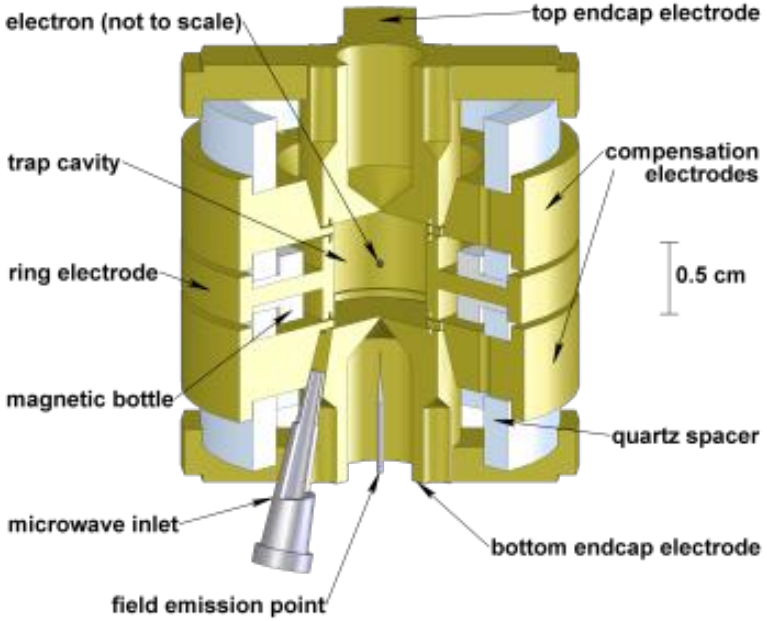
$$\frac{g}{2} = \frac{\omega_s}{\omega_c} = 1 + \frac{\omega_a}{\omega_c}$$

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

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

$$+$$

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

$$\downarrow$$

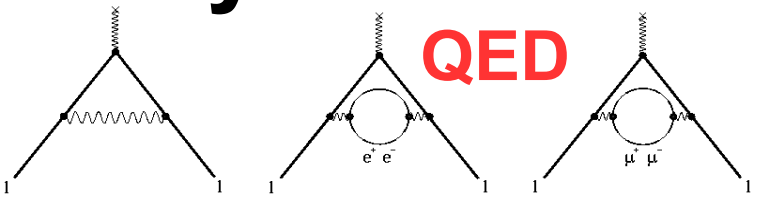
$$\frac{1}{\alpha} = 137.035\,999\,084\,(51)\,[0.37\ ppb]$$

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

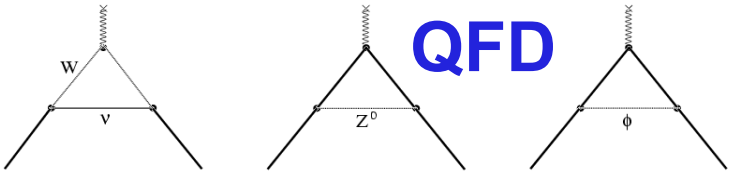
a_μ

Beyond QED : muon anomaly

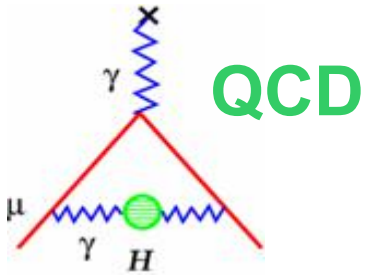
Generated via radiative corrections



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

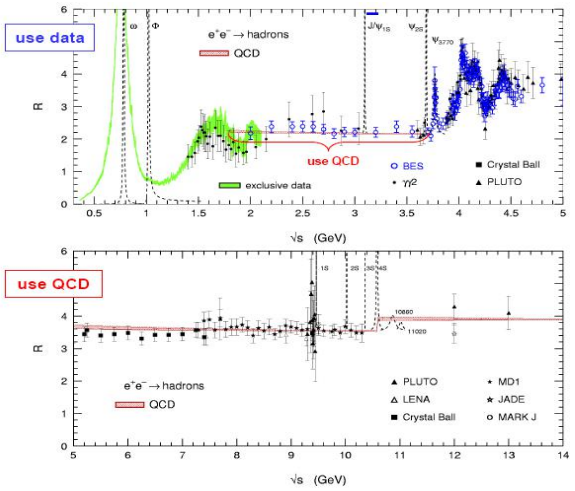


1,000,000 : 60 : 1



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

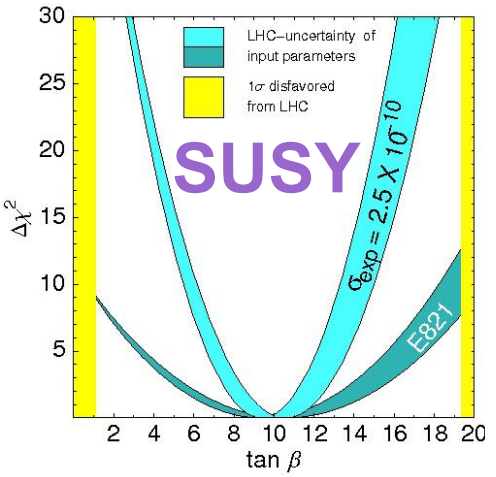
QCD dominates theory uncertainty (~0.5ppm)



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

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

(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)

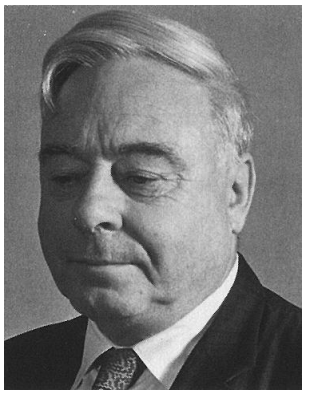
measure

0.112 609 5261(29)

Precession in a storage ring

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

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

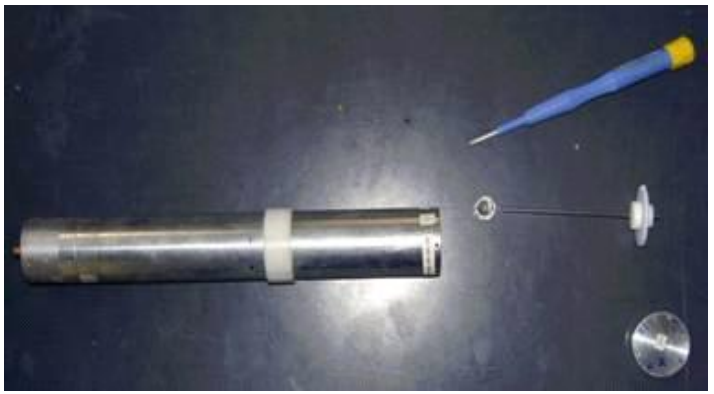


$$\omega_a = \omega_s - \omega_\beta = a\frac{e}{mc}B$$

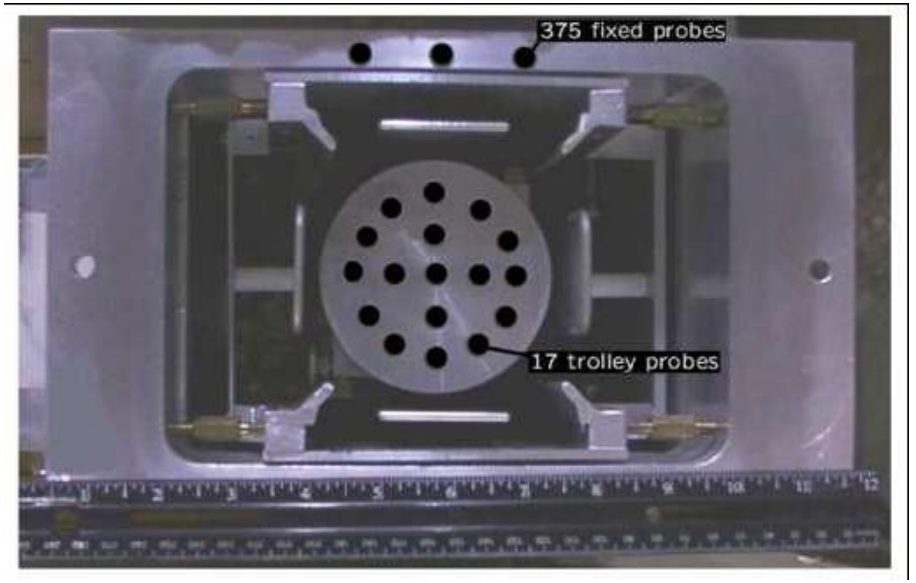
Measure spin precession & magnetic field

Storage ring @ BNL

4D magnetic field tracking

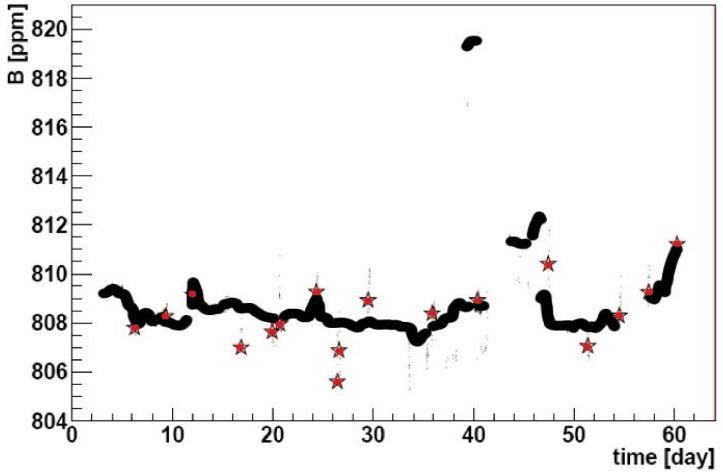


Beam profile weighing &
t interpolation

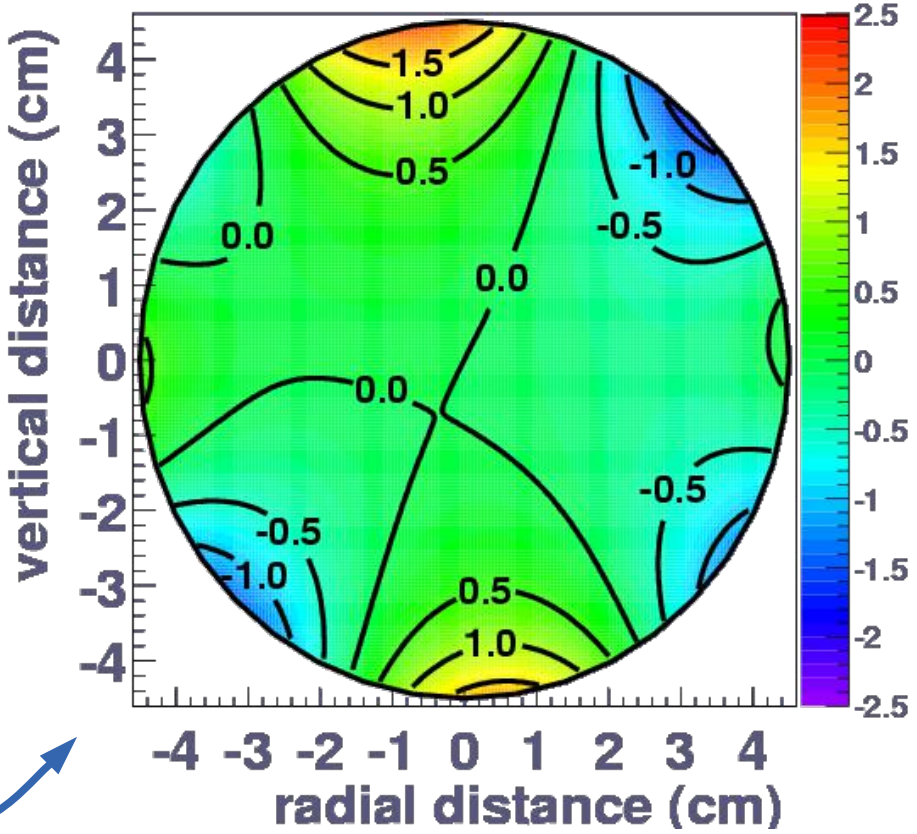


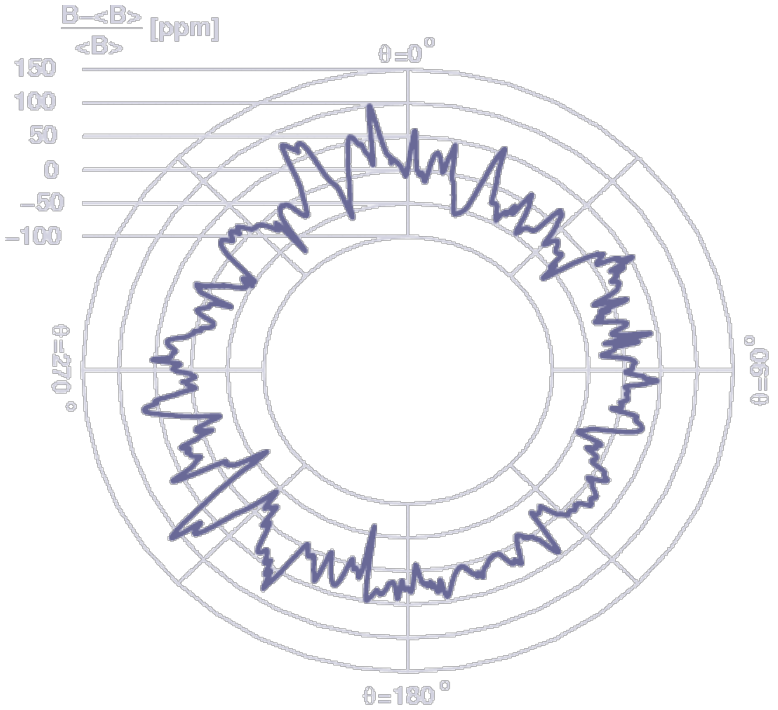
φ averaging &
(x,y) multipole expansion

4D magnetic field tracking



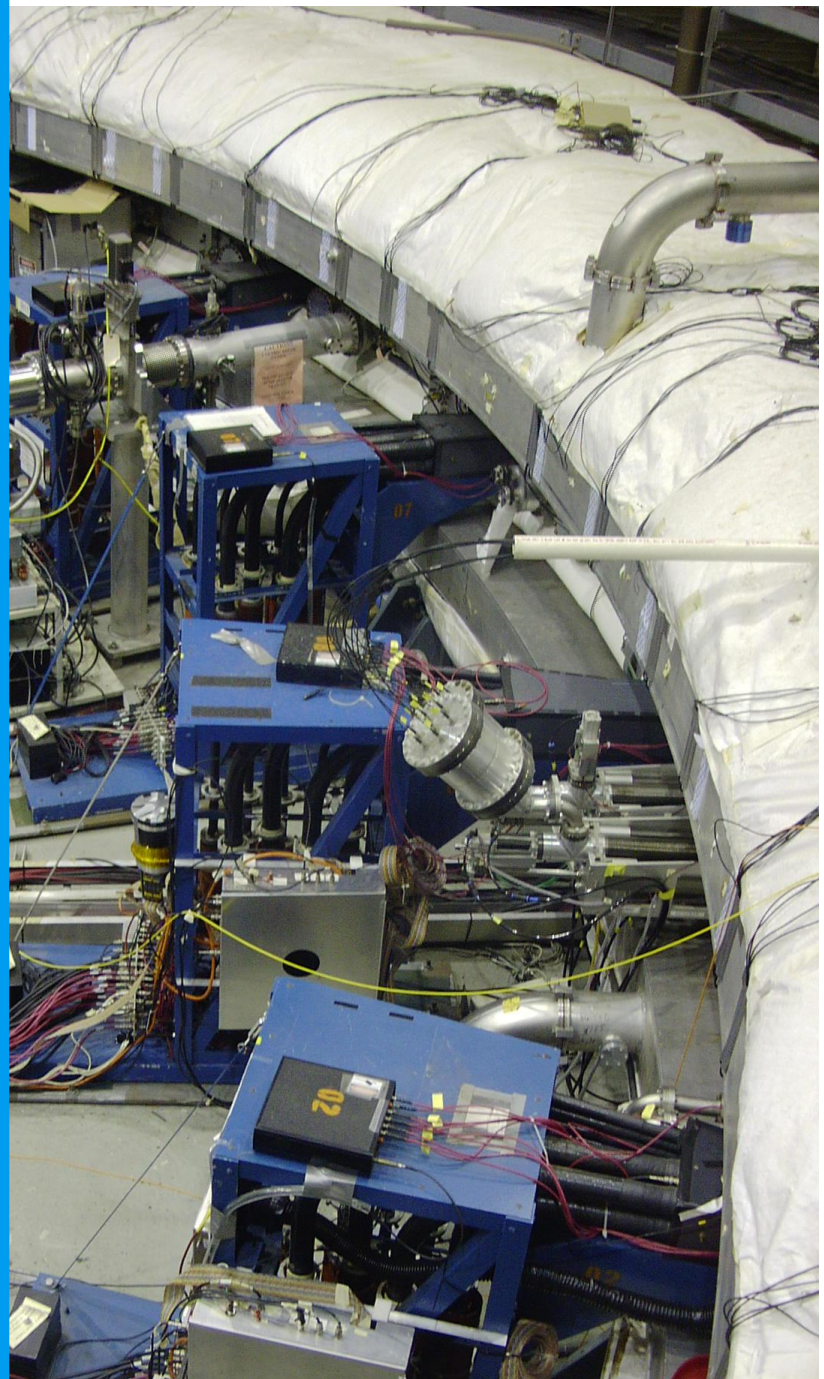
Beam profile weighing &
t interpolation





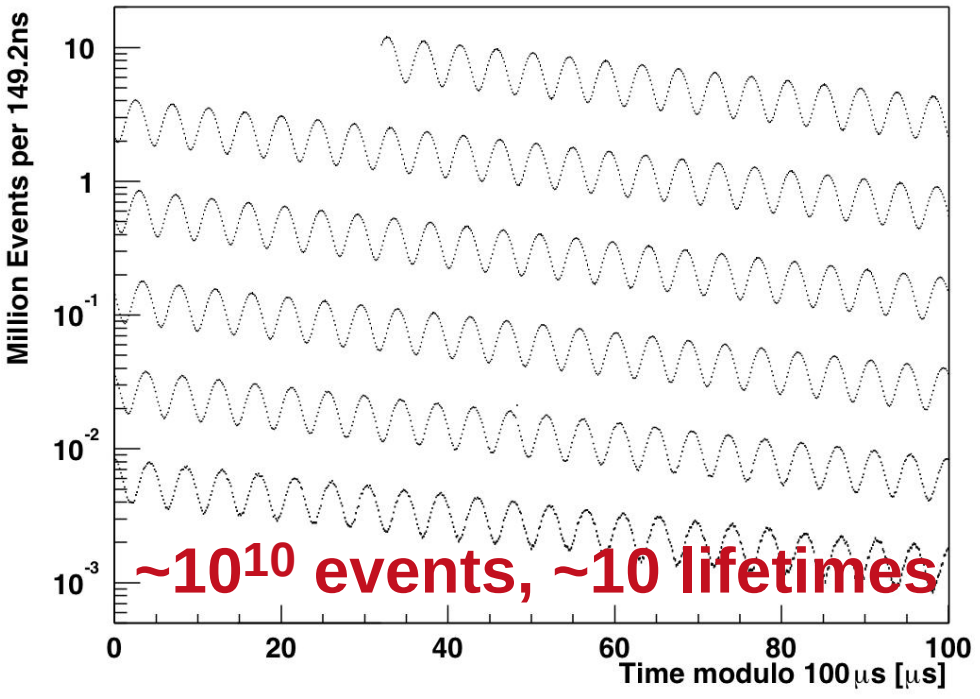
φ averaging &
(x,y) multipole expansion

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?

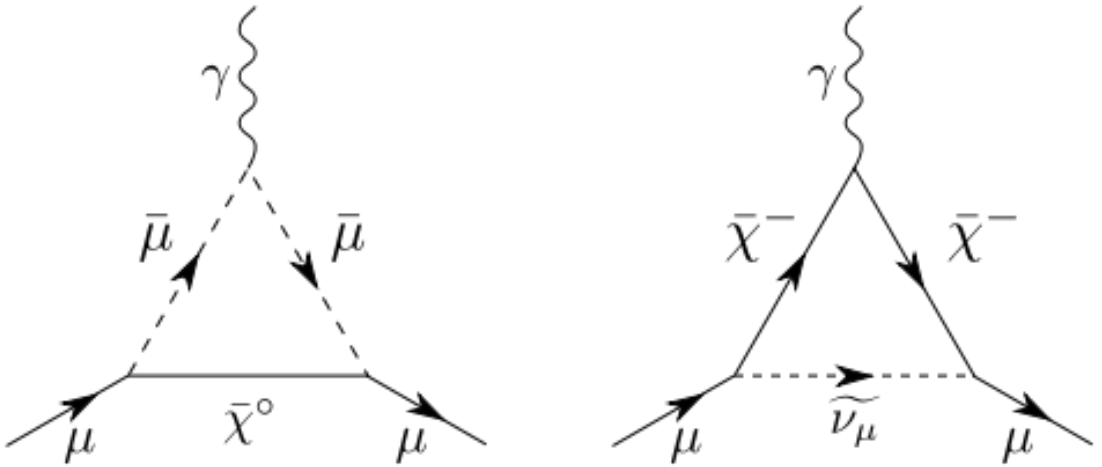
Year	a_μ	σa_μ	Ref.	
1961	0.001145	0.000022	Charpak	CERN
1965	0.001162	0.000005	Charpak	
1966	0.001165	0.000003	Farley	
1969	0.001060	0.000067	Henry	
1972	0.00116616	0.00000031	Bailey	
1975	0.001165895	0.000000027	Bailey	
1979	0.001165910	0.000000012	Bailey	
1979	0.001165936	0.000000012	Bailey	
1999	0.001165925	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

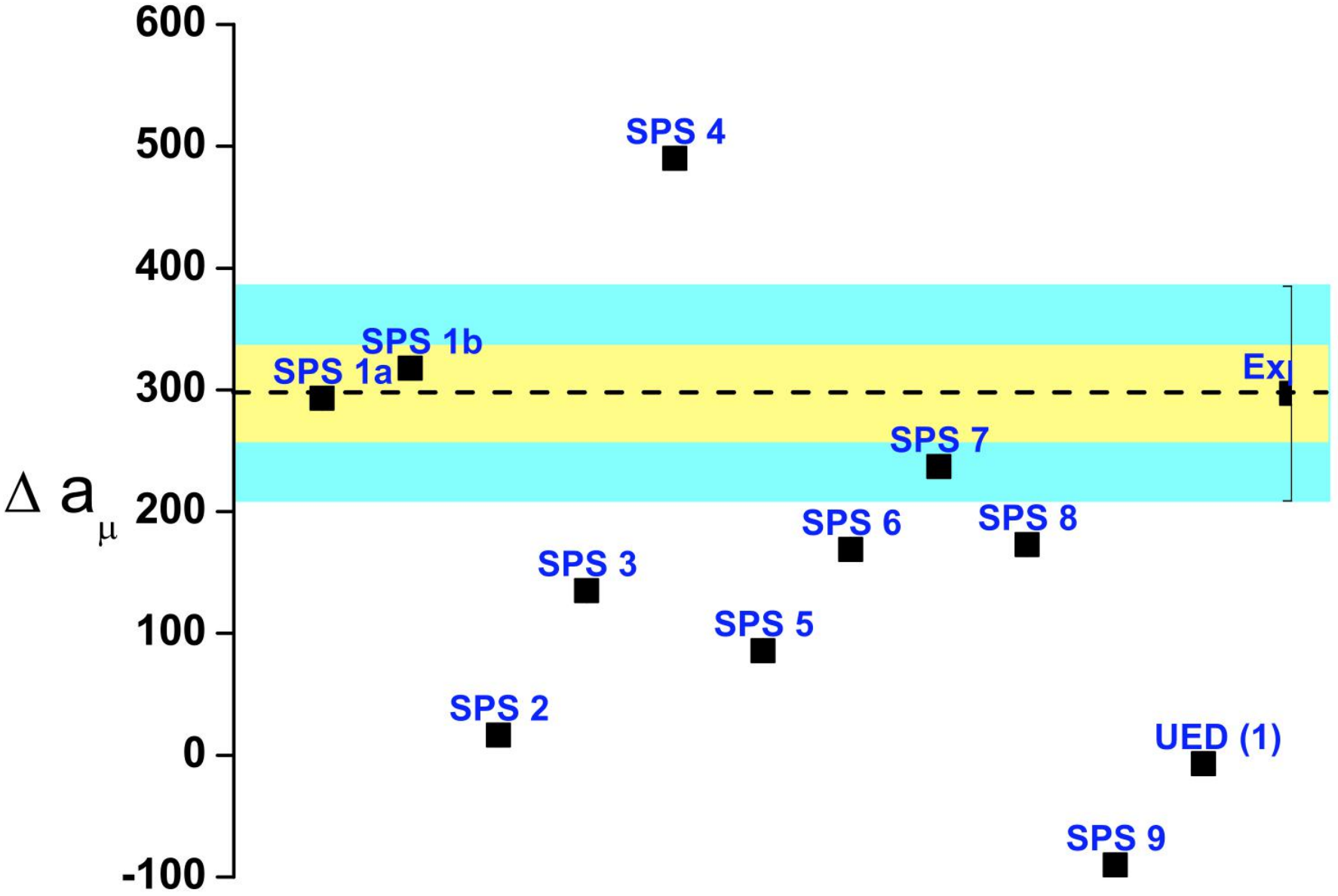


$$a_\mu(\Lambda) \simeq \frac{m_\mu^2}{\Lambda^2} \simeq 1100 \times 10^{-11} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2$$

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

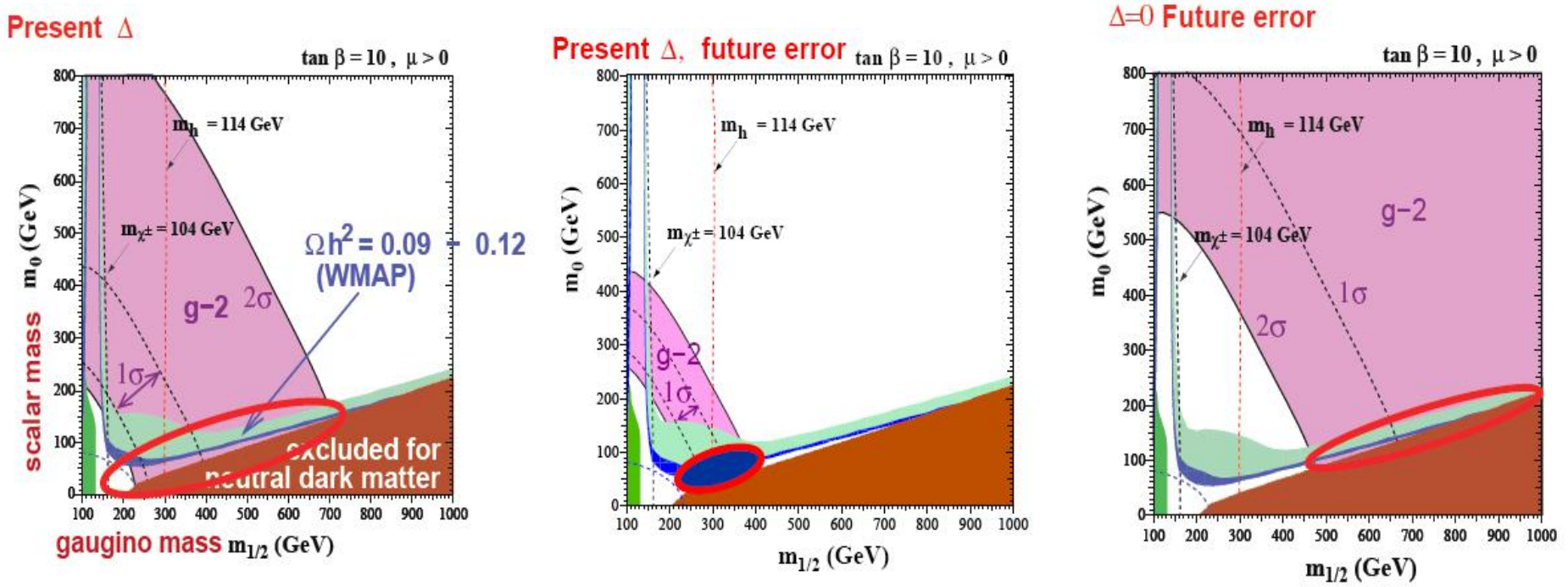
$$a_\mu(\mathrm{SUSY}) \simeq \mathrm{sgn}\,(\mu)\ 130 \times 10^{-11}\ \tan\beta\ \left(\frac{100\ \mathrm{GeV}}{\Lambda}\right)^2$$

Some plausible scenarios (Snowmass)



Reach of g-2

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



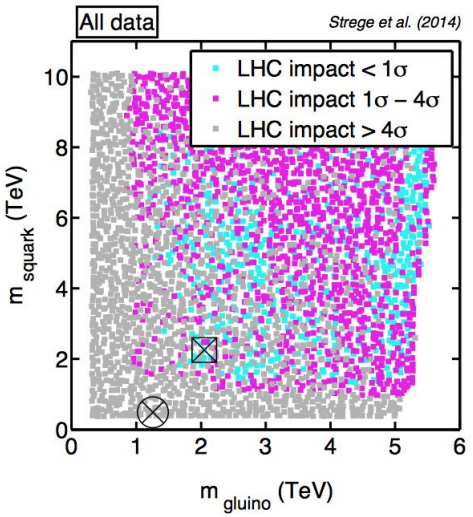
The (g-2) discrepancy is consistent with other constraints on the SUSY LSP being the dark matter candidate.

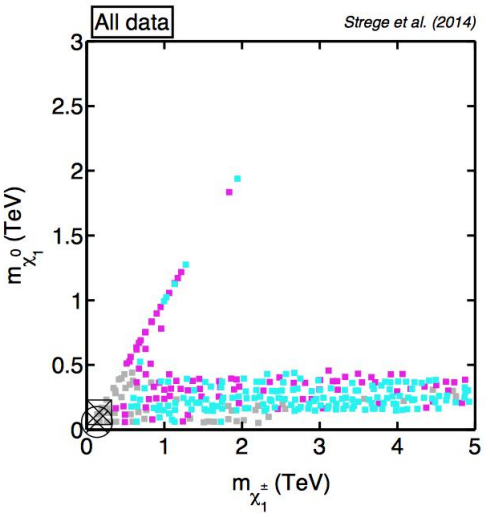
With m_{LSP} known (LHC?), g-2 sensitive to tanβ

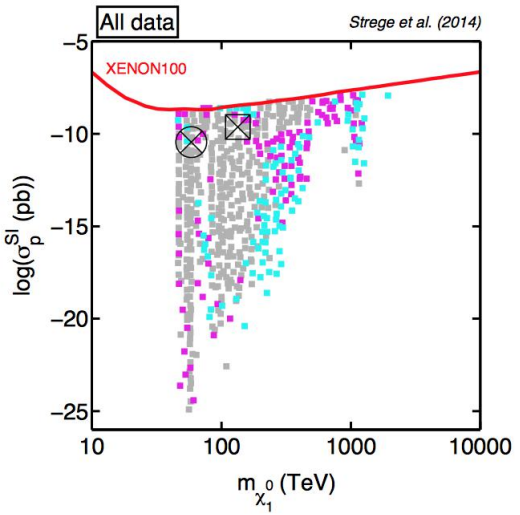
CMSSM calculation Following Ellis, Olive, Santoso, Spanos, from K. Olive

SUSY : g-2 & LHC

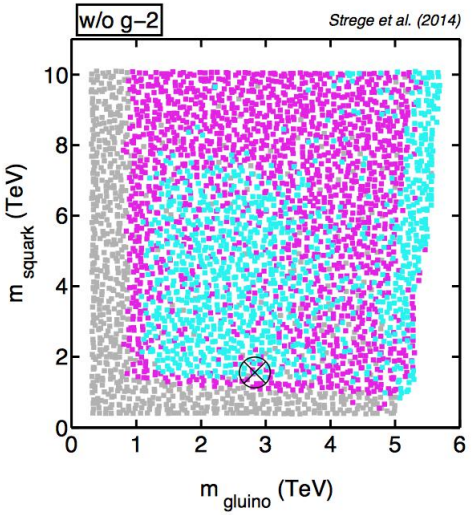
arXiv:1405.0622

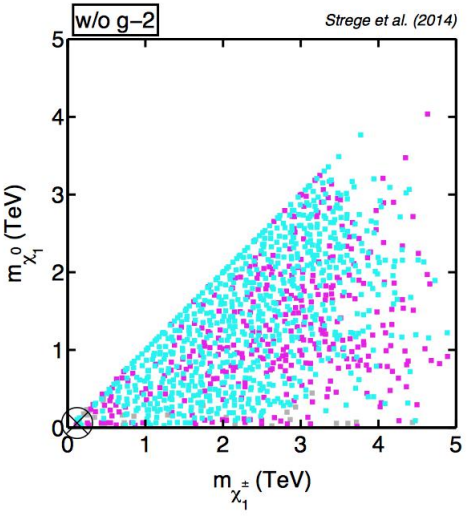


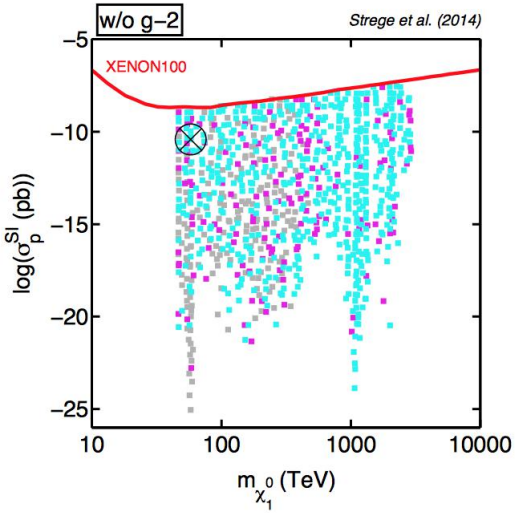




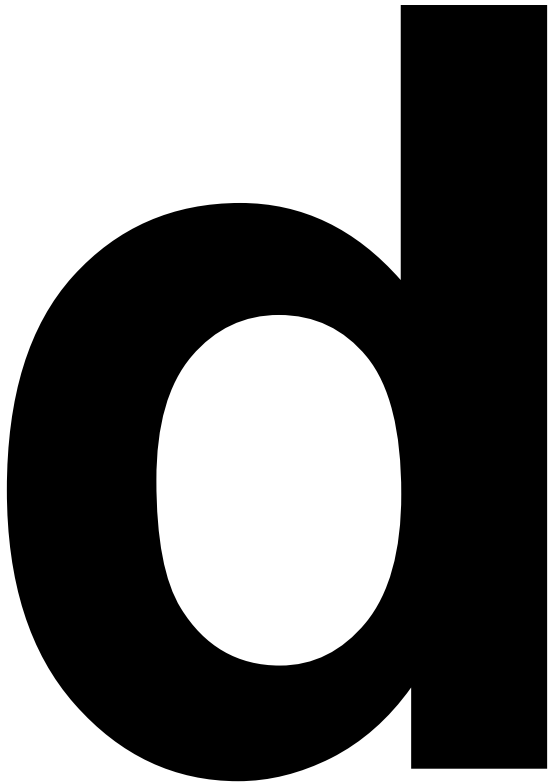
With g-2







Without g-2

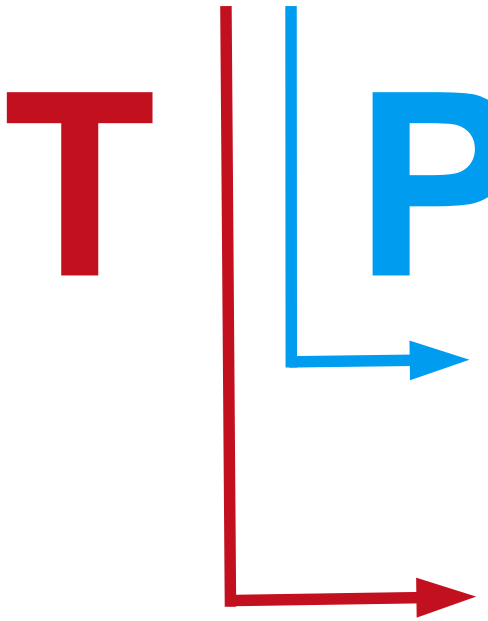

d

Permanent EDMs violate T/CP and P

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

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

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



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

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

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

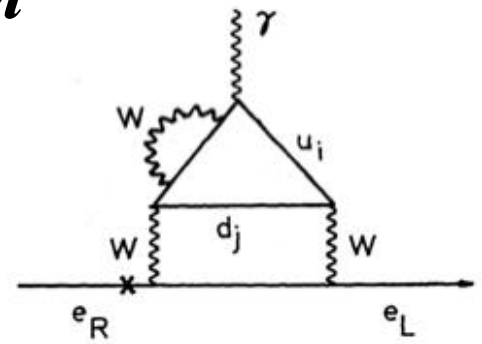
EDMs in the Standard Model : δ_{CP}

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

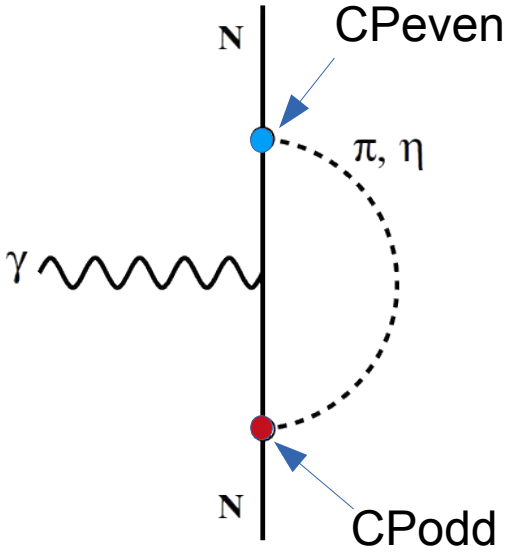
I.B. Khriplovich, S.K. Lamoreaux, *CP Violation Without Strangeness*, Springer, 1997

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)

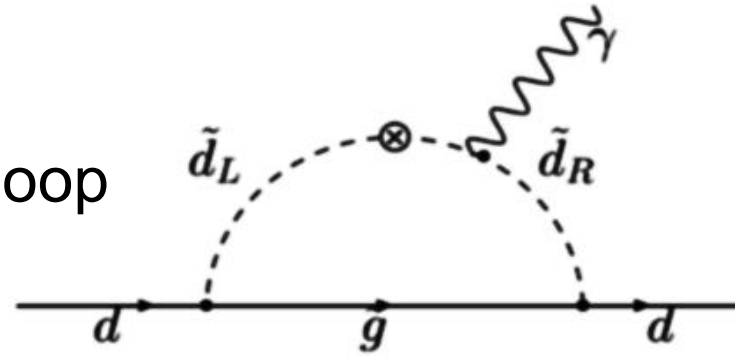
Experimentally, $|\theta| < 10^{-9}$ (from the neutron EDM)

Strong CP problem

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

EDMs from New Physics

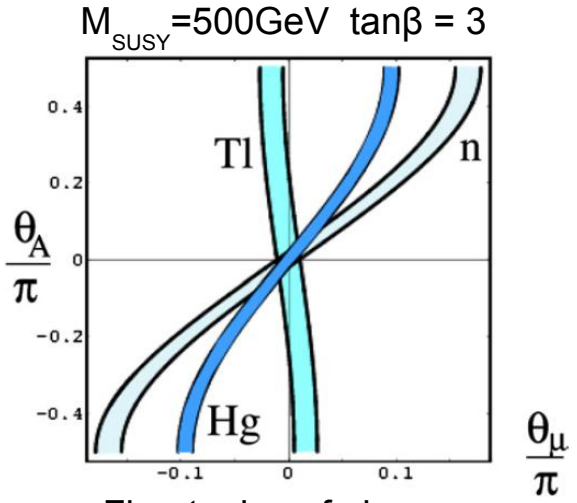
~ all "new physics" : extra CPV, often 1-loop



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

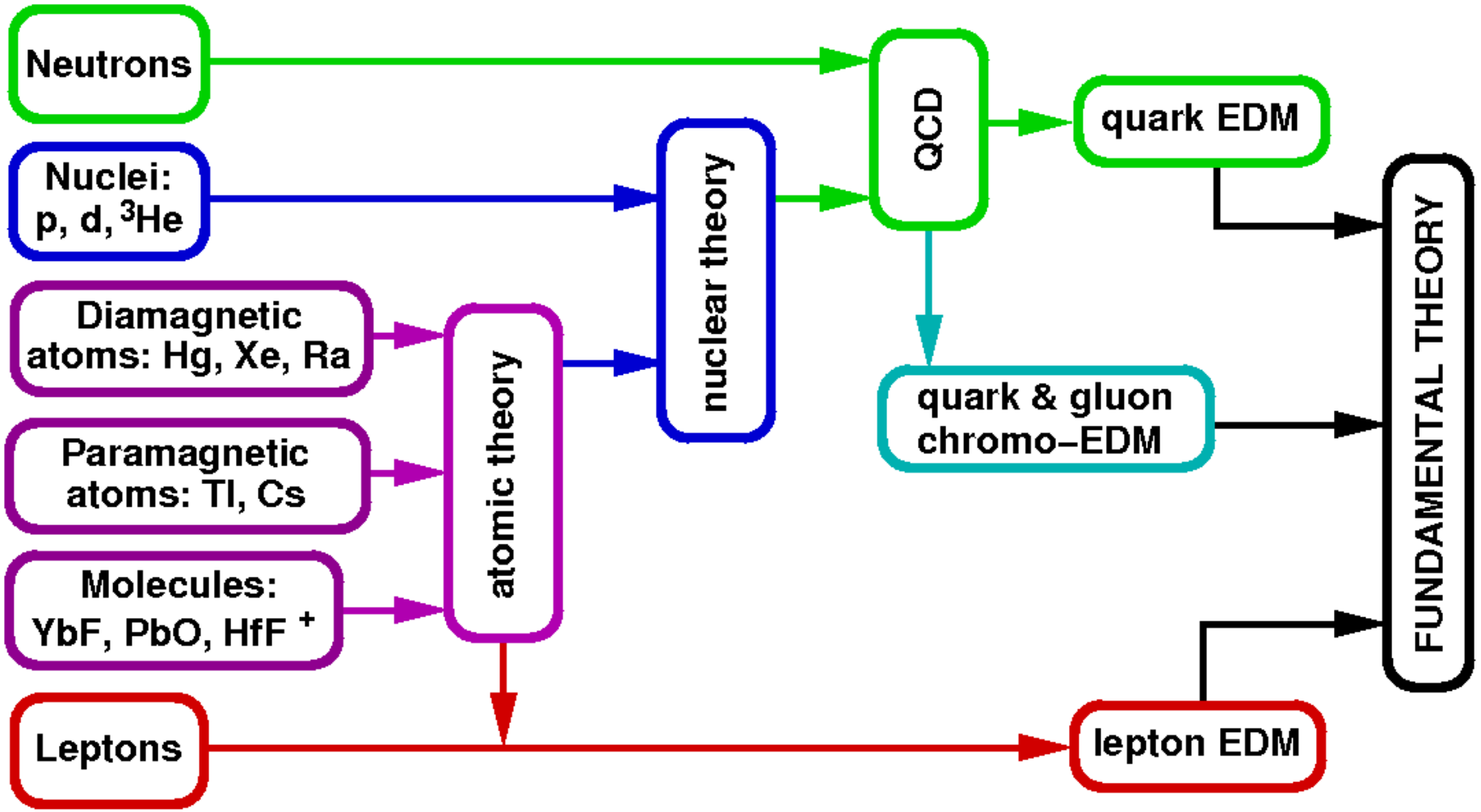
SUSY CP Problem

- 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

EDM-induced spin precession

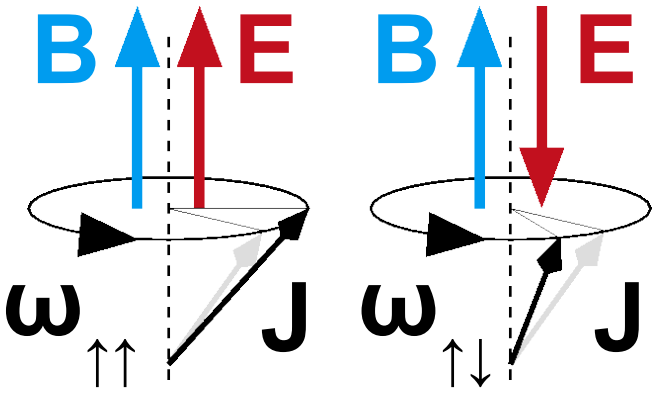
Prepare spin polarized ensemble

Interaction with electric field

Measure spin evolution

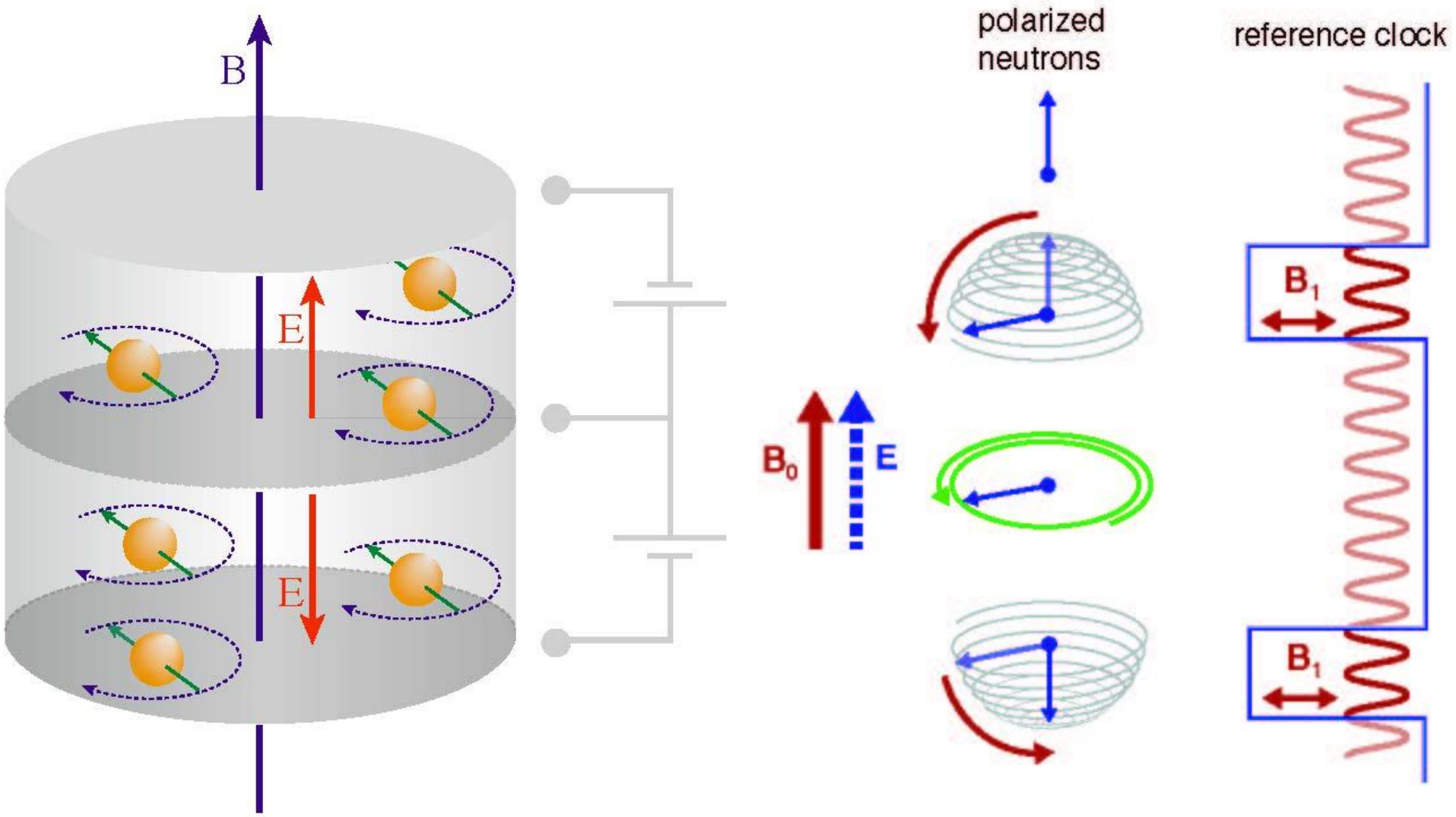
$$\frac{d\langle \vec{J} \rangle}{dt} = (\mu \vec{B} + d \vec{E}) \times \langle \hat{J} \rangle$$

$\vec{\omega}$

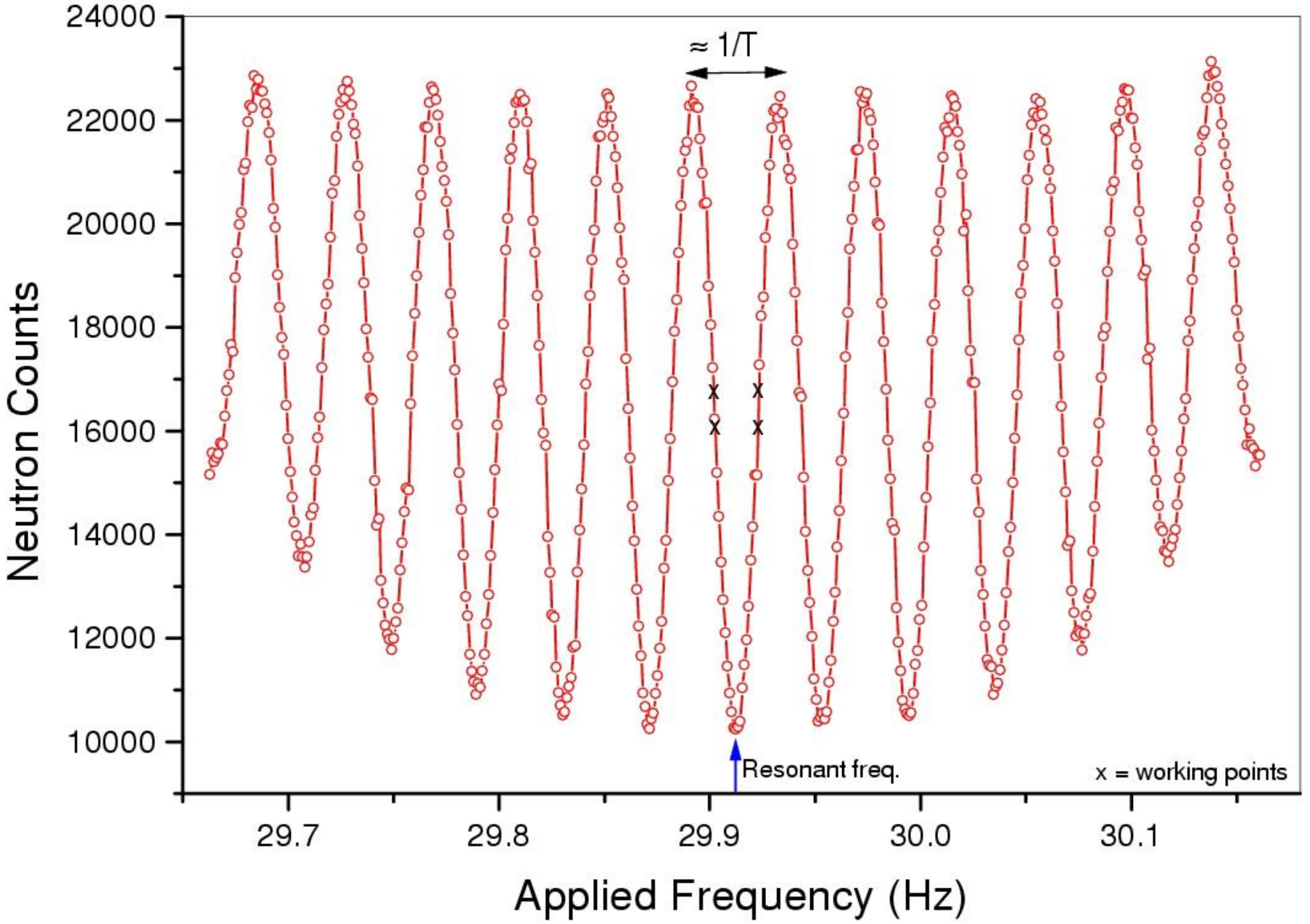


Traditional technique for neutral systems

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

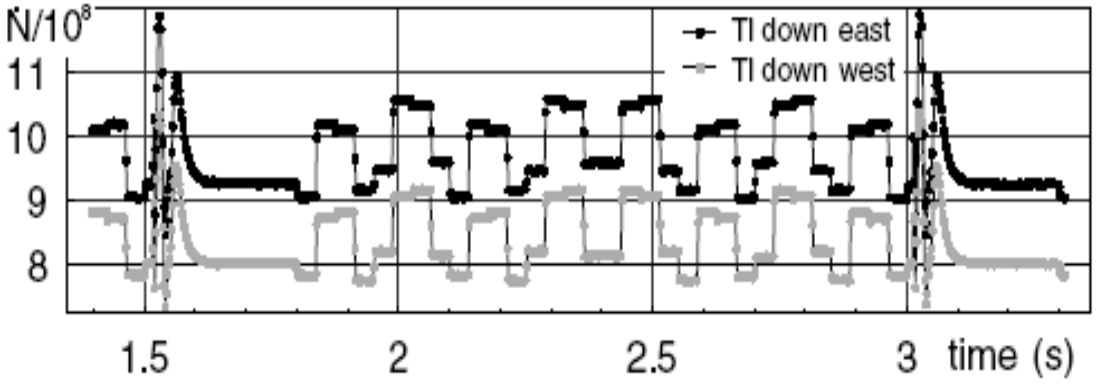
Polarization (pump)/ Polarimetry (fluorescence

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



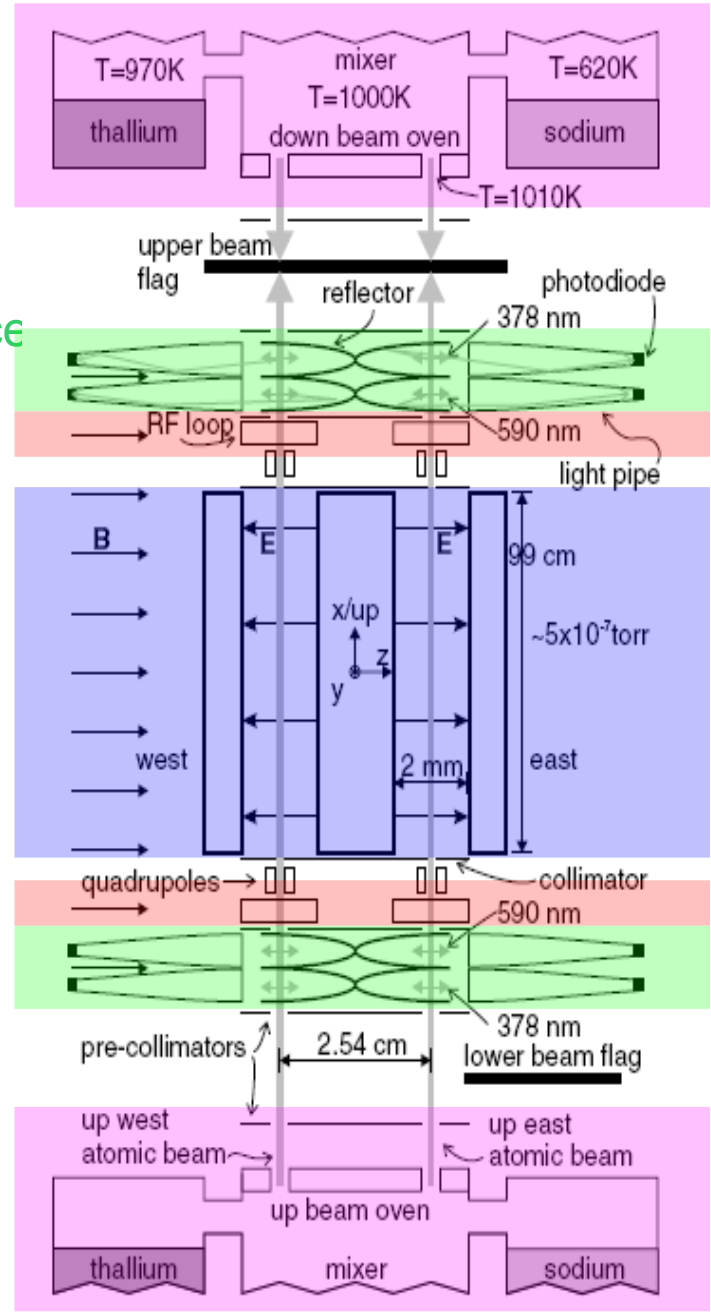
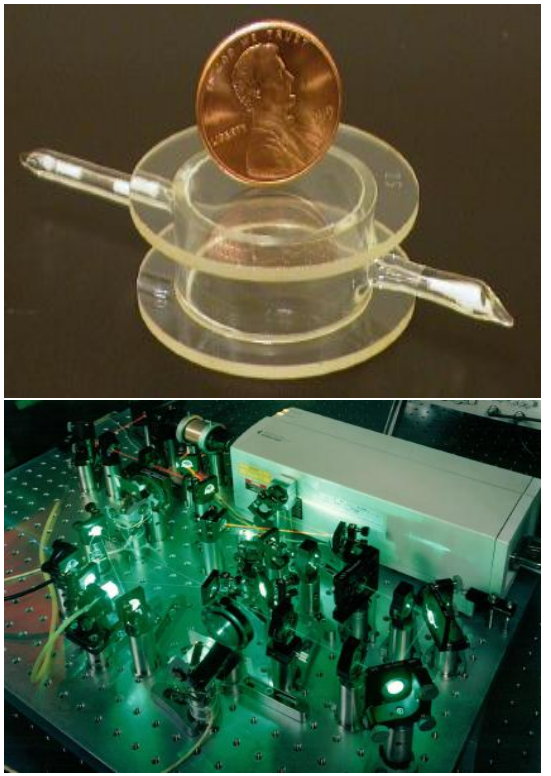


FIG. 1. Schematic diagram of the experiment; not to scale.

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}



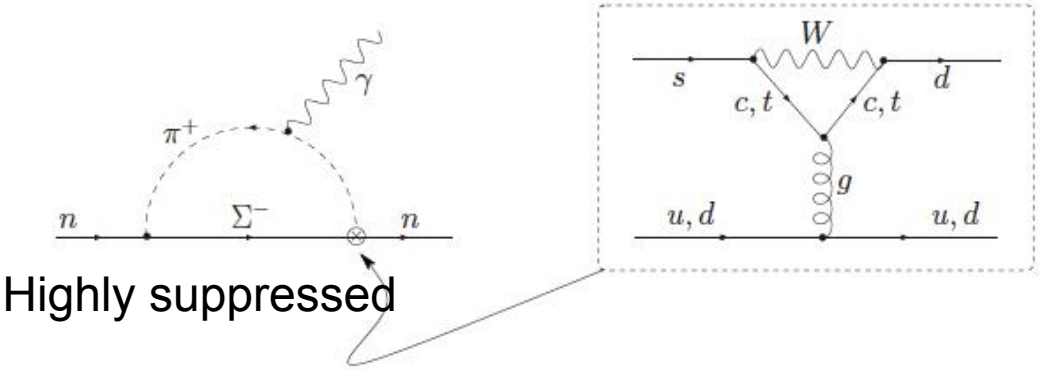
$\delta\nu_{stat}$ = 0.13 nHz (7.5 ppt)

1 cycle per 244 years

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

BSM reach

arXiv:1201.4252

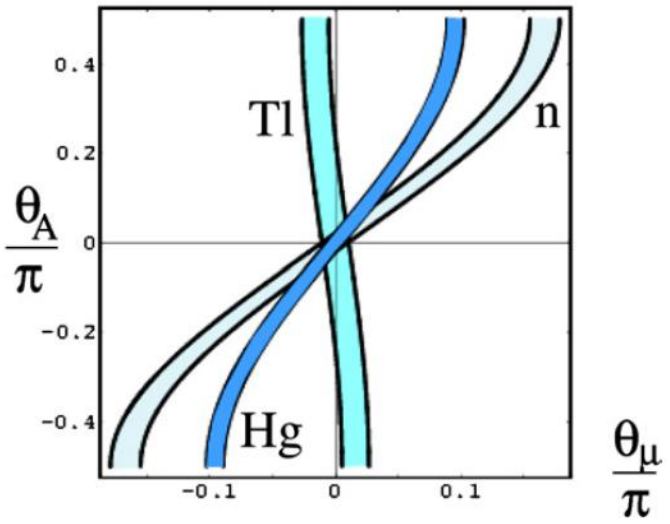


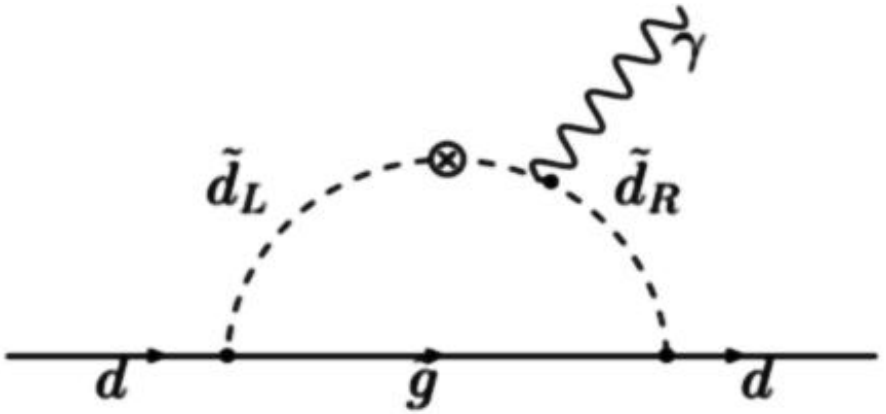
Highly suppressed

Clean(est) tool to find new CPV

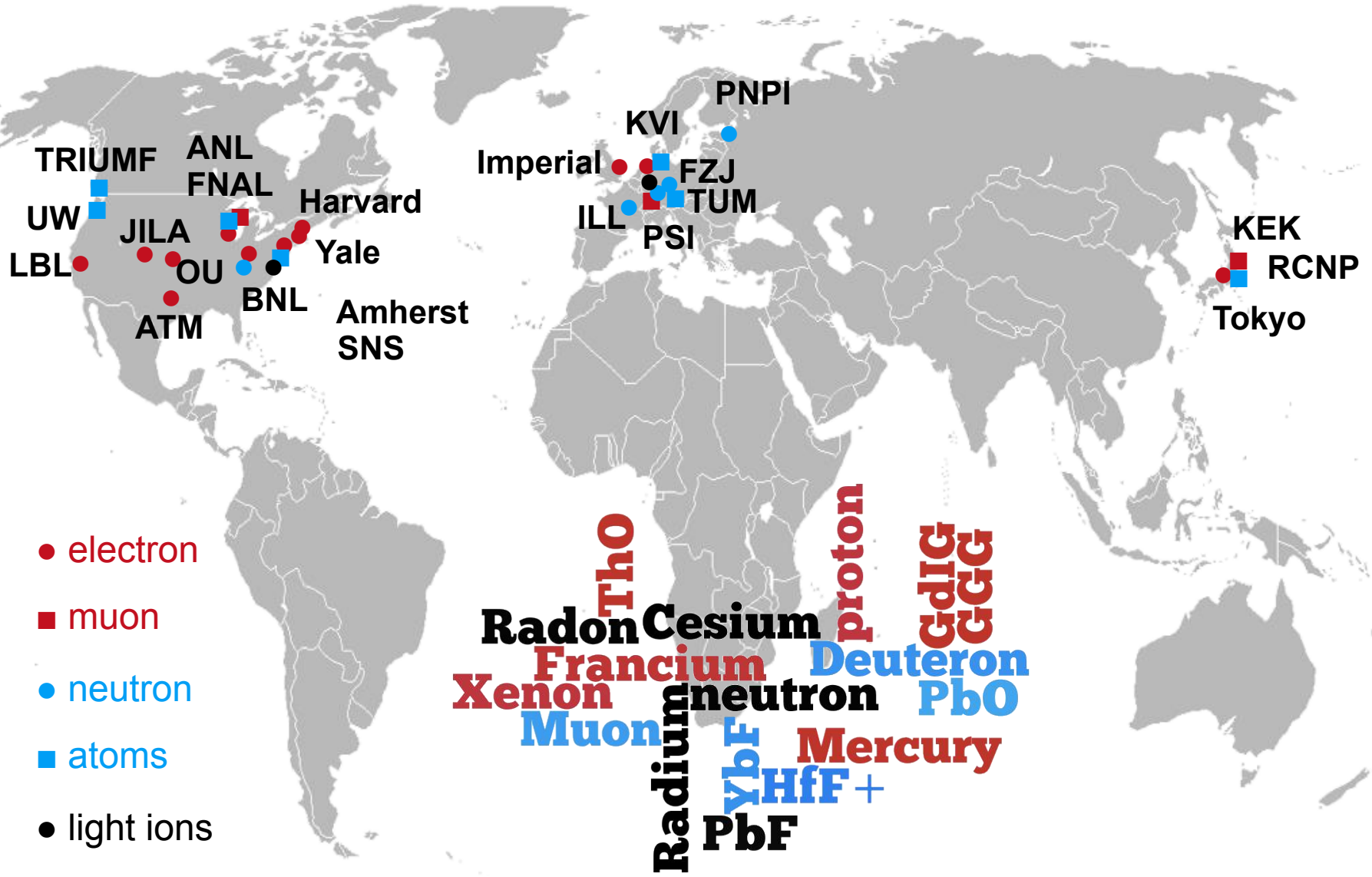
$$d_n(NP) \sim \sin\delta_{CP}\left(\frac{1\ TeV}{M_{SUSY}}\right)^2 \times 10^{-25}\ e\cdot cm$$

SUSY CP Problem





Efforts Worldwide

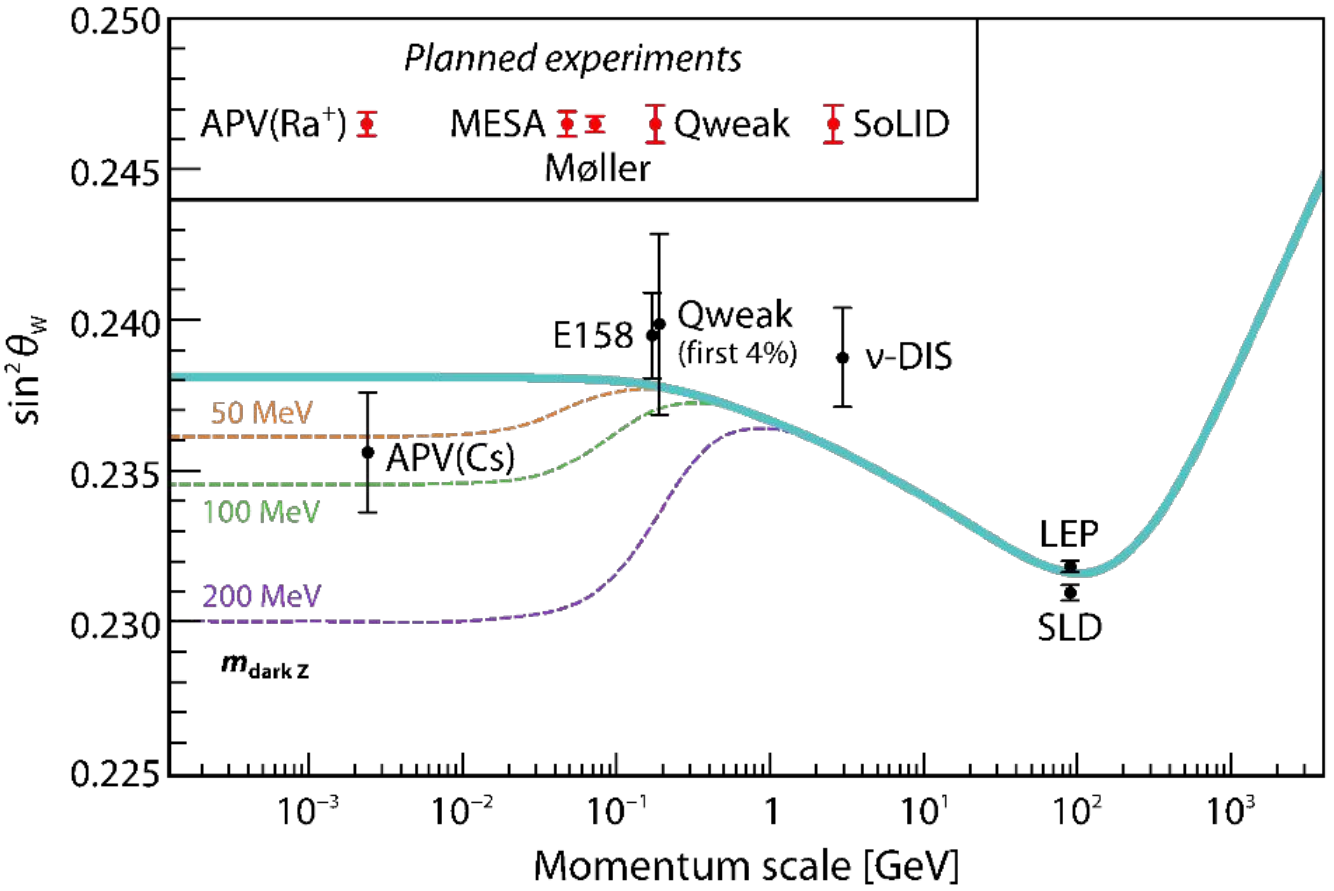


An undoubtedly incomplete list; inspired by Dave DeMille & Rob Timmermans

θW

Electroweak unification

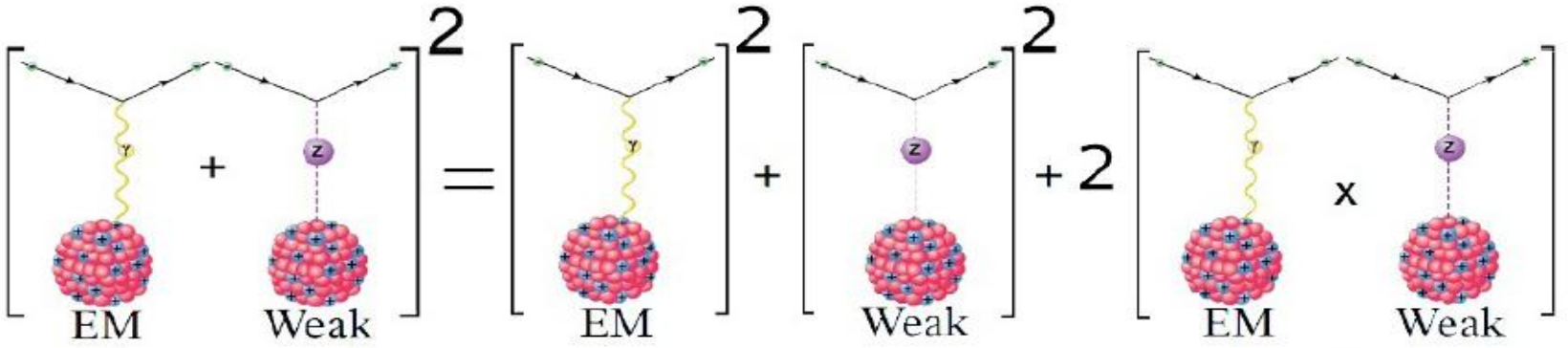
$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \longrightarrow e = g\sin\theta_W \longleftarrow \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W}$$



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

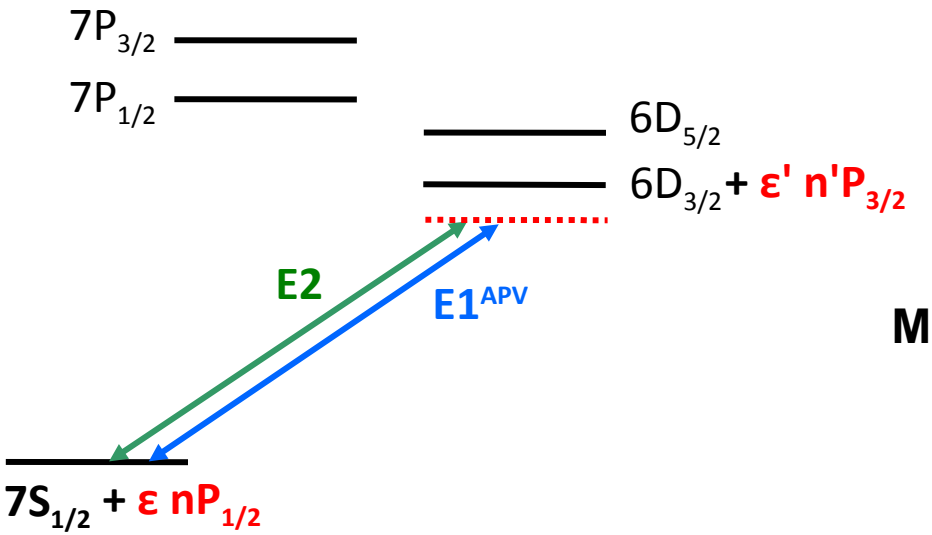
Recent Theory work: (just a few examples)

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



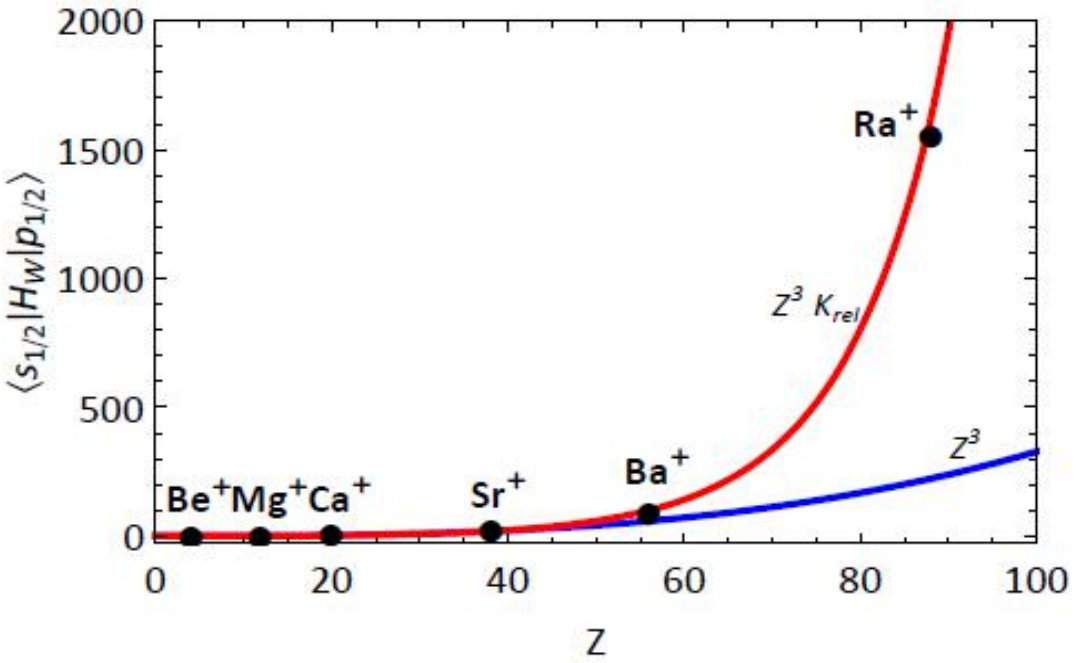
$$E1_{APV} = k\,Q_W$$

Measure — **Infer**

Calculate atomic wavefunction

Intrinsic sensitivity of Ra^+

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



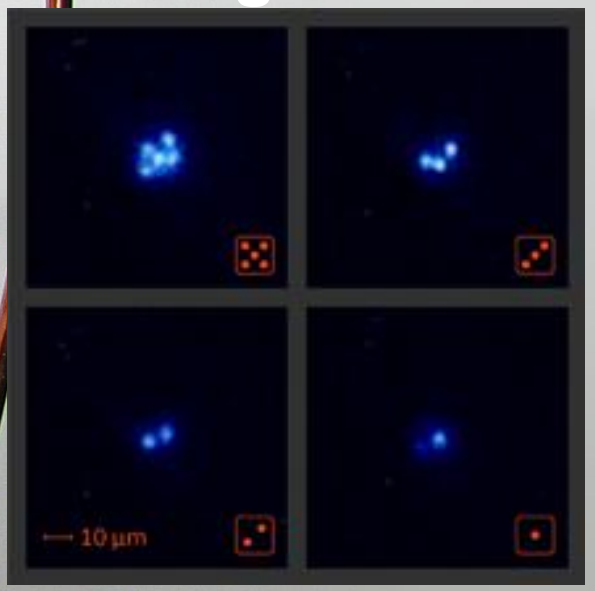
$$E1^{APV} = 46.4(1.4)\times 10^{-11}\, i e a_0 (-Q_W / N)$$

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

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

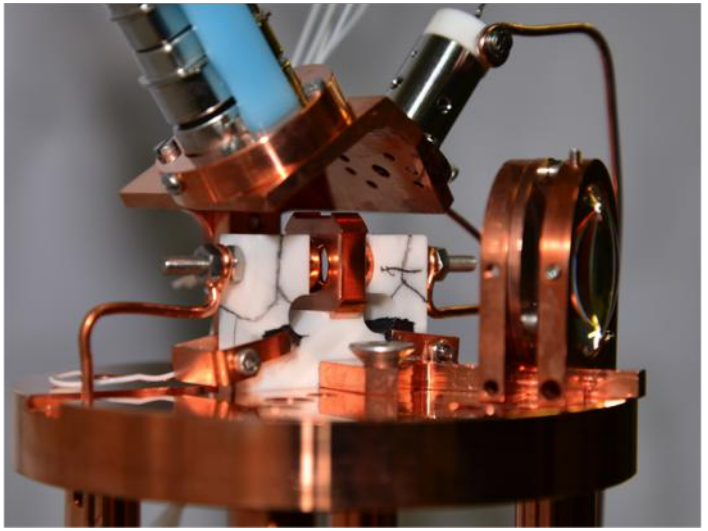
L.W. Wansbeek et al., Phys. Rev. A 78, 050501(R) (2008)

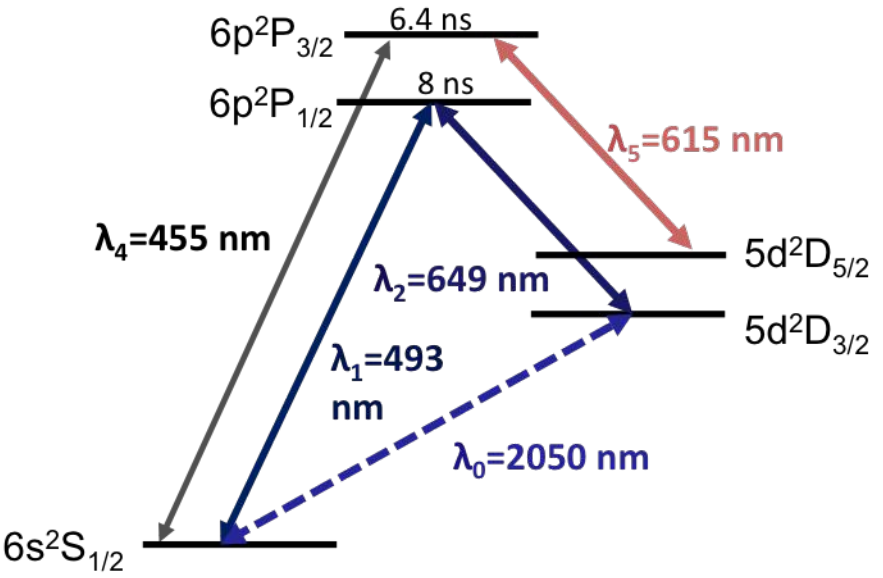
Barium/Radium APV setup

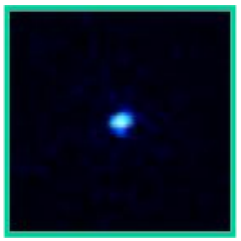


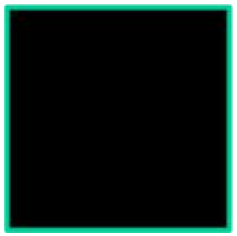
Single ion sufficient
Localize << λ
10 days → 1/5 Cs

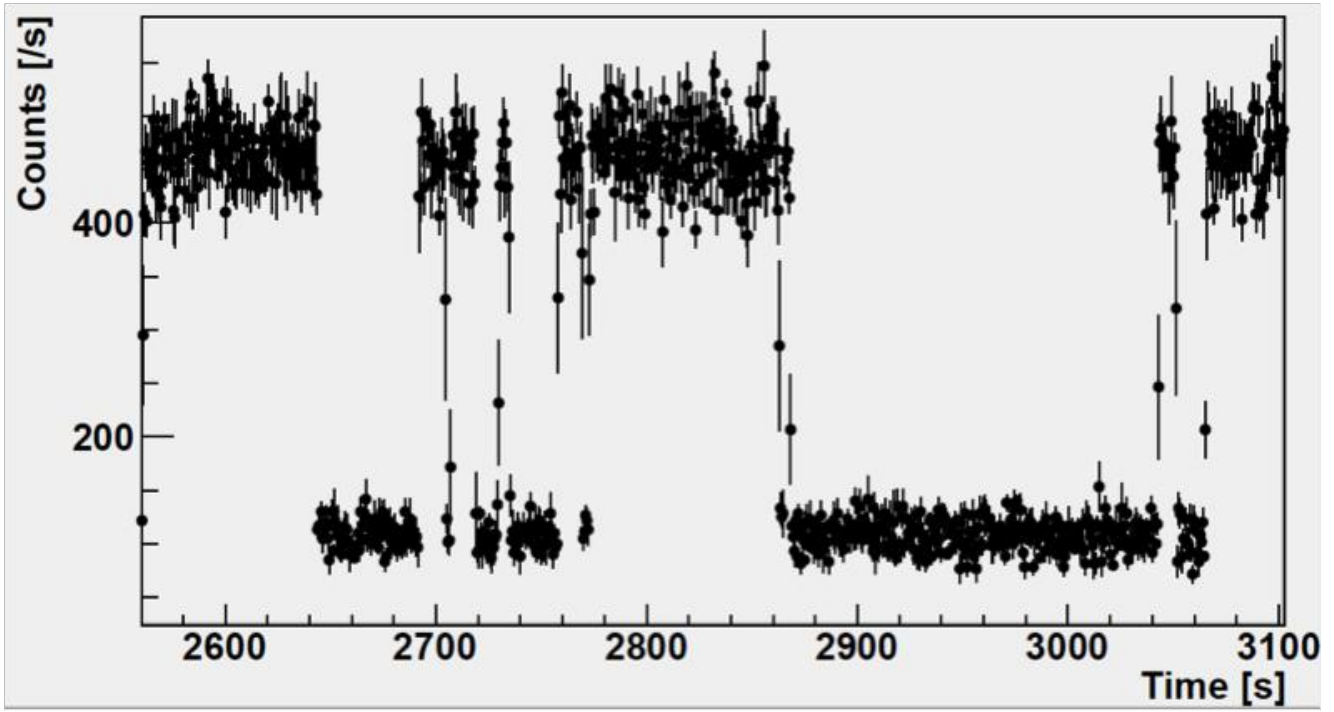
Quantum jump spectroscopy











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

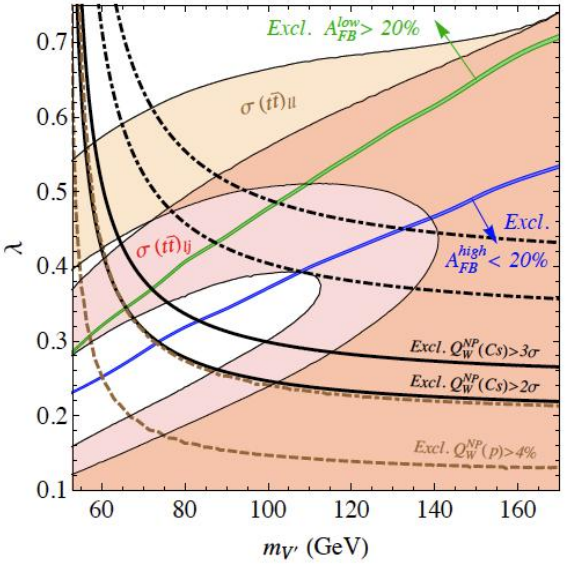
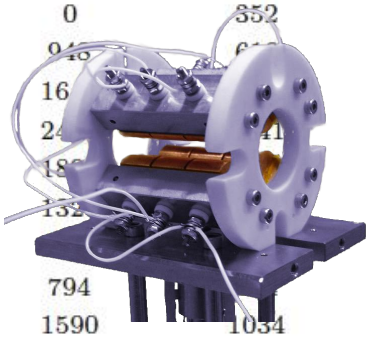


TABLE I: Mass bounds from various APV observables. The second column contain the mass bounds from the actual measurement in Eqn. 1 at 95% CL. The remaining columns contain the masses that future APV experiments will be able to exclude, given a measurement that is in agreement with the SM prediction.

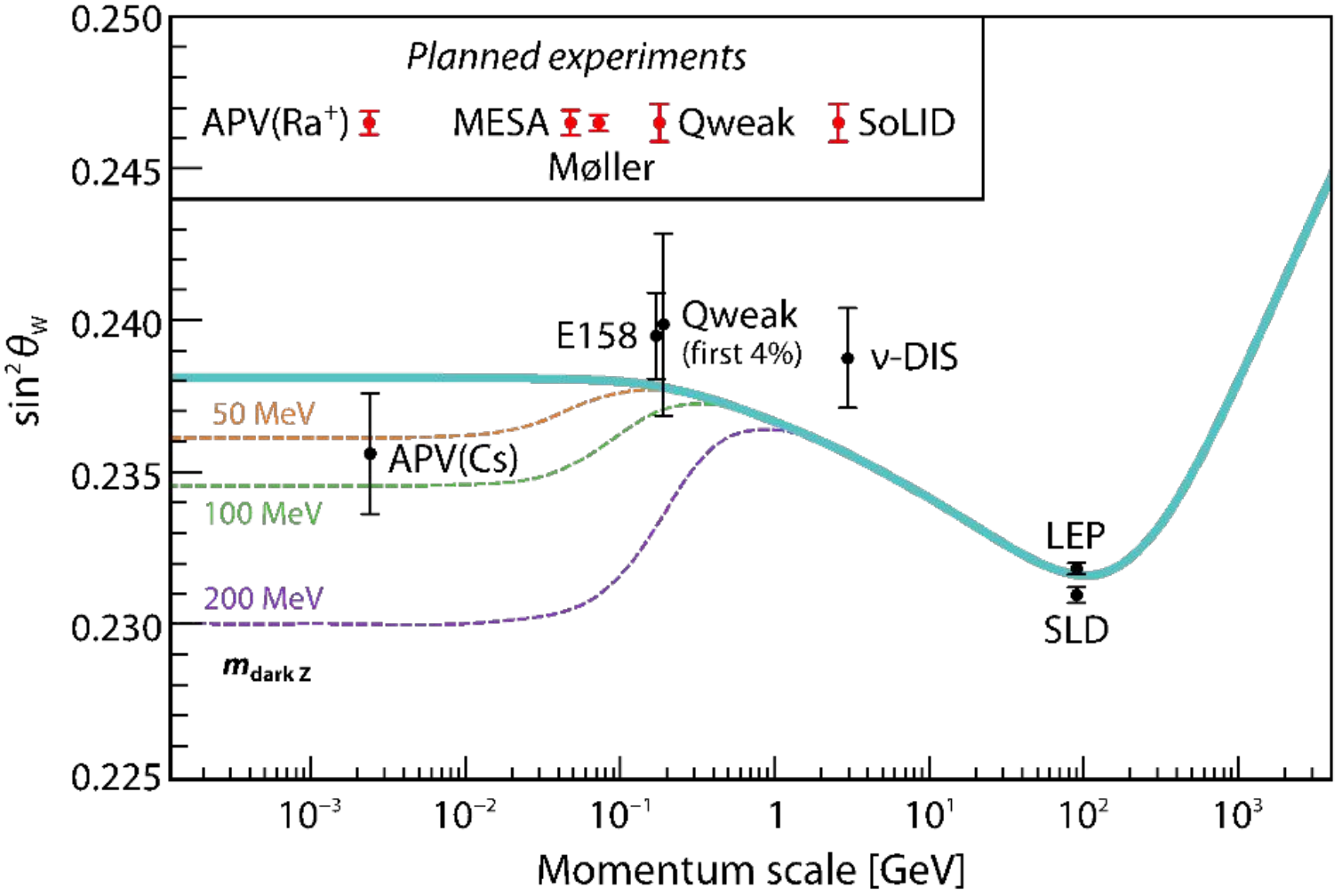
Model	$Q_W(^{133}_{55}\mathrm{Cs})$ 0.48% 95% CL	$Q_W(^{208}_{87}\mathrm{Fr})$ 0.1% 95% CL	$\mathcal{R}_{\mathrm{Fr}}(121,122)$ 0.3%, 95% CL	$\mathcal{R}_{\mathrm{Fr}}(121,122)$ 0.1%, 95% CL	$\mathcal{R}_{\mathrm{Yb}}(98,100)$ 0.3%, 95% CL	$\mathcal{R}_{\mathrm{Yb}}(98,100)$ 0.1%, 95% CL	Q_W^p 4.1% 95% 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?

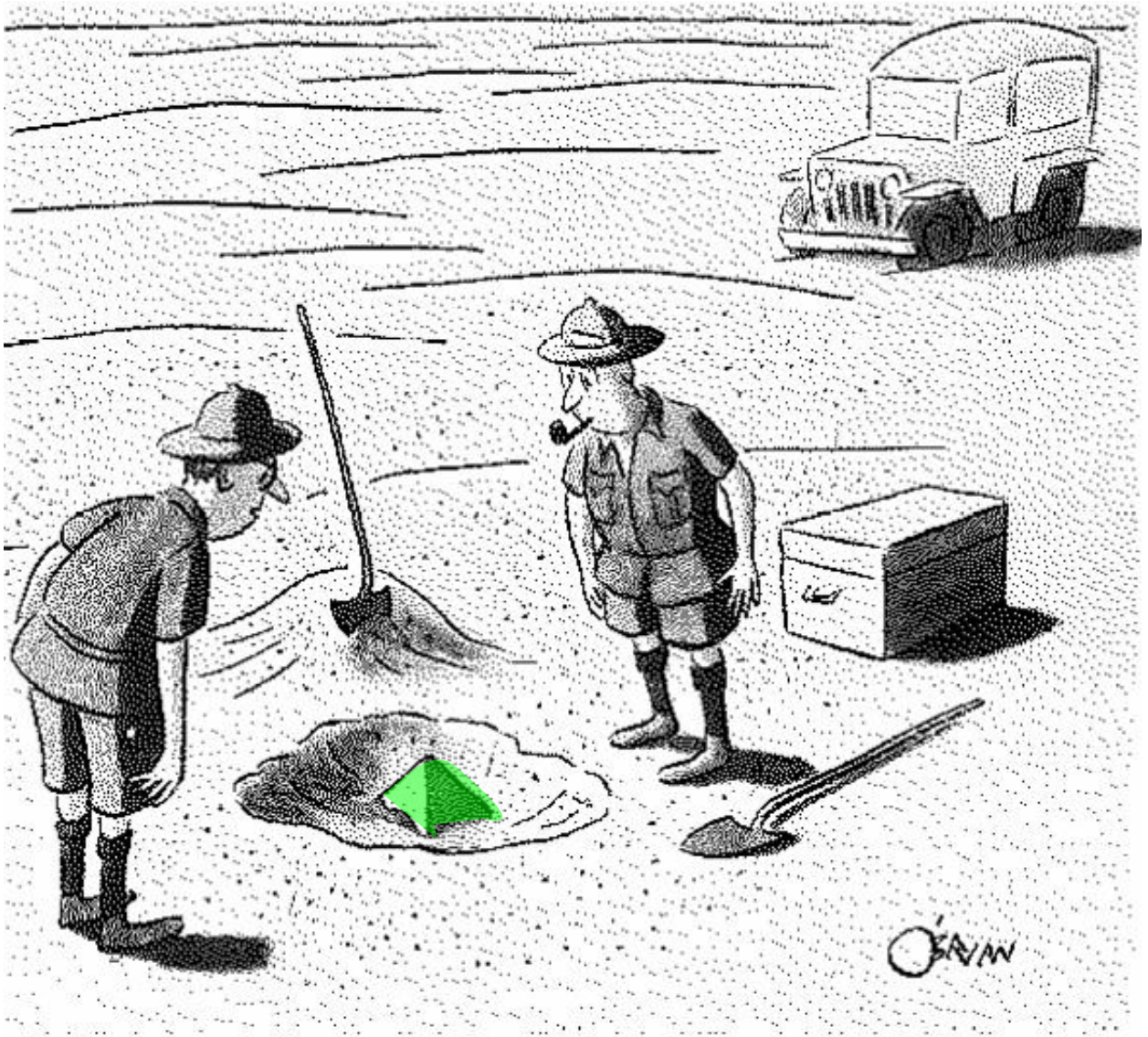
Selected experiments

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