

High-Energy Physics  
from  
Low-Energy  
Symmetry Studies

David Hanneke

Michelson Postdoctoral Prize Lectures

14 May 2010

# High Energy Physics

$$E = mc^2 = hc/\lambda$$

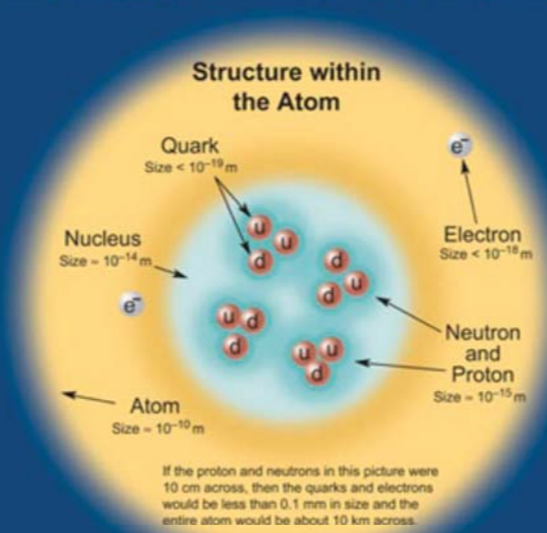
## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

**FERMIONS** matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino*	(0-0.13) × 10 <sup>-9</sup>	0
e electron	0.000511	-1
$\nu_\mu$ middle neutrino*	(0.009-0.13) × 10 <sup>-9</sup>	0
$\mu$ muon	0.106	-1
$\nu_\tau$ heaviest neutrino*	(0.04-0.14) × 10 <sup>-9</sup>	0
$\tau$ tau	1.777	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
u up	0.002	2/3
d down	0.005	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	173	2/3
b bottom	4.2	-1/3



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

**BOSONS** force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.39	-1
$W^+$	80.39	+1
$Z^0$ Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
g gluon	0	0

**Color Charge**  
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons in strong interactions, color-charged particles interact by exchanging gluons.

**Quarks Confined in Mesons and Baryons**  
Quarks and gluons cannot be isolated - they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature: mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), neutron (udd), lambda  $\Lambda$  (uds), and omega  $\Omega^-$  (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  (u $\bar{d}$ ), kaon  $K^+$  (u $\bar{s}$ ),  $B^0$  (d $\bar{d}$ ), and  $\eta_c$  (c $\bar{c}$ ). Their charges are +1, -1, 0, 0 respectively.

### Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

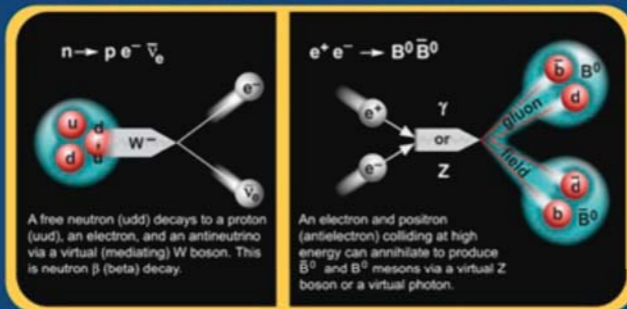
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

Visit the award-winning web feature *The Particle Adventure* at [ParticleAdventure.org](http://ParticleAdventure.org)

This chart has been made possible by the generous support of  
U.S. Department of Energy  
U.S. National Science Foundation  
Lawrence Berkeley National Laboratory  
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### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron  $\beta$  (beta) decay.

An electron and positron colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual Z boson or a virtual photon.

### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

#### Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

#### Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

#### Dark Matter?

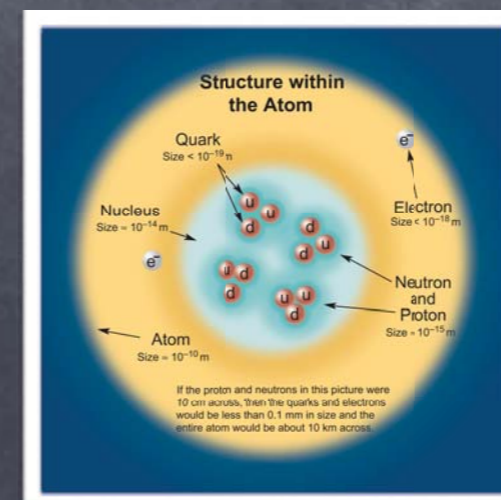
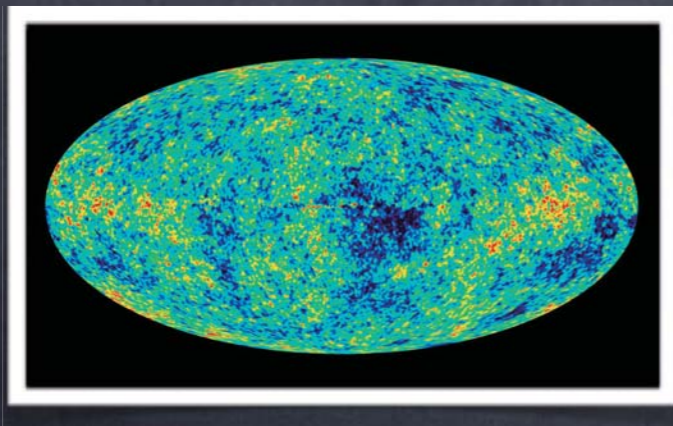
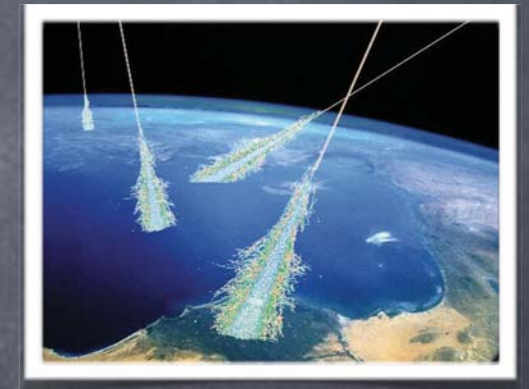
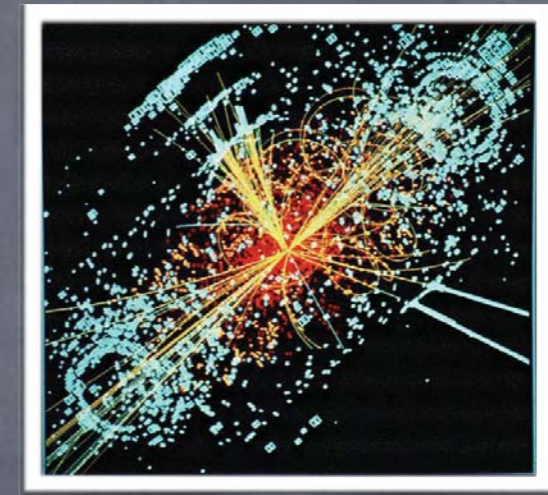
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

#### Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

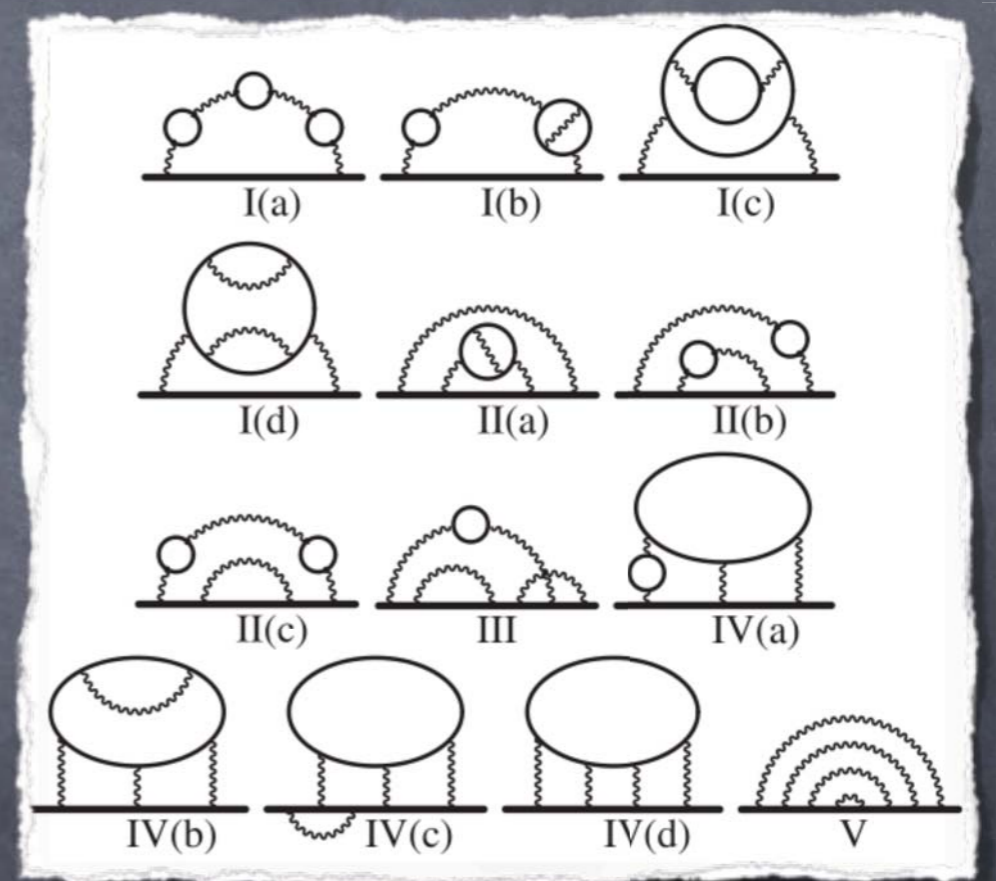
# How to do high-energy physics

- Make high-energy particles
  - Accelerators
- Find high-energy particles
  - Cosmic rays
  - Dark matter searches
  - Astrophysics/cosmology
- Find high-energy virtual particles
  - Precision measurement



# Precision Measurements

- Look for high-energy (vacuum) effects
- Cheap, small
- Fruitful ground: things that are forbidden in the low-energy theory



G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom,  
Phys. Rev. Lett. **97**, 030802  
(2006). Ibid. **99** 039902(E) (2007)

# Symmetries

- Discrete

- Charge conjugation  $e^{-} \rightarrow e^{+}$

- Parity  $\vec{x} \rightarrow -\vec{x}$

- Time-reversal  $t \rightarrow -t$

- Continuous: Lorentz invariance

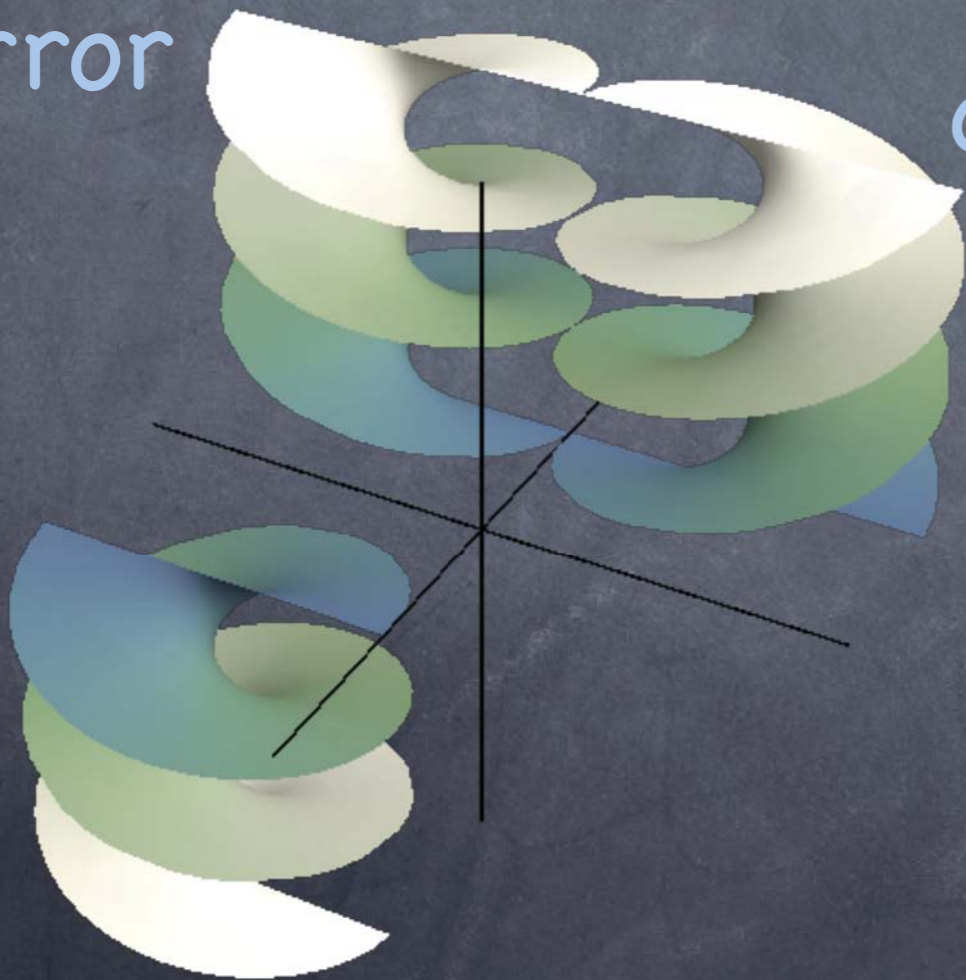
# Parity

$$\vec{x} \rightarrow -\vec{x}$$

• “mirror” symmetry

mirror

original



P(original)

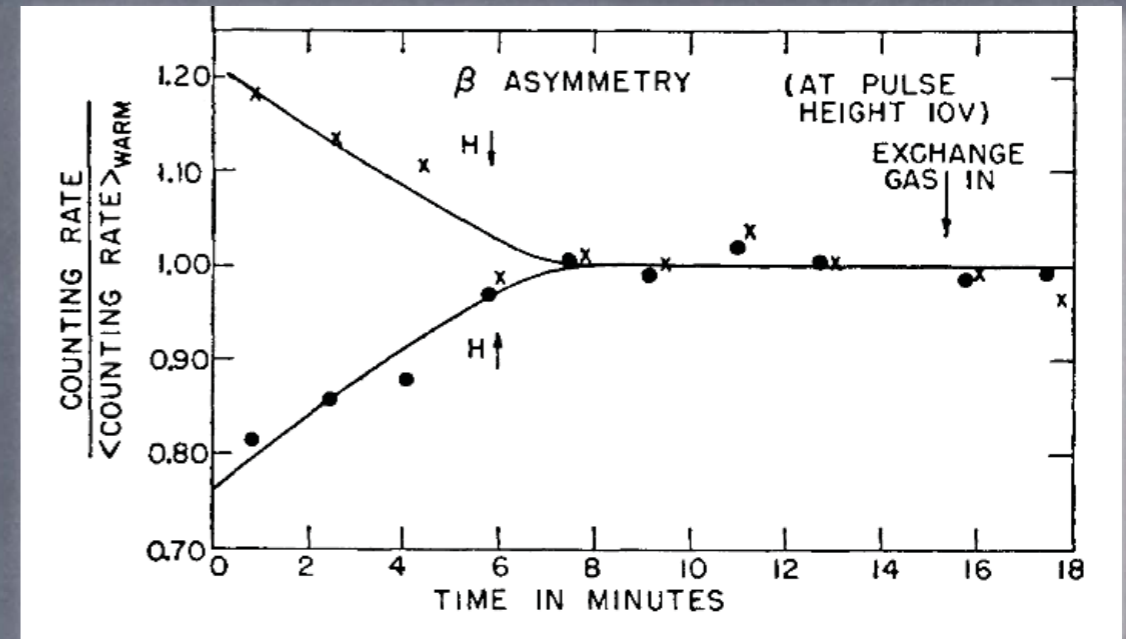
	+	-
	even	odd
m		$\vec{x}$
q		$\vec{p}$
+ B		$\vec{E}$
$\vec{J}$		

scalars,  
pseudovectors

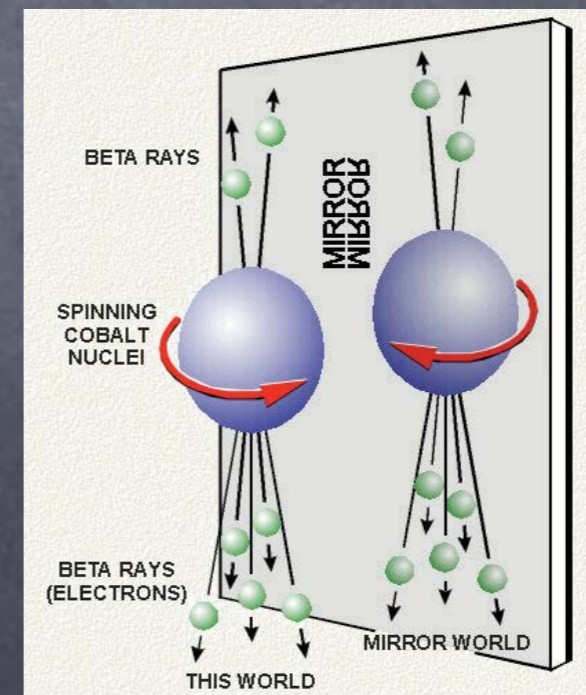
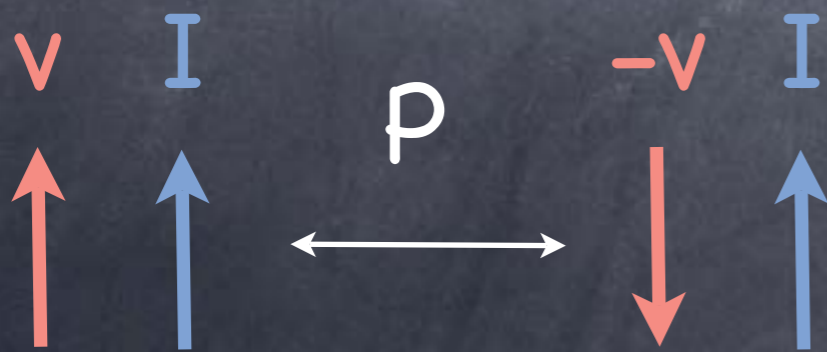
vectors

# Parity in $\beta$ -Decay

- Parity is violated in weak interactions
- Electrons are preferentially emitted antiparallel to the nuclear spin of  $^{60}\text{Co}$



C. S. Wu, et al., Phys. Rev. 105 1413-1415 (1957)



<http://www.nist.gov/physlab/general/parity>

# Parity in Atomic Transitions

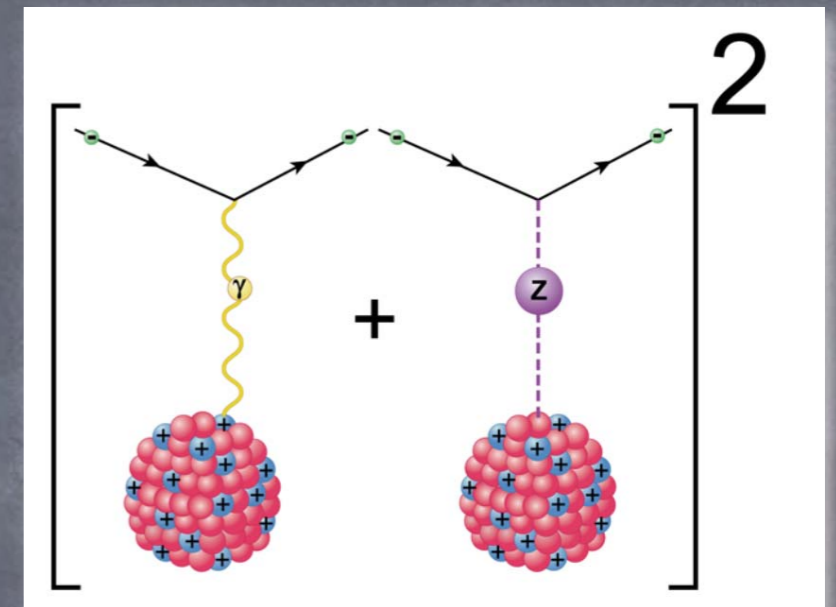
- E1 transitions connects levels of opposite parity

$$A_{ba} \propto \langle \psi_b | \vec{x} | \psi_a \rangle$$

- PNC mixes levels of opposite parity

$$|P'_+\rangle = |P_+\rangle + \epsilon |P_-\rangle$$

$$\epsilon \propto \frac{Z^3}{\Delta E}$$

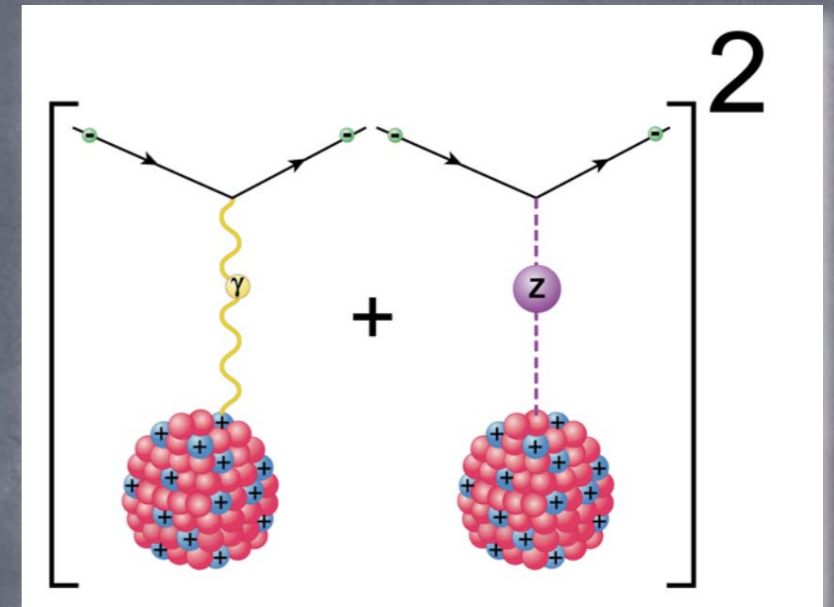
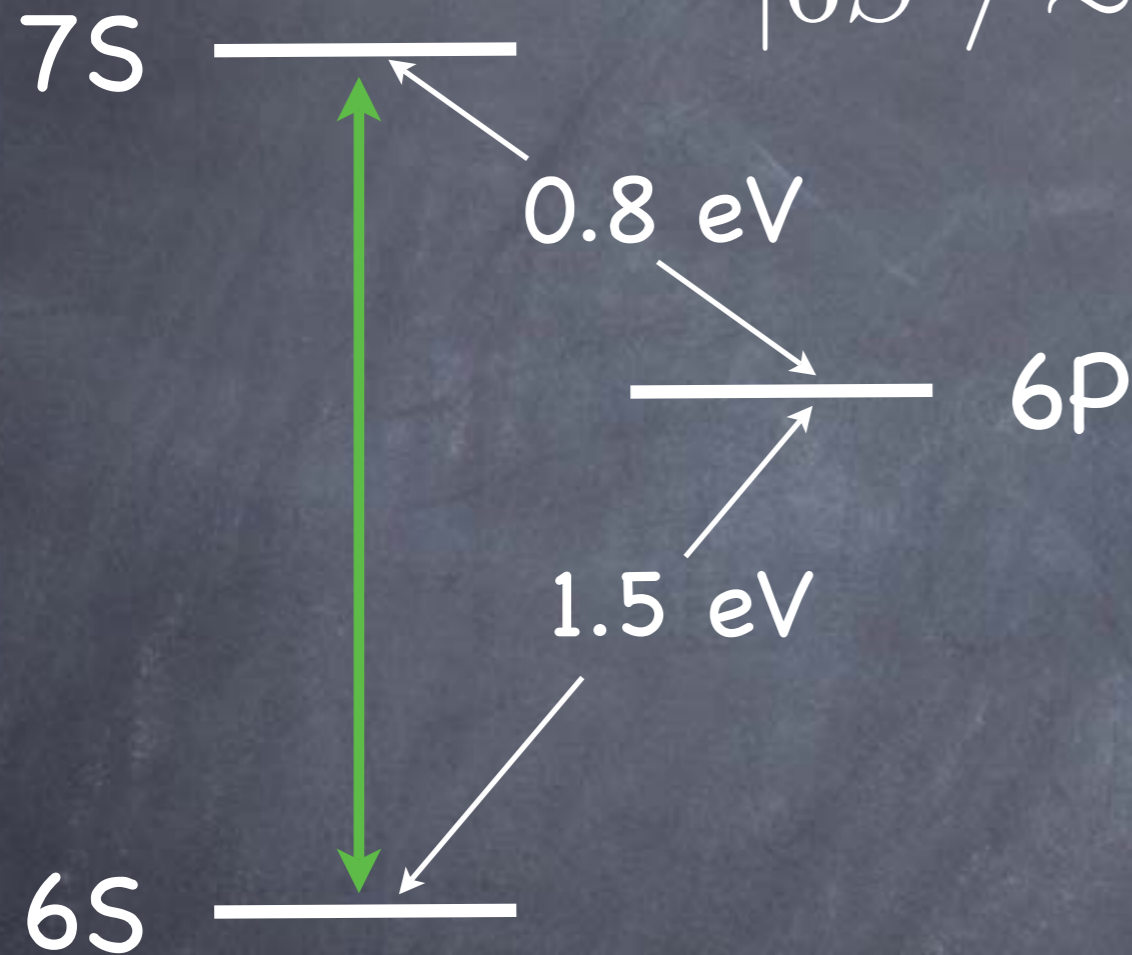


K. Jungmann, Physics 2 68 (2009)



# Parity Violation in Cs

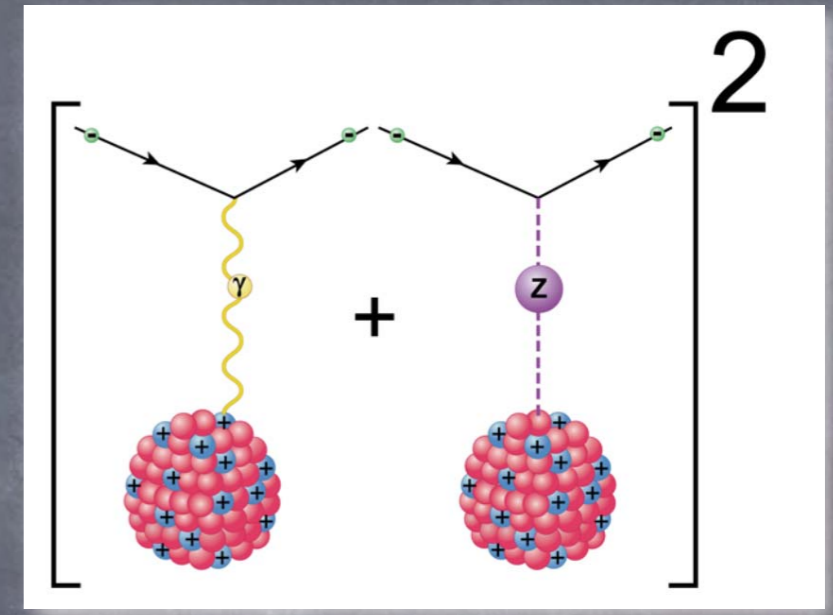
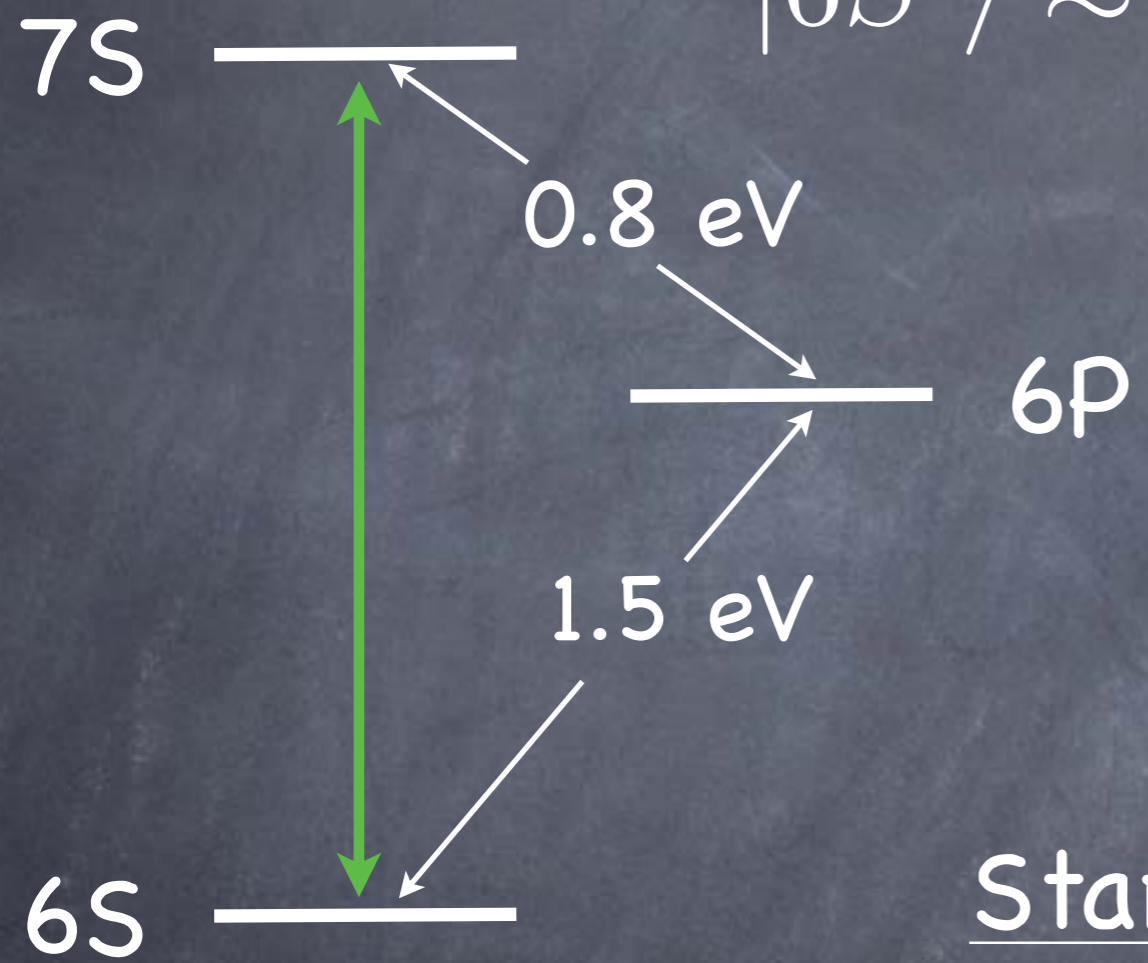
$$|6S'\rangle \approx |6S\rangle - i10^{-11} |6P\rangle$$



K. Jungmann, Physics 2 68 (2009)

# Parity Violation in Cs

$$|6S'\rangle \approx |6S\rangle - i10^{-11} |6P\rangle$$



K. Jungmann, Physics 2 68 (2009)

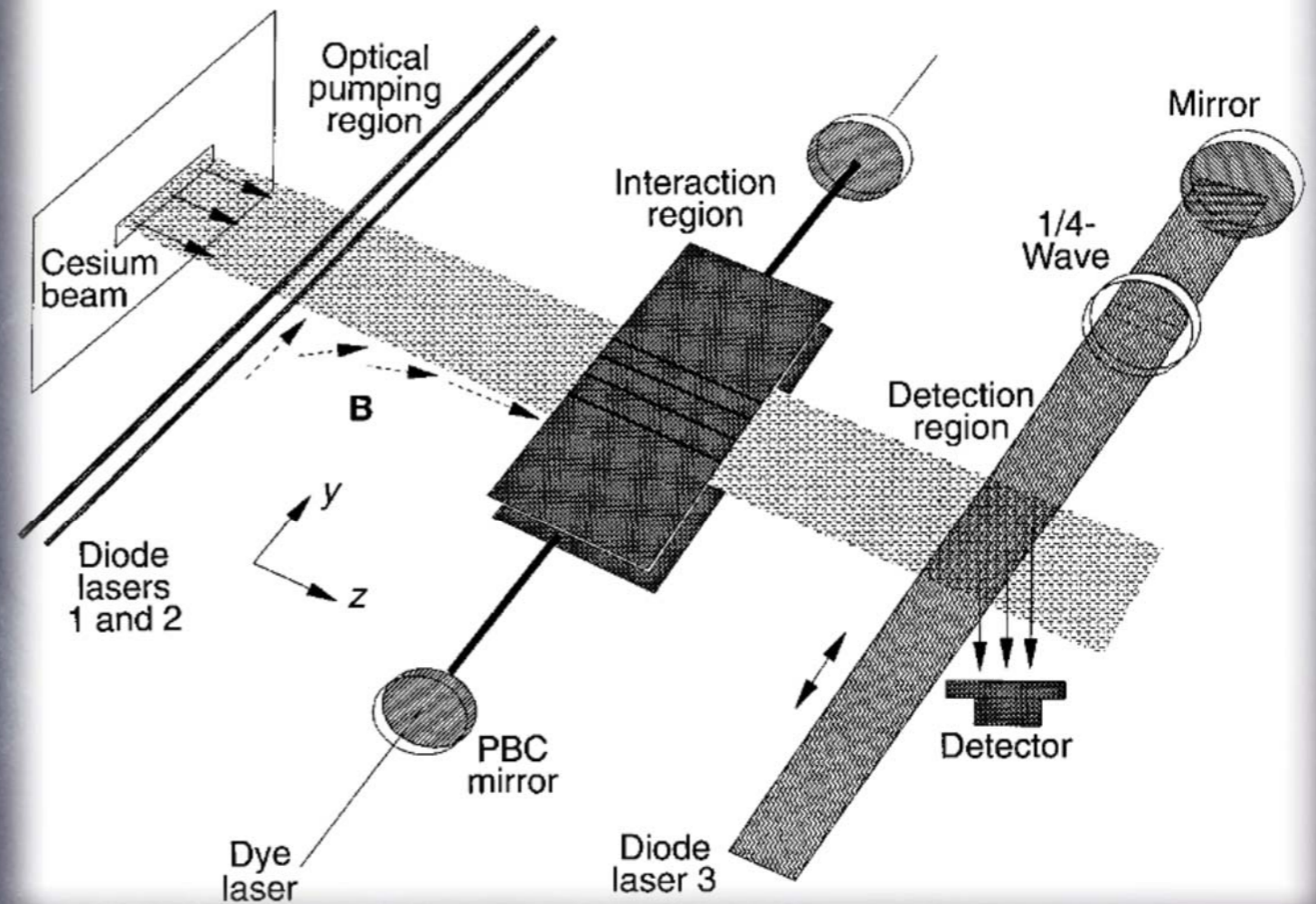
Stark-induced transition  
 Electric field mixes levels of  
 opposite parity

$$R = |A_E + A_{PNC}|^2 = |A_E|^2 + 2 \text{Re}[A_E A_{PNC}^*] + |A_{PNC}|^2$$

# Parity Violation in Cs

$$\frac{A_{\text{PNC}}}{A_{\text{E}}} \sim 10^{-5}$$

0.5% accuracy,  
statistics limited



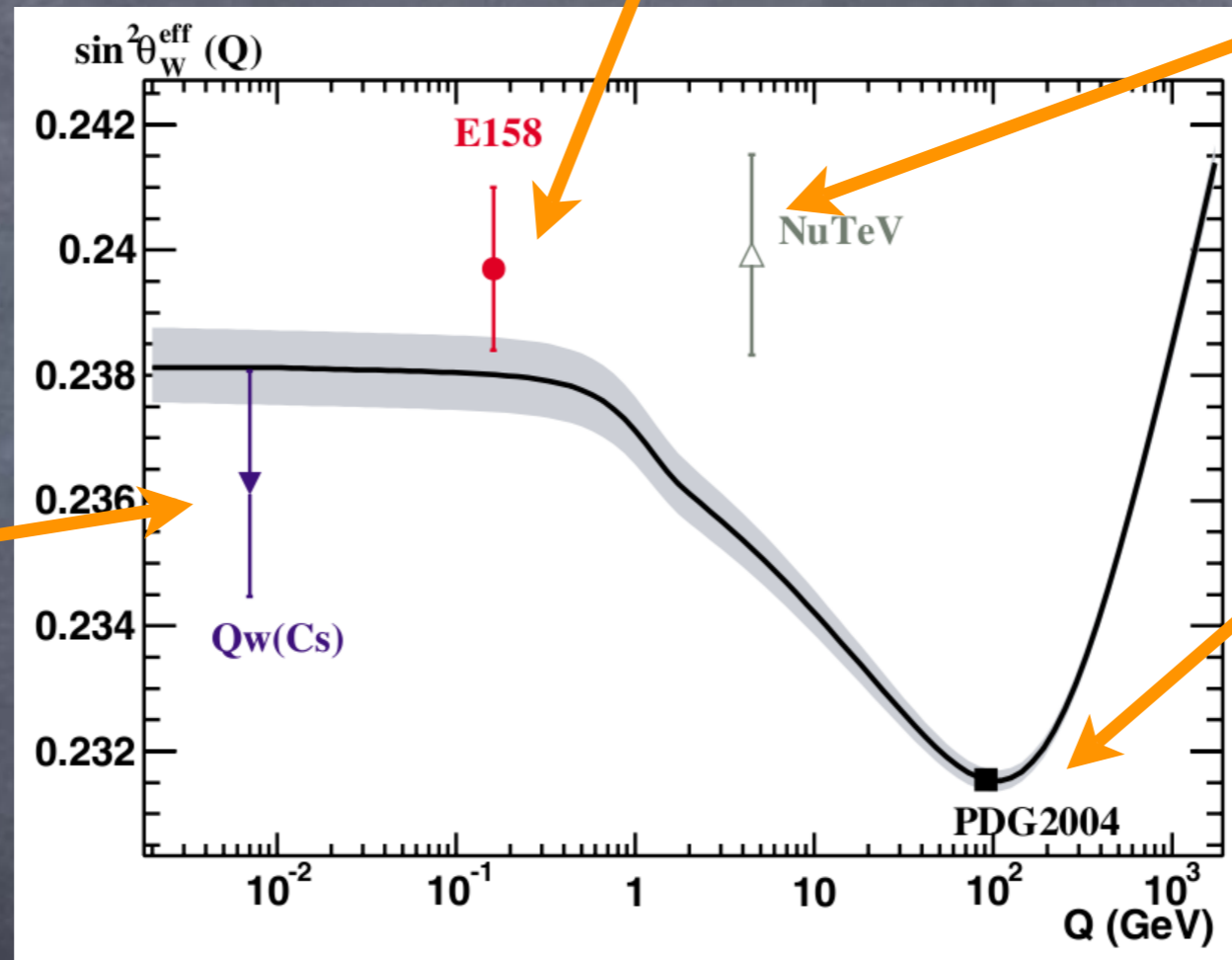
C. S. Wood, et al., Science 275 1759-1763 (1997)

# Weak Mixing Angle

$$\cos \theta_W = \frac{M_W}{M_Z}$$

$e^-/e^-$  scattering

$\nu$ /nucleon scattering



atomic Cs

$e^+/e^-$  collisions

P. L. Anthony, et al, Phys. Rev. Lett. 95 081601 (2005)

$$Q_w = -N + (1 - 4 \sin^2 \theta_W) Z$$

# Current P-violation Efforts

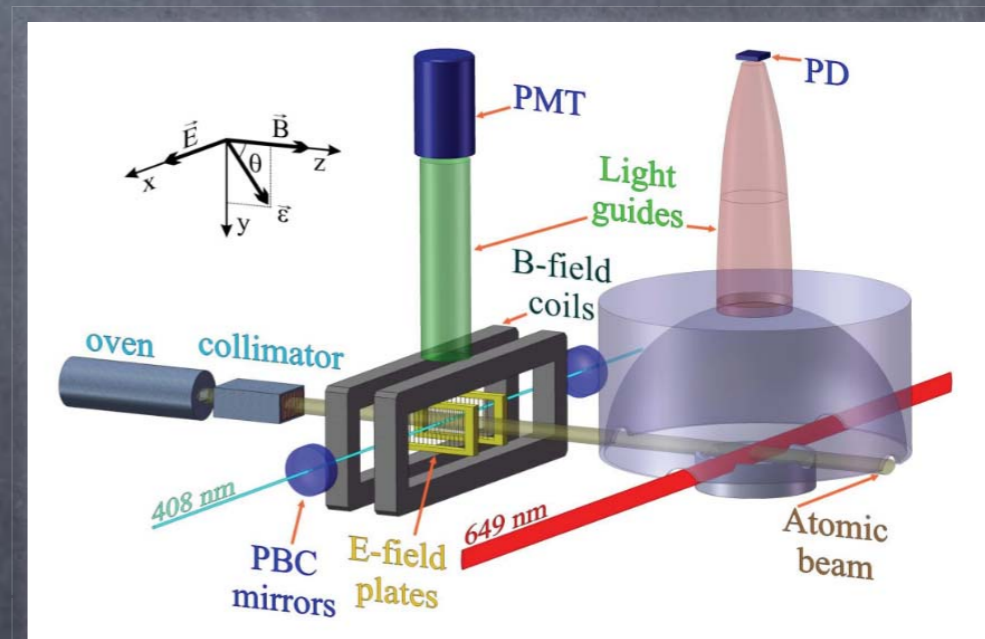
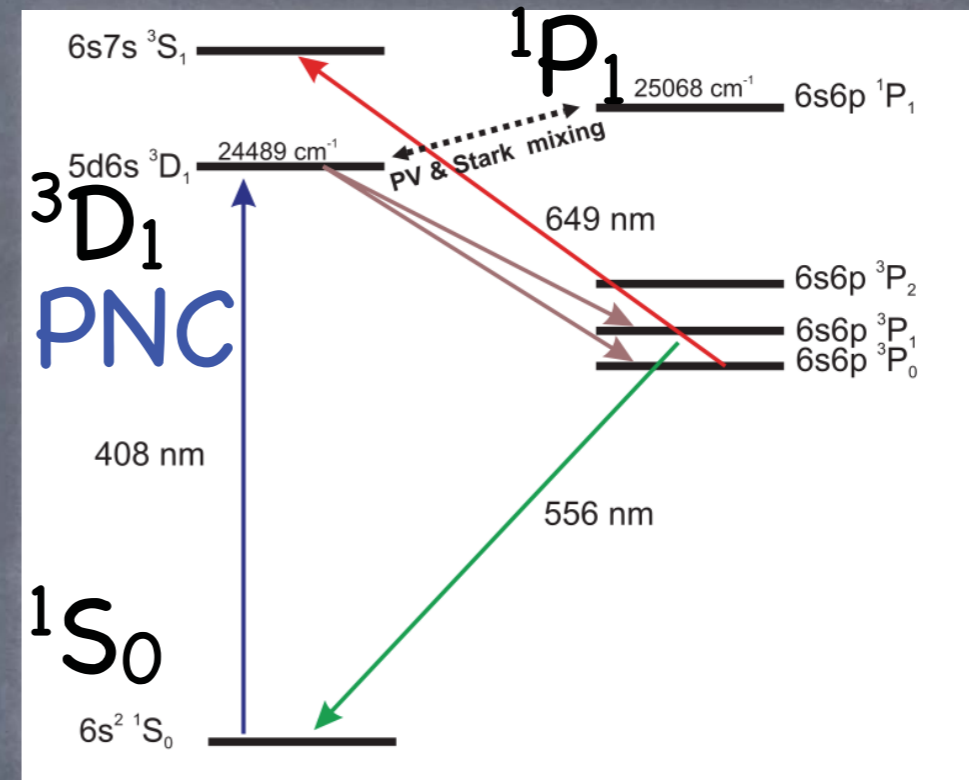
- Yb: 100x larger PNC amplitude than Cs

- Measured to 16%

- 7 stable isotopes

$$Q_w = -N + (1 - 4 \sin^2 \theta_W) Z$$

- Other ongoing efforts: Fr, Ba<sup>+</sup>, Ra<sup>+</sup>



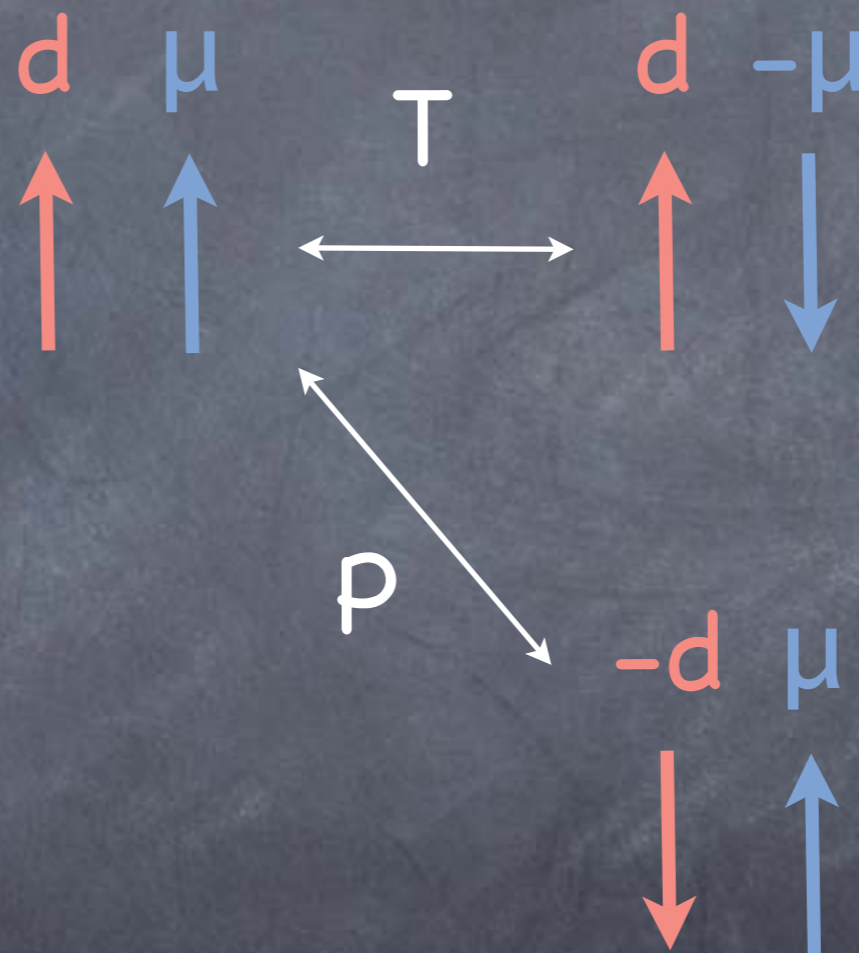
K. Tsigutkin, et al, Phys. Rev. Lett. **103** 071601 (2009)

K. Tsigutkin, et al, Phys. Rev. A **81** 032114 (2010)

# Time-Reversal

$$t \rightarrow -t$$

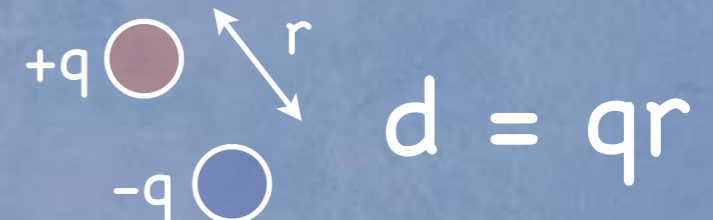
- Related to CP-violation (and hence matter/antimatter asymmetry)
- Intrinsic electric dipole moments are forbidden



	+	-
	even	odd
$m$		$\dagger$
$q$		$\vec{p}$
$\vec{x}$		$\vec{B}$
$\vec{E}$		$\vec{J}$
$\vec{d}$		$\vec{\mu}$

# Electric Dipole Moments

## Classical EDM



## Experimental limits

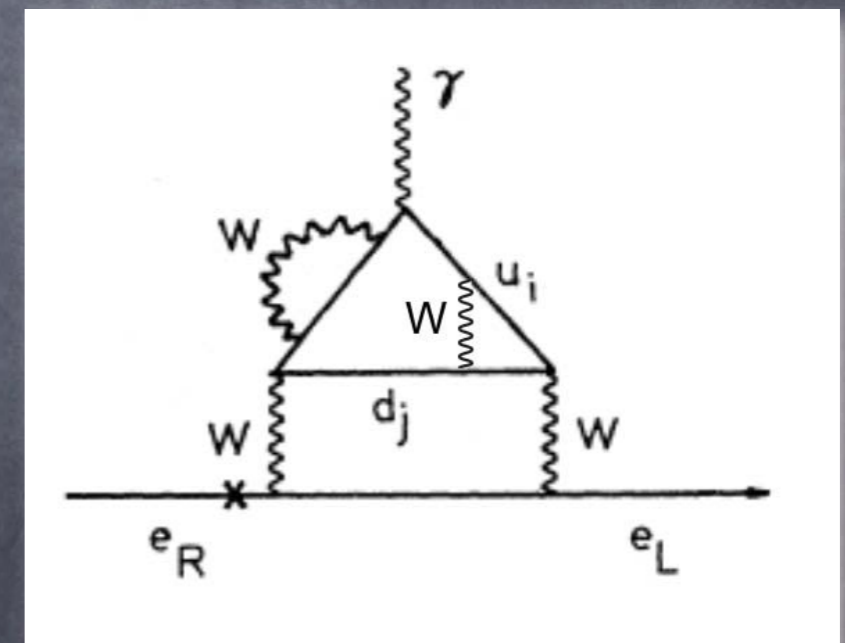
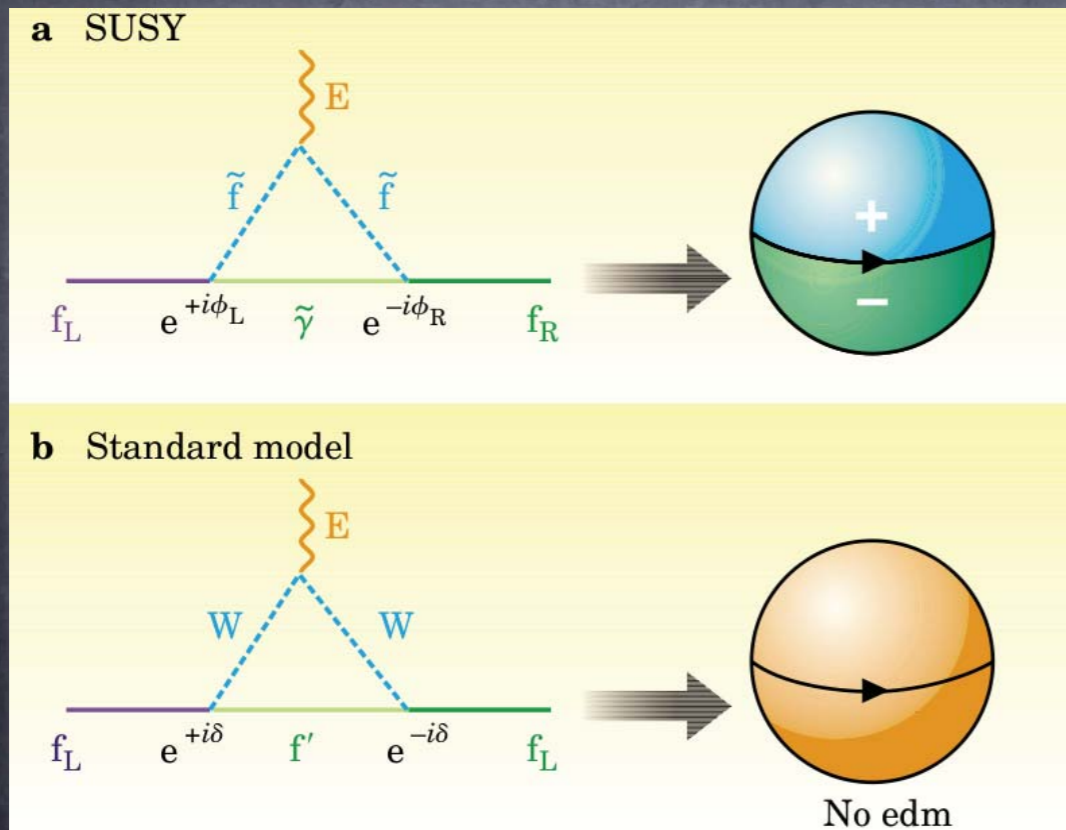
$$|d(e)| \leq 1.6 \times 10^{-27} e \cdot \text{cm}$$

$$|d(n)| \leq 2.9 \times 10^{-26} e \cdot \text{cm}$$

$$|d(^{199}\text{Hg})| < 3.1 \times 10^{-29} e \cdot \text{cm}$$

strong CP problem

$$|d(e)|_{\text{SM}} < 10^{-40} e \cdot \text{cm}$$



W. Bernreuther & M. Suzuki,  
Rev. Mod. Phys. **63** 313-340 (1991)

S. Bickman, Yale Ph.D. Thesis (2007)

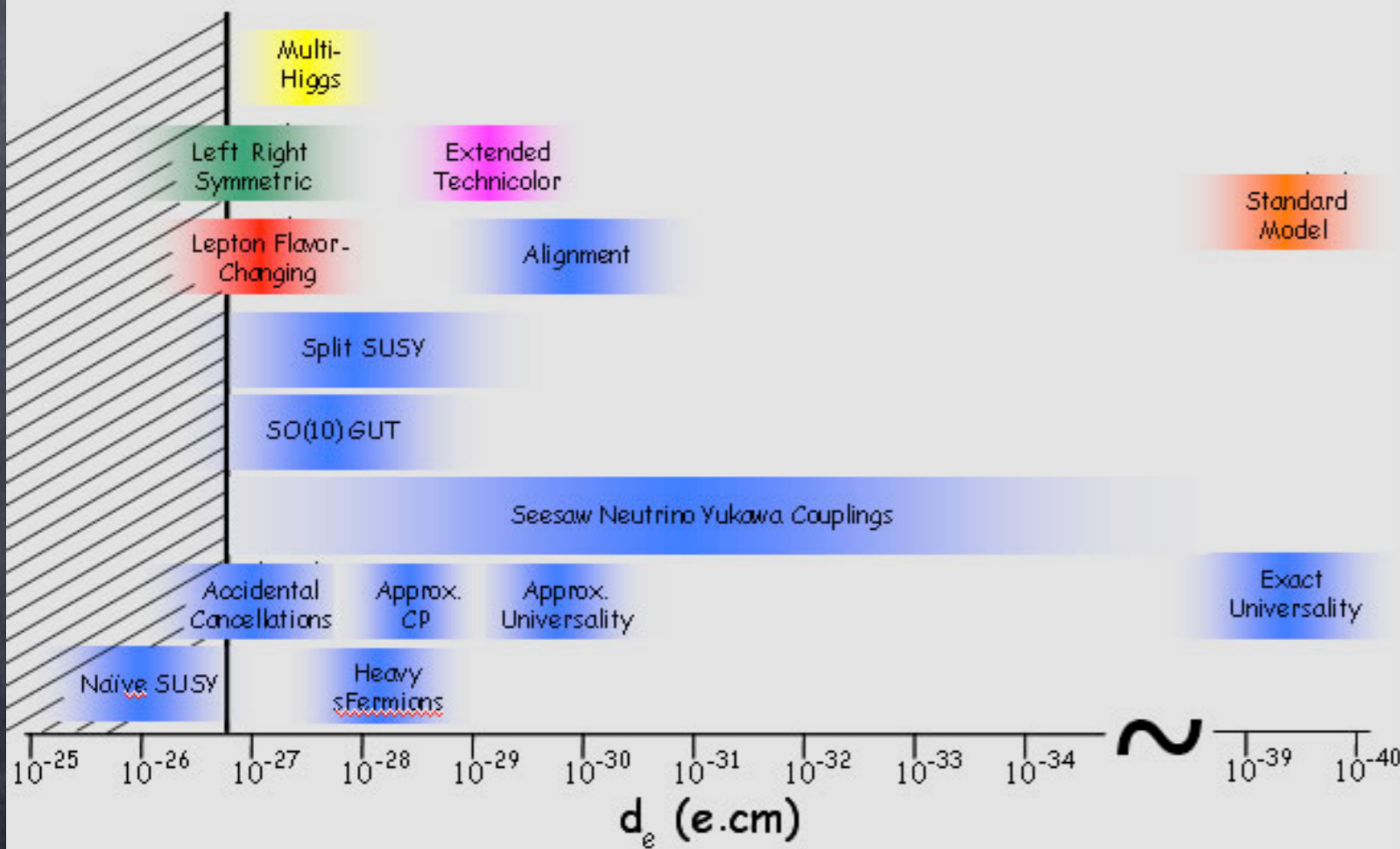
# EDM constraints

electron

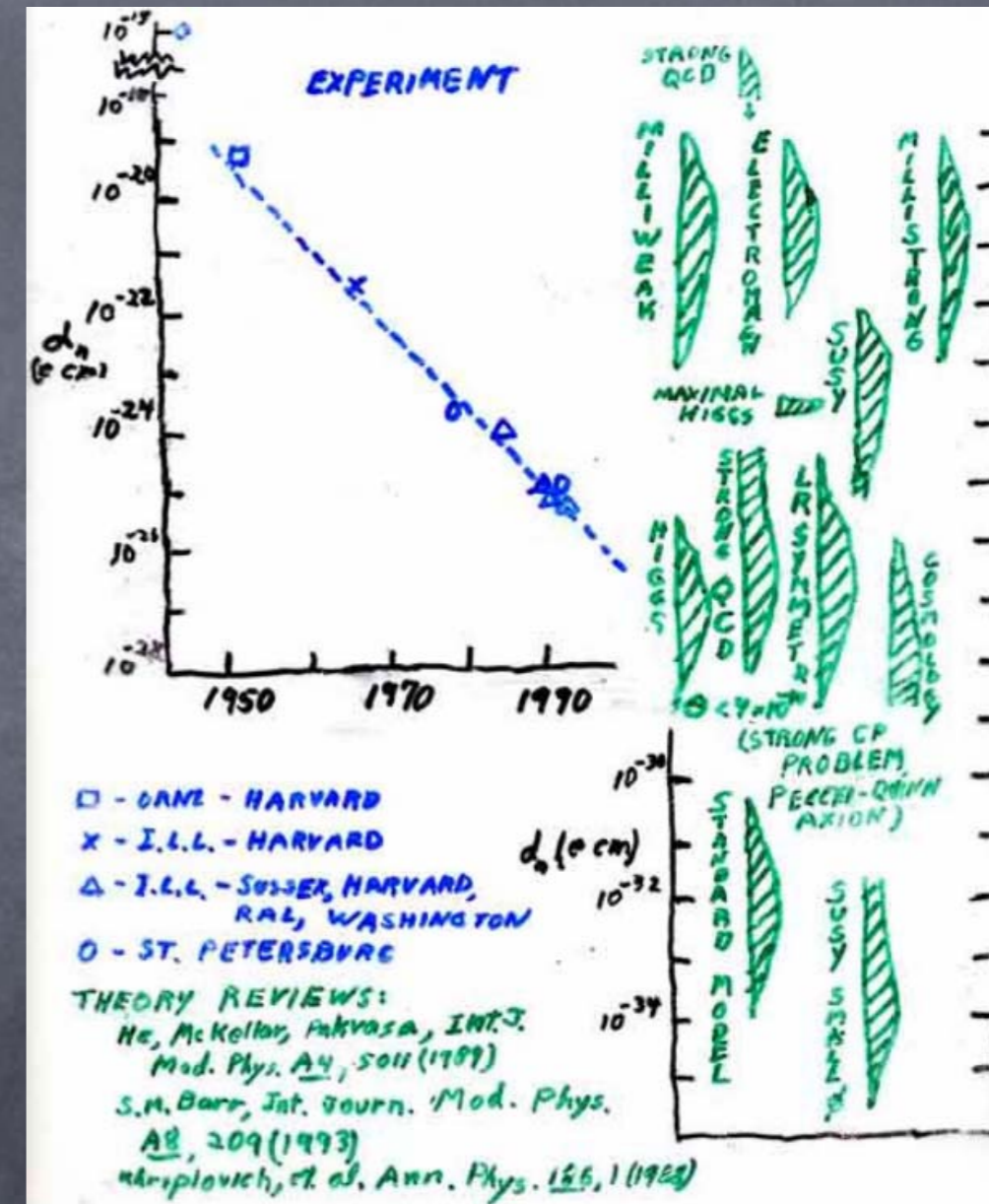
neutron

## Searching for new physics with the electron EDM

Berkeley  
(2002)



Data compiled by D. DeMille, Yale  
Plot from <http://hussle.harvard.edu>



Data compiled by N. Ramsey, Harvard



# EDM Searches

- Use something with a MDM and no electric monopole moment
- Constant  $B$ , modulate (a large!)  $E$

$$\nu_+ = 2(\mu B + dE) / h$$

$$\nu_- = 2(\mu B - dE) / h$$

- Spend years on the systematics
- Atomic EDM
  - Relativistic effects enhance an electron EDM for high- $Z$  atoms
  - Suppressed relative to nuclear EDM by  $10^{-3} - 10^{-4}$



e.g. atom,  
neutron

# Electron EDM

B. C. Regan, et al, Phys. Rev. Lett. 88 071805 (2002)

- Thallium EDM
- Ramsey interference with optical state prep/measurement
- 8 atomic beams
  - Th +E/-E for differential  $d \cdot E$
  - Th up/down for differential  $\mathbf{v} \times \mathbf{E}$
  - Sodium as co-magnetometer
- 256 apparatus configurations

$$\nu_+ = 2(\mu B + dE) / h$$

$$\nu_- = 2(\mu B - dE) / h$$

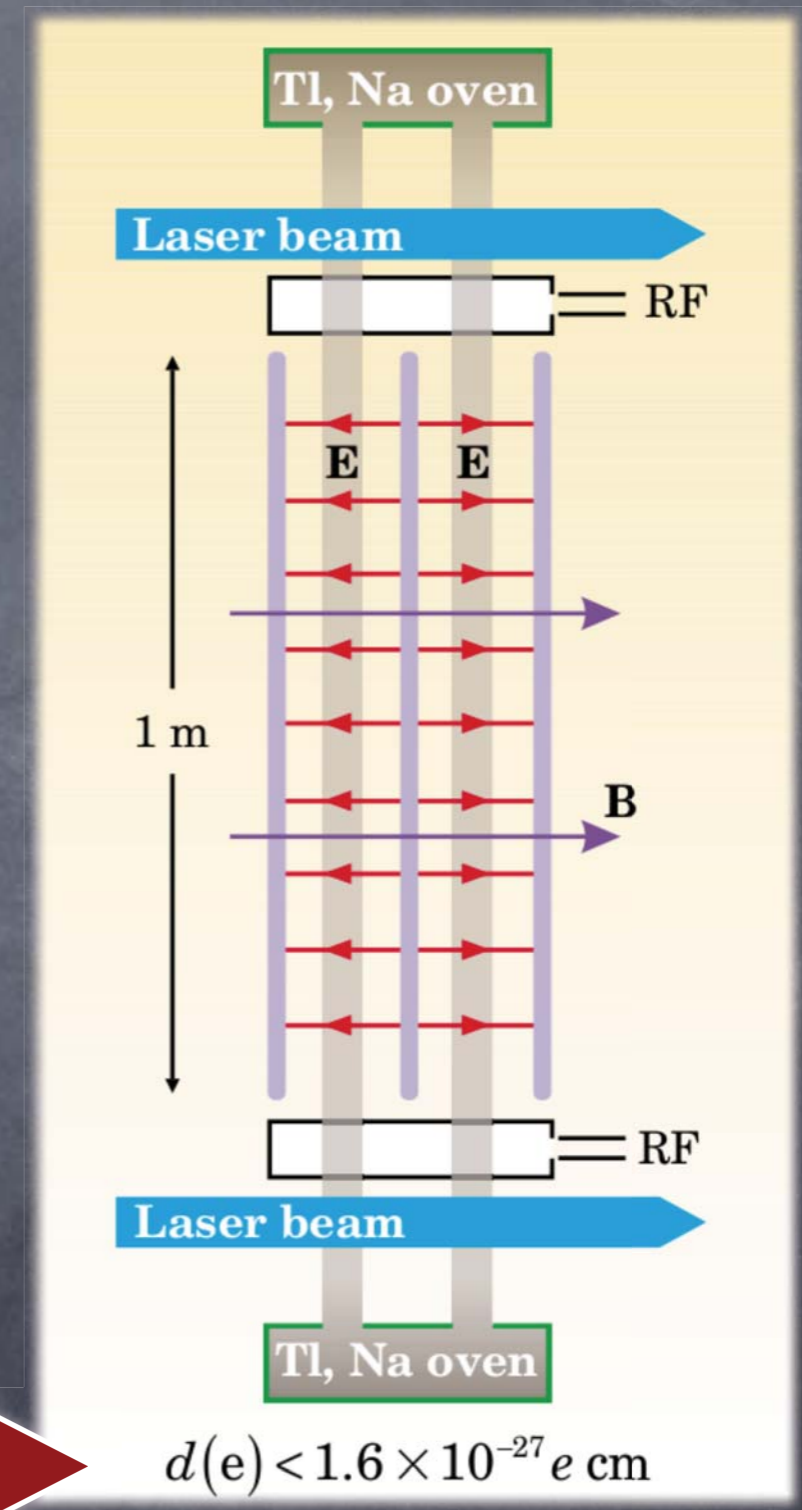


Figure from N. Fortson, et al,  
Phys. Today, June 2003, 33-39

# Ongoing Searches for T-violation

- Ultracold atoms
  - Increase the coherence times
- Polar molecules
  - 100 GV/cm
  - Flip spin instead of  $E$  ( $\Omega$ -doublet)
- Solid-state
  - Statistics advantage (lots of  $e^-$ )
  - Apply  $E$ , look for magnetization



Cs: U. Texas, Penn State,  
Princeton, Berkeley

Fr: Osaka U.

YbF: Imperial College

PbF: U. Oklahoma

HfF<sup>+</sup>: JILA

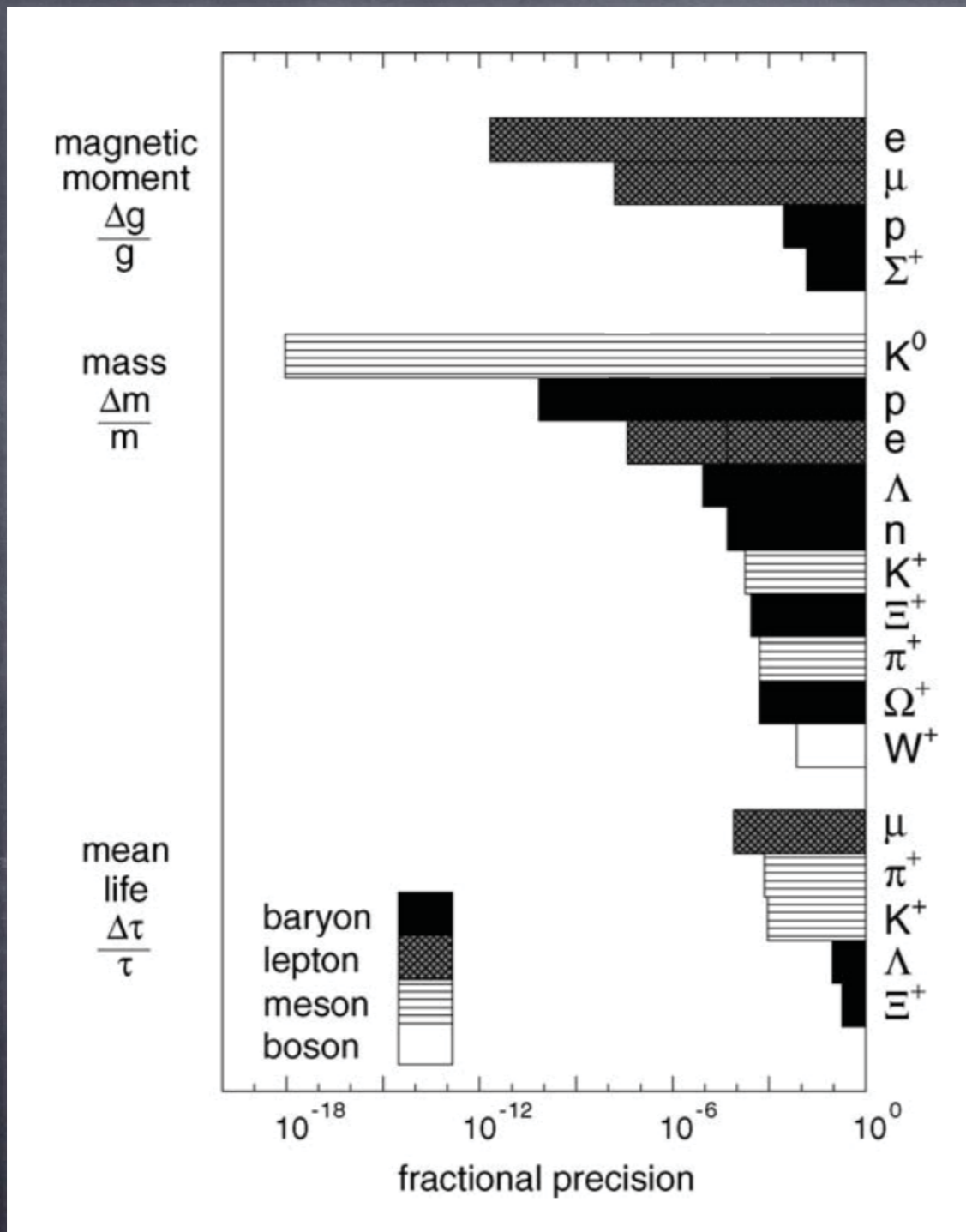
ThO: Harvard/Yale

PbO\*: Yale

Gd<sub>3</sub>Ga<sub>5</sub>O<sub>12</sub>: Yale, Indiana

Gd<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub>: Amherst

# CPT Violation



Data from PDG

Figure from G. Gabrielse, Int. J. Mass Spec. 251 273-280 (2006)

	+	-
	even	odd
	m	q
	$\vec{p}$	+
	$\vec{E}$	$\vec{X}$
	$\vec{B}$	$\vec{J}$

CPT is a symmetry of any Lorentz-invariant, local QFT with a Hermitian Hamiltonian

# Electron/positron g-values

## Positrons from beta decay



VOLUME 59, NUMBER 1

PHYSICAL REVIEW LETTERS

6 JULY 1987

### New High-Precision Comparison of Electron and Positron $g$ Factors

Robert S. Van Dyck, Jr., Paul B. Schwinberg, and Hans G. Dehmelt  
*Department of Physics, University of Washington, Seattle, Washington 98195*  
(Received 23 March 1987)

Single electrons and positrons have been alternately isolated in the same compensated Penning trap in order to form the geonium pseudoatom under nearly identical conditions. For each, the  $g$ -factor anomaly is obtained by measurement of both the spin-cyclotron difference frequency and the cyclotron frequency. A search for systematic effects uncovered a small (but common) residual shift due to the cyclotron excitation field. Extrapolation to zero power yields  $e^+$  and  $e^-$   $g$  factors with a smaller statistical error and a new particle-antiparticle comparison:  $g(e^-)/g(e^+) = 1 + (0.5 \pm 2.1) \times 10^{-12}$ .

PACS numbers: 14.60.Cd, 06.30.Lz, 12.20.Fv, 32.30.Bv

$$g_{e^-}/g_{e^+} = 1 + (0.5 \pm 2.1) \times 10^{-12}$$

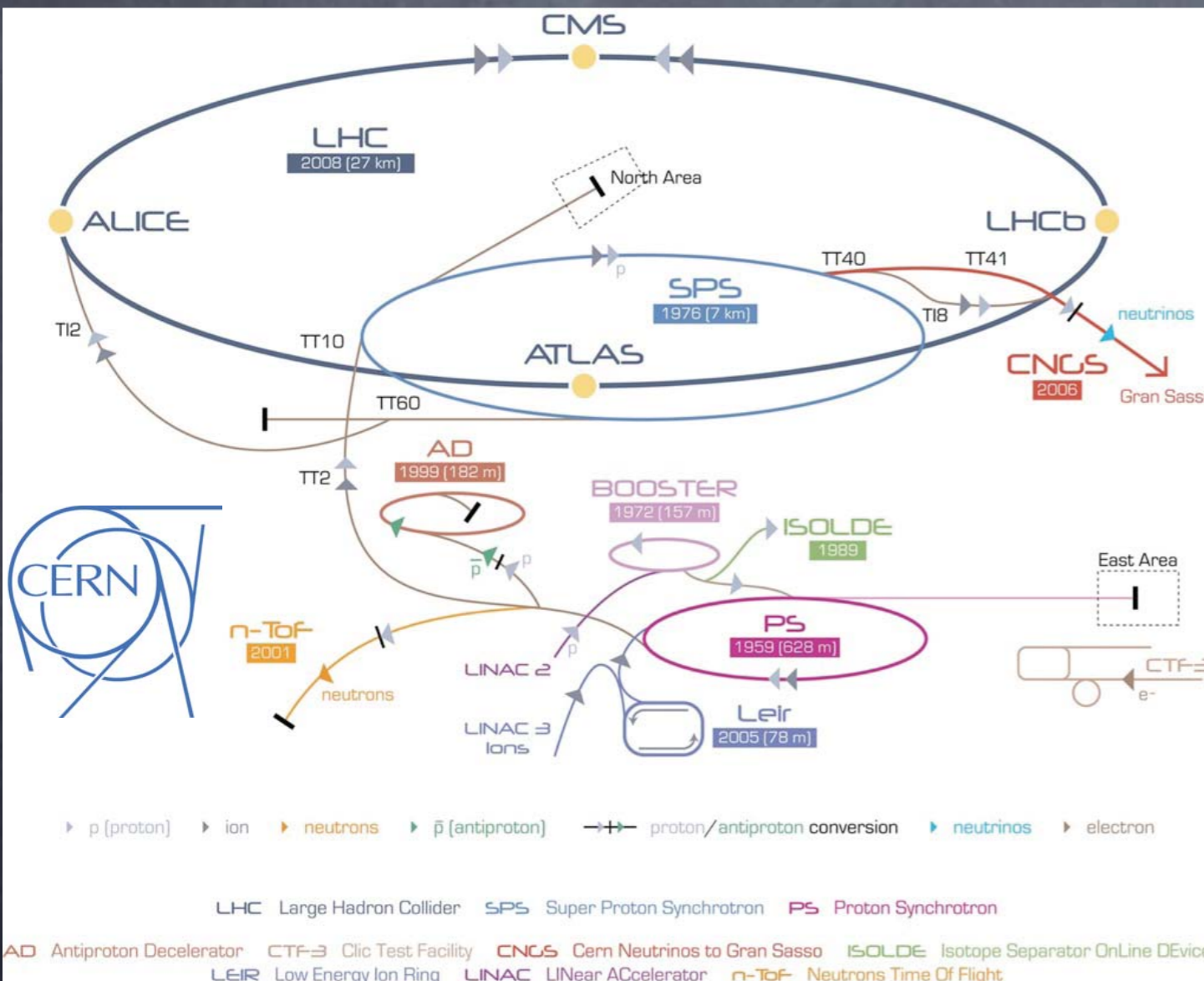
Ongoing work for 15x improvement

# Antiprotons

Low-Energy Antiproton Ring (LEAR, at CERN): 1982-1996

Antiproton Decelerator (AD, at CERN): 2000-present

Facility for Antiproton and Ion Research (FAIR, at GSI): 2014?



PS:  $10^{13}$  p @ 26 GeV

iridium wire target:

$3 \times 10^7$  pbar @ 2.75 GeV

AD slows them to 5.3 MeV

Slow with matter

(He/SF<sub>6</sub> gases): 3.5 MeV

Slow with matter

(Be foil): few keV

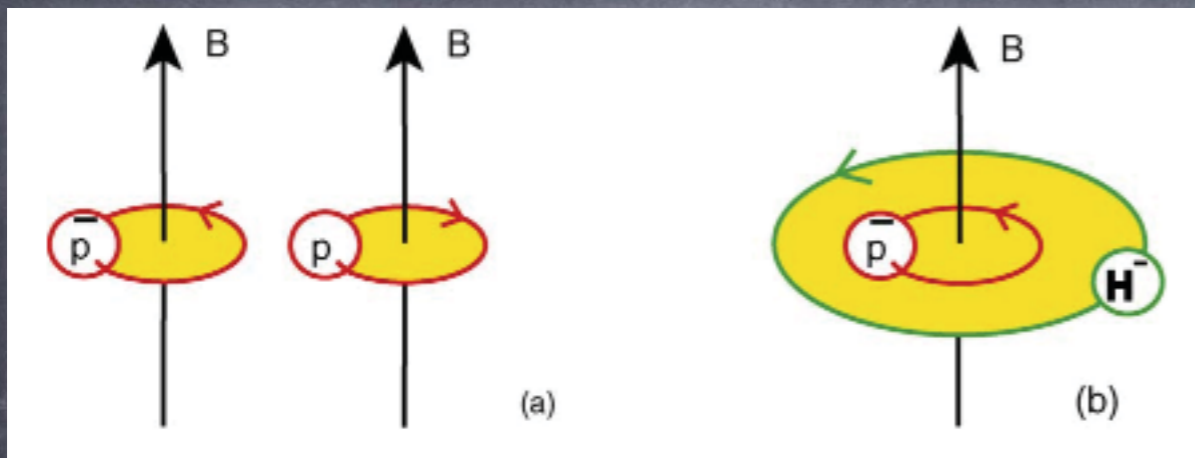
"Catch"  $10^4$  in an ion trap

Cool with e<sup>-</sup> to 4.2 K (0.3 meV)

# Proton/antiproton

## Charge-to-mass ratio

$$\frac{(q/m)[\bar{p}]}{(q/m)[p]} = 1 - (1.6 \pm 0.9) \times 10^{-10}$$



$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$

G. Gabrielse, et al, Phys. Rev. Lett. **82** 3198 (1999)

G. Gabrielse, Int. J. Mass Spec. **251** 273-280 (2006)

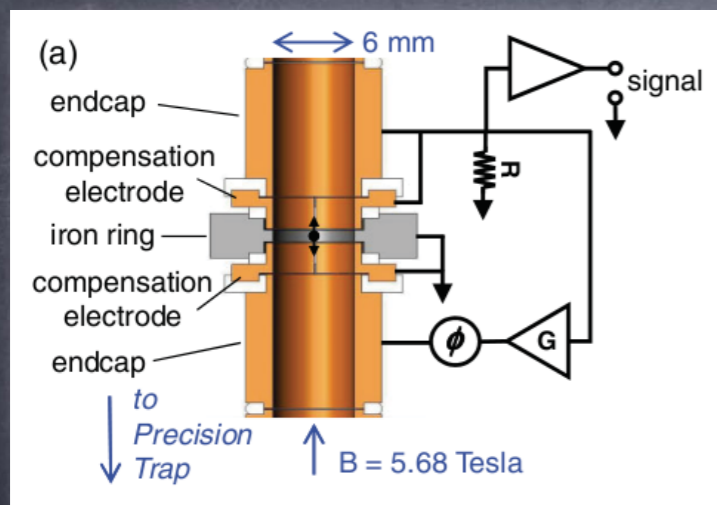
# Proton/antiproton

## Magnetic Moment

$$\begin{array}{l} \text{exotic atoms } (\bar{p} \text{ } ^{208}\text{Pb}) \longrightarrow \\ \text{hydrogen spectroscopy} \longrightarrow \end{array} \left| \frac{\mu_{\bar{p}}}{\mu_p} \right| = 1.0026 \pm 0.0029 \quad \frac{\mu_e}{\mu_p} \sim 650$$

## Competition for million-fold improvement

Harvard, Gerald Gabrielse

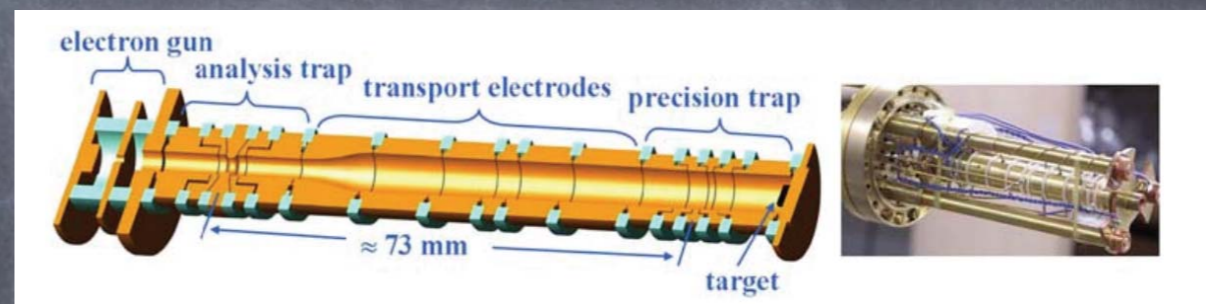


60 mHz on 553 kHz

N. Guise, et al, Phys. Rev. Lett. **104** 143001 (2010)

MPIK, GSI, J. Gutenberg U.

Klaus Blaum, Wolfgang Quint, Jochen Walz



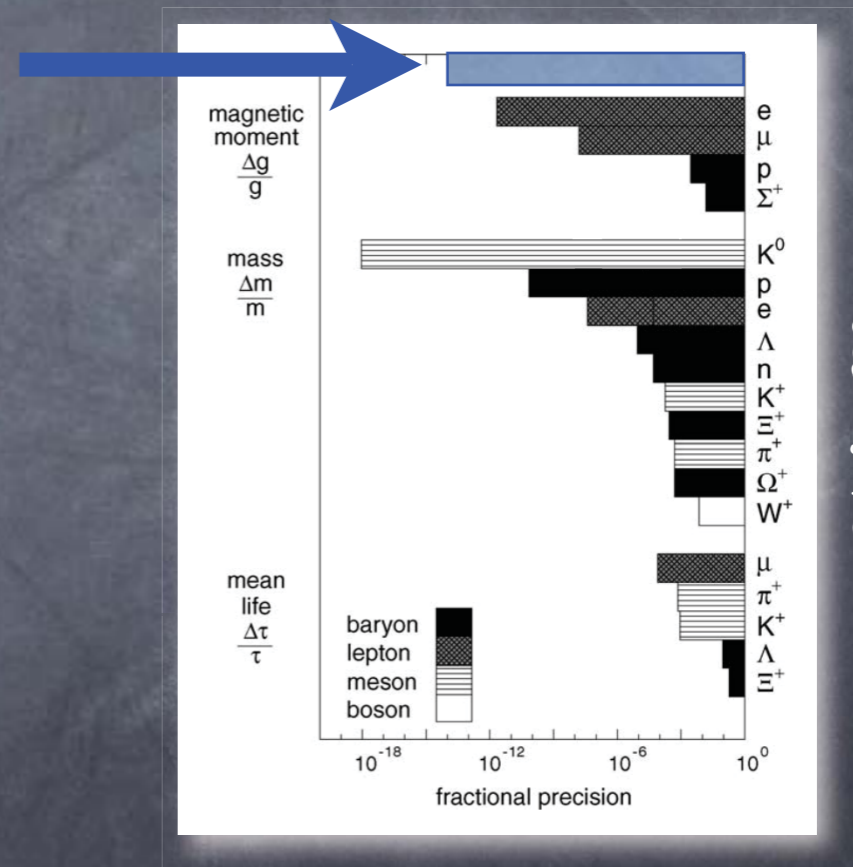
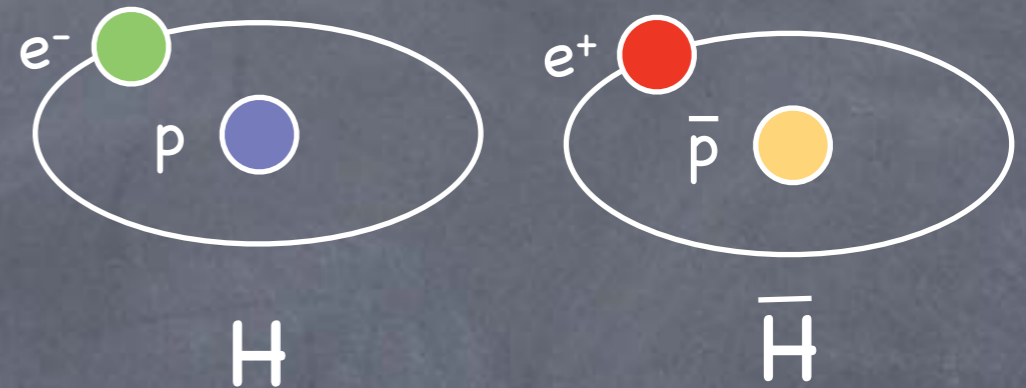
252 mHz on 692 kHz

C. C. Rodegheri, et al, Hyperfine Interactions **194** 93-98 (2009)



# Antihydrogen

- combined lepton/baryon system
- Goal: 1S-2S (121 nm)
  - measured to  $10^{-14}$  in hydrogen
- Making  $\bar{H}$  is now "routine"
- Four main collaborations: ATRAP, ALPHA (formed from ATHENA), ASACUSA, AEGIS

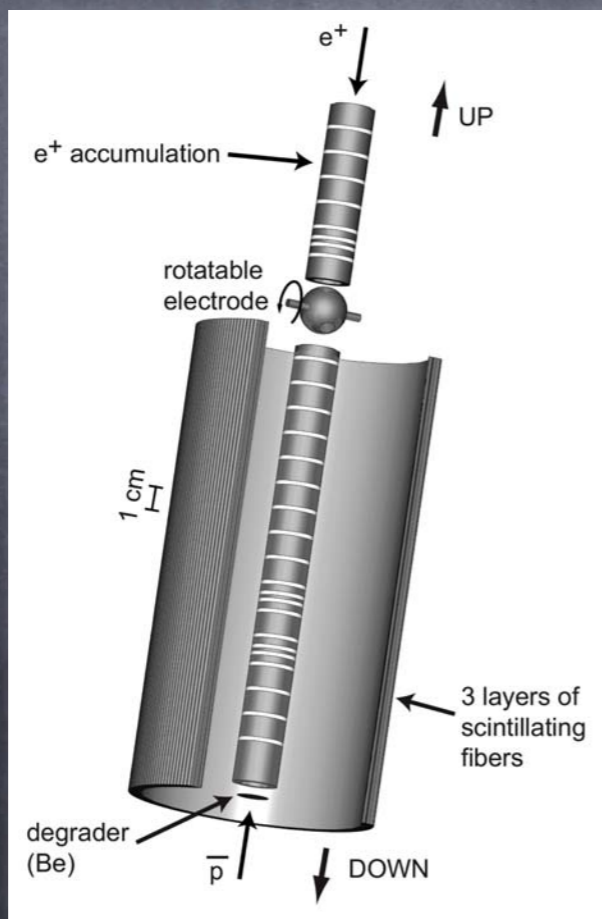
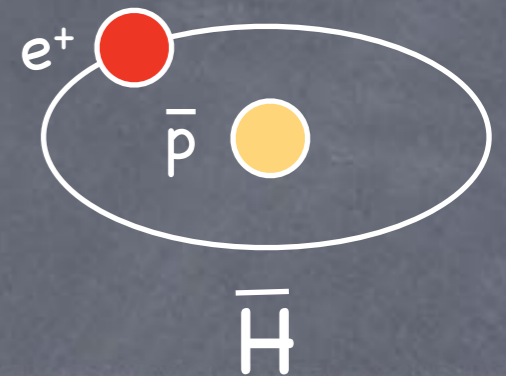


Data from PDG  
Figure from G. Gabrielse, Int. J. Mass Spec. 251 273-280 (2006)

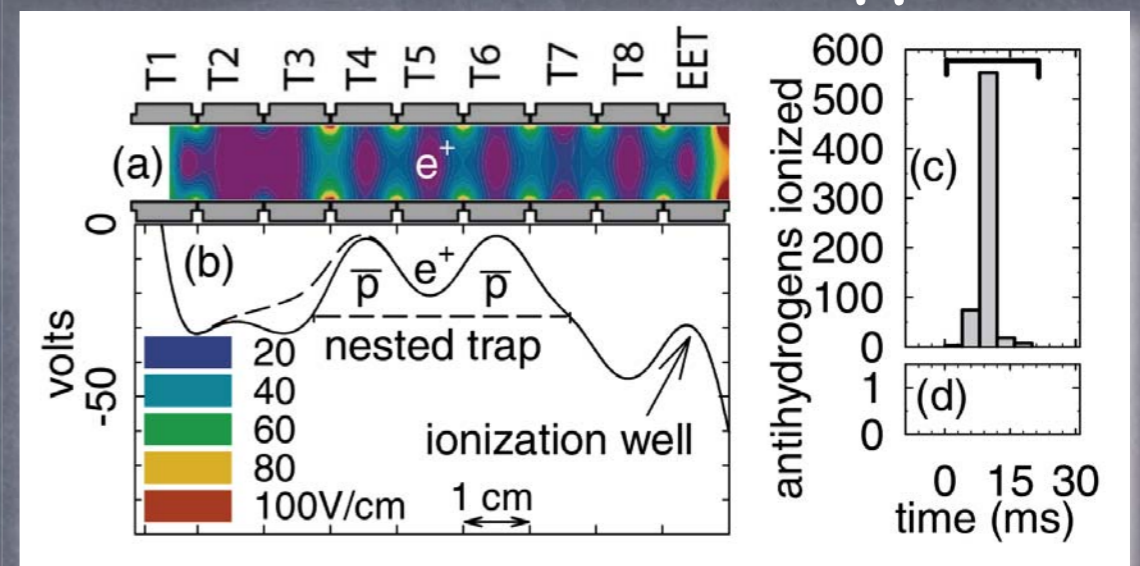
$$\frac{R_\infty[\bar{H}]}{R_\infty[H]} = \frac{1 + m[e^-]/M[p]}{1 + m[e^+]/M[\bar{p}]} \left( \frac{m[e^+]}{m[e^-]} \right) \left( \frac{q[\bar{p}]}{q[p]} \right)^2 \left( \frac{q[e^+]}{q[e^-]} \right)^2$$

# Antihydrogen Production

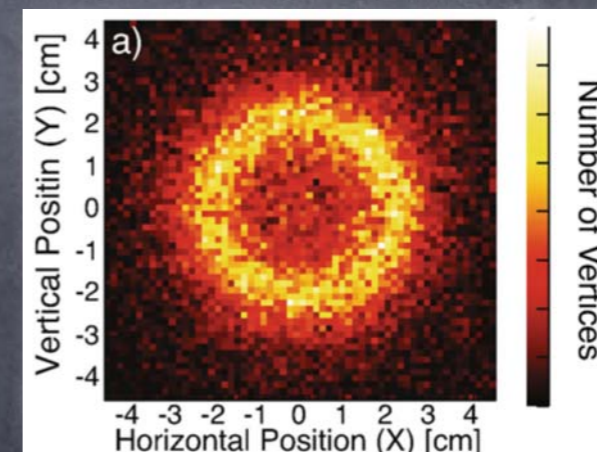
- Need to trap  $\bar{p}$  and  $e^+$  simultaneously
- Three-body recombination
 
$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$
- Annihilation detection



A. Speck, Ph.D. Thesis, Harvard 2005



G. Gabrielse, et al, (ATRAP) Phys. Rev. Lett. 89 213401 (2002)



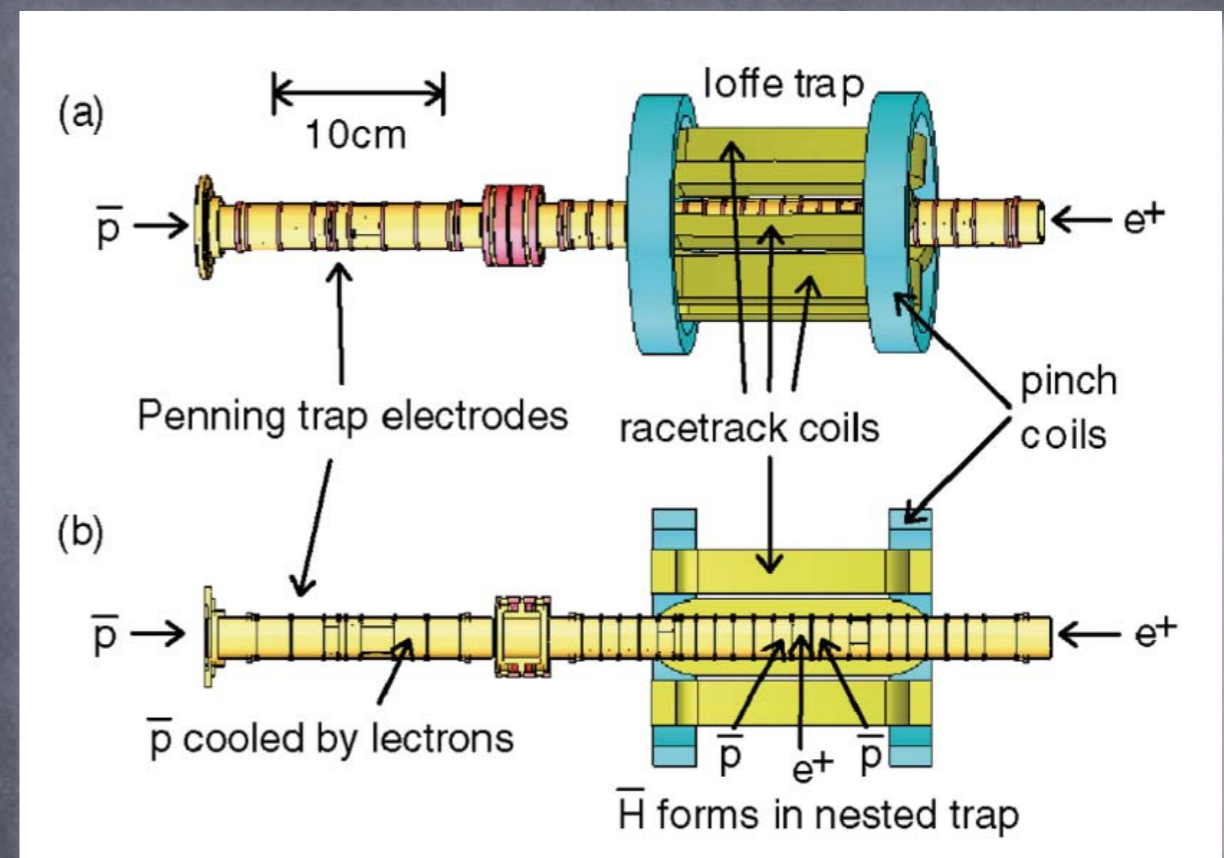
G. B. Andresen, et al, (ALPHA), Phys. Lett. B 685 141 (2010)

See also, M. Amoretti, et al, (ATHENA) Nature 419 456-459 (2002)

# Trapping Antihydrogen

- Combined Penning-Ioffe trap
- $\bar{H}$  has been produced in such a trap
- No trapping demonstration...yet

$$U = -\vec{\mu} \cdot \vec{B}$$



G. Gabrielse, et al, (ATRAP), Phys. Rev. Lett. 100 113001 (2008)

See also, G. Gabrielse, Physics Today, March 2010, 68-69

See also, G. B. Andresen, et al, (ALPHA), Phys. Lett. B 685 141 (2010)

# What could break CPT?

CPT is a symmetry of any Lorentz-invariant, local QFT with a Hermitian Hamiltonian

## Standard Model Extension

- Phenomenological “low-energy” framework
- Spontaneous Lorentz violation (and some CPT violation)
- Preserves gauge structure, coordinate invariance, etc.

$$\begin{aligned}\mathcal{L}^{\text{QED}} &= \bar{\psi}\gamma^\mu (i\hbar c\partial_\mu - qcA_\mu)\psi - mc^2\bar{\psi}\psi - \frac{1}{4\mu_0}F^{\mu\nu}F_{\mu\nu} \\ \mathcal{L}^{\text{SME}} &= -a_\mu\bar{\psi}\gamma^\mu\psi - b_\mu\bar{\psi}\gamma_5\gamma^\mu\psi + c_{\mu\nu}\bar{\psi}\gamma^\mu(i\hbar c\partial^\nu - qcA^\nu)\psi \\ &\quad + d_{\mu\nu}\bar{\psi}\gamma_5\gamma^\mu(i\hbar c\partial^\nu - qcA^\nu)\psi - \frac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi \\ &\quad + \frac{1}{2\hbar}(k_{\text{AF}})^\kappa\epsilon_{\kappa\lambda\mu\nu}\sqrt{\frac{\epsilon_0}{\mu_0}}A^\lambda F^{\mu\nu} - \frac{1}{4\mu_0}(k_{\text{F}})_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu}\end{aligned}$$

# Michelson-Morley Experiment

THE  
AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.\*

PRL 103, 090401 (2009)

PHYSICAL REVIEW LETTERS

week ending  
28 AUGUST 2009

## Laboratory Test of the Isotropy of Light Propagation at the $10^{-17}$ Level

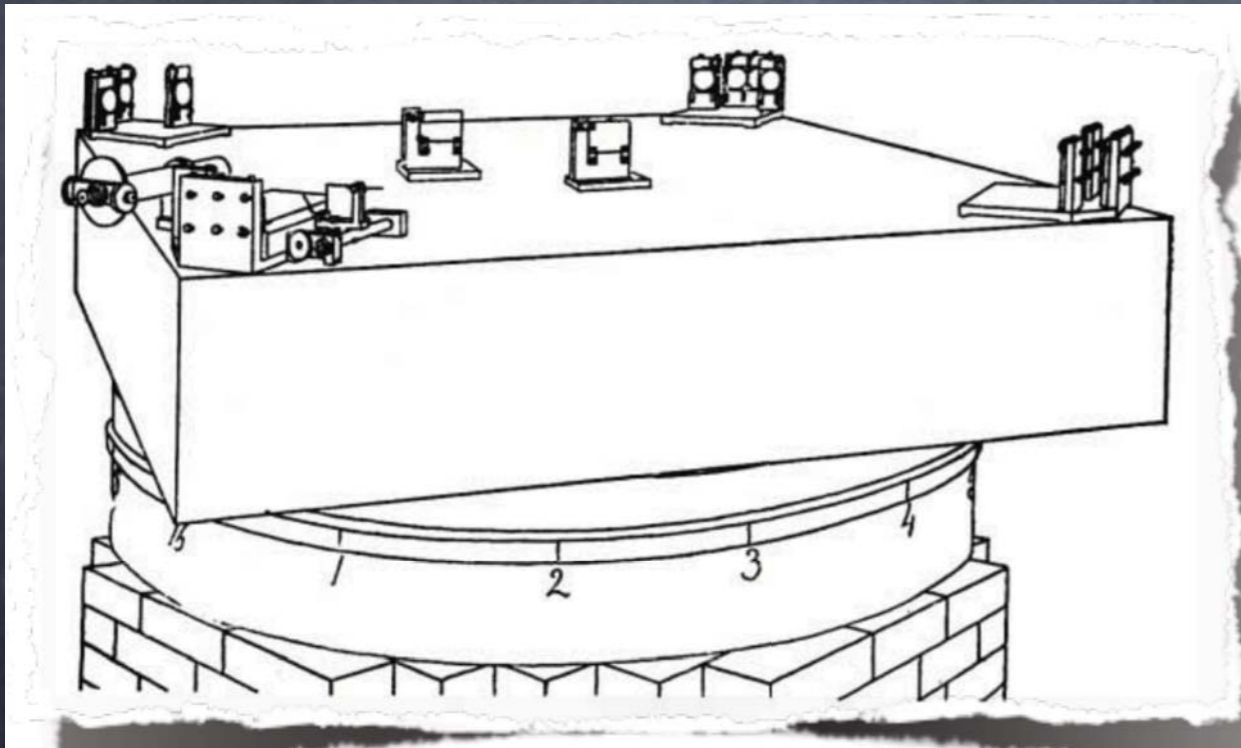
Ch. Eisele, A. Yu. Nevsky, and S. Schiller

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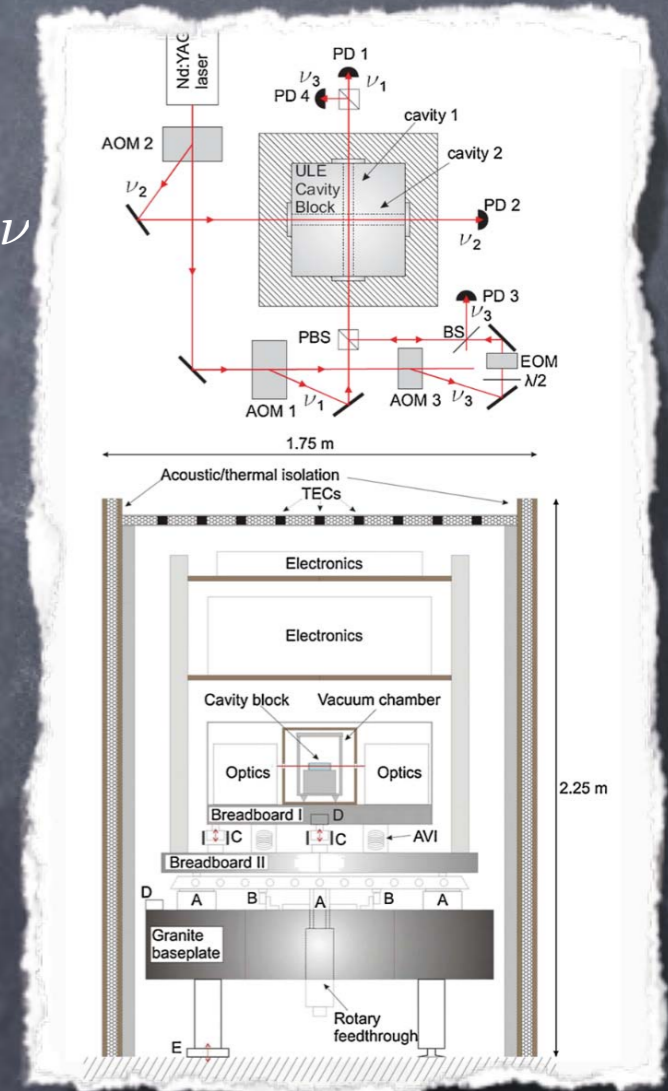
(Received 12 June 2008; revised manuscript received 7 August 2009; published 2 August 2009)

$$\mathcal{L} = -\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu}$$

$$-\frac{1}{4\mu_0} (k_F)_{\kappa\lambda\mu\nu} F^{\kappa\lambda} F^{\mu\nu}$$



A. A. Michelson & E. W. Morley, Am. J. Sci. XXXIV 333-345 (1887)



# Conclusions

- P: study weak interaction at low energies
- T, CPT, Lorentz: search for physics beyond SM
- Low-energy, precision measurements can do high-energy physics

Thank you for  
a great week!