

Нарушение четности в атомах и высокоточное определение констант электрослабого взаимодействия

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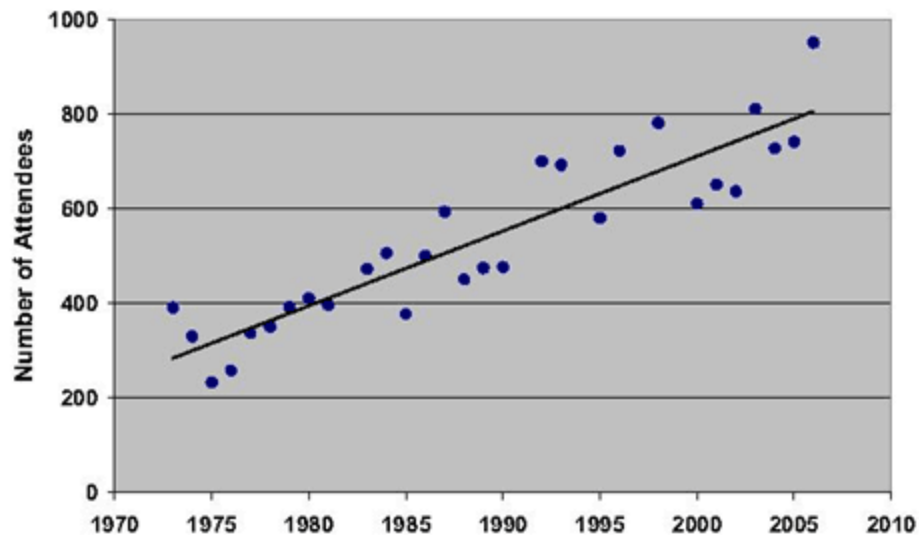
Физический факультет университета Невады, Рино, США

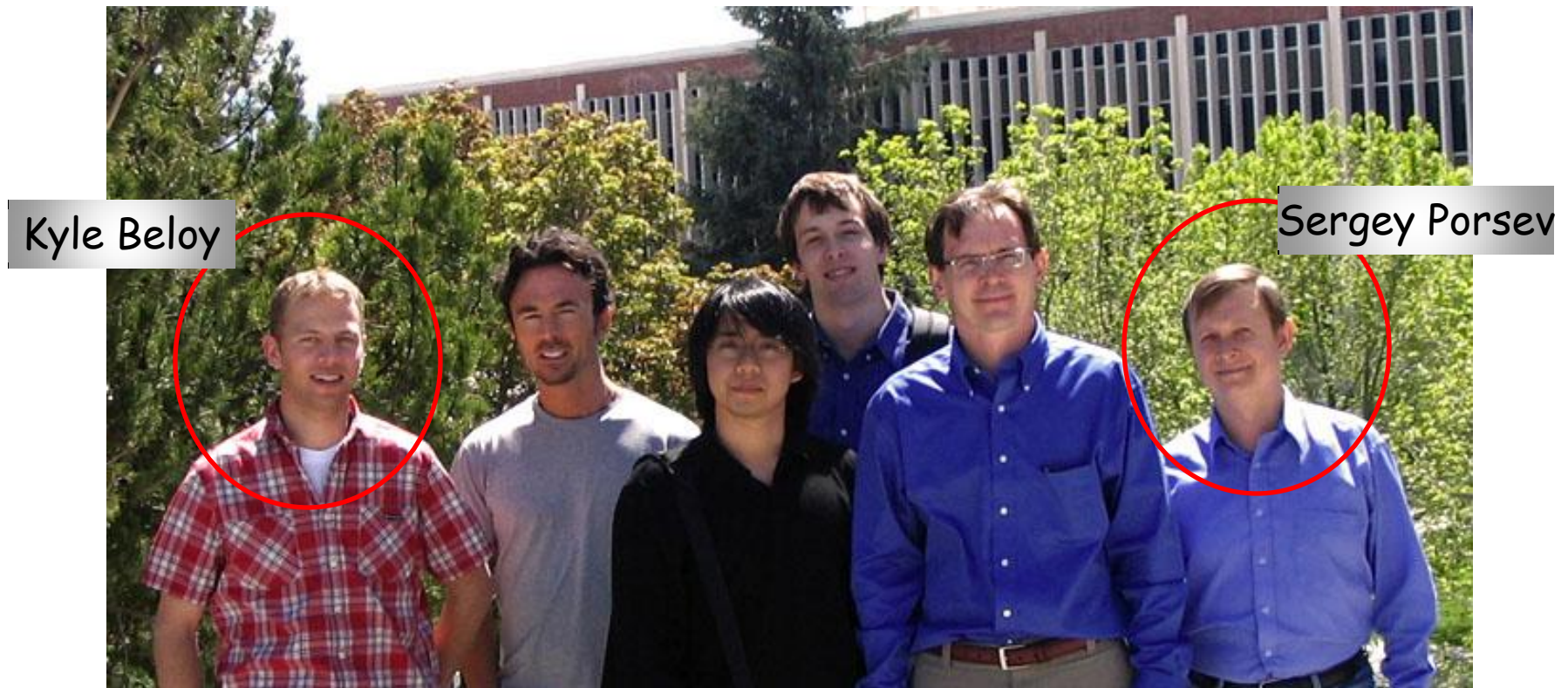
Atomic physics



3 Nobel prizes over the last 11 years (1997, 2001, 2005)

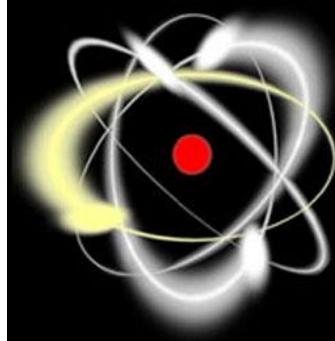
**Attendance of APS meetings
Division Of Atomic, Molecular And Optical Physics**





Reno theoretical atomic physics group
Also thanks to E. Emmons & C. Cannon (earlier efforts)

Listening to an atom

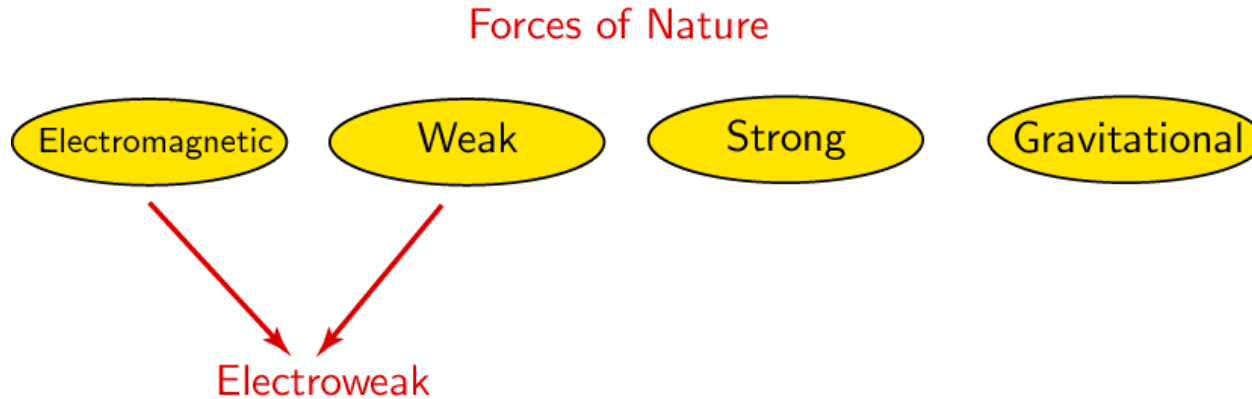


- ❑ Coulomb forces $\oplus$ Quantum Electro-Dynamics
 $\Rightarrow$ a relatively simple interpretation
- ❑ Unprecedented control over internal and external degrees of freedom
 $\Rightarrow$ precision 16-digit spectroscopy

429 228 004 229 873.65 (37) Hz

*Campbell et al.,
Metrologia 45 (2008)*

Standard Model and beyond

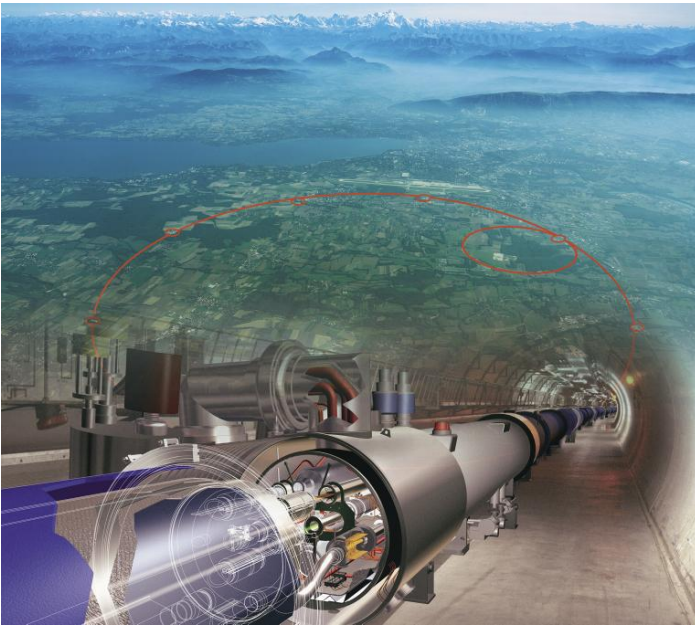


Standard Model = Electroweak + QCD (strong)

Extensions : GUT, Superstrings, SUSY, ...

Large Hadron Collider

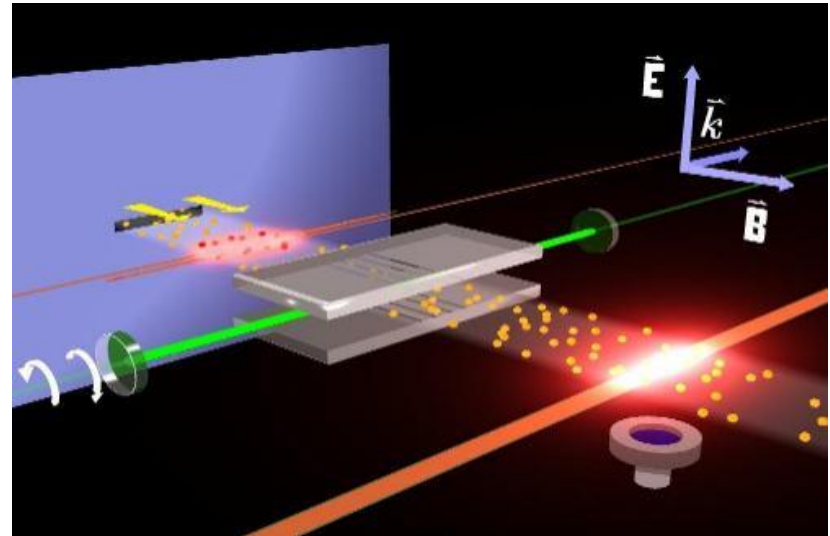
“The grandest scientific instrument ever built”



- ❑ 27 km (17 mile) long tunnel
- ❑ Straddles borders of Switzerland and France
- ❑ \$10 bln price tag

Atomic searches for new physics

*Table top experiment with ^{133}Cs atoms
on parity violation
Boulder (C. Wieman group)*

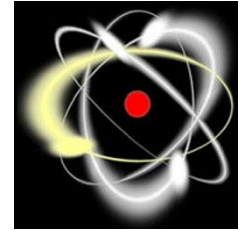


1 eV $\Rightarrow$ New physics constraints at 1 TeV mass scale

Atomic experiments are both unique and complementary to particle physics experiments



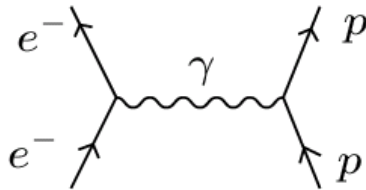
Atomic parity violation (APV)



Parity transformation: $\mathbf{r}_i \rightarrow -\mathbf{r}_i$

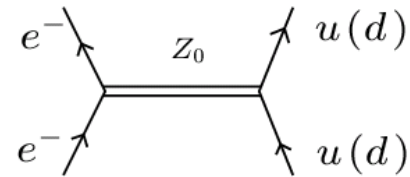
$[H_{\text{atomic}}, \mathbf{P}] = 0 \Rightarrow$ Atomic stationary states are eigenstates of Parity

Electromagnetic



Conserve parity

Electroweak



Do not conserve parity

Z-boson exchange spoils parity conservation

What is the strength of electroweak coupling of quarks and electrons?

Historical notes

- ⇒ Zel'dovich 1958: APV idea; optical activity; effect too small?
- ⇒ Realization that P-violation may be observable in heavy atoms (Bouchiat & Bouchiat 1974)
- ⇒ First observation: optical rotation in ^{209}Bi (Barkov & Zolotarev 1978)
- ⇒ Other observations: Tl, Pb, Cs atoms, Yb (2008)
- ⇒ Most accurate (0.35%) experiment in ^{133}Cs (Colorado 1997)

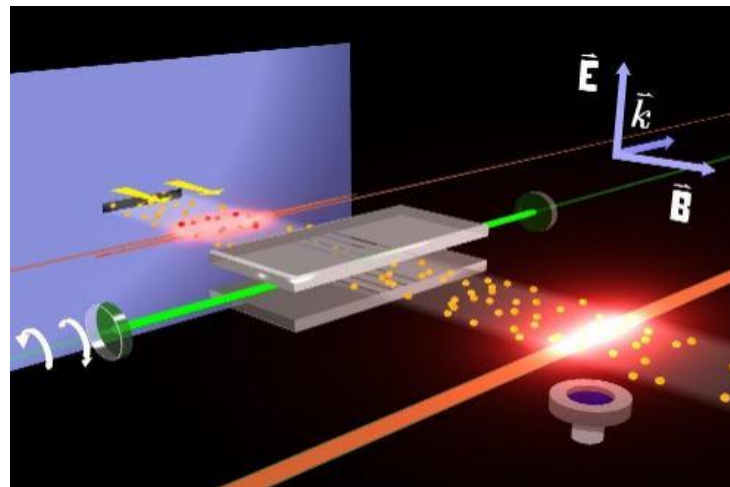
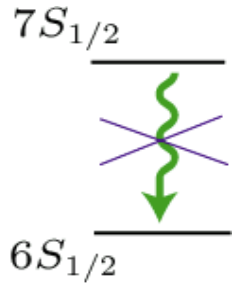


Table-top APV experiment using Stark-interference by Colorado group

Today: new result

The most accurate to-date probe of the
low-energy electroweak sector of
the Standard Model

Parity-violating 7S-6S amplitude in Cs

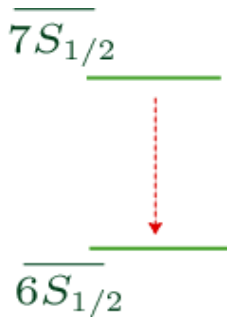


$$\langle 7S_{1/2} | D | 6S_{1/2} \rangle \equiv 0$$

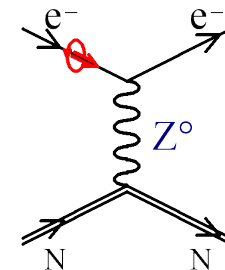
$$D = \sum_{i=1}^N -e \mathbf{r}_i$$

Electric-dipole transition is forbidden by the **parity** selection rules

Weak interaction leads to an admixture of states of opposite parity



$$E_{\text{PV}} = \langle \overline{7S_{1/2}} | D | \overline{6S_{1/2}} \rangle \neq 0$$



Tiny effect $E_{\text{PV}} \sim 10^{-11}$ atomic units

Weak charge extraction

$$H_W = Q_W \times \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r)$$

Weak charge

neutron distribution

$$E_{PV} = k_{PV} Q_W$$

measured

computed

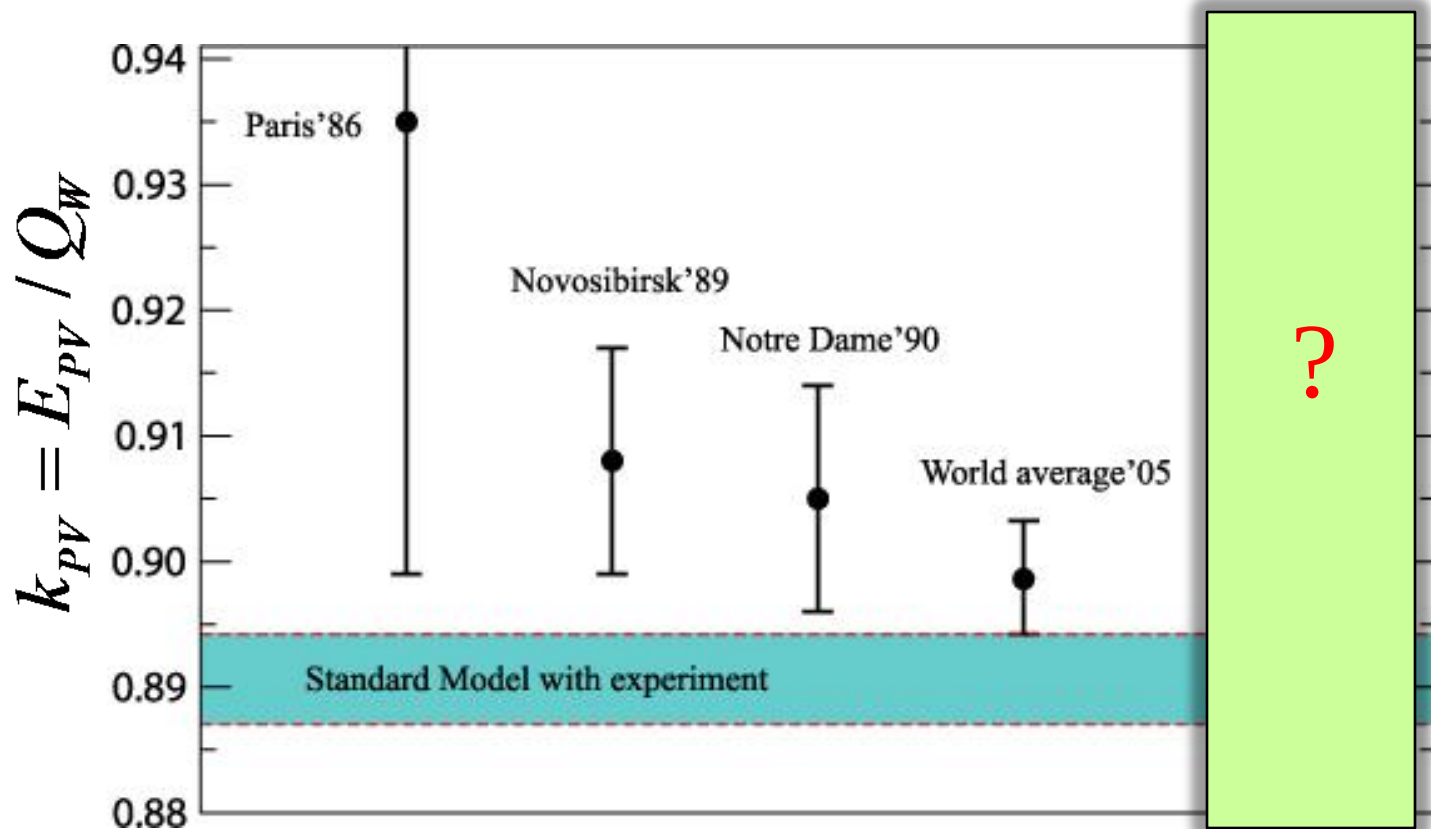
Signature of new physics:

$$Q_W^{\text{inferred}} = ? = Q_W^{\text{SM}}$$

Theoretical progress

$$E_{PV} = k_{PV} Q_W^{\text{inferred}}$$

measured $\nearrow$ k_{PV} $\nwarrow$ atomic-structure calculations



$$\sigma_Q = \sqrt{(\sigma_{\text{expt}})^2 + (\sigma_{\text{theor}})^2}$$
$$\sigma_{\text{expt}} = 0.35\% < \sigma_{\text{theor}} = 0.5\%$$

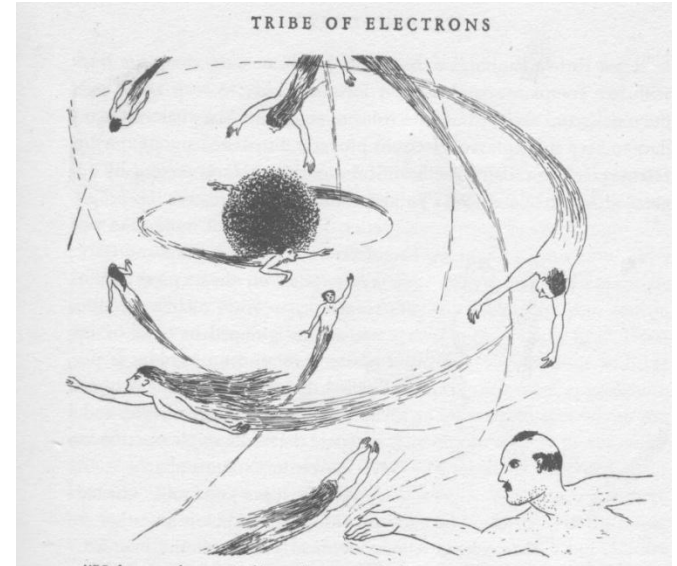
How to reduce σ ?

Theoretical uncertainty is limited by
an accuracy of solving
the basic correlation atomic-structure
problem

Why is it so difficult?

Cs atom: correlated motion of 55 electrons
55x3=165 coordinates
For a coarse 10-point grid per dimension

of points in Hilbert space 10^{165}



Exceeds estimated number of atoms in the Universe

Requirements to atomic-structure calculations

- Weak interaction occurs in the nucleus

$$\frac{v}{c} \sim \alpha Z \approx 0.5 \quad \text{for Cs}$$

Ab initio relativistic calculations based on **Dirac equation**

- Calculations should have **uncertainty better than 0.35%**

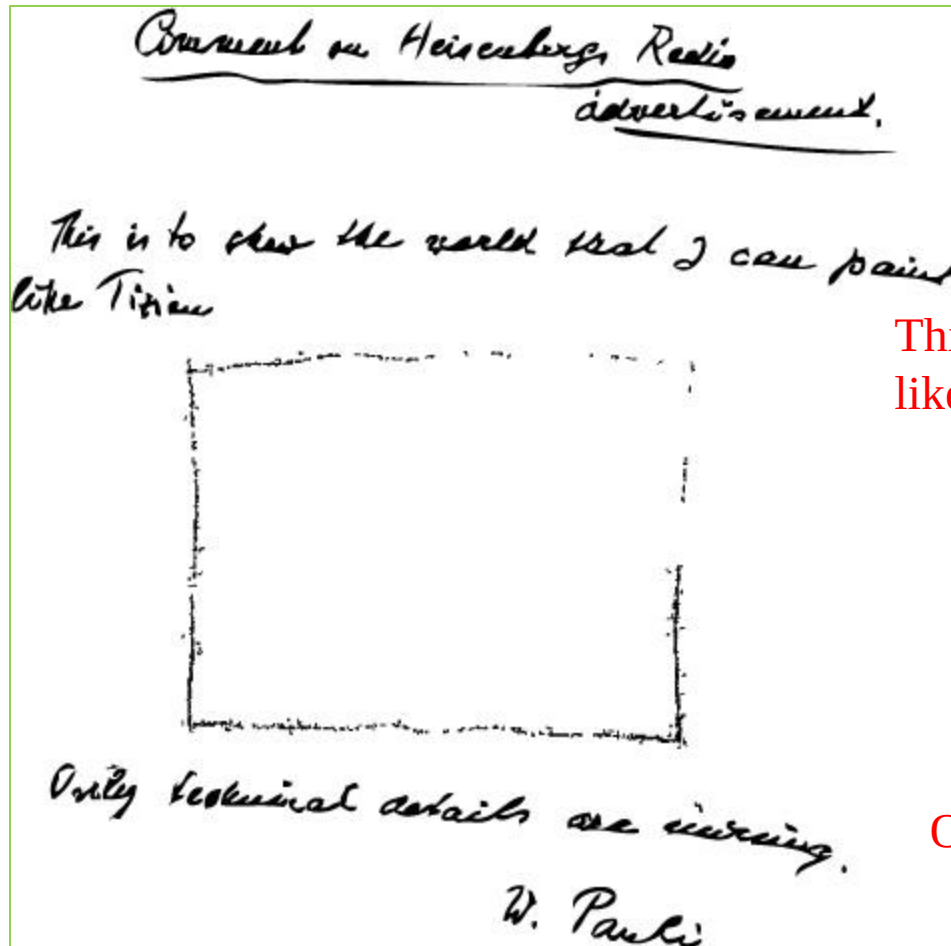
Hartree-Fock calculations are off by 50% for
important atomic properties

Many-body perturbation theory

Treat interaction beyond the Hartree-Fock as a perturbation

Technically difficult task: 100 Gb of storage, several weeks of CPU time

Pauli's letter



This is to show the world that I can paint like Titian

Only technical details are missing

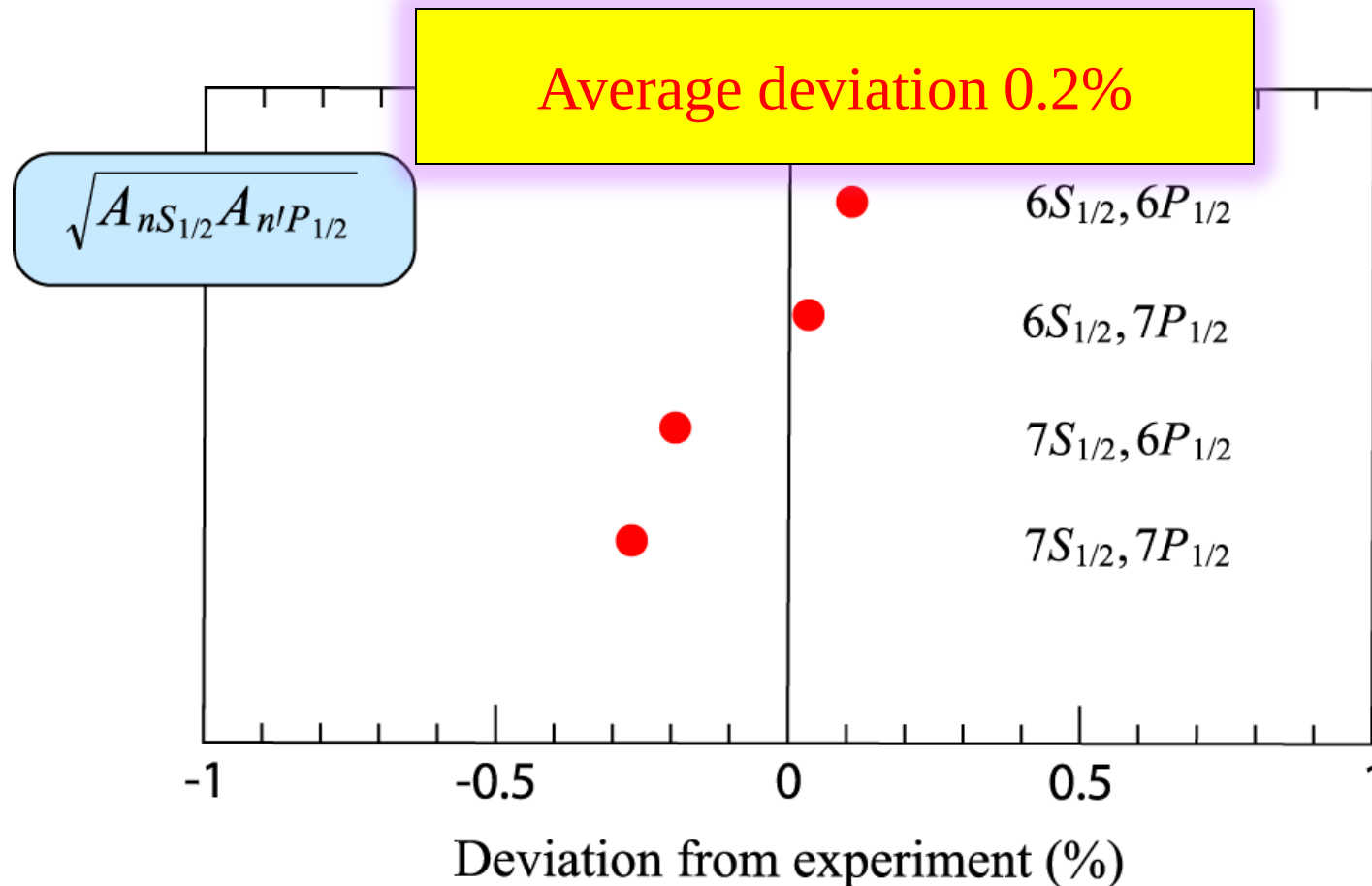
PV amplitude

$$E_{\text{PV}} = \sum_n \frac{\langle 7S_{1/2} | \textcolor{blue}{D} | nP_{1/2} \rangle \langle nP_{1/2} | \textcolor{red}{H}_W | 6S_{1/2} \rangle}{E_{6S} - E_{nP_{1/2}}} + \text{c.c.}(6S \leftrightarrow 7S)$$

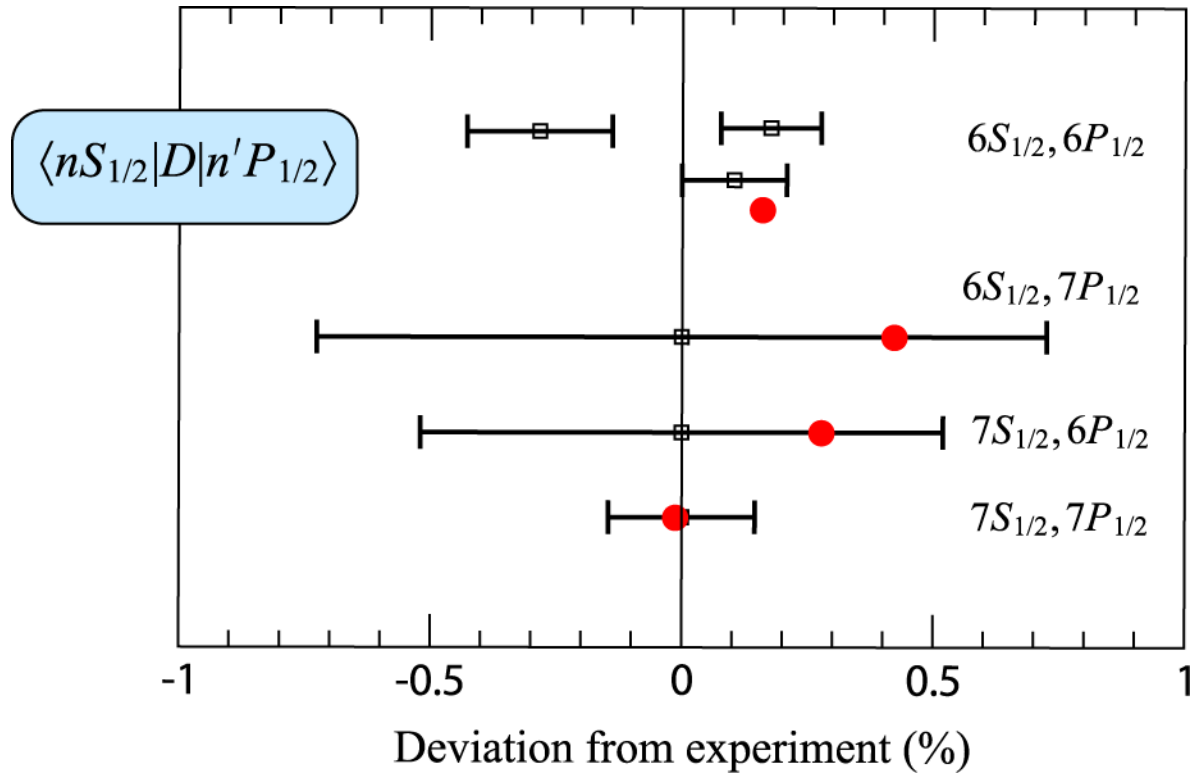
$$H_W = \textcolor{red}{Q}_W \times \frac{G_F}{\sqrt{8}} \gamma_5 \rho_n(r)$$

Accuracy is important

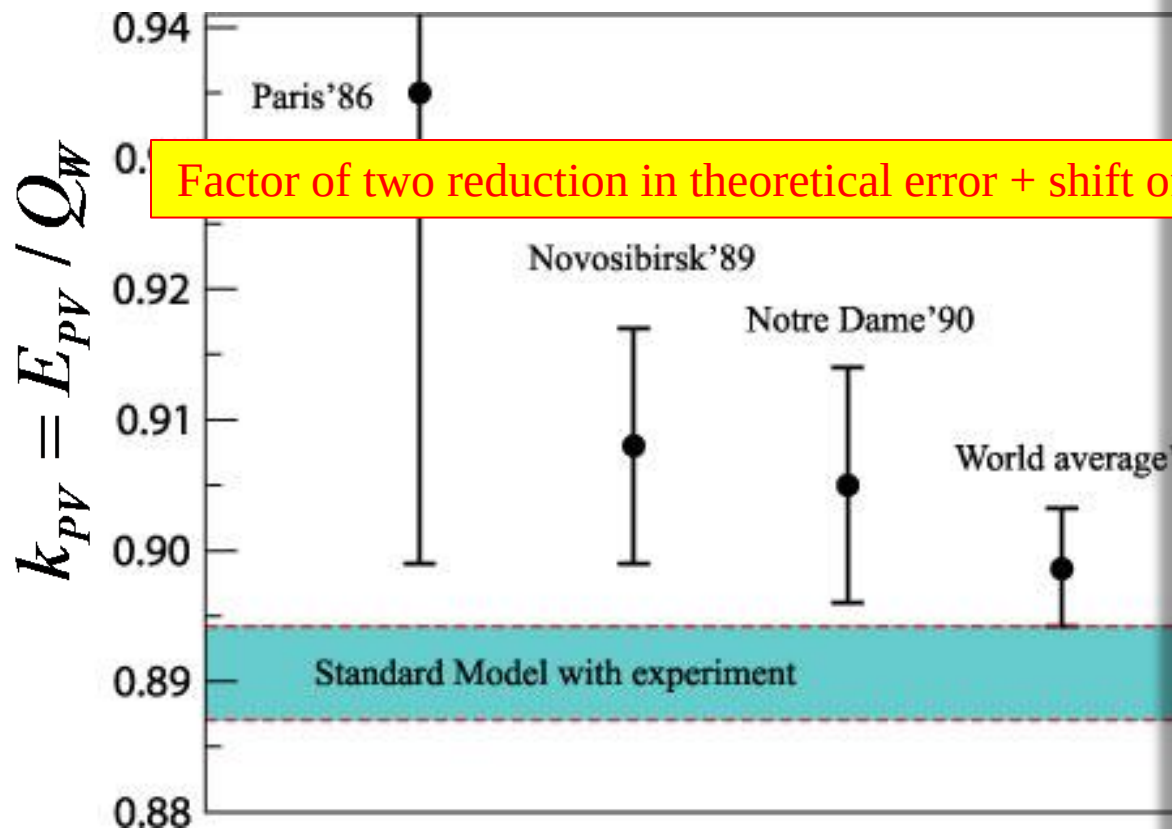
Theoretical accuracy: weak interaction



Theoretical accuracy: dipoles



Theoretical progress



Implications for particle physics

Weak charge of ^{133}Cs

$$\left. \begin{array}{l} \text{Atomic experiment} \\ \text{Atomic theory} \end{array} \right\} \begin{array}{l} E_{\text{PV}} \\ E_{\text{PV}} / Q_W \end{array} \Rightarrow Q_W^{\text{inferred}} = -73.16(29)_{\text{expt}} (20)_{\text{theor}}$$

Standard Model $Q_W^{\text{SM}} = -73.16(3)$

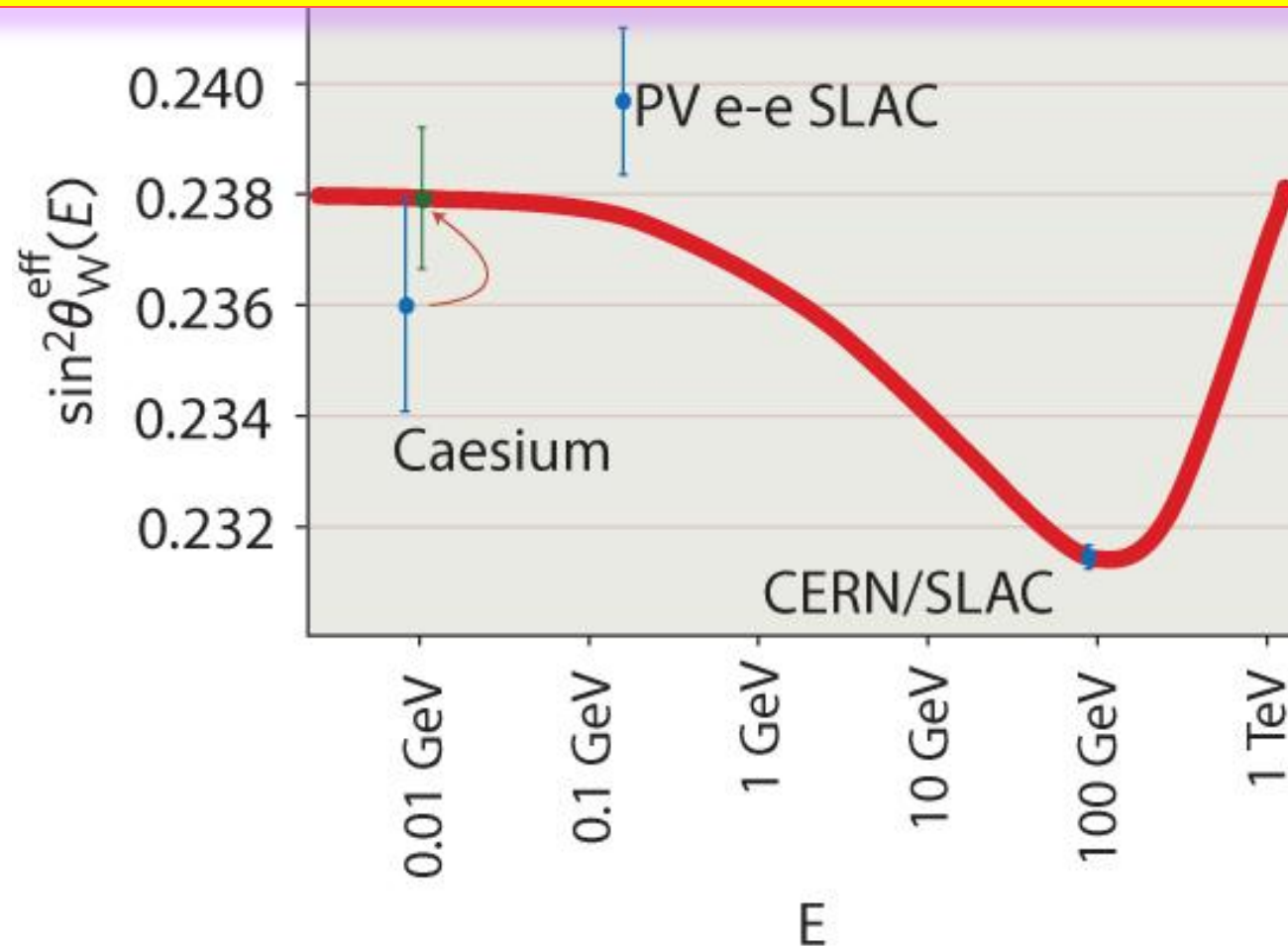
Perfect agreement with the Standard Model

Experiment: Wood *et al.* (1997); Bennett and Wieman (1999) (Boulder group)

Theory: S.G. Porsev, K. Beloy, A. Derevianko Phys. Rev. Lett. (2009)

Running of electroweak coupling

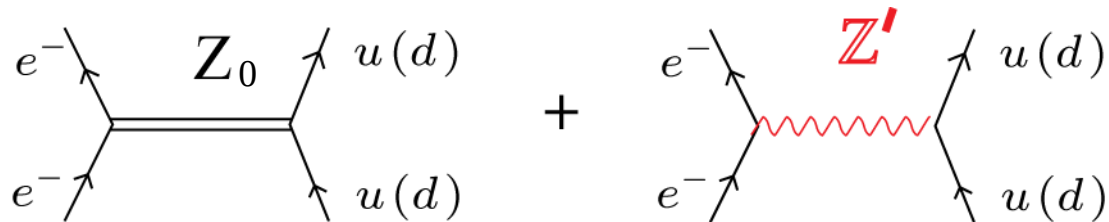
Running confirmed over energy span 10 MeV $\rightarrow$ 100 GeV



Adopted from Czarnecki & Marciano, Nature (2005)

extra Z bosons (Z')

- Copious in grand unified theories and string theories
- Potential carriers of the “fifth” force of Nature
- LHC: the cleanest signal of new physics



APV is uniquely sensitive to Z'

$$Q_W^{\text{inferred}} - Q_W^{\text{SM}} \approx \left(\frac{0.736 \text{ TeV} / c^2}{M_{Z'_\chi}} \right)^2$$

Marciano & Rosner

Implications: extra Z bosons (Z')

Specific example: Z'_χ in SO(10) GUT

$$Q_W^{\text{inferred}} - Q_W^{\text{SM}} \approx \left(\frac{0.736 \text{ TeV} / c^2}{M_{Z'_\chi}} \right)^2 \quad \text{Marciano \& Rosner}$$

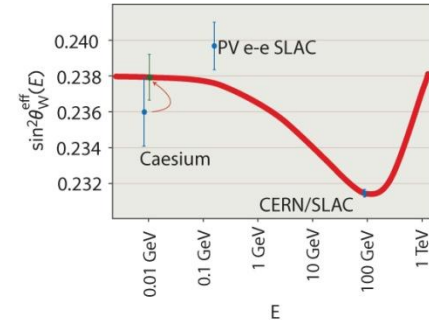
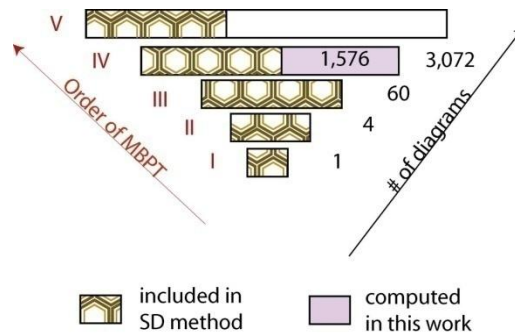
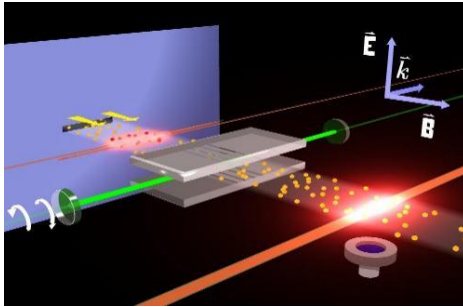
Our result implies: $M_{Z'_\chi} > 1.4 \text{ TeV}/c^2$

Direct search at Tevatron collider :

$$M_{Z'_\chi} > 0.82 \text{ TeV}/c^2$$

LHC discovery reach: 2 TeV initially; 5 TeV full luminosity

"New physics" summary



- ❑ Perfect agreement with the Standard Model
- ❑ Lower limit on mass of Z' is raised
- ❑ Running of electroweak coupling confirmed over energy span of four orders of magnitude
- ❑ Applications of developed codes: van der Waals interaction, atom-wall interaction, lifetimes, exotic nuclear moments, **atomic clocks** ...