Title: Testing QED with positronium state

Date: Aug 26, 2014 01:00 PM

URL: http://pirsa.org/14080038

Abstract: The theory of quantum electrodynamics is recognized for the most accurate predictions in physics confirmed by experiment. I review the recent results on high precision tests of QED with an emphasize on the study of the positronium bound state.

QED in a nutshell

$$\overline{\Psi}\left(i\gamma^{\mu}D_{\mu} - m_e\right)\Psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

How accurate is QED?

- Fine structure constant ❶
  - *Rydberg constant from hydrogen/deuterium spectrum*

    $$R_\infty = \frac{\alpha^2 m_e c}{4\pi\hbar}$$
  - *electron/rubidium mass ratio from cyclotron frequency*

    $$\frac{m_e}{m_{Rb}} = \frac{\omega_{Rb}}{\omega_e}$$
  - *rubidium mass/Planck constant ratio from recoil*

    $$v_{rec} = \frac{\hbar k}{m_{Rb}}$$

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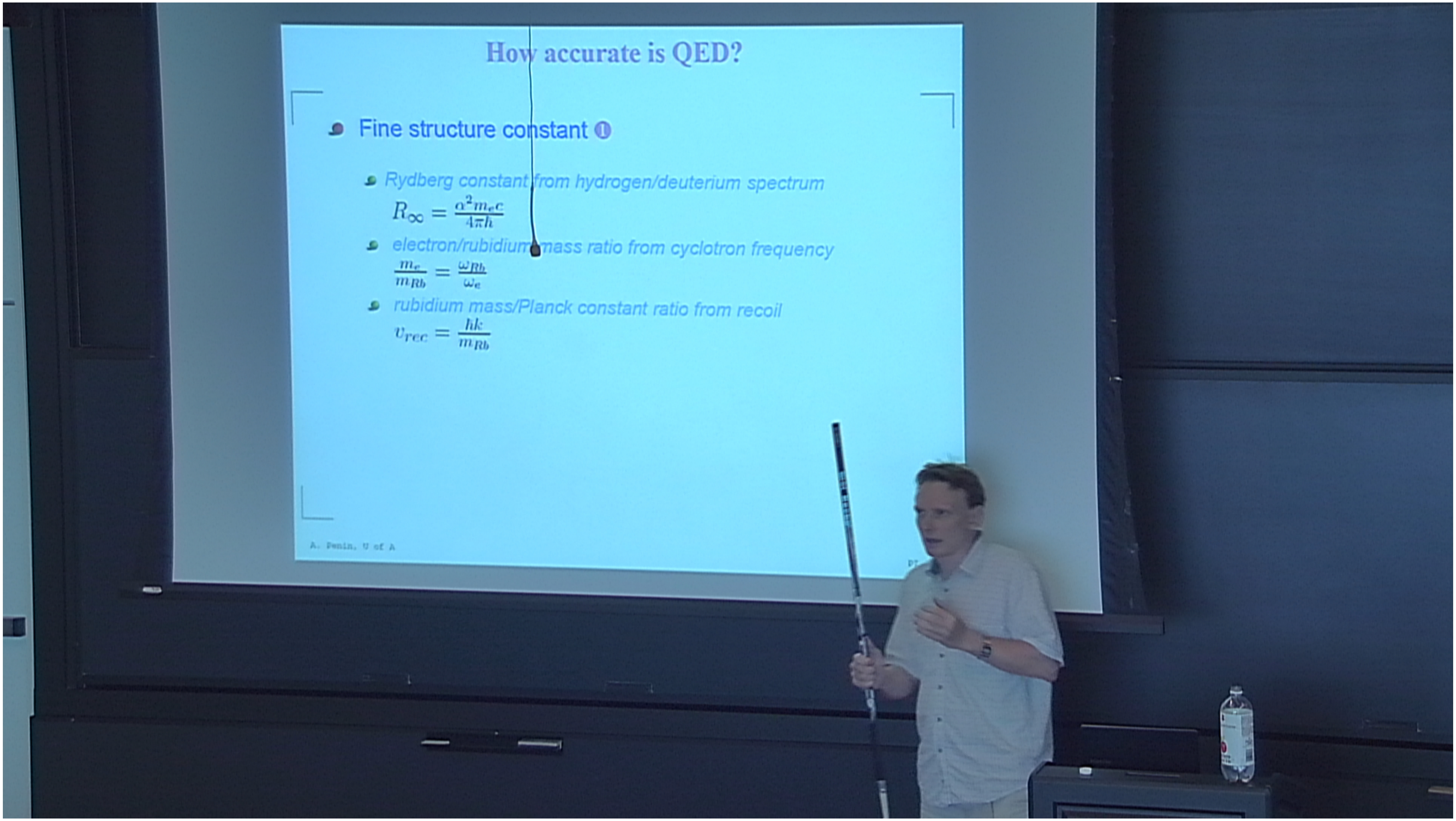
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A. Penin, U of A

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- Fine structure constant ❷
  - *electron anomalous magnetic moment* $(\bar{\mu} = \frac{ge}{2m_e c}\bar{s})$
    $$\frac{g}{2} = 1 + \frac{\alpha}{2\pi} + \dots$$
  - *geonium spectrum*
    $$\frac{g}{2} = \frac{\omega_s}{\omega_c}$$

How accurate is QED?

- Most precise prediction/measurement
  - *Fine structure constant (hydrogen spectrum, Rb recoil)*

    $$\alpha^{-1} = 137.03599905(9)$$

    R. Bouchendira, P Clade, S. Guellati-Khelifa, F. Nez, and F. Biraben (2011)
  - *Fine structure constant (Electron $g-2$, geonium spectrum)*

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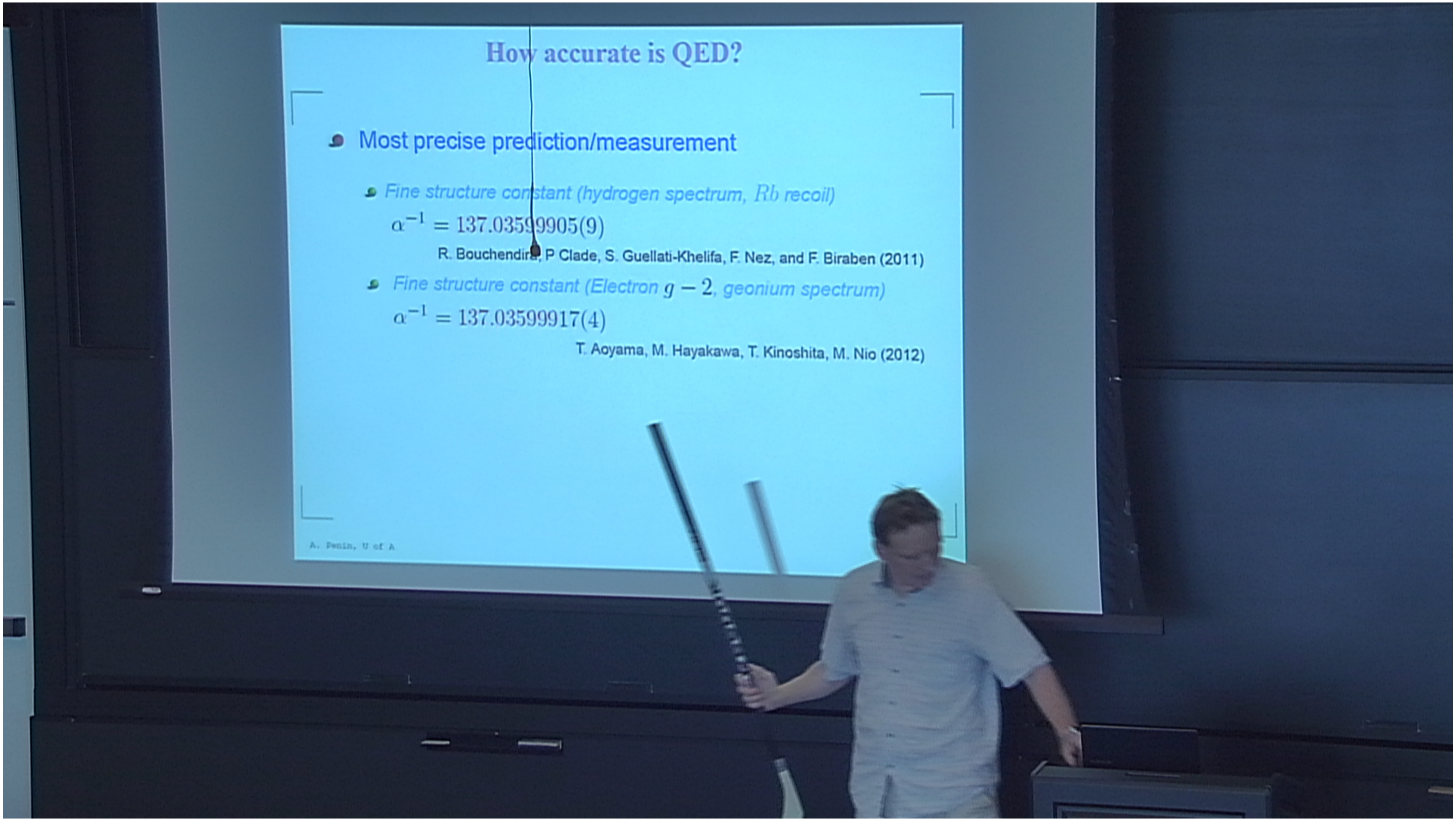
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- Biggest problem so far
  - $\sim 7\sigma$ *mismatch of proton charge radius (hydrogen vs muon hydrogen Lamb shift)*

Positronium bound state

- Basic facts
  - *pure QED system*
  - *"ortho" and "para" spin states*
  - *decays:* p-Ps $\rightarrow 2n\gamma$, o-Ps $\rightarrow (2n+1)\gamma$
  - *best observables: width* Γ_o, *hyperfine splitting* $\Delta\nu = E_o - E_p$
  - *QED prediction:* $\mathcal{O}(\alpha^3 \ln(\alpha))$

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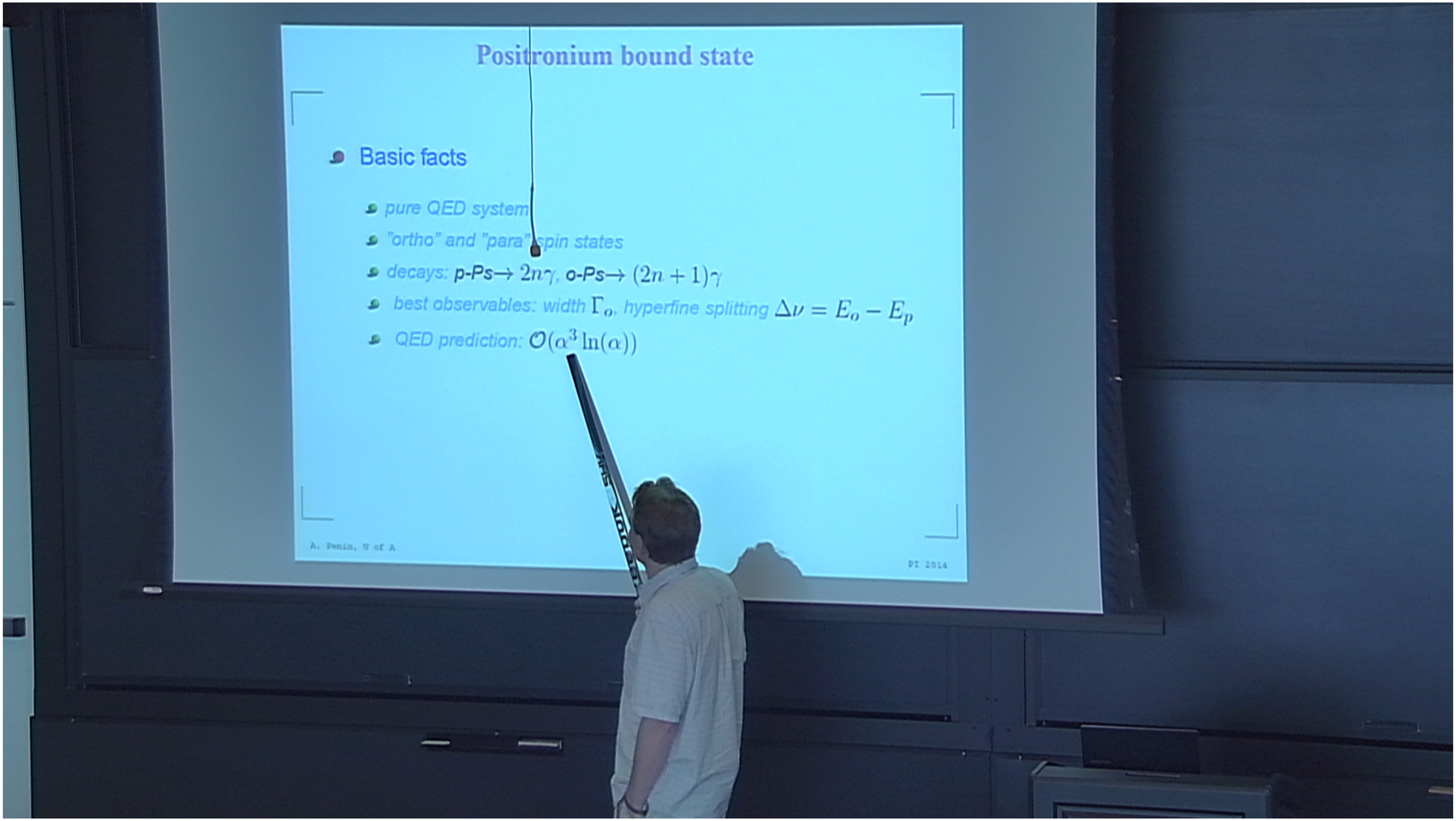
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  - *QED prediction:* $\mathcal{O}(\alpha^3 \ln(\alpha))$
- Why interesting?
  - o-Ps *mixes with an off-shell photon at Born level*

  ↪ *sensitive to exotic new physics*

Positronium bound state

- Large extra dimensions

S.Gninenko, N.Krasnikov, A. Rubbia (2003)

  - *modified gravitational potential* $V(r) = -G\frac{m_1 m_2}{r}\left(1 + \frac{1}{k^2 r^2}\right)$
  - *effect on decay width* $\delta\Gamma_o \sim \frac{1}{\alpha^2}\frac{m_e}{k}\Gamma_o$

- Mixing of “normal” photon with “dark” or “mirror” photon

Glashow (1986)

  - *kinetic mixing* $\epsilon F^{\mu\nu} F_{\mu\nu}$
  - *effect on HFS* $\delta\Delta\nu \sim \epsilon\Delta\nu$

Positronium bound state

- "Puzzles"
  - $\sim 5\sigma$ *mismatch of QED and experiment on* Γ_o
  - $\sim 2.5\sigma$ *mismatch of QED and experiment on* $\Delta\nu$

Orthopositronium life time measurements

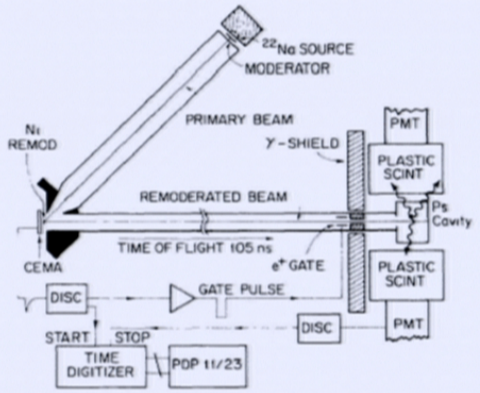
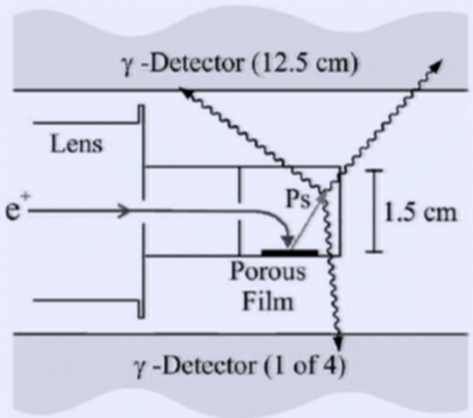


FIG. 1. Time-tagged and gated slow positron beam used to measure the orthopositronium decay rate.

Ann Arbor experiment 1990



Ann Arbor experiment 2003

Positronium bound state

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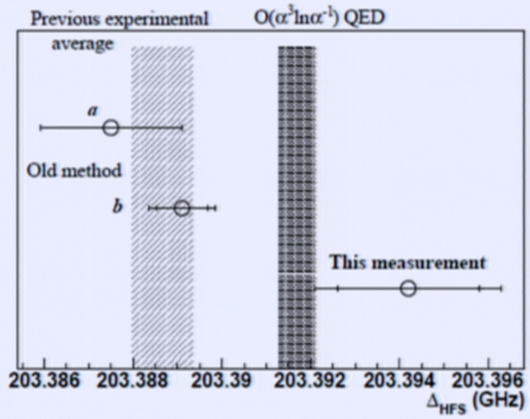
    RESOLVED
  - $\sim 2.5\sigma$ *mismatch of QED and experiment on* $\Delta\nu$

Positronium HFS



Experiment

$\Delta\nu^{\rm exp} = 203.387\,5(16)$ GHz A. P. Mills, Jr., *et al.* Phys. Rev. Lett. **34**, 246 (1975)

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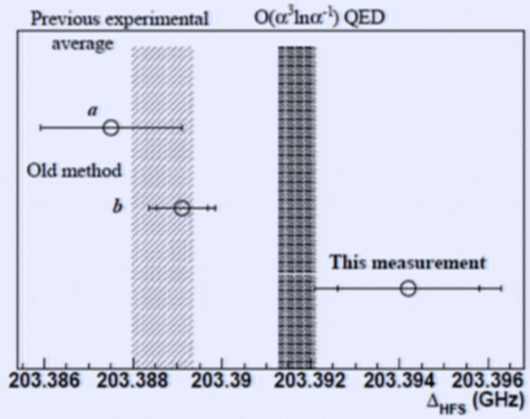

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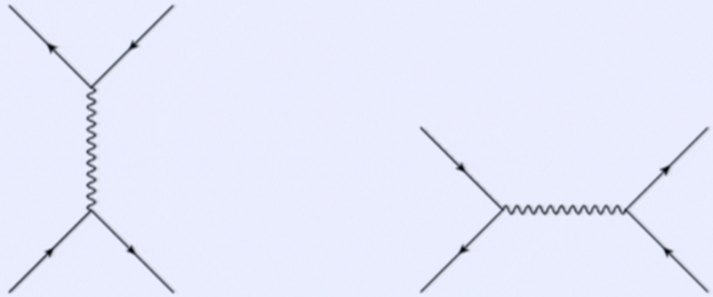
Basic theory

- Born/Breit spin-dependent interaction

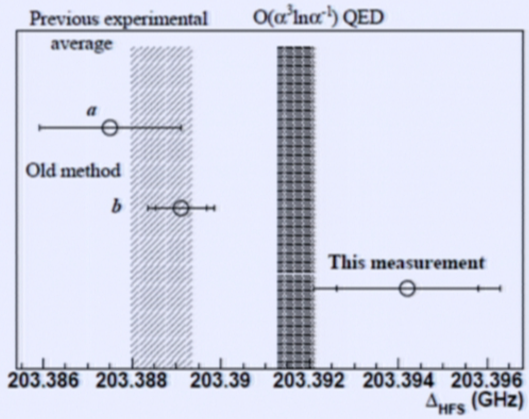


$$\delta_{hfs}\mathcal{H} = \left(\left[\frac{4}{3}\right]_{sct} + [1]_{ann}\right)\frac{\pi\alpha}{m_e^2}\delta(\boldsymbol{r})\boldsymbol{S}^2\,,$$

- Leading order HFS

$$\Delta\nu^{LO} = \left(\left[\frac{1}{3}\right]_{sct} + \left[\frac{1}{4}\right]_{ann}\right)\alpha^4 m_e$$

Positronium HFS



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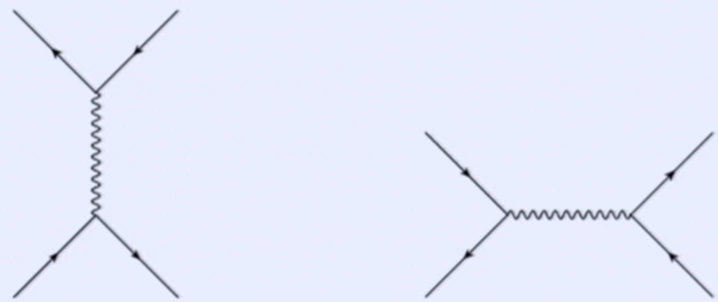

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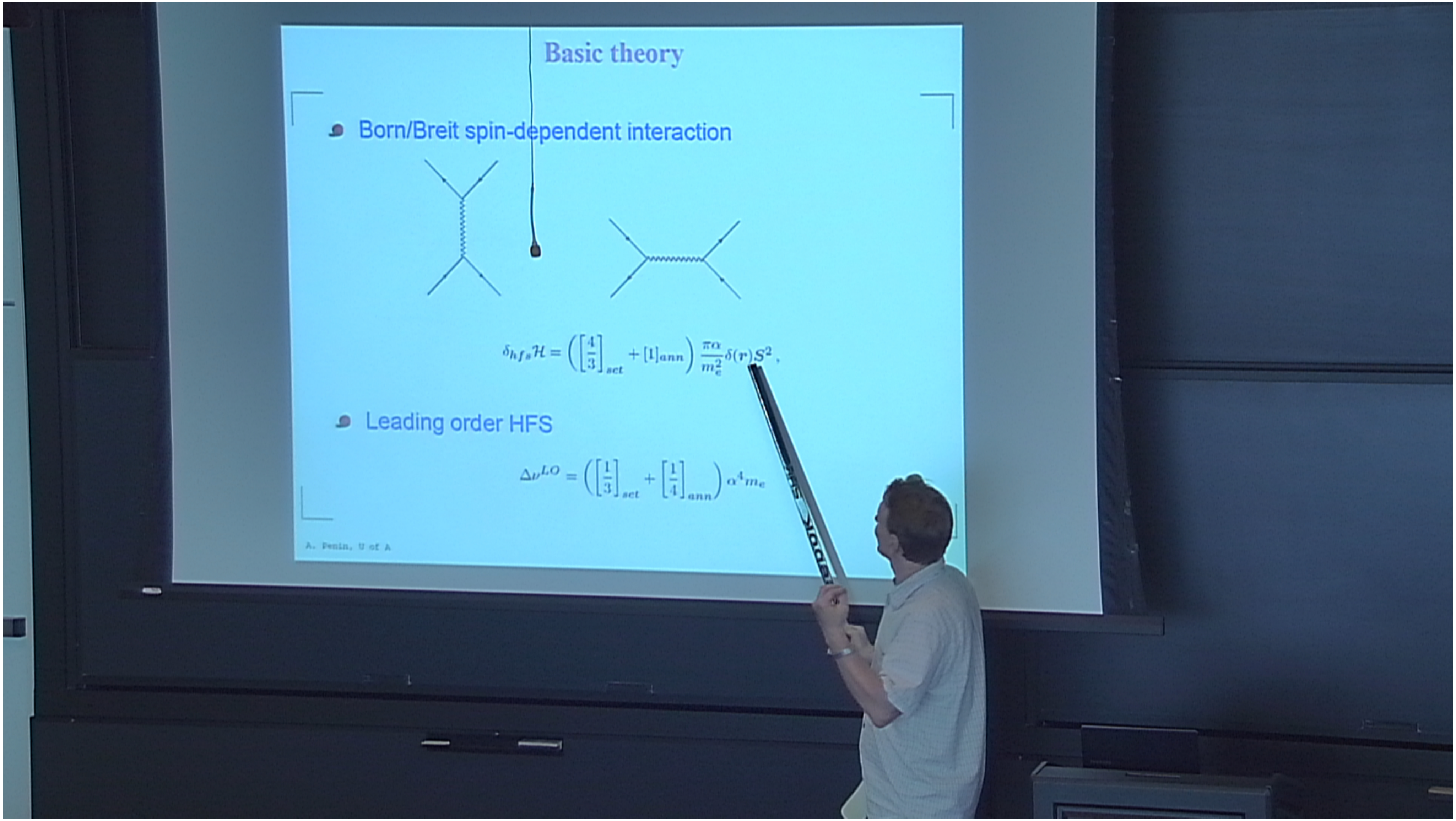
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QED corrections

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QED corrections

$$\Delta\nu^{\rm th} = \Delta\nu^{LO}\left\{1 - \frac{\alpha}{\pi}\left(\frac{32}{21} + \frac{6}{7}\ln 2\right) - \right.$$
$$+ \left(\frac{\alpha}{\pi}\right)^2\left[-\frac{5}{14}\pi^2\ln\alpha + \frac{1367}{378} - \frac{5197}{2016}\pi^2 + \left(\frac{6}{7} + \frac{221}{84}\pi^2\right)\ln 2 - \frac{159}{56}\zeta(3)\right]$$
$$\left. + \left(\frac{\alpha}{\pi}\right)^3\left[-\frac{3}{2}\pi^2\ln^2\alpha + \left(-\frac{62}{15} + \frac{68}{7}\ln 2\right)\pi^2\ln\alpha + D\right]\right\},$$

- Anatomy of $\mathcal{O}(\alpha^2)$ nonlogarithmic term
  - *47% scattering contribution*
  - *32% one-photon annihilation contribution*
- This work
  - *one-photon annihilation contribution to* D

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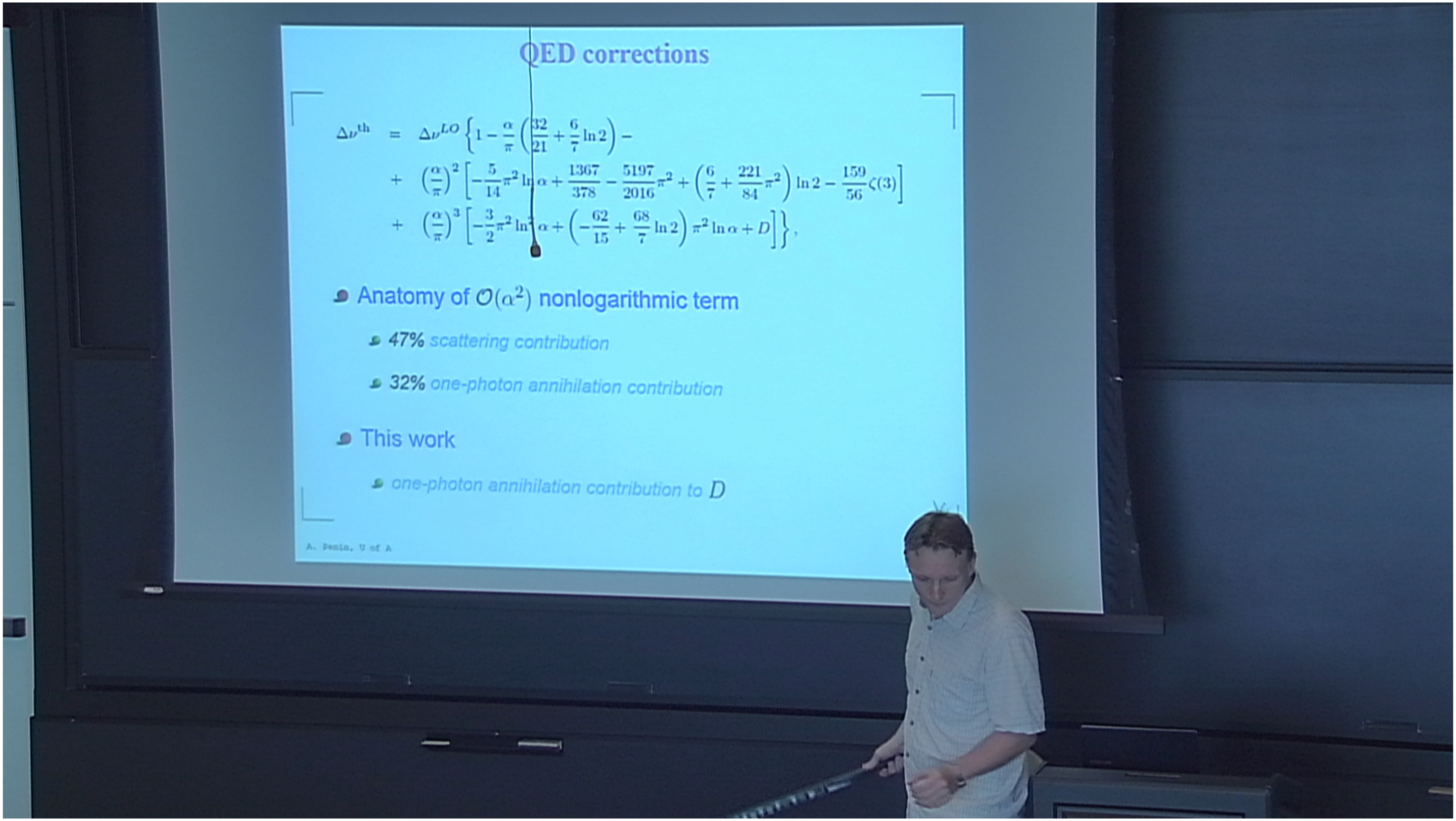
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Formula of success

pNRQED + Dim.Reg. = $\mathcal{O}(\alpha^7 m_e)$

Nonrelativistic effective theory

- Multiscale problem:
  - *hard* m_e
  - *soft* vm_e
  - *ultrasoft* v^2m_e
- Coulombic bound state
  ↪ Schrödinger equation
- How to derive Schrödinger equation from QED?
  ↪ pNRQED

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- How to derive Schrödinger equation from QED?
  ↪ pNRQED

QED → NQED → pNRQED (Caswell, Lepage; Pineda, Soto)

$$\overline{\Psi}\left(i\gamma^\mu D_\mu - m_e\right)\Psi$$

↓ hard modes integrated out

$$\psi^\dagger\left(iD_0 + \frac{\boldsymbol{D}^2}{2m_e}\right)\psi + \frac{1}{8m_e^3}\psi^\dagger\boldsymbol{D}^4\psi - \frac{c_F\, e}{2m_e}\psi^\dagger\boldsymbol{\sigma}\cdot\boldsymbol{B}\psi + \ldots$$

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Loops in the Effective Theory

- How to separate the regions of virtual momenta?

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↪ **Regions are separated in dimensional regularization!**

- Effective theory in dimensional regularization
  (Pineda, Soto; Czarnecki, Melnikov, Yelkhovsky; Beneke, Signer, Smirnov; Kniehl, Penin, Smirnov, Steinhauser)
  - *no new scales*
  - *gauge, Lorenz invariance*
  - *“build-in” matching*

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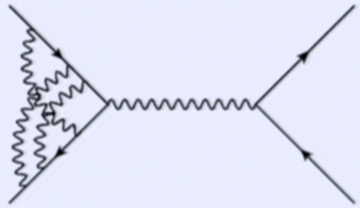
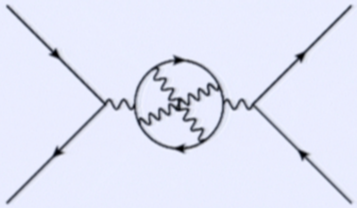
Structure of the corrections to HFS



irreducible



reducible

- Master formula

$$\Delta^{1-\gamma}_{ann}\nu = \frac{\alpha^4 m_e}{4}\frac{R_o}{1+P_o}.$$

Irreducible contribution

- Vacuum polarization at the bound state pole

$$\lim_{E\to E_o} \Pi(q^2) = \frac{\alpha}{4\pi} \frac{R_o}{E/E_o - 1 - i\varepsilon},$$

- Effective theory decomposition

$$R_o = \left(c_v - \frac{E_o}{m_e}\frac{d_v}{6} + \ldots\right)^2 \left(1 + \frac{E_o}{2m_e}\right)^{-2} \frac{|\psi_o(0)|^2}{|\psi^C(0)|^2}$$

- Positronium wave function

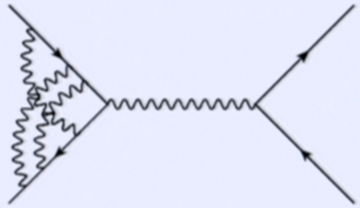
$$\left(-\frac{\boldsymbol{\partial}^2}{m_e} - \frac{\alpha}{|\boldsymbol{r}|} + \delta\mathcal{H} - E\right)\psi_o(\boldsymbol{r}) = 0$$

  - *subject to ultrasoft corrections*

Irreducible contribution

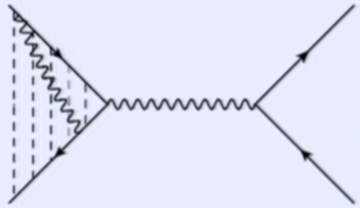
- Bottlenecks:
  - *three-loop hard vertex correction*

P. Marquard, J. Piclum, D. Seidel and M. Steinhauser, Phys. Rev. D **89**, 034027 (2014)



  - *ultrasoft corrections*

M. Beneke, Y. Kiyo and A. A. Penin, Phys. Lett. B **653**, 53 (2007)



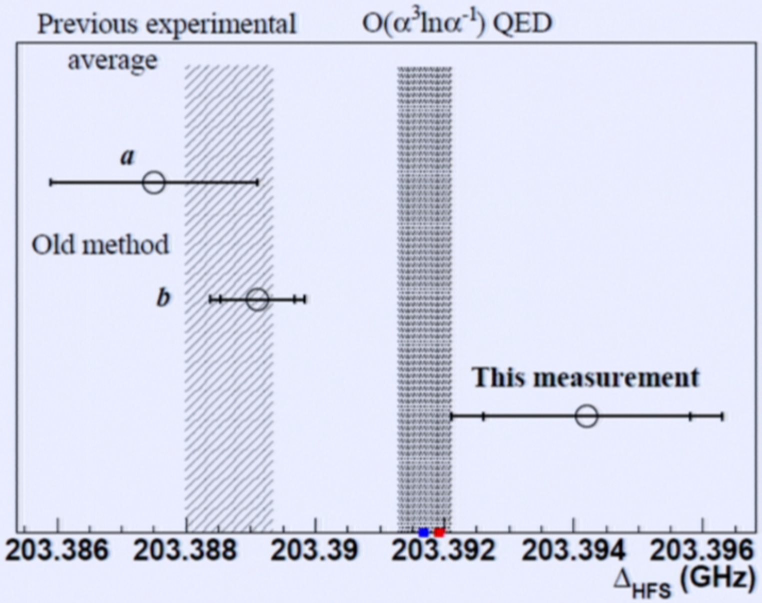
Final result

$$D_{ann}^{1-\gamma} = \frac{3}{7}\left[-\frac{49309}{1458} + \left(\frac{16573}{3240} - \frac{65}{9}\ln 2 + \delta_o^{us}\right)\pi^2 - \frac{221}{18}\zeta(3) - \frac{109}{864}\pi^4 + 2c_{v\,0}^{(3)} - p_{h\,0}^{(3)}\right] = 84.8 \pm 0.5$$

- Structure of the corrections $\mathcal{O}(m_e\alpha^7)$
  - *Bethe logarithm* δ_o^{us} *gives* $D_{ann}^{1-\gamma} \approx 80$
  - *scattering contribution estimate* $D_{sct} \approx \frac{4\pi^2}{7}\delta_o^{us} \approx 106$
  - *relativistic contributions (electron* $g-2$*, electron loops):* $D \sim 1$

G. Adkins, R. Fell; M. Eides, V. Shelyuto

Final result



$$\Delta^{1-\gamma}_{ann}\nu = 217 \pm 1\ \text{kHz}$$

Summary

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  - *first result of "full complexity" is now available*
  - *favors one the conflicting experiments*
- QED is doing rather well so far
- Full $\mathcal{O}(m_e\alpha^7)$ result and more accurate measurements are crucial to give QED a hard time

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- *Positronium could be an alternative gate to a BSM physics in the era of the total SM success at the LHC*