# QED tests and searches for new physics with positronium decays

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Ortho-positronium and Para-positronium systems

QED bound states of an electron and a positron

Decays dominated by QED processes

Rare and exotic decays - evidence for anything else ?
- searching for extra forces

Constraints from other processes: QED and Standard Model work very well !

Krakow, September 12, 2018

# QED as precision science

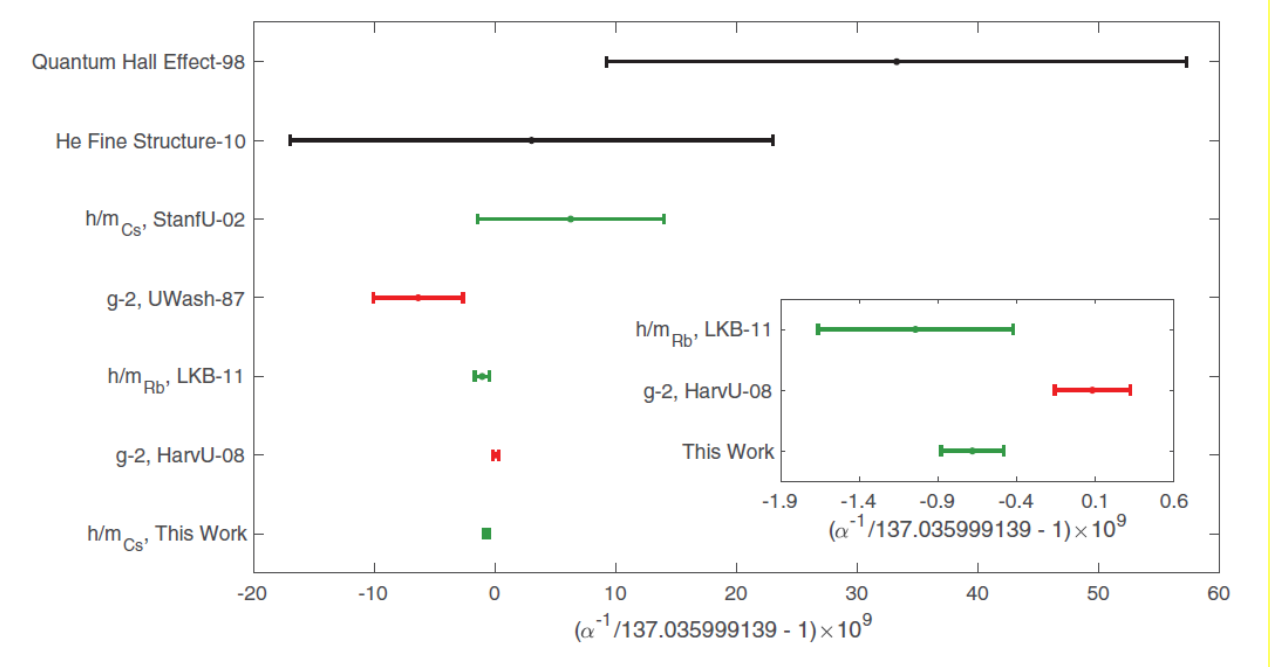
- Measuring the fine structure constant alpha

$$a_e^{\mathrm{exp}} = 0.001159652180 73(28)$$

  - Indirect through electron magnetic moment, g-2

[D Hanneke, et al PRL 100 (2018) 120801]

  - Direct in atom interferometry and Quantum Hall Effect




- Electron EDM

[RH Parker et al, Science 360 (2018) 191]

# QED as precision science

- Electron $a_e = (g-2)/2$

$$a_e^{\mathrm{exp}} = 0.00115965218073(28)$$

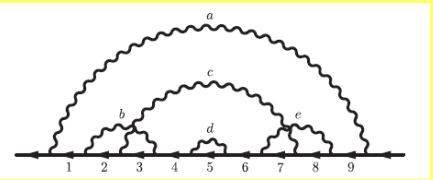
PHYSICAL REVIEW D **97,** 036001 (2018)

**Revised and improved value of the QED tenth-order electron anomalous magnetic moment**

Tatsumi Aoyama,[1,2] Toichiro Kinoshita,[3,4] and Makiko Nio[2]

  - Calculated up to 5-loop Feynman diagrams

$$a_e^{\mathrm{QED}} = \frac{\alpha}{2\pi} - 0.328478965579293\ldots\left(\frac{\alpha}{\pi}\right)^2 + 1.181241456587\ldots\left(\frac{\alpha}{\pi}\right)^3 - 1.912245764\ldots\left(\frac{\alpha}{\pi}\right)^4 + 6.675(192)\left(\frac{\alpha}{\pi}\right)^5$$




$$a_e^{\mathrm{SM}} = a_e^{\mathrm{QED}} + 0.03053(23) \times 10^{-12}\ (\mathrm{weak}) + 1.6927(120) \times 10^{-12}\ (\mathrm{hadronic})$$

- Other measurements of alpha

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\mathrm{At}}}{m_{\mathrm{e}}}\frac{h}{m_{\mathrm{At}}}$$

  - Atomic physics, measurements of atomic masses and Rydberg constant

# QED as precision science

- Suppose we take seriously the „discrepancy"

$$a_e^{\rm exp} - a_e^{th}|_{Cs} = (-88 \pm 36) \times 10^{-14}$$

- Interpret in terms of new heavy exchanges

$$|\Delta a_e^{\rm NewPhysics}| \approx m_e^2 \ / \ \Lambda^2$$

$\Lambda$ bigger than $\sim 500$ GeV

- Or very light exchanges

$$|\Delta a_e^{\rm NewPhysics}| \approx \frac{1}{16\pi^2} g_X^2$$

$m_X^2 \ll m_e^2$

$g_X^2/4\pi$ is about $1.1 \times 10^{-11}$

- Electron EDM constraint

$$|d_e| < 8.7 \times 10^{-29} e\,\text{cm}$$

$\Lambda > 1 - 3 \ TeV$

# QED as precision science

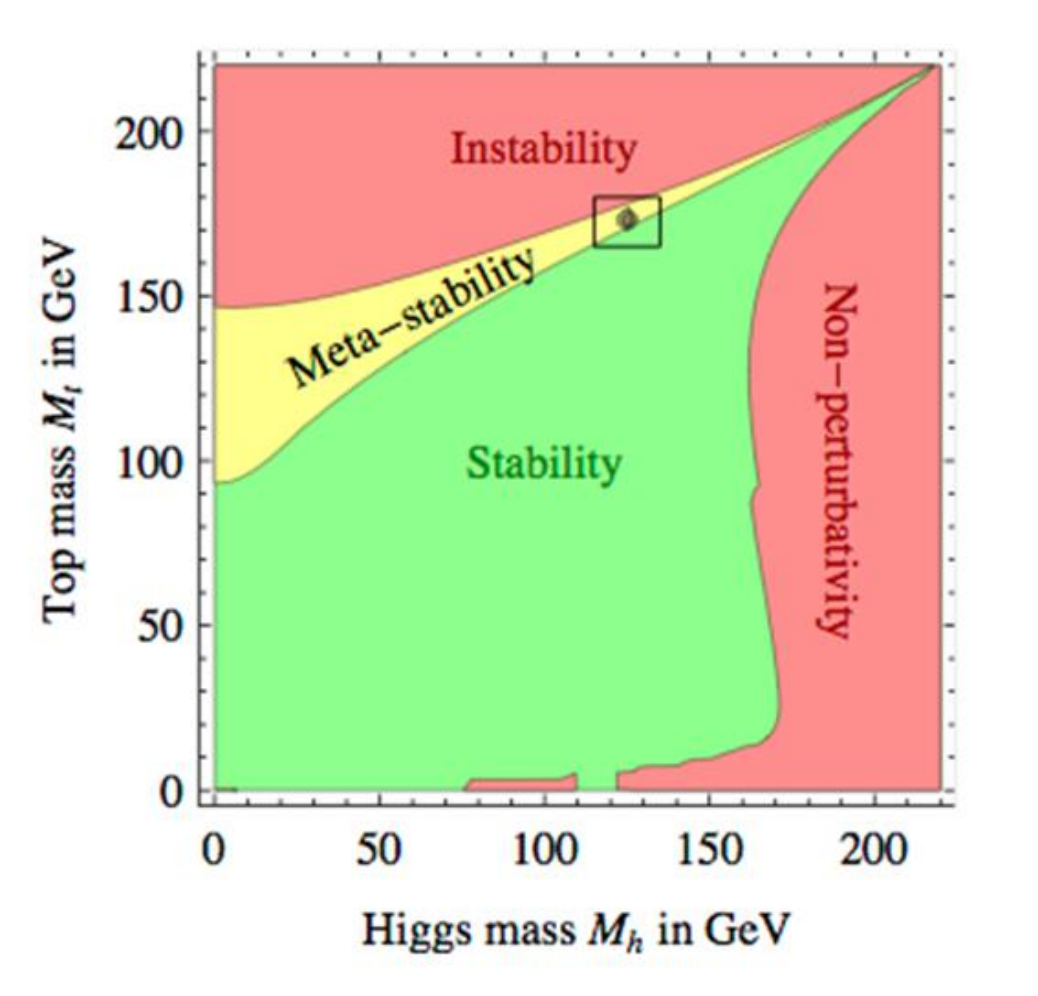
- If you want to suggest and/or look for some new (symmetry breaking) interaction, this new interaction has to respect the constraints from the electron (g-2) and EDM measurements.

- E.g. Suppose some new C or CP violating interaction coupling to the electron, how big is its effect in (g-2) and the EDM ?

# Electroweak results from LHC

- LHC: So far just Standard Model Higgs and no BSM, SUSY ...

- Remarkable: the Higgs and top mass sit in window of possible parameter space where the Standard Model is a consistent theory up to the Planck mass close to the border of a stable and meta-stable vacuum.




$$V(\phi) = \mu^2 \phi\phi^* + \lambda(\phi\phi^*)^2$$

# New physics

- Needed for
  - Matter – antimatter asymmetry in the Universe
  - Neutrino masses
  - Dark matter
  - Connection to the cosmological constant / dark energy ?
- Energy scale unknown and not yet determined by experiments
- Also, unification at the highest scales or emergence in the UV ?

# Decay rates in QED

- Theory and experiment for o-Ps

$$\Gamma(o-Ps \to 3\gamma, 5\gamma) = \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}\left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]$$

- QED TH error 100 times present experimental error, which is at the level of the O ($\alpha^2$) QED term or BR of $10^{-4}$

$$\Gamma = 7.039979(11)\mu s^{-1}$$

$$\Gamma = 7.0401 \pm 0.0007\mu s^{-1}$$

- Weak interactions, BR < $10^{-21}$ , QCD corrections waiting to be calculated
- Anything else ... New physics ? Light mass constraint from g-2 → BR ~ $10^{-6}$

- Cf p-Ps

$$\Gamma_p = 7989.6178(2)\mu s^{-1}$$

$$\Gamma_p = 7990.9(1.7)\mu s^{-1}$$

# Axions

- Strong CP puzzle
  - Big eta-prime mass in QCD generated through gluon topological potential in the vacuum
  - *Can* also generate strong CP violation but not observed (n EDM)
  - Possible solution involves new light mass pseudoscalar axion particle (so far, also not observed)

- DM candidate if mass within 1eV and 3 meV

$$\Gamma(o-Ps \rightarrow \gamma a) = \frac{4}{3\pi}\,\alpha^4\, m_e^3 \frac{f_e^2}{M^2}\left(1-\frac{m_a^2}{m_{o-Ps}^2}\right)$$

- Experimental constraints improving with time on BR for o-Ps decay

- Axion + photon, BR < 4 x $10^{-25}$ (above parameters)
  $10^{-6}$ – $10^{-11}$ (Bernreuther and Nachtmann, 1981)

# Invisibles

- Mirror matter as DM candidate and o-Ps [K. Kacprzak talk, this meeting]
- Extra dimensions ...

- ETHZ experiments in vacuum

$$BR(o-Ps \rightarrow \text{invisible}) < 5.9 \times 10^{-4}, \quad 90\% CL$$

$$\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F^{m}_{\mu\nu}$$

$$\epsilon < 3.1 \times 10^{-7} \quad 90\% CL$$

- And in medium

$$BR(o-Ps \rightarrow \text{invisible}) < 4.2 \times 10^{-7}$$

- What can we do with JPET ?

- Astrophysics constraints
(primordial $He^4$ abundance from Standard Model)

$$\epsilon \leq 3 \times 10^{-8}$$

# CP violation (?)

- CP violation : CKM in the quark sector, possible effect with neutrinos
- Electron EDM (asymmetric charge distribution along spin axis)

$$|d_e| < 8.7 \times 10^{-29} e\text{cm}$$

- o-Ps observables [M. Silarski talk, this meeting]

$$A_{CP} = ((\vec{S}_{OP}.\vec{k}_1)(\vec{S}_{OP}.(\vec{k}_1 \times \vec{k}_2)).$$

- Why expect to see something ?
- Strong constraint from electron EDM
  - Any CP violation at very high scales or with very weak coupling
  - or
  - Phase Cancellation in EDM

    (this interpretation if J-PET sees something)

# J-PET possibilities

- J-PET with 4th layer geometry
- Detection possibilities, Efficiency with prompt photons ~ 0.1
- With ~ 3,000 measured o-Ps decays per second (3 gamma),

  Expect about $9.4 \times 10^{10}$ long lived o-Ps in 365 days of running

- With 30 MBq → $2 \times 10^{9}$ long lived o-Ps
- With this set-up, statistics expected to be very competitive with best current measurements with at most one year full time data taking

  - [Details soon coming, S.D. Bass, W. Krzemien, P. Moskal]
  - [Simulations in preparation, + K. Kacprzak, E. Perez del Rio, ...]