New precise measurement of the hyperfine splitting of positronium

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Positronium and its hyperfine structure (HFS)

Positronium (Ps)

- The bound state of an electron (e-) and a positron (e+)

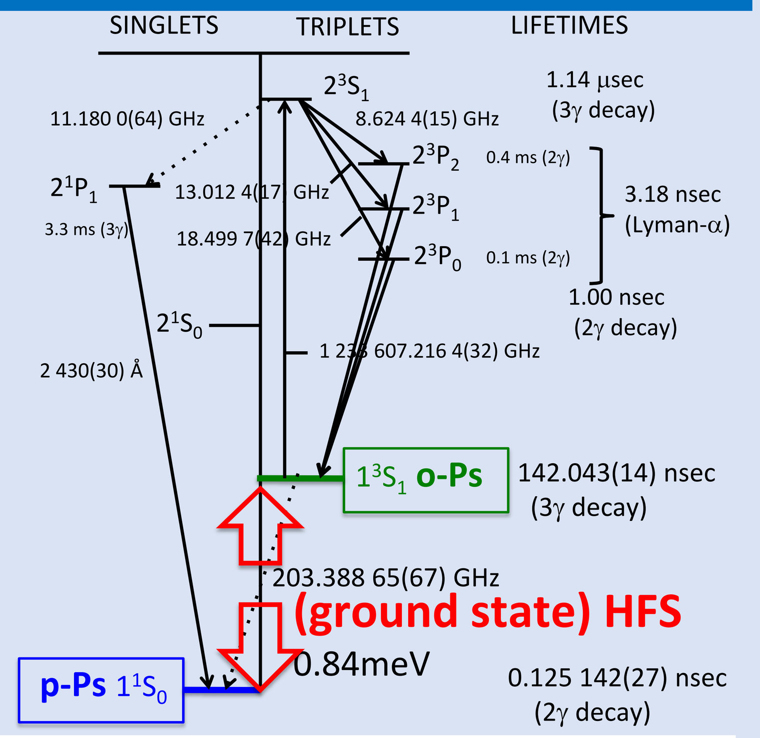
Hyperfine splitting (HFS)

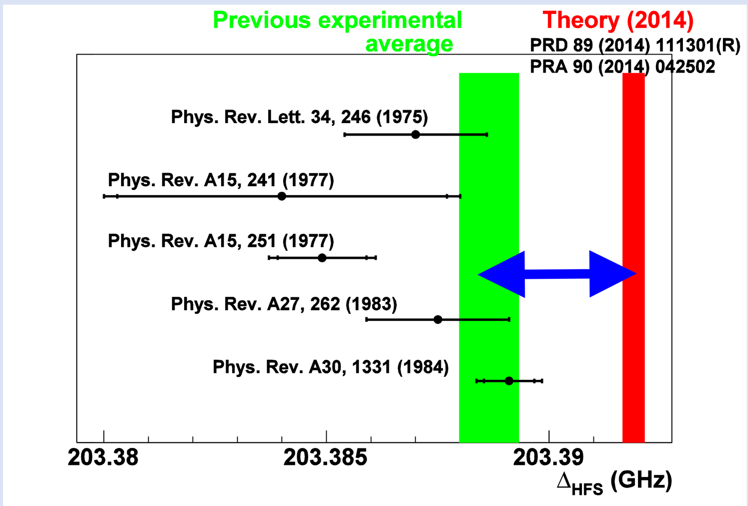
- The energy splitting between o-Ps and p-Ps
- The value of HFS

Experimental average
203.3**88 65**(67) GHz (3.3 ppm)
Theory
203.3**91 90**(25) GHz (1.2 ppm)

- The measured values are **consistent with each other** and **lower than the theoretical Calculations**

16 ppm (4.5 σ) significant discrepancy





Measurement using the Zeeman effect

How to measure the HFS?

In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Annihilate into 2 γ-rays).

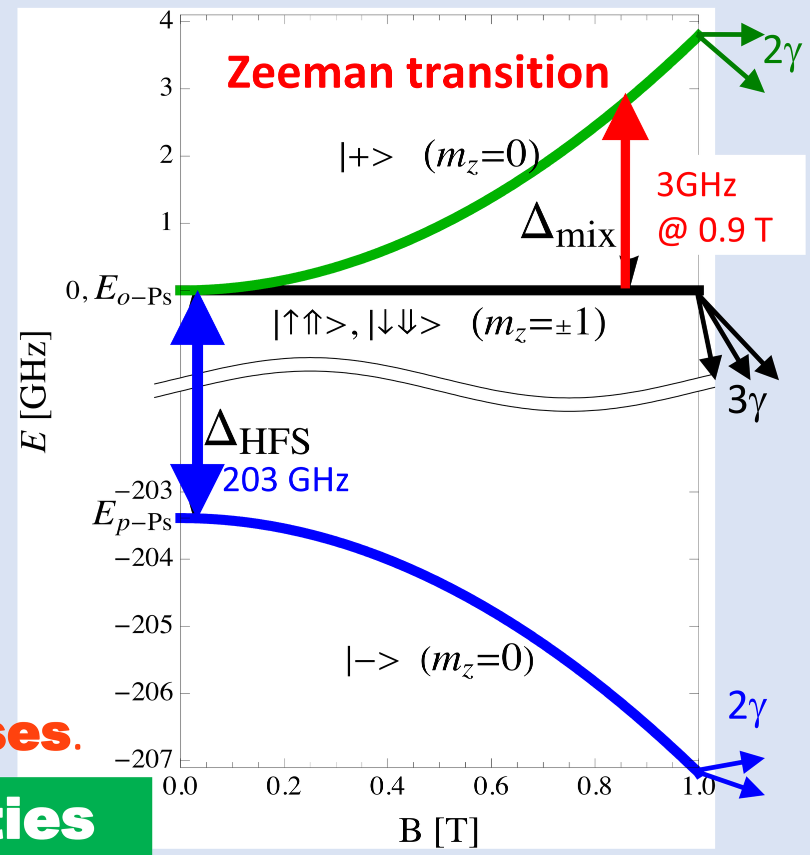
Precisely measure the Δ_{mix} and calculate Δ_{HFS} by the equation,

$$\Delta_{mix} \approx \frac{1}{2}\Delta_{HFS}\left(\sqrt{1+4x^2}-1\right),$$

$$x = \frac{g'\mu_B B}{h\Delta_{HFS}}.$$

This is not precise enough, so we solve time evolution of density matrix.

Transition → 2 γ decay rate increases.



Possible systematic uncertainties in the previous experiments

1. ***Non-uniformity of the magnetic field***
2. ***Underestimation of the material effect***
   - Unthermalized o-Ps effect can be significant *cf.* o-Ps lifetime puzzle (1990's)

Experimental setup

To **reduce possible systematic uncertainties**, we use the following **new methods**.

2 *β-tagging system* →Solve systematic error from *non-thermalized Ps*.

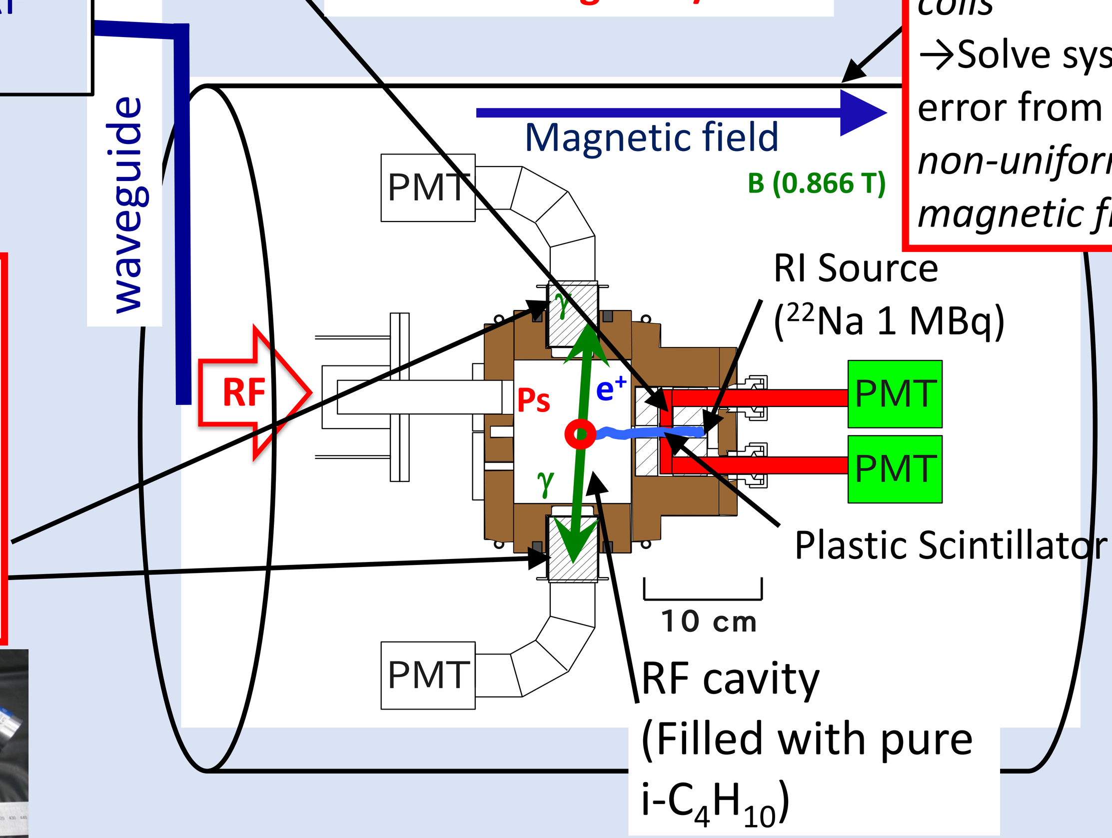
- Tag e⁺ from the ^{22}Na by thin (0.1 mm) plastic scintillator. → *t=0*

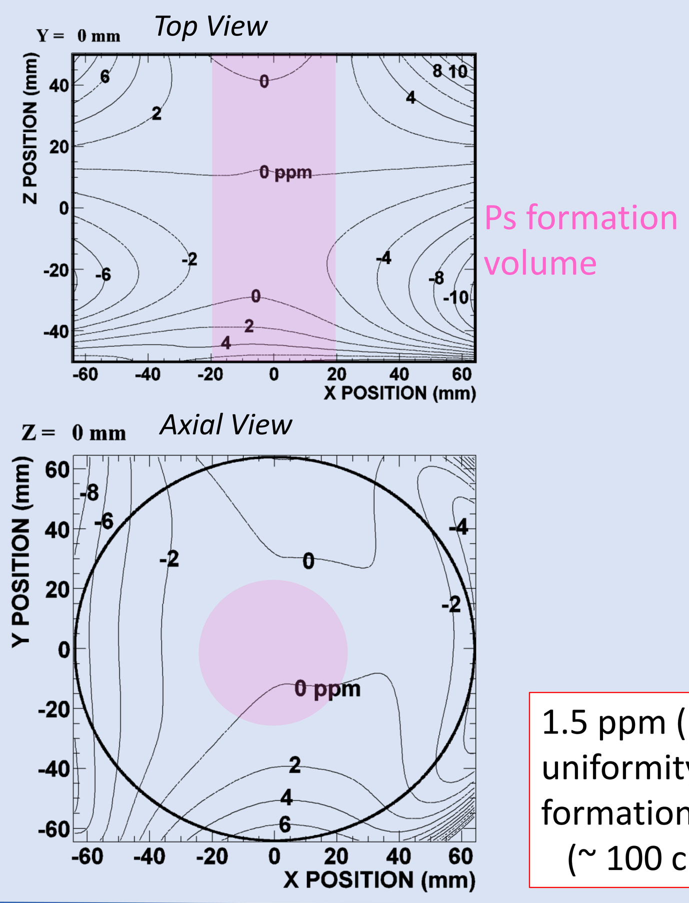
- **Treat Ps thermalization correctly**
- **20 times higher S/N**

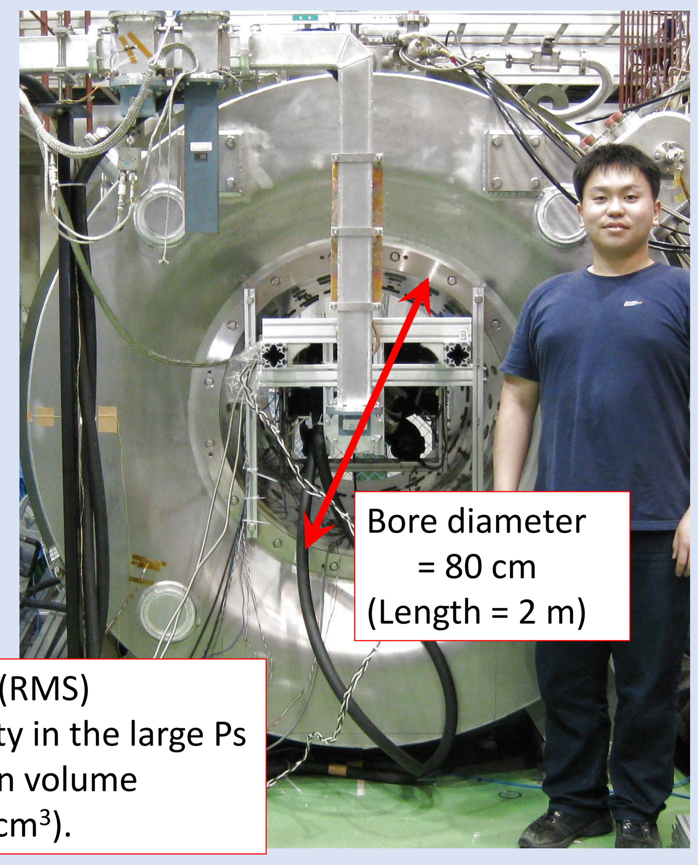
1 *Large bore superconducting magnet + compensation coils* →Solve systematic error from *non-uniformity of magnetic field.*

High power RF (500W CW)

2 *High performance γ-ray detectors* ($LaBr_3$ scintillators) →Solve systematic error from *non-thermalized Ps.*



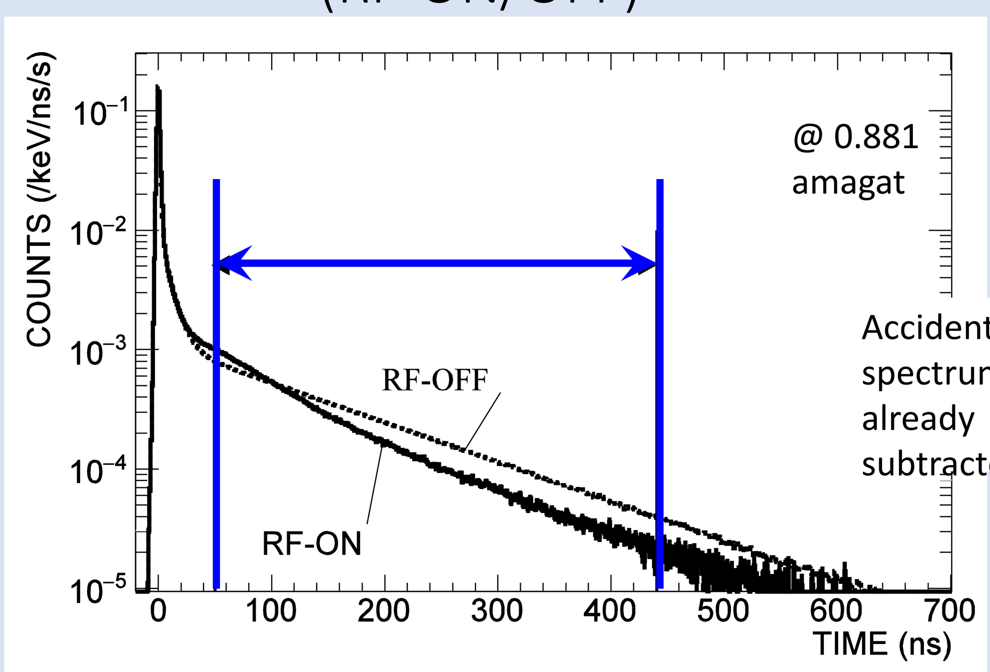




1.5 ppm (RMS) uniformity in the large Ps formation volume (~ 100 cm³).

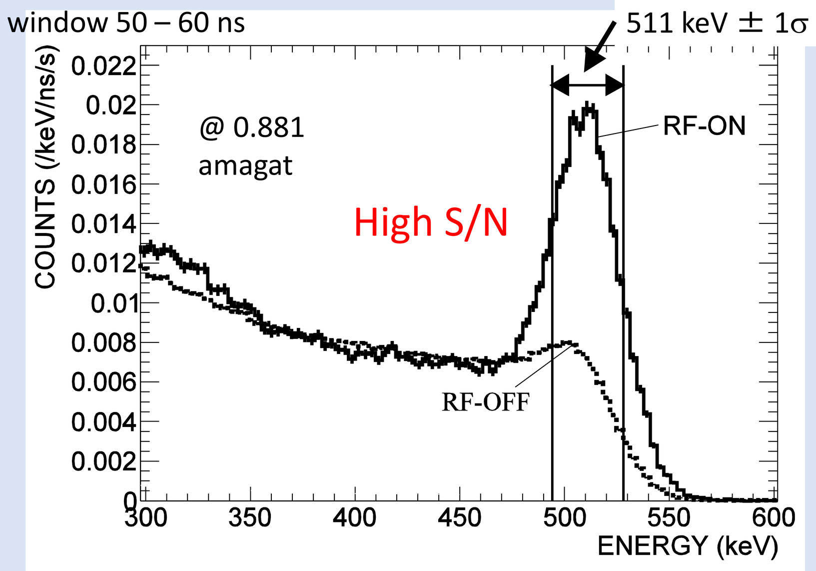
Analysis and Result

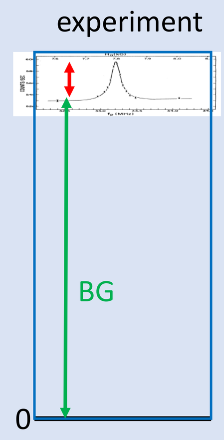
Comparison of timing spectra (RF-ON/OFF)



Lifetime is clearly shortened by RF due to the Zeeman transition.

Comparison of energy spectra (RF-ON/OFF)

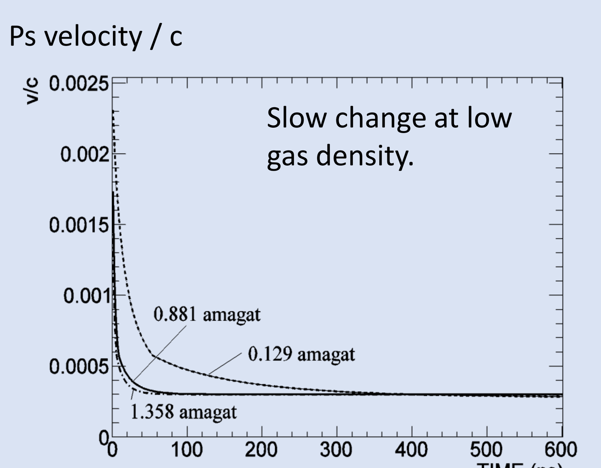


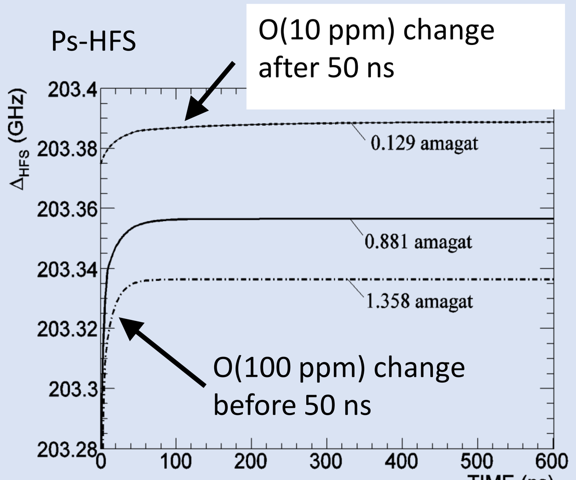


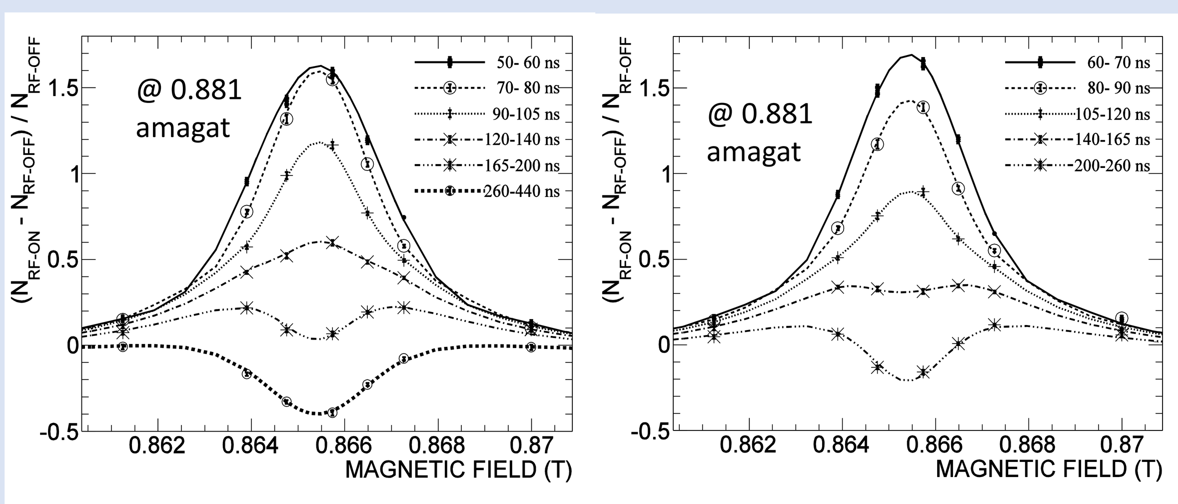
2γ decay rate increases because of the Zeeman transition. Use (RF-ON — RF-OFF) / RF-OFF of count rates in the 511 keV ± 1σ energy window.

Fitting of resonance lines taking into account time evolution of Ps-HFS

- Scanned by Magnetic Field with the fixed RF frequency and power.
- 50—440 ns is divided to 11 sub timing windows.
- Simultaneous fit of all of the gas density, magnetic field strength, and (sub) timing windows.
- Time evolution of Ps velocity (thermalization) and Δ_{HFS} (∝ $nv^{3/5}$) is taken into account (Thanks to Prof. A. P. Mills, Jr. (UC Riverside) for useful discussions)



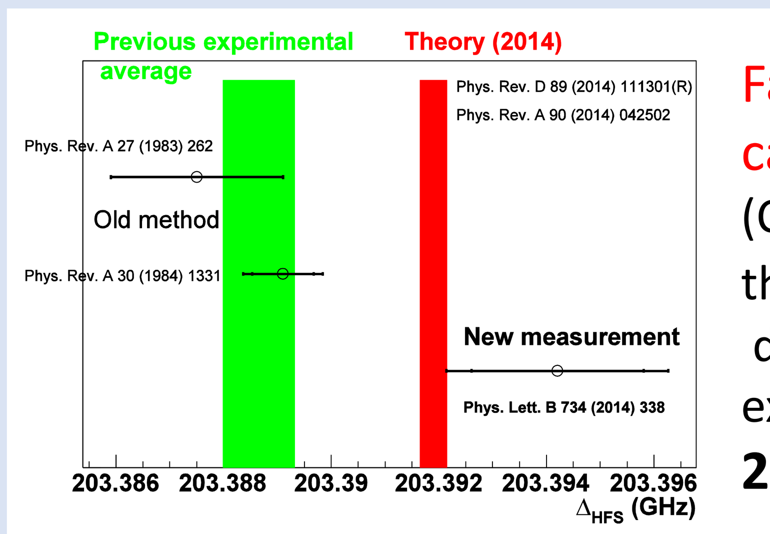




χ^2/ndf = 633.3 / 592 (p = 0.12)

Data are well described by theory.

Result 1: Center value favors QED



Favors QED calculation (Consistent with theory within **1.1σ**, disfavors previous experiments by **2.6σ**)

New result taking into account the Ps thermalization is:
Δ_{HFS} = 203.394 2 ± 0.001 6 (stat., 8.0 ppm) ± 0.001 3 (sys., 6.4 ppm) GHz (total uncertainty = 10 ppm)

Result 2: Ps thermalization effect = 10 ppm

Fittings of resonance lines WITHOUT taking into account the time evolutions (Ps thermalization)

→ Gives **10 ± 2 ppm smaller** Ps-HFS value in vacuum
(χ^2/ndf=721.1/592, p=2x10⁻⁴)

This difference is large enough to explain the 16 ± 4 ppm discrepancy.

Ps thermalization effect is crucial for precision measurement of Ps-HFS.

Future prospects

Measurement in vacuum using slow positron beam (hopefully better than 1 ppm result within 4—5 years)

- High statistics (scan in vacuum instead of extrapolation, higher power RF without discharge)
- Completely free from material effect
- Short measurement period reduces systematic errors