Precise measurement of positronium hyperfine splitting using the Zeeman effect

A. Ishida[1], Y. Sasaki[1], G. Akimoto[1], T. Suehara[2], T. Namba[2],

S. Asai[1], T. Kobayashi[2], H. Saito[3], M. Yoshida[4], K. Tanaka[4], A. Yamamoto[4]

[1]Department of Physics, the University of Tokyo

[2]International Center for Elementary Particle Physics (ICEPP), the University of Tokyo

[3]Department of General Systems Studies, the University of Tokyo

[4]High Energy Accelerator Research Organization (KEK)
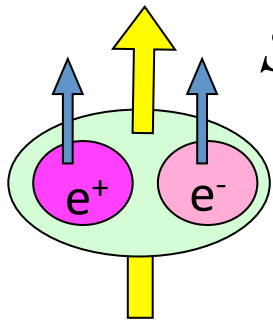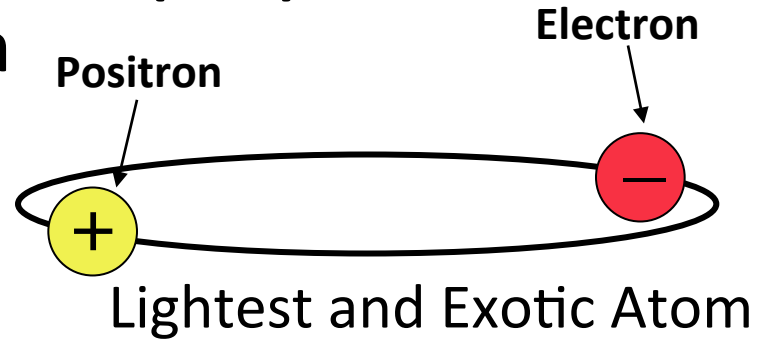
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Outline

- Positronium Hyperfine Splitting (Ps-HFS)
- Our New Experiment
- Current Result
- Prospects

Positronium (Ps)

- Bound state of an electron (e⁻) and a positron (e⁺)

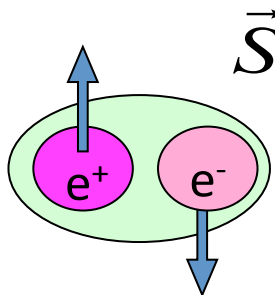- Precision test of bound-state QED.

Positron   **Electron**

Lightest and Exotic Atom

$\vec{S}$ = 1 (Triplet）

Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

o-Ps → 3γ (, 5γ, …)

o-Ps

Lifetime 142 ns

$\vec{k}_2$ $\vec{S}$ $\vec{k}_1$

o-Ps

$\vec{k}_3$

Continuous spectrum

$\vec{S}$ = 0 (Singlet）

Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2γ (, 4γ, …)

p-Ps

Lifetime 125 ps

$-\vec{k}_1$ $\vec{k}_1$

p-Ps

Monochromatic 511 keV

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Positronium Hyperfine Splitting (Ps-HFS)
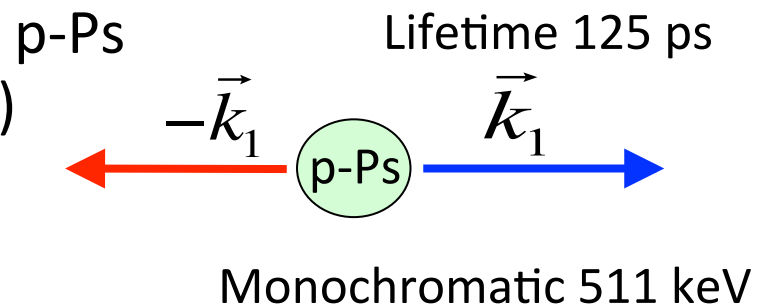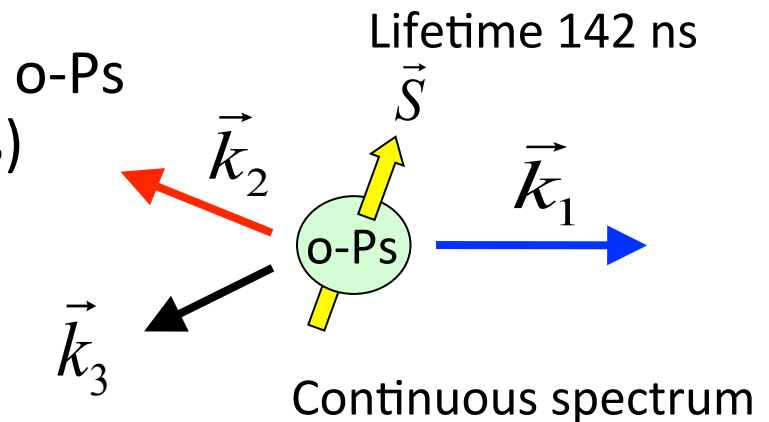
SINGLETS · TRIPLETS · LIFETIMES

Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)

2^3S_1 — 1.14 μsec (3γ decay)

11.180 0(64) GHz

8.624 4(15) GHz

2^1P_1 — 3.3 ms (3γ)

2^3P_2 — 0.4 ms (2γ)

13.012 4(17) GHz

2^3P_1

18.499 7(42) GHz

2^3P_0 — 0.1 ms (2γ)

3.18 nsec (Lyman-α)

2^1S_0

1.00 nsec (2γ decay)

1 233 607.216 4(32) GHz

2 430(30) Å

1^3S_1 **o-Ps** — 142.043(14) nsec (3γ decay)

203.388 65(67) GHz

(ground state) HFS

p-Ps 1^1S_0 — 0.84meV — 0.125 142(27) nsec (2γ decay)

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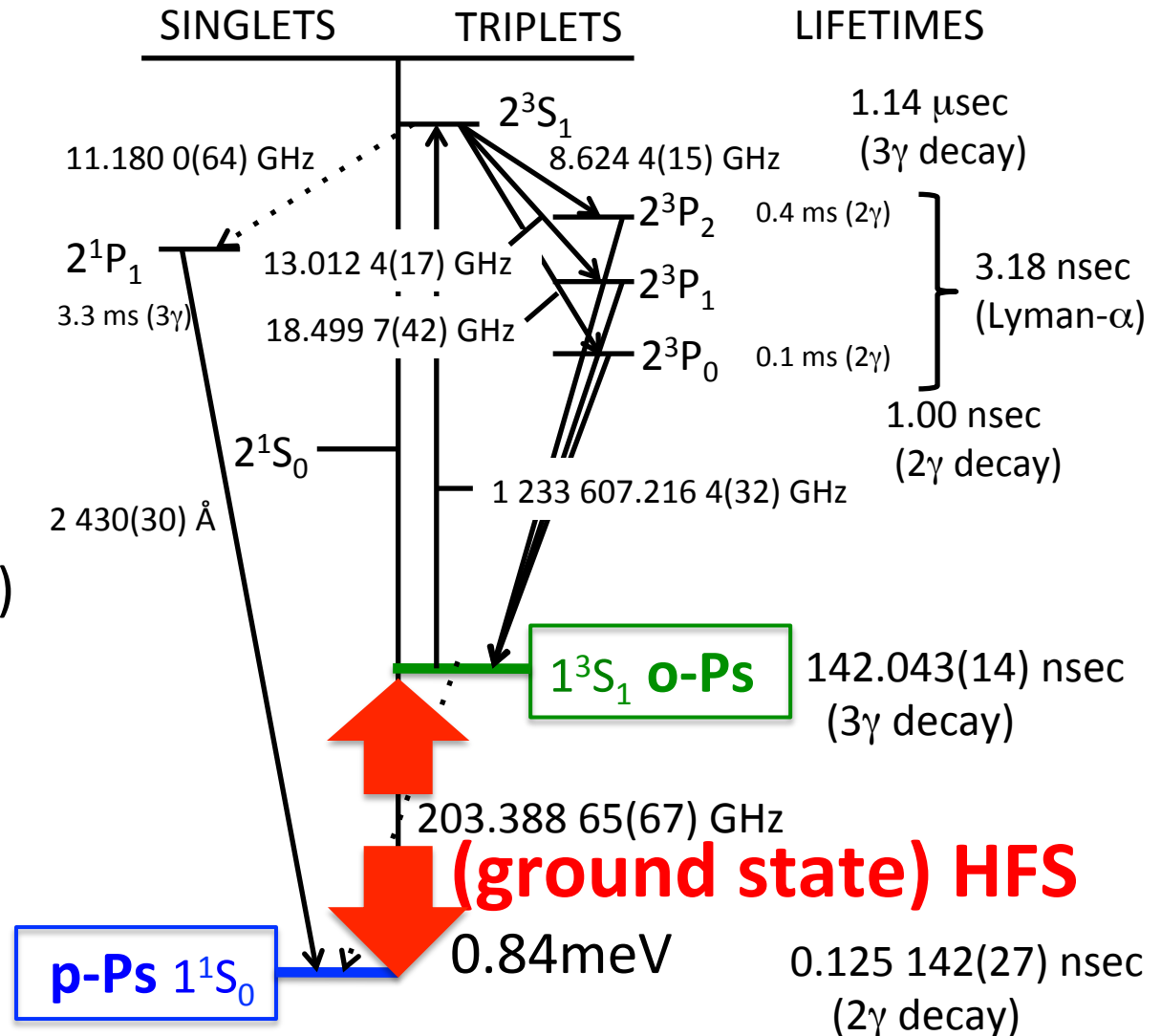
Discrepancy Between Experiments and Theory

Experimental results are consistently lower than theory.

Independent and most accurate Experimental average

Theory (2000)

Phys. Rev. Lett. 34, 246 (1975)

Phys. Rev. A15, 241 (1977)

Phys. Rev. A15, 251 (1977)

Phys. Rev. A27, 262 (1983)

Phys. Rev. A30, 1331 (1984)

203.38   203.385   203.39

Δ_{HFS} **(GHz)**

Experimental average
203.388 65(67) GHz
(3.3 ppm)

$O(\alpha^3 \ln \alpha)$
QED theory
203.391 69(41) GHz
(2.0 ppm)
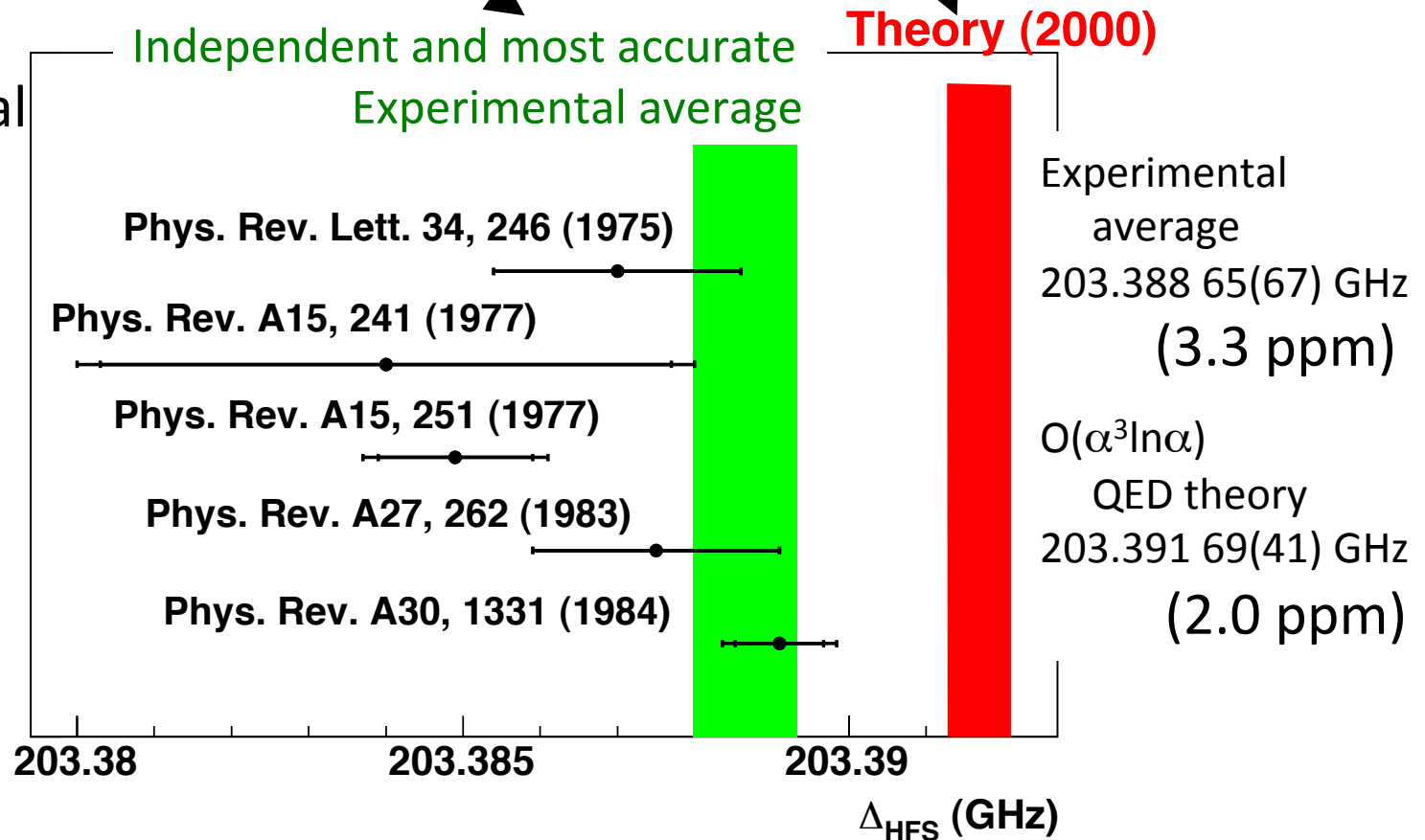
15 ppm (3.9 σ) significant discrepancy
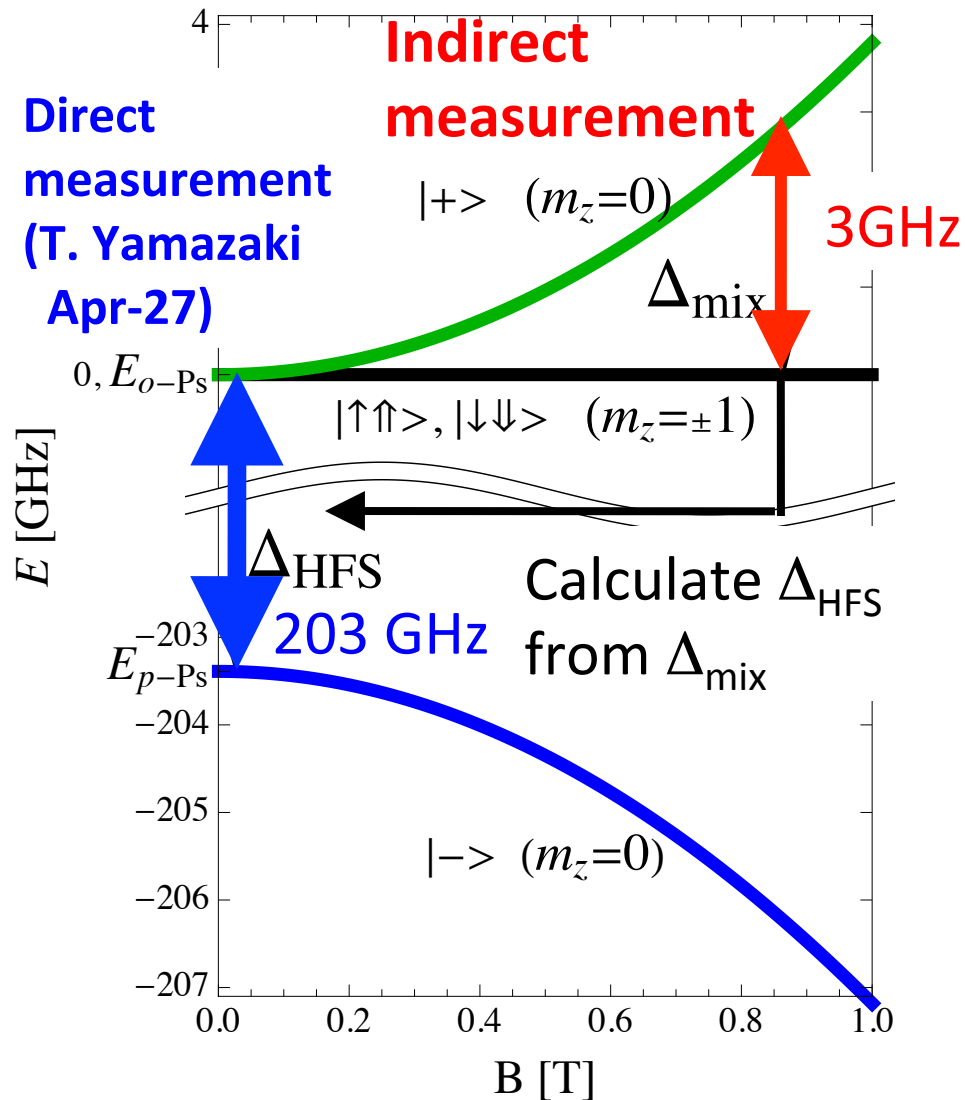
Possible reasons for the discrepancy

- **Common systematic uncertainties in the previous experiments**
  - Underestimation of material effects. Unthermalized o-Ps can have a significant effect especially at low material density. *cf. o-Ps lifetime puzzle (1990's)*
  - Non-uniformity of the magnetic field. It is quite difficult to get ppm level uniform field in a large Ps formation volume.

- **Need new development on calculation of bound-state QED or New physics beyond the Standard Model.**

> We have proposed new methods free from these systematic errors.
> We will provide an independent check for the discrepancy.

Experimental Technique
Indirect Measurement using Zeeman Effect

Direct measurement (T. Yamazaki Apr-27)

Indirect measurement

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$0, E_{o-Ps}$

$|+>\quad (m_z=0)$

Δ_{mix}

3GHz

$|\uparrow\Uparrow>, |\downarrow\Downarrow>\quad (m_z=\pm1)$

Δ_{HFS}

203 GHz

Calculate Δ_{HFS} from Δ_{mix}

E [GHz]

-203

E_{p-Ps}

-204

-205

-206

-207

$|->\quad (m_z=0)$

$0.0\quad 0.2\quad 0.4\quad 0.6\quad 0.8\quad 1.0$

B [T]

In a static magnetic field, the **p-Ps** state mixes with the **m$_Z$=0 state of o-Ps** (Annihilate into 2 γ-rays).
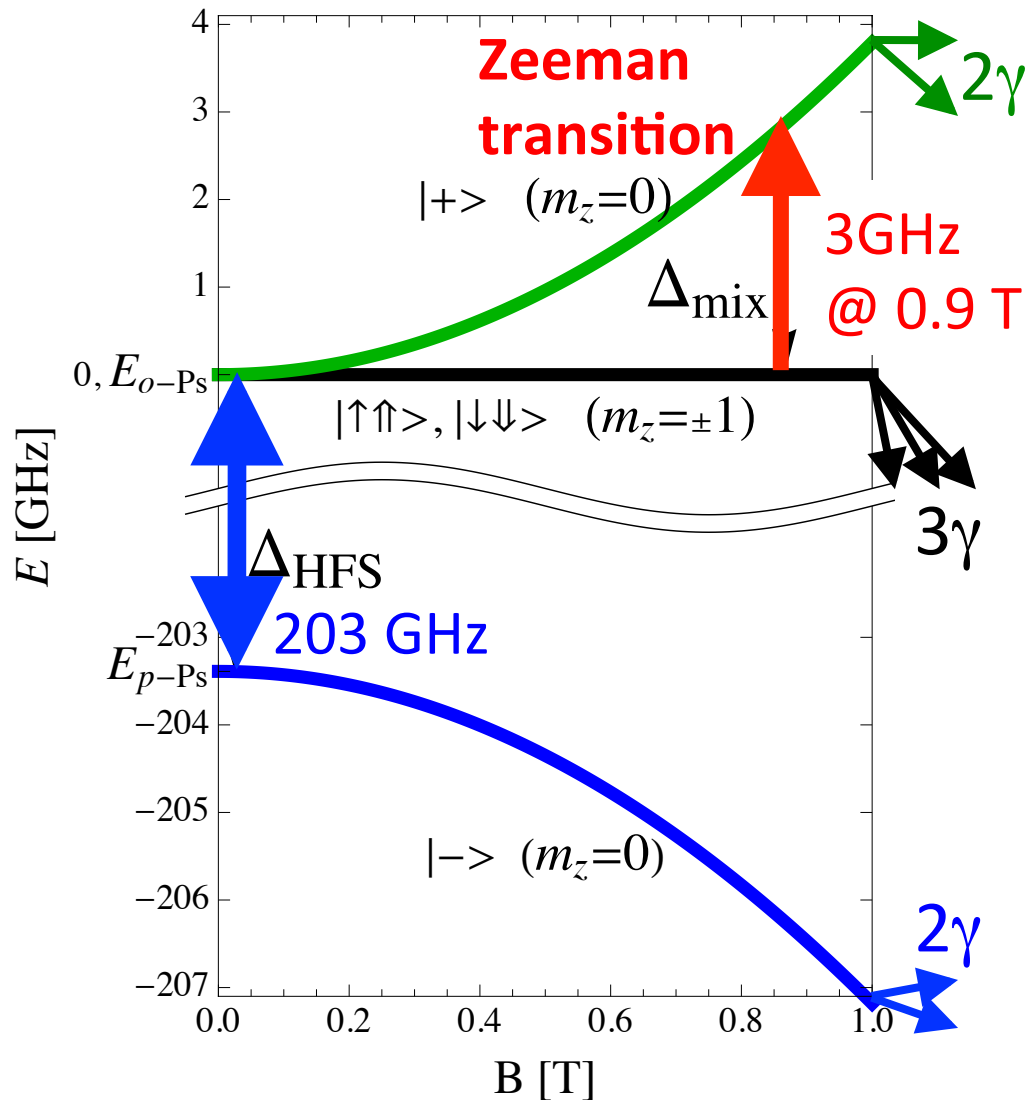
Precisely measure the Δ_{mix} and calculate Δ_{HFS} by the equation,

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

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

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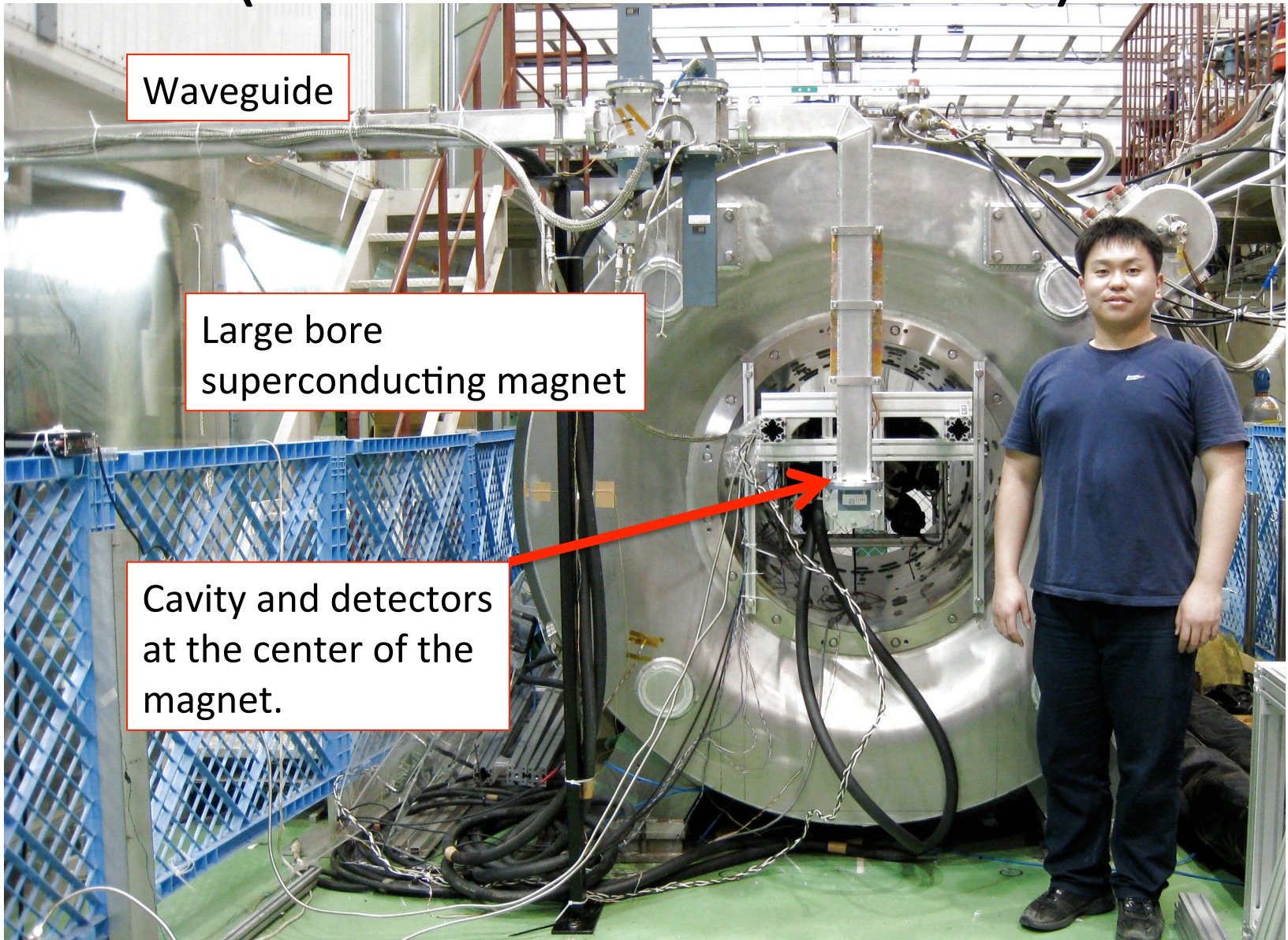# Experimental Technique
Indirect Measurement using Zeeman Effect

When a microwave field with a frequency of Δ_{mix} is applied, transitions between the $m_z=0$ and $m_z=\pm1$ states of o-Ps are induced.

$\rightarrow$ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases. This increase is our experimental signal.
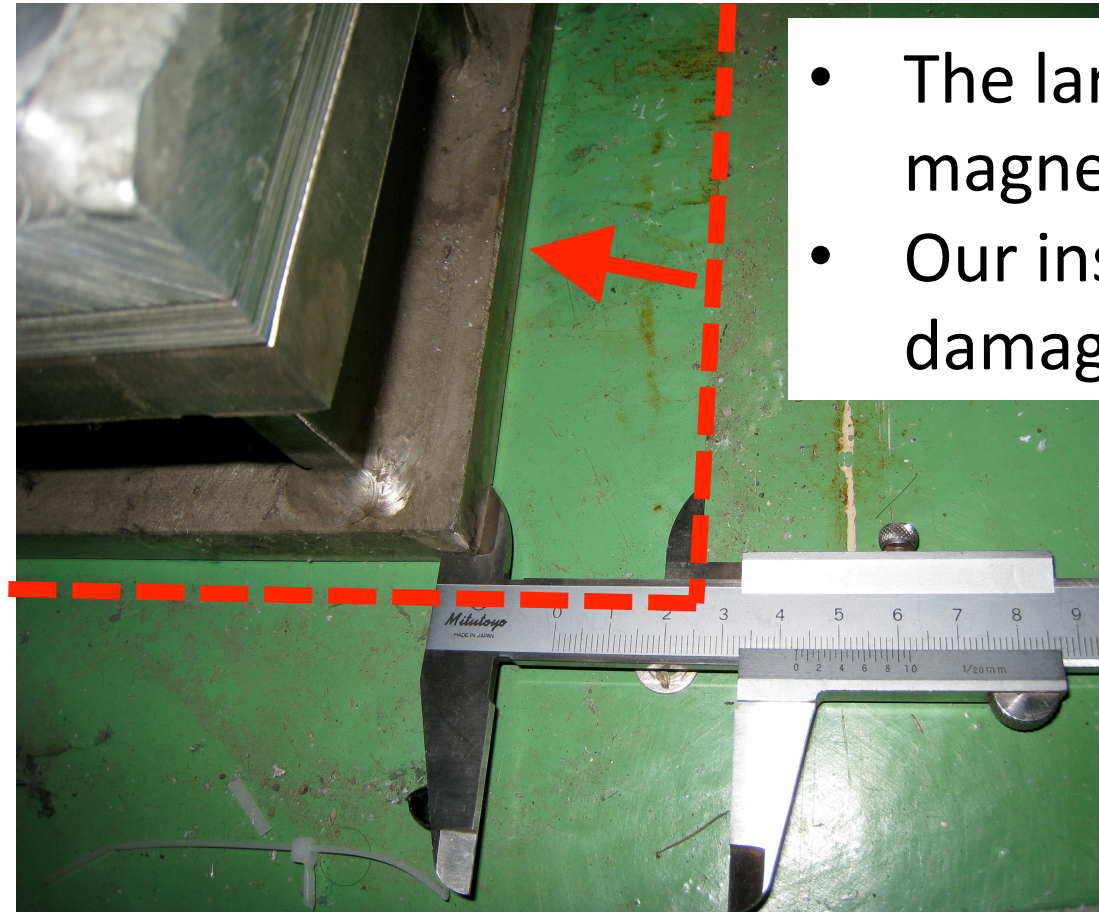
$\rightarrow$ This is the same approach as previous experiments.

Measurement @ KEK
(Jul 2010 – 11 Mar 2011)

Waveguide

Large bore superconducting magnet

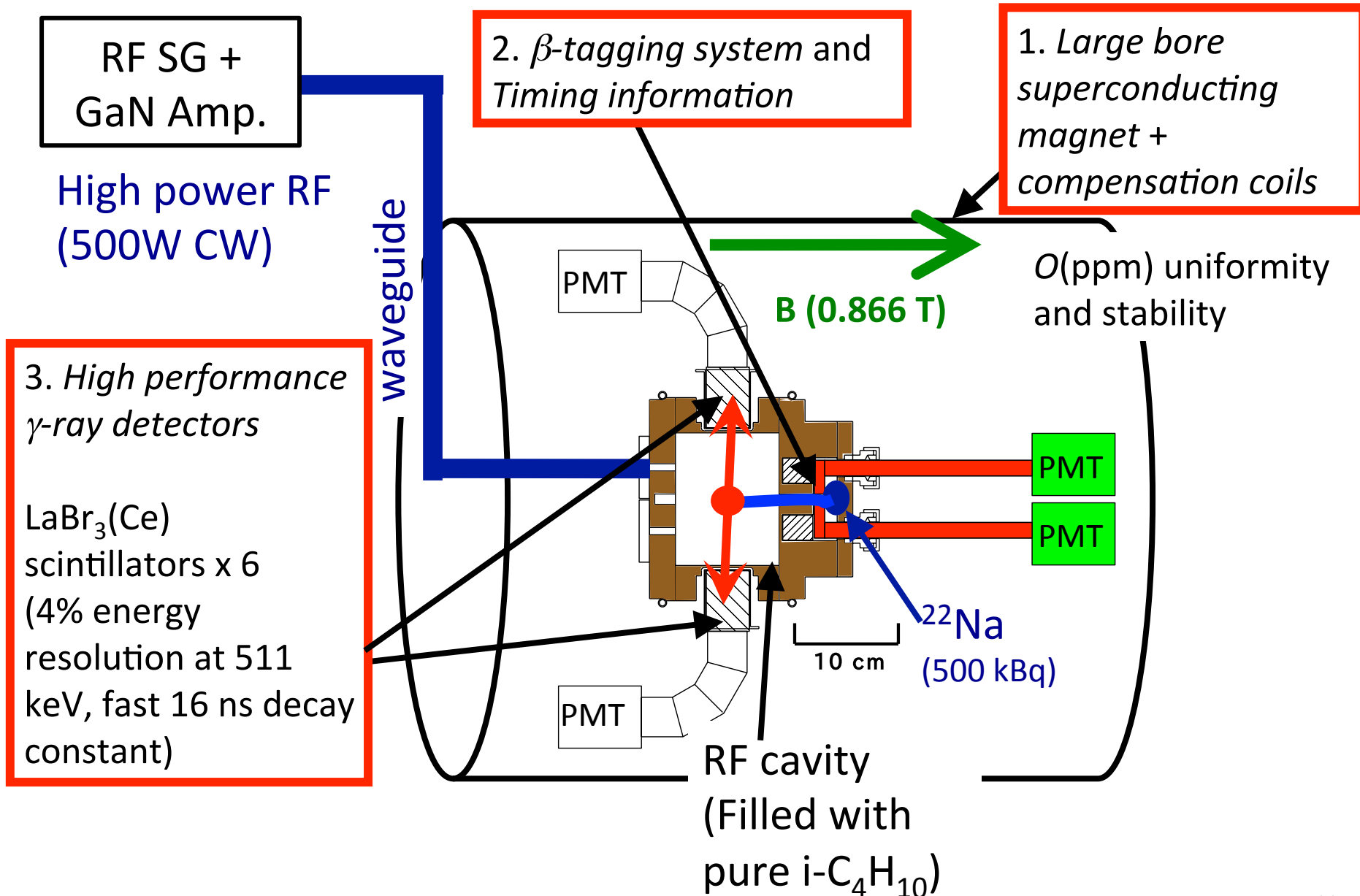Cavity and detectors at the center of the magnet.

Earthquake on 11 Mar 2011

- The large bore superconducting magnet (13 t) moved 4.3 cm.
- Our instruments were not damaged.

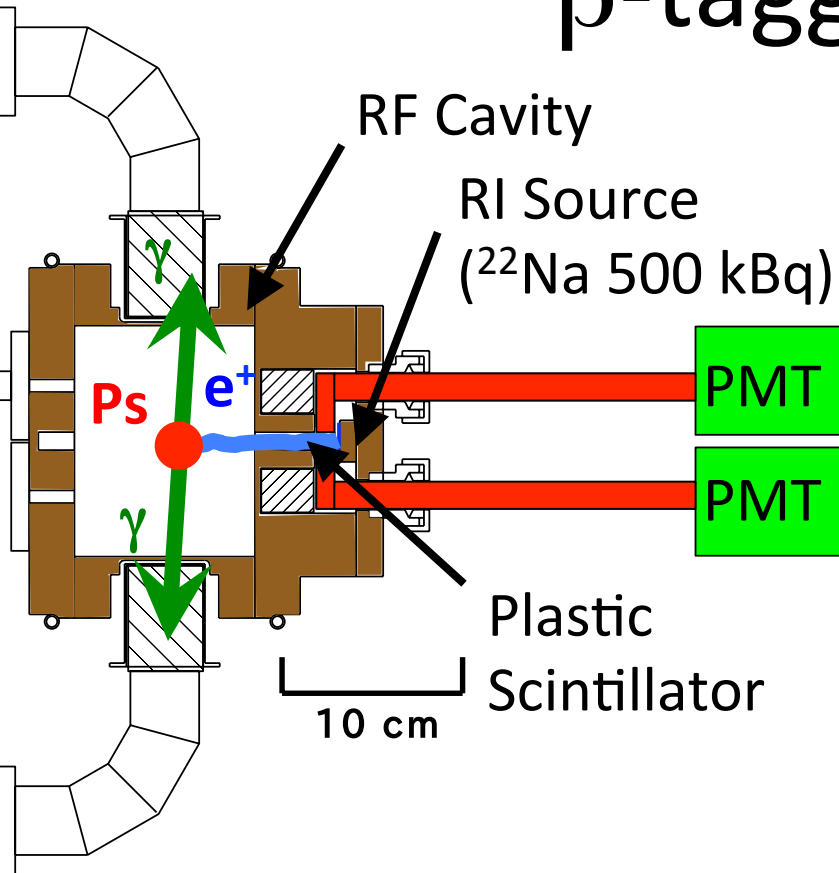- Due to lack of electric power supply, we now stop measurement.
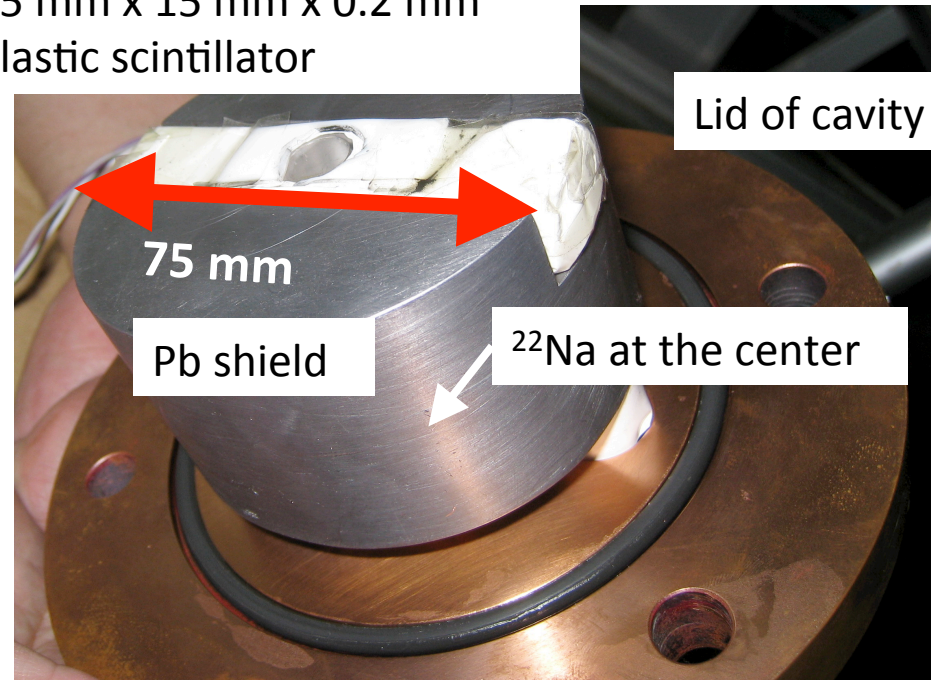
©TEPCO

Our new Experiment

RF SG + GaN Amp.

High power RF (500W CW)

waveguide

2. *β-tagging system* and *Timing information*

1. *Large bore superconducting magnet + compensation coils*

B (0.866 T)

O(ppm) uniformity and stability

3. *High performance γ-ray detectors*

LaBr$_3$(Ce) scintillators x 6 (4% energy resolution at 511 keV, fast 16 ns decay constant)

PMT

PMT

PMT

PMT

10 cm

^{22}Na (500 kBq)

RF cavity (Filled with pure i-C$_4$H$_{10}$)

β-tagging system

RF Cavity

RI Source (^{22}Na 500 kBq)

Ps **e$^+$** γ γ

PMT

PMT

Plastic Scintillator

10 cm

- Tag e$^+$ from the ^{22}Na by thin (0.2 mm) plastic scintillator.

$$\rightarrow \quad t=0$$

15 mm x 15 mm x 0.2 mm Plastic scintillator

75 mm

Lid of cavity

Pb shield

^{22}Na at the center

- DAQ Trigger is made by coincidence of e$^+$ tag signal and γ-ray detection.
- Time difference of these signals is Ps life time of each event.

Analysis (Timing Spectra)

Timing Spectra

RF ON
RF OFF

Suppress Prompt and Accidental backgrounds with a Timing window of 35 ns – 155 ns

→ **20 times higher S/N**

Unthermalized o-Ps events are also suppressed.

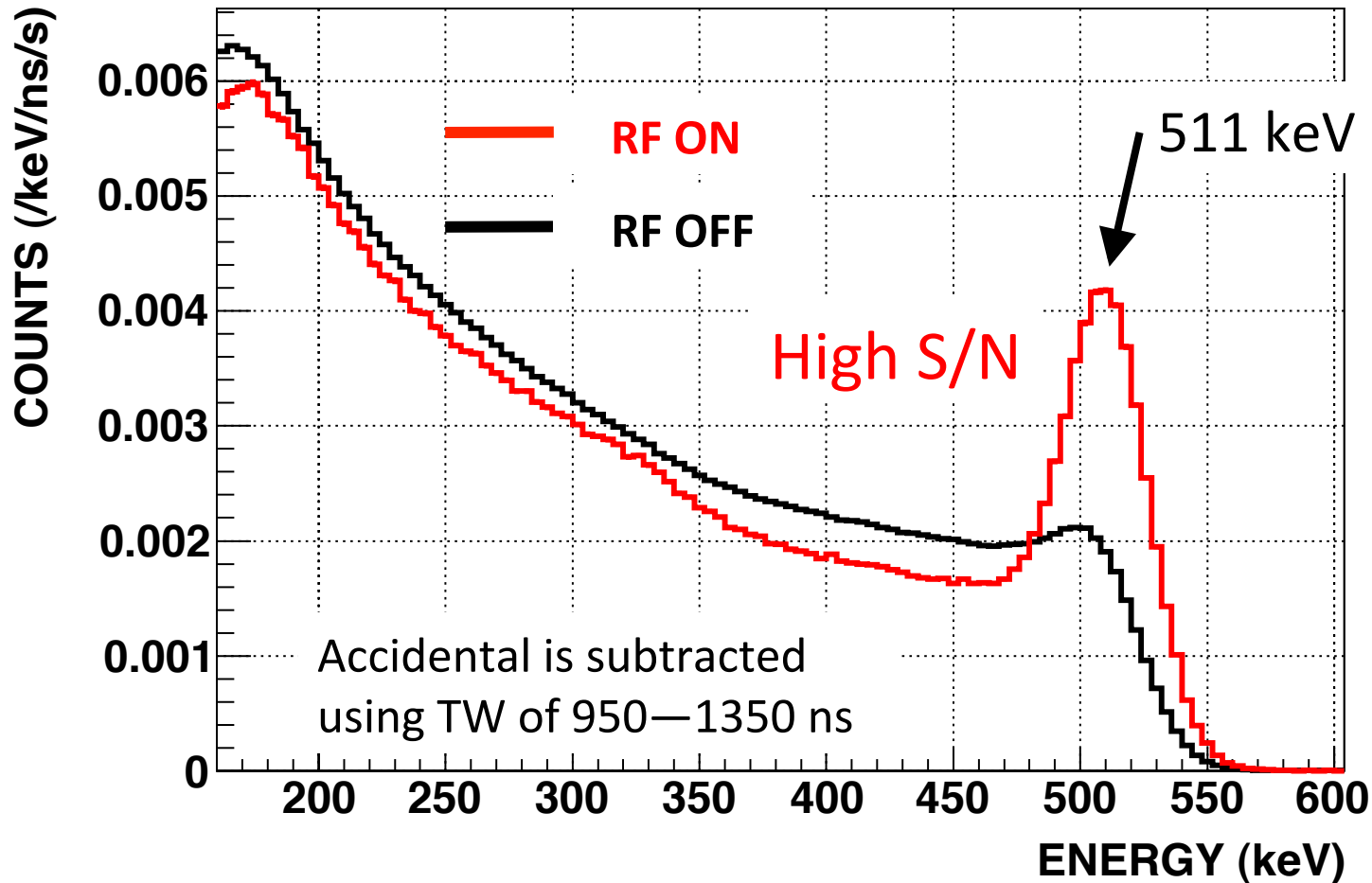Short Component ($m_z = 0$)

Long Component ($m_z = \pm 1$)

COUNTS (/keV/ns/s)

TIME (ns)
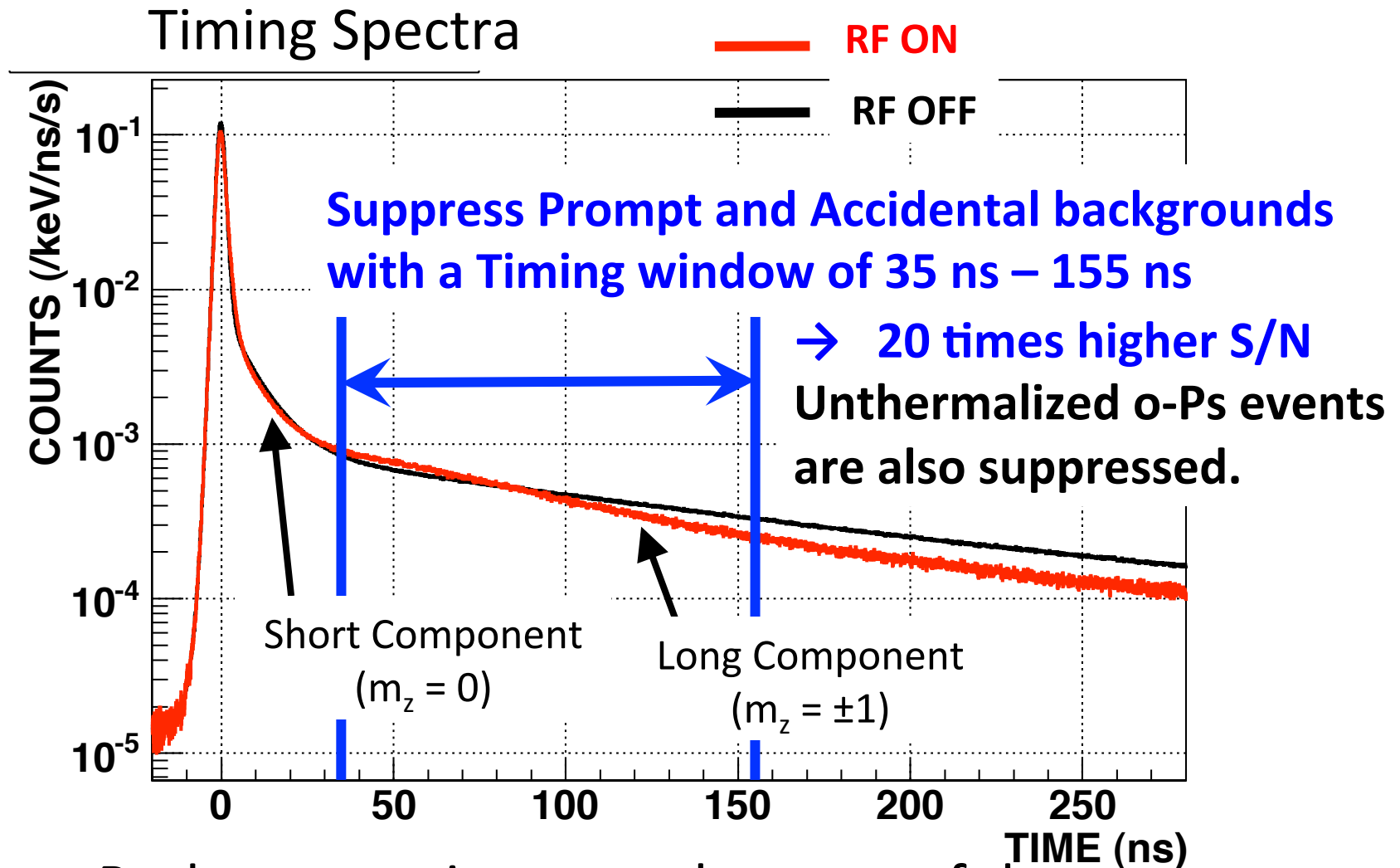
Ps decay rate increases because of the Zeeman transition.

Analysis (Energy Spectra)

2γ decay rate increases because of the Zeeman transition. Zeeman transition probability is calculated from the difference between RF-ON and RF-OFF.
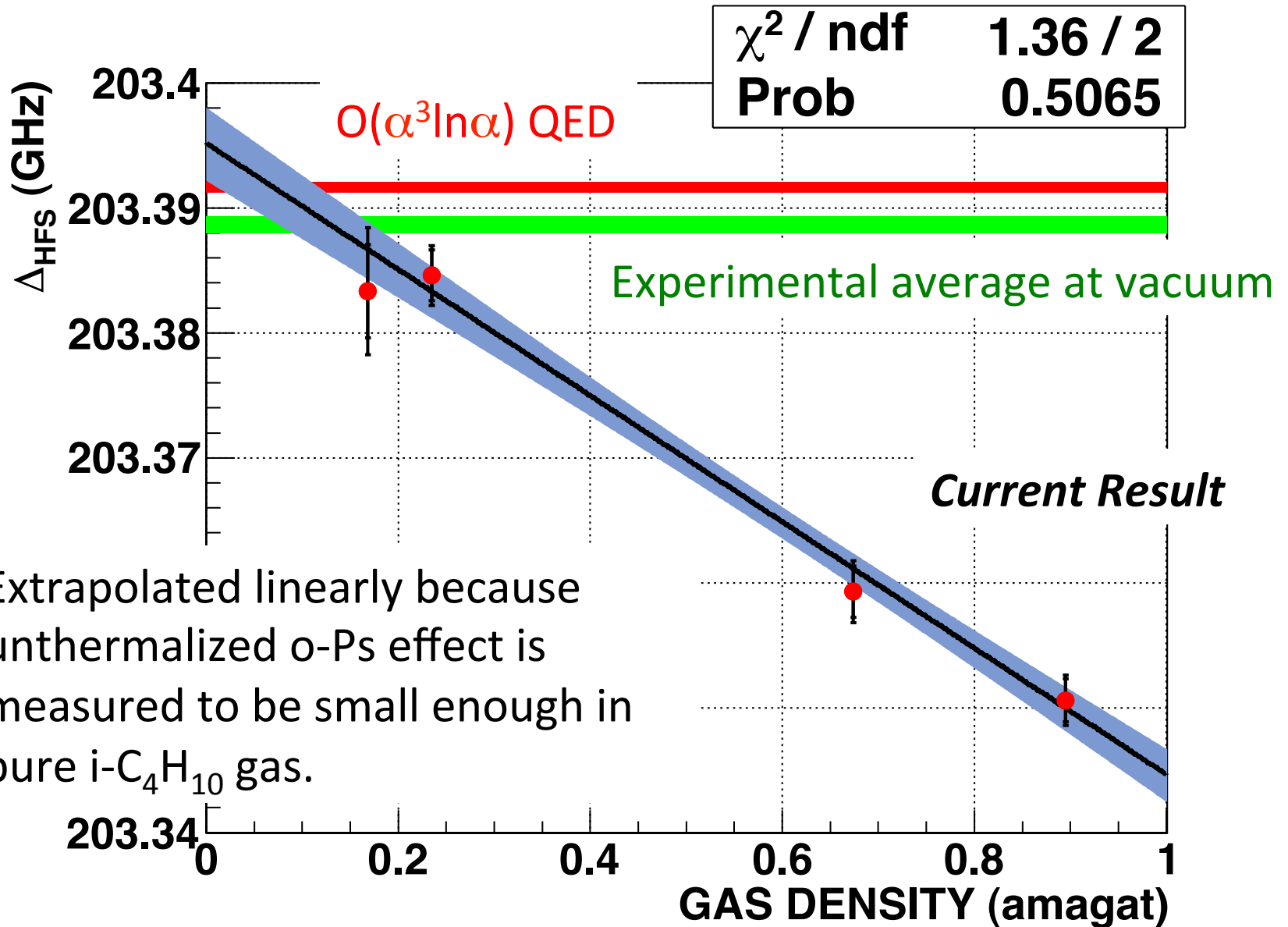
Resonance Line (0.895 amagat)

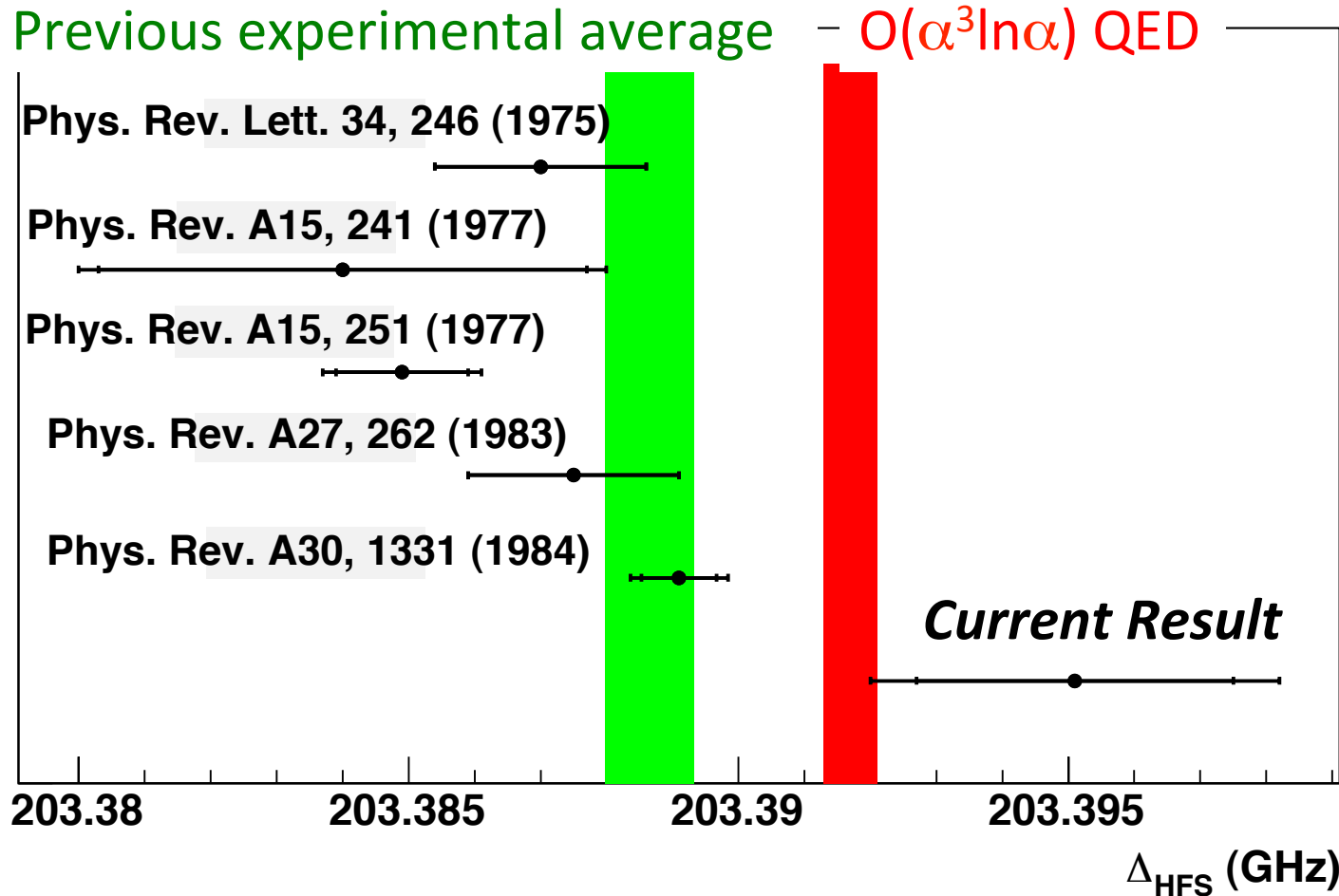Scanned by Magnetic Field with the fixed RF frequency and power.

Fitted by theoretical line calculated from Hamiltonian
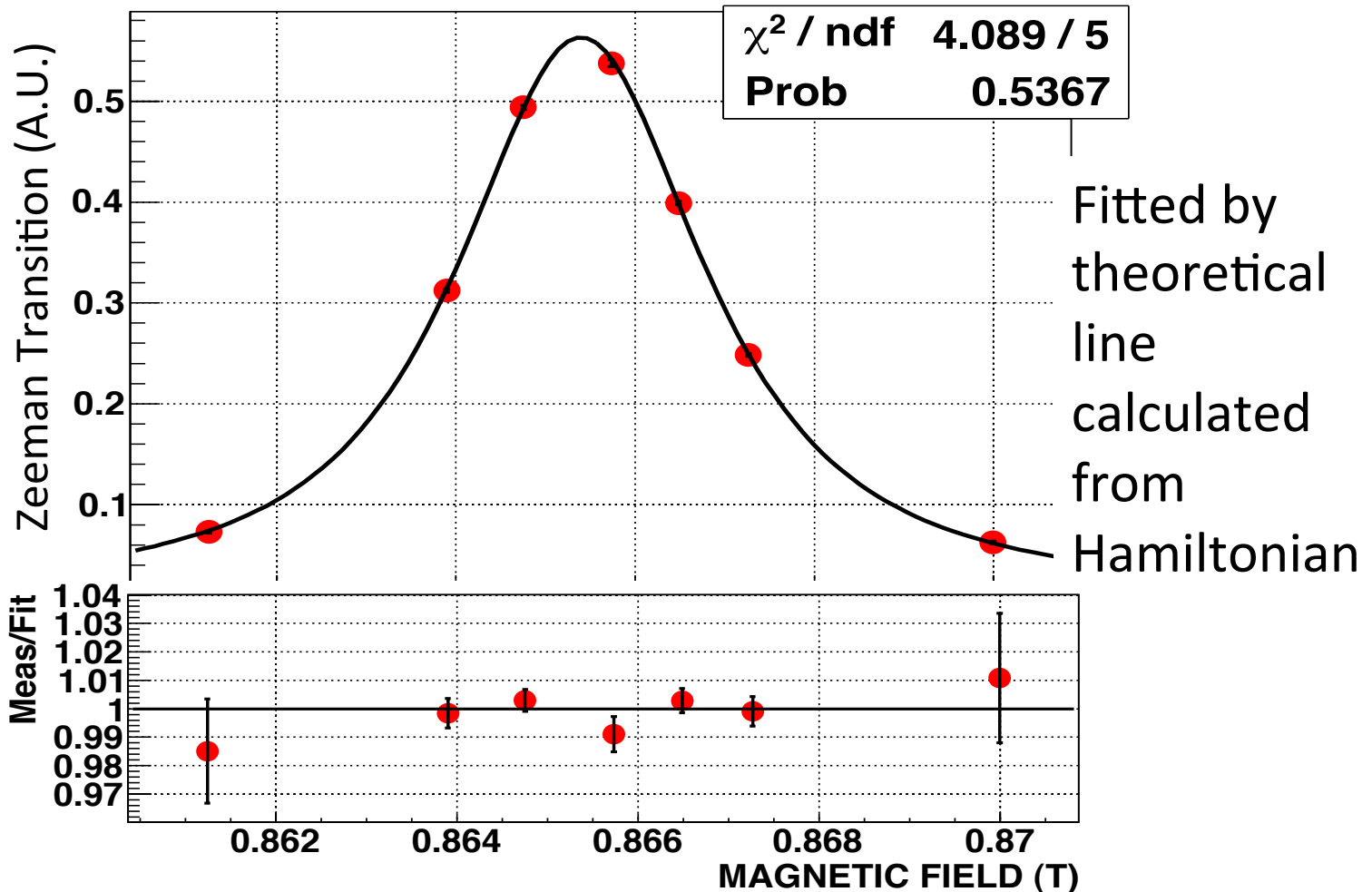
Δ_{HFS} = 203.3506(20) GHz (9.8 ppm) (Including errors from MC stat. ,P, and Q)

→ Obtain the Δ_{HFS} in vacuum with density correction.

Gas Density Dependence

χ^2 / ndf   1.36 / 2
Prob   0.5065

O($\alpha^3\ln\alpha$) QED

Δ_{HFS} (GHz)

203.4
203.39
203.38
203.37
203.34

Experimental average at vacuum

Current Result

Extrapolated linearly because unthermalized o-Ps effect is measured to be small enough in pure i-C_4H_{10} gas.

0   0.2   0.4   0.6   0.8   1
GAS DENSITY (amagat)

Current Result

Current Result

$$\Delta_{HFS} = 203.3951 \pm 0.0024 \text{ (stat., 12ppm)}$$
$$\pm 0.0019 \text{ (sys., 9.5 ppm) GHz}$$

Systematic Errors　(Current result)

Source	ppm in Δ_{HFS}
Non-uniformity	1.8
Offset and reproducibility	1.0
NMR measurement	1.0
Estimation using MC simulation	7.0
Ps thermalization	3.0
RF Power	2.9
Q_L value of RF cavity	4.3
RF frequency	1.0
Quadrature sum	9.5

Magnetic field

Detection efficiency

Material effect

RF

Prospects

- <u>Material Effect</u>: Currently we assumed that HFS depends on gas density linearly. If the unthermalized Ps contribution is large, the dependence is not linear. According to previous thermalization measurement (Skalsey et al.), thermalization effect is estimated to be less than 3 ppm with i-C_4H_{10} gas. We are now precisely measuring the Ps thermalization using different technique.

- <u>RF System</u>: The experimental environment (temperature) control → O(ppm) uncertainty

- <u>Detection efficiency</u>: Currently it is estimated by Monte Carlo simulation. It will be carefully studied and will be estimated by real data. → O(ppm) uncertainty

- <u>Statistics</u>: 12 ppm has been obtained.

A measurement with a precision of O(ppm) is expected within a year.

Conclusion

The current result of

HFS = 203.3951 ± 0.0024 (stat., 12 ppm)
± 0.0019 (sys., 9.5 ppm)

has been obtained so far.

- Our experiment is free from possible common uncertainties in previous experiments (Non-uniformity of magnetic field, Ps thermalization effect).

- A new result with an accuracy of O(ppm) will be obtained within a year which will be an independent check of the discrepancy.