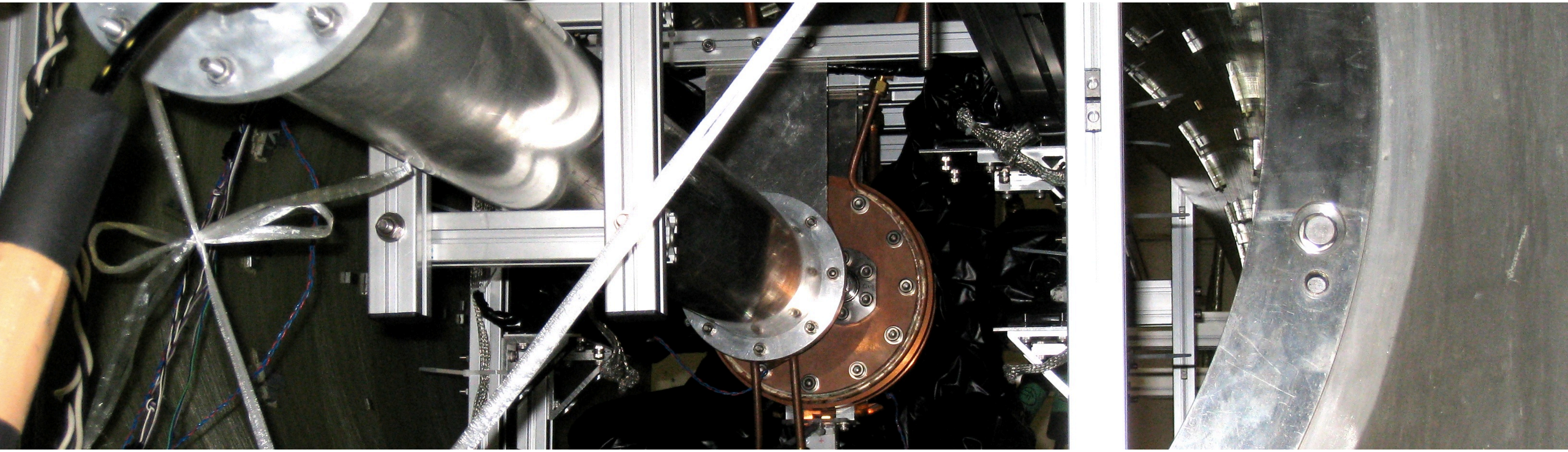
Precise measurement of positronium hyperfine splitting using the Zeeman effect



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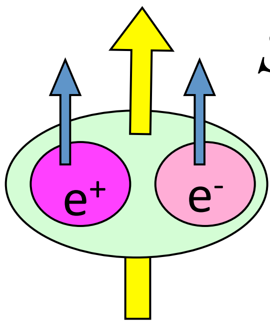
Outline

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

Positronium (Ps)

- Bound state of an electron (e^-) and a positron (e^+)
- Precision test of bound-state Quantum ElectroDynamics (QED).

Lightest and Exotic Atom



$\vec{S}$ = 1 (Triplet)

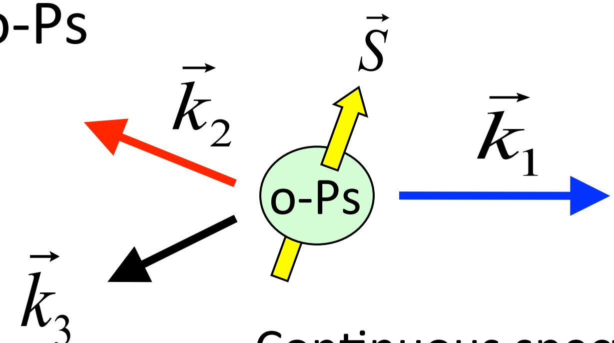
Ortho-positronium (o-Ps)

Spin=1 The same quantum number as photon

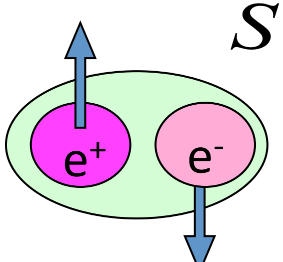
o-Ps → 3γ (, 5γ, ...)

o-Ps

Lifetime 142 ns



Continuous spectrum



$\vec{S}$ = 0 (Singlet)

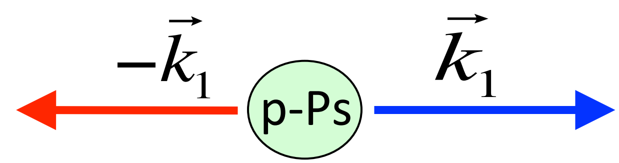
Para-positronium (p-Ps)

Spin=0 Scalar particle

p-Ps → 2γ (, 4γ, ...)

p-Ps

Lifetime 125 ps

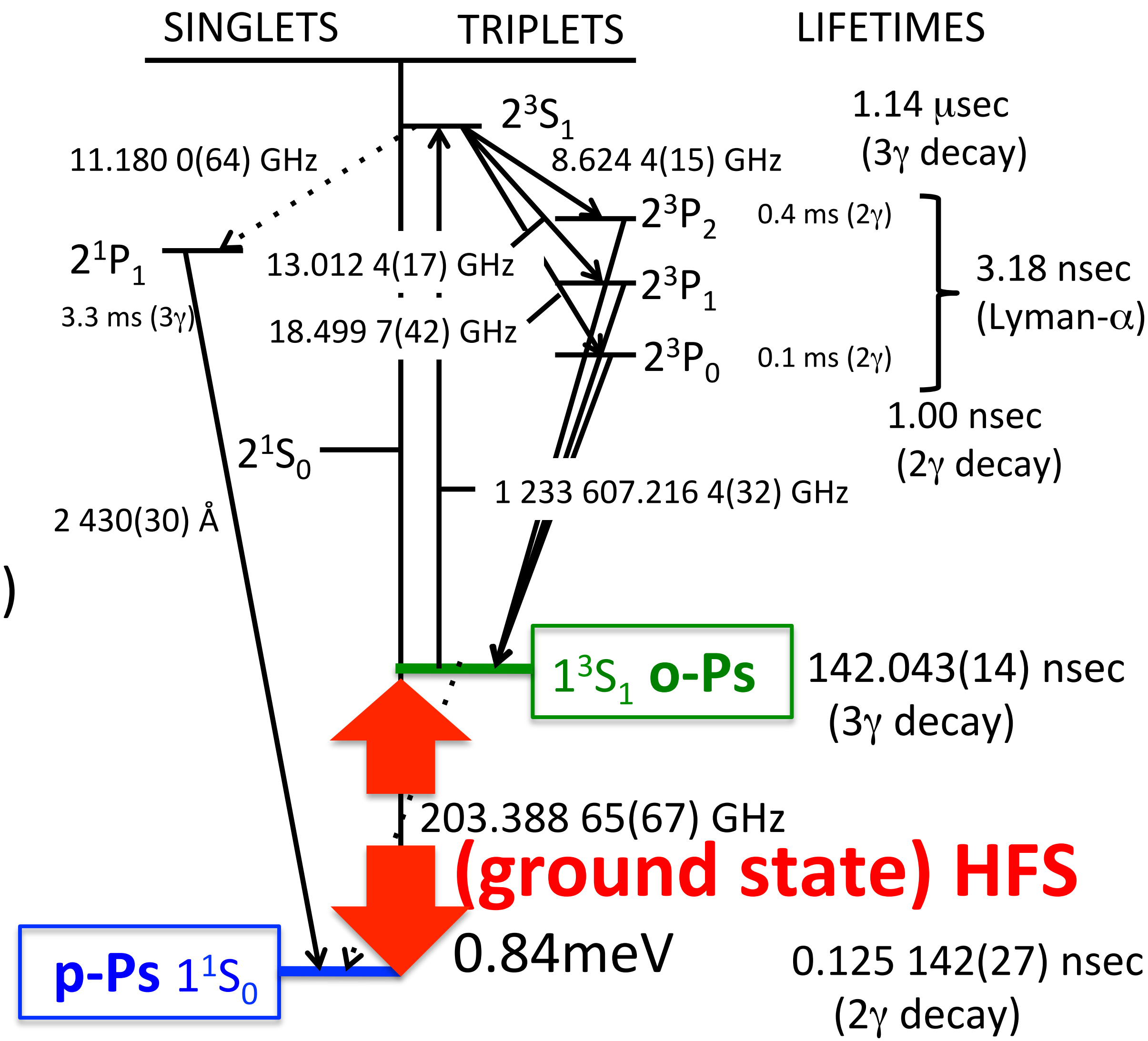


Monochromatic 511 keV

Positronium Hyperfine Splitting (Ps-HFS)

Energy difference between two spin eigenstates of the ground state Ps

→ Ps-HFS (203 GHz)



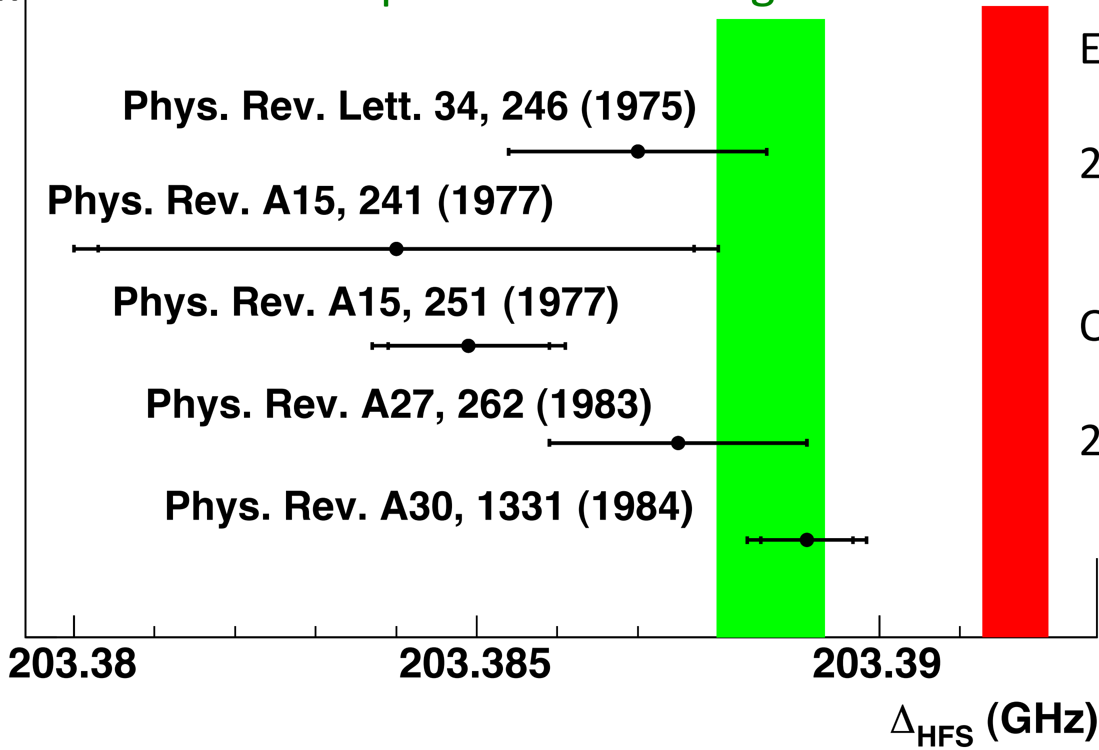
Discrepancy Between Experiments and Theory

Experimental results are consistently lower than theory.

Independent and most two accurate experimental average

Theory (2000)

Phys. Rev. Lett. 85, 5094



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

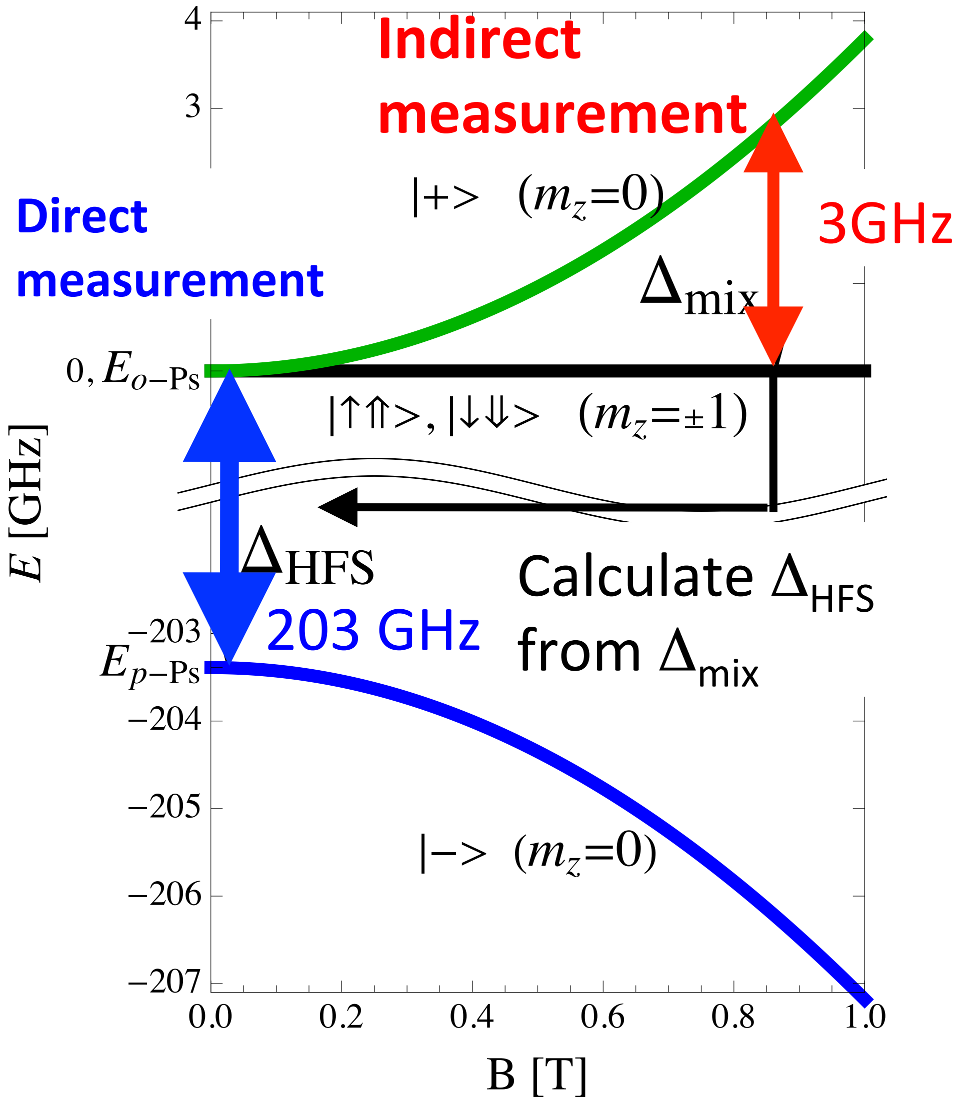
Possible reasons for the discrepancy

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

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

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

Experimental Technique
Indirect Measurement using Zeeman Effect



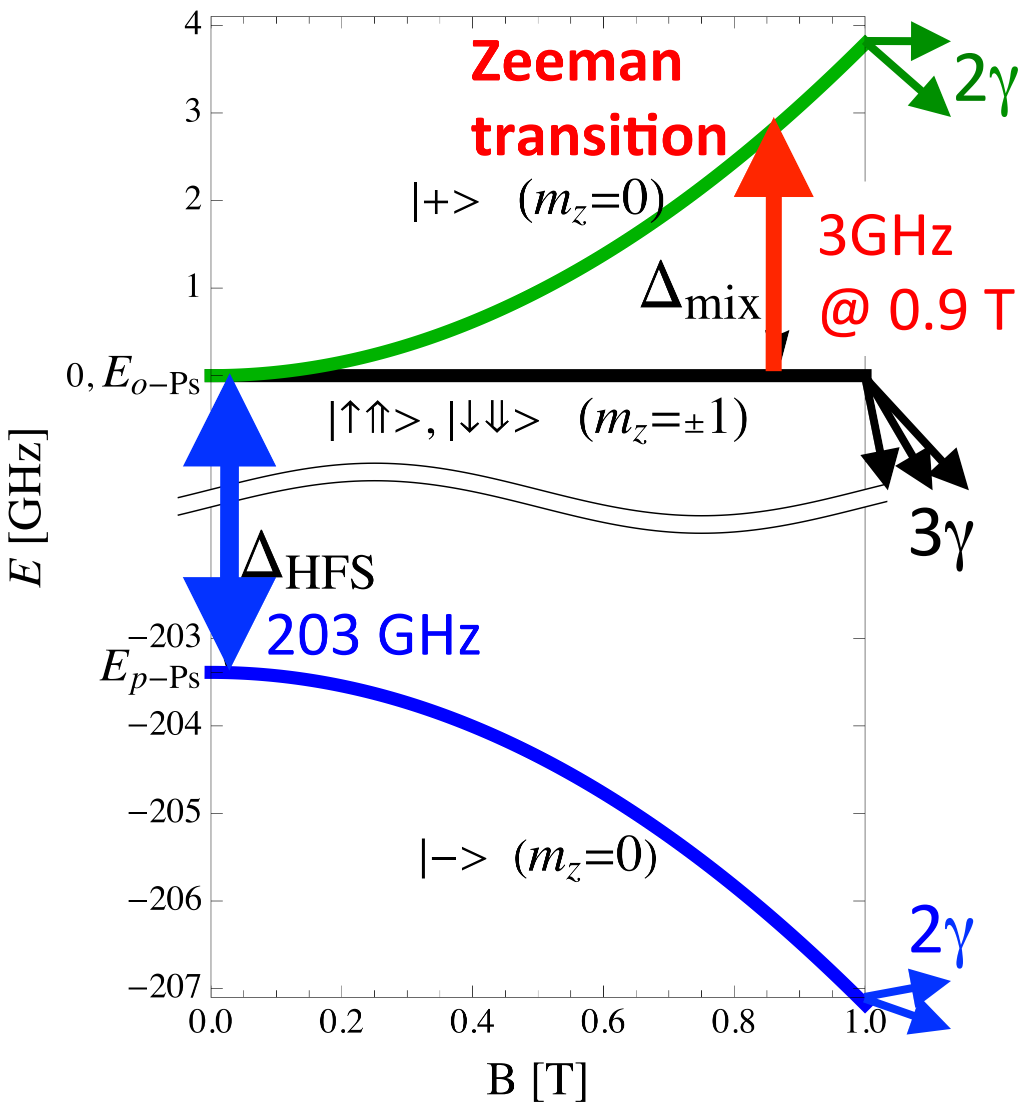
In a static magnetic field, the **p-Ps** state mixes with the **m_z=0 state of o-Ps** (Annihilate into 2 γ-rays).

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

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

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

Experimental Technique
Indirect Measurement using Zeeman Effect

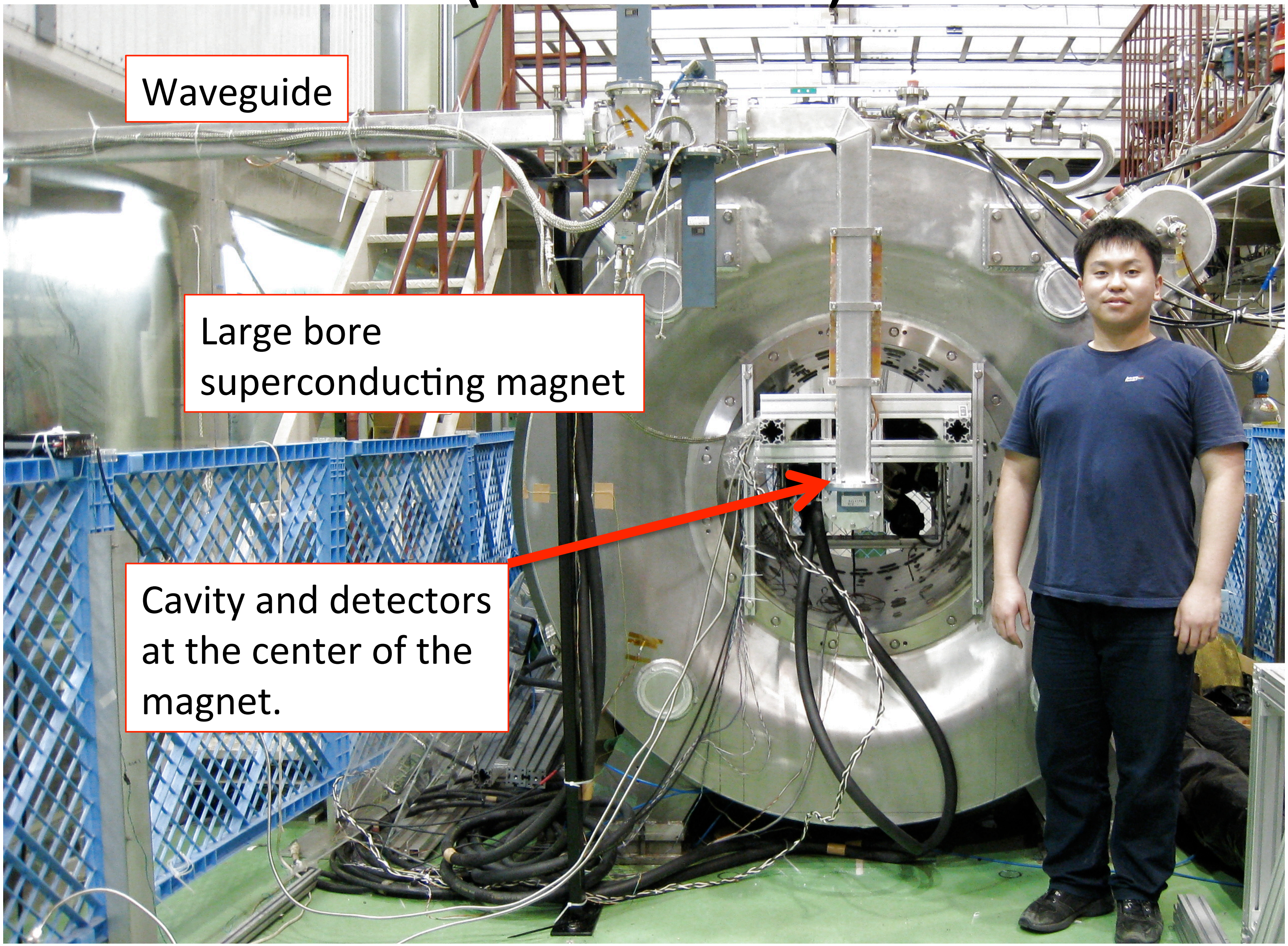


When a microwave field with a frequency of Δ_{mix} is applied, transitions between the m_Z=0 and m_Z=±1 states of o-Ps are induced.

→ 2γ-ray annihilation (**511 keV monochromatic signal**) rate increases.
This increase is our experimental signal.

→This is the same approach as previous experiments.

Measurement @ KEK (Jul 2010 –)



Our new Experiment

RF SG +
GaN Amp.

High power RF
(500W CW)

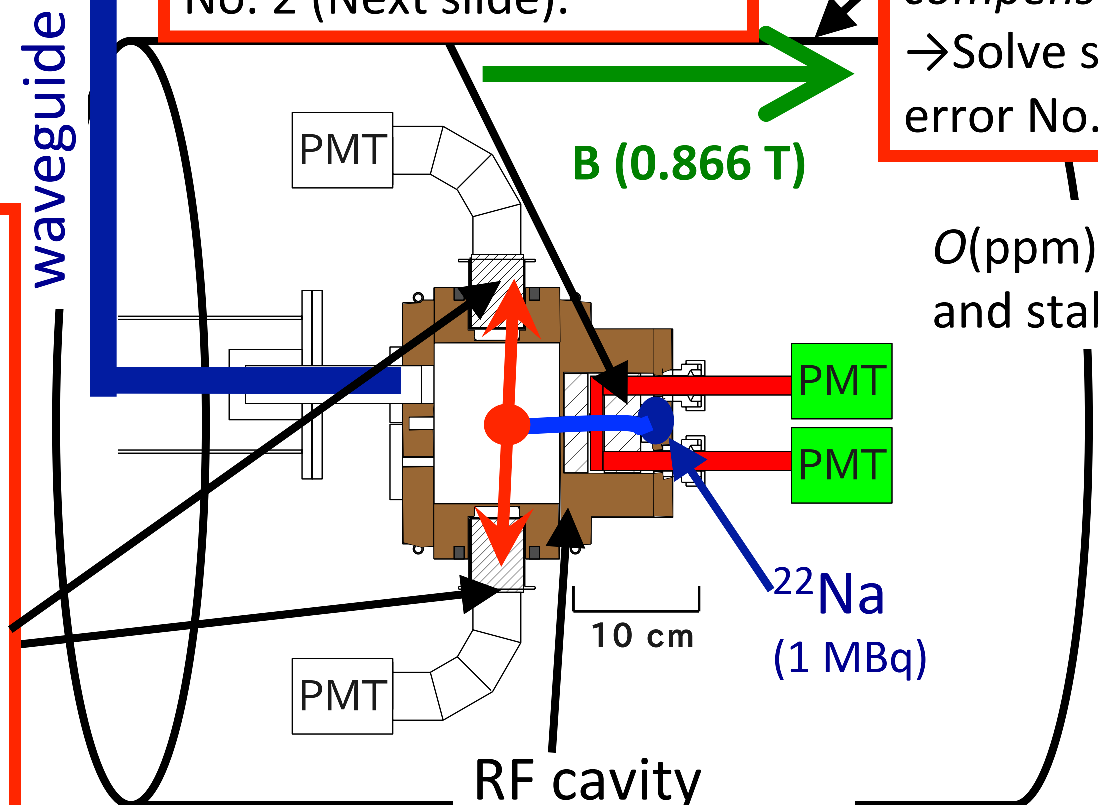
β-tagging system and *Timing information*
→Solve systematic error No. 2 (Next slide).

Large bore superconducting magnet +
compensation coils
→Solve systematic error No. 1.

High performance γ-ray detectors

$LaBr_3(Ce)$ scintillators x 6
(4% energy resolution at 511 keV, fast 16 ns decay constant)

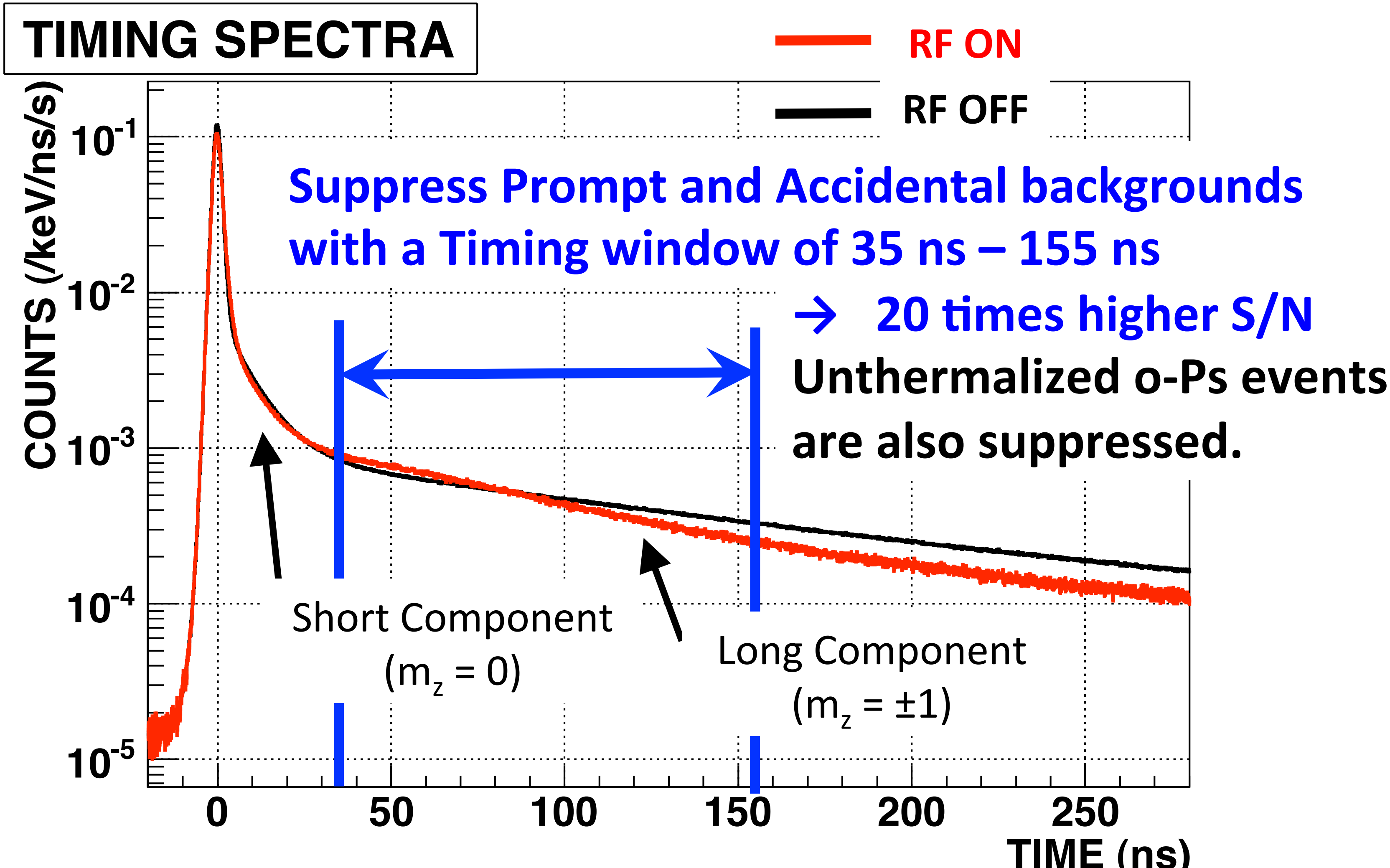
→Solve systematic error No. 2.



O(ppm) uniformity and stability

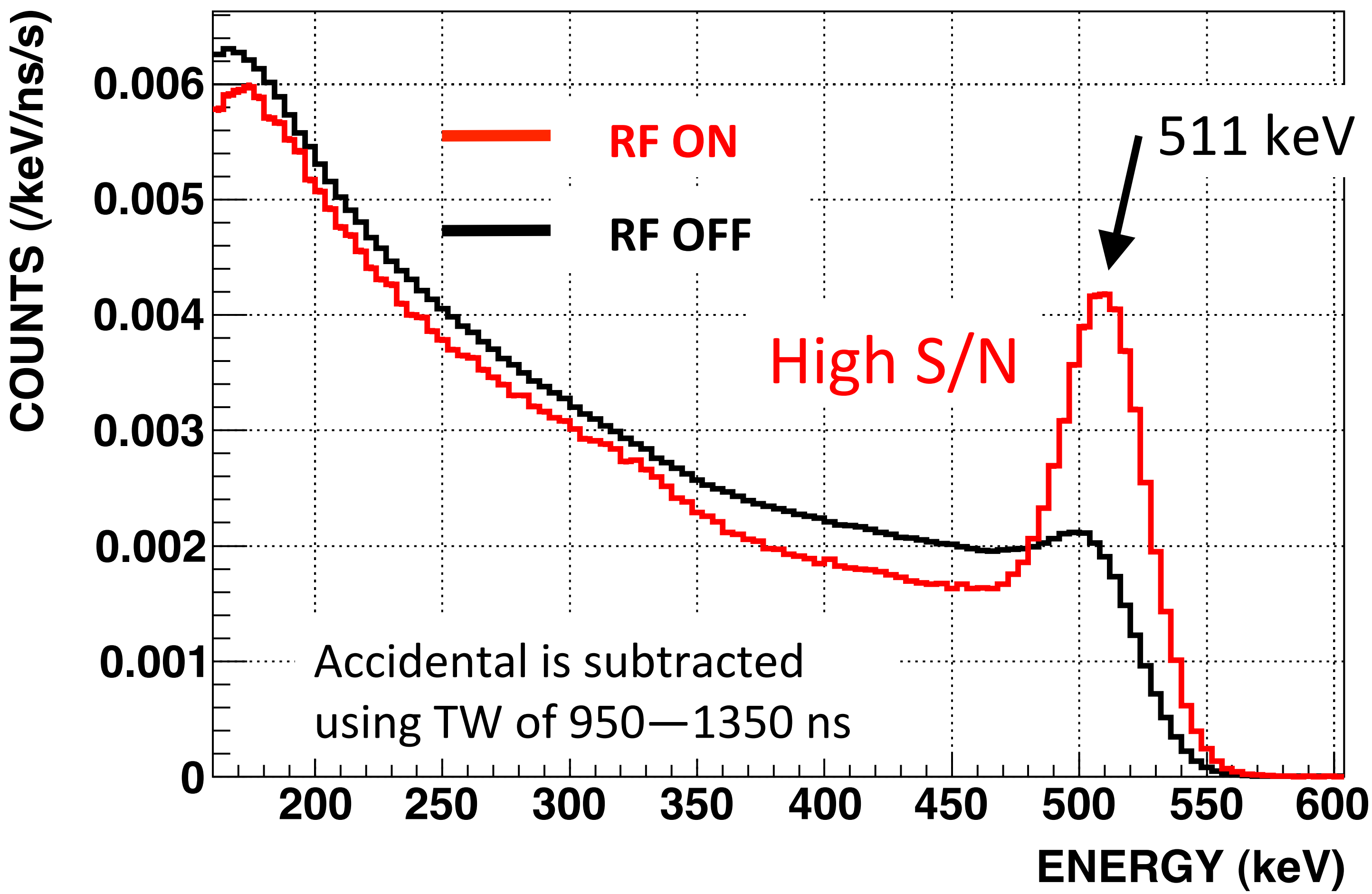
RF cavity
(Filled with pure i-C_4H_{10})

Analysis (Timing Spectra)



In the previous experiment, the timing information was not taken.
→ Previous experimental data were contaminated by significant BGs & data contained fast (non-thermalized) Ps events.

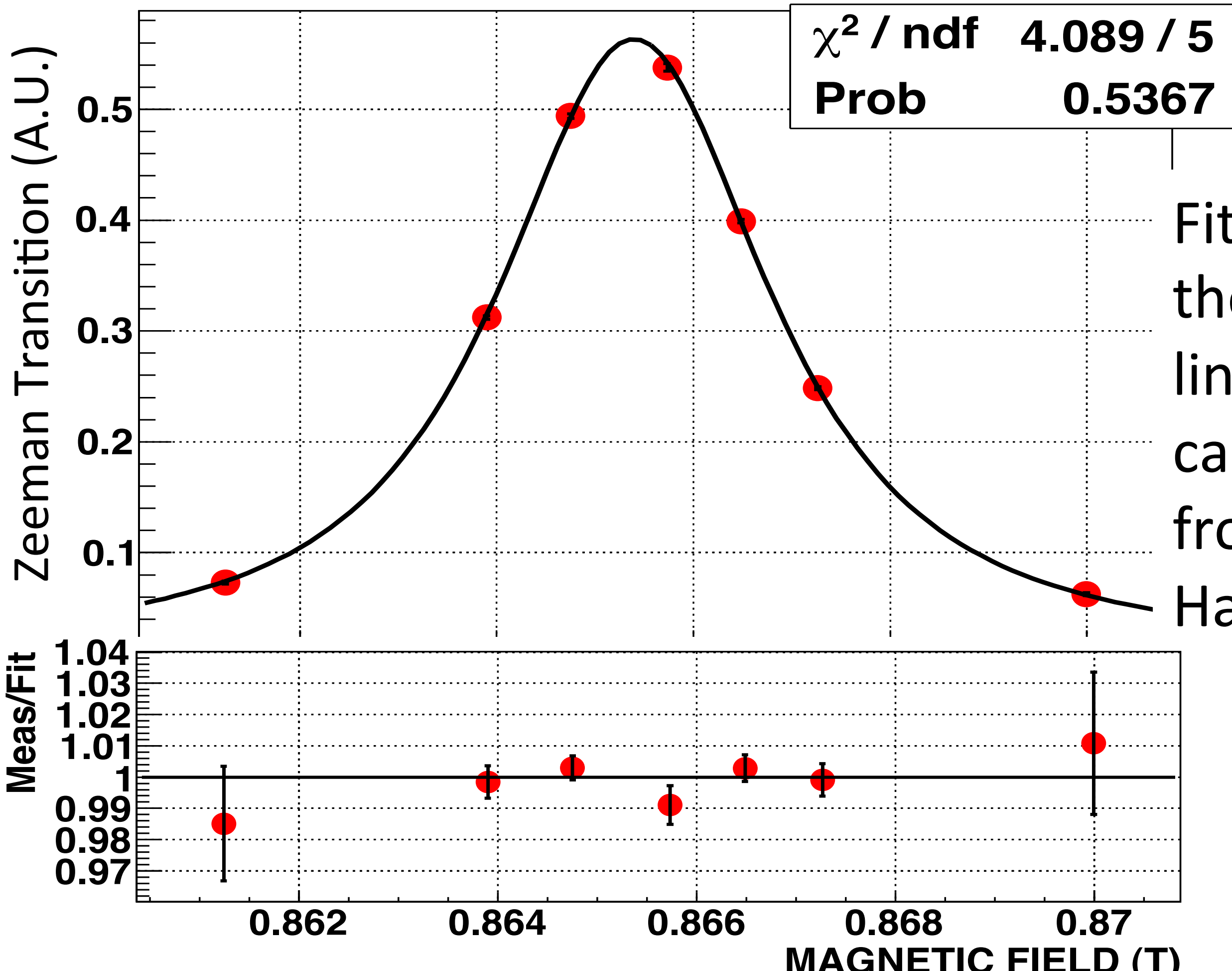
Analysis (Energy Spectra)



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 (0.883 amagat)

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

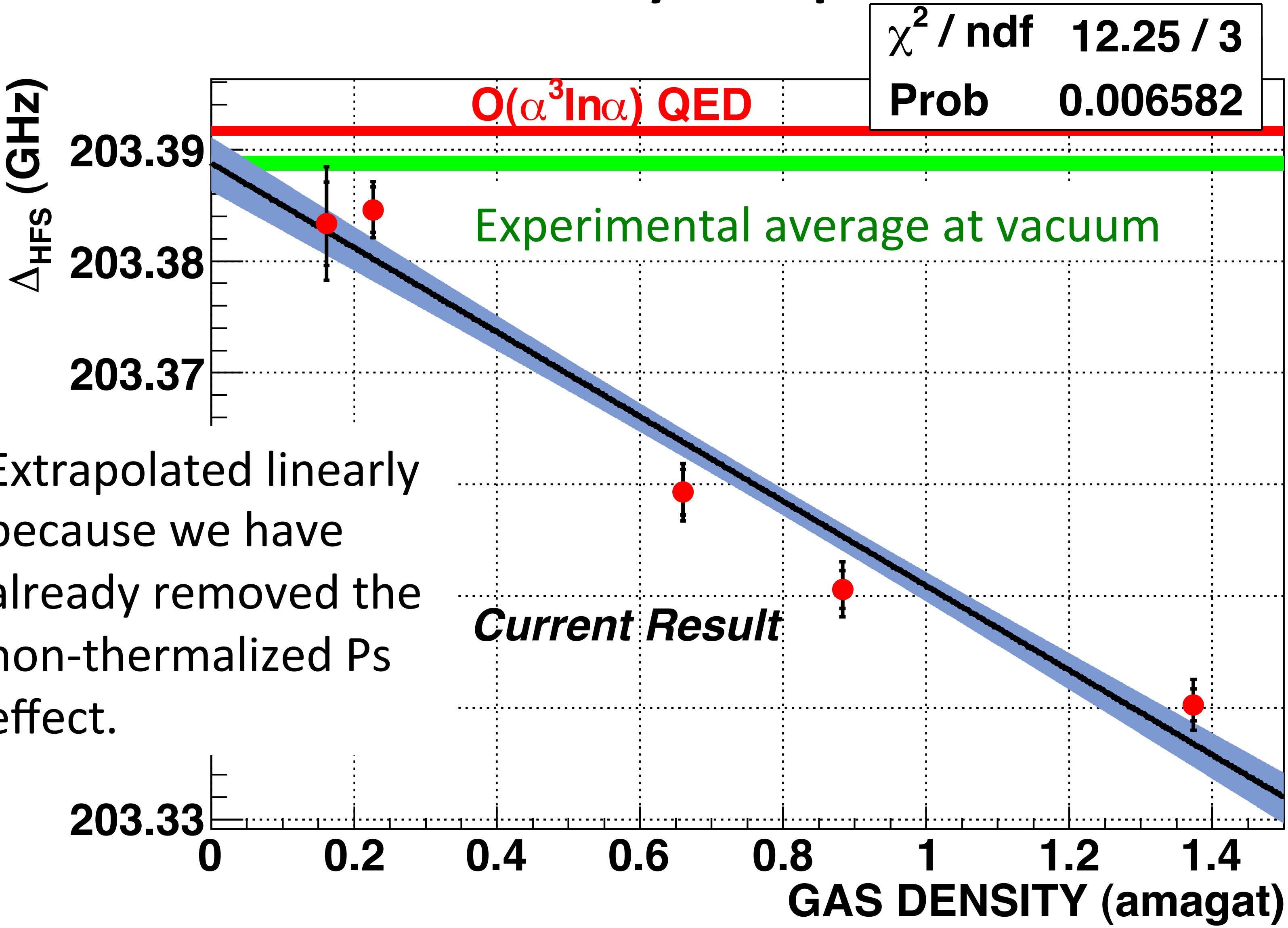


Fitted by theoretical line calculated from Hamiltonian

Δ_{HFS} = 203.3506(20) GHz (9.8 ppm)

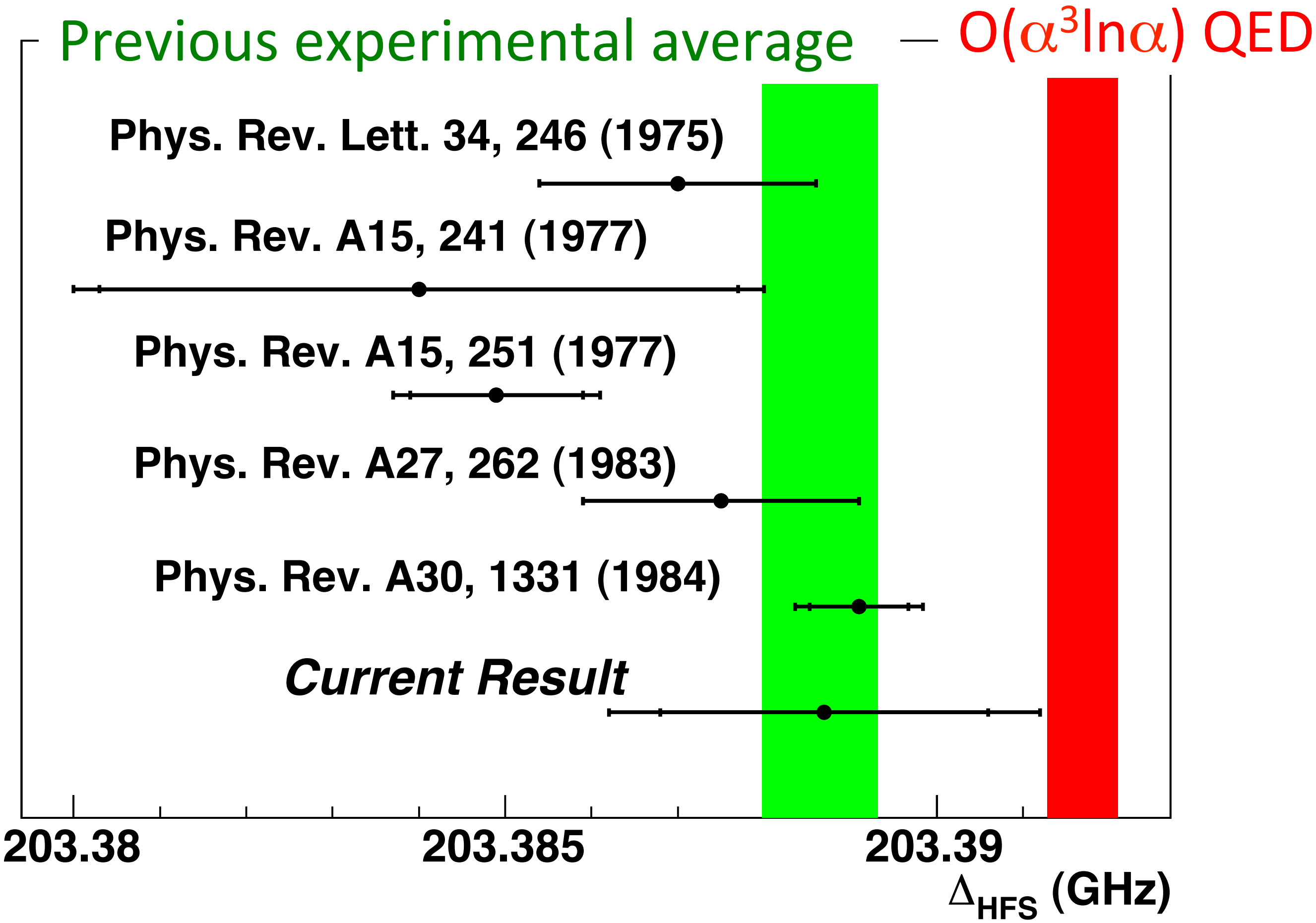
→ Obtain the Δ_{HFS} in vacuum with density correction.

Gas Density Dependence



Extrapolated linearly because we have already removed the non-thermalized Ps effect.

Current Result



Current Result

$$\Delta_{HFS} = 203.3887 \pm 0.0019 \text{ (stat., 9.2ppm)}$$
$$\pm 0.0016 \text{ (sys., 8.0 ppm) GHz}$$

Systematic Errors (Current result)

	Source	ppm in Δ_{HFS}
Magnetic field	Non-uniformity	1.8
	Offset and reproducibility	1.0
	NMR measurement	1.0
Detection efficiency	Estimation using MC simulation	5.4
Material effect	Ps thermalization	3.0
RF	RF Power	1.9
	Q_L value of RF cavity	4.5
	RF frequency	1.0
	Quadrature sum	8.0

We can reduce these large systematic errors as shown in the next slide.

Prospects

- Detection efficiency: Currently it is estimated by Monte Carlo simulation. It will be carefully studied and will be estimated by real data. → O(ppm) uncertainty
- Material Effect: 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.
- RF System: The experimental environment (temperature) control → O(ppm) uncertainty
- Statistics: 9.2 ppm has been obtained. We can achieve 3 ppm statistical error within about a year by taking more statistically sensitive points.

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

Conclusion

The current result of

HFS = 203.3887 ± 0.0019 (stat., 9.2 ppm)

± 0.0016 (sys., 8.0 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 about a year which will be an independent check of the discrepancy.