Recent progress on new light boson search with isotope shifts

2023/12/15

@ NCTS Annual Theory Meeting

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Collaboration with M. Tanaka (Osaka U) and

Quantum Optics group (Kyoto U)

New discovery and photon

Photon : massless vector boson without self interaction

Special and general relativity

Quantum mechanics

> Quantization
Black body radiation and photoelectric effect

> Local causality
Bell’s inequality violation

> Quantum field theory
Anomalous magnetic moments

Precision atomic spectroscopy

Measurement of transition energy with laser

> Precise determination of laser frequency

Yb^{+}: 642 121 496 772 645.12 Hz (3.2×10^{-18})

1602.03908: N.Huntemann, et al.

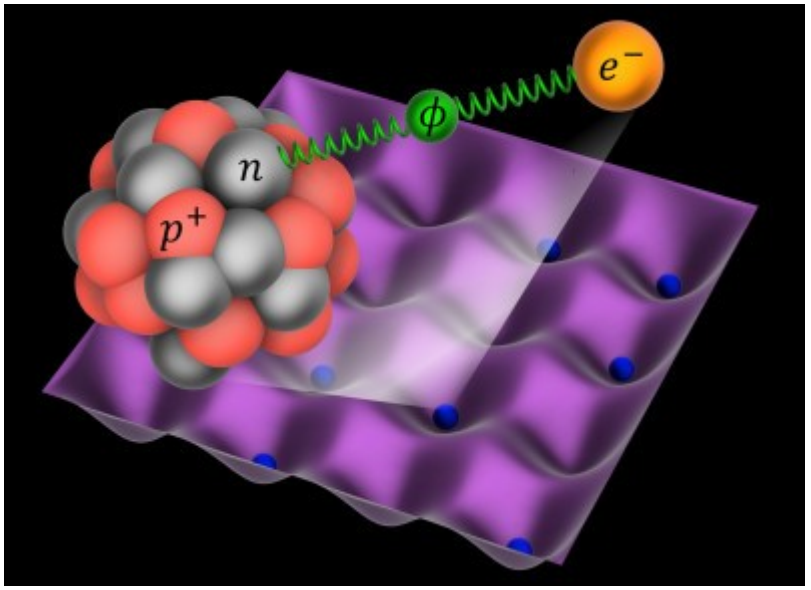
> Rapidly developed with the interest to clock, QC, etc.

1. Measuring absolute frequencies is difficult

2. We cannot extract new physics contribution there

> Spectra shifts among isotopes

Contents



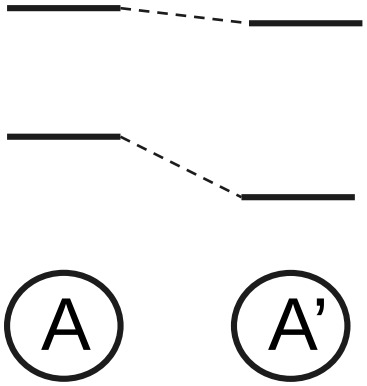
Isotope shifts and King relation

$$\Delta H = \Delta K + \Delta V$$

$$\delta\nu_i^{A'A} = K_i \delta\mu^{A'A} + F_i \delta\langle r^2 \rangle^{A'A}$$

Mass shift — Inverse mass diff.

Field shift — Nuclear size diff

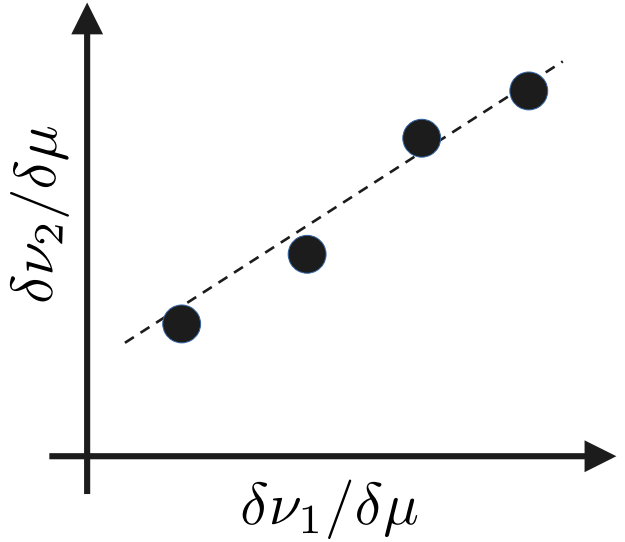


Transitions follow a linear relation

1963, W.H. King

$$\frac{\delta\nu_2}{\delta\mu} = \frac{F_2}{F_1}\frac{\delta\nu_1}{\delta\mu} + K_2 - \frac{F_2}{F_1}K_1$$

Independent of isotopes



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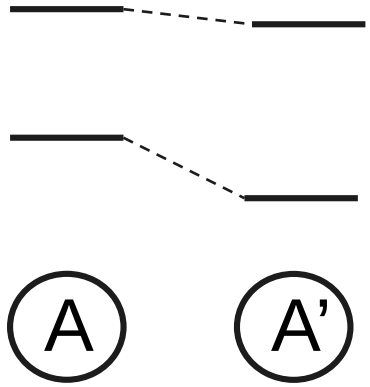
$$\Delta H = \Delta K + \Delta V$$

$$\delta\nu_i^{A'A} = K_i \delta\mu^{A'A} + F_i \delta\langle r^2\rangle^{A'A} + ?$$

Mass shift — Inverse mass diff.

Field shift — Nuclear size diff



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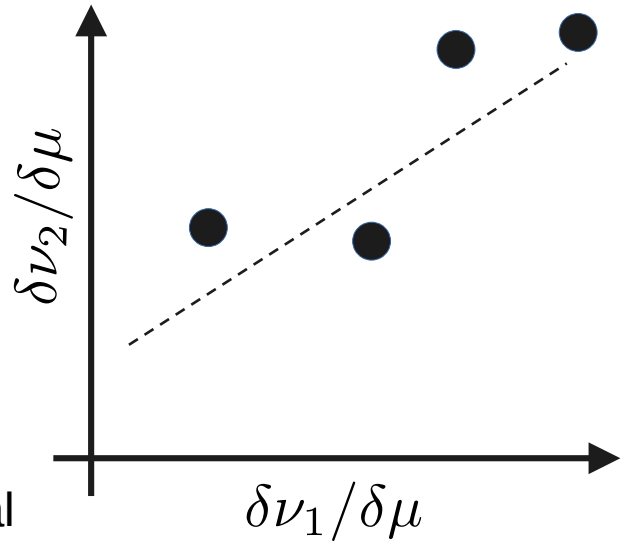


1601.05087: C. Delaunay, et al
1704.05068: J.C. Berengut, et al

Violation and generalization of King relation

Higher order contributions also violate the relation

FS22: 2nd order perturbation $\propto [\delta\langle r^2\rangle]^2$

1709.00600: V.V.Flambaum, et al

FS4 : Next leading order moment $\propto \delta\langle r^4\rangle$

1710.11443: K.Mikami, M.Tanaka, YY
1911.05345: M.Tanaka, YY

The King relation is equation to write nuclear factors

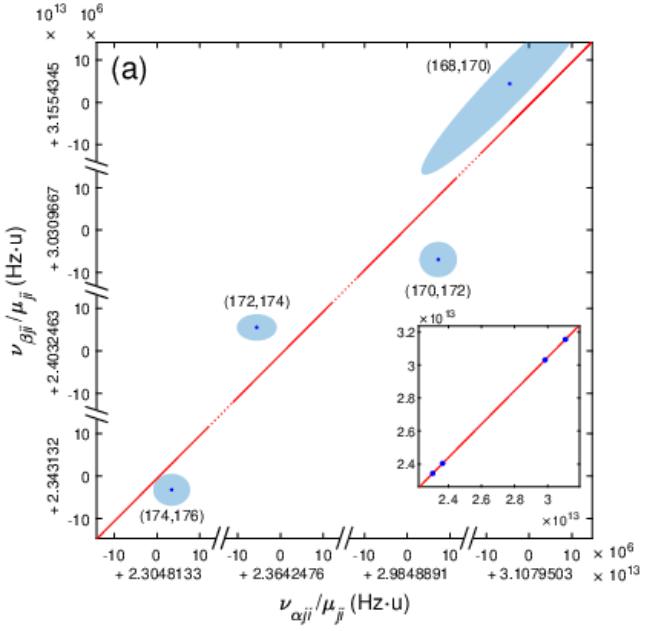
$$\delta\vec{\nu} = \begin{pmatrix} \vdots & \vdots & \\ K_i & F_i & \cdots \\ \vdots & \vdots & \end{pmatrix} \begin{pmatrix} \delta\mu \\ \delta\langle r^2\rangle \\ \vdots \end{pmatrix}$$

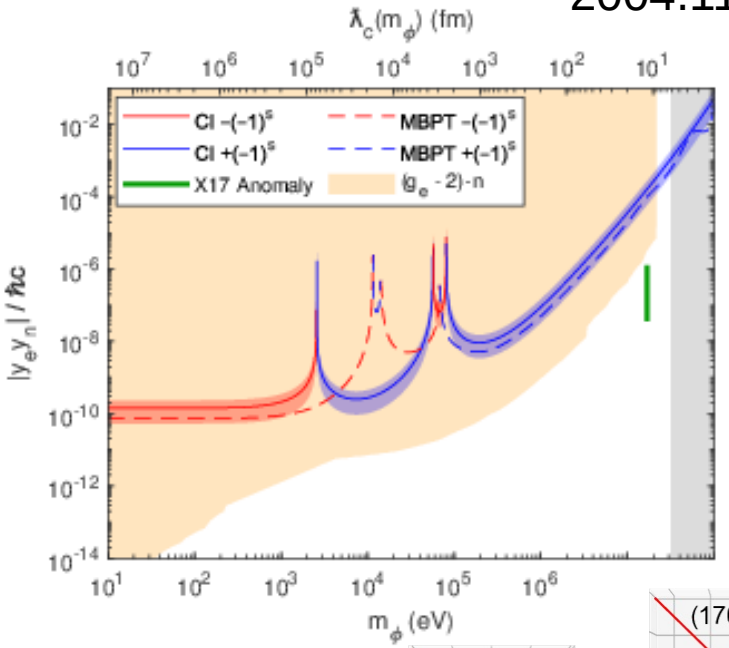
> $\delta\mu = f_1\delta\nu_1 + f_2\delta\nu_2 + \cdots$

Early experimental results with Yb

Non linearity is observed but excluded

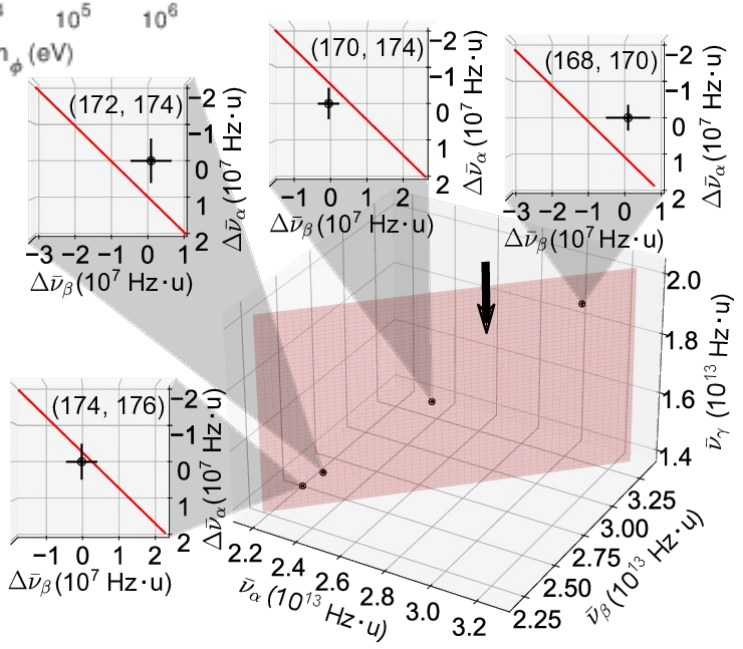
2004.11383: I.Counts, et al





At least 2 higher order sources are observed

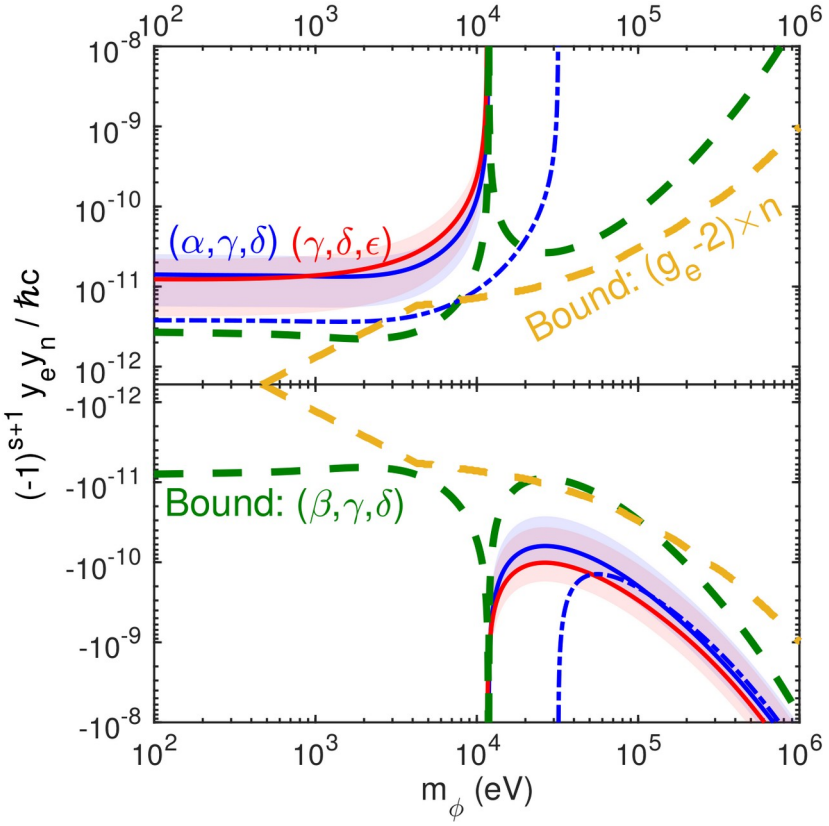
2110.13544: K.Ono, YY, et al

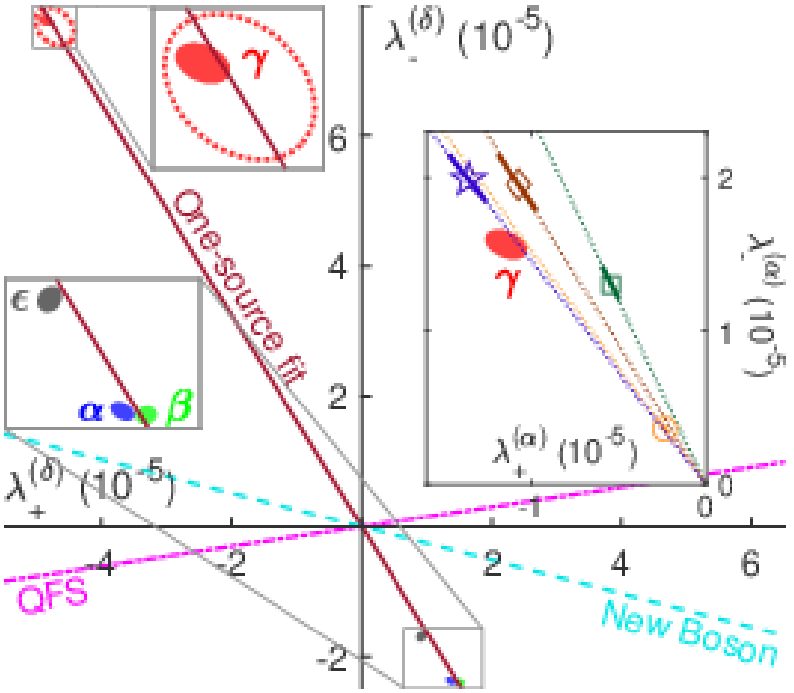


Recent experimental results

5 transitions are measured with Yb

2111.01429: N.L.Figueroa, et al
2201.03578: J. Hur, et al





Ca gives us similar limit on new physics

(Higher order contributions have not been observed yet)

Issues

1. Combine all transition data

   > The generalized King relation can do it

   > Use dual King relation

2. Extract more information from data

   > Test the origins of the higher order sources

   > Constrain nuclear isotope dependence

Combined analysis

Including more transitions are trivial

$$\delta\vec{\nu} = \begin{pmatrix} \vdots & \vdots & \\ K_i & F_i & \cdots \\ \vdots & \vdots & \end{pmatrix} \begin{pmatrix} \delta\mu \\ \delta\langle r^2\rangle \\ \vdots \end{pmatrix}$$

Add as an additional nuclear factor

$$0 = K_{n+1}\delta\mu + F_{n+1}\delta\langle r^2\rangle + \cdots - \delta\nu_{n+1}$$

Linear relations to be fit

$$\delta\mu = f_1\delta\nu_1 + f_2\delta\nu_2 + \cdots$$

$$\delta\nu_{n+1} = f_1'\delta\nu_1 + f_2'\delta\nu_2 + \cdots$$

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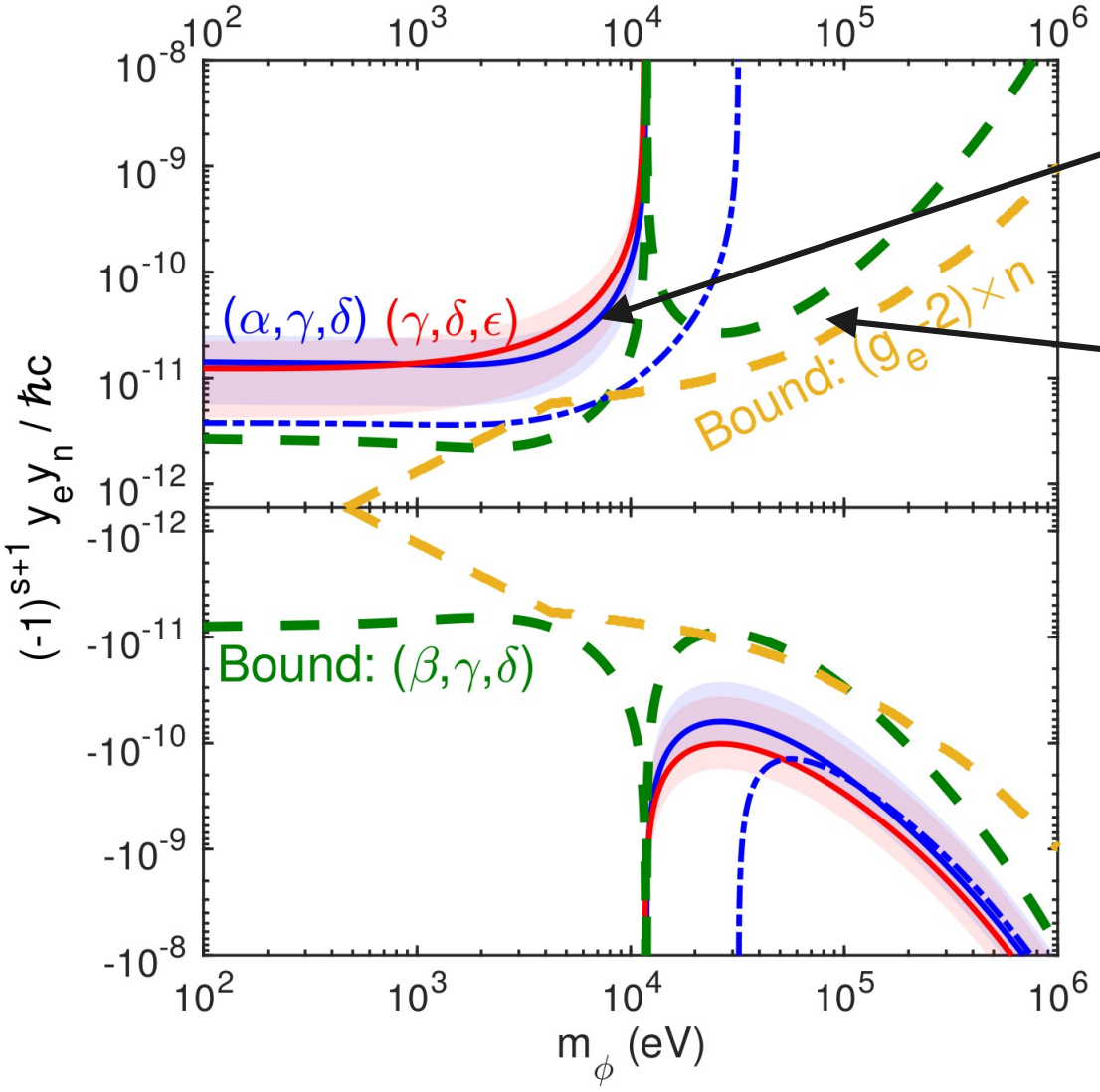
$$\delta\mu = f'_n\delta\nu_n + f'_2\delta\nu_2 + \cdots$$

Read out results



Two higher order sources are observed

One higher order source is observed

Two higher order sources are inevitable for observed Yb isotope shifts (4.7σ)

Observed higher orders cannot be new physics

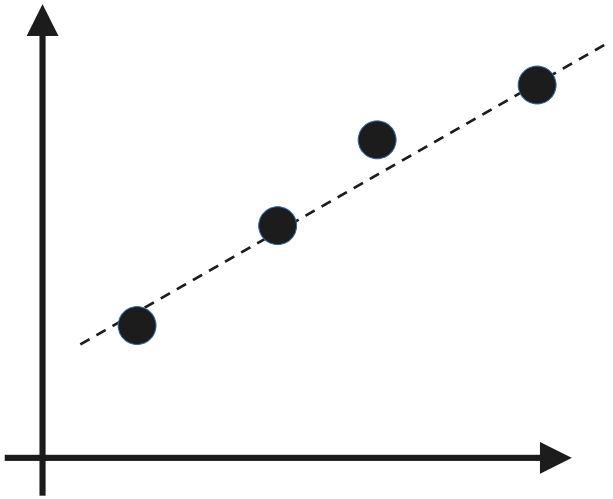
Dual King relation

2209.14126: YY

Isotope shift does not care electronic/nuclear factors

$$\delta\nu_i^{A'A} = K_i\delta\mu^{A'A} + F_i\delta\langle r^2\rangle^{A'A}$$

Different isotope pairs follow another linear relation



$$\delta\nu^{A_3A} = a_1\delta\nu^{A_1A} + a_2\delta\nu^{A_2A}$$

New transitions follow the same relation.

It provides the same fit result with the original one

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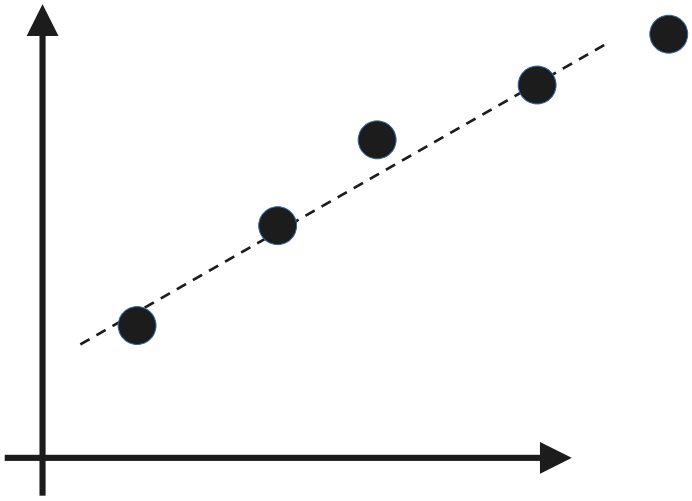

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Nuclear isotope dependence

Ratios of nuclear factors are constrained by isotope shifts

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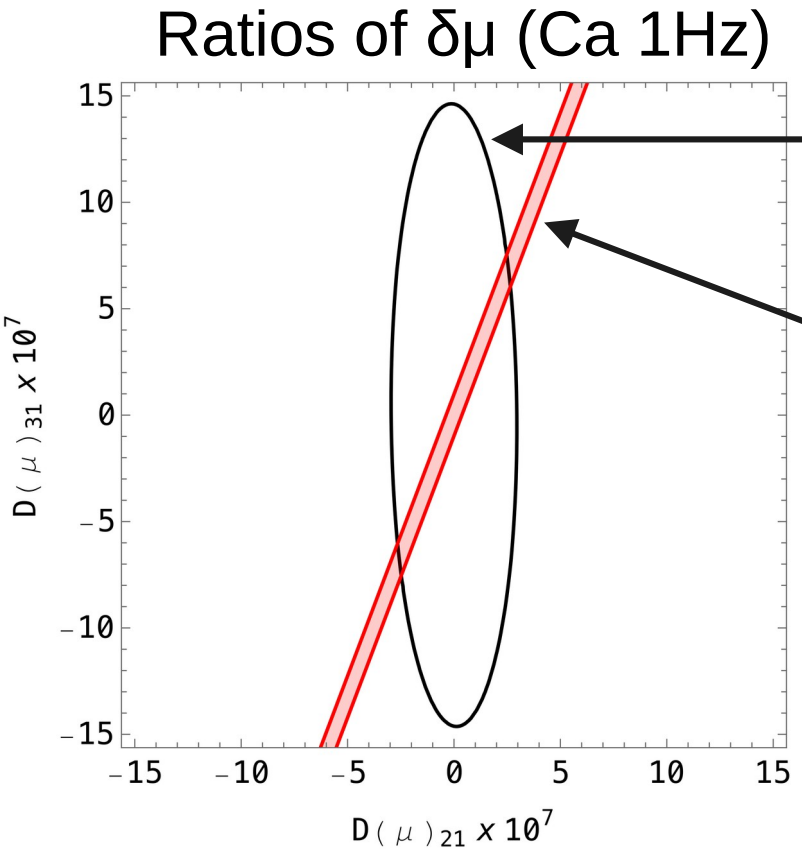

Constraints by direct mass measurements

Constraints by isotope shifts (x 10^2)

$\delta\langle r^2 \rangle$ gets the same constraint

Coefficient analysis

2312.1xxxx: M.Tanaka, YY, et al

Available isotope pairs of Yb are 4

> At least 2 higher order isotope shifts are observed

> New physics is not included there

> More fit parameters than data

Cancel a source with other transitions

$$\delta\mu = f_1\delta\nu_1 + f_2\delta\nu_2 + f_3\delta\nu_3 + f_4\delta\nu_4$$

$$\downarrow \quad \delta\nu_i \ni H_i\delta\eta$$

$$f_4 = -\frac{f_1H_1 + f_2H_2 + f_3H_3}{H_4}$$

Consistency of FS22 and FS4

Are electronic factors reliable? > No!

FS22	D5	D3	F7	P0	D2	(/D5)	D3	F7	P0	D2
AMBiT	81.91	83.25	-201.1	54.28	75.32		1.016	-2.455	0.6623	0.9196
GRASP	42.57	43.20	-112.3				1.015	-2.639		
RPA	28.53	28.53			23.34		1.000			0.8181

Consistent in 10% level

Data can be consistently fit assuming 6–8% of errors

	FS22				FS4			
(/D5)	D3	F7	P0	D2	D3	F7	P0	D2
FS22+?	1.013	-2.200	0.6262	0.8197				
FS4 +?					1.078	-2.523	0.5897	0.7879
FS22+FS4	1.061	-2.335	0.6574	0.8123	1.080	-2.526	0.5894	0.7949
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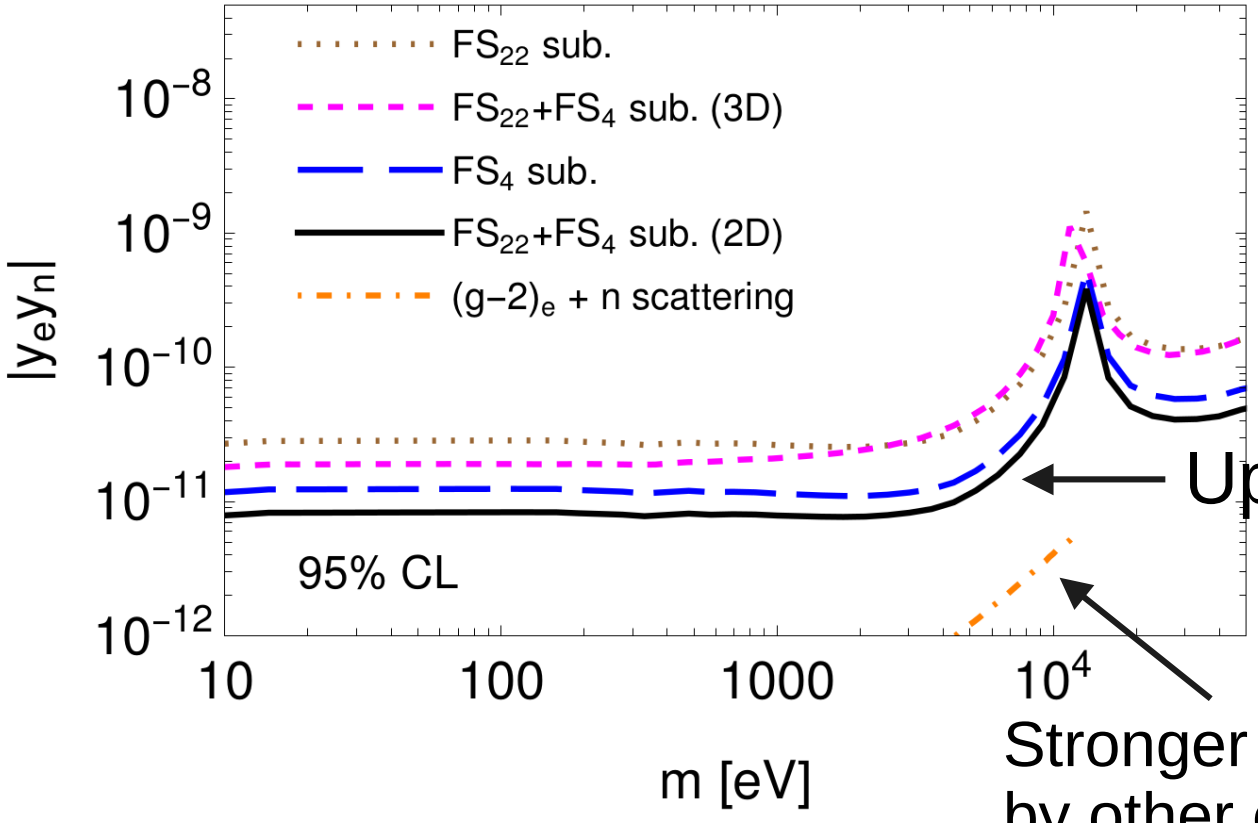
New physics bonds

Subtract higher orders and constrain new physics



Upper bounds ~ 10^{-11}

Stronger constraint is obtained by other experiment

c.f., latest bound with Ca is the same level

Conclusion

Theoretical understanding of isotope shift is required

> Generalized King relation to study many data

> Electronic factor calculations should be important

> Dual King relation

> Strong constraints on nuclear factors