Nuclear ground-state properties in the context of V_{ud} and the 4-sigma tension in the CKM unitarity test

Stephan Malbrunot-Ettenauer

CERN Research Physicist

V_{ud} and CKM unitarity

mass eigenstates & weak eigenstates

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L$$

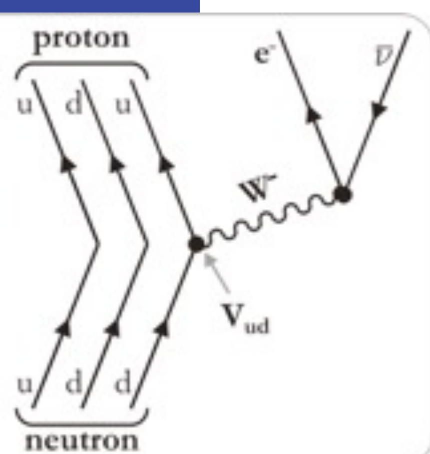
Cabibbo–Kobayashi –Maskawa matrix

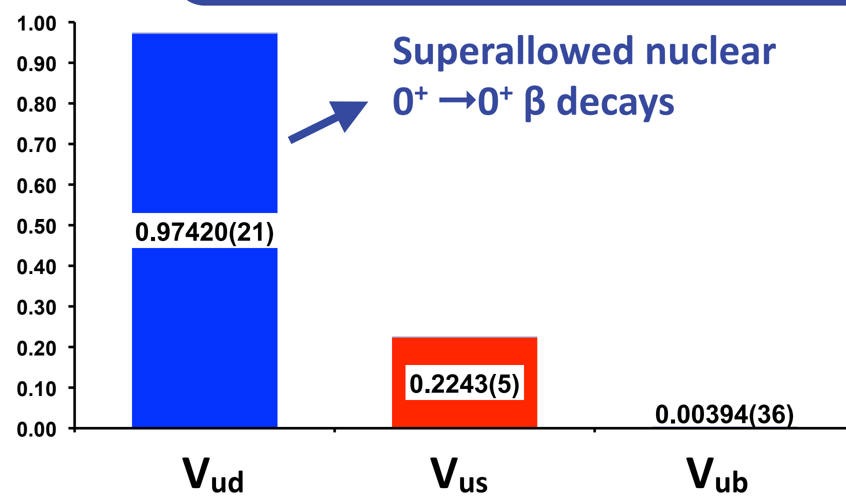
β - decay

→ experimental test of unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta_{CKM}$$

$\Delta_{CKM} = 6(5) \cdot 10^{-4}$





PDG 2019

superallowed $0^+ \rightarrow 0^+$ β decays

experimental input

$$\mathcal{F}t = (1+\delta_R)(1+\delta_{NS}-\delta_C)ft = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{const} \rightarrow \left|V_{ud}\right| = \frac{G_V}{G_F}$$

radiative

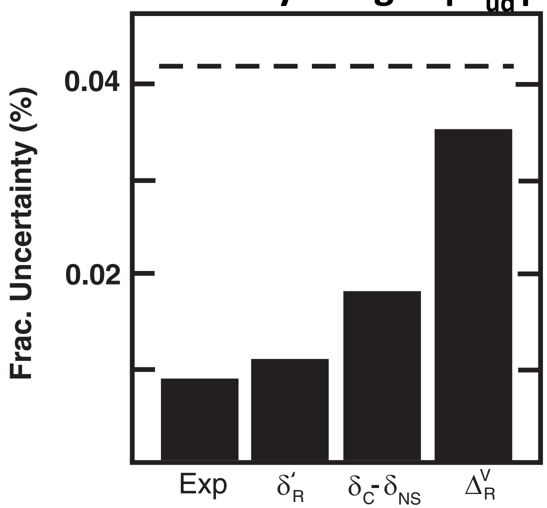
nucl. struct.

isospin-sym. breaking

inner radiative

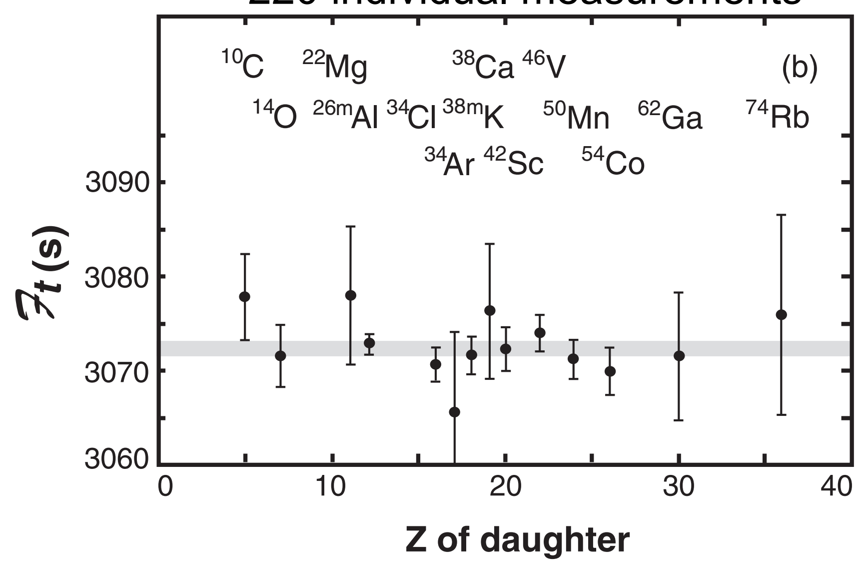
theoretical corrections (small)

uncertainty budget $|V_{ud}|^2$:



J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)

14 precision cases based on ≈220 individual measurements



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radiative — nucl. struct. — isospin-sym. breaking — inner radiative

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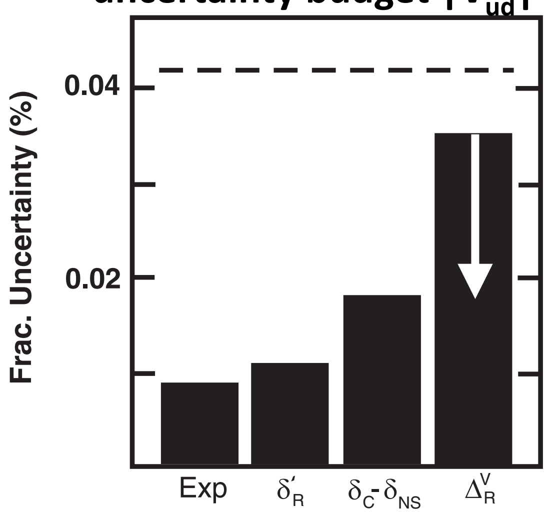


J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)

new calculation of Δ_R^V

- ➡ reducing uncertainty by ~2
- ➡ tension to CKM unitarity

$$\Delta_{CKM} = 16(4) \cdot 10^{-4}$$

C.-Y. Seng et al., PRL 121, 241804 (2018)

- ➡ are theoretical uncertainties (in δ_{NS}) in other corrections underestimated?

C.-Y. Seng et al., arXiv:1812.03352 (accepted PRD)

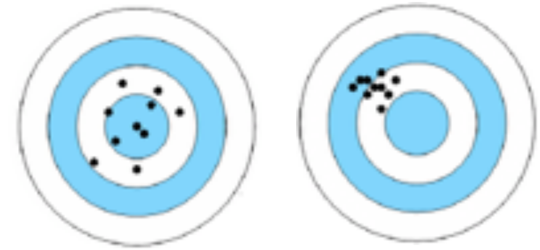
- ➡ (also applies to neutron β decay)

strongly motivates new studies

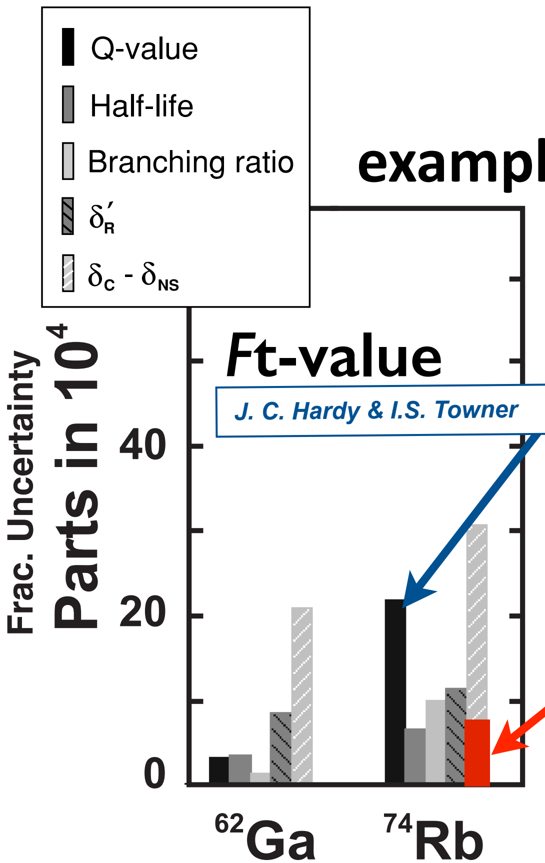
ISOLDE

nuclear ground state properties & V_{ud}

obtained through atomic physics techniques
⇒ superb precision and accuracy



accurate, but not precise — precise, but not accurate



example of ^{74}Rb

Q-value

⇒precision Penning-trap mass measurements

A. Kellerbauer et al., PRL 93, 072502 (2004)
PRC 76, 045504 (2007)
SME et al., PRL 107, 272501 (2011)
PRC 91, 045504 (2015)

all $0^+ \rightarrow 0^+$ cases done in Penning traps

ISB corrections

≈20 % due to charge radius R_c

⇒ accessible through laser spectroscopy

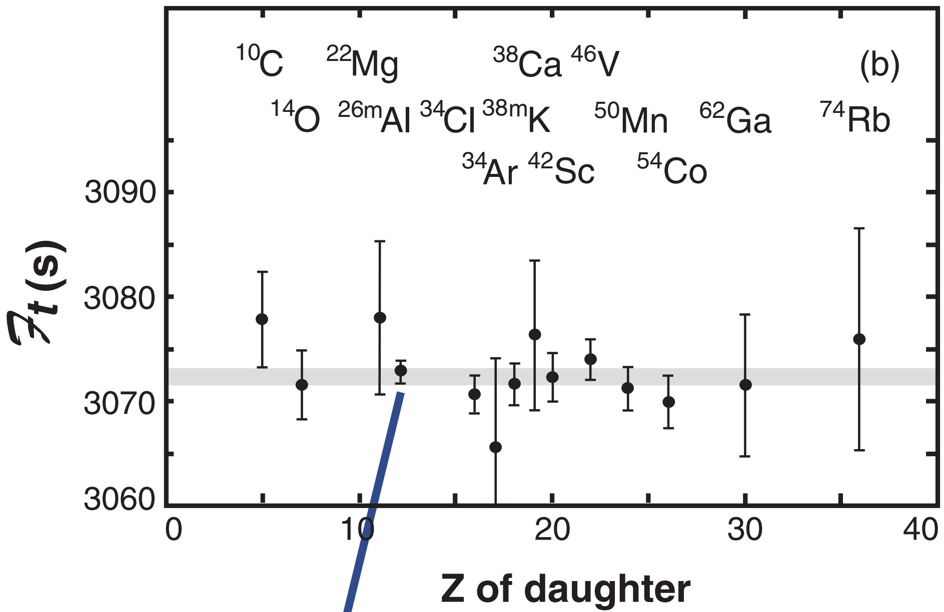
E. Mané et al., PRL 107, 212502 (2011)

not known experimentally for many $0^+ \rightarrow 0^+$ cases!

nuclear ground state properties & V_{ud}

$$Ft = ft(1+\delta_R)(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)} = \text{const}$$

$$|V_{ud}| = \frac{G_V}{G_F}$$



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- most precisely studied superallowed β emitter
- rivals precision of all other 13 cases combined

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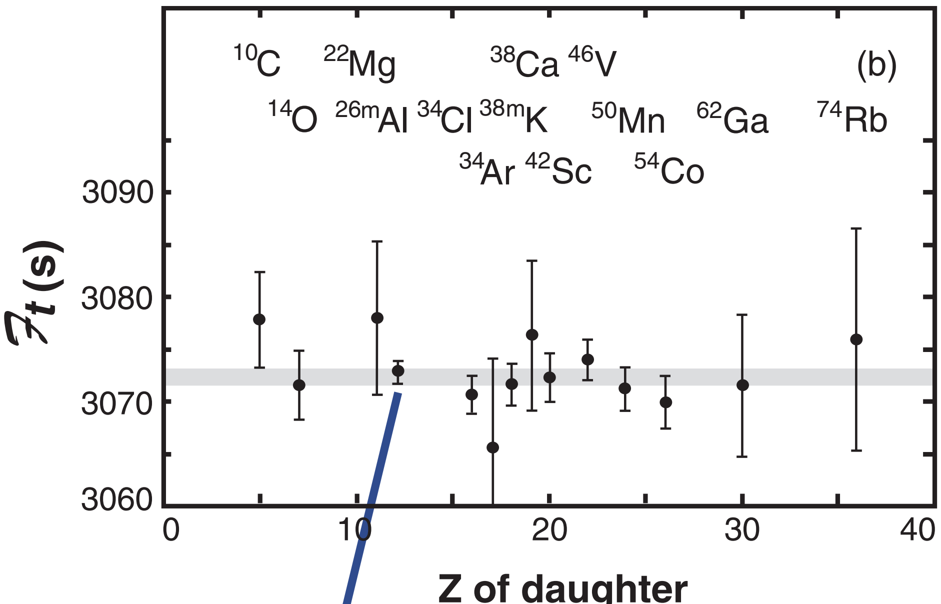

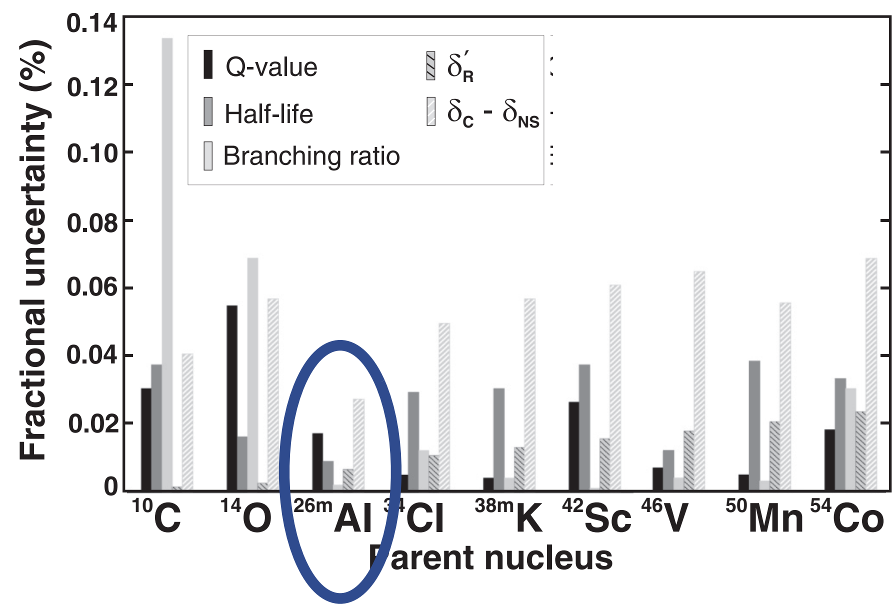

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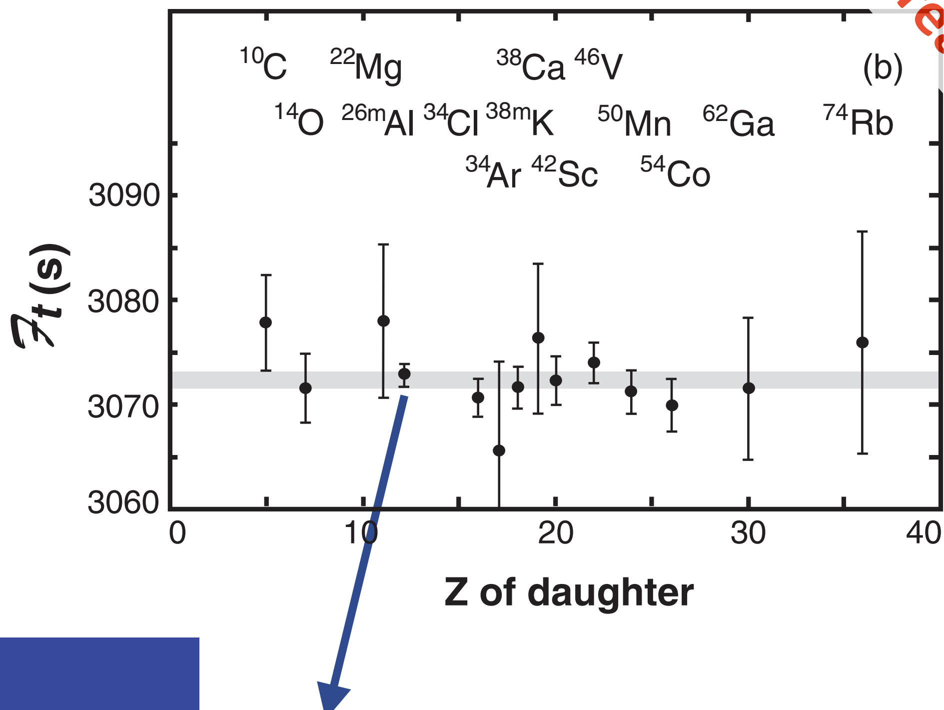

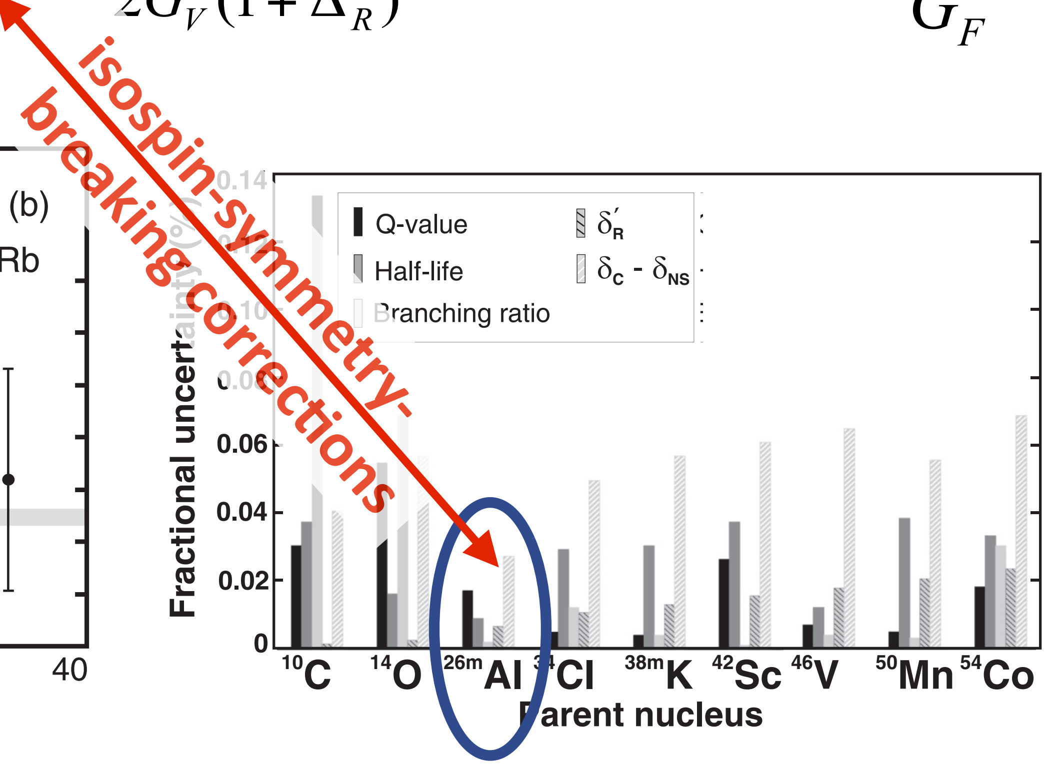

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ISB corrections δ_c

$$\delta_C = \delta_{C1} + \delta_{C2}$$

configuration mixing within the restricted shell model space

radial overlap correction

^{26m}Al

δ_{C1} = 0.030(10) %
δ_{C2} = 0.280(15) %

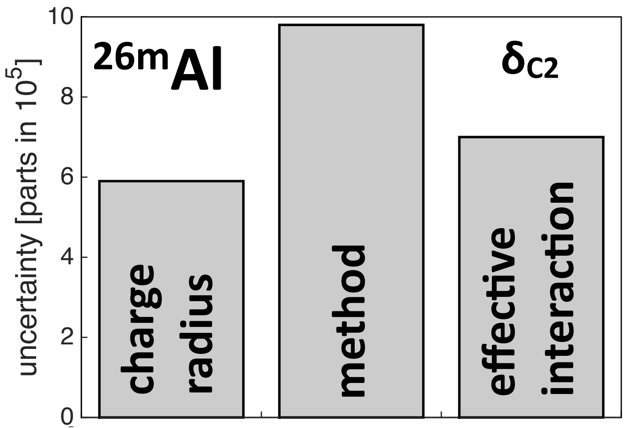
I. S. Towner & J. C. Hardy, PRC 66, 035501 (2002).
I. S. Towner & J. C. Hardy, PC 77, 025501 (2008).

δ_{C2}: shell model based on Saxon-Woods radial functions

$$V_C(r) = Ze^2/r, \quad \text{for} \quad r \geqslant R_c,$$
$$= \frac{Ze^2}{2R_c}\left(3 - \frac{r^2}{R_c^2}\right), \quad \text{for} \quad r < R_c,$$

- nuclear charge radius enters here
- often not known experimentally (e.g. ^{26m}Al)

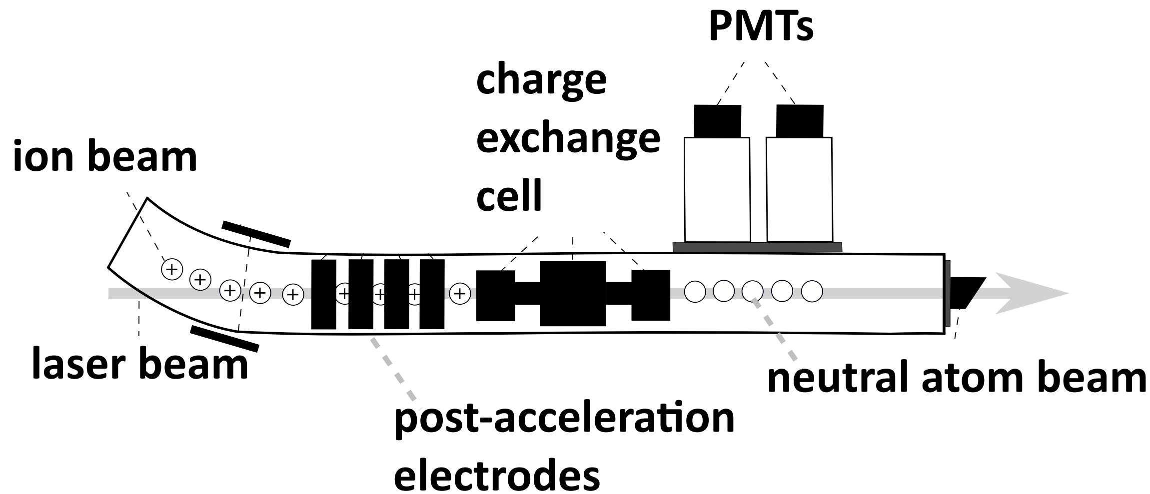
⇒extrapolation based on stable isotopes (and inflated uncertainties)

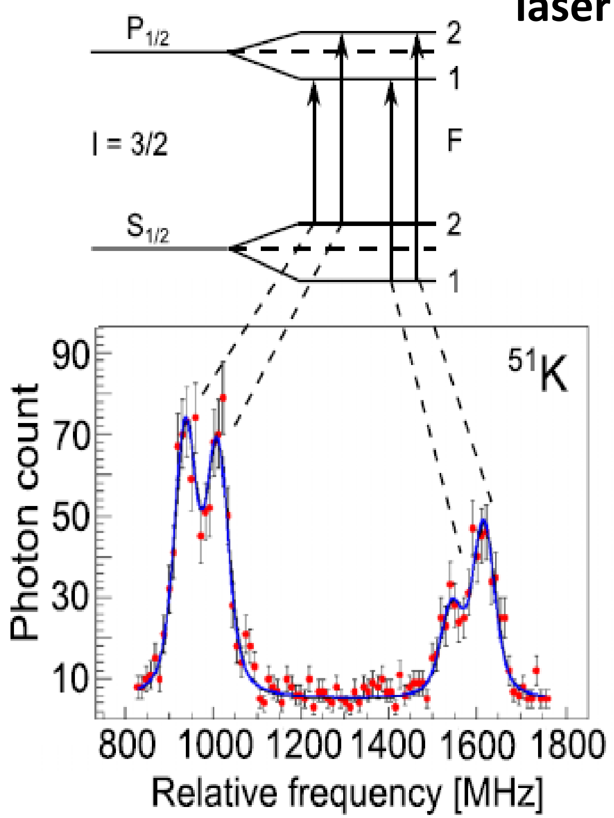


I. S. Towner private communications (2016).

measurement to place $\langle r^2 \rangle$ on solid experimental grounds

Collinear Laser Spectroscopy (CLS)



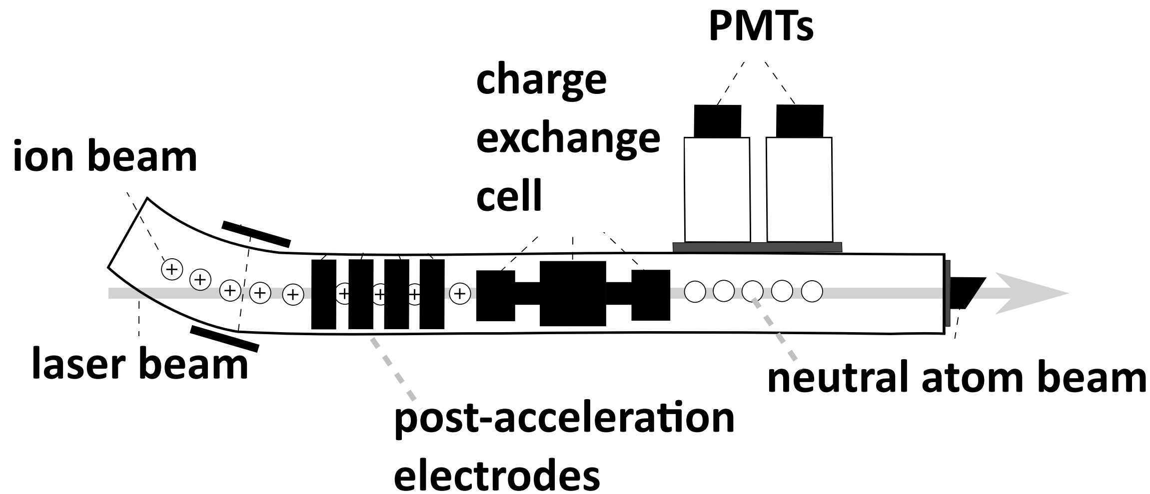


> 30 keV to eliminate Doppler broadening

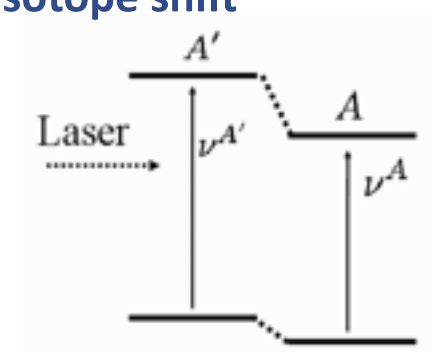
$$\delta\nu \propto \frac{\delta E}{\sqrt{E}}$$

K. Blaum et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)

Measurement at COLLAPS/ISOLDE



isotope shift



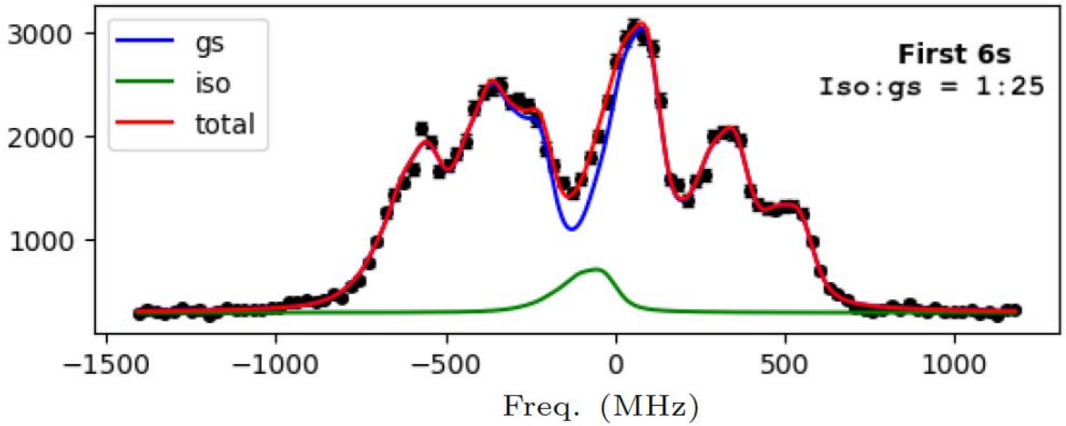
$$\delta\nu^{A,A'} = M\frac{A'-A}{A\cdot A'} + F\,\delta\langle r^2\rangle^{A,A'}$$

difference in ms charge radii

mass and field shift factors from atomic physics calculation

L. Filippin et al., Phys. Rev. A, 94, 062508 (2016)

^{26}Al results at COLLAPS



unexpectedly low ratio of isomer to ground state

Preliminary

H. Heylen et al. @ COLLAPS

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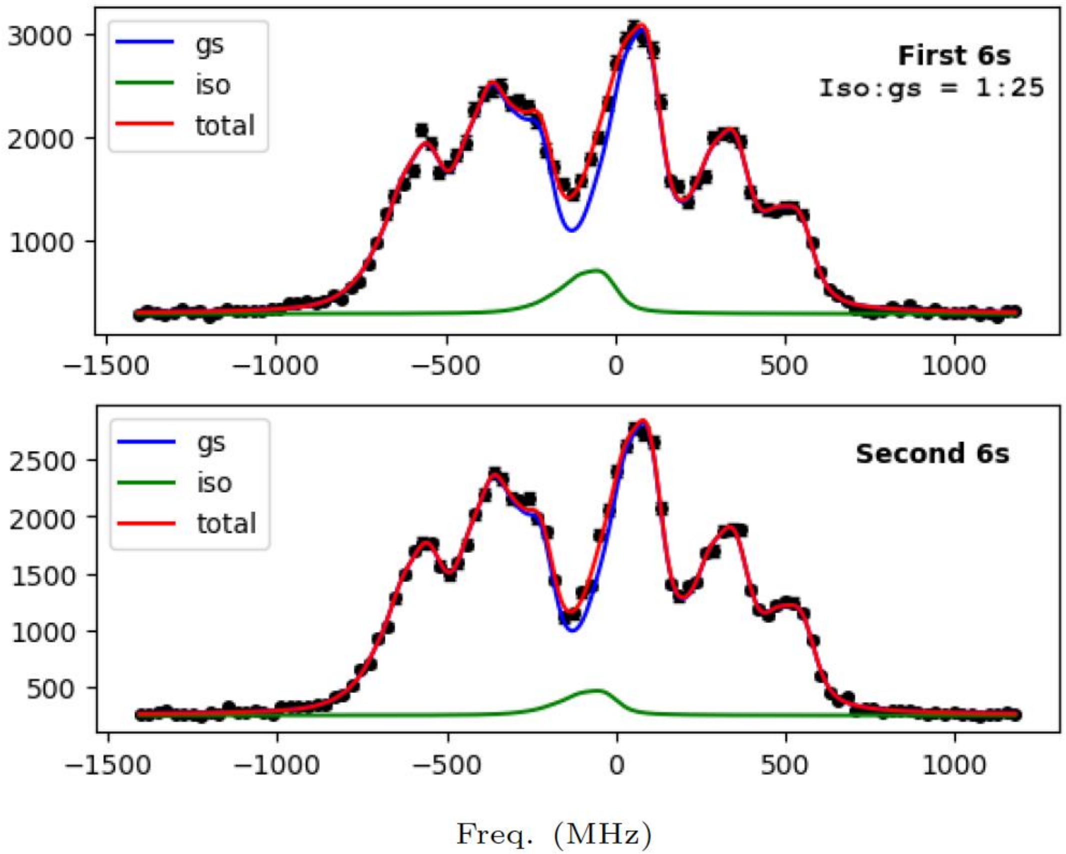

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Preliminary

<u>Intensity ratio first 6s/second 6s:</u>

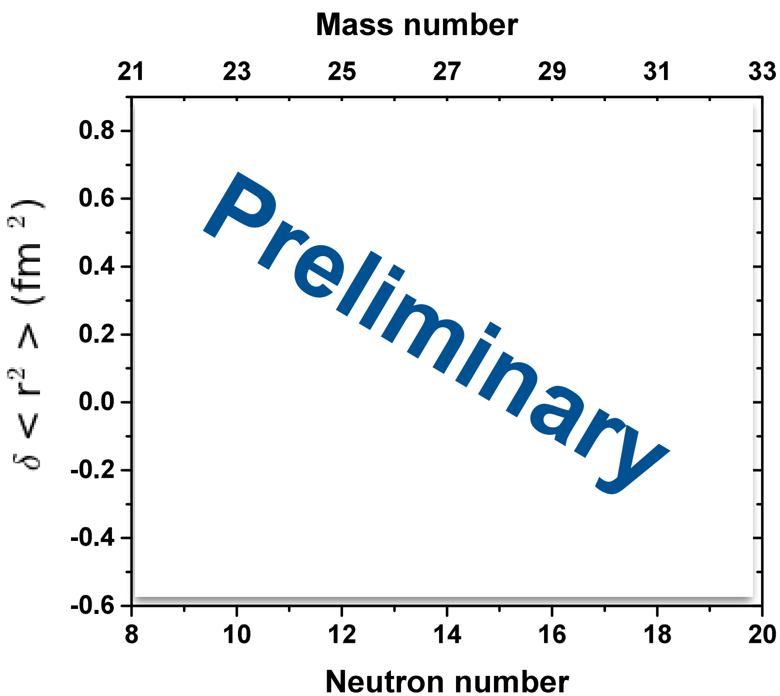
Gs: 0.94(1) [$T_{1/2}$ = 7 x10^5 y]

Iso: 0.56(4) [$T_{1/2}$ = 6.34 s]

H. Heylen et al. @ COLLAPS

Al charge radii

Preliminary



$$\delta\nu^{A,A'} = M\frac{A' - A}{A \cdot A'} + F\delta\langle r^2\rangle^{A,A'}$$

F = [74.0 – 77.5] MHz/fm^2

M = [-239 – -224] GHz u

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Conclusion

- sizeable theoretical uncertainties (due to M)
- $R_{26m} > R_{26gs} > R_{27}$

H. Heylen et al. @ COLLAPS

ISOLDE

Al charge radii

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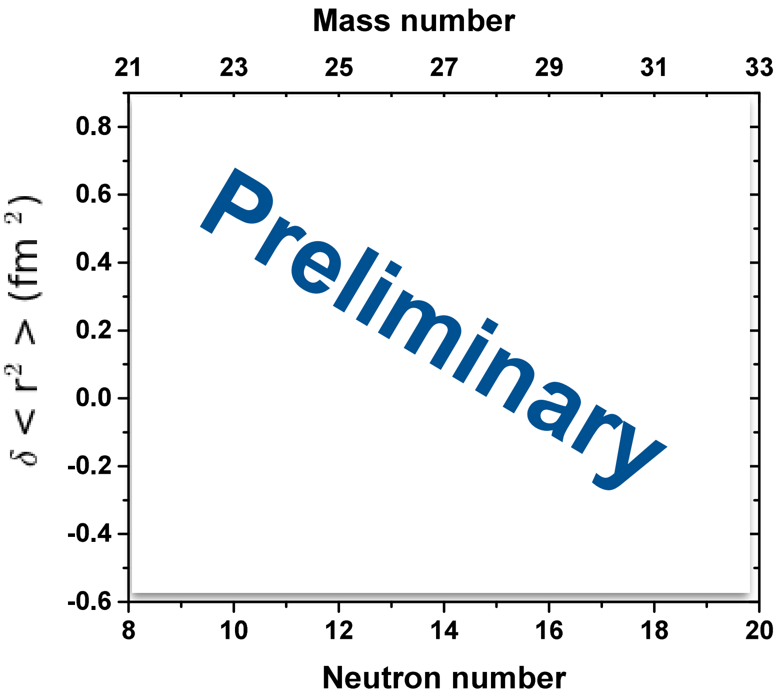

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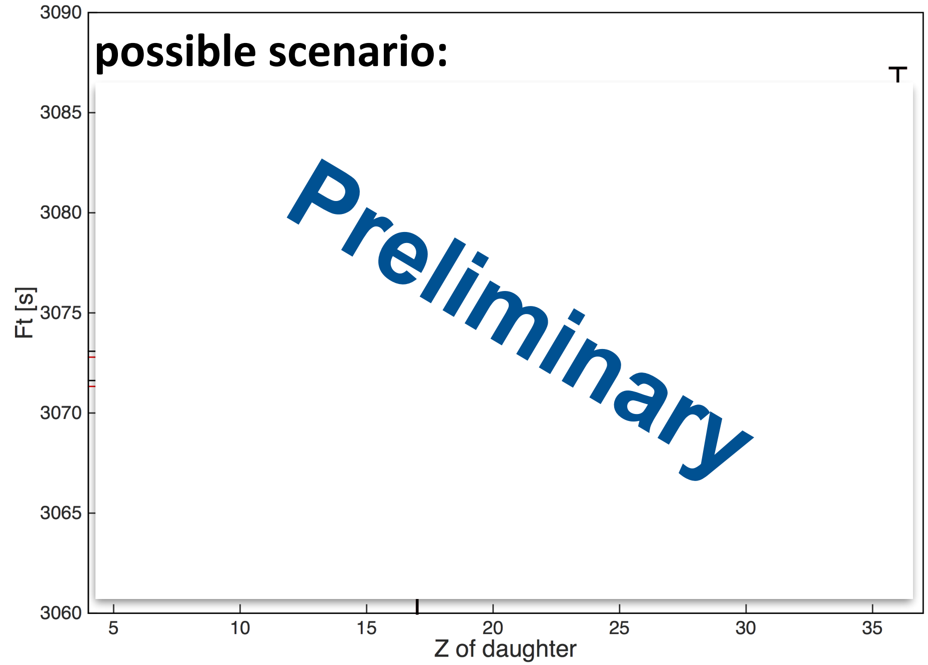
H. Heylen et al. @ COLLAPS

nuclide	$<r_c^2>$ [fm^2]		reference
^{27}Al	9.37(02)	r_c compilation	I. Angeli, At. Data Nucl. Data Tables 87, 185 (2004)
^{26m}Al	9.24(12)	extrapolation for V_{ud}	Towner & Hardy PRC 66, 035501 (2002)

implications



single measurement would move <Ft> by $\sim\sigma/2$

⇒would reduce tension in CKM unitarity test

open questions:

- reliable value of r_c in ^{27}Al (and uncertainty)?

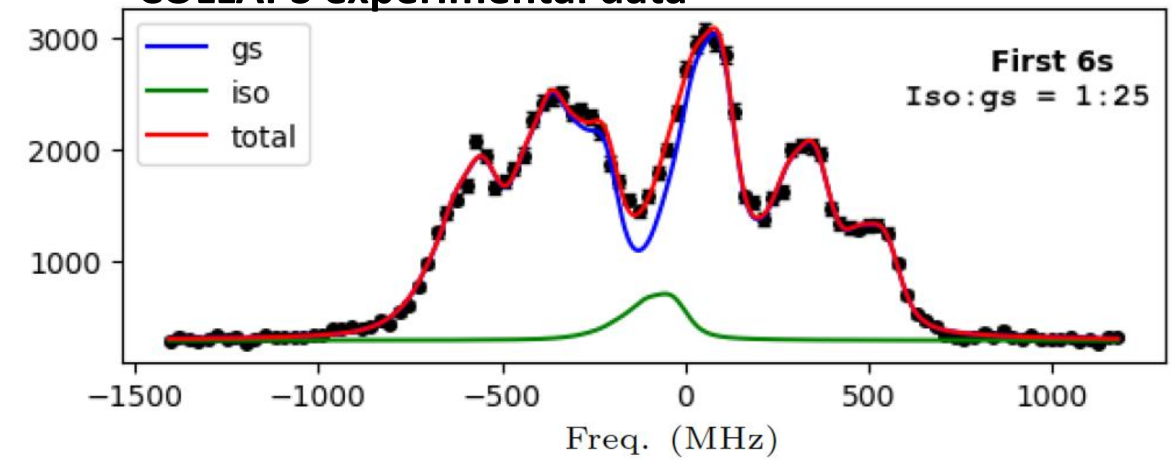
$$R(A') = \sqrt{R^2(A) + \delta \langle r^2 \rangle^{AA'}}.$$

- more precise mass shift factor M (atomic theory)?
- improved experimental data on isotope shift

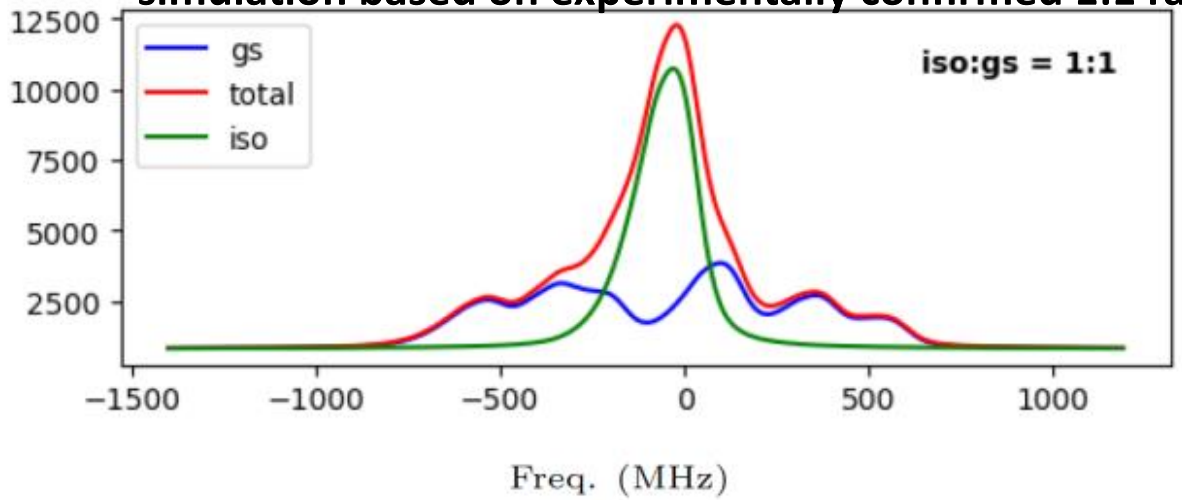
} **would also increase uncertainty**

^{26m}Al at JYFL

COLLAPS experimental data



simulation based on experimentally confirmed 1:1 ratio at JFYL



approved proposal ⇒ measurement late 2019 / early 2020

Summary and Outlook

- new calculation of inner radiative corrections Δ_R^V **for** V_{ud}
- **⇒tension in CKM unitarity (1st row)**

  $$\Delta_{CKM} = 16(4) \cdot 10^{-4}$$

- **nuclear ground state properties could play a central role,**
  - transition energies
  - R_c as input parameter for δ_c
- **^{26m}Al**
  - most precisely studied case
  - Δ_{Ft} dominated by δ_c
  - R_c experimentally unknown!
  - COLLAPS indicates sizeable shift in R_c and hence <Ft> value
  - prepare for new measurements
- new CLS methods to test nucl. theory

CKM's 1st row downhill

Δ_R jump

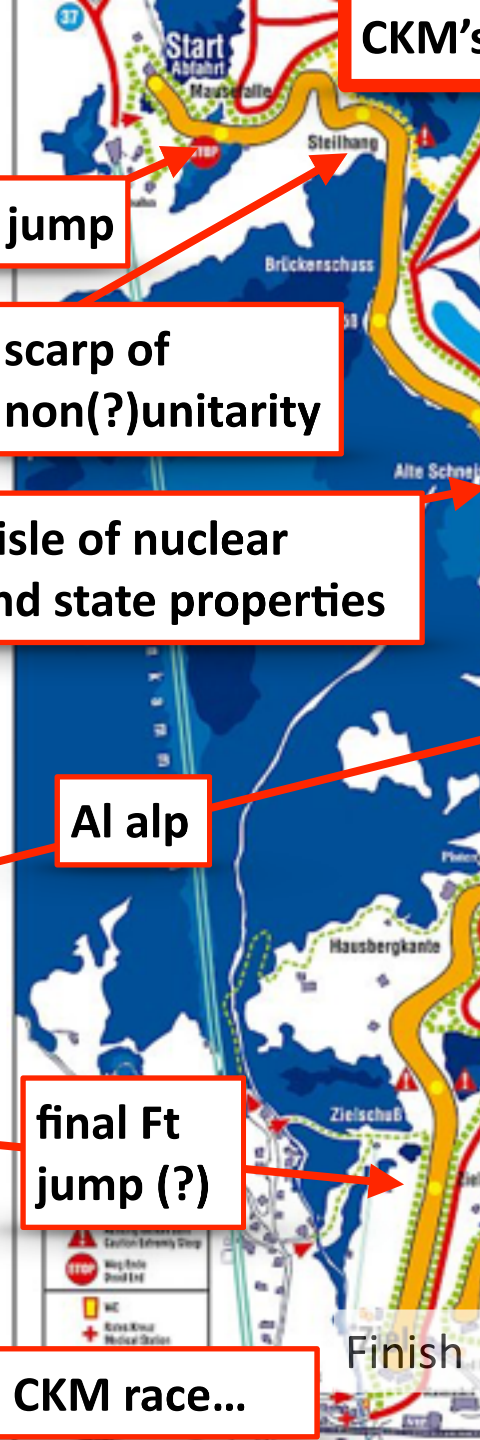
scarp of non(?)unitarity

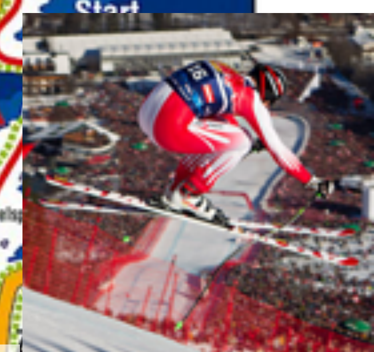
old aisle of nuclear ground state properties

Al alp

final Ft jump (?)

prepare for next CKM race…





THANK YOU!

M. L. Bissell, K. Blaum, B. Cheal, R. F. Garcia Ruiz, W. Gins, C. Gorges, H. Heylen, A. Kanellakopoulos, S. Kaufmann, S. Lechner, B. Maaß, S. Malbrunot-Ettenauer, R. Neugart, G. Neyens, W. Nörtershäuser, L. V. Rodríguez, R. Sánchez, Z. Y. Xu, X. F. Yang, D. T. Yordanov