Determination of V_{ud} Overview

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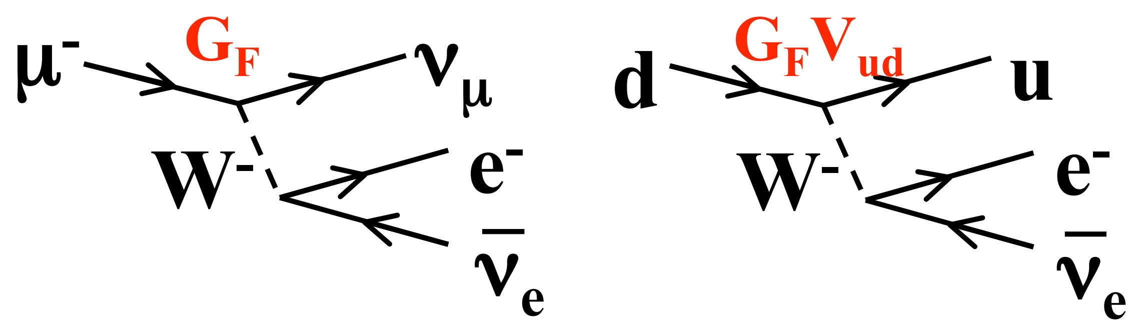
Outline

- **Introduction**
- **Superallowed $0^+ \rightarrow 0^+$ nuclear β decay**
- **Neutron β decay**
  - Correlation measurements
  - Lifetime measurements
- **Summary**

Lepton-Quark Universality and V_{ud}

Essence: Compare muon and d quark weak coupling



Problem: No free d-quarks! (But CVC)

→ Study pion, nuclei, and free neutron decay and correct for "extra structure"

***eg* nucleon charged current**

$$< p\,|\,J_{CC}\,|\,n > \;=\; < p\,|\,V_{ud}\,\bar{u}\gamma_\mu(1-\gamma_5)d\,|\,n >$$

$$= V_{ud}\,\overline{u_p}\left(g_V\gamma_\mu + g_A\gamma_\mu\gamma_5 + i\frac{g_M}{2m_n}\sigma_{\mu\nu}q^\nu\right)u_n$$

$$g_V(q^2 \to 0) = 1\,(\text{CVC}), \qquad g_A(q^2 \to 0) \approx -1.27$$

$$G_V = G_F V_{ud}\, g_V(q^2 \to 0), \qquad G_A = G_F V_{ud}\, g_A(q^2 \to 0)$$

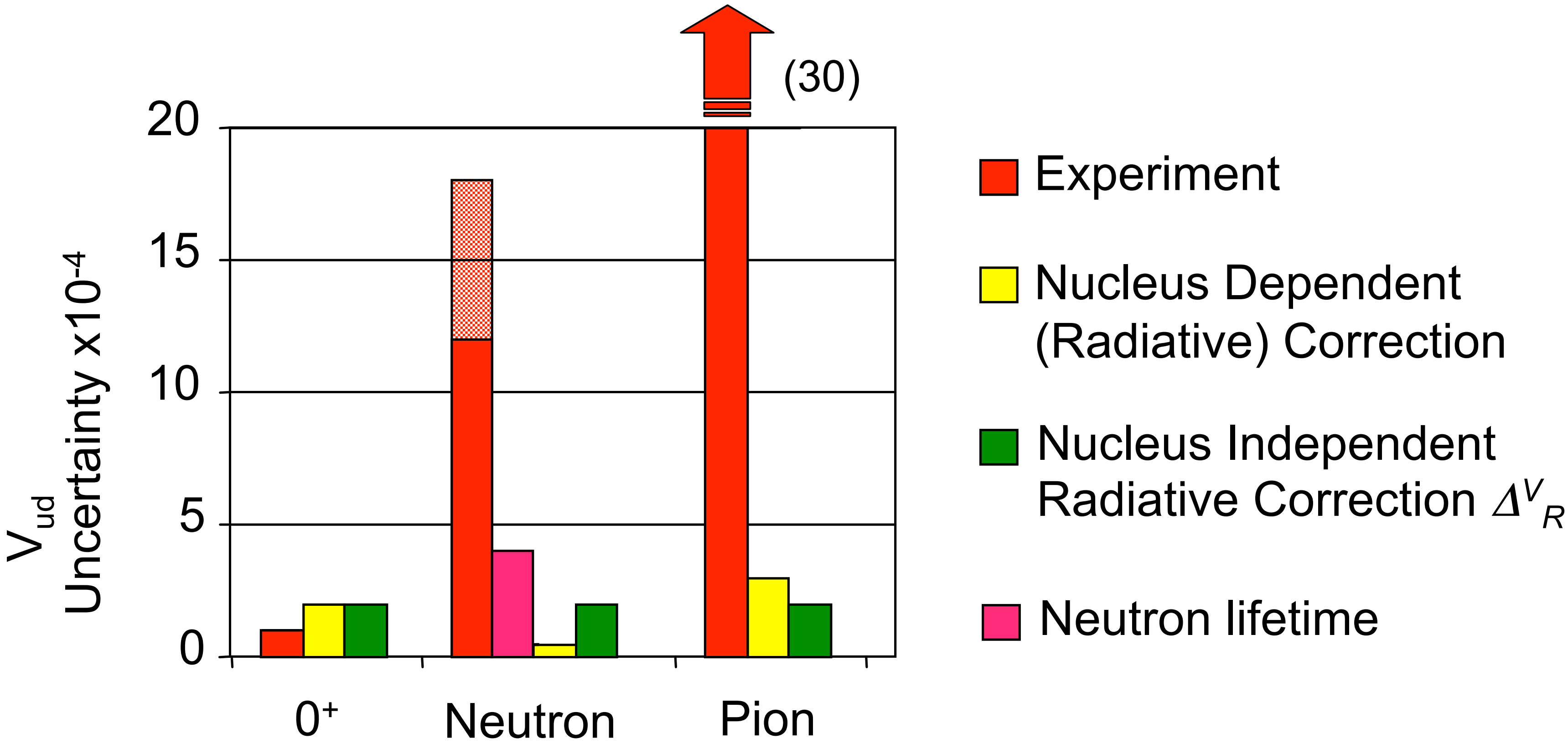
How to Measure V_{ud}?

$$|V_{ud}|^2 = \frac{G_V^{\ 2}}{G_F^{\ 2}(1+\Delta_R^V)} \propto \frac{1}{G_F^{\ 2}(1+\Delta_R^V)} \frac{\Gamma_\beta}{f^R}$$

- **$0^+ \rightarrow 0^+$ nuclear β decay**
  - No axial current at tree level
  - Various nuclear corrections
- **Pion β decay ($\pi^+ \rightarrow \pi^0 e^+ \nu_e$)**
  - No axial current
  - Experimentally very challenging: BR only 10^{-8}
- **Neutron β decay**
  - No nuclear correction
  - There is contribution from G_A

    → Need to measure $\lambda = G_A/G_V$

Comparison of Different Methods



$0^+ \rightarrow 0^+$: V_{ud} = 0.97377 ± 0.00027

Neutron: V_{ud} = 0.9746 ± 0.0019

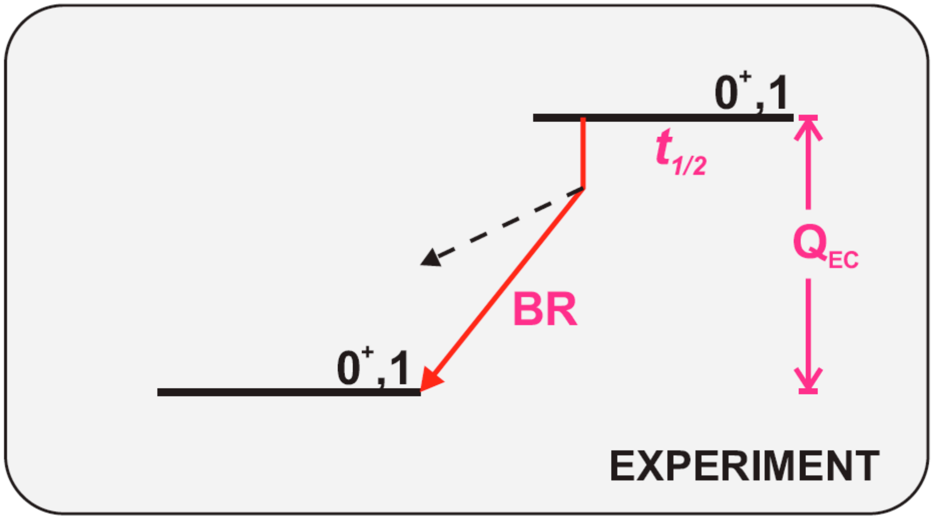
Pion: V_{ud} = 0.9728 ± 0.0030

Sources: Blucher and Marciano, Review in PDG06; Abele *et al.*, PRL**88**, 211801(2002); Pocanic *et al.*, PRL**93**,181803 (2004); Abele *et al*., Eur. Phys. J. C**33**,1 (2004)

Superallowed $0^+ \rightarrow 0^+$ nuclear β decay

Basic weak decay equation

$$ft = \frac{K}{G_V^{\,2}\langle \tau \rangle} = \frac{K}{|V_{ud}|^2 G_F^{\,2}\langle \tau \rangle}$$



f = statistical rate function: $f(Z, Q_{EC})$

t = partial half life = $t_{1/2}$/BR

G_V = vector coupling constant

$\langle\tau\rangle$ = Fermi matrix element

Including radiative corrections

$$\mathcal{F}t = ft(1+\delta_R')\left[1-(\delta_C-\delta_{NS})\right] = \frac{K}{2|V_{ud}|^2 G_F^{\,2}(1+\Delta_R)}$$

Slide courtesy of John Hardy

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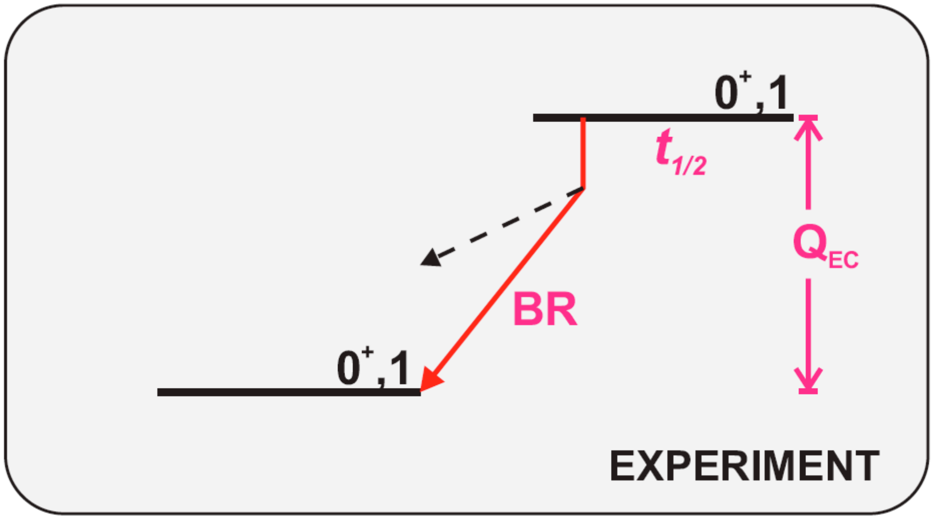

Including radiative corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})] = \frac{K}{2|V_{ud}|^2 G_F^{\,2}(1+\Delta_R)}$$

δ_R': $f(Z,Q_{EC})$ ~ 1.5%

$\delta_C - \delta_{NS}$: f(nuclear structure) 0.3-0.7%

Δ_R: $f(Z,Q_{EC})$ ~ 2.4%

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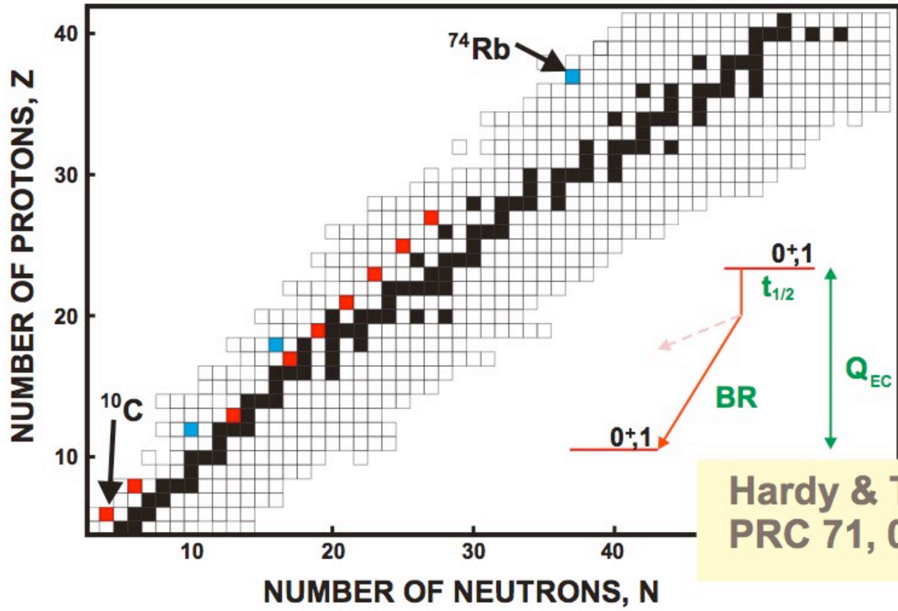
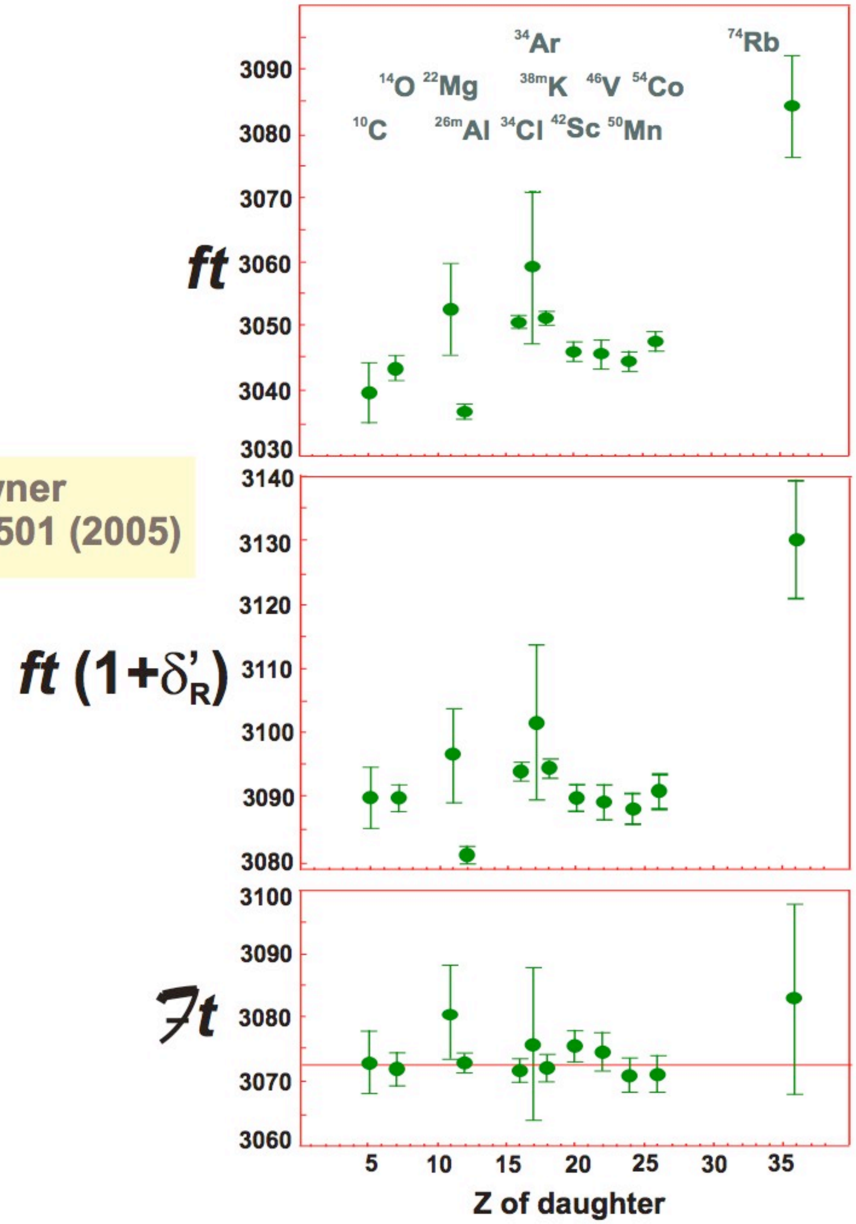
World Data for $0^+ \rightarrow 0^+$ Decay, 2005



Hardy & Towner
PRC 71, 055501 (2005)



- 9 cases with *ft*-values measured to ~0.1% precision; 3 more cases with <0.4% precision.
- ~125 individual measurements with compatible precision

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^{\,2}\,(1 + \Delta_R)}$$

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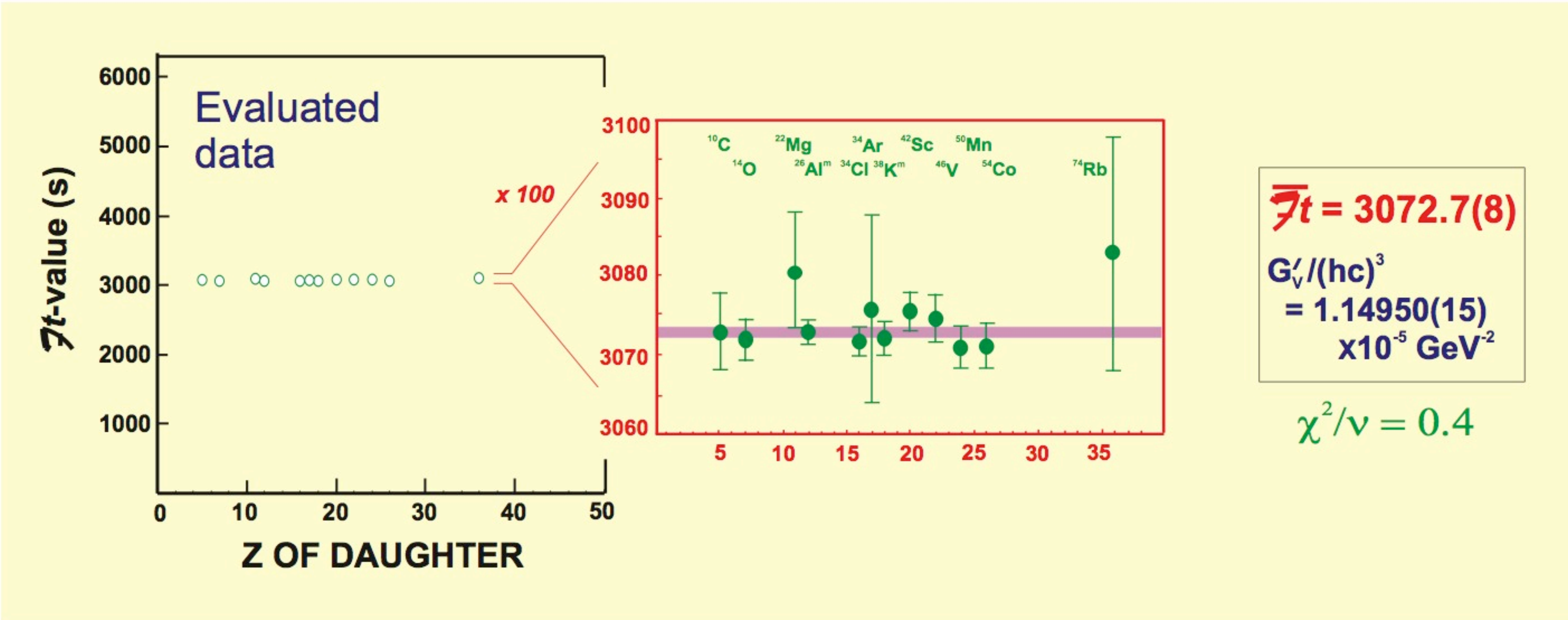
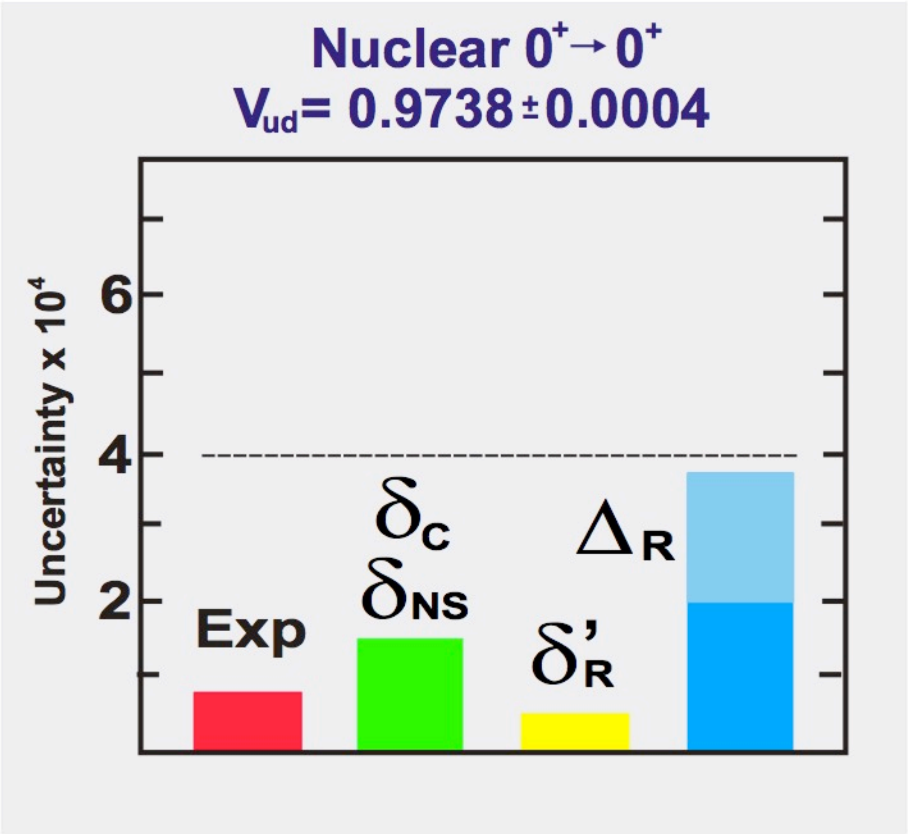
World Data for $0^+ \rightarrow 0^+$ Decay, 2005



$$|V_{ud}| = 0.9738 \pm 0.0004$$ (using Δ_R=2.40(8)%)

Slide courtesy of John Hardy

Recent Developments and Future Direction



- **Improved calculation of radiative correction Δ_R (Marciano and Sirlin PRL 96, 032002 (2006))**
  - Uncertainty reduced by a factor of two
- **Nuclear-structure-dependent corrections, δ_c and δ_{NC}, being tested by experiment**
  - Increase measured precision on 9 best *ft*-values
  - Measure new $0^+ \rightarrow 0^+$ decays with 18<A<42 (T_Z=-1)
  - Measure new $0^+ \rightarrow 0^+$ decays with A>62 (T_Z=0)

Slide courtesy of John Hardy

Recent or Current Experiments

Q_{EC} values:

Argonne (Canadian Penning trap)

^{46}V Savard *et al.*, PRL 95, 102501 (2005)

^{10}C, ^{14}O, ^{26}Al^{m}, ^{34}Cl, ^{42}Sc

Jyvaskyla (JYFLTRAP)

^{62}Ga Eronen *et al.* PLB 636, 191 (2006)

^{26}Al^{m}, ^{42}Sc, ^{46}V Eronen *et al.*, PRL in press (2006)

NSCL (LEBIT)

^{38}Ca Bollen *et al.*, PRL 96, 152501 (2006)

Munich Tandem

^{46}V

Half-lives:

Auckland/Canberra

^{50}Mn Barker & Byrne, PRC 73, 064306 (2006)

Texas A&M

^{34}Cl, ^{34}Ar Iacob *et al.* PRC in press

^{10}C, ^{38}Ca

Branching ratios:

TRIUMF

^{62}Ga Hyland *et al.*, PRL 97, 102501 (2006)

Texas A&M

^{14}O Towner & Hardy, PRC 72, 055501 (2005)

^{34}Ar, ^{38}Ca

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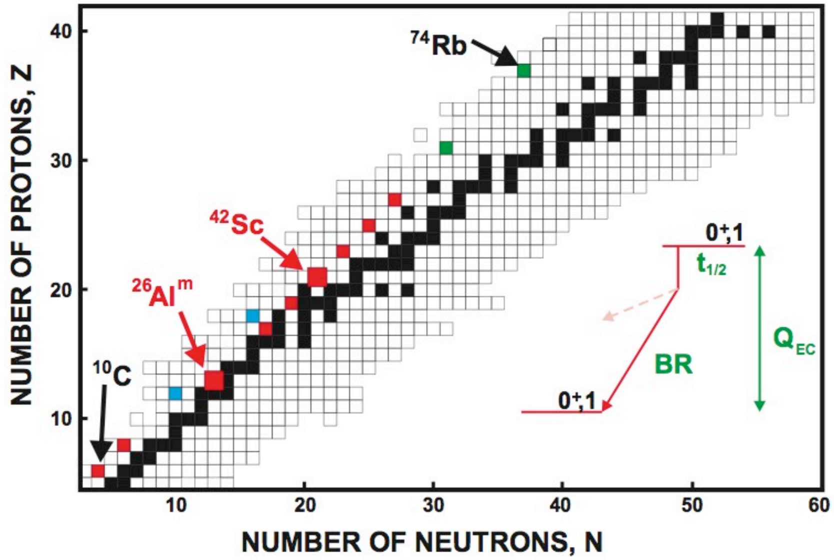
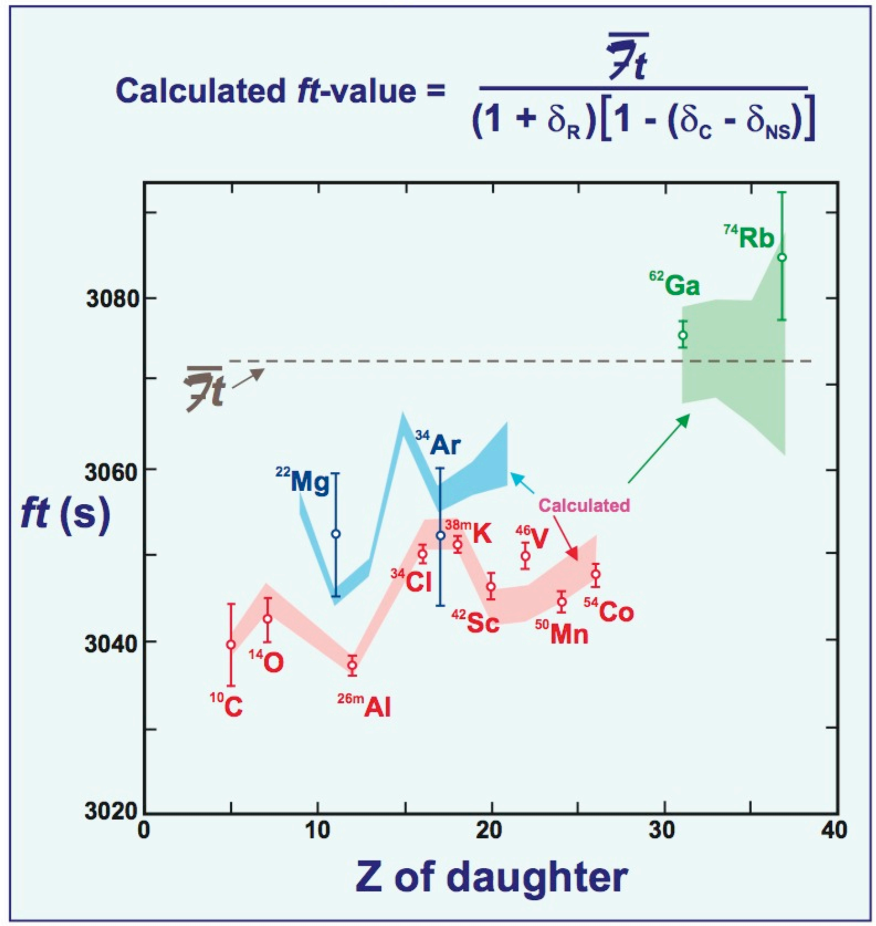
Status of Results as of November 2006



What's new?

- ✔ ^{62}Ga: new case added
- ✔ ^{34}Ar: $t_{1/2}$ results improved
- ✔ ^{46}V: Q_{EC} value improved
- ✔ ^{26}Al, ^{42}Sc: Q_{EC} values improved

Updated results + re-fit



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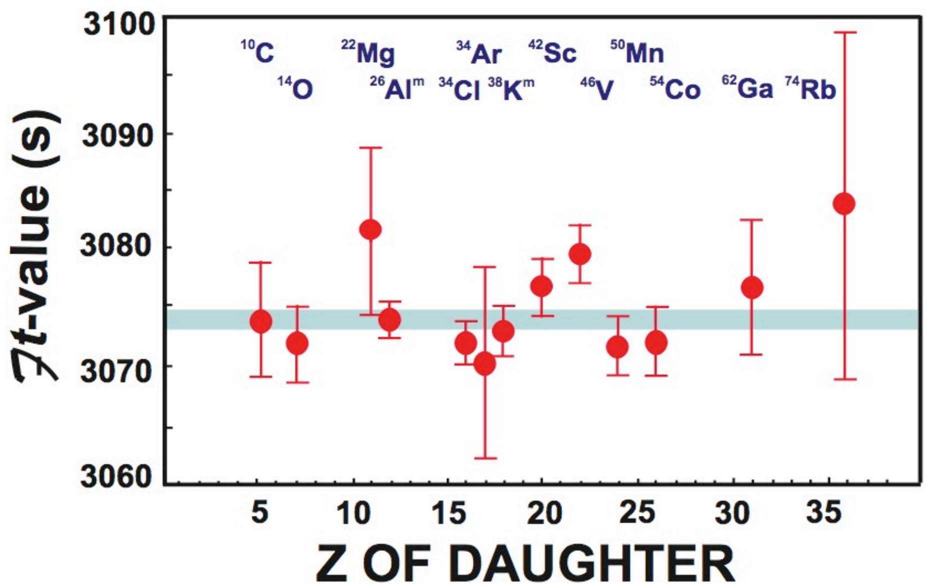
Status of Results as of November 2006



$\overline{\mathcal{F}t}$ = 3073.9(8)

$\chi^2/\nu = 0.9$

V_{ud} = 0.97378(27)

2005 Review:

V_{ud} = 0.97380(40)

Most of the reduction in the uncertainty on V_{ud} since 2005 comes from the improvement in the calculated radiative correction Δ_R.

Slide courtesy of John Hardy

Neutron β decay and V_{ud}

$$|V_{ud}|^2 = \frac{G_V{}^2}{G_F{}^2(1+\Delta_R^V)}$$

Neutron lifetime

$$\tau^{-1} = Kf^R(G_V{}^2 + 3G_A{}^2)$$

(τ = 885.7±0.8 s PDG2006)

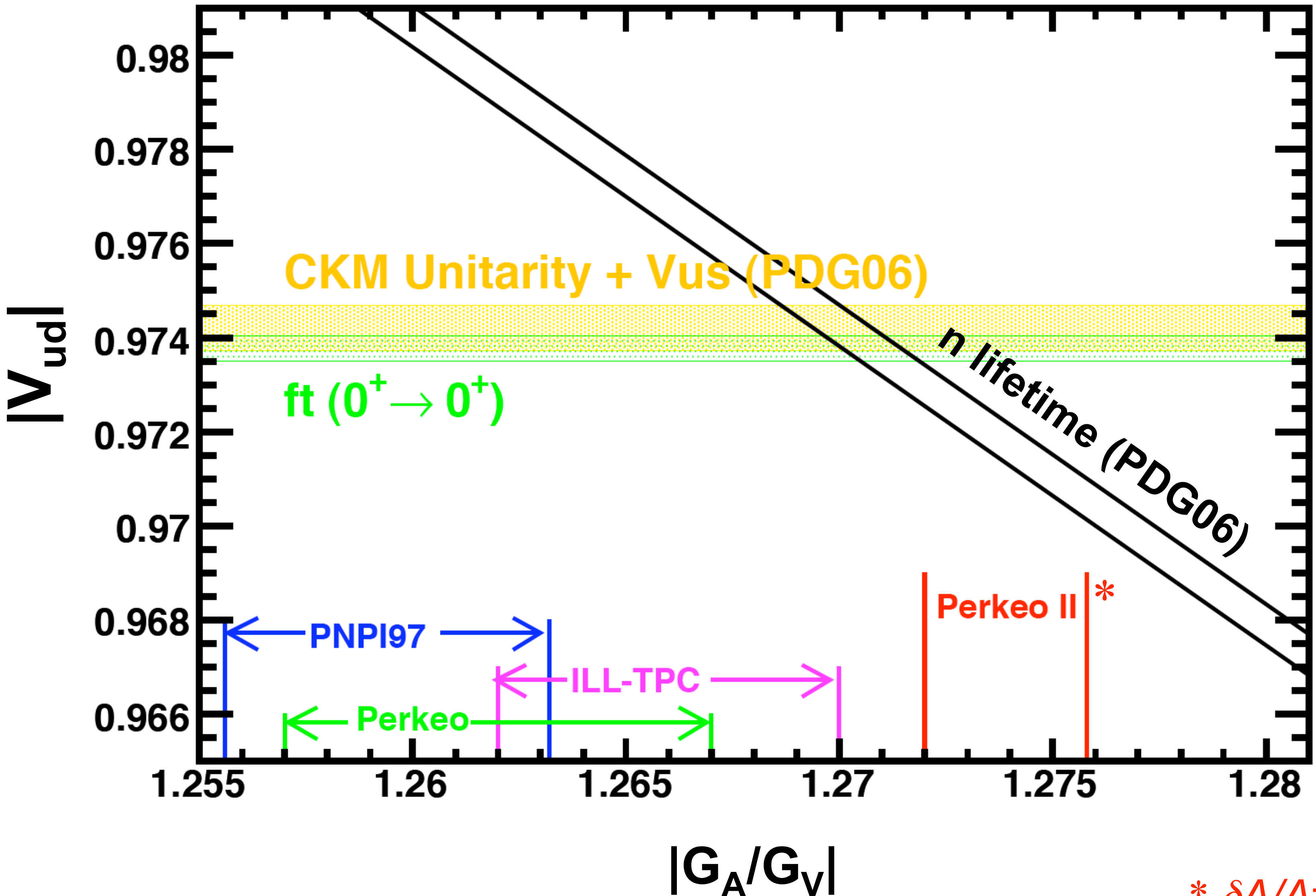
Angular correlation in polarized neutron decay (Jackson *et al* '57)

$$d\Gamma = d\Gamma_0 \times \left[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu}\right)\right]$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}, \quad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}, \quad B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2} \qquad \lambda \equiv \frac{G_A}{G_V}$$

δλ/δa ~ 3.3; *a* = –0.103 ± 0.004 (PDG2006)
δλ/δA ~ 2.6; *A* = –0.1173 ± 0.0013 (PDG2006)
δλ/δ*B* ~ 13.4; *B* = –0.981 ± 0.004 (PDG2006)

V_{ud} Experimental Status



* $\delta A/A$=0.6%

Contribution to the V_{ud} uncertainty

$0^+ \rightarrow 0^+$

$$|V_{ud}|^2 = \frac{2984.48(5)\ \mathrm{s}}{ft(1+RC)}$$

Contribution	δV_{ud} (10^{-4})
δ_{exp}	1.1
δ_{nucl}	1.5
Δ_R	1.9
total	2.7

neutron

$$|V_{ud}|^2 = \frac{4908.7(1.9)\ \mathrm{s}}{\tau_n(1+3\lambda^2)}$$

Contribution	δV_{ud} (10^{-4})
τ_n ($\delta\tau_n$ = 0.8 s)[1]	4
λ ($\delta A/A$ = 0.6%)[2]	12
Δ_R	2
total	13

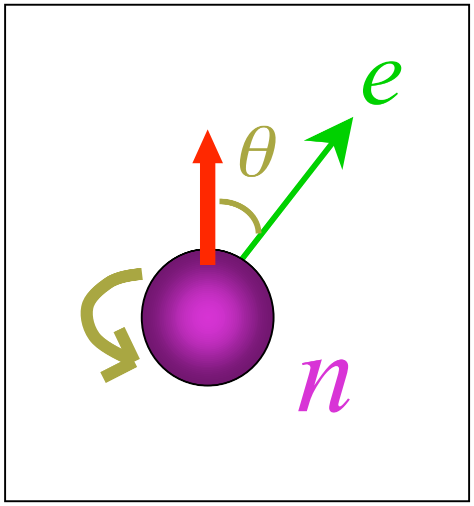
[1]PDG06 [2]Perkeo II

Marciano and Sirlin, PRL **96**, 032002 (2006)

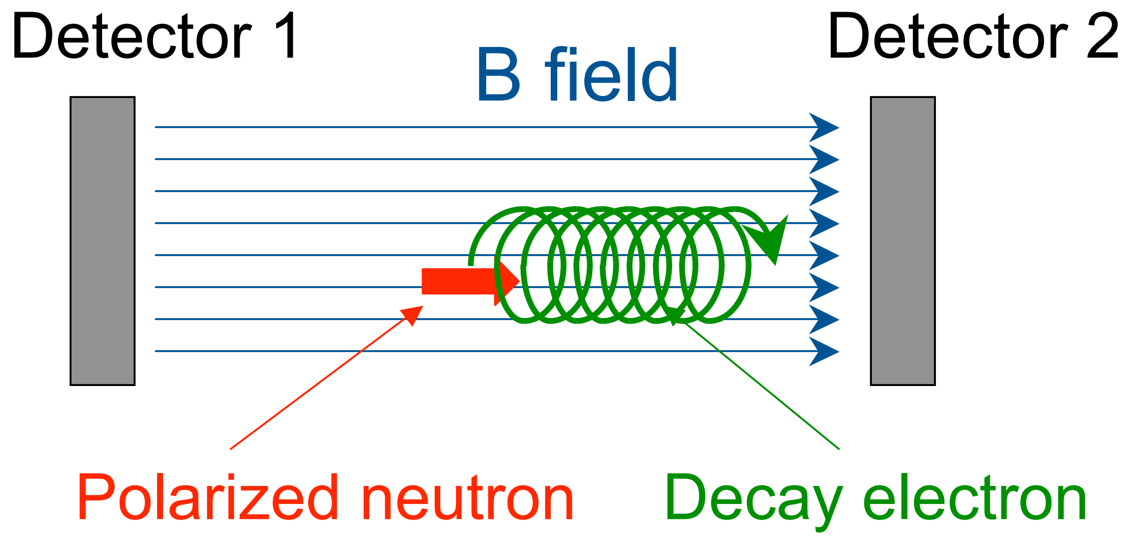
Ongoing/Future Experiments

Experiment	Location	Status	Remarks
Perkeo II	ILL	Analysis	Data taking completed in 2004
Perkeo III	ILL	Construction	Measures A
aSPECT	FRM-II	Data taking/ Analysis	Measures a
aCorn	NIST	Construction	Measures a
UCNA	LANL	Construction/ Commissioning	Uses UCN to measure A to $\delta A/A$ = 0.2%
abBA	ORNL-SNS	Proposal/ Detector development	Simultaneous measurement of a, b, B, A to $\delta A/A$ = 0.1% (stat), $\delta a/a$ = 0.1% (stat)
Nab	ORNL-SNS	Proposal	Uses unpolarized neutrons to measure a, b
PANDA	ORNL-SNS	Proposal	Measures C (=A+B)

Principle of the *A*-coefficient Measurement



$$dW=[1+\beta P A\cos\theta]d\Gamma(E)$$



$$A_{\exp}(E)=\frac{N_1(E)-N_2(E)}{N_1(E)+N_2(E)}\approx\langle P\rangle A\beta\langle\cos\theta\rangle$$

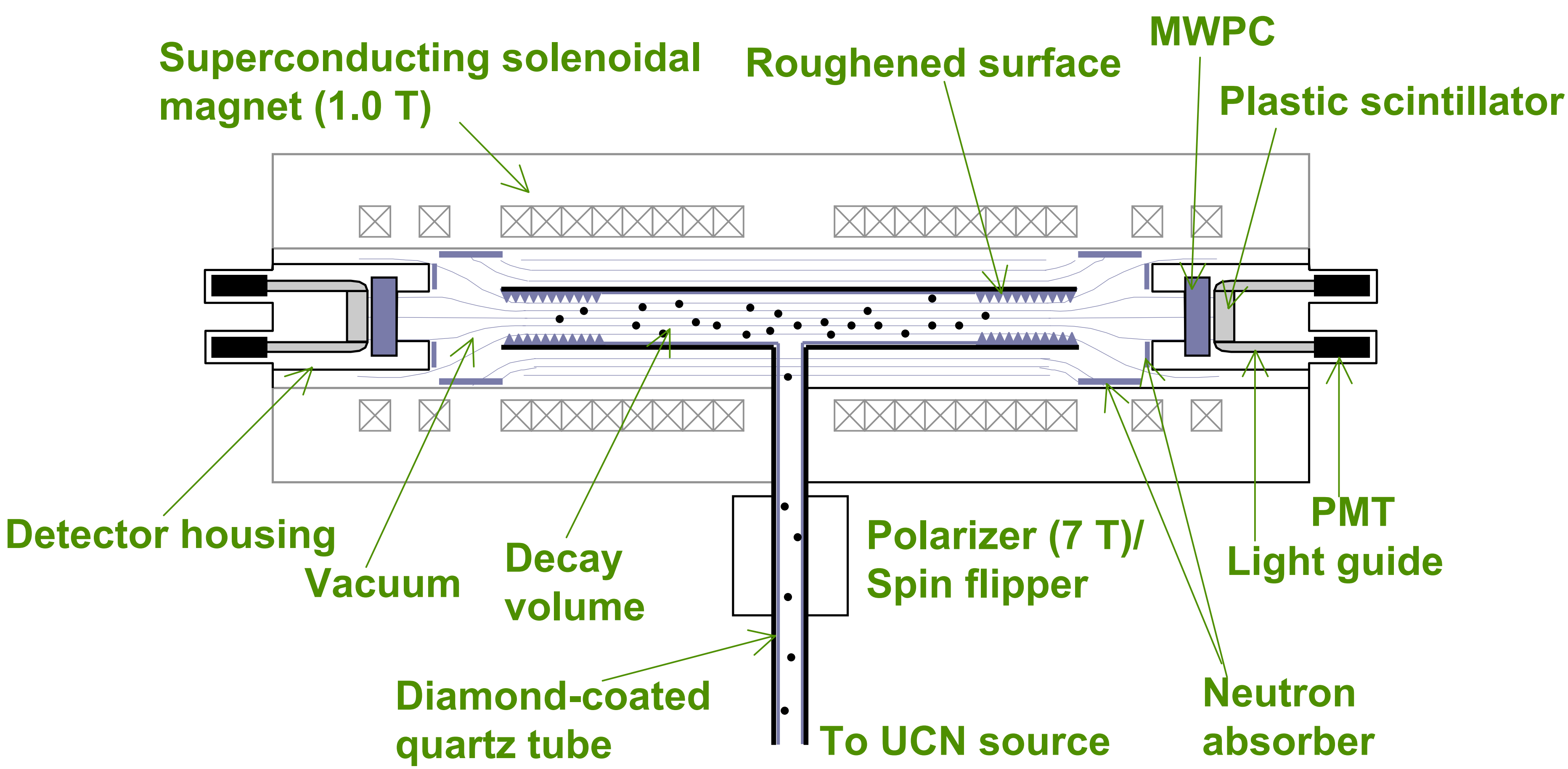
(End point energy = 782 keV)

Potential sources of systematics

- Neutron polarization determination
- Background
- Detector related effects (eg backscattering)

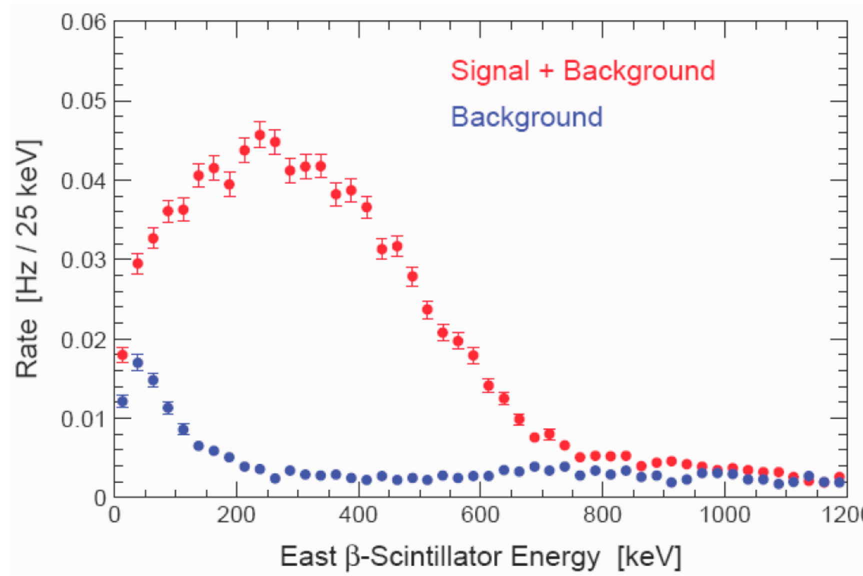
UCNA Experiment

- **First β correlation measurement using UCN**
  - >99% polarization using a 7 T magnetic field
  - Background suppression by the use of a pulsed UCN source
- **Ultimate goal: 0.2% measurement of A (*δA/A* = 0.2%)**



UCNA — Status

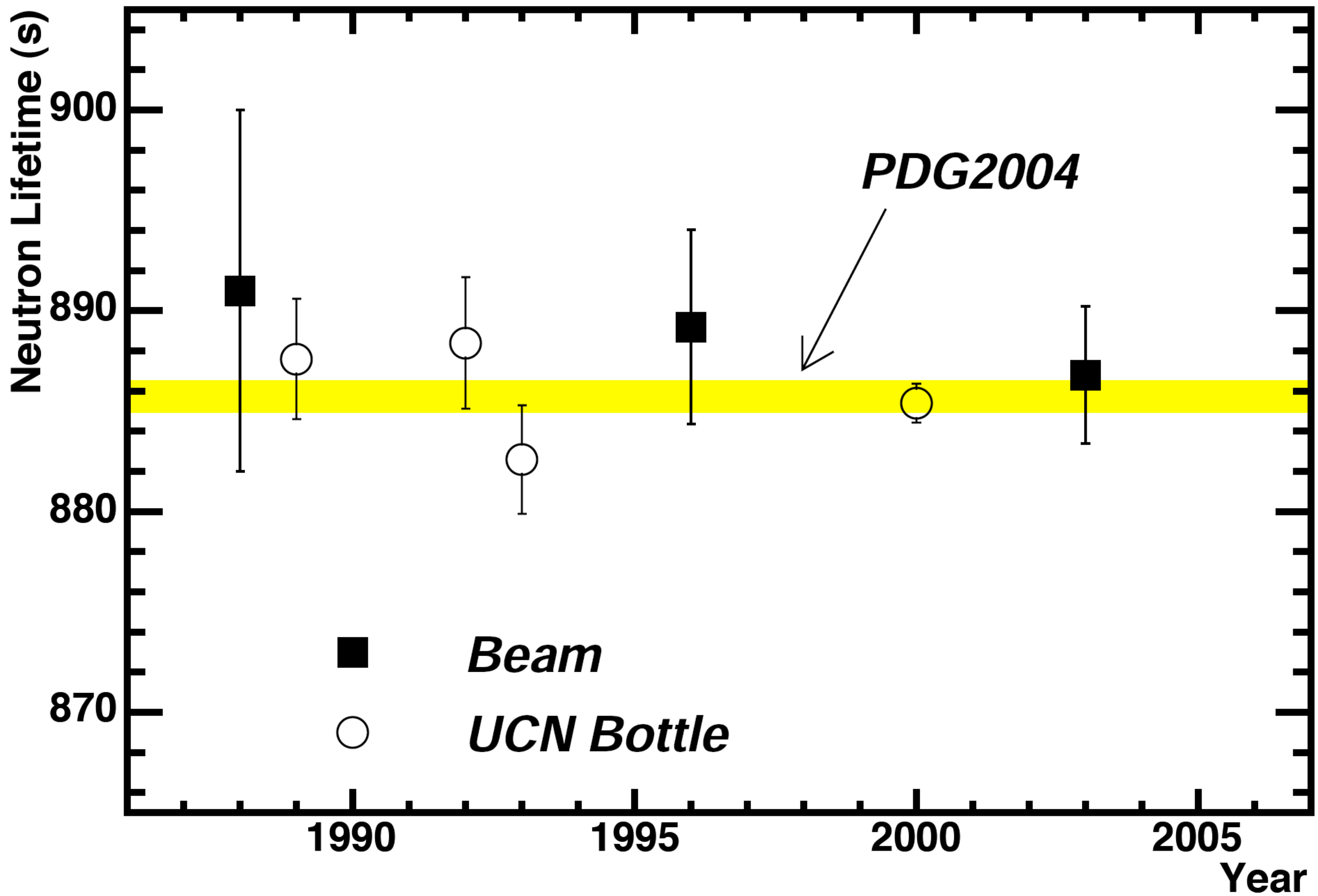
- **Status**
  - UCN source: commissioning
  - Beta detector: completed
  - Polarizer/spin flipper: commissioning
  - Neutron guides: construction
- **Plan**
  - 2007: Commissioning, 1% measurement
  - 2008–: Physics run for 0.2% measurement
- **Future plans**
  - Measurements of other correlation coefficients
  - Use of silicon detector



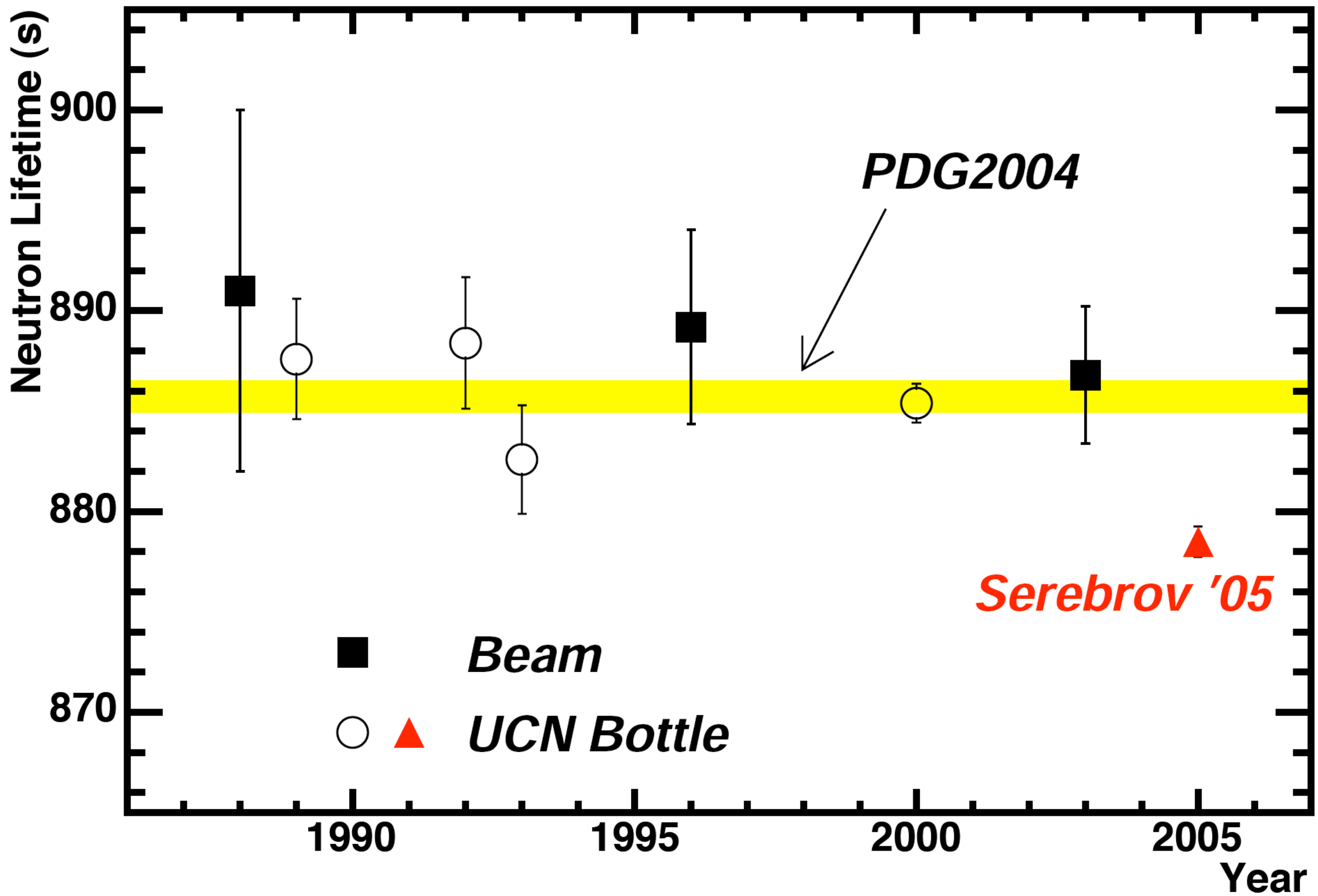
S/N in 200-400 keV = 13

Neutron β decay spectrum obtained during the 2006 commissioning run: first β decay spectrum obtained from UCN!

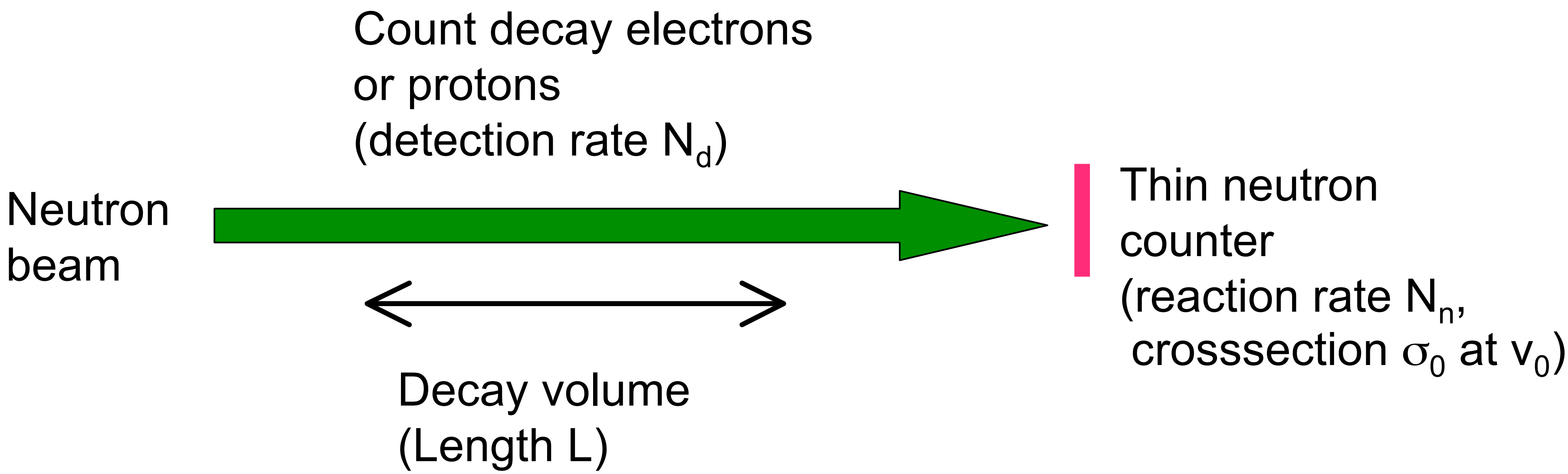
Neutron Lifetime



Neutron Lifetime



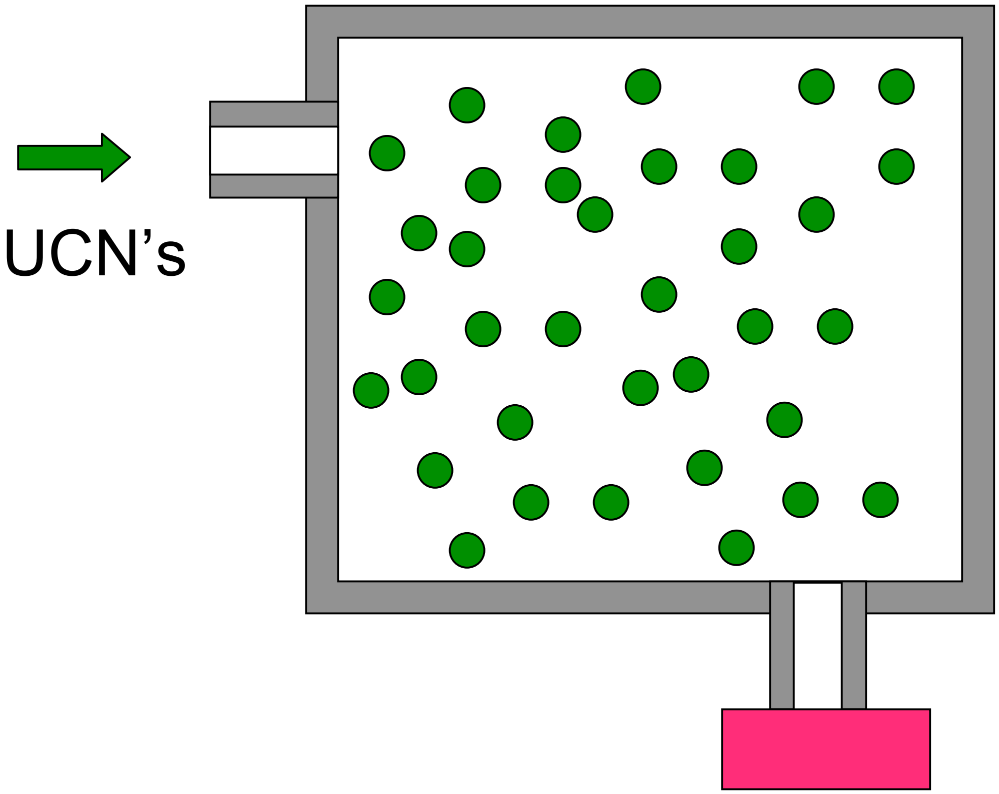
Beam Method



$$N_d = \frac{1}{\tau_n} N \quad \Rightarrow \quad N_d = \frac{1}{\tau_n}[L N_n \sigma_0 v_0 (\rho x)]$$

Problem: Decay volume length and neutron flux measurement

Bottle Method

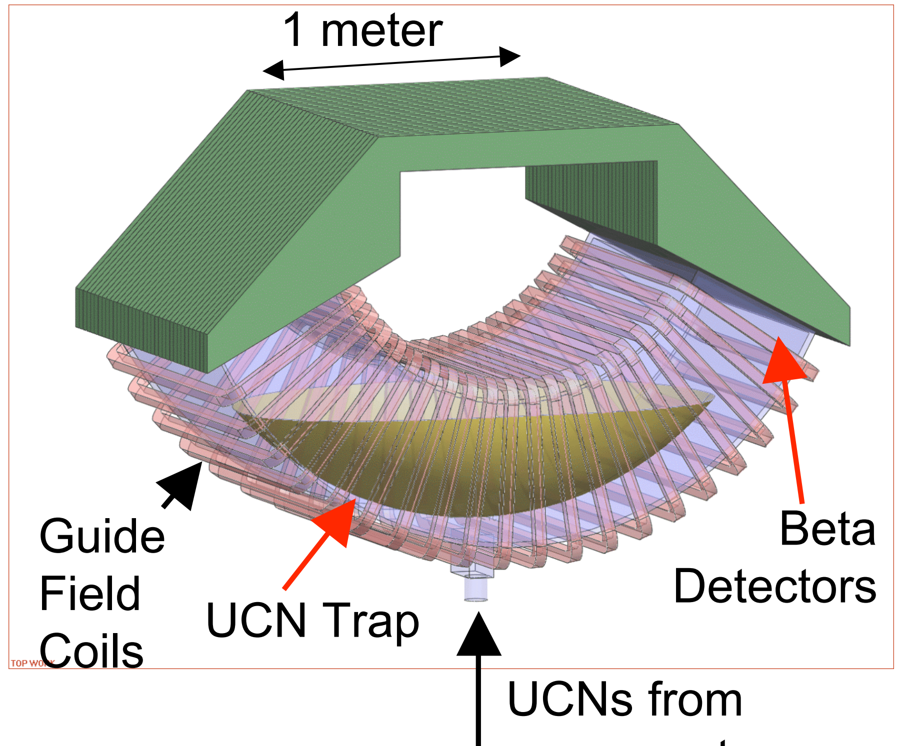


$$N(t) = N(0)\exp(-t/\tau_n)$$

Problem: neutrons lost through interactions with the wall

New Method — Magnetic/Gravo-magneto trap

- **Confine UCN using the magnetic force or the magnetic + gravitational force**
  - Note: $\mu \bullet \mathbf{B}$ =100neV for B=1.7 T; mgh = 100neV for h = 1 m
- **Experiments are being developed at NIST, LANL, Munich, Gatchina …**
- **New systematic effects**
  - Marginally trapped neutrons
  - Solution: chaotic cleaning



Conceptual design for LANL neutron lifetime experiment

Summary

- **Current determination of V_{ud} comes from superallowed β decays.**
- **Much activity is now focused on reducing the uncertainty by experimentally testing the structure-dependent correction terms.**
- **Neutron decay, free from nuclear structure dependent corrections, can potentially provide theoretically cleaner determination of V_{ud}.**
- **Necessary technologies being developed for precision measurements of neutron decay parameters.**
- **Active experimental program exist for both correlation and lifetime measurements.**