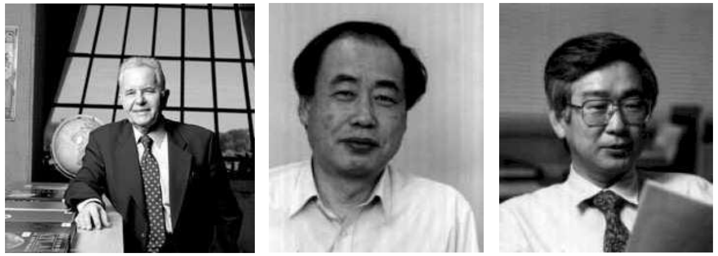
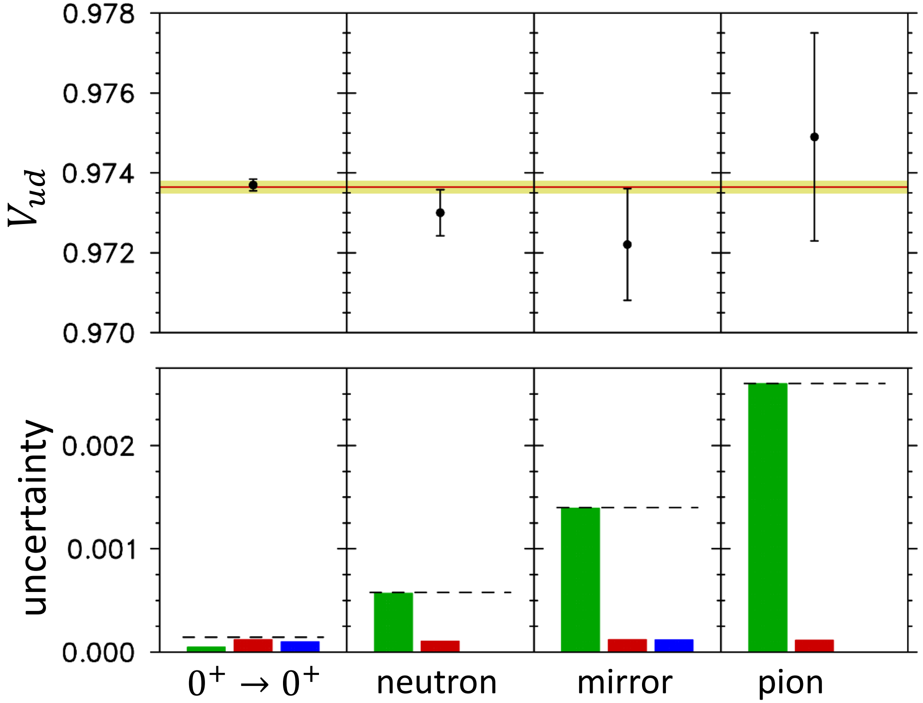
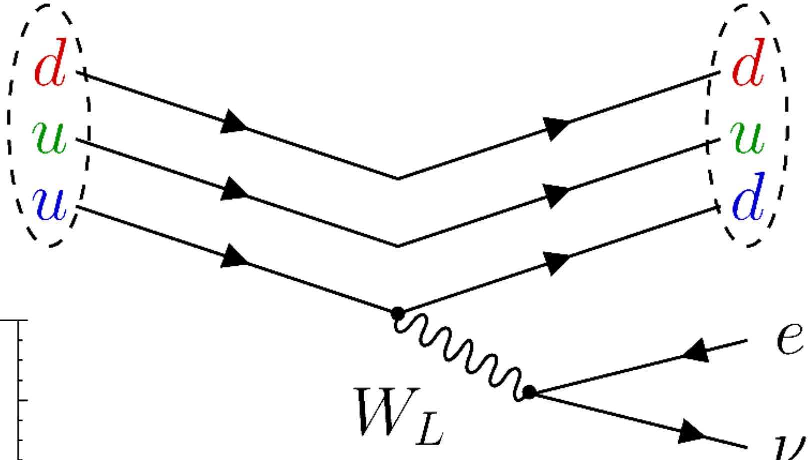
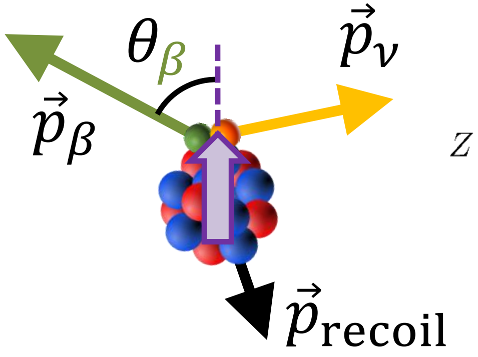
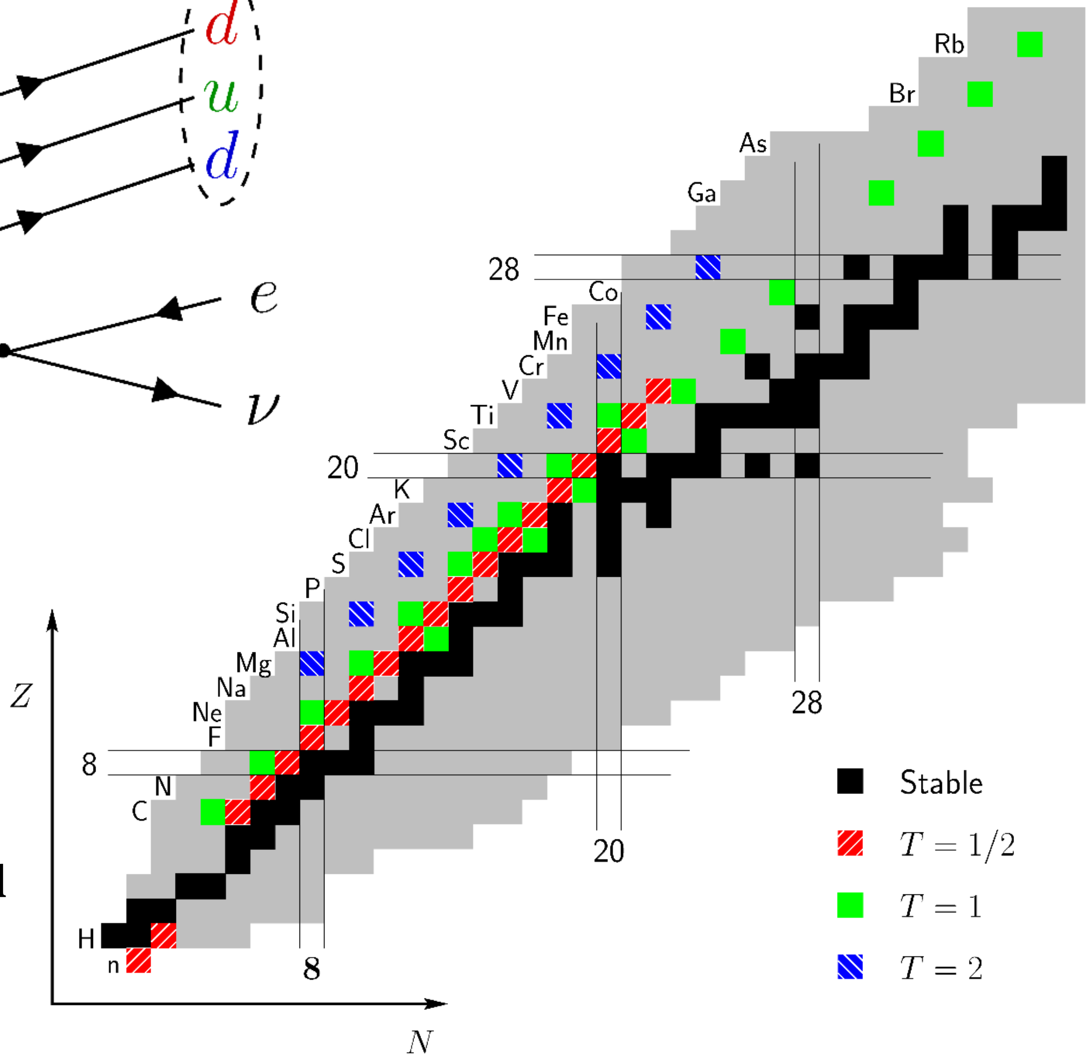
Outlook for the determination of V_{ud}











Dan Melconian, Texas A&M – ECT*, Apr 2019

Outline

- Introduction
  - Stuff you probably already know
- Present status
  - $0^+ \rightarrow 0^+$ superallowed decays
  - $T = 1/2$ transitions
  - Pion decays
  - CKM unitarity
- Looking forward
  - Inner radiative corrections
  - ISB calculations
  - Experimental efforts on existing and new nuclei
- Summary and outlook

Everyone here knows this, but…

Cabibbo

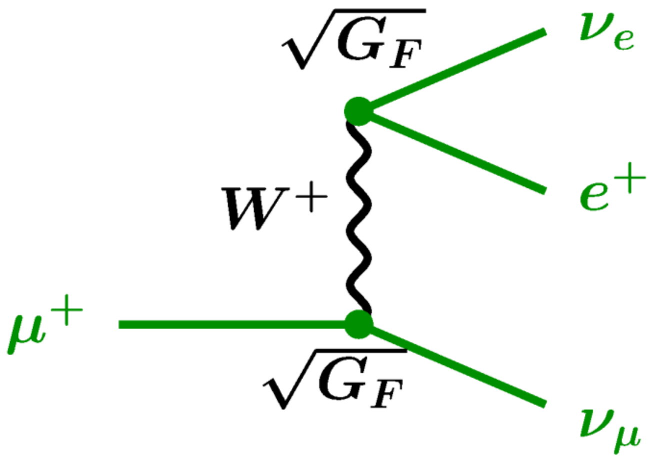
mass eigenstates
≠ weak eigenstates

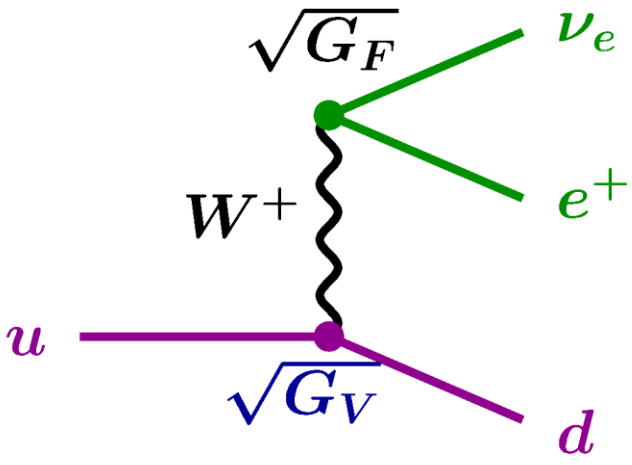
$$V_{ud} = G_V / G_F$$

Kobayashi

Maskawa

generalized Cabibbo's theory to three generations





weak eigenstates ↓ mass eigenstates ↘

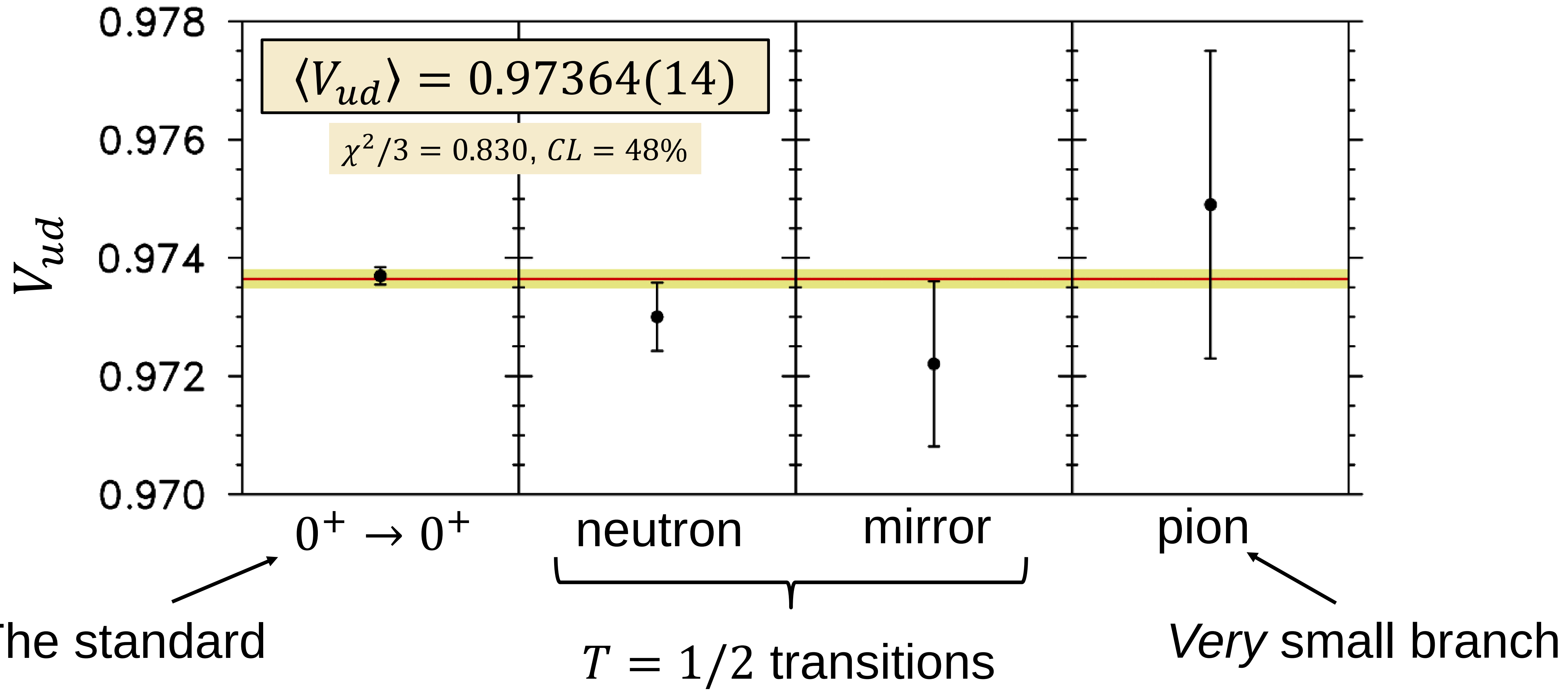
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix

Unitarity condition: $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$

Cutting to the chase

- The current status of V_{ud} (using Seng's Δ_R^V and latest PERKEO III result):
  - Seng, Gorchtein, Patel and Ramsey-Musolf, PRL **121**, 241084 (2018)
  - Markisch, *et al.*, arXiv:1812.04666 (submitted to PRL)



$0^+ \rightarrow 0^+$ Transitions

- These purely Fermi transitions are theoretically well-understood within the Standard Model

$$\binom{\text{phase}}{\text{space}}\binom{\text{partial}}{\text{half life}} = ft \approx \frac{K/G_F^2}{V_{ud}^2(M_F^2 + M_{GT}^2)}$$

$K/G_F^2 \rightarrow$ 5968.864(6) s; $M_F^2 \rightarrow$ 2; $M_{GT}^2 \rightarrow$ 0

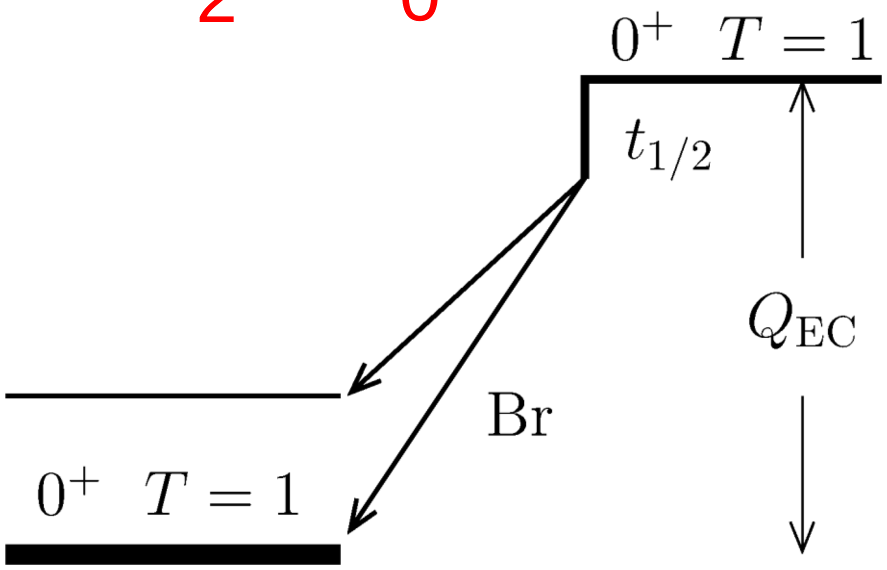
where

$$f(Z, Q_{EC}) = \int F(Z,E)S(E)\, pE(E-E_0)^2 dE$$
$$\sim Q_{EC}^{\mathbf{5}}$$

is the phase space factor and

$$t(t_{1/2}, \mathrm{Br}) = \frac{t_{1/2}}{\mathrm{Br}}(1 + P_{EC})$$

is the partial half life



As we know, it's not *quite* that simple

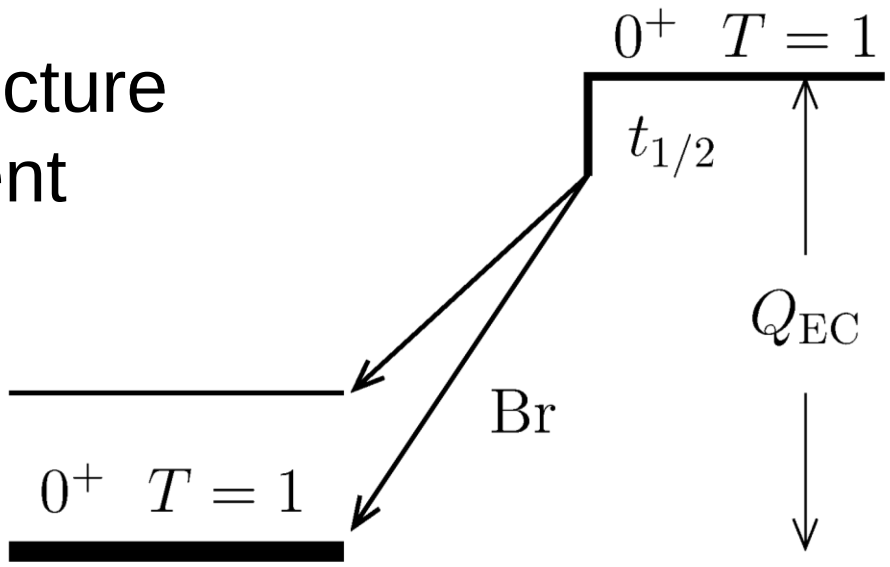
- One must include small radiative and isospin-symmetry breaking corrections

$$\mathcal{F}t = ft(1+\underbrace{\delta_R'}_{\sim 1.5\%})[1-(\underbrace{\delta_C - \delta_{NS}}_{0.3-1.5\%})] = \frac{K/G_F^2}{2V_{ud}^2(1+\underbrace{\Delta_R^V}_{\sim 2.4\%})}$$

- δ_R': radiative correction, depends on Z and Q_{EC}
- δ_C: isospin-symmetry-breaking correction
- δ_{NS}: radiative correction

(δ_C and δ_{NS}: nuclear structure dependent)

- Δ_R^V: radiative correction common to any extraction of V_{ud}



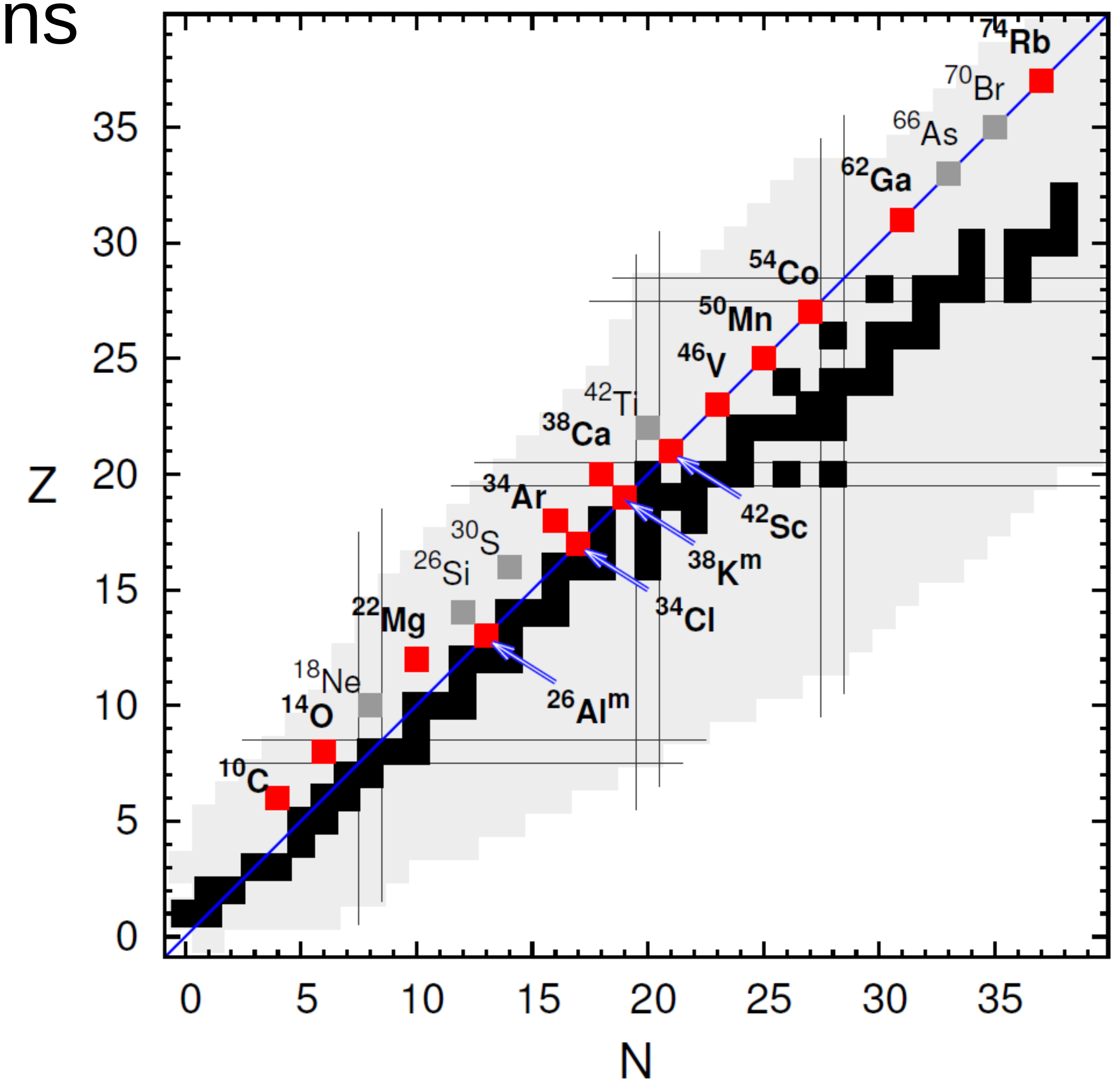
Theoretical uncertainties: 0.05 – 0.10% ???

Extracting V_{ud} from $0^+ \rightarrow 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

2. From many transitions, test CVC and the correction terms

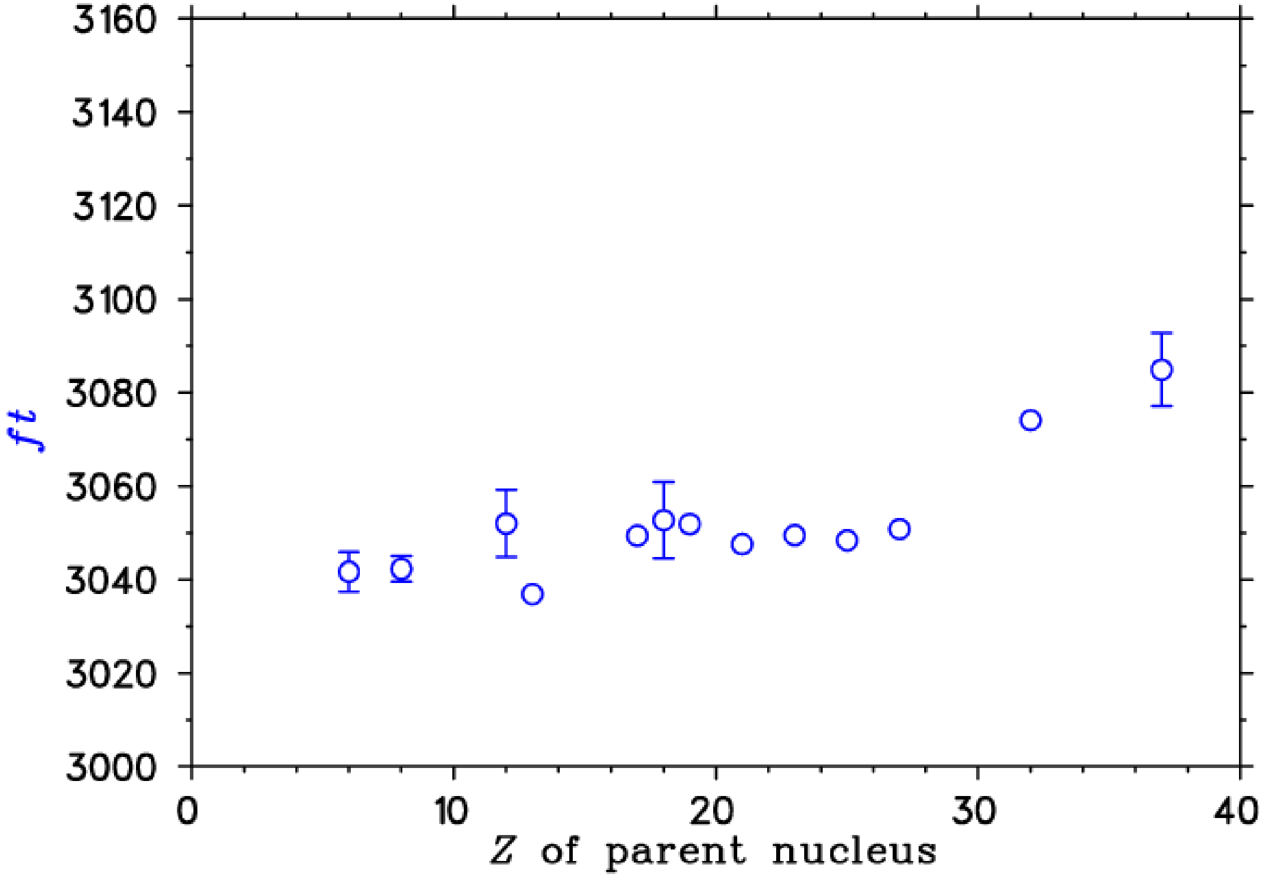


Extracting V_{ud} from $0^+ \to 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

2. From many transitions, test CVC and the correction terms

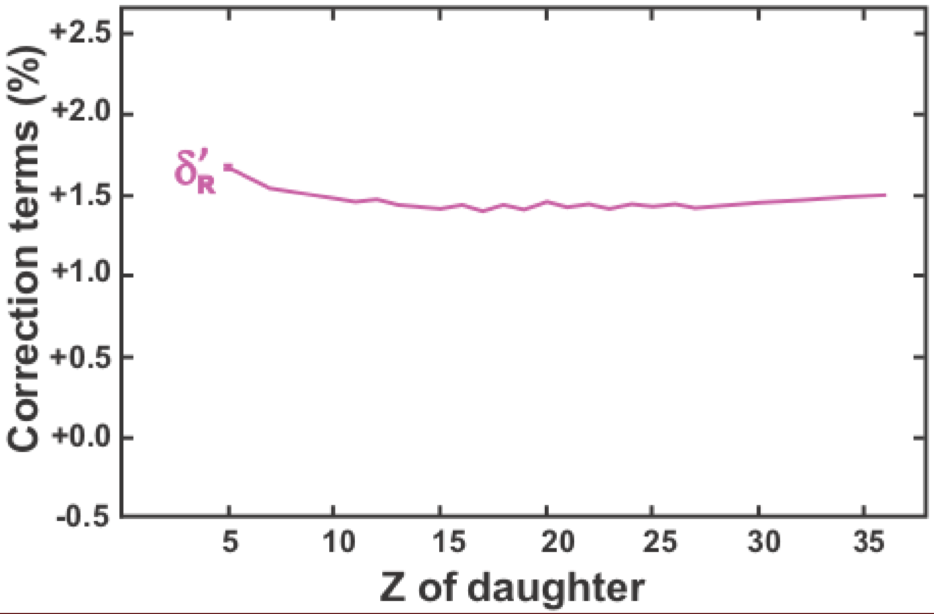


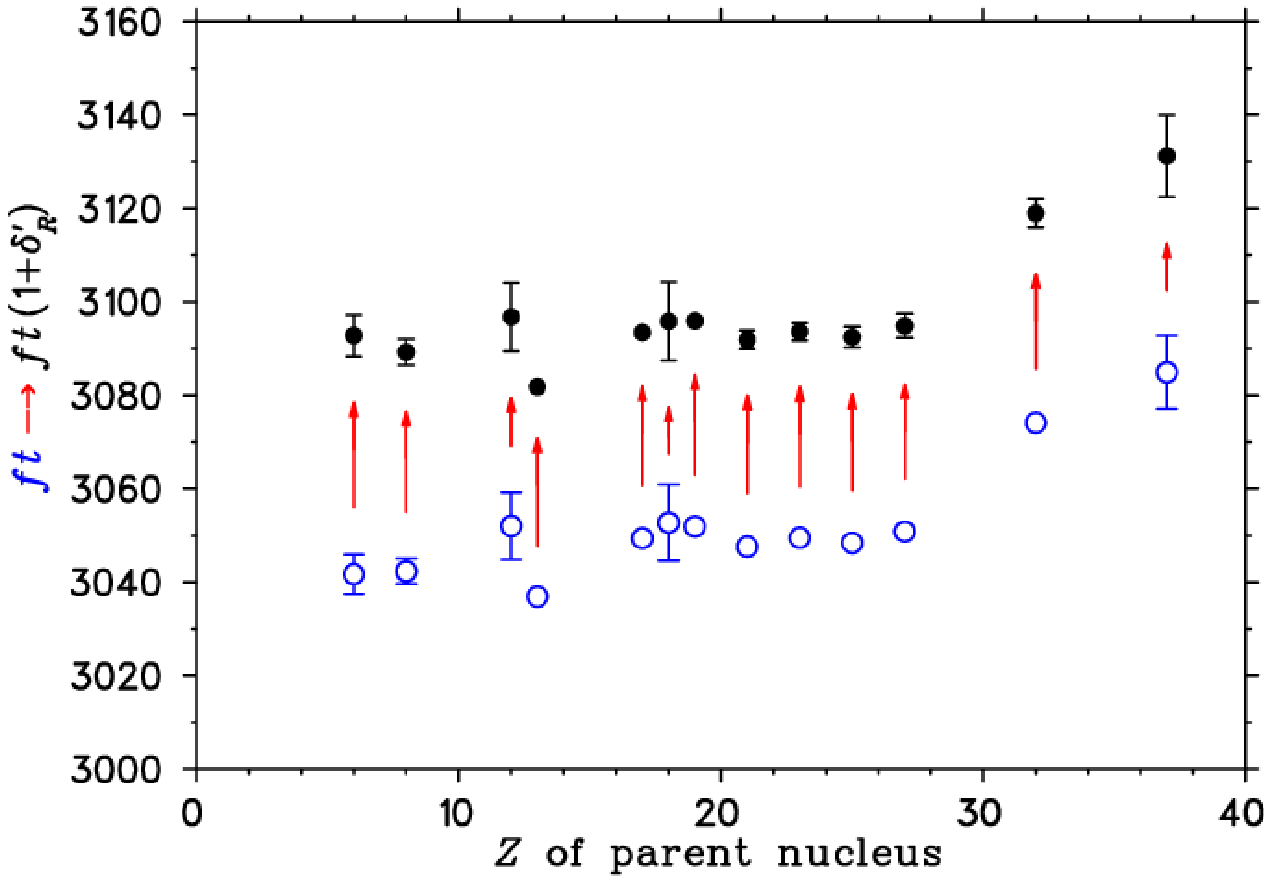
Extracting V_{ud} from $0^+ \to 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

2. From many transitions, test CVC and the correction terms



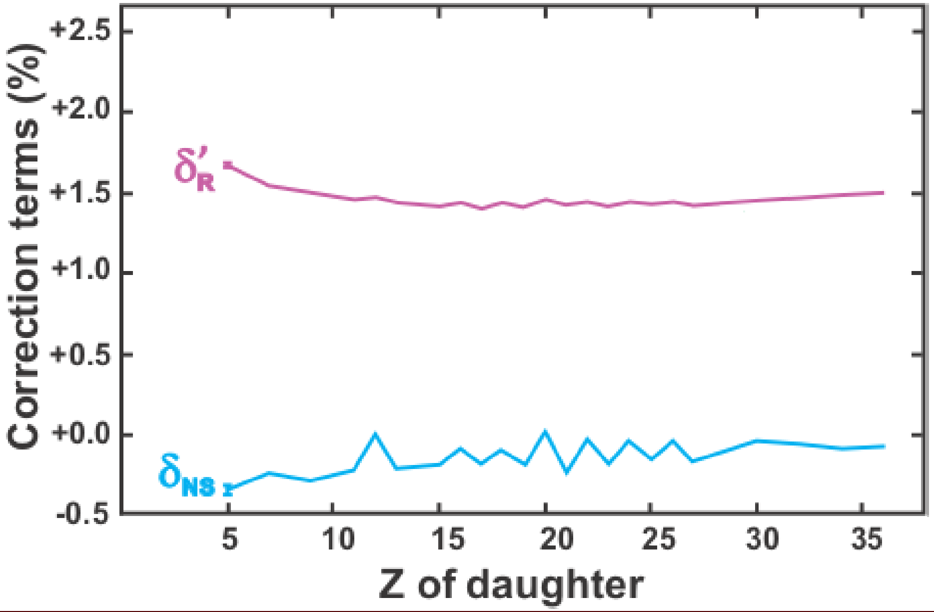


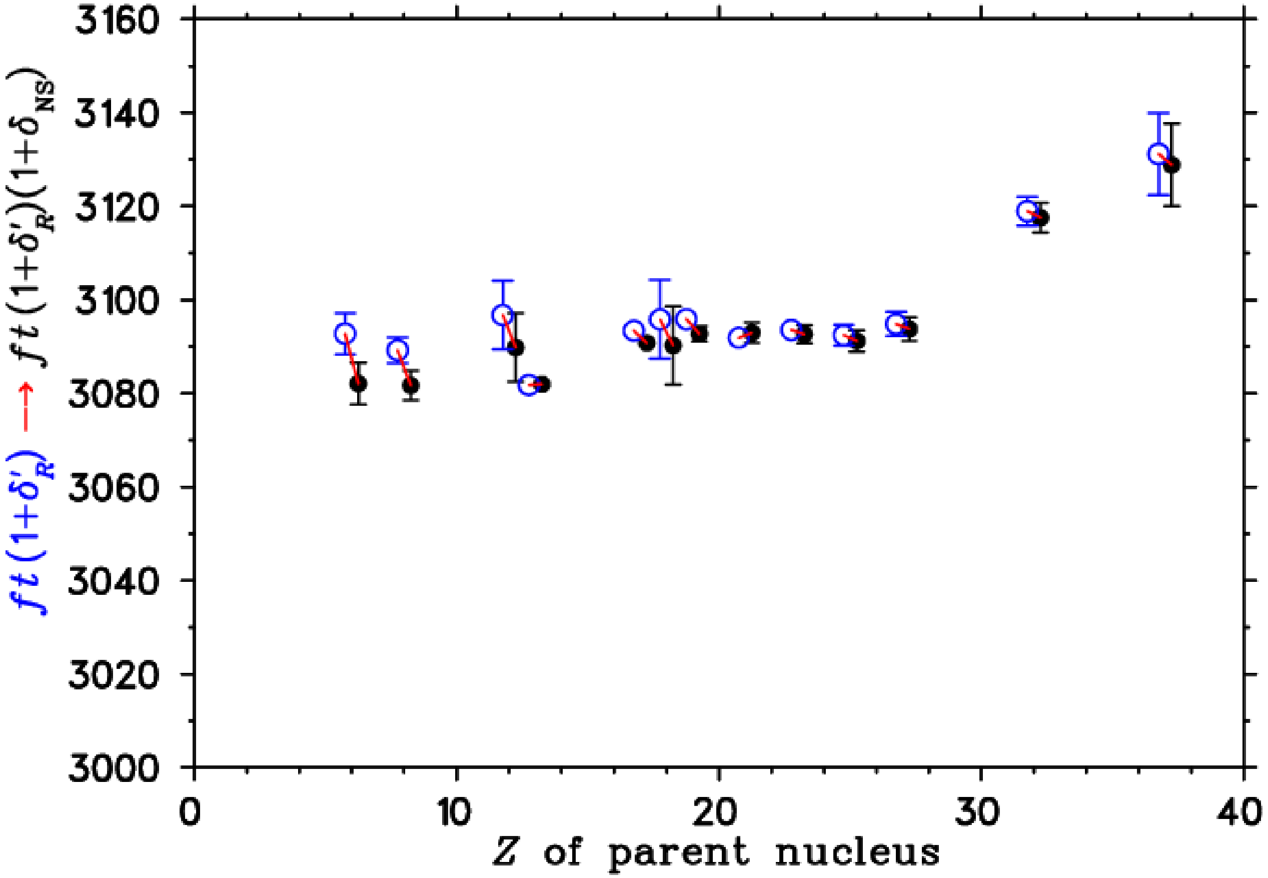
Extracting V_{ud} from $0^+ \to 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

2. From many transitions, test CVC and the correction terms



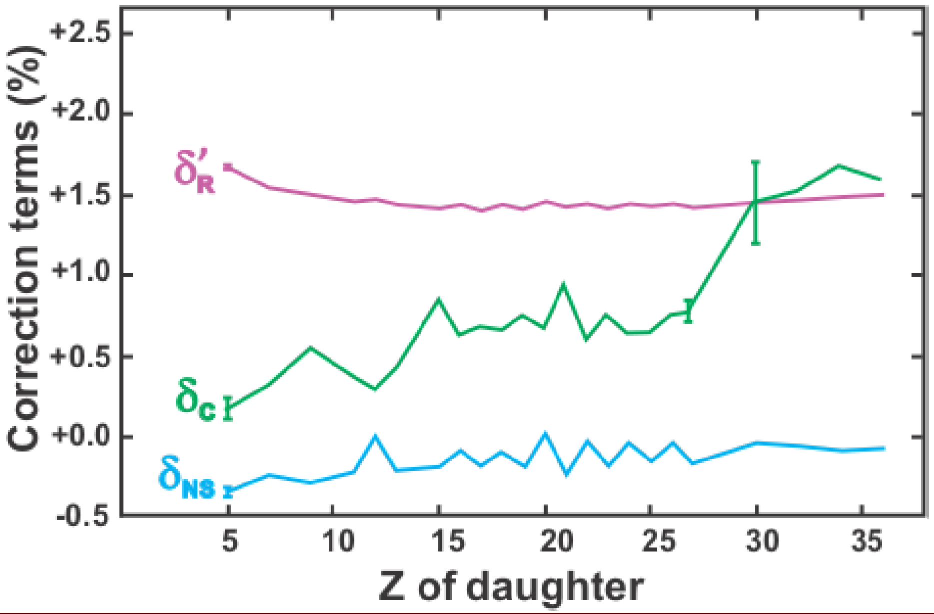


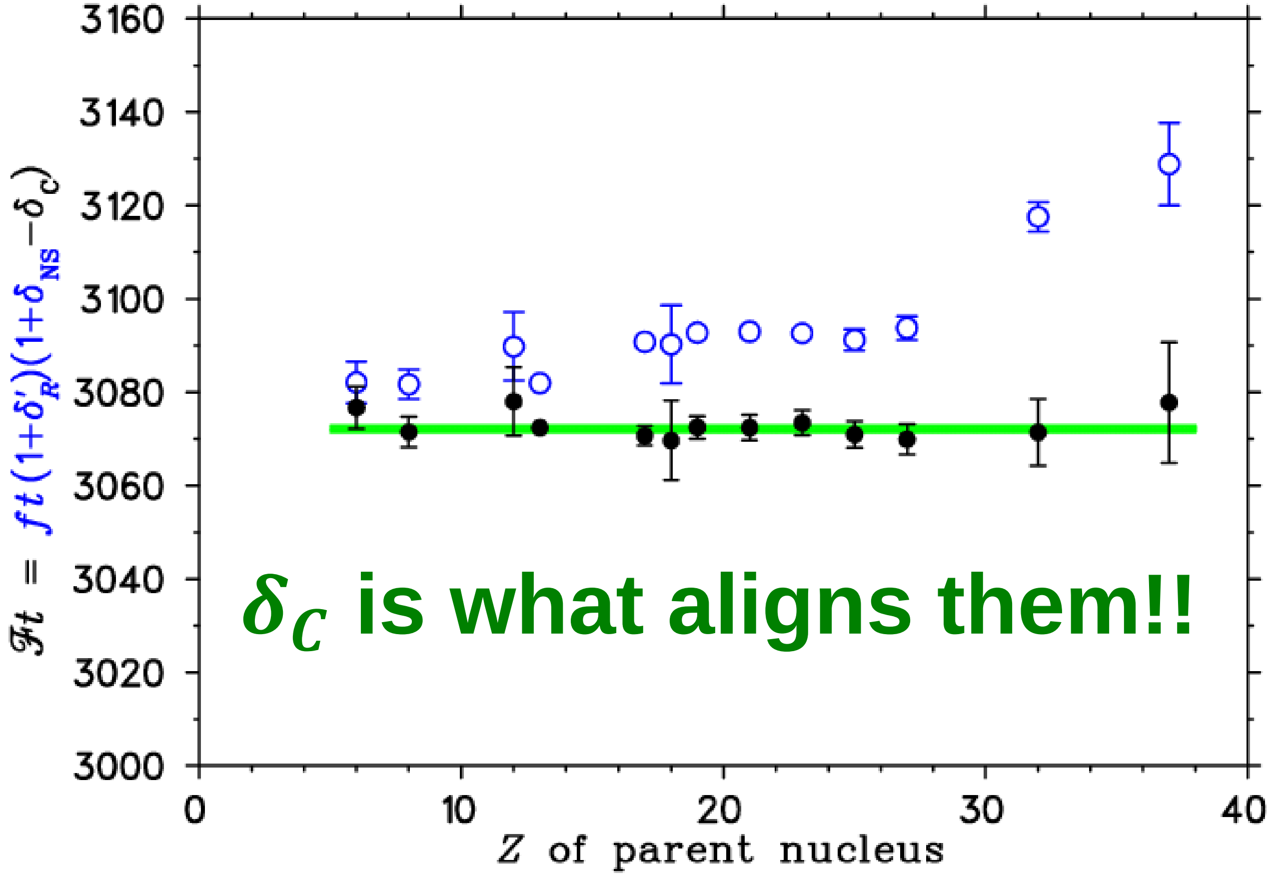
Extracting V_{ud} from $0^+ \rightarrow 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})]$$

2. From many transitions, test CVC and the correction terms





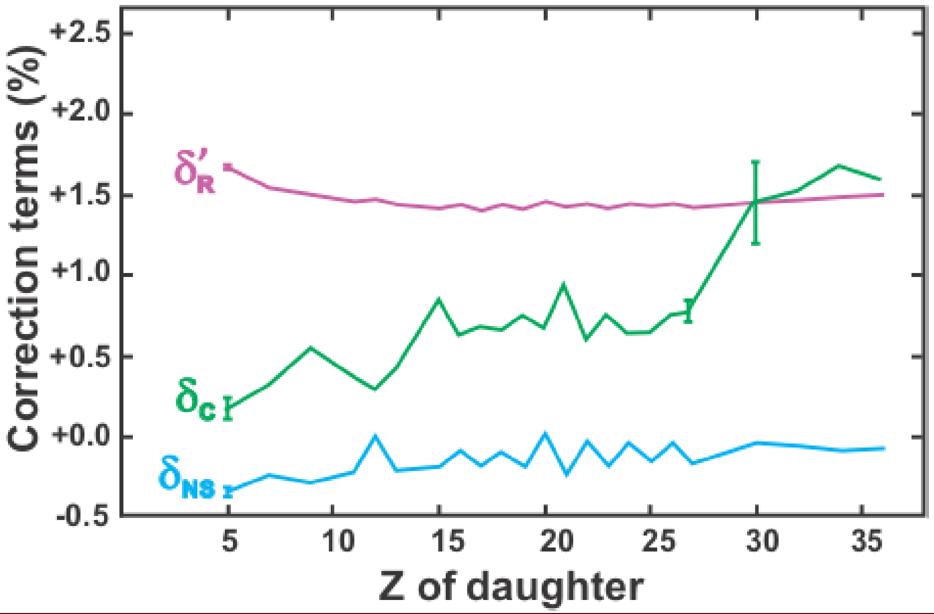
δ_C is what aligns them!!

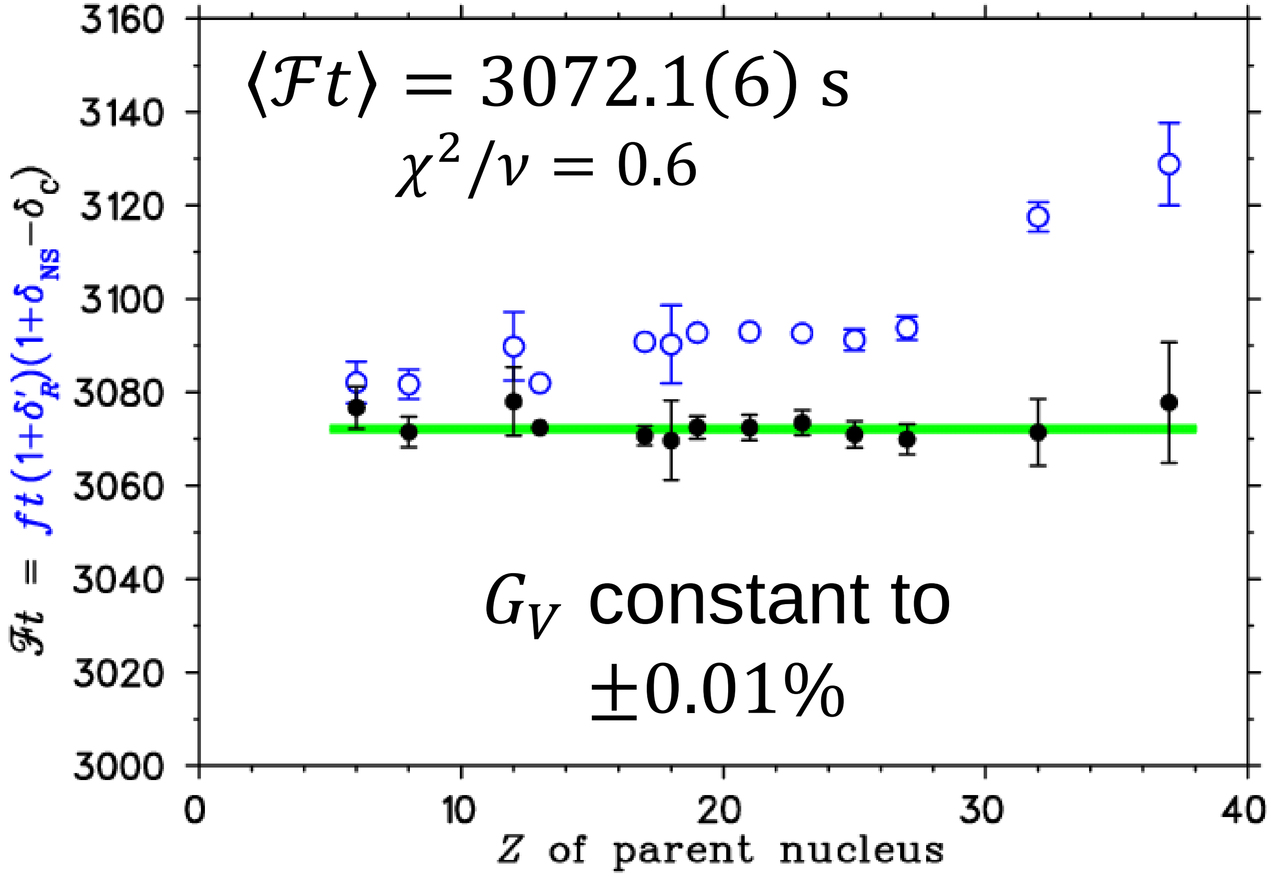
Extracting V_{ud} from $0^+ \rightarrow 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1 + \delta_R')[1 - (\delta_C - \delta_{NS})]$$

2. From many transitions, test CVC and the correction terms





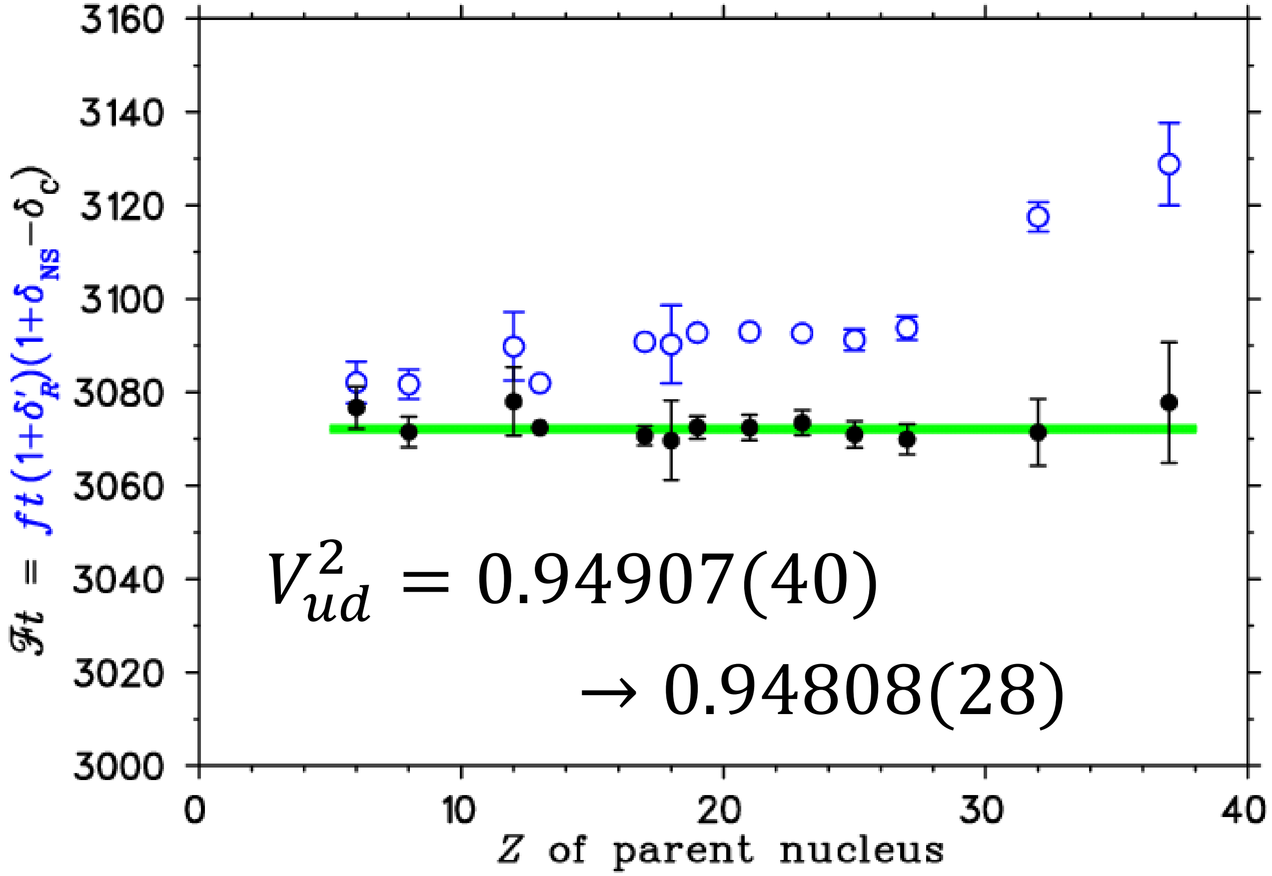
Extracting V_{ud} from $0^+ \to 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

2. From many transitions, test CVC and the correction terms
3. With CVC verified, determine $\langle\mathcal{F}t\rangle$ and

$$V_{ud}^2 = \frac{K/G_F^2}{2\langle\mathcal{F}t\rangle(1+\Delta_R^V)}$$



$V_{ud}^2 = 0.94907(40)$

$\to 0.94808(28)$

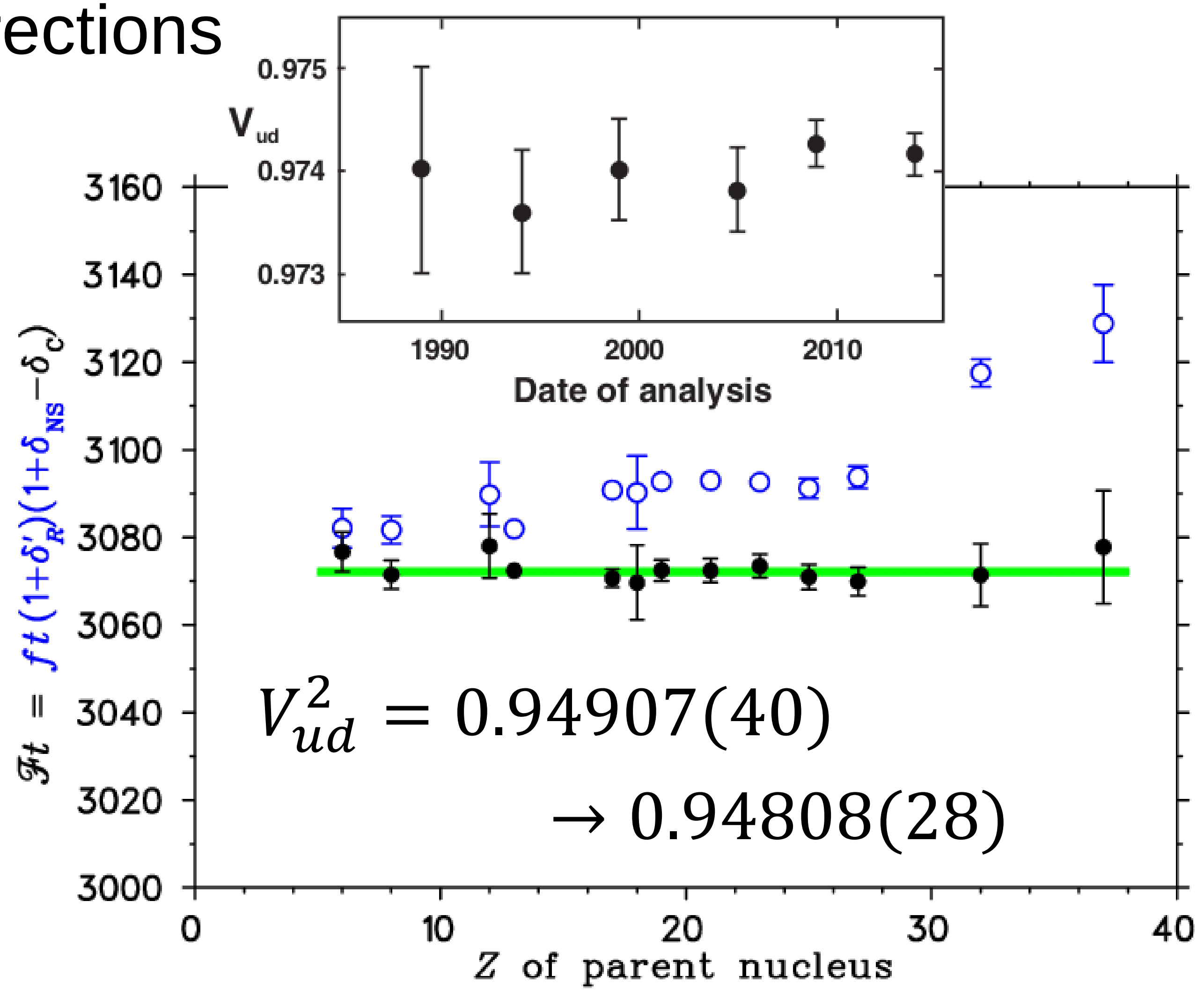
Extracting V_{ud} from $0^+ \to 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

$$\mathcal{F}t = ft(1 + \delta_R')[1 - (\delta_C - \delta_{NS})]$$

2. From many transitions, test CVC and the correction terms
3. With CVC verified, determine $\langle \mathcal{F}t \rangle$ and

$$V_{ud}^2 = \frac{K/G_F^2}{2\langle \mathcal{F}t \rangle (1 + \Delta_R^V)}$$



$$V_{ud}^2 = 0.94907(40)$$

$$\to 0.94808(28)$$

Extracting V_{ud} from $0^+ \rightarrow 0^+$ decays

1. Experimentally determine the $\mathcal{F}t$ value by measuring Q_{EC}, $t_{1/2}$ and the branching ratio, and applying corrections

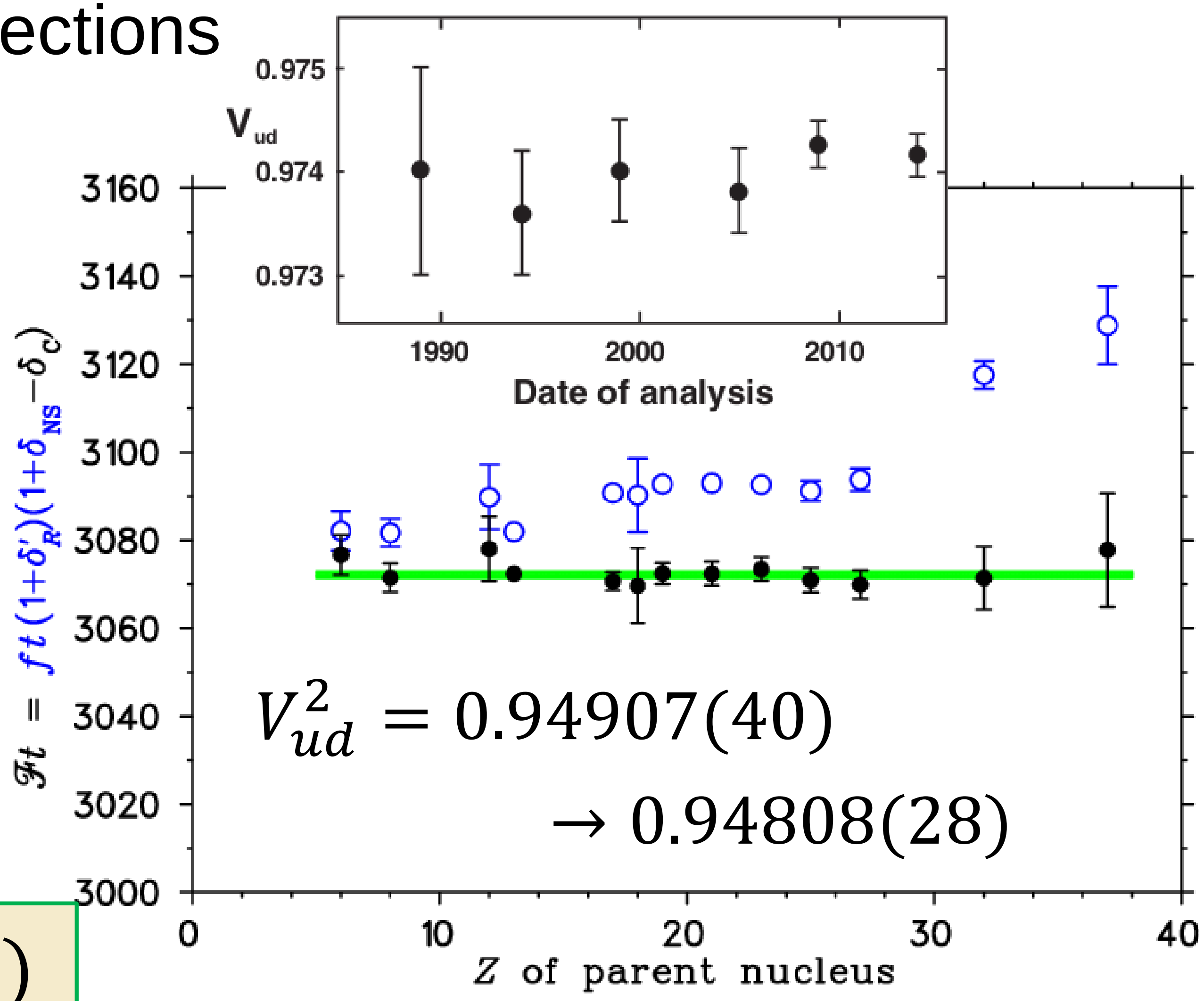
$$\mathcal{F}t = ft(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})]$$

2. From many transitions, test CVC and the correction terms

3. With CVC verified, determine $\langle\mathcal{F}t\rangle$ and $$V_{ud}^2 = \frac{K/G_F^2}{2\langle\mathcal{F}t\rangle(1 + \Delta_R^V)}$$

4. Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99841(36)$$



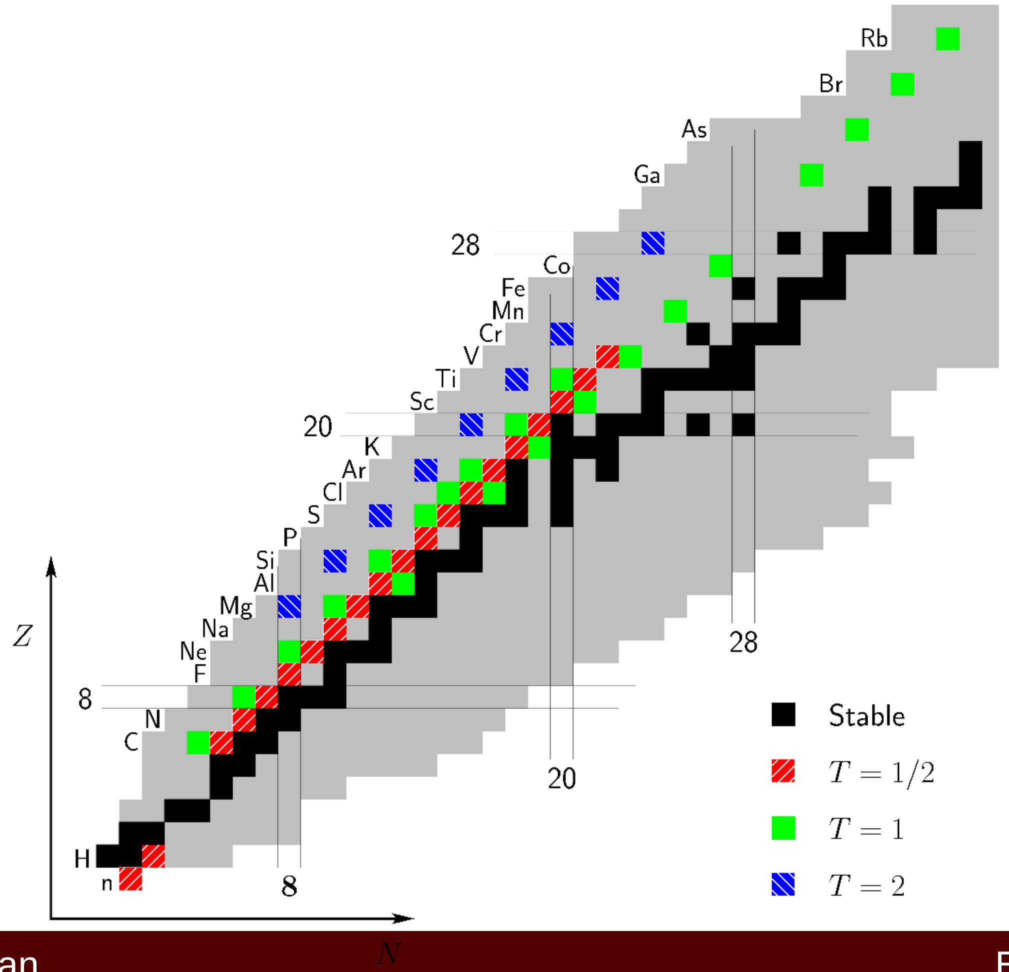
$V_{ud}^2 = 0.94907(40)$

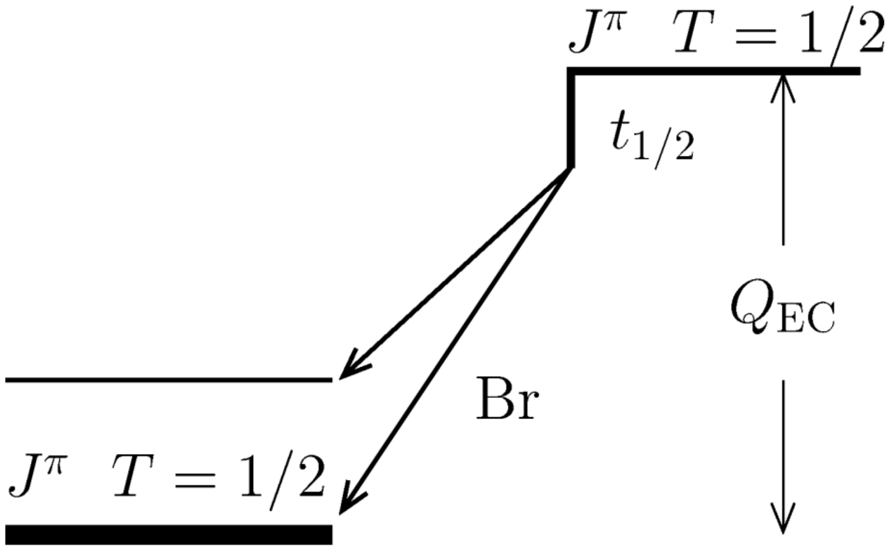
$\rightarrow 0.94808(28)$

$T = 1/2$ transitions – neutron and mirror decays

- These isobaric analogue decays are also theoretically tractable, but experimentally more difficult (mirrors) and/or limited (only one neutron)

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})] = \frac{K/G_F^2}{V_{ud}^2(1+\Delta_R^V)(M_F^2+(G_A/G_F)^2 M_{GT}^2)}$$





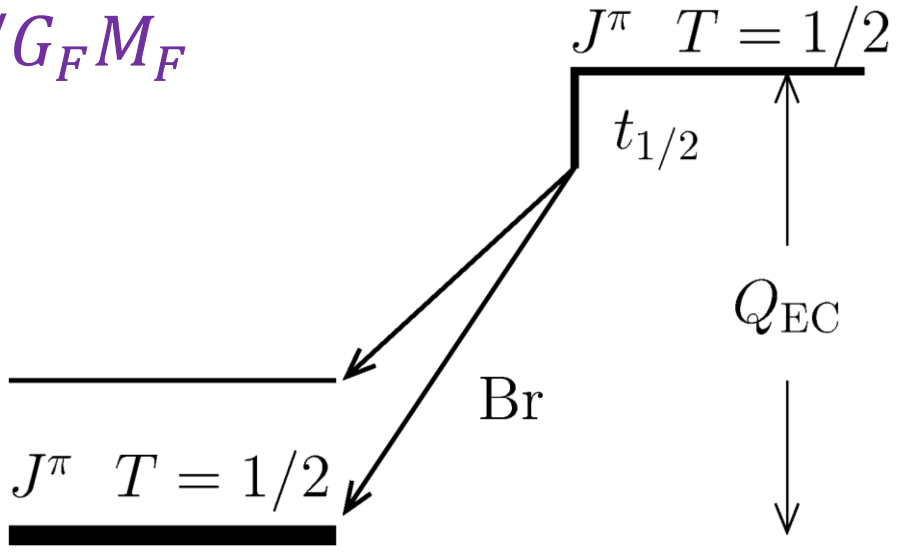
$T = 1/2$ transitions – neutron and mirror decays

- These isobaric analogue decays are also theoretically tractable, but experimentally more difficult (mirrors) and/or limited (only one neutron)

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})] = \frac{K/G_F^2}{V_{ud}^2(1+\Delta_R^V)(M_F^2 + (G_A/G_F)^2 M_{GT}^2)}$$

???

- The neutron: $M_{GT} = \sqrt{3}$, but must measure $\lambda = G_A/G_F$
- Mirror transitions: must measure $\rho = G_A M_{GT}/G_F M_F$



$T = 1/2$ transitions – neutron and mirror decays

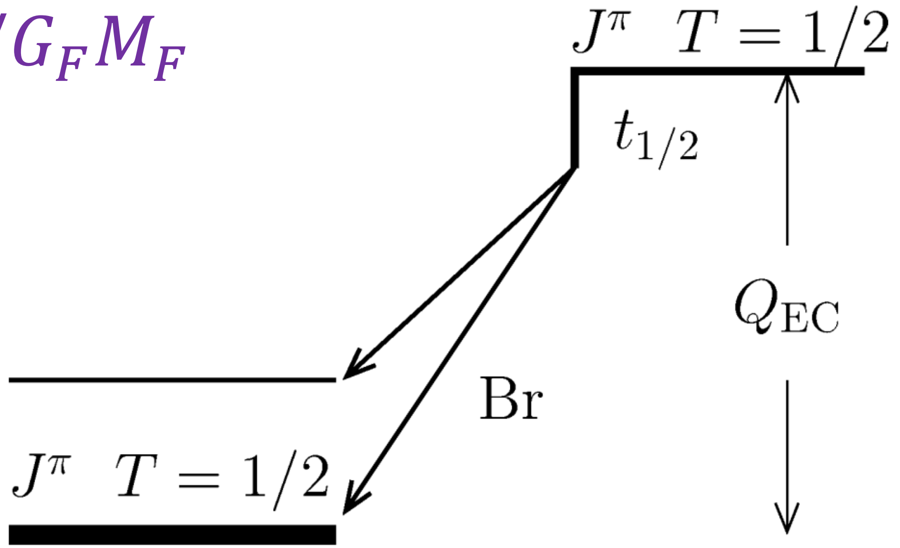
- These isobaric analogue decays are also theoretically tractable, but experimentally more difficult (mirrors) and/or limited (only one neutron)

$$\mathcal{F}t = ft(1+\delta'_R)[1-(\delta_C-\delta_{NS})] = \frac{K/G_F^2}{V_{ud}^2(1+\Delta_R^V)(M_F^2+(G_A/G_F)^2 M_{GT}^2)}$$

???

- The neutron: $M_{GT} = \sqrt{3}$, but must measure $\lambda = G_A/G_F$
- Mirror transitions: must measure $\rho = G_A M_{GT}/G_F M_F$

$\Rightarrow$ must additionally measure a correlation parameter, e.g. A_β, and/or $a_{\beta\nu}$, and/or …



+ correlation parameter(s)

$T = 1/2$ transitions – neutron and mirror decays

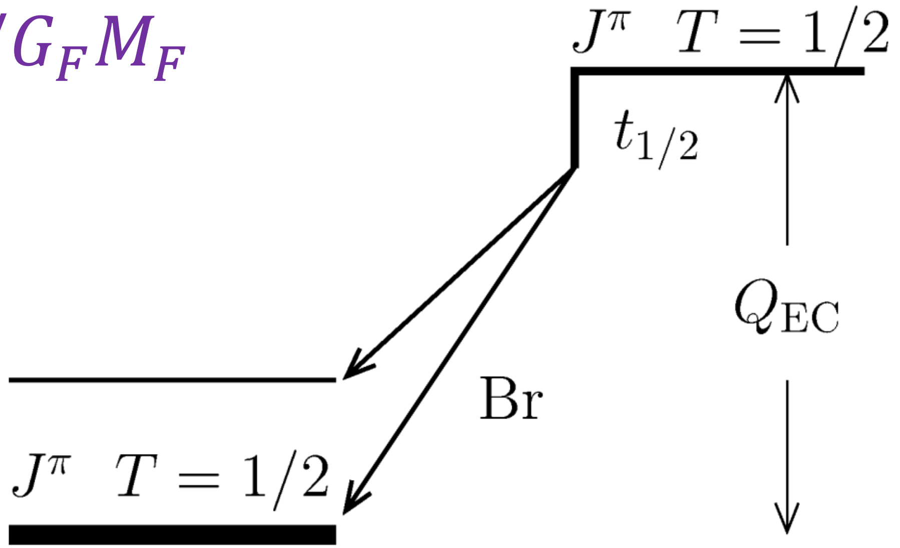
- These isobaric analogue decays are also theoretically tractable, but experimentally more difficult (mirrors) and/or limited (only one neutron)

$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})] = \frac{K/G_F^2}{V_{ud}^2(1+\Delta_R^V)(M_F^2+(G_A/G_F)^2 M_{GT}^2)}$$

???

- The neutron: $M_{GT} = \sqrt{3}$, but must measure $\lambda = G_A/G_F$
- Mirror transitions: must measure $\rho = G_A M_{GT}/G_F M_F$

$\Rightarrow$ must additionally measure a correlation parameter, e.g. A_β, and/or $a_{\beta\nu}$, and/or …



+ correlation parameter(s)

- Significant plus: **no** δ_C or δ_{NS} corrections for the neutron!

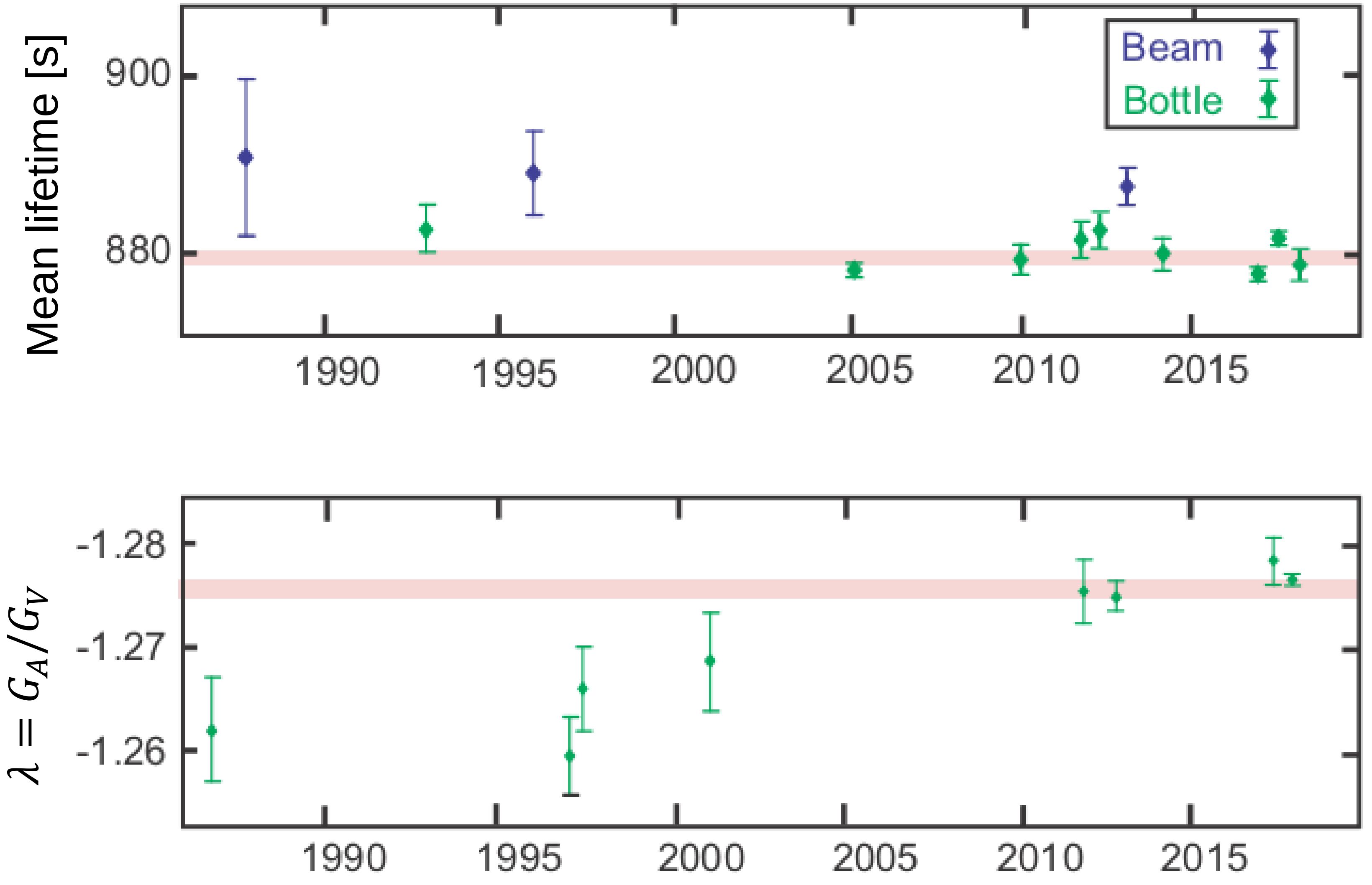
Summary of neutron decay

- No time to talk about recent efforts (but see Albert Young's talk from last week!)

$$\tau = 879.7(8)\ s$$
$$\chi^2/\nu = 3.8$$

Beam: 888.1 ± 2.0 s

Bottle: 879.4 ± 0.6 s



$$\lambda = -1.2764(6)$$

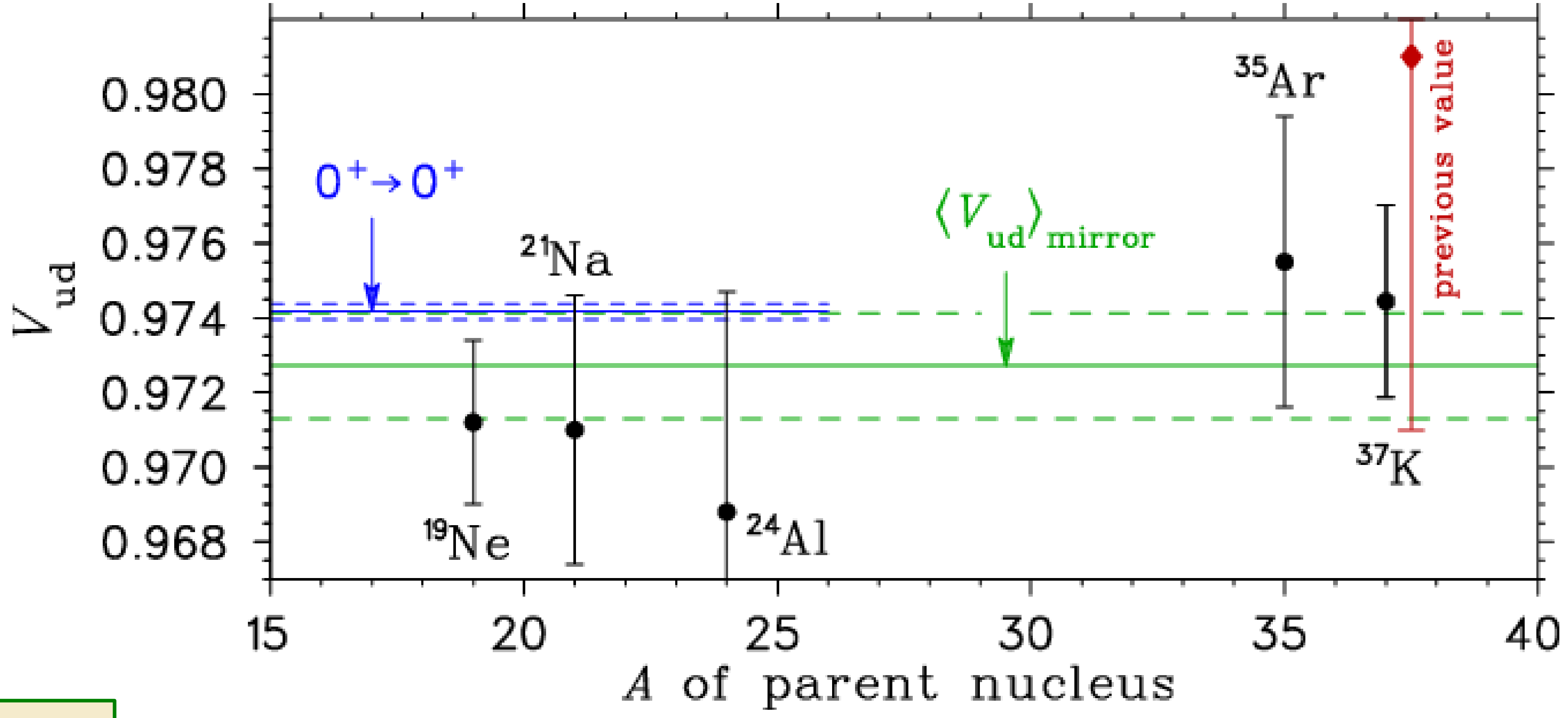
(PERKEO III result arXiv:1812.04666)

$$V_{ud} = 0.9730(6)$$

(lots of activity here)

Summary of mirror transitions

- And Albert talked about ^{19}Ne†, but a few other cases have been measured as well:
  - All uncertainties dominated by their correlation measurement(s)
  - Tough to imagine these will be truly competitive with $0^+ \rightarrow 0^+$ decays…



$$V_{ud} = 0.9722(14)$$

†Or at least I thought he was…

And there's the decay of the pion

- Like the neutron, theoretically clean with no δ_C nor δ_{NS} corrections

$$\pi^+ \to \pi^0 + e^+ + \nu_e$$

- Masses and lifetime known precisely enough, but

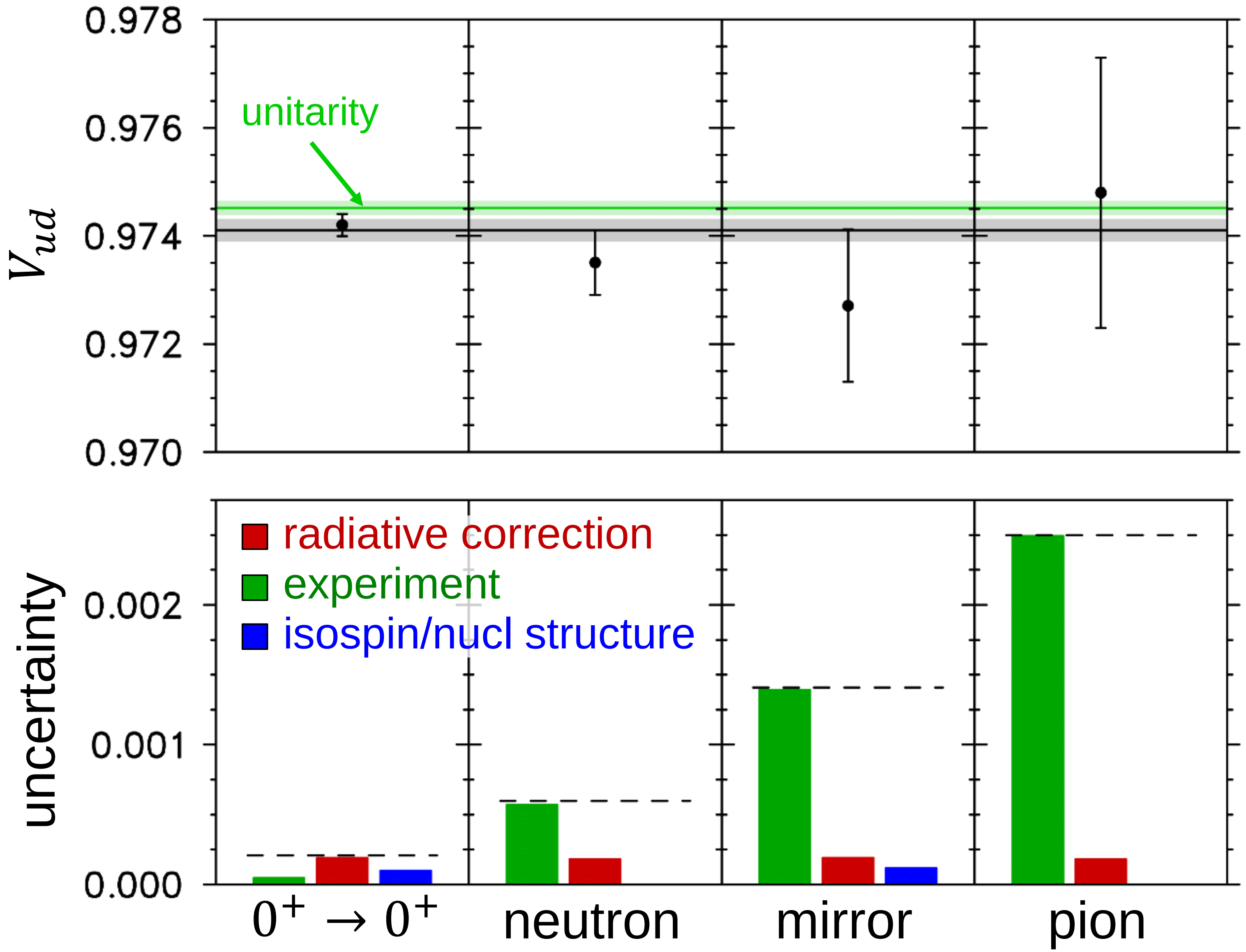
$$\mathrm{Br} = 1.036(7) \times 10^{-8}$$

is a ***really*** small branch!

$$V_{ud} = 0.9743(25)$$

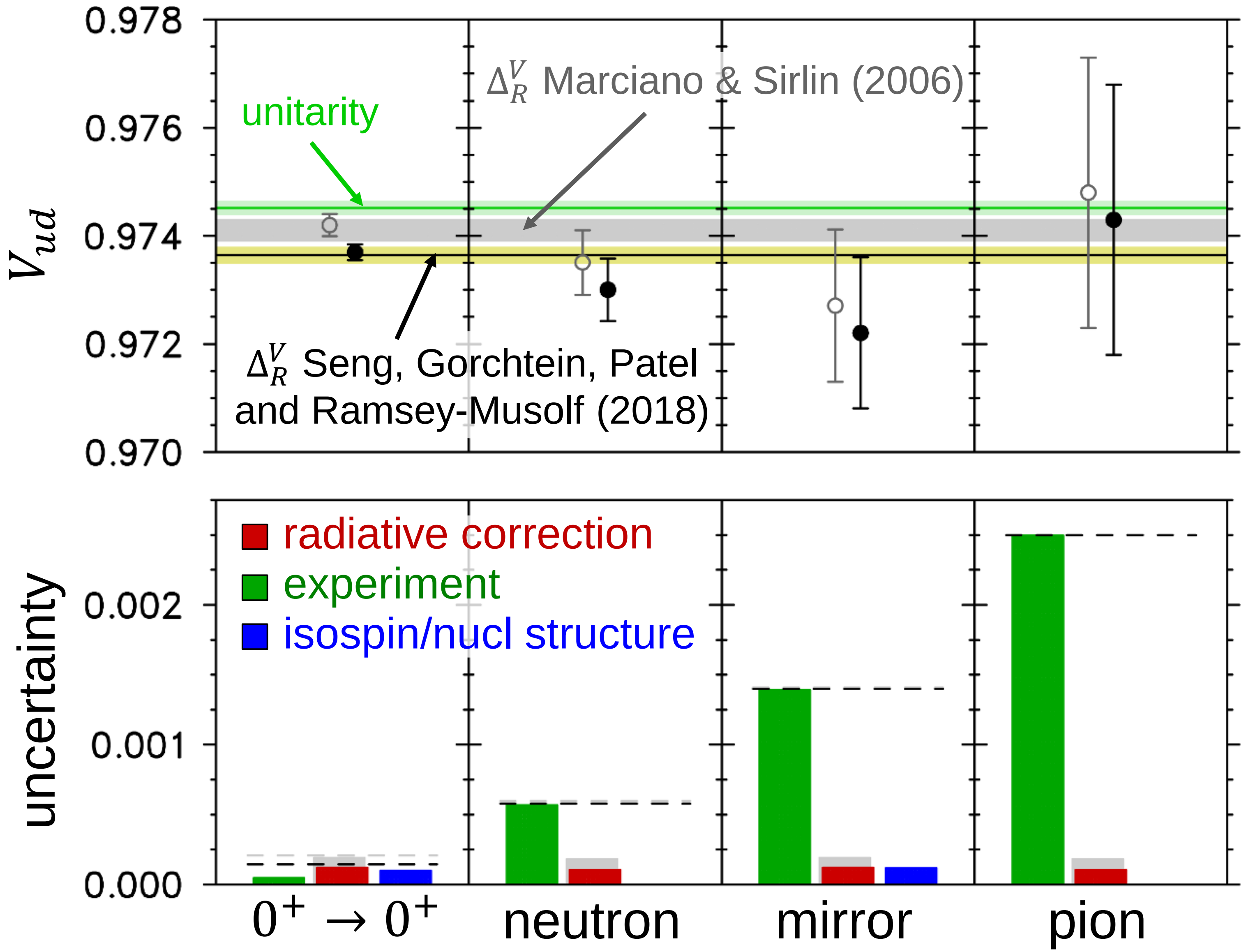
- No (ambitious) plan to improve the branching ratio, not likely this will get more precise in the near future.

Summary of current status of V_{ud}



- $0^+ \rightarrow 0^+$:
  $V_{ud} = 0.9742(2)$
- The neutron
  $V_{ud} = 0.9735(6)$
- Mirror transitions
  $V_{ud} = 0.9727(14)$
- The pion
  $V_{ud} = 0.9748(25)$

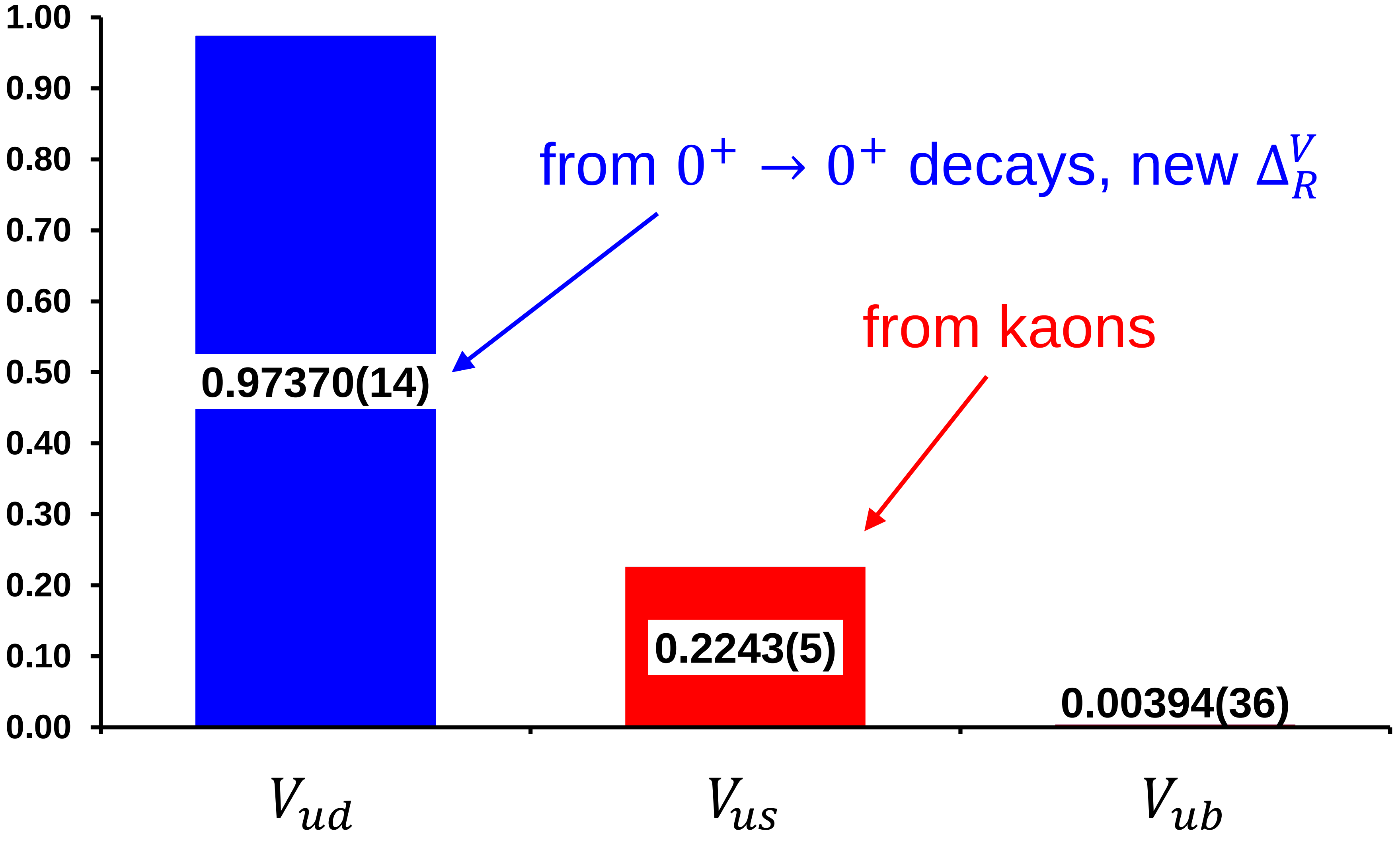
Summary of current status of V_{ud}



- $0^+ \to 0^+$:
  $V_{ud} = 0.9742(2)$
  $\to\ 0.9737(1)$
- The neutron
  $V_{ud} = 0.9735(6)$
  $\to\ 0.9730(6)$
- Mirror transitions
  $V_{ud} = 0.9727(14)$
  $\to\ 0.9722(14)$
- The pion
  $V_{ud} = 0.9748(25)$
  $\to\ 0.9743(25)$

Summary of current status of CKM unitarity

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



Summary of current status of CKM unitarity

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

- $V_{ud}^2 = 0.94798(27)$
  from nuclear, neutron and π^+ decays; Δ_R^V from Seng *et* al., PRL **121**, 241804 (2018)

- $V_{us}^2 = 0.05031(22)$
  from kaon decays (PDG)

- $V_{ub}^2 = 0.00002$
  from B decays (negligible)

$$\Rightarrow \quad \Delta_{\text{CKM}} = 1.69(35) \times 10^{-5}$$

is **still** dominated by $\Delta_R^V = 2.467(22)\%$
(though kaons barely behind now)

> If the uncertainty in Δ_R^V is further reduced by $3\times$:
> $\Rightarrow$ uncertainty in $V_{ud}^2 \rightarrow 0.00020$
> and uncertainty in $\Delta_{\text{CKM}} \rightarrow 0.00030$
>
> – JCH

Looking ahead

- "What is the inner radiative correction, Δ_R?"
  - Currently the most important and impactful way to improve the unitarity test
- "How much can we believe the ISB corrections? Can we test them?"
  - At the moment, HF shell model the only one to truly satisfy CVC
- "Can we improve existing cases with $\Delta\mathcal{F}t \lesssim 0.25\%$?"
  - Maybe, but with ~220 measurements going into 15 ft values…it ain't easy to make a dent
- "Can we add new $0^+ \rightarrow 0^+$ transitions with $\Delta\mathcal{F}t \lesssim 0.25\%$?"
  - Yes, but will require theoretical progress in heavier nuclei
- "How much progress can be made with $T = 1/2$ transitions?"
  - The neutron still has problems (beam vs bottle), but is only 4× less precise than $0^+ \rightarrow 0^+$, and there is a lot of experiments in progress and planned
  - Determining $\rho = G_A M_{GT} / G_V M_F$ is very hard…(but ^{19}Ne and ^{37}K, at least, have potential)
- "Can V_{ud} from the pion be improved?"
  - Not in the forseeable future…

"What is the inner radiative correction, Δ_R?"

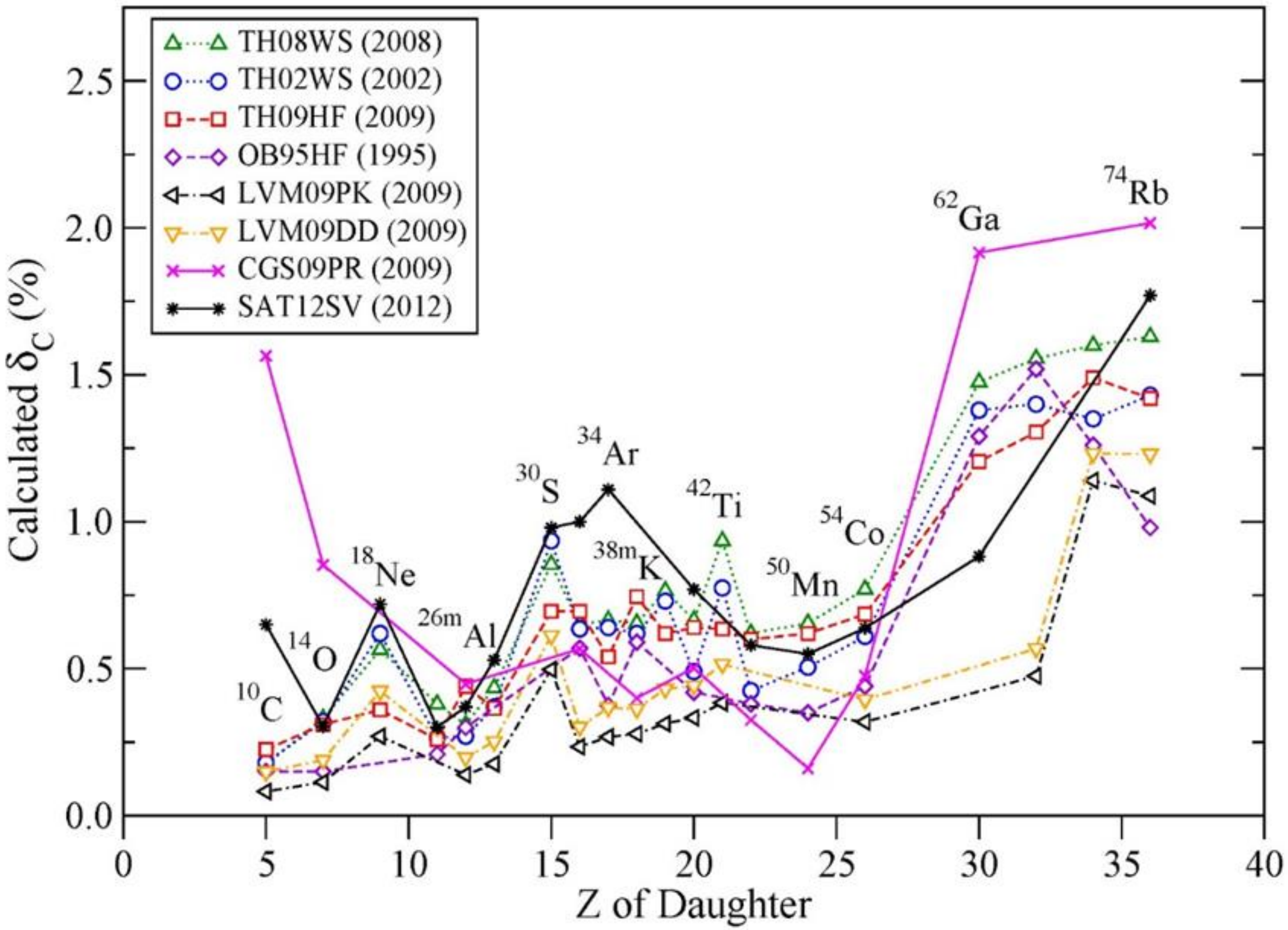
- Marciano & Sirlin made a huge stride in 2006: $\Delta_R^V = 2.361(38)\%$
  - 0.38% uncertainty in Δ_R^V still dominated unitarity test
- Even more ground-breaking: Seng, Gorchtein, Patel and Ramsey-Musolf, PRL **121**, 241804 (2018)
  - Reduces the uncertainty by a nearly a factor of 2: $\boldsymbol{\Delta_R^V = 2.467(22)\%}$
- If correct and no double-counting, leads to $\boldsymbol{\Delta_{\mathrm{CKM}} = 16(4) \times 10^{-4}}$
  - Uncertainty in Δ_R^V still dominates unitarity test, and now there is tension with unitarity!

Is there really a $\boldsymbol{4\sigma}$ effect?

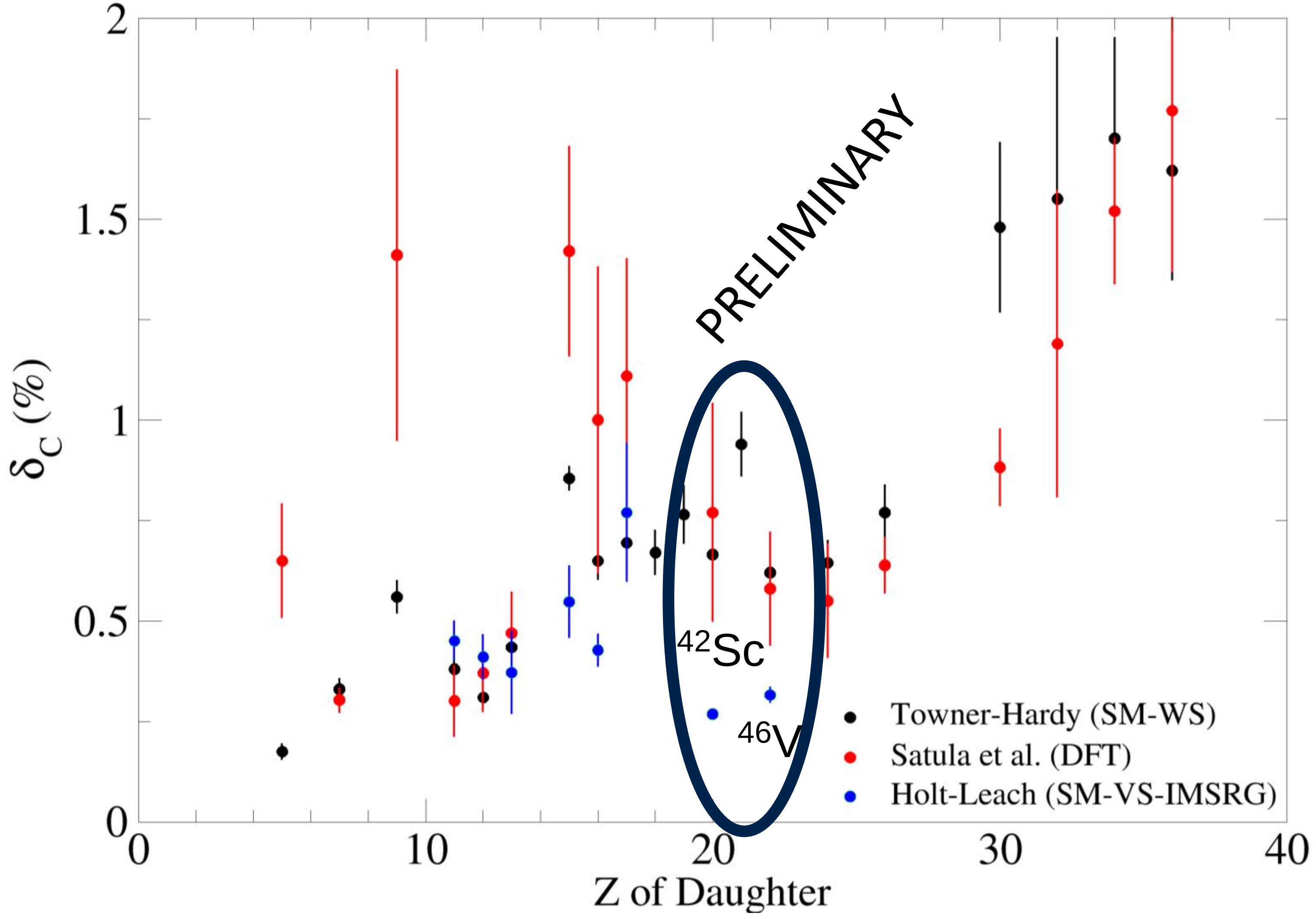
Exciting times (again)!

"How much can we believe the ISB corrections?"

- Flurry of activity circa 2010 to provide complementary calculations
  - Shell Model
  - Relativistic Hartree-Fock
  - Random Phase Approximation
  - Energy Density Functional
- Only the Woods-Saxon shell model [TH] able to confirm CVC
- DFT indicates absolute scale of WS SM
- Newest kids on the block: Holt and Leach
- Reliable theoretical uncertainties?



Nuclear Isospin Symmetry Breaking (ISB) Calculations



- Using χ-EFT + VS-IMSRG now extends *ab-initio* shell-model techniques up to the *pf*-shell and beyond
- Can calculate M_F directly to extract δ_C

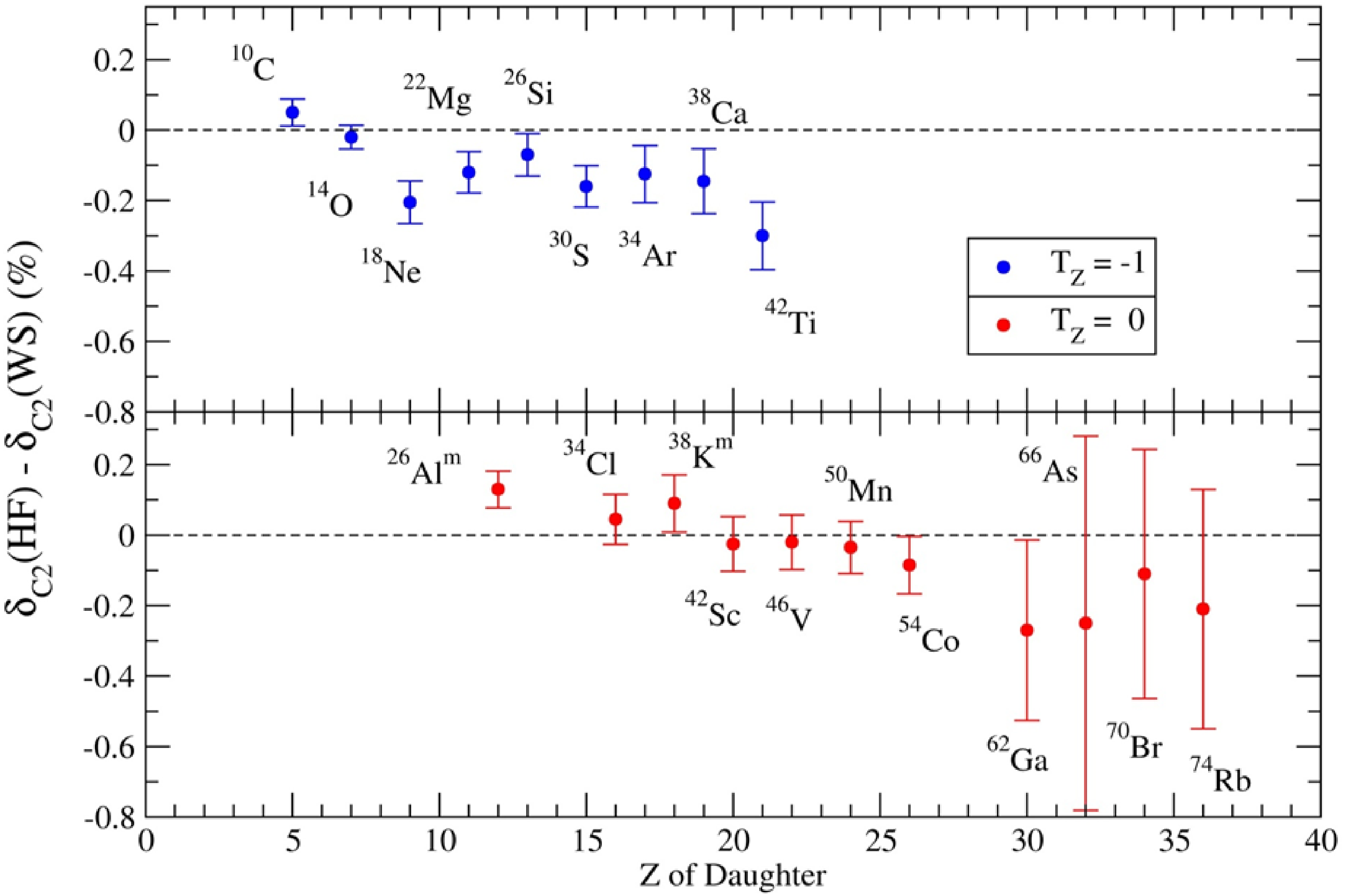
$$\delta_C = 1 - \frac{|M_F|^2}{|M_F^0|^2}$$

$$= 1 - \frac{|M_F|^2}{2}$$

J.C. Hardy and I.S. Towner, Phys. Rev. C **91**, 025501 (2015)
W. Satula et al., Phys. Rev. C **86**, 054316 (2012)
J.D. Holt and K.G. Leach, in progress (2018)

"How much can we believe the ISB corrections?"

- Hartree-Fock vs Woods-Saxon (just theory vs theory) radial overlap corrections: there is a Z-dependence



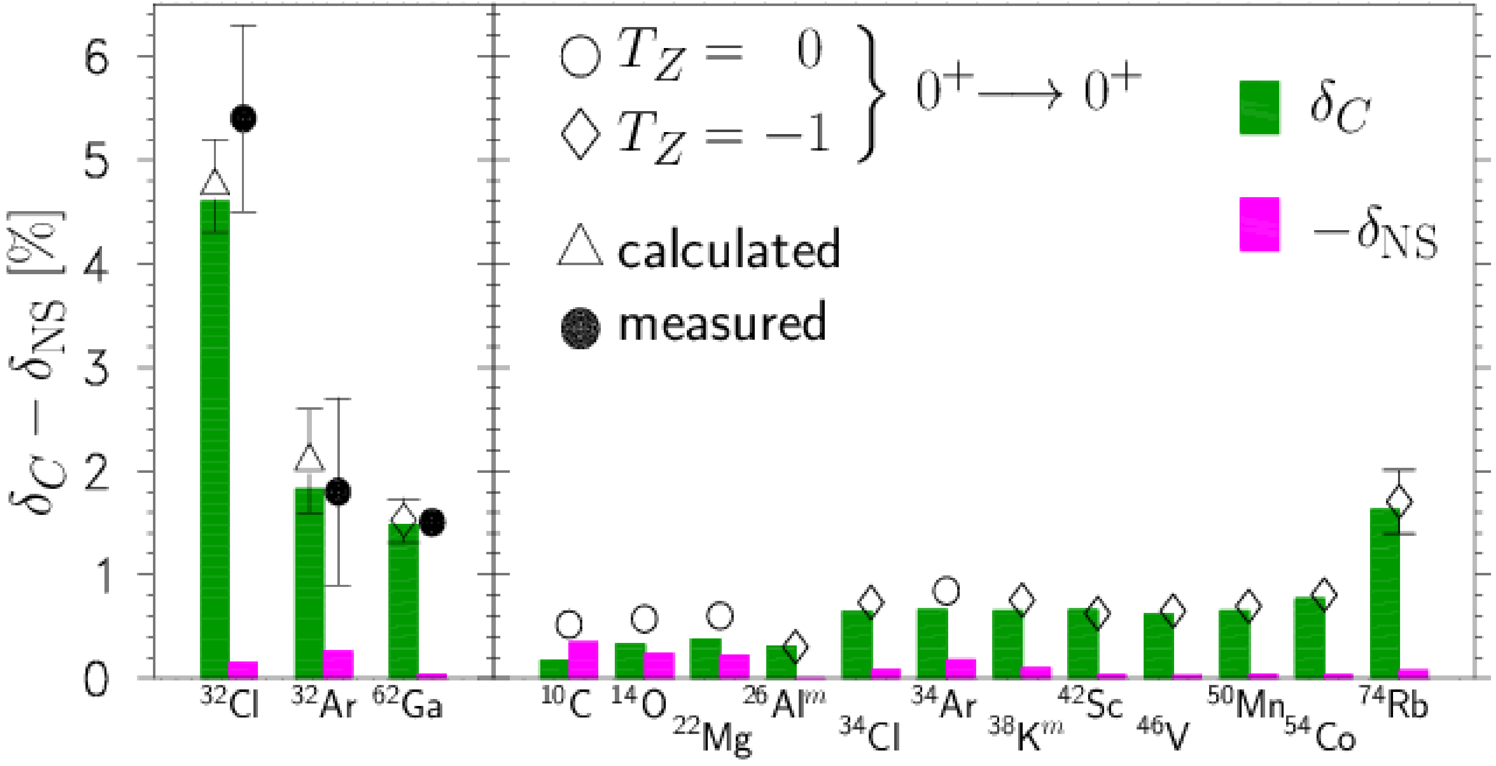
"*…it would be nice to have our theory colleagues dig into [this] and explain.*"

– C.Svennson

Courtesy of C. Svennson

"Can we test calculations of ISB corrections?"

- Yes! We've been trying to for years, actually…
  - ^{62}Ga [Hyland et al, PRL **97** (2006)]: 1.42(11)% vs 1.38%
  - ^{32}Ar [Bhattacharya et al., PRC **77** (2008)]: 2.1(8)% → 1.8(8)% vs 2.0%
  - ^{32}Cl [Melconian et al., PRL **107** (2011)]: 5.3(9)% vs 4.6%

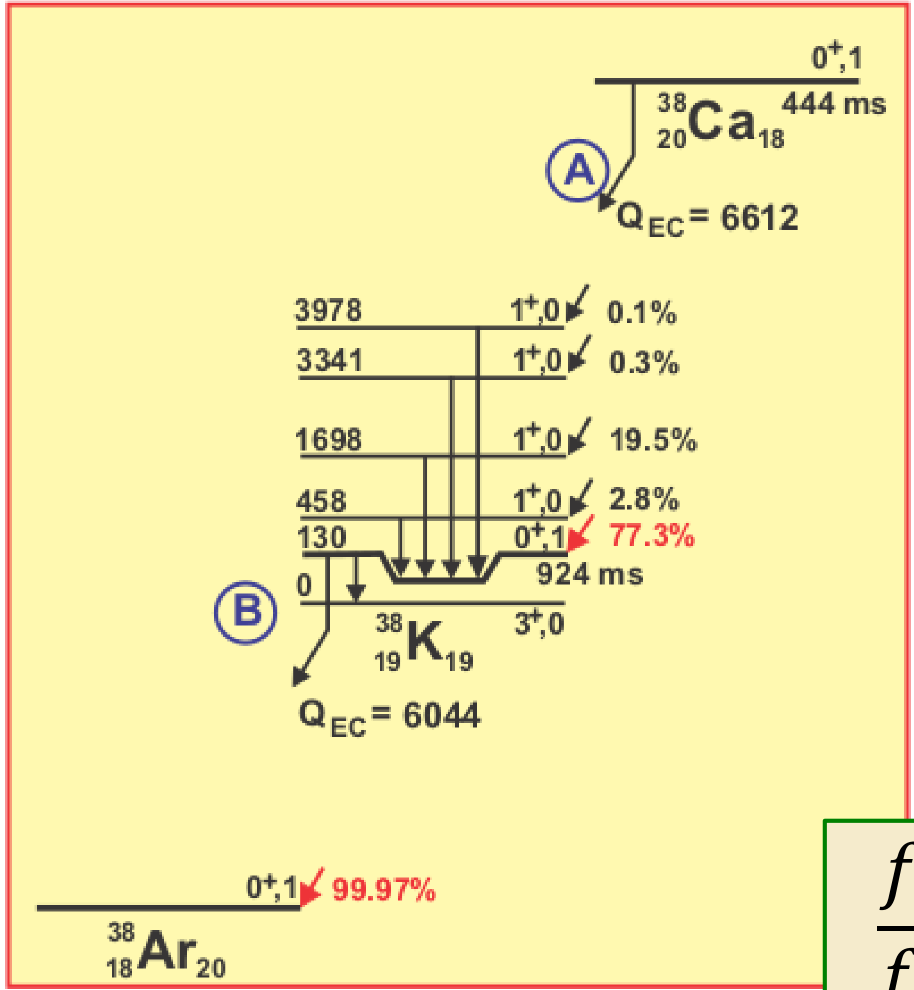


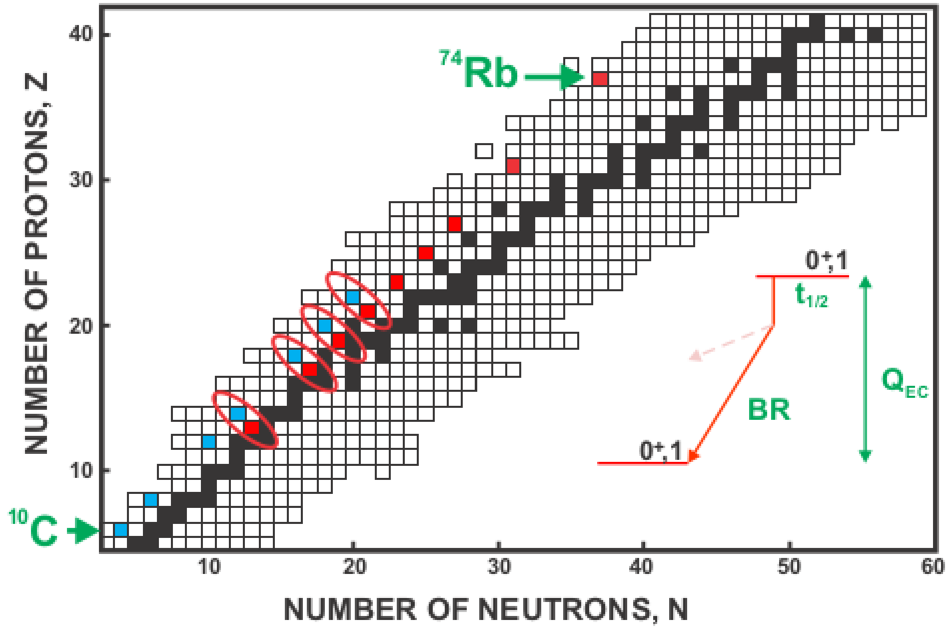
$$\mathcal{F}t = ft(1+\delta_R')[1-(\delta_C-\delta_{NS})]$$

$$\Leftrightarrow \quad \delta_C = 1 + \delta_{NS} - \frac{\mathcal{F}t^{\text{others}}}{ft^{\text{exp}}(1+\delta_R')}$$

WS vs HF: Mirror $0^+ \rightarrow 0^+$ transition pairs

- Ratio of $0^+ \rightarrow 0^+$ pairs less sensitive to theoretical uncertainties:





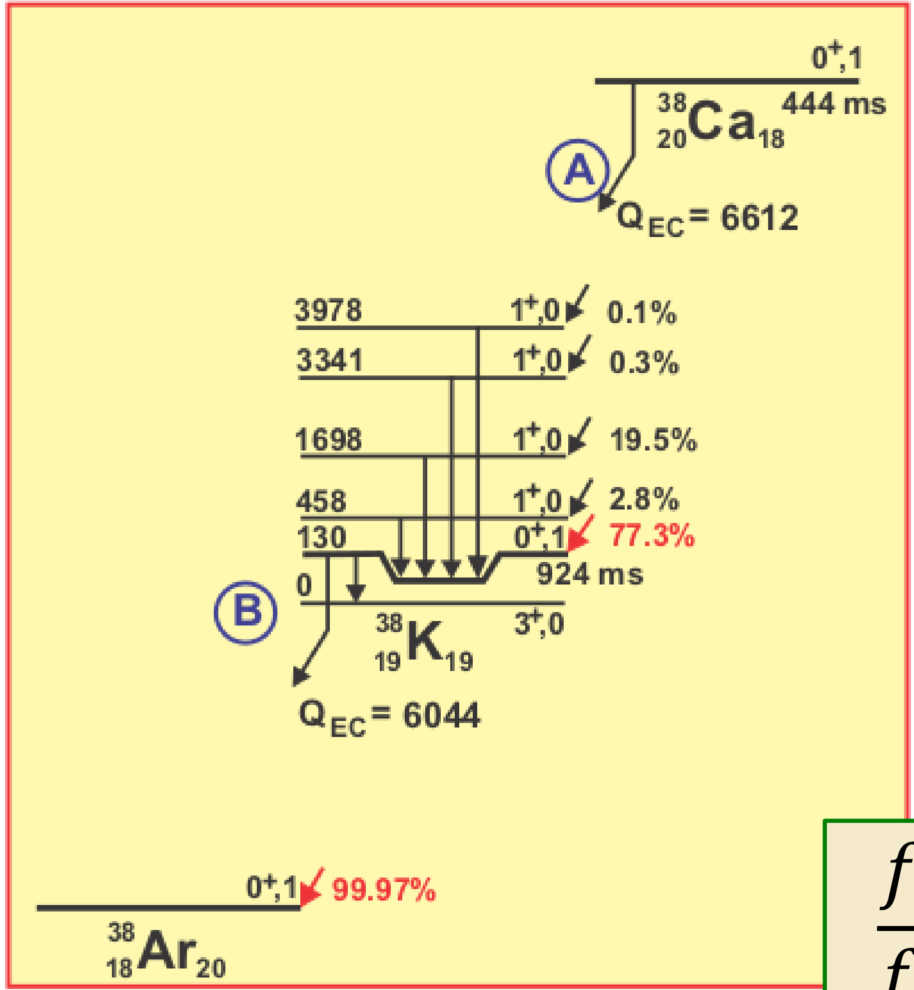
$$\frac{\mathcal{F}t_A}{\mathcal{F}t_B} = 1 = \frac{ft_A(1+\delta_R'^A)[1-(\delta_C^A-\delta_{NS}^A)]}{ft_B(1+\delta_R'^B)[1-(\delta_C^B-\delta_{NS}^B)]}$$

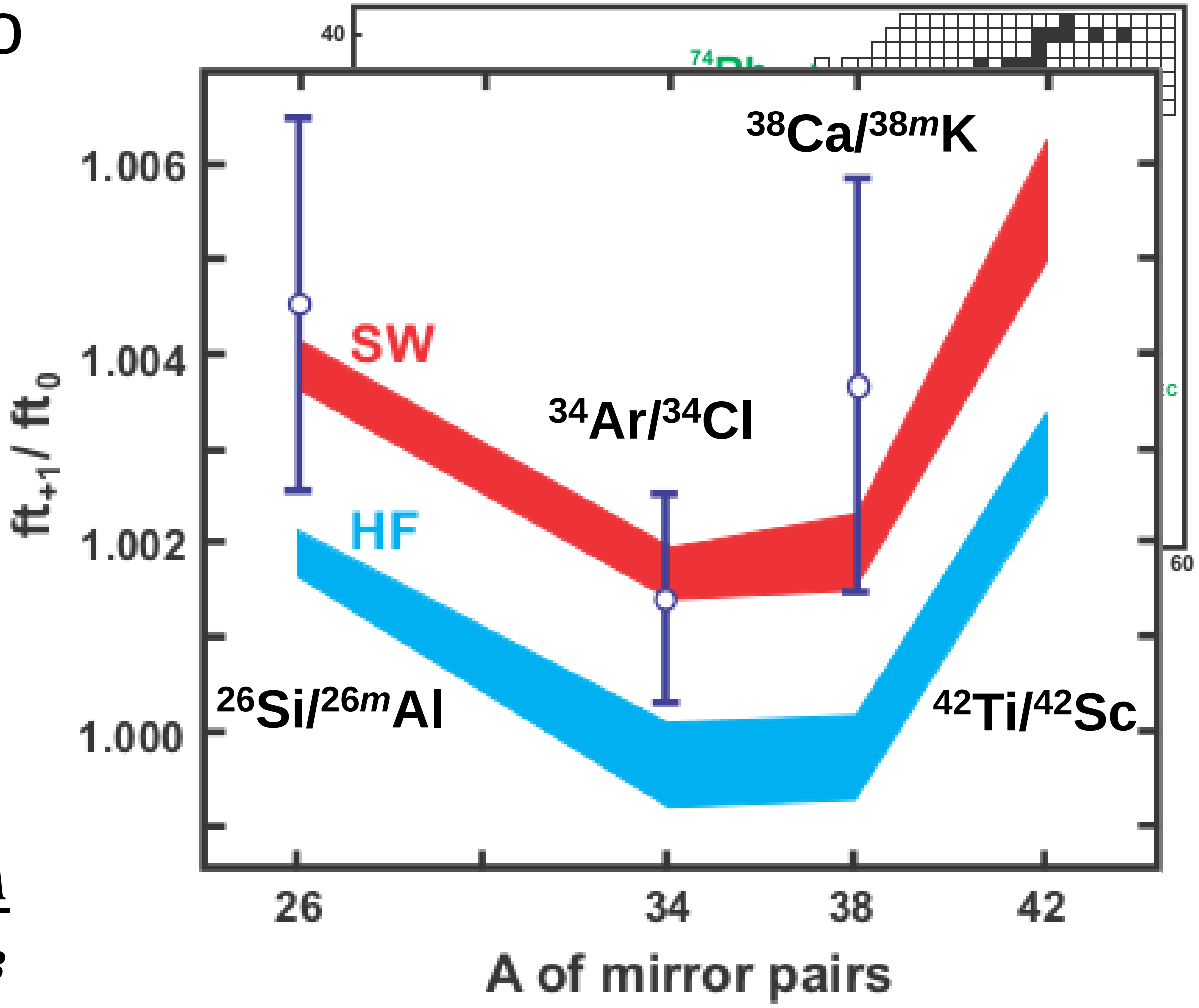
$$\Rightarrow \quad \frac{ft_A}{ft_B} = \frac{(1+\delta_R'^B)[1-(\delta_C^B-\delta_{NS}^B)]}{(1+\delta_R'^A)[1-(\delta_C^A-\delta_{NS}^A)]}$$

$$\frac{ft_A}{ft_B} \approx 1 + \left(\delta_R'^B - \delta_R'^A\right) + \left(\delta_{NS}^B - \delta_{NS}^A\right) + \left(\delta_C^B - \delta_C^A\right)$$

WS vs HF: Mirror $0^+ \to 0^+$ transition pairs

- Ratio of $0^+ \to 0^+$ pairs less sensitive to theoretical uncertainties:





$$\frac{\mathcal{F}t_A}{\mathcal{F}t_B} = 1$$

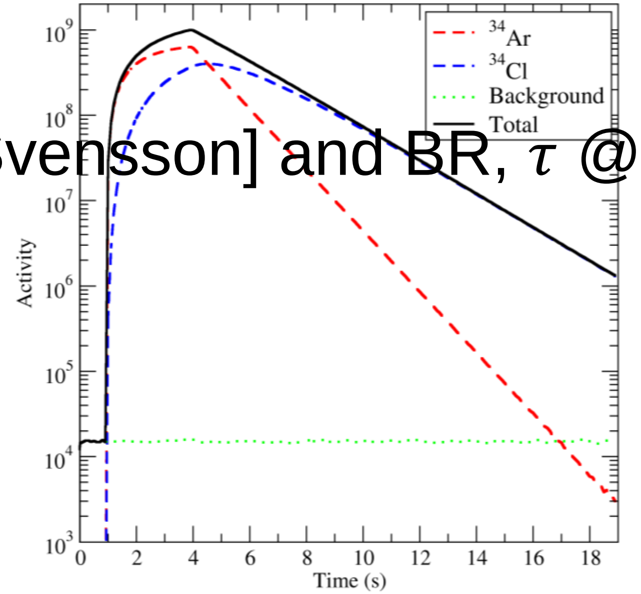
$$\Rightarrow \quad \frac{ft_A}{ft_B}$$

$$\frac{ft_A}{ft_B} \approx 1 + \left(\delta_R'^B - \delta_R'^A\right) + \left(\delta_{NS}^B - \delta_{NS}^A\right) + \left(\delta_C^B - \delta_C^A\right)$$

"Can we improve existing cases with $\Delta\mathcal{F}t \lesssim 0.25\%$?"

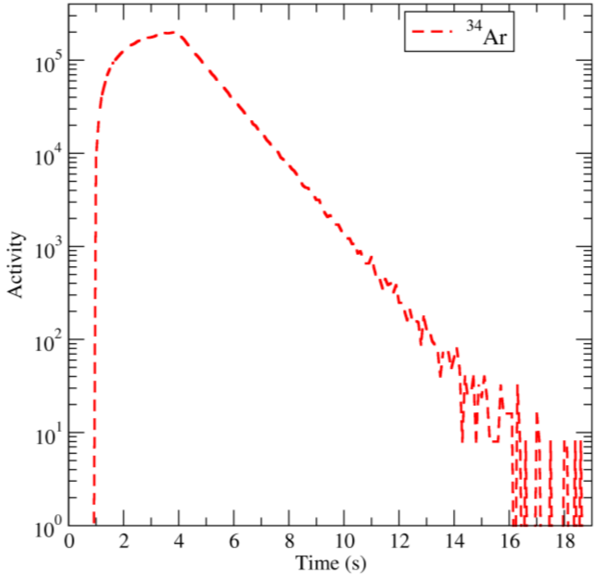
- There is already so many precision experiments, significant improvements is not practical in most cases
- Cases being investigated:
  - ^{22}Mg – BR @ GRIFFIN/TRIUMF [Svensson] and BR, τ @ ISOLDE [Blank] and Q_{EC} @ TITAN [Leach]
  - ^{26}Si† – BR @ TAMU [Hardy]
  - ^{30}S – BR @ GANIL/LISE3 [Blank]
  - ^{34}Ar† – BR, τ @ TAMU and @ GRIFFIN
  - ^{42}Ti† – BR @ TAMU
  - ^{62}Ga – check 0^+ exc state in ^{62}Zn @ GRIFFIN

Beta Activity



β-counting suffers from a large covariance between the ^{34}Ar and ^{34}Cl lifetimes

Gamma Activity

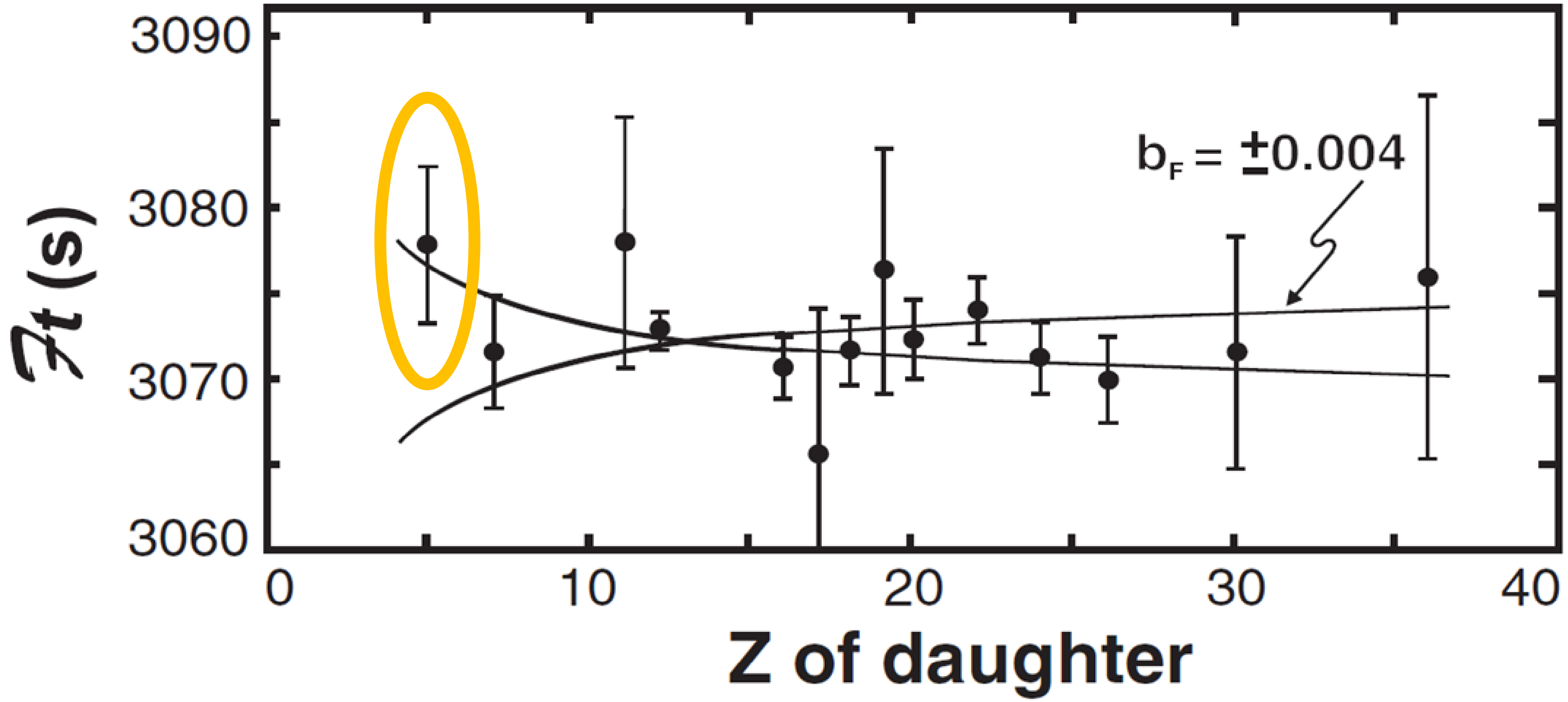


Gate on γ-ray transitions in the ^{34}Cl daughter

†mirror $0^+ \rightarrow 0^+$

Perhaps the most interesting (even if not for V_{ud}…)

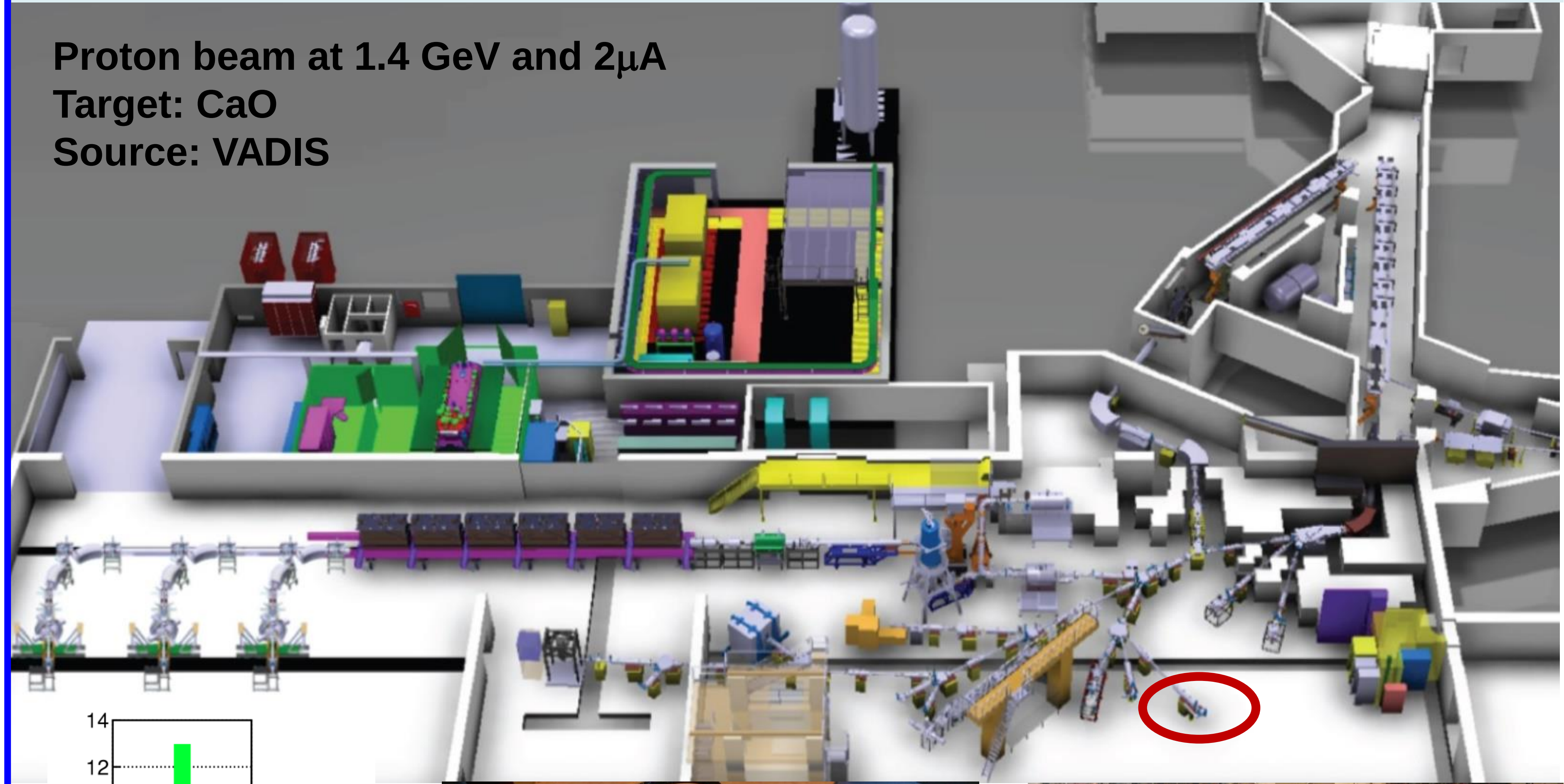
- ^{10}C: lowest Z of precisely measured superallowed, and so will impact the search for scalar currents

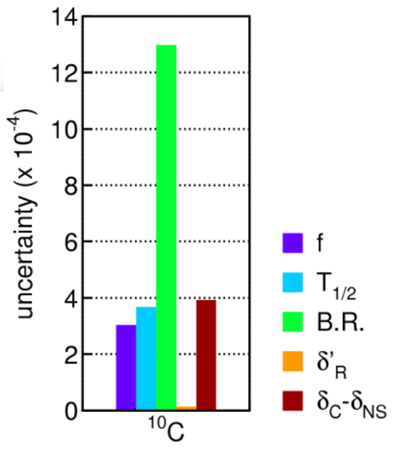


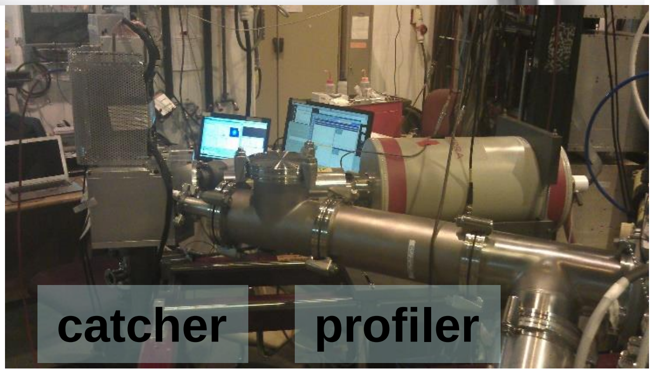
- Eronen & Hardy @ TAMU: BR analysis in progress
- Blank @ ISOLDE: BR analysis in progress
- Svensson @ TRIUMF: τ recently improved

^{10}C measurement at ISOLDE

Courtesy of B. Blank

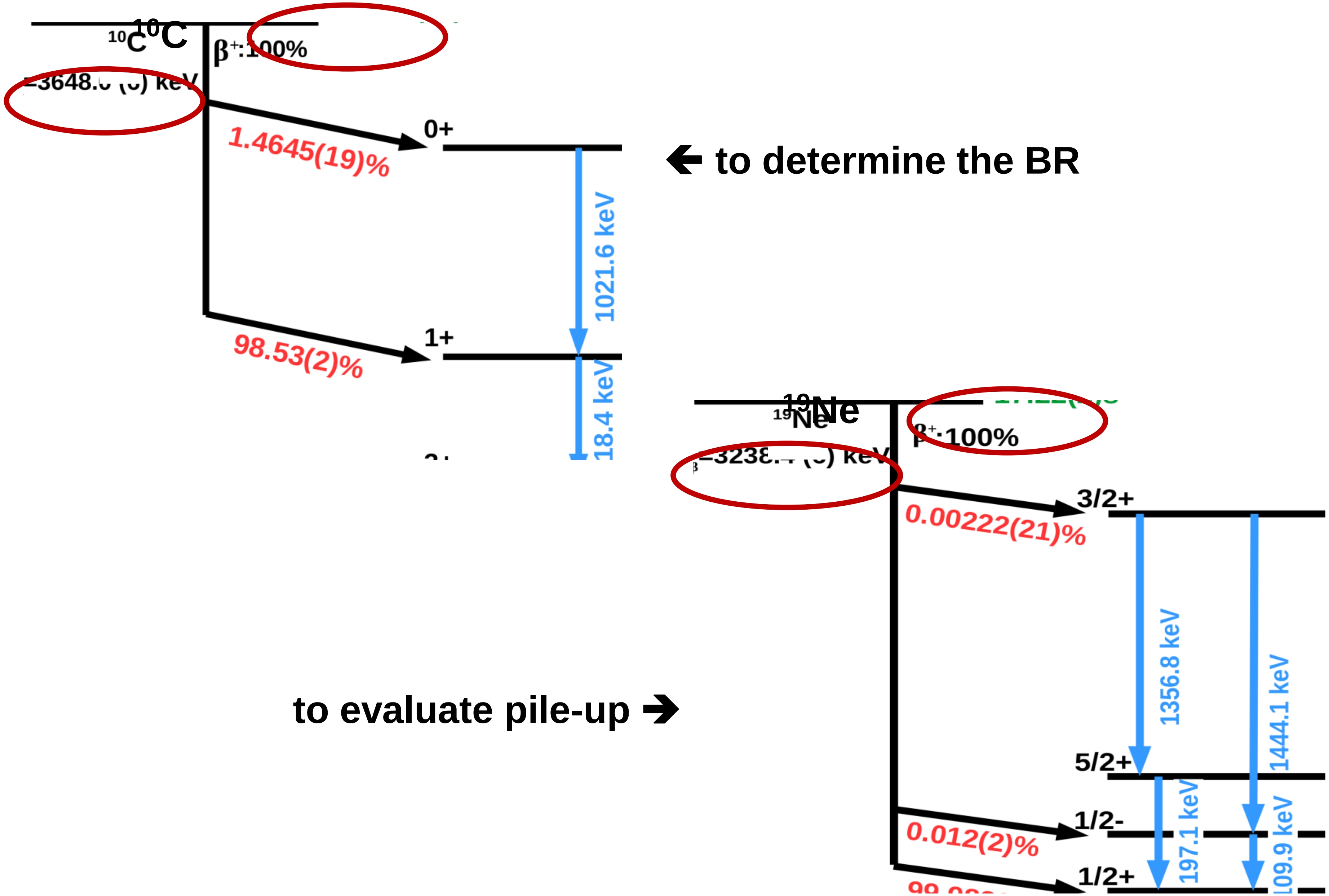






$^{10}C/^{19}Ne$ decay scheme

Courtesy of B. Blank

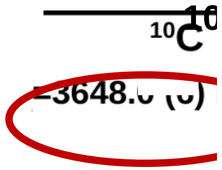


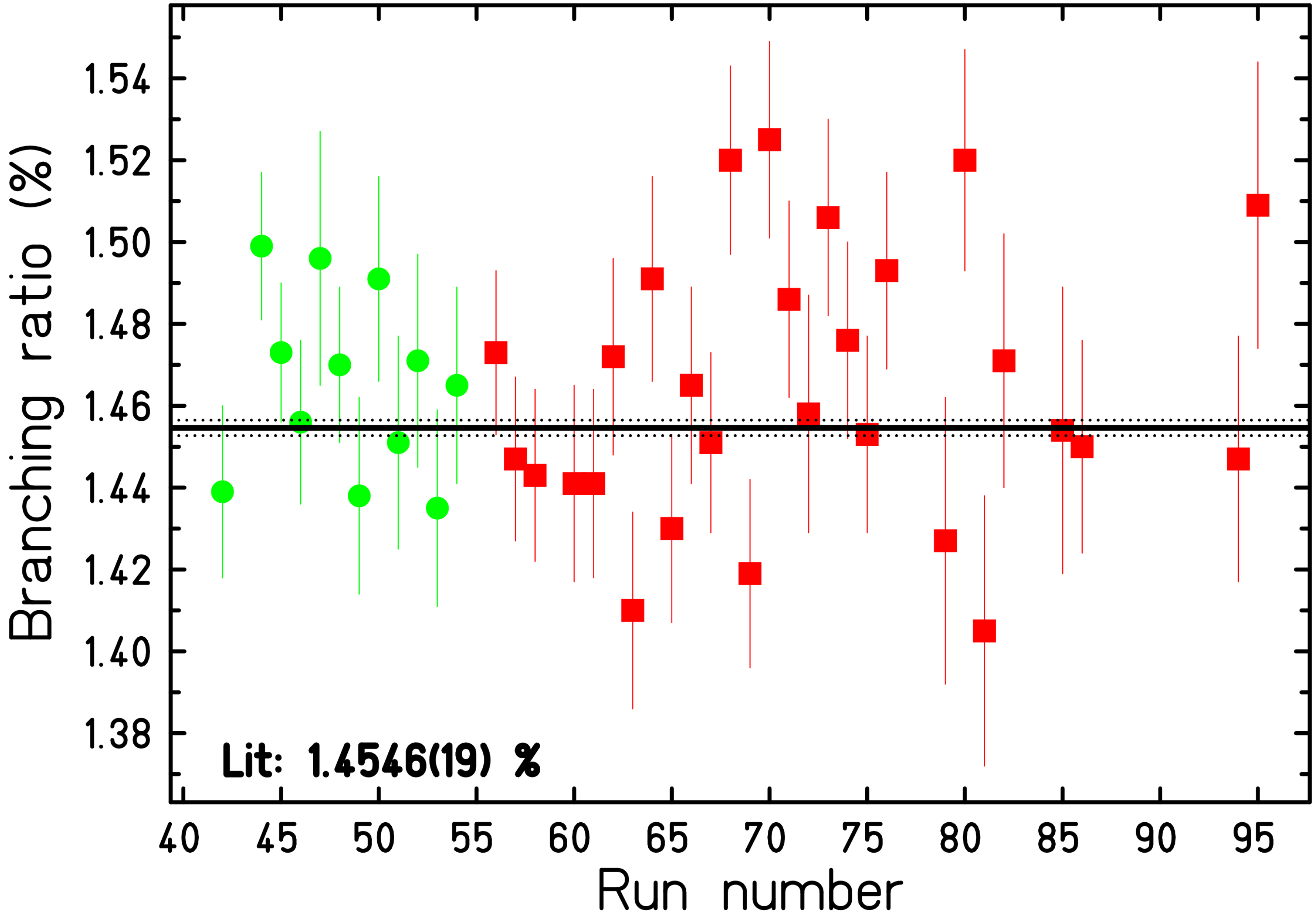
← to determine the BR

to evaluate pile-up →

$^{10}C/^{19}Ne$ decay scheme

Courtesy of B. Blank



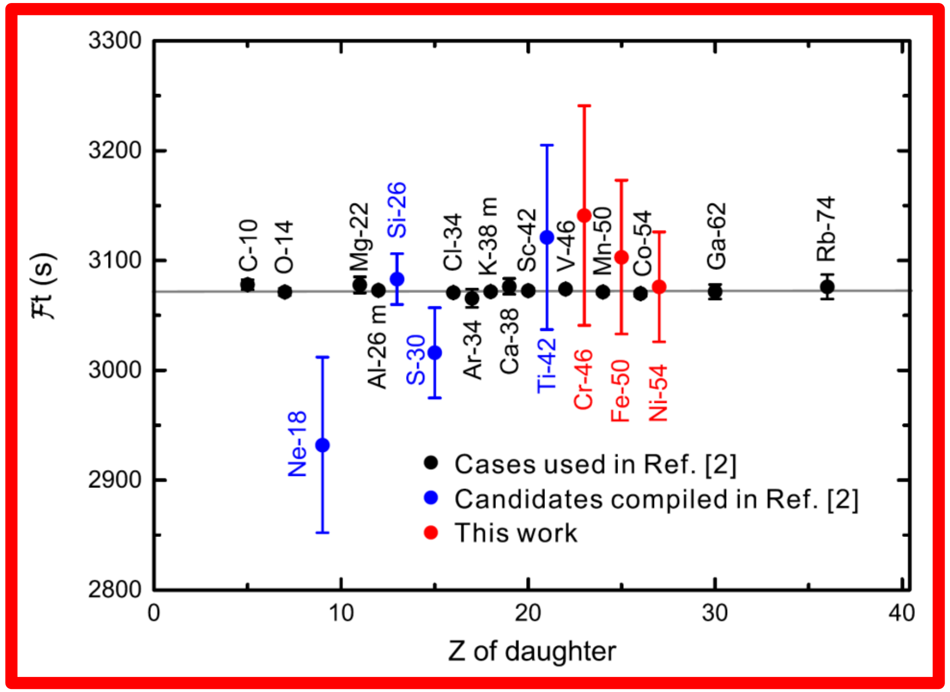


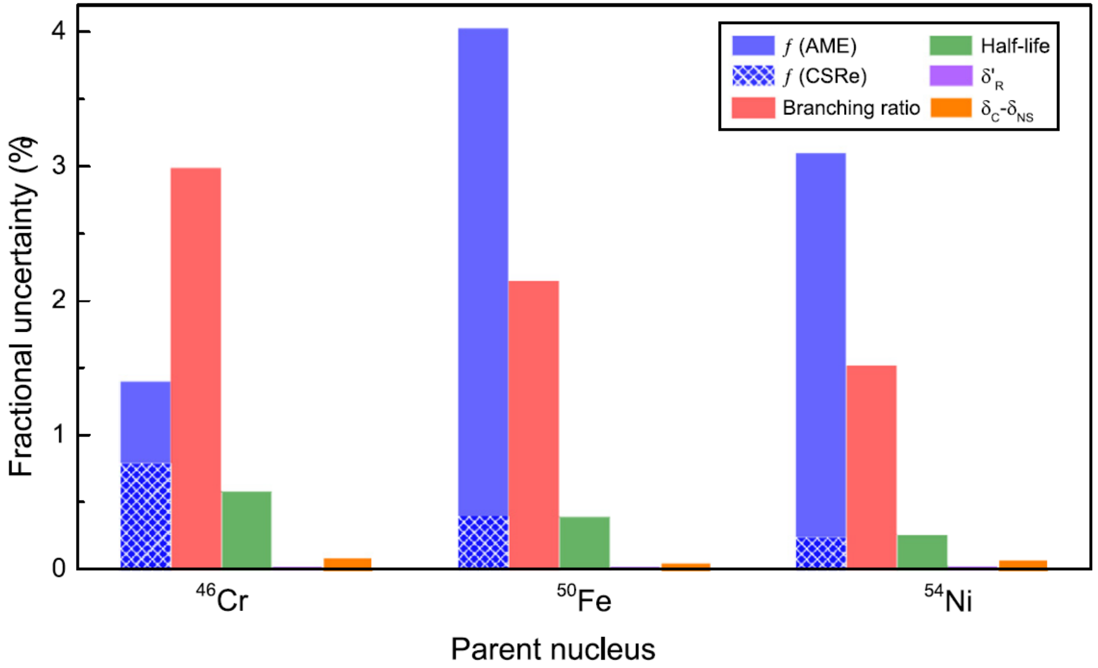
…to be fully analysed

global correction, not yet run by run

"Can we add new $0^+ \rightarrow 0^+$ transitions with $\Delta\mathcal{F}t \lesssim 0.25\%$?"

- Yes, maybe? Cases I'm aware of:
  - ^{46}Cr – BR, τ, Q_{EC} @ EURISOL-DF (Eronen)
  - ^{50}Fe – BR, τ, Q_{EC} @ EURISOL-DF (Eronen) and TITAN (Leach)
  - ^{54}Ni – BR, τ, Q_{EC} @ EURISOL-DF (Eronen)





Courtesy of T. Eronen, who points out "*These will never compete in precision with lower-A cases. Important for (isospin symmetry breaking) corrections*"

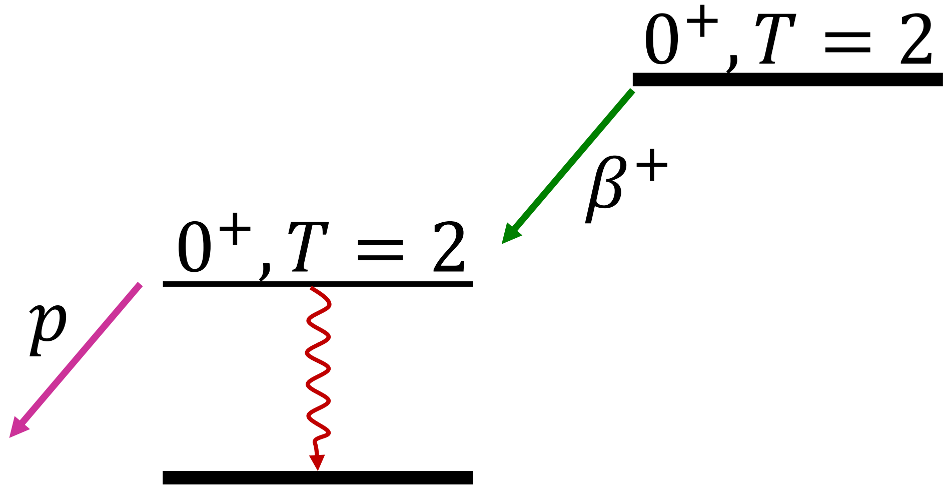
"Can we add new $0^+ \rightarrow 0^+$ transitions with $\Delta\mathcal{F}t \lesssim 0.25\%$?"

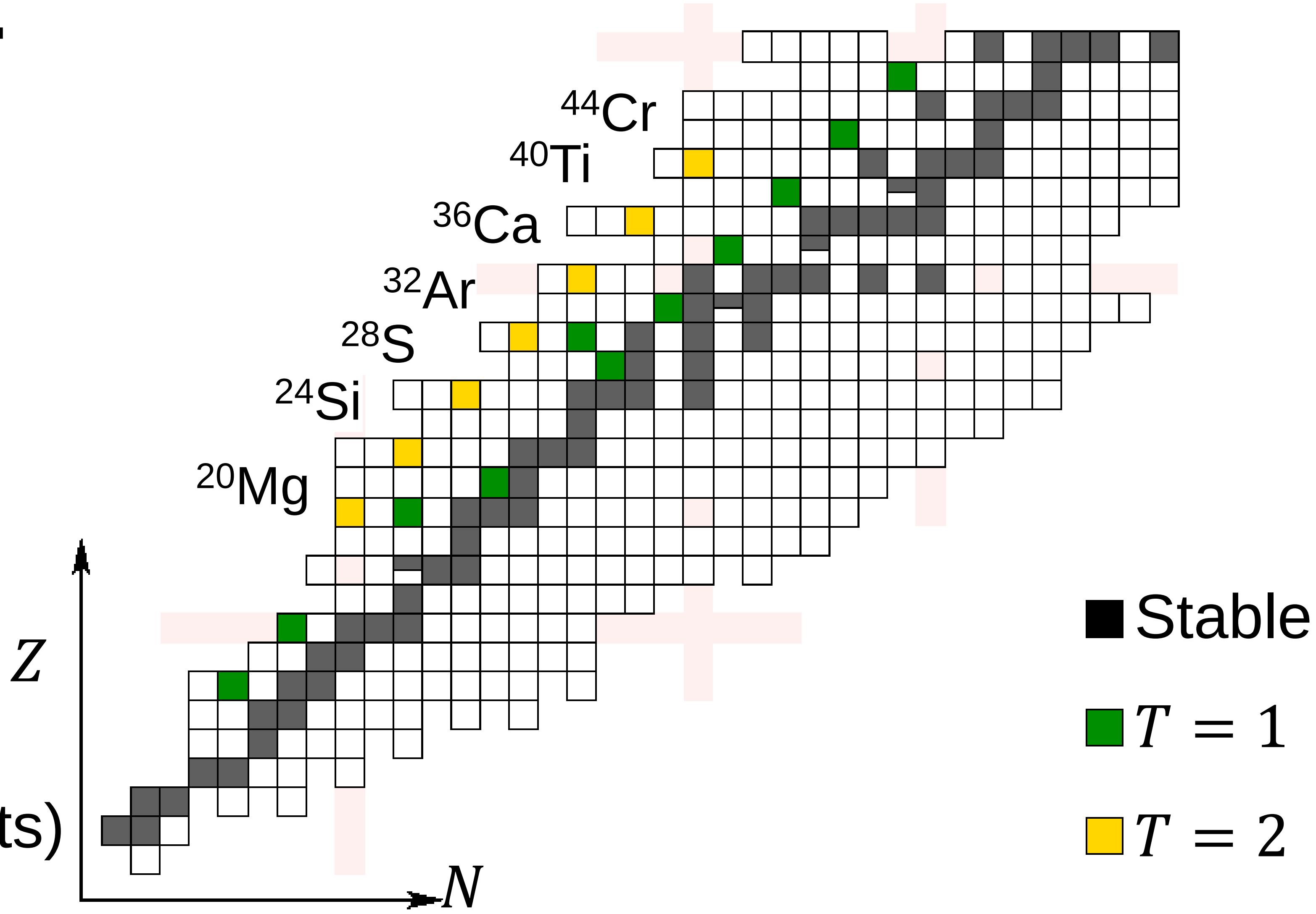
- Yes, maybe? Cases I'm aware of:
  - ^{46}Cr – BR, τ, Q_{EC} @ EURISOL-DF (Eronen)
  - ^{50}Fe – BR, τ, Q_{EC} @ EURISOL-DF (Eronen) and TITAN (Leach)
  - ^{54}Ni – BR, τ, Q_{EC} @ EURISOL-DF (Eronen)

- Heavier cases:
  - ^{58}Zn – BR, τ @ BigRIPS/RIKEN (Blank)
  - ^{66}As – Q_{EC} @ TITAN/TRIUMF (Leach)
  - ^{70}Br – Q_{EC} @ TITAN/TRIUMF (Leach)
  - ^{74}Rb – Q_{EC} @ TITAN/TRIUMF (Leach)

- The problem: shell model is not as well characterized above $A = 56$
  - "*Who's going to give beamtime and funding for boring spectroscopy?*" – JCH

More cases that may help with ISB corrections

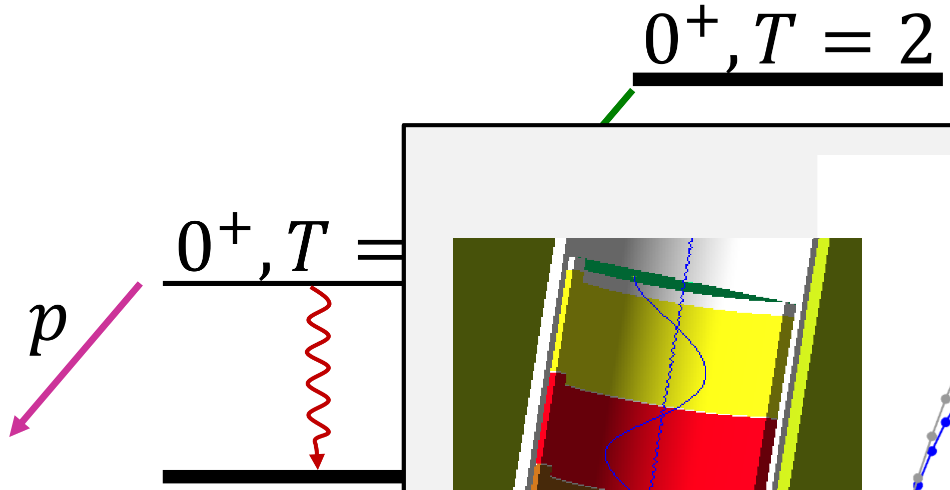


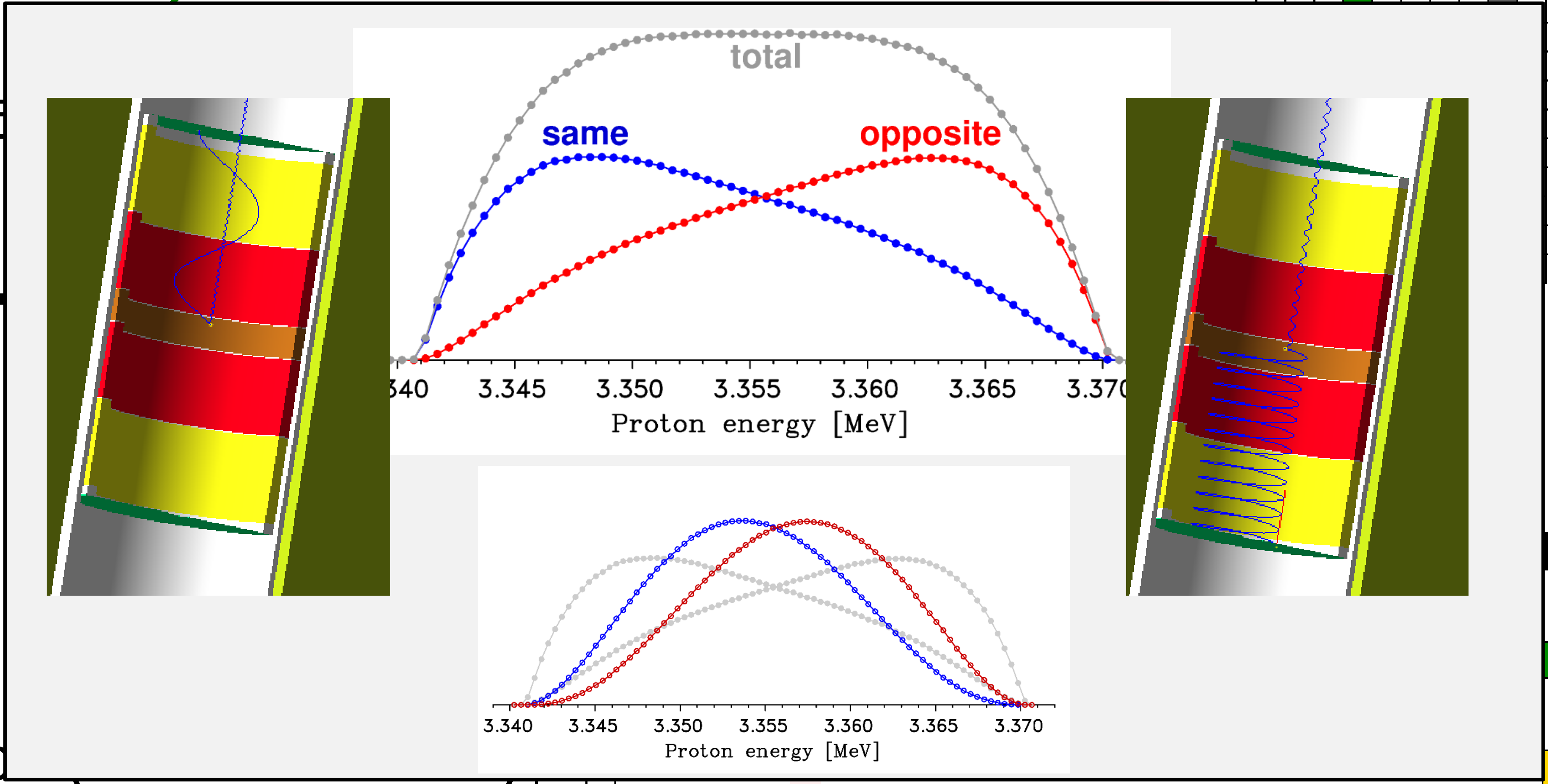


β-ν correlation (scalar currents)

ft values (ISB corrections)

More cases that may help with ISB corrections





Stable

$T = 1$

$T = 2$

β-ν correlatio

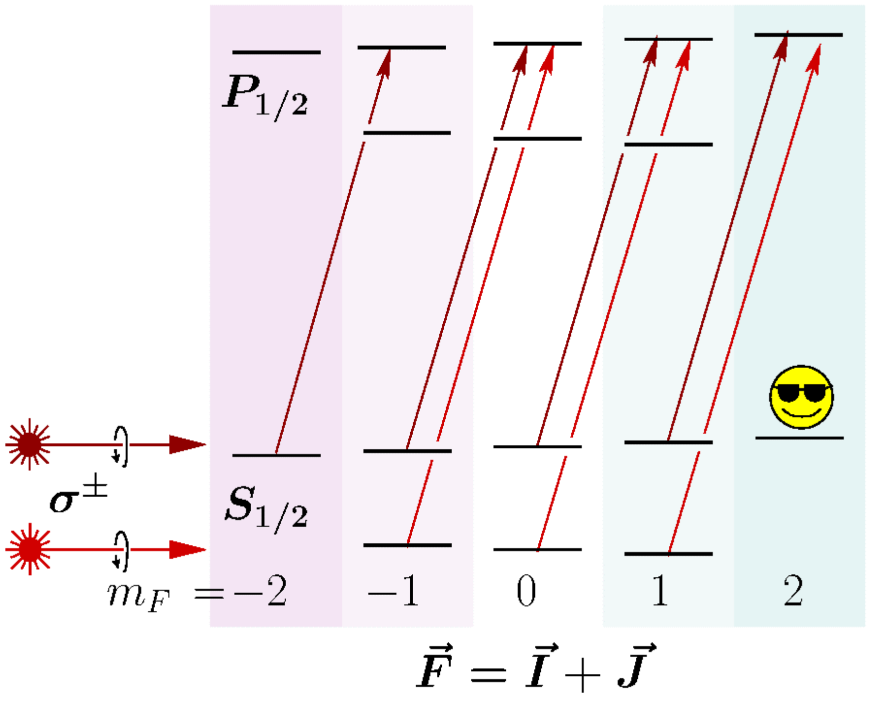
ft values (ISB corrections)

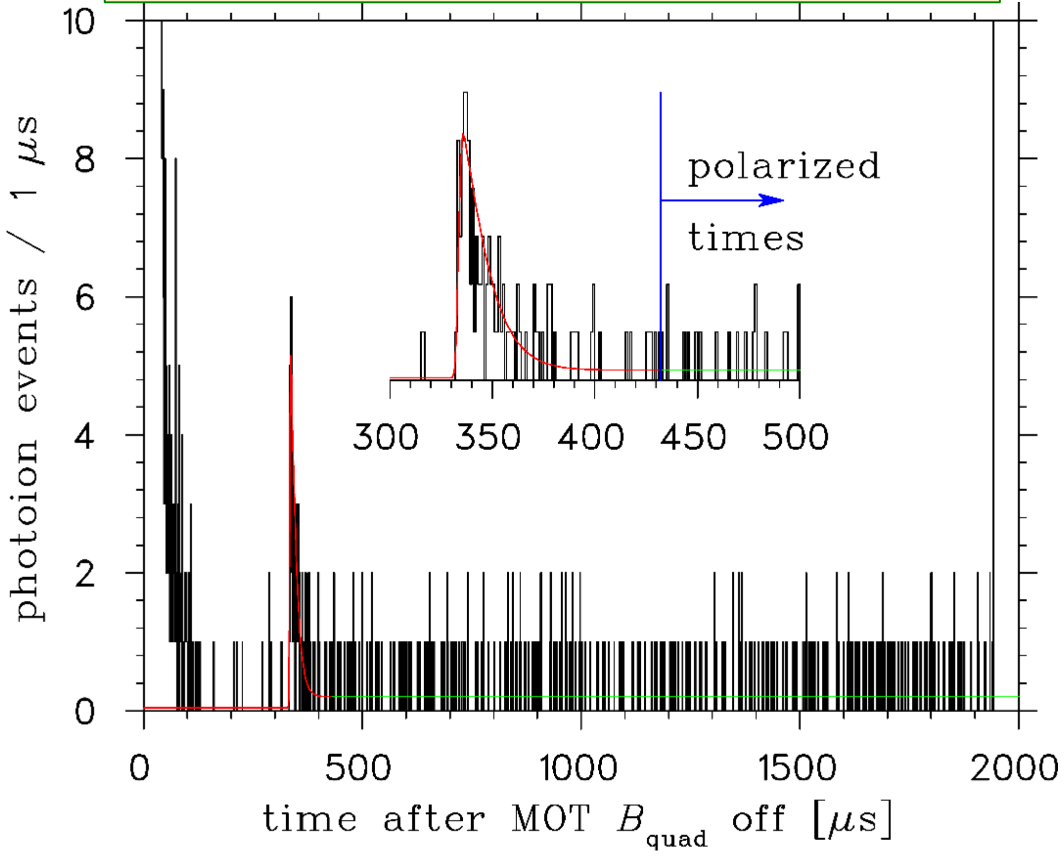
And WISArD (will be sooner)

"How much progress can be made with $T = 1/2$ transitions?"

- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%

$$\langle |P_{\mathbf{nucl}}| \rangle = 0.9913(9)$$





“How much progress can be made with $T = 1/2$ transitions?”

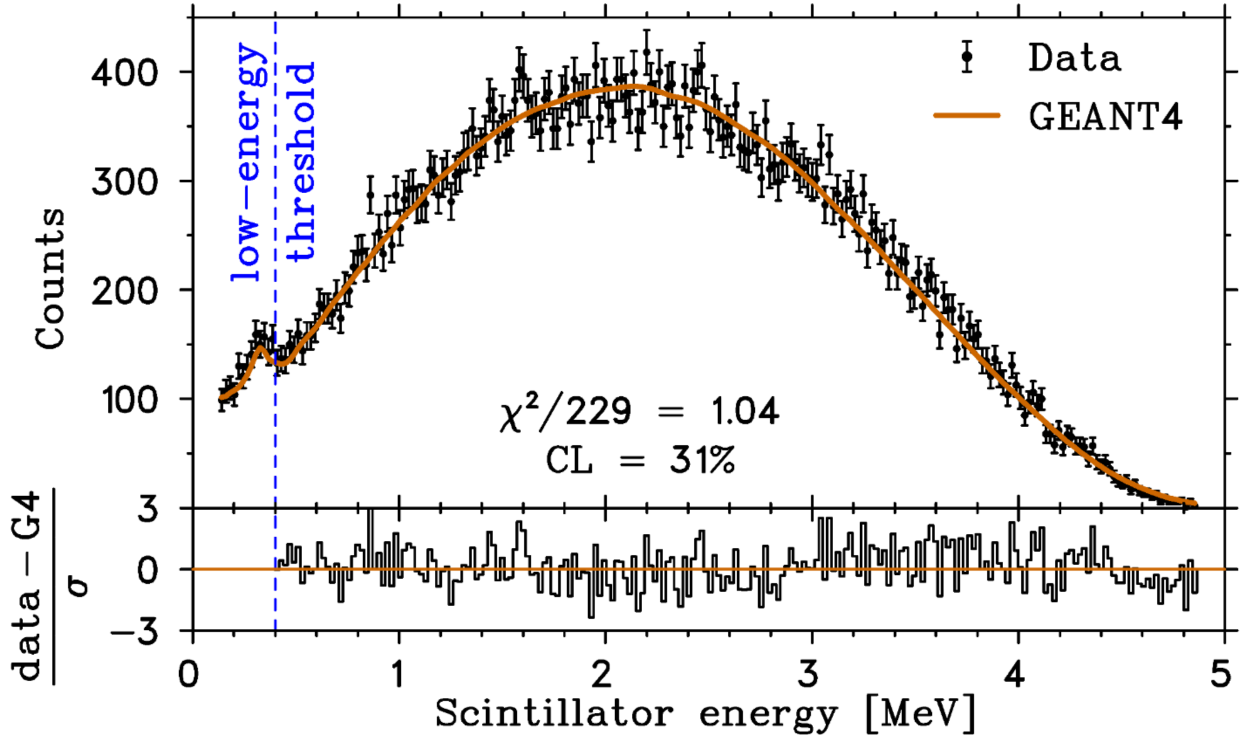
- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%
  - Recent A_β to 0.3%; $\leq 0.1\%$ in sight

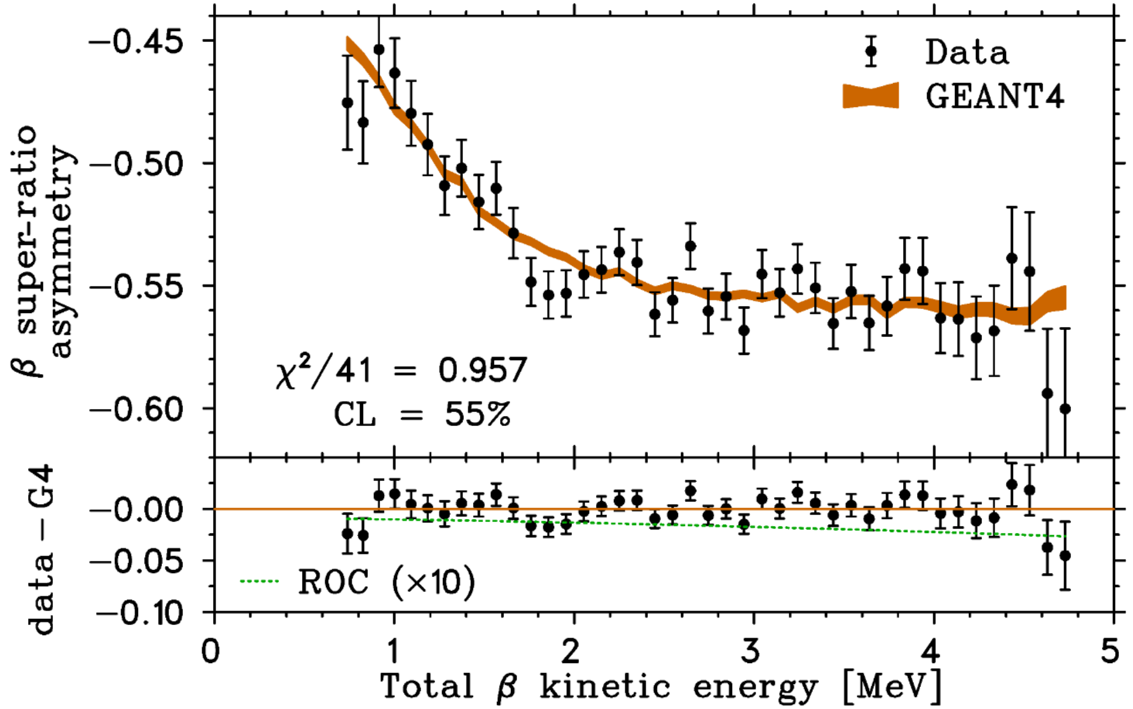
Fenker PRL **120** 062502 (2018)

$$A_\beta^{\text{meas}} = -0.5707(19)$$

vs

$$A_\beta^{\text{SM}} = -0.5706(7)$$





"How much progress can be made with $T = 1/2$ transitions?"

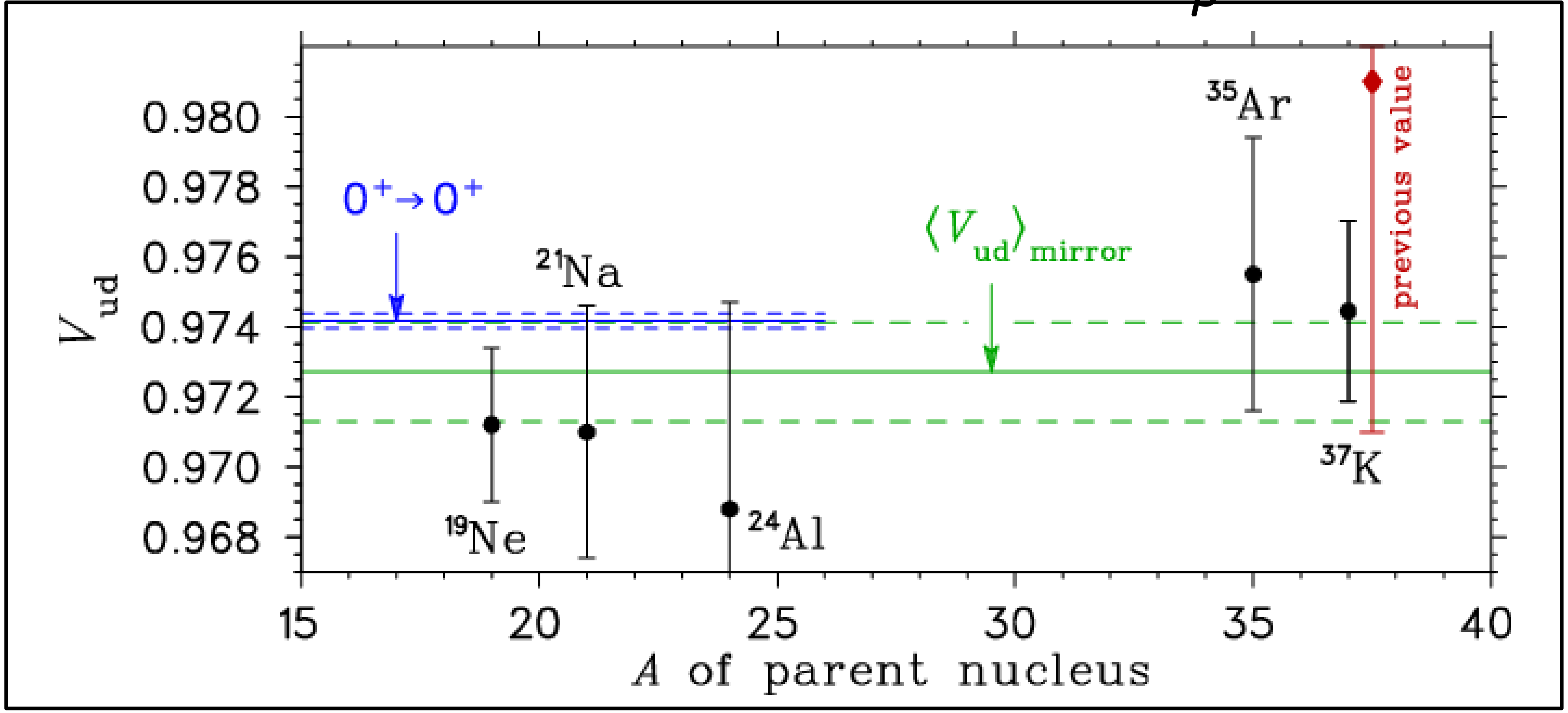
- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%
  - Recent A_β to 0.3%; $\leq 0.1\%$ in sight

Fenker PRL **120** 062502 (2018)

$$A_\beta^{\mathrm{meas}} = -0.5707(19)$$

vs

$$A_\beta^{\mathrm{SM}} = -0.5706(7)$$



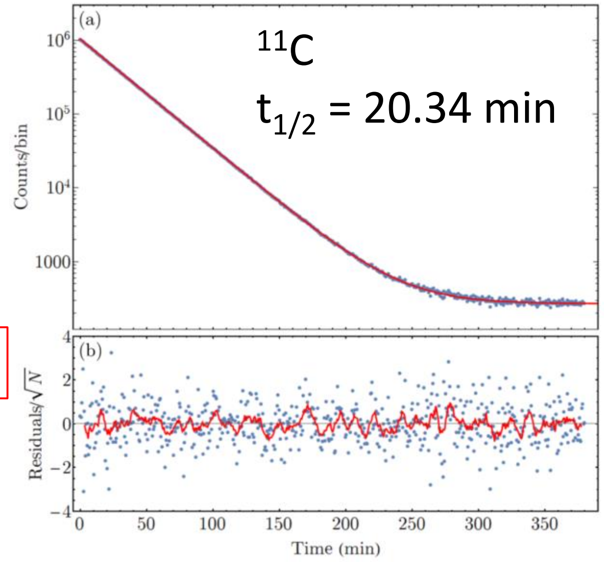
“How much progress can be made with $T = 1/2$ transitions?”

- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%
  - Recent A_β to 0.3%; $\leq 0.1\%$ in sight
- St. Benedict @ TwinSol – $a_{\beta\nu}$ using a Paul trap

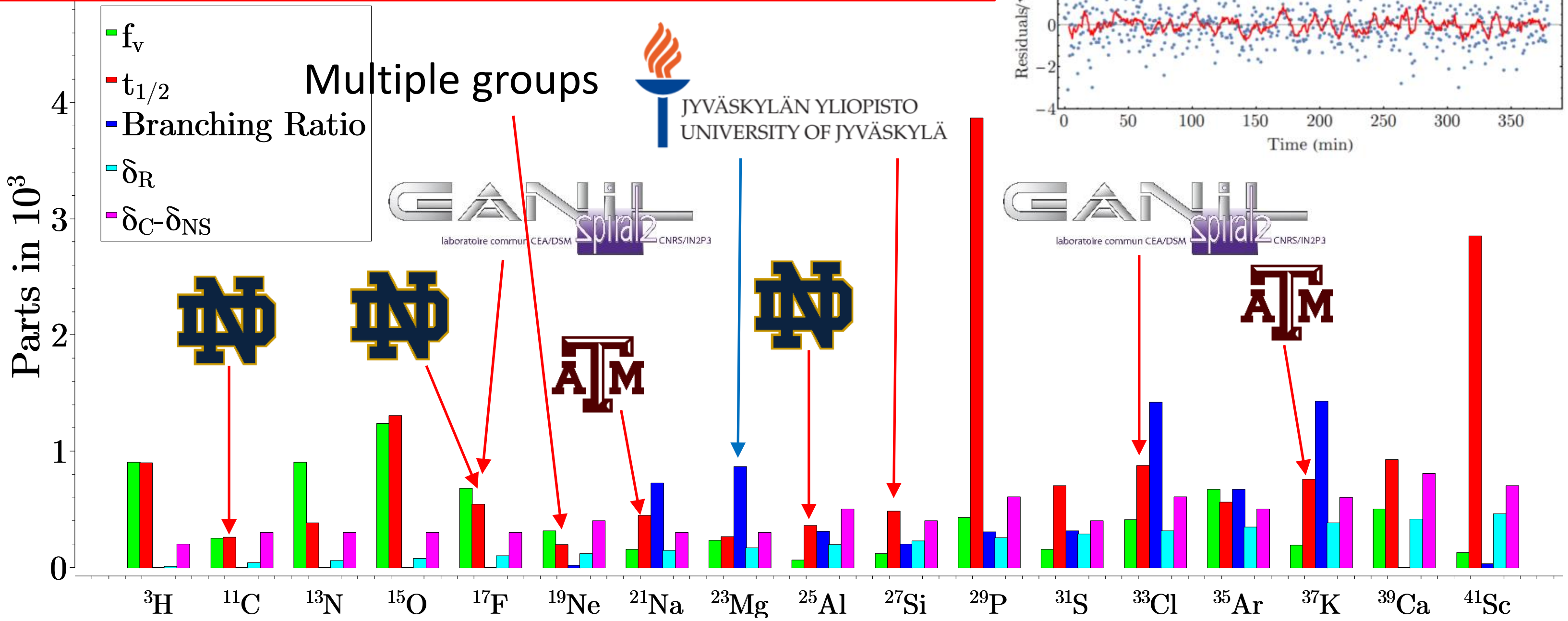
Courtesy of M. Brodeur

Half-lives measured @ ND

- ^{17}F: M. Brodeur *et al.*, PRC **93**, 025503 (2016)
- ^{25}Al: J. Long *et al.*, PRC **96**, 015502 (2017)
- ^{11}C: A. Valverde *et al.*, PRC **97**, 035503 (2018)
- ^{20}F: D. Burdette *et al.*, PRC **99**, 015501 (2019)



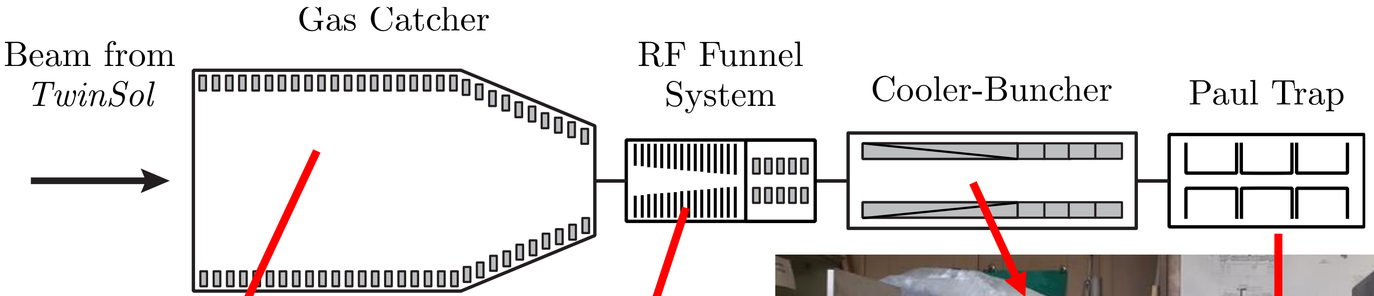
Current relative uncertainties of mirror ft-values quantities

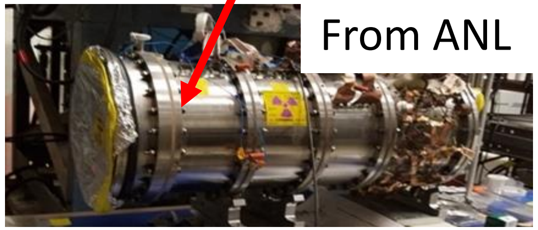


Courtesy of M. Brodeur

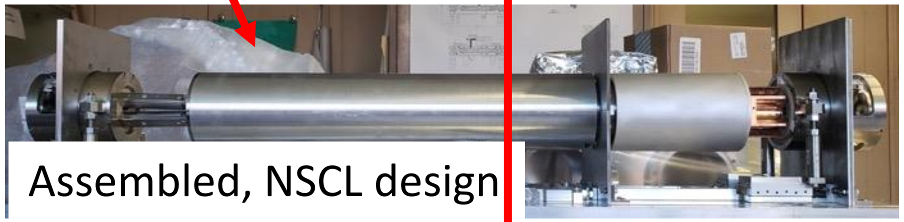
St. Benedict status

Superallowed Transitions Beta Neutrino Decay Ion Coincidance Trap



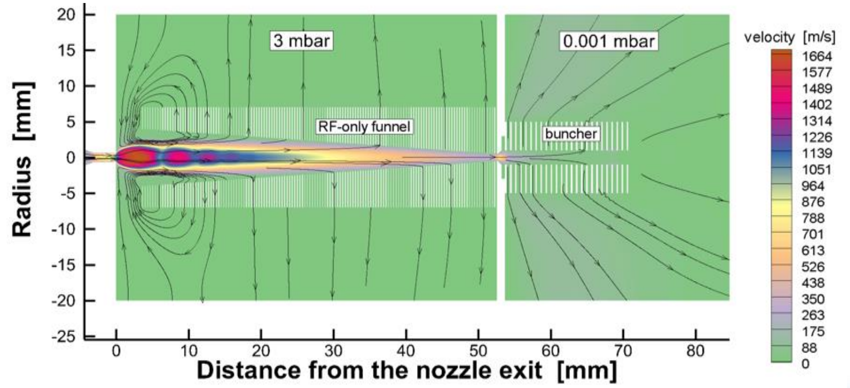


From ANL

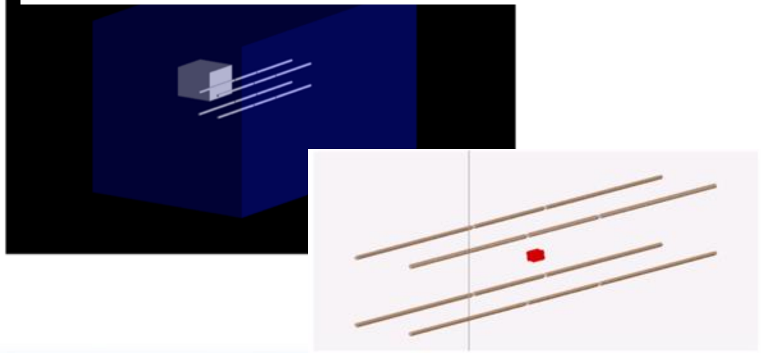


Assembled, NSCL design

RF funnel + SPIG (simulated, under design)



Paul trap: Being simulated/designed



"How much progress can be made with $T = 1/2$ transitions?"

- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%
  - Recent A_β to 0.3%; 0.1% in sight
- St. Benedict @ TwinSol – $a_{\beta\nu}$ using a Paul trap
- LPCTrap2 @ GANIL – $a_{\beta\nu}$ using a Paul trap

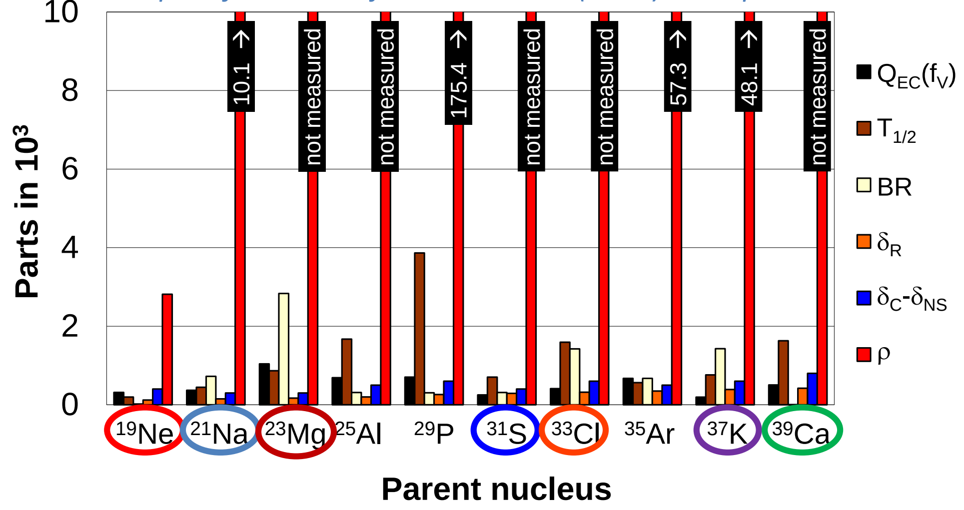
Courtesy of E. Lienard

CVC, V_{ud} & CKM: *ft* values measurements

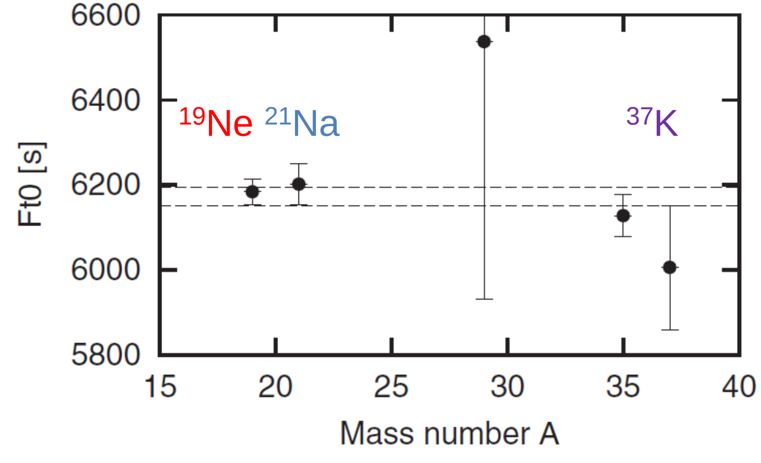
Subject discussed in details in the next talk (Bertram Blank)

- *Nuclear mirrors*

adapted from Severijns et al. PRC78 (2008) and updated



Naviliat et al. PRL102 (2009)



^{19}Ne	$T_{1/2}$: *Broussard et al. PRL112 (2014)*
^{21}Na	M: *Mukherjee et al. EPJA35 (2008)*
	$T_{1/2}$: *Grinyer et al. PRC91 (2015)*
^{23}Mg	M: *Saastamoinen et al. PRC80 (2009)*
	$T_{1/2}$, BR: *Magron et al. EPJA53 (2017)*
^{31}S	M: *Kankainen et al. PRC82 (2010)*
	$T_{1/2}$: *Bacquias et al. EPJA48 (2012)*
^{33}Cl	$T_{1/2}$: *Grinyer et al. PRC92 (2015)*
^{37}K	$T_{1/2}$: *Shidling et al. PRC90 (2014)*
^{39}Ca	$T_{1/2}$: *Blank et al. EPJA44 (2010)*

The scientific community involved in this field... BUT

V_{ud} (2009) = 0.9719 (17)

↓

V_{ud} (2017) = 0.9721 (17) !!

⇒ *For V_{ud} determination, ρ improvements are necessary ...*

Courtesy of E. Lienard

CVC, V_{ud} & CKM: *ft* values measurements

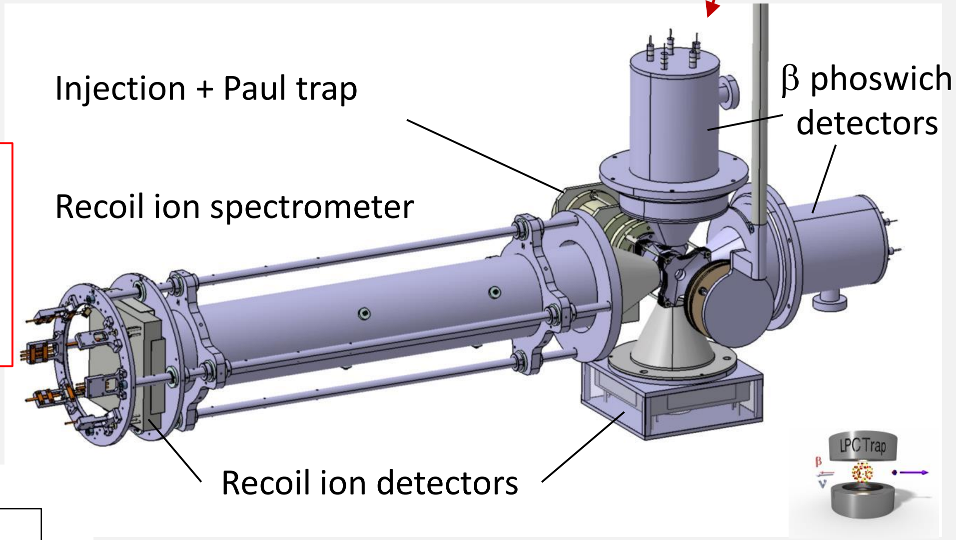
Subject discussed in details in the next talk (Bertram Blank)

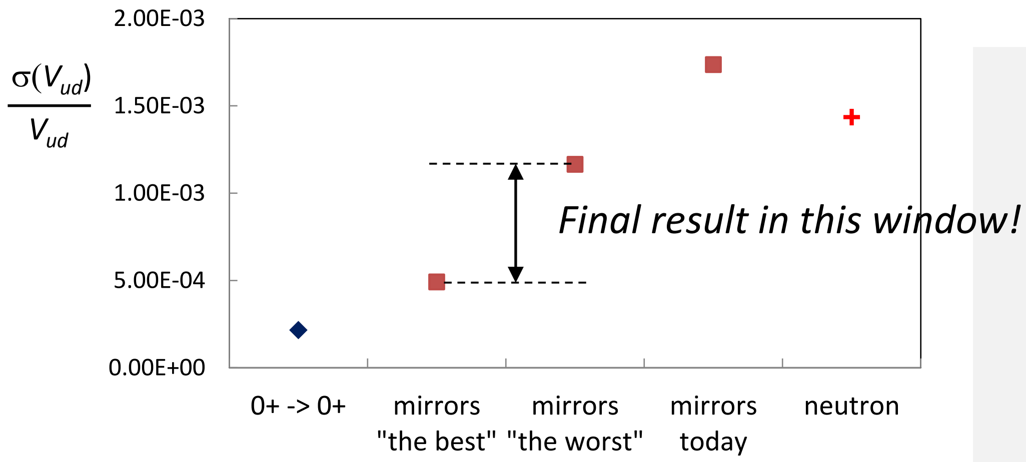
- *Nuclear mirrors*

Perspectives @ GANIL: Measurement of a in several mirror decays using LPCTrap2

Ion	$T_{1/2}$ (s)	Expected rate (pps)
^{21}Na	22.49	6.5E+08
^{23}Mg	11.32	2.1E+08
^{33}Cl	2.51	3.4E+07
^{37}K	1.22	7.4E+08

SPIRAL production > 10^7 pps





In any case, a significant improvement on V_{ud} is reachable

@ LIRAT and DESIR

“How much progress can be made with $T = 1/2$ transitions?”

- Albert covered the neutron and ^{19}Ne
- ^{37}K @ TRINAT/TRIUMF [Melconian & Behr]
  - High nuclear polarization: 99.13(9)%
  - Recent A_β to 0.3%; 0.1% in sight
- St. Benedict @ TwinSol – $a_{\beta\nu}$ using a Paul trap
- LPCTrap2 @ GANIL -- $a_{\beta\nu}$ using a Paul trap

Progress is slow, and it will be hard to compete directly with the precision of $0^+ \rightarrow 0^+$ decays

More cases for models to provide ISB corrections, perhaps make CVC test more stringent

Summary and outlook

- After decades of work, it is getting hard to improve the CKM unitarity test
- Greatest progress to be made is through theoretical improvements
  - Δ_R^V of course
  - Improved modelling of heavy nuclei
  - New approaches to complement WS shell model
- Experimentally:
  - Mirror $0^+ \rightarrow 0^+$ promise a sensitive test of theoretical corrections
  - ^{10}C is hard, but better BR will improve already impressive search for scalar currents
  - The neutron is slowly approaching the precision of $0^+ \rightarrow 0^+$, and ultimately does not have $\delta_C - \delta_{NS}$ corrections

But probably the best way to conclude:

SUMMARY AND OUTLOOK

1. Analysis of superallowed $0^+ \rightarrow 0^+$ nuclear β decay confirms CVC to ±0.011% and thus yields V_{ud} = 0.97420(21).
2. The three other experimental methods for determining V_{ud} yield consistent results; the neutron-decay result is only a factor of 4 less precise and agrees completely.
3. The current value for V_{ud}, when combined with the PDG values for V_{us} and V_{ub}, satisfies CKM unitarity to ±0.05%.

4. The largest contribution to V_{ud} uncertainty is from the inner radiative correction, Δ_R. Very little reduction in V_{ud} uncertainty is possible without improved calculation of Δ_R.
5. Transition-dependent corrections have been tested by requiring consistency among the 14 known transitions (CVC), and agreement with mirror-transition pairs.
6. Improved and new correction terms are appearing. They will need to be tested for compatibility with CVC.

Thanks to many who gave me slides and comments, particularly:

- John Hardy
- Carl Svensson
- Bertram Blank
- Tommi Eronen
- Kyle Leach
- Etienne Lienard
- Maxime Brodeur

U.S. DEPARTMENT OF ENERGY | Office of Science