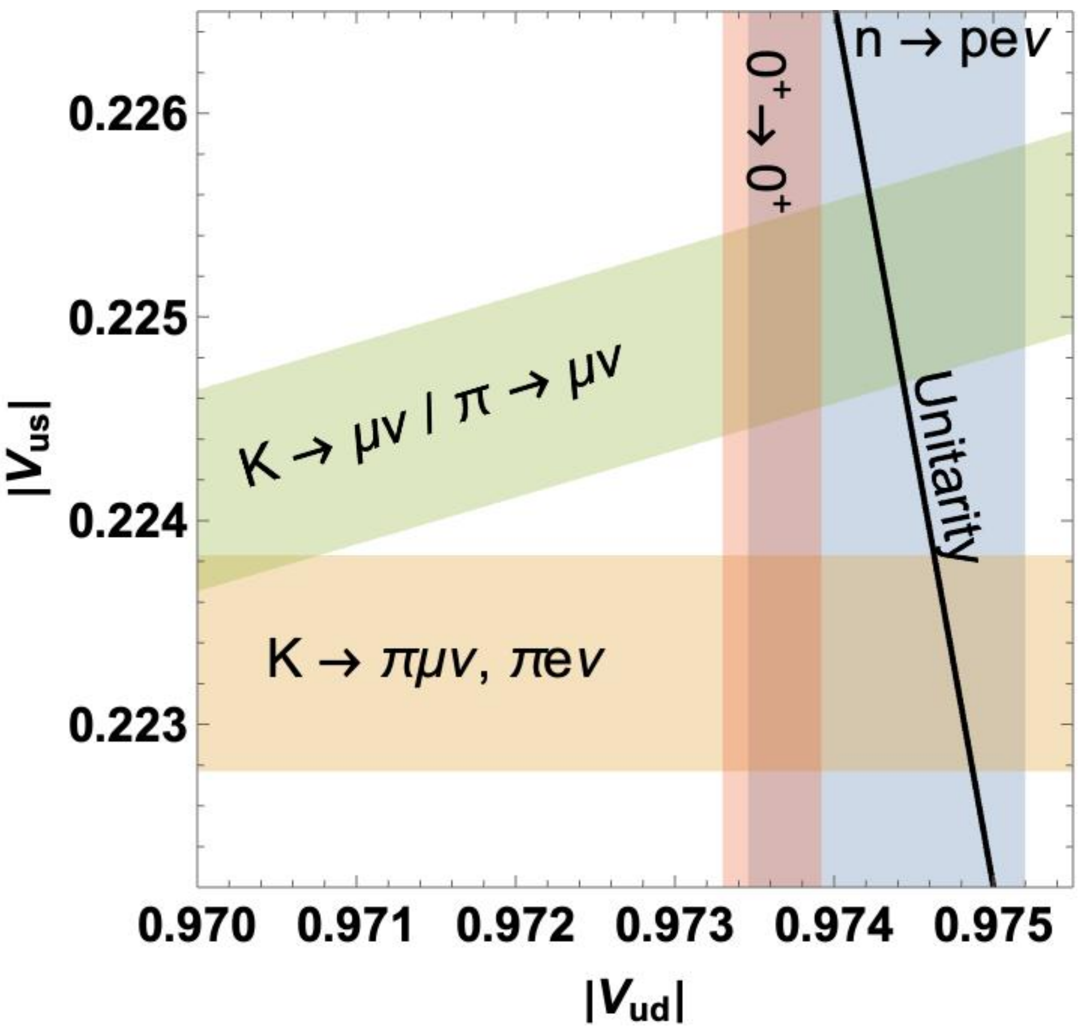
Precision Tests of the Standard Model with Cabibbo Unitarity and Nuclear β-Decays



Misha Gorshteyn

Universität Mainz

Collaborators:

Chien-Yeah Seng
Michael Gennari
Mehdi Drissi
Petr Navratil
Ben Ohayon
Bijaya Sahoo
John Behr
N. Cargioli

Neutron beta decay review: MG, Seng, Universe **2023**, 9(9), 422, arXiv:**2307.01145**
Nuclear beta decay review: MG, Seng, Ann.Rev.Part.Nucl.Sci. 74 (2024) 23-47, arXiv:**2311.00044**

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Outline

Beta decay, radiative corrections and the Standard Model

Cabibbo anomaly: have we found BSM?

Summary of experimental measurements

Radiative corrections to β-decays: overall setup

γW-box: Dispersion Theory, lattice QCD and EFT

Nuclear corrections

Summary & Outlook

What to work on to win a Nobel prize?

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Beta decay has been an excellent choice for a century!

1896- Becquerel discovers spontaneous radioactivity of uranium, identified β with the electron

1898- Curie-Sklodowska, Curie discover polonium and radium

1903

1899- Rutherford systematized α, β, γ rays, identified α with He-4

1908

1934- F.&I. Joliot-Curie discovered β^+ decay with β^+ - positron

1935

1956- Lee & Yang proposed parity non conservation in β-decay, confirmed by Wu experiment

1957

1961- Glashow proposed electroweak unification

1967- Weinberg & Salam implemented Higgs mechanism

1973- Neutral weak current discovered at CERN

1979

1973- Kobayashi, Maskawa: 3-flavor quark mixing matrix

2008

That was the bright side…

Niepce de Saint-Victor: observed radioactivity in 1857 cited in Becquerel-father's book

Cox, McIlwraith, Kurrelmeier (1928); Chase (1929-30)
"Apparent evidence of polarization in a beam of beta rays"

1930: Pauli postulated existence of neutrinos
1934: Fermi formulated the contact theory of beta decay

1938: Klein predicted $M_W \sim \sqrt{4\pi\alpha\sqrt{2}/G_F} \sim 100\,GeV$

1957: Wu's experiment was crucial to prove Lee-Yang's conjecture, but Chien-Shiung Wu was not awarded the NP

1963- Cabibbo: proposed 2-flavor quark mixing
to reconcile μ, β, K decay rates

Precision Era: V-A + Radiative Corrections

V - A theory (Sudarshan&Marshak and Gell-Mann&Feynman 1957); S-PS not excluded

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RC to muon decay - UV finite for V-A but divergent for S-PS

Muon lifetime $\tau_\mu = 2196980.3(2.2) ps$ —> Fermi constant $G_\mu = 1.1663788(7) \times 10^{-5} GeV^{-2}$

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Kinoshita, Sirlin, Behrends, …

UV cut-off

1-loop RC to spectrum: $$\Delta P^0 d^3 p = \frac{\alpha}{2\pi} P^0 d^3 p \left[6 \ln \frac{\Lambda}{M_p} + \text{finite} \right]$$

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Is weak interaction universal for leptons and hadrons?

1967: Sirlin applied current algebra:
general UV behavior of β decay rate at 1-loop

$$\frac{\alpha}{2\pi} P^0 d^3p \; 3[1+2\bar{Q}] \ln(\Lambda/M)$$

$\bar{Q}$: average charge of fields involved: $1+2\bar{Q}_{\mu,\nu_\mu} = 0$ but $1+2\bar{Q}_{n,p} = 2$

Finiteness of RC to muon decay was accidental!

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Eventually, massive W-boson renders RC to beta decay UV-finite

Precision, Universality and CKM unitarity

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Kaon and hyperon decays? ($\Delta S = 1$) — even smaller coupling!

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Cabibbo: strength shared between 2 generations

$$|G_V^{\Delta S=0}| = \cos\theta_C G_\mu$$

$$|G_V^{\Delta S=1}| = \sin\theta_C G_\mu$$

Cabibbo unitarity: $\cos^2\theta_C + \sin^2\theta_C = 1$

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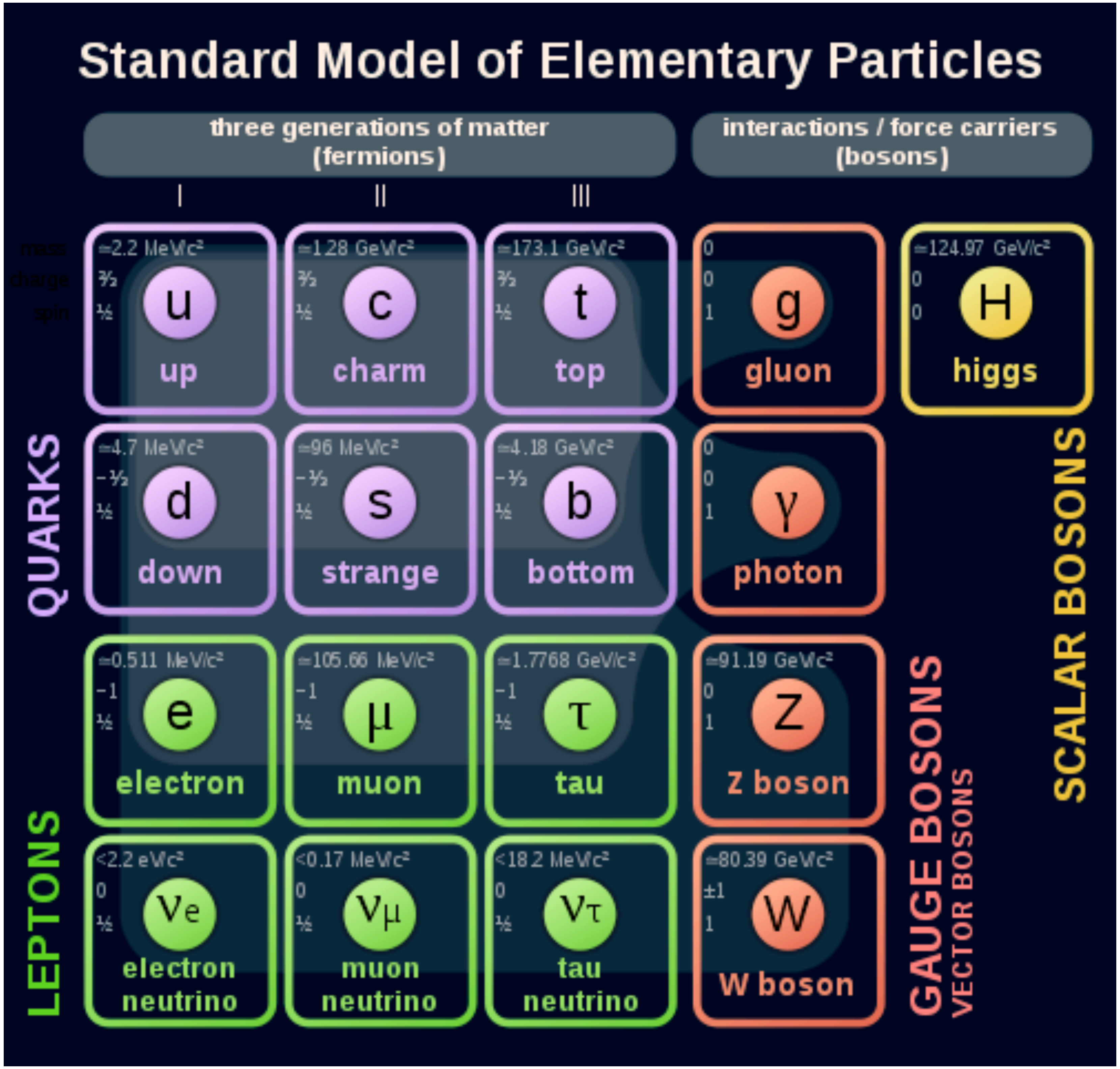
Kobayashi & Maskawa: 3 flavors + CP violation — CKM matrix V

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

CKM unitarity - completeness of the SM: $VV^\dagger = \mathbf{1}$

Top row unitarity constraint: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Detailed understanding of β decays largely shaped the Standard Model



Cabibbo Angle Anomaly:
Status and BSM interpretation

Status of Cabibbo unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 0.9985(6)_{V_{ud}}(4)_{V_{us}}$$
$$\sim 0.95 \qquad \sim 0.05 \qquad \sim 10^{-5}$$

V_{ud} and V_{us} determinations inconsistent with the SM

Superallowed nuclear β : $|V_{ud}| = 0.9737\,(3)$

At variance with kaon decays + Cabibbo unitarity

$K \to \pi \ell \nu$: $|V_{us}| = 0.2233(5)$

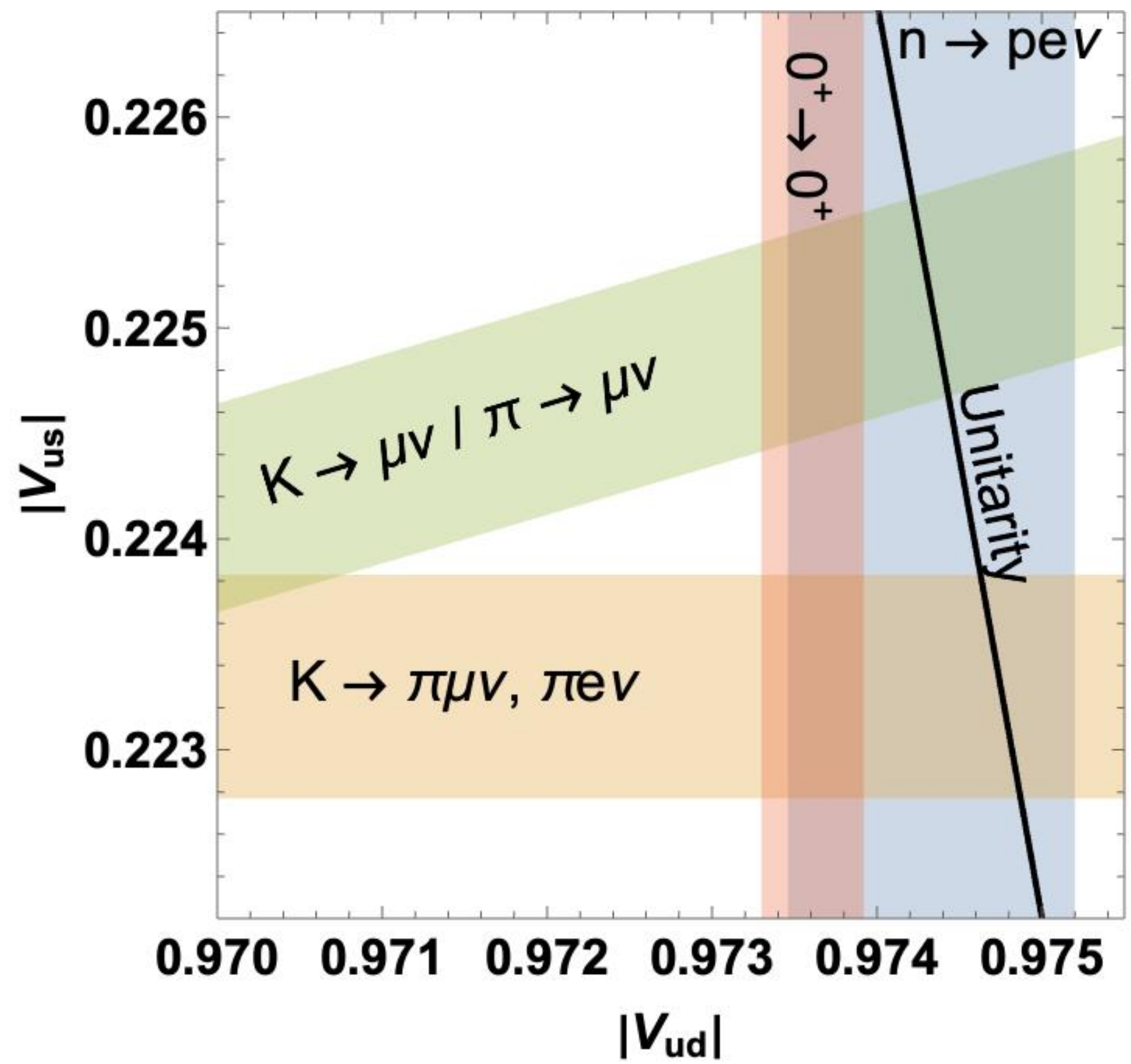
Unitarity $\to |V_{ud}| = \sqrt{1 - |V_{us}|^2} = 0.9747(1)$

$\dfrac{K \to \mu\nu}{\pi \to \mu\nu}$: $|V_{us}/V_{ud}| = 0.2311(5)$

Unitarity $\to |V_{ud}| = [1 + |V_{us}/V_{ud}|^2]^{-1/2} = 0.9743(1)$

PDG $[S = 2.5]$: $|V_{us}| = 0.2243(8)$

Unitarity $\to |V_{ud}| = 0.9745(2)$



But consistent with the free neutron decay: $|V_{ud}| = 0.9743\,(9)$

CAA summary - 3 anomalies!

3 observables: $\lvert V_{us}\rvert^{K\ell 3}$, $\lvert V_{us}/V_{ud}\rvert^{K\mu 2}$, V_{ud} 2 quantities to determine: V_{us}, V_{ud} ▶	**3 ways to test unitarity**

$$\Delta^{(1)}_{\text{CKM}} = |V_{ud}|^2 + |V^{K_{\ell 3}}_{us}|^2 - 1$$ **= –0.00176(56) –3.1σ**

$$\Delta^{(2)}_{\text{CKM}} = |V_{ud}|^2 \left[1 + \left(\left|\frac{V_{us}}{V_{ud}}\right|^{K_{\mu 2}}\right)^2\right] - 1$$ **= –0.00098(58) –1.7σ**

$$\Delta^{(3)}_{\text{CKM}} = |V^{K_{\ell 3}}_{us}|^2 \left[\left(\frac{1}{|V_{us}/V_{ud}|^{K_{\mu 2}}}\right)^2 + 1\right] - 1$$ **= –0.0164(63) –2.6σ**

Can it be a signal of BSM?

CAA in presence of RH currents

Cirigliano et al.
PLB 838 (2023)

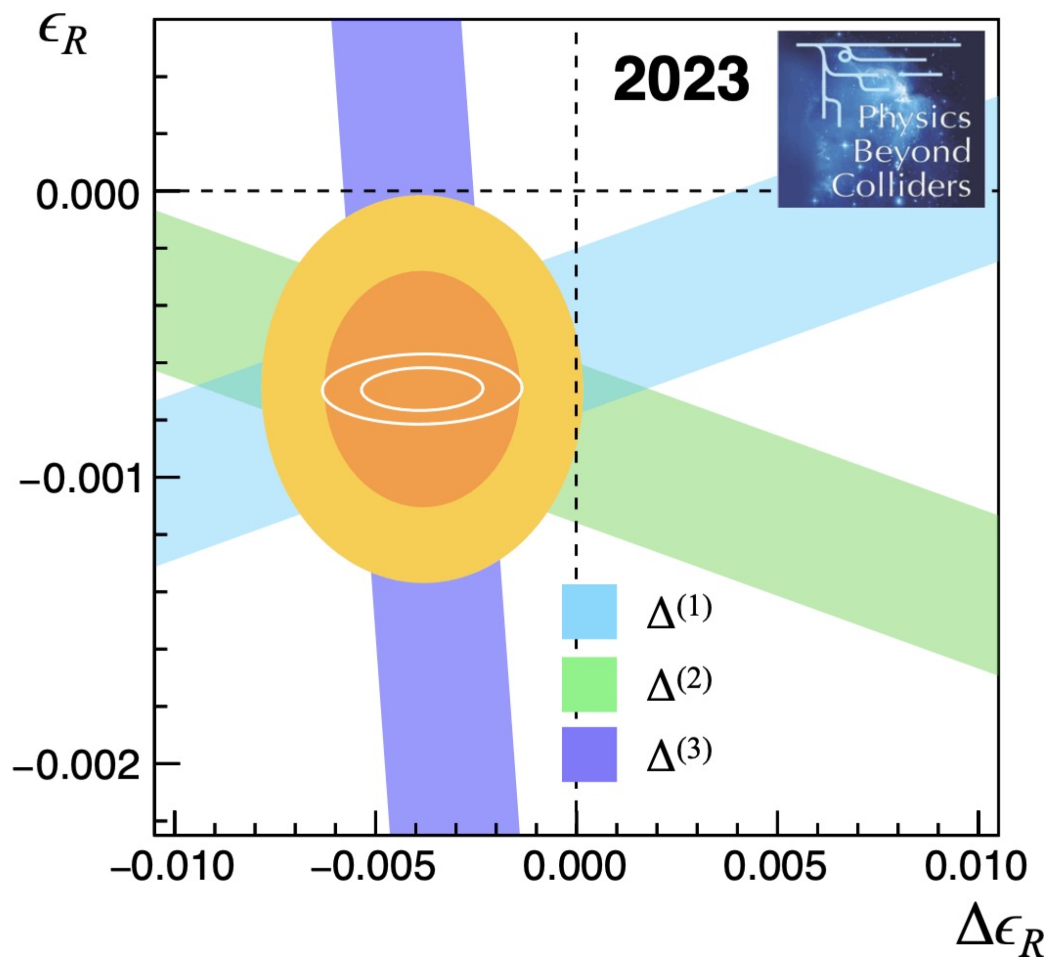
- In SM, W couples only to LH chiral fermion states
- New physics with couplings to RH currents could explain both unitarity deficit and $K_{\ell 3}$-$K_{\mu 2}$ difference
- Define ϵ_R = admixture of RH currents in non-strange sector
  $\epsilon_R + \Delta\epsilon_R$ = admixture of RH currents in strange sector

$$\Delta^{(1)}_{\text{CKM}} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2$$
$$\Delta^{(2)}_{\text{CKM}} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2$$
$$\Delta^{(3)}_{\text{CKM}} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)$$

$$r \equiv \left(\frac{1 + \Delta^{(2)}_{\text{CKM}}}{1 + \Delta^{(3)}_{\text{CKM}}}\right)^{1/2} = \frac{\left.\frac{V_{us}}{V_{ud}}\right|_{K_{\ell 2}/\pi_{\ell 2}}}{\frac{V_{us}^{K_{\ell 3}}}{V_{ud}^{\beta}}} = 1 - 2\Delta\epsilon_R$$

From current fit:

$\epsilon_R = -0.69(27) \times 10^{-3}$ (2.5σ)
$\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}$ (2.4σ)
$\epsilon_R = \Delta\epsilon_R = 0$ excluded at 3.1σ



Review the "σ" that defines the significane of the Cabibbo angle anomaly!

V_{us} from world data

V_{us} / V_{ud} from $K_{\mu 2} = K \to \mu\nu / \pi_{\mu 2} = \pi \to \mu\nu$

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi_{\mu 2(\gamma)}} m_{K^\pm}}\right)^{1/2} \frac{1 - m_\mu^2/m_{\pi^\pm}^2}{1 - m_\mu^2/m_{K^\pm}^2}\left(1 - \frac{1}{2}\delta_{\mathrm{EM}} - \frac{1}{2}\delta_{SU(2)}\right)$$

Inputs from experiment:

From $K^\pm$ BR fit: [**KLOE**, CNTR]

BR($K^\pm_{\mu 2(\gamma)}$) = 0.6358(11)
$\tau_{K\pm}$ = 12.384(15) ns

From PDG:

BR($\pi^\pm_{\mu 2(\gamma)}$) = 0.9999
$\tau_{\pi\pm}$ = 26.033(5) ns

Inputs from theory:

δ_{EM} Long-distance EM corrections

$\delta_{SU(2)}$ Strong isospin breaking
$f_K/f_\pi \to f_{K\pm}/f_{\pi\pm}$

f_K/f_π Ratio of decay constants

Cancellation of lattice-scale uncertainties from ratio

NB: Most lattice results already corrected for $SU(2)$-breaking: $f_{K\pm}/f_{\pi\pm}$

* slides ~~stolen~~ from M. Moulson CKM'23

New development: QCD + QED on the Lattice

Giusti et al.
PRL 120 (2018)

First lattice calculation of EM corrections to P_{l2} decays

- Ensembles from ETM
- N_f = 2+1+1 Twisted-mass Wilson fermions

$\boldsymbol{\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0122(16)}$

- Uncertainty from quenched QED included (0.0006)

Compare to ChPT result from Cirigliano, Neufeld ’11:

$\boldsymbol{\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0112(21)}$

Di Carlo et al.
PRD 100 (2019)

Update, extended description, and systematics of Giusti et al.

$\boldsymbol{\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0126(14)}$

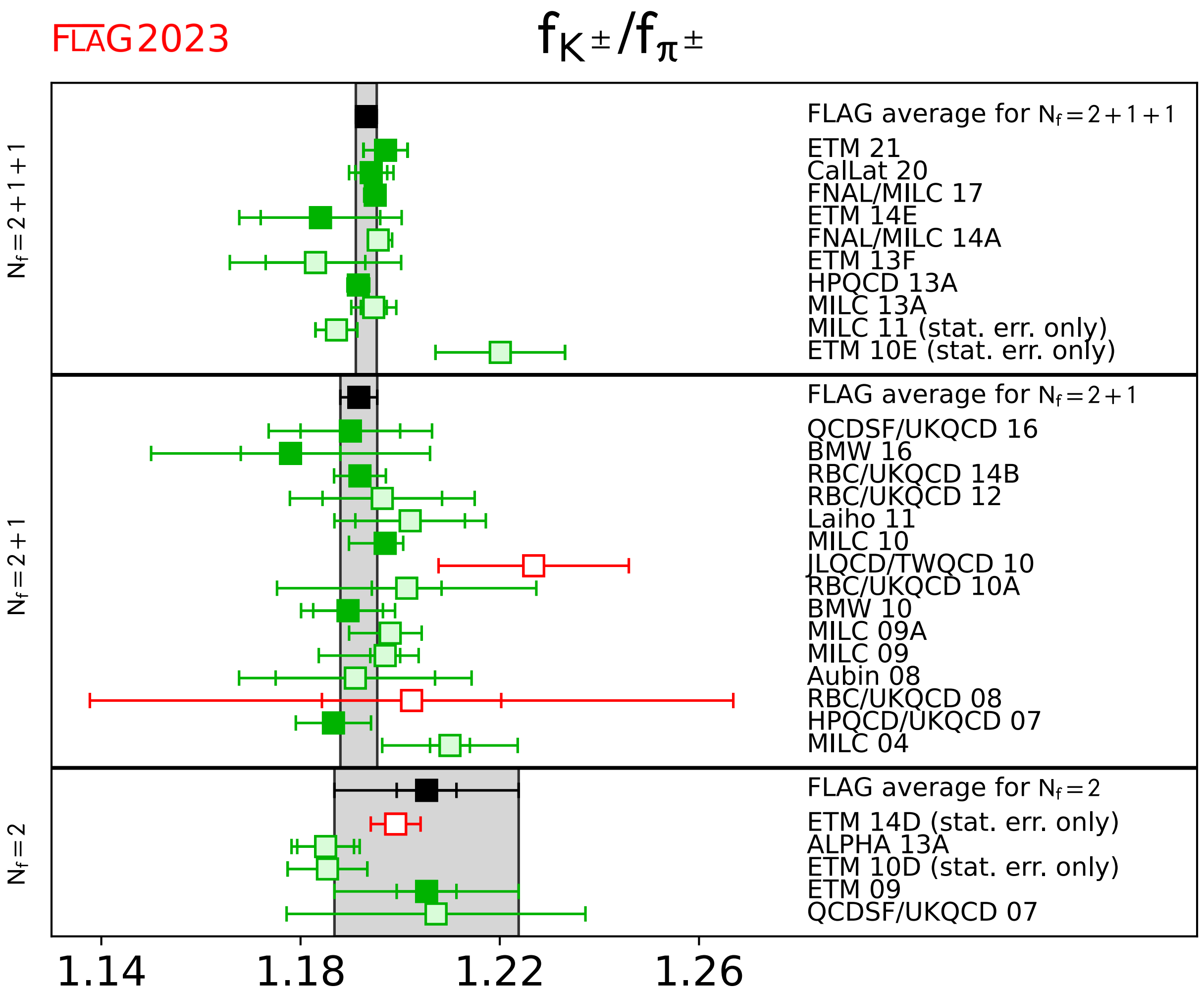
$\boldsymbol{|V_{us}/V_{ud}| \times f_K/f_\pi = 0.27679(28)_{\mathrm{BR}}(20)_{\mathrm{corr}}}$

f_K/f_π on the lattice and result for V_{us}/V_{ud}

Some lattice groups include strong isospin breaking, others work in isospin limit

Isospin breaking $$\frac{f_{K^\pm}}{f_{\pi^\pm}} = \frac{f_K}{f_\pi}\sqrt{1+\delta_{SU(2)}}$$

ISB from χPT $$\delta_{SU(2)} \approx \sqrt{3}\,\epsilon_{SU(2)}\left[-\frac{4}{3}\left(f_K/f_\pi - 1\right) + \frac{2}{3(4\pi)^2 f_0^2}\left(M_K^2 - M_\pi^2 - M_\pi^2 \ln\frac{M_K^2}{M_\pi^2}\right)\right]$$



LQCD ($N_f = 2+1+1$):

$f_{K^\pm}/f_{\pi^\pm} = 1.1934(19)$ $\qquad f_K/f_\pi = 1.1978(22)$

LQCD ($N_f = 2+1$):

$f_{K^\pm}/f_{\pi^\pm} = 1.1917(37)$ $\qquad f_K/f_\pi = 1.1946(34)$

$$\boxed{\frac{|V_{us}|}{|V_{ud}|} = 0.23108(23)_{\text{exp}}(42)_{\text{lat}}(16)_{\text{ISB}}(51)_{\text{tot}} = 0.22\,\%}$$

V_{us} from $K\ell 3 = K \to \pi e \nu, \pi \mu \nu$

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\text{EW}} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\text{EM}}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2 1/2 for K^+, 1 for K^0

S_{EW} Universal SD EW correction (1.0232)

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios: K_S, K_L, $K^\pm$
- Kaon lifetimes

$I_{K\ell}(\{\lambda\}_{K\ell})$ Integral of form factor over phase space: λs parameterize evolution in t

- K_{e3}: Only λ_+ (or λ_+', λ_+'')
- $K_{\mu 3}$: Need λ_+ and λ_0

Inputs from theory:

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)

$\Delta_K^{SU(2)}$ Form-factor correction for $SU(2)$ breaking

$\Delta_{K\ell}^{\text{EM}}$ Form-factor correction for long-distance EM effects

Fit to $K\ell 3$ branching ratios of K_S, K_L, $K^{\pm}$

Fit to K_S rate data (2022)

7 input measurements:

- **KLOE '06** BR $\pi^0\pi^0/\pi^+\pi^-$
- **NA48** $\Gamma(K_S \to \pi e\nu)/\Gamma(K_L \to \pi e\nu)$, τ_S
- **KLOE '11** τ_S
- **KTeV '11** τ_S
- **KLOE-2 '22** BR $\pi e\nu/\pi^+\pi^-$ **New!**
- **KLOE-2 '20** BR $\pi\mu\nu/\pi^+\pi^-$

2 possible constraints:

- Σ **BR = 1**
- **BR(K_{e3})/BR($K_{\mu3}$) = 0.6640(17)**
  From ratio of phase-space integrals from current fit to dispersive $K_{\ell 3}$ form factor parameters

Only sum constraint used for fit

Parameter	Value
BR($\pi^+\pi^-(\gamma)$)	69.20(5)%
BR($\pi^0\pi^0$)	30.69(5)%
BR(K_{e3})	7.15(6) × 10^{-4}
BR($K_{\mu3}$)	4.56(20) × 10^{-4}
τ_S	89.58(4) ns

χ^2/ndf = 0.36/3 (Prob = 95%)

Little correlation for K_{e3} $K_{\mu3}$ from fit

10-20% correlations with $\pi^0\pi^0/\pi^+\pi^-$

Input measurements essentially unchanged

Fit to K_L rate data (2010)

21 input measurements:

- **5 KTeV** ratios
- **NA48** BR(K_{e3}/2 track)
- **4 KLOE** BRs
  with dependence on τ_L
- **KLOE, NA48** BR($\pi^+\pi^-/K_{\ell 3}$)
- **KLOE, NA48** BR($\gamma\gamma/3\pi^0$)
- **BR($2\pi^0/\pi^+\pi^-$) from K_S fit, Re ε'/ε**
- **KLOE** τ_L from $3\pi^0$
- **Vosburgh '72** τ_L
- **KTeV** BR($\pi^+\pi^-\gamma/\pi^+\pi^-(\gamma)$)
- **E731, 2 KTeV** BR($\pi^+\pi^-\gamma_{\mathrm{DE}}/\pi^+\pi^-\gamma$)

1 constraint: Σ BR = 1

Parameter	Value	S
BR(K_{e3})	0.4056(9)	1.3
BR($K_{\mu3}$)	0.2704(10)	1.5
BR($3\pi^0$)	0.1952(9)	1.2
BR($\pi^+\pi^-\pi^0$)	0.1254(6)	1.3
BR($\pi^+\pi^-(\gamma_{\mathrm{IB}})$)	1.967(7) × 10^{-3}	1.1
BR($\pi^+\pi^-\gamma$)	4.15(9) × 10^{-5}	1.6
BR($\pi^+\pi^-\gamma_{\mathrm{DE}}$)	2.84(8) × 10^{-5}	1.3
BR($2\pi^0$)	8.65(4) × 10^{-4}	1.4
BR($\gamma\gamma$)	5.47(4) × 10^{-4}	1.1
τ_L	51.16(21) ns	1.1

χ^2/ndf = 19.8/12 (Prob = 7.0%)

Essentially same result as 2010 fit

Current PDG (since '09): **37.4/17** (0.30%)

Fit to $K^{\pm}$ rate data (2014)

17 input measurements:

- **3 old τ values in PDG**
- **KLOE τ**
- **KLOE BR $\mu\nu$, $\pi\pi^0$**
- **KLOE BR K_{e3}, $K_{\mu3}$**
  with dependence on τ
- **NA48/2 BR $K_{e3}/\pi\pi^0$, $K_{\mu3}/\pi\pi^0$**
- **E865 BR K_{e3}/KDal**
- **3 old BR $\pi\pi^0/\mu\nu$**
- **KEK-246 $K_{\mu3}/K_{e3}$**
- **KLOE BR $\pi\pi\pi$, $\pi\pi^0\pi^0$**
- (Bisi '65 BR $\pi\pi^0\pi^0/\pi\pi\pi$ removed)

1 constraint: Σ BR = 1

Much more selective than PDG fit
PDG '16: 35 inputs, 8 parameters

Parameter	Value	S
BR($\mu\nu$)	63.58(11)%	1.1
BR($\pi\pi^0$)	20.64(7)%	1.1
BR($\pi\pi\pi$)	5.56(4)%	1.0
BR(K_{e3})	5.088(27)%	1.2
BR($K_{\mu3}$)	3.366(30)%	1.9
BR($\pi\pi^0\pi^0$)	1.764(25)%	1.0
$\tau_{\pm}$	12.384(15) ns	1.2

χ^2/ndf = 25.5/11 (Prob = 0.78%)

compare PDG '16: 53/28 (0.26%)

With **ISTRA+ '14 BR($K^-_{e3}/\pi^-\pi^0$)**

- **BR(K_{e3}) = 5.083(27)%**
- Negligible changes in other parameters, fit quality

Compared to Kl2:

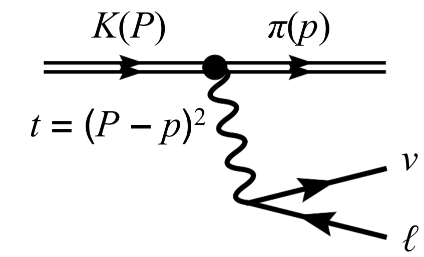
Many decay channels

multiple consistency checks possible

$K - \pi$ transition form factors

Hadronic matrix element:

$$\langle \pi | J_\alpha | K \rangle = f(0) \times \left[\tilde{f}_+(t)(P+p)_\alpha + \tilde{f}_-(t)(P-p)_\alpha \right]$$



K_{e3} decays: Only **vector form factor:** $\tilde{f}_+(t)$

$K_{\mu 3}$ decays: Also need **scalar form factor:** $\tilde{f}_0(t) = \tilde{f}_+ + \tilde{f}_- \dfrac{t}{m_K^2 - m_\pi^2}$

To extract V_{us}: need a phase-space integral over the form factor

Parametrize FFs —> best option: dispersion representation

Perform a fit to Dalitz plot

Dispersive + ChPT parametrization

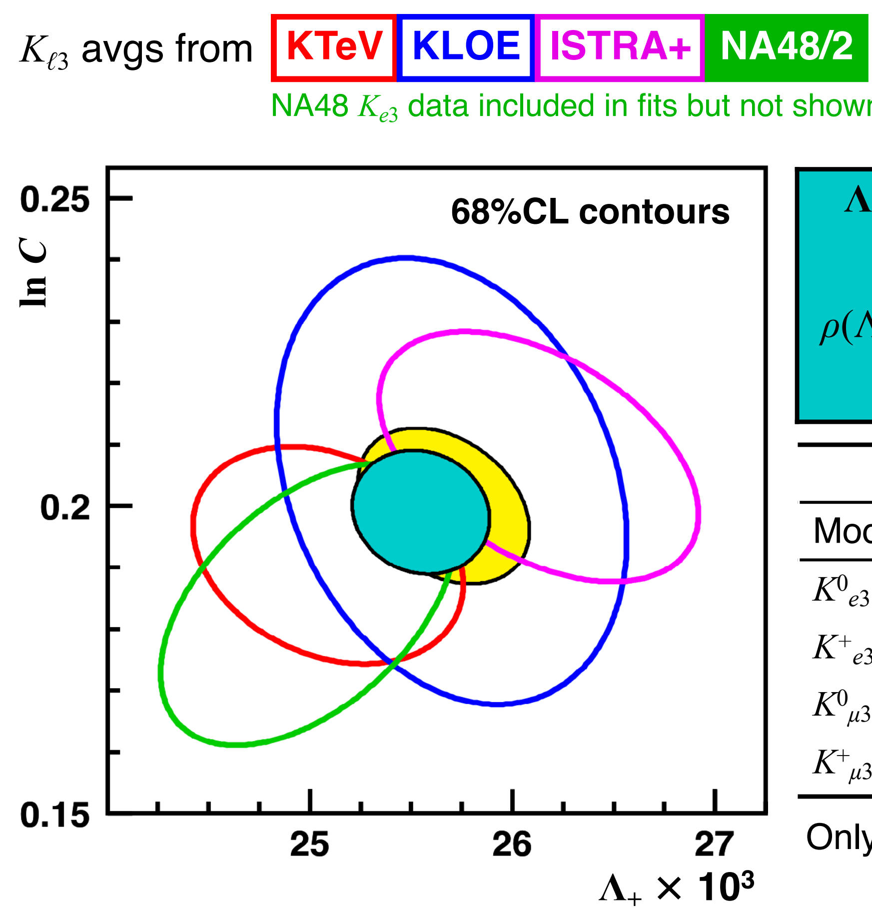
Bernard et al. '09

$$\tilde{f}_+(t) = \exp\left[\frac{t}{m_\pi^2} (\Lambda_+ - H(t)) \right]$$

$$\tilde{f}_0(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2} (\ln C - G(t)) \right]$$

H,G: obtained from K-π phase shifts

Λ_+, $\ln C$ - free parameters



2010 fit | Current

$\Lambda_+ \times 10^3$	=	**25.55 ± 0.38**
ln C	=	**0.1992(78)**
$\rho(\Lambda_+, \ln C)$	=	−0.110
χ^2/ndf	=	7.5/7 (38%)

Integrals

Mode	Update	2010
$K^0{}_{e3}$	**0.15470(15)**	0.15476(18)
$K^+{}_{e3}$	**0.15915(15)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10247(15)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10553(16)**	0.10559(17)

Only tiny changes in central values

Long-distance EM correction

Mode-dependent corrections $\Delta^{\mathrm{EM}}{}_{K\ell}$ to phase-space integrals $I_{K\ell}$ from EM-induced Dalitz plot modifications

- Values depend on acceptance for events with additional real photon(s)
- All recent measurements assumed fully inclusive

FlaviaNet analysis and updates used Cirigliano et al. '08

- Comprehensive analysis at fixed order e^2p^2

Seng et al.
JHEP 07 (2022)

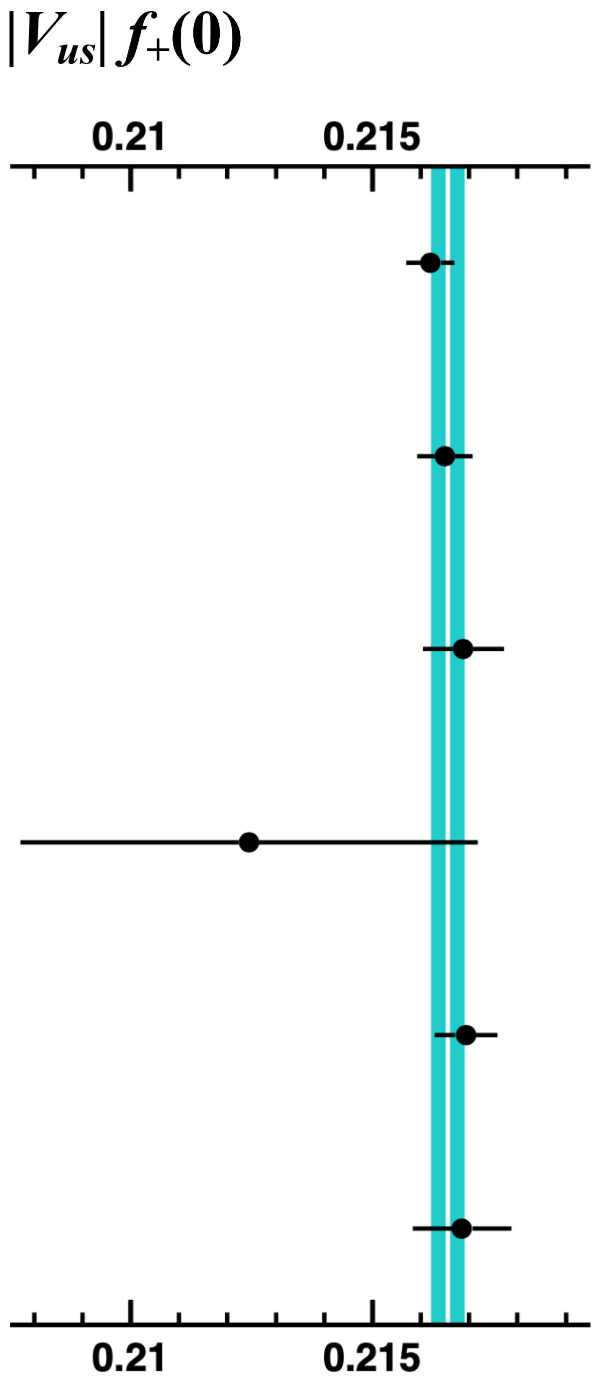
Calculation of complete EW RC using hybrid current algebra and ChPT with resummation of largest terms to all chiral orders

- Reduced uncertainties at O(e^2p^4)
- Lattice evaluation of QCD contributions to γW box diagrams
- Conventional value of S_{EW} subtracted from results for use with standard formula for V_{us}

	Cirigliano et al. '08	Seng et al. '21
$\Delta^{\mathrm{EM}}(K^0{}_{e3})$ [%]	0.50 ± 0.11	**0.580 ± 0.016**
$\Delta^{\mathrm{EM}}(K^+{}_{e3})$ [%]	0.05 ± 0.12	**0.105 ± 0.023**
$\Delta^{\mathrm{EM}}(K^+{}_{\mu 3})$ [%]	0.70 ± 0.11	**0.770 ± 0.019**
$\Delta^{\mathrm{EM}}(K^0{}_{\mu 3})$ [%]	0.01 ± 0.12	**0.025 ± 0.027**

Seng, Galviz, Meißner 1910.13208; Seng, Galviz, MG, Meißner 2103.04843; Seng, Galviz, MG, Meißner 2203.05217; Feng, MG, Jin, Ma, Seng 2003.09798; Ma, Feng, MG, Jin, Seng 2102.12048

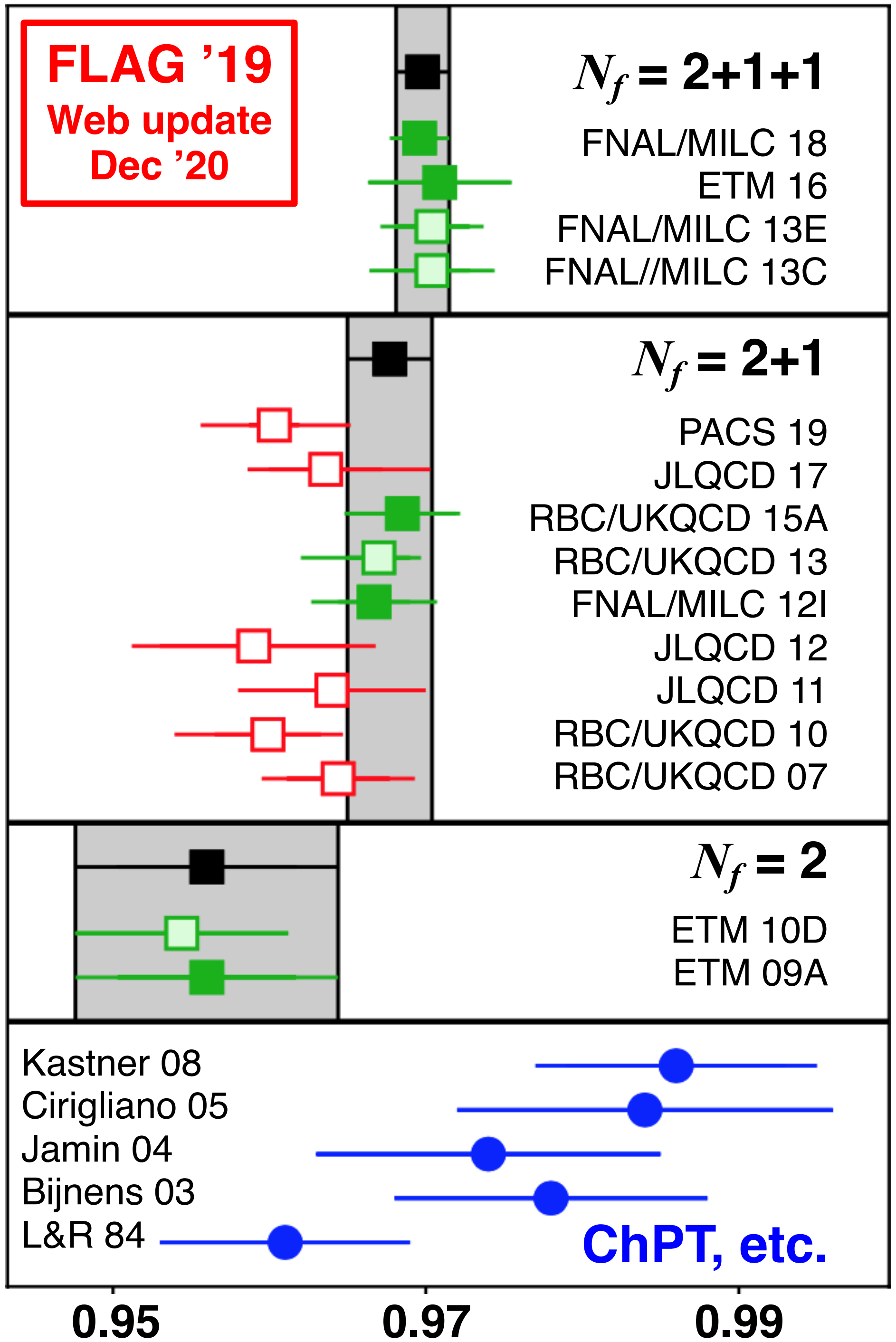
$|V_{us}|f_+(0)$ from world data



			Approx. contrib. to % err from:			
		% err	BR	τ	Δ	Int
$K_L e3$	0.2162(5)	0.23	0.09	0.20	0.02	0.05
$K_L \mu 3$	0.2165(6)	0.26	0.15	0.18	0.02	0.07
$K_S e3$	0.2169(8)	0.39	0.38	0.02	0.02	0.05
$K_S \mu 3$	0.2125(47)	2.2	2.2	0.02	0.02	0.08
$K^{\pm} e3$	0.2169(6)	0.30	0.27	0.06	0.11	0.05
$K^{\pm} \mu 3$	0.2168(10)	0.47	0.45	0.06	0.11	0.08

Average: $|V_{us}|\,f_+(0)$ = 0.21656(35) **χ^2/ndf = 1.89/5 (86%)**

$f_+(0)$ on the lattice and extraction of $|V_{us}|$



FLAG '21 averages:

N_f = 2+1+1 **$f_+(0)$ = 0.9698(17)**

Uncorrelated average of:

FNAL/MILC 18: HISQ, 5sp, $m_\pi \to 135$ MeV, new ensembles added to FNAL/MILC 13E

ETM 16: TwMW, 3sp, $m_\pi \to 210$ MeV, full q^2 dependence of f_+, f_0

N_f = 2+1 **$f_+(0)$ = 0.9677(27)**

Uncorrelated average of:

FNAL/MILC 12I: HISQ, $m_\pi \sim 300$ MeV

RBC/UKQCD 15A: DWF, $m_\pi \to 139$ MeV

JLQCD 17 not included because only single lattice spacing used

ChPT **$f_+(0)$ = 0.970(8)**

Ecker 15, Chiral Dynamics 15:
Calculation from Bijnens 03,
with new LECs from Bijnens, Ecker 14

$$|V_{us}| = 0.22330(35)_{\text{exp}}(39)_{\text{lat}}(8)_{\text{IB}}$$
$$(53)_{\text{tot}} = 0.24\ \%$$

Summary on $|V_{us}|$

High-precision world data on leptonic and semileptonic decay channels

Theoretical evaluation of form factors, decay constants, radiative corrections as important as data

Past ~5 years: ChPT is officially superseded by lattice; LQCD results very consistent!

Great consistency among semileptonic channels

$K\mu 2$ channel: first ever QCD+QED calculation on the lattice

$$\Delta^{(3)}_{\rm CKM} = |V_{us}^{K_{\ell 3}}|^2 \left[\left(\frac{1}{|V_{us}/V_{ud}|^{K_{\mu 2}}}\right)^2 + 1\right] - 1 \quad \mathbf{= -0.0164(63)} \quad \mathbf{-2.6\sigma}$$

$K\mu 2$ - $K\ell 3$ discrepancy confirmed
Cabibbo anomaly even w/o info on V_{ud}!
Upcoming exp. Belle II, NA62, K0T0

$$\text{Unitarity} \to |V_{ud}^{K\ell 3}| = \sqrt{1 - |V_{us}^{K\ell 3}|^2} = 0.9747(1)$$

$$\text{Unitarity} \to |V_{ud}^{K\mu 2}| = [1 + |(V_{us}/V_{ud})^{K\mu 2}|^2]^{-1/2} = 0.9743(1)$$

Hyperon and tau decays: not precise enough or inconsistent — Belle II, Super Tau-Charm Factory?

$|V_{us}| = 0.2250(27)$ (Hyperon Decays)

$|V_{ud}^{\rm Hyp}| = 0.9743(6)$

$|V_{us}| = 0.2207(14)$ (Tau Decays)

$|V_{ud}^{\tau}| = 0.9753(3)$

V_{ud} from world data

V_{ud} from neutron decay

Neutron decay: 2 measurements needed

$$|V_{ud}|^2 = \frac{5024.7\ \mathrm{s}}{\tau_n(1+3g_A{}^2)(1+\Delta_R^V)}$$

RC Δ_R^V: bottleneck since 40 years

Pre-2018: $\Delta_R^V = 0.02361(38)$ *Marciano, Sirlin PRL 2006*
Post-2018: $\Delta_R^V = 0.02479(21)$ *MG, Seng Universe 2023*

Since 2018: DR+data+pQCD+EFT+LQCD
Δ_R^V uncertainty: factor 2 reduction

C-Y Seng et al., PRL 2018; PRD 2019
A. Czarnecki, B. Marciano, A. Sirlin, PRD 2018
K. Shiells et al, PRD 2021; L. Hayen PRD 2021
P-X Ma, X. Feng, MG, L-C Jin, et al *2308.16755*

Experiment: factor 3-5 uncertainties improvement; discrepancies in τ_n and g_A

3.4σ

$g_A = -1.27641(56)$ **PERKEO-III** *B. Märkisch et al, Phys.Rev.Lett. 122 (2019) 24, 242501*

$g_A = -1.2677(28)$ **aSPECT** *M. Beck et al, Phys. Rev. C101 (2020) 5, 055506; 2308.16170*

4σ

$\tau_n = 877.75(28)^{+16}_{-12}$ **UCNτ** *F. M. Gonzalez et al. Phys. Rev. Lett. 127 (2021) 162501*

$\tau_n = 887.7(2.3)$ **BL1 (NIST)** *Yue et al, PRL 111 (2013) 222501*

PDG average

$$|V_{ud}^{\text{free n}}| = 0.9743\,(3)_{\tau_n}\,(8)_{g_A}\,(1)_{RC}[9]_{total}$$

Single best measurements only

$$|V_{ud}^{\text{free n}}| = 0.9740\,\boxed{(2)_{\tau_n}\,(3)_{g_A}}\,(1)_{RC}[4]_{total}$$

V_{ud} from semileptonic pion decay

Pion decay $\pi^+ \to \pi^0 e^+ \nu_e$: theoretically cleanest, experimentally tough

$$|V_{ud}|^2 = \frac{0.9799}{(1+\delta)} \frac{\Gamma_{\pi\ell 3}}{0.3988(23)\,\mathrm{s}^{-1}}$$

$$|V_{ud}^{\pi\ell 3}| = 0.9739\,(27)_{exp}\,(1)_{RC}$$

RC to semileptonic pion decay

δ uncertainty: factor 3 reduction

ChPT: $\delta = -\,0.0334(10)_{\mathrm{LEC}}(3)_{\mathrm{HO}}$ *Cirigliano et al, 2003; Passera et al, 2011*

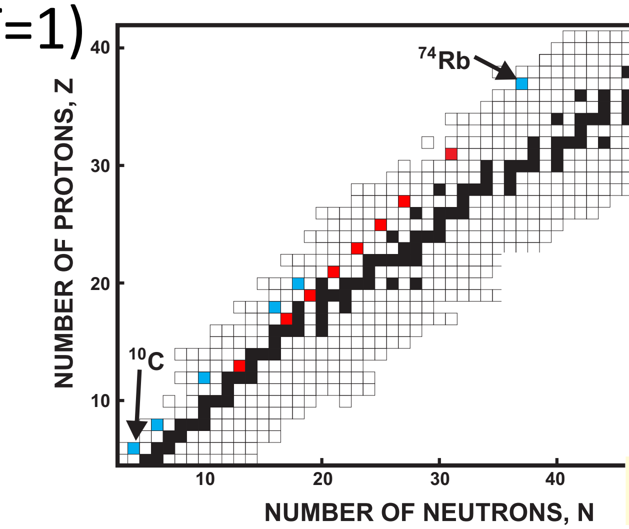
DR + LQCD + ChPT: $\delta = 0.0332(1)_{\gamma W}(3)_{\mathrm{HO}}$ *Feng et al, 2020; Yoo et al, 2023*

Future exp: 1 o.o.m. (PIONEER @ PSI)

Talk by Saul Cuen-Rochin on Monday

V_{ud} from superallowed $0^+ - 0^+$ nuclear decays

1. Transitions within $J^P=0^+$ isotriplets (T=1)
2. Elementary process: p—>ne$^+\nu$
3. Only conserved vector current
4. 15 measured to better than 0.2%
5. Internal consistency as a check
6. SU(2) good —> corrections ~small



$^{10}_{6}\mathrm{C} \to ^{10}_{5}\mathrm{B}$
$^{14}_{8}\mathrm{O} \to ^{14}_{7}\mathrm{N}$
$^{18}_{10}\mathrm{Ne} \to ^{18}_{9}\mathrm{F}$
$^{22}_{12}\mathrm{Mg} \to ^{22}_{11}\mathrm{Na}$
$^{26}_{14}\mathrm{Si} \to ^{26}_{13}\mathrm{Al}$
$^{30}_{16}\mathrm{S} \to ^{30}_{15}\mathrm{P}$
$^{34}_{18}\mathrm{Ar} \to ^{34}_{17}\mathrm{Cl}$
$^{38}_{20}\mathrm{Ca} \to ^{38}_{19}\mathrm{K}$
$^{42}_{22}\mathrm{Ti} \to ^{42}_{21}\mathrm{Sc}$
$^{46}_{24}\mathrm{Cr} \to ^{46}_{23}\mathrm{V}$
$^{50}_{26}\mathrm{Fe} \to ^{50}_{25}\mathrm{Mn}$
$^{54}_{28}\mathrm{Ni} \to ^{54}_{27}\mathrm{Co}$

$^{26m}_{13}\mathrm{Al} \to ^{26}_{12}\mathrm{Mg}$
$^{34}_{17}\mathrm{Cl} \to ^{34}_{16}\mathrm{S}$
$^{38m}_{19}\mathrm{K} \to ^{38}_{18}\mathrm{Ar}$
$^{42}_{21}\mathrm{Sc} \to ^{42}_{20}\mathrm{Ca}$
$^{46}_{23}\mathrm{V} \to ^{46}_{22}\mathrm{Ti}$
$^{50}_{25}\mathrm{Mn} \to ^{50}_{24}\mathrm{Cr}$
$^{54}_{27}\mathrm{Co} \to ^{54}_{26}\mathrm{Fe}$
$^{62}_{31}\mathrm{Ga} \to ^{62}_{30}\mathrm{Zn}$
$^{66}_{33}\mathrm{As} \to ^{66}_{32}\mathrm{Ge}$
$^{70}_{35}\mathrm{Br} \to ^{70}_{34}\mathrm{Se}$
$^{74}_{37}\mathrm{Rb} \to ^{74}_{36}\mathrm{Kr}$

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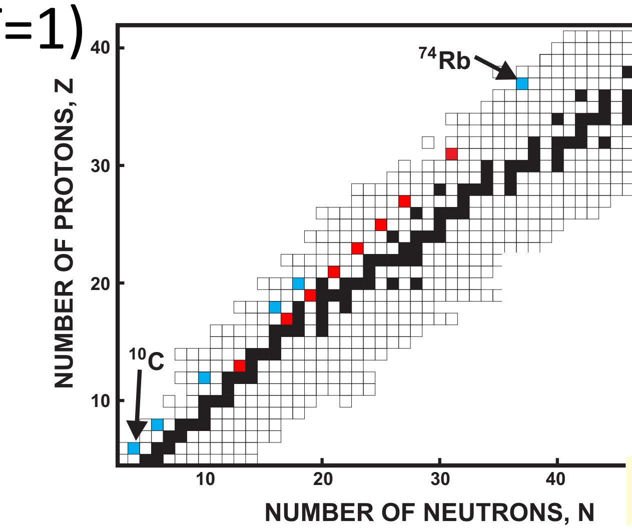

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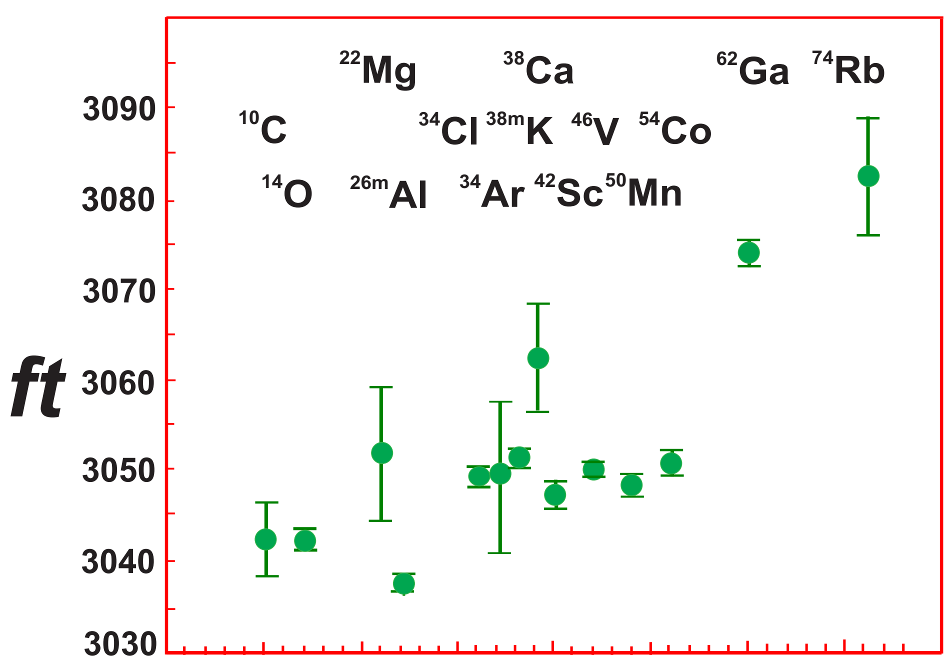
${}^{70}_{35}\mathrm{Br} \to {}^{70}_{34}\mathrm{Se}$
${}^{74}_{37}\mathrm{Rb} \to {}^{74}_{36}\mathrm{Kr}$

Exp.: **f** - phase space (Q value)

t - partial half-life ($t_{1/2}$, branching ratio)



ft values: same within ~2% but not exactly!

Reason: SU(2) slightly broken

a. RC (e.m. interaction does not conserve isospin)

b. Nuclear WF are not SU(2) symmetric (proton and neutron distribution not the same)

V_{ud} extraction: Universal RC and Universal Ft

To obtain Vud —> absorb all decay-specific corrections into universal **Ft**

$$ft(1 + \mathrm{RC} + \mathrm{ISB}) = \mathscr{F}\mathrm{t}(1 + \Delta_R^V) = \mathrm{ft}(1 + \delta_R')(1 - \delta_C + \delta_{NS})(1 + \Delta_R^V)$$

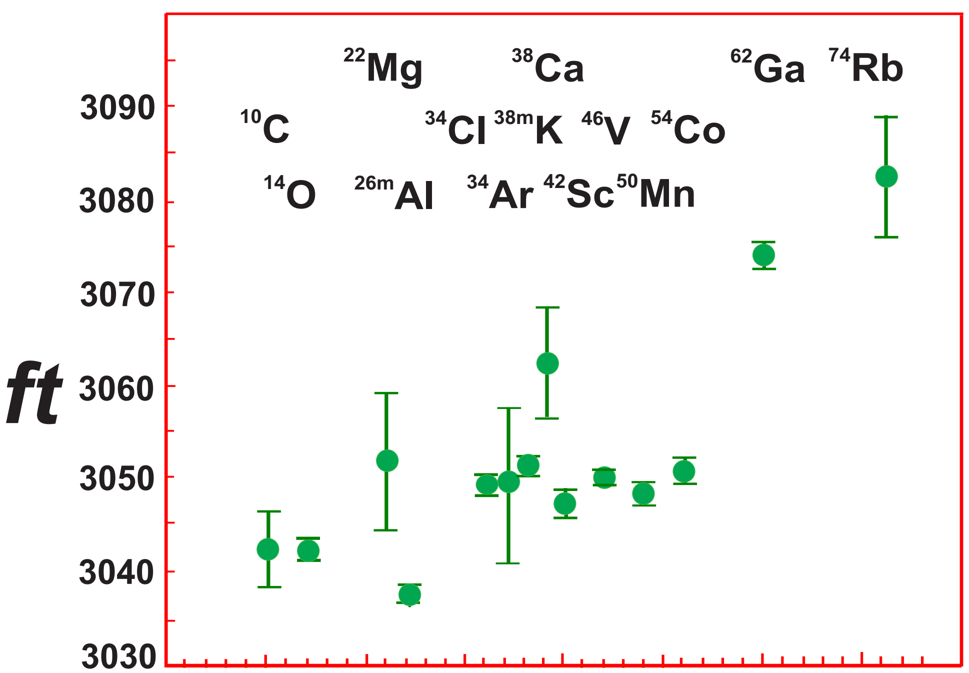
~ Measured QED Isospin-breaking Nuclear structure Universal RC

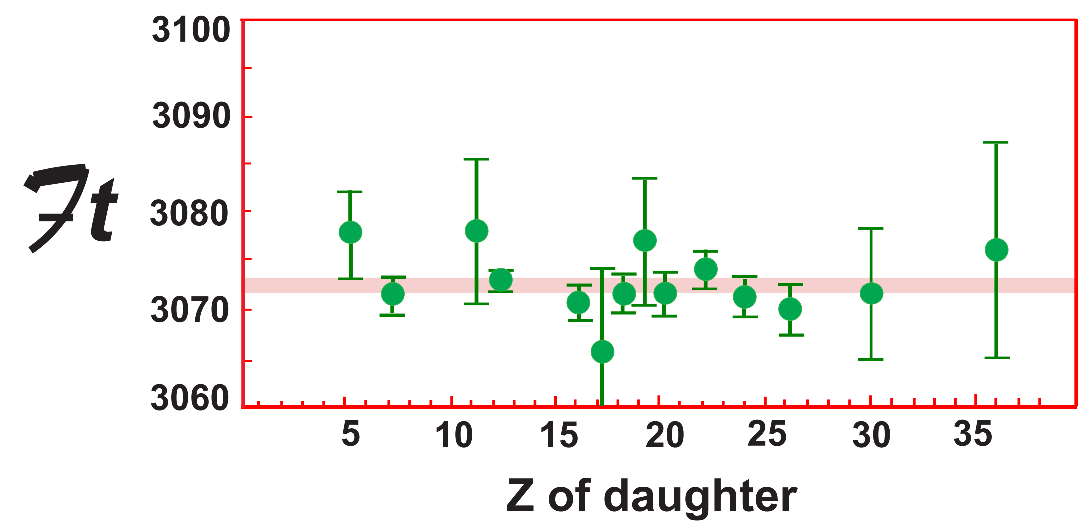
V_{ud} extraction: Universal RC and Universal Ft

To obtain Vud —> absorb all decay-specific corrections into universal **Ft**

$$ft(1+\mathrm{RC}+\mathrm{ISB}) = \mathscr{F}\mathrm{t}(1+\Delta_R^V) = \mathrm{ft}(1+\delta_R')(1-\delta_C+\delta_{NS})(1+\Delta_R^V)$$

~ Measured QED Isospin-breaking Nuclear structure Universal RC





Average of 14 decays Hardy, Towner 1972 - 2020

Pre-2018: $\overline{\mathscr{F}t} = 3072.1 \pm 0.7\, s$

PDG 2024: $\overline{\mathscr{F}t} = 3072 \pm 2\, s$

$$|V_{ud}|^2 = \frac{2984.43s}{\mathscr{F}t(1+\Delta_R^V)}$$

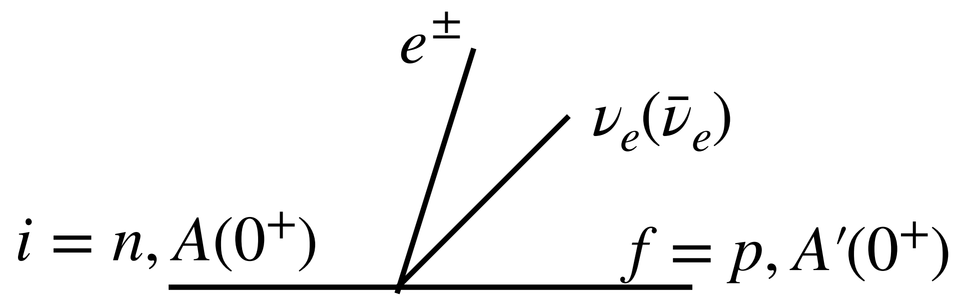
$$|V_{ud}^{0^+-0^+}| = 0.9737\,(1)_{exp,\,nucl}\boxed{(3)_{NS}}(1)_{RC}[3]_{total}$$

Are all SM contributions under control?

Radiative Corrections to beta decay: Overall Setup

RC to beta decay: overall setup

Tree-level amplitude



$\sim V_{ud}$

Radiative corrections to tree-level amplitude $\sim \alpha/2\pi \approx 10^{-3}$

Precision goal for V_{ud} extraction 1×10^{-4}

Electron carries away energy E < Q-value of a decay

E-dep RC: $$\frac{\alpha}{2\pi}\left(\frac{E}{\Lambda}, \ln\frac{E}{\Lambda}, \ldots\right)$$

Energy scales Λ

Λ

Weak boson scale
$M_Z, M_W \sim 90\,\mathrm{GeV}$

Hadronic scale
$\Lambda_{\mathrm{had}} = 300\,\mathrm{MeV}$

Universal

Nuclear scale
$\Lambda_{\mathrm{nuc}} = 10 - 30\,\mathrm{MeV}$

Nuclear structure dependent
(QCD)

Decay Q-value (endpoint energy)
$Q_{if} = M_i - M_f = 1 - 10\,\mathrm{MeV}$

Nucleus-specific

Electron mass
$m_e \approx 0.5\,\mathrm{MeV}$

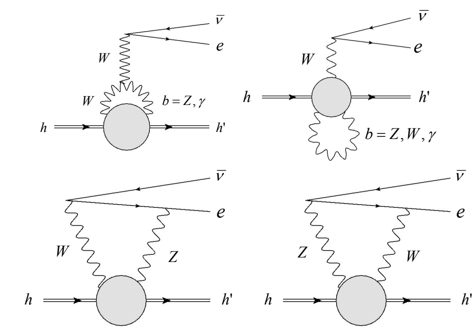
Nuclear structure independent
(QED)

RC to beta decay: separating scales

Generically: only IR and UV extremes feature large logarithms!
Works by Sirlin (1930-2022) and collaborators: all large logs under control

IR: Fermi function (Dirac-Coulomb problem) + Sirlin function (soft Bremsstrahlung)

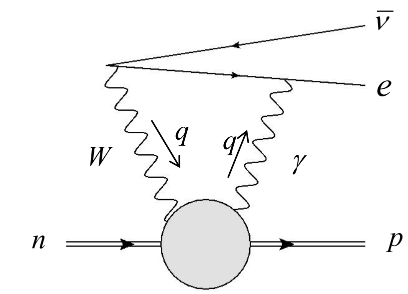
UV: large EW logs + pQCD corrections



Inner RC:
energy- and model-independent

W,Z - loops
UV structure of SM

γW-box: sensitive to all scales



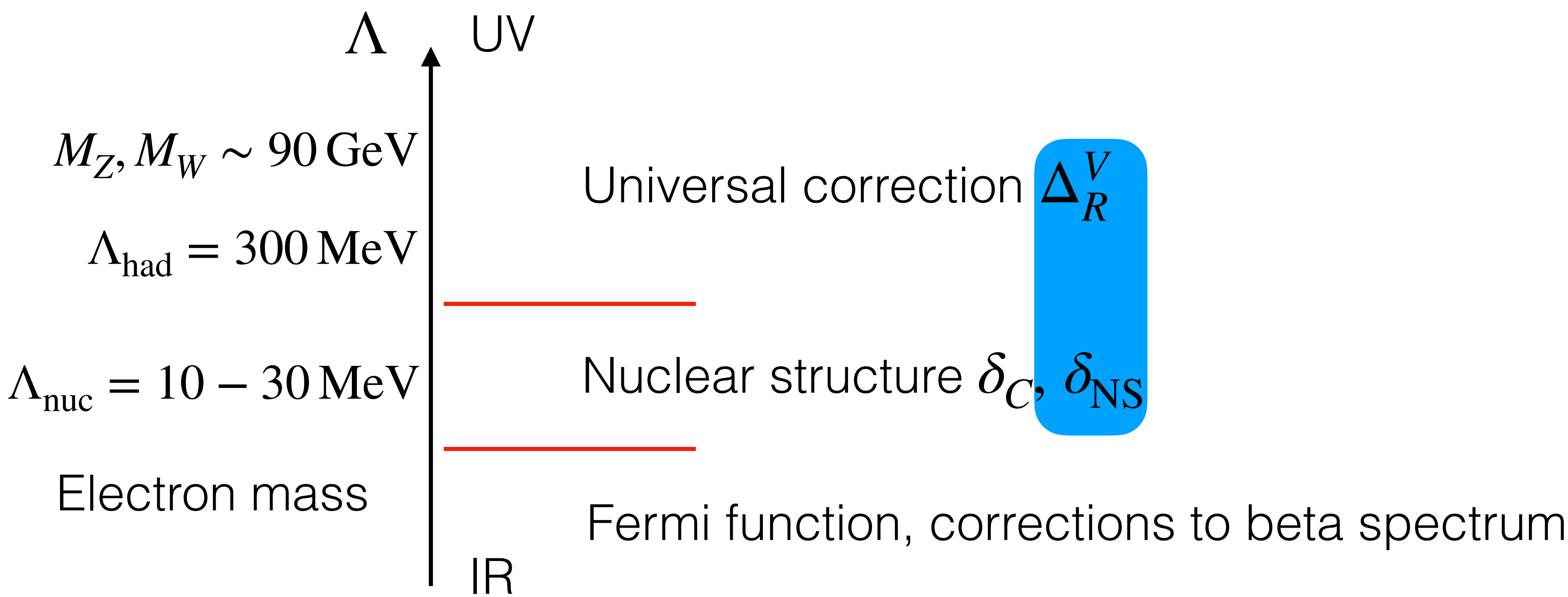
New method for computing EW boxes: dispersion theory
Combine exp. data with pQCD, lattice, EFT, ab-initio nuclear

UV-sensitive γW-box on free neutron Δ_R^V: Sirlin, Marciano, Czarnecki 1967 - 2006

$$g_V^2 = |V_{ud}|^2 \left[1 + \frac{\alpha}{2\pi} \left\{ 3 \ln \frac{M_Z}{M_p} + \ln \frac{M_Z}{M_W} + \tilde{a}_g \right\} + \delta_{\rm QED}^{HO} + 2\Box_{\gamma W} \right]$$

Nuclear structure: $\delta_{\rm NS} = 2(\Box_{\gamma W}^{\rm Nucl} - \Box_{\gamma W}^{\rm free\,n})$

All non-enhanced terms $\sim \alpha/2\pi \sim 10^{-3}$ — only need to ~10%

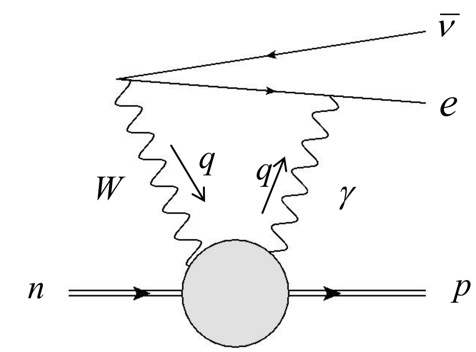


Unified Formalism for Δ_R^V and δ_{NS}

Dispersion Theory of the γW-box

γW-box by Marciano & Sirlin

$$\Box^{VA}_{\gamma W} = 4\pi\alpha \mathrm{Re}\int \frac{d^4q}{(2\pi)^4}\frac{M_W^2}{M_W^2+Q^2}\frac{Q^2+\nu^2}{Q^4}\frac{T_3(\nu,Q^2)}{M\nu}$$



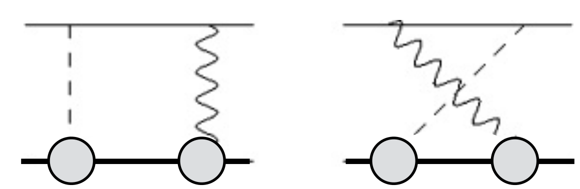
$Q^2 = -q^2$
$\nu = (pq)/M$

Marciano & Sirlin used loop techniques:
$$\Box^{VA}_{\gamma W} = \frac{\alpha}{8\pi}\int_0^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}F(Q^2)$$

Short distance Q^2>> $\quad F^{\mathrm{DIS}}(Q^2) = \frac{1}{Q^2}$
$$\Box^{\mathrm{DIS}}_{\gamma W} = \frac{\alpha}{8\pi}\int_{\Lambda^2}^\infty \frac{dQ^2 M_W^2}{M_W^2+Q^2}F^{\mathrm{DIS}}(Q^2) = \frac{\alpha}{4\pi}\ln\frac{M_W}{\Lambda}$$

Finite Q^2 -
pQCD corrections:
$$F^{\mathrm{DIS}} = \frac{1}{Q^2} \to \frac{1}{Q^2}\left[1 - \frac{\alpha_s^{\overline{MS}}}{\pi}\right]$$

Long distance Q^2<< - elastic box



MS 1987: asymptotic + pQCD + Born
$$\left[\Delta_R^V\right]^{\gamma W} = \frac{\alpha}{2\pi}\left[\ln\frac{M_W}{\Lambda} + A_g + 2C_B\right]$$

~4.1 -0.24 1.85

Problem: connecting short and long distances

γW-box by Marciano & Sirlin

MS 2006 update

Short distance: DIS to N³LO

$$F^{\mathrm{DIS}} = \frac{1}{Q^2} \to \frac{1}{Q^2}\left[1 - \frac{\alpha_s^{\overline{MS}}}{\pi} - C_2\left(\frac{\alpha_s^{\overline{MS}}}{\pi}\right)^2 - C_3\left(\frac{\alpha_s^{\overline{MS}}}{\pi}\right)^3\right]$$

GLS and Bjorken SR to N3LO
Larin, Vermaseren 1997

$$Q^2 > Q_2^2$$

Interpolate between them

Vector Dominance Model Ansatz

$$F^{\mathrm{INT}}(Q^2) = -\frac{1.490}{Q^2+m_\rho^2} + \frac{6.855}{Q^2+m_A^2} - \frac{4.414}{Q^2+m_{\rho'}^2}$$

$$Q^2 < Q_1^2$$

Long distance: Born

$$F(Q^2) = F^B(Q^2)$$

$$\left[\Delta_R^V\right]^{\gamma W} = \frac{\alpha}{2\pi}\left[\underbrace{\ln\frac{M_W}{\Lambda}}_{\sim 3.86} + \underbrace{A_g + 2C_B}_{1.78}\right]$$

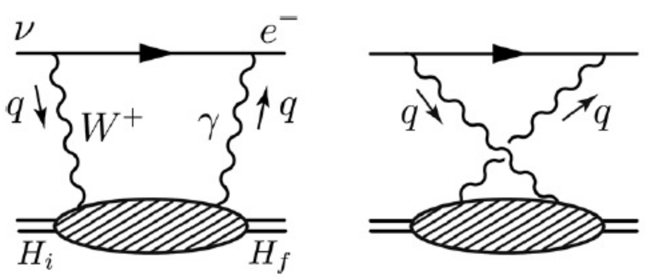
$$\left[\Delta_R^V\right]^{\gamma W} = \frac{\alpha}{2\pi}\left[\underbrace{\ln\frac{M_W}{\Lambda}}_{\sim 3.77} + A_g + \underbrace{C^{Int}}_{0.14(14)} + \underbrace{2C_B}_{1.66}\right]$$

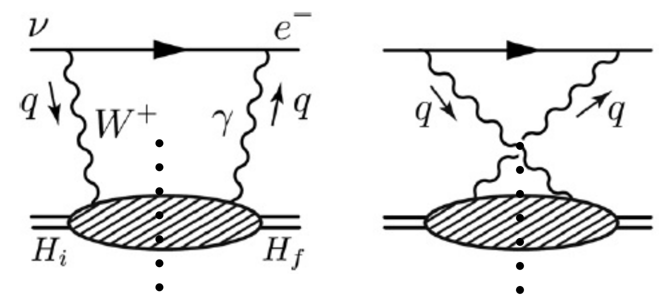
Uncertainty reduced by a factor ~2

γW-box from dispersion relations

Model-dependent part or RC: γW-box

$$\delta\mathfrak{M}^b_{\gamma W} = -i\frac{G_F V_{ud} e^2}{\sqrt{2}} L_\lambda \int \frac{d^4k}{(2\pi)^4} \frac{m_W^2}{m_W^2 - k^2} \frac{\epsilon^{\mu\nu\alpha\lambda} k_\alpha}{[(p_e - k)^2 - m_e^2]k^2} T_{\mu\nu}$$





Generalized Compton tensor
time-ordered product — complicated!

Commutator (Im part) - only on-shell
hadronic states — related to data

$$\int dx e^{iqx} \langle H_f(p) \,|\, T\{J^\mu_{em}(x) J^{\nu,\pm}_W(0)\} \,|\, H_i(p)\rangle$$

$$\int dx e^{iqx} \langle H_f(p) \,|\, [J^\mu_{em}(x), J^{\nu,\pm}_W(0)] \,|\, H_i(p)\rangle$$

γW-box from dispersion relations

Model-dependent part or RC: γW-box

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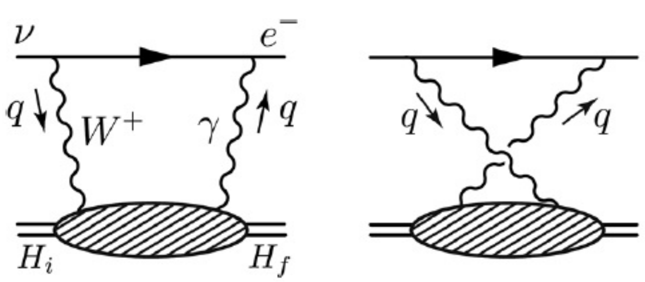
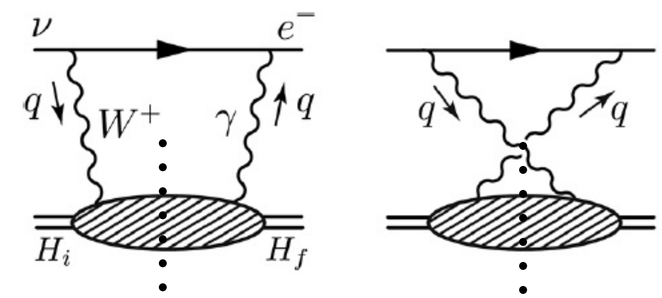


Generalized Compton tensor time-ordered product — complicated!



Commutator (Im part) - only on-shell hadronic states — related to data

$$\int dx e^{iqx}\langle H_f(p)\,|\,T\{J^\mu_{em}(x)J^{\nu,\pm}_W(0)\}\,|\,H_i(p)\rangle$$

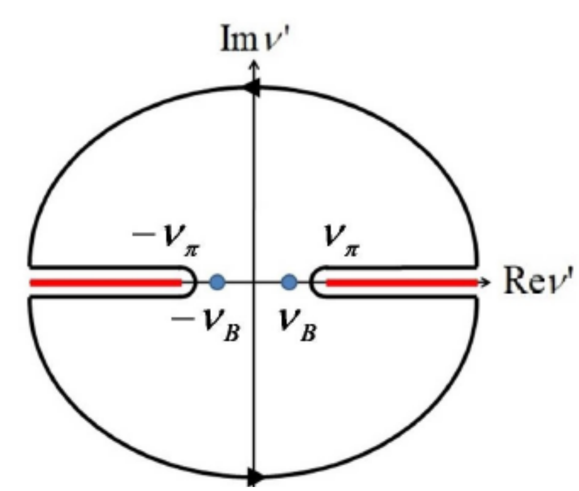
Generalized (non-diagonal) Compton amplitudes

$$\int dx e^{iqx}\langle H_f(p)\,|\,[J^\mu_{em}(x), J^{\nu,\pm}_W(0)]\,|\,H_i(p)\rangle$$

Interference structure functions

Amplitudes = analytic functions inside the contour C in the complex ν-plane with singularities on the real axis - poles + cuts

Discontinuity ~ structure functions $\quad \mathrm{Im}\, T_i^{\gamma W}(\nu, Q^2) = 2\pi F_i^{\gamma W}(\nu, Q^2)$



Universal RC from dispersion relations

Cauchy theorem (dispersion relation) + some algebra

$$\Box^{b,\mathrm{e}}_{\gamma W}(E_e) = \frac{\alpha}{\pi}\int_0^\infty dQ^2 \frac{M_W^2}{M_W^2+Q^2}\int_{\nu_{\mathrm{thr}}}^\infty \frac{d\nu'}{\nu'}\frac{\nu'+2\sqrt{\nu'^2+Q^2}}{(\nu'+\sqrt{\nu'^2+Q^2})^2}\frac{F_{3,-}(\nu',Q^2)}{Mf_+(0)} + \mathcal{O}(E_e^2)$$

$$\Box^{b,\mathrm{o}}_{\gamma W}(E_e) = \frac{2\alpha E_e}{3\pi}\int_0^\infty dQ^2 \int_{\nu_{\mathrm{thr}}}^\infty \frac{d\nu'}{\nu'}\frac{\nu'+3\sqrt{\nu'^2+Q^2}}{(\nu'+\sqrt{\nu'^2+Q^2})^3}\frac{F_{3,+}(\nu',Q^2)}{Mf_+(0)} + \mathcal{O}(E_e^3)$$

Structure functions are measurable or may be related to data

Universal RC from dispersion relations

Cauchy theorem (dispersion relation) + some algebra

$$\Box^{b,\mathrm{e}}_{\gamma W}(E_e) = \frac{\alpha}{\pi}\int_0^\infty dQ^2 \frac{M_W^2}{M_W^2+Q^2}\int_{\nu_{\mathrm{thr}}}^\infty \frac{d\nu'}{\nu'}\frac{\nu'+2\sqrt{\nu'^2+Q^2}}{(\nu'+\sqrt{\nu'^2+Q^2})^2}\frac{F_{3,-}(\nu',Q^2)}{M f_+(0)} + \mathcal{O}(E_e^2)$$

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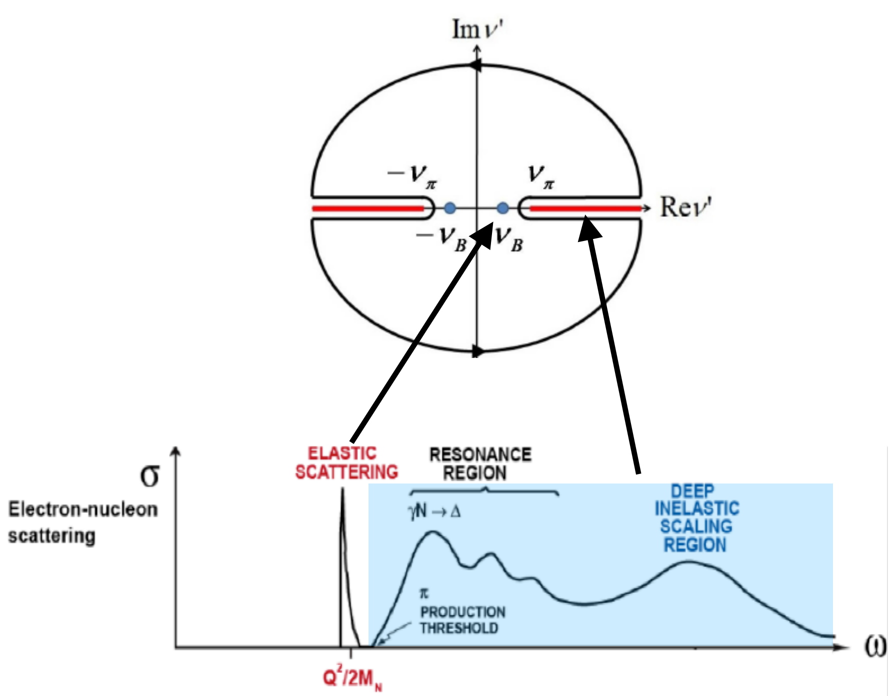
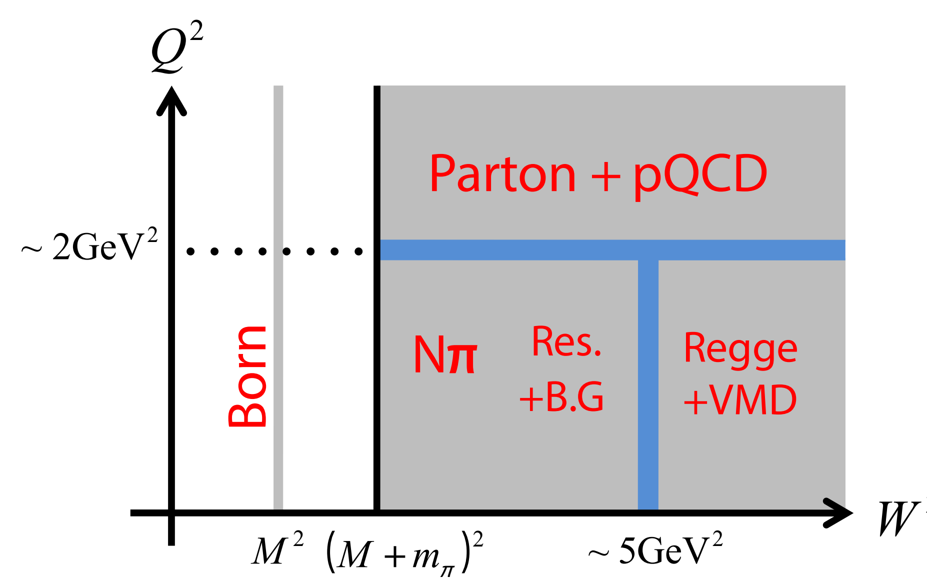
Structure functions are measurable or may be related to data

Dispersion in energy:
scanning hadronic intermediate states



Dispersion in Q^2:
scanning dominant physics picture



Input into dispersion integral - $\nu/\bar{\nu}$ data

Isospin symmetry: Mixed CC-NC γW SF (no data) <—> Purely CC WW SF (inclusive neutrino data)

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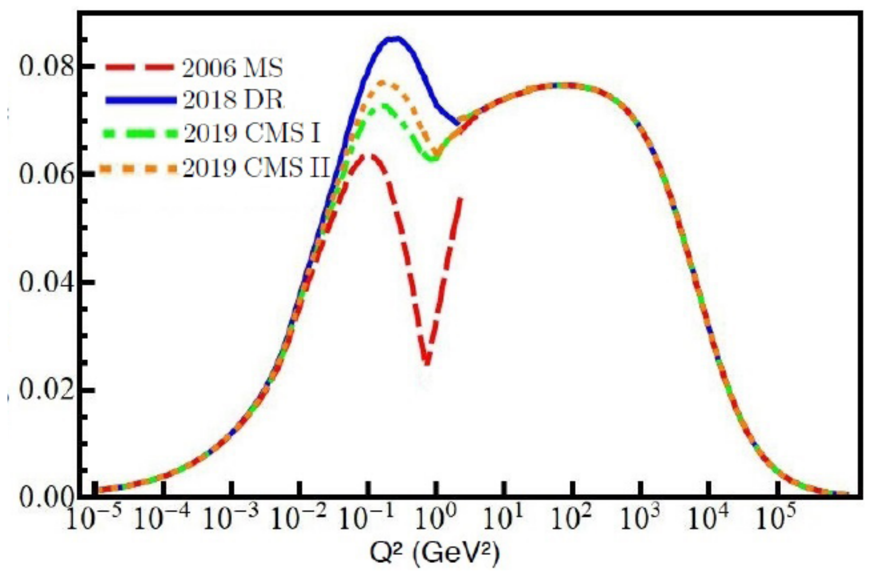
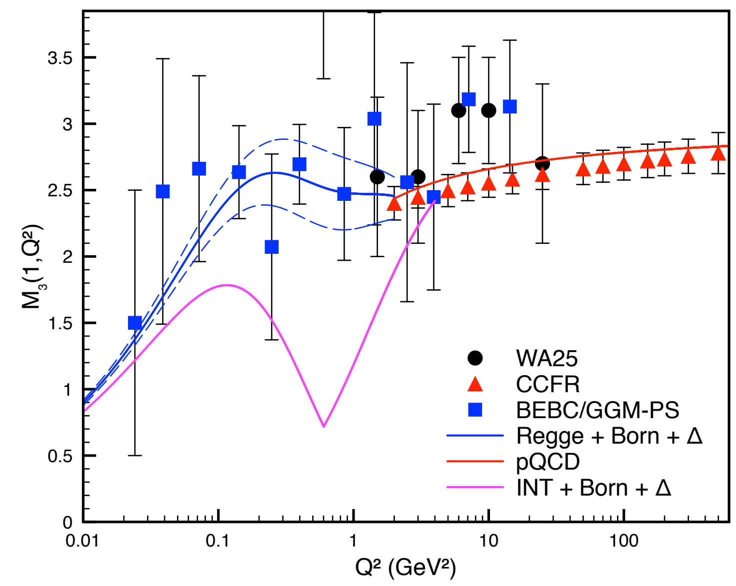
Free neutron γW box



Neutrino scattering data



Marciano, Sirlin 2006: $\Delta_R^V = 0.02361(38)$ —> $|V_{ud}| = 0.97420(10)_{Ft}(18)_{RC}$

DR (Seng et al. 2018): $\Delta_R^V = 0.02467(22)$ —> $|V_{ud}| = 0.97370(10)_{Ft}(10)_{RC}$

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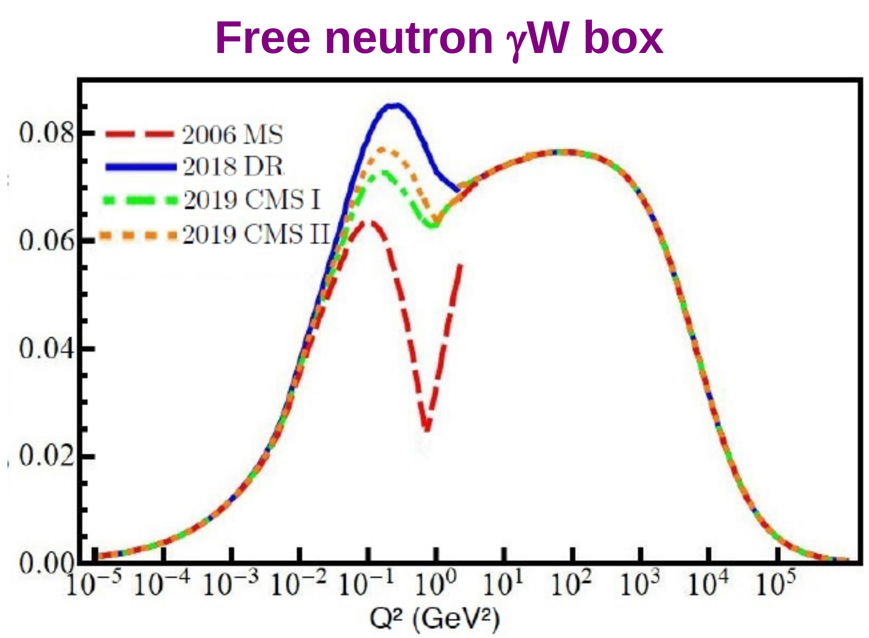

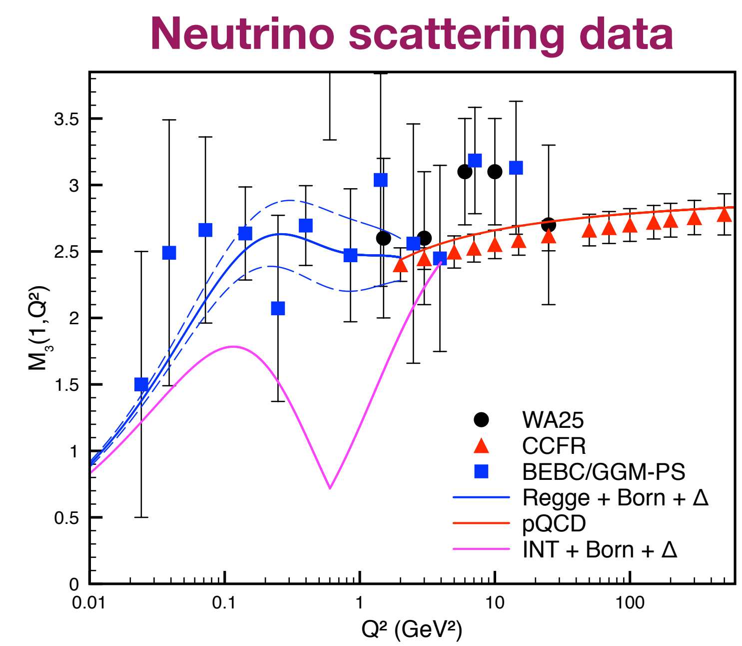

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Shift upwards by 3σ + reduction of uncertainty by factor 2

Confirmed by lattice QCD:

LQCD on pion + pheno: $\Delta_R^V = 0.02477(24)_{\mathrm{LQCD}^\pi\mathrm{+pheno}}$ **Seng, MG, Feng, Jin, 2003.11264** **Yoo et all, 2305.03198**

LQCD on neutron: $\Delta_R^V = 0.02439(19)_{\mathrm{LQCD}^n}$ **Ma, Feng, MG et al 2308.16755**

EFT: scale separation for free n

Cirigliano et al, 2306.03138

Effective Field Theory: explicit separation of scales + RGE running between

- SM —> LEFT (no H,t,Z,W) —> ChPT —> NR QED
- Formal consistency built in, RGE, transparent error estimation (naturalness)
- Precision limited by matching (LEC) and HO — relies on inputs (e.g. γW-box from DR)
- To improve: need to go to higher order — new LECs, still tractable?
- At present: order $O(\alpha, \alpha\alpha_s, \alpha^2)$ — realistic to go beyond?

$$\frac{\mathrm{d}\Gamma_n}{\mathrm{d}E_e} = \frac{G_F^2\,|V_{ud}|^2}{(2\pi)^5}\,(1+3\lambda^2)\;p_e E_e (E_0 - E_e)^2\,[g_V(\mu_\chi)]^2\,F_{NR}(\beta)\Big(1+\delta_{\mathrm{RC}}(E_e,\mu_\chi)\Big)\Big(1+\delta_{\mathrm{recoil}}(E_e)\Big)$$

$\lambda = g_A/g_V$
Extract from Experiment

vector coupling

$\pi^2, 1/\beta$
Enhanced

$\mathcal{O}(\alpha)$
[no logs]

$\mathcal{O}(m_e/m_N)$

Total RC: $1 + \Delta_{\mathrm{TOT}} = 1.07761(27)\,\%$

Total RC from DR: $1 + \Delta_{\mathrm{TOT}} = 1.07735(27)\,\%$

Good agreement within errors!

Nuclear-Structure RC δ_{NS}

History of δ_{NS}: γW-box on nuclei

Jaus, Rasche 1990

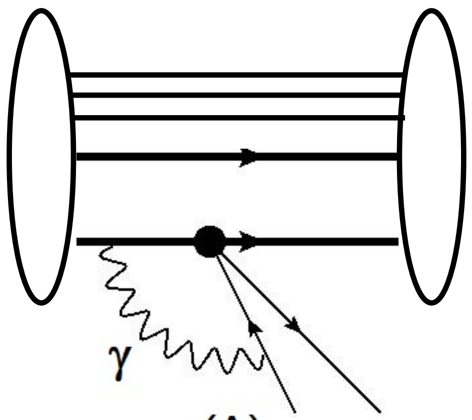
γ and W on same nucleon —> already in Δ_R^V: drop!

Towner 1994

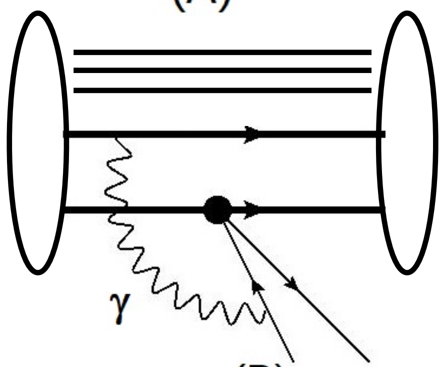
Nucleons are bound — free-nucleon RC modified: δ_{NS}^A

Jaus, Rasche 1990; Hardy, Towner 1992-2020

γ and W on distinct nucleons —> only in nuclei: δ_{NS}^B



(A)



(B)

History of δ_{NS}: γW-box on nuclei

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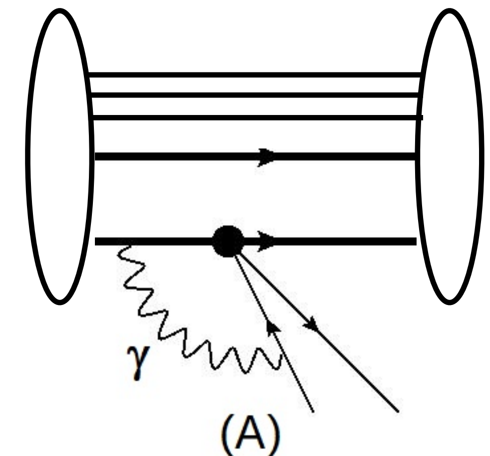
Towner 1994

Nucleons are bound — free-nucleon RC modified: δ_{NS}^A



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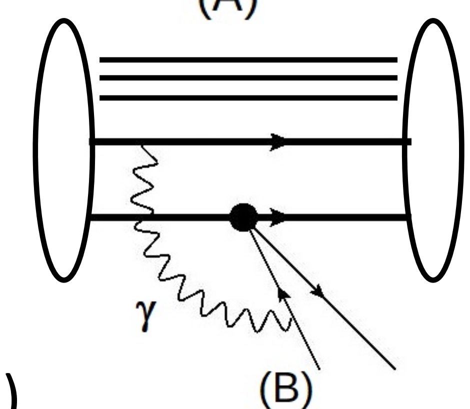

Seng et al. 2018: continuum contribution (quasielastic nucleon knockout)
— can check the δ_{NS}^A calculation explicitly in dispersion theory in Fermi gas model

MG 2019: energy dependence non negligible: $\mathscr{F}t = ft(1 + \delta_{NS}^A + \delta_{NS}^{\text{E-dep}} + \dots)$

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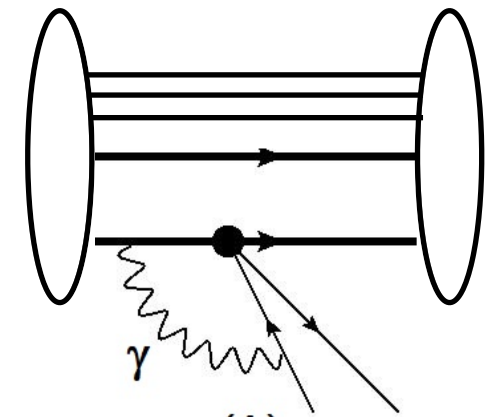

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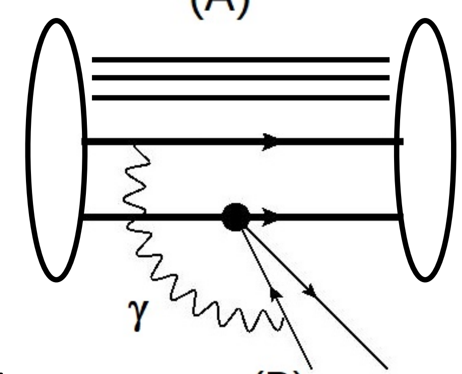

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MG 2019: energy dependence non negligible: $\mathscr{F}t = ft(1 + \delta_{NS}^A + \delta_{NS}^{\mathrm{E-dep}} + \ldots)$

Old estimate: $\delta\mathscr{F}t = -(1.8 \pm 0.4)s \quad + \quad (0 \pm 0)s$

New estimate: $\delta\mathscr{F}t = -(3.5 \pm 1.0)s \quad + \quad (1.6 \pm 0.5)s$

Two effects cancel but introduce 100% uncertainty: $\mathscr{F}t = (3072.1 \pm 0.7)s \rightarrow \mathscr{F}t = (3072 \pm 2)s$

Has to be checked in modern ab-initio nuclear theory

Dispersion theory of δ_{NS} with ab-initio input

Low-momentum part of the loop: account for nucleon d.o.f. only

Ab-initio methods: *A. Ekström et al,* ***2212.11064***

NN interaction from chiral EFT: systematically improvable, self consistent

Solve many-body QM problem with potential derived from χEFT

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First case study: ${}^{10}C \to {}^{10}B$ in No-Core Shell Model (NCSM)

NCSM result for ${}^{10}C \to {}^{10}B$:

$$\delta_{\rm NS} = -\,0.406(39)\,\%$$

M. Gennari et al, **2405.19281**

Compare to Hardy-Towner

$$\delta_{\rm NS} = -\,0.347(35)\,\% \qquad (2014)$$

$$\delta_{\rm NS} = -\,0.400(50)\,\% \qquad (2020)$$

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Second case study: $^{14}O \to {}^{14}N$: EFT + Green's Function Monte Carlo method (GFMC)

GFMC result for: $^{14}O \to {}^{14}N$

$$\delta_{NS}^{(0)} = -\,(1.76+0.11\pm0.88)\cdot 10^{-3}$$

*V. Cirigliano et al, **2405.18469***

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$$\delta_{NS,B} = -\,1.96(50)\cdot 10^{-3}$$

Large error: unknown contact term

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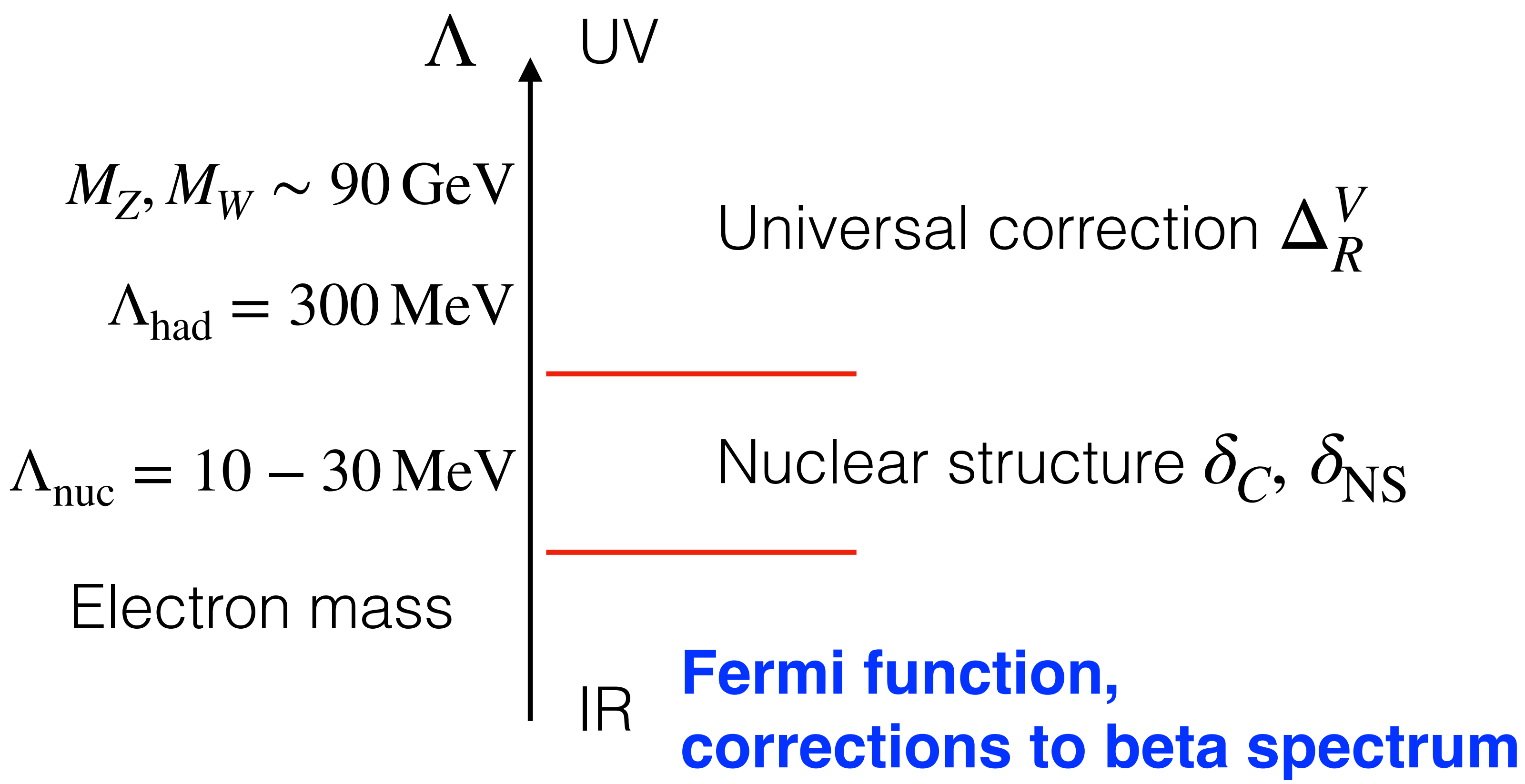
More to come in the near future!



Nuclear Corrections

QED: Corrections to Decay Spectrum

$$f = m_e^{-5} \int_{m_e}^{E_0} dE_e \boxed{|\vec{p}_e| E_e (E_0 - E_e)^2} F(E_e) C(E_e) Q(E_e) R(E_e) r(E_e)$$

Unperturbed beta spectrum

Fermi function: e^+ in Coulomb field of daughter nucleus

Shape factor: spatial distribution of decay

Recoil correction

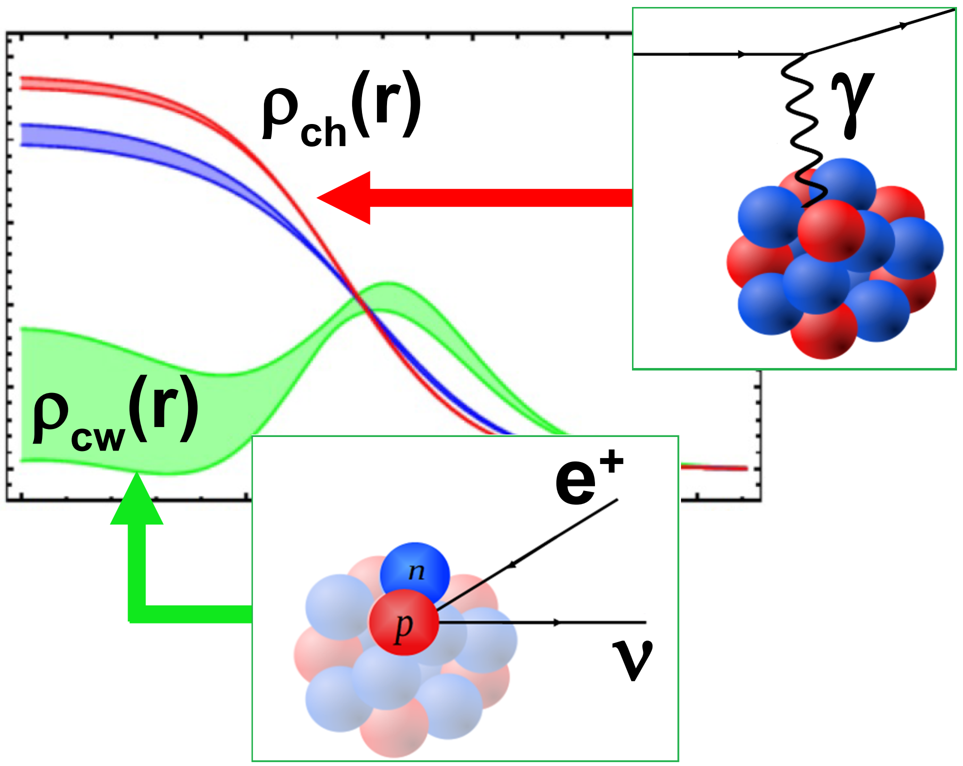
Atomic screening and overlap corrections

Traditionally: assumed that decay probability is equally distributed across the entire nucleus

Recent development:
isospin symmetry + known charge distributions

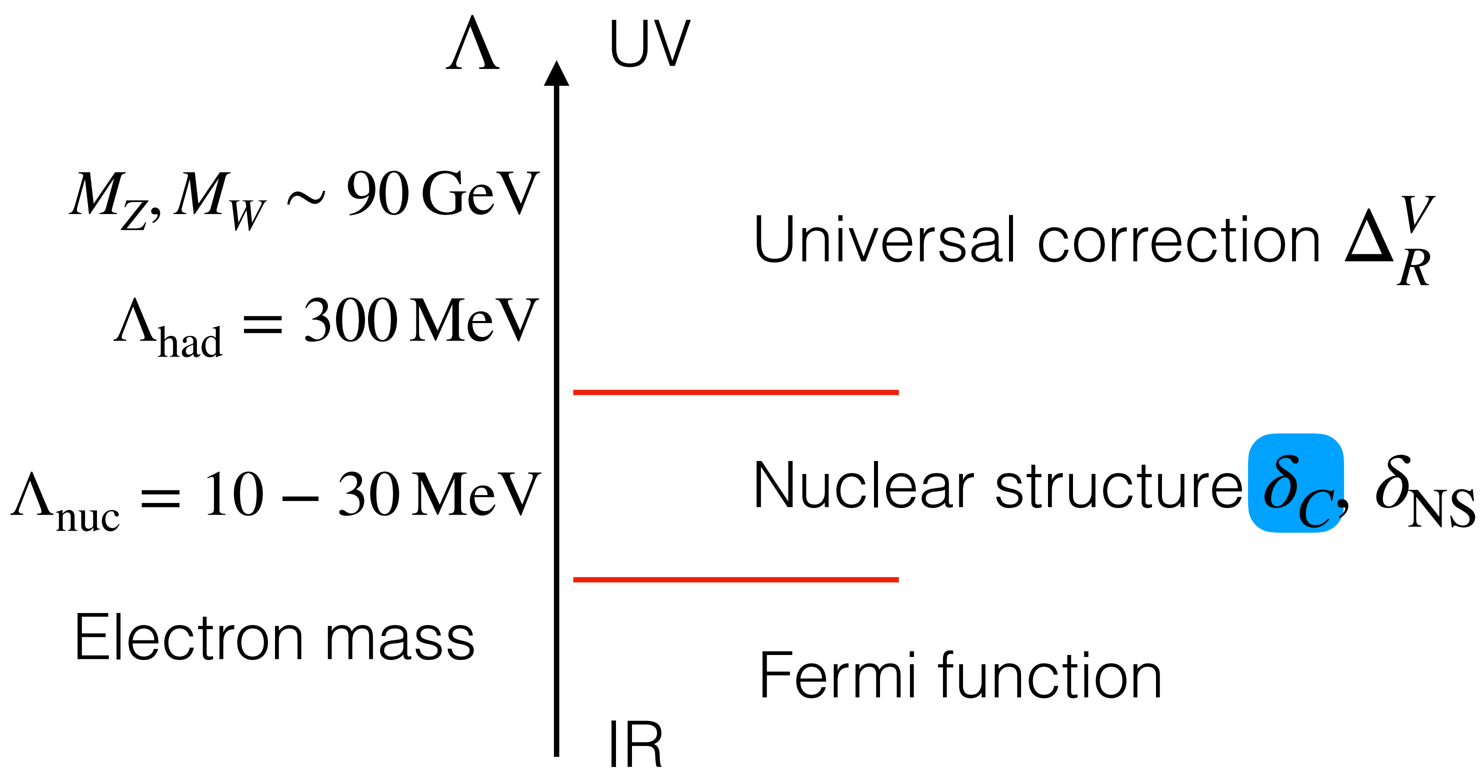
Only the outer protons can decay:
all neutron states in the core occupied

Photon probes the entire nuclear charge



Relative shift in f-values downwards of 0.01-0.1%
Non-negligible given the precision goal 0.01%

Seng, 2212.02681
MG, Seng 2311.16755



Isospin breaking in nuclear WF: δ_C

Tree-level effect — ISB "large"

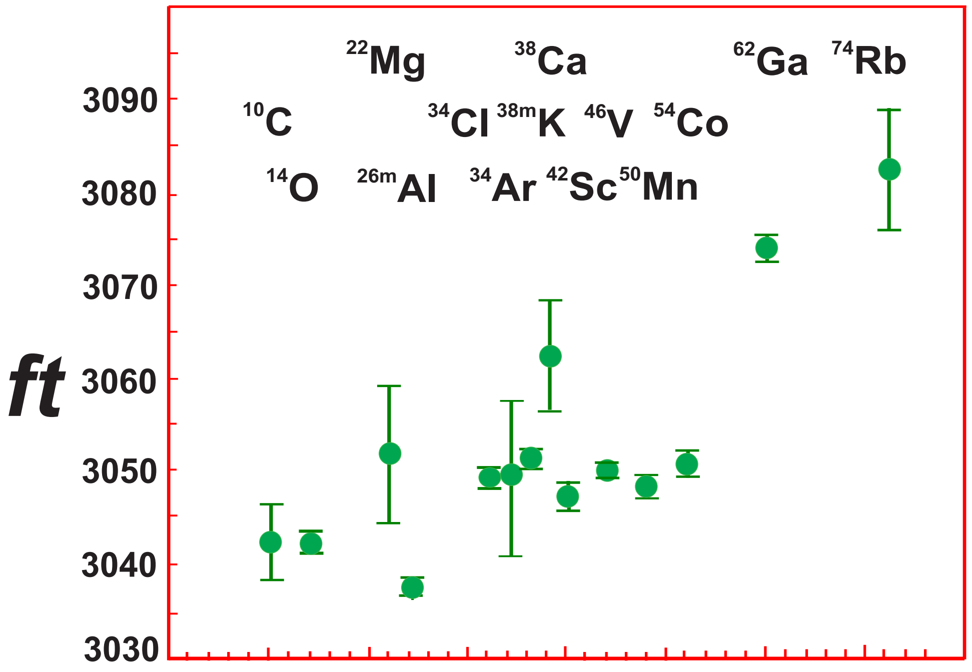
Isospin symmetry breaking in superallowed β-decay

Tree-level Fermi matrix element

$$M_F = \langle f \,|\, \tau^+ \,|\, i \rangle$$

τ^+ — Isospin operator

$|\,i\rangle,\ |\,f\rangle$ — members of T=1 isotriplet



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Tree-level Fermi matrix element

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τ^+ — Isospin operator
$|\, i \rangle, \,|\, f \rangle$ — members of T=1 isotriplet

If isospin symmetry were exact, $M_F \rightarrow M_0 = \sqrt{2}$

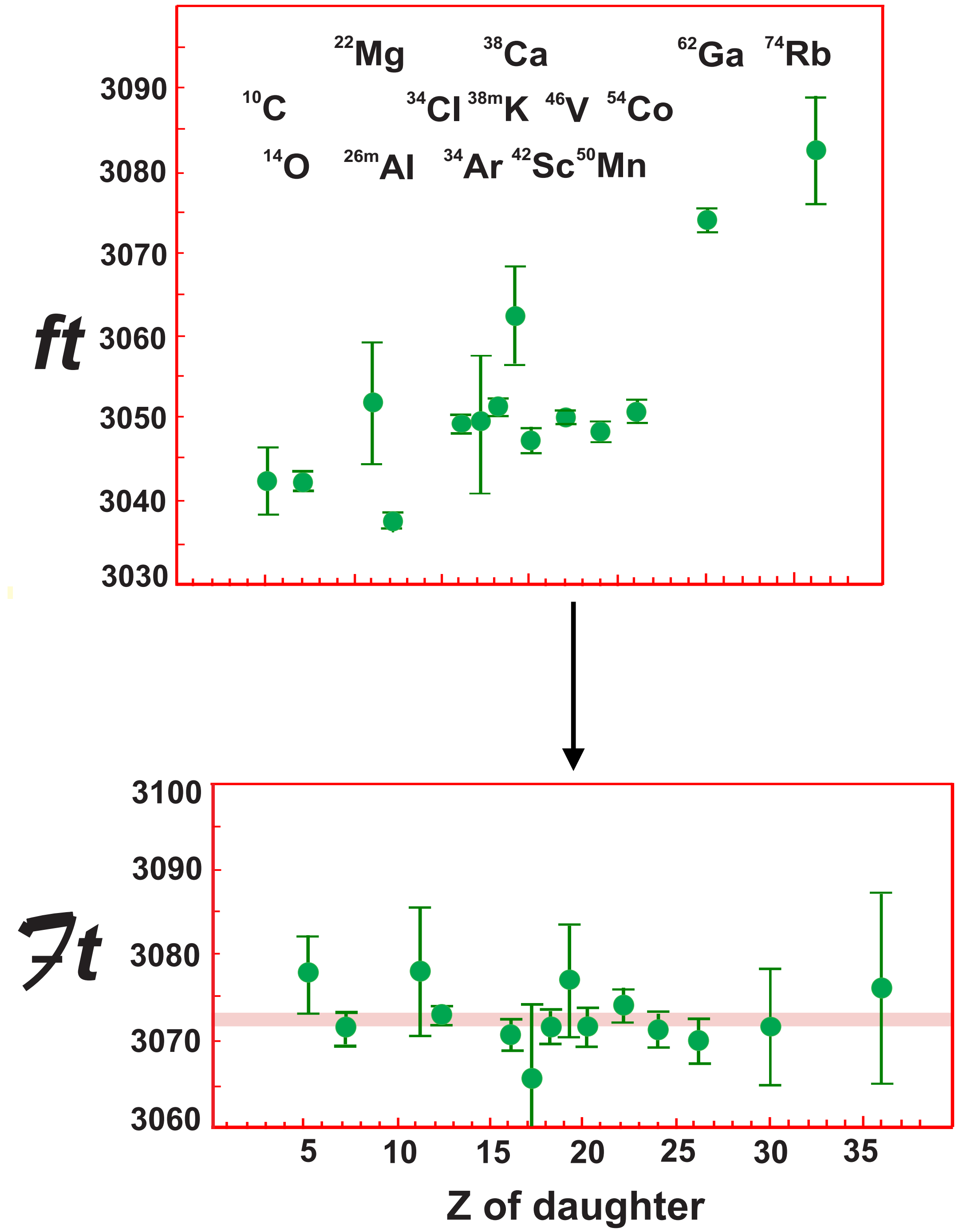
Isospin symmetry is broken in nuclear states
(e.g. Coulomb, nucleon mass difference, …)

In presence of isospin symmetry breaking (ISB):
$|\, M_F \,|^2 = |\, M_0 \,|^2 (1 - \delta_C)$ MacDonald 1958

ISB correction almost singlehandedly aligns ft-values!

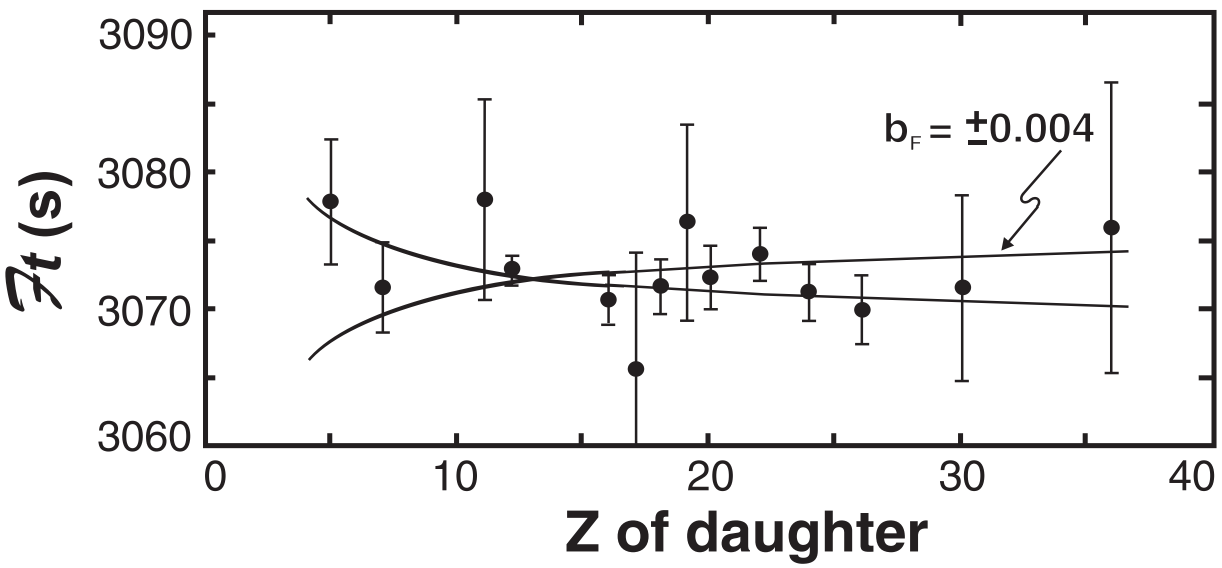
$$\delta_C \sim 0.17\% - 1.6\% \,!$$

Crucial for V_{ud} extraction



J. Hardy, I. Towner, Phys.Rev. C 91 (2014), 025501

BSM searches with superallowed beta decays



Induced scalar CC —> Fierz interference bF

$$\mathcal{F}t^{SM} \to \mathcal{F}t^{SM}\left(1 + b_F \frac{m_e}{\langle E_e \rangle}\right)$$

$b_F = -0.0028(26)$ ~ consistent with 0

Independently of V_{ud} and CKM unitarity: internal consistency of the data base with SM!

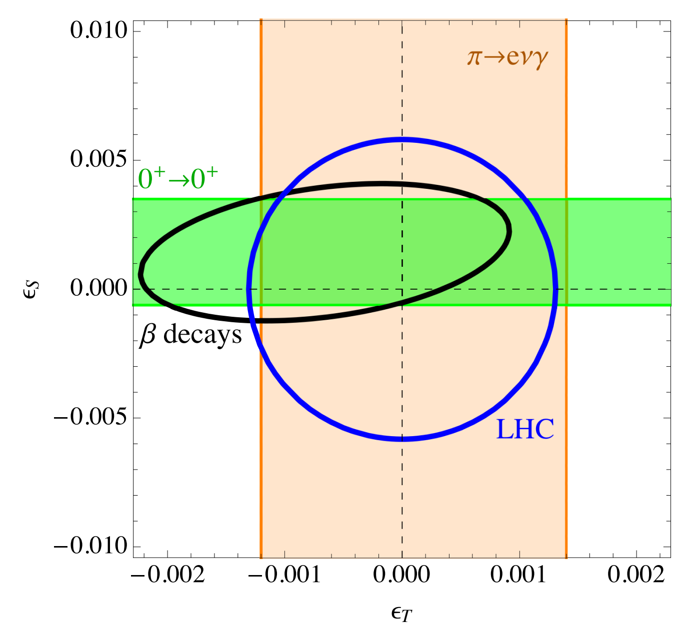
Like $\Delta^{(3)}_{\mathrm{CKM}}$ does not require other experimental inputs to make a statement on (B)SM

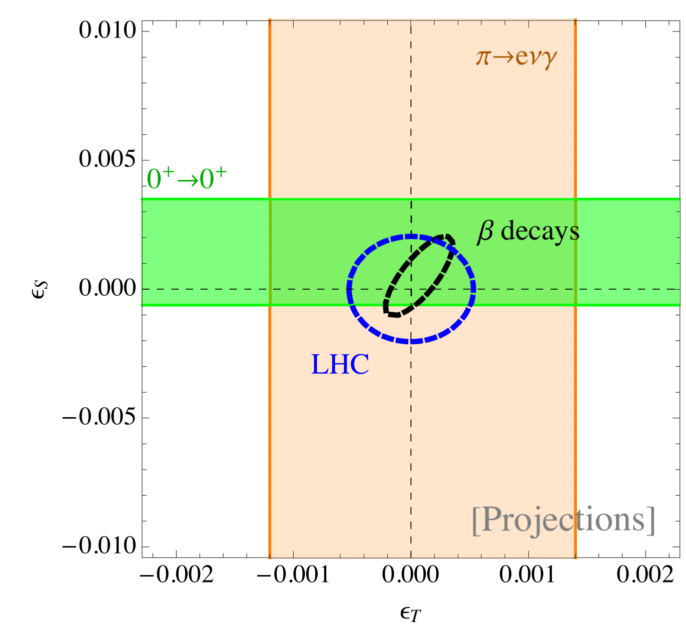
Entangled with nuclear theory uncertainties — a global effort of nuclear theory community needed

S, T interaction flips helicity:
Suppressed at high energy

Beta decay vs. LHC on S,T
Complementarity now and in the future!

Gonzalez-Alonso et al 1803.08732



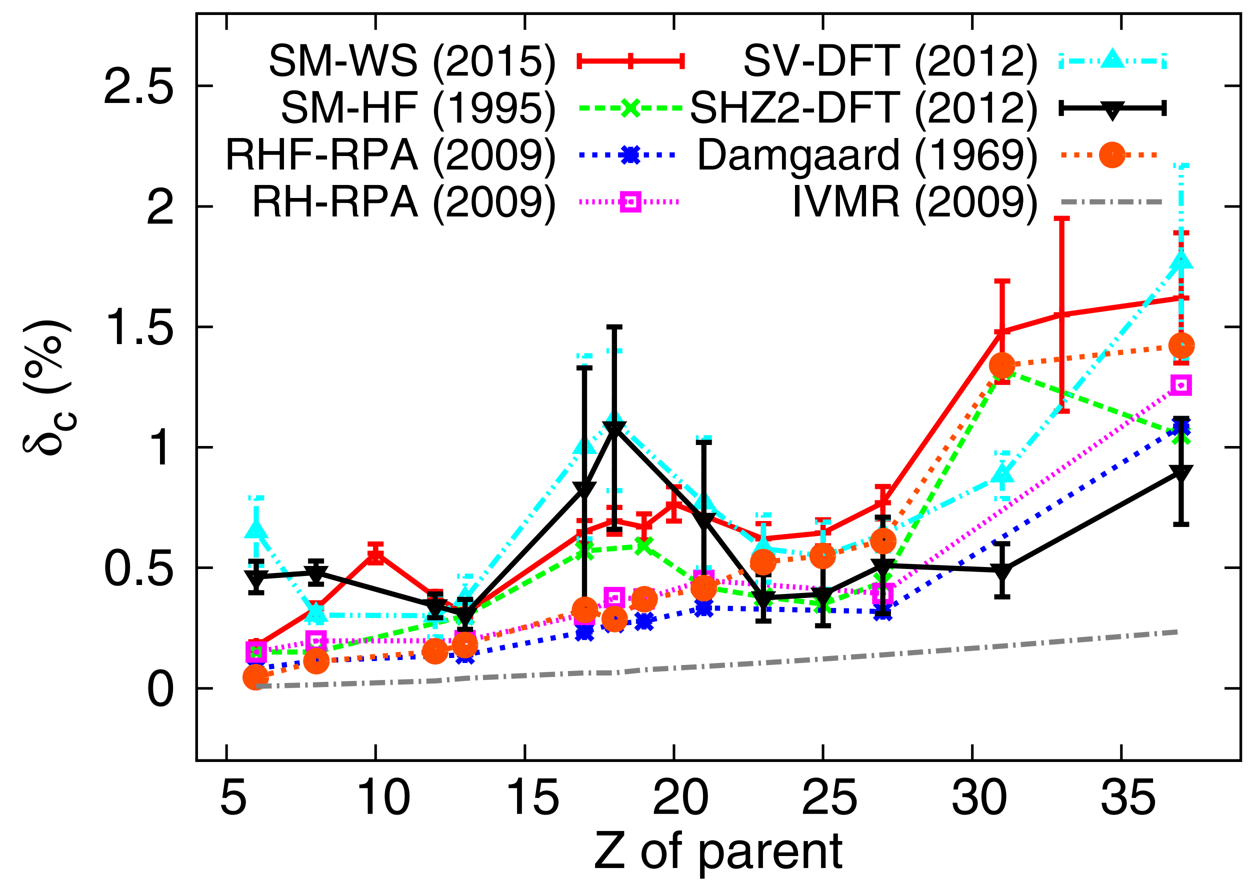


Nuclear model dependence of δ_C

J. Hardy, I. Towner, Phys.Rev. C 91 (2014), 025501

			RPA				
	SM-WS	SM-HF	PKO1	DD-ME2	PC-F1	IVMR[a]	DFT
$T_z = -1$							
^{10}C	0.175	0.225	0.082	0.150	0.109	0.147	0.650
^{14}O	0.330	0.310	0.114	0.197	0.150		0.303
^{22}Mg	0.380	0.260					0.301
^{34}Ar	0.695	0.540	0.268	0.376	0.379		
^{38}Ca	0.765	0.620	0.313	0.441	0.347		
$T_z = 0$							
^{26m}Al	0.310	0.440	0.139	0.198	0.159		0.370
^{34}Cl	0.650	0.695	0.234	0.307	0.316		
^{38m}K	0.670	0.745	0.278	0.371	0.294	0.434	
^{42}Sc	0.665	0.640	0.333	0.448	0.345		0.770
^{46}V	0.620	0.600					0.580
^{50}Mn	0.645	0.610					0.550
^{54}Co	0.770	0.685	0.319	0.393	0.339		0.638
^{62}Ga	1.475	1.205					0.882
^{74}Rb	1.615	1.405	1.088	1.258	0.668		1.770
χ^2/ν	1.4	6.4	4.9	3.7	6.1		4.3[b]

L. Xayavong, N.A. Smirnova, Phys.Rev. C 97 (2018), 024324



HT: χ^2 as criterion to prefer SM-WS; V_{ud} and limits on BSM strongly depend on nuclear model

Nuclear community embarked on ab-initio δ_C calculations (NCSM, GFMC, CC, IMSRG)
Especially interesting for light nuclei accessible to different techniques!

Data-Driven δ_C from nuclear radii

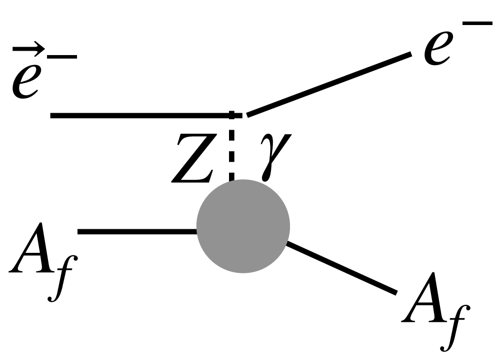
ISB-sensitive combinations of radii can be constructed **Seng, MG 2208.03037; 2304.03800; 2212.02681**

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2$$

$\Delta M_B^{(1)} = 0$ used for ft-value in isospin limit

$$\Delta M_A^{(1)} \equiv -\langle r_{\mathrm{CW}}^2\rangle + \left(\frac{N_1}{2}\langle r_{n,1}^2\rangle - \frac{Z_1}{2}\langle r_{p,1}^2\rangle\right)$$

Neutron radius: measurable with PV e$^-$ scattering!



$$A^{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\frac{Q_W}{Z}\frac{F_{NW}(Q^2)}{F_{Ch}(Q^2)}$$

$$R_{\mathrm{NW}} \approx R_n$$

Z-boson couples to neutrons, photon - to protons;
PV asymmetry at low Q^2 sensitive to the difference $\langle r_{n,1}^2\rangle - \langle r_{p,1}^2\rangle$ - neutron skin
Extensive studies in neutron rich nuclei (PREX, CREX) —> input to physics of neutron stars

Upcoming exp. program at Mainz (MREX)
Neutron skins of stable daughters (e.g. Mg-26, Ca-42, Fe-54)
PV asymmetry on C-12 for a sub-% measurement of R_n **N. Cargioli, MG et al, 2407.09743**
Unexpected connections via neutron skins:
ISB for precision tests vs. EoS of neutron-rich matter

Summary & Outlook

Cabibbo Angle Anomaly at 2-3σ

Future experiments:

Neutron: UCNτ, τSPECT ($\delta\tau_n:\ 0.4 \to 0.1s$); PERC, Nab ($\delta g_A : 4 \to 1 \times 10^{-4}$)

Competitive! But: resolve existing discrepancies (e.g. “beam-bottle” lifetime)

Kaon decays: NA62, BELLE II $K\ell 3$ vs $K\mu 2$ (+ Lattice effort!)

Pion: $\pi^+ \to \pi^0 e^+ \nu$ PIONEER @ PSI (δBR: 0.3%—>0.03%) but 2033+

Nuclear uncertainties under scrutiny: δ_{NS} in ab-initio and EFT

δ_C & δ_{NS} for 15 decays from ^{10}C to ^{74}Rb — Community effort required!

Nuclear charge radii across superallowed isotriplets

Stable: μ-atoms @ PSI, radii of unstable nuclei @ ISOLDE, TRIUMF

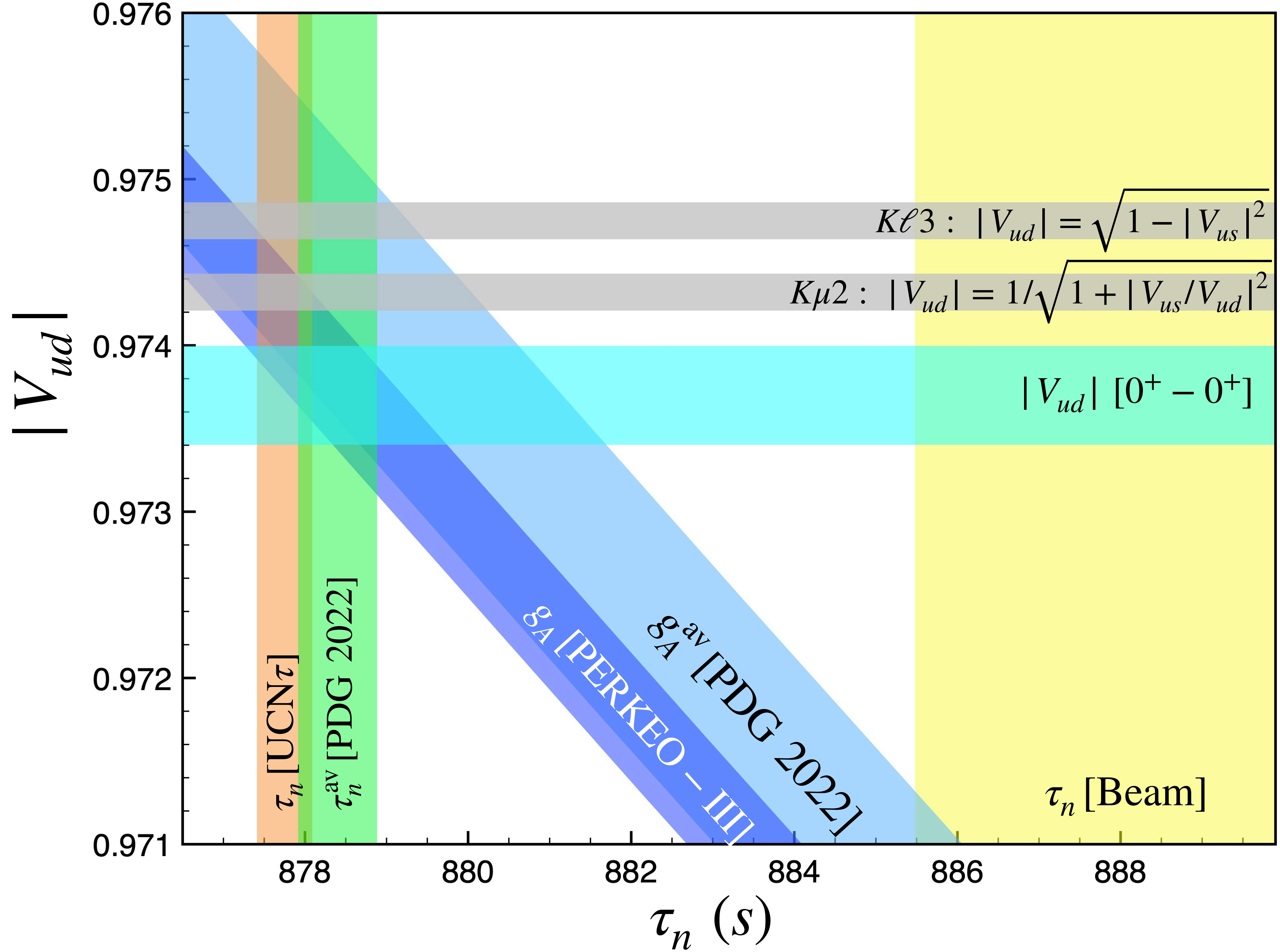
Neutron skins of stable daughters with PVES @ MESA

Interplay with the nuclear EoS program: neutron skin via symmetry energy vs. ISB

BSM: Cabibbo anomaly(ies) and superallowed dataset consistency

Backup

Status of Cabibbo Unitarity

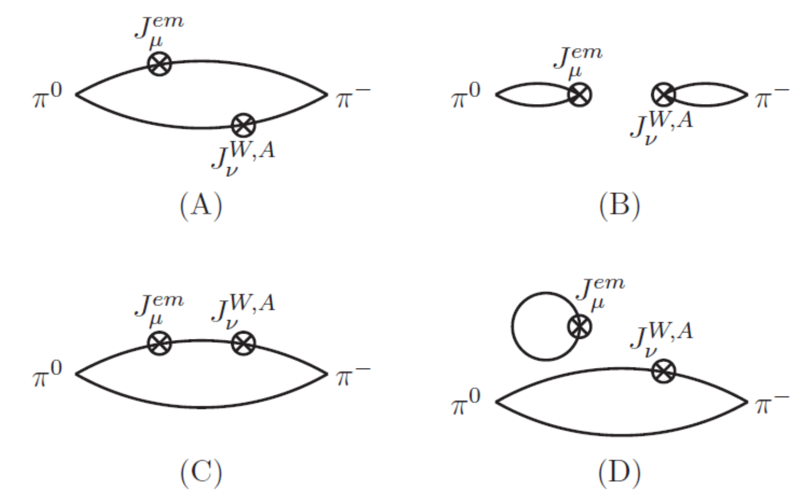


γW-box from DR + Lattice QCD input

Currently available neutrino data at low Q^2 - low quality;
Look for alternative input — compute Nachtmann moment $M_3^{(0)}$ on the lattice

First direct LQCD computation $\pi^- \to \pi^0 e^- \nu_e$

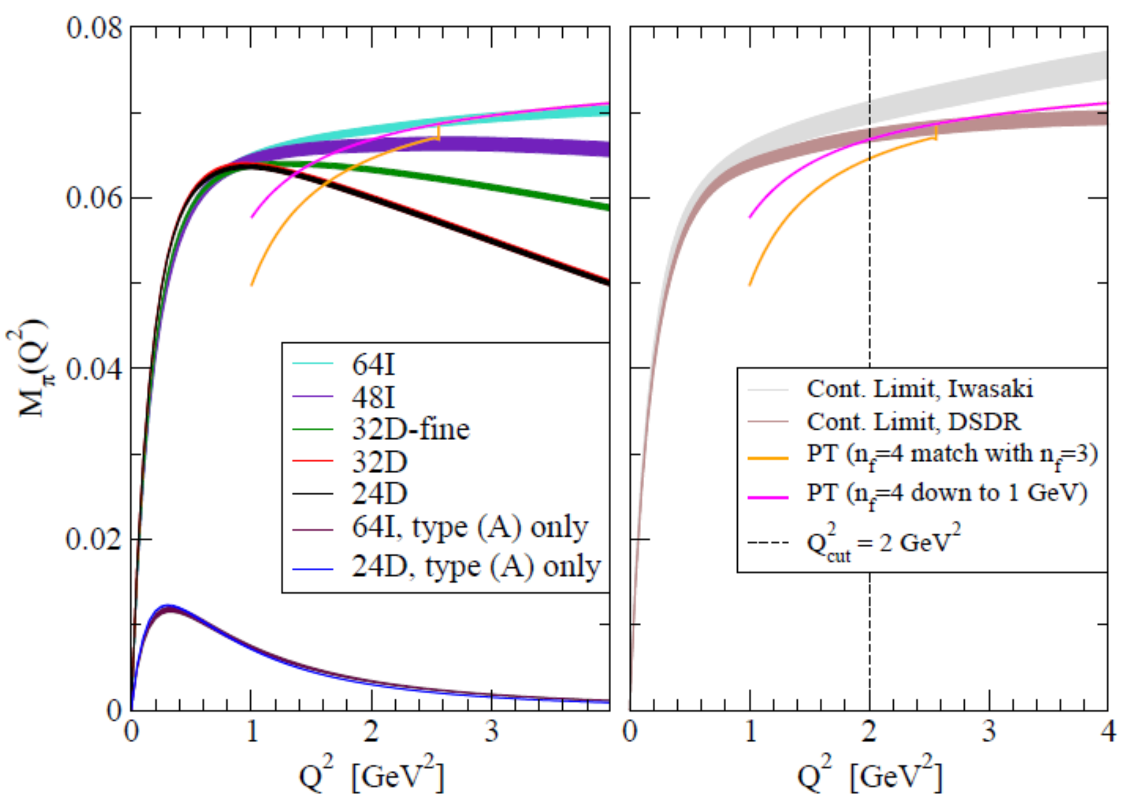
Feng, MG, Jin, Ma, Seng 2003.09798



Quark contraction diagrams

5 LQCD gauge ensembles at physical pion mass
Generated by RBC and UKQCD collaborations
w. 2+1 flavor domain wall fermion

Match onto pQCD at $Q^2 \sim 2\,\mathrm{GeV}^2$



(before cont. extrapolation) (after cont. extrapolation)

$$\Box_{\gamma W}^{VA,\pi} = 2.830(11)_{\rm stat}(26)_{\rm sys}$$

Independent calculation by Los Alamos group

Yoo et all, 2305.03198

$$\Box_{\gamma W}^{VA,\pi} = 2.810(26)_{\rm stat+sys}$$

First lattice QCD calculation of γW-box

Direct impact for pion decay $\pi^+ \to \pi^0 e^+ \nu_e$

$$|V_{ud}|^2 = \frac{0.9799}{(1+\delta)} \frac{\Gamma_{\pi\ell 3}}{0.3988(23)\,\mathrm{s}^{-1}}$$

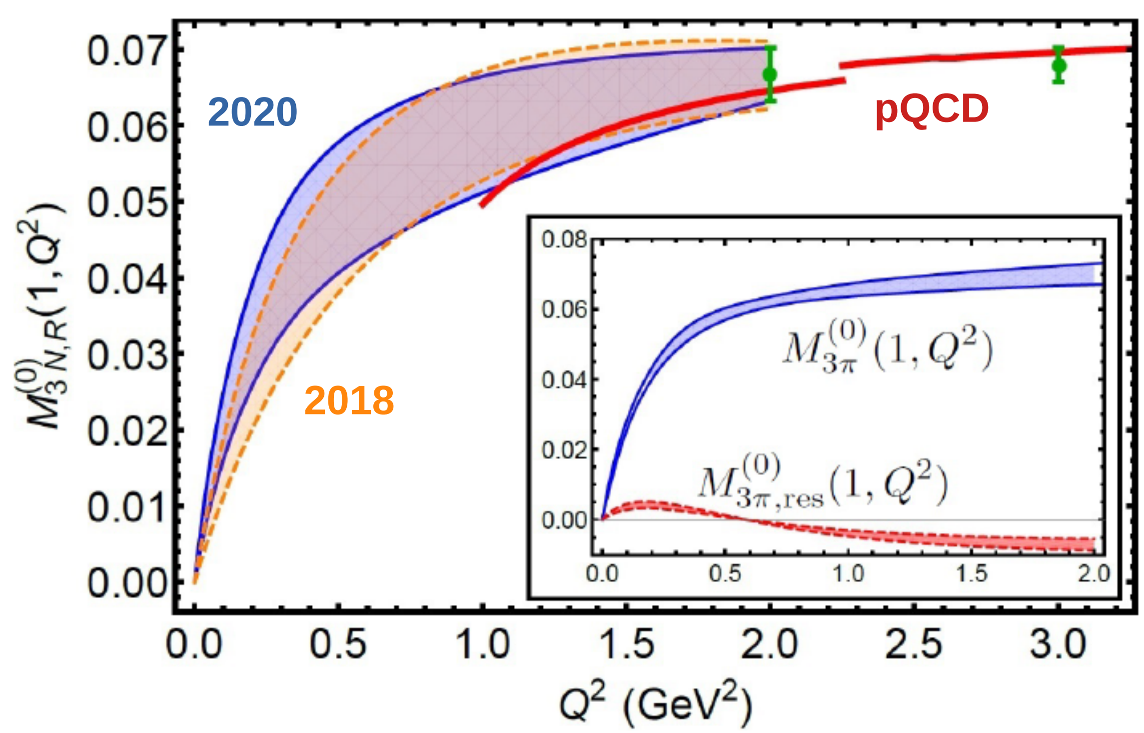
Previous calculation of δ — in ChPT

Cirigliano, Knecht, Neufeld and Pichl, EPJC 2003

Significant reduction of the uncertainty!

$$\delta: \quad 0.0334(10)_{\mathrm{LEC}}(3)_{\mathrm{HO}} \to 0.0332(1)_{\gamma W}(3)_{\mathrm{HO}}$$

Indirectly constrains the free neutron γW-box
— requires some phenomenology
Based on Regge universality & factorization



Independent confirmation

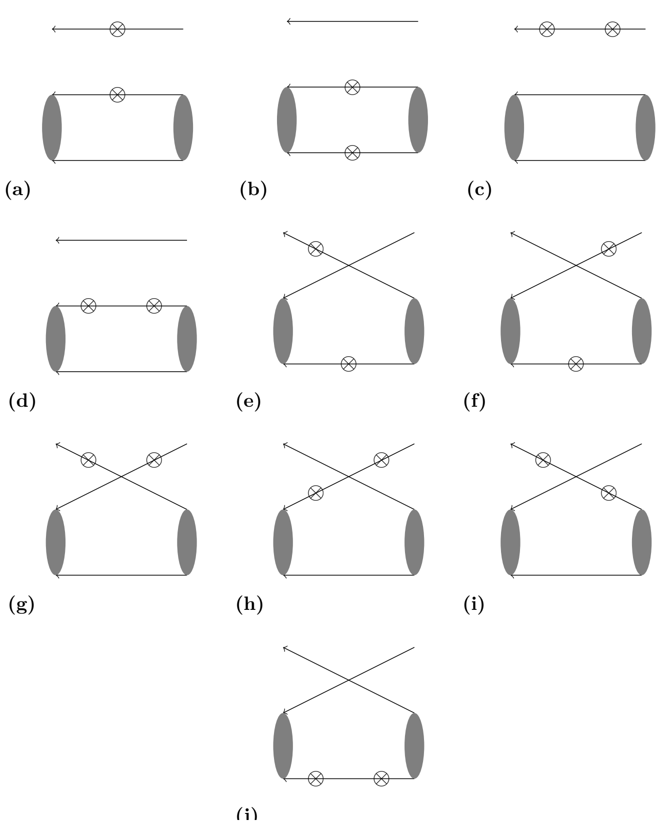
$$\Delta_R^V = 0.02467(22)_{\mathrm{DR}} \to 0.02477(24)_{\mathrm{LQCD+DR}}$$

Seng, MG, Feng, Jin, 2003.11264

First LQCD calculation of γW-box on the neutron

Much more challenging than pion:

Numerically heavier
Excited state contamination requires longer time
Large contribution from low Q $\sim g_A \mu^V$ absent for pion

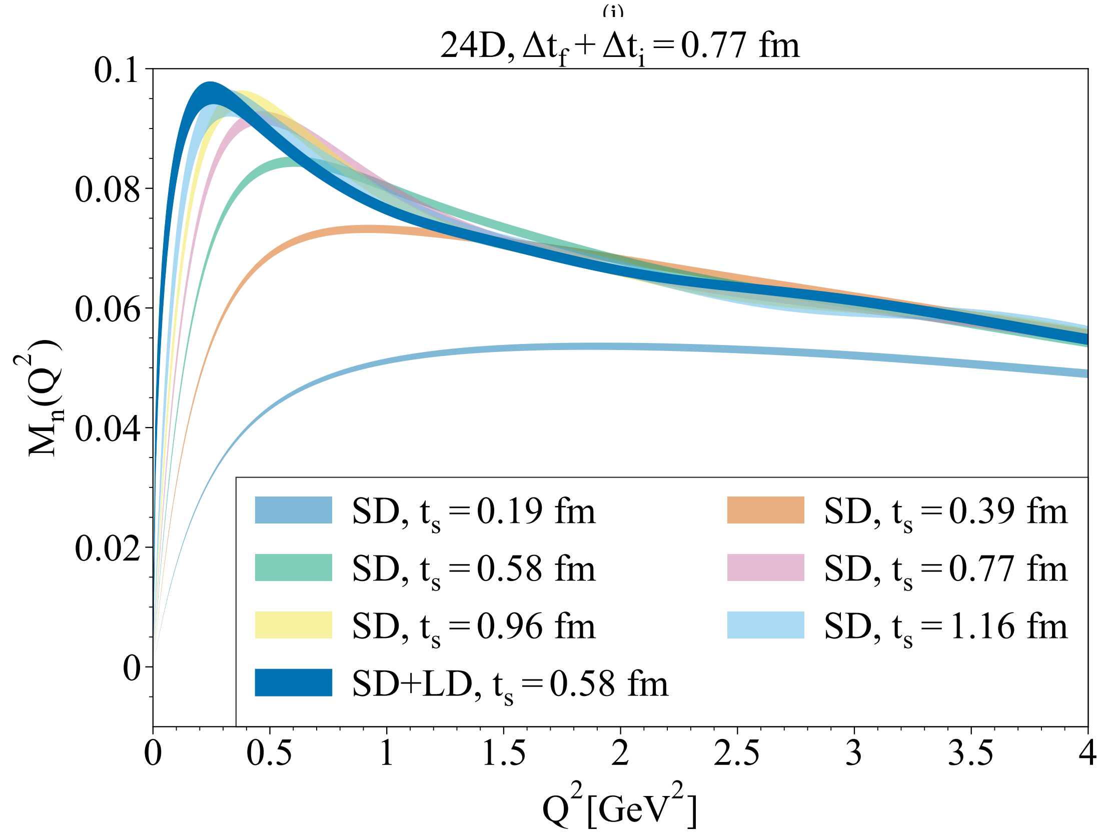


Split into long/short distance separated by t_s

$$M_n(Q^2) = M_n^{\mathrm{SD}}(Q^2, t_s) + M_n^{\mathrm{LD}}(Q^2, t_s, t_g)$$

RBC/UKQCD 2+1 domain wall fermion

Ensemble	m_π [MeV]	L	T	a^{-1} [GeV]	N_{conf}
24D	142.6(3)	24	64	1.023(2)	207
32D-fine	143.6(9)	32	64	1.378(5)	69

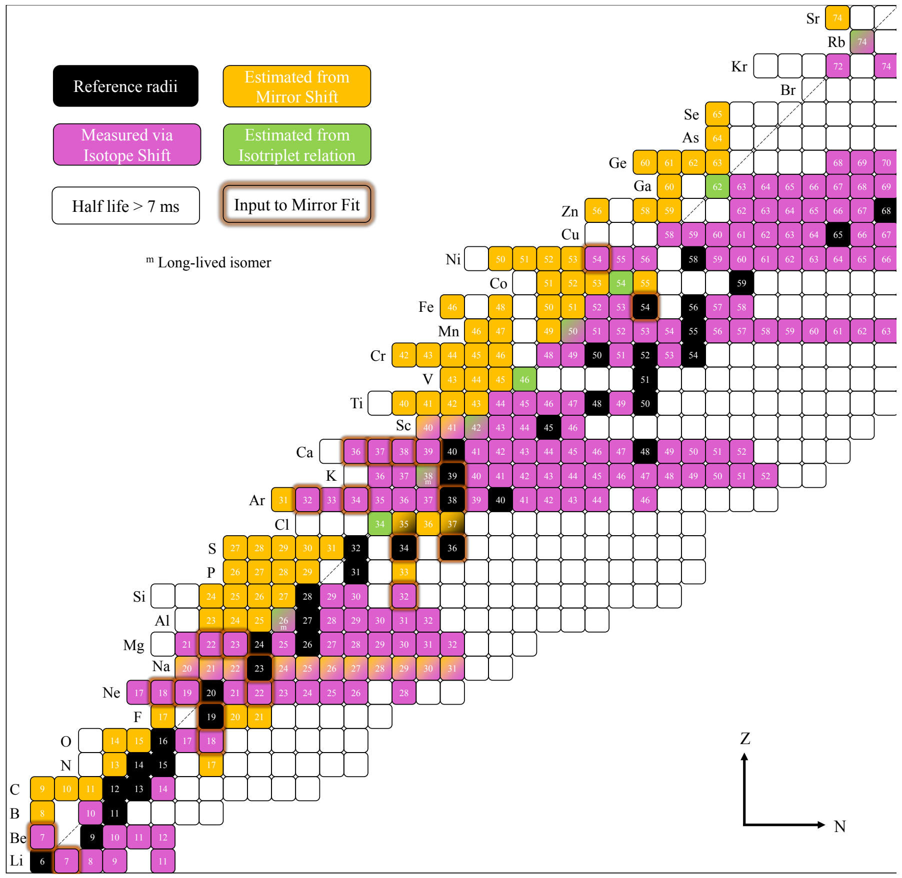


$$\Delta_R^V = 0.02439(19)_{\mathrm{LQCD}} \text{ vs } 0.02467(22)_{\mathrm{DR}}$$

The result slightly lower than DR;
Finer lattice calculations underway

Ma, Feng, MG et al 2308.16755

Global fit to charge radii off mirror nuclei



B. Ohayon, 2409.08193

Experimental input:

reference radii from muonic atoms;
measured isotope shifts

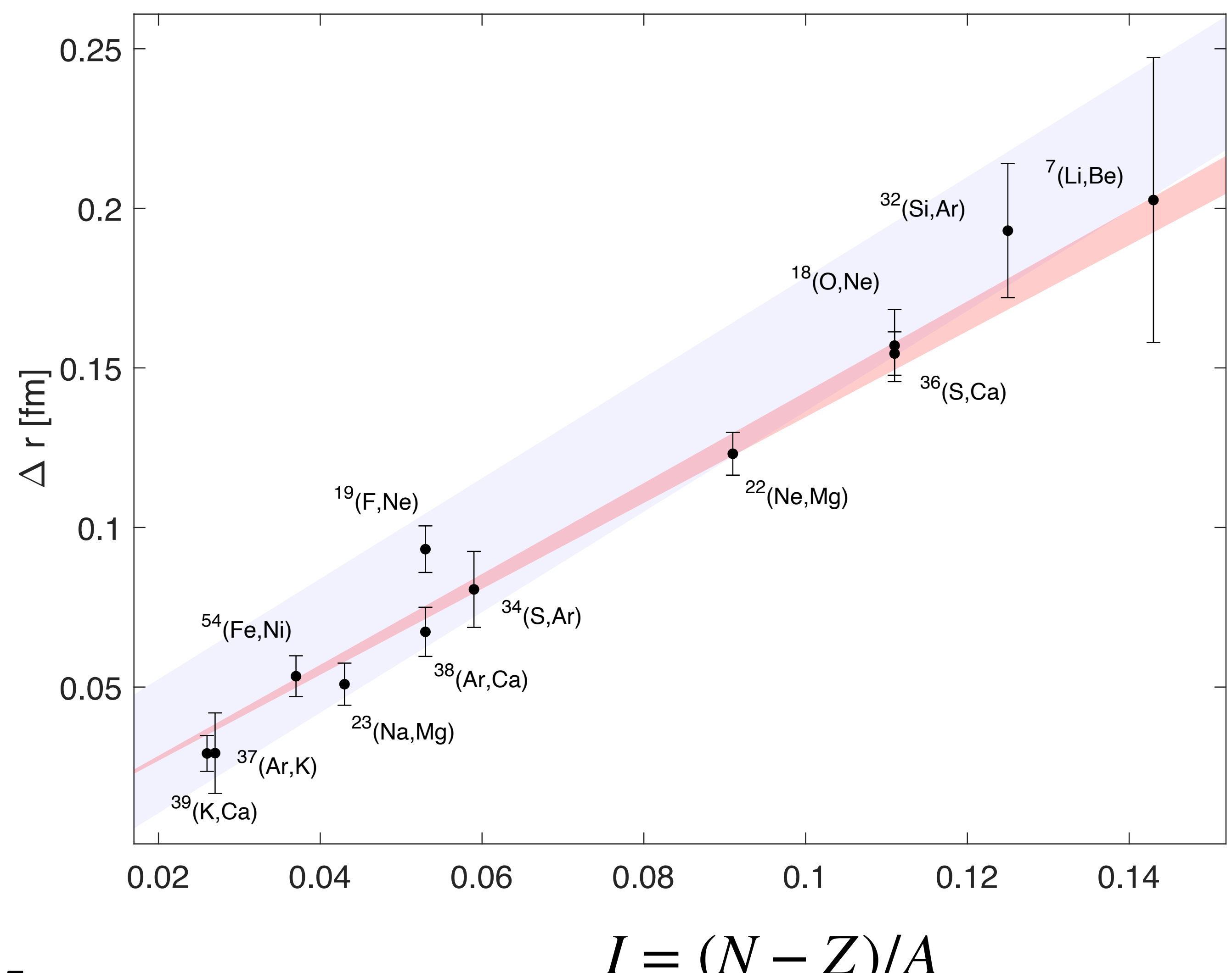
$$\boxed{\Delta_I = r_{N,Z}(I) - r_{Z,N}(I) = 1.382(34) \times I \text{ fm}}$$

$$I = (N-Z)/A$$

Linear fit to known radii in isotriplets (red)
predictions for unknown radii

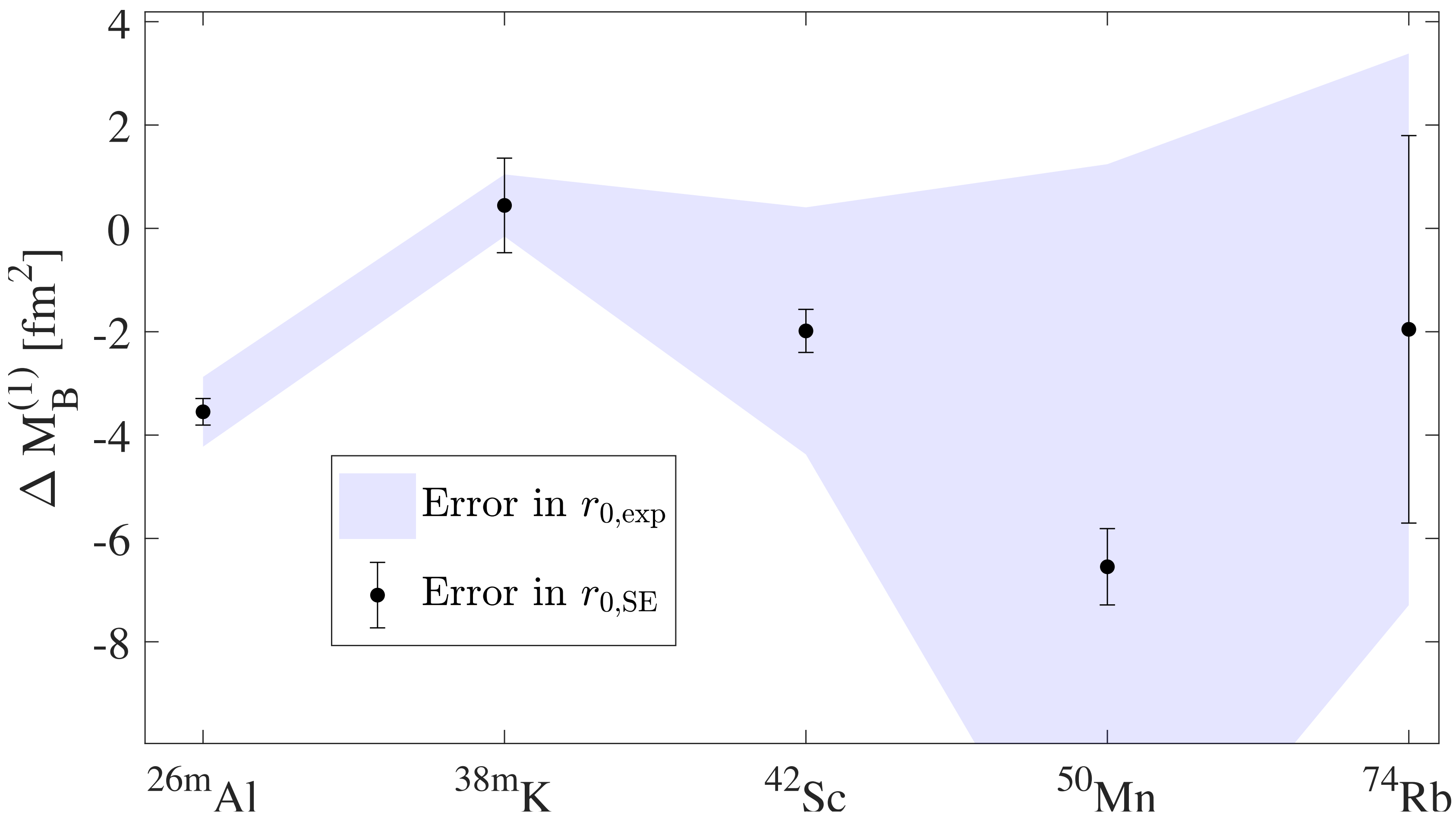
Compare to ab-initio theory estimate (blue)

Navario et al, Phys.Rev.Lett 130



Global fit to charge radii off mirror nuclei

B. Ohayon, 2409.08193



δ_{NS} in ab-initio nuclear theory

M. Gennari, M. Drissi, MG, P. Navratil, C.-Y. Seng, arXiv: **2405.19281**

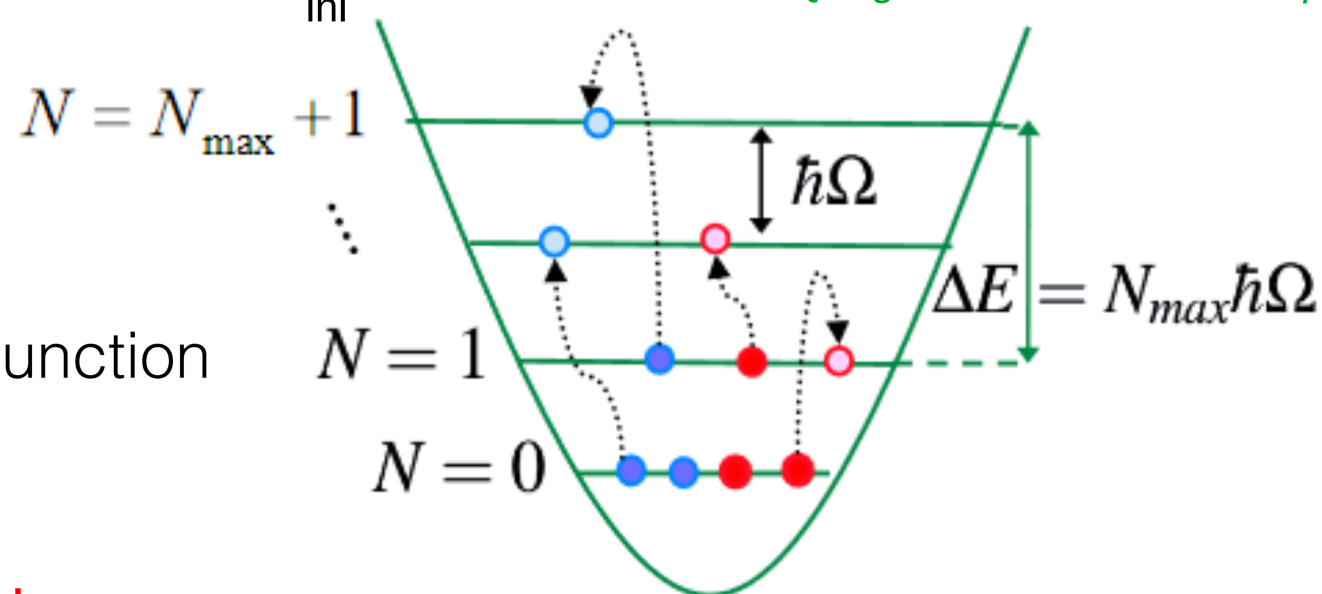
Low-momentum part of the loop: account for nucleon d.o.f. only

First case study: ${}^{10}C \to {}^{10}B$ in No-Core Shell Model (NCSM)

Many-body problem in HO basis with separation Ω and up to $N = N_{max} + N_{Pauli}$

- Nuclear interactions from Chiral EFT:
  - NN-N^{4}LO+3N$_{lnl}$
  - NN-N^{4}LO+3N*$_{lnl}$

Entem, Machleidt and Nosyk, 2017 PRC;
Gysbers et al., 2019 Nature;
Kravvaris, Navrátil, Quaglioni, Hebborn and Hupin, 2023 PLB



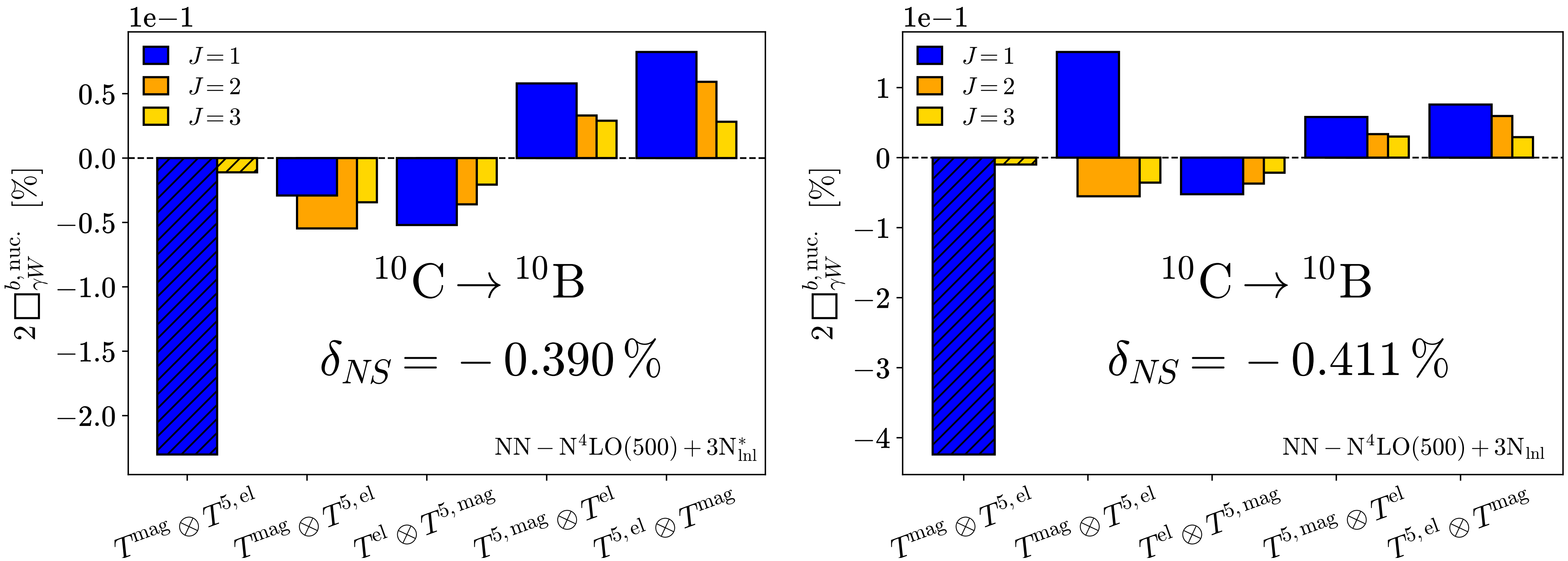
Evaluate the m.e. of nuclear Green's function

$$G(z) \equiv \frac{1}{z - H_0}$$

Difficulty:
Inverting a
large matrix!

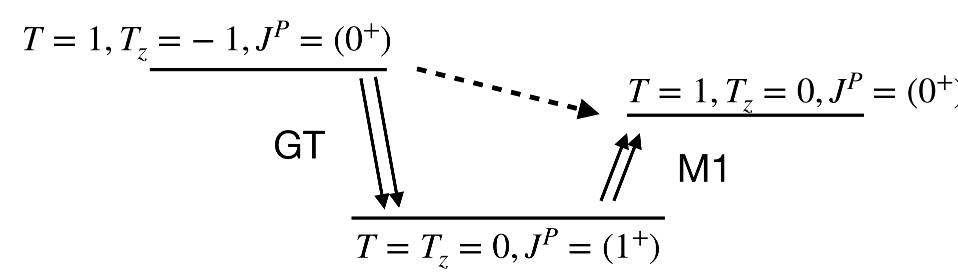
Lanczos continuous fraction method

Ab-initio δ_{NS}: numerical results

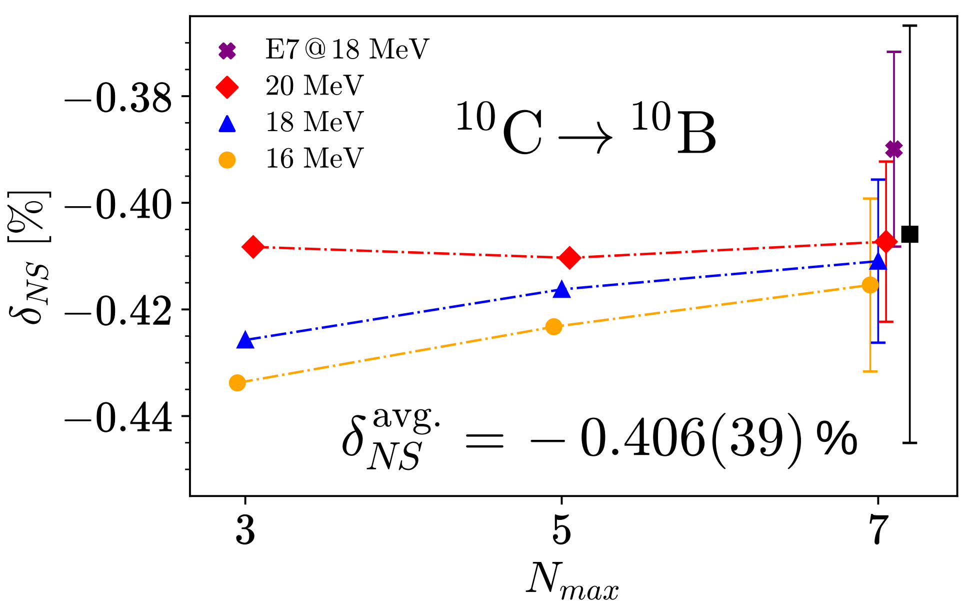


Large negative contribution: low-lying 1^+ level in ^{10}B

Large GT and M1 rates favor a two-step process



Check **Ω-independence** and **convergence w.r.t. N_{max}**



Final result for $^{10}C \to {}^{10}B$:

$$\delta_{\mathrm{NS}} = -0.406(39)\,\%$$

arXiv: **2405.19281**

Compare to Hardy-Towner (old-fashion SM)

$$\delta_{\mathrm{NS}} = -0.347(35)\,\% \qquad (2014)$$
$$\delta_{\mathrm{NS}} = -0.400(50)\,\% \qquad (2020)$$

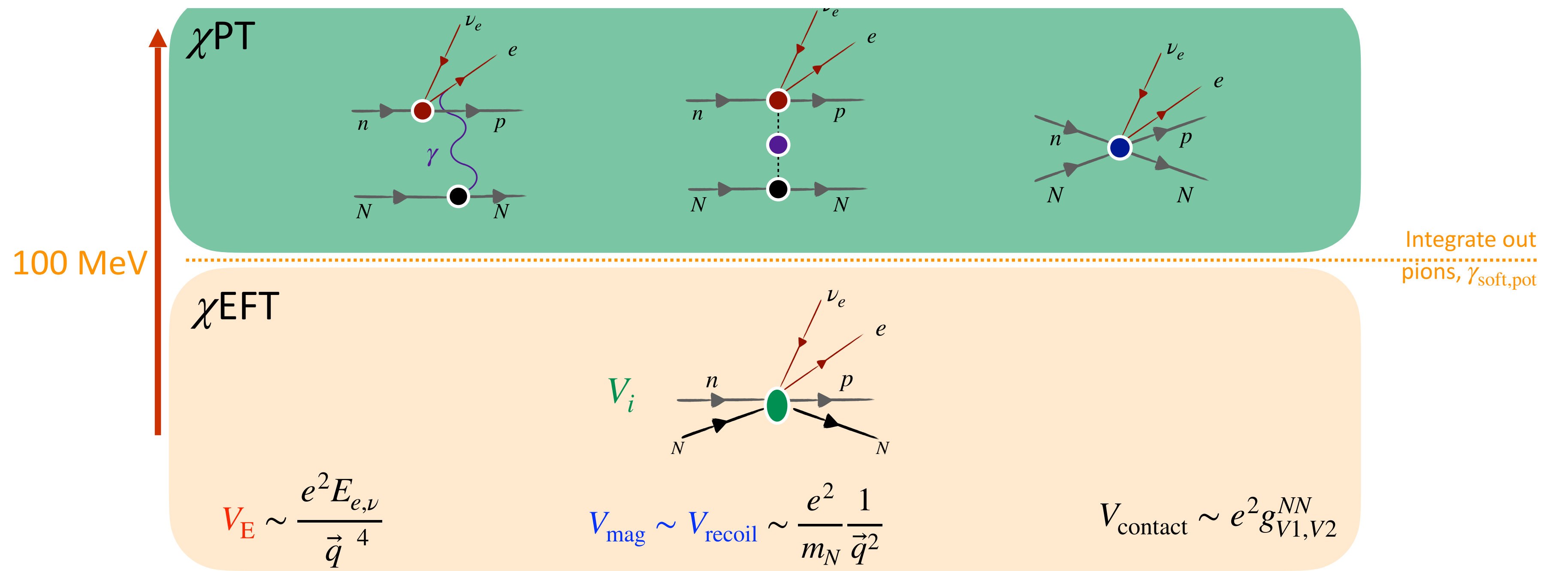
Ab-initio δ_{NS} in EFT: $^{14}O \to {}^{14}N$ with Variational Monte Carlo

V. Cirigliano et al, arXiv: **2405.18469**

$$\delta_{NS}^{(0)} = -(1.76 + 0.11 \pm 0.88) \cdot 10^{-3}$$

Uncertainty:
assuming unknown
counter term to be of
"natural size"

$$g_{V1,V2}^{NN} = 1/(4 m_N F_\pi^2)$$



Compare to Hardy-Towner 2020: $\delta_{NS,B} = -1.96(50) \cdot 10^{-3}$

Promising avenue: all logs under control and are consistent
Downside: EFT non-renormalizable —> unknown counter terms external to the theory
Need extra input (dispersion theory; explicit modeling; fit to data)