Nuclear physics for the precise extraction of Vud

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Outline

1. **Precision frontier and the CKM unitarity**
2. **V_{ud} from beta decays**
3. **Inputs at tree-level**
   - Weak decay form factors
   - Isospin-breaking correction
4. **Inputs at loop-level**
   - Nucleus-independent radiative corrections
   - Nucleus-dependent radiative corrections
5. **Summary and outlook**

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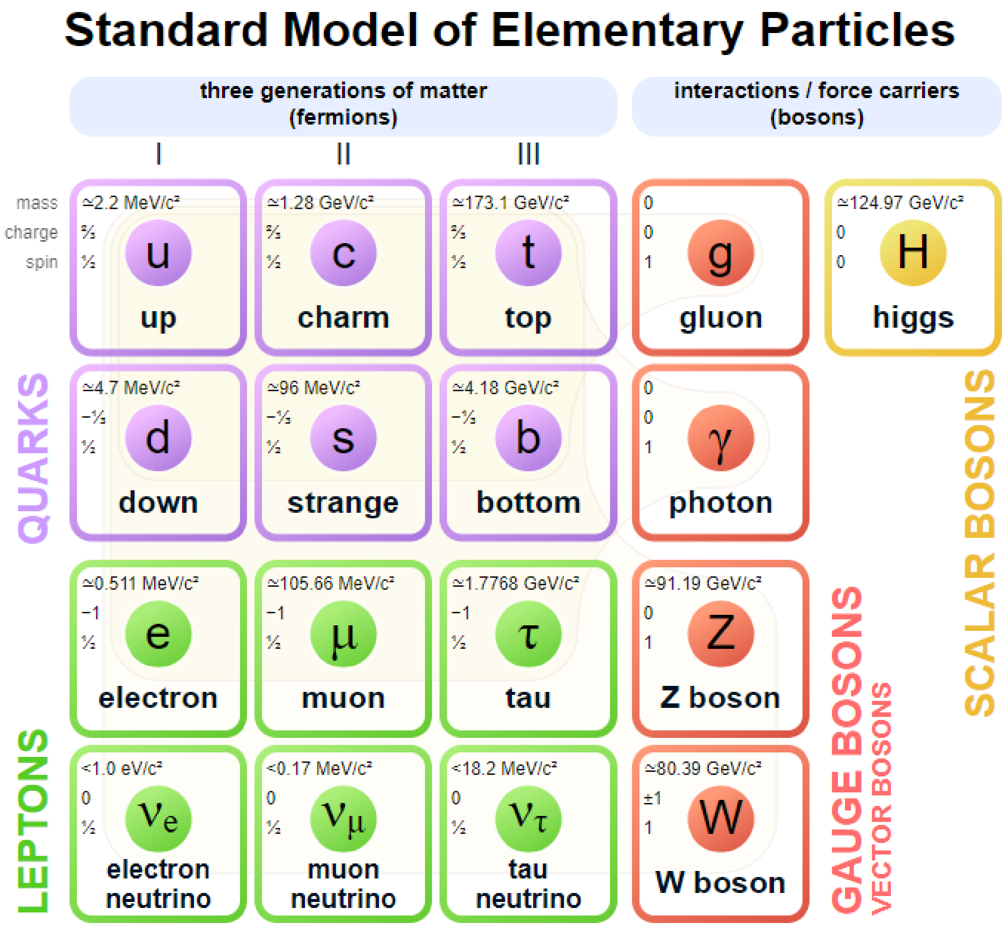
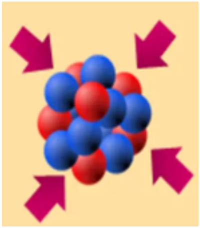
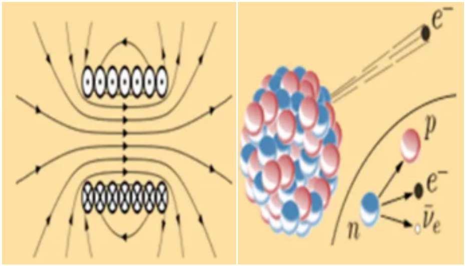


Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)		
	I	II	III			
mass charge spin	≃2.2 MeV/c^2 ⅔ ½ u **up**	≃1.28 GeV/c^2 ⅔ ½ c **charm**	≃173.1 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≃124.97 GeV/c^2 0 0 H **higgs**	
QUARKS	≃4.7 MeV/c^2 −⅓ ½ d **down**	≃96 MeV/c^2 −⅓ ½ s **strange**	≃4.18 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**		**SCALAR BOSONS**
	≃0.511 MeV/c^2 −1 ½ e **electron**	≃105.66 MeV/c^2 −1 ½ μ **muon**	≃1.7768 GeV/c^2 −1 ½ τ **tau**	≃91.19 GeV/c^2 0 1 Z **Z boson**	**GAUGE BOSONS** **VECTOR BOSONS**	
LEPTONS	<1.0 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c^2 0 ½ ν_τ **tau neutrino**	≃80.39 GeV/c^2 ±1 1 W **W boson**		

Image credit: Wikipedia





$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$

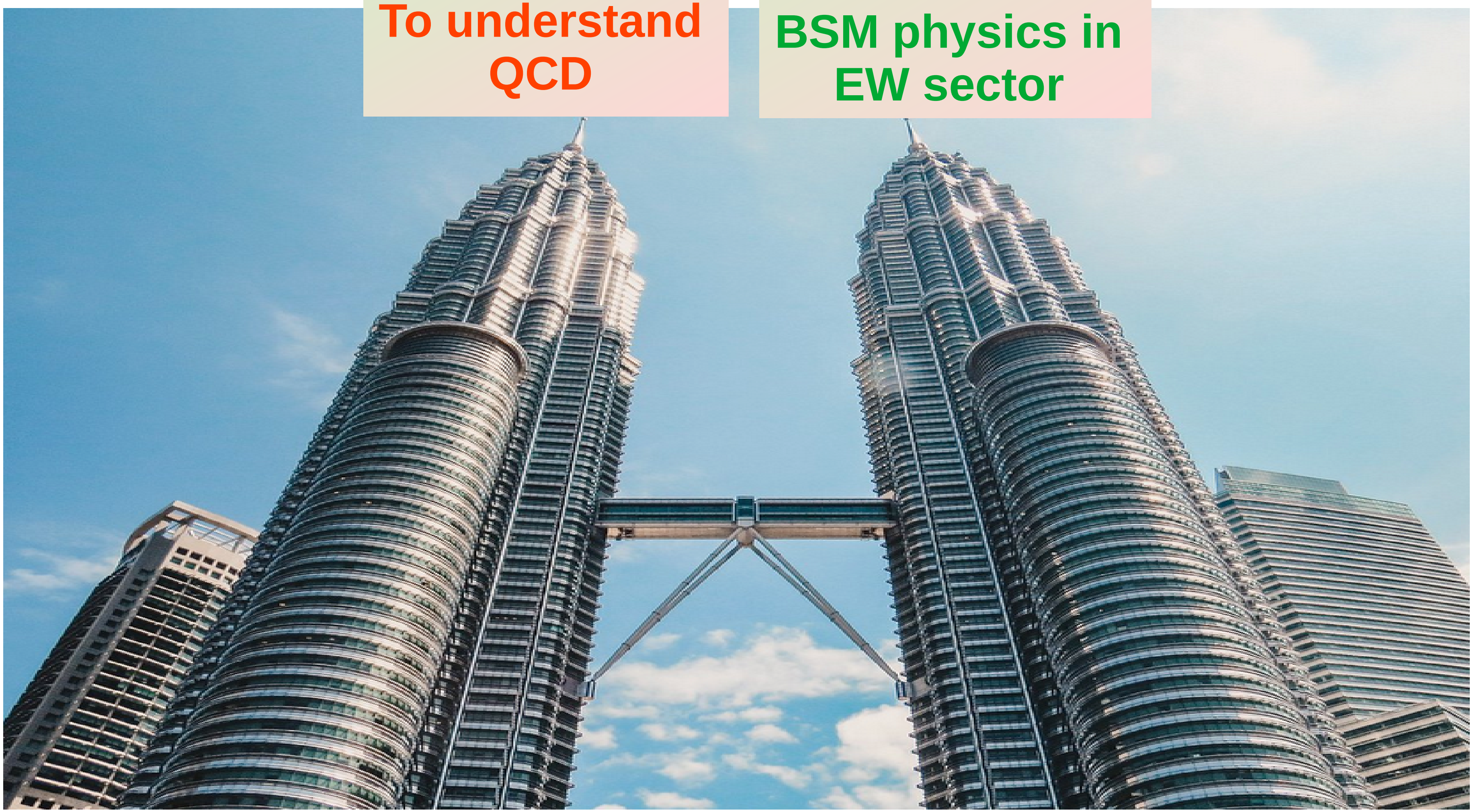
Strong (QCD)

Electroweak

Two Ultimate Goals in Nuclear and Particle Physics (my opinion)

To understand QCD

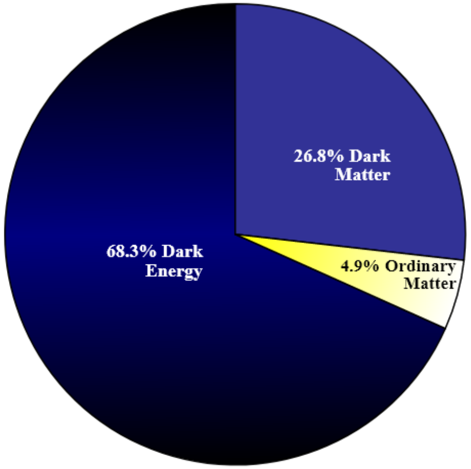
To discover BSM physics in EW sector



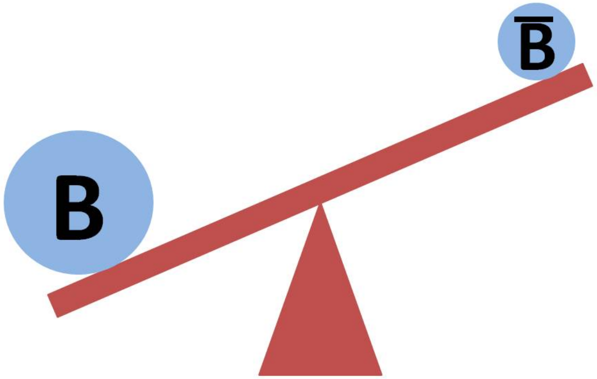
Petronas Twin Towers, Kuala Lumpur, Malaysia

Many unresolved problems call for physics beyond the Standard Model (BSM) !

Image credit: Wikipedia

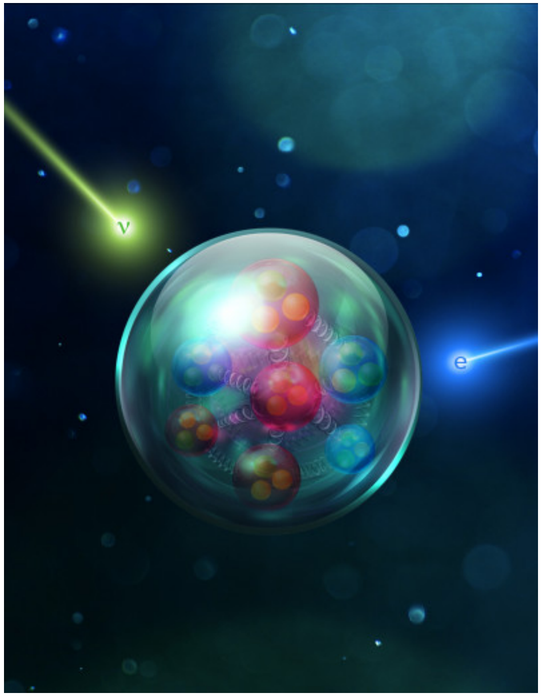


What is the origin of dark energy and dark matter?

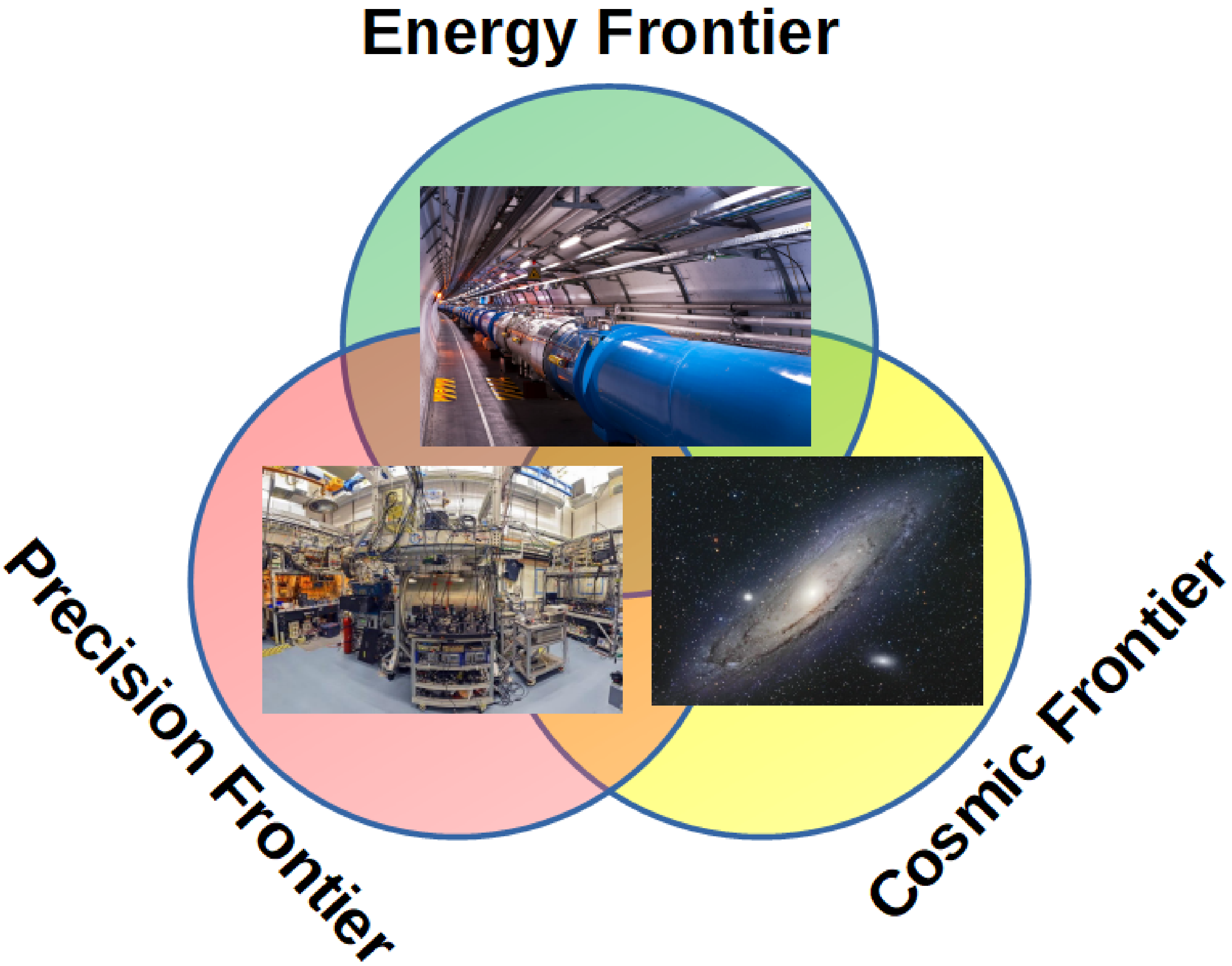


Why is there much more matter than antimatter in the observed universe?

Image credit: Jefferson Lab



What is the nature of the neutrino mass?



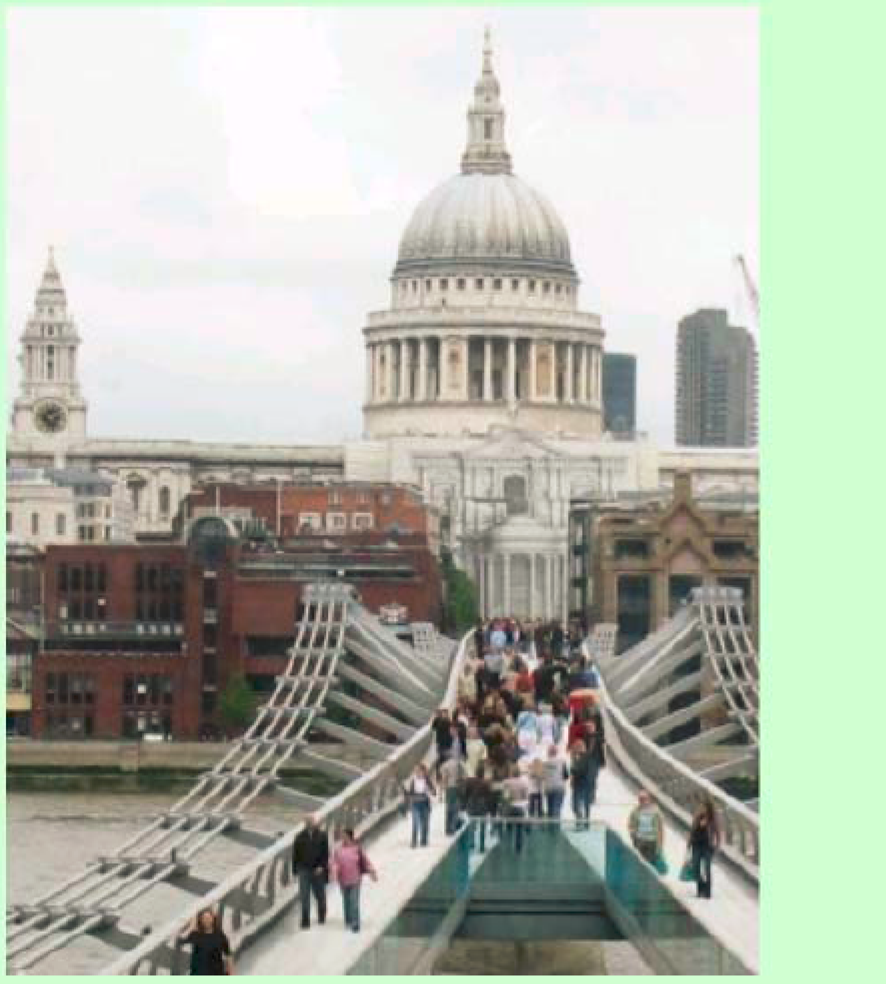
Energy Frontier

Precision Frontier

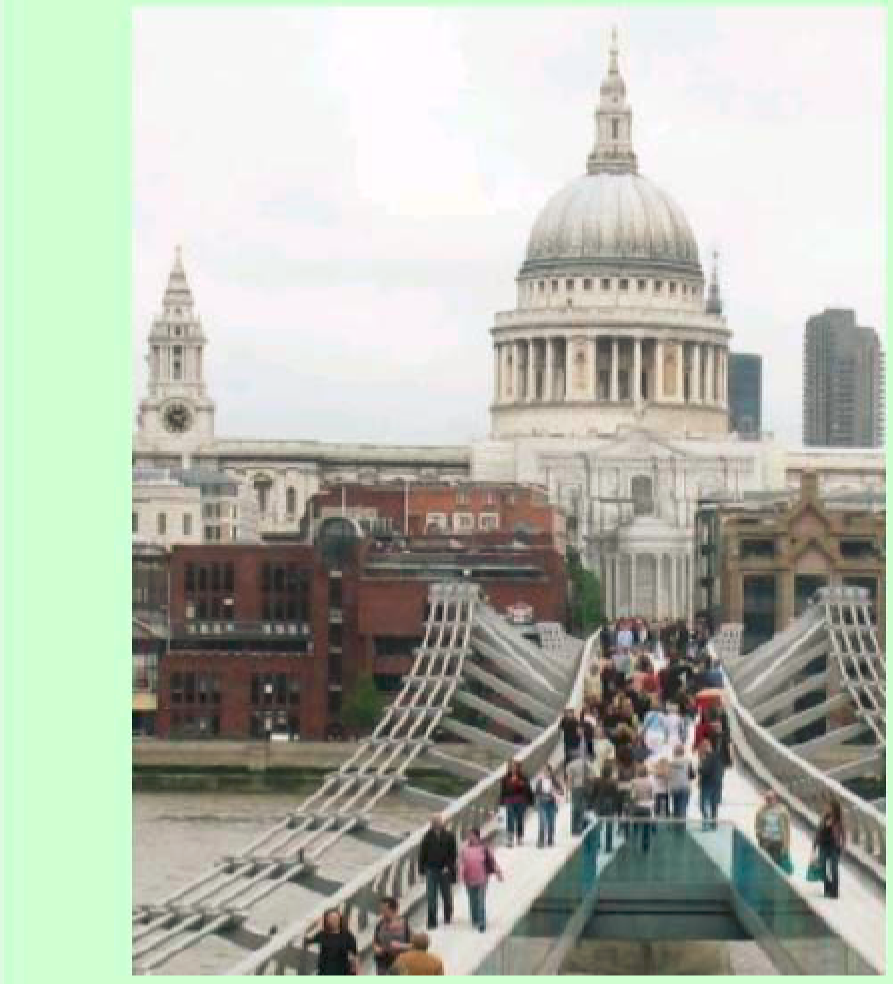
Cosmic Frontier

Precision Frontier: Measure things very precisely, and look for their **deviations** from SM prediction!

Precision Frontier



Standard Model Prediction



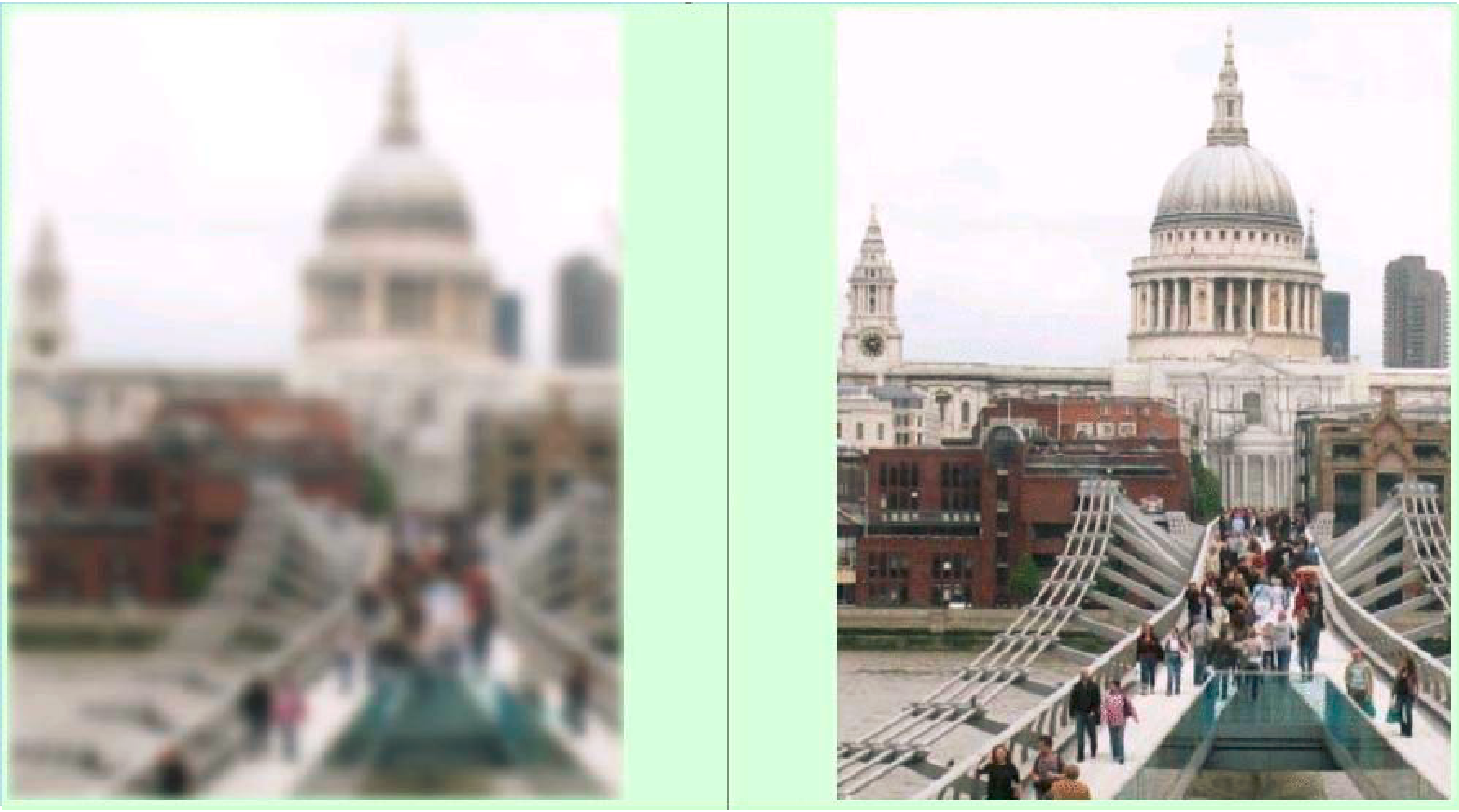
Experimental Result

Precision Frontier

Standard Model Prediction

Experimental Result

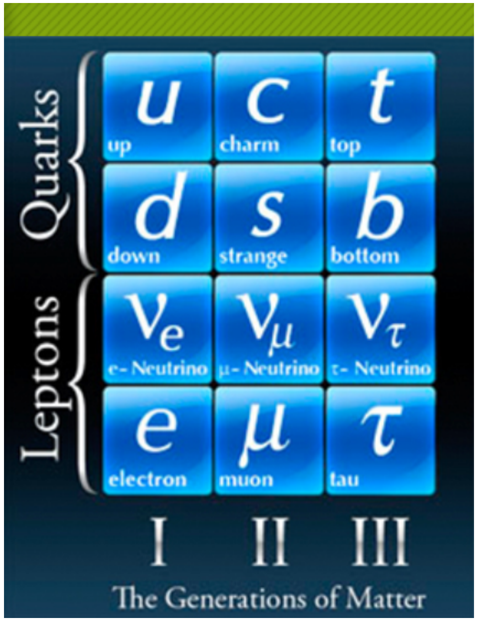
Precision Frontier



Standard Model Prediction

Experimental Result

Example: Charged weak decays and CKM unitarity

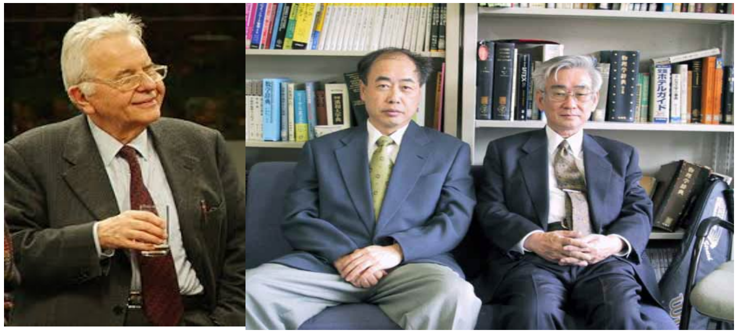


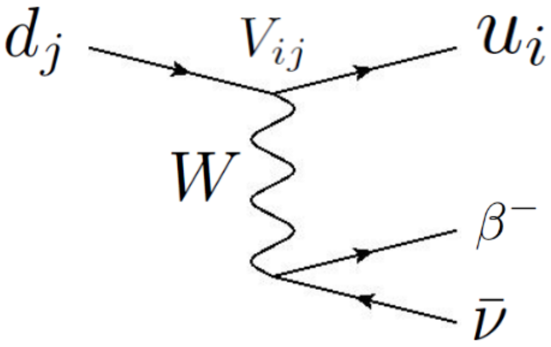
Three generations of quarks and leptons

Massive quarks ==> Generation mixing

$$\psi_{d,f} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_f = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_m$$

Cabibbo-Kobayashi-Maskawa (CKM) matrix





Weak interaction universality ==>
Unitarity of the measured CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Can be tested at **0.01%** level! Probes new physics at the scale:

$$\left(\frac{v_{\mathrm{H}}}{\Lambda_{\mathrm{BSM}}}\right)^2 \sim 0.01\% \quad \Longrightarrow \quad \Lambda_{\mathrm{BSM}} \sim 20\ \mathrm{TeV}$$

Competitive to high-energy experiments!

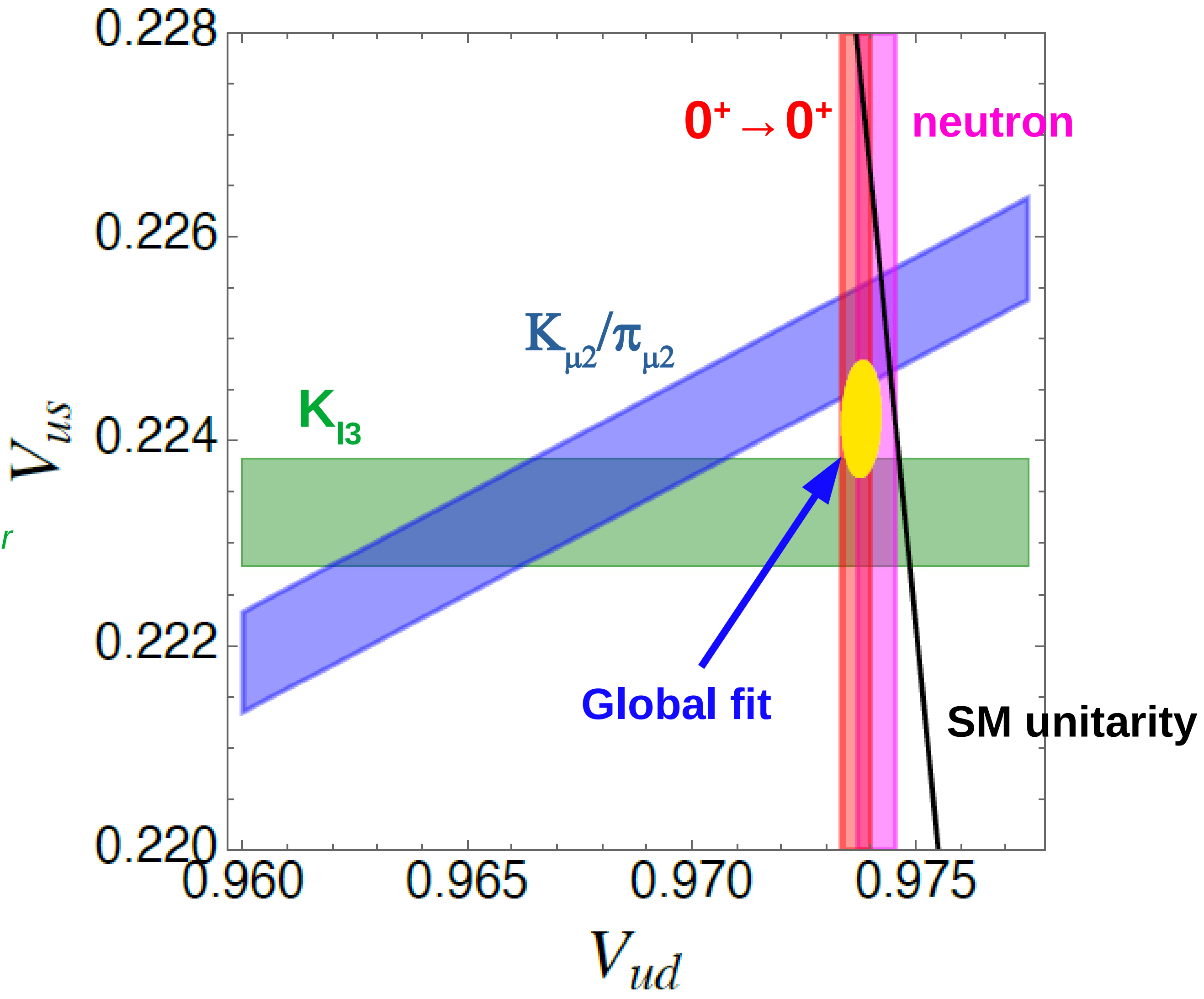
“First-row CKM unitarity”:

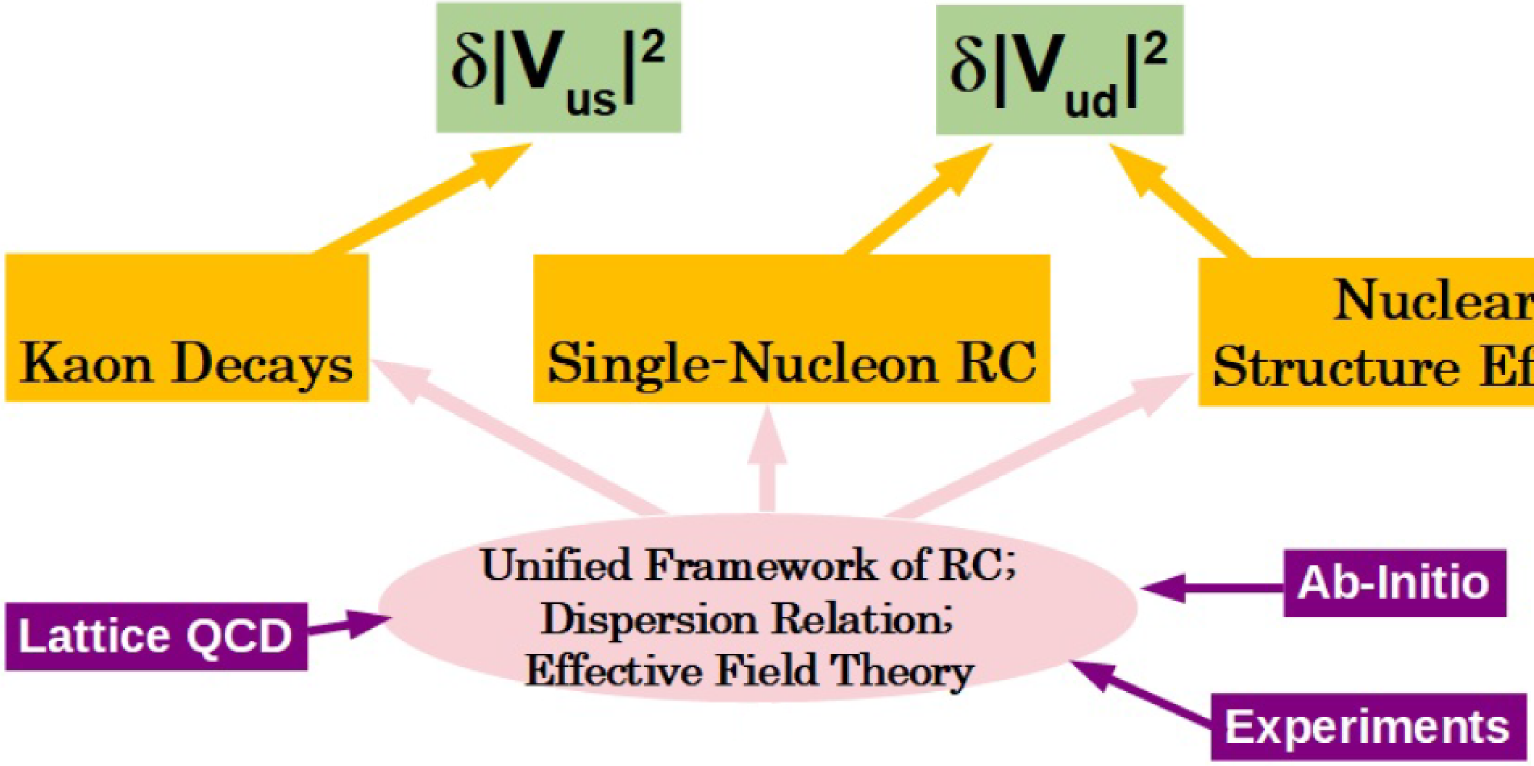
$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1}$$

Global fit:

$\boxed{2.8\sigma}$ deficit

Cirigliano, Crivellin, Hoferichter and Moulson, 2023 PLB





$\delta|V_{us}|^2$

$\delta|V_{ud}|^2$

Kaon Decays

Single-Nucleon RC

Nuclear Structure Effects

Unified Framework of RC;
Dispersion Relation;
Effective Field Theory

Lattice QCD

Ab-Initio

Experiments

$$|V_{ud}|^2 \sim 0.95 \quad \Longrightarrow \quad \text{precision goal} \sim 0.01\%$$

$$|V_{us}|^2 \sim 0.05 \quad \Longrightarrow \quad \text{precision goal} \sim 0.1\%$$

Perfect example of strong-electroweak interplay

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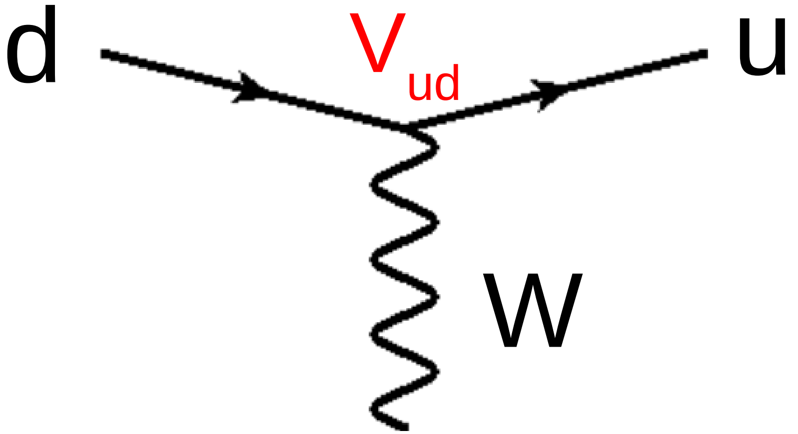
V_{ud}: The most precisely-studied CKM matrix element



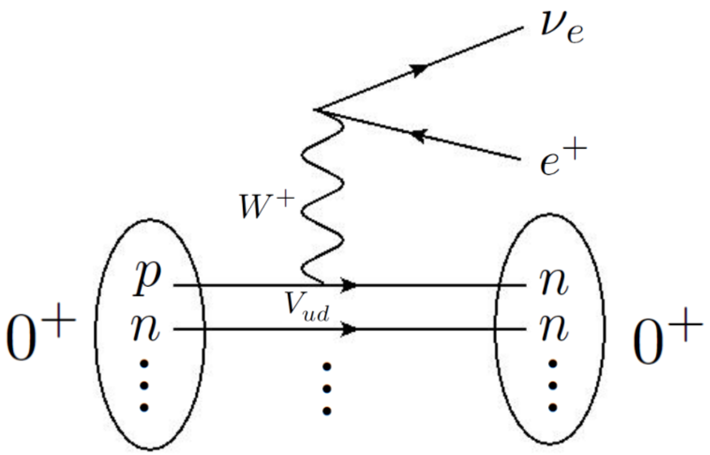
Pion: $\pi^+ \to \mu^+ \nu_\mu \quad \text{or} \quad \pi^0 e^+ \nu_e$

Neutron: $n \to p e \nu_e$

Nucleus: $i \to f e \nu_e$

“Superallowed” beta decays of I=1, $J^p=0^+$ nuclei

$$\boxed{i(0^+) \to f(0^+) + e^+ + \nu_e}$$



Provides the **best measurement of V_{ud} :**

- Tree-level amplitude is (almost) known
- **23** measured transitions
- **15** with ft-precision better than **0.23%**

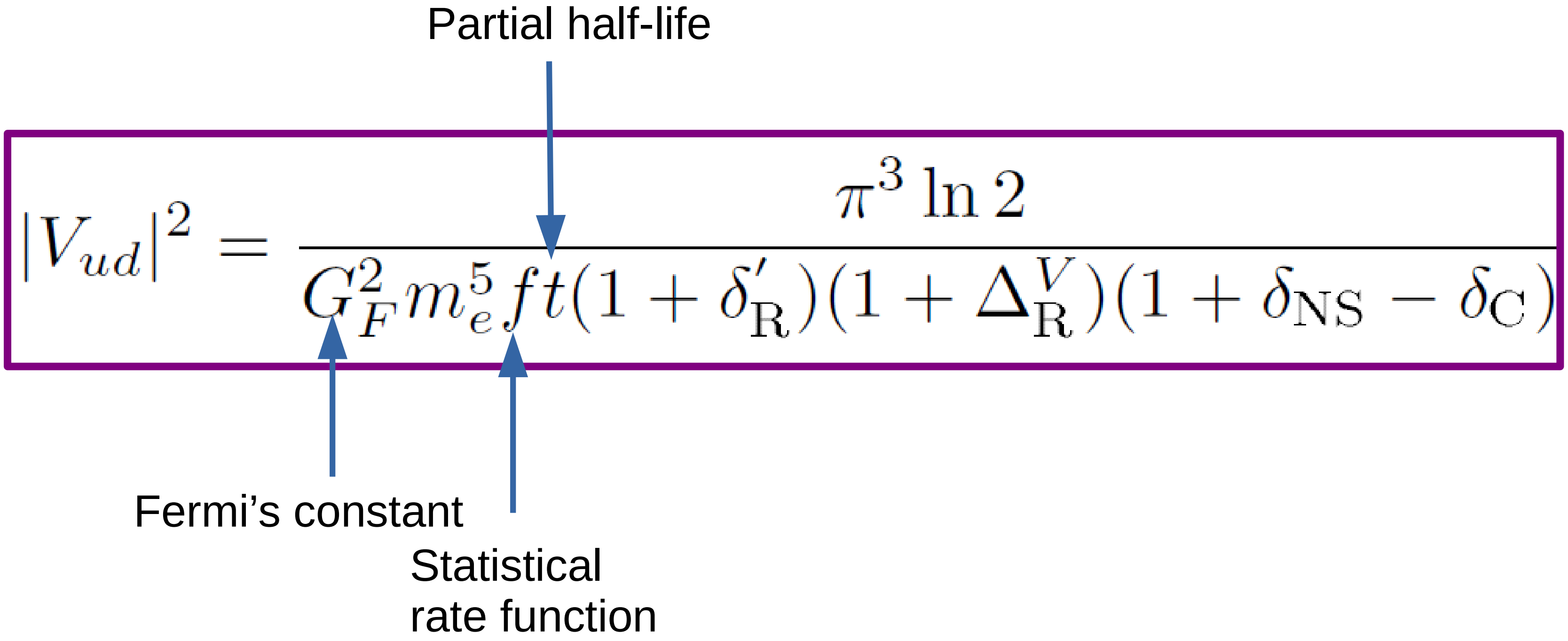
Hardy and Towner, 2020 PRC

Master Formula

$$\boxed{|V_{ud}|^2 = \frac{\pi^3 \ln 2}{G_F^2 m_e^5 ft(1+\delta'_{\mathrm{R}})(1+\Delta_{\mathrm{R}}^V)(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})}}$$

Master Formula

Experimental Inputs:



Partial half-life

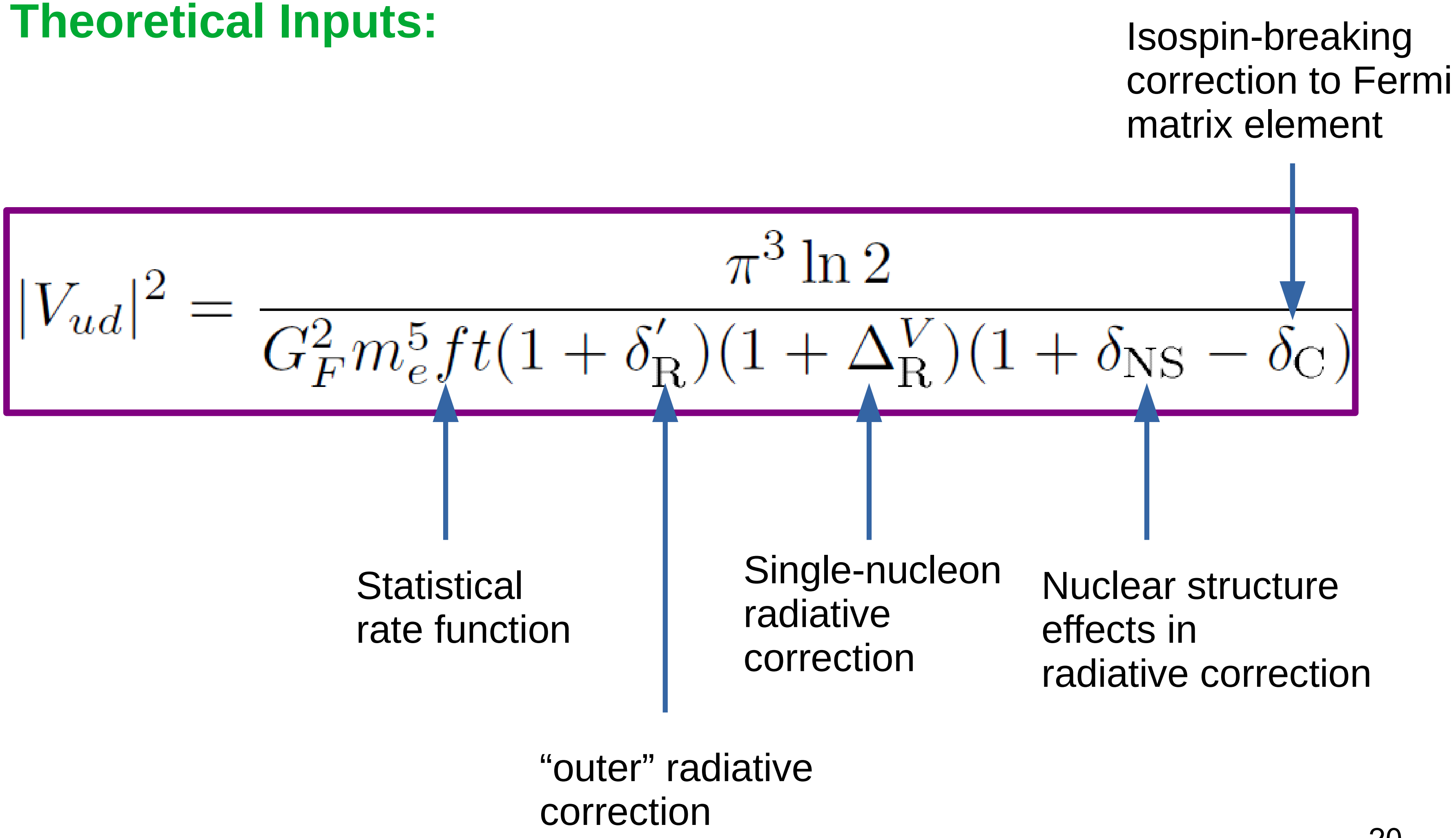
$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{G_F^2 m_e^5 f t (1+\delta'_{\mathrm{R}})(1+\Delta^V_{\mathrm{R}})(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})}$$

Fermi's constant

Statistical
rate function

Master Formula

Theoretical Inputs:



Isospin-breaking correction to Fermi matrix element

$$\boxed{|V_{ud}|^2 = \frac{\pi^3 \ln 2}{G_F^2 m_e^5 ft(1+\delta'_{\mathrm{R}})(1+\Delta_{\mathrm{R}}^V)(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})}}$$

Statistical rate function

Single-nucleon radiative correction

Nuclear structure effects in radiative correction

“outer” radiative correction

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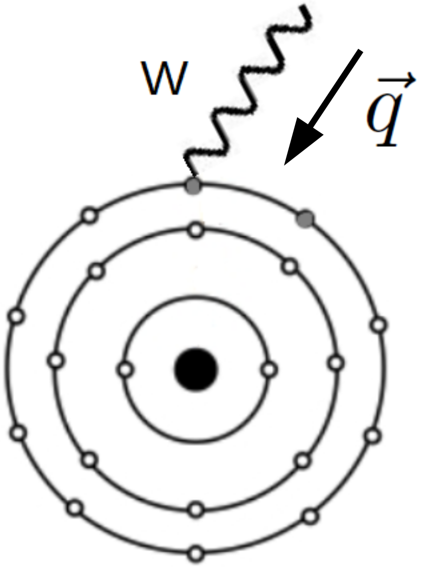
Superallowed decays at tree level



Charged weak decay matrix element:

$$\boxed{f_+(\vec{q}^2) = M_F(1 + \bar{f}_+(\vec{q}^2))}$$

Fermi matrix element

q^2-dependence

Treatment of q^2-dependence:

1. Conventional shell-model calculation

Hardy and Towner, 2005 PRC

$$\langle f|O|i\rangle = \sum_{\alpha\beta} \underbrace{\langle\alpha|O|\beta\rangle}_{\text{single-nucleon transition M.E}} \overbrace{\langle f|a_\alpha^\dagger a_\beta|i\rangle}^{\text{One-body density M.E}}$$

single-nucleon states → $\alpha\beta$

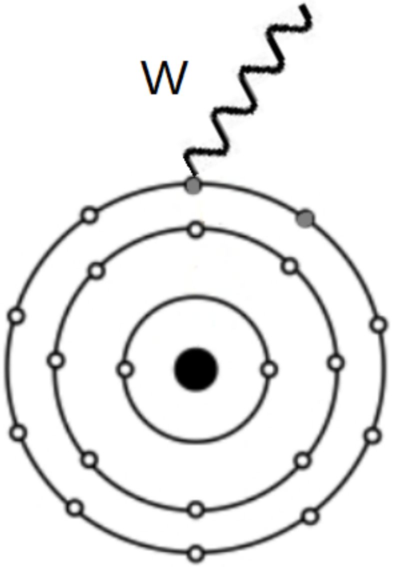
Difficult to quantify theory uncertainty!

Treatment of q^2-dependence:

2. Relate it to a distribution

$$\bar{f}_+(\vec{q}^{\,2}) \xleftrightarrow{\text{Fourier transform}} \rho_{\mathbf{cw}}(r)$$

$\rho_{\mathbf{cw}}(r)$: Distribution of “active” nucleons eligible for weak transitions in a nucleus



Treatment of q^2-dependence:

2. Relate it to a distribution

$$\bar{f}_+(\vec{q}^{\,2}) \xleftrightarrow{\text{Fourier transform}} \rho_{\mathrm{cw}}(r)$$

“Semi” data-driven approach:

Wilkinson, 1993 Nucl.Inst.Meth.Phys.Res.A;
Hayen et al., 2018 RMP

$$\rho_{\mathrm{cw}}(r) = \rho_{\mathrm{ch}}(r) + \delta\rho(r)$$

Nuclear charge distribution (data)

Assume small, estimate using shell model

Treatment of q^2-dependence:

2. Relate it to a distribution

$$\bar{f}_+(\vec{q}^{\,2}) \xleftrightarrow{\text{Fourier transform}} \rho_{\mathrm{cw}}(r)$$

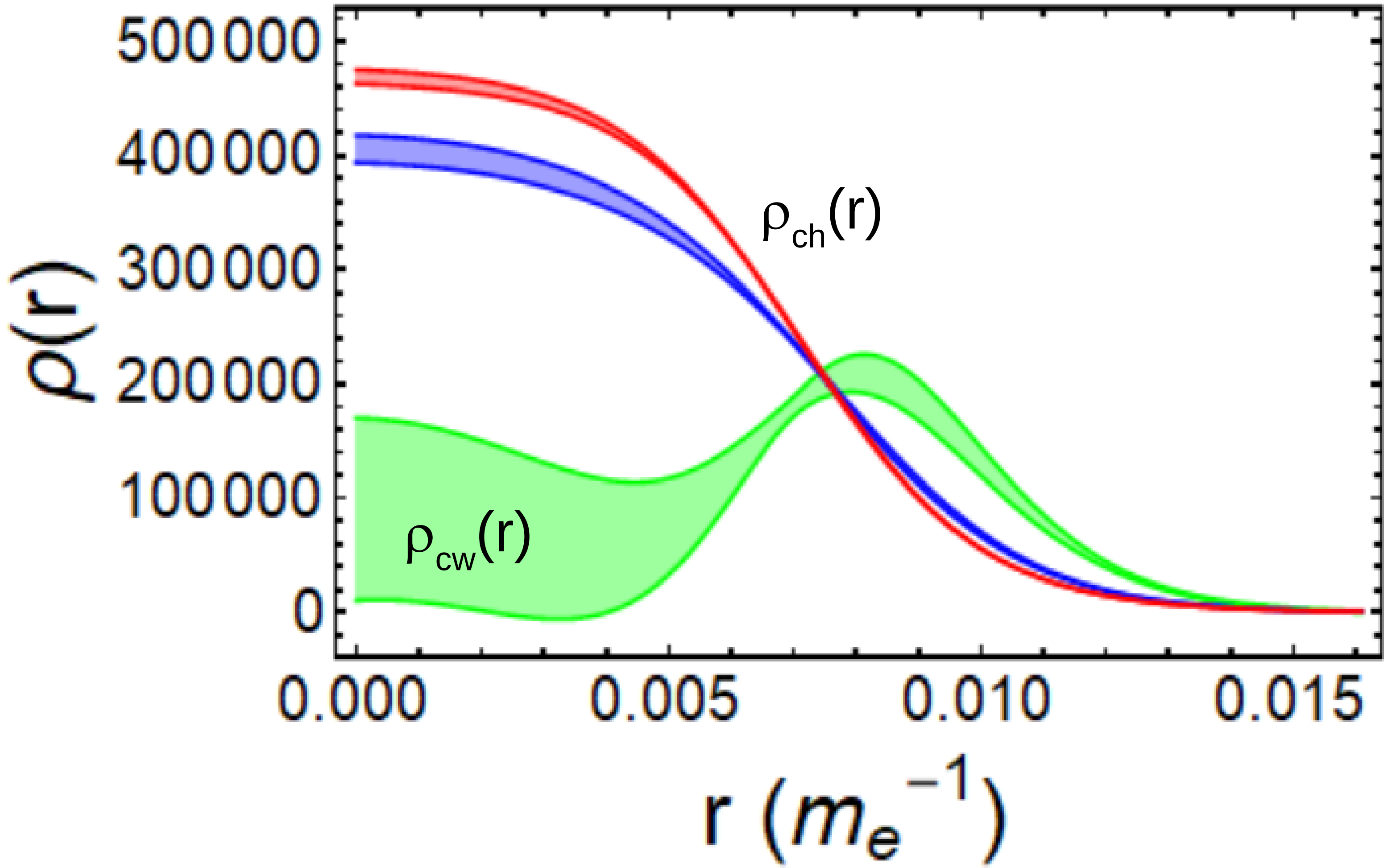
Fully data-driven approach:

Relate to **a pair** of **nuclear charge distributions** using **CVC**

Hostein, 1974 RMP; CYS, 2023 PRL

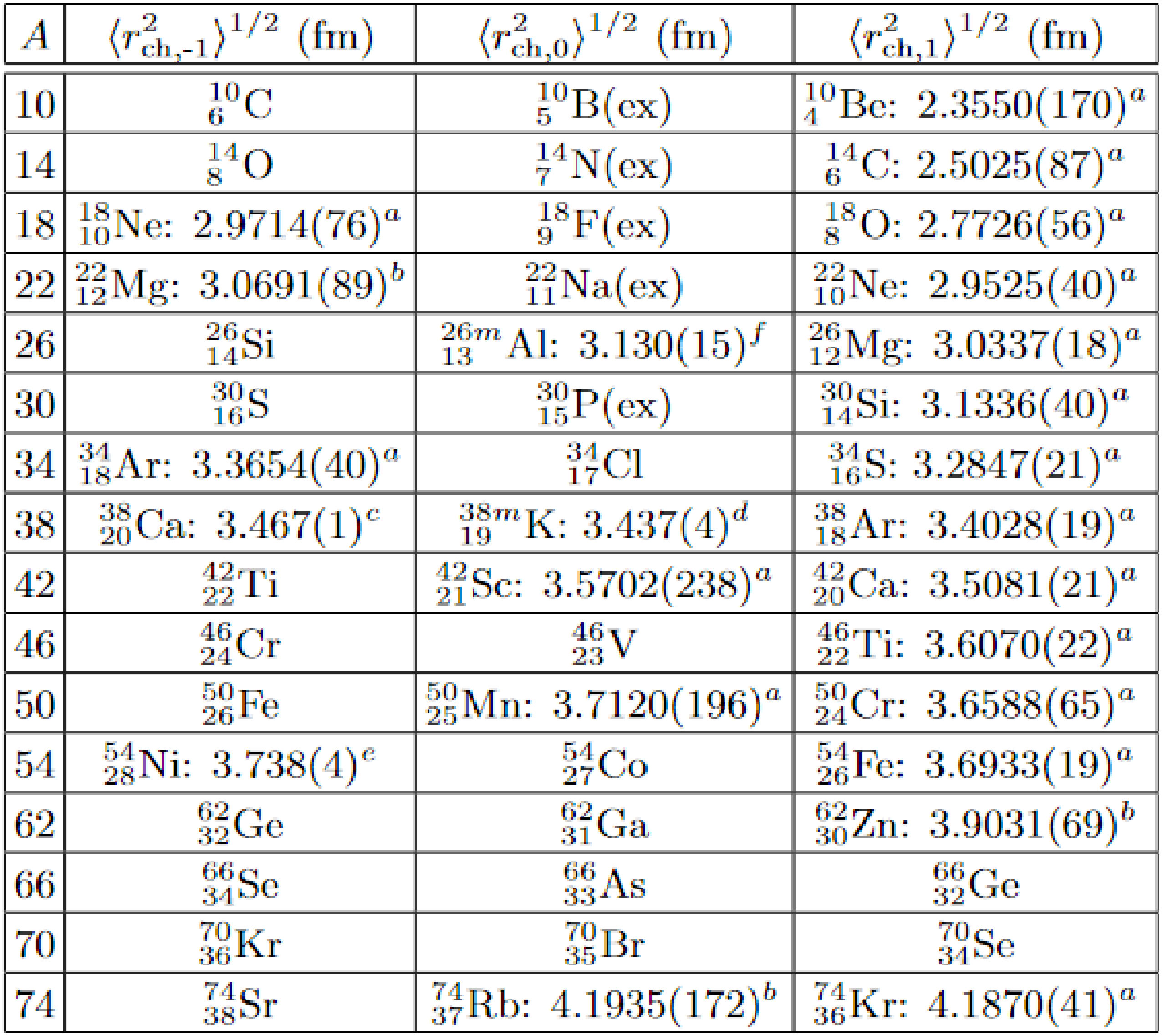
$$\boxed{\begin{aligned}\rho_{\mathrm{cw}}(r) &= \rho_{\mathrm{ch},1}(r) + Z_0\left(\rho_{\mathrm{ch},0}(r) - \rho_{\mathrm{ch},1}(r)\right)\\ &= \rho_{\mathrm{ch},1}(r) + \frac{Z_{-1}}{2}\left(\rho_{\mathrm{ch,-1}}(r) - \rho_{\mathrm{ch},1}(r)\right)\end{aligned}}$$

A=22



“Semi” data-driven approach not well-justified!

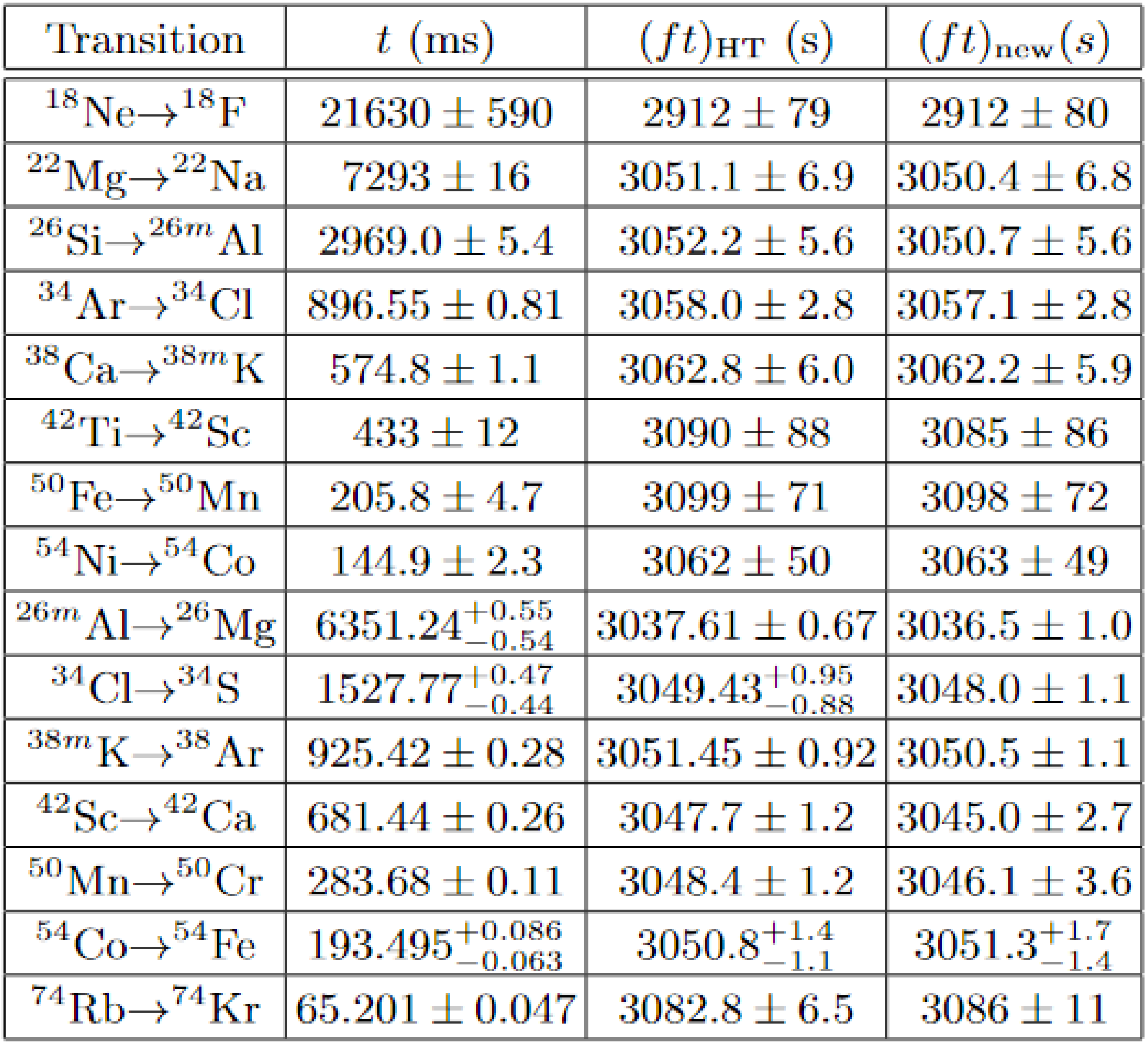
Measured nuclear charge radii



A	$\langle r^2_{\text{ch},-1}\rangle^{1/2}$ (fm)	$\langle r^2_{\text{ch},0}\rangle^{1/2}$ (fm)	$\langle r^2_{\text{ch},1}\rangle^{1/2}$ (fm)
10	$^{10}_{6}$C	$^{10}_{5}$B(ex)	$^{10}_{4}$Be: 2.3550(170)^a
14	$^{14}_{8}$O	$^{14}_{7}$N(ex)	$^{14}_{6}$C: 2.5025(87)^a
18	$^{18}_{10}$Ne: 2.9714(76)^a	$^{18}_{9}$F(ex)	$^{18}_{8}$O: 2.7726(56)^a
22	$^{22}_{12}$Mg: 3.0691(89)^b	$^{22}_{11}$Na(ex)	$^{22}_{10}$Ne: 2.9525(40)^a
26	$^{26}_{14}$Si	$^{26m}_{13}$Al: 3.130(15)^f	$^{26}_{12}$Mg: 3.0337(18)^a
30	$^{30}_{16}$S	$^{30}_{15}$P(ex)	$^{30}_{14}$Si: 3.1336(40)^a
34	$^{34}_{18}$Ar: 3.3654(40)^a	$^{34}_{17}$Cl	$^{34}_{16}$S: 3.2847(21)^a
38	$^{38}_{20}$Ca: 3.467(1)^c	$^{38m}_{19}$K: 3.437(4)^d	$^{38}_{18}$Ar: 3.4028(19)^a
42	$^{42}_{22}$Ti	$^{42}_{21}$Sc: 3.5702(238)^a	$^{42}_{20}$Ca: 3.5081(21)^a
46	$^{46}_{24}$Cr	$^{46}_{23}$V	$^{46}_{22}$Ti: 3.6070(22)^a
50	$^{50}_{26}$Fe	$^{50}_{25}$Mn: 3.7120(196)^a	$^{50}_{24}$Cr: 3.6588(65)^a
54	$^{54}_{28}$Ni: 3.738(4)^c	$^{54}_{27}$Co	$^{54}_{26}$Fe: 3.6933(19)^a
62	$^{62}_{32}$Ge	$^{62}_{31}$Ga	$^{62}_{30}$Zn: 3.9031(69)^b
66	$^{66}_{34}$Se	$^{66}_{33}$As	$^{66}_{32}$Ge
70	$^{70}_{36}$Kr	$^{70}_{35}$Br	$^{70}_{34}$Se
74	$^{74}_{38}$Sr	$^{74}_{37}$Rb: 4.1935(172)^b	$^{74}_{36}$Kr: 4.1870(41)^a

High-precision study of light nuclei charge radii: See Evgeny Epelbaum's talk

Shell model Data-driven



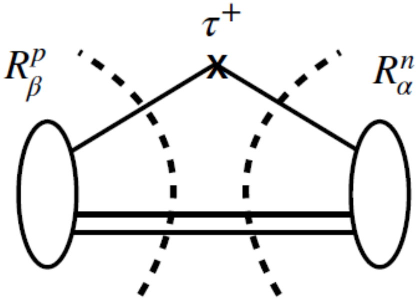
Transition	t (ms)	$(ft)_{\mathrm{HT}}$ (s)	$(ft)_{\mathrm{new}}(s)$
$^{18}\mathrm{Ne}\to^{18}\mathrm{F}$	21630 ± 590	2912 ± 79	2912 ± 80
$^{22}\mathrm{Mg}\to^{22}\mathrm{Na}$	7293 ± 16	3051.1 ± 6.9	3050.4 ± 6.8
$^{26}\mathrm{Si}\to^{26m}\mathrm{Al}$	2969.0 ± 5.4	3052.2 ± 5.6	3050.7 ± 5.6
$^{34}\mathrm{Ar}\to^{34}\mathrm{Cl}$	896.55 ± 0.81	3058.0 ± 2.8	3057.1 ± 2.8
$^{38}\mathrm{Ca}\to^{38m}\mathrm{K}$	574.8 ± 1.1	3062.8 ± 6.0	3062.2 ± 5.9
$^{42}\mathrm{Ti}\to^{42}\mathrm{Sc}$	433 ± 12	3090 ± 88	3085 ± 86
$^{50}\mathrm{Fe}\to^{50}\mathrm{Mn}$	205.8 ± 4.7	3099 ± 71	3098 ± 72
$^{54}\mathrm{Ni}\to^{54}\mathrm{Co}$	144.9 ± 2.3	3062 ± 50	3063 ± 49
$^{26m}\mathrm{Al}\to^{26}\mathrm{Mg}$	$6351.24^{+0.55}_{-0.54}$	3037.61 ± 0.67	3036.5 ± 1.0
$^{34}\mathrm{Cl}\to^{34}\mathrm{S}$	$1527.77^{+0.47}_{-0.44}$	$3049.43^{+0.95}_{-0.88}$	3048.0 ± 1.1
$^{38m}\mathrm{K}\to^{38}\mathrm{Ar}$	925.42 ± 0.28	3051.45 ± 0.92	3050.5 ± 1.1
$^{42}\mathrm{Sc}\to^{42}\mathrm{Ca}$	681.44 ± 0.26	3047.7 ± 1.2	3045.0 ± 2.7
$^{50}\mathrm{Mn}\to^{50}\mathrm{Cr}$	283.68 ± 0.11	3048.4 ± 1.2	3046.1 ± 3.6
$^{54}\mathrm{Co}\to^{54}\mathrm{Fe}$	$193.495^{+0.086}_{-0.063}$	$3050.8^{+1.4}_{-1.1}$	$3051.3^{+1.7}_{-1.4}$
$^{74}\mathrm{Rb}\to^{74}\mathrm{Kr}$	65.201 ± 0.047	3082.8 ± 6.5	3086 ± 11

Gorchtein and CYS, 2311.00044

Isospin symmetry breaking (ISB) correction

Full Fermi matrix element:

$$\boxed{\begin{aligned} M_F^2 &= |\langle f|\tau_+|i\rangle|^2 \\ &= (M_F^0)^2(1-\delta_\mathrm{C}) \end{aligned}}$$



Isospin limit

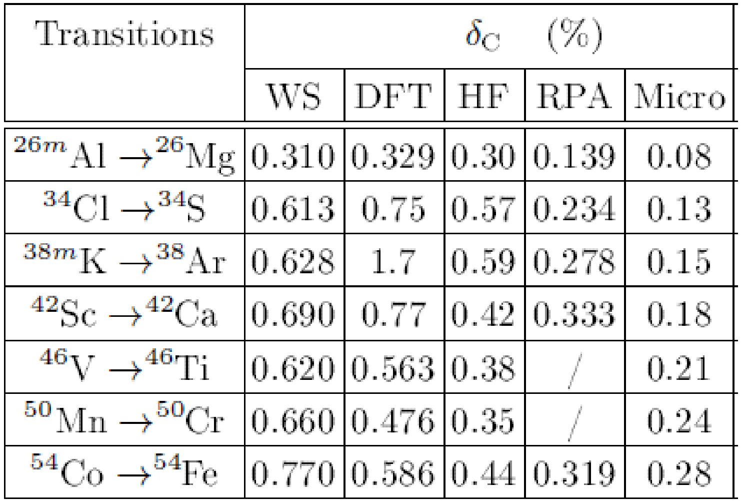
ISB correction,
primarily Coulomb (C)

(0.1-1)%

Symmetry broken due to:

1. **Proton’s electric charge**
2. **$M_p \neq M_n$**

6 decades of δ_C -calculations show huge model-dependence!

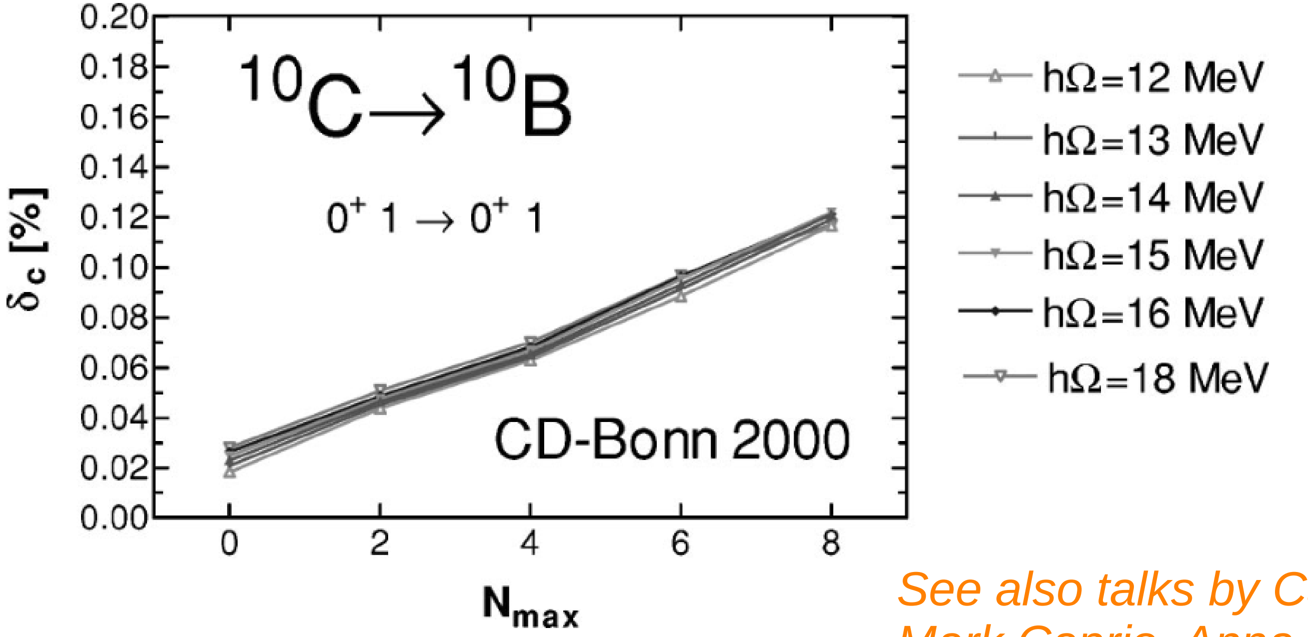


Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	0.310	0.329	0.30	0.139	0.08
$^{34}\mathrm{Cl} \rightarrow {}^{34}\mathrm{S}$	0.613	0.75	0.57	0.234	0.13
$^{38m}\mathrm{K} \rightarrow {}^{38}\mathrm{Ar}$	0.628	1.7	0.59	0.278	0.15
$^{42}\mathrm{Sc} \rightarrow {}^{42}\mathrm{Ca}$	0.690	0.77	0.42	0.333	0.18
$^{46}\mathrm{V} \rightarrow {}^{46}\mathrm{Ti}$	0.620	0.563	0.38	/	0.21
$^{50}\mathrm{Mn} \rightarrow {}^{50}\mathrm{Cr}$	0.660	0.476	0.35	/	0.24
$^{54}\mathrm{Co} \rightarrow {}^{54}\mathrm{Fe}$	0.770	0.586	0.44	0.319	0.28

(Selected model results)

Ab-initio study with no-core shell model (NCSM) returned **non-convergent** result!

Caurier, Navratil, Ormand and Vary, 2002 PRC



Intruder states effects

See also talks by Calvin Johnson, Mark Caprio, Anna McCoy, Patrick Fasano...

Similar convergence issue in other ISB-observables:

1. Quadrupole moments in mirror nuclei

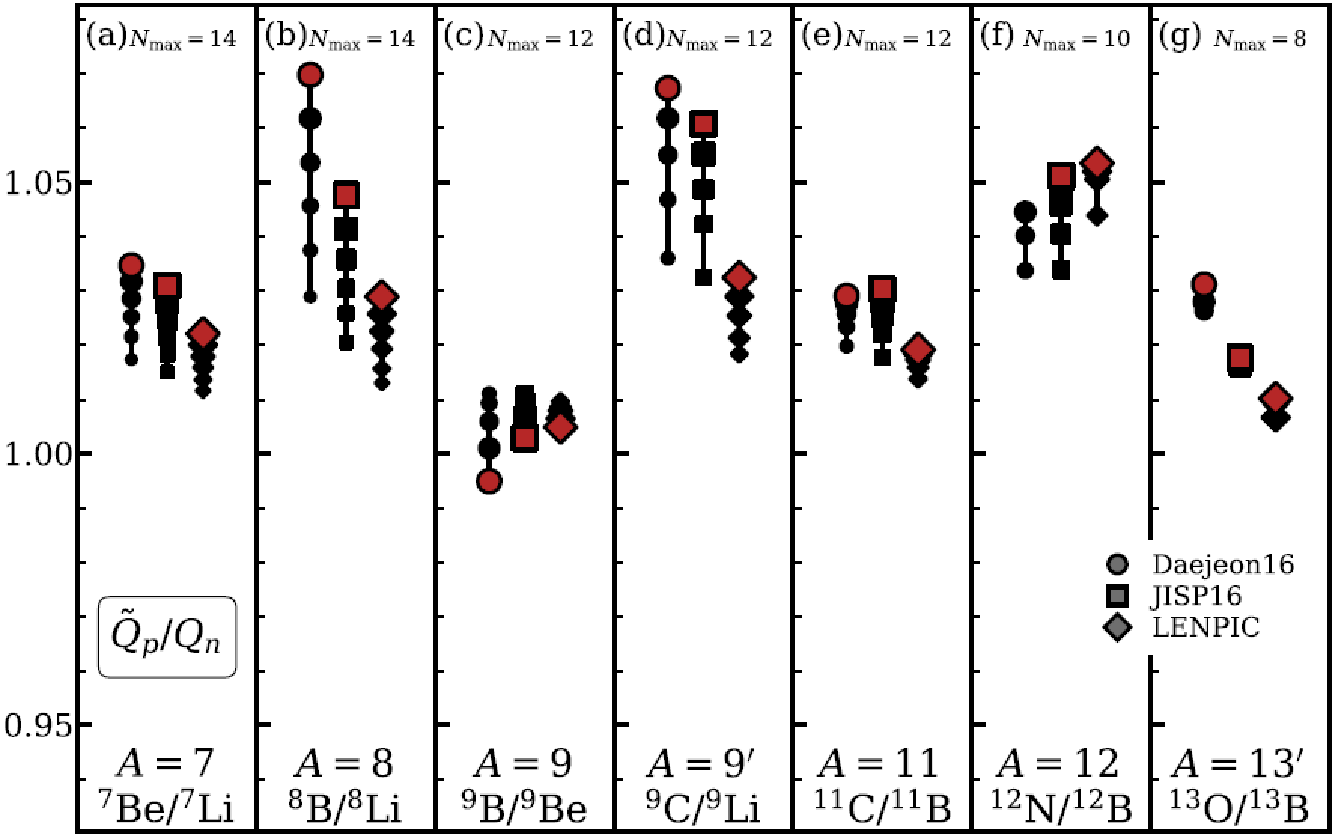
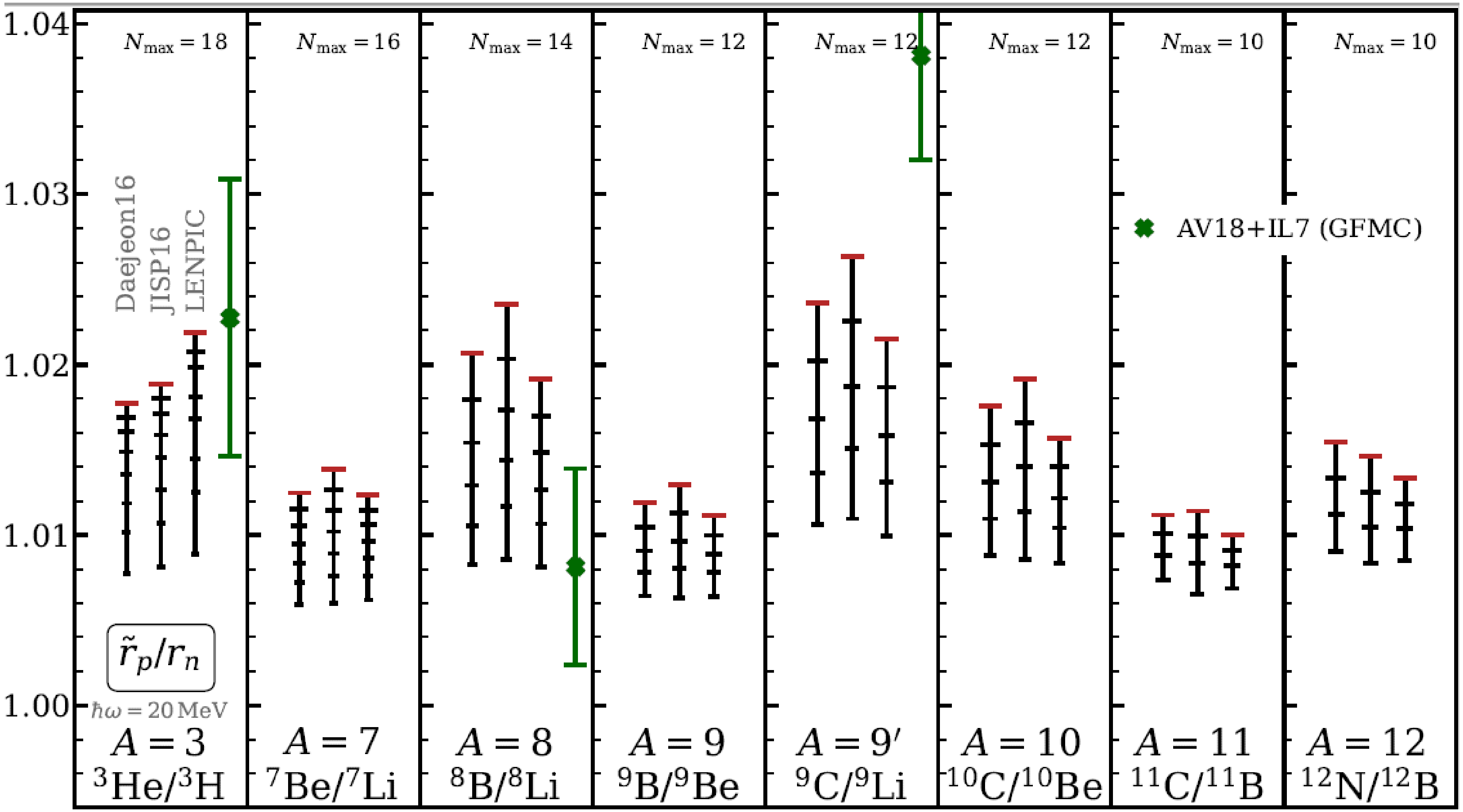


FIG. 7. Ratio of Q_p in one member of mirror pair to Q_n in the other, calculated with the Daejeon16 (circles), JISP16 (squares), and LENPIC (diamonds) interactions at fixed $\hbar\omega$ (15, 20, and 25 MeV, respectively, for the three interactions). Calculated values are shown for successive even values of $N_{\max}$ (increasing symbol size), from $N_{\max} = 4$ to the maximum value for that mirror pair, indicated at top.

Caprio, Fasano, Maris and McCoy, 2021 PRC

Similar convergence issue in other ISB-observables:

2. RMS radii in mirror nuclei



Mark Caprio, preliminary results

Perturbative representation of ISB:

Miller and Schwenk, 2008 PRC; 2009 PRC

$$H = H_0 + V$$

← ISB potential

Energy eigenstates: $H|n\rangle = E_n|n\rangle \;,\;\; H_0|n) = E_n^0|n)$

Wigner-Brillouin perturbation theory:

$$|n\rangle = \sqrt{Z_n}\left[|n) + \frac{1}{E_n - \Lambda_n H \Lambda_n}\Lambda_n V|n)\right]$$

Normalization factor

Projection operator: $\Lambda_n = 1 - |n)(n|$

Perturbative expansion makes underlying physics more transparent!

Correction to M_F starts from **second order** in ISB interaction:

Behrends and Sirlin, 1960 PRL;Ademollo and Gatto, 1964 PRL

$$\boxed{\begin{aligned}\delta_C \quad \approx \quad & -\frac{d}{dz}\Bigg\{\Big[(i|VG(z)V|i)+(f|VG(z)V|f) \\ & -\frac{2}{M_F^0}(f|VG(z)\tau_+V|i)\Big]-g.s.\Bigg\}_{z=E_g^0}\end{aligned}}$$

ground-state contribution

Depends on **off-diagonal** matrix elements of V (unlike mass-splitting)

Nuclear Green's function: $$G(z)\equiv\frac{1}{z-H_0}$$

See Michael Gennari's talk

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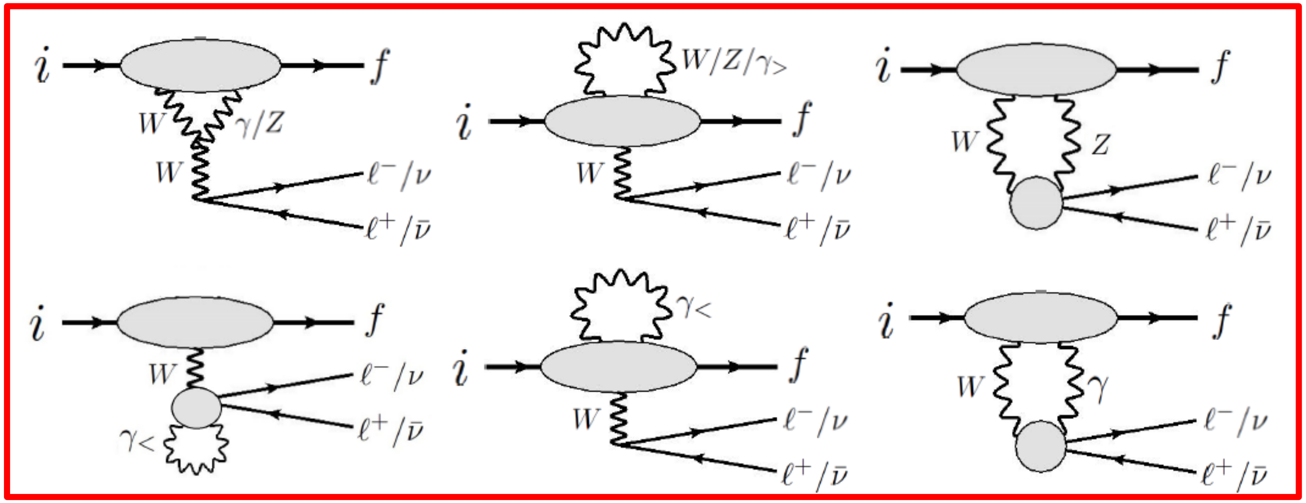
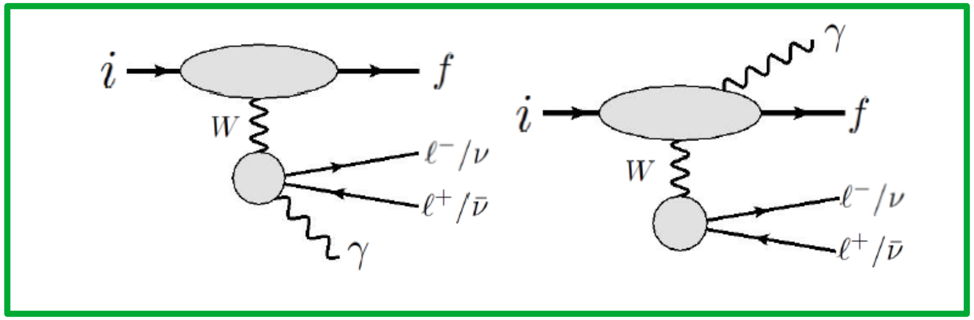
4. **Inputs at loop-level**
   - Nucleus-independent radiative corrections
   - Nucleus-dependent radiative corrections
5. Summary and outlook

Radiative Corrections



Loop corrections



Bremsstrahlung corrections

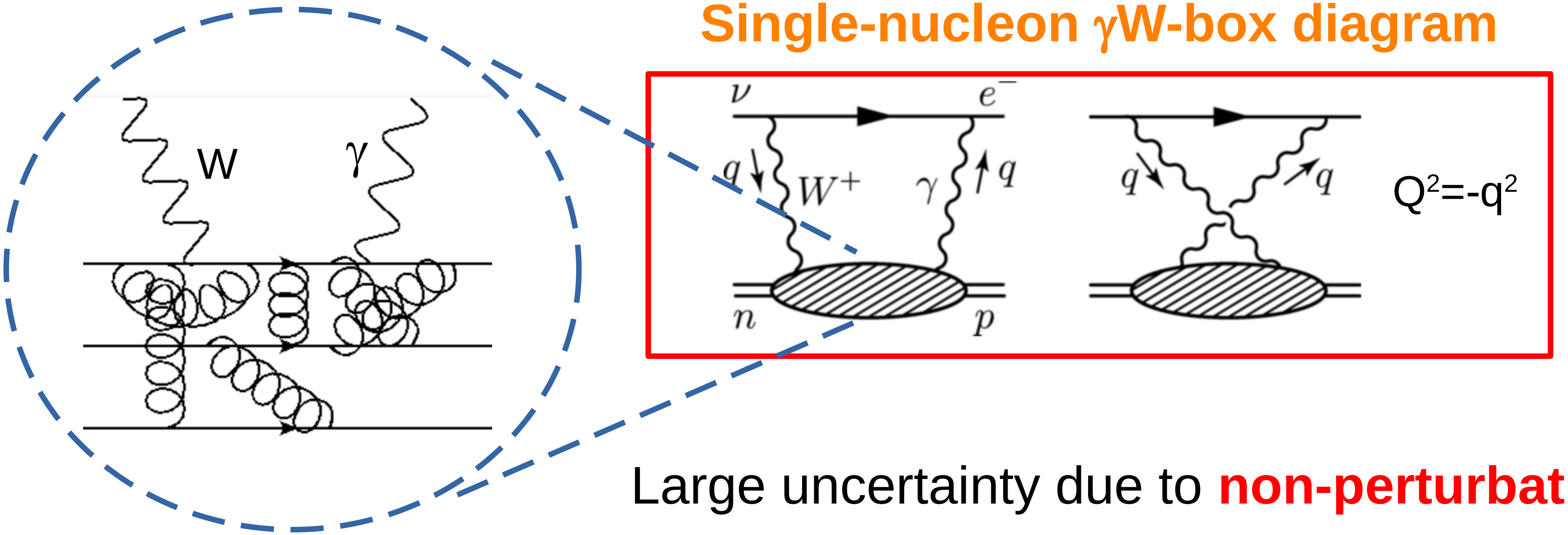
$$\text{Full R.C.} = \Delta_R^V + \delta_{\text{NS}}$$

Nucleus-independent

Nucleus-dependent

Nucleus-independent RC

Single-nucleon γW-box diagram

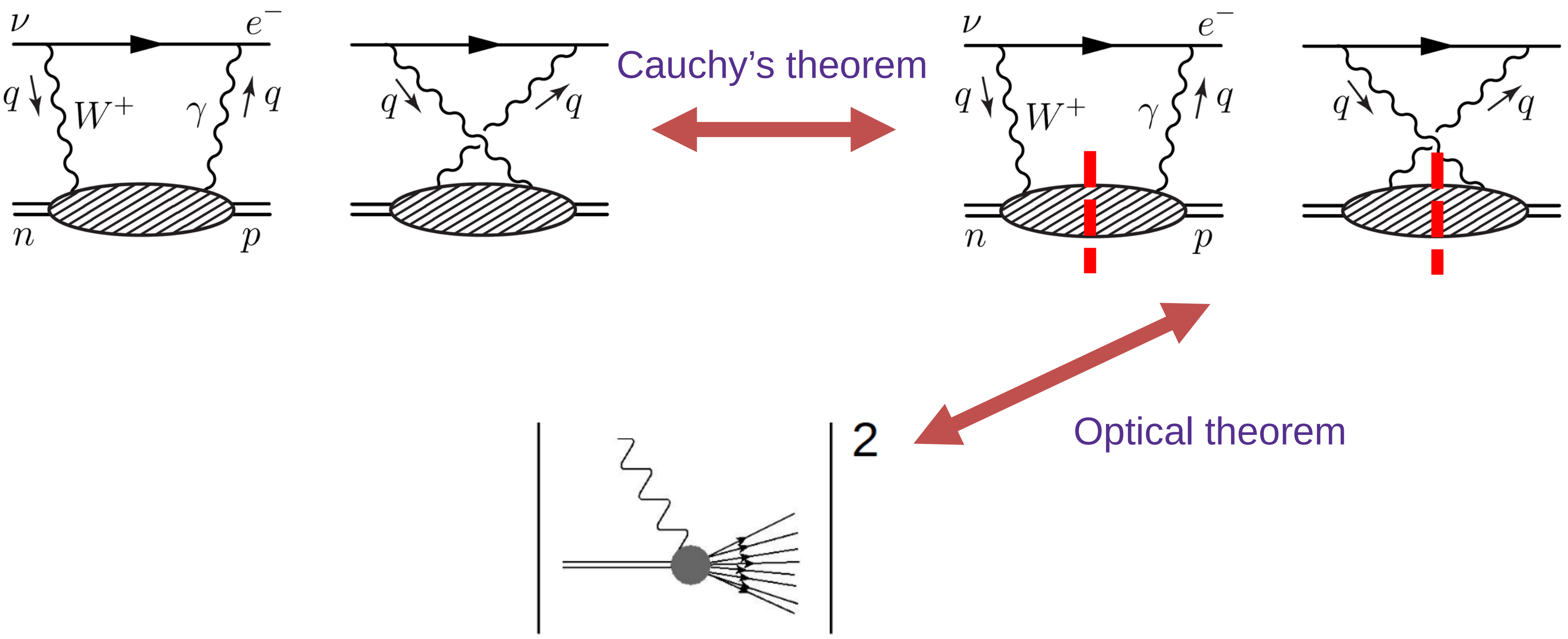


Large uncertainty due to **non-perturbative QCD** at Q^2~1 GeV^2.

Methods to evaluate:

1. Dispersion relation (DR) --- relate the loop integral to experimentally-measurable structure functions

CYS, Gorchtein, Patel and Ramsey-Musolf, 2018 PRL;
Shiells, Blunden and Melnitchouk, 2021 PRD



Cauchy's theorem

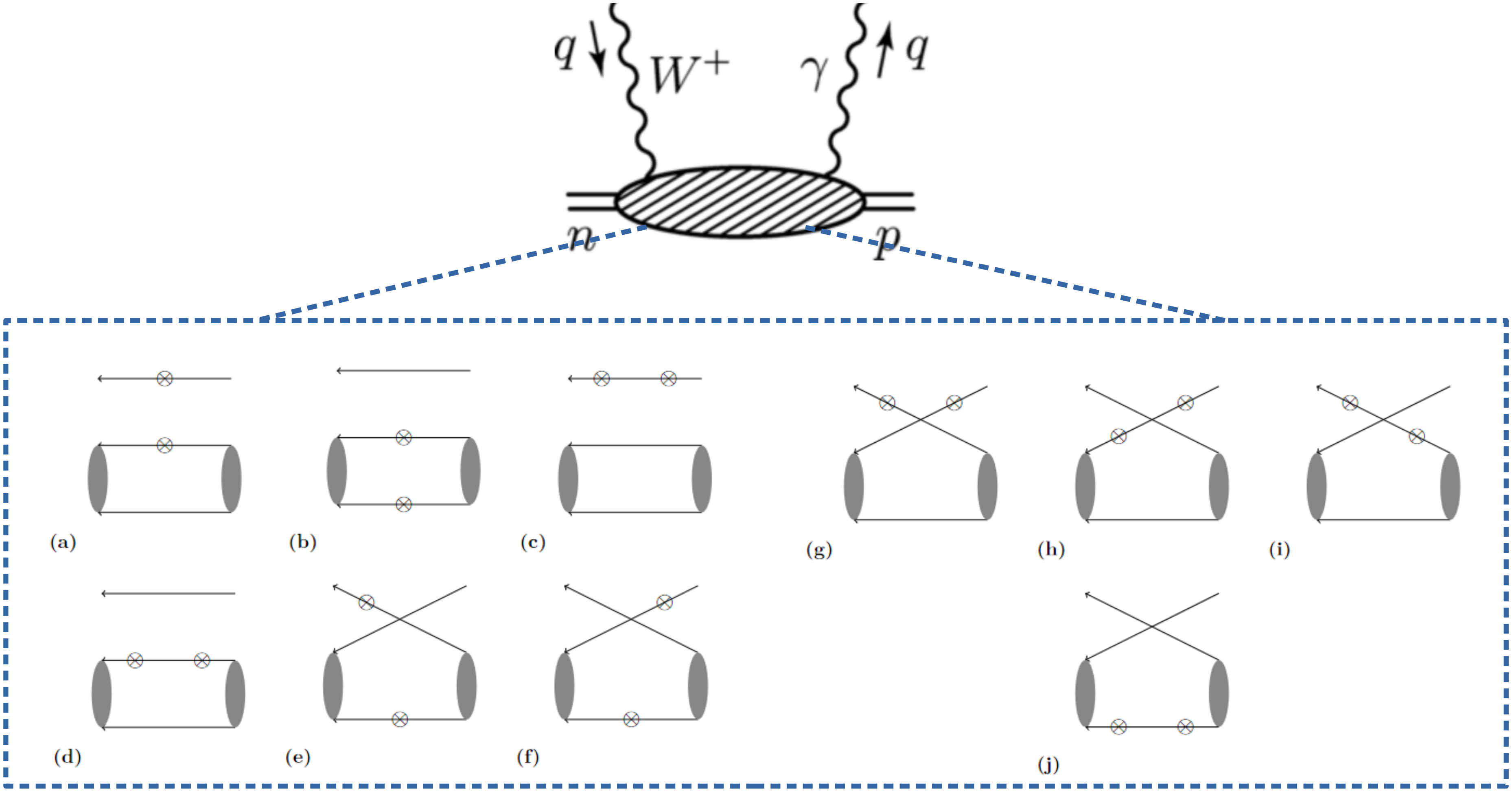
Optical theorem

Data: $\nu(\bar{\nu})p \to e^{\pm}X$ structure functions

Methods to evaluate:

2. Lattice QCD --- Compute the shaded blob directly

Feng, Gorchtein, Jin, Ma and CYS, 2020 PRL; Ma et al., 2308.16755

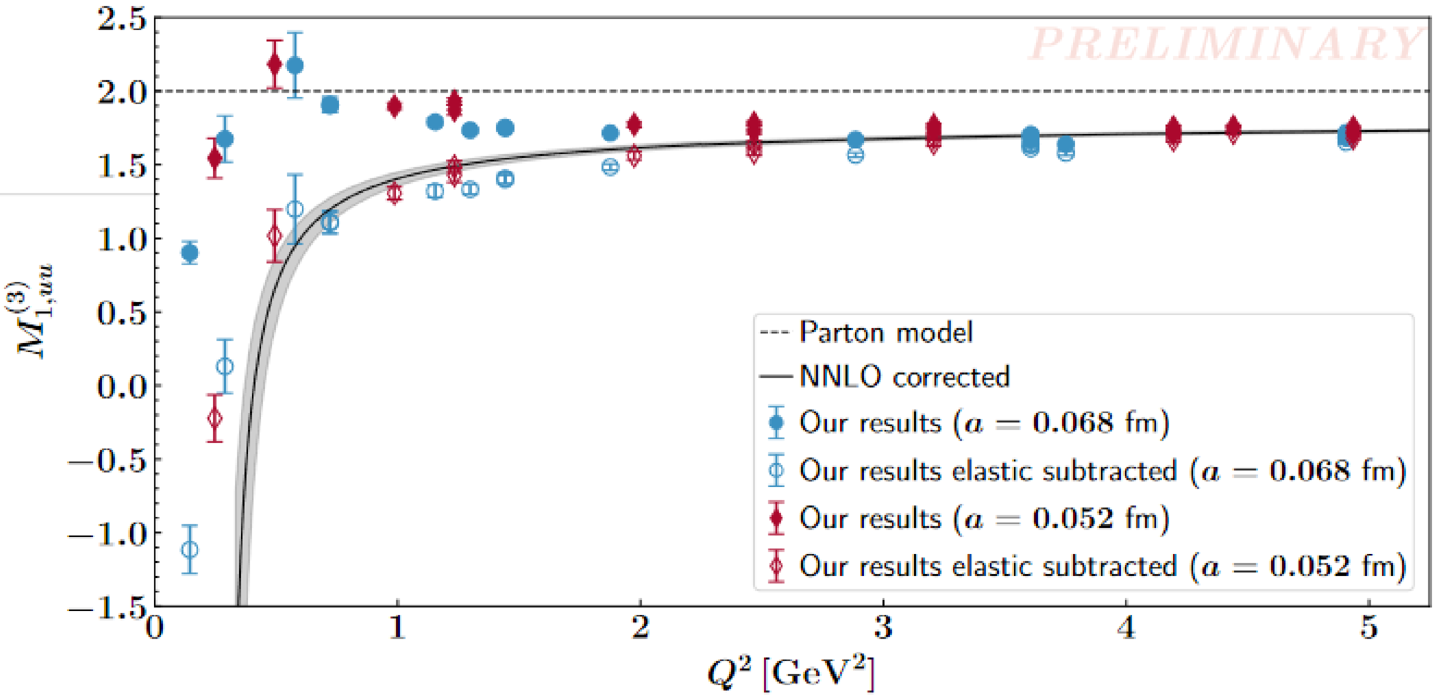


Methods to evaluate:

2. Lattice QCD --- Structure function from **Feynman-Hellmann theorem** *Can et al., 2402.00255*

$$S(\lambda) = S_0 + \lambda_1 \int d^4z \cos(q\cdot z)\mathcal{J}_\mu(z) + \lambda_2 \int d^4y \sin(q\cdot y)\mathcal{J}_\nu^A(y),$$

$$\frac{\mathcal{F}_3(\omega,Q^2)}{\omega} = \frac{Q^2}{\mathbf{q}_2}\frac{\partial^2 E_{N_\lambda}(\mathbf{p})}{\partial\lambda_1\partial\lambda_2}\bigg|_{\lambda=0}$$



Kadir Utku Can, INT Workshop INT-24-87W

Different evaluations of the nucleus-independent RC:

Pre-2018

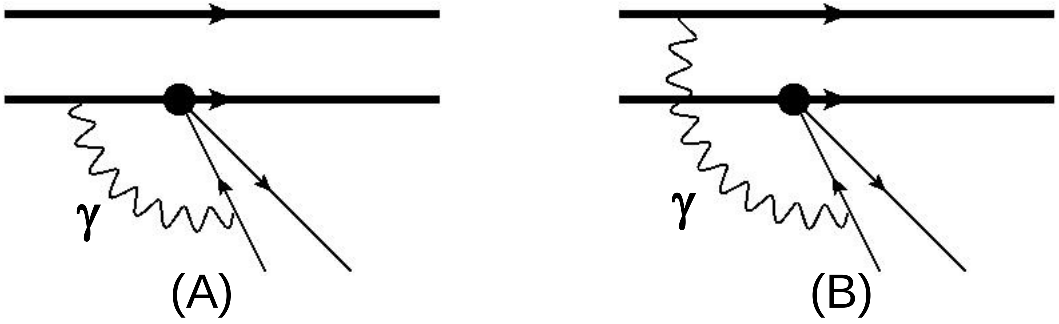
Method	Δ_R^V	
Phenomenological	0.02361(38)	*Marciano and Sirlin, 2006 PRL*
DR with neutrino data (1)	0.02467(22)	*CYS, Gorchtein, Patel and Ramsey-Musolf, 2018 PRL*
DR with neutrino data (2)	0.02471(18)	*Shiells, Blunden and Melnitchouk, 2021 PRD*
DR with indirect lattice data	0.02477(24)	*CYS, Feng, Gorchtein and Jin, 2020 PRD*
Non-DR (1)	0.02426(32)	*Czarnecki, Marciano and Sirlin, 2019 PRD*
Non-DR (2)	0.02473(27)	*Hayen, 2021 PRD*
Lattice	0.02439(19)	*Ma et al., 2308.16755*

Post-2018

$$\Delta_R^V \uparrow \Longrightarrow |V_{ud}| \downarrow$$

Nucleus-dependent inner RC, δ_{NS}

Classical viewpoint:



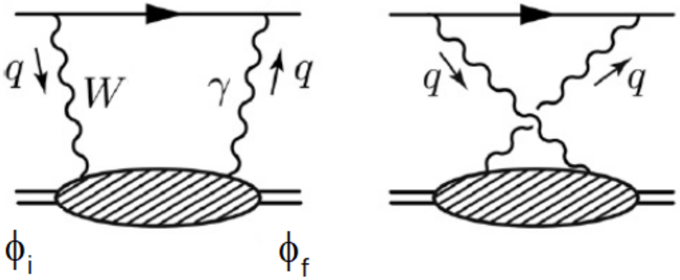
Type A: Nuclear medium effect, "quenched" couplings
Type B: Two-nucleon effects

Both computed with NR nuclear models!

Jaus and Rasche, 1990 PRD;
Barker et al., 1992 NPA;
Towner, 1992 NPA, 1994 PLB

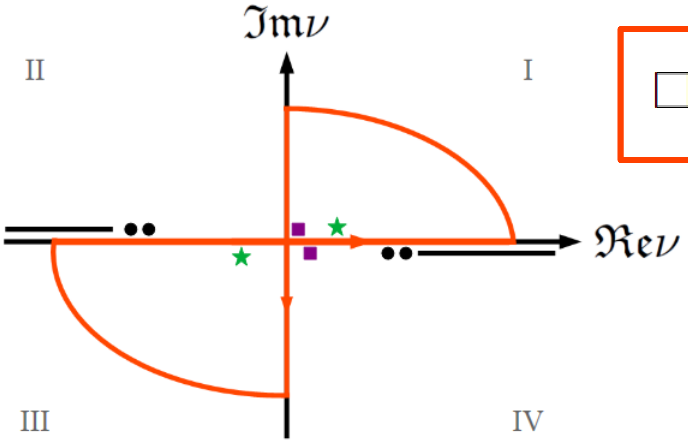
Modern viewpoint:

δ_{NS} in terms of **the difference between the nuclear and nucleon γW-box diagram**



$$\boxed{\Box^{\text{nucl.}}_{\gamma W} = \Box^{n}_{\gamma W} + \underbrace{\left[\Box^{\text{nucl.}}_{\gamma W} - \Box^{n}_{\gamma W}\right]}_{\sim\frac{1}{2}\,\delta_{NS}}}$$

Wick-rotation of the loop integral:

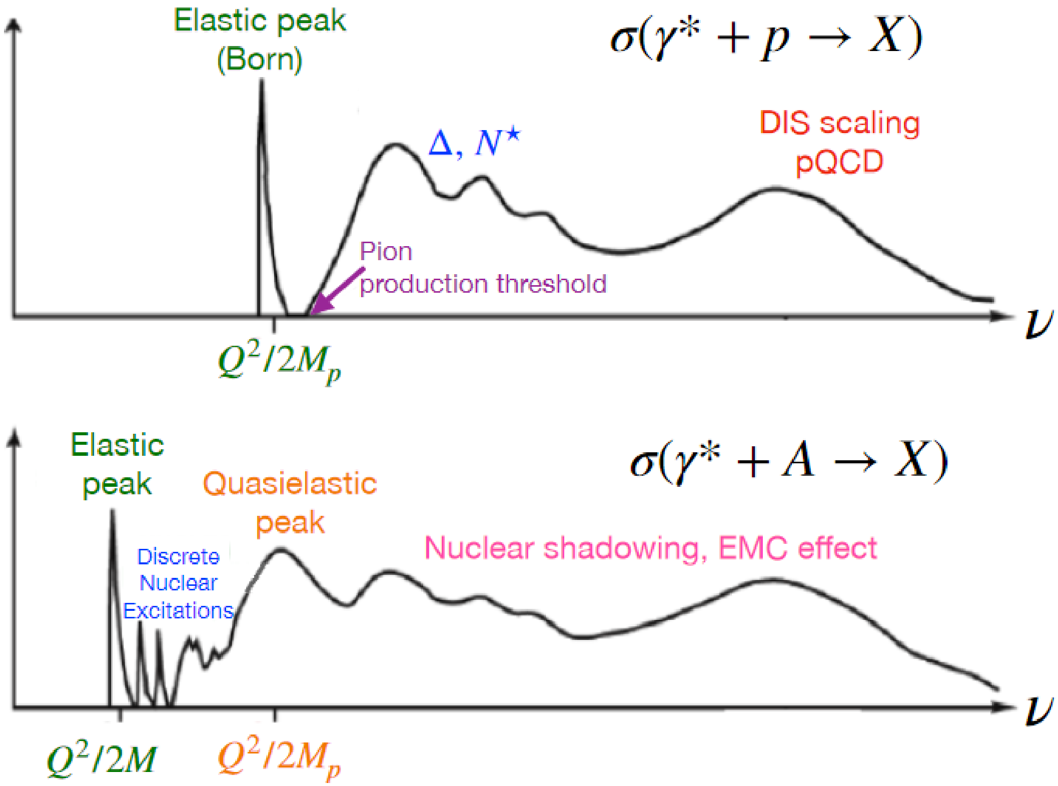


$$\boxed{\Box^{\text{nucl.}}_{\gamma W} = \underbrace{(\Box^{\text{nucl.}}_{\gamma W})_{\text{Wick}} + (\Box^{\text{nucl.}}_{\gamma W})_{\text{res},e}}_{\text{Analytic to } E_e} + \underbrace{(\Box^{\text{nucl.}}_{\gamma W})_{\text{res,nucl}}}_{\text{Non-analytic to } E_e}}$$

The first two terms probe the **nuclear response function**:

$$R^{xy}(\nu, Q^2) \sim \sum_X \delta(M + q_0 - E_X)\langle f|J^x_{\text{em}}|X\rangle\langle X|J^y_W|i\rangle$$

See Francesca Bonaiti's talk

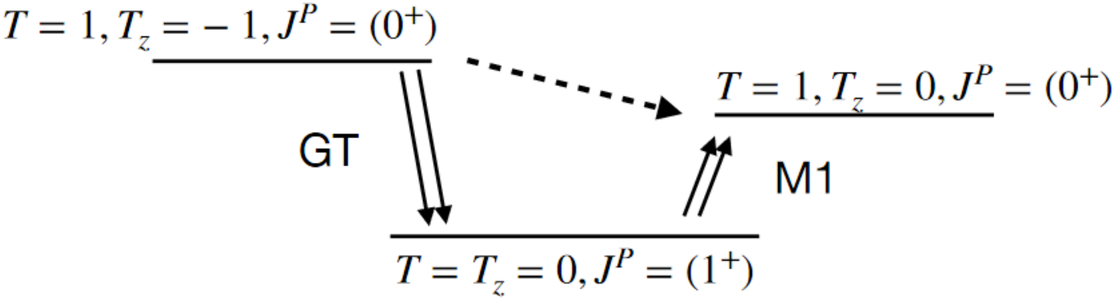


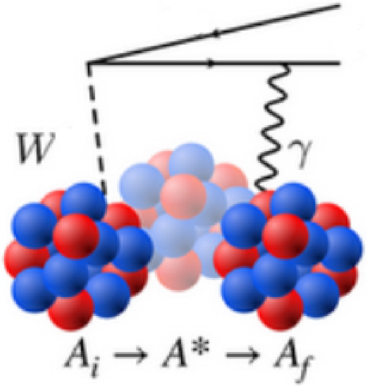
Can be studied using ab-initio methods! *See Michael Gennari's talk*

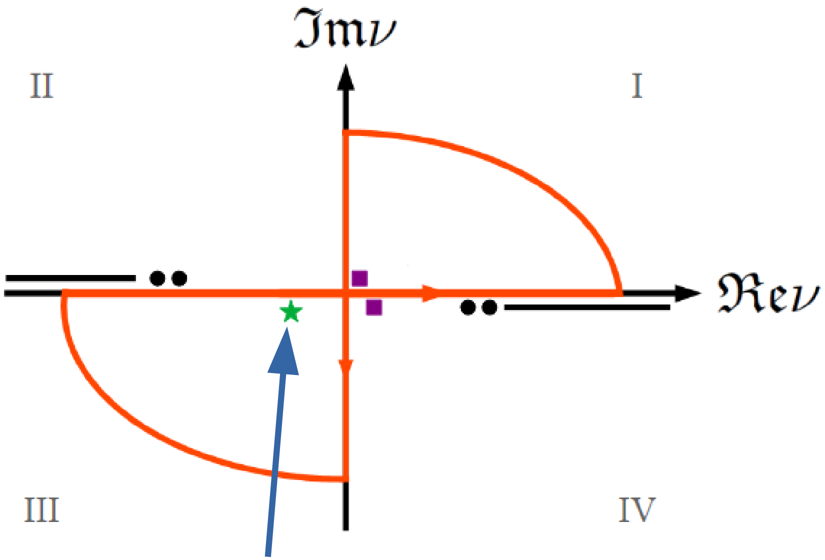
Residue contribution

Mehdi Drissi, Michael Gennari, Petr Navratil

If the daughter nucleus is an **excited state**:







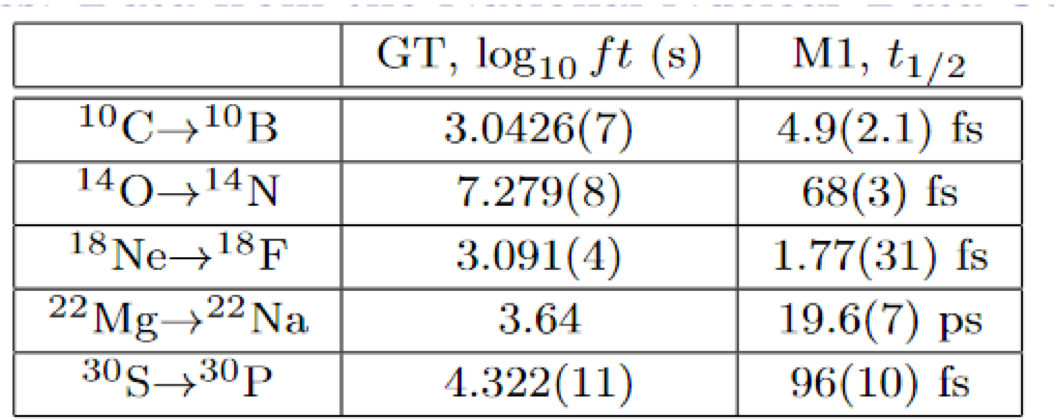
A **residue contribution** from pole in 3rd quadrant

Residue due to a low-lying $J^P=1^+$ state:

$$\mathfrak{Res}\,T_3 \propto \langle f(0^+)|J^x_{\rm em}(\vec{q})|f(1^+)\rangle\langle f(1^+)|J^y_W(-\vec{q})|i(0^+)\rangle$$

M1-transition **GT-transition**

Matrix elements can be inferred from **M1** and **GT**-transition rates!



	GT, $\log_{10} ft$ (s)	M1, $t_{1/2}$
^{10}C→^{10}B	3.0426(7)	4.9(2.1) fs
^{14}O→^{14}N	7.279(8)	68(3) fs
^{18}Ne→^{18}F	3.091(4)	1.77(31) fs
^{22}Mg→^{22}Na	3.64	19.6(7) ps
^{30}S→^{30}P	4.322(11)	96(10) fs

From IAEA / NNDC website

Motivations for future experiments!

Ab-initio calculation? See Thomas Papenbrock's talk

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Current quoted value:

$$\boxed{|V_{ud}|_{0^+} = 0.97361(5)_{\mathrm{exp}}(6)_{\delta_R'}(4)_{\delta_\mathrm{C}}(28)_{\delta_\mathrm{NS}}(10)_\mathrm{RC}}$$

Gorchtein and CYS, 2311.00044

Included:

- (Averaged) new calculations of Δ_R^V
- Preliminary re-evaluation of δ_{NS}

NOT Included:

- Fully data-driven determination of *ft*-values
- Ab-initio calculation of δ_C and δ_{NS}

Result is preliminary, use with care!!

Valuable inputs in the future:

Experiment:

- Nuclear charge radii
- Nuclear M1-transition rates
- Nucleon/nuclear structure functions
- ...

Lattice QCD:

- Independent evaluation of nucleon structure functions
- ...

Ab-initio calculation:

- Controlled studies of δ_C and δ_{NS}
- ...