Workshop on Flavor Changing and Conserving Processes
Villa Orlando, Anacapri
September 29 - October 1 2025

Status of the Cabibbo angle determination

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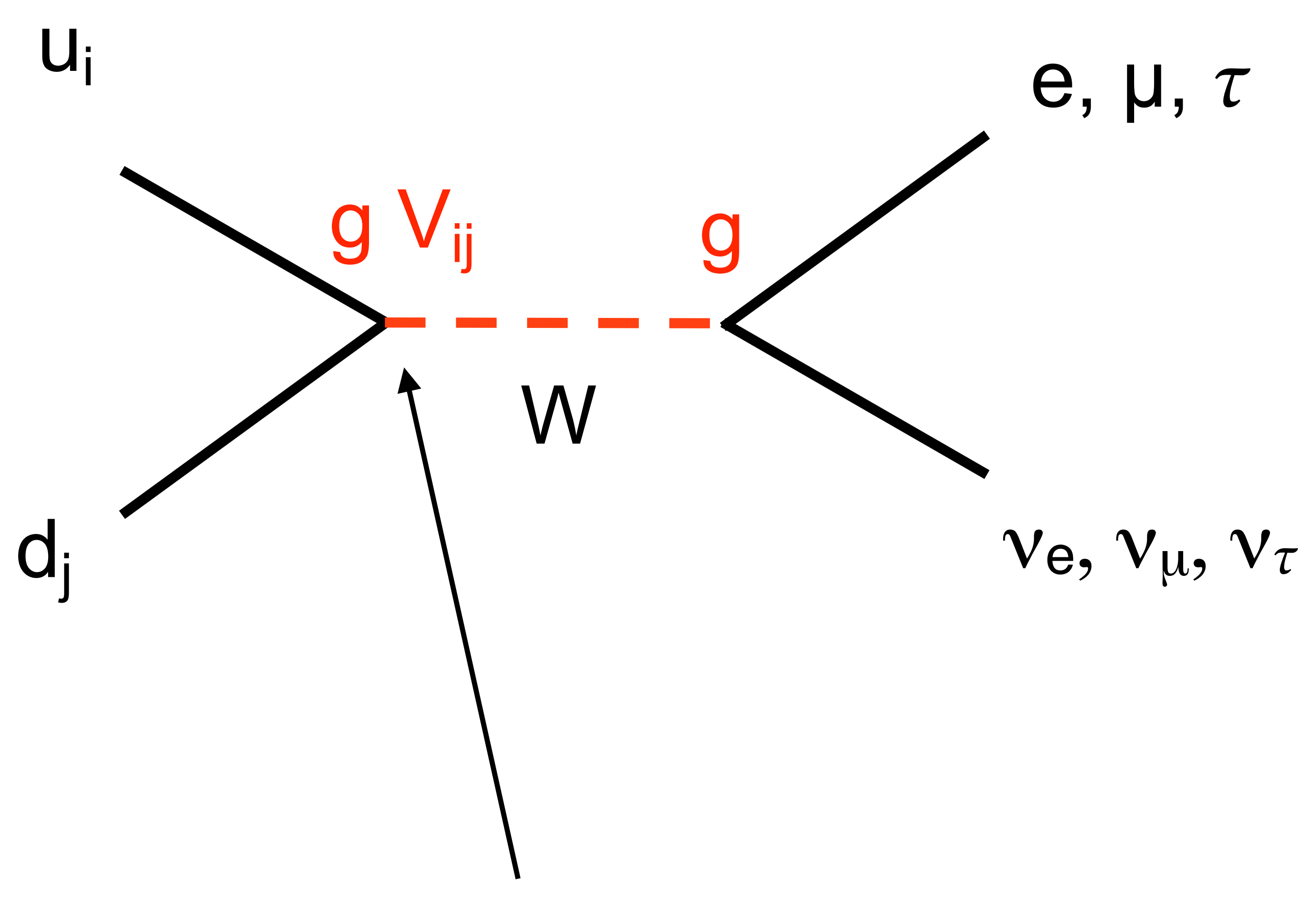
Semi-leptonic charged-current processes

- In the SM, W exchange between L-handed fermions ⇒ “V-A” currents & universality relations



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa

Cabibbo universality (CKM unitarity)

~0..95 ~0.05 ~1.5 $\times 10^{-5}$

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

$\delta V_{ud}/V_{ud}$ ~ 0.03% $\delta V_{us}/V_{us}$ ~ 0.2% $\delta V_{ub}/V_{ub}$ ~ 5%

V_{ud} and V_{us} are the most accurately known elements of the CKM matrix ⇒

I^{st} row provides the most stringent test of universality & sensitivity to new physics

Semi-leptonic charged-current processes

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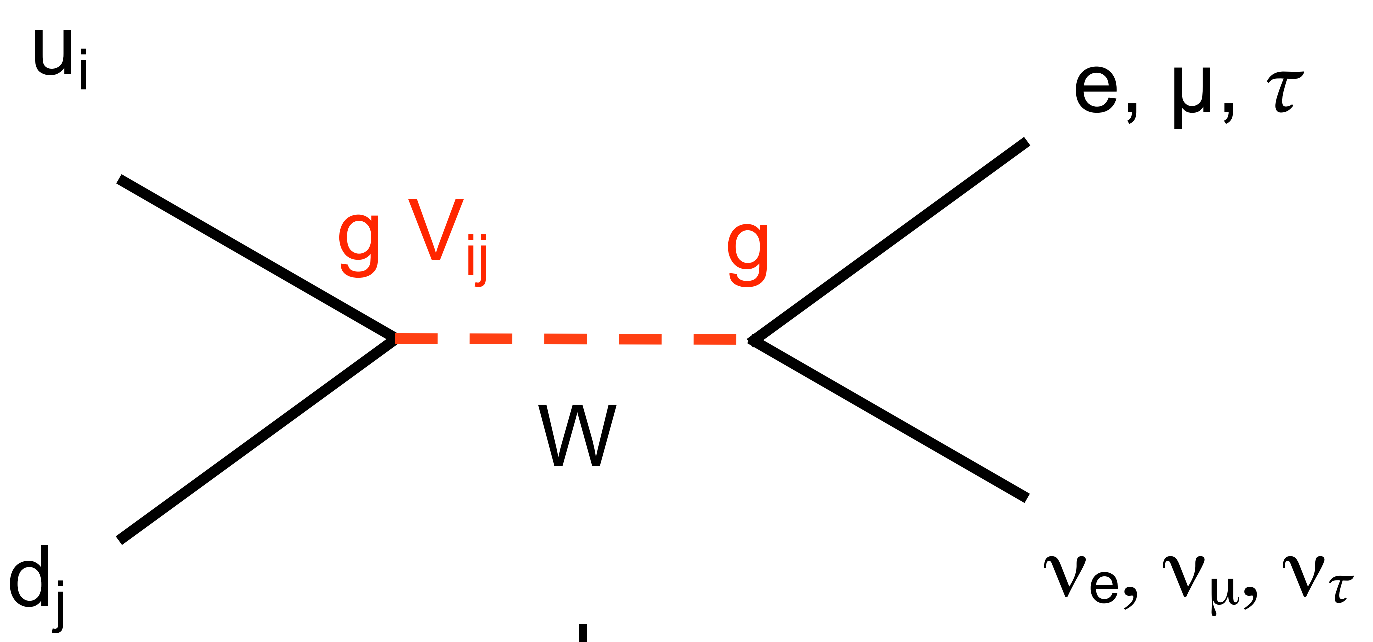

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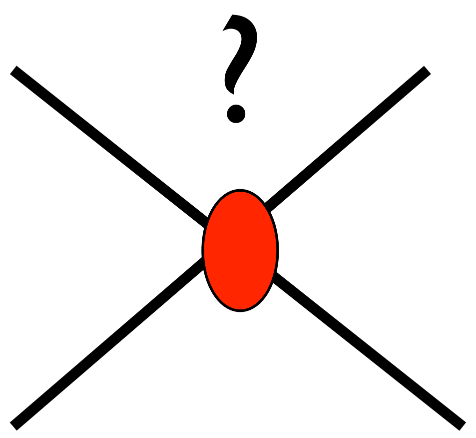


at low energy

$G_F^{(\mu)}\, V_{ij} \sim 1/v^2\, V_{ij}$

$1/\Lambda^2$

New physics can spoil universality: $|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1 + O\left(\frac{v^2}{\Lambda^2}\right)$

Current precision ⇒ probe effective scale Λ ~ 10 TeV

Compelling but challenging!

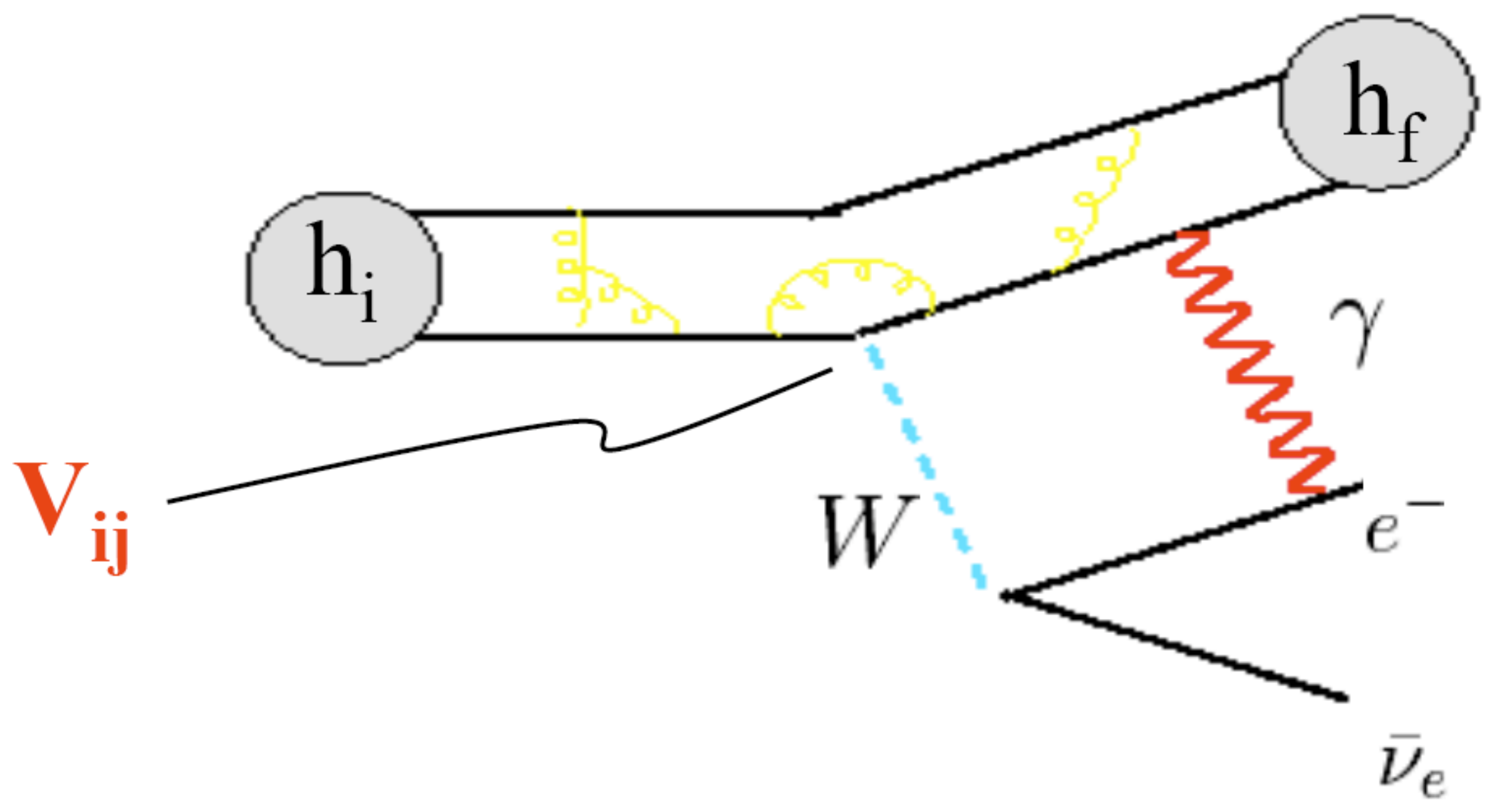
Outline

- Overview: paths to V_{ud} & V_{us} and current puzzles
- A closer look:
    - Status and prospects for selected channels
    - Radiative corrections to neutron and nuclear decays in EFT

Paths to V_{ud} & V_{us}: status and puzzles

Paths to V_{ud} and V_{us}

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^0 e \nu$ Nucl. $0^+ \to 0^+$	$n \to p e \nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi \, l \, \nu$	$\Lambda \to p e \nu, \ldots$	$K \to \mu\nu$	$\tau \to h_S \nu$

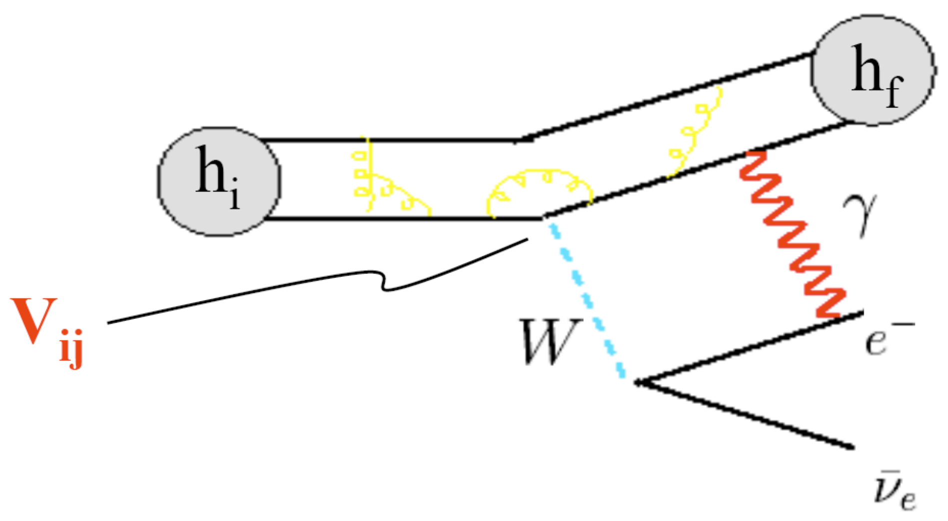


The challenge of CKM precision tests

Extract $V_{us}=\sin\theta_C=\lambda$ and $V_{ud}=\cos\theta_C \simeq 1 - \lambda^2/2$

with *sub-percent precision* from *decays involving hadrons*

(currently $\delta\lambda/\lambda \sim 0.2\text{-}0.5\%$)



$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

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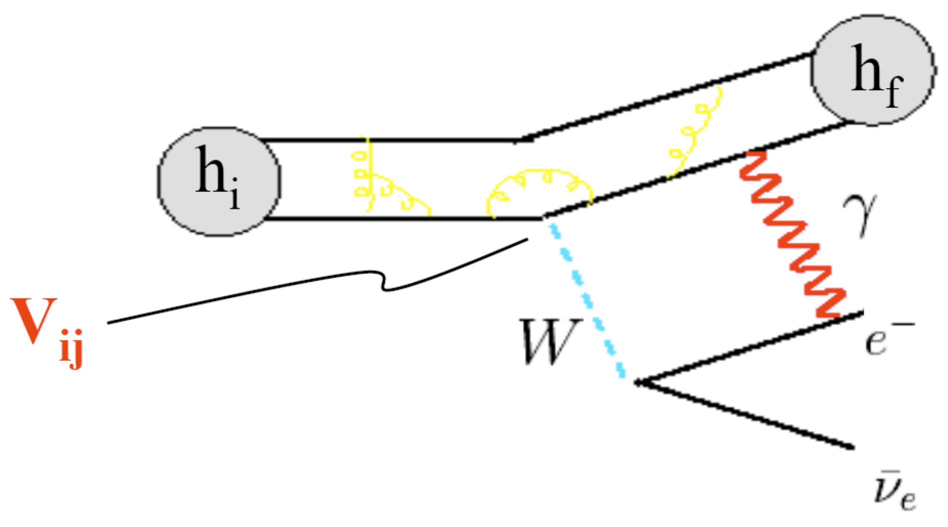

$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1 + \Delta_R) \times F_{\rm kin}$$

Lifetimes, BRs

Muon decay

Experimental input

Q-values, form factors, … → phase space

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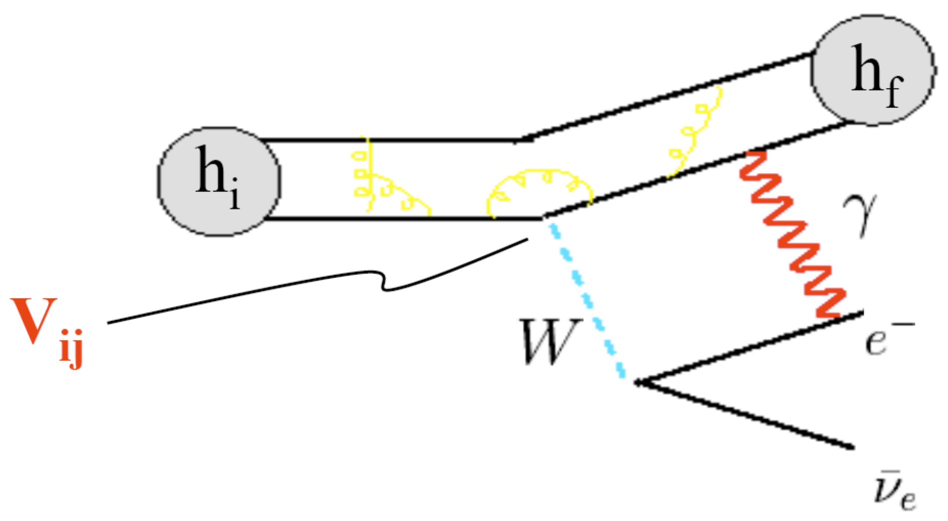

$$\Gamma = G_F^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\Delta_R) \times F_{\rm kin}$$

Theory input

Hadronic / nuclear matrix elements of the weak V-A current, including small corrections such as those induced by electromagnetic radiative corrections $[(\alpha/\pi) \sim 2. \times 10^{-3}]$

Hadronic matrix elements

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^0 e\nu$ Nucl. $0^+ \to 0^+$	$n \to pe\nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi l \nu$	$\Lambda \to pe\nu, \ldots$	$K \to \mu\nu$	$\tau \to h_S\nu$

Hadronic matrix elements: 'Vector - Axial' quark current

V

V, A

A

V, A

Berhends-Sirlin
Ademollo-Gatto

Traditionally "Golden modes":
$\langle f | V_\mu | i \rangle$ known in SU(2) [SU(3)] limit
&
corrections are 2nd order in
SU(2) [SU(3)] breaking.
Computed in lattice QCD for $K \to \pi$

Need experimental input on
$\langle f | A | i \rangle / \langle f | V | i \rangle$

For neutron and hyperons,
Lattice QCD catching up but
not as precise as experiment

$\langle 0 | A_\mu | M \rangle$
(decay constants)
from Lattice QCD
[~0.2%]

Use combination of
data and theory
(pQCD + lattice QCD)

Radiative corrections

	Hadron decays			Lepton decays
V_{ud}	$\pi^{\pm} \to \pi^{0} e \nu$ Nucl. $0^{+} \to 0^{+}$	$n \to p e \nu$ Nucl. mirror decays	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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Electroweak radiative corrections

Mesons and neutron:
well developed Effective Field Theory (EFT) framework, with non-perturbative input from lattice QCD and / or dispersive methods — systematically improvable

For leptonic meson decays:
full lattice QCD+QED available

Recent activity to assess nuclear structure uncertainties:

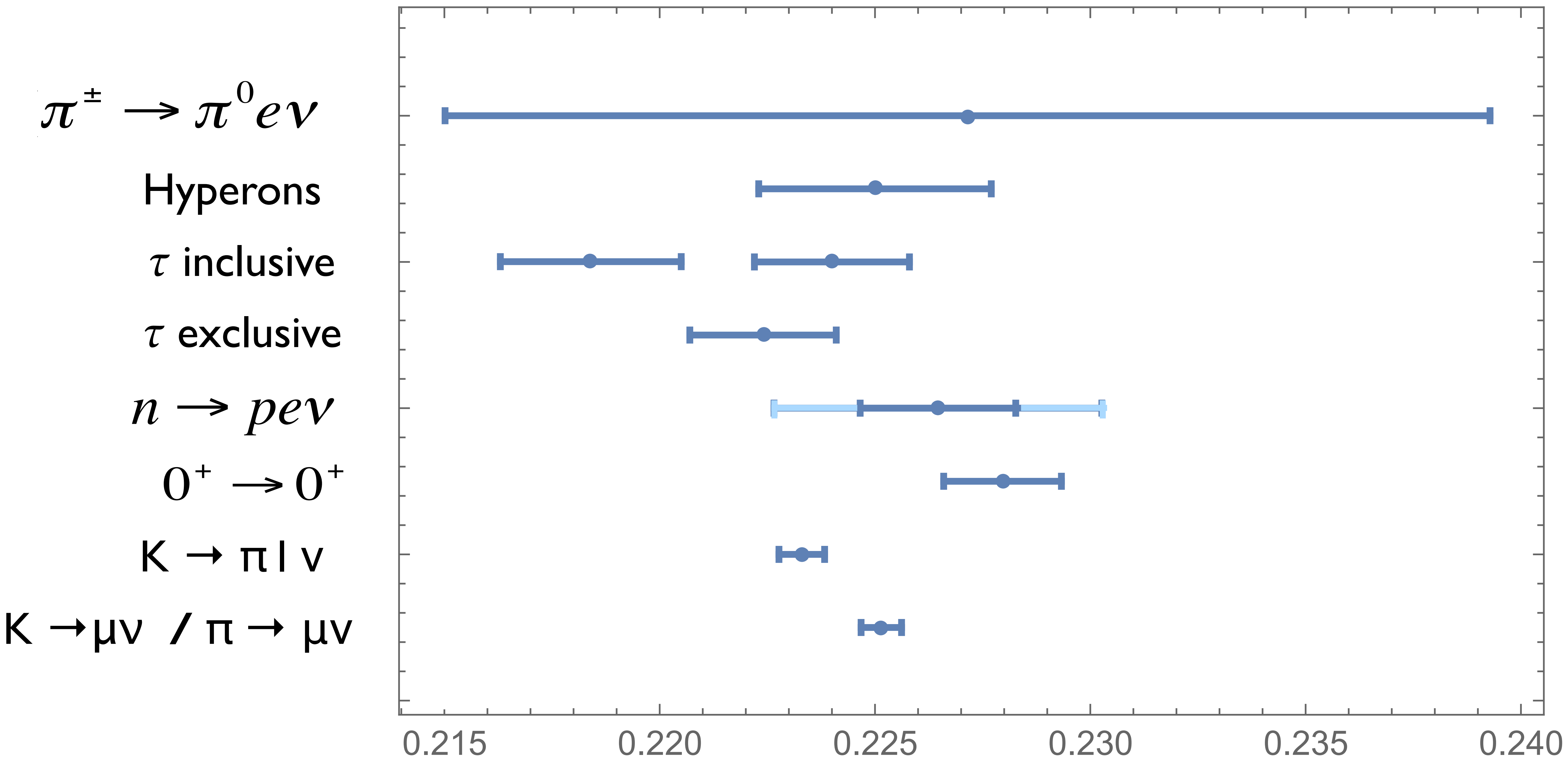
- Dispersive approach
- Chiral EFT

For exclusive channels, difficult to estimate the hadronic structure-dependent effects. Lattice QCD+QED?

The Cabibbo angle — global view

Convert V_{ud} to V_{us} via unitarity

[References given in following slides]



V_{us}

Fractional uncertainty	Largest uncertainty
5.3%	EXP
1.2% +?	EXP + TH
0.8% + ?	EXP + TH
0.8% + ?	EXP + TH
0.8% (1.7%) (PDG)	EXP
0.6% + ?	TH
0.24%	EXP + TH
0.21%	TH

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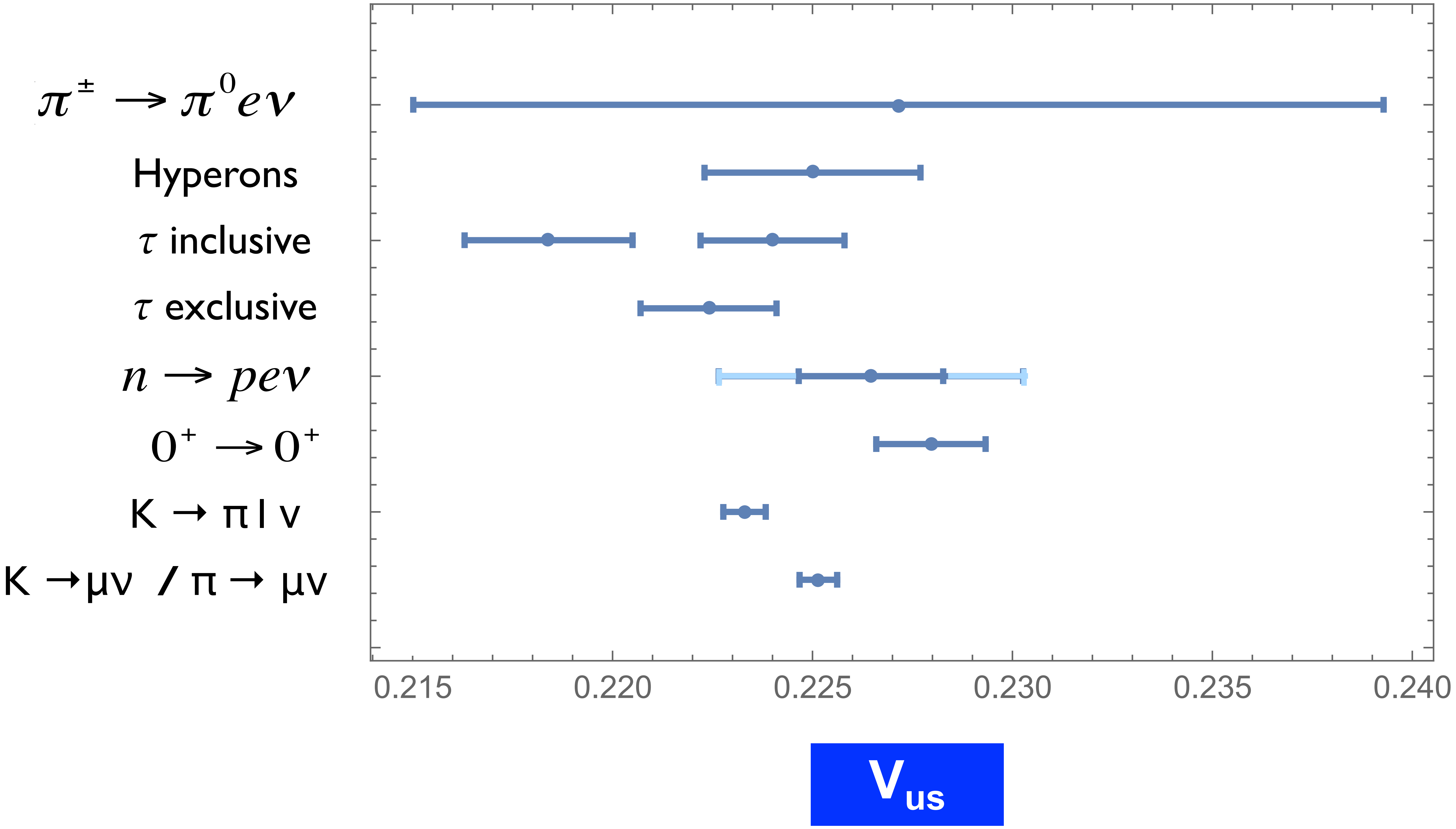
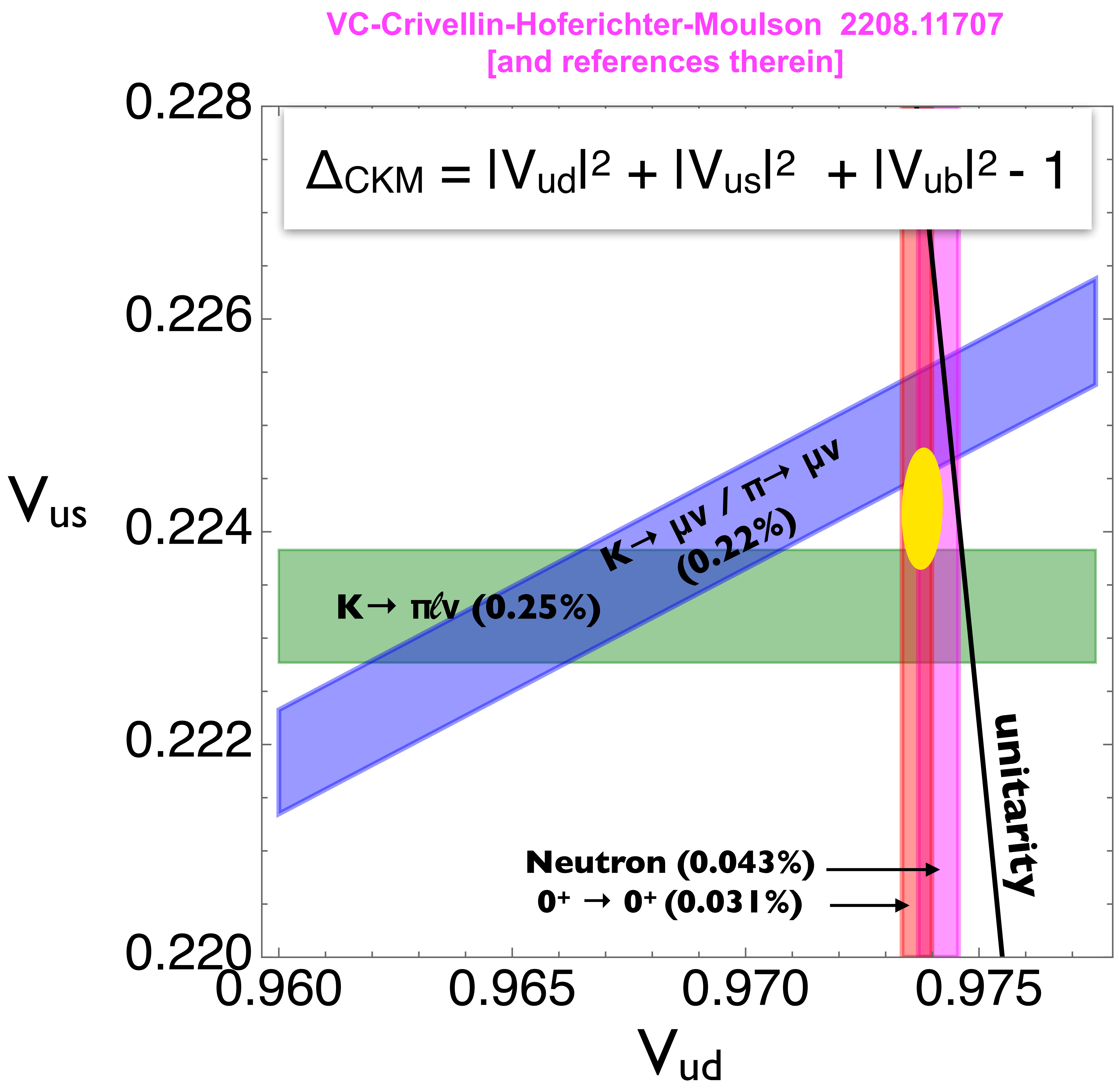


	Fractional uncertainty	Largest uncertainty
$\pi^{\pm} \to \pi^0 e \nu$	5.3%	EXP
Hyperons	1.2% +?	EXP + TH
τ inclusive	0.8% + ?	EXP + TH
τ exclusive	0.8% + ?	EXP + TH
$n \to p e \nu$	0.8% (1.7%) (PDG)	EXP
$0^+ \to 0^+$	0.6% + ?	TH
$K \to \pi l \nu$	0.24%	EXP + TH
$K \to \mu\nu \;/\; \pi \to \mu\nu$	0.21%	TH

Tension among the most precise determinations

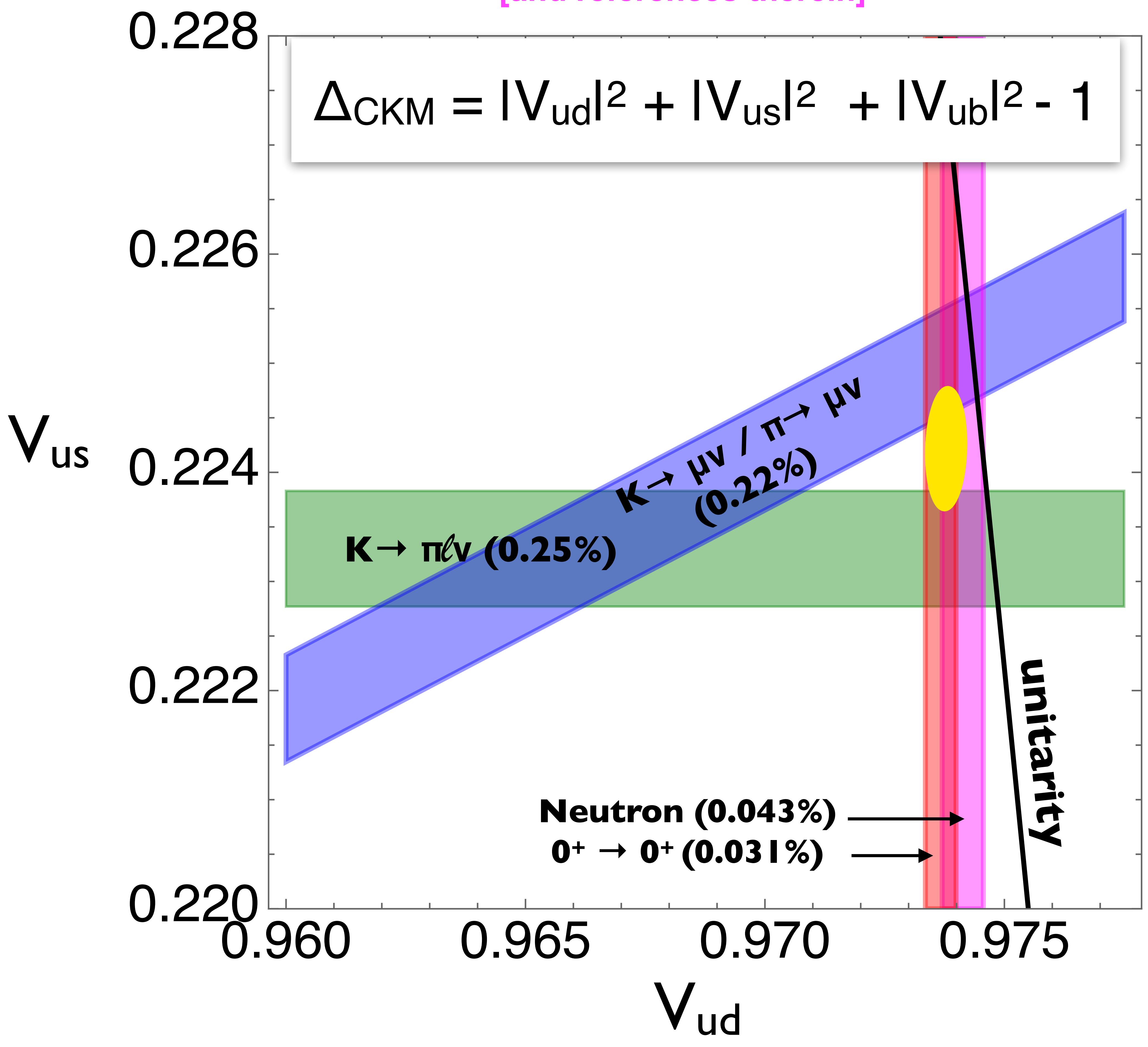
Tensions in the V_{ud}-V_{us} plane



- Bands don't intersect in the same region on the unitarity circle
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

Tensions in the V_{ud}-V_{us} plane

VC-Crivellin-Hoferichter-Moulson 2208.11707
[and references therein]

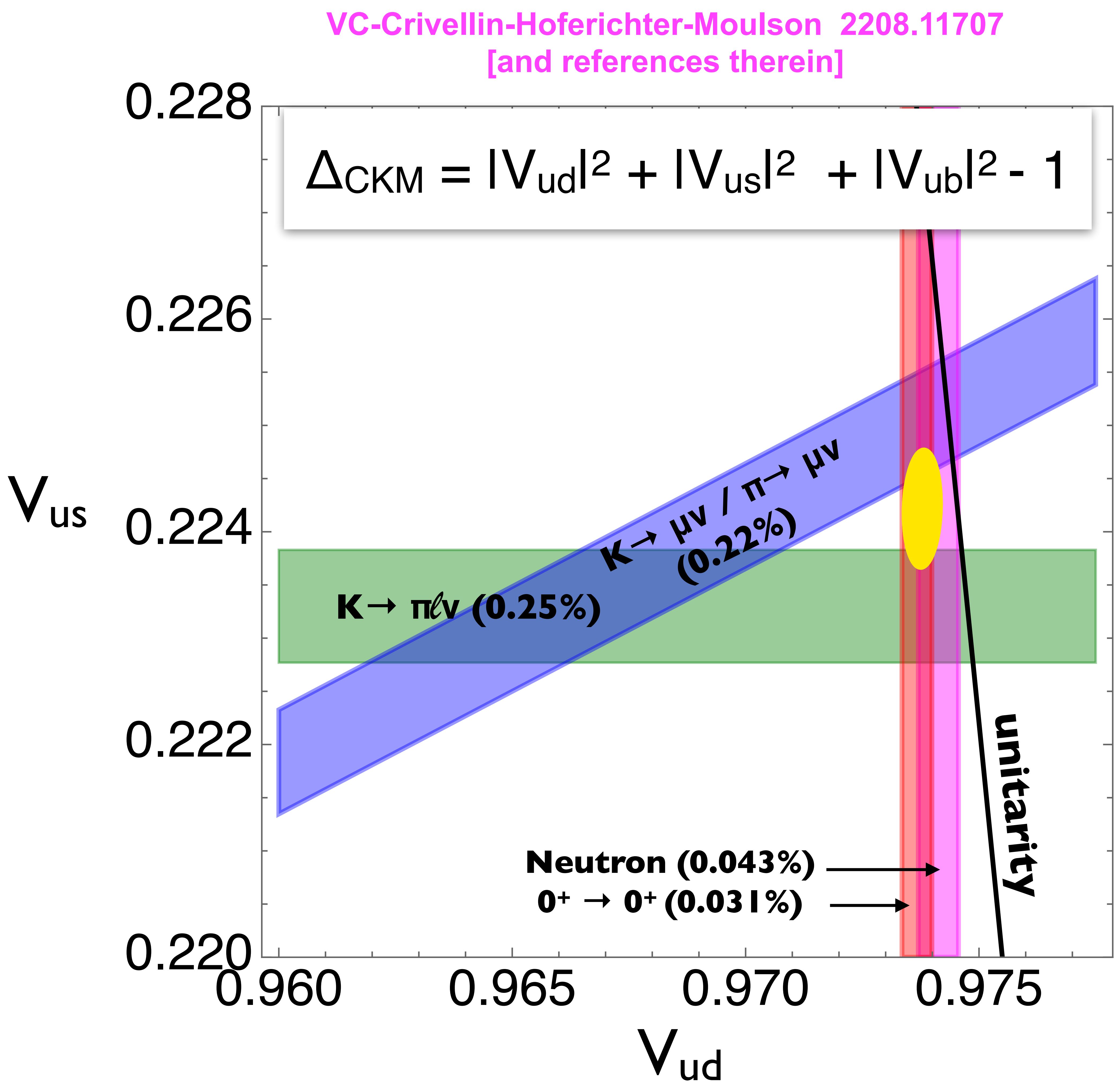


- Bands don't intersect in the same region on the unitarity circle
- ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)

For the enthusiasts

- Until ~2018, bands *did* intersect in the same region on the unitarity circle (< 2σ)
- *Main* changes since then:
  - V_{us} from Kl3 decreased (<V> increased with smaller uncertainty, 2+1+1 lattice QCD) MILC Collab.
  - V_{ud} decreased (radiative corrections in nuclear & neutron increased with smaller uncertainty, dispersive) Seng et al., 1807.10197

Tensions in the V_{ud}-V_{us} plane



Next

- Closer look at selected channels
- Emphasis on recent developments in radiative corrections

A closer look at selected channels

	Hadron decays			Lepton decays
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V_{ud} from pion β decay

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma)) = \frac{G_\mu^2 |V_{\rm ud}|^2 m_{\pi^+}^5 \left|f_+^\pi(0)\right|^2}{64\pi^3}(1 + {\rm RC}_\pi) I_\pi ,$$

- Vector form factor

$$f_+(0) = 1 - \frac{1}{(4\pi F_\pi)^2}\frac{(M_{K^+}^2 - M_{K_0}^2)^2_{\rm QCD}}{24 M_K^2} = 1 + O\left(\frac{m_u - m_d}{\Lambda_{\rm QCD}}\right)^2$$

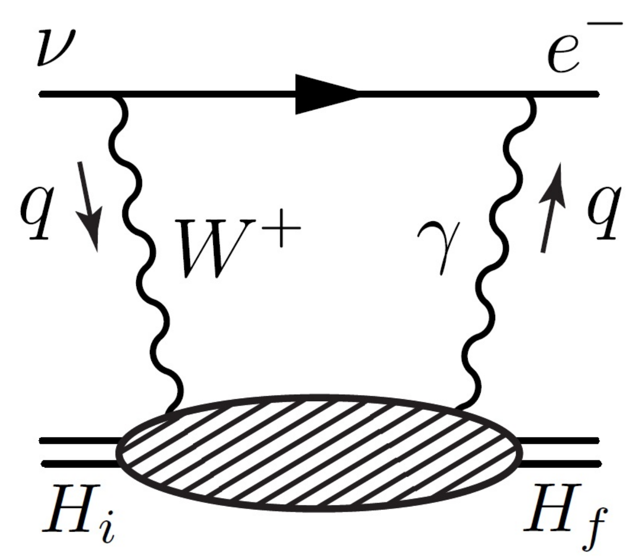
- Radiative corrections

$\boxed{{\rm RC}_\pi = 0.0342(10)}$ (ChPT) $\longrightarrow$ $\boxed{{\rm RC}_\pi = 0.0332(1)_{\gamma W}(3)_{HO}}$

VC-Neufeld-Pichl 2002

Box diagram in Lattice QCD

Feng, Gorchtein, Jin, Ma, Seng, 2003.09798



Theory in good shape (cleanest channel)

0.3% total error on V_{ud} dominated by BR = $1.036(6)\times10^{-8}$ [PIBETA , hep-ex/ 0312030]

$$V_{ud}^{(\pi\beta)} = 0.97386\,(281)_{BR}\,(9)_{\tau_\pi}\,(14)_{RC}\,(28)_{I_\pi}\,[283]_{\rm total}$$

Uncertainty in π^0 mass! [M. Hoferichter]

Experiment needs order-of-magnitude improvement in precision to be competitive → PIONEER @ PSI

2203.01908

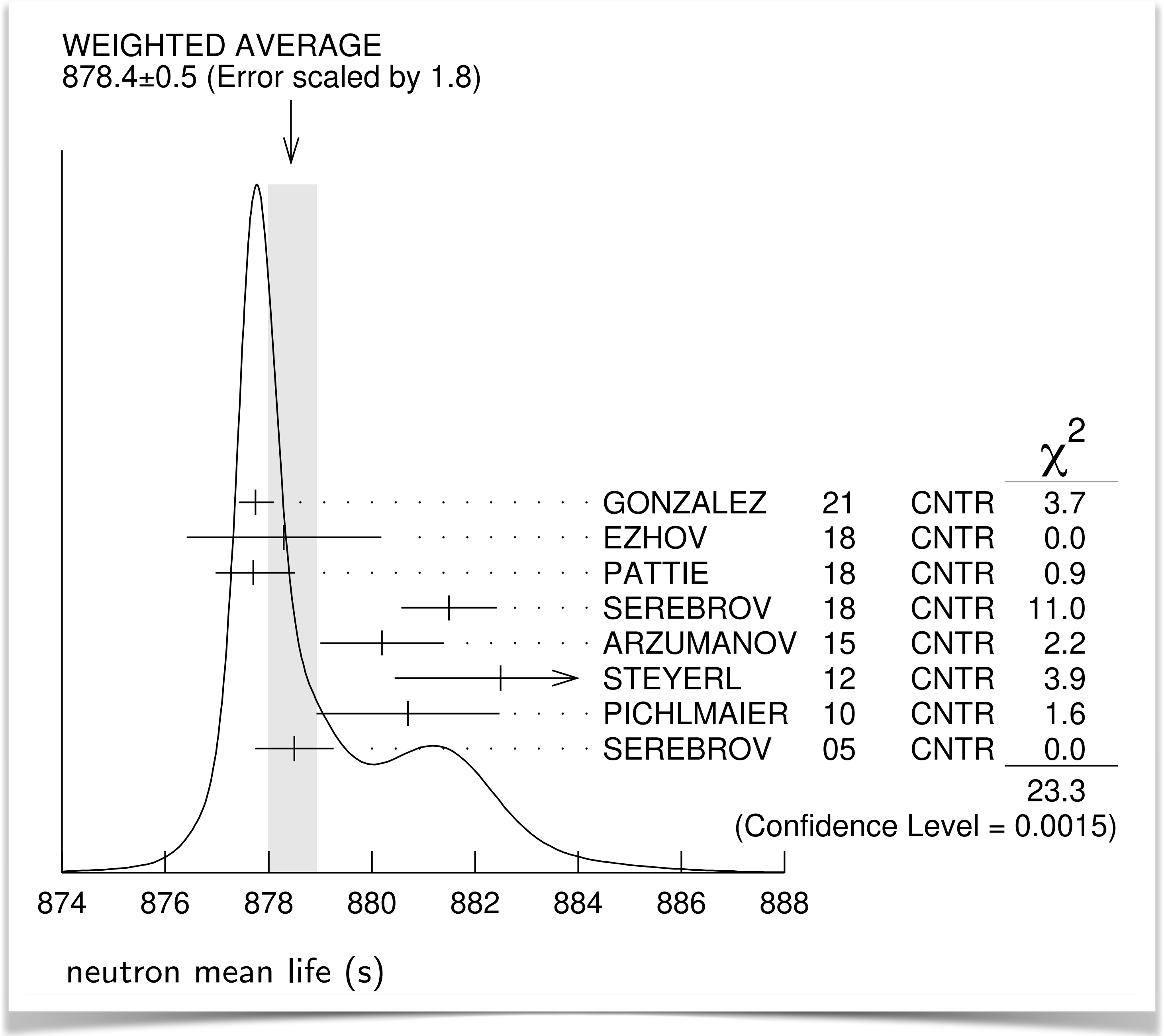
V_{ud} from neutron decay

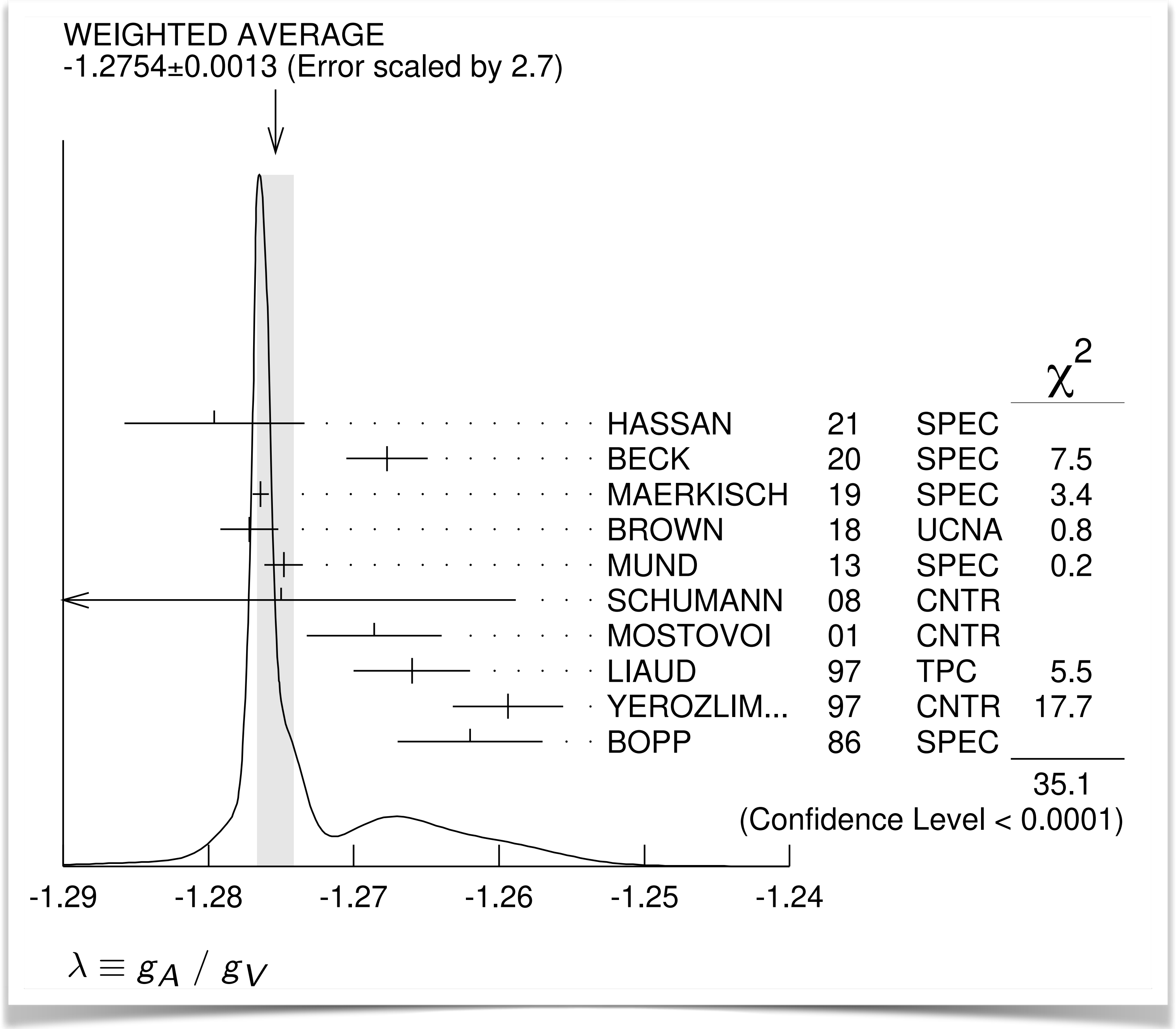
$\lambda = g_A/g_V$

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1+3\lambda^2) \cdot f_0 \cdot (1+\Delta_f) \cdot (1+\Delta_R),$$

Sirlin 1967-1978-1982
Seng et al. 1807.10197,
Czarnecki et al, 1907.06737,
Shiells et al. 2012.01580
Hayen 2010.07262 ,
Gorchtein-Seng 2106.09185

- **Radiative corrections:** radiative corrections in the Sirlin framework with dispersive input
- **Experimental input:** PDG averages include large scale factor, particularly for g_A/g_V





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- Radiative corrections: radiative corrections in the Sirlin framework with dispersive input
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Single most precise measurements of lifetime and λ imply very competitive V_{ud}!

Maerkish et al, 1812.04666 Gonzalez et al, 2106.10375

$$V_{ud}^{\text{n,PDG}} = 0.97441(3)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\text{total}}$$

$$V_{ud}^{\text{n,best}} = 0.97413(3)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[43]_{\text{total}}$$

VC, Crivellin, Hoferichter. Moulson 2208.11707
and references therein

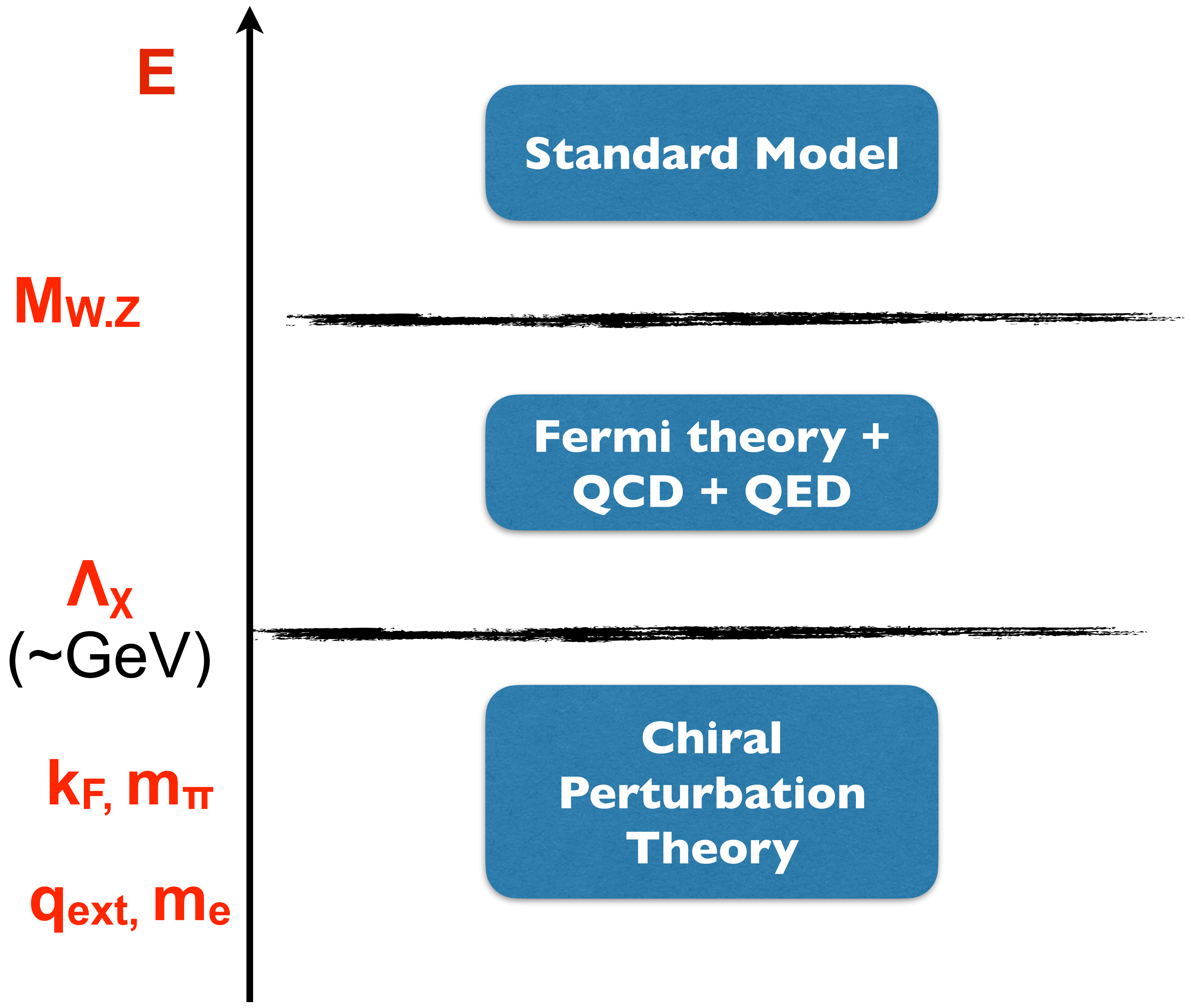
Need improvements in lifetime and g_A/g_V.
Within reach in next 5 years

Development: EFT for radiative corrections

VC, W. Dekens, E. Mereghetti, O.Tomalak, 2306. 03138

- ‘End-to-end’ EFT approach for neutron decay, motivated by widely separated scales

$$\Lambda_{BSM} \gg M_W \gg \Lambda_\chi \gg Q \sim k_F \sim m_\pi \gg m_e \sim q_{ext}$$



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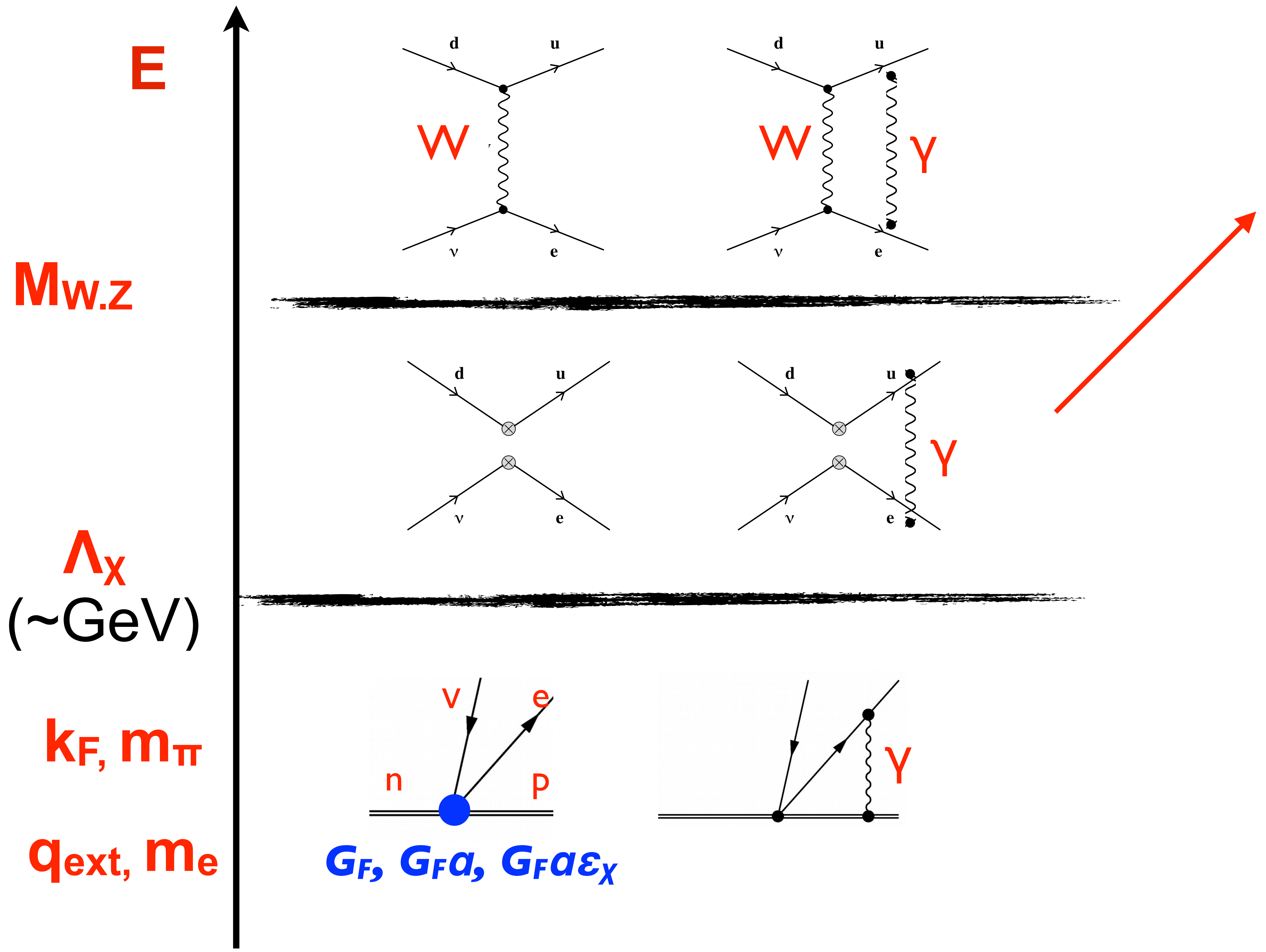

$$\mathcal{L}_{\rm Fermi} = -\frac{G_F}{\sqrt{2}} V_{ud}\, C_\beta(\mu)\; \bar{\ell}\gamma_\alpha(1-\gamma_5)\nu_\ell\, \bar{u}\gamma^\alpha(1-\gamma_5)d + \ldots$$

$C_\beta(\mu) \sim 1 + \#\, (\alpha/\pi)\ln(M_W/\mu) + \ldots$

Known to LL $\sim (\alpha \ln(M_W/\mu))^n$ and NLL $\sim \alpha\, (\alpha_s \ln(M_W/\mu))^n$, $\alpha\, (\alpha \ln(M_W/\mu))^n$

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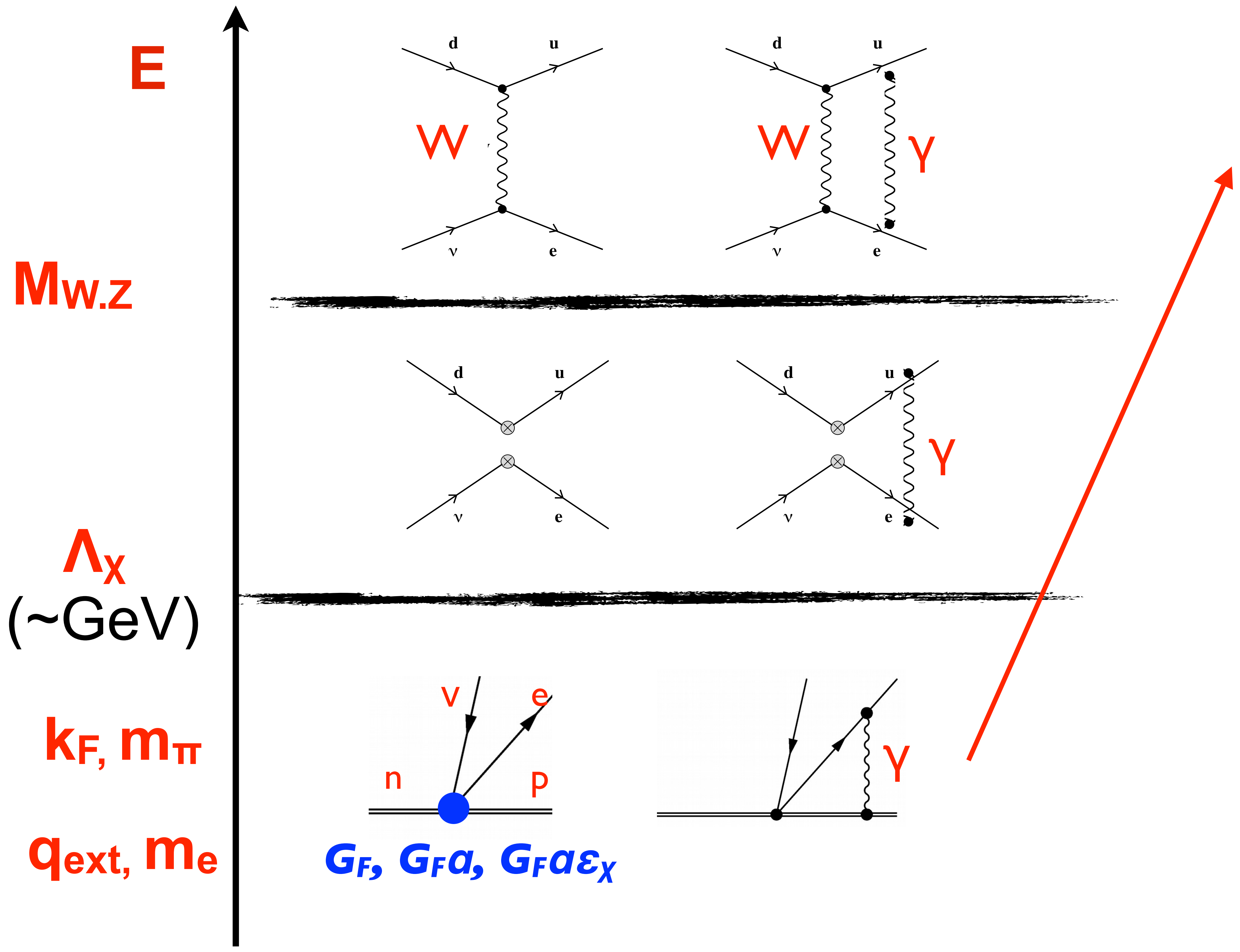

$$\mathcal{L}_{\not\pi} = -\sqrt{2} G_F V_{ud}\, \bar{e}\gamma_\mu P_L \nu_e\, \bar{N}\left(g_V v_\mu - 2 g_A S_\mu\right)\tau^+ N \; + \; \ldots$$

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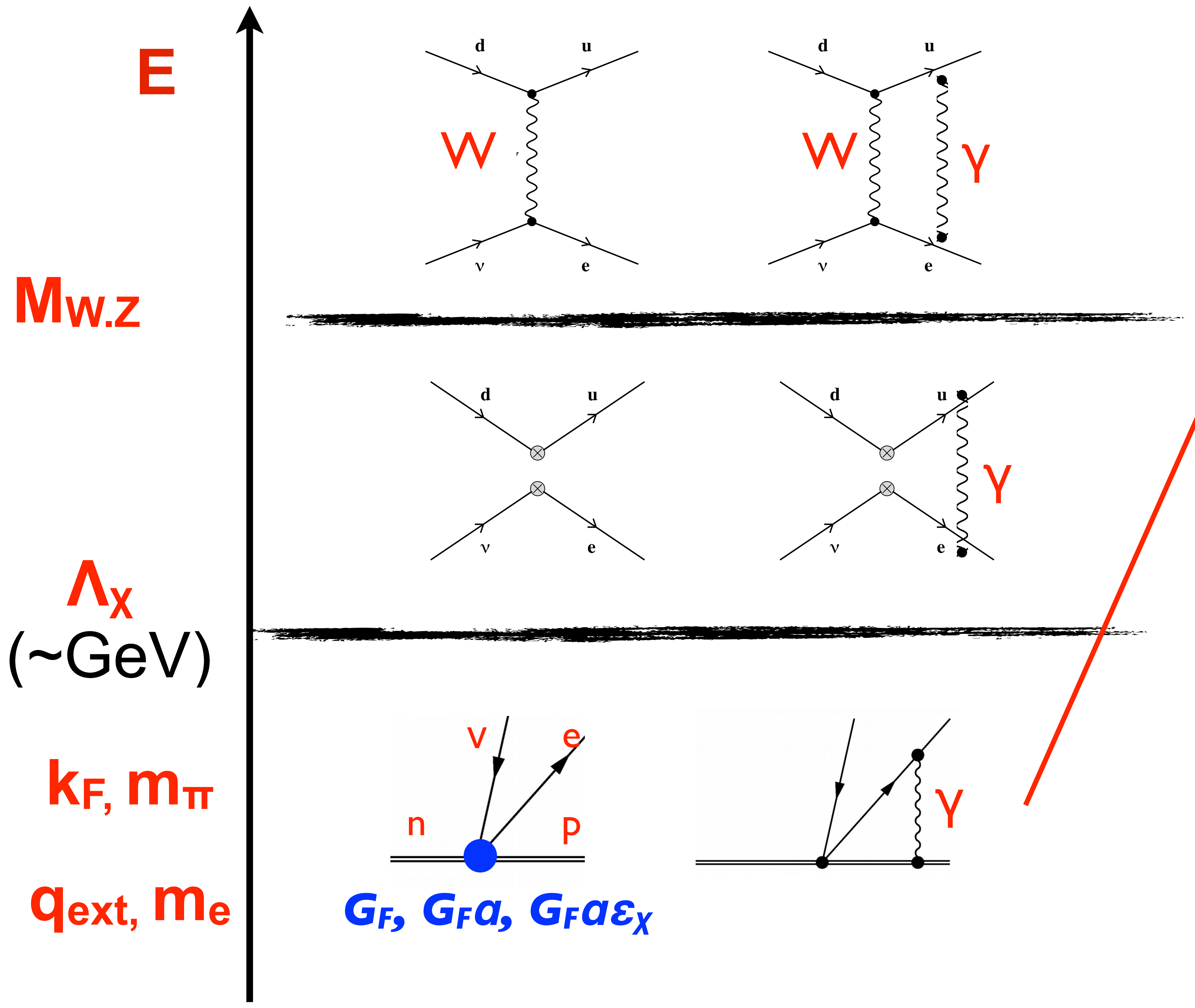

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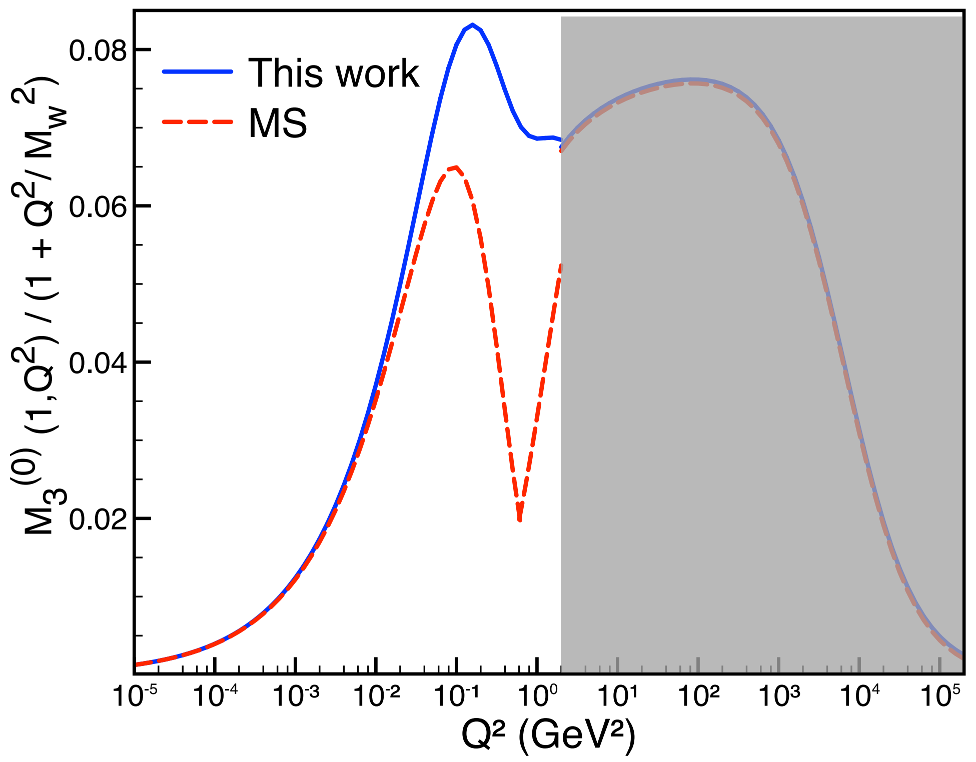
Matching LEFT → ChPT at NLL approximation

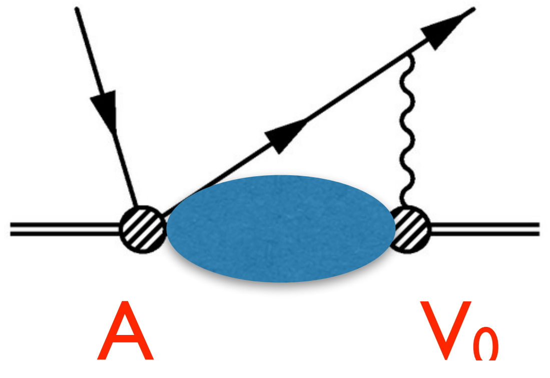
$$g_V(\mu_\chi) = U(\mu_\chi, \Lambda_\chi)\left[1 + \overline{\Box}^V_{\text{Had}} + \frac{\alpha(\Lambda_\chi)}{\pi}\kappa\right] U(\Lambda_\chi, \mu_W)\, C_\beta(\mu_W)$$

NLL RGEs in Fermi theory



Non-perturbative contribution proportional to the γ-W 'box

[Seng et al. 1807.10197, 2308.16755]



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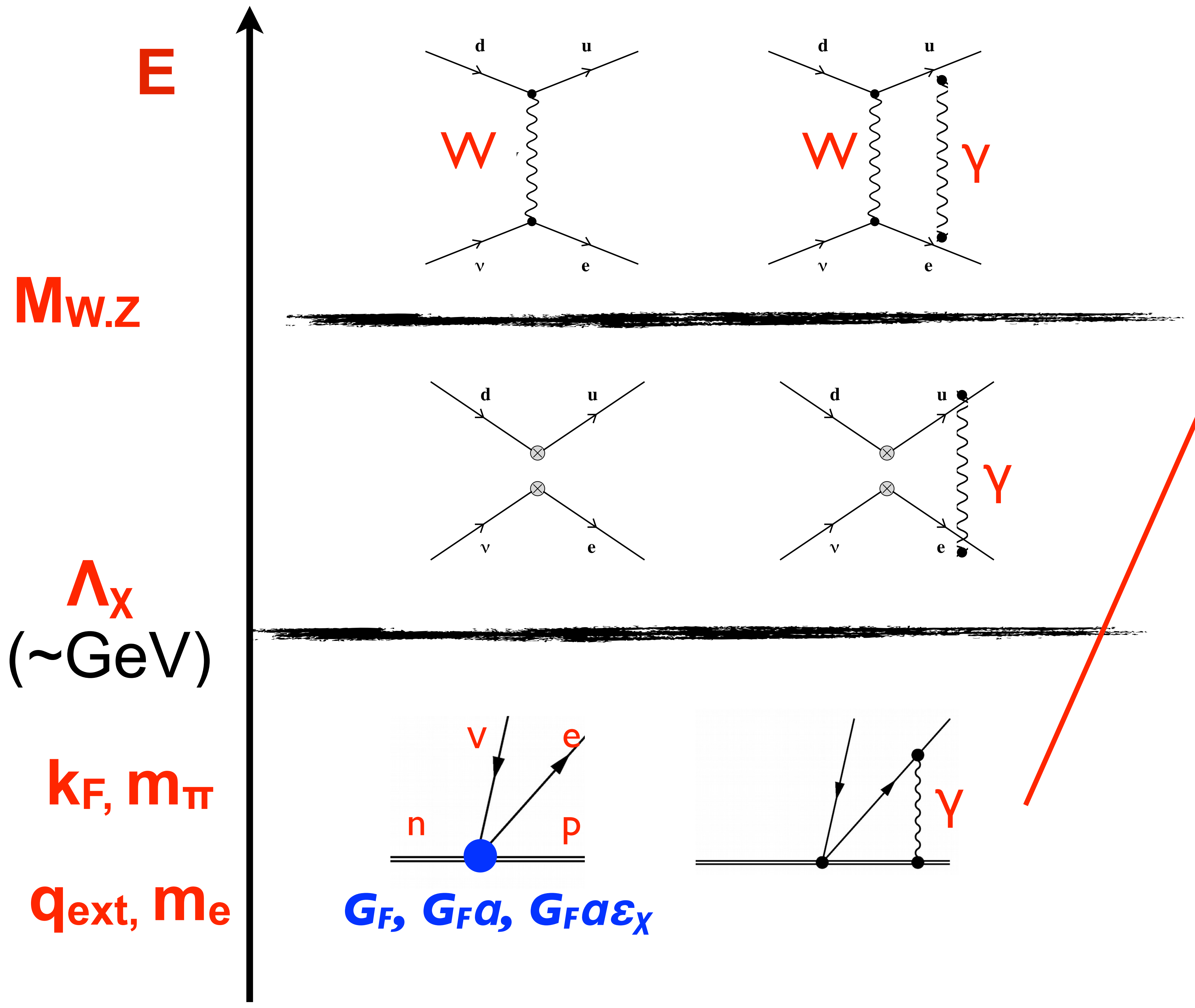

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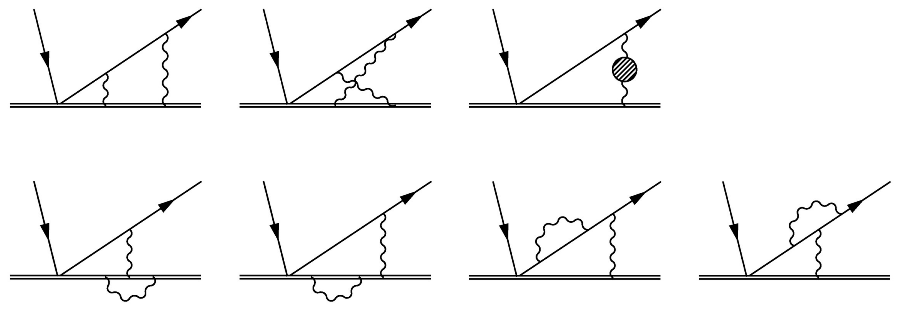
NLL RGE in ChPT

NLL ~ $\alpha\,(\alpha \ln(\Lambda_\chi/m_e))^n$



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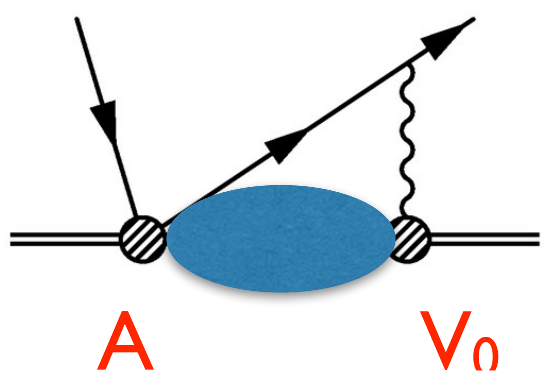

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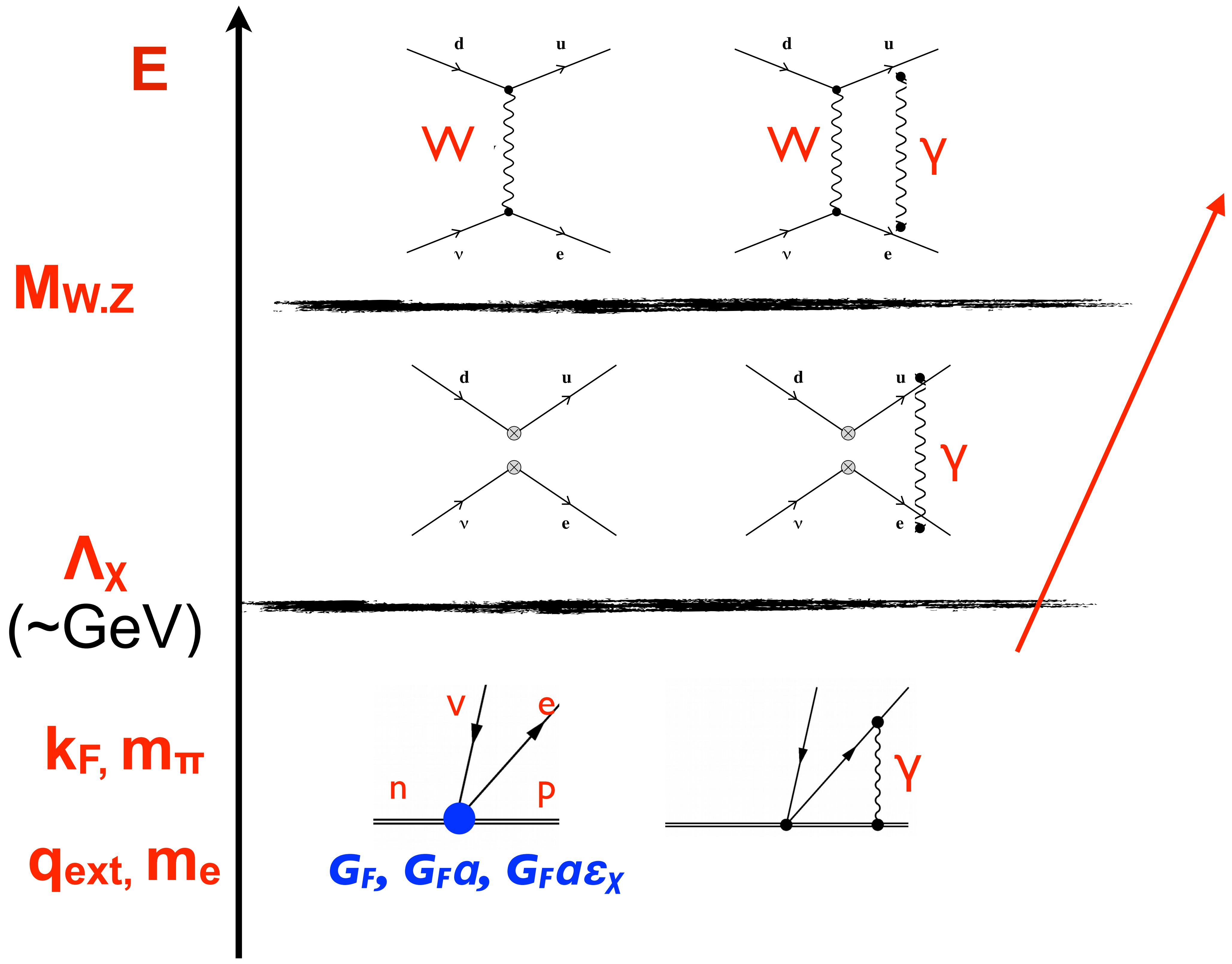
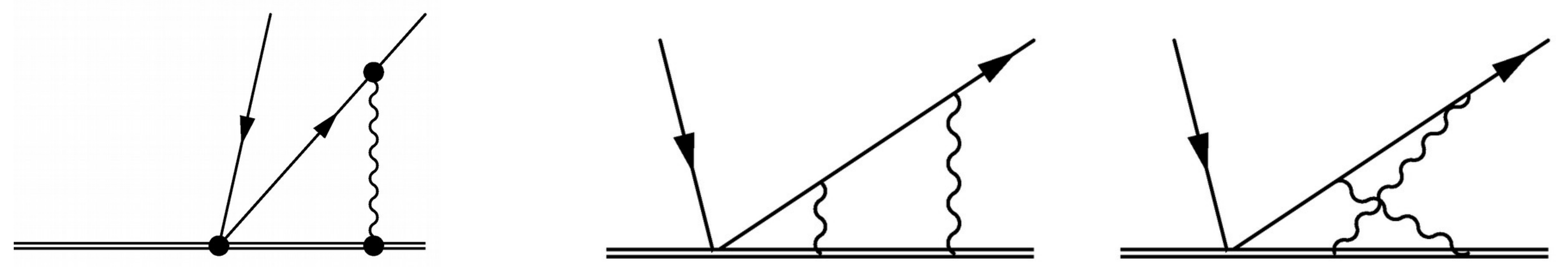


O(α, α²) matrix element in the low-energy EFT



No large logs but enhanced contributions ~ (πα/β), which we re-sum via the non-relativistic Fermi function *ansatz*

$$F_{NR}(\beta) = \frac{2\pi\alpha}{\beta}\frac{1}{1-e^{-\frac{2\pi\alpha}{\beta}}} \approx 1 + \frac{\pi\alpha}{\beta} + \frac{\pi^2\alpha^2}{3\beta^2} + \ldots \xrightarrow[m\to 0]{} 1 + \pi\alpha + \frac{\pi^2\alpha^2}{3} + \ldots$$

Enhanced terms are related to IR divergences in the loops, RG-based re-summation leads to (for $m_e \to 0$)

$$\exp\left[\frac{\pi\alpha}{\beta}\right] \xrightarrow[m\to 0]{} 1 + \pi\alpha + \frac{\pi^2\alpha^2}{2} + \ldots$$

Griend-Cao-Hill-Plestid 2501.17916

Impact on V_{ud}

$\lambda = g_A/g_V$

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1+3\lambda^2) \cdot f_0 \cdot (1+\Delta_f) \cdot (1+\Delta_R),$$

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Griend-Cao-Hill-Plestid 2501.17916

Griend-Cao-Hill-Plestid 2501.17916

$$\Delta_f = 3.573(5)_{\alpha\times\mathrm{recoil}}\,\% \quad \rightarrow \quad \Delta_f = 3.584(5)_{\alpha\times\mathrm{recoil}}\,\%$$

-0.024%

(Compared to pre-EFT analysis)

$$\Delta_R = 4.044(24)_{\mathrm{Had}}(8)_{\alpha\alpha_s^2}(7)_{\alpha\epsilon_\chi^2}(5)_{\mu_\chi}[27]_{\mathrm{total}}\ \%$$

+0.061%

Impact on V_{ud}

$\lambda = g_A/g_V$

$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3} (1+3\lambda^2) \cdot f_0 \cdot (1+\Delta_f) \cdot (1+\Delta_R),$$

$$\downarrow$$

$$V_{ud}^{\mathrm{n,PDG}} = 0.97424(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\mathrm{total}}$$

$$V_{ud}^{\mathrm{n,best}} = 0.97396(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\mathrm{total}}$$

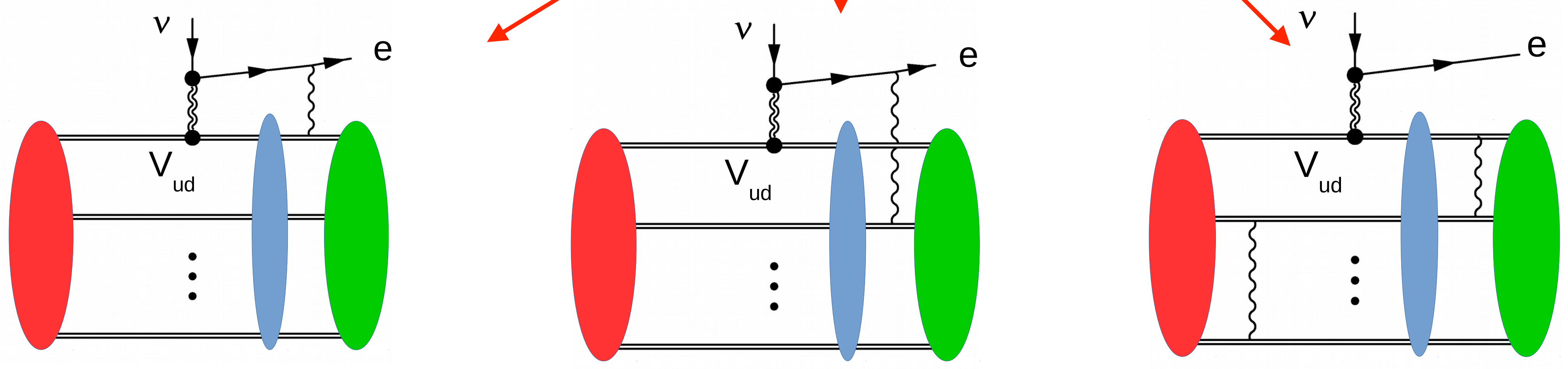
Overall shift of -0.0175% in V_{ud} (neutron) compared to pre-EFT literature —

larger than hadronic-structure uncertainty and relevant for target precision of 0.02%

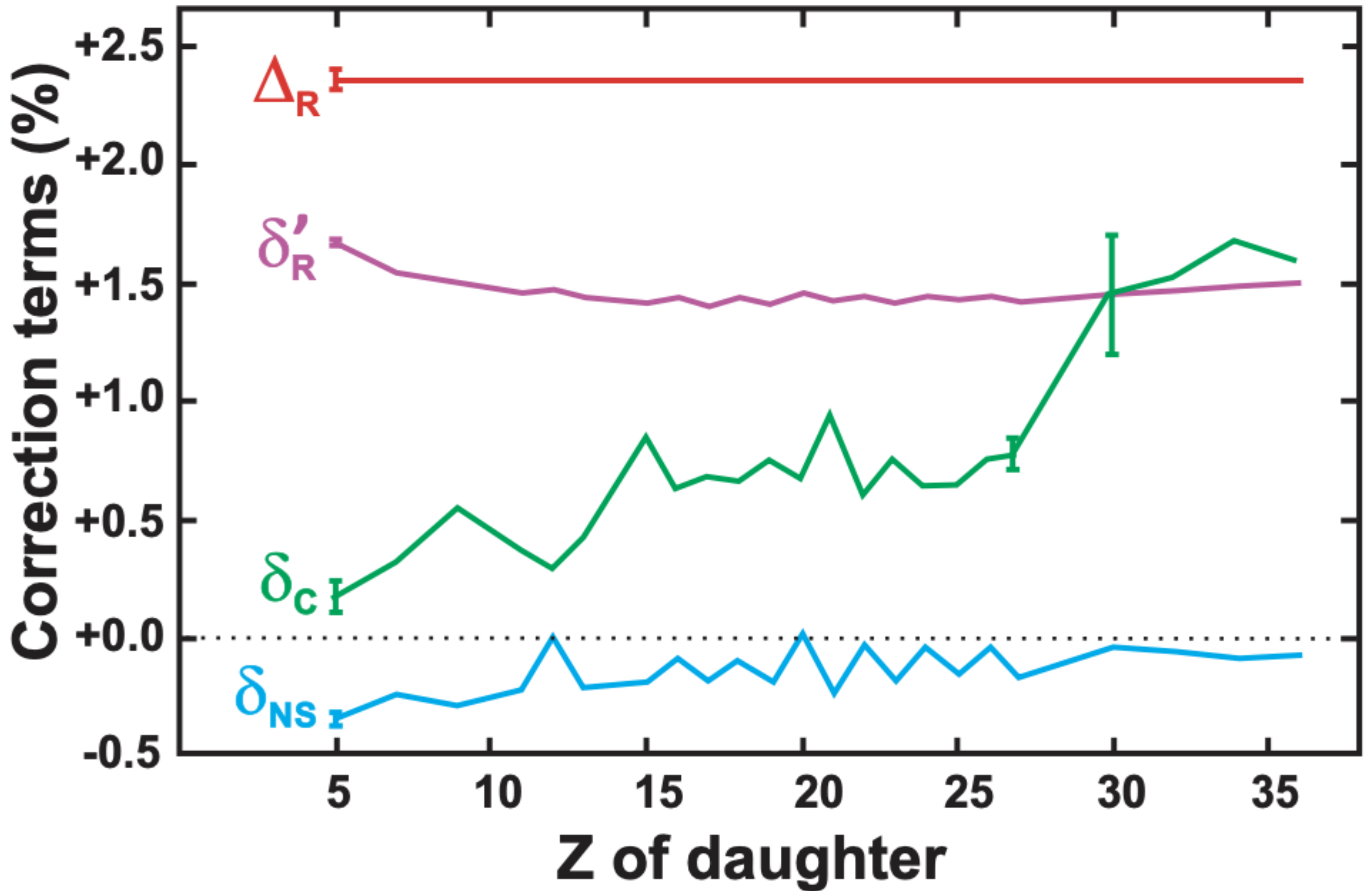
V_{ud} from nuclear $0^+ \rightarrow 0^+$ beta decays

$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{ft\left(1 + \delta'_R + \delta_{NS} - \delta_C + \Delta_R^V\right)}$$

Point-like nucleus
'outer corrections'
(Z, $(E_e)^{max}$)



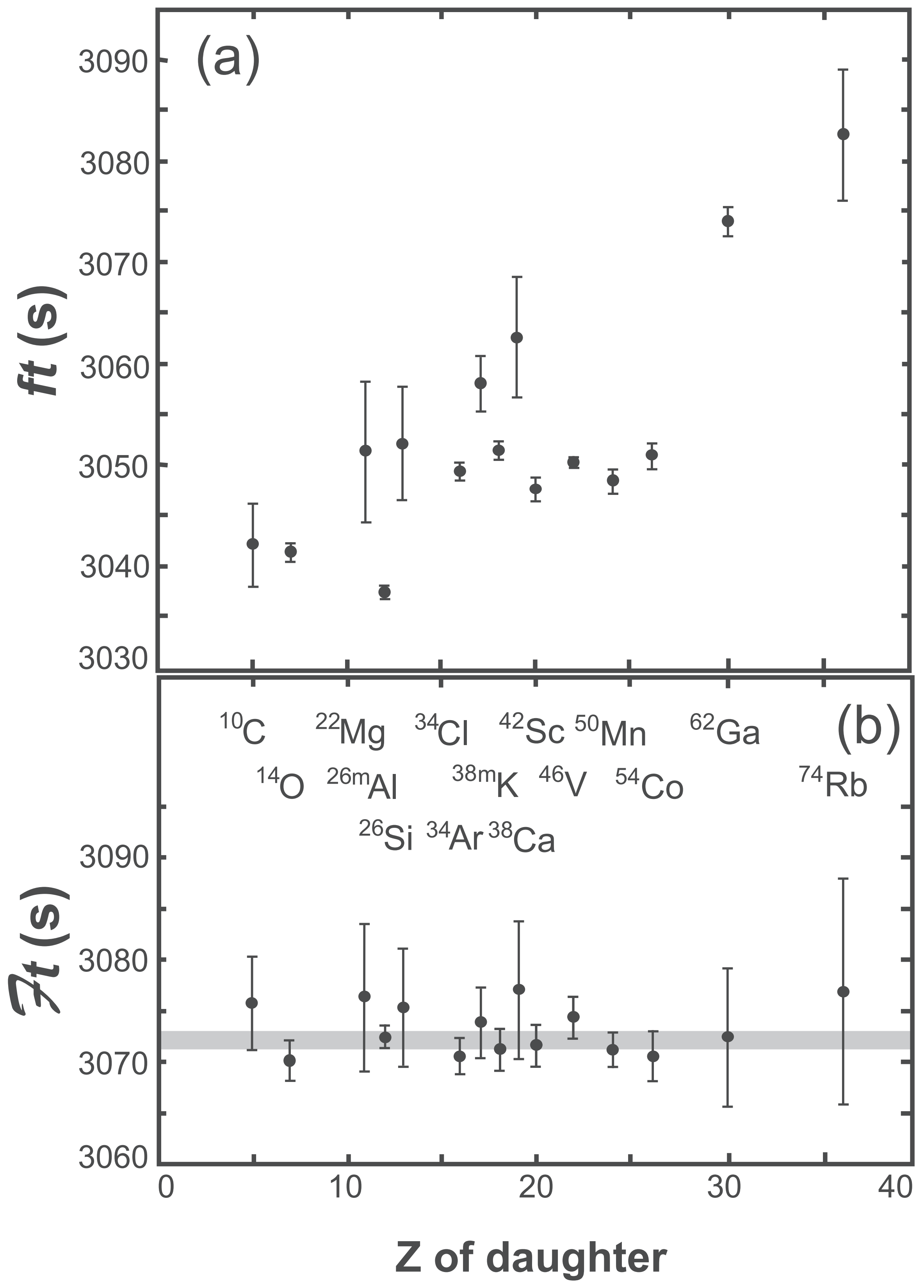
Single nucleon
`γ-W box'



Hardy-Towner, PRC 2020

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

Hardy-Towner, PRC 2020



$$|V_{ud}|^2 = \frac{2984.432(3)\ s}{\boxed{ft\left(1+\delta'_R+\delta_{NS}-\delta_C\right.}\left.+\Delta_R^V\right)}$$

$\boxed{\mathcal{F}t}$

$$V_{ud}^{0^+\rightarrow 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta_R^V}(27)_{\rm NS}[32]_{\rm total}$$

Lots of activity

- New analysis of nuclear weak form factors and phase space f
- New approaches towards structure dependent corrections $\delta_{C,NS}$
- Controlled uncertainties will be achieved for a range of A=10, 14, …

Gorchtein, Seng 2311.00044
and references therein

EFT for multi-nucleon systems

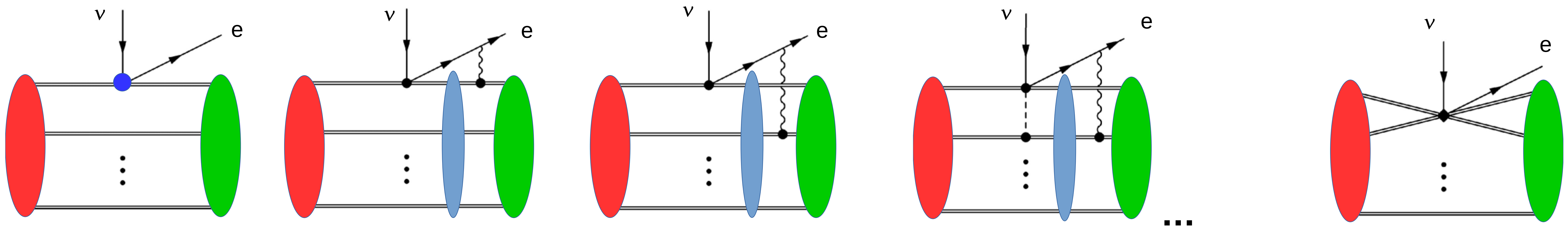
VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

- Chiral EFT (NN, NNN, …) with dynamical leptons and photons

- Hard photons leave behind local multi-nucleon electroweak operators (as in the one-nucleon case)

$$\mathcal{L}_W^{2b} = -\sqrt{2}e^2 G_F V_{ud}\ \bar{e}_L\gamma_0\nu_L \times$$
$$N^\dagger\tau^+N\ \left(e^2 g_{V1}^{NN}\ N^\dagger N + e^2 g_{V2}^{NN}\ N^\dagger\tau^3 N\right)$$

- Soft, potential, and ultra-soft photons contribute to multi-nucleon amplitudes



Soft:	$(q^0, \lvert\mathbf{q}\rvert) \sim Q \sim k_F$
Potential:	$(q^0, \lvert\mathbf{q}\rvert) \sim (Q^2/m_N,\ Q)$
Ultrasoft	$(q^0, \lvert\mathbf{q}\rvert) \sim Q^2/m_N << k_F$

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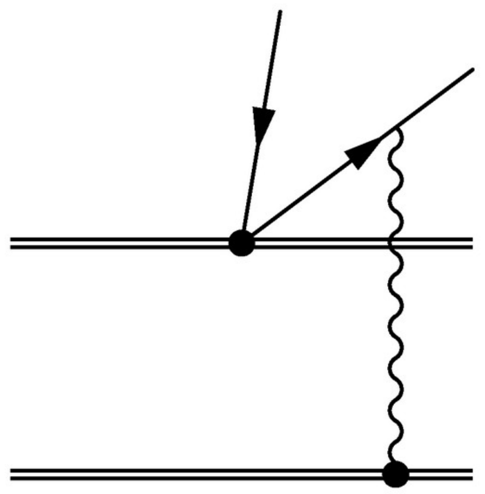
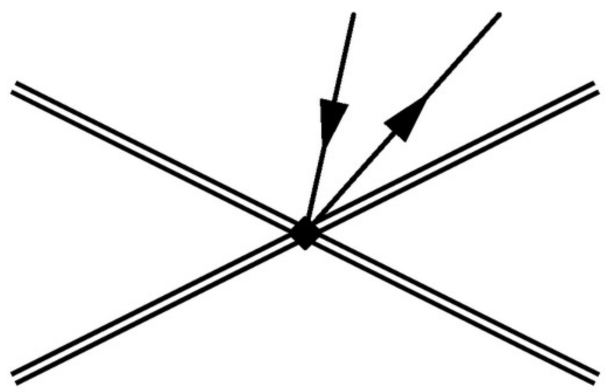
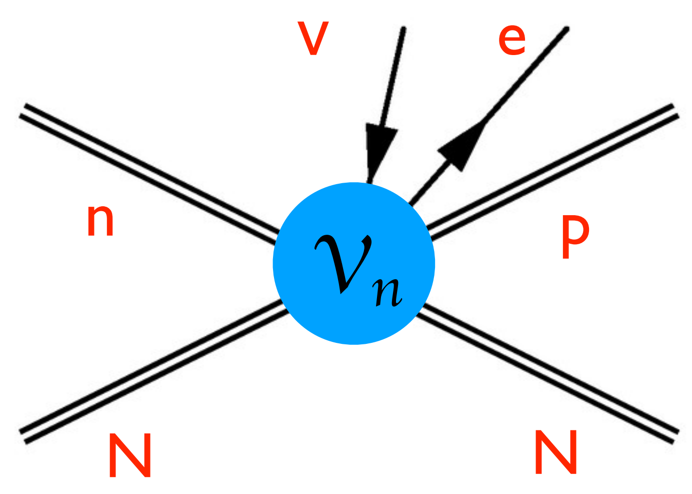
- 'Integrate out' soft & potential photons (and π's) → obtain EW n-body transition operators ('potentials')







$$\mathcal{V}_E \sim \frac{e^2\, E_{e,\nu}}{\mathbf{q}^4} \qquad \mathcal{V}_{\rm mag} \sim \frac{e^2}{m_N \mathbf{q}^2} \qquad \mathcal{V}_{\rm contact} \sim e^2\, g_{V_1,V_2}^{NN} \sim e^2\, \frac{1}{\Lambda_\chi F_\pi^2}$$

$G_F \alpha \varepsilon_\pi$ $\quad$ $G_F \alpha \varepsilon_\chi$ $\quad$ $\varepsilon_\chi = Q/\Lambda_\chi$ $\quad$ $G_F \alpha \varepsilon_\chi$

$$H_{EW} \supset \sqrt{2} G_F V_{ud}\ \bar{e}_L \gamma_0 \nu_L \times \sum_n c_n\, \mathcal{V}_n$$

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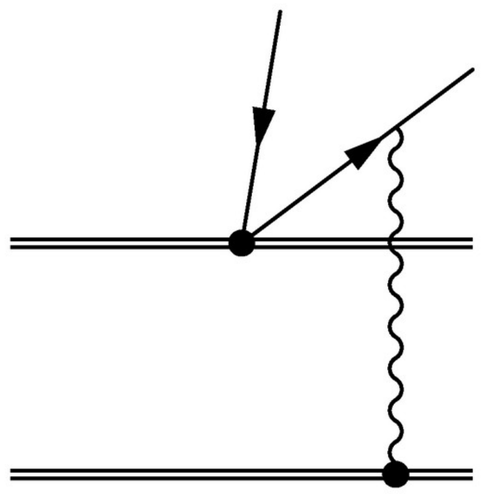

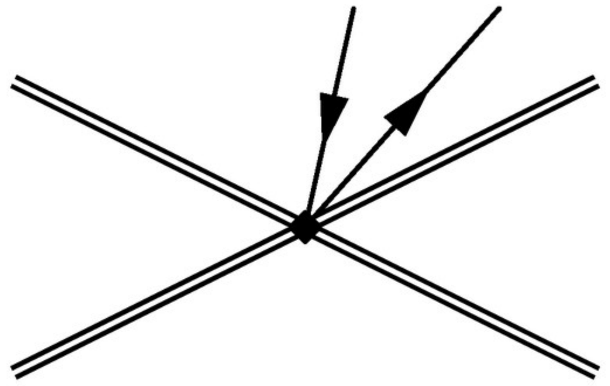

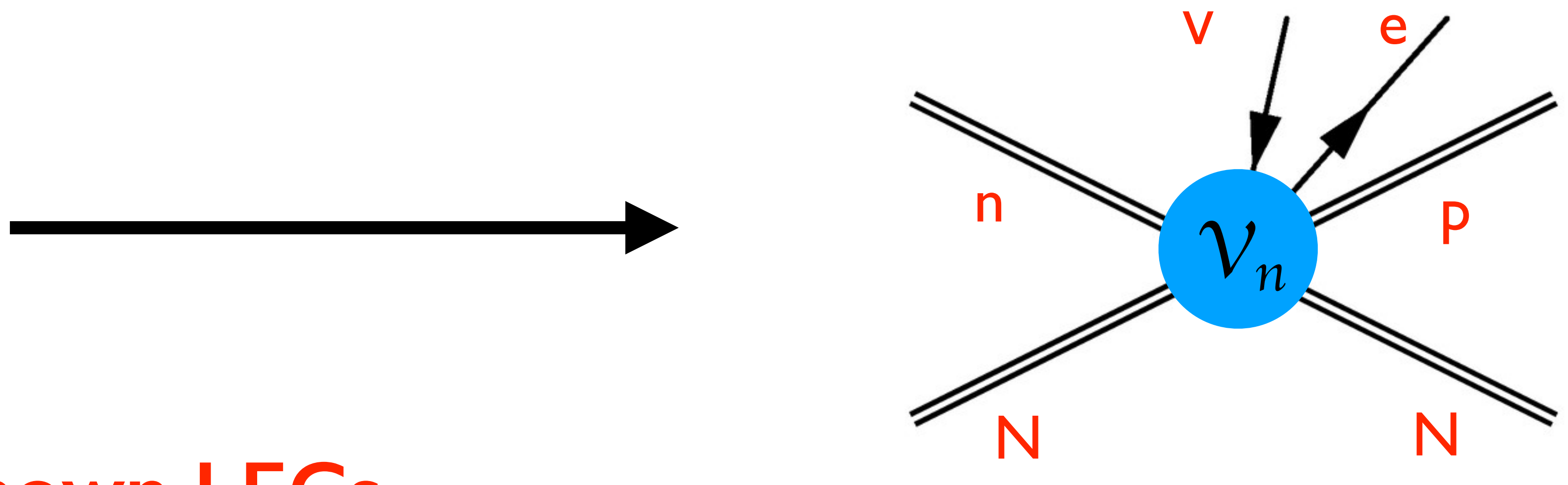

Currently unknown LECs

$$\mathcal{V}_E \sim \frac{e^2\, E_{e,\nu}}{\mathbf{q}^4} \qquad \mathcal{V}_{\text{mag}} \sim \frac{e^2}{m_N \mathbf{q}^2} \qquad \mathcal{V}_{\text{contact}} \sim e^2\, g_{V_1,V_2}^{NN} \sim e^2 \frac{1}{\Lambda_\chi F_\pi^2}$$

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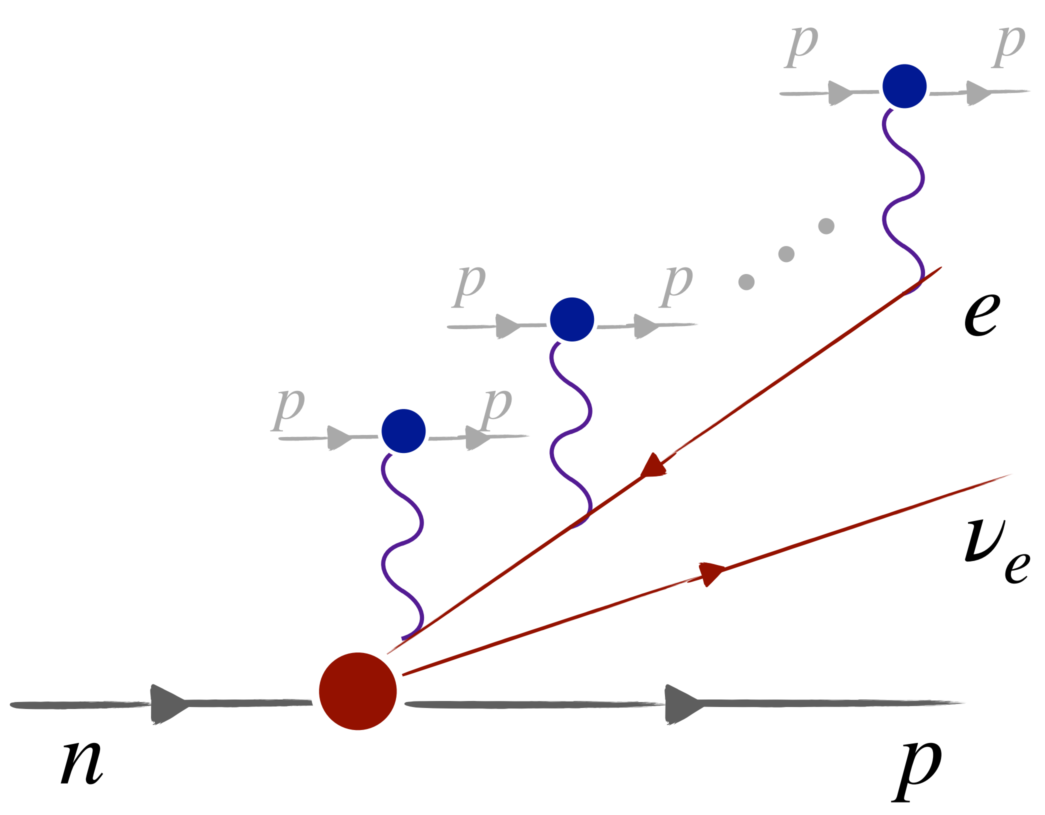
- 'Integrate out' soft & potential photons (and π's) → obtain EW n-body transition operators ('potentials')

- Ultrasoft photons: Z-dependent running of effective couplings between m_π and m_e & matrix elements at $\mu \sim m_e$



Courtesy of W. Dekens

Impact on V_{ud}: exploratory studies in QMC

- $^{14}O \rightarrow {}^{14}N$: δ_{NS} contributions in rough agreement with corresponding terms in Hardy-Towner 2020

VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

$$V_{ud}\big|_{^{14}O} = 0.97411(10)_{\rm exp}(12)_{g_V}(22)_{\mu}(12)_{\delta_C}(43)_{g_V^{NN}}[55]_{\rm tot}$$

Residual scale dependence due to missing terms of O(α²Z) in the Fermi function

Largest uncertainty from unknown LECs.
Assumes $g^{NN}_{V1,V2} = 1/(4 m_N F_\pi^2)$

$$V_{ud}^{\rm HT}\big|_{^{14}O} = 0.97405[37]_{\rm tot}$$

(31) from δ_{NS}

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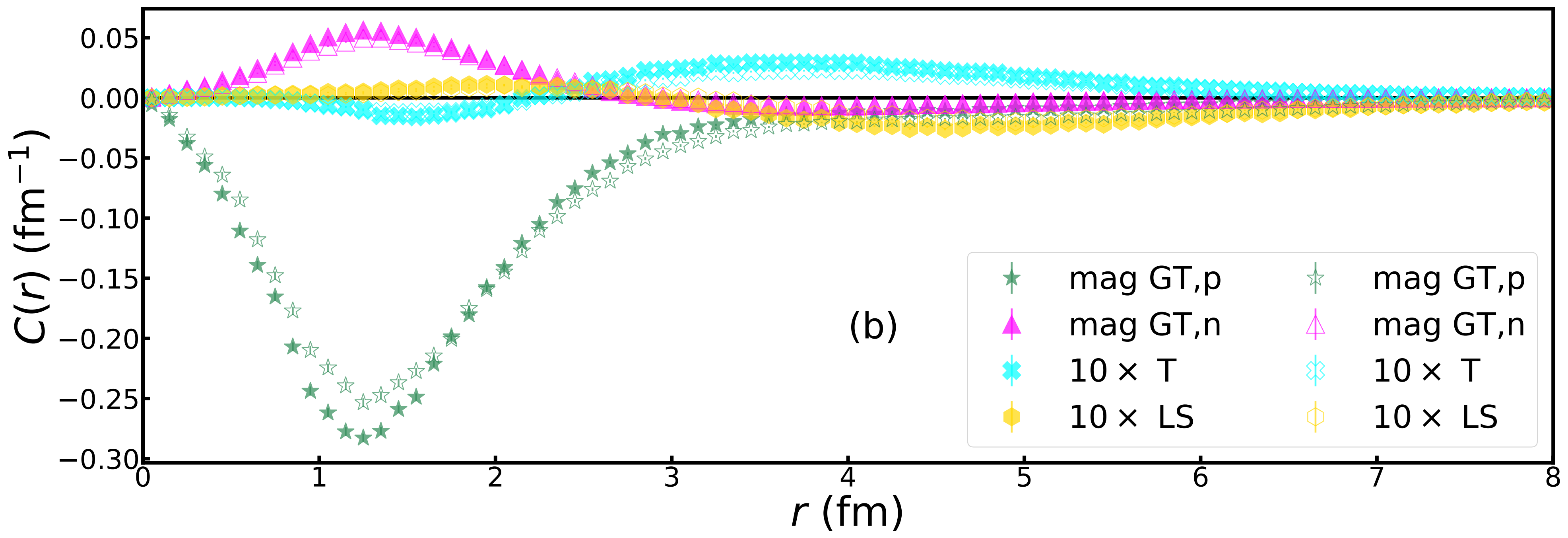
- $^{10}C \rightarrow {}^{10}B$:

$$V_{ud}|_{^{10}C} = 0.97355(66)_{\rm exp}(12)_{g_V}(17)_{\mu}(9)_{\delta_C}(38)_{g_V^{\rm NN}}$$

0.02% spread from use of different chiral Hamiltonians

King-Carlson-Flores-Gandolfi-Mereghetti-Pastore-Piarulli-Wiringa, arXiv:2509.07310



Empty and filled symbols correspond to two different chiral interactions

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$$V_{ud}\big|^{\rm HT}_{^{10}C} = 0.97318(66)_{\rm exp}(9)_{\Delta_R^V}(24)_{\delta_{\rm NS}}(9)_{\delta_C}$$

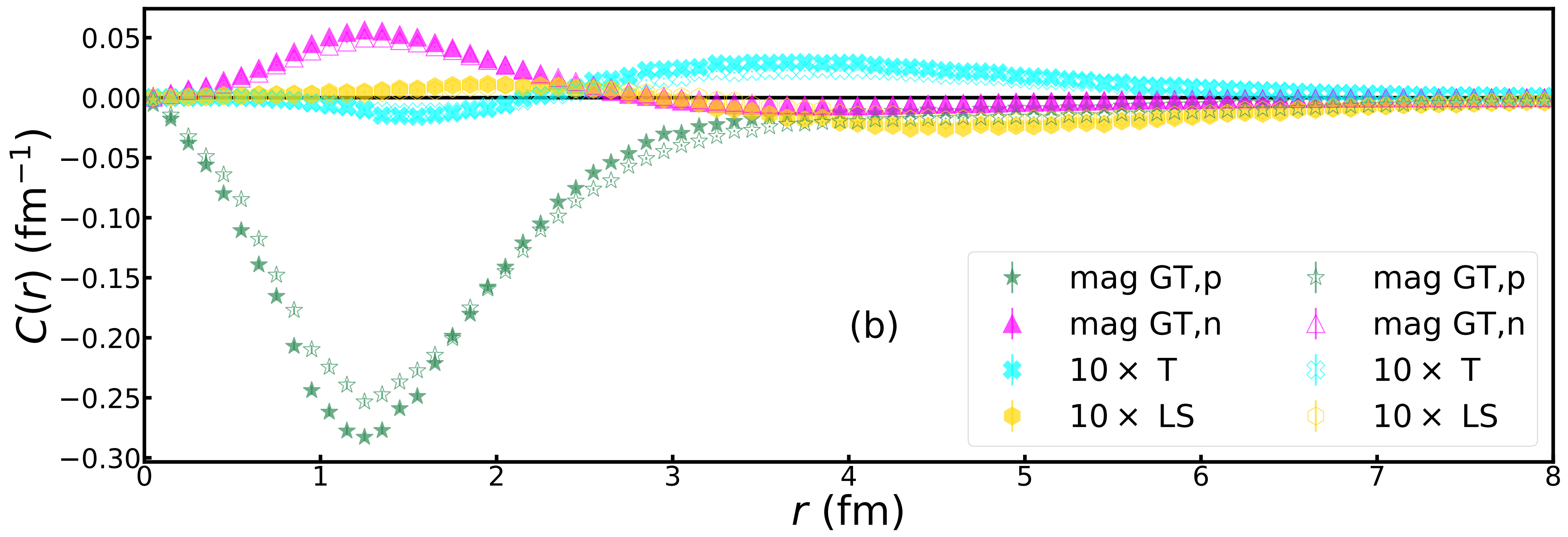
$$V_{ud}\big|^{\rm NCSM}_{^{10}C} = 0.97317(66)_{\rm exp}(9)_{\Delta_R^V}(16)_{\delta_{\rm NS}}(9)_{\delta_C}$$

Reasonable agreement with HT & dispersive + NCSM

0.02% spread from use of different chiral Hamiltonians

Gennari, Drissi, Gorchtein, Navratil,, Seng, Phys. Rev. Lett. 134, 012501 (2025)

King-Carlson-Flores-Gandolfi-Mereghetti-Pastore-Piarulli-Wiringa, arXiv:2509.07310

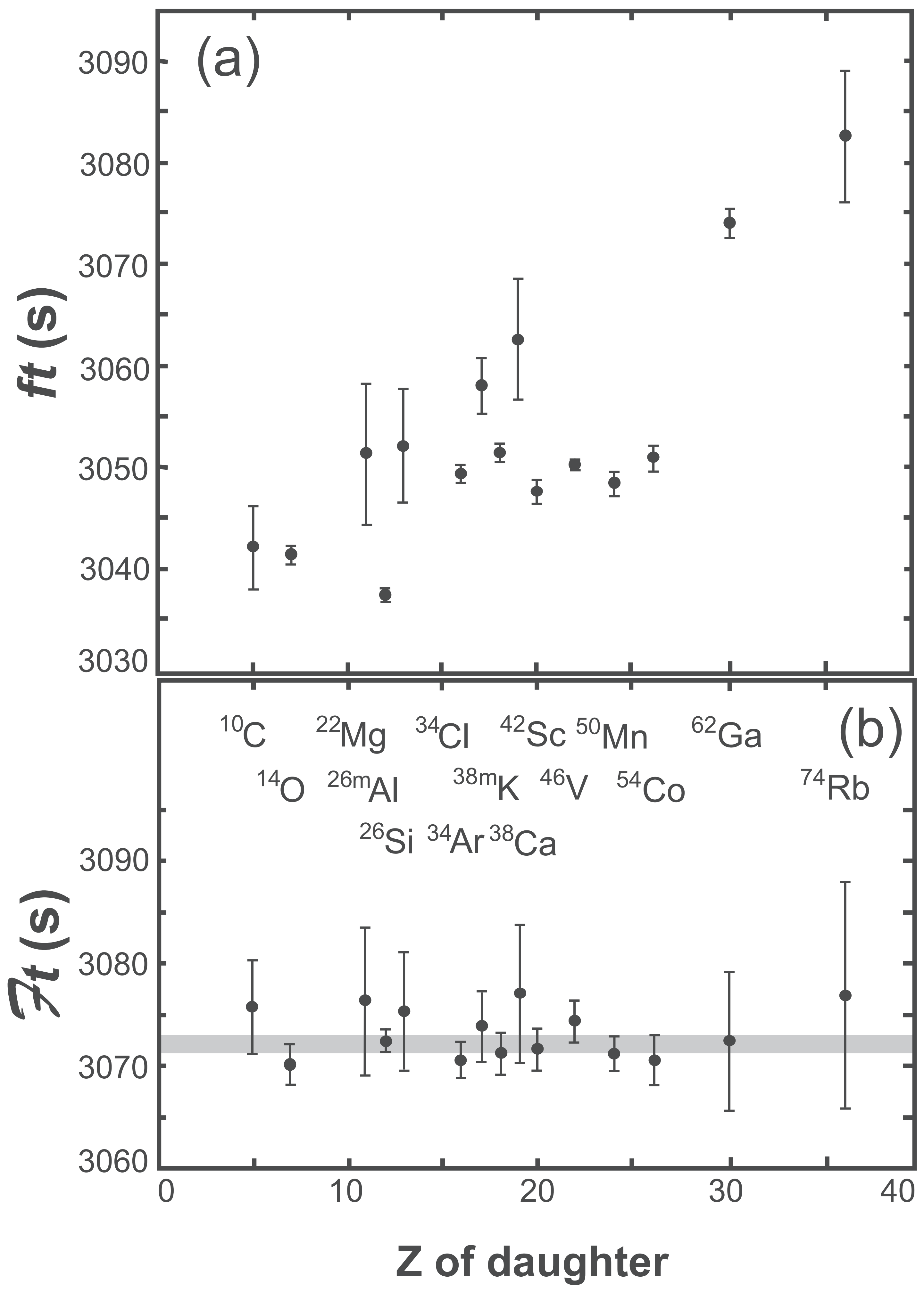


Empty and filled symbols correspond to two different chiral interactions

Path forward in the EFT approach

VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

Hardy-Towner, PRC 2020



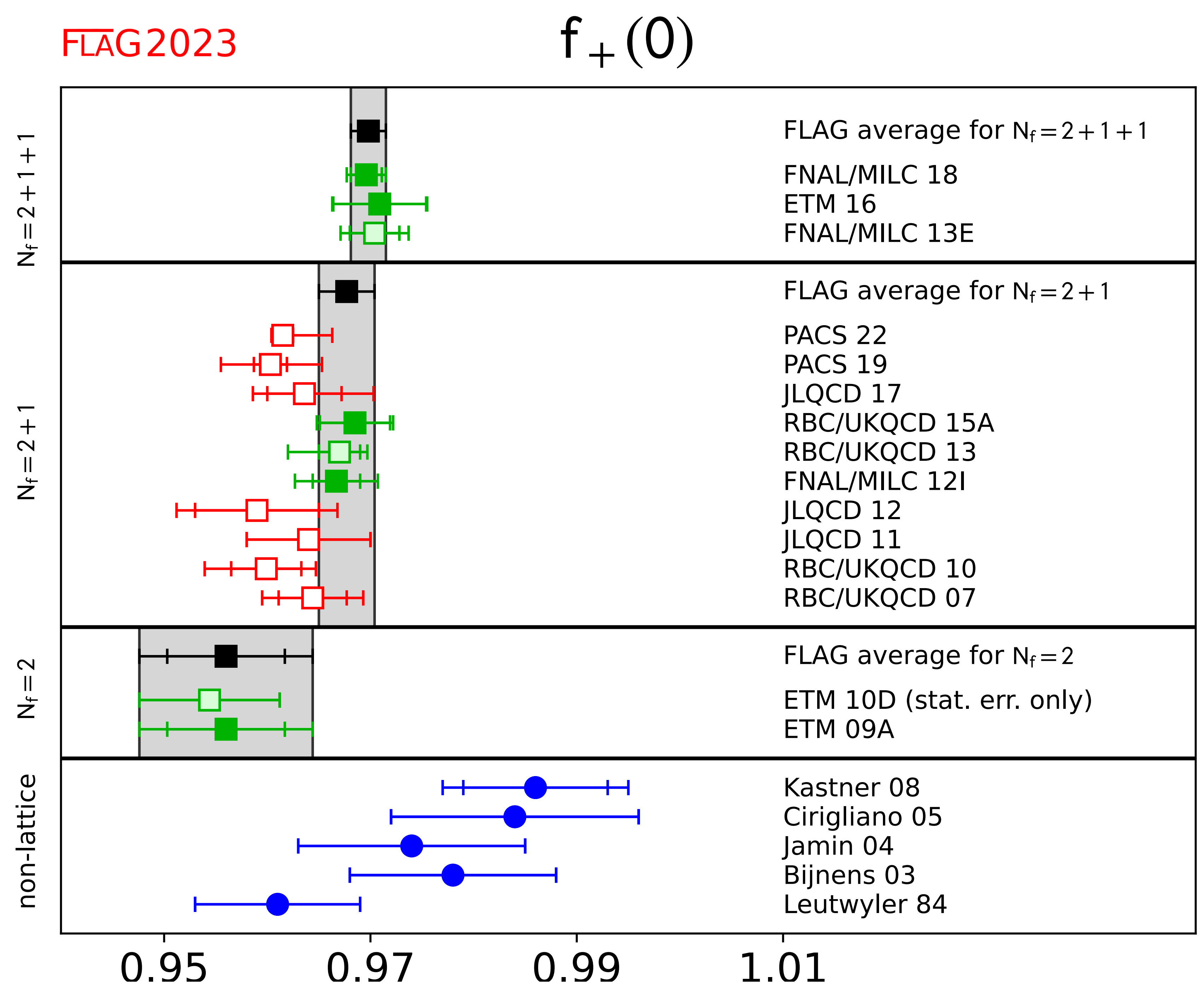
- EFT has identified new method to compute structure-dependent corrections and (temporarily) increased the uncertainty. But in the long run it will allow for robust uncertainty quantification

- LECs can be obtained by
  - Fitting data (along with V_{ud} and possibly BSM effective couplings) once NME calculations for several isotopes become available
  - Theory: dispersive analysis, Lattice QCD

V_{us} from $K \to \pi l \nu$ decays

$$\Gamma_{K\to\pi\ell\nu(\gamma)} = \frac{C_K^2 G_F^2 S_{EW} |V_{us}|^2 M_K^5}{192\pi^3} |f_+^{K\pi}(0)|^2 I_{K\ell}\left(1 + 2\Delta_{K\ell}^{EM} + 2\Delta_K^{IB}\right)$$

- Lattice calculations of <π|V|K> @ 0.2%: $f_+^{K\pi}(0) = 0.9698(17)$



- New radiative corrections based on current algebra + lattice QCD + ChPT. Consistent with old ChPT, with reduced uncertainties

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

NEW: Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217. Ma et al. 2102.12048
OLD: VC, Giannotti, Neufeld 0807.4607

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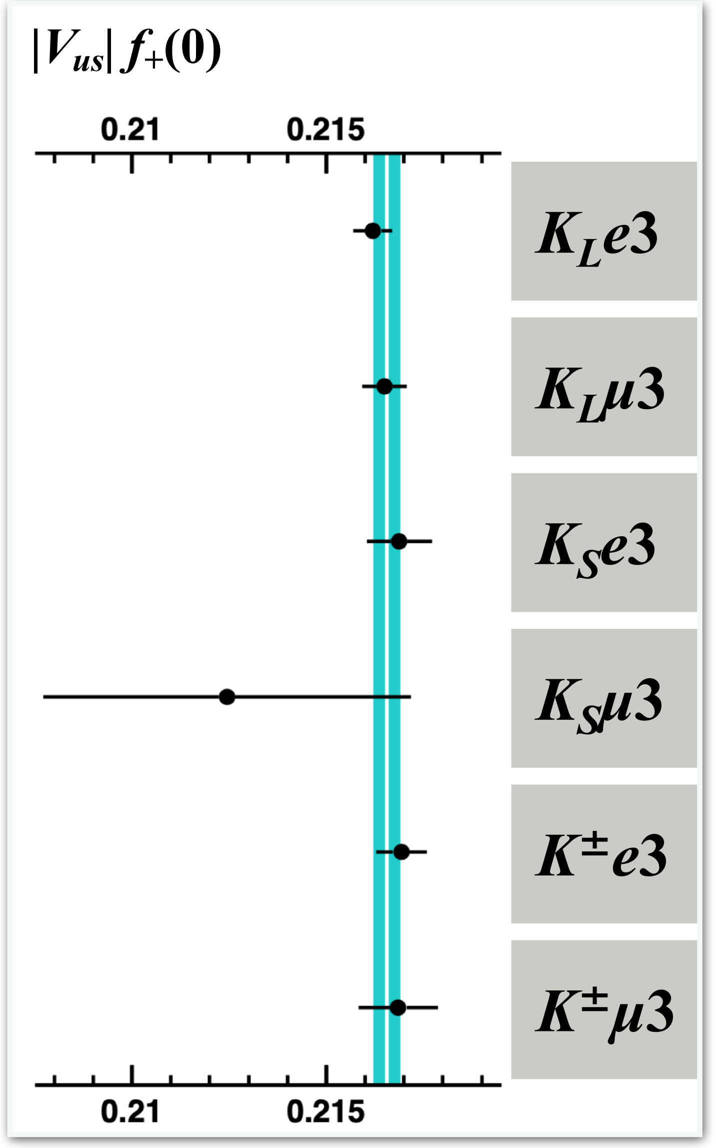
- New radiative corrections based on current algebra + lattice QCD + ChPT. Consistent with old ChPT, with reduced uncertainties

- Experimental input has received only small updates since 2010

Flavianet WG, 1005.2323 Moulson 1704.04104



$$V_{us}^{K\ell 3} = 0.22330(35)_{\rm exp}(39)_{f_+}(8)_{\rm RC+IB}[53]_{\rm total}$$

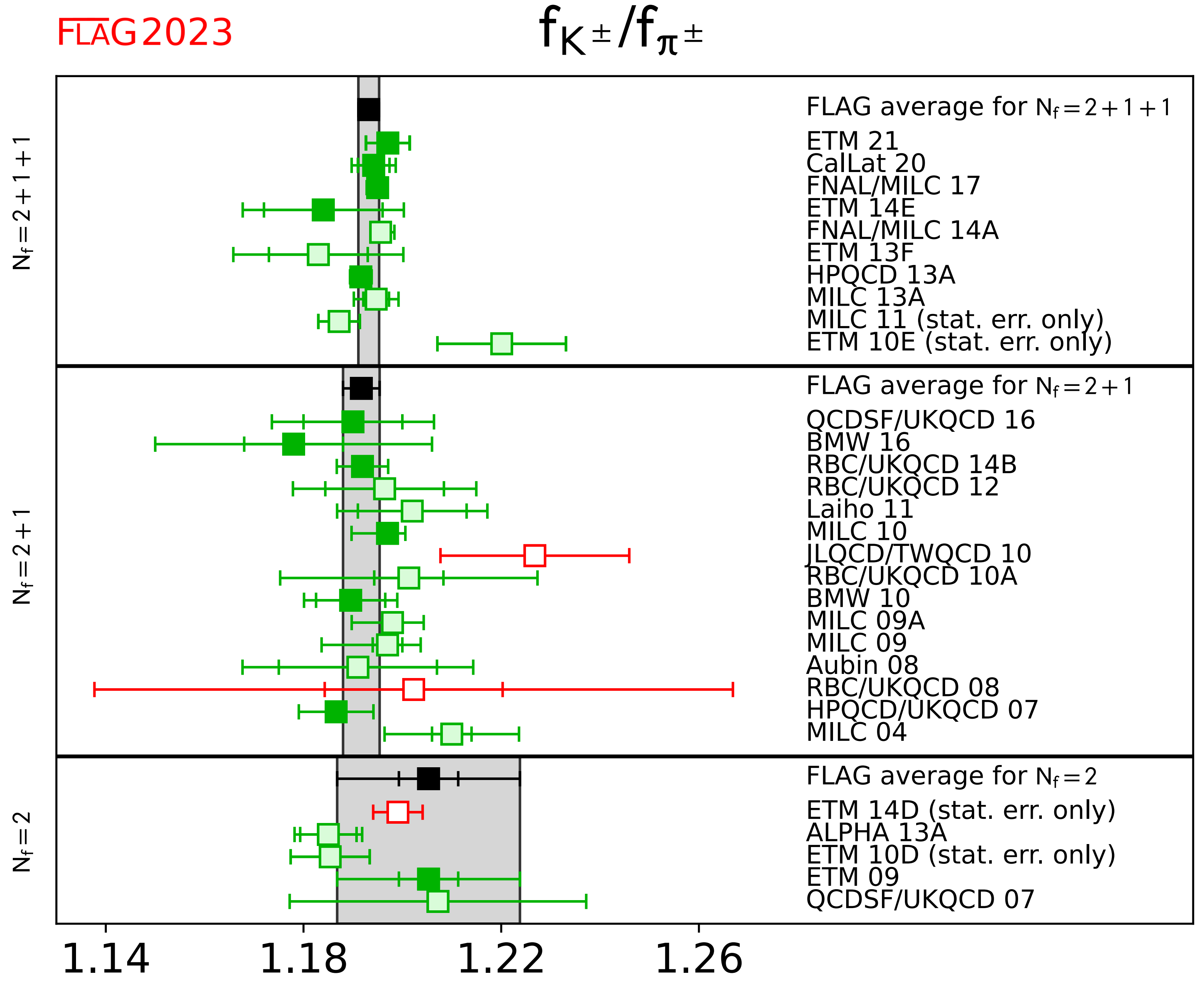
Potential issue: definition of 'isosymmetric QCD' in lattice ($f_+(0)$) vs calculations of $\Delta^{EM, IB}$

V_{us} from $K \to \mu\nu$ decays

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K\to\mu\nu(\gamma)}}{\Gamma_{\pi\to\mu\nu(\gamma)}}\frac{m_{\pi^\pm}}{m_{K^\pm}}\right)^{1/2} \frac{1-m_\mu^2/m_{\pi^\pm}^2}{1-m_\mu^2/m_{K^\pm}^2}\left(1-\frac{\Delta^{K\pi}_{\mathrm{RC+IB}}}{2}\right)$$

- Lattice QCD calculations of F_K/F_π are at the 0.2% level
- First calculations of radiative and isospin-breaking corrections in LQCD. Compatible with ChPT, factor of ~2 more precise

ChPT: VC-Neufeld, 1102.0563	**LQCD1: Di Carlo et al., 1904.08731**	**LQCD2: Boyle et al., 2211.12865**
$\Delta^{K\pi}_{\mathrm{RC+IB}} = -1.12(21)\%$	$\Delta^{K\pi}_{\mathrm{RC+IB}} = -1.26(14)\%$	$\Delta^{K\pi}_{\mathrm{RC+IB}} = -0.86(40)\%$



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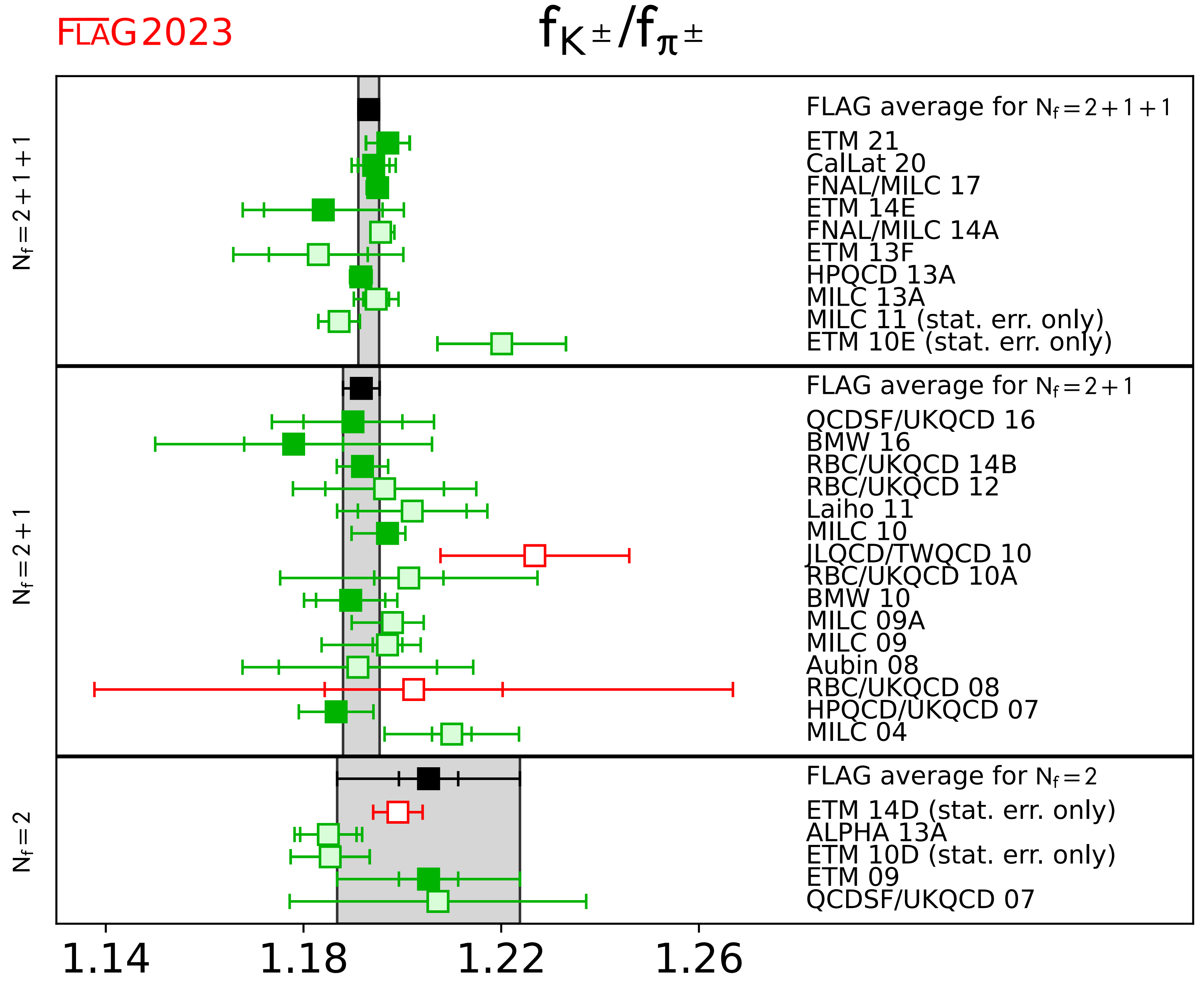

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Potential issue:

$K_{\mu 2}$ BR dominated by one measurement (KLOE)

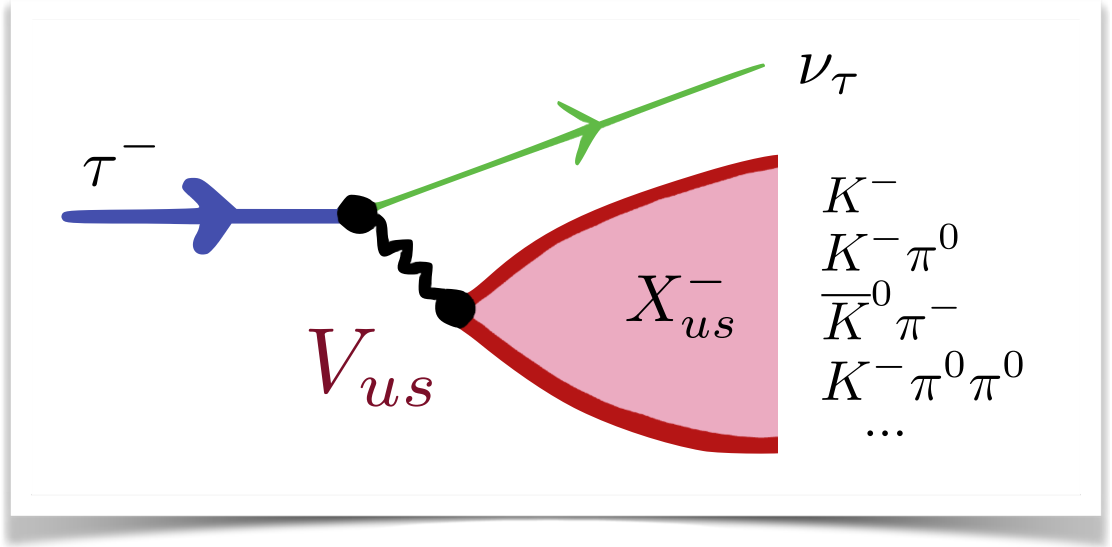
$K_{\mu 3}/K_{\mu 2}$ BR measurement at 0.2-0.5% would have significant impact (NA62)

$$\left.\frac{V_{us}}{V_{ud}}\right|_{K_{\ell 2}/\pi_{\ell 2}} = 0.23108(23)_{\mathrm{exp}}(42)_{F_K/F_\pi}(16)_{\mathrm{RC+IB}}[51]_{\mathrm{total}}$$

V_{us} from tau decays

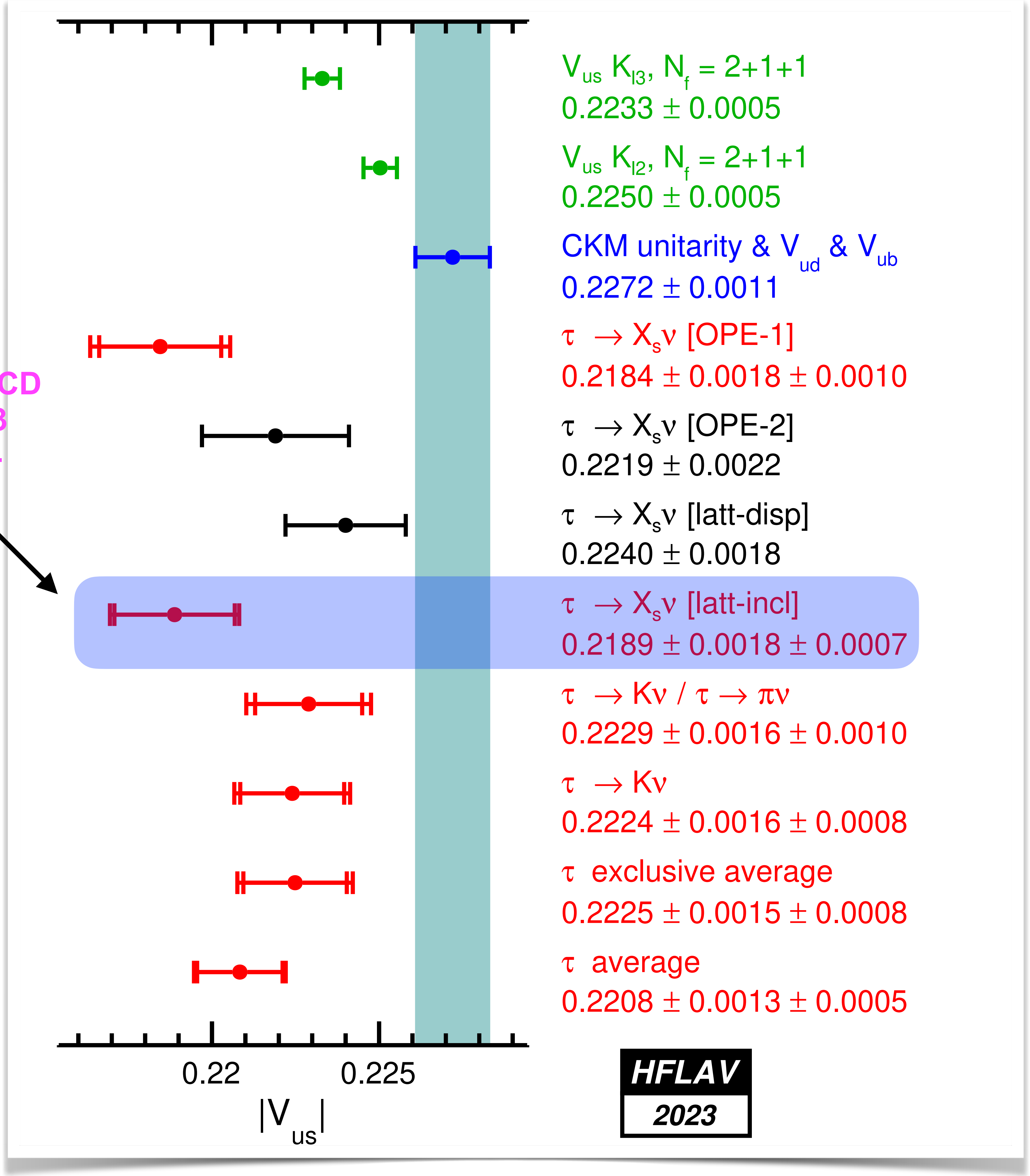
- Inclusive ($\tau \to X_s \nu$): need integrated spectral functions (exp) + theory (pQCD (OPE) → Lattice QCD)

M. Di Carlo's talk at CKM 2025



- Exclusive ($\tau \to K\nu$ / $\tau \to \pi\nu$): need partial widths, decay constants (LQCD) & radiative corrections

Iso-symmetric Lattice QCD
Evangelista et al. 2023
Alexandrou et al 2024



Experimental prospects:

Belle-II and possibly
tau-charm factory & FCC-ee

Theory prospects:

(1) Radiative corrections are a bottleneck for exclusive modes;

(2) lattice QCD provides first-principles inclusive determination
(in the future also including IB)

Summary of expected / desired developments

- Experiment:
  - Neutron decay: aim for $\delta\tau_n \sim 0.1$s [UCNτ+] and $\delta g_A/g_A \sim 0.01\%$ [PERC] to get $\delta V_{ud} \sim 1.5\ 10^{-4}$
  - Pion beta decay BR: 6x to 10x at PIONEER phases II, III [~10 years]
  - New $K_{\mu3}/K_{\mu2}$ BR measurement @0.2% at NA62 will shed light on Kl3 vs Kl2 tension
  - τ decays: Belle-II will reduce experimental uncertainties by > 2x

- Theory:
  - Radiative corrections in lattice QCD+QED or hybrid: $K \to \pi l \nu$, $\pi^+ \to \pi^0 e^+ \nu$, $n \to p e \nu$, $\tau \to K\nu$, τ inclusive
  - Nuclear decays: EFT for radiative corrections coupled to first-principles nuclear calculations for δ_{NS}, δ_C

Summary and outlook

The Cabibbo angle is the cornerstone of the CKM matrix and the
Cabibbo universality test is a precision tool to explore what may lie beyond the Standard Model

- Current tensions in Cabibbo universality test could point to new physics at $\Lambda \sim$ few TeV

**For a detailed analysis in the SM-EFT see
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021**

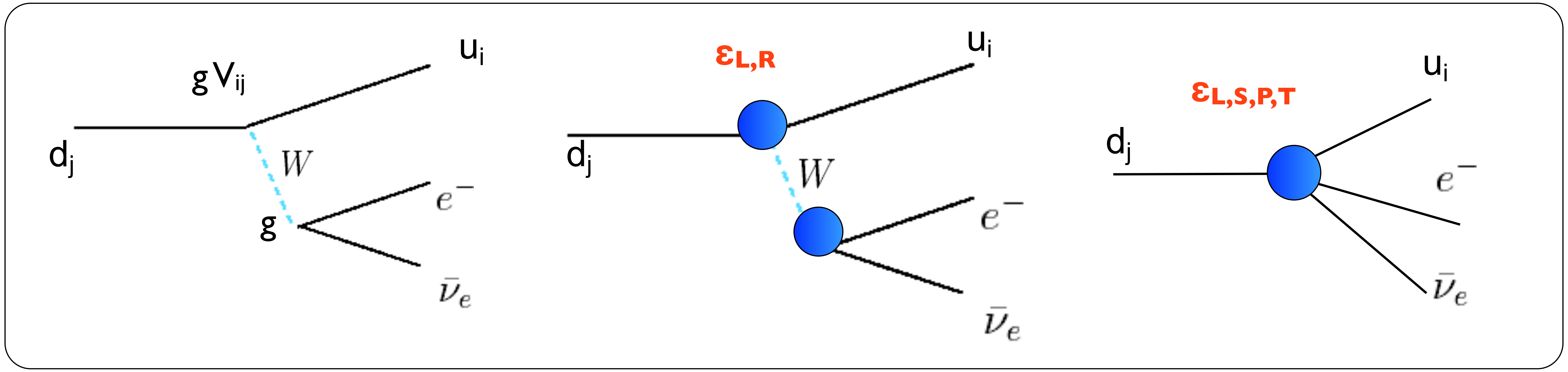
- However, further scrutiny is needed
  - Experiment: neutron, K, π, τ
  - Theory: lattice QCD+QED for neutron, K, π, τ ; EFT+ ‘ab-initio’ methods for nuclei

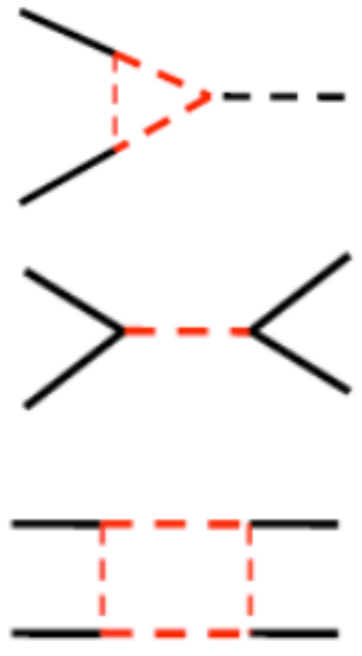
Expect decisive improvements in the 5-10 year frame

Backup

Cabibbo universality
and
physics beyond the Standard Model

Semileptonic processes beyond the SM





W_R, H^+, leptoquarks, Vector-Like quarks, Z', SUSY,…

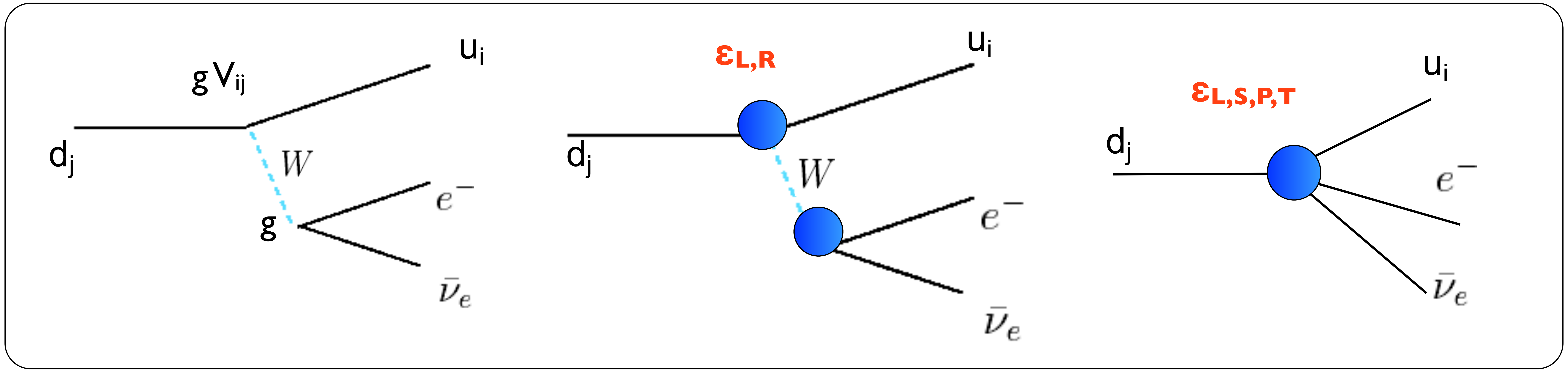
E << Λ $\downarrow$ $\varepsilon_\Gamma \sim \tilde{\varepsilon}_\Gamma \sim (v/\Lambda)^2$

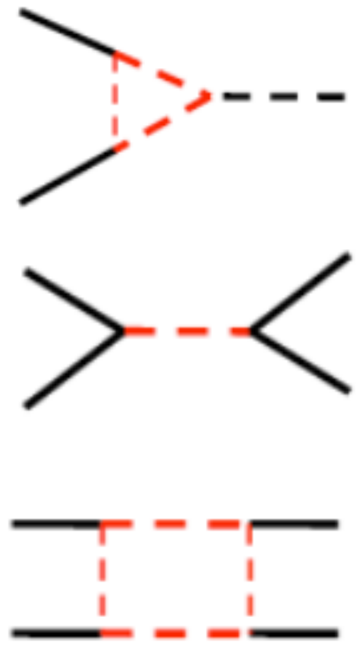
$$\boxed{\mathcal{L}_{\rm SM} - \frac{G_F V_{ud_j}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma^{(j)}\ \bar{\ell}\Gamma\nu_L \cdot \bar{u}\Gamma d_j \ + \ \tilde{\epsilon}_\Gamma^{(j)}\ \bar{\ell}\Gamma\nu_R \cdot \bar{u}\Gamma d \right]}$$

$$\Gamma = L, R, S, P, T$$

BSM effects parameterized by 10(ud) +10(us) effective couplings at E ~ GeV
They map into vertex corrections and 4-Fermion interactions above the EW scale

Semileptonic processes beyond the SM





W$_R$, H$^+$, leptoquarks, Vector-Like quarks, Z', SUSY,…

E << Λ

$\varepsilon_\Gamma \sim \tilde{\varepsilon}_\Gamma \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud_j}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma^{(j)}\ \bar{\ell}\Gamma \nu_L \cdot \bar{u}\Gamma d_j \ + \ \tilde{\epsilon}_\Gamma^{(j)}\ \bar{\ell}\Gamma \nu_R \cdot \bar{u}\Gamma d \right]$$

$$\Gamma = L, R, S, P, T$$

$\Delta_{\rm CKM}$ tension confirmed: points to specific new physics

$\Delta_{\rm CKM}$ tension removed: strong constraints, complementary to traditional 'precision electroweak observables'

Corrections to V_{ud} and V_{us}

$$|\bar{V}_{ud}|^2_i = |V_{ud}|^2 \left(1 + \sum_\alpha C_{i\alpha}\epsilon_\alpha\right)$$

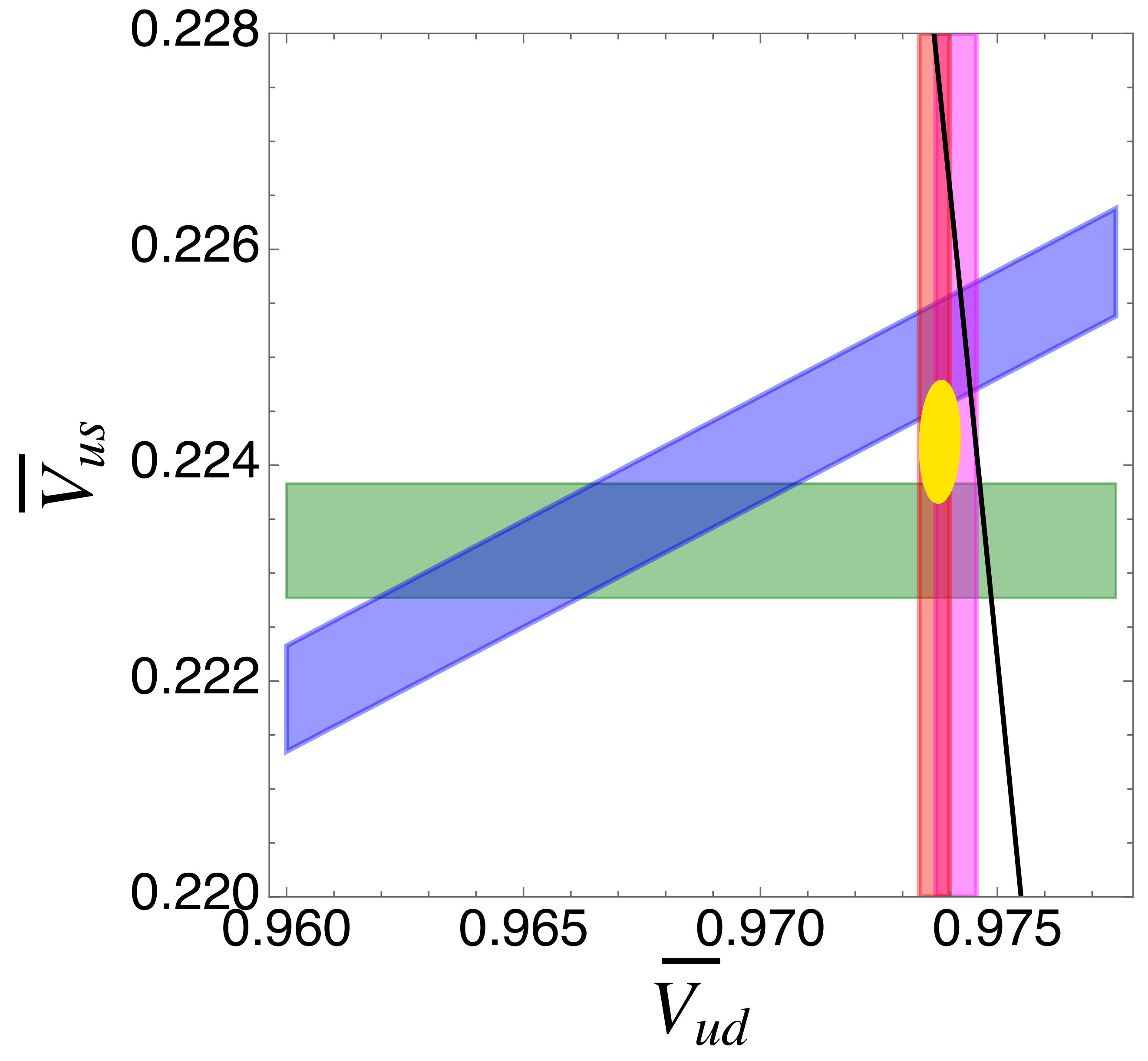
$$|\bar{V}_{us}|^2_j = |V_{us}|^2 \left(1 + \sum_\alpha C_{j\alpha}\epsilon_\alpha\right)$$

Channel-dependent CKM elements extracted in the 'SM-like analysis'

Elements of the unitary CKM matrix

Known coefficients

BSM effective coupligs



Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

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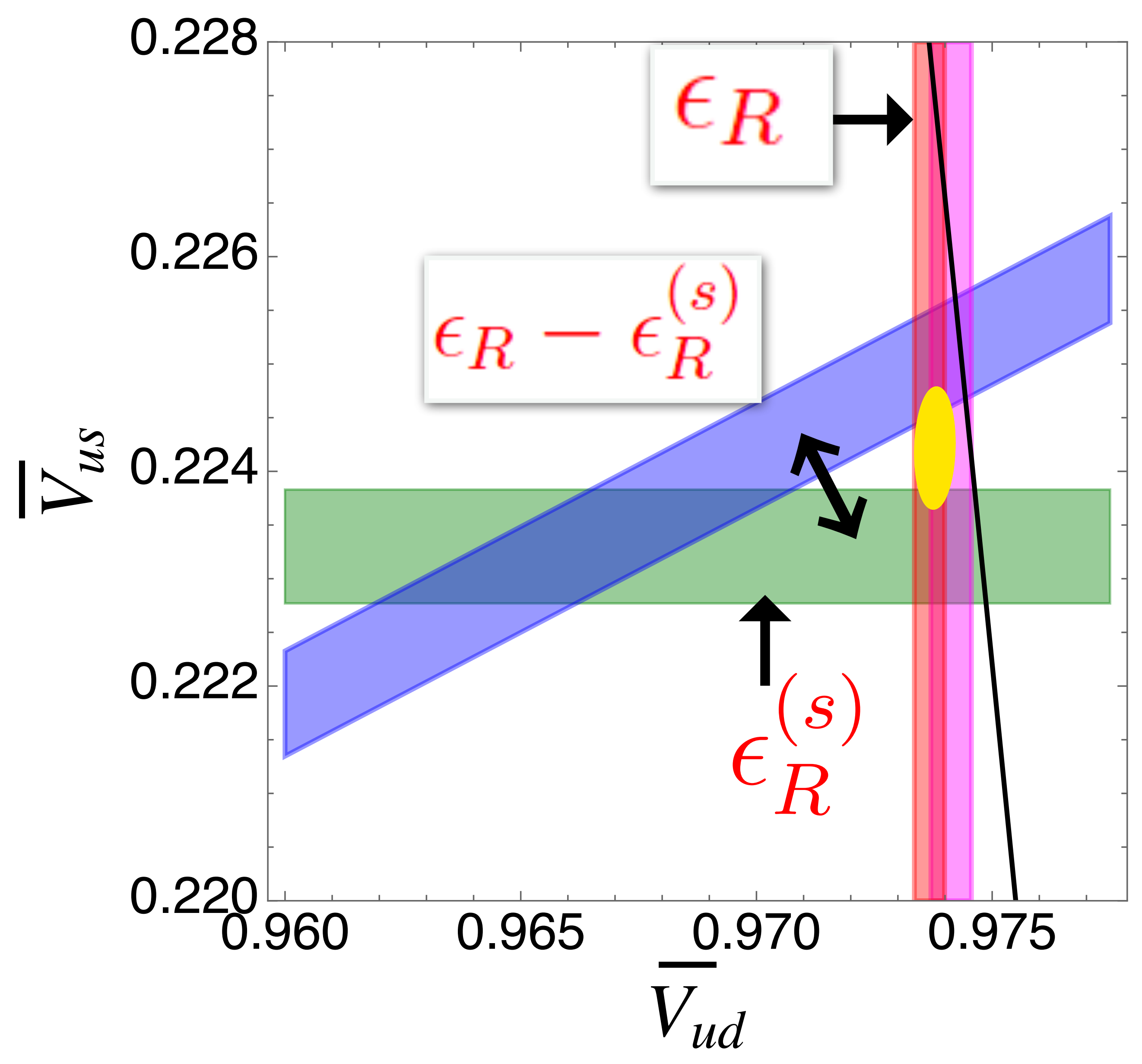


Find set of ε's so that V_{ud} and V_{us} bands meet on the unitarity circle

Simplest 'solution': right-handed (V+A) quark currents

CKM elements from vector (axial) channels are shifted by $1+\varepsilon_R$ $(1-\varepsilon_R)$.

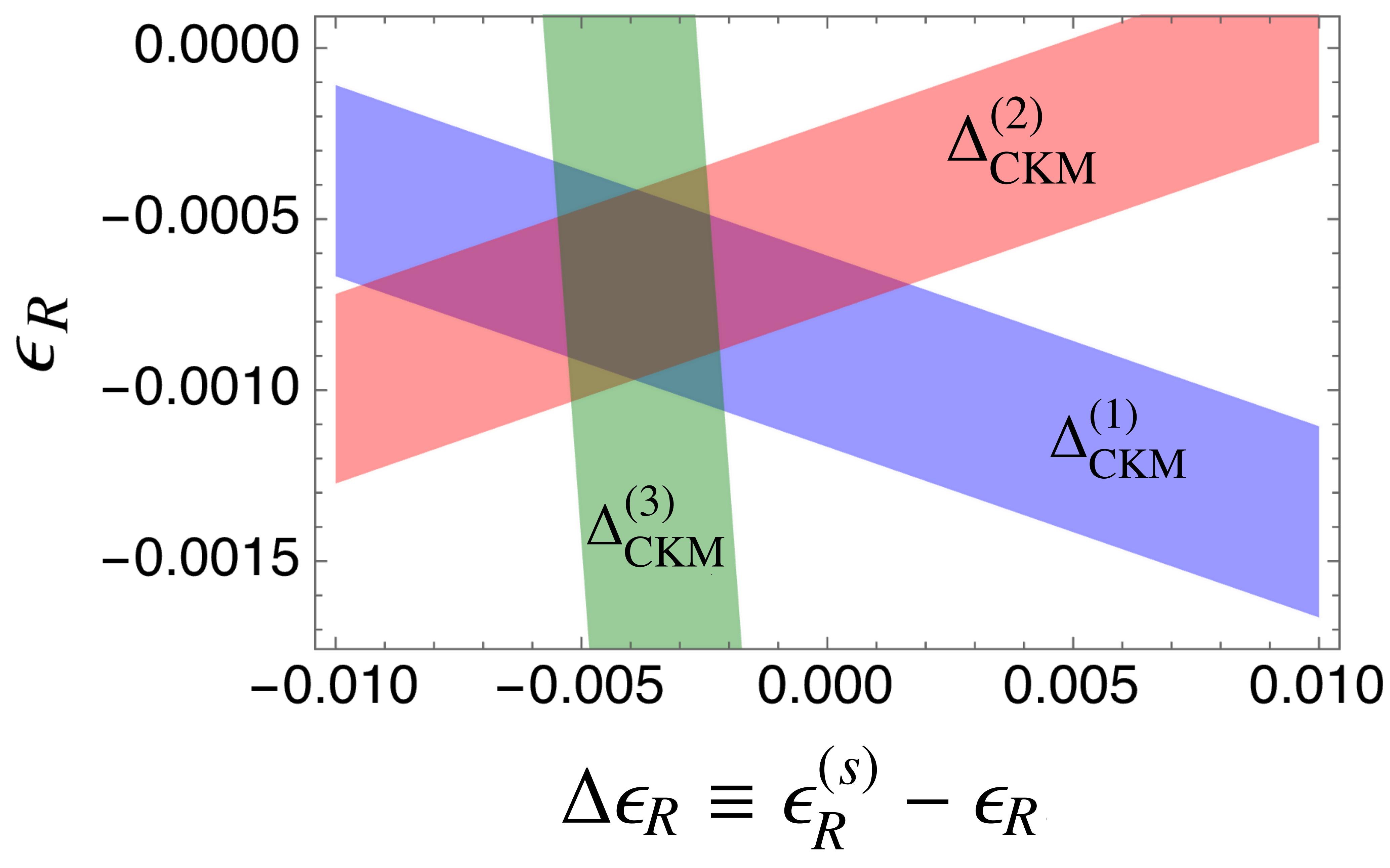
V_{us}/V_{ud} , V_{ud} and V_{us} shift in correlated way, can resolve all tensions!

Alioli et al 1703.04751
Grossman-Passemar-Schacht 1911.07821
VC-Crivellin-Hoferichter-Moulson 2208.11707
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

For other BSM explanations, see A. Crivellin 2207.02507 and references therein

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



$$
\begin{aligned}
\Delta^{(1)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.76(56) \times 10^{-3} \\
\Delta^{(2)}_{CKM} &= |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell 2}/\pi_{\ell 2},\beta}|^2 - 1 \\
&= -0.98(58) \times 10^{-3} \\
\Delta^{(3)}_{CKM} &= |V_{ud}^{K_{\ell 2}/\pi_{\ell 2},K_{\ell 3}}|^2 + |V_{us}^{K_{\ell 3}}|^2 - 1 \\
&= -1.64(63) \times 10^{-2}
\end{aligned}
$$

↓

$$
\boxed{\begin{aligned}
\epsilon_R &= -0.69(27) \times 10^{-3} \\
\Delta\epsilon_R &= -3.9(1.6) \times 10^{-3}
\end{aligned}}
$$

$\Lambda_R \sim$ 5-10 TeV

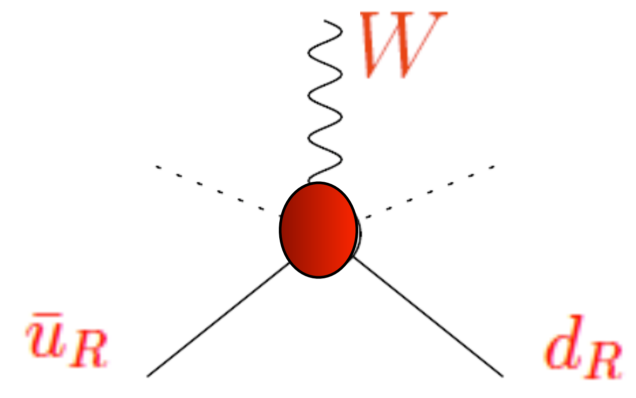
- Preferred ranges are not in conflict with other constraints from β decays, nor from $K \to (\pi\pi)_{I=2}$
- Does the R-handed current explanation survive after taking into account high energy data?

VC, Hayen, deVries, Mereghetti, Walker-Loud, 2202.10439
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

ε_R: high scale origin and constraints

For a detailed analysis in the SM-EFT see
VC, W. Dekens, J. De Vries, E. Mereghetti, T. Tong, 2311.00021

$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

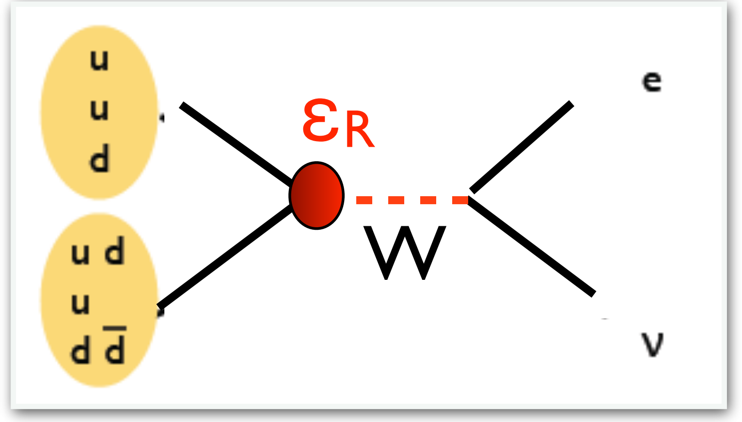


- ε_R originates from SU(2)xU(1) invariant vertex corrections

- ε_R only weakly constrained by LHC processes

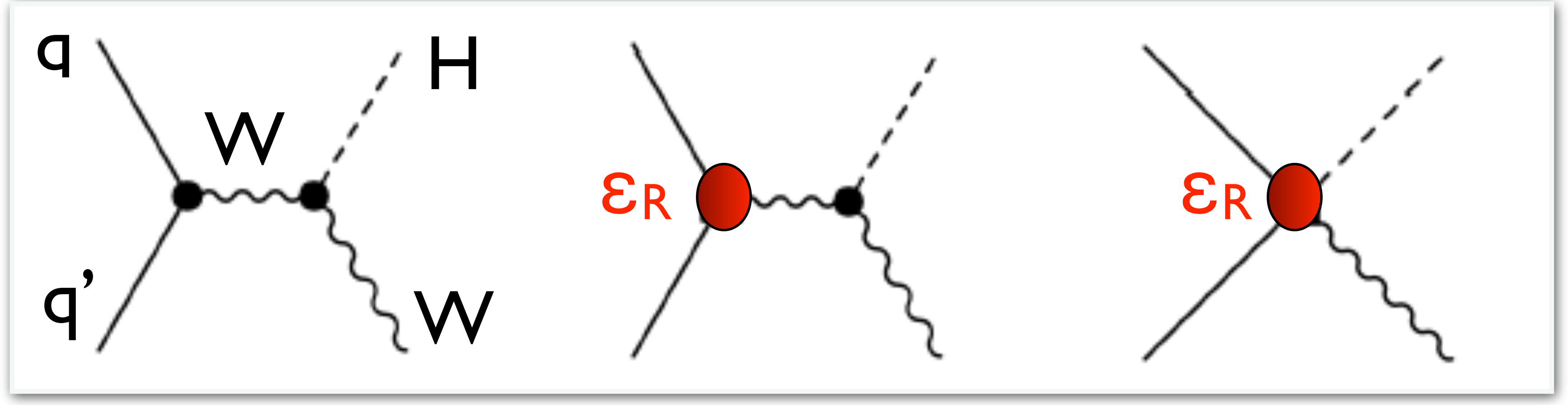
Same shape as the SM W exchange → weak sensitivity

pp → eν + X



VC, Graesser, Gonzalez-Alonso 1210.4553

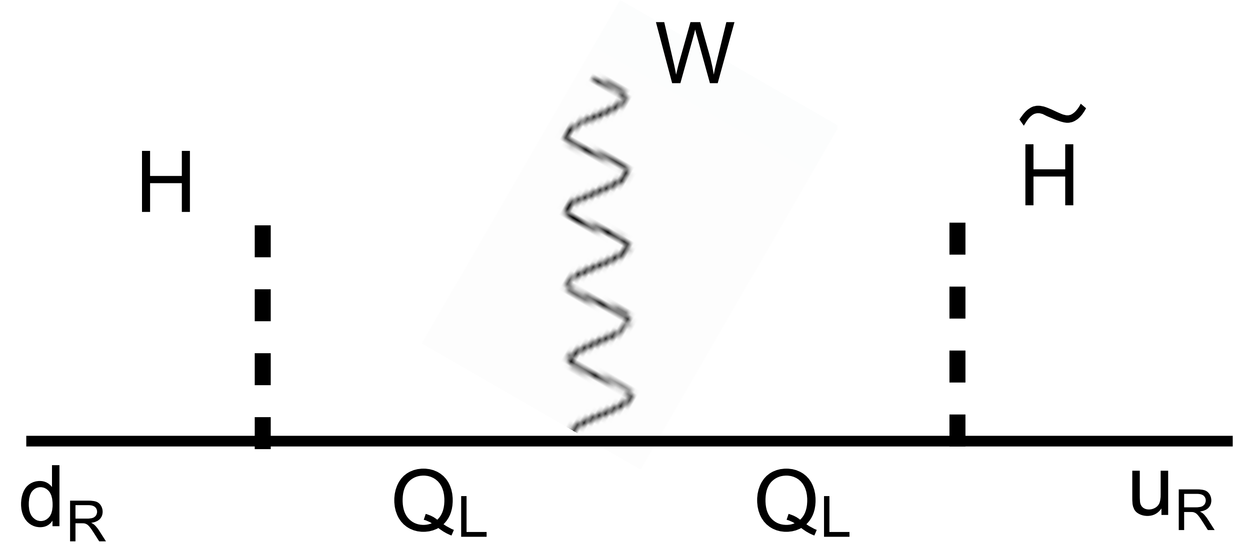
Associated Higgs +W production



S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

Current LHC results allow for to ε_R ~ 5%

- ε_R can be generated at tree level by W_L-W_R mixing in LRSM or by exchange of vector-like quarks**



**Belfatto-Berezhiani 2103.05549. … **Belfatto-Trifinopoulos 2302.14097

Additional backup

Nuclear decay rate in EFT

VC, W. Dekens,, J.de Vries, S. Gandolfi, M. Hoferichter, E, Mereghetti, 2405.18469, 2405.18464

- EFT-based decay rate formula reorganizes 'traditional' corrections using EFT principles

Ultra-soft
Point-like nucleus, O(α/π)
[Sirlin function]

Hard, soft, potential
Isospin-breaking in wave functions <f |τ^+ |i>

Ultra-soft
Point-like nucleus,
O((πα)^m Z^n)
[Fermi function**]

Additional corrections: nuclear EW form factor, nuclear recoil, atomic effects.

$$\frac{1}{t} = \frac{G_F^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} \left[C_{\rm eff}^{(g_V)}(\mu) \right]^2 \times \left[1 + \bar{\delta}'_R(\mu)\right] \left(1 + \bar{\delta}_{\rm NS}\right) \left(1 - \bar{\delta}_C\right) \bar{f}(\mu),$$

All large logs from RGEs (μ>m$_e$)
Hard and (ultra) soft

Structure-dependent radiative correction <f |$\mathcal{V}_n$ |i>
Hard, soft, potential

** See also. K. Borah, R. Hill, R. Plestid, 2309.07343, 2309.15929, 2402.13307

- Need for improvement
  - *Two currently unknown LECs contributing to δ_{NS} to $O(G_F \alpha \varepsilon_\chi)$*
  - Two- and three- body potentials to $O(G_F\alpha(\varepsilon_\chi)^2)$: may be relevant at 0.01%, needed to check EFT convergence
  - Non-logarithmic terms of $O(\alpha^2 Z)$ in the Fermi function (finite parts of two-loop diagrams)

V_{us} from hyperon decays

$$\Gamma = \frac{G_F^2}{60\pi^3}(M_B - M_b)^5(1-3\delta)|V_{us}|^2|f_1^{B\to b}(0)|^2(1+\Delta_{RC})\left[1+3\left|\frac{g_1^{B\to b}(0)}{f_1^{B\to b}(0)}\right|^2+\cdots\right]$$

$$\delta = \frac{M_B - M_b}{M_B + M_b}$$

- Use SU(3) limit for vector form factor $f_1(0)$
- Extract g_1/f_1 from data

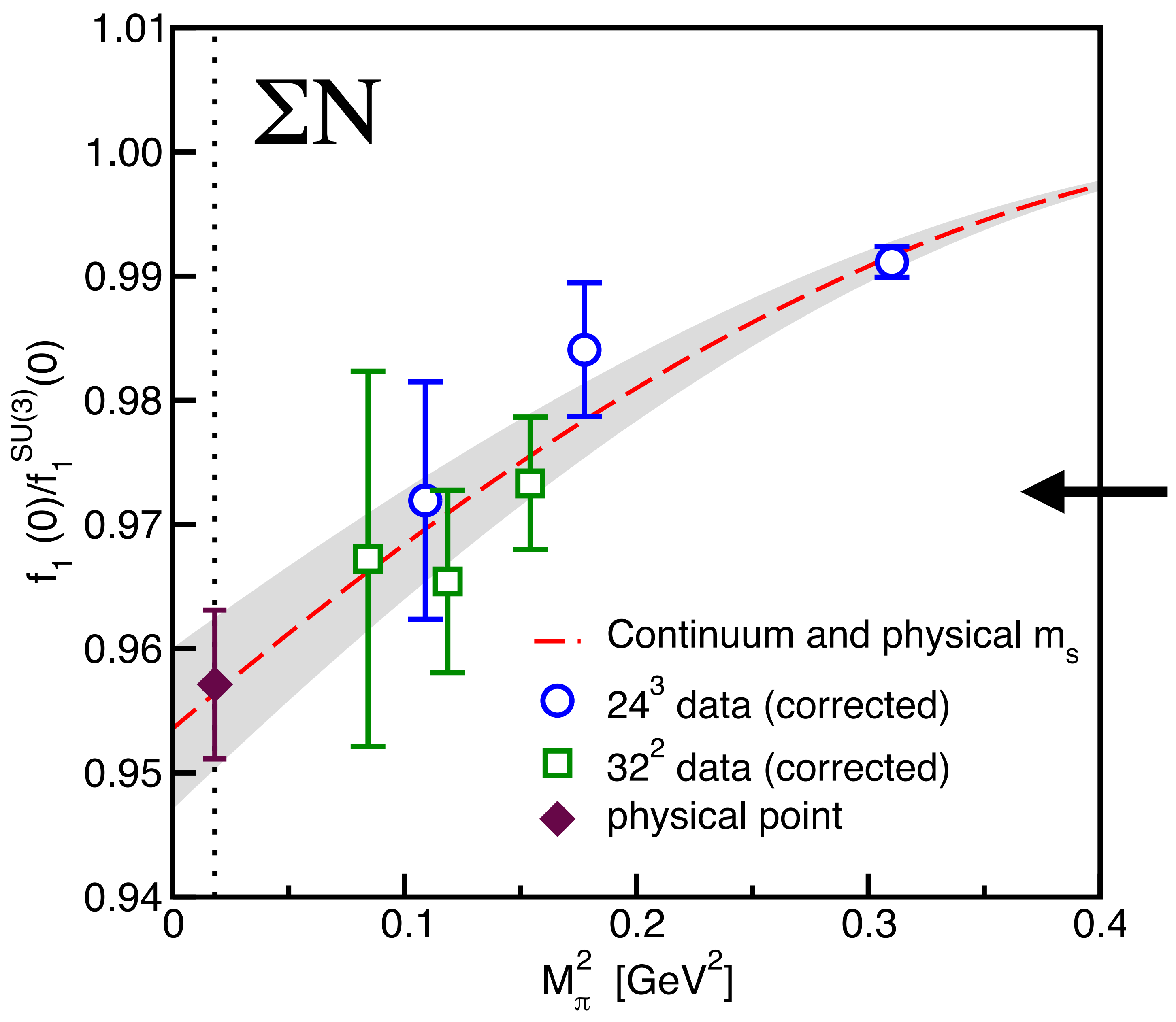
Cabibbo-Swallow-Winston. hep-ph/0307298

Decay Process	Rate (μsec^{-1})	g_1/f_1	V_{us}
$\Lambda \to p e^- \bar{\nu}$	3.161(58)	0.718(15)	0.2224 ± 0.0034
$\Sigma^- \to n e^- \bar{\nu}$	6.88(24)	−0.340(17)	0.2282 ± 0.0049
$\Xi^- \to \Lambda e^- \bar{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}$	0.876(71)	1.32(+.22/ − .18)	0.209 ± 0.027
Combined	—	—	0.2250 ± 0.0027

V_{us} @ %-level in best channels.
No theoretical uncertainty included

- ~~SU~~(3) in $f_1(0)$: quark model, $1/N_c$, ChPT → LQCD
- Negative shift of few percent with uncertainty ~1%

2+1, DWF, 2 lattice spacings



Guadagnoli et al., heo-ph/0606181.

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Sasaki 1708.04008

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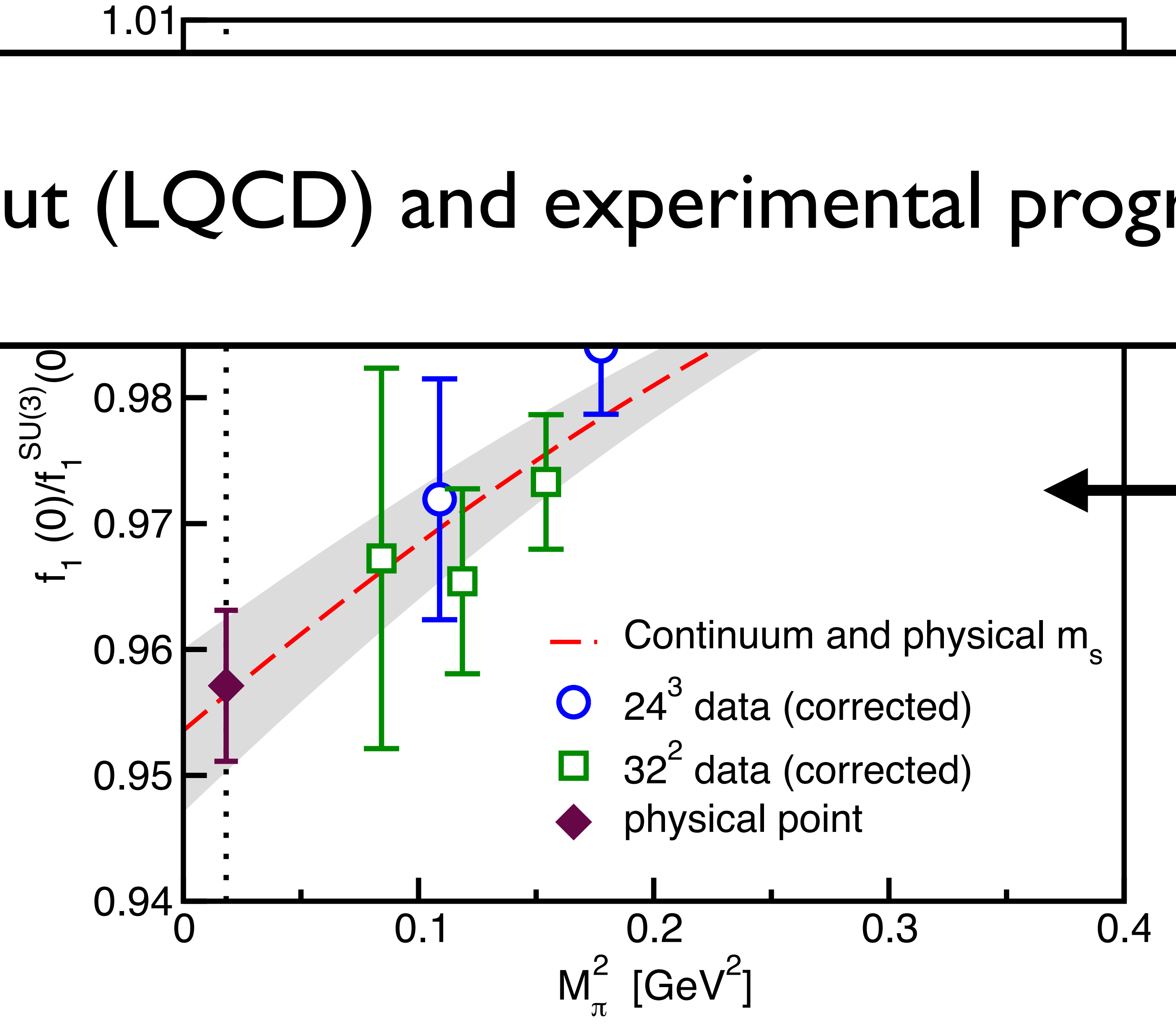

Sasaki 1708.04008

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Competitive extraction of V_{us} will require improved theory input (LQCD) and experimental progress (LHCb?)