Snowmass Rare and Precision Measurements Frontier Spring Meeting
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CKM first row unitarity: challenges and opportunities

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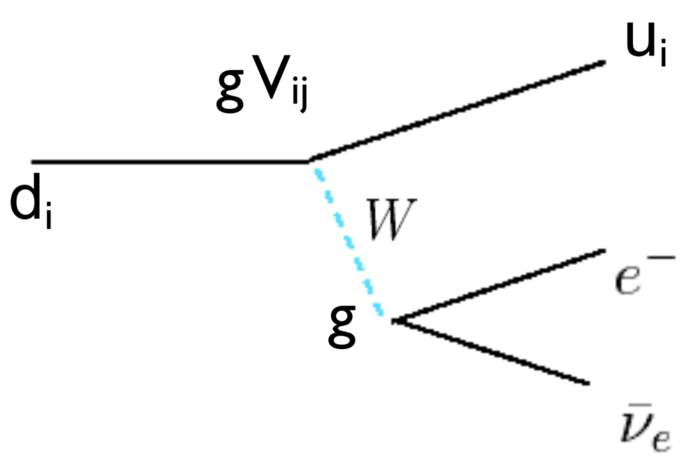
Outline

- Introduction: semi-leptonic decays in the SM and beyond
- Paths to extracting V_{ud} and V_{us}
- Status of 1st row CKM unitarity test: Cabibbo Angle Anomaly
  - Possible explanations within the Standard Model
  - BSM explanations in EFT language
- Conclusions and outlook

Semileptonic decays in the SM and beyond

- In the SM, W exchange $\Rightarrow$ V-A currents, universality relations



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

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

Cabibbo-Kobayashi-Maskawa

Lepton universality

$$[G_F]_e/[G_F]_\mu = 1$$

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

Cabibbo universality

Semileptonic decays in the SM and beyond

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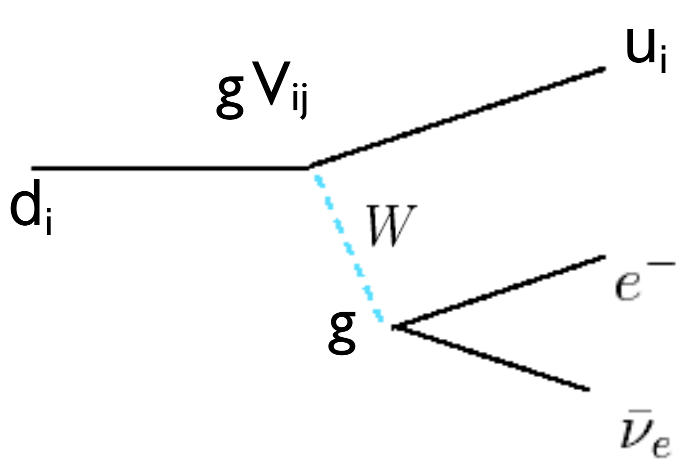
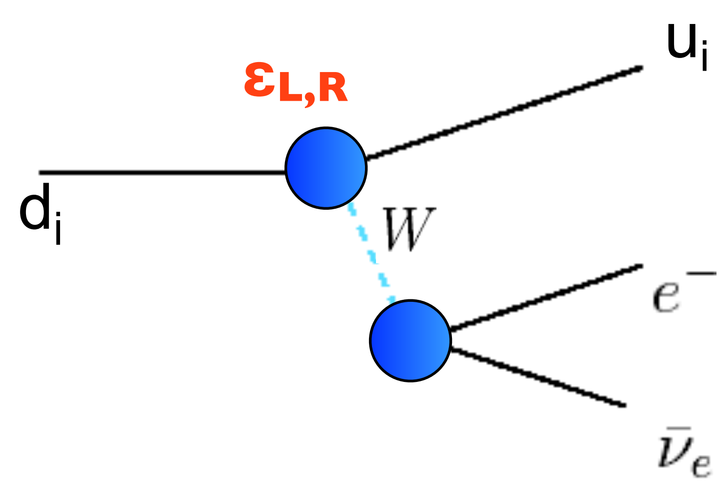
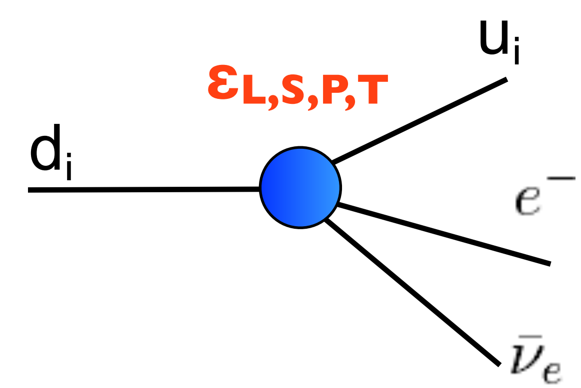
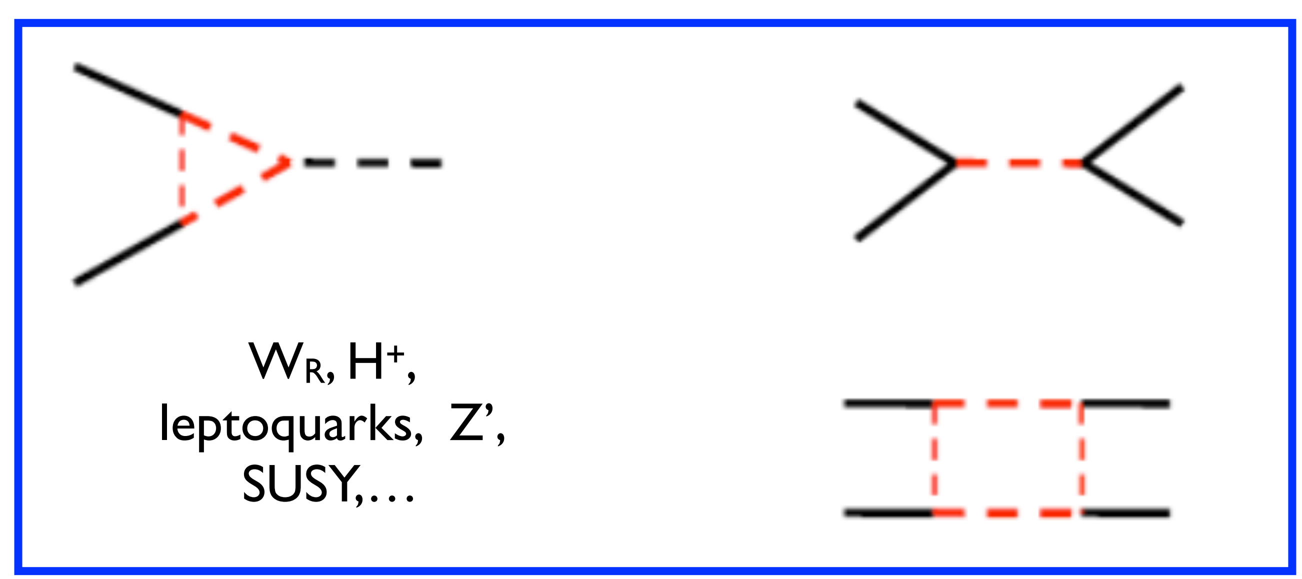






$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$ $\quad$ $1/\Lambda^2$ $\quad$ $1/\Lambda^2$

- BSM effects $\varepsilon \sim (v/\Lambda)^2$, can spoil universality. Precision in 0.1-0.01% probes Λ > 10 TeV



Cabibbo universality tests

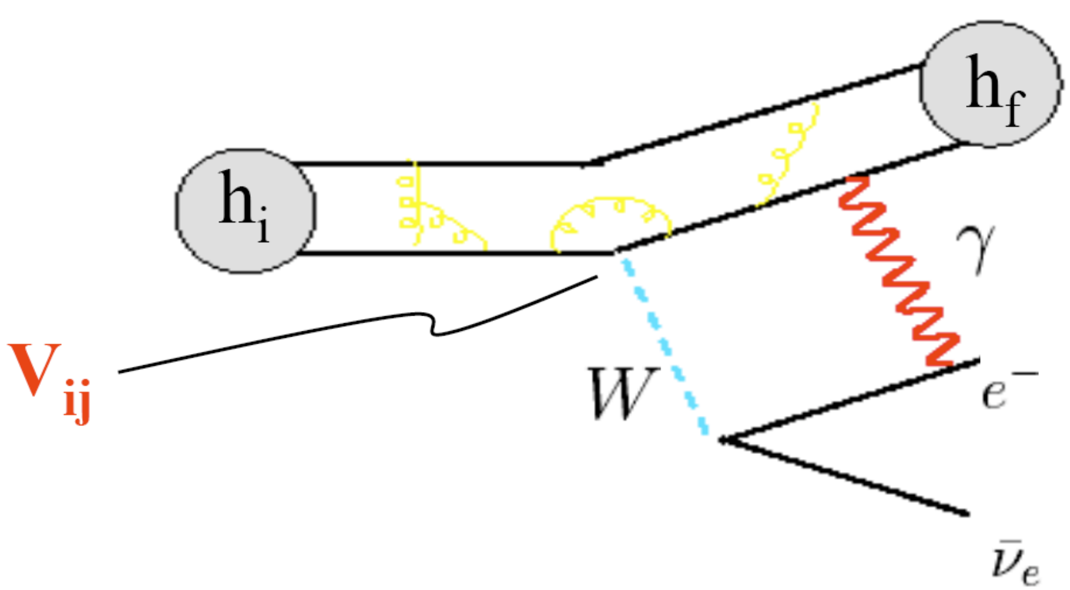
- Extract V_{ij} from semileptonic processes (beta decays, …)

$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections



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Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections

$$|\bar{V}_{ij}|^2 = |V_{ij}|^2 \times \left(1 + \sum_\alpha c_k^\alpha \, \epsilon_\alpha\right)$$

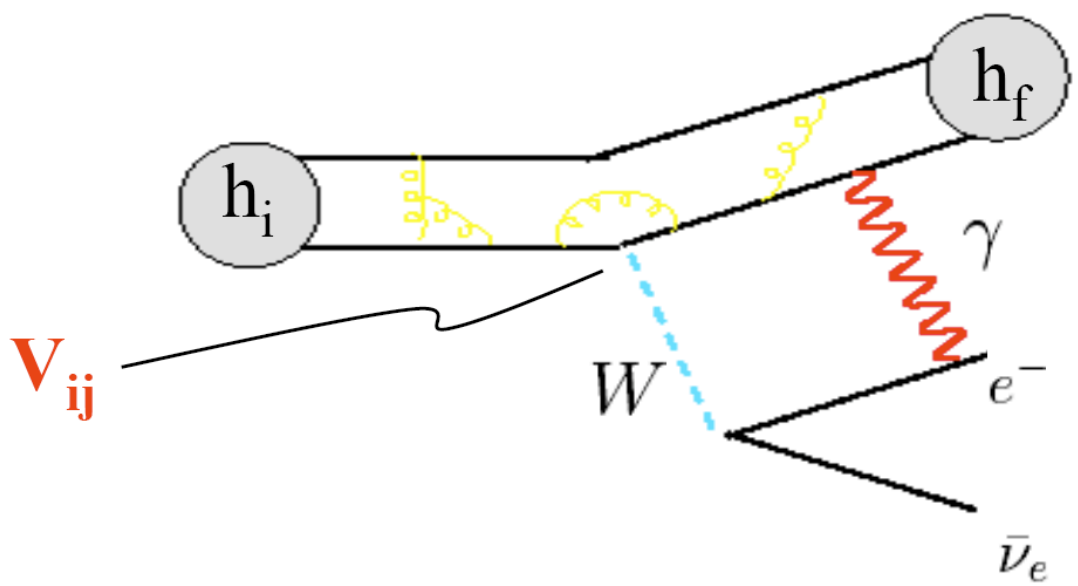
Calculable coefficients

BSM effective couplings

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi\, l\, \nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\tau \to h_S\nu$



Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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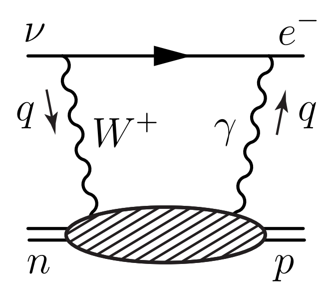
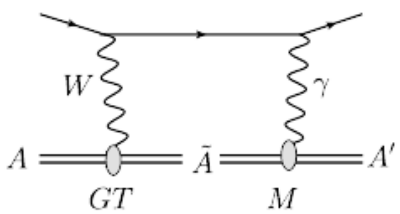
- "Golden modes" (V current): normalization known in SU(2) [SU(3)] limit, corrections are 2nd order in SU(N) breaking.

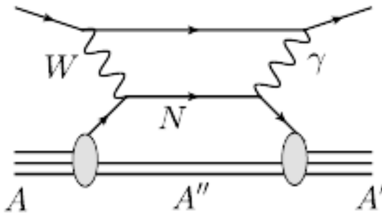
- Nuclear decays: Recent analysis of "inner" radiative corrections with dispersive methods (smaller errors). New structure-deep corrections pointed out (larger error)



Seng et al, 1812.03352

Czarnecki-Marciano-Sirlin 1907.06737





Survey by Hardy-Towner, PRC 2020

Seng et al, 1807.10197

Gorchtein 1812.04229

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^{\pm} \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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- "Golden modes" (V current): normalization known in SU(2) [SU(3)] limit, corrections are 2nd order in SU(N) breaking.

- Kaon decays:
  - New analysis of radiative corrections based on Sirlin's formalism + lattice. Compatible with older ChPT analysis, but order-of-magnitude smaller uncertainty.
  - Lattice calculations of <π|V|K> keep improving (0.2%)
  - Expt. input has received small updates since 2010

Seng et al, 1910.13209, 2103.00975. 2103.4843. 2107.14708. 2203.05217
Ma et al. 2102.12048

VC, Giannotti, Neufeld 0807.4607

FLAG 21, Aoki et al., 2111.09849

Flavianet WG, 1005.2323
Moulson 1704.04104

Paths to V_{ud} and V_{us}

V_{ud}	$\boxed{0^+ \to 0^+}$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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- "Golden modes" (V current): normalization known in SU(2) [SU(3)] limit, corrections are 2nd order in SU(N) breaking.

- Pion beta decay:
  - Theory in great shape: calculation of radiative corrections with input on γ-W box from lattice QCD
  - Expt. needs order-of-magnitude improvement in precision in order to be competitive. First steps with PIONEER experiment

Feng, Gorchtein, Jin, Ma, Seng , 2003.09798

PIONEER 2203.01908

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ ($\pi^\pm \to \pi^0 e \nu$)	$n \to p e \bar{\nu}$ (Mirror transitions)	$\pi \to \mu\nu$	$\tau \to h_{NS}\nu$
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- Both V and A currents contribute: need experimental input on <A>
- Neutron decay:
  - Recent advances in lifetime and β asymmetry measurement (g_A) make neutron's δV_{ud} much closer to that of nuclear decays
  - Theoretically "cleaner" — no nuclear structure
- Mirror transitions: V_{ud} uncertainty is >3 greater than the one in $0^+ \to 0^+$
- Hyperon decays: currently lower expt. and theoretical precision

Gonzalez et al, 2106.10375

Maerkish et al, 1812.04666

Falkowski et al. 2110.13797

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e\nu)$	$n \to pe\bar{\nu}$ (Mirror transitions)	$\boxed{\pi \to \mu\nu}$	$\tau \to h_{NS}\nu$
V_{us}	$K \to \pi l \nu$	$\Lambda \to pe\bar{\nu},\ldots$	$\boxed{K \to \mu\nu}$	$\tau \to h_S\nu$

- A current transitions: most precise constraint on V_{us}/V_{ud}
- Lattice QCD calculations of F_K/F_π have reached <0.2%
- First calculation of radiative and isospin-breaking corrections in Lattice QCD have appeared. Compatible with ChPT but factor of ~2 more precise
- Expt. input hasn't changed since 2010

FLAG 21, Aoki et al., 2111.09849

Di Carlo et al., 1904.08731

VC-Neufeld, 1102.0563

Flavianet WG, 1005.2323
Moulson 1704.04104

Paths to V_{ud} and V_{us}

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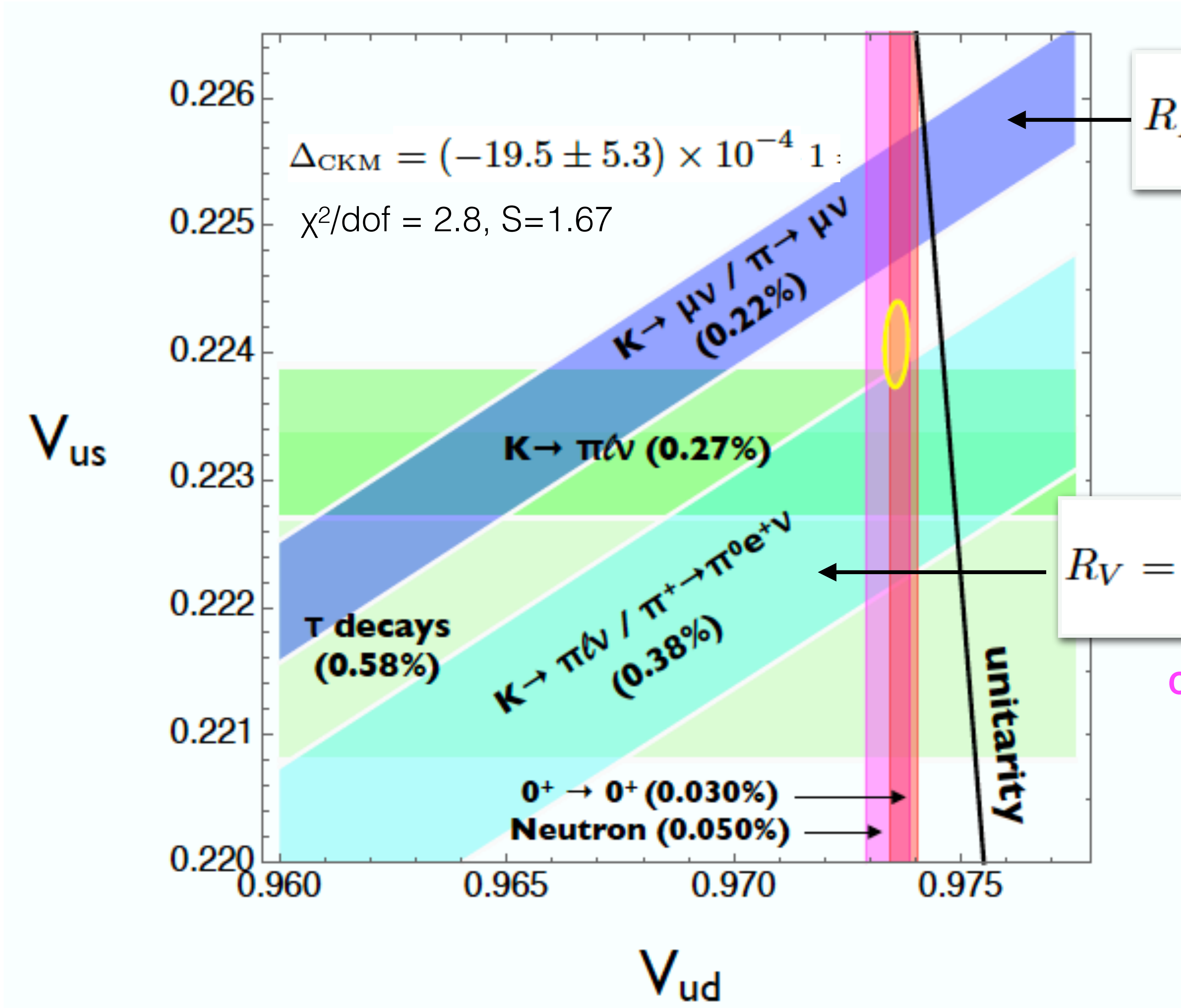
V_{us}	$K \to \pi l \nu$	$\Lambda \to pe\bar{\nu},\ldots$	$K \to \mu\nu$	$\boxed{\tau \to h_S\nu}$

- Use OPE to calculate inclusive BRs — very different theory "systematics"
- Information from both inclusive and exclusive modes
- Currently less competitive than K decays in the precision on V_{us}

See HFLAG WG (1909.12524) and references therein

CKM unitarity test

Bryman, VC, Crivellin, Inguglia 2111.05338



$$R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

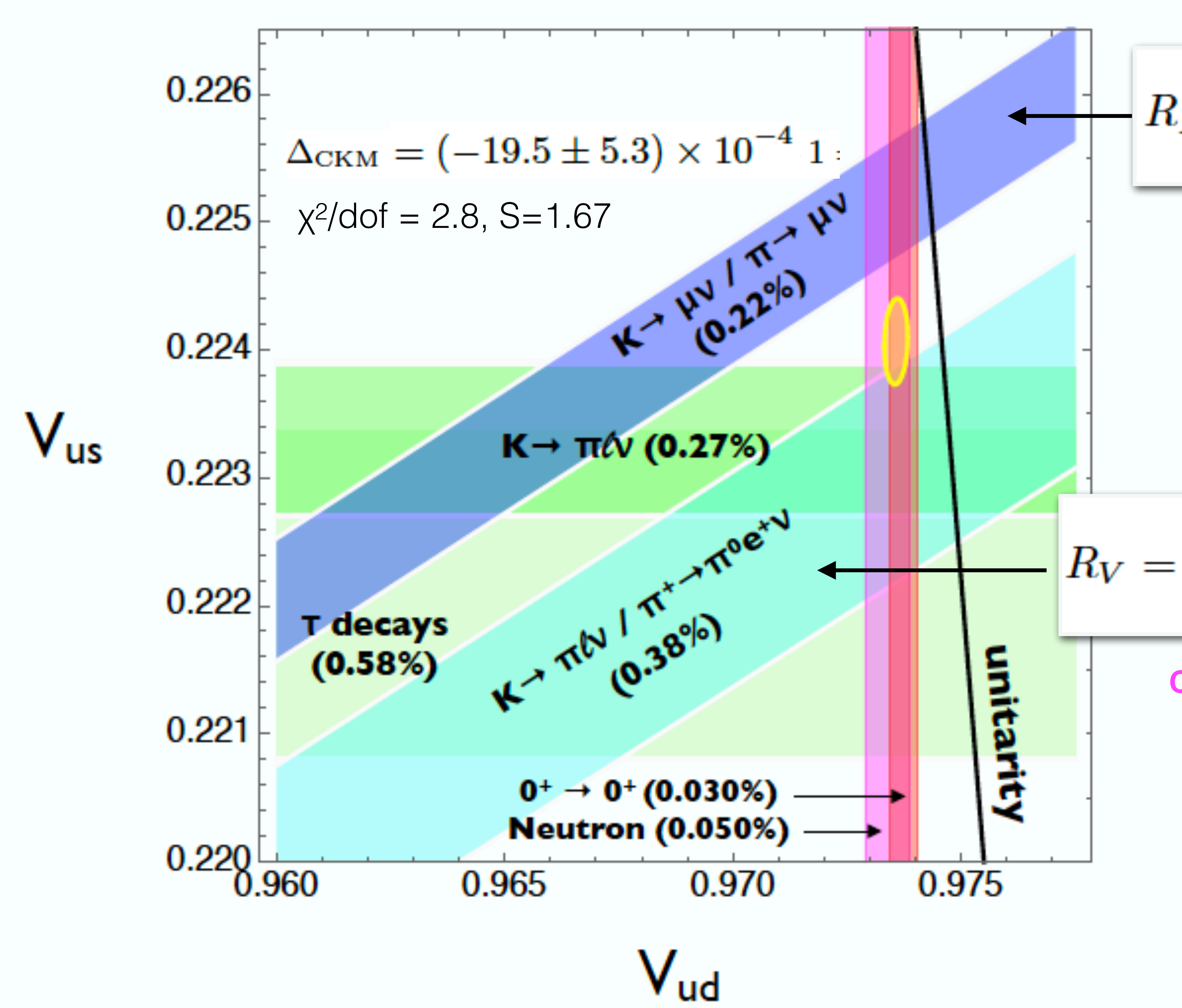
Marciano, hep-ph/0402299

$$R_V = \frac{\Gamma(K_L \to \pi^{\pm} e^{\mp}\nu(\gamma))}{\Gamma(\pi^{+} \to \pi^{0} e^{+}\nu(\gamma))}$$

Czarnecki, Marciano, Sirlin 1911.04685

CKM unitarity test

Bryman, VC, Crivellin, Inguglia 2111.05338



$$R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

Marciano, hep-ph/0402299

$$R_V = \frac{\Gamma(K_L \to \pi^\pm e^\mp \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))}$$

Czarnecki, Marciano, Sirlin 1911.04685

Is this a hint of new physics?

Standard Model explanations?

1. Hadronic matrix elements

- K-π vector form factor normalization: $f_+^K(0)$: 0.970(2) → 0.961(4)

$$\Gamma(K_L \to \pi^\mp e^\pm \nu(\gamma)) = \frac{G_\mu^2 |V_{us}|^2 m_{K_L}^5 \left|f_+^K(0)\right|^2}{192\pi^3}(1 + \mathrm{RC}_K) I_K$$

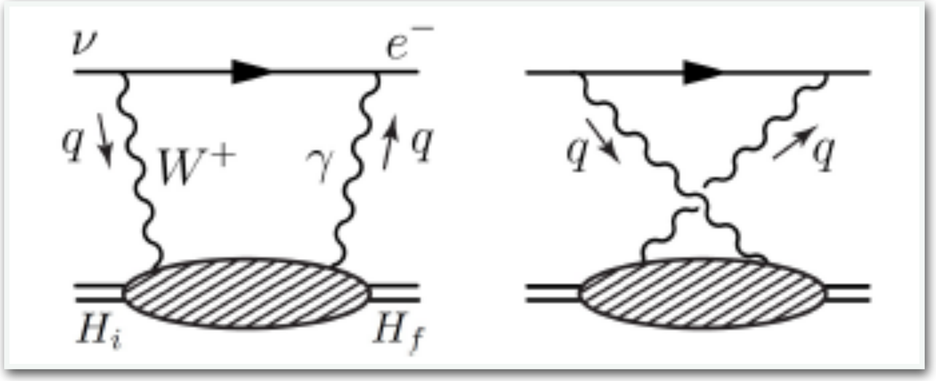
Czarnecki, Marciano, Sirlin 1911.04685, PRD

It would amount to a ~25% effect on the computed SU(3) breaking correction $f_+(0)-1$. Not likely, in my opinion

- Similarly, uncertainty estimate on F_K/F_π would have to be off by several theoretical "standard deviations"

Standard Model explanations?

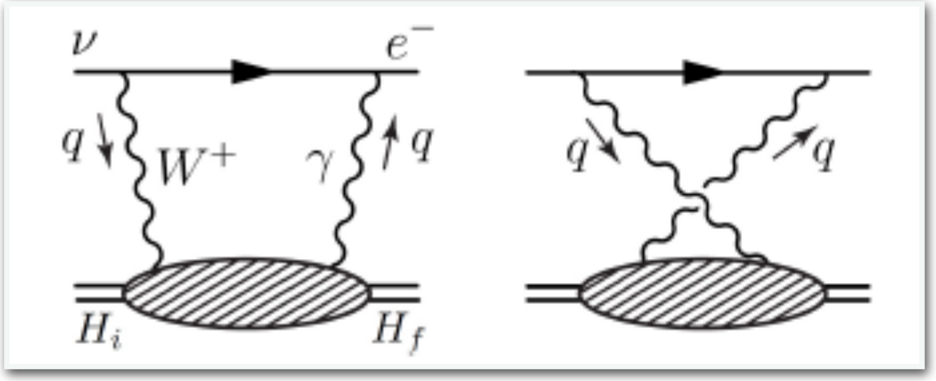
2. Radiative corrections



- R_A : RC + isospin breaking in ChPT and LQCD agree. Only full-fledged LQCD calculation of radiative corrections so far
- Pion beta decay: RC with input from LQCD (γ-W box)
- $K \to \pi e \nu$, $K \to \pi \mu \nu$: partially rely on lattice QCD (γ-W box); improvable
- Neutron decay: need lattice QCD calculation
- Nuclear decays: improvable with EFT + ab-initio calculations, which provide a way to quantify uncertainty

Standard Model explanations?

2. Radiative corrections



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The frontier is:

QCD+QED on the lattice for meson and neutron decay

EFT+ ab-initio calculations in nuclei: good prospects for ^{10}C and ^{14}O decays

BSM explanations?

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

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

Channel-dependent, extracted CKM elements

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

Low-energy effective Lagrangian (I)

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

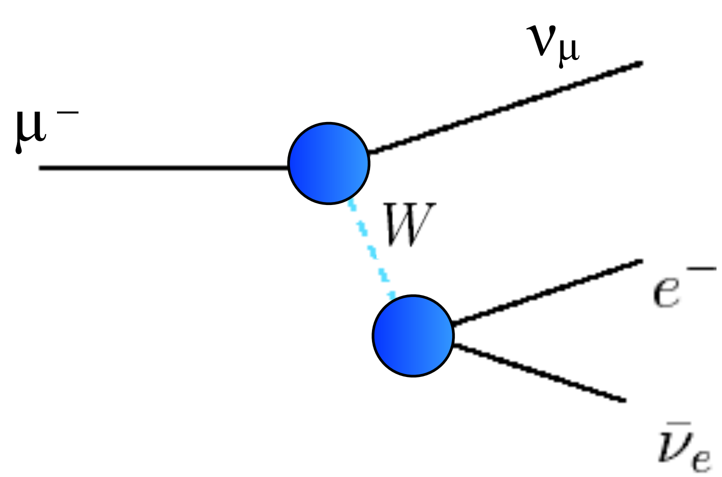
Leptonic interactions

$$\mathcal{L}_{CC}^{(\mu)} = -\frac{G_F^{(0)}}{\sqrt{2}} \left(1 + \epsilon_L^{(\mu)}\right) \bar{e}\gamma^\rho(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu \gamma_\rho (1-\gamma_5)\mu \ + \ \ldots$$

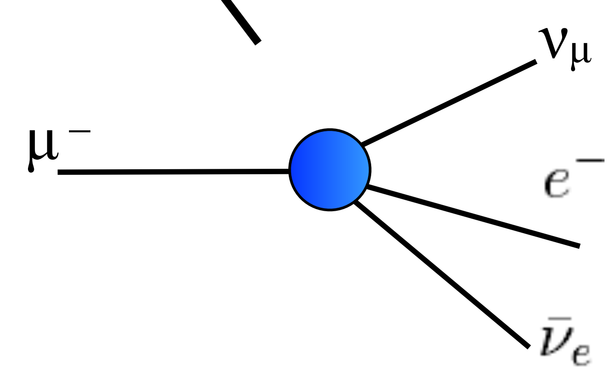
$$G_F^{(\mu)} = G_F^{(0)} \left(1 + \epsilon_L^{(\mu)}\right)$$

$$\epsilon_L^{(\mu)} = \epsilon_{W\ell}^{ee} + \epsilon_{W\ell}^{\mu\mu} + \epsilon_{4\ell}$$

$\varepsilon_i \sim (v/\Lambda)^2$



Vertex corrections



4-fermion contact interaction

Low-energy effective Lagrangian (2)

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

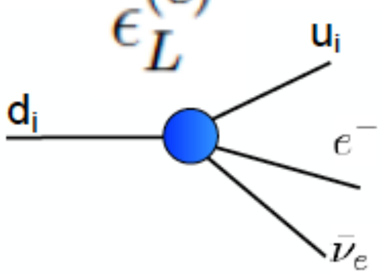
VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Semi-leptonic interactions

$$\begin{aligned}\mathcal{L}_{\rm CC} \;=\; -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[&\left(\delta^{ab} + \epsilon_L^{ab}\right) \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u}\gamma^\mu (1-\gamma_5) d \\ &+ \epsilon_R^{ab} \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u}\gamma^\mu (1+\gamma_5) d \\ &+ \epsilon_S^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} d \\ &- \epsilon_P^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u}\gamma_5 d \\ &+ \epsilon_T^{ab} \; \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5) \nu_b \cdot \bar{u}\sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.}\end{aligned}$$

$\varepsilon_i \sim (v/\Lambda)^2$

$\epsilon_L^{(c)}$

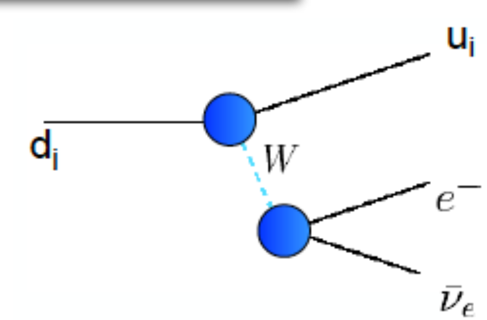


$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$$

Vertex + contact 4-Fermi

$$[\epsilon_L^{(v)}]^{ab} = \epsilon_{W\ell}^{ab} + \epsilon_{Wq}$$

W-lepton and W-quark vertex corrections



Low-energy effective Lagrangian (2)

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

$$\frac{G_F^{(\mu)} V_{ud}}{\sqrt{2}} \left(1 - \epsilon_L^{(\mu)}\right)$$

Semi-leptonic interactions

$$\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Bigg[\left(\delta^{ab} + \epsilon_L^{ab}\right) \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1-\gamma_5) d \\
& + \epsilon_R^{ab} \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1+\gamma_5) d \\
& + \epsilon_S^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} d \\
& - \epsilon_P^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} \gamma_5 d \\
& + \epsilon_T^{ab} \; \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5) \nu_b \cdot \bar{u} \sigma^{\mu\nu} (1-\gamma_5) d \Bigg] + \text{h.c.}
\end{aligned}$$

$\varepsilon_i \sim (v/\Lambda)^2$

Beta decays sensitive to

$$\epsilon_L^{ee} - \epsilon_L^{(\mu)} = -\epsilon_{W\ell}^{\mu\mu} + \epsilon_{Wq} + [\epsilon_L^{(c)}]^{ee} - \epsilon_{4\ell}$$

Low-energy effective Lagrangian (2)

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB

VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Semi-leptonic interactions

$$
\begin{aligned}
\mathcal{L}_{CC} = & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[\left(\delta^{ab} + \epsilon_L^{ab}\right) \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1-\gamma_5) d \\
& + \epsilon_R^{ab} \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1+\gamma_5) d \\
& + \epsilon_S^{ab} \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} d \\
& - \epsilon_P^{ab} \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} \gamma_5 d \\
& + \epsilon_T^{ab} \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5) \nu_b \cdot \bar{u} \sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.}
\end{aligned}
$$

$\varepsilon_i \sim (v/\Lambda)^2$

$\varepsilon_{S,T,P}$ and $\varepsilon_L^{(c)}$ are constrained by other probes (including LHC) to levels that make them unlikely source of the Cabibbo angle anomaly

Δ_{CKM} and LFUV

- 'Turn on' only vertex corrections to leptons

$$|\bar{V}_{ud}|^2_{0^+\to 0^+} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

$$|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

$$|\bar{V}_{us}|^2_{Ke3} = |V_{us}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

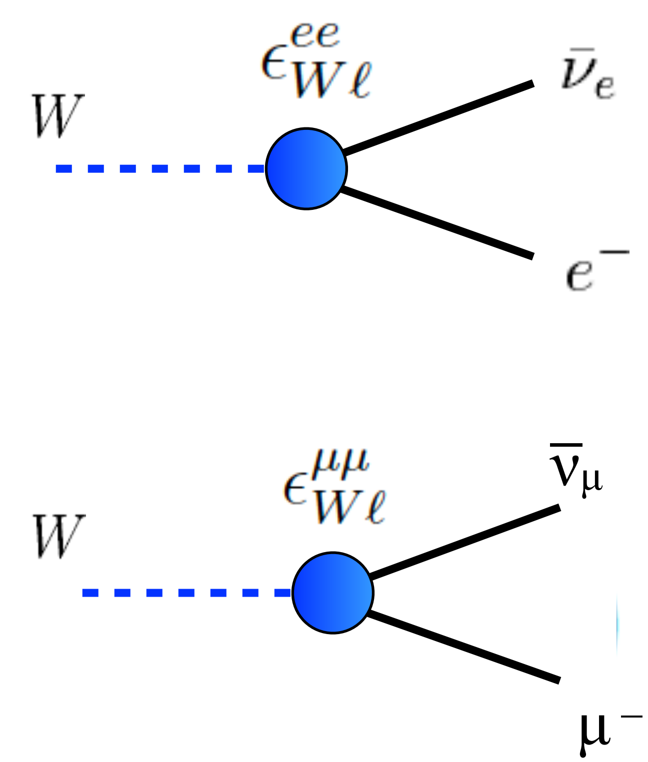
Relevant for R_V

$$|\bar{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

$$|\bar{V}_{us}|^2_{K\mu 2} = |V_{us}|^2 \left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$

Relevant for R_A

$$|\bar{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$



Δ_{CKM} and LFUV

- 'Turn on' only vertex corrections to leptons

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$$|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

Relevant for R_V

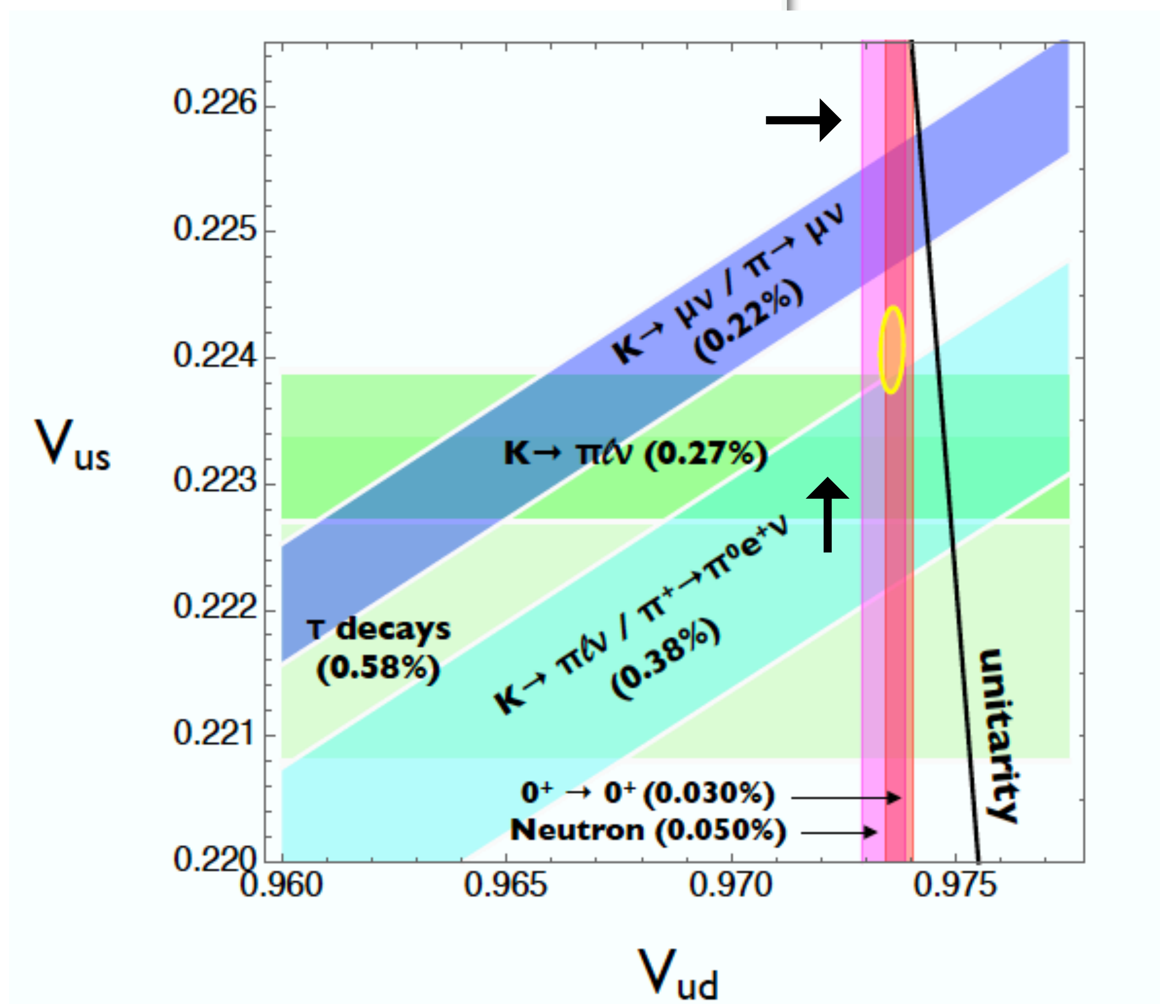
$$|\bar{V}_{us}|^2_{Ke3} = |V_{us}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

$$|\bar{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

Relevant for R_A

$$|\bar{V}_{us}|^2_{K\mu 2} = |V_{us}|^2 \left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$

$$|\bar{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2 \left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$



- Shift the location of the $V_{ud,us}$ bands:
  non-zero value of $(\varepsilon_{Wl})^{\mu\mu}$
- No resolution of Kl3 vs Kl2 and R_V vs R_A tension

Δ_{CKM} and LFUV

- 'Turn on' only vertex corrections to leptons

$$|\bar{V}_{ud}|^2_{0^+\to 0^+} = |V_{ud}|^2\left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

$$|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2\left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

Relevant for R_V

$$|\bar{V}_{us}|^2_{Ke3} = |V_{us}|^2\left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

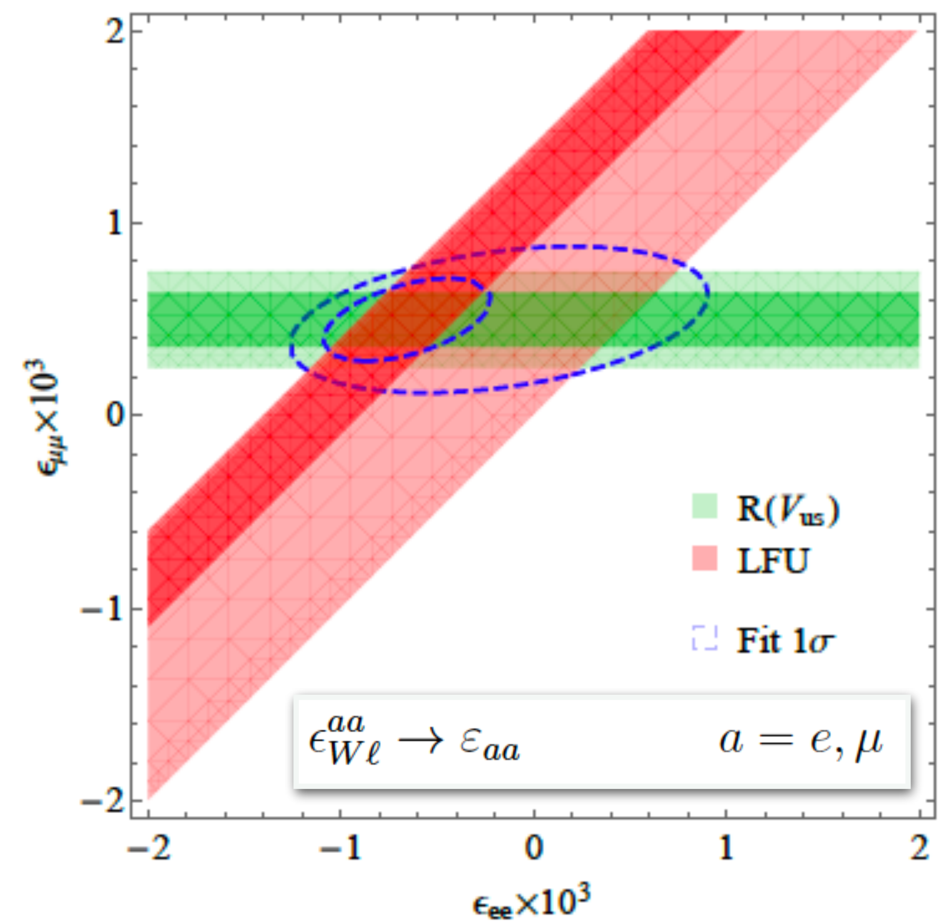
$$|\bar{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2\left(1 - 2\,\epsilon^{\mu\mu}_{W\ell}\right)$$

Relevant for R_A

$$|\bar{V}_{us}|^2_{K\mu 2} = |V_{us}|^2\left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$

$$|\bar{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2\left(1 - 2\,\epsilon^{ee}_{W\ell}\right)$$

Crivellin-Hoferichter 2002.07184, PRL



- Shift the location of the $V_{ud,us}$ bands: non-zero value of $(\varepsilon_{Wl})^{\mu\mu}$
- No resolution of Kl3 vs Kl2 and R_V vs R_A tension

- Connection with $\pi\to e\nu$/ $\pi\to\mu\nu$

$$r_\pi = 1 + 2\left(\epsilon^{ee}_{W\ell} - \epsilon^{\mu\mu}_{W\ell}\right)$$

(and other LFU probes)

Δ_{CKM} and R-handed currents

- Right-handed currents (in the 'ud' and 'us' sectors)

Grossman-Passemar-Schacht 1911.07821 JHEP
Alioli et al 1703.04751, JHEP

$$
\begin{aligned}
|\bar{V}_{ud}|^2_{0^+\to 0^+} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
|\bar{V}_{us}|^2_{Ke3} &= |V_{us}|^2\left(1+2\,\epsilon_R^{(s)}\right)\\
|\bar{V}_{ud}|^2_{\pi e3} &= |V_{ud}|^2\left(1+2\,\epsilon_R\right)\\
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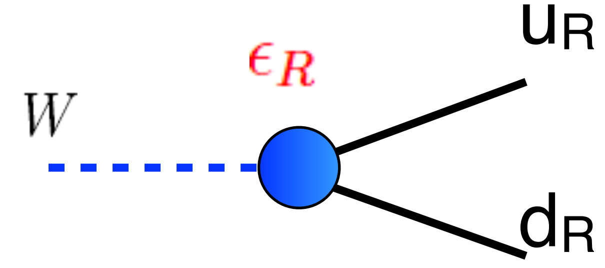
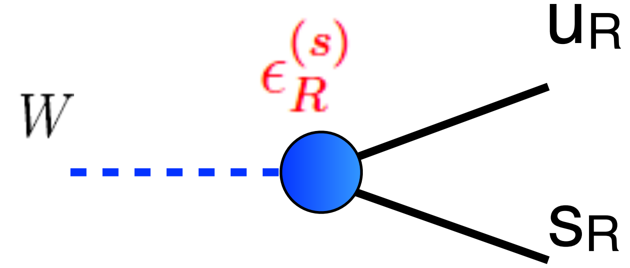
|\bar{V}_{ud}|^2_{\pi\mu 2} &= |V_{ud}|^2\left(1-2\,\epsilon_R\right)
\end{aligned}
$$

Relevant for R_V

Relevant for R_A





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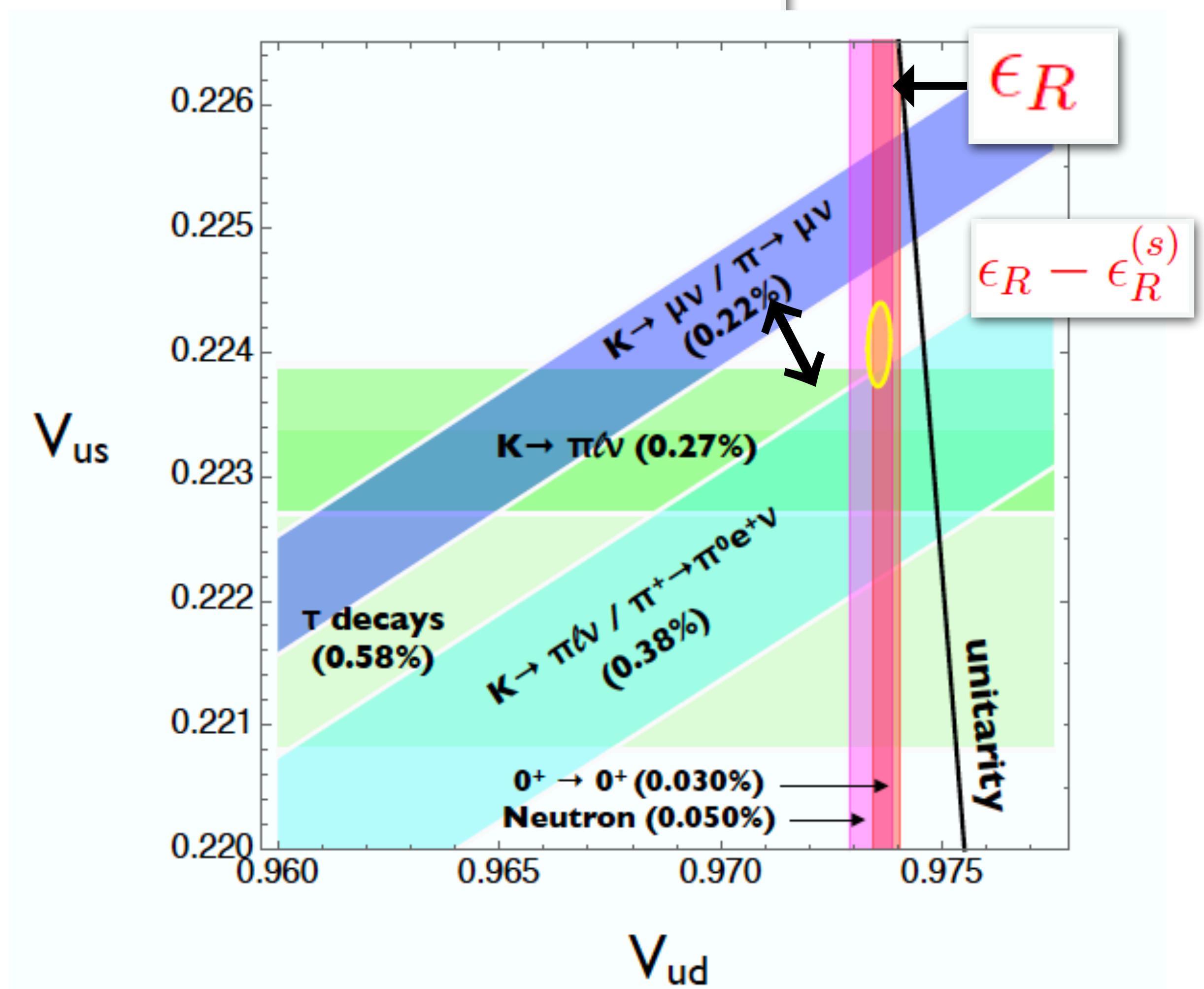


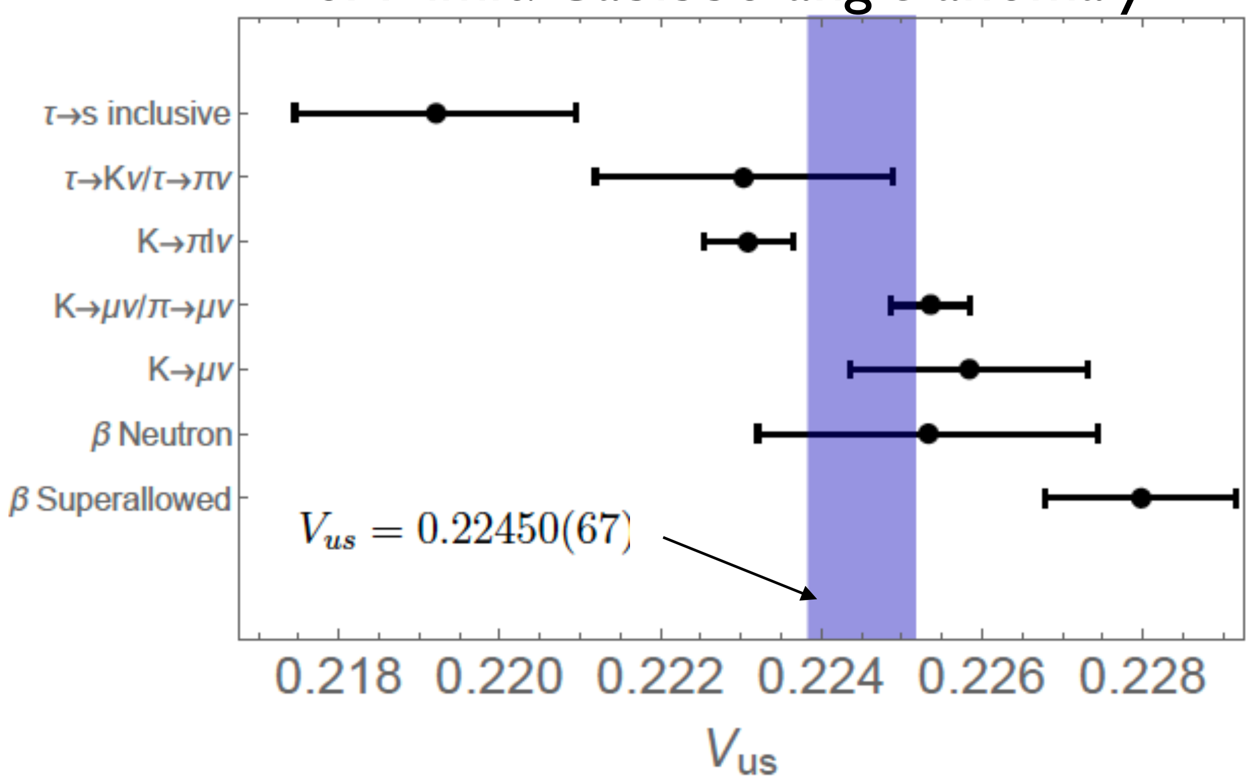
- R_V, R_A , V_{ud} and V_{us} bands shift in correlated way, can resolve all tensions!

Δ_{CKM} and R-handed currents

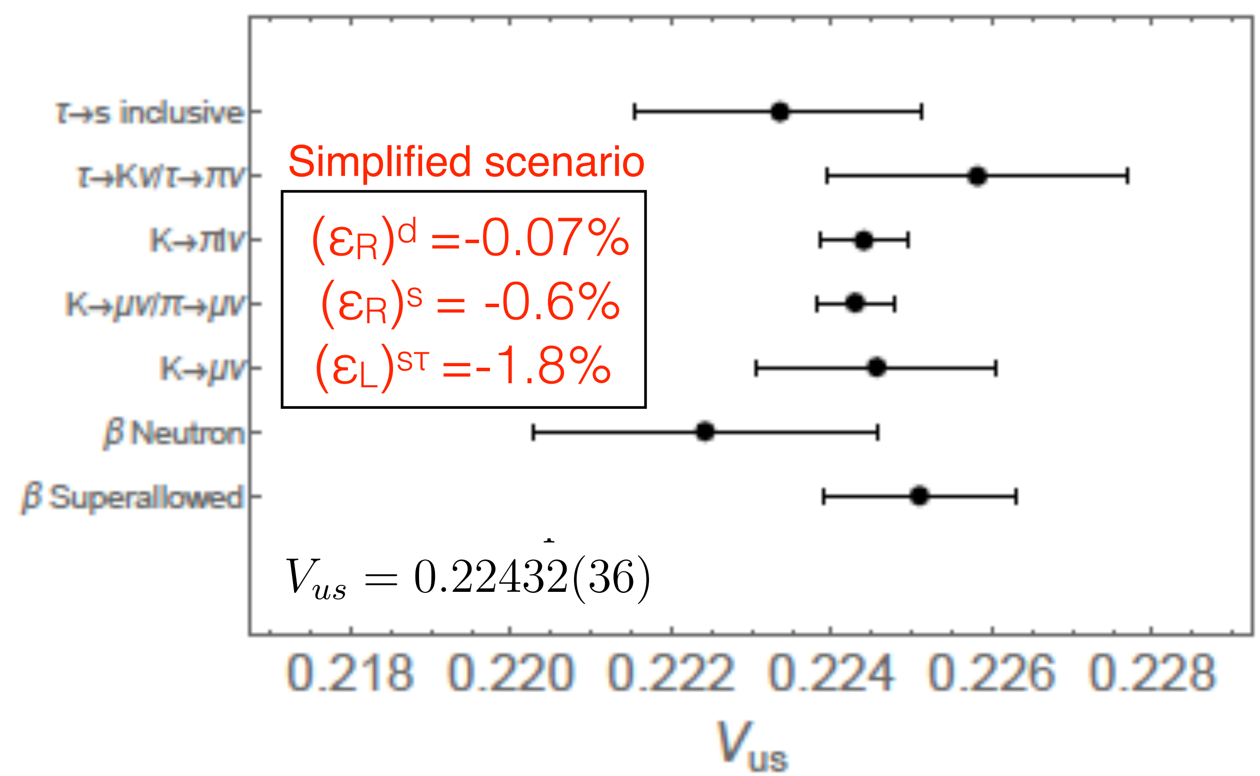
VC, Diaz-Calderon, Falkowski, Gonzalez-Alonso, Rodriguez-Sanchez 2112.02087

- Global fit to CC processes involving light quarks and all lepton families
- SM hypothesis (ε_i=0) disfavored (p-value 0.3%)

SM limit: Cabibbo angle anomaly



Anomaly removed by turning on the ε_R couplings



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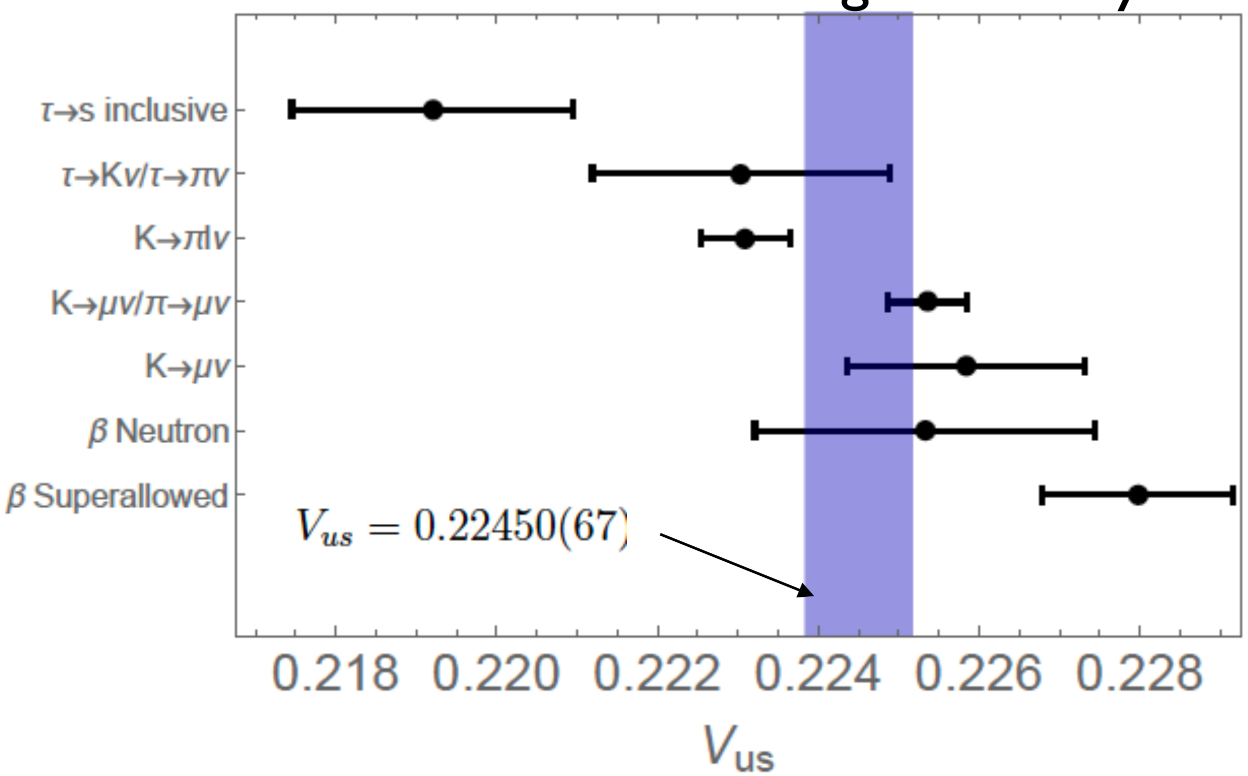

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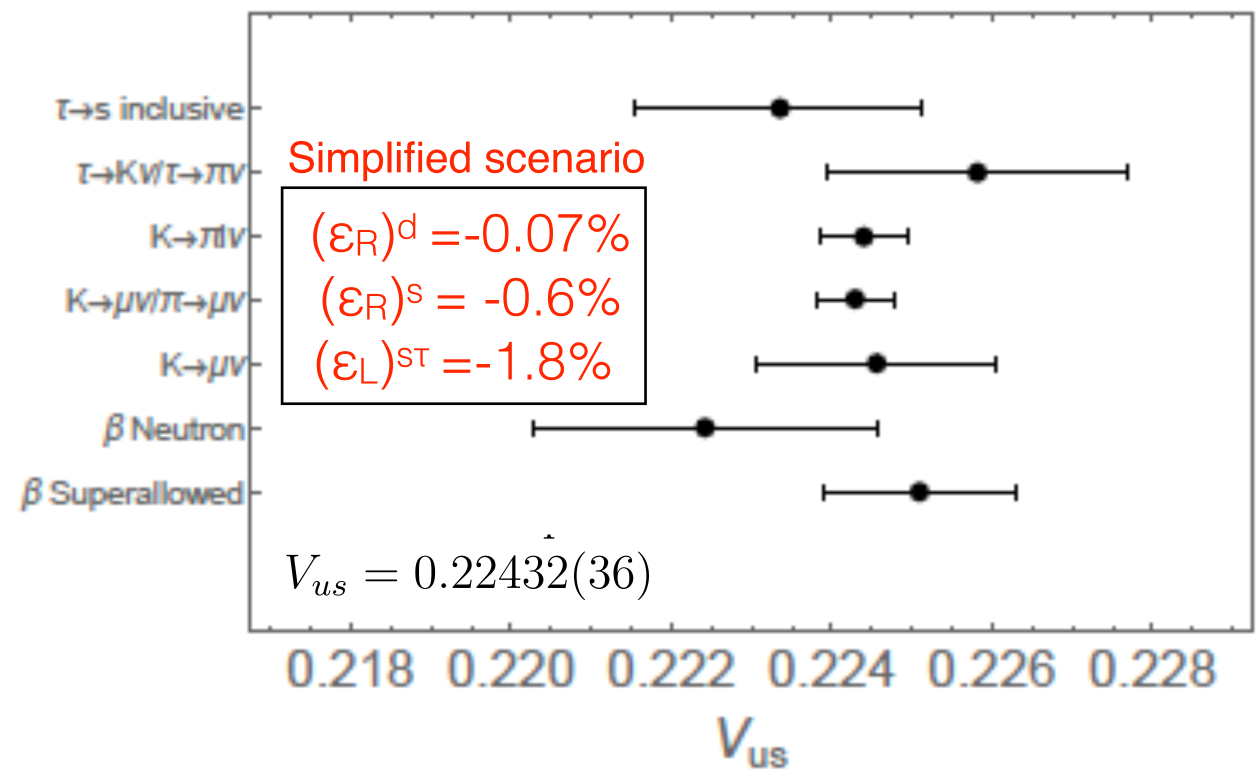


- Intriguing hints ⇒ guidance for BSM model-building [Many papers]
- Can match from LEFT to SMEFT and look at collider and precision EW constraints on the BSM couplings that are (dis)favored by the Cabibbo anomaly

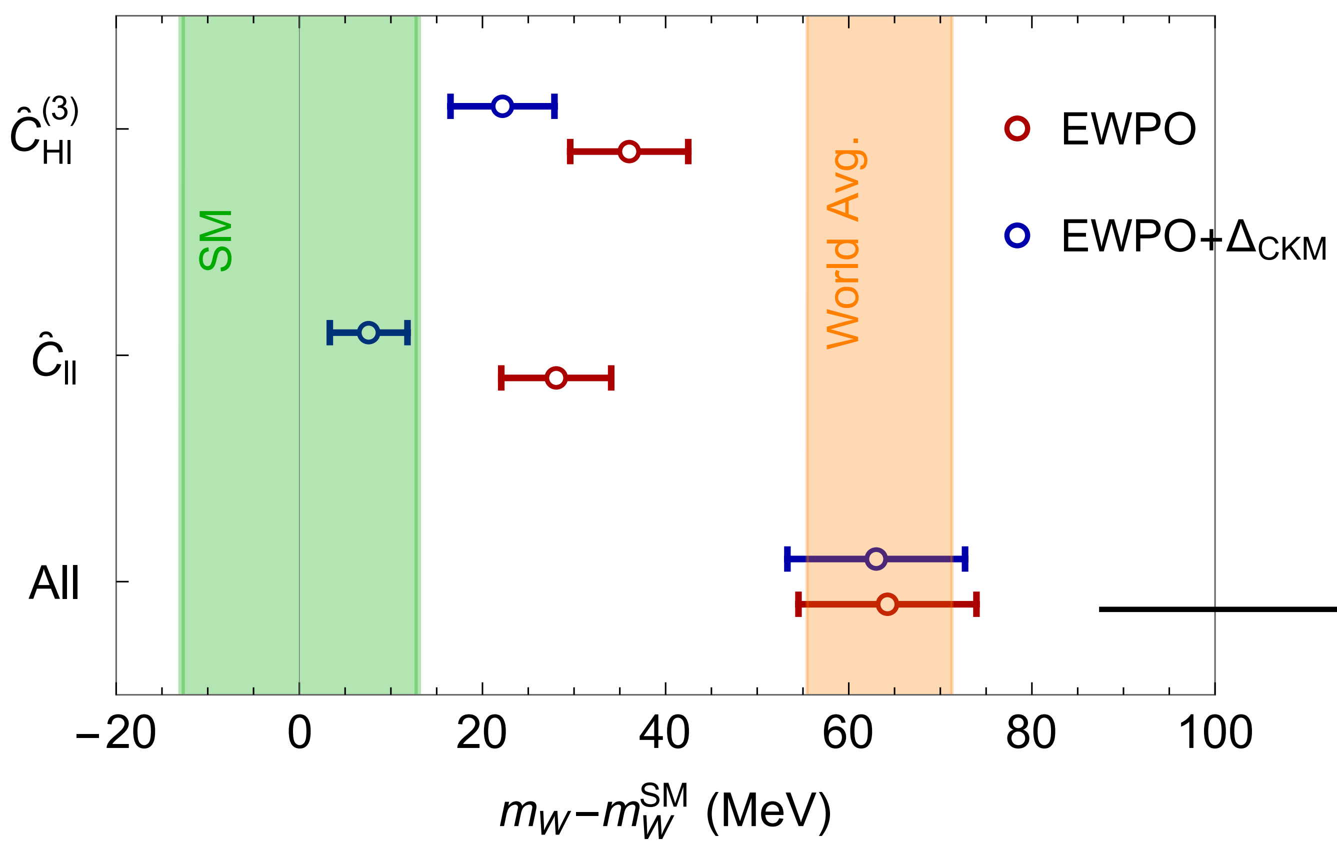
Connection with M_W?

VC, Dekens, deVries, Mereghetti, Tong 2204.08440

- Explanations of M_W anomaly in SMEFT (beyond oblique corrections) are in tension with current CKM unitarity

deBlas et al 2204.04204,
Bagnaschi et al 2204.05260, …

$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - C_{ll} \right) \right]$$



$$\Delta_{\rm CKM} = v^2 \left[C_\Delta - 2\, C_{lq}^{(3)} \right]$$

$$C_\Delta = 2 \left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + \hat{C}_{ll} \right]$$

Assume flavor-universal couplings

$$\longrightarrow \quad \Delta_{\rm CKM}^{\rm EWfit} = -(0.012 \pm 0.005)\,,$$

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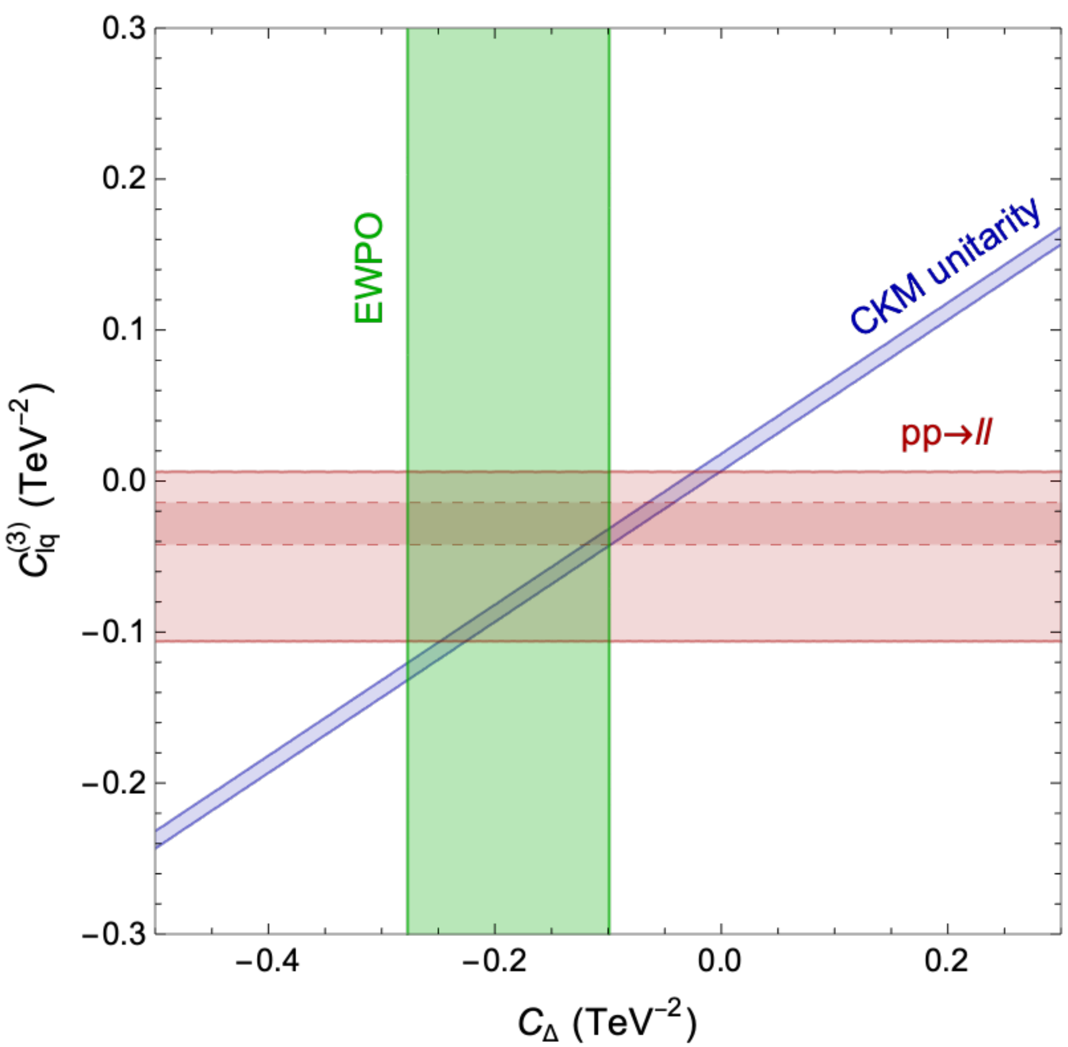

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$$C_\Delta = 2 \left[C_{Hq}^{(3)} - C_{Hl}^{(3)} + \hat{C}_{ll} \right]$$

Assume flavor-universal couplings

- Decouple by turning on $C_{lq}^{(3)}$: but constraints from Drel-Yan at LHC are catching up and will test this scenario

Conclusions & Outlook

- The Cabibbo angle anomaly is one of few low-energy "cracks" in the SM, probing new physics up to $\Lambda \sim 20$ TeV — big deal if confirmed!

- A number of explanations are currently possible
  - SM 'deficiencies': need controlled radiative corrections!
    Lattice QCD, EFT, and ab-initio nuclear structure are the way to go
  - BSM explanations: most likely "vertex corrections" in the EFT language
  - Experimental input?

- New precision measurements in K, π, and neutron decay are very desirable, and will shed light on the anomaly as these systems are theoretically simpler than nuclei