INDIANA UNIVERSITY
BLOOMINGTON

Jefferson Lab

Cabibbo angle anomaly: statistical assessment & New Physics interpretations

Emilie Passemar
epassema@indiana.edu
Indiana University/Jefferson Laboratory/IFIC Valencia

Implications of LHCb measurements and future prospects
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Based on *JHEP 07 (2020) 068,*
Y. Grossman, E.P. and S. Schacht

Outline

1. Introduction and Motivation: Cabbibo angle anomaly

2. Statistical Assessment

3. New Physics Interpretations

4. Conclusion and Outlook

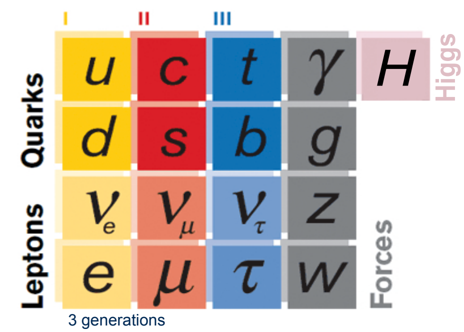
1. Introduction and Motivation

1.1 Test of the Standard Model: V_{us} and CKM unitarity

- Extraction of the Cabibbo-Kobayashi-Maskawa matrix element V_{us}
  - Fundamental parameter of the Standard Model

  Description of the weak interactions:

$$\mathcal{L}_{EW} = \frac{g}{\sqrt{2}} W_\alpha^+ \left(\bar{D}_L V_{CKM} \gamma^\alpha U_L + \bar{e}_L \gamma^\alpha \nu_{e_L} + \bar{\mu}_L \gamma^\alpha \nu_{\mu_L} + \bar{\tau}_L \gamma^\alpha \nu_{\tau_L} \right) + \text{h.c.}$$



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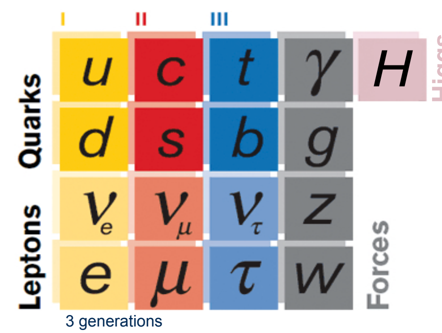
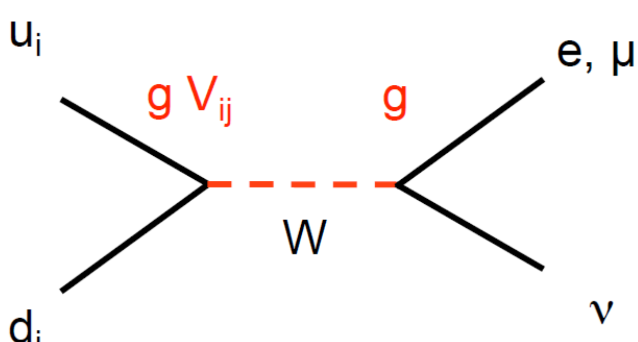
Unitary matrix



  - Check unitarity of the first row of the CKM matrix:

⇒ *Cabibbo Universality:* $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \stackrel{?}{=} 1$

Negligible ~2x10-5 (B decays)



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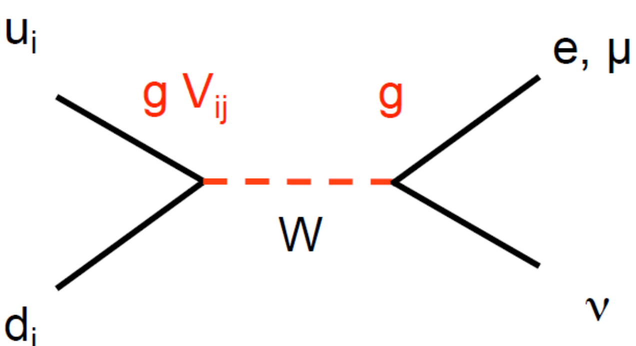
Gauge coupling

  - Universality: Is G_F from μ decay equals to G_F from π, K, nuclear β decay?

$$G_\mu^2 = (g_\mu g_e)^2 / M_W^4 \quad \stackrel{?}{=} \quad G_{\text{CKM}}^2 = (g_q g_\ell)^2 \left(|V_{ud}|^2 + |V_{us}|^2\right) / M_W^4$$



1.2 Constraining New Physics

- Extraction of the Cabibbo-Kobayashi-Maskawa matrix element V_{us}
  - ➢ Fundamental parameter of the Standard Model

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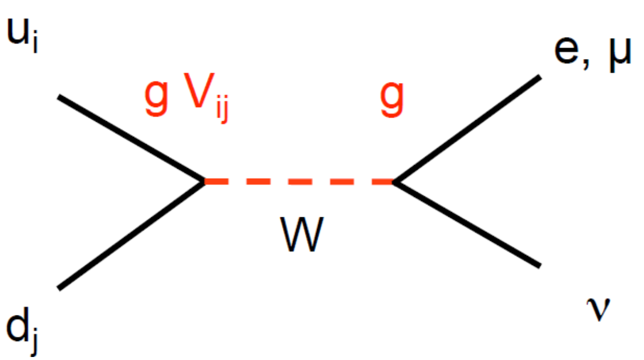
$$\mathcal{L}_{EW} = \frac{g}{\sqrt{2}} W_{\alpha}^{+} \left(\bar{D}_L V_{CKM} \gamma^{\alpha} U_L + \bar{e}_L \gamma^{\alpha} \nu_{eL} + \bar{\mu}_L \gamma^{\alpha} \nu_{\mu L} + \bar{\tau}_L \gamma^{\alpha} \nu_{\tau L} \right) + \mathrm{h.c.}$$

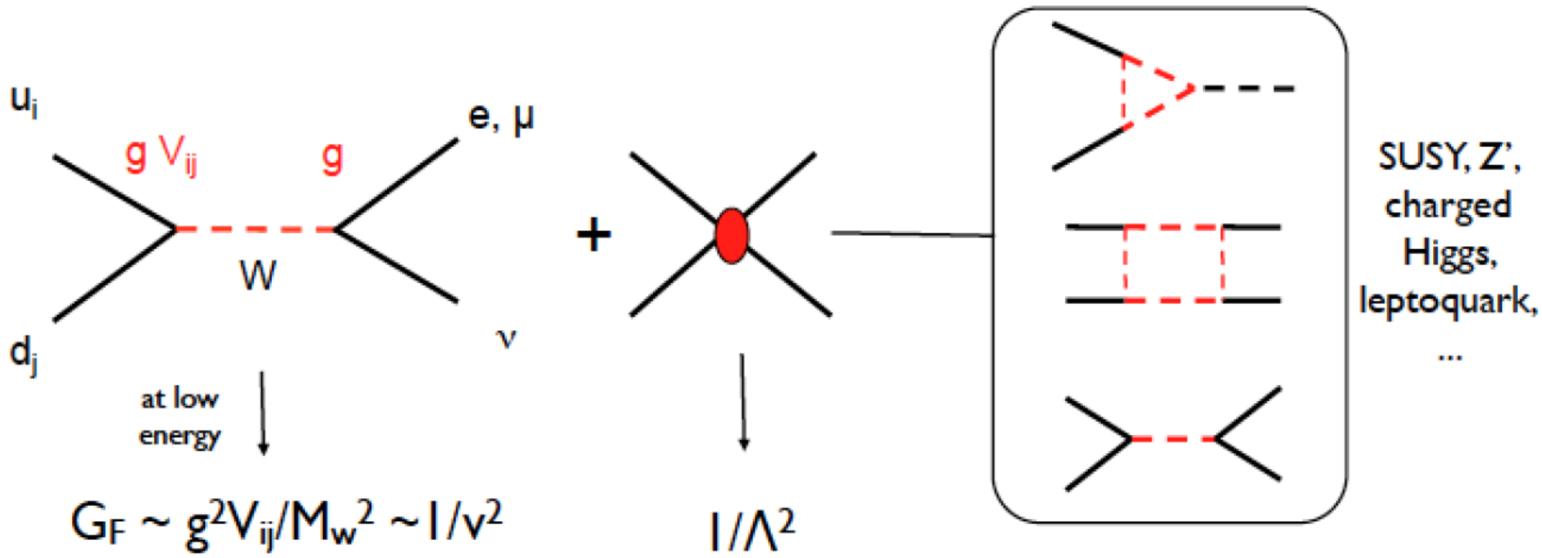
- Look for *new physics*
  - ➢ In the Standard Model : W exchange ⇨ only V-A structure



1.2 Constraining New Physics

- BSM: sensitive to tree-level and loop effects of a large class of models

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



BSM effects : $\Delta \sim \frac{c_n}{g^2}\frac{M_W^2}{\Lambda^2} \leq 10^{-2} - 10^{-3} \longleftrightarrow \Lambda \sim 1\text{-}10$ TeV

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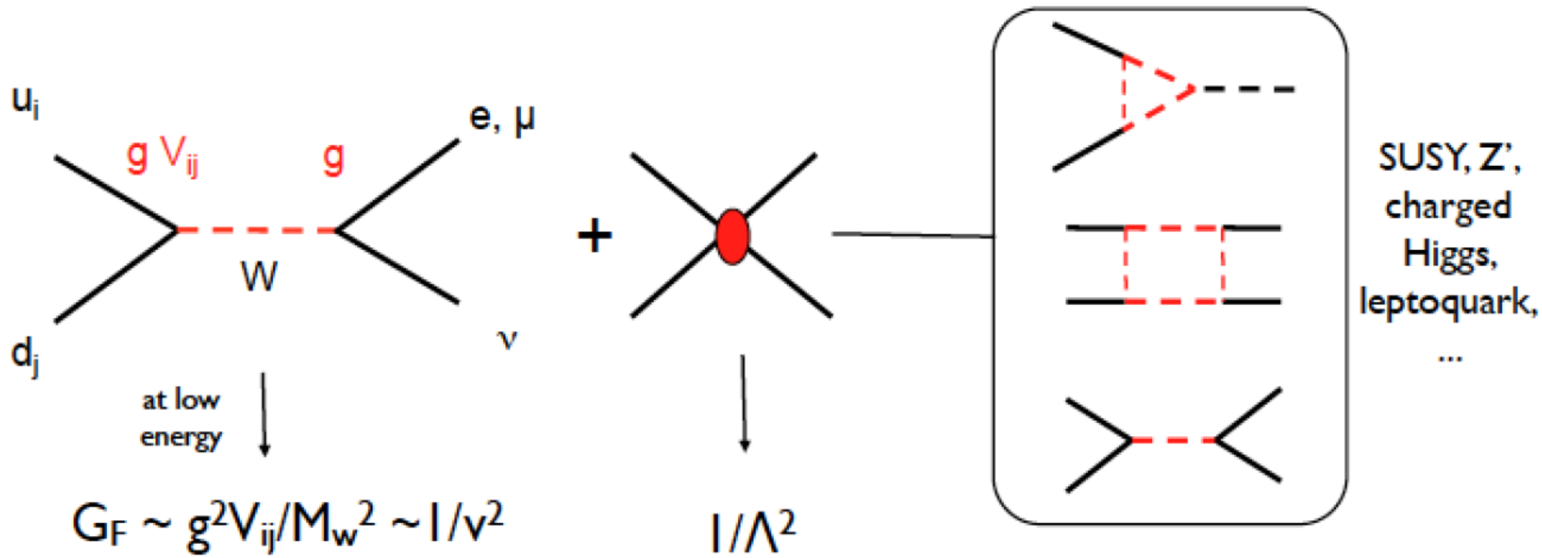
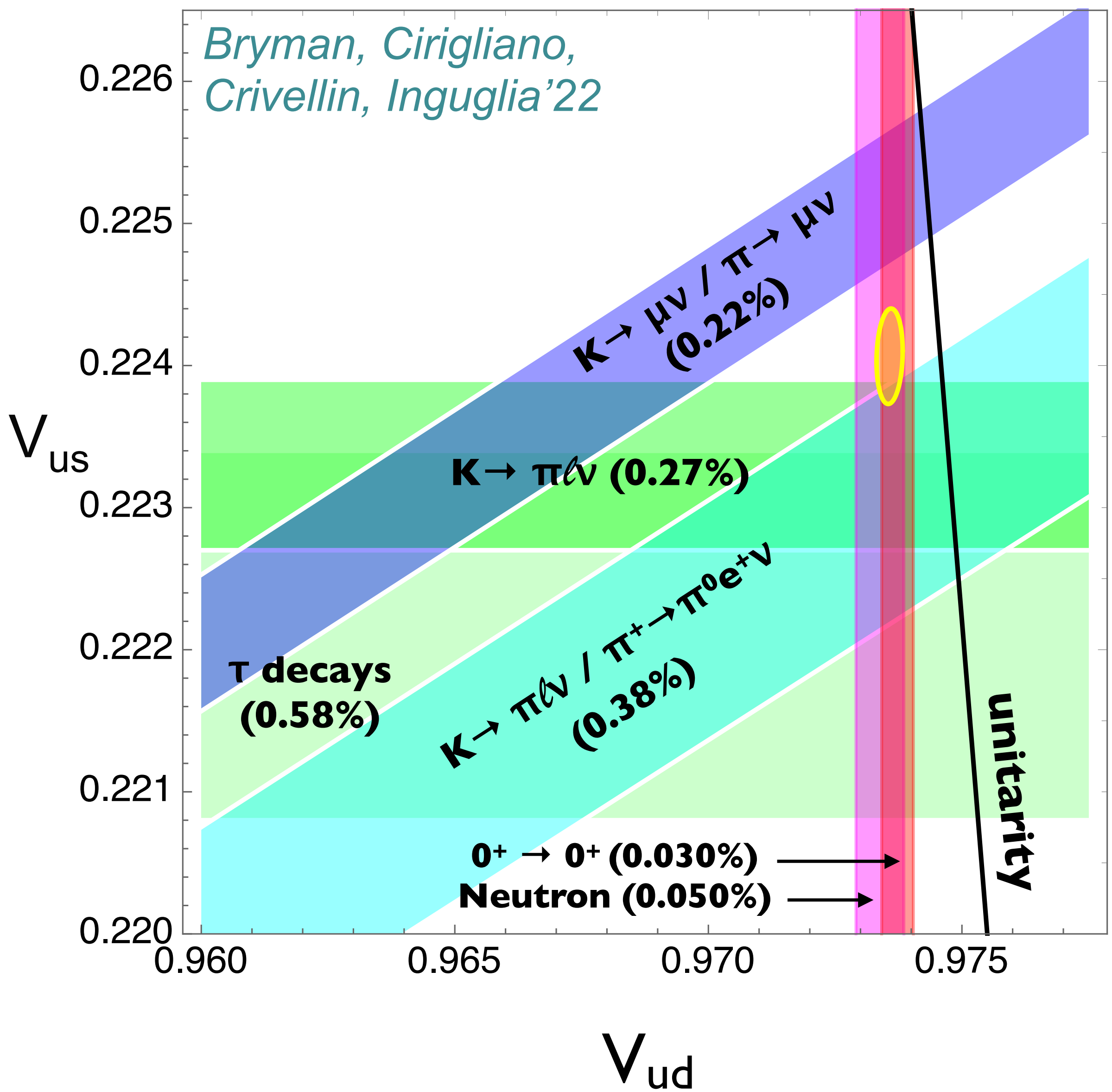


- Look for new physics by comparing the extraction of V_{us} from different processes: helicity suppressed $K_{\mu 2}$, helicity allowed K_{l3}, hadronic τ decays

1.2 Cabibbo angle anomaly

Moulson & E.P.@CKM2021



$|V_{ud}| = 0.97373(31)$

$|V_{us}| = 0.2231(6)$

$|V_{us}|/|V_{ud}| = 0.2311(5)$

Fit results, no constraint

$V_{ud} = 0.97365(30)$

$V_{us} = 0.22414(37)$

$\chi^2/\text{ndf} = 6.6/1\ (1.0\%)$

$\Delta_{CKM} = -0.0018(6)$

−2.7σ

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

Negligible ~2x10^{-5} (B decays)

Paths to V_{ud} and V_{us}

- From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi^\pm \to \pi^0 e \nu_e$	$n \to p e \nu_e$	$\pi \to l \nu_l$
V_{us}	$K \to \pi l \nu_l$	$\Lambda \to p e \nu_e$	$K \to l \nu_l$

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

Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections

Recent progress on 1) Hadronic matrix elements from lattice QCD
2) Radiative corrections from dispersive methods + Lattice QCD

Seng, Gorchtein, Patel, Ramsey-Musolf'18,'19

1.2 Cabibbo angle anomaly

- At the moment discrepancy between:
  - $V_{us}^{K_{\ell 3}}$, $\left(V_{us}/V_{ud}\right)^{K_{\ell 2}}$, V_{ud}^{β} and CKM unitarity
  - $V_{us}^{K_{\ell 3}}$ and V_{ud}^{β}
  - $V_{us}^{K_{\ell 3}}$ and $\left(V_{us}/V_{ud}\right)^{K_{\ell 2}}$

2. Statistical Assessment

2.1 CKM unitarity test

- 2 types of tests:
  - Universality test of Cabibbo angle within the SM
    Assess the goodness of fit of the one-parameter null hypothesis

$$\theta_C = \theta_1 = \theta_2 = \cdots = \theta_n$$

for n different experimental determinations of the Cabbibo angle with different observables

$$\Rightarrow \quad \nu_{\text{SM test}} = n - 1$$

  - CKM unitarity test: use 2 parameters V_{us} and Δ_{CKM}

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

Test the null-hypothesis $\Delta_{CKM} = 0$ against the general case $\Delta_{CKM} \neq 0$

$$\Delta\chi^2_{\text{unitarity test}} \equiv \chi^2_{\text{min, unitary}} - \chi^2_{\text{min, non-unitary}}$$

2.2 Comparison of SM test and CKM unitarity test

- $\chi^2_{\text{SM test}} = \chi^2_{\text{min, unitary}}$ BUT

- For SM test ⇨ assess the goodness-of-fit of the Cabibbo angle universality hypothesis

- For CKM unitarity test ⇨ comparison of the hypotheses of unitary vs. non-unitary.

$$\Delta\chi^2_{\text{unitarity test}} \equiv \chi^2_{\text{min, unitary}} - \chi^2_{\text{min, non-unitary}}$$

⇨ *Different number of dofs*

$\nu_{\text{unitarity test}} = 1$ and $\nu_{\text{SM test}} = n - 1$

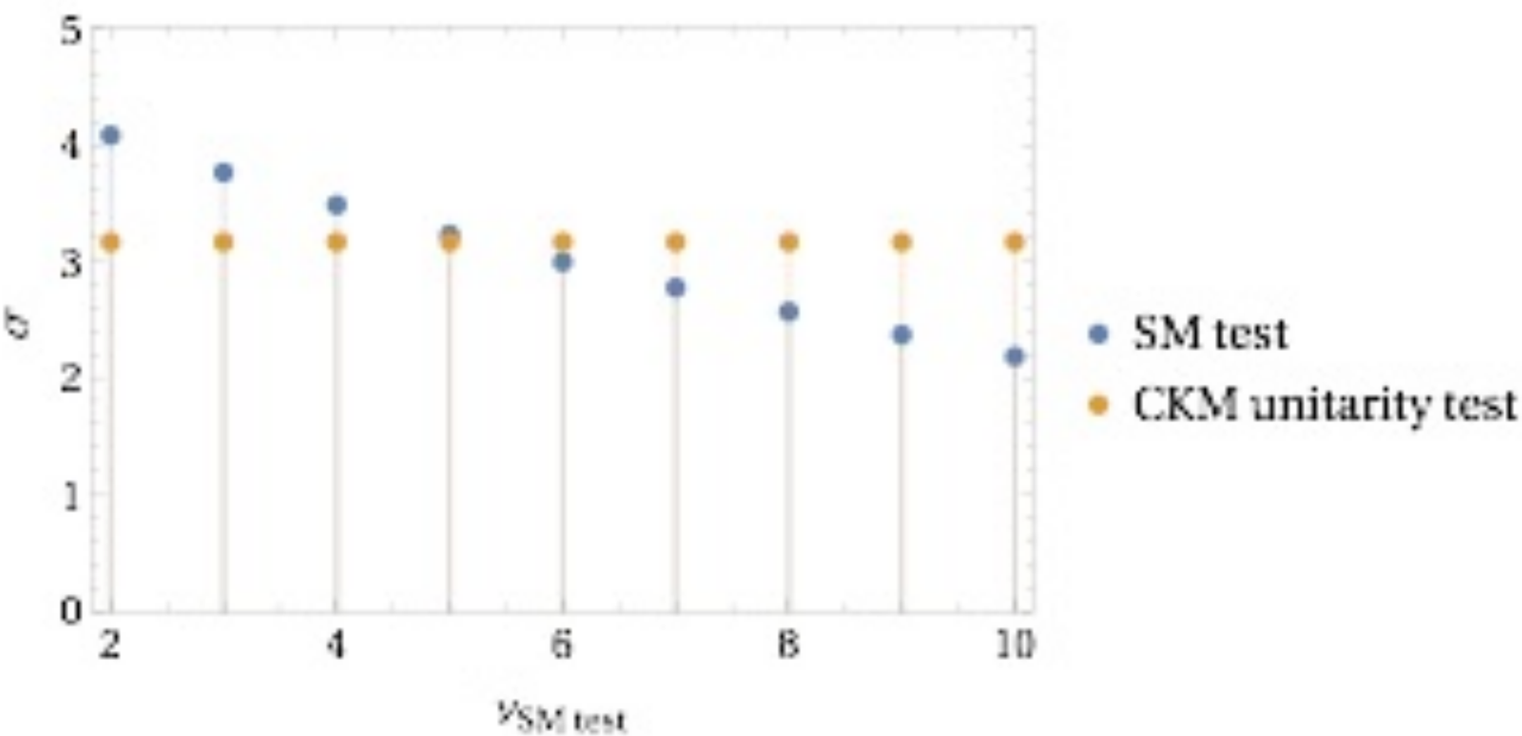
2.2 Comparison of SM test and CKM unitarity test

n	1	2	≥ 3
$\chi^2_{\text{SM test}}$	0	χ^2	$\chi^2 > \Delta\chi^2_{\text{unitarity test}}$
$\nu_{\text{SM test}}$	0	1	$n - 1 \geq 2$
$p_{\text{SM test}}$	1	p	$\neq p_{\text{unitarity test}}$
$z_{\text{SM test}}$	0	z	$\neq z_{\text{unitarity test}}$
$\Delta\chi^2_{\text{unitarity test}}$	0	χ^2	$< \chi^2_{\text{SM test}}$
$\chi^2_{\text{min, unitary}}$	0	χ^2	χ^2
$\chi^2_{\text{min, non-unitary}}$	0	0	> 0
$\nu_{\text{unitarity test}}$	1	1	1
$p_{\text{unitarity test}}$	1	p	$\neq p_{\text{SM test}}$
$z_{\text{unitarity test}}$	0	z	$\neq z_{\text{SM test}}$

➡ Test results are different starting from *3 observables*

2.2 Comparison of SM test and CKM unitarity test

- Two-sided p-value: $p = 1 - P_{\nu/2}(\chi^2/2)$
- Significance of rejection of the SM: $z = \sqrt{2}\,\mathrm{Erf}^{-1}(1-p)$
- Toy example for comparison of significances of the rejection of the SM and CKM unitarity for fixed $\Delta\chi^2_{\mathrm{SM\ test}} = 20$ and $\Delta\chi^2_{\mathrm{unitarity\ test}} = 10$



2.3 Flaw of unitarity tests

- When using CKM unitarity tests ⇨ only 2 parameters V_{us} and Δ_{CKM}

  Comparison of a one-parameter fit to a two-parameter fit only
  No matter how many measurements #d.o,f of the CKM unitarity test is always fixed

- When tension in 2 measurements among 3 ⇨ no significant difference

- When tension in 3 measurements ⇨ the significances for the rejection of the SM via the Cabibbo angle and CKM unitarity are different

Antonelli et al.'09,'11
Gonzalez-Alonso &. Martin Camalich'16
Grossman, E.P., Schacht'20

2.4 Application to K_{l3}, K_{l2} and superallowed β decays

Fit	n	$\chi^2_{\mathrm{SM\ test}}$	$\nu_{\mathrm{SM\ test}}$	$p_{\mathrm{SM\ test}}$	$z_{\mathrm{SM\ test}}$	$\Delta\chi^2_{\mathrm{unitarity\ test}}$	$p_{\mathrm{unitarity\ test}}$	$z_{\mathrm{unitarity\ test}}$
$K_{l3}+K_{l2}$	2	8.5	1	0.0036	$2.9\ \sigma$	8.5	0.0036	$2.9\ \sigma$
$K_{l3}+K_{l2}+\beta$ (SGPRM)	3	30.0	2	$3.1\cdot 10^{-7}$	$5.1\ \sigma$	22.8	$1.8\cdot 10^{-6}$	$4.8\ \sigma$
$K_{l2}+\beta$ (SGPRM)	2	11.6	1	0.00065	$3.4\ \sigma$	11.6	0.00065	$3.4\ \sigma$
$K_{l3}+\beta$ (SGPRM)	2	30.0	1	$4.4\cdot 10^{-8}$	$5.5\ \sigma$	30.0	$4.4\cdot 10^{-8}$	$5.5\ \sigma$
$K_{l3}+K_{l2}+\beta$ (CMS)	3	16.5	2	0.00027	$3.6\ \sigma$	9.0	0.0027	$3.0\ \sigma$
$K_{l2}+\beta$ (CMS)	2	3.6	1	0.056	$1.9\ \sigma$	3.6	0.056	$1.9\ \sigma$
$K_{l3}+\beta$ (CMS)	2	15.1	1	0.00010	$3.9\ \sigma$	15.1	0.00010	$3.9\ \sigma$

SGPRM: Seng, Gorchtein, Patel, Ramsey-Musolf'18,'19
CMS: Czarnecki, Marciano, Sirlin'19

Sign of rejection of Cabibbo angle universality

Sign of CKM unitarity rejection

⇨ Test results are different starting from *$n \geq 3$*

3. New Physics Interpretations

3.1 Right-handed currents

Bernard, Oertel, E.P., Stern'08

$$\mathcal{L}_{\mathrm{W}} = \frac{e(1-\xi^2\rho_L)}{\sqrt{2}s}\left\{\bar{\mathrm{N}}_L V_{\mathrm{MNS}}\gamma^\mu L_L + (1+\delta)\bar{\mathrm{U}}_L V_L \gamma^\mu D_L + \epsilon \bar{\mathrm{U}}_R V_R \gamma^\mu D_R\right\} W_\mu^+ + \mathrm{h.c}\,.$$

- See also *Antonelli et al.'09*

  Alioli, Cirigliano, Dekens, de Vries, Mereghetti'17

  T. Kitahara@HC2NP 2019

3.1 Right-handed Currents

$$V_{us}^{K_{l3}} = \left|\sin\theta_C + \varepsilon_s\right| \,, \quad \longleftarrow \text{Vector s quark}$$

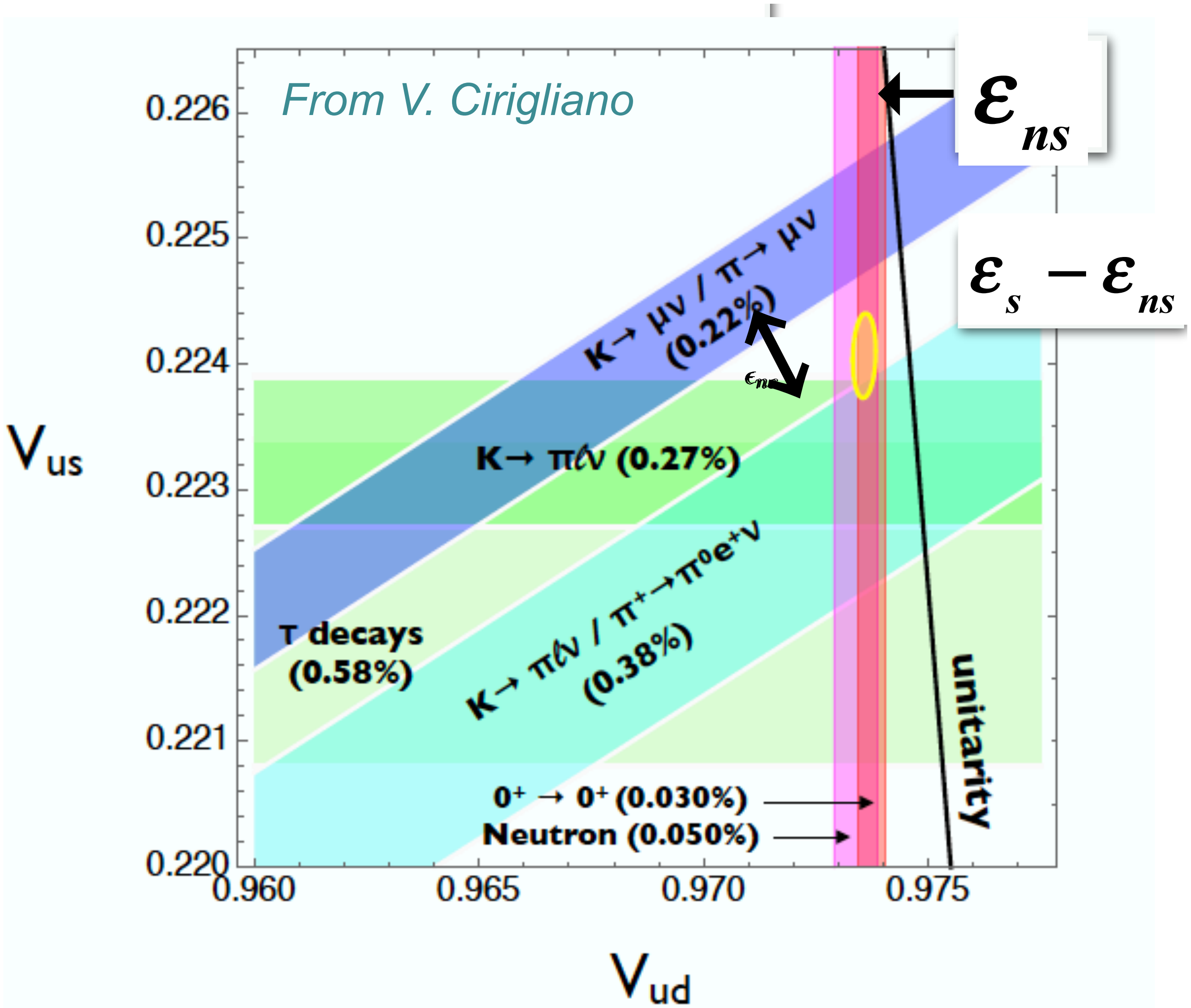
$$\left(\frac{V_{us}}{V_{ud}}\right)^{K_{l2}} = \left|\frac{\sin\theta_C - \varepsilon_s}{\cos\theta_C - \varepsilon_{ns}}\right| \,, \quad \longleftarrow \text{Axial}$$

$$V_{ud}^{\beta} = \left|\cos\theta_C + \varepsilon_{ns}\right| \,. \quad \longleftarrow \text{Vector no s quark}$$

$$\left(\frac{V_{us}}{V_{ud}}\right)^{K_{\ell 3}} = \left|\frac{\sin\,\theta_{\rm C} + \epsilon_{\rm s}}{\cos\,\theta_{\rm C} + \epsilon_{\rm ns}}\right| \quad \longleftarrow \text{Vector}$$

- The SM is obtained in the limit $\varepsilon_s = \varepsilon_{ns} = 0$.
- Perfect fit to data $\boxed{\chi^2_{\rm min,RH} = 0}$
- Not obvious how to define CKM unitarity test in this case

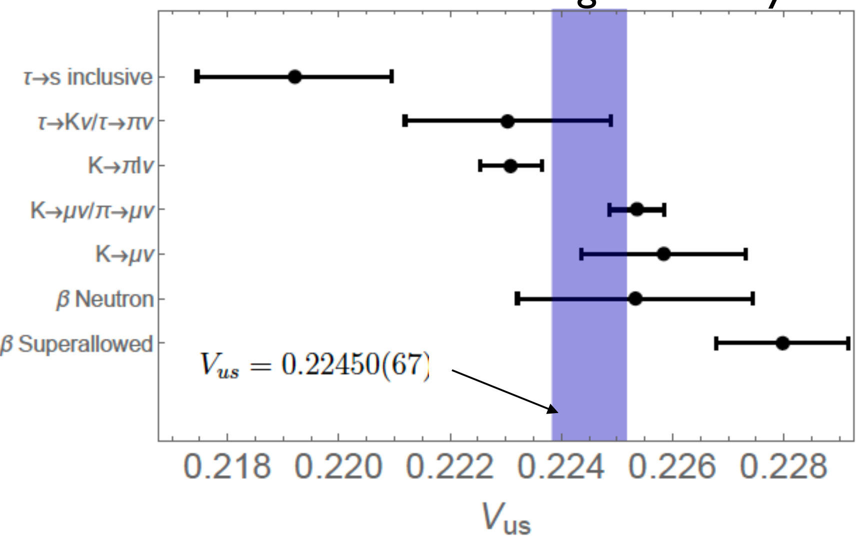
3.1 Right-handed Currents



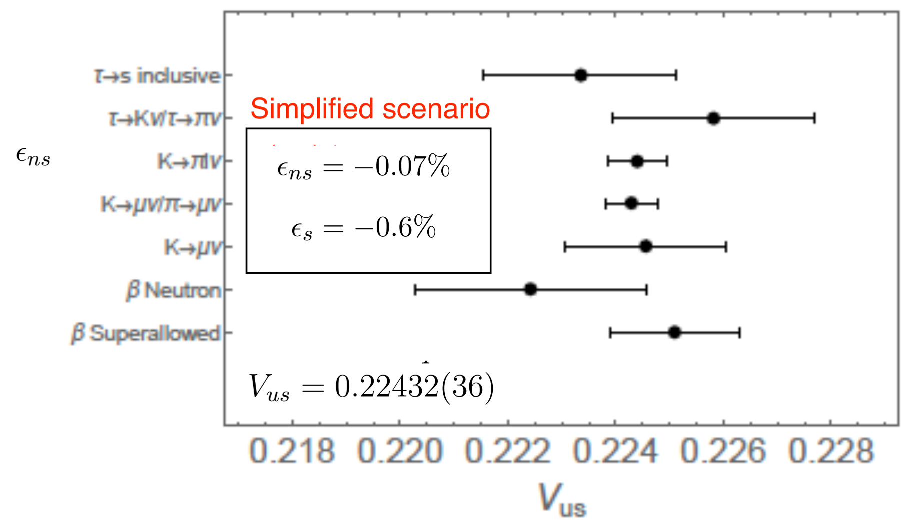
4.1 Right-handed Currents

- Global fit to CC processes involving light quarks and all lepton families
- SM hypothesis ($\varepsilon_s = \varepsilon_{ns} = 0$) disfavored (p-value 0.3%)

SM limit: Cabibbo angle anomaly



Anomaly removed by turning on the ε_R couplings



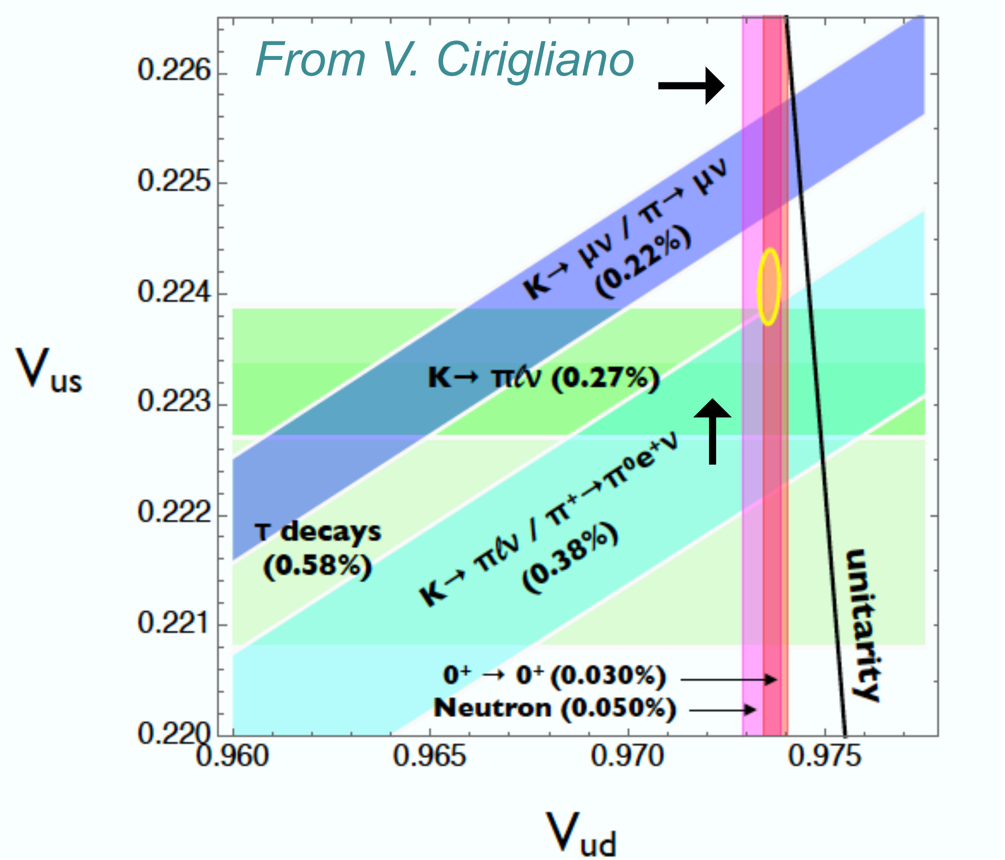
Cirigliano, Diaz-Calderon, Falkowski, Gonzalez-Alonso, Rodriguez-Sanchez'21

3.2 Other New Physics Models

- 4th quark b' *Belfatto, Beradze, Berezhiani'19*
- Gauge horizontal family symmetry
- Turn on only vertex corrections to leptons *Crivellin & Hoferichter'21*

⇨ Shift the location of the Vud,us bands but do not solve the tension between ratios

And many more....



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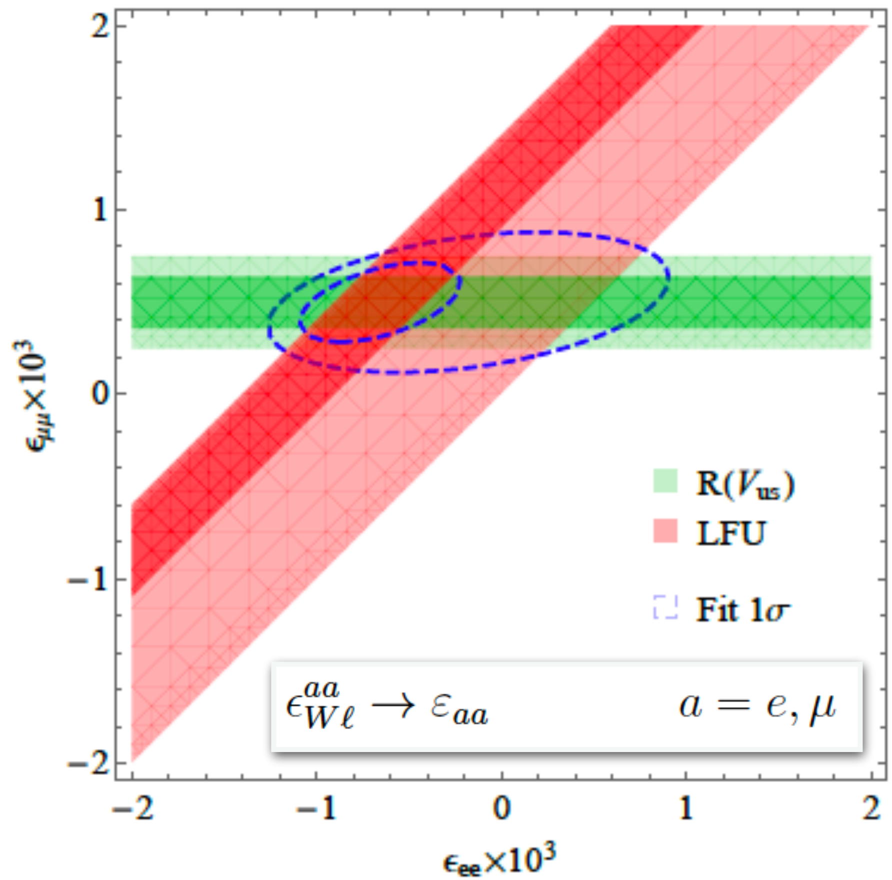

Connection with π→eν/ π→μν

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

(and other LFU probes)

And many more….

4. Conclusion and Outlook

4.1 Conclusion

- Recent precision determinations of V_{us} and V_{ud} enable unprecedented tests of the SM and constraints on possible NP models like right-handed currents.
- A SM test via the test of the Cabibbo angle universality goes beyond just a test of CKM unitarity and gives different test results if more than two observables are taken into account.
- In a CKM unitarity test one compares a constrained fit with a fit of free floating V_{us} and V_{ud}. The latter can not necessarily describe the data as well as a BSM model, in case the patterns go beyond just violating unitarity. This matters starting from three independent observables being taken into account.

  ⇨ Test the SM by testing for the universality of the Cabibbo angle

- If the anomaly persists ⇨ RHCs could explain it

4.2 Experimental Prospects for V_{us} (Snowmass)

On Kaon side

Cirigliano et al'22

- *NA62* could measure several BRs: $K_{\mu3}/K_{\mu2}$, $K \rightarrow 3\pi$, $K_{\mu2}/K \rightarrow \pi\pi$
- Note that the high precision measurement of BR($K_{\mu2}$) (0.3%) comes only from a single experiment: KLOE. It would be good to have another measurement at the same level of accuracy

- *LHCb* : could measure BR($K_S \rightarrow \pi\mu\nu$) at the < 1% level?
  $K_S \rightarrow \pi\mu\nu$ measured by KLOE-II but not competitive
  τ_S known to 0.04% (vs 0.41% for τ_L, 0.12% for $\tau_\pm$)

- V_{us} from Tau decays at *Belle II*:
  Belle II with 50 ab^{-1} and ~4.6 x 10^{10} τ pairs will improve V_{us} extraction from τ decays
  Inclusive measurement is an opportunity to have a complete independent extraction of V_{us} ⇨ not easy as you have to measure many channels

⇨ $$|V_{us}| = 0.2184 \pm 0.0018_{exp} \pm 0.0011_{th}$$

To be competitive theory error will have to be improved as well

HFLAV'21

V_{us} from Hyperon decays

V_{us} can be measured from Hyperon decays:

- $\Lambda \rightarrow p e \nu_e$ Possible measurement at *BESIII, Super τ-Charm factory?*
- Possibilities at *LHCb*? *Talk by Dettori@FPCP20*

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K_S^0 \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K_L^0 \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

R = ratio of production

ϵ = ratio of efficiencies

- To be able to extract V_{us} one needs to compute form factors precisely

⇨ Lattice effort from *RBC/UKQCD*

5. Back-up