V_{ud} in the CKM matrix: unitary test*

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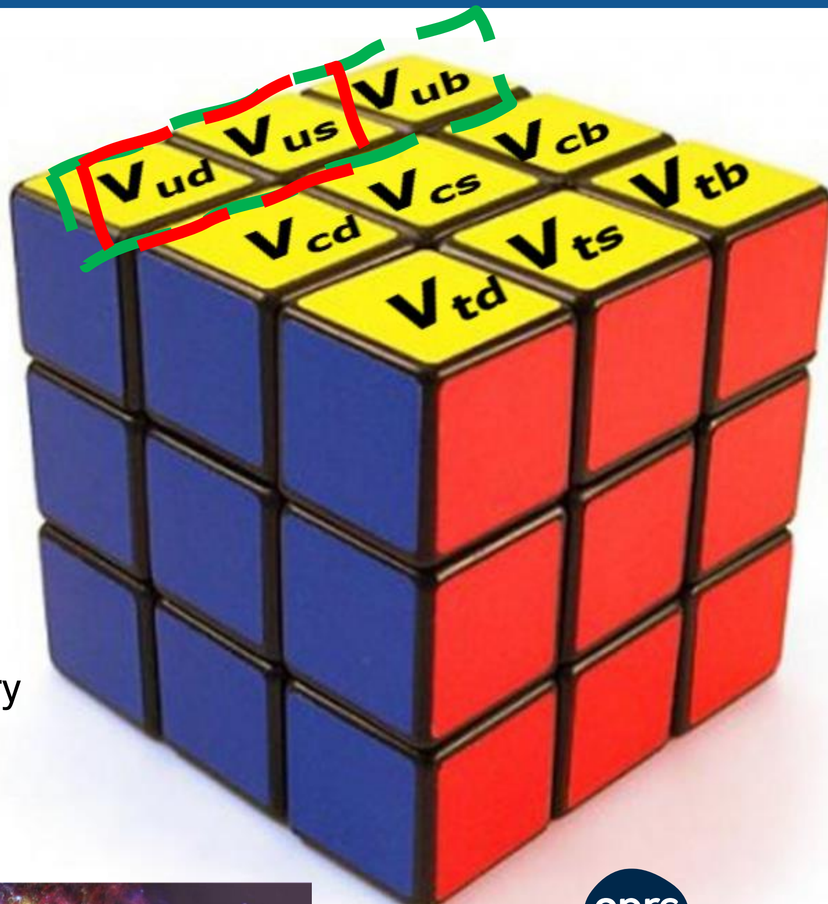
GANIL Caen, Nov. 5th 2024

Workshop on Vud from pion, neutron and nuclear beta decay



*Is there a problem with V_{us}
➔ The Cabibbo anomaly ?

🙏 Credits to
E. Passemar
(IFIC Valencia/Indiana Univ)
+ **A. Teixeira** @ CS IN2P3 24 (LPCA)
+ CKM WS 2023 WG1 summary
+ PDG 2024

INTENSITY frontier GDR-InF

RESANET Réactions, structure et Astrophysique Nucléaires: Expériences et Théories

cnrs NUCLÉAIRE & PARTICULES

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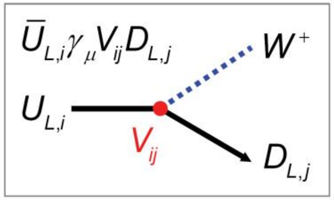
The Standard Model (SM) & the Unitary CKM Matrix
➔ mixing of the 3 quarks families & CP violation

- the Higgs boson gives mass to elementary bosons & fermions (quarks, leptons) through Yukawa couplings, but there is not only that ! :

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger [\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j] + \text{h.c}$$



charged currents (EW) imply transitions between quark families : quarks decays [there are no neutral current changing flavour (FCNC) at tree level (i.e., GIM mechanism)].

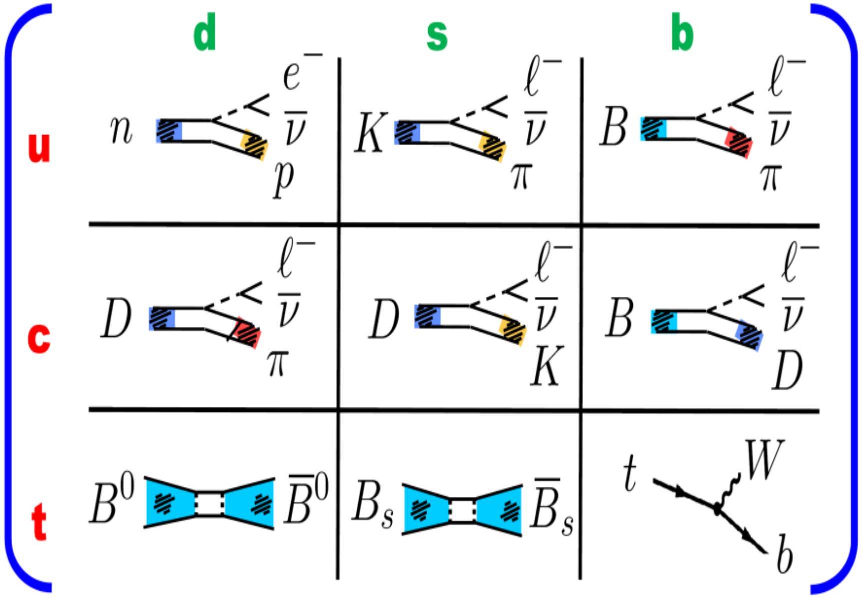
$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

$$+ \mathcal{O}(\lambda^4) \qquad (VV^\dagger = 1)$$

- strong hierarchy in EW V_{ij} couplings for the 3 families (wrt diagonal couplings $\propto\lambda^N \approx (0.225)^N$:
  ➔ Cabibbo angle = V_{us}).
- KM (Kobayashi-Maskawa) mechanism : 3 generations ➔ 4 params: A, λ, ρ & 1 complex part η which phase is the unique source of CPV in SM.

The CKM Matrix, the unitary triangle & the very rich phenomenology of quark flavours

V_{CKM} =



➔4 parameters (A, λ, ρ & η) to be obtained/tested wrt. data: nucleons, K, D, $B_{(s)}$ & top quark physics.

➔ unitarity relation in B_d system (1rst line/3rd column):

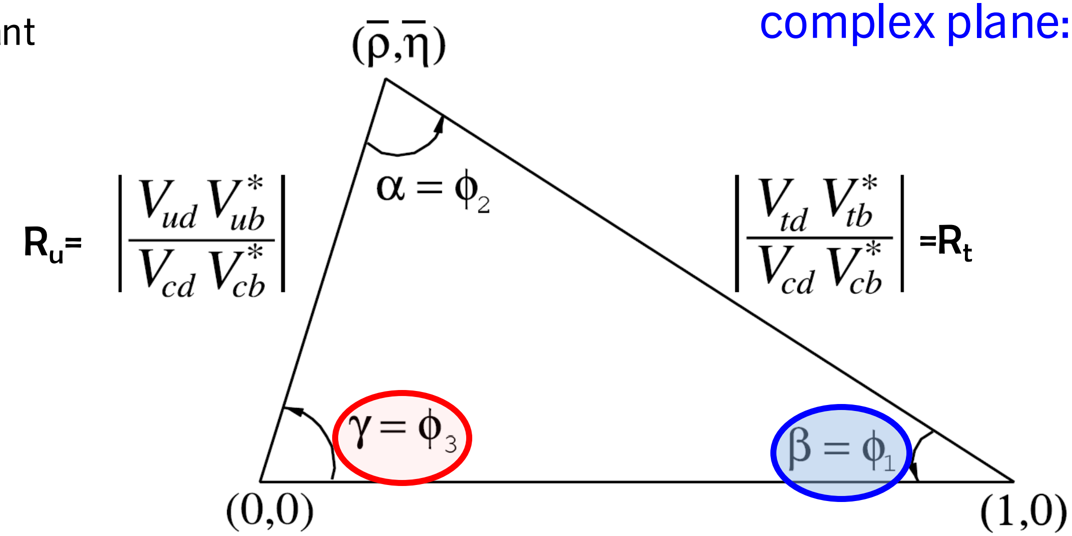
$$\boxed{\begin{array}{c}\dfrac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \dfrac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0 \\ O(1) + O(1) + O(1)\end{array}}$$

Unitarity triangle in the ($\bar{\rho}$,$\bar{\eta}$) complex plane:

Parametrisation « à la Wolfenstein » phase invariant & valid at any orders in λ @ CKMfitter *(EPJ C41, 1-131, 2005)* :

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\boxed{\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$



The CKM Matrix, testing the unitarity paradigm in the first line/row

CKM paradigm of flavour mixing: FV encoded in *strongly hierarchical* ***unitary*** matrix

Les deux infinis

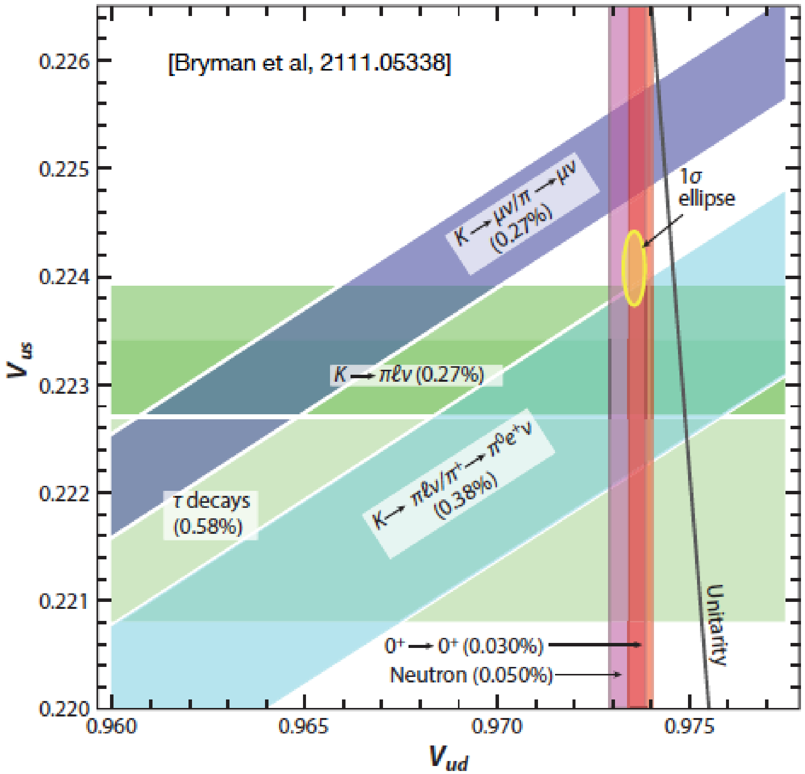
Mostly **successful description** of **hadron flavour dynamics!**

EW fit and **V_{CKM} fit** appear to be in good agreement with **SM hypotheses!**

But recent **tensions** in the determination of the "Cabibbo angle" (and of V_{ud} and V_{us})

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1 \;\Rightarrow\; \sin\theta_C = V_{ud}\,, \cos\theta_C = V_{us}$$

$$\Rightarrow\; \Delta_{\text{CKM}} = |\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 - 1 = 0$$



Negligible

Phenomenological determination of

$\bar{V}_{ud}$ and $\bar{V}_{us}$ (recall that $|\bar{V}_{ub}| \approx \mathcal{O}(10^{-3})$)

$\Rightarrow$ **test unitarity of 1st row of CKM**

Overview of $\bar{V}_{ud}$ and $\bar{V}_{us}$ constraints:

nuclear, nucleon, meson & τ decays (1σ bands for V_{ij})

Global fit: $V_{ud} = 0.97379 \pm 0.00025$

$V_{us} = 0.22405 \pm 0.00035$

$\Rightarrow \Delta_{\text{CKM}} = (-19.5 \pm 5.3) \times 10^{-4}$

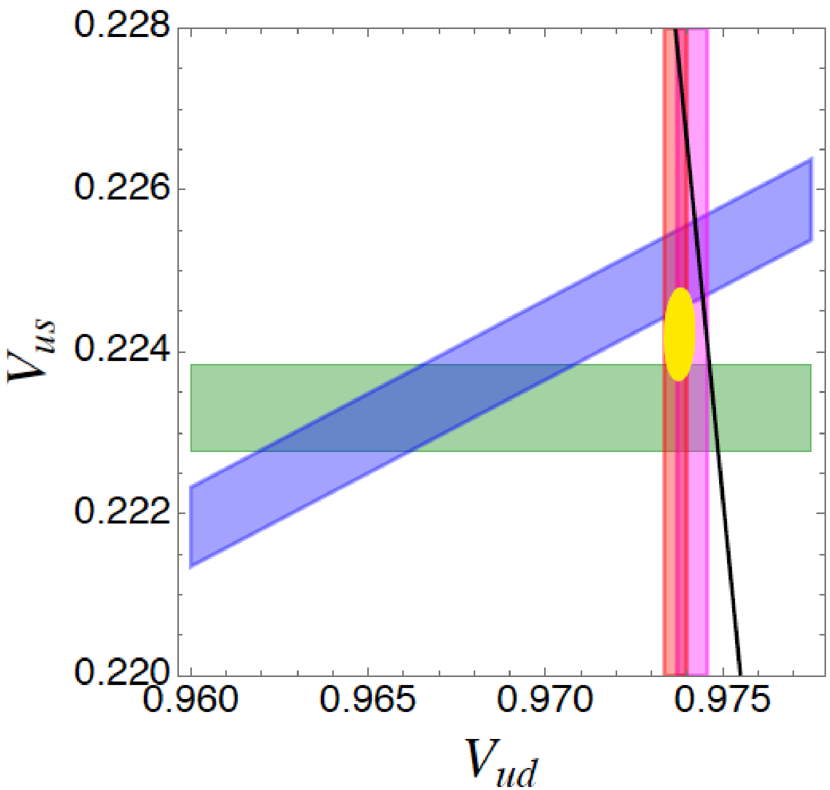
[Crivellin et al, 2212.06862]

$\Rightarrow$ Deviation from **SM unitarity** @ 2.8σ

The CKM Matrix, testing the unitarity paradigm in the first line/row

One year back at CKM23 WS @ Santiago de Compostela

Tension in first-row unitarity



Ciriglino, Crivellin, Hoferichter, Moulson 2023

- Three bands from
  - $K_{\ell 3} = K \to \pi \ell \nu_\ell$
  - $\pi_{\ell 2}/K_{\ell 2}$
  - β decays (superallowed, neutron)
- Tensions

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

$$\Delta_{\text{CKM}}^{K_{\ell 2}-K_{\ell 3}} = -0.016(6)\ [2.6\sigma]$$

$$\Delta_{\text{CKM}}^{K_{\ell 2}-\beta} = -0.0010(6)\ [1.7\sigma]$$

$$\Delta_{\text{CKM}}^{K_{\ell 3}-\beta} = -0.0018(6)\ [3.1\sigma]$$

$$\Delta_{\text{CKM}}^{\text{global}} = -0.0018(6)\ [2.8\sigma]$$

- Need to improve V_{ud}, V_{us}!

In the TODAY/GANIL workshop we review the V_{ud} determination and prospects
I will talk a bit more on V_{us} in this talk

The CKM Matrix, testing the unitarity paradigm in the first line/row

Standard-model coupling of quarks and leptons to W:

$$\frac{g}{\sqrt{2}} W_\alpha^+ \left(\overline{\mathbf{U}}_L \mathbf{V}_{\mathrm{CKM}} \gamma^\alpha \mathbf{D}_L + \overline{e}_L \gamma^\alpha \nu_{e\,L} + \overline{\mu}_L \gamma^\alpha \nu_{\mu\,L} + \overline{\tau}_L \gamma^\alpha \nu_{\tau\,L} \right) \quad + \quad \mathrm{h.c.}$$

↑ *Single gauge coupling*

↑ *Unitary matrix*

$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}^2| + |V_{us}^2| + \cancel{|V_{ub}^2|} - 1$$

$\approx 2\times10^{-5}$

Most precise test of CKM unitarity!

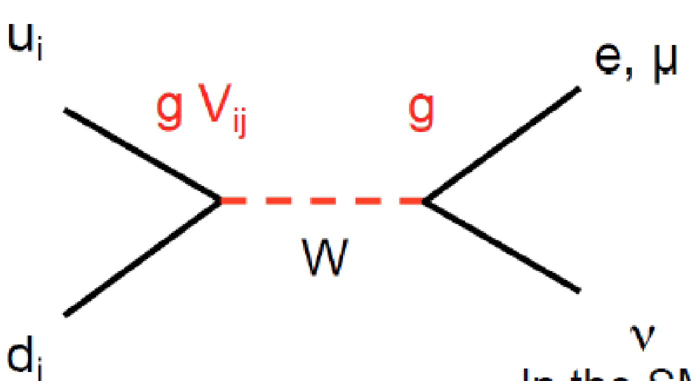
$$G_{\mathrm{CKM},ij} \sim G_\mu V_{ij} \sim (g^2/M_W^2)\, V_{ij}$$

$$\delta G_{\mathrm{CKM}} \sim 1/\Lambda^2 \quad \leftarrow \text{energy scale for NP}$$

BSM effects scale as $(M_W{}^2/g^2)/\Lambda^2$

For measurement of Δ_{CKM} with total uncertainty σ:

- Scale probed is $\Lambda \sim (M_W/g)/\sqrt{\sigma}$
- For $\sigma \sim 10^{-4} \longrightarrow$ probe $\boldsymbol{\Lambda \sim}$ **20 TeV**



This is the so called Cabibbo Anomaly

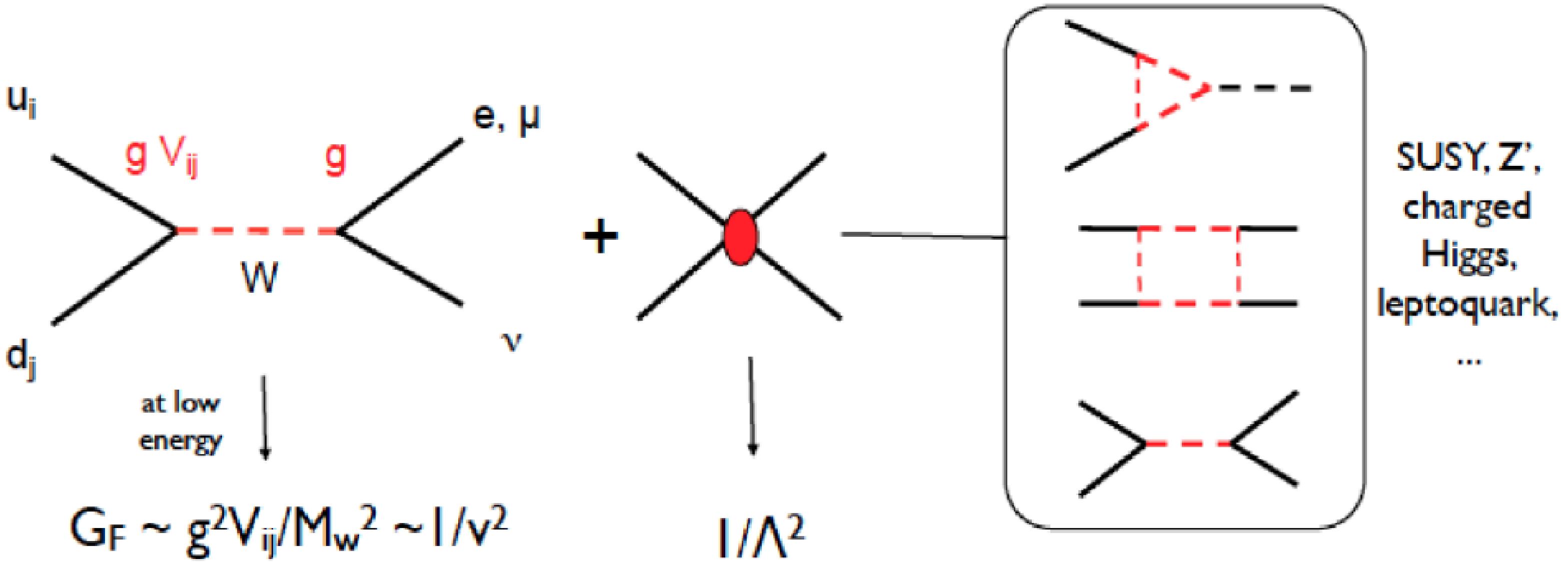
$|V_{ud}| = \cos\theta_C$ and $|V_{us}| = \sin\theta_C$

In the SM: W exchange ⟹ V – A structure only

The CKM Matrix, testing the unitarity paradigm in the first line/row
Constraining BSM/New Physics ?

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

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



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

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}	$K \to \pi l \nu_l$ Kl3	$\Lambda \to p e \nu_e$	$K \to l \nu_l$ Kl2

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

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

Determination of V_{ud}

One year back at CKM23 WS @ Santiago de Compostela
WG1 summary

1. **Superallowed β decays** ($0^+ \to 0^+$ nuclear transitions) Talk by M. Gorchtein
   - $+$: many isotopes to average
   - $-$: nuclear uncertainties
2. **Neutron decay** ($n \to pe^+\bar{\nu}_e$) Talks by W. Dekens, B. Märkisch, U. Schmidt
   - $+$: no nuclear uncertainties
   - $-$: need neutron lifetime τ_n and decay asymmetry $\lambda = g_A/g_V$
3. **Pion β decay** ($\pi^+ \to \pi^0 e^+\bar{\nu}_e$) Talk by M. Hoferichter
   - $+$: theoretically pristine
   - $-$: experimentally challenging

MUCH MORE in the TODAY/GANIL workshop we review the V_{ud} determination and prospects

Determination of V_{us} from kaon decays

One year back at CKM23 WS @ Santiago de Compostela
WG1 summary

Talk by M. Moulson:

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

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

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

S_{EW} Universal SD EW correction (1.0232)

Inputs from experiment:

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

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

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

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

Inputs from theory:

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

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

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

Determination of V_{us} from kaon decays

One year back at CKM23 WS @ Santiago de Compostela
WG1 summary

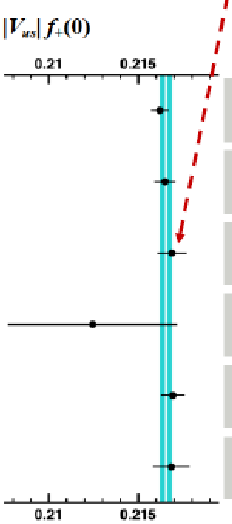
New KLOE measurement of $K_S \to \pi \ell \nu$

Talk by A. Passeri: JHEP 02 (2023) 098

KLOE: analysis of the data sample (1.63 fb^{-1}) collected in 2004-05, measured ratio:

$$\mathcal{R} = \frac{\Gamma(K_S \to \pi e \nu)}{\Gamma(K_S \to \pi^+\pi^-)} = \frac{N_{\pi e \nu}}{\epsilon_{\pi e \nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon = (1.0338 \pm 0.0054_{\text{stat}} \pm 0.0064_{\text{syst}}) \times 10^{-3}$$

$$\mathcal{B}(K_S \to \pi e \nu) = (7.153 \pm 0.037_{\text{stat}} \pm 0.044_{\text{syst}}) \times 10^{-4} = (7.153 \pm 0.058) \times 10^{-4}$$



		% err	BR	τ	Δ	Int
K_Le3	0.2162(5)	0.23	0.09	0.20	0.02	0.05
$K_L\mu3$	0.2165(6)	0.26	0.15	0.18	0.02	0.07
K_Se3	0.2169(8)	0.39	0.38	0.02	0.02	0.05
$K_S\mu3$	0.2125(47)	2.2	2.2	0.02	0.02	0.08
$K^\pm e3$	0.2169(6)	0.30	0.27	0.06	0.11	0.05
$K^\pm\mu3$	0.2168(10)	0.47	0.45	0.06	0.11	0.08

(Approx. contrib. to % err from: BR, τ, Δ, Int)

Average (M. Moulson):

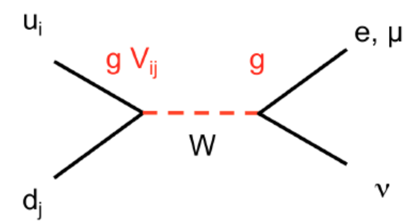
$$|V_{us}| f_+(0) = 0.21656(35)$$

Determination of V_{us} / V_{ud} and K_{l2} decays

One year back at CKM23 WS @ Santiago de Compostela WG1 summary

From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \to 0^+$ $\pi^\pm \to \pi^0 e\nu_e$	$n \to pe\nu_e$	$\pi \to l\nu_l$
V_{us}	$K \to \pi l\nu_l$ (Kl3)	$\Lambda \to pe\nu_e$	$K \to l\nu_l$ (Kl2)



Talk by M. Moulson:

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

Inputs from experiment:

From $K^\pm$ BR fit:

$\mathrm{BR}(K^\pm_{\mu 2(\gamma)}) = 0.6358(11)$

$\tau_{K\pm} = 12.384(15)$ ns

From PDG:

$\mathrm{BR}(\pi^\pm_{\mu 2(\gamma)}) = 0.9999$

$\tau_{\pi\pm} = 26.033(5)$ ns

Inputs from theory:

δ_{EM} Long-distance EM corrections

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

f_K/f_π Ratio of decay constants

Cancellation of lattice-scale uncertainties from ratio

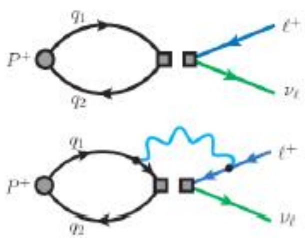
NB: Most lattice results already corrected for $SU(2)$-breaking: $f_{K\pm}/f_{\pi\pm}$

Determination of V_{us} / V_{ud} from Lattice

One year back at CKM23 WS @ Santiago de Compostela
WG1 summary

Talk by F. Erben:

- Experiment very accurately determines $|V_{us}/V_{ud}| f_{K^+}/f_{\pi^+}$ [PDG, Prog. Theor. Exp. Phys. 2022, 083C01]
- Ratio of decay constants f_{K^+}/f_{π^+} can also be accuratley determined from lattice QCD
- sub-percent precision: **isospin-breaking** and **QED effects** need to be controlled!



Final result:

$$\frac{|V_{us}|}{|V_{ud}|} = \left[\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} \frac{m_K}{m_\pi} \frac{(m_\pi^2 - m_\mu^2)}{(m_K^2 - m_\mu^2)}\right]^{1/2} \frac{f_\pi}{f_K}\left(1 - \frac{1}{2}\delta R_{K\pi}\right)$$

with values from experiment, FLAG lattice average, and this calculation:

$$\delta R_{K\pi} = -0.0086(3)_{\mathrm{stat.}}(^{+11}_{-4})_{\mathrm{fit}}(5)_{\mathrm{disc.}}(5)_{\mathrm{quench.}}(39)_{\mathrm{vol.}}$$

leading to

$$\frac{|V_{us}|}{|V_{ud}|} = 0.23154(28)_{\mathrm{exp.}}(15)_{\delta R_{K\pi}}(45)_{\delta R_{K\pi},\mathrm{vol.}}(65)_{f_\pi/f_K}$$

- our uncertainty is dominated by finite-volume error due to single lattice spacing - this will improve drastically in the near future! [Matteo Di Carlo, plenary at Lattice23]
- result in agreement with only other lattice calculation [Di Carlo et al., Phys.Rev.D 100 (2019) 3, 034514]
- $|V_{us}|/|V_{ud}|$ uncertainty dominated by f_π/f_K lattice average

New work: Prospects for a lattice calculation of the rare decay $\Sigma^+ \to p\,\ell^+\ell^-$, [F. Erben et al., JHEP 04 (2023) 108]

V_{us} and V_{us}/V_{ud} from kaons, first-row fit

One year back at CKM23 WS @ Santiago de Compostela
WG1 summary

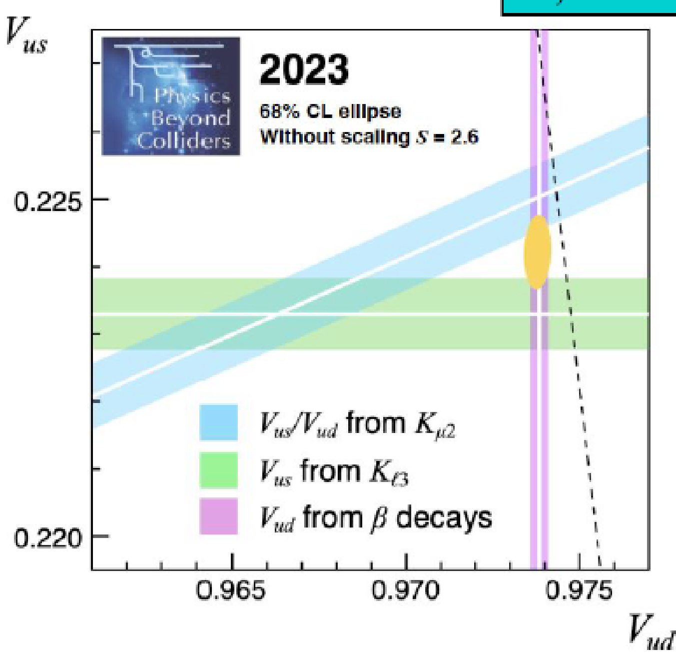
Summary for V_{us} from kaon decays and first-row global fit (M. Moulson)

$K_{\ell 3}$ — $V_{us} = 0.22330(35)_{exp}(39)_{lat}(8)_{IB}$ $(53)_{tot} = 0.24\%$
$f_+(0) = 0.9698(17)$
$N_f = 2+1+1$

$K_{\mu 2}$ — $V_{us}/V_{ud} = 0.23108(23)_{exp}(42)_{lat}(16)_{IB}$ $(51)_{tot} = 0.22\%$
$f_K/f_\pi = 1.1978(22)$
$N_f = 2+1+1$

Fit results:

$V_{ud} = 0.97378(26)$
$V_{us} = 0.22422(36)$
$\chi^2/\mathrm{ndf} = 6.4/2$ (4.1%)
$\Delta_{CKM} = -0.0018(6)$
-2.8σ



Prospects for V_{us} from kaon decays :

- New measurement of $K_{\mu 3}/K_{\mu 2}$ at NA62
- Precision measurements at proposed HIKE High Intensity Kaon Experiments:
  - Phase I, K^+ beam
  - Phase II, K_L beam

See e.g. HIKE by A. Romano
But HIKE has been cancelled last winter

Paths to V_{ud} and V_{us}

- From kaon, pion, baryon and nuclear decays

V_{ud}	$0^+ \rightarrow 0^+$ $\pi^\pm \rightarrow \pi^0 e \nu_e$	$n \rightarrow p e \nu_e$	$\pi \rightarrow l \nu_l$
V_{us}	$K \rightarrow \pi l \nu_l$ Kl3	$\Lambda \rightarrow p e \nu_e$	$K \rightarrow l \nu_l$ Kl2

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

Channel-dependent effective CKM element

Hadronic matrix element

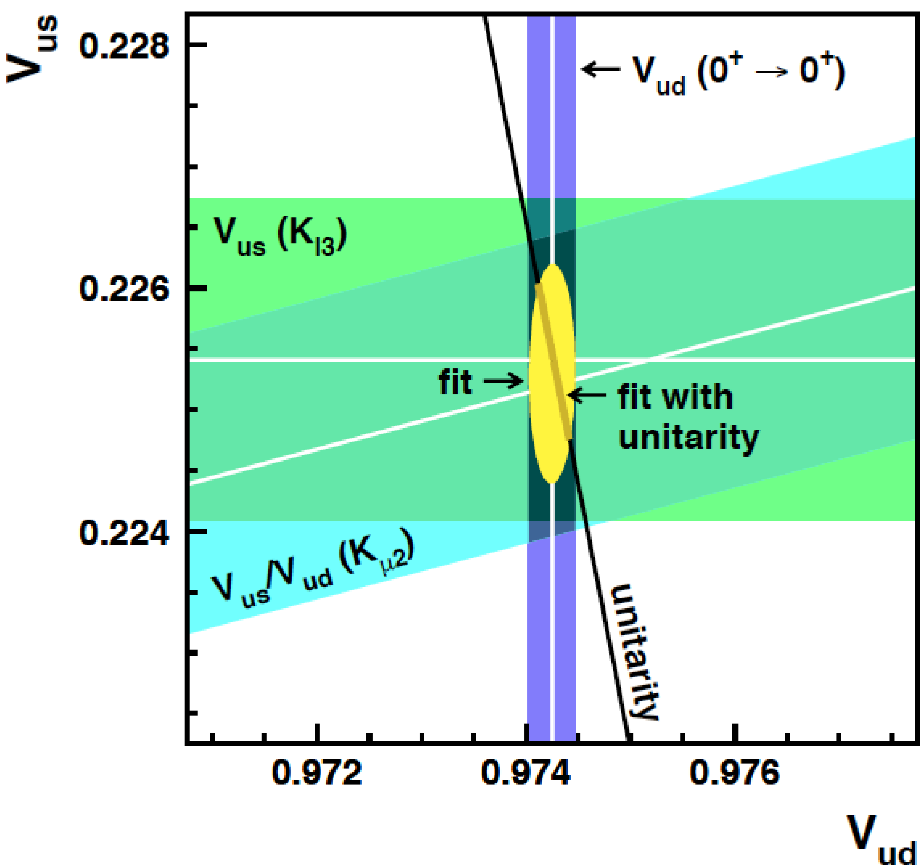
Radiative corrections

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

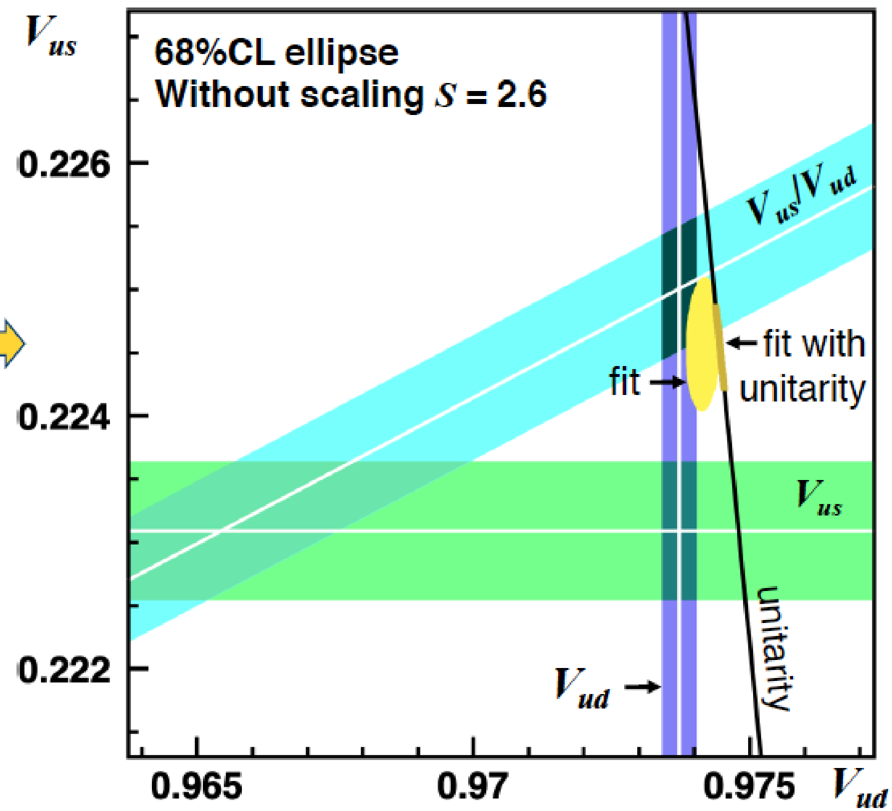
Why this anomaly ?

Changes on V_{us} and V_{ud} over 10 years since 2011

Flavianet Kaon WG: *Antonelli et al'11*



Moulson & E.P.@CKM2021



Changes on V_{us} and V_{ud} over 10 years since 2011

- Almost no change on the experimental side since 2011

Flavianet Kaon WG: *Antonelli et al'11*

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Channel-dependent effective CKM element

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Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections

- Changes in *theoretical* inputs:
  - Impressive progress on hadronic matrix element computations from *lattice QCD* for V_{us} and V_{us}/V_{ud} extraction from Kaon decays

FLAG'21

Changes on V_{us} and V_{ud} over 10 years since 2011

- Almost no change on the experimental side since 2011

Flavianet Kaon WG: *Antonelli et al'11*

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

Channel-dependent effective CKM element

Hadronic matrix element

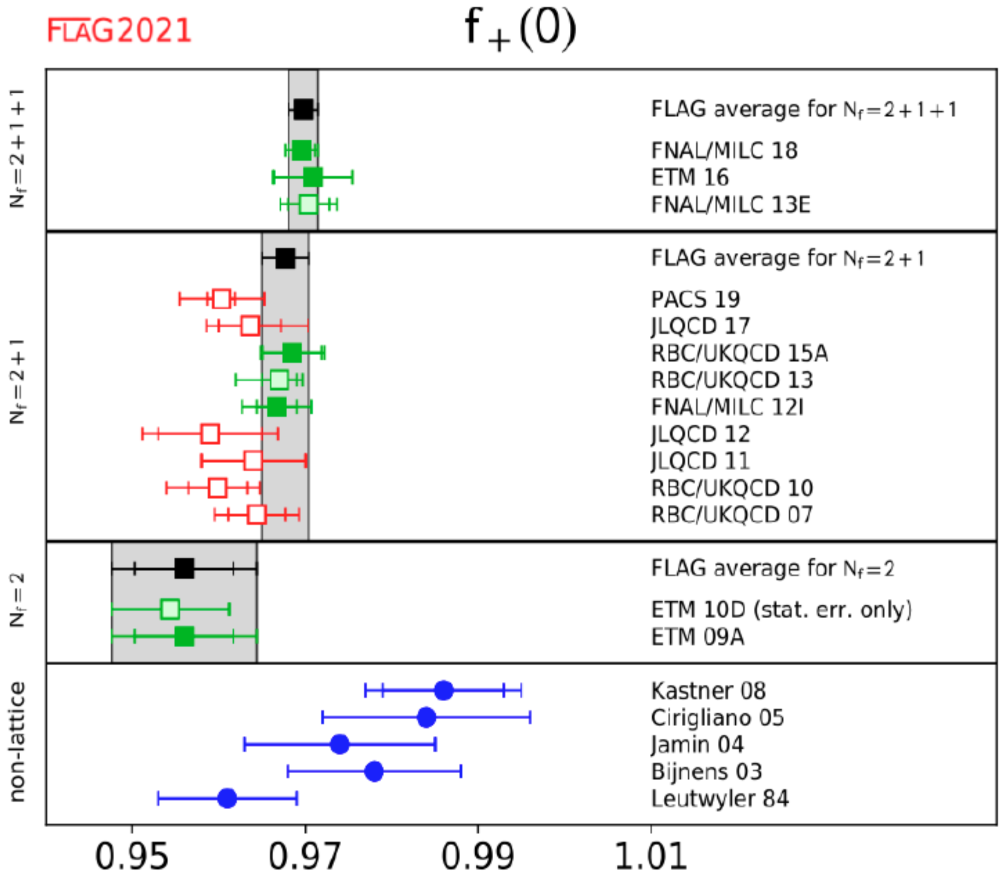
Radiative corrections

- Changes in *theoretical* inputs:
  - Impressive progress on hadronic matrix element computations from lattice QCD for V_{us} and V_{us}/V_{ud} extraction from Kaon decays
  - Radiative corrections from dispersive methods for V_{ud} extraction

Seng et al.'18'19, Gorshteyn'18, Cirigliano et al.'22,'24

$f_+(0)$ from Lattice QCD

- Recent progress on Lattice QCD for determining $f_+(0)$



$$f_+(0)^{FLAG21}_{N_f=2+1+1} = 0.9698(17)$$

0.18% uncertainty

to be compared to

$$f_+(0)^{FLAG16}_{N_f=2+1+1} = 0.9704(32)$$

$$f_+(0)^{2010}_{N_f=2+1} = 0.959(50)$$

Uncertainty divided by ~2 w/ 2016 and by 25 w/ 2011!

Lattice uncertainties at the same level as exp.

-3.2σ away from unitarity!

2011: $V_{us} = 0.2254(5)_{exp}(11)_{lat}$ → $V_{us} = 0.2231(4)_{exp}(4)_{lat}$

14

V_{us} / V_{ud} from K_{l2}/π_{l2}

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

- Recent progress on radiative corrections computed on lattice:

Di Carlo et al.'19

- Main input hadronic input: f_K/f_π

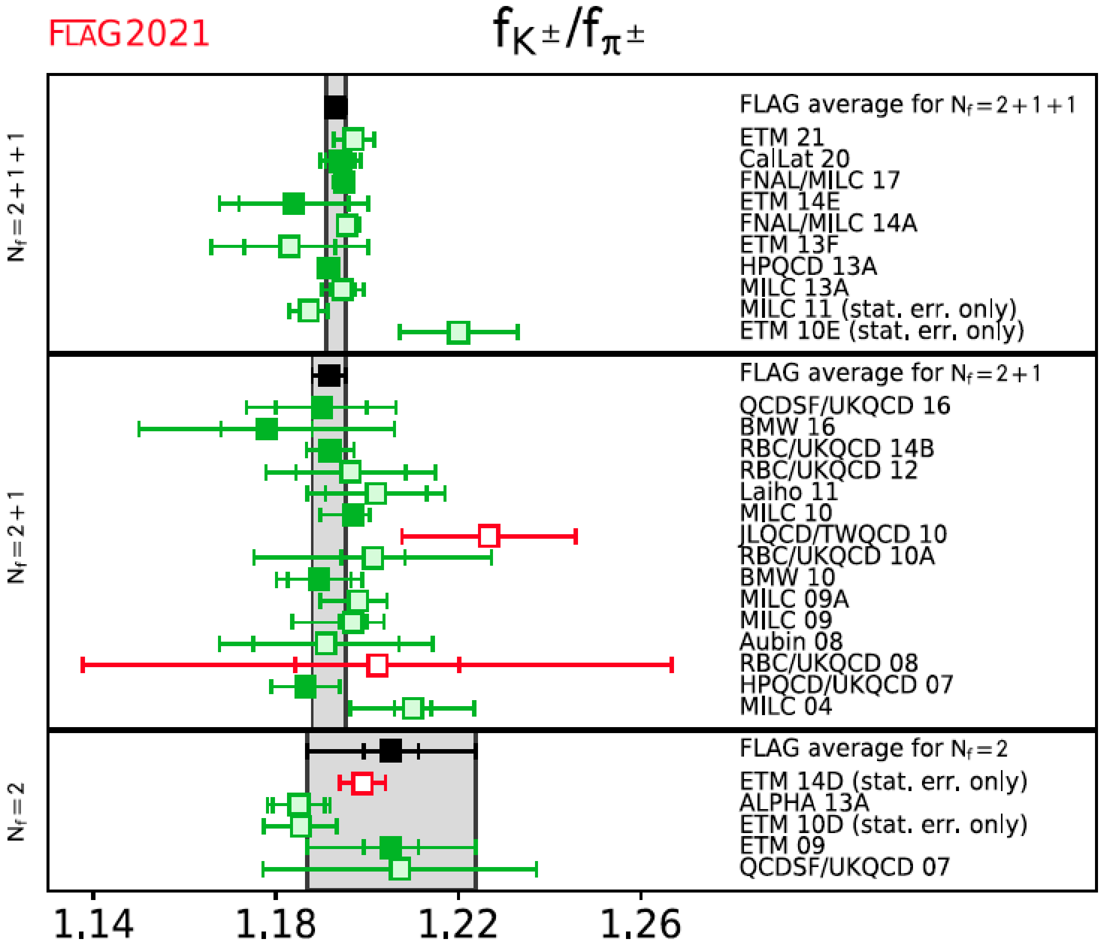
- In 2011: $V_{us}/V_{ud} = 0.2312(4)_{exp}(12)_{lat}$

- In 2021: $V_{us}/V_{ud} = 0.2311(3)_{exp}(4)_{lat}$ the lattice error is reducing by a factor of 3 compared to 2011! It is now of the same order as the experimental uncertainty.

-1.8σ away from unitarity

f_K/f_π from LQCD

Progress since 2018: ⇨ new results from *ETM'21* and *CalLat'20*



Emilie Passemar

Now Lattice collaborations include SU(2) IB corr.
For N_f=2+1+1, FLAG2021

$$f_{K^+}/f_{\pi^+} = 1.1932(21)$$

0.18% uncertainty

Results have been stable over the years

For average substract IB corr.

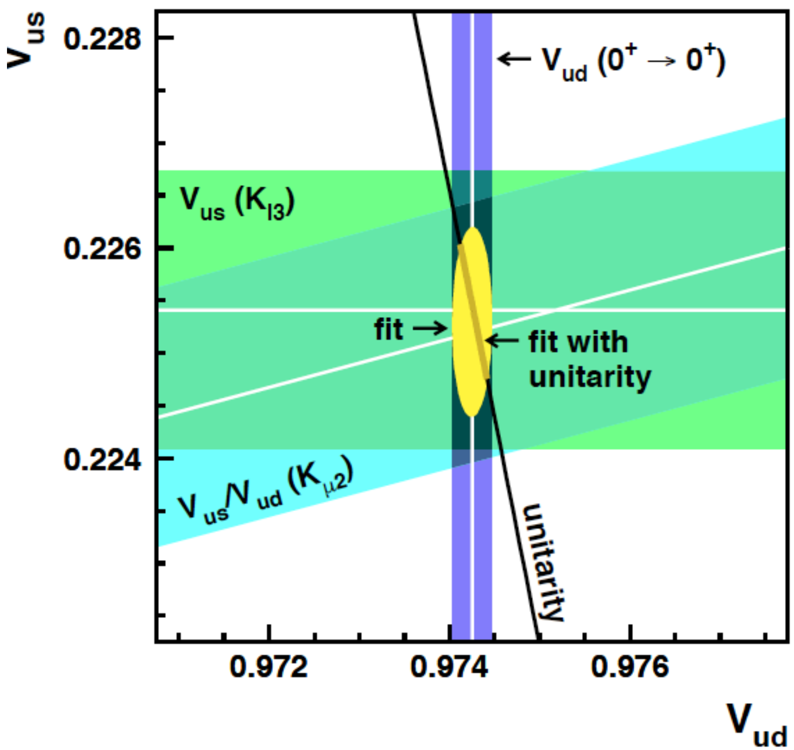
$$f_K/f_\pi = 1.1967(18)$$

In 2011: $f_K/f_\pi = 1.193(6)$

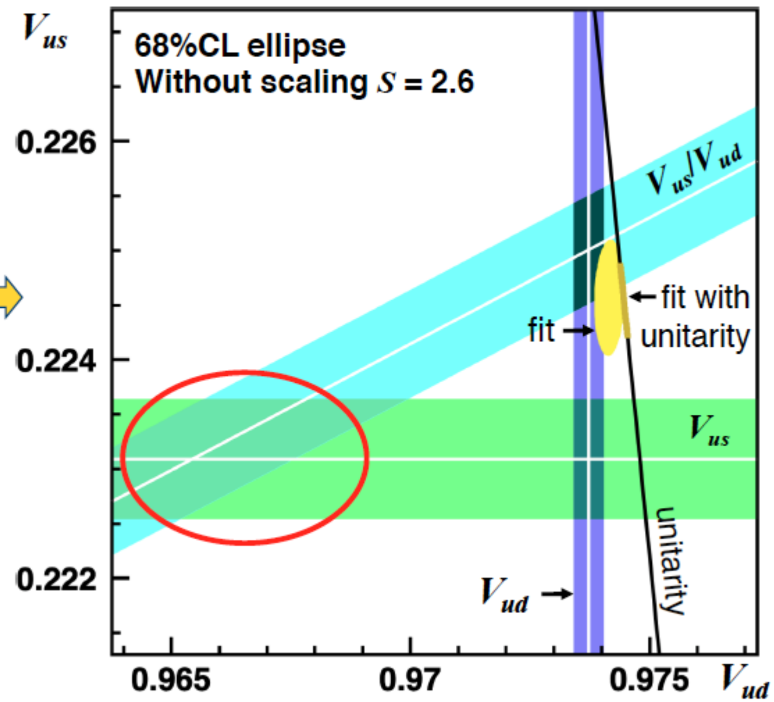
⇨ $V_{us}/V_{ud} = 0.\ 23108(29)_{exp}(42)_{lat}$

Changes on V_{us} and V_{ud} over 10 years since 2011

Flavianet Kaon WG: *Antonelli et al'11*



Moulson & E.P.@CKM2021



V_{ud} from $0^+ \to 0^+$ super-allowed β decays

See Talk by Misha Gorshteyn @CKM2021

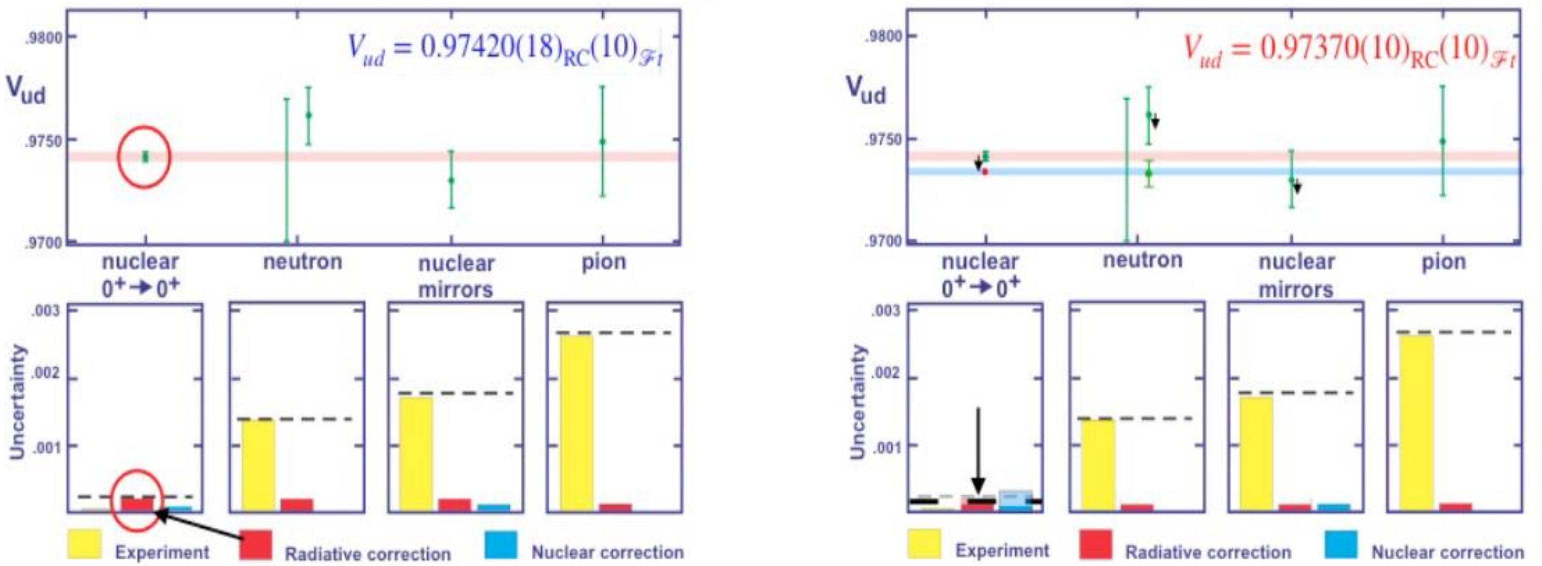
Figure adapted from J. Hardy

PDG 2018:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{V_{ud}}(2)_{V_{us}}$$

PDG 2020:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$$

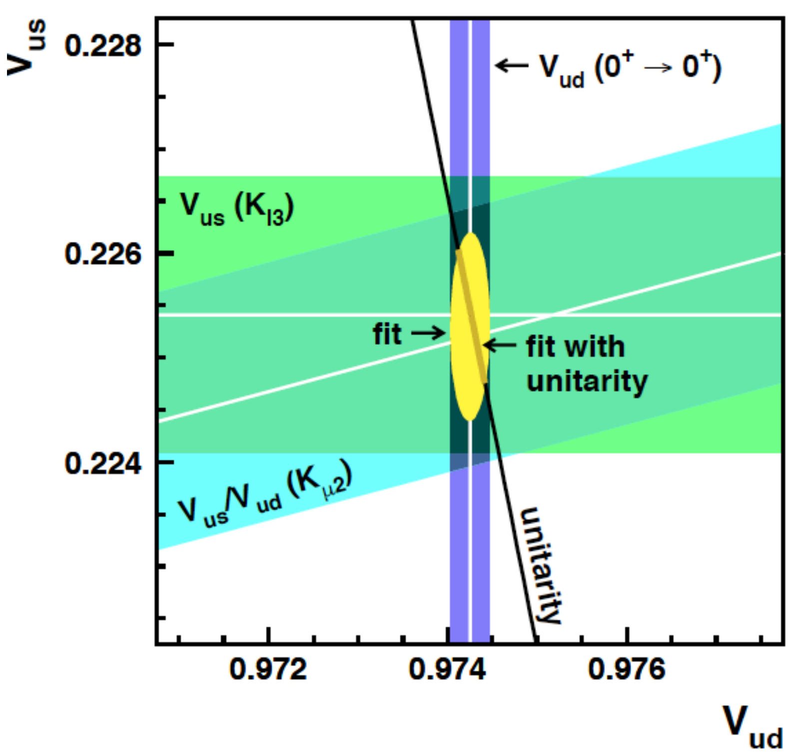


Recent improvement on the theoretical RCs +Nuclear Structure Corrections

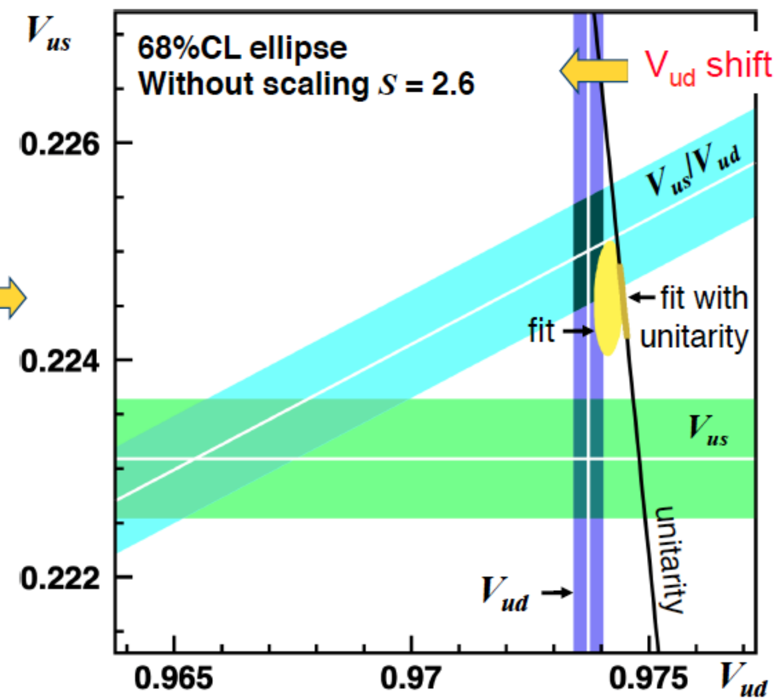
⇨ Use of a data driven dispersive approach *Seng et al.'18'19, Gorshteyn'18*

Changes on V_{us} and V_{ud} over 10 years since 2011

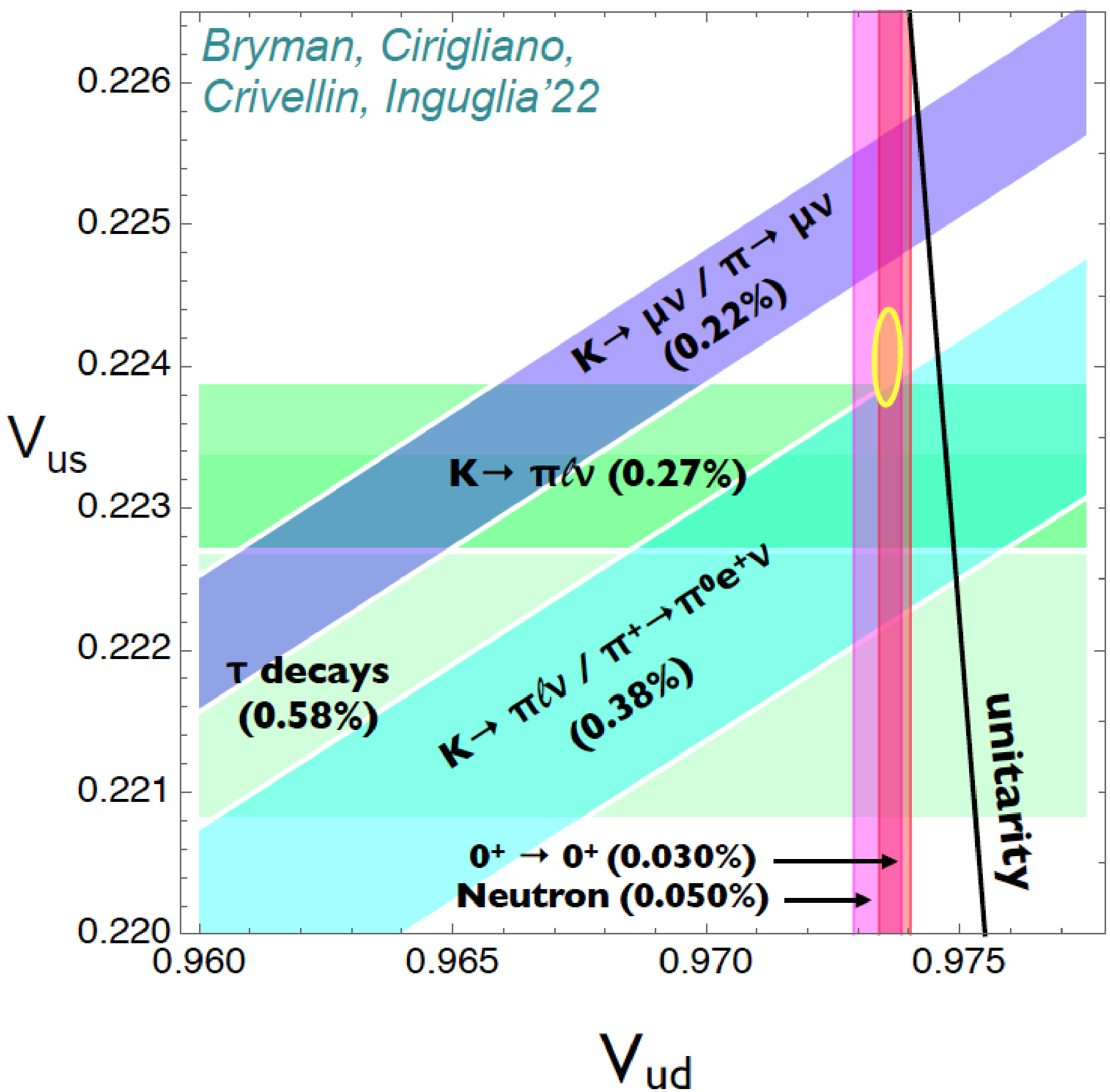
Flavianet Kaon WG: *Antonelli et al'11*



Moulson & E.P.@CKM2021



The Cabibbo anomaly as of about TODAY



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

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

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

Fit results, no constraint

$V_{ud} = \mathbf{0.97365(30)}$

$V_{us} = \mathbf{0.22414(37)}$

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

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

-2.7σ

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

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

28

Prospects

Experimental prospects on V_{us}

On Kaon side

Cirigliano et al'22

- *NA62* could measure several BRs: $K_{\mu 3}/K_{\mu 2}$, $K \to 3\pi$, $K_{\mu 2}/K \to \pi\pi$
- Note that the high precision measurement of $BR(K_{\mu 2})$ (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 $BR(K_S \to \pi\mu\nu)$ at the < 1% level?
  $K_S \to \pi\mu\nu$ 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

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

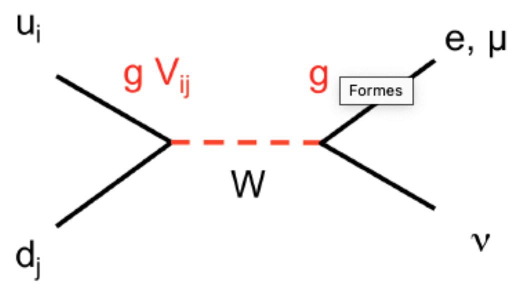
To be competitive theory error will have to be improved as well

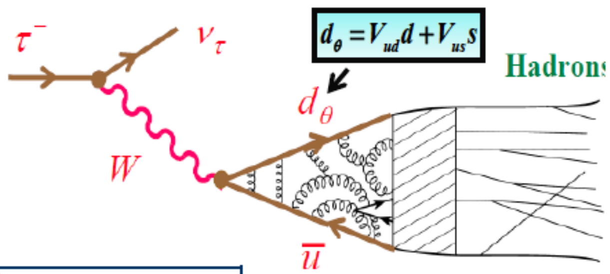
HFLAV'21

Can the TAU physics help us for 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}	$K \to \pi l \nu_l$	$\Lambda \to p e \nu_e$	$K \to l \nu_l$



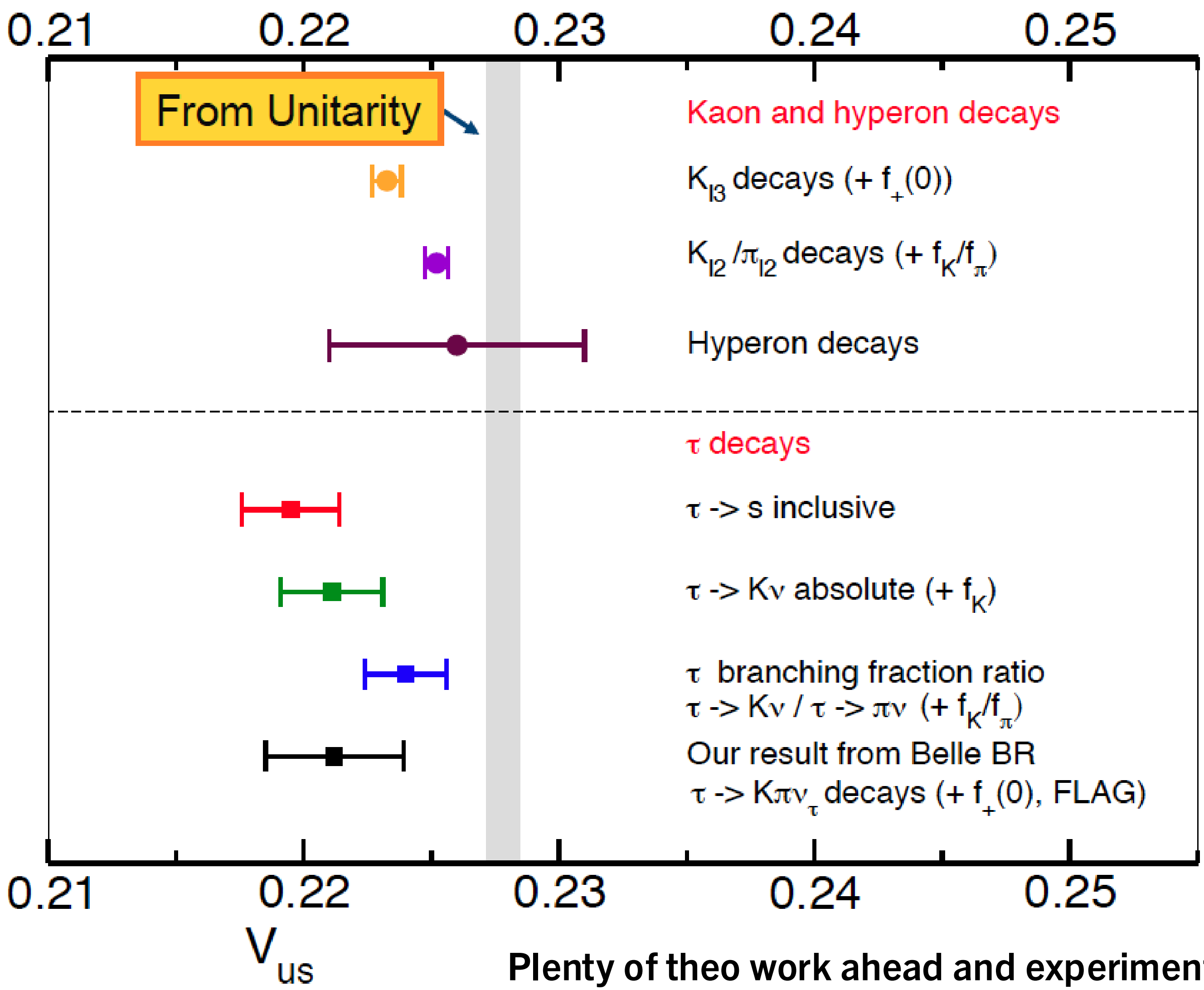


- From τ decays (crossed channel)

V_{ud}	$\tau \to \pi\pi\nu_\tau$		$\tau \to \pi\nu_\tau$	$\tau \to h_{NS}\nu_\tau$
V_{us}	$\tau \to K\pi\nu_\tau$		$\tau \to K\nu_\tau$	$\tau \to h_S\nu_\tau$ (inclusive)

Can the TAU physics help us for V_{us} ?

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



Plenty of theo work ahead and experimental field is a time for Belle II in Japan (a super tau charm factory in Beijing ?) More at
[E. Passsemar Belle II 2024 Oct. Physics Week]

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	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 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*

V_{us} from hyperon decay at LHCb ?

[Phys. Rev. Lett. 114 no. 16, (2015)]

$$\Lambda \to p\, \mu^- \bar{\nu}_\mu$$

[J. High Energ. Phys. 2019, 48 (2019)]
[J. Phys. Conf. Ser. 1526 012022 (2020)]

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} \qquad R^{\mu e}_{\mathrm{SM}} = \sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\operatorname{arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right) = 0.153 \pm 0.008$$

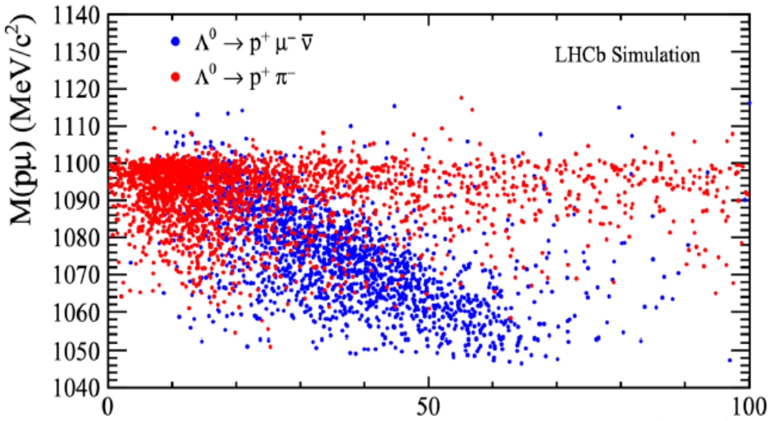
- **Clean theoretical prediction** for the decay rate (going to order δ^2)

$\Delta = M_1 - M_2$ $\quad f_1(0) =$ *hyperon vector charge*

$\delta = \frac{M_1 - M_2}{M_1}$ $\quad g_1(0) =$ *hyperon axial charge*

- $|$**V**$_{\mathbf{us}}|$ can be extracted from the BF
- Adding **hyperons** results to the puzzle

$$|V_{us}|^2 \simeq \frac{\Gamma^{\mathrm{SM}}(B_1 \to B_2 \mu^- \bar{\nu}_\mu)\, 60\pi^3}{R^{\mu e} G_F^2\, f_1(0)^2 \Delta^5 \left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\right]}$$



[LHCB-FIGURE-2019-006]

- Best branching ratio measurement from BESIII (2021):
  $\mathcal{B}(\Lambda \to p\, \mu^- \bar{\nu}_\mu) = (1.48 \pm 0.21) \times 10^{-4}$ (**14.19 % Uncertainty**)

Dataset: 5.4 fb^{-1} @ $\sqrt{s}$ = 13 TeV (Run2), Norm. : $\boldsymbol{\Lambda \to p\, \pi^-}$
44K pre-selected signal events → **~1.5 % stat. unc.**
Dominated by systematic uncertainties
Publication expected **early next year**
$\boldsymbol{\Xi^- \to \Lambda\, \mu^- \bar{\nu}_\mu}$ proposed as the next natural step

See A. Brea at the implications of LHCb measurements and future prospects
CERN, 23–25 October 2024

V_{us} from hyperon decay at LHCb ?

$$\Lambda \to p\, \mu^- \bar{\nu}_\mu$$

The main observable for this analysis is the LFU observable $R_{\mu,e}$. Vus can also be derived, but we can't compete with the kaon measurements. As it is explained in the slide, we expect a statistical uncertainty around ~1.5% but we also expect to be dominated by systematic uncertainties. I can not provide the final uncertainty of our measurement, but I would say that you can use ~ 7% (half of the BESIII measurement uncertainty, as an estimate).

I have attached how we are deriving the Vus value. The uncertainty from the theoretical part in Vus^2 is 26/437 (see equation 25), so ~6%. So, in our final Vus result, we may be dominated by theoretical uncertainties. That's why we decided to present this at the implications, because it would be great to see an effort from the theoretical side to try to improve the predictions.

Anyway, If I am not wrong, with the numbers that I provide I think that the final Vus extraction from this decay will have ~5% of uncertainty.

See A. Brea at the implications of LHCb measurements and future prospects
CERN, 23–25 October 2024

Theoretical prospects for V_{us}

- Lattice Progress on hadronic matrix elements: decay constants, FFs

- Full QCD+QED decay rate on the lattice,for **Leptonic decays of kaons and pions** ⇒ Inclusion of EM and IB corrections :
  - Perturbative treatment of QED on lattice established
  - Formalism for K_{l2} worked out

- Application of the method for **semileptonic Kaon** (K_{l3}) **and Baryon decays**

⇒ **Aim: Per mille level within 10 years**

prospects for V_{ud}

Workshop on Vud from pion, neutron and nuclear beta decay

5 nov. 2024, 14:00 → 6 nov. 2024, 13:00 Europe/Paris

GANIL

Description The workshop will be hosted at the Maison d'Hôtes of GANIL.

The topics to be discussed are:

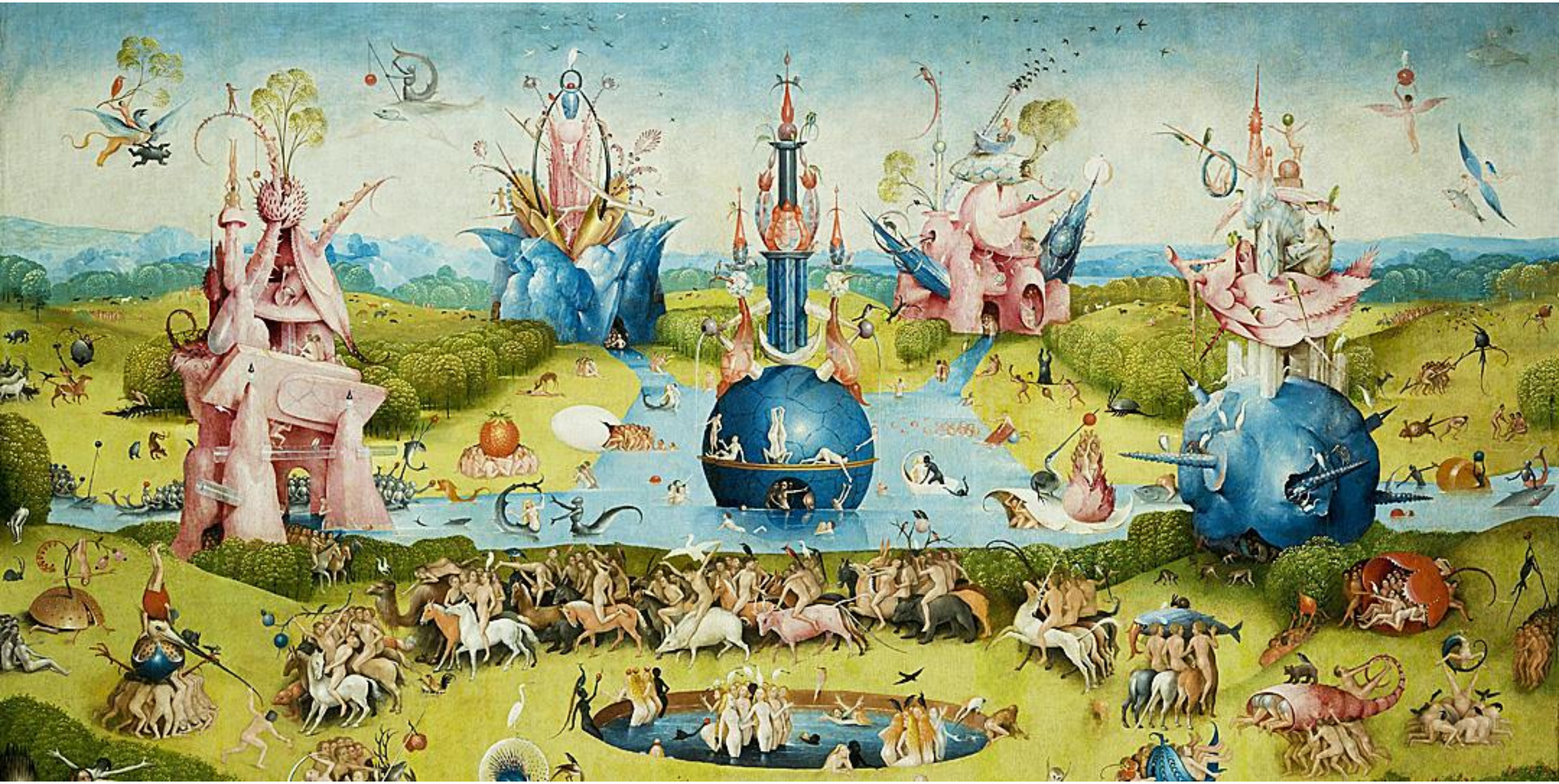
- Impact of Vud on the search for new physics, CKM fitters viewpoint
- Status and prospects on experimental measurements
  - Vud from pion decay - the PIONEER experiment
  - Vud from neutron decay, half-life and Ab measurements
  - Vud from nuclear superallowed decays - half life and BR measurements
  - Vud from nuclear mirror decays – half-life, BR & correlation measurements
- Vud theoretical corrections – status and prospects

The workshop is a joint event of the GDR Intensity Frontier and of the GDR RESANET

INTENSITY frontier GDR-InF

RESANET Réactions, structure et Astrophysique Nucléaires: Expériences et Théories

Some New Physics interpretations



adding Right-handed currents to the SM*

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

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

- See also *Antonelli et al.'09*
  Alioli, Cirigliano, Dekens, de Vries, Mereghetti'17
  T. Kitahara@HC2NP 2019

*already advocated a few years ago by A.Buras, KGemmler & G.Isidori to interpret V_{ub} inclusive vs exclusive discrepancies

adding Right-handed currents to the SM

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

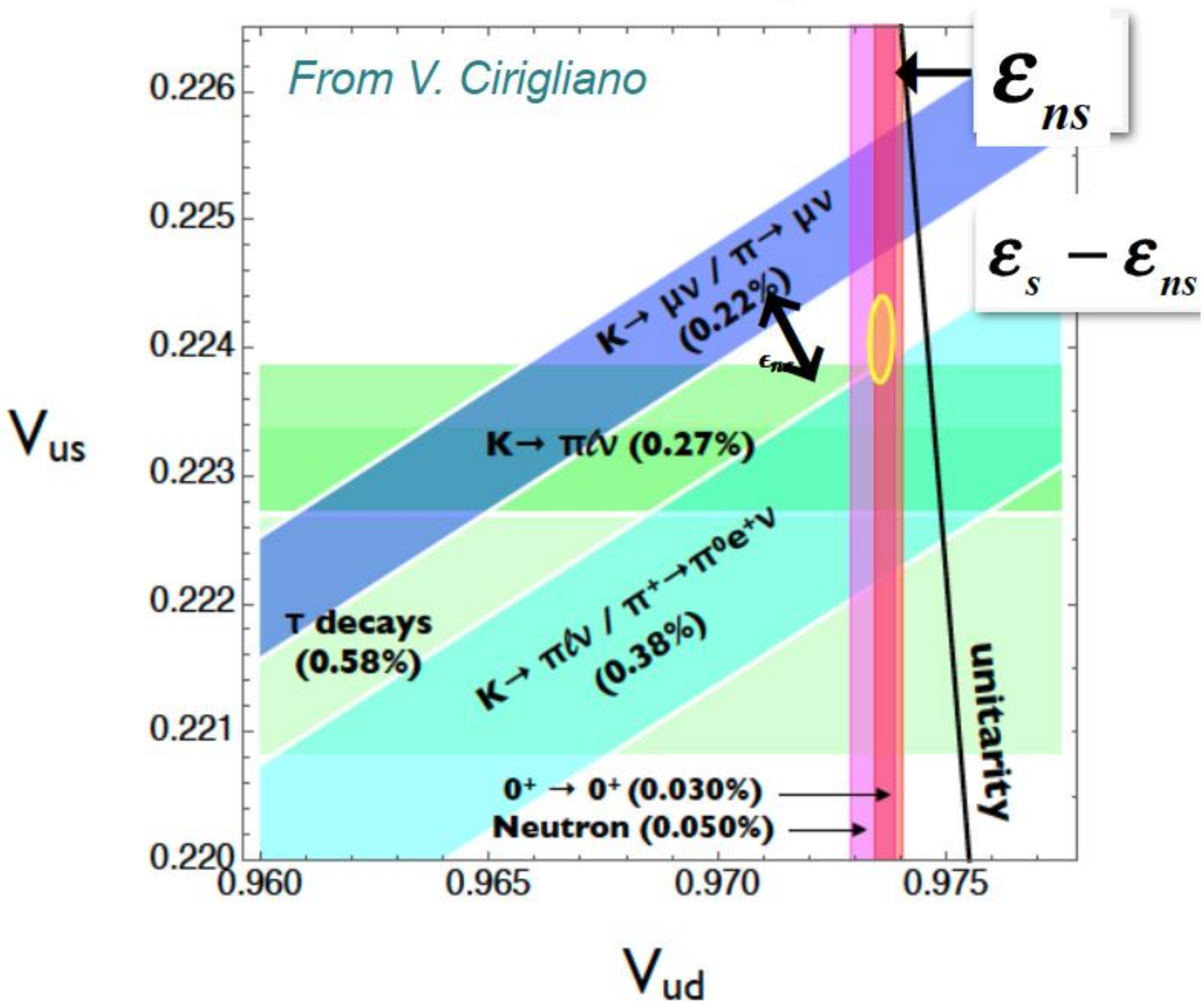
$$\left(\frac{V_{us}}{V_{ud}}\right)^{K_{l2}} = \left|\frac{\sin\theta_C - \varepsilon_s}{\cos\theta_C - \varepsilon_{ns}}\right| , \longleftarrow \boxed{\text{Axial}}$$

$$V_{ud}^{\beta} = |\cos\theta_C + \varepsilon_{ns}| \;. \longleftarrow \boxed{\text{Vector no s quark}}$$

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

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

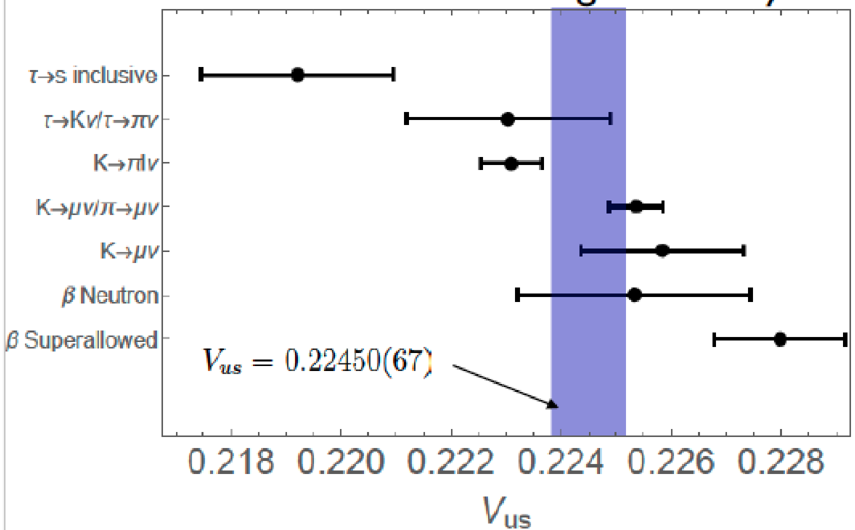
adding Right-handed currents to the SM



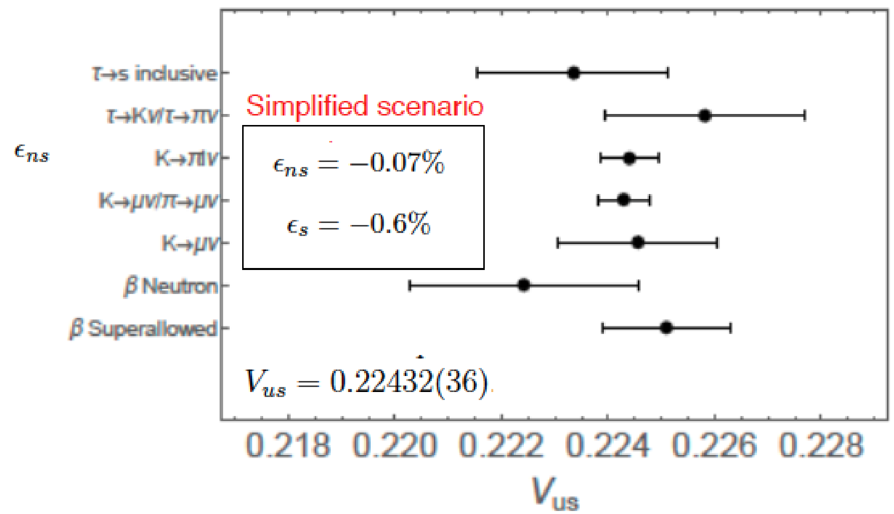
adding Right-handed currents to the SM

- 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



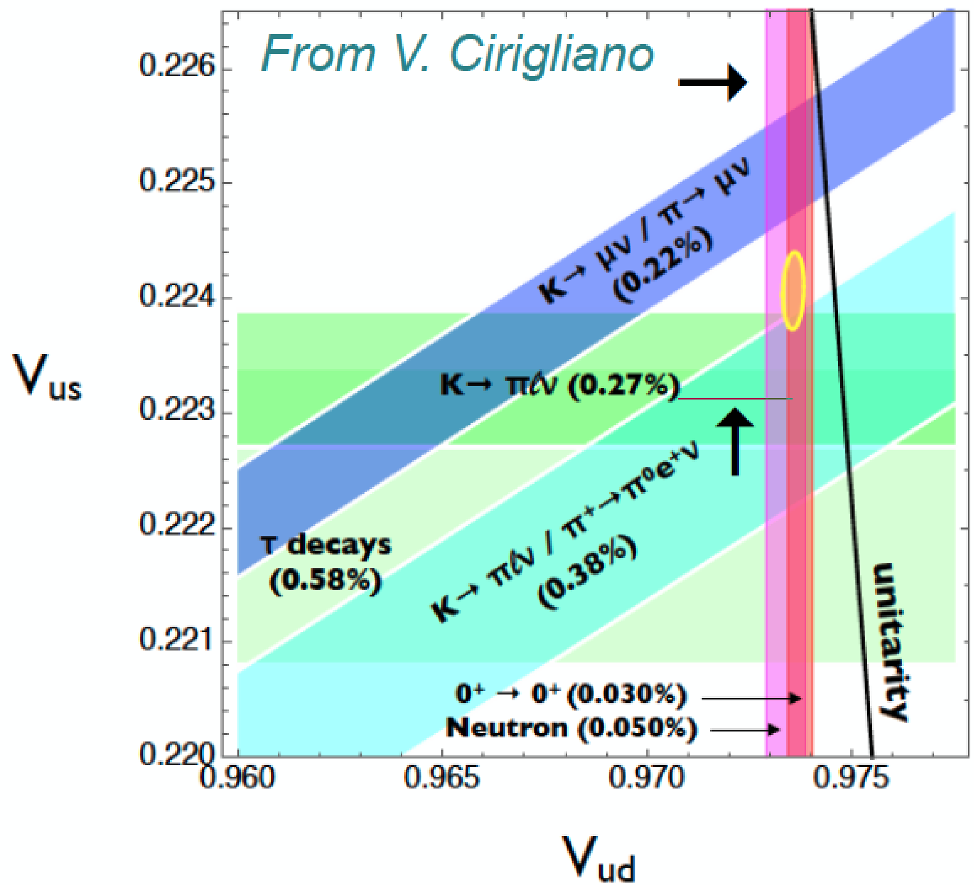
Cirigliano, Diaz-Calderon, Falkowski, Gonzalez-Alonso, Rodriguez-Sanchez'21

Other NP Models on the market

- 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....



Emilie Passemar

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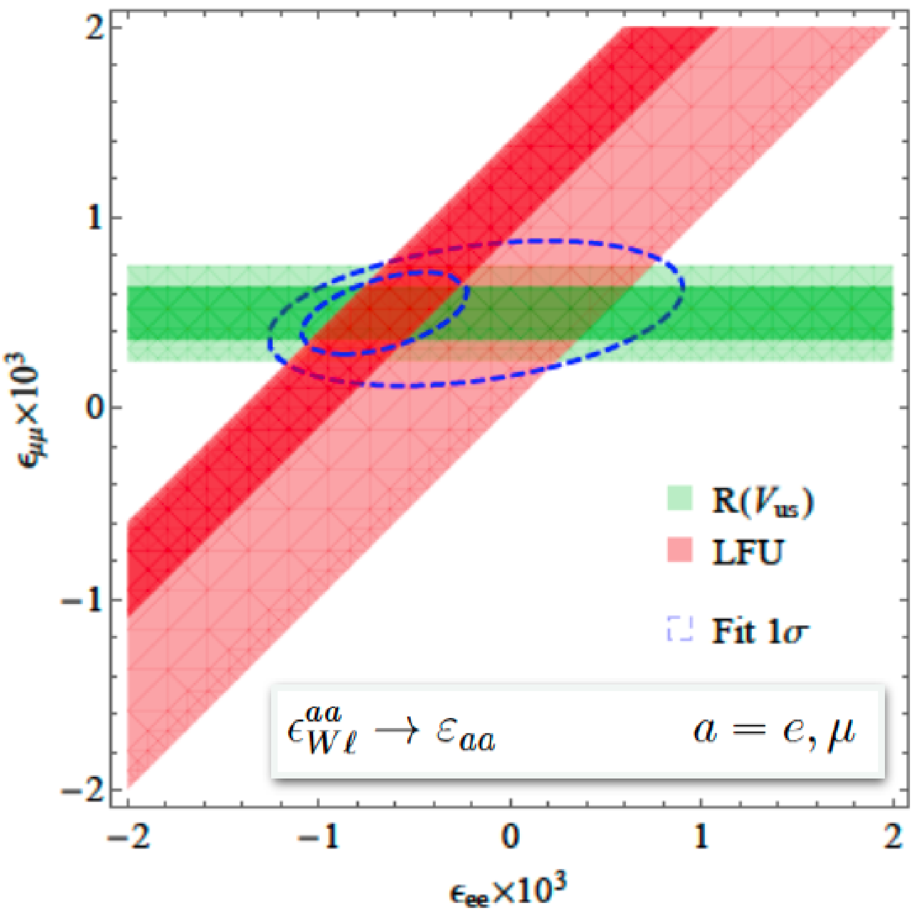


Connection with π→eν/ π→μν

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

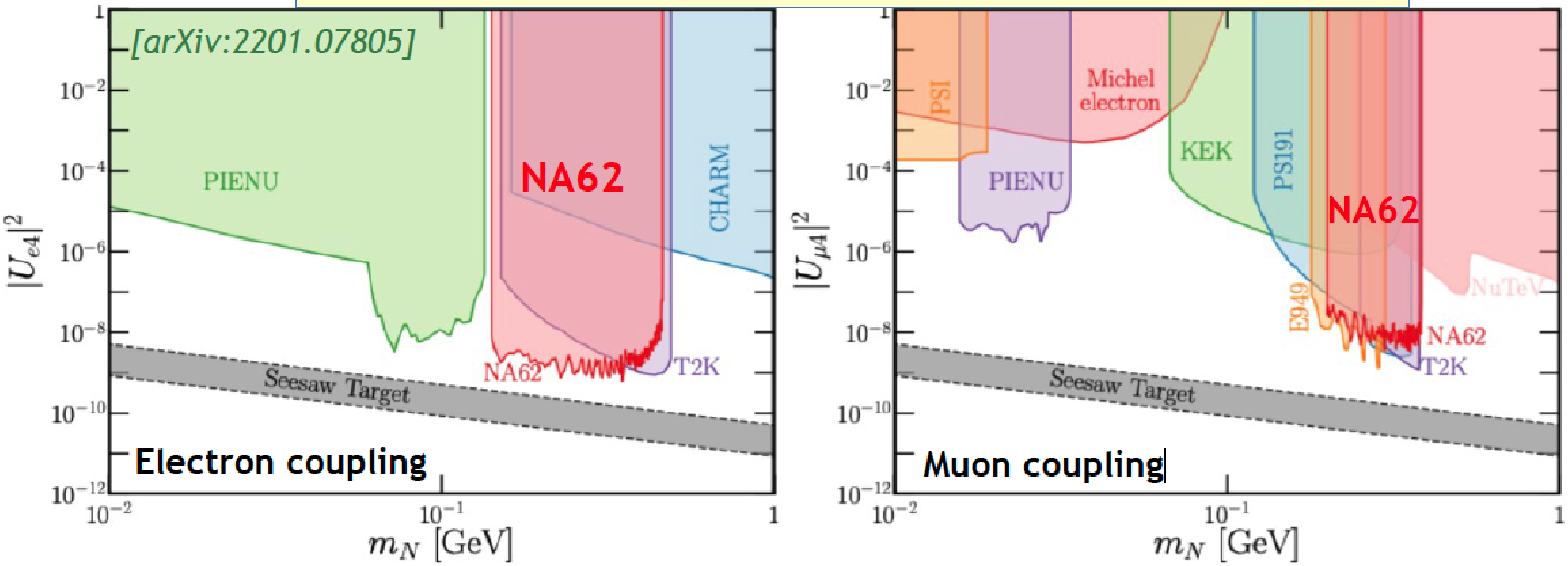
(and other LFU probes)

And many more....

Emilie Passemar

Example: constraints on Heavy Neutral Leptons
Synergy Kaon/pion experiments

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



- Strongest $|U_{e4}|^2$ limits below **400 MeV**: **$K^+, \pi^+ \rightarrow e^+N$** from *NA62* & *PIENU*.
- Also important limits on $|U_{\mu 4}|^2$ from *E949*, *NA62* and *PIENU*.
- *NA62/E949* limits are complementary to HNL *decay* searches at T2K.
- Next-generation **K^+** and **p+** experiments (*NA62^{++}*, *PIONEER*) to improve by up to factor **10**, reaching the seesaw bound.

For a review see: https://arxiv.org/pdf/2203.08039

Conclusion and Outlook

- Recent precision determinations of V_{us} and V_{ud} enable unprecedented tests of the SM and constraints on possible NP models
- Tensions in unitarity of 1st row of CKM matrix have reappeared!
- We need to work hard to understand where they come from:
  - On experimental side:
    For V_{us}, new measurements in kaons (*NA62:* $K_{\mu 3}/K_{\mu 2}$, *LHCb?*)
    but mainly in tau decays from *Belle II*
    V_{us} from hyperon decays? ⇨ *BESSIII*, *LHCb*?
  - For V_{ud}, understand the situation of the neutron lifetime, beta decay of pion? ⇨ *PIONEER* Consider $R_V = \Gamma\left(K \to \pi l \nu(\gamma)\right) / \Gamma\left(\pi^+ \to \pi^0 e^+ \nu(\gamma)\right)$
    Czarnecki, Marciano, Sirlin'20
  - On theory side:
    Calculate very precisely radiative corrections, isospin breaking effects and matrix elements
    Be sure the uncertainties are under control
  - If these tensions are confirmed ⇨ what do they tell us?

The first row of the CKM matrix (i.e.: Cabibbo angle even w.o. V_{ub}) contains mysteries motivating measurements/theory work at Intensity Frontier