Rare pion decays: theory perspective

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PIONEER Collaboration Meeting University of Washington, Oct 16-18 2023

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NEER collaboration meetin

INSTITUTE for NUCLEAR THEORY

 $G_F(\beta) \sim g^2 V_{ij}/M_w^2 \sim G_F(\mu) V_{ij}$

- Rare pion decays offer a theoretically 'clean' way to test the SM universality relations
	- Precise exp. + theory may reveal BSM effects from heavy new physics
	- Direct sensitivity to light new particles (sterile neutrinos, axion-like, Majoron...)

CC processes the SM are mediated by W exchange between L-handed fermions \Rightarrow universality relations

Lepton flavor universality

Cabibbo universality (Quark-Lepton universality)

Rare pion decays: weak universality and beyond

$$
\pi \rightarrow eV
$$

$$
\pi^{\pm} \rightarrow \pi^0 e^{\pm}V
$$

$$
[G_F^{(0)}]_e/[G_F^{(0)}]_\mu = 1
$$

$$
|V_{ud}|^2 + |V_{us}|^2 + |\mathcal{Y}_{ub}|^2 = 1
$$

Outline

• Resource: theory talks at the 2022 Rare Pion Decay Workshop

Physics insights on RPD program

Cervantes and Velasquez Room, UC Santa Cruz

LFU tests across energy scales

Cervantes and Velasquez Room, UC Santa Cruz

Coffee

Cervantes and Velasquez Room, UC Santa Cruz

Meson decays as probes of light new physics

Cervantes and Velasquez Room, UC Santa Cruz

Tests for sterile neutrino effects

Cervantes and Velasquez Room, UC Santa Cruz

Status and prospects of the first-row CKM unitarity te

Cervantes and Velasquez Room, UC Santa Cruz

The case for New Physics at PIONEER

Cervantes and Velasquez Room, UC Santa Cruz

https://indico.cern.ch/event/1175216/timetable/#20221006.detailed

• The Standard Model baseline: theoretical status of

- $R_{e/\mu}(\pi) = \Gamma(\pi \rightarrow eV(\gamma)) / \Gamma(\pi \rightarrow \mu V(\gamma))$
- $\Gamma(\Pi^{\pm} \to \Pi^0 e^{\pm} V(V))$
- Rare π decays as a probe of new physics:
	- Sensitivity to light and weakly coupled particles (brief)
	- Impact on lepton flavor universality tests
	- Impact on Cabibbo universality test ('active' anomaly)

Outline

The Standard Model baseline

$R_{e/\mu}(\pi) = \Gamma(\pi \rightarrow eV(\gamma)) / \Gamma(\pi \rightarrow \mu V(\gamma))$ in the SM

• Helicity suppressed the SM (V-A structure), zero if $m_e \rightarrow 0$

• Despite involving a hadron, this ratio can be predicted with high precision. Why?

Image Copyright: Bergische Universität Wuppertal, Theoretische Physik, Fachbereich C

∂ *Theoretical analysis of R_{e/μ}(π)* electromagnetic coupling *e*. In this setup, one can write sensitive probes of R_{all}(π) well as *e*^o and *e*ⁿ and *e*ⁿ operators, in particular, in particular, in particular, induced or induced in the ratio *R^P ^e/µ* and the hadronic structure dependence appears only through EW corrections. analysis of $R_{e/u}$ ⁽¹¹⁾

$$
\mathsf{P} = (\mathsf{T}, \mathsf{K}) \qquad R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2} \right)^2
$$

 $\frac{1}{2}$ m_π *m*² *e* K *, μ* \overline{a} **b** $\frac{1}{2}$ *n*² *M*₂ of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio \mathcal{L}_c electromagnetic coupling *e*. In this setup, one can write of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio α electromagnetic coupling *e*. In this setup, one can write

 $Q \sim m_{\pi, K, \mu}/\Lambda_{\chi}$, $\Lambda_{\chi} \sim 4\pi F_{\pi} \sim 1.2 \text{ GeV}$ $Q \sim m_{\pi, K, \mu} / \Lambda_{\chi}$) $\Lambda_{\chi} \sim 4 \pi F_{\pi} \sim 1.2 \text{ GeV}$

of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio α , 2. Because of these features and the precise experimental measurements, the ratios *R^P* The most recent theoretical calculations of *R^P* $\mathcal{C}(\mathcal{C})$, the low energy effective $\mathcal{C}(\mathcal{C})$ of $\mathcal{C}(\mathcal{C})$ of $\mathcal{C}(\mathcal{C})$ of $\mathcal{C}(\mathcal{C})$ of $\mathcal{C}(\mathcal{C})$ FeV sensitive probes of all SM extensions that induce nonuniversal corrections to *W*!ν couplings as well as *e*^o and α ⁿuscalar, in particular, in part

- F_π drops in the e/µ ratio \rightarrow hadronic structure dependence appears only through EM corrections tha a
- Organize calculation in EFT (ChPT): .
Aize
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re dependence appears only through EM corrections ire dependence appears only through EPI corrections (53). This framework provides a controller expansion expansi

The most recent theoretical calculations of *R^P*

e/µ $\begin{array}{l} \text{contact (LEC):}\\ \text{intrinsic cancels}\end{array}$ ¹ ⁺ &*^P ^e*2*Q*⁰ ⁺ &*^P ^e*2*Q*² ⁺ &*^P* No contact (LEC): contribution cancels in the ratio! *^e*4*Q*⁰ . The 2 **2 WO CONTACT (LEC):**
2 contribution cancels (a) contribution cancels
and the matic stated in the matic order corrections in a second to include the matic order corrections in a second corrections in a second considered consider consider consider corrections in a sec are not helicity suppressed and behavior suppressed and behavior suppressed and behavior suppressed and behavio
Property as a *P*P suppressed and behavior suppressed and behavior suppressed and behavior suppressed and beha

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∂ *Theoretical analysis of R_{e/μ}(π)* electromagnetic coupling *e*. In this setup, one can write sensitive probes of R_{all}(π) well as *e*^o and *e*ⁿ and *e*ⁿ operators, in particular, in particular, in particular, induced or induced in the ratio *R^P ^e/µ* and the hadronic structure dependence appears only through EW corrections. analysis of $R_{e/u}$ ⁽¹¹⁾ Here we have kept all the terms needed to reach an uncertainty of Ω−4 for the ratio. **electromagnetic corrections analysis of Ke/μ⁽¹⁹)** $Theta$ metre all the terms needed to $R_{e/\mu}$ α electromagnetic corrections &*^P*

*m*²

µ

#

*m*²

*m*²

^P − *m*²

 $\Delta_{e^4Q^0}^{(\pi)} = 0.055(3)\%$

 Λ ^{(π})
 e^4C

where the control
where the control of the control of
where the control of the control

and the SM experimental to the SM experience of the SM Use RGE to resum large IR logs (Marciano and Sirlin 1993)

re dependence appears only through EM corrections ire dependence appears only through EPI corrections (53). This framework provides a controller expansion expansi ratio \rightarrow hadronic structure dependence appears only through EM corrections

of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio α , 2. Because of these features and the precise experimental measurements, the ratios *R^P* FeV sensitive probes of all SM extensions that induce nonuniversal corrections to *W*!ν couplings as *^P* [−] *^m*² *^e*2*Q*⁰ correspond to the pointlike approximation for πs and *K*s, and leading logarithmic correction \mathcal{P} 0*.*003%. Numerically, one !nds &^π

• Organize calculation in EFT (ChPT):
\n
$$
Q \sim m_{\pi, K, \mu} / \Lambda_{\chi}
$$
 $\Lambda_{\chi} \sim 4\pi F_{\pi} \sim 1.2 \text{ GeV}$

Theoretical analysis of $R_{e/\mu}(\pi)$	
$P = (\pi K) \left(R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2} \right)^2 \times \left[1 + \Delta_{e^2Q^0}^p + \Delta_{e^2Q^2}^p + \Delta_{e^2Q^4}^p + \cdots + \Delta_{e^4Q^6}^p + \cdots \right] \right)$	
$\cdot F_{\pi}$ drops in the e/ μ ratio \rightarrow hadronic structure dependence appears only through EM corrections	
\cdot Organize calculation in EFT (ChPT): NLO correction \leftrightarrow point-like mesons (Kinoshita 59)	
\cdot NLO correction \leftrightarrow point-like mesons (Kinoshita 59)	
\cdot	

- F_π drops in the e/µ ratio \rightarrow hadronic structure dependence appears only through EM corrections tha a budget.
	- Organize calculation in EFT (ChPT): .
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- NLO correction ↔ point-like mesons (Kinoshita 59) \overline{O} er. Part. Part. 2022.
Text. Part. Sci. 2022. oint-like mesons (Kinoshita 59) from the structure of the structure contribution to $\frac{1}{2}$ ($\frac{1}{2}$ ($\frac{1}{2}$) but are formally of $\frac{1}{2}$ ($\frac{1}{2}$) but are formally of $\frac{1}{2}$ ($\frac{1}{2}$) but are formally of $\frac{1}{2}$ ($\frac{1}{2}$) but are

$$
\left(\begin{array}{cc} \Delta_{e^2 Q^0}^\pi & \sim & -3\alpha/\pi \end{array}\right)
$$

. 4.

e²/₂3524 ± 0.00015) × 10−4524 ± 0.00015 ± 0.00015 ± 0.00015 ± 0.00015 ± 0.00015 ± 0.00015

 $\hat{Q}^0 =$

estimated within large- N_c inspired resonance model (satisfying QCD s.d. result, largest uncertainty

. 3. model-independent single and double logs

∂ *Theoretical analysis of R_{e/μ}(π)* electromagnetic coupling *e*. In this setup, one can write rithms and an a priori unknown low energy coupling constant, which was estimated in large-*N*^C QCD (where *N*^C is the number of colors) (47, 48) and found to contribute negligibly to the error their expressions are well known (54). The hadronic structure dependence . The hadronic structure dependence !
The hadronic structure dependence !rst appears through the hadronic structure dependence . The hadronic struct 2, which features both the calculable double-chiral loga-

of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio α

$$
P = (\pi, K) \left[R_{e/\mu}^{(P)} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2} \right)^2 \times \left[1 + \Delta_{e^2 Q^0}^P + \Delta_{e^2 Q^2}^P + \Delta_{e^2 Q^4}^P + \dots + \Delta_{e^4 Q^0}^P + \dots \right] \right]
$$

 $|$ enend • Structure dependence appears at NNLO in ChPT! $f(x) = \frac{1}{2\pi} \int_0^1 \frac{1}{y^2} \, dy \, dx \quad \text{for all } x \in \mathbb{R}^d$ ● Structure dependence appears at NNLO in ChP1 **2.1.1. Pion decays.** In the π case (*P* = π±), one usually de!nes the ratio to be fully photon **inclusive, such it is infrared safe. As a consequence**, one R

$$
\Delta_{e^2 Q^2}^{\pi} = 0.053(11)\%
$$

$$
\Delta_{\pi}^{\pi} = 0.073(3)\%
$$

$$
\Delta_{e^2 Q^4}^{\pi} = 0.073(3)\%
$$

1) One- and two-loop diagrams \Rightarrow

*^e*2*Q*⁰ correspond to the pointlike approximation for πs and *K*s, and

rithms and an a priori unknown low energy coupling constant, which was estimated in large-*N*^C

of the decay rates in terms of a power counting scheme characterized by the dimensionless ratio α , 2. *.* 3.

*m*²

**Marciano-Sirlin, 1993, PRL →

VC-Rosell 0707.3439, PRL VC-Rosell 0707.3439, PRL**

 $R_{e/\mu}^{(\pi)}=1.23524(015)\times10^{-4}$

 $e/7 \pm 0.0023$) $x10^{-4}$ ($\pm 0.19\%$) 0.9990 ± 0.0009 (\pm ± 0.0009 ($\pm 0.09\%$) aseline for $\frac{1}{2}$ the next $+QED$ $(40023)x10^{-4}$ (4019%) $= 0.9990 + 0.0009$ $(+0.09\%)$ $2 - 0.000$ \exp / $\pm \Omega$ 10/ ²*G^F ^Vud ^e*¯*µPL*⌫*^e ^N*¯ (*g^V ^v^µ* ²*gASµ*) ⌧ ⁺*^N* ⁺ *...* $f^{exp} = (1.2327 \pm 0.0023)x10^{-4}$ ($\pm 0.19\%$) / / $(PDG):$ $R_{e/u}^{exp} = (1.2327 \pm 0.0023)x10^{-4}$ ($\pm 0.19\%$) $\frac{e}{2} = 0.9990 \pm 0.0009 \text{ } (\pm 0.09\%)$ $\text{pads} \ (R_{e/u}^{\text{exp}} \leq \pm 0.1\%)$ *e* e/μ *x g g* μ μ $=(1.2327\pm0.0023)x10^{-4}$ (\pm $\leq \pm$ $= 0.9990 \pm 0.0009$ (±

 $\mu = 1.2002 \pm (010) \times$

 $P = (\pi, K)$

 $1 + \Delta^P_{e^2Q^0} + \Delta^P_{e^2Q^2} + \Delta^P_{e^2Q^4} + \cdots + \Delta^P_{e^4Q^0} + \cdots$ $\overline{}$

Theory **Experiment** E_{Y} experiment Pheory 2: Theory 2: Th

∂ *Theoretical analysis of R_{e/μ}(π)* electromagnetic coupling *e*. In this setup, one can write Test eti Test

*m*² **PIENU Coll. , PRL 2015

PDG 2020 PDG 2020**

$$
R^{(P)}_{e/\mu} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2} \right)^2 \times \left[1 - \right.
$$

$$
R_{e/\mu}^{(\pi)} = 1.23270(230) \times 10^{-4}
$$

R(⇡)

 $\frac{2}{\mu}|V_{ud}|^2 m_{\pi^+}^5 \left|f_+^{\pi}(0)\right|^2 (1+{\rm RC}_\pi)I_\pi,$

• Decay rate

$$
\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma)) = \frac{G_\mu^2}{}
$$

Pion beta decay

M. Hoferichter, 2022

• Decay rate

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

• Phase space $I_{\pi} = 7.3766(43) \times 10^{-8}$

$$
10^{-8} \sim \left(\frac{m_{\pi^+} - m_{\pi^0}}{m_{\pi^+}}\right)^5
$$

Pion beta decay

- Phase space $I_{\pi} = 7.3766(43) \times$
- Vector form factor at t=0, controlled by isospin and its breaking α form fostor at \pm 0 controlled by isospin and its broaking

Behrends-Sirlin 1962 VC-Neufeld-Pichl hep-ph/0209226, EPJC

$$
\left| \langle \pi^0(p_0) | d\gamma_\mu u | \pi^+(p_+) \rangle \right| = \sqrt{2} f_+(t) \left(p_+ + p_0 \right)_{\mu} \qquad t = (p_+ - p_0)^2
$$

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

$$
10^{-8} \sim \left(\frac{m_{\pi^+} - m_{\pi^0}}{m_{\pi^+}}\right)^5
$$

M. Hoferichter, 2022

• Decay rate

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

Pion beta decay

• Decay rate

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

• Radiative corrections: Current algebra \rightarrow ChPT to O(e²p²) \rightarrow Lattice QCD

$$
\boxed{\mathrm{RC}_{\pi}=0.0342(10)}\boxed{\left(\mathrm{ChPT}\right)}
$$

Sirlin 1978 VC-Neufeld-Pichl 2002, EPJC Desxotes-Genon Moussallam 2005, EPJC Passera et al., 2011

$$
Re_{\pi} = 0.0332(1)_{\gamma W}(3)_{HO} \left[(LQCD) \right]
$$

Feng, Gorchtein, Jin, Ma, Seng , 2003.09798, PRL

PIBETA Coll. , hep-ex/031230, PRL $\mathsf{M} \cap \mathsf{R}$ and $\mathsf{M} \cap \mathsf{R}$ and $\mathsf{M} \cap \mathsf{M}$ and $\mathsf{M} \cap \mathsf{M}$ rections is provided in Appendix A, leading to the values of the val

- 0.3% uncertainty dominated by $BR = 1.036(6)x10^{-8}$ $WRR = 1.036(6)x10^{-8}$
- Next largest uncertainty from phase space! R
- For reference, the current best determination is *|Vud|* ² ⁺ *[|]Vus[|]* ² ⁺ *[|]Vub[|]*

Test

Test

 $\overline{\mathbf{r}}$ sea_/ • Decay rate

Pion beta decay Model (SM). In particular, the first-row unitarity relation,

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

$$
V_{ud}^{0^+ \to 0^+} = 0.97367(11)_{exp}(13)_{\Delta_V^R}(27)_{NS}[32]_{total}
$$

|*Vud*|

² ⁺ [|]*Vus*[|]

² ⁺ [|]*Vub*[|]

M. Hoferichter 2022

= 1, (1)

$$
\begin{aligned}\n\text{Pion beta decay} \\
\text{F}(\pi^+ \to \pi^0 e^+ \nu(\gamma)) &= \frac{G_\mu^2 |V_{\text{ud}}|^2 m_{\pi^+}^5 |f_+^{\pi}(0)|^2}{64\pi^3} (1 + \text{RC}_{\pi}) I_{\pi}, \\
\text{extraction of } V_{\text{ud}} \\
V_{ud}^{(\pi\beta)} &= 0.97386 (281)_{BR} (9)_{\tau_{\pi}} (14)_{RC} (28)_{I_{\pi}} [283]_{\text{total}} \\
\text{ertainty dominated by BR} &= 1.036(6) \times 10^{-8} \\
\text{PIBETA coll., hep-ex/031230, PRL}\n\end{aligned}
$$

• Current extraction of V_{ud}

Rare pion decays as a probe of new physics

- What kind of new physics are rare pion decays probing?
- Light and weakly coupled? Heavy?

Decreasing Coupling Strength

BSM sensitivity

- What kind of new physics are rare pion decays probing?
- Light and weakly coupled? Heavy? Both!

Decreasing Coupling Strength

Sensitivity to light new physics

• There is sensitivity to a variety of new particles / interactions

From Jeff Dror's talk at Rare Pion Decay workshop

Sterile neutrinos

- Sensitivity to sterile neutrino mass & mixing
- π + ev₄ provides strongest bounds on $|U_{eq}|^2$ for m_{V4} ~ I-140 MeV
- PIONEER improvement: order of magnitude

• Recent study of general lepto-philic axion

Altmanshofer-Dror-Gori 2209.00665, PRL _
م

Axion-like particles

2

Many scenarios affect CC weak processes: W', charged Higgs, Vector-like leptons and quarks, leptoquarks, ...

Sensitivity to heavy new physics

-
- Their effect captured by 'low-energy' effective theory at $E \ll M_{\text{new}}$

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

 ${\cal L}^{(\mu)}_{CC} = - \frac{G^{(0)}_F}{\sqrt{2}}$ *F* 2 $\sqrt{2}$ $1 + \epsilon$ (*µ*) *L* \setminus $\bar{e}\gamma^{\rho}(1-\gamma_5)\nu_e\cdot\bar{\nu}_{\mu}\gamma_{\rho}(1-\gamma_5)\mu + \dots$ *G*(*µ*) *^F* ⁼ *^G*(0) $\frac{1}{2}$ (*µ*) μ W *^L*CC ⁼ *G*(0) *^F Vud* ex correct $\frac{i}{i}$ *ab* + ✏ *^e*¯*aµ*(1 5)⌫*^b · ^u*¯*^µ*(1 5)*^d* $\mu^ \mu$ ⁻ νµ Vertex corrections 4-fermion contact interaction

$$
b \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \bigg] + \text{h.c.}
$$

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

Leptonic interactions

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

F

L

$$
\left(\theta + \epsilon_L^{ab}\right) \bar{e}_a \gamma_\mu (1 - \gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d
$$

Semi-leptonic interactions

GeV-scale effective Lagrangian

VC, Gonzalez-Alonso, Jenkins 0908.1754, NPB VC, Graesser, Gonzalez-Alonso 1210.4553, JHEP

$$
\mathcal{L}_{CC}^{(\mu)} = -\frac{G_{F}^{(0)}}{\sqrt{2}} \left(1 + \epsilon_{L}^{(\mu)}\right) \bar{e}\gamma^{\rho}(1 - \gamma_{5})\nu_{c} \cdot \bar{\nu}_{\mu}\gamma_{\rho}(1 - \gamma_{5})\mu + \dots
$$
\n
$$
\mathcal{L}_{CC} = -\frac{G_{F}^{(0)}V_{ud}}{\sqrt{2}} \times \left[\left(\delta^{ab} + \epsilon_{L}^{ab}\right) \bar{e}_{a}\gamma_{\mu}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}\gamma^{\mu}(1 - \gamma_{5})d\right]
$$
\n
$$
+ \epsilon_{R}^{ab} \bar{e}_{a}\gamma_{\mu}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}\gamma^{\mu}(1 + \gamma_{5})d
$$
\n
$$
+ \epsilon_{S}^{ab} \bar{e}_{a}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}d
$$
\n
$$
- \epsilon_{P}^{ab} \bar{e}_{a}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}\gamma_{5}d
$$
\n
$$
+ \epsilon_{S}^{ab} \bar{e}_{a}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}\gamma_{5}d
$$
\n
$$
+ \epsilon_{S}^{ab} \bar{e}_{a}\sigma_{\mu\nu}(1 - \gamma_{5})\nu_{b} \cdot \bar{u}\sigma^{\mu\nu}(1 - \gamma_{5})d + \text{h.c.}
$$
\n
$$
\Sigma_{F}
$$

| Leptonic interactions |

ετ

Probing LFU with Re/μ(π) 1 + ✏*ee ^L* ✏*^R ^B me P* ŗ $\frac{1}{1}$ P *mµ µµ P* Ĩ $\mathsf{with}\ \mathsf{R}_{\mathsf{a}/\mathsf{b}}(\mathsf{n})$

R(⇡)

$$
\left\{\frac{\epsilon_L^{ee} - \epsilon_R - \frac{B_0}{m_e} \epsilon_P^{ee}}{\epsilon_L^{\mu\mu} - \epsilon_R - \frac{B_0}{m_\mu} \epsilon_P^{\mu\mu}}\right\}^2 + \dots
$$
\nNon-interfering terms with the following terms:

 $\epsilon_A \equiv \epsilon_L - \epsilon_R$

 $\Lambda_A \sim 5.5$ TeV

h

R(⇡)

*e/µ*iSM

✏*ee*

i
I

i
I

$$
\boxed{-1.9 \times 10^{-3} < \epsilon_A^{ee} - \epsilon_A^{\mu\mu} < -0.1 \times 10^{-3} \qquad \epsilon_A}
$$

$$
\bigwedge\nolimits_{\mathsf{A}}
$$

• BSM axial-current contribution

Probing LFU with R_{e/\mu}(
$$
\pi
$$
)
\n
$$
\frac{R_{e/\mu}^{(\pi)}}{R_{e/\mu}^{(\pi)}} = \frac{\left|1 + \epsilon_L^{ee} - \epsilon_R - \frac{B_0}{m_e} \epsilon_P^{ee}\right|^2}{\left|1 + \epsilon_L^{\mu\mu} - \epsilon_R - \frac{B_0}{m_\mu} \epsilon_P^{\mu\mu}\right|^2} + \cdots
$$
\nNon-interfering terms with

- BSM pseudoscalar contribution
	- Not helicity suppressed! *V* (⇡)

$$
\text{pressed!} \qquad \qquad \boxed{B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu) + m_d(\mu)}} \qquad \qquad \text{R}_0/m_e = 3.6 \times 10^3.
$$
\n
$$
\Rightarrow \text{[Eq]}^{\text{aa}} \neq \kappa \text{ m}_\text{a} \qquad \qquad \epsilon_P^{ee} < 5.4 \times 10^{-7} \qquad \qquad \text{A}_\text{P} \sim 330 \text{ TeV}
$$

R(⇡)

h

• LFU violation \leftrightarrow [ε_P]αα ≠ κ m_α

R(⇡)

*e/µ*iSM

1 + ✏*ee ^L* ✏*^R ^B* ŗ $\frac{1}{1}$ *µµ ^L* ✏*^R ^B*

i
I

Probing LFU with R_{e/\mu}(
$$
\pi
$$
)
\n
$$
\frac{R_{e/\mu}^{(\pi)}}{R_{e/\mu}^{(\pi)}} = \frac{\left|1 + \epsilon_L^{ee} - \epsilon_R - \frac{B_0}{m_e} \epsilon_P^{ee}\right|^2}{\left|1 + \epsilon_L^{\mu\mu} - \epsilon_R - \frac{B_0}{m_\mu} \epsilon_P^{\mu\mu}\right|^2} + \cdots
$$
\nNon-interfering terms with

- BSM pseudoscalar contribution
	- Not helicity suppressed! *V* (⇡)

R(⇡)

h

- LFU violation \leftrightarrow [ε_P]αα ≠ κ m_α
- Marginalizing w.r.t. ε_Ρεχ

R(⇡)

*e/µ*iSM

1 + ✏*ee ^L* ✏*^R ^B* ŗ $\frac{1}{1}$ *µµ ^L* ✏*^R ^B*

i
I

$$
\epsilon_P^{ee} < 5.4 \times 10^{-7}
$$

 $\Lambda_{\rm P} \sim 330$ TeV

 $\epsilon_P^{ee} < 5.5 \times 10^{-4}$

 $\Lambda_{P} \sim 10$ TeV

$$
\text{pressed!} \qquad \qquad B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu) + m_d(\mu)} \qquad \longrightarrow \qquad \frac{B_0/m_e = 3.6 \times 10^3}{\text{ @ } \mu = 2 \text{ GeV}}
$$

Re/μ(π) vs other probes of LFU LEFT = − g22 = g2 1 F W !!
!!!

• Comparison possible within a given class of models Comparison possible within a given class of models.

3.1. Effective Field Theory

$$
\mathcal{L} \supset -i \frac{g_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu P_L \nu_j W^-_\mu
$$

$$
g_{\ell} = g_{2} (1 + \epsilon_{\ell \ell}) \t\t\mathcal{E} \t\t\mathcal{E}
$$

 \overline{p} is negative \overline{p}

2

 $1 + \frac{1}{2}$

fi,NP

B

A. Pich, 2012.07099

Bryman, VC, Crivellin, Inguglia,

[2111.05338](https://arxiv.org/abs/2111.05338), ARNPS

 A^{α}

Re/μ(π) vs other probes of LFU LEFT = − g22 = g2 1 F W !!
!!!

• Comparison possible within a given class of models Comparison possible within a given class of models.

3.1. Effective Field Theory

by radiative lepton decays ! → !& Section 3.1.4. In order to extract *Vud* from beta decays, the Fermi constant determined from the muon lifetime Annu. Rev. Nucl. Part. Sci. 2022.72:69-91. Downloaded from www.annualreviews.org Access provided by 2601:601:a401:f6c0:7caf:f679:f839:d5c0 on 10/14/23. See copyright for approved use. *K K W W B ^e B B* ^W PW WS SP W P W P o ^W ^W o o o o o o * * * * *K K K K W W e e e e e B B B B B B B B B B* WP ^W SP ^S P SP ^S P o o o o o o o o o / *^e g g* ^W 0.9978 0.0018 1.00 0.00 . 0.00 r r r o *K K* ^W P o o *W W* ^W P o o *B ^e B B* WS SP o o * * * * *K K K K W W e e e B B B B B B B B B B* WP ^W SP ^S P SP ^S P o o o o o o o o o / *^e g g* ^W 0.9978 0.0018 1.00 0.00 . 0.00 r r r o

 \overline{p} is negative \overline{p}

A. Pich, 2012.07099
A. Pich, 2012.07099
Pyman, VC, Crivellin, Inguglia,
2111.05338, ARNPS
g_{μ} / g_{e}
g_{μ} / g_{e}
$B_{\tau \to \mu} B_{\tau \to e} = \frac{ g_{\mu}(0.0016) }{ g_{\mu} - g_{\mu} } = 0.0016$
$B_{\tau \to \mu} B_{\tau \to \tau} B_{\tau \to e} = \frac{ g_{\mu}(0.0017) }{ g_{\mu} - g_{\mu} } = 0.0018$
$B_{\tau \to \mu} B_{\tau \to \tau} B_{\tau \to \tau} = B_{\mu} 1.9017$
$B_{\tau \to \mu} B_{\tau \to \tau} B_{\tau \to \tau} = B_{\mu} 1.9010$
$B_{\tau \to \mu} B_{\tau \to \tau} B_{\tau \to \tau} = B_{\mu} 1.9010$

2

 $1 + \frac{1}{2}$

fi,NP

B

Bryman, VC, Crivellin, I

Re/μ(π) vs other probes of LFU

- Comparison possible within a given class of models
- Instructive example: LFU violation in vertex corrections, probed by decays of W, τ , K, π
- Global fit [except for B decays]:

$\mathcal{U}, \mathcal{U}, \mathbb{N}, \mathbb{N}$

 $\epsilon_{\tau\tau}$ - $\tilde{\mathbf{z}}$ $\breve{\mathcal{I}}$

 $($

 \overline{a}

 \overline{a}

 \overline{a}

m I FU in

 $\ell = \{e, \mu\}$

For the **inclusive tag**, significance of the result

 $\rm g: BF = [2.8 \pm 0.5 \pm 0.5] \times 10^{-5}$ $\text{Tr} \triangleq \left[\text{Howeyf} \right] \text{for light}$ $BF = [2.4$ eptog tlavors: 10^{-5} $leptpq$ flavors:

0.2

0.3

0.35

0.4

R(D*)

0.25 v_3 • Can be explained by a number of models, e.g. leptoquarks with specific flavor couplings

$$
\begin{array}{c}\n\text{Extract V}_{\text{ud}} = \cos\theta_{\text{C}} \text{ and } \text{V}_{\text{us}} = \sin\theta_{\text{C}} \text{ fr} \\
\text{I} = G_F^2 \times |V_{ij}|^2 \times |M_{\text{had}}|^2 \times \\
\hline\n\text{KM element} \text{Hadronic matrix} \\
\text{element}\n\end{array}
$$

Cabibbo universality tests

 $\bar{\nu}_e$

Cabibbo universality tests

$$
|V_{us}|^2 + |V_{ub}|^2 - 1 = 0
$$

The Cabibbo angle anomaly

Test

 $^{2} \times |M_{\rm had}|^{2} \times (1 + \Delta_R) \times F_{\rm kin}$

- The 'anomalies':
	- \sim 3σ effect in global fit (Δ _{CKM}= -1.48(53) ×10-3)
	- V_{ud} and V_{us} from different processes \rightarrow different Δ_{CKM}
	- ~3σ problem in meson sector (KI2 vs KI3)

$$
\Gamma = G_F^2 \times |V_{ij}|^2 \times
$$

The Cabibbo angle anomaly

Test

 $^{2} \times |M_{\rm had}|^{2} \times (1 + \Delta_R) \times F_{\rm kin}$

- Expected experimental improvements
	- neutron decay (will match nominal nuclear uncertainty)
	- possibly new $K_{\mu3}/K_{\mu2}$ BR measurement at NA62 & HIKE
	- pion beta decay (3x to 10x at PIONEER phases II, III)
- Further theoretical scrutiny of SM prediction
	- Lattice gauge theory: $K \rightarrow \pi$ vector f.f., rad. corr. for KI3
	- EFT for neutron and nuclei, with goal $\delta\Delta_{\rm R} \sim 2 \times 10^{-4}$

$$
\Gamma = G_F^2 \times |V_{ij}|^2 \times
$$

• …

The Cabibbo angle anomaly

Test

 $^{2} \times |M_{\rm had}|^{2} \times (1 + \Delta_R) \times F_{\rm kin}$

- Expected experimental improvements
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	- EFT for neutron and nuclei, with goal $\delta\Delta_{\rm R} \sim 2 \times 10^{-4}$

$$
\Gamma = G_F^2 \times |V_{ij}|^2 \times
$$

• …

What about new physics explanations?

Corrections to V_{ud} and V_{us}

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

Right-handed quark couplings

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

 $\sqrt{|\vec{V}|^2}$ $\sqrt{|\vec{V}|^2}$ $\sqrt{2}$ $\begin{bmatrix} Vud|0^+ \rightarrow 0^+ & - & |Vud| & 1 \end{bmatrix}$ requires a dedicated experimentally campaign, as planned at the PIONEER experiment \mathcal{N} . T_{max} information on $\sqrt{2}$ $\sqrt{$ $\left| V_{ud} \right|_{n \to p e \bar{\nu}}^2 = \left| V_{ud} \right|^2 \left(1 + 2 \epsilon_R \right)$ ly noticed by $\sum_{i=1}^n$ on *Vus*/*Vud*, while *K*`³ decays give direct access to *Vus* when the $|\bar{V}|^2 = |V|^2 |1 + 2\epsilon^{(8)}|$ $\begin{bmatrix} \n1' \text{ us } R \text{ e3} \\
1' \text{ us } R \n\end{bmatrix}$ for decay constants, form factors, and radiative corrections, are $\sqrt{1 + \epsilon^2}$ 19 ϵ *Vus* = 0.23108(23)exp(42)*FK*/*F*⇡ (16)IB[51]total, $V_{\rm g}$ ² $V_{\rm g}$ ² $(1-2\epsilon_{\rm p}^{(s)})$ ^{$(1-2\epsilon_{\rm p}^{(s)})$} where the errors refer to experiment, lattice input for the matrix \mathcal{N}_{max} $\sum_{i=1}^n a_i$ $|V_{ud}|_{\pi_{u2}}^2 = |V_{ud}|^2 |1 - 2\epsilon_R|$ situation depicted in Fig. 1: one hand, the one hand, Test \int_1^2 \int_1^2 $\sum_{i=1}^{n}$ $\sqrt{2}$ (1 \sum s^2 (1)

the *K*`² and *K*`³ constraints intersect away from the unitarity ements from vector (axial) channels **a** $\mathbf v$ uq and $\mathbf v$ us onnu mi

• CKM elements from vector (axial) channels are shifted by $1 + \varepsilon_R$ (1- ε_R). V_{us}/V_{ud} , V_{ud} and V_{us} shift in anti-correlated way, can resolve all tensions! bands correspond to *V*0+!0⁺ *ud* (leftmost, red) and *^V*n, best *ud* (rightmost, violet). The e shifted by $I + \varepsilon_R$ ($I - \varepsilon_R$). sponds to (*Vus*/*Vud*)*K*`2/⇡`² . The unitarity circle is denoted by the black solid line. The 68% C.L. ellipse from a fit to all four constraints is depicted in yellow (*Vud* = 0.97378(26), *Vus* = 0.22422(36), 2/dof = 6.4/2, *p*-value 4.1%), P $(R - E_R)$.

ity in the correlation of the correlation of the correlation with di-density in the correlation with di-density
In the correlation with di-density in the correlation with di-density in the correlation with di-density in th

Unveiling R-handed quark currents? In general, a single parameter is not sucient to explain both mvelling K-nanded quark cur ators, and we therefore introduce two parameters ✏*R*, ✏ *^R* (or ments in Eq. (8) as extracted from the (vector-current mediated) **UNVEITING K-Handed quark curt** the α -particle decays by α -particle decays by 1 , α re- α re- α re- α re- α re- α 111] and leptons [112, 113], as modifications of the Fermi convening K-nanded quark slope (green) correspond to (3) t_{1} ones the opposite case (13). Note that in each case the three bands essentially ho T_r

CKM introduced in Eq. (8).

sectors, respectively. We are the CKM electronic at first order in \mathcal{R} the CKM electronic at first order in \mathcal{R}

numbers change to

✏*^R* ⁼ 0.67(27) ⇥ ¹⁰³ [2.5], ✏*^R* ⁼ 1.8(1.6) ⇥ ¹⁰³ [1.1], (12) low the current one would give ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13) This shows that the proposed measurement would have a significant would CKM as observed in Table 1. impact of the proposed new measurement of the *K*µ3/*K*µ² branching fraction

$$
\Delta_{CKM}^{(1)} = |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell3}}|^2 - 1
$$

= -1.76(56) × 10⁻³

$$
\Delta_{CKM}^{(2)} = |V_{ud}^{\beta}|^2 + |V_{us}^{K_{\ell2}/\pi_{\ell2}, \beta}|^2 - 1
$$

= -0.98(58) × 10⁻³

$$
\Delta_{CKM}^{(3)} = |V_{ud}^{K_{\ell2}/\pi_{\ell2}, K_{\ell3}|^2 + |V_{us}^{K_{\ell3}}|^2 - 1
$$

= -1.64(63) × 10⁻²

^R (or

Test

Test

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CKM introduced in Eq. (8).

sectors, respectively. We are the CKM electronic at first order in \mathcal{R} the CKM electronic at first order in \mathcal{R}

✏*^R* ⁼ 0.67(27) ⇥ ¹⁰³ [2.5], ✏*^R* ⁼ 1.8(1.6) ⇥ ¹⁰³ [1.1], (12) V^2) *R* $\frac{1}{2}$ a conclusion whether or not further or not low the current one would give ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13) CKM as observed in Table 1. less constraining and are not reported in Fig. 2. In particular, ✏*^R* │
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│
│ The corresponding corresponding constraints are shown in Fig. 2 and point α and point α and point α CKM, while ✏*^R* is obtained With a projection of the *K*
2008 branching ratio ratio
2008 branching ratio r

numbers change to

 \overline{a} **R** ~ 5-10 Te $\overline{}$ $\overline{}$ $\Lambda_{\rm R}$ ~ 5-10 TeV

$$
\Delta_{CKM}^{(1)} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(2)} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(3)} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)
$$

\n
$$
\epsilon_R = -0.69(27) \times 10^{-3}
$$

\n
$$
\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}
$$

Unveiling R-handed quark currents? In general, a single parameter is not sucient to explain both mvelling K-nanded quark cur ators, and we therefore introduce two parameters ✏*R*, ✏ *^R* (or ments in Eq. (8) as extracted from the (vector-current mediated) **UNVEITING K-Handed quark curt** the α -particle decays by α -particle decays by 1 , α re- α re- α re- α re- α re- α 111] and leptons [112, 113], as modifications of the Fermi convening K-nanded quark slope (green) correspond to (3) t_{1} ones the opposite case (13). Note that in each case the three bands essentially three-particle decays are contained by $1 + \frac{1}{2}$, the ones from $1 + \frac{1}{2}$ $\frac{1}{2}$ $\$ nded quark currents? sulting in $\frac{1}{2}$ 1 quark currents:

from the combination

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In the correlation with di-density in the correlation with di-density in the correlation with di-density in th

to quantify right-handed currents in the non-strange and strange and strange and strange and strange and stran
The non-strange and strange and strang

CKM introduced in Eq. (8).

sectors, respectively. We are the CKM electronic at first order in \mathcal{R} the CKM electronic at first order in \mathcal{R}

$\frac{1}{\sqrt{2}}$ $\Delta_{CKM}^2 = 2\epsilon$ $\Delta_{\rm CKM}^{(2)}$ + $\Delta_{\rm CKM}^{(3)}$ + $\Delta_{\rm CKM}$ $\Delta_{CKM} = 2\epsilon$ $\Delta_{\rm CKM}^{(1)}$ (2) CKM ⁼ ²✏*^R* ²✏*RV*² 0.005 0.010 $\epsilon_p \equiv \epsilon_p^{(S)} - \epsilon_p$ to non-zero values for both ✏*^R* and ✏*R*. ✏*^R* can be isolated by Figure 2: Constraints in the ✏*R*–✏*^R* plane from the (*i*) CKM introduced in Eq. (8). $T_{\rm max}$ CKM. The bands with small 10.0010 correspond to (1) Δ_{CK} CKM $\left\{1, \ldots, 1, \ldots, 2, \ldots \right\}$ $-0.010 - 0.005 - 0.000 - 0.005 - 0.005$ overlap by construction, since *Vud*, *Vus*, subject to the unitarity constraint, and $\Delta \epsilon_R \equiv \epsilon_R^{(S)} - \epsilon_R$ $\overline{1}$ CKM ⁼ ²✏*^R* ⁺ ²✏*RV*² (3) CKM = 2✏*^R* + 2✏*^R* $\Lambda^{(1)}$ to non-zero values for both $\begin{bmatrix} 1 \end{bmatrix}$ Δ CKM CKM and (2) -0.005 0.000 *r* ⌘ the impact of our proposed in particular control in the control of our proposed in the con-

C (2) $\Lambda^{(2)}$ Δ_{CKM} and $\Delta_{CKM}^{(3)}$ between *K*`² and *K*`3. This discussion becomes most transpar- $\begin{bmatrix} \mathfrak{S} \ \mathfrak{v} \end{bmatrix}$ -0.0010 $\Delta_{CEM}^{(1)}$ $\bigwedge^{(3)}$ $\begin{bmatrix} -0.0015 \end{bmatrix}$ -0.010 -0.005 0.000 0.005 0.010 (*s*) $\frac{f(S)}{R} - \epsilon_R$ **VC-Crivellin-Hoferichter-Moulson 2208.11707 Son 2208.11707** Δ \triangle CKN *CKM* ⁼ *[|]^V ^K*`2*/*⇡`2*, K*`³ ⁼ 1*.*64(63) ⇥ ¹⁰² VC -Crivellin-Hoferichter-Moulson 2208.11707 $\Omega.0000$ function revealing Δ $\Delta_{\rm CKM}^{(2)}$ non-value of anishing value of \overline{R} is mainly decay of \overline{R} \mathcal{L} $\Delta_{CKM}^{(1)}$ $\Delta_{CKM}^{(3)}$ the sensitivity of R to the diagram of R -0.010 $\begin{matrix} 10 & -0.005 & 0.000 & 0.005 \end{matrix}$ $\Delta \epsilon_R \equiv \epsilon_R^{(S)} - \epsilon_R$

✏*^R* ⁼ 0.67(27) ⇥ ¹⁰³ [2.5], ✏*^R* ⁼ 1.8(1.6) ⇥ ¹⁰³ [1.1], (12) V^2) *R* $\frac{1}{2}$ a conclusion whether or not further or not $\frac{a_4}{a_1}$ $2.0 \pm 0.0 / 0$ low the current one would give ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13) CKM as observed in Table 1. We note here that other probes of ✏*^R* and ✏*^R* are currently less constraining and are not reported in Fig. 2. In particular, ✏*^R* $m = 0.6$ [\]\, 0.2(1) │
│
│
│ α ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], The corresponding corresponding constraints are shown in Fig. 2 and point α and point α and point α CKM, while ✏*^R* is obtained With a projection of the *K*
2008 branching ratio ratio
2008 branching ratio r $\overline{a_A}$

CKM and (2)

CKM

Vud

K`2/⇡`²

numbers change to

 \overline{a} **R** ~ 5-10 Te $\overline{}$ $\overline{}$ $\Lambda_{\rm R}$ ~ 5-10 TeV *CKM* ⁼ *[|]^V ^K*`2*/*⇡`2*, K*`³ *ud |* ² ⁺ *[|]^V ^K*`³ $7R \sim 3 - 10$ iev

$$
\frac{\lambda^{\exp}}{\lambda^{\text{QCD}}} = 1 + \delta_{\text{RC}} - 2\epsilon_R
$$

VK`³ *us*

> \overline{a} \overline{a}

 $\frac{1}{2}$ $(1, 2)$ $\%$ FLAG 1 = (2*.*⁴ *[±]* ²*.*2)%

$$
\Delta_{CKM}^{(1)}
$$
\n
$$
\Delta_{CKM}^{(2)}
$$
\n
$$
-0.0006
$$
\n
$$
\Delta_{CKM}^{(2)}
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-0.0016
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\Delta_{CKM}^{(3)}
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\Delta_{CKM}^{(1)}
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\Delta_{CKM}^{(3)}
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\Delta_{CKM}^{(3)}
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$$
\epsilon_R = -0.69(27) \times 10^{-3}
$$
\n
$$
\Delta \epsilon_R = -3.9(1.6) \times 10^{-3}
$$

$$
\lambda = \frac{g_A}{g_V}
$$

 $\lambda = \frac{g_A}{g_V}$
\n $\delta_{RC} \simeq (2.0 \pm 0.6)\%$

Unveiling R-handed quark currents? In general, a single parameter is not sucient to explain both mvelling K-nanded quark cur ators, and we therefore introduce two parameters ✏*R*, ✏ *^R* (or ments in Eq. (8) as extracted from the (vector-current mediated) **UNVEITING K-Handed quark curt** the α -particle decays by α -particle decays by 1 , α re- α re- α re- α re- α re- α 111] and leptons [112, 113], as modifications of the Fermi convening K-nanded quark slope (green) correspond to (3) t_{1} ones the opposite case (13). Note that in each case the three bands essentially three-particle decays are contained by $1 + \frac{1}{2}$, the ones from $1 + \frac{1}{2}$ $\frac{1}{2}$ $\$ nded quark currents? sulting in $\frac{1}{2}$ ng K-nanded quark currents: *R* **Unveiling R-handed** ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13)

r ⌘ r. VC, Hayen, deVries, Mereghetti, Walker-Loud, VC, Hayen, deVries, Mereghetti, Walker-Loud, $\epsilon_R \, = \, -0.2(1.2)\%$ VC, Hayen, deVries, Mereghetti, Walker-Loud, $\epsilon_R = -0.2(1.2)\%$ 2202.10439 **2202.10439**

r ⌘

from the combination

Test

less constraining and are not reported in Fig. 2. In particular, ✏*^R*

 t atain the average of \overline{t} ges are not in o Preferred ranges are not in $\frac{1}{2}$ + $\frac{1}{2}$ $\text{Int } \beta$ decays λ^{QCD} • Preferred ranges are not in λ^{exp} conflict with other
constraints from R decays $\sqrt{\lambda^{QCD}} = 1 + \theta_{\rm RC} - 2\epsilon_R$ three-particle decays are contaminated by 1 + ✏, the ones from conflict with other $\frac{1}{\sqrt{\rm QCD}} = 1 + \delta_{\rm RC} - 2\delta$ constraints from β decays constraints from p decays

ity in the correlation of the correlation of the correlation with di-density in the correlation with di-density
In the correlation with di-density in the correlation with di-density in the correlation with di-density in th

 $\overline{\mathsf{sm}}$ $\begin{array}{ccc}\n\blacksquare & \blacksquare & \blacksquare & \blacksquare\n\end{array}$ **BBB** \rightarrow TT $\overline{1}$ $\overline{2}$ 1
1
1 ϵ $(\lambda$ *Vud K*`2/⇡`² *VK*`³ • V_{ud} extracted from $\Gamma(\Pi^{\pm} \to \Pi^{0} e^{\pm} V(Y))$, neutron decay, and $0^{+} \to 0^{+}$ should be the same numbers change to the change of the chan
The change of the change o \mathbf{R} and \mathbf{R} and \mathbf{R} and \mathbf{R} are \mathbf{R}

Unveiling R-handed quark currents? In general, a single parameter is not sucient to explain both mvelling K-nanded quark cur ators, and we therefore introduce two parameters ✏*R*, ✏ *^R* (or ments in Eq. (8) as extracted from the (vector-current mediated) **UNVEITING K-Handed quark curt** the α -particle decays by α -particle decays by 1 , α re- α re- α re- α re- α re- α 111] and leptons [112, 113], as modifications of the Fermi convening K-nanded quark slope (green) correspond to (3) nded quark currents? ones the opposite case (13). Note that in each case the three bands essentially three-particle decays are contained by $1 + \frac{1}{2}$, the ones from $1 + \frac{1}{2}$ $\frac{1}{2}$ $\$ sulting in $\frac{1}{2}$ 1 quark currents:

CKM introduced in Eq. (8).

sectors, respectively. We are the CKM electronic at first order in \mathcal{R} the CKM electronic at first order in \mathcal{R}

✏*^R* ⁼ 0.67(27) ⇥ ¹⁰³ [2.5], ✏*^R* ⁼ 1.8(1.6) ⇥ ¹⁰³ [1.1], (12) V^2) *R* $\frac{1}{2}$ less constraining and are not reported in Fig. 2. In particular, ✏*^R* low the current one would give ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13) CKM as observed in Table 1. less constraining and are not reported in Fig. 2. In particular, ✏*^R* lattice QCD [28, 127, 128], up to a recently uncovered electro-The corresponding corresponding constraints are shown in Fig. 2 and point α and point α and point α CKM, while ✏*^R* is obtained With a projection of the *K*
2008 branching ratio ratio
2008 branching ratio r at 0.2 above the current measurement, the current measurement, the above the ab

numbers change to

us r ⌘ e
J1 ion impli

$$
\Delta_{CKM}^{(1)} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(2)} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(3)} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)
$$

\n
$$
\epsilon_R = -0.69(27) \times 10^{-3}
$$

\n
$$
\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}
$$

\n
$$
\Delta\epsilon_R \sim 5 \text{ - } 10 \text{ TeV}
$$

 $\overline{}$

- $\frac{1}{2}$ Ers neip taisity this so thus concerns a concerns a concerns a concerns a corresponding to the corresponding ϵ this scenario? This RH solut $\frac{1}{2}$ + $\frac{1$ hic s • Can PIONEER help falsify this scenario? This RH solution im • Can PIONEER help falsify this scenario? This RH solution implies
	- nded qua

from the combination

 \overline{a} $Per order in (v/\Lambda)$ Impact on \mathbb{R}_μ ⁽¹⁹). The N-nanded quark couplings are LFO up to higher order in (8/7) • No impact on R_{e/μ}^(π): the R-handed quark couplings are LFU up to higher order in (v/Λ)

ity in the correlation of the correlation of the correlation with di-density in the correlation with di-density
In the correlation with di-density in the correlation with di-density in the correlation with di-density in th

CKM introduced in Eq. (8).

sectors, respectively. We are the CKM electronic at first order in \mathcal{R} the CKM electronic at first order in \mathcal{R}

✏*^R* ⁼ 0.67(27) ⇥ ¹⁰³ [2.5], ✏*^R* ⁼ 1.8(1.6) ⇥ ¹⁰³ [1.1], (12) V^2) *R* $\frac{1}{2}$ \blacksquare low the current one would give ✏*^R* ⁼ 0.70(27) ⇥ ¹⁰³ [2.6], ✏*^R* ⁼ 5.7(1.6) ⇥ ¹⁰³ [3.5]. (13) CKM as observed in Table 1. magnetic correction [129]. This results in ✏*^R* = 0.2(1.2)%. The corresponding corresponding constraints are shown in Fig. 2 and point α and point α and point α CKM, while ✏*^R* is obtained With a projection of the *K*
2008 branching ratio ratio
2008 branching ratio r

numbers change to

were realized. Using current input from Eqs. (5) and (7), one obtains: • Does the R-handed current explanation survive after taking i

gh energy data? high energy data? low the current one would give $\overline{}$ *ud* • Does the R-handed current explanation survive after taking into account high energy data?

$$
\Delta_{CKM}^{(1)} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(2)} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,
$$

\n
$$
\Delta_{CKM}^{(3)} = 2\epsilon_R + 2\Delta\epsilon_R (2 - V_{us}^2)
$$

\n
$$
\epsilon_R = -0.69(27) \times 10^{-3}
$$

\n
$$
\Delta\epsilon_R = -3.9(1.6) \times 10^{-3}
$$

\n
$$
\Delta_R \sim 5-10 \text{ TeV}
$$

Unveiling R-handed quark currents? In general, a single parameter is not sucient to explain both mvelling K-nanded quark cur ators, and we therefore introduce two parameters ✏*R*, ✏ *^R* (or ments in Eq. (8) as extracted from the (vector-current mediated) **UNVEITING K-Handed quark curt** the α -particle decays by α -particle decays by 1 , α re- α re- α re- α re- α re- α 111] and leptons [112, 113], as modifications of the Fermi convening K-nanded quark slope (green) correspond to (3) t_{1} ones the opposite case (13). Note that in each case the three bands essentially three-particle decays are contained by $1 + \frac{1}{2}$, the ones from $1 + \frac{1}{2}$ $\frac{1}{2}$ $\$ nded quark currents? sulting in $\frac{1}{2}$ 1 quark currents:

from the combination

High scale origin of ε^R $\mathbf{H} = \mathbf{H} + \mathbf{H}$ ale of Bill of al H igh scale origin of \mathcal{E}_R QeW (ο lpdn) (ο lpdn)
| lpdn (ο lpdn) (ο \mathbf{u} g (September 1911) de la componentación de la
História CK
Here and the set of th

 $\mathcal{L}(\mathcal{$

de Barcelona (d. 1982)
1905 - Paris Carolina (d. 1992)
1916 - Paris Carolina (d. 1992)

 R UIRTRES TON SU(2) originates from $SU(2) \times U(1)$ invariant vertex correct Urginates in Unit SU(Z)XU(T) litvariant vertex currection • ER originates from SU(2)xU(1) invariant vertex corrections

 $\overline{}$

CG f ABCGAVE

4 : X2H2

QHG H†H G^A

Q(3)

Hl (H†i

 $\mathcal{L}(\mathcal{$

 $\overline{}$

←→D ^I

re generated by W_L-W_R mixing in Left-Right symmetric models or by exchange of

 $\overline{}$

motric modo \ldots or \ldots \ldots \ldots \ldots \overline{a} Qed (¯epγµer)(¯ dsγµdt) $\overline{}$ \sim QHW B " H†τ ^IH W "I µνBµ^ν QdB (¯qpσµ^ν dr)H Bµ^ν ^QHud + h.c. ⁱ(H!†DµH)(¯upγµdr) be generated by WL-W_p mixing in Left-Right symmetric models, or by exchange of vector Δ by exchanger ϵ ctc • Can be generated by W_L-W_R mixing in Left-Right symmetric models or by exchange of vector-like quarks

 $\mathcal{L}(\mathcal{$

 \sim

QHG H†H G^A

 $\mathcal{H}(\mathcal{H})$

G (ABCG) f ABCG!

^QHG! ^H†^H ^G!^A

^µH)(¯lpτ ^Iγ^µlr)

 $\frac{1}{2}$: $\frac{1}{2}$: $\frac{1}{2}$: $\frac{1}{2}$: $\frac{1}{2}$: $\frac{1}{2}$: $\frac{1}{2}$

Current LHC results allow for to $\epsilon_R \sim 5\%$

Contributes to associated Higgs + W production at the LHC

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

Contribute tp $pp \rightarrow eV+X$ at the LHC

New contribution has same shape as the SM W exchange \rightarrow weak sensitivity

High Energy constraints on ε_R are weak

VC, Graesser, Gonzalez-Alonso 1210.4553 Alioli-Dekens-Girard-Mereghetti 1804.07407 Gupta et al. 1806.09006

…

An explicit model?

• Vector-like quarks:

$$
W, Z, Y \quad \text{WOM}
$$

Belfatto-Trifinopoulos 2302.14097

• It can not only fix the Cabibbo angle anomaly, but also the W-mass anomaly (CDF result ~70 larger than SM)

• Testable at the High Luminosity LHC and FCC

Conclusions & Outlook

- Rare pion decays enable stringent tests of the universality of weak interactions, probing new physics from very high scale as well as light and weakly coupled particles
- PIONEER will explore unconstrained parameter space in several models involving particles that are light and very weakly coupled: dedicated analyses?
- 10x improvement in R_{e/μ}(π) = $\Gamma(\pi \rightarrow eV(Y))$ / $\Gamma(\pi \rightarrow \mu V(Y))$ will probe very high effective scales, up to Λ_P ~ 30-1000 TeV and Λ_A ~ 30 TeV
- 3x improvement in $π_β$ can help diagnose BSM origin of the Cabibbo angle anomaly (CAA). A \sim 20 x improvement will provide V_{ud} with smallest theory uncertainty

Backup

Paths to V_{ud} and V_{us}

$$
V_{ud} \begin{array}{|c|c|c|c|} \hline 0^+ \rightarrow 0^+ & n \rightarrow pe\overline{v} & \pi \rightarrow \mu\nu \\ (\pi^+ \rightarrow \pi^0 e \nu) & \text{(Mirror transitions)} & \\ V_{us} & K \rightarrow \pi & V & (\Lambda \rightarrow pe\overline{v}, \dots) & K \rightarrow \mu\nu \end{array}
$$

mediating the decay $Quark current \longrightarrow \nabla$ $V, A \longrightarrow A$

(Hadronic τ decays)

V, A

Input from *many* experiments and *many* theory papers

Paths to V_{ud} and V_{us} s to V_{ud} and V_{us}

can be probed with high precision, from a combination, from a combination, from a combination, from a combination of

 $M_{\rm H}$, the first-row unitarity relation, the first-row unitarity relation, the first-row unitarity relation, α

Comment1: Modern approaches to rad. corr. build upon Sirlin current algebra formulation from the '60 & '70s New wave of "inner" radiative corrections (n, nuclei) initiated by dispersive analysis of Seng, Gorchtein, Patel, wave of the nuclear corrections (ii, nuclei) inteaces by dispersive analysis of serig, coreficent
Ramsey-Musolf 2018, all the way to very recent lattice QCD calculation by Ma et al, 2308.16755 Modern approaches to rad corr build upon Sirlin current algebra formulation from the '60 & '70s n oaches to rau. corr. bunu upon on inretural angebra formulation from th
adiative corrections (n nuclei) initiated by dispersive analysis of Seng Gor we as the neutron decay. A comparative review of the constraints review of the set *V*n, best

> *A A**A**C <i>COV) COV) COV) COV)* *****COV) COV) COV)* **COV) COV)** VMD is used and is assigned a generous 100% uncer-*us |* been adopted in Refs. [3, 12]. Keeping this additional nu-**Seng et al. 1812.03352** tainty. Performing the integration over *Q*² in (6) yields ⁼ 0*.*98(58) ⇥ ¹⁰³ clear uncertainty seems warranted also in view of concerns **Gorchtein 1812.04229 Hardy-Towner, PRC 2020**

See talk by Chien Yeah Sen Seng for status of other corrections

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

$$
V_{ud}^{\text{off}} = 0.97367(11)_{exp}(13)_{\Delta_V^R}(27)_{NS}[32]_{total}
$$

Paths to V _{ud} and V _{us}			
V_{ud}	$0^+ \rightarrow 0^+$	$n \rightarrow pe\overline{v}$	$\pi \rightarrow \mu\nu$
V_{us}	$K \rightarrow \pi \mid v$	$(\Lambda \rightarrow pe\overline{v}, \dots)$	$K \rightarrow \mu\nu$
n approaches to rad. corr. build upon Sirlin current algebra formulation from the '60			
er'' radiative corrections (n, nuclei) initiated by dispersive analysis of Seng, Gorchete			
off 2018, all the way to very recent lattice QCD calculation by Ma et al, 2308.1675.			
2984.432(3) s			

mation on the neutron lifetime ⌧*ⁿ* and, in addition, on the nucleon isovector axial charge = *gA*/*gV*, which at the relevant precision is extracted from experimental measurements of the asymmetry in polarized neutron decay. With current world where the first error arises from the property \mathbf{r} the phase factor $f(x)$ especially the value of carries an inflated uncertainty due to

Maerkish et al, 1812.04666 especially the value of \mathbf{M} and \mathbf{M} and \mathbf{M} and \mathbf{M} and \mathbf{M} and \mathbf{M} which is getting close to the sensitivity of superallowed the sensitivity of superallowed \sim 1812.04 \sim

Gonzalez et al, 2106.10375

 $\lambda - a$ imply more information than suggested by the global averages. $\lambda = \mathbf{g}_{\mathcal{A}}$ $\lambda = g_\mathcal{A}/g_V$

the experimental situation in the experimental situation in the kaon sector, especially in the fact that the global fit to kaon sector, especially in the global fit to kaon data as well as well as well as well as well as w point out that a measurement of the *K*^µ3/*K*^µ² branching fraction at the level of 0.2% would have considerable impact on clarifying *K*^µ² channel is currently dominated by a single experiment. Such a measurement, as possible for example at NA62, would further \blacksquare element. The master is matter for master for master for master for master \sim mation on the neutron lifetime ⌧*ⁿ* and, in addition, on the nu-

decay for the control of nuclear uncertainties but re-decay for nuclear uncertainties but re-decay for nuclear
This option is free of nuclear uncertainties but re-decay for the control of nuclear uncertainties but re-deca

V _{ud}	0^+	0^+	$n \rightarrow pe\overline{v}$
$(\pi^{\pm} \rightarrow \pi^0 e^{-\cdot})$	\dots		
V_{us}	$K \rightarrow \pi$	$W_{EIGHTED AVERAGE}$	

measurements Most precise

 $\int_{ud}^{n, \text{ best}} = 0.97413(3) f(13) \Delta_R(33) \lambda(20) \tau_n$ [43]total₁ - m

$$
V_{ud}^{n, PDG} = 0.97
$$
<sup>874–876–878–880–882–884–886–888

$$
V_{ud}^{n, best} = 0.97413(3)f(13)_{\Delta_R}(33)_{\lambda}(20)_{\tau_n}[43]_{\text{total}}
$$</sup>

Unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) ma-

trix [1, 2] has a long trix [1, 2] has a long trix [1, 2] has a precision as a precision test of the Standard
The Standard Control of the Standard Control of the Standard Control of the Standard Control of the Standard C

Model (SM). In particular, the first-row unitarity relation,

τn

Corrections to V_{ud} and V_{us}

• General case

 $\mathcal{E}_S^{(s)}$: shifts the slope of the scalar form factor, at levels well below EXP and TH uncertainties

$$
2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right) + c_{0^+}^S(Z) \epsilon_S^{ee}
$$
\n
$$
2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right) + c_n^S \epsilon_S^{ee} + c_n^T \epsilon_T^{ee}
$$
\n
$$
2\left(\epsilon_L^{ee(s)} + \epsilon_R^{(s)} - \epsilon_L^{(\mu)}\right)
$$
\n
$$
2\left(\epsilon_L^{ee} + \epsilon_R - \epsilon_L^{(\mu)}\right)
$$
\n
$$
2\left(\epsilon_L^{\mu\mu(s)} - \epsilon_R^{(s)} - \epsilon_L^{(\mu)}\right) - 2\frac{B_0}{m_\ell} \epsilon_P^{\mu\mu(s)}
$$
\n
$$
2\left(\epsilon_L^{\mu\mu} - \epsilon_R - \epsilon_L^{(\mu)}\right) - 2\frac{B_0}{m_\ell} \epsilon_P^{\mu\mu}
$$

 $\mathsf{E}\mathsf{T}^{(s)}$: suppressed by mlept/mk

Axion-like particles

- a- π^0 mixing induces the decay $\pi^+ \rightarrow$ aev
- Would affect E_{cal} distribution in PIENU and the γγ opening angle distribution in PIBETA

Altmanshofer-Gori-Robinson 1909.00005

