“Insights” on the Rare Pion Decay Program “Pioneer”

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A Homage To Alberto Sirlin (1930-2022)
"Pioneer" and Master of EW Radiative Corrections

Important original contributions to SM Renormalization, Phenomenology, Precision Measurements & "New Physics" searches including: Muon decay → G_F, Nuclear Beta Decays, V_{ud} W & Z Masses, Neutrino Scattering, Atomic physics, Tau decays … Rare Pion Decays…

Pioneer Experiment Goals (Test Lepton & CKM Universality)

1) $R_{e/\mu} = BR(\pi^+ \to e^+ \nu(\gamma))_{exp} / BR(\pi^+ \to \mu^+ \nu(\gamma))_{exp}$ *10-15 x improvement Phase I*
2) $BR(\pi^+ \to \pi^0 e^+ \nu(\gamma))_{exp} \to V_{ud}$ Pristine Theory (Unique). *3-10 x better! Phase II & III*

Popular Experimental Hints of New Physics

Anomalous Magnetic Moments $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM}$= 251(41)$_{exp}$(43)x10^{-11}$_{th}$ 4.2σ! e^+e^- data vs Lattice QCD 1.5σ?

$\Delta a_e = a_e^{exp} - a_e^{SM}$ = - 87(28)$_{exp}$(23)$_\alpha$(2)$_{th}$x10^{-14}

Δa_e (-2.4σ or +1.6σ) depends on α *from Cs vs Rb differ by 5.5 σ*

Recent Result:* *Fan, Myers, Sukra, Gabrielse improvement of* **a_e^{exp} *by factor of 2.2 agreement! with 2008 exp*

B→ $K^{(*)} l^+ l^-$ decays & Possible electron-muon universality breakdown 3σ?

* **CDF II m_W=80.433(9)GeV vs Global EW Fit (without M_W^{exp}) → m_W=80.359(3)GeV 7 sigma difference!!**

First Row CKM Unitarity Violation? (see C.-Y. Seng, Mod. Phys. Lett. (2022) for a recent review)

Current $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ = 0.9985(6)? ~2.5σ effect

V_{ud} = 0.97373(31) from beta decays (Nuclear Unc?)

V_{us} = 0.2243(5) from $K_{\mu 2}$ & K_{l3} ave.

V_{ub} ~ 4x10^{-3} negligible effect

Axial Current $|V_{us}|/|V_{ud}|$= 0.23131(51) from $K_{\mu 2}/\pi_{\mu 2}$ + unitarity → V_{ud} = 0.97428(11) V_{us}=0.22536(47)

Vector Current $|V_{us}|/|V_{ud}|$= 0.22910(77) from K_{l3}/π_{e3} +unitarity → V_{ud} = 0.97475(17) V_{us}=0.22331(72)

2.4σ *difference*

ACK TO ARTICLE

High-precision measurement of the W boson mass with the CDF II detector
Fig. 5

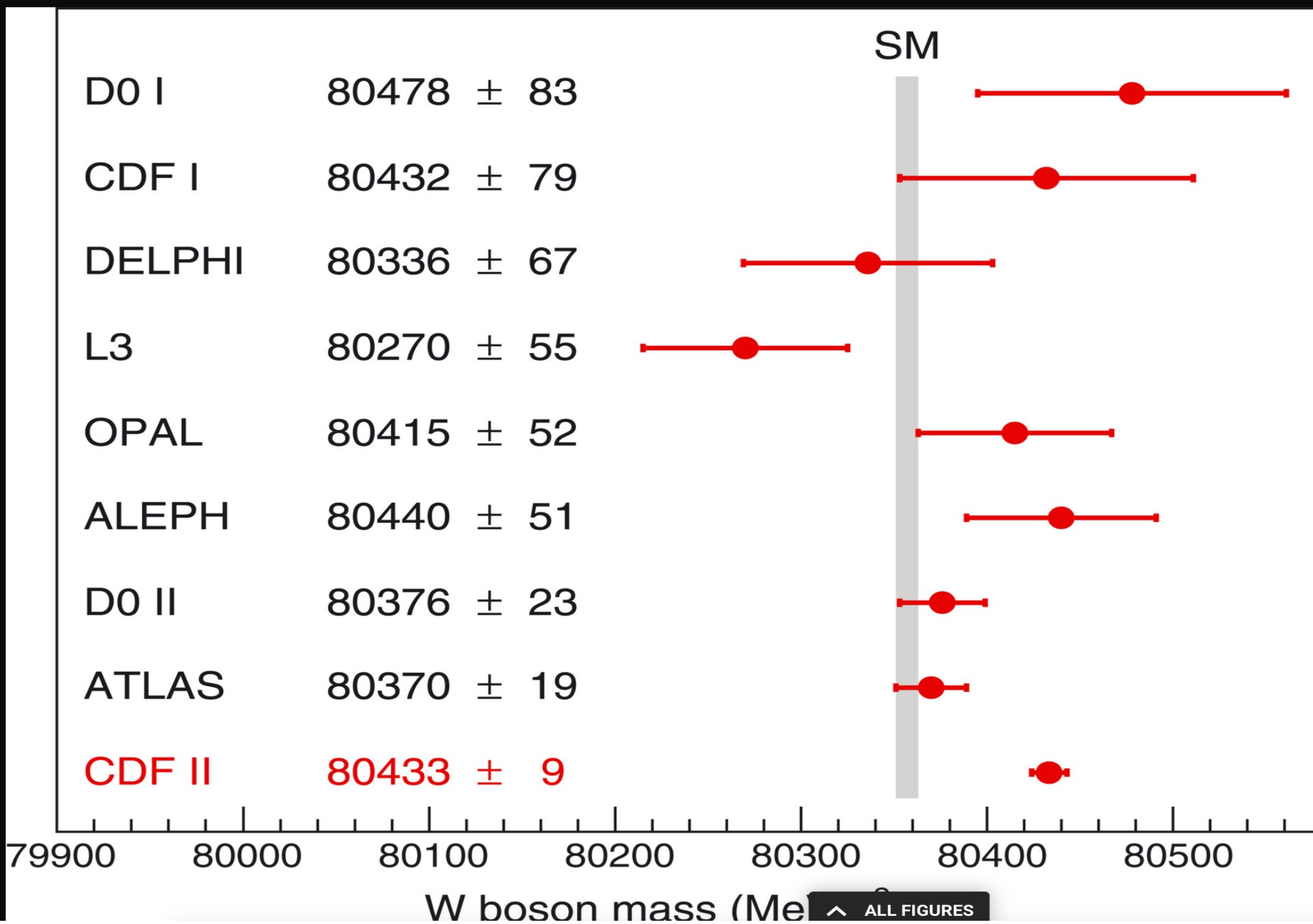

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Fig. 5.
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Radiative Inclusive Charged Pion Decays

(Current Status PDG 2022).

$$\Gamma(\pi \to l\bar{\nu}_l(\gamma)) = \frac{G_\mu^2 |V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2 [$$

- $BR(\pi^+ \to \mu^+ \nu(\gamma))_{\text{exp}} = 0.9998770(4)$

  Determines $|f_\pi V_{ud}|$=127.13(0.02)(0.13)$_{RC}$MeV

  Lattice Flag Ave. f_π= 130.2(0.8)MeV → V_{ud} =0.9764(60)(2) not competitive by factor 20

  V_{ud}=0.9740(27) → **f_π= 130.5(0.4)MeV**

- $BR(\pi^+ \to e^+ \nu(\gamma))_{\text{exp}} = 1.2325(23)\text{x}10^{-4}$ *vs* $BR(\pi^+ \to e^+ \nu(\gamma))_{\text{SM}} = 1.2350(1)\text{x}10^{-4}$

  (Includes $BR(\pi^+ \to e^+ e^- e^+ \nu)_{\text{exp}} = 3.2(5)\text{x}10^{-9}$ part of radiative inclusive).

- $BR(\pi^+ \to \pi^0 e^+ \nu(\gamma))_{\text{exp}}$ =$1.036(6)\text{x}10^{-8}$ ***PIBETA Exp***. Determines $|f_+^\pi(0)V_{ud}|$=0.9740(27)

$f_+^\pi(0)=1-O(10^{-5})$ Behrends – Sirlin Theorem (1960)

make certain BRs are Radiative Inclusive!

$\pi^\pm$ **Lifetime : τ_π = 2.6033(5)x10^{-8}sec** **New Measurement Warranted?**

$$R_{e/\mu} = \Gamma(\pi^+ \to e^+ \nu(\gamma))/\Gamma(\pi^+ \to \mu^+ \nu(\gamma))$$

Test of Electron-Muon Universality

1959) T. Kinoshita: QED radiative corrections reduce $R_{e/\mu}$
In a V-A theory by 3.9% for point-like pions
to 1.2326x10^{-4} (ignoring strong interactions)
for radiative inclusive decay rates.

$$R_0 = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28\times10^{-4},$$

Main effect $-3\frac{\alpha}{\pi}\ln(\frac{m_\mu}{m_e}) = -16\frac{\alpha}{\pi} = -3.72\%$

1976) WJM & A. Sirlin Theorem: Strong interaction effects on mass singularities ($\ln(M/m_l)$ *terms*) present in partial decay rates but *cancel for radiative inclusive decay rates* (*infrared safe*).

1993) WJM & A. Sirlin: Radiative Corrections to π_{l2} Decays (generic SM formula)

$$\Gamma(\pi\to l\bar{\nu}_l(\gamma)) = \frac{G_\mu^2|V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_l^2 \left(1-\frac{m_l^2}{m_\pi^2}\right)^2 \left[1+\frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\rho}\right)\right] \times\left[1-\frac{\alpha}{\pi}\left\{\frac{3}{2}\ln\left(\frac{m_\rho}{m_\pi}\right)+C_1+C_2\frac{m_l^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_l^2}+C_3\frac{m_l^2}{m_\rho^2}+\cdots\right\}\right]\left[1+\frac{\alpha}{\pi}F(x)\right],$$

+ Leading Logs Summation, C_2 calculated and expect C_1 to largely cancel in ratio, we used $C_3 = 0 \pm 10$ (*conservative*) $\to$ $R_{e/\mu} = \mathbf{1.2352(5)x10^{-4}}$ 1993 SM Prediction

2007 Cirigliano and Rosell evaluate $R_{e/\mu}$= 1.2352(1)x10^{-4} in SM using Chiral Pert. Theory. Small uncertainty (Pioneer uses $\pm 1.5x10^{-8}$). Could be slightly further improved using RGE to include NLO corrections.

First Row CKM Unitarity

A. Sirlin: (1973-1978) Standard Model Semi-Leptonic Radiative Corrections Finite & Calculable 2.32% $universal$ normalization using **G_μ=1.1663787(6)x10^{-5} GeV^{-2}** based on

τ_μ=2.1969803(22)x10^{-6}sec ***(today's value from MuLAN 2010)***

3 Generation CKM mixing via unitary matrix V_{CKM}

$|V^0_{ud}|^2+|V^0_{us}|^2+|V^0_{ub}|^2=1$ First Row Bare Natural Relation

EW Radiative Corrections Finite and calculable relative to τ_μ . **Different weak $U(1)_Y$ hypercharges lead to different RC.**

$(ud)_L\ Y=\frac{1}{3}\ and\ (\nu e)_L$ Y=-1 doublets → divergences become $\ln(m_Z/m_p)$ corrections

20 sigma quantum loop confirmation of SM radiative corrections!

SIRLIN'S UNIVERSAL Δ^V_R TO NUCLEAR & NEUTRON BETA DECAYS

Universal Δ^V_R = **$\alpha/2\pi[3\ln(m_Z/m_p)$+$\ln(m_Z/m_A)+2C+A_{QCD}$]**

$3\alpha/2\pi\ln(m_Z/m_p)$ short-distance ***not*** renormalized by strong int.

$[\alpha/2\pi[\ln(m_Z/m_A)+2C+A_{QCD}]$ Induced by axial-current loop

m_A=1.2GeV long/short distance matching scale

$C=0.8g_A(\mu_N+\mu_P)$=0.891 (long distance γW Box diagram)

A_{QCD}= $-\alpha_s/\pi(\ln(m_Z/m_A)$+cons)=-0.34 QCD Correction

$[\alpha/\pi\ln(m_Z/m)]^n$ leading logs summed via renormalization group $\simeq$+0.001

Next to leading short distance logs~-0.0001, small?

and $-\alpha^2\ln(m_p/m_e)$=-0.00043 estimated (for neutron decay)

Czarnecki, WJM, Sirlin (CMS)(2004)

2006 matching short and long distance γW (VA) Box Diagram 1+ **RC** =**1.0390(4) WJM &Sirlin**

*2018 **DR(dispersion Relation) give I+RC =1.0399(2)) Seng, Gorchtein, Patel, Ramsey-Musolf (PRL2018)**

Δ^V_R ➔ 0.02467(22) → V_{ud}=0.97370(14) $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2$=0.9985(5)

3 sigma tension with Unitarity! Quit while you are ahead.

Status of First Row CKM Unitarity (The Cabibbo Anomaly)

- **$|V_{ud}|$=0.97373(14)(27)$_{NS}$ Superallowed (15 Nucl. β Decays)** Hardy &Towner. Unitarity→ 0.9742
- $|V_{ud}|$ = 0.97330(30)$_{\tau n}$(30)$_{gA}$)(10)$_{RC}$ neutron PDG world ave.
- $|V_{ud}|$ = 0.97390(270)$_{exp}$(10)$_{th.}$ π_{e3} $\pi^+ \to \pi^0 e\nu(\gamma)$ Very Clean Theory $\pm$ 0.01% but BR $\sim 10^{-8}$!

- $|V_{us}|$ = 0.2243(6)$_{ave}$ 1.6 PDG Scale factor from average of K_{l3} → 0.2234(6) & $K_{\mu 2}$ →0.2252(6) tension

$|V_{ub}|$ = 4x10^{-3}. negligible effect on unitarity sum

$|V_{ud}|^2$+$|V_{us}|^2$ $|V_{ub}|^2$=0.9985(5) 3 sigma deviation (Cabibbo Anomaly)

- Recent shorter neutron lifetime and larger g_A favors larger V_{ud} + unitarity restored?

Current degree of Unitarity violation in the eye of the beholder.

PIONEER GOALS

Potential improvement of $\frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$, f_π, V_{ud} & $R_V \equiv \frac{\Gamma(K\to\pi e\nu(\gamma))}{\Gamma(\pi\to\pi^0 e\nu(\gamma))} \to \frac{Vus}{Vud}$

SM: $\mathbf{f_\pi} V_{ud} = 127.13(0.02)(0.13)_{RC}$MeV → $\mathbf{f_\pi}$= 130.49(13)MeV $\pm 0.1\%$ vs lattice130.2(8)MeV $\pm 0.6\%$

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

RC_π= 0.0332(3)

$\mathbb{I}_\pi$=7.376x10^{-8} phase space suppression

Combined with Kl3 decay rates leads to $R_V = V_{us}/V_{ud} = 0.22908(66)_\pi(41)_K(20)_{lat}(2)_{\tau\pi}(1)_{RC}$

Recall R_A -> $\frac{V_{us}}{V_{ud}}$**=0.23131(45) from** $\mathbf{K_{\mu 2}/\pi_{\mu 2}}$ **2.3 sigma difference currently**

$$R_A \equiv \frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} \text{ vs } R_V \equiv \frac{\Gamma(K\to\pi e\nu(\gamma))}{\Gamma(\pi\to\pi^0 e\nu(\gamma))}$$

Axial current CKM $\frac{V_{us}}{V_{ud}} = \mathbf{0.23131(45)}$.

Vector Current CKM $\frac{V_{us}}{V_{ud}}$ = $0.22908(66)_{\pi}(41)_{K}(20)_{lat}(2)_{\tau\pi}(1)_{RC}$

Reduction of pion beta decay by about a factor of 3 would make them comparable

Reduction by a factor of 10 would be unique V_{ud} determination

Current Difference: Lattice $f_+^K(0)$ problem?

Status of SM Charged Pion & Kaon Radiative Inclusive Decay Rates
& Future Improvements expected from the PIONEER Exp. at PSI

1) $BR(\pi \to \mu\nu(\gamma))_{exp}$ = 0.9998770(4) → $\Gamma(\pi \to \mu\nu(\gamma))$ = 2.5280(5)x10^{-14} MeV → $f_\pi|V_{ud}|$=127.13(1)$_{exp}$(17)$_{RC}$ MeV

$\pi^\pm$ Lifetime : τ_π = 2.6033(5)x10^{-8}sec

$\Gamma(K \to \mu\nu(\gamma))$ = 3.379(7)x10^{-14} MeV. → $f_K|V_{us}|$=35.09(4)$_{exp}$(4)$_{RC}$ MeV

Γ(all)=2.5284(5)x10^{-14} MeV (unc. $\pm 0.02\%$)

$R_A \equiv \frac{\Gamma(K\to\mu\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} \to \frac{V_{us}}{V_{ud}}$=0.23131(45)

τ_π Improvement by order of magnitude?

useful but not required

$\frac{f_K|Vus|}{f_\pi|Vud|}$ = 0.27602(29)$_{exp}$(24)$_{RC}$ + Lattice f_K/f_π = 1.1932(19) + unitarity & $|V_{ub}|^2 \approx 0$

V_{ud} =0.97426(10) V_{us}=0.22543(43) SM Prediction Deviation → "New Physics"

2) Electron Decay Mode: $\frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$=1.2352(1)x10^{-4} very precise (radiative inclusive) SM theory prediction. Universality Test

1.2327(28)x10^{-4} Exp. → Pioneer goal factor 10 -15 improvement

Constrains many examples of BSM new physics see (Bryman et al. Ann. Rev. N&P)

3) Pion Beta Decay: Current $BR(\pi \to \pi^0 e\nu(\gamma))_{exp}$ =1.038(6)x10^{-8} → V_{ud} =0.9740(28)$_{exp}$(1)$_{th}$ very clean precise theory

$$BR(\pi \to \pi^0 e\nu(\gamma)) = \frac{\Gamma(\pi\to\pi^0 e\nu(\gamma))}{1.00012327\,\Gamma(\pi\to\mu\nu(\gamma))} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} \times \frac{\Gamma(\pi\to\pi^0 e\nu(\gamma))}{\Gamma(\pi\to e\nu(\gamma)}\Big|_{exp}$$

$$R_V \equiv \frac{\Gamma(K\to\pi e\nu(\gamma))}{\Gamma(\pi\to\pi^0 e\nu(\gamma))} \to \frac{V_{us}}{V_{ud}} = 0.22908(66)_\pi(41)_K(20)_{Lat.}$$

$$\Gamma(\pi \to \pi^0 e\nu(\gamma)) = BR(\pi \to \pi^0 e\nu(\gamma))/\tau_\pi$$

Pioneer (Phase 2): factor of 3 improvement in $BR(\pi \to \pi^0 e\nu(\gamma))_{exp}$ + improvement in K_{l3} & Lattice → R_V factor 3 improvement

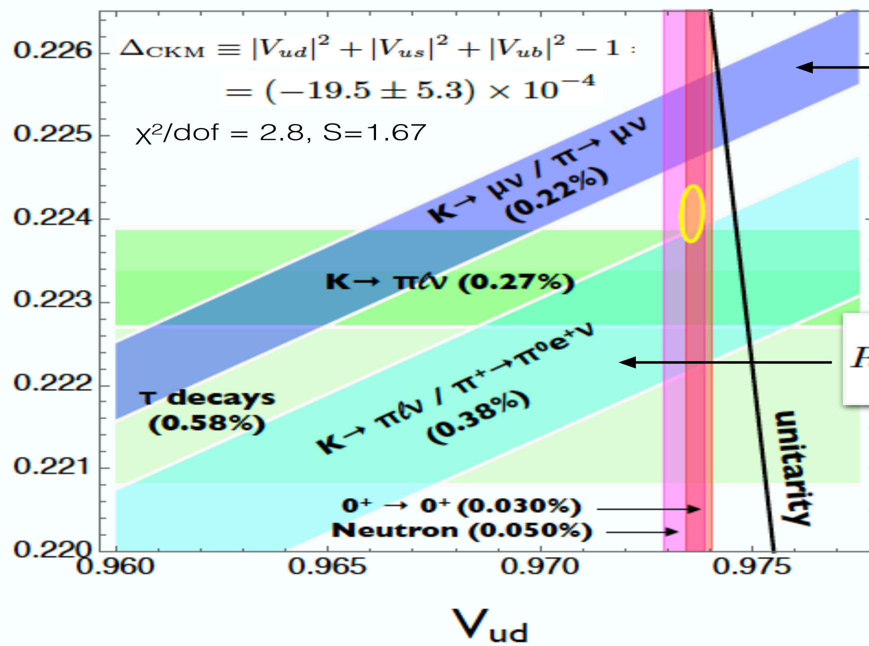
Pioneer (Phase 3) Overall factor 10 improvement? → Potentially best determination of V_{ud} but difficult systematics

Slide from V. Cirigliano's Pioneer talk

Cabibbo universality and BR($\pi^\pm \to \pi^0 e^\pm \nu(\gamma)$)

- Status of V_{ud} and V_{us} determinations: tension with SM hypothesis

Bryman, VC, Crivellin, Inguglia 2111.05338



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

Marciano, hep-ph/0402299

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

Czarnecki, Marciano, Sirlin 1911.04685

R_V is nearly competitive with R_A.

3x improvement in PIBETA BR, would lead to competitive V_{us}/V_{ud} @ 0.2%.

Realistic short term goal

Summary of Charged Pion Properties & PIONEER Goals

τ_π= 2.6033(5) x 10^{-8} sec. Known to $\pm 0.02\%$. Defines Potential Sensitivity Goals

3 (radiative inclusive) Decay Modes 2 Axial & 1 Vector Current Primary Amplitude

1) **$BR(\pi \to \mu\nu(\gamma))$ = 0.9998770(4)** $\Gamma(\pi \to \mu\nu(\gamma))$ = **2.5280(5)x10^{-14} MeV**

SM prediction = 1.5642(3)x10^{-18}/MeV x$|V_{ud} f_\pi|^2$

Lattice Flag Ave. f_π= 130.2(0.8) V_{ud} =0.9764(60)(2)

V_{ud}= 0.97373(30) $\to$ f_π= 130.56(4)

1st row unitarity & V_{us}/V_{ud}=0.23131(45) $\to$ V_{ud}=0.97426(10) $\to$ f_π =130.48(1)MeV

2) $\Gamma(\pi \to e\nu(\gamma))/\Gamma(\pi \to \mu\nu(\gamma))$=1.2352(1)x10^{-4} SM prediction

1.2327(28)x10^{-4} Current Experimental determination

3) $$BR(\pi \to \pi^0 e\nu(\gamma)) = \frac{\Gamma(\pi\to\pi^0 e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))} \times \frac{\Gamma(\pi\to\pi^0 e\nu(\gamma))}{\Gamma(\pi\to e\nu(\gamma))}\Big|_{exp}$$

$$R_V \equiv \frac{\Gamma(K\to\pi e\nu(\gamma))}{\Gamma(\pi\to\pi^0 e\nu(\gamma))} \to \frac{V_{us}}{V_{ud}} = 0.22908(66)_\pi(41)_K(20)_{Lat.}$$ Reduce π_{e3} & K_{l3} uncertainties

Pioneer: expect phase 2 factor of 3 improvement in $BR(\pi \to \pi^0 e\nu(\gamma))_{exp}$ & V_{ud}+ K_{l3}?, Lattice?$\to$ R_V

Phase 3 Long term goal: factor of 10 improvement in $BR(\pi \to \pi^0 e\nu(\gamma))$ & V_{ud}! Unique Capability