INDIANA UNIVERSITY
BLOOMINGTON

Jefferson Lab

Extraction of V_{us} from experimental measurements

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Outline :

1. Introduction and Motivation
2. V_{us} from K_{l3} decays
3. V_{us}/V_{ud} from $K_{\ell 2}/\pi_{\ell 2}$ decays
4. V_{us} and Unitarity of the CKM matrix
5. Conclusion and outlook

1. Introduction and Motivation

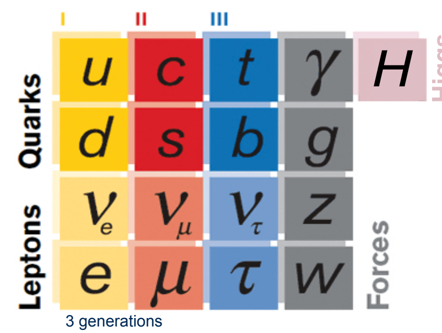
1.1 Test of the Standard Model: V_{us} and CKM unitarity

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

    Description of the weak interactions:

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

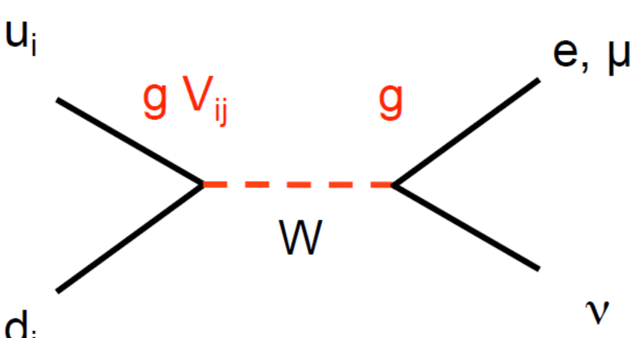
Unitary matrix



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

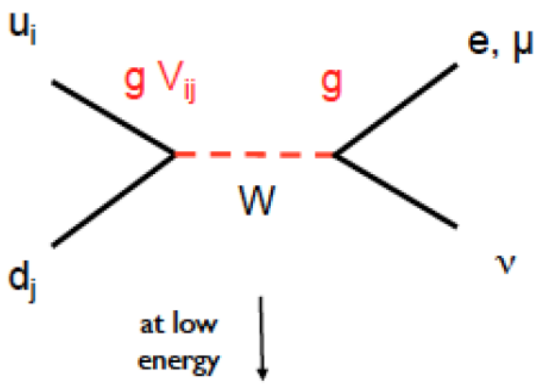
⇨ *Cabibbo Universality:* $\boxed{|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} \stackrel{?}{=} 1}$

Negligible ~2x10[-5] (B decays)



1.2 Constraining New Physics

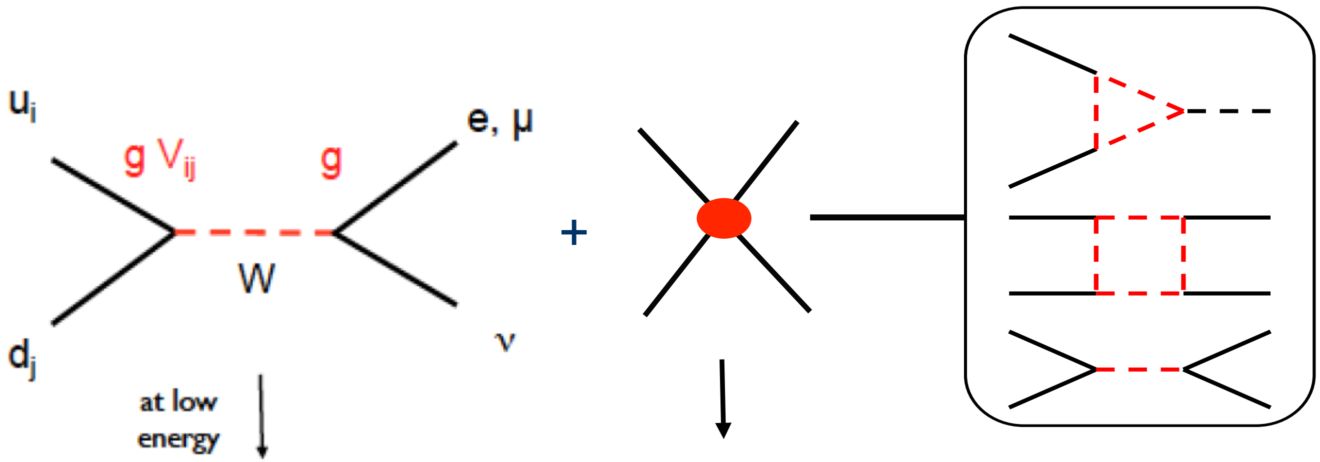
- In the SM, W exchange ⇒ V-A currents, universality



$$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$$

1.2 Constraining New Physics

- In the SM, W exchange ⇒ V-A currents, universality



SUSY, Z', Charged Higgs Leptoquarks…

$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$ $\qquad$ $1/\Lambda^2$

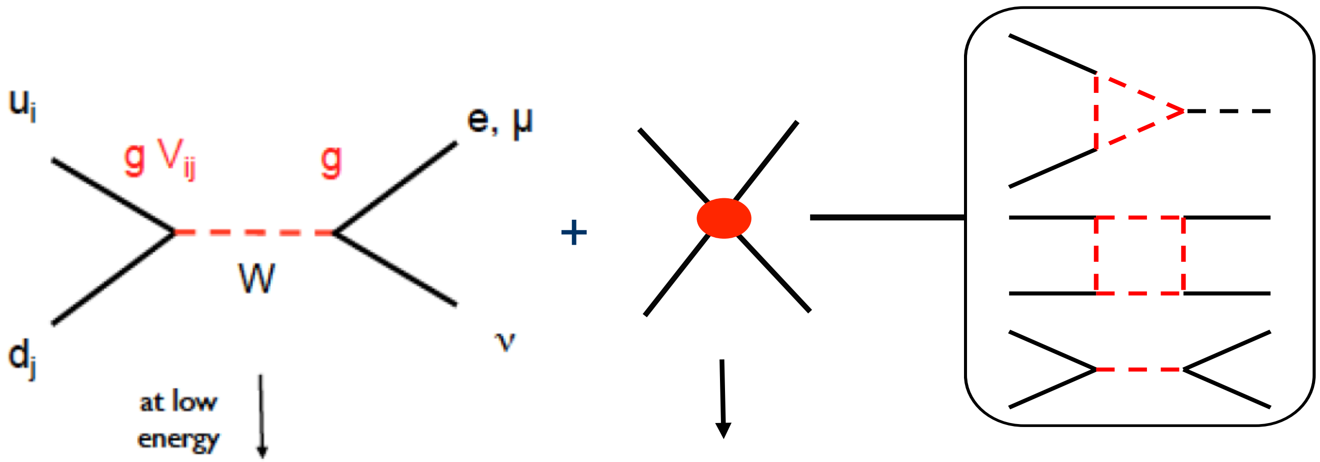
$$\boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}}$$

- Broad sensitivity to BSM scenarios :

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

1.2 Constraining New Physics

- In the SM, W exchange ⇒ V-A currents, universality



SUSY, Z', Charged Higgs Leptoquarks…

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

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

- Broad sensitivity to BSM scenarios :

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

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

1.3 Some history

- 2002 Old $K \to \pi l \nu_l$ data gave $\boxed{\Delta_{CKM} = 1 - |V_{ud}|^2 - |V_{us}|^2 = 0.0035(15)}$

  ⇨ PDG 2004: a 2.3σ hint of *unitarity violation*?

- 2003: BNL E865 measured: $BR\left(K^+ \to \pi^0 e^+ \nu_e\right) = 5.13(10)\%$

  ⇨ Value of V_{us} consistent with unitarity

- 2004 – present: Many new measurements from **KTeV**, **ISTRA+**, **KLOE**, **NA48**
  - BRs, lifetimes, form-factors
  - Much higher statistics than older measurements
  - Proper account of correlations between measurements

  ⇨ Isospin breaking, radiative corrections start to matter: computed within ChPT

- 2008 – beyond: Progress in the computation of hadronic elements from lattice QCD as well as isospin breaking and EM effects

1.4 Experiment, Theory & Evaluation

- V_{us} from K_{l3} & K_{l2}:
  - ~100 measurements of ~10 experimental parameters
  - 40+ lattice results for 2 hadronic matrix elements
  - Radiative and SU(2) breaking corrections computed using ChPT

FlaviA net Kaon WG
2006-2010 (EU 6FP)

Experimental averages, fits, etc
Selection of results (experiments, corrections)
Evaluation, discussion and intepretation

Final report: EPJC 69 (2010) 399

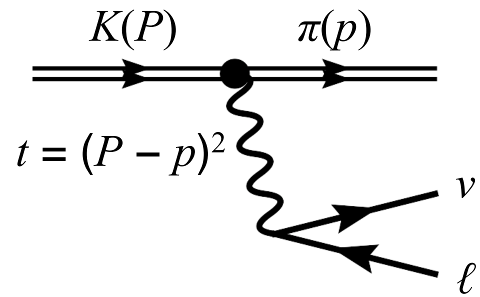
Here update based on
Moulson & Passemar@CKM'2018
Moulson@UMass, Amherst'2019

- Corresponding effort to synthesize results from lattice QCD: *Flavor Lattice Averaging Group (FLAG)*

FLAG Review 2019: **arXiv 1902.08191**

2. V_{us} from K_{l3} decays

2.1 V_{us} from K_{l3} : Master Formula



- Master formula for $K \to \pi l \nu_l$: $K = \{K^+, K^0\}$, $l=\{e,\mu\}$

$$\boxed{\Gamma\left(K \to \pi l \nu\left[\gamma\right]\right) = Br(K_{l3})/\tau = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}\left(1 + 2\Delta_{\mathrm{EM}}^{Kl} + 2\Delta_{\mathrm{SU(2)}}^{K\pi}\right)}$$

Experimental inputs:

$\Gamma\left(K_{l3}\right)$ Rates with well-determined treatment of radiative decays
- Branching ratios
- Kaon lifetimes

$I_{Kl}\left(\lambda_{Kl}\right)$ Integral of form factor over phase space: λs parametrize evolution in $t=q^2$

Inputs from theory:

S_{EW}^K Universal short distance EW corrections

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

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

$\Delta_{\mathrm{SU(2)}}^{K\pi}$ Form-factor correction for SU(2) breaking

2.2 Updates: $K^{\pm}$ BRs and lifetimes

KLOE-2
PLB 738 (2014)

BR($\pi^+\pi^+\pi^-$) = 0.05565(31)(25) (0.7%)

- **No good measurements of BR($\pi^+\pi^+\pi^-$) in 2010 fit**
- Reconstruct 2 tracks in small fiducial volume near interaction region; evaluate missing mass for 3rd track
- Fully inclusive of radiation, but radiative corrections handled differently from other KLOE measurements
- Significant impact on value of BR($\mu\nu$) from fit
  Correlation between BR($\mu\nu$), BR($\pi^+\pi^+\pi^-$) = −0.75

ISTRA+
PAN 77 (2014)

BR($K^-_{e3}/\pi^-\pi^0$) = 0.2423(15)(37) (1.6%)

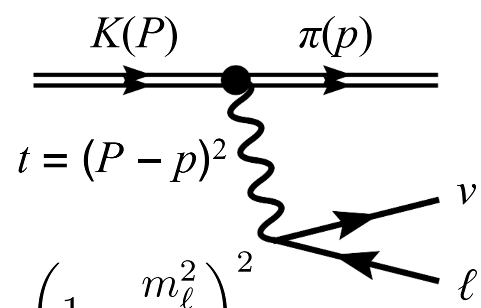
- Claimed to be fully inclusive for $K_{e3\gamma}$
  - No mention of radiative corrections
  - Many cuts, mainly topological
  - 3 different selections, at least 1 may be largely inclusive
- Included in PDG ’15 fit
- **Treated as preliminary here (not in $K^{\pm}$ BR fit)**

2.3 Updates on Phase Space Integrals

- Master formula for $K \to \pi l \nu_l$: $K = \{K^+, K^0\}$, $l=\{e,\mu\}$

$$\Gamma\left(K \to \pi l \nu[\gamma]\right) = \frac{Br(K_{l3})}{\tau} = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K |V_{us}|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 \boxed{I_{Kl}} \left(1 + 2\Delta_{\mathrm{EM}}^{Kl} + 2\Delta_{\mathrm{SU(2)}}^{K\pi}\right)$$

Hadronic matrix element:



$$\left\langle \pi^-(p) \right| \bar{s}\gamma_\mu u \left| K^0(P) \right\rangle = f_+^{K^0\pi^-}(0)\left[(P+p)_\mu \bar{f}_+^{K^0\pi^-}(t) + (P-p)_\mu \bar{f}_-^{K^0\pi^-}(t)\right]$$

- Phase space integrals: $$I_{K\ell} = \frac{2}{3}\int_{m_\ell^2}^{t_0} \frac{dt}{M_K^8}\,\bar{\lambda}^{3/2}\left(1+\frac{m_\ell^2}{2t}\right)\left(1-\frac{m_\ell^2}{2t}\right)^2 \times \left(\bar{f}_+^2(t) + \frac{3m_\ell^2\Delta_{K\pi}^2}{(2t+m_\ell^2)\bar{\lambda}}\bar{f}_0^2(t)\right),$$

- In K_{e3} decays: only vector FF $\bar{f}_+^{K^0\pi^-}(t)$

- In $K_{\mu3}$ decays, also need the scalar FF $$\boxed{\bar{f}_0(t) = \bar{f}_+(t) + \frac{t}{m_K^2 - m_\pi^2}\bar{f}_-(t)}$$

- For V_{us}, need integral over phase space of squared matrix element: Parameterize form factors and fit distributions in *t* (or related variables)

$K\pi$ form factor parametrizations

- Parametrizations based on Taylor expansion:

$$\bar{f}_{+,0}(t) = 1 + \lambda_{+,0}\left(\frac{t}{m_{\pi^\pm}^2}\right) \quad \text{or} \quad \bar{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m_{\pi^\pm}^2}\right) + \lambda''_{+,0}\left(\frac{t}{m_{\pi^\pm}^2}\right)^2$$

Very simple parametrization but limited in energy range and not physically motivated: many parameters and strong correlations between them

⇒ unstable fits

- Physically motivated parametrizations:
  – Pole parametrization

$$\bar{f}_{+,0}(t) = \left(\frac{M_{V,S}^2}{M_{V,S}^2 - t}\right)$$

Well motivated for the vector (K* resonance)
But for the scalar M_S?

  – Dispersive parametrization

Bernard, Oertel, E.P., Stern'06,'09

$$\bar{f}_{+}(t) = \exp\left[\frac{t}{m_\pi^2}\left(\Lambda_+ - H(t)\right)\right] \quad \text{and} \quad \bar{f}_{0}(t) = \exp\left[\frac{t}{m_K^2 - m_\pi^2}\left(\ln C - G(t)\right)\right]$$

Kπ scattering phase

$K_{\ell 3}$ form factor data

- Form-factor parameter measurements in FlaviaNet 2010 fit:

  K_L: KTeV, KLOE, NA48 (K_{e3} only)

  K^-: ISTRA+

- Even if not in the original publications, all experiments have:
  - Obtained results for Taylor, pole, and dispersive parameterizations
  - Supplied parameter correlation coefficients

New measurements:

NA48/2
JHEP 1810 (2018)

$2.3 \times 10^6\ K^{\pm}_{\mu 3}$
$4.4 \times 10^6\ K^{\pm}_{e3}$

Updating 2012 preliminary

K^+ and K^- simultaneously acquired in dedicated minimum-bias run

Taylor, pole, and dispersive fits with complete investigation of systematics

OKA
JETPL 107 (2018)

$5.25 \times 10^6\ K^{+}_{e3}$

Extraordinarily high precision claimed, esp. for λ_+', λ_+''

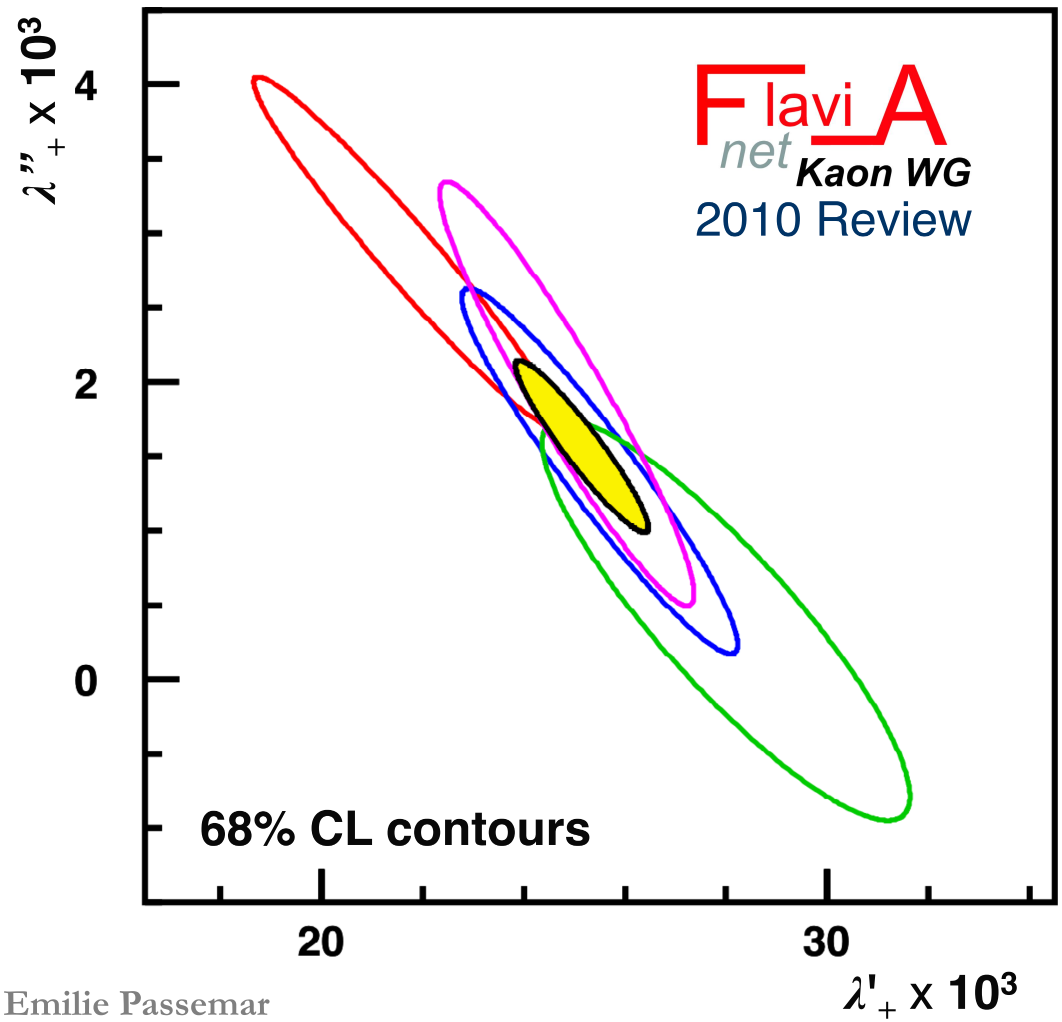
Rudimentary discussion of systematics

Not yet included in updated K_{e3} fit

See talk by *Gianluca Lamanna*

Fit to K_{e3} form-factor slopes: 2010

Slopes from KTeV KLOE ISTRA+ NA48 2010 fit



Slope parameters x 10^3

$$\lambda'_+ = \mathbf{25.15 \pm 0.87}$$

$$\lambda''_+ = \mathbf{1.57 \pm 0.38}$$

$$\rho(\lambda'_+, \lambda''_+) = -0.941$$

$$\chi^2/\text{ndf} = 5.3/6\ (51\%)$$

Excellent compatibility

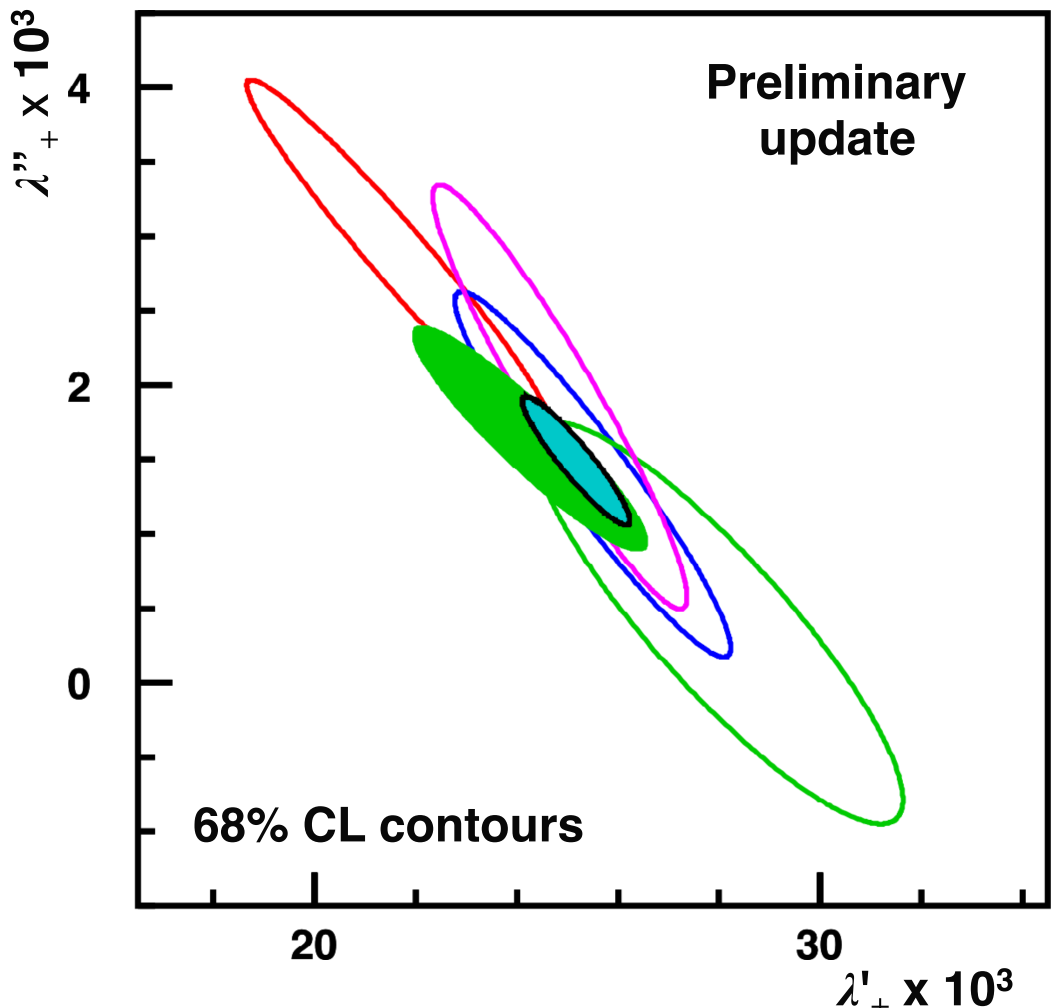
Significance of $\lambda''_+ > 4\sigma$

$I(K^0_{e3})$ = **0.15463(21)**

$I(K^+_{e3})$ = **0.15900(22)**

Fit to K_{e3} form-factor slopes: Update

Slopes from KTeV KLOE ISTRA+ NA48 NA48/2 Update



Slope parameters x 10^3

λ'_+ = **25.17 ± 0.70**

λ'_+ = **1.49 ± 0.29**

$\rho(\lambda'_+, \lambda''_+)$ = −0.929

χ^2/ndf = 6.4/10 (61%)

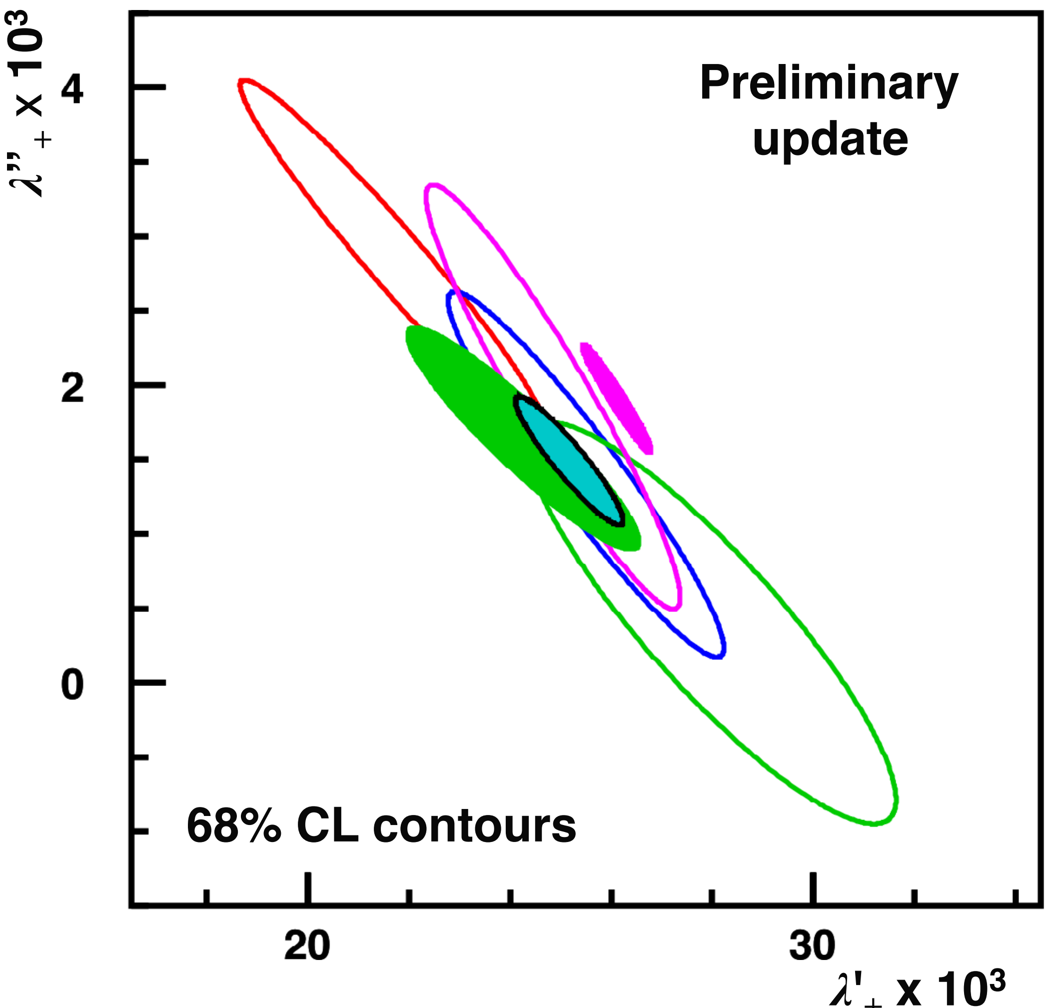
Excellent compatibility
Very small change in λ'_+

$I(K^0_{e3})$ = 0.15463(21)

$I(K^+_{e3})$ = 0.15900(22)

Fit to K_{e3} form-factor slopes: Update

Slopes from **KTeV** **KLOE** **ISTRA+** **NA48** **NA48/2** **Update**



Slope parameters x 10^3

$$\lambda'_+ = \mathbf{25.17 \pm 0.70}$$
$$\lambda'_+ = \mathbf{1.49 \pm 0.29}$$
$$\rho(\lambda'_+, \lambda''_+) = -0.929$$
$$\chi^2/\text{ndf} = 6.4/10\ (61\%)$$

OKA
JETPL 107 (2018)

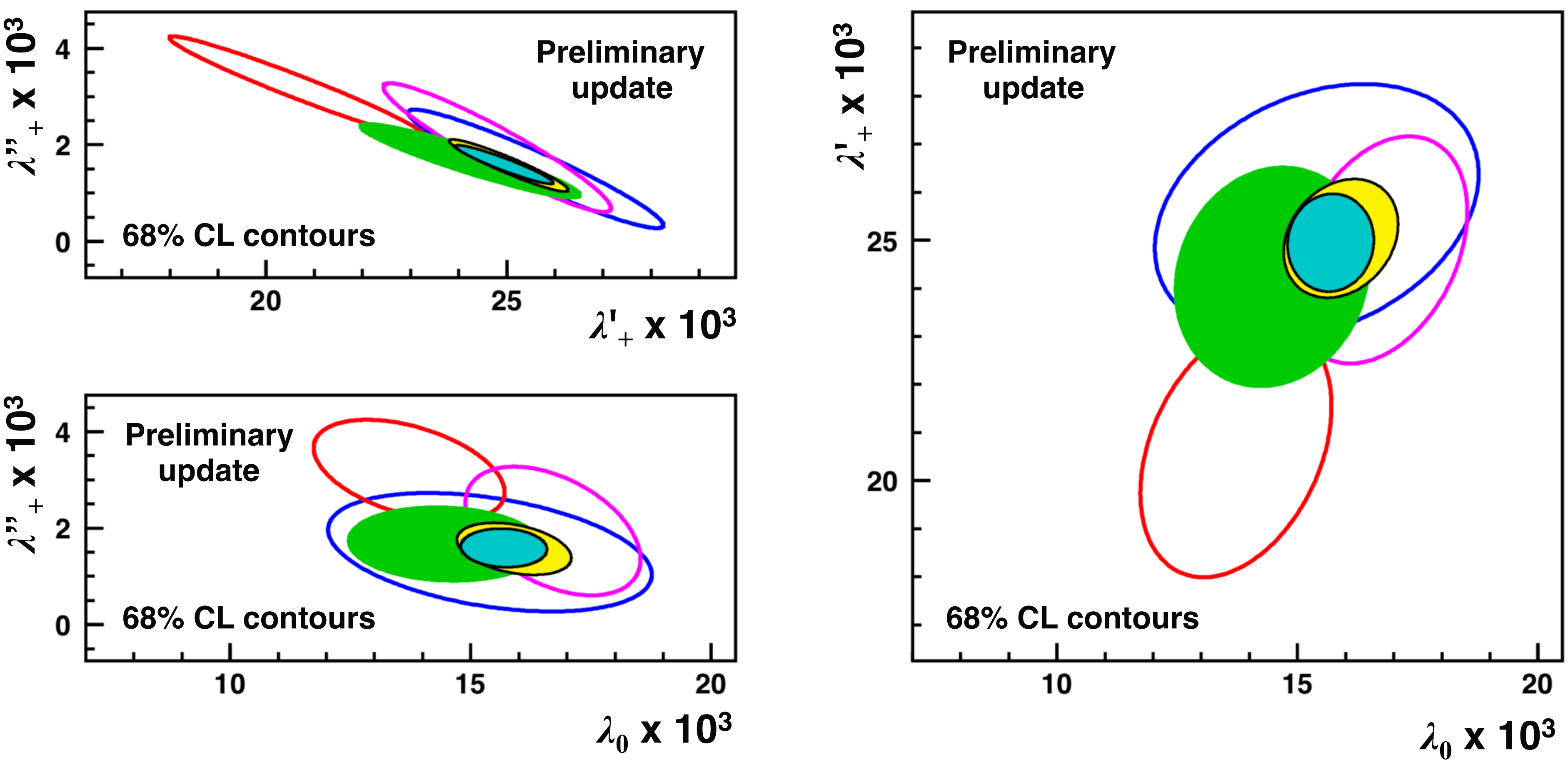
Not included in the fit

- If included: χ^2/ndf → 45/10 ($P \sim 10^{-6}$)

Fits to K_{e3} + $K_{\mu3}$ form-factor slopes: Update

KTeV | KLOE | ISTRA+ | NA48/2 2010 fit | Update

NA48 K_{e3} data included in fits but not shown



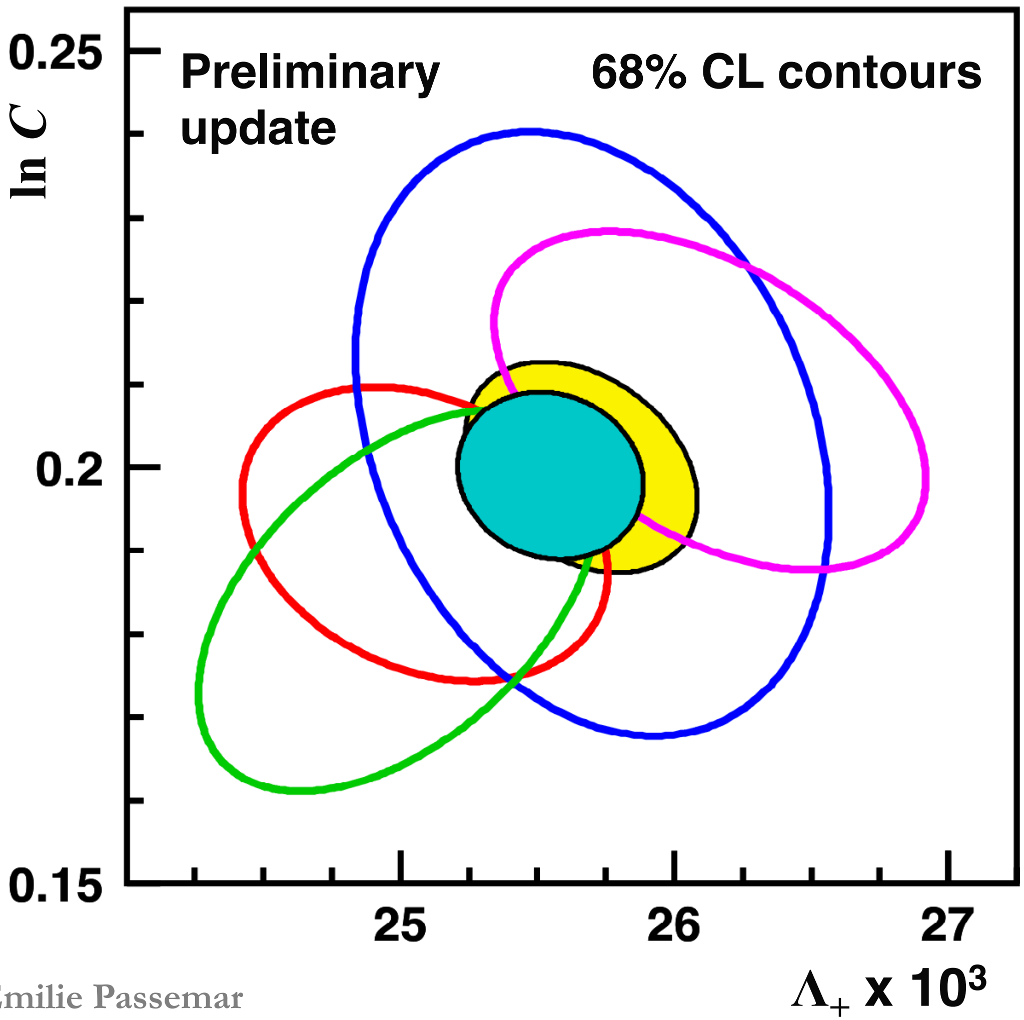
2010: χ^2 = 12.1/8 (P = 14.5%) Update: χ^2 = 13.4/11 (P = 26.8%)

Dispersive parameters for $K_{\ell 3}$ form factors

$K_{\ell 3}$ avgs from KTeV KLOE ISTRA+ NA48/2

NA48 K_{e3} data included in fits but not shown

2010 fit | Update



$\Lambda_+ \times 10^3$	=	**25.55 ± 0.38**
$\ln C$	=	**0.1992(78)**
$\rho(\Lambda_+, \ln C)$	=	−0.110
χ^2/ndf	=	7.5/7 (38%)

Integrals		
Mode	Update	2010
$K^0{}_{e3}$	**0.15470(15)**	0.15476(18)
$K^+{}_{e3}$	**0.15915(15)**	0.15922(18)
$K^0{}_{\mu 3}$	**0.10247(15)**	0.10253(16)
$K^+{}_{\mu 3}$	**0.10553(16)**	0.10559(17)

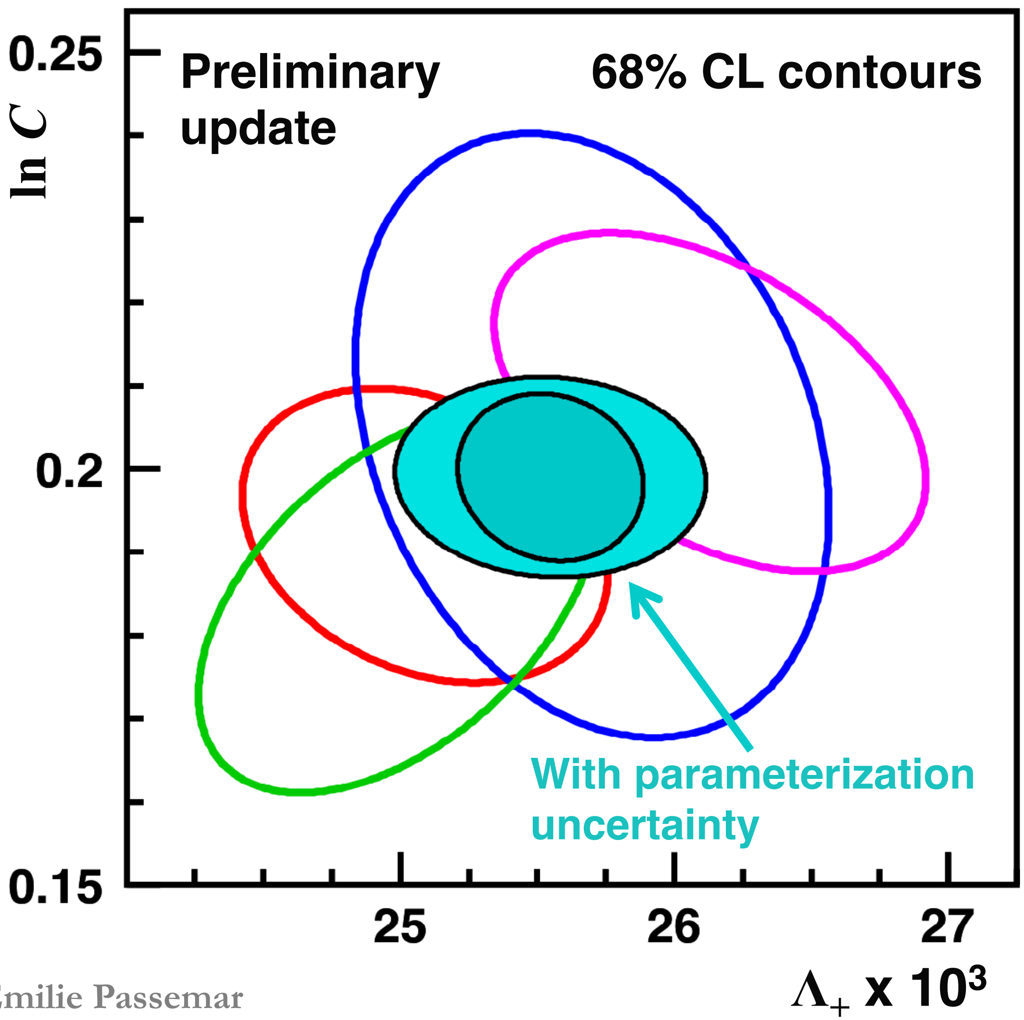
Only tiny changes in central values

Dispersive parameters for $K_{\ell 3}$ form factors

$K_{\ell 3}$ avgs from **KTeV** **KLOE** **ISTRA+** **NA48/2**

NA48 K_{e3} data included in fits but not shown

2010 fit **Update**



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χ^2/ndf	=	7.5/7 (38%)

Fit results include common uncertainty from $H(t)$, $G(t)$:

$\sigma_{\text{param}}(\Lambda_+) = 0.3 \times 10^{-3}$

$\sigma_{\text{param}}(\ln C) = 0.0040$

KTeV, Bernard et al.'09

Confidence ellipses shown **without** common uncertainty (except as indicated)

2.4 Electromagnetic and isospin breaking corrections

- Master formula for

$$\boxed{\Gamma\left(K\to\pi l\nu[\gamma]\right)=\frac{Br(K_{l3})}{\tau}C_K^2\frac{G_F^2 m_K^5}{192\pi^3}S_{EW}^K|V_{us}|^2\left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}\left(1+2\Delta_{\rm EM}^{Kl}+\boxed{2\Delta_{\rm SU(2)}^{K\pi}}\right)}$$

- Short distance electroweak correction *Sirlin'82*

$$\boxed{S_{\rm ew}=1+\frac{2\alpha}{\pi}\left(1+\frac{\alpha_S}{4\pi}\right)\log\frac{m_Z}{m_\rho}+O\left(\frac{\alpha\alpha_S}{\pi^2}\right)} \Rightarrow \boxed{S_{\rm ew}=1.0232(3)}$$

Cirigliano, Giannotti, Neufeld'08

- Long distance EM corrections: $\Delta_{\rm EM}^{K\ell}$ Computed in ChPT at $O(p^2e^2)$

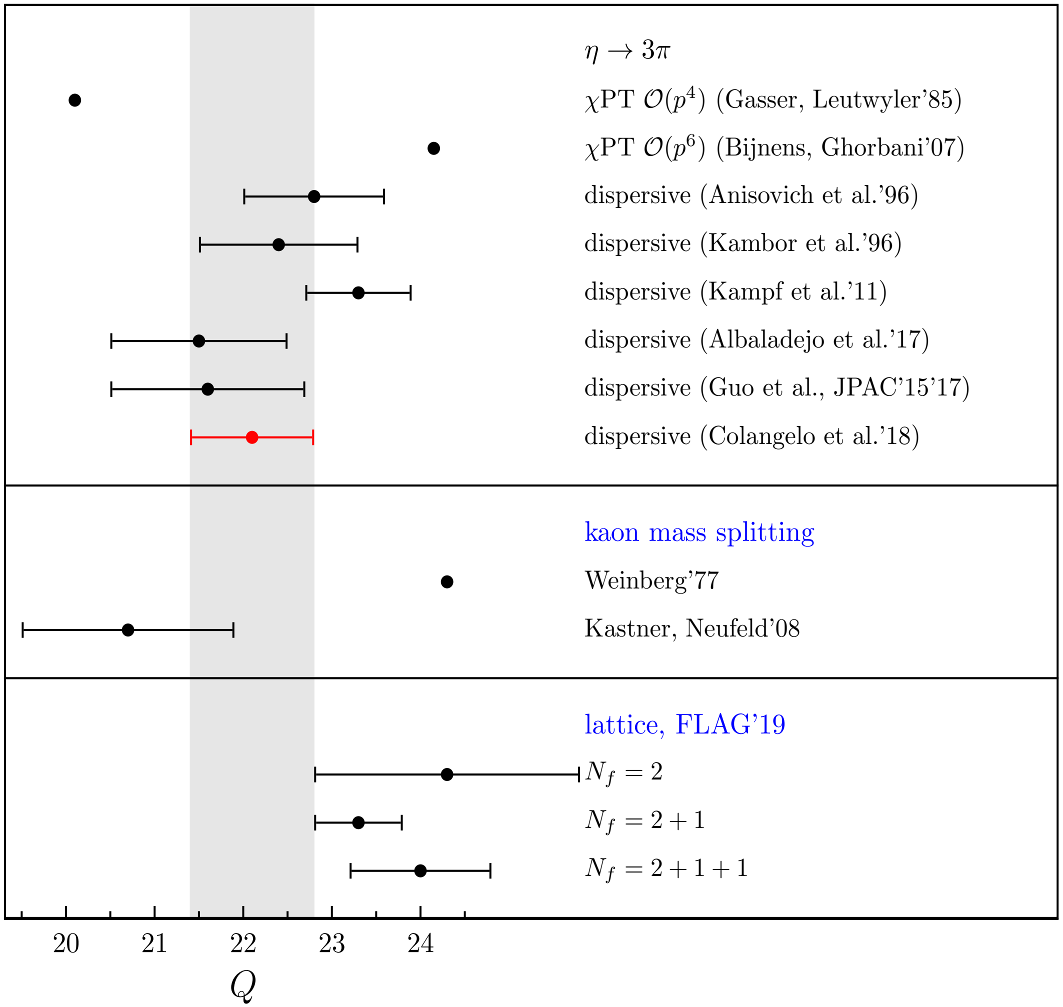
- Isospin breaking : $\boxed{\Delta_{\rm SU(2)}^{K\pi}=\frac{f_+^{K^+\pi^0}(0)}{f_+^{K^0\pi^-}(0)}-1}$ *Gasser & Leutwyler'85* $\left[\hat{m}\equiv\frac{m_d+m_u}{2}\right]$

Computed in ChPT at O(p⁴): $\Delta_{\rm SU(2)}^{K\pi}=\frac{3}{4}\frac{1}{Q^2}\left[\frac{\overline{M}_K^2}{\overline{M}_\pi^2}+\frac{\chi_{p^4}}{2}\left(1+\frac{m_s}{\hat{m}}\right)\right]=2.61(17)\%$

Inputs from lattice QCD and from $\eta\to3\pi$ analysis for Q $\boxed{Q^2\equiv\frac{m_s^2-\hat{m}^2}{m_d^2-m_u^2}}$

Input on Q

Previous to new results on Q, uncertainty on $\Delta^{SU(2)}$ leading contributor to uncertainty on V_{us} from $K^{\pm}$ decays **—can it be reduced?**



Continuing progress + systematic review of existing results for light-quark masses may help

Recent dispersion relation analyses of $\eta \to 3\pi$ Dalitz plot

e.g. Colangelo, Lanz, Leutwyler, E.P'18

1.6 fb^{-1} KLOE '04 -'05 data

Continuing progress on lattice

E.g. **BMW '16** PRL 117

N_f = 2+1 QCD, 5sp, m_π phys

Partially quenched QED

Q = 23.4(4)$_{st}$(3)$_{sy}$(4)$_{QED}$

but some tension

2.4 Electromagnetic and isospin breaking corrections

- Master formula for

$$\boxed{\Gamma\left(K\to\pi l\nu[\gamma]\right)=\frac{Br(K_{l3})}{\tau}C_K^2\frac{G_F^2 m_K^5}{192\pi^3}S_{EW}^K|V_{us}|^2\left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}\left(1+2\Delta_{\rm EM}^{Kl}+\boxed{2\Delta_{\rm SU(2)}^{K\pi}}\right)}$$

- Short distance electroweak correction $\Rightarrow$ $\boxed{S_{\rm ew}=1.0232(3)}$ *Sirlin'82*

- Long distance EM corrections: Computed in ChPT at $O(p^2e^2)$ *Cirigliano, Giannotti, Neufeld'08*

- Isospin breaking : $\boxed{\Delta_{\rm SU(2)}^{K\pi}=\frac{f_+^{K^+\pi^0}(0)}{f_+^{K^0\pi^-}(0)}-1}$

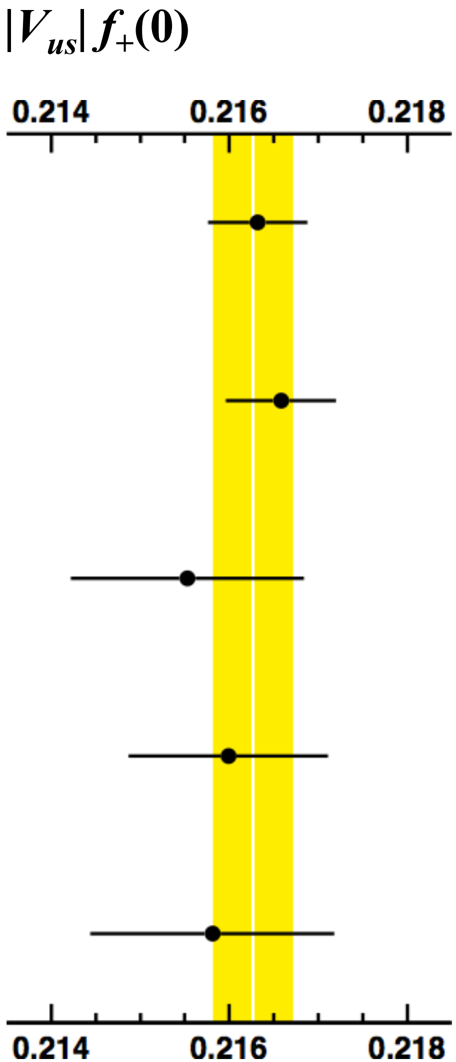
Computed in ChPT at O(p⁴): $\Delta_{\rm SU(2)}^{K\pi}=\frac{3}{4}\frac{1}{Q^2}\left[\frac{\overline{M}_K^2}{\overline{M}_\pi^2}+\frac{\chi_{p^4}}{2}\left(1+\frac{m_s}{\hat{m}}\right)\right]=2.61(17)\%$

Gasser & Leutwyler'85

Inputs from lattice QCD and from $\eta\to3\pi$ analysis for Q

Test by evaluating V_{us} from $K^\pm$ and K^0 data with **no** corrections:
Equality of V_{us} values would require $\Delta^{SU(2)}$ **= 2.82(38)%**

2.5 $|V_{us}| f_+(0)$ from world data: 2010

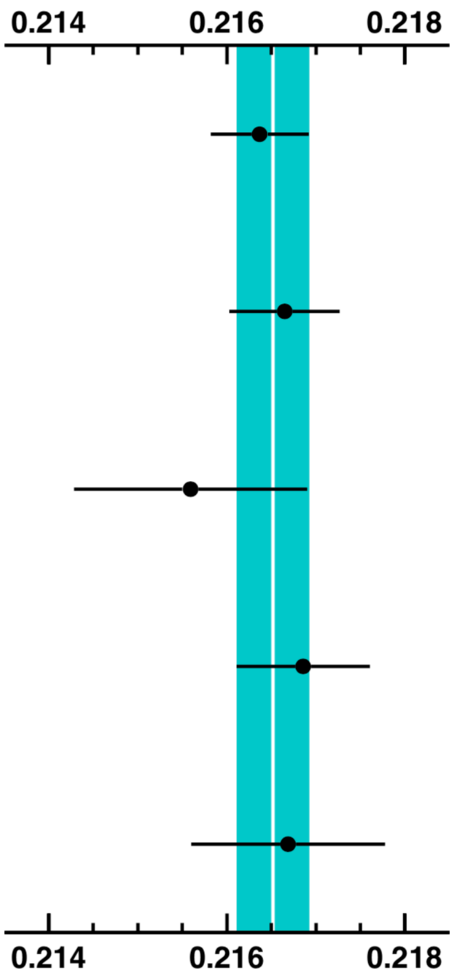


		% err	BR	τ	Δ	Int
			Approx. contrib. to % err from:			
K_Le3	**0.2163(6)**	**0.26**	0.09	0.20	0.11	0.06
$K_L\mu3$	**0.2166(6)**	**0.29**	0.15	0.18	0.11	0.08
K_Se3	**0.2155(13)**	**0.61**	0.60	0.03	0.11	0.06
$K^\pm e3$	**0.2160(11)**	**0.52**	0.31	0.09	0.40	0.06
$K^\pm\mu3$	**0.2158(14)**	**0.63**	0.47	0.08	0.39	0.08

Average: $|V_{us}| f_+(0)$ = 0.2163(5) χ^2**/ndf = 0.77/4 (94%)**

2.5 $|V_{us}| f_+(0)$ from world data: Update

$|V_{us}| f_+(0)$



Approx. contrib. to % err from:

		% err	BR	τ	Δ	Int
$K_L e3$	0.2164(6)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
$K_S e3$	0.2156(13)	0.61	0.60	0.02	0.11	0.05
$K^\pm e3$	0.2169(8)	0.35	0.27	0.06	0.21	0.05
$K^\pm \mu 3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

Average: $|V_{us}| f_+(0)$ = 0.21652(41) χ^2/ndf = 0.98/4 (91%)

2.6 Determination of $f_+(0)$

- SU(3) breaking in $f_+(0)$
  - CVC + Ademollo-Gatto theorem: $f_+^{K^0\pi^-}(0) - 1 = O\left((m_s - m_u)^2\right)$

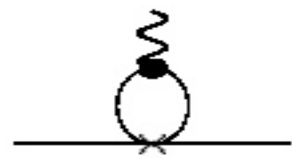
$$\boxed{f_+^{K^0\pi^-}(0) = 1 \; + \; \underbrace{f_{p^4}}_{O(m_q)} \; + \; \underbrace{f_{p^6}}_{O(m_q^2)} \; + \ldots}$$

chiral expansion

- f_{p4}:

Gasser & Leutwyler'85

→ One loop graph :



→ First order in m_q, 2^{nd} order in $(m_s - m_u)$ ⇒ $f_{p^4} \sim \dfrac{(m_s - m_u)^2}{m_s}$

→ No local operators, UV finite, free of uncertainties

⇒ $\boxed{f_{p^4} = -0.0227}$

2.6 Determination of $f_+(0)$

- SU(3) breaking in $f_+(0)$
  - CVC + Ademollo-Gatto theorem: $f_+^{K^0\pi^-}(0) - 1 = O\left((m_s - m_u)^2\right)$

$$\boxed{f_+^{K^0\pi^-}(0) = 1 + \underbrace{f_{p^4}}_{O(m_q)} + \underbrace{f_{p^6}}_{O(m_q^2)} + \ldots}$$

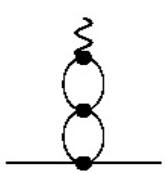
chiral expansion

Bijnens & Talavera'02

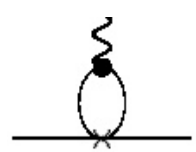
  - f_{p6}:

$$\boxed{f_{p^6}} = f_{p^6}^{2-\text{loops}}(\mu) + f_{p^6}^{\mathrm{L_i}\times\text{loop}}(\mu) + f_{p^6}^{\text{tree}}(\mu)$$

$$\boxed{f_{p^6}^{2-\text{loops}}(M_\rho) = 0.0113} \qquad \boxed{f_{p^6}^{L_i\times\text{loop}}(M_\rho) = -0.0020}$$



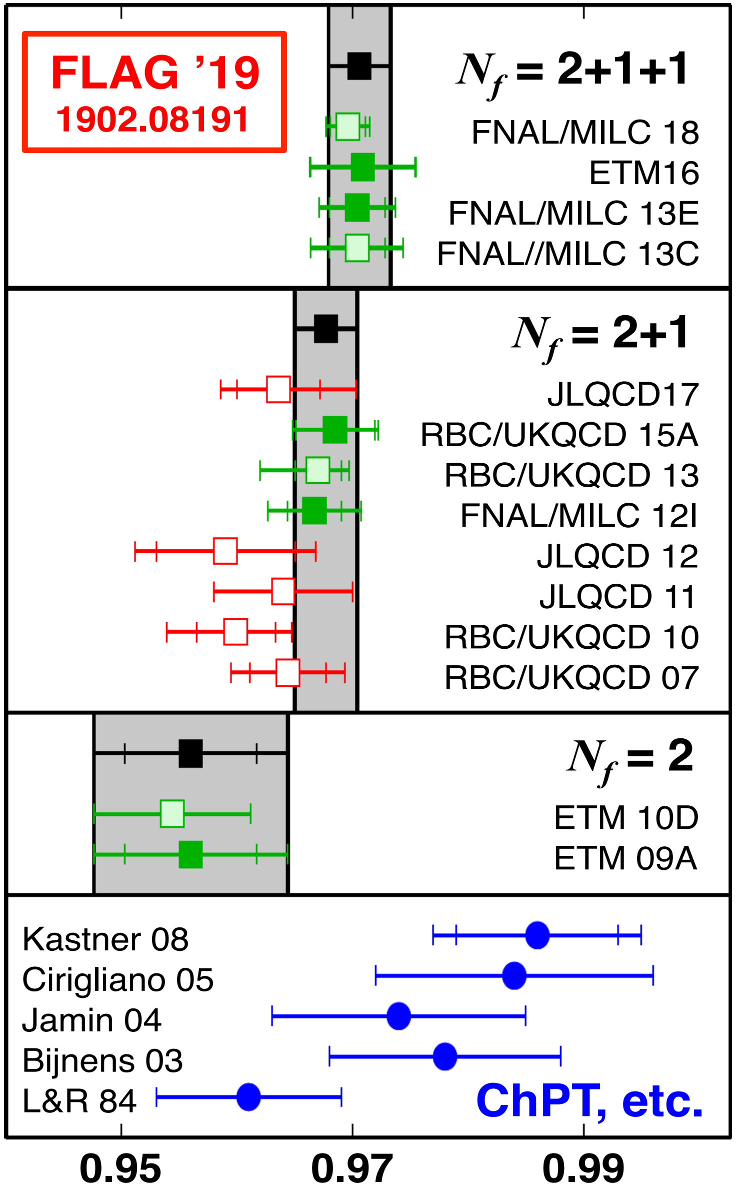
Large positive
chiral loop cont.



$$\boxed{8\frac{\left(M_K^2 - M_\pi^2\right)^2}{F_\pi^2}\left[\frac{\left(L_5^r(M_\rho)\right)^2}{F_\pi^2} - C_{12}^r(M_\rho) - C_{34}^r(M_\rho)\right]}$$

LECs not fixed by chiral symmetry:
quark model, large-Nc estimates, *LQCD*

2.6 Determination of $f_+(0)$



FLAG '19 averages:

N_f = 2+1 $f_+(0)$ **= 0.9677(27)**
Uncorrelated average of:
RBC/UKQCD 15A: DWF, $m_\pi \to$ 139 MeV
FNAL/MILC 12I: HISQ, $m_\pi \sim$ 300 MeV

N_f = 2+1+1 $f_+(0)$ **= 0.9704(32)**
FNAL/MILC 13E: HISQ, $m_\pi \to$ 135 MeV

Recent updates:

N_f = 2+1 $f_+(0) = \mathbf{0.9636(^{+62}_{-65})}$ PRD96 (2017)
JLQCD: Overlap, $m_\pi \to$ 300 MeV
Exact chiral symmetry, one lattice spacing

N_f = 2+1+1 $f_+(0)$ **= 0.9709(44)(9)(11)** PRD 93 (2016)
ETM 16: TwMW, 3sp, $m_\pi \to$ 210 MeV
Full q^2 dependence of f_+, f_0
$f_+(0)$ **= 0.9696(15)(11)** PRD 99 (2019)
FNAL/MILC update 13E

ChPT:

N_f = 2+1 $f_+(0)$ **= 0.970(8)** Chiral Dynamics 15
Ecker 15: According to Bijnens 03
New LECs from Bijnens, Ecker 14

2019 averages for $f_+(0)$

N_f = 2+1+1

$$f_+(0) = \mathbf{0.9698(17)}$$

FNAL/MILC18 preliminary replaces FNAL/MILC13E in FLAG average

ETM16	$0.9709(44)(9)(11)_{\text{ext}}$
FNAL/MILC18	0.9696(15)(11)

N_f = 2+1

$$f_+(0) = \mathbf{0.9677(27)}$$

FLAG average, Nov 2016 update

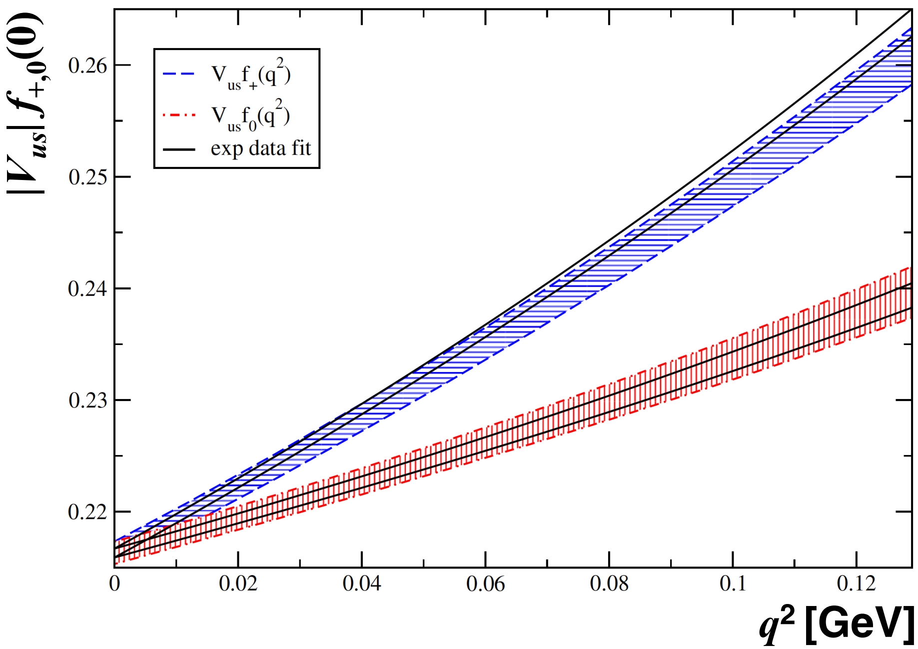
JLQCD17 not included because only 1 lattice spacing used

FNAL/MILC12I	0.9667(23)(33)
RBC/UKQCD15A	0.9685(34)(14)

2.7 q^2 dependence of $K\pi$ form factors

ETM
PRD 93 (2016)

N_f **= 2+1+1** Twisted-mass Wilson fermions
3 lattice spacings, smallest $m_\pi \to 210$ MeV
Results for full q^2 dependence of f_+, f_0



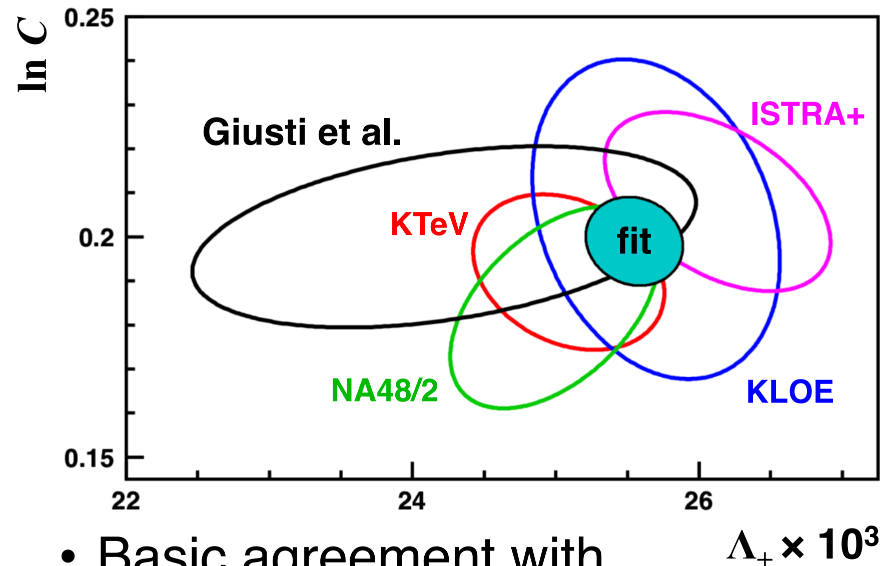
Fit synthetic data points with dispersive parameterization

Λ_+ **= 24.22(1.16) × 10^{-3}**

ln C = 0.1998(138)

$\rho(\Lambda_+, f_+(0)) = -0.228$
$\rho(\ln C, f_+(0)) = -0.719$
$\rho(\Lambda_+, \ln C) = +0.376$

$f_+(0) = 0.9709(44)_{st}(9)_{sy}(11)_{ext}$



- Basic agreement with experimental results
- Confirms basic correctness of lattice calculations for $f_+(0)$
- In the near future FF parameters will be obtained on lattice?

2.8 Extraction of V_{us}

- Decay rate master formula

$$\boxed{\Gamma\left(K \to \pi l \nu\left[\gamma\right]\right) = Br(K_{l3})/\tau = C_K^2 \frac{G_F^2 m_K^5}{192\pi^3} S_{EW}^K \left|V_{us}\right|^2 \left|f_+^{K^0\pi^-}(0)\right|^2 I_{Kl}\left(1 + 2\Delta_{\mathrm{EM}}^{Kl} + 2\Delta_{\mathrm{SU(2)}}^{K\pi}\right)}$$

- N_f=2+1

FLAG'19
N_f = 2+1

$$\boxed{f_+(0) = 0.9677(27)}$$

$$\boxed{f_+(0)\left|V_{us}\right| = 0.21652 \pm 0.00041_{\mathrm{exp}}} \Rightarrow \boxed{\left|V_{us}\right| = 0.22375 \pm 0.00043_{\mathrm{exp}} \pm 0.00062_{\mathrm{lat}}}$$

-1.6σ with unitarity

- N_f=2+1+1

FLAG'19
N_f = 2+1+1

$$\boxed{f_+(0) = 0.9698(17)}$$

$$\boxed{f_+(0)\left|V_{us}\right| = 0.21652 \pm 0.00041_{\mathrm{exp}}} \Rightarrow \boxed{\left|V_{us}\right| = 0.22326 \pm 0.00043_{\mathrm{exp}} \pm 0.00039_{\mathrm{lat}}}$$

-2.2σ with unitarity

3. V_{us}/V_{ud} from $K_{\ell 2}/\pi_{\ell 2}$ decays

3.1 Master formula for V_{us}/V_{ud} from $K_{\ell 2}/\pi_{\ell 2}$ decays

- From K_{l2}/π_{l2}:

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

Inputs from theory:

Cirigliano, Neufeld '11

$\delta_{\rm EM}$ **= –0.0069(17)**

Long-distance EM corrections

$\delta_{SU(2)}$ **= –0.0043(5)(11)**

Strong isospin breaking

$f_K/f_\pi \to f_{K\pm}/f_{\pi\pm}$

Lattice: f_K/f_π

Cancellation of lattice-scale uncertainties from ratio

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

Inputs from experiment:

Updated $K^\pm$ BR fit:

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

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

PDG:

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

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

$$\boxed{|V_{us}/V_{ud}| \times f_{K\pm}/f_{\pi\pm} = 0.27599(37)}$$

No $SU(2)$-breaking correction

3.2 Electromagnetic corrections

Giusti et al.
PRL 120 (2018)

First lattice calculation of EM corrections to P_{l2} decays

- Ensembles from ETM
- N_f = 2+1+1 Twisted-mass Wilson fermions

$\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0122(16)$

- Uncertainty from quenched QED included (0.0006)

Compare to ChPT result from Cirigliano, Neufeld '11:

$\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0112(21)$

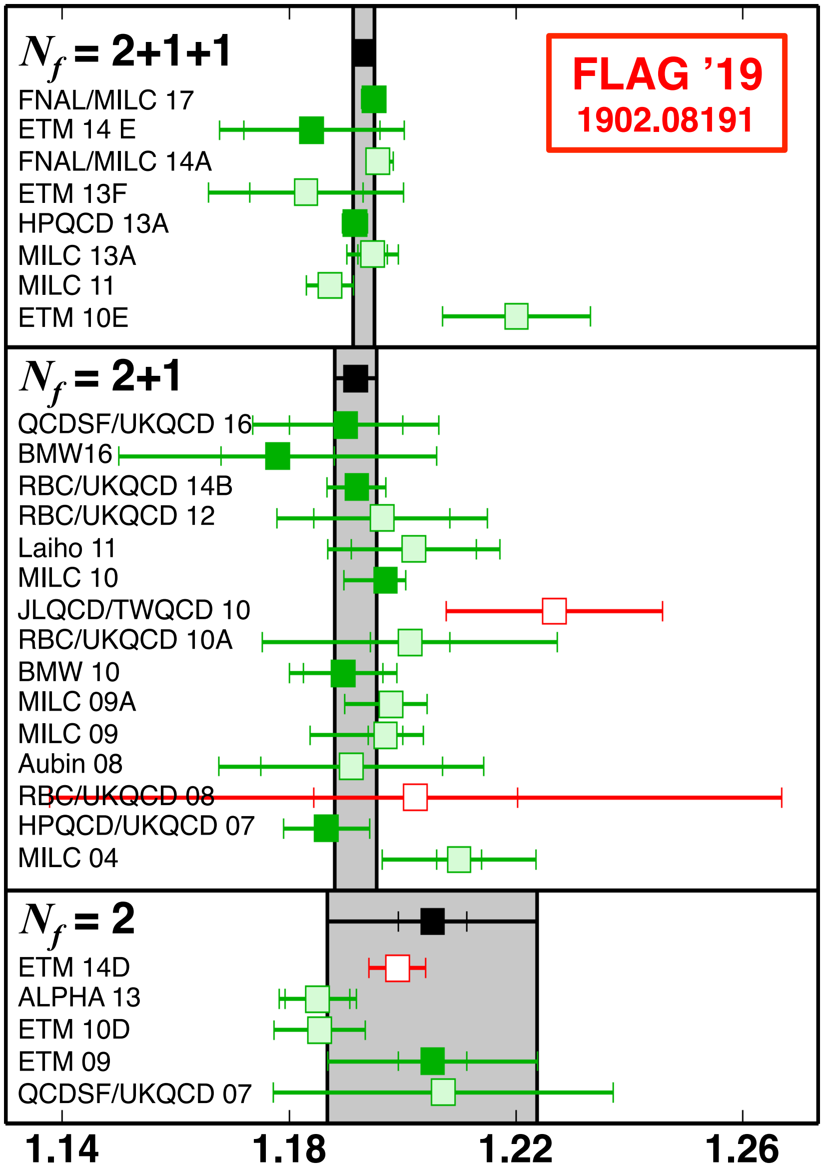
Di Carlo et al.
1904.08731

Update, extended description, and systematics of Giusti et al.

$\delta_{SU(2)} + \delta_{\mathrm{EM}} = -0.0126(14)$

$$|V_{us}/V_{ud}| \times f_K/f_\pi = 0.27679(28)_{\mathrm{BR}}(20)_{\mathrm{corr}}$$

3.3 Lattice results for f_K/f_π



FLAG '19 averages:

N_f = 2+1+1 $f_{K\pm}/f_{\pi\pm}$ **= 1.1932(19)**

Includes:

FNAL/MILC 17:
- HISQ, 4sp, m_π phys
- Updates MILC 13A, FNAL/MILC 14A

HPQCD 13A
- HISQ, 3sp, m_π phys,
- Same ensembles as FNAL/MILC 17

ETM 14E
- TwM, 3sp, m_π = 210-450 MeV

N_f = 2+1 $f_{K\pm}/f_{\pi\pm}$ **= 1.1917(37)**

Recent measurements:

QCDSF/UKQCD 16:
- Clover, 4sp, $m_\pi \to$ 220 MeV

BMW16:
- Clover, 5sp, $m_\pi \to$ 139 MeV

RBC/UKQCD 14B:
- DWF, m_π = 139 MeV
- f_K and f_π separately (isospin limit)

3.3 Lattice results for f_K/f_π

Recalculate FLAG averages for results without $SU(2)$-breaking
Isospin-limit results as reported in original papers

N_f = 2+1+1 **f_K/f_π = 1.1967(18)**

FNAL/MILC17	$1.1980(^{+13}_{-19})$	Correlated uncertainties
HPQCD13A	1.1948(15)(18)	
ETM14E	1.188(15)	Uncorrelated uncertainty

N_f = 2+1 **f_K/f_π = 1.1946(34)***

QCDSF/UKQCD17	1.192(10)(13)
BMW16	1.182(10)(26)
RBC/UKQCD14B	1.1945(45)
BMW10	1.192(7)(6)
HPQCD/UKQCD07	1.198(2)(7)

*MILC10 omitted from average because unpublished

3.4 V_{us} from K_{l2} + V_{ud} ($0^+ \to 0^+$)

$$|V_{us}/V_{ud}| \times f_K/f_\pi = 0.27679(34)$$

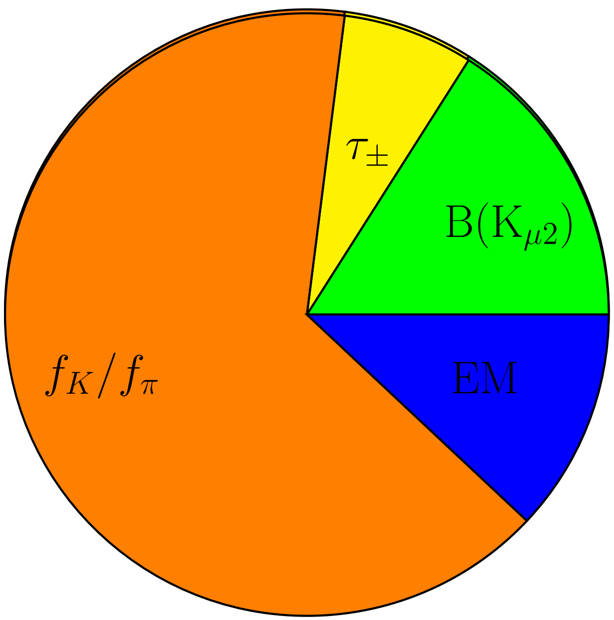
$\delta_{SU(2)} + \delta_{EM} = -0.0126(14)$ from Di Carlo et al. '19

$N_f = 2+1$ $\quad$ $V_{us}/V_{ud} = 0.23170(29)_{exp}(66)_{lat}$

$f_K/f_\pi = 1.1946(34)$

$N_f = 2+1+1$ $\quad$ $V_{us}/V_{ud} = 0.23129(29)_{exp}(35)_{lat}$

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



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

3.4 V_{us} from K_{l2} + V_{ud} $(0^+ \to 0^+)$

$|V_{us}/V_{ud}| \times f_{K\pm}/f_{\pi\pm}$ = 0.27679(34) and $|V_{ud}|$ = 0.97418 (21)

$\delta_{SU(2)} + \delta_{EM}$ = –0.0126(14) from Di Carlo et al. '19

N_f = 2+1 f_K/f_π = 1.1946(34)	V_{us} = 0.22572(28)$_{exp}$(64)$_{lat}$(05)$_{ud}$ Δ_{CKM} = +0.00003(13)$_{exp}$(29)$_{lat}$(43)$_{ud}$	= +0.1σ
N_f = 2+1+1 f_K/f_π = 1.1967(18)	V_{us} = 0.22532(28)$_{exp}$(34)$_{lat}$(05)$_{ud}$ Δ_{CKM} = –0.00015(13)$_{exp}$(15)$_{lat}$(43)$_{ud}$	= –0.3σ

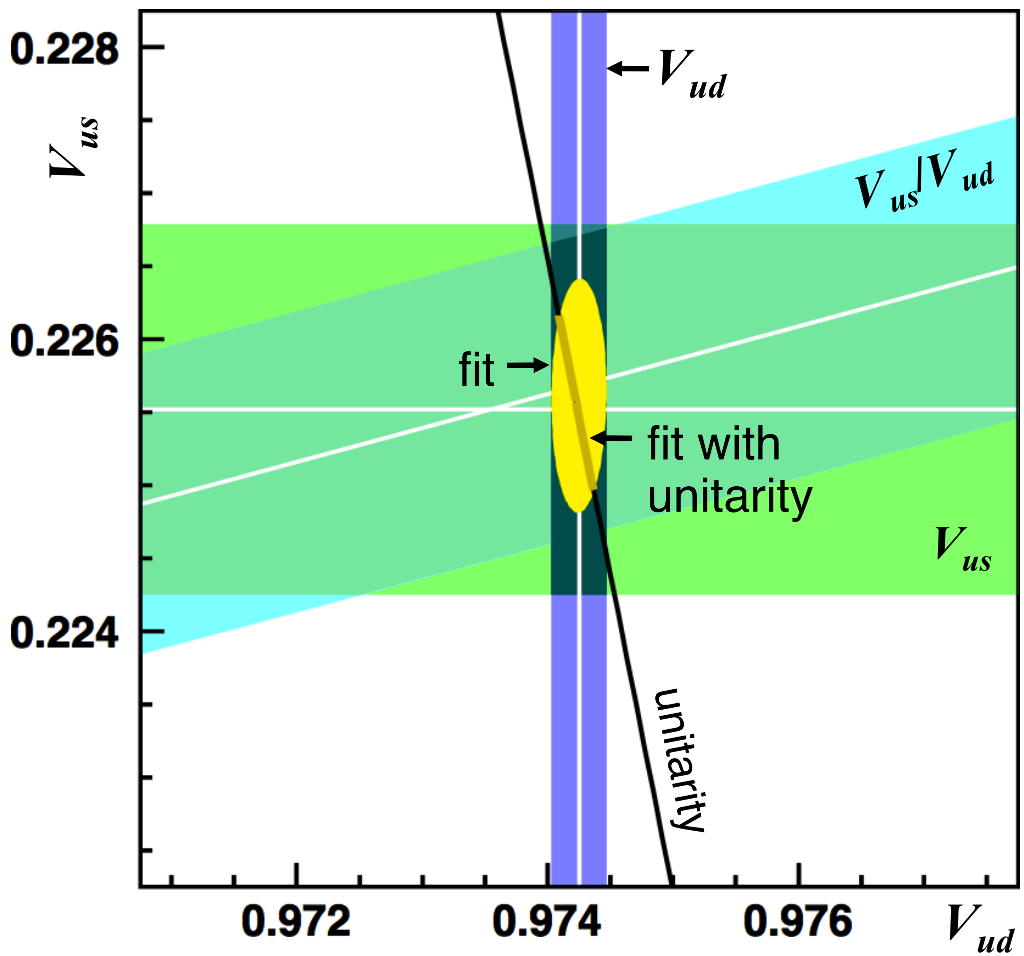
$K_{\ell 2}$ results give better agreement with unitarity via V_{ud} than $K_{\ell 3}$ results (–2σ)

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

4. V_{us} and Unitarity of the CKM matrix

4.1 V_{us} and CKM unitarity: All data, N_f=2+1

Use $f_+(0)$ = 0.959(5) and f_K/f_π = 1.193(5)
Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$



$|V_{ud}|$ = **0.97425(22)**
$|V_{us}|$ = **0.2255(13)**
$|V_{us}|/|V_{ud}|$ = **0.2317(11)**

Fit results, no constraint

V_{ud} = **0.97425(22)**
V_{us} = **0.2256(8)**
χ^2/ndf = 0.01/1 (92%)
Δ_{CKM} = **+0.0001(6)**

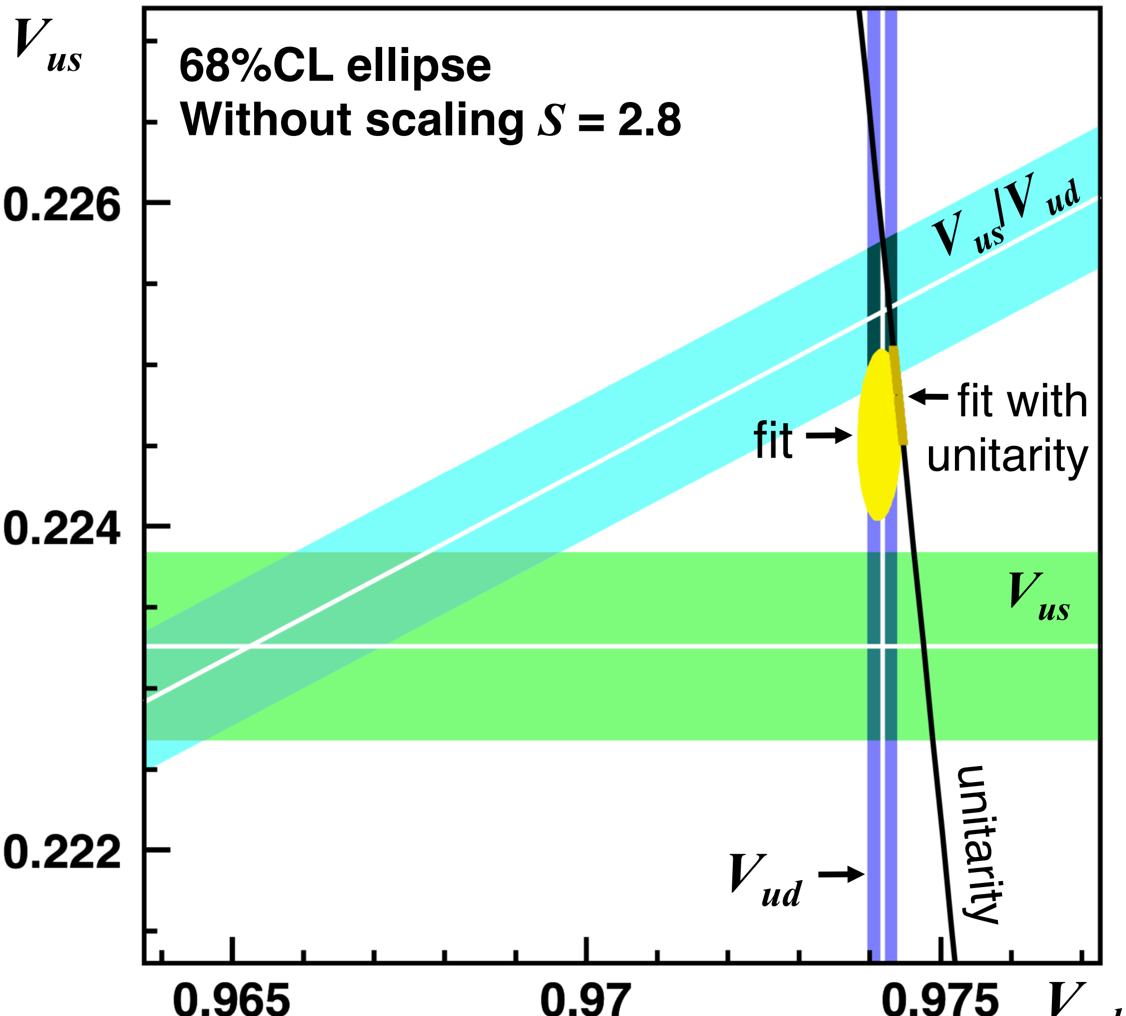
Fit results, unitarity constraint

V_{ud} = **0.97423(14)**
V_{us} = **0.2255(6)**
χ^2/ndf = 0.03/2 (99%)

Status in 2010

4.2 V_{us} and CKM unitarity: All data, "Conv." V_{ud}

N_f **= 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ **= 0.9698(17),** f_K/f_π **= 1.1967(18)**



$|V_{ud}|$ = 0.97418(21)
$|V_{us}|$ = 0.2233(6)
$|V_{us}|/|V_{ud}|$ = 0.2313(5)

Fit results, no constraint

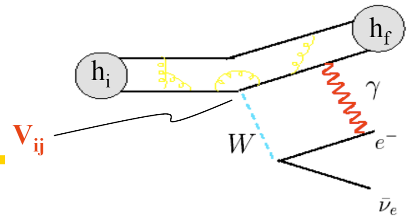
V_{ud} **= 0.97414(21)**
V_{us} **= 0.22456(35)**
χ^2/ndf = 8.0/1 (0.5%)
Δ_{CKM} **= –0.00062(45)**
-1.4σ

With scale factor S **= 2.8**

V_{ud} **= 0.97414(60)**
V_{us} **= 0.2246(10)**

Update

4.3 V_{ud} from $0^+ \longrightarrow 0^+$



$$\frac{1}{t} = \frac{G_\mu^2 |V_{ud}|^2 m_e^5}{\pi^3 \log 2} f(Q)\ (1 + RC) \longrightarrow f\,t\ (1 + RC) = \frac{2984.48(5)\ s}{|V_{ud}|^2}$$

$$(1 + RC) = (1 - \delta_C)\ (1 + \delta_R)\ (1 + \Delta_C)$$

$\langle f|\tau_+|i\rangle = \sqrt{2}\,(1 - \delta_C/2)$

Coulomb distortion
of wave-functions

$\delta_C \sim 0.5\%$

Towner-Hardy
Ormand-Brown

Nucleus-dependent
rad. corr.
(Z, E^{max} ,nuclear structure)

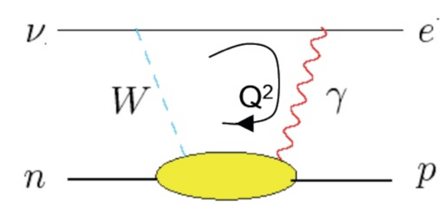
$\delta_R \sim 1.5\%$

Sirlin-Zucchini '86
Jaus-Rasche '87

Nucleus-independent
short distance rad. corr.

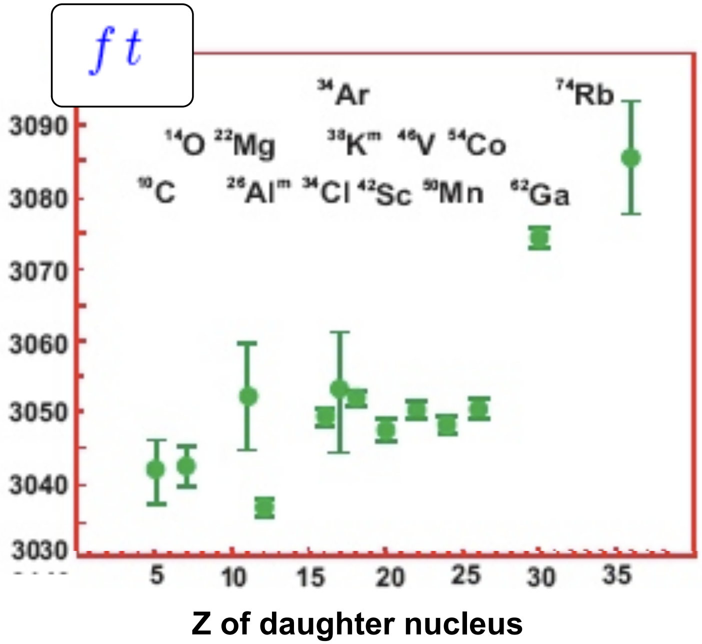
$\Delta_R \sim 2.4\%$

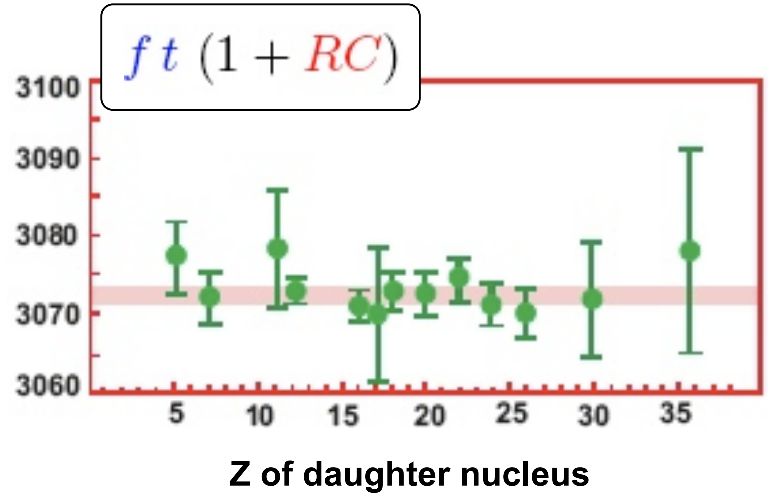
Marciano-Sirlin '06



4.3 V_{ud} from $0^+ \to 0^+$

Hardy@Amherst'19

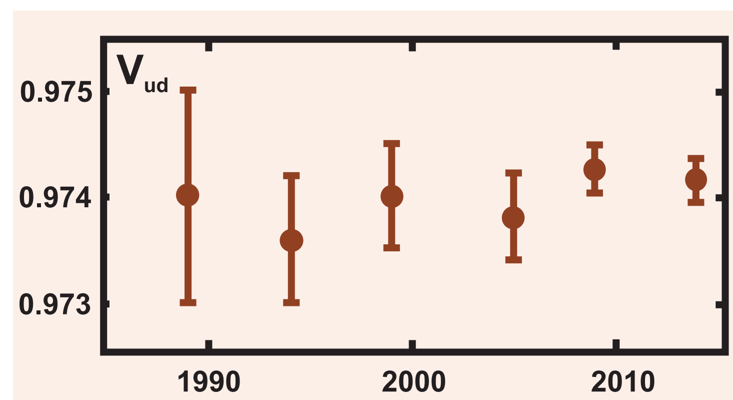




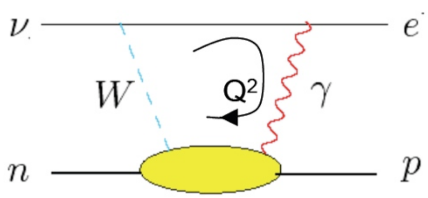
$$|V_{ud}| = 0.97418(21)$$

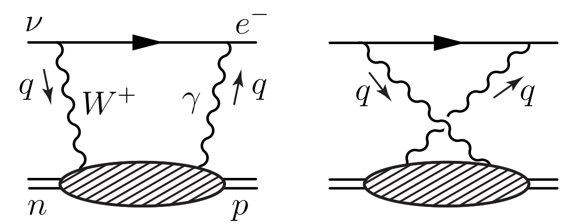
Improvements over years :

- Survey of 150 measurements of 13 different $0^+ \to 0^+$ β decays
- 27 new *ft* measurements including Penning-trap measurements for QEC
- Improved EW radiative corrections
  Marciano & Sirlin'06
- New *SU*(2)-breaking corrections
  Towner & Hardy'08



4.4 New Radiative Corrections for $0^+ \rightarrow 0^+$





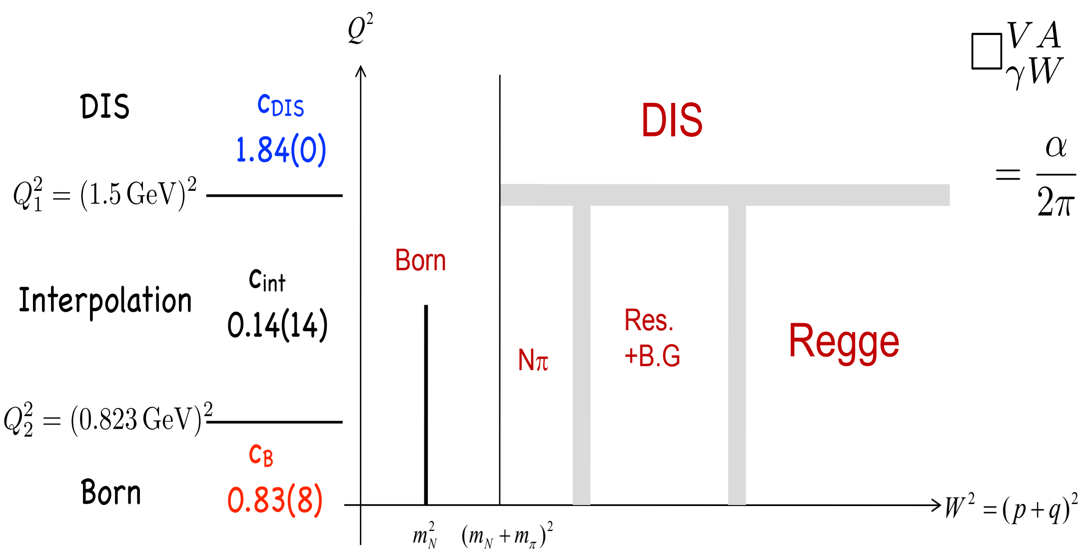
Gorchtein@CIPANP'18
Amherst'19

Marciano & Sirlin'06

$$\Box_{\gamma W}^{VA} = \frac{\alpha}{2\pi}[c_B + c_{int} + c_{DIS}] = \frac{\alpha}{2\pi}[0.83(8) + 0.14(14) + 1.84(0)]$$

$$\Box_{\gamma W}^{MS} = \frac{\alpha}{2\pi} 2.79(17) = 3.24(20) \times 10^{-3}$$

New evaluation: *Seng, Gorchtein, Patel & Ramsey-Musolf'18*



$$\Box_{\gamma W}^{VA} = \frac{\alpha}{2\pi}[c_B + c_{piN} + c_{\text{Res}} + c_{\text{Regge}} + c_{DIS}]$$

$$= \frac{\alpha}{2\pi}[0.91(5) + 0.044(5) + 0.01(1) + 0.238(14) + 1.84(0)]$$

$$\boxed{\Box_{\gamma W}^{\text{New}} = \frac{\alpha}{2\pi} 3.03(5) = 3.51(6) \times 10^{-3}}$$

4.4 New Radiative Corrections for $0^+ \rightarrow 0^+$

$$|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

- Conventional calculation:

$$\Delta_R^V = 0.02361(38)$$

Marciano & Sirlin'06

- Dispersion Relations:

$$\Delta_R^V = 0.02467(22)$$

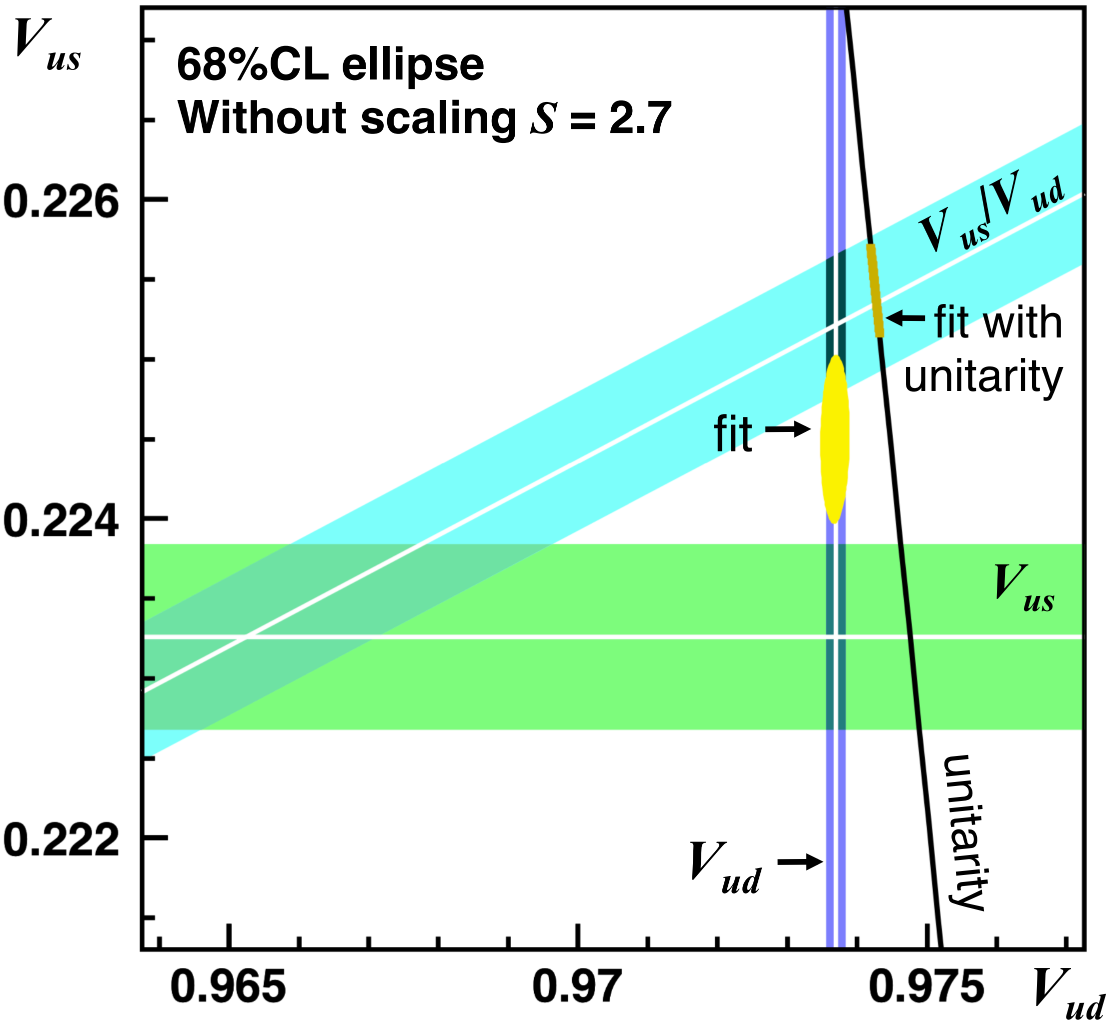
Seng, Gorchtein, Patel & Ramsey-Musolf'18

$$\boxed{|V_{ud}| = \mathbf{0.97418(10)_{Ft}(18)_{\Delta_R^V}}} \Rightarrow \boxed{|V_{ud}| = \mathbf{0.97370(10)_{Ft}(11)_{\Delta_R^V}}}$$

~1.8σ smaller

4.5 V_{us} and CKM unitarity: All data, New Vud

N_f = 2+1+1: Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ = 0.9698(17), f_K/f_π = 1.1967(18)



$|V_{ud}|$ = 0.97370(14)
$|V_{us}|$ = 0.2233(6)
$|V_{us}|/|V_{ud}|$ = 0.2313(5)

Fit results, no constraint

V_{ud} = **0.97368(14)**
V_{us} = **0.22450(35)**
χ^2/ndf = 7.2/1 (0.7%)
Δ_{CKM} = **–0.00154(32)**
–4.8σ

With scale factor S = **2.7**

V_{ud} = **0.97368(38)**
V_{us} = **0.2245(9)**

New Radiative Corrections for $0^+ \rightarrow 0^+$

$$|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

- Conventional calculation:

$$\Delta_R^V = 0.02361(38)$$

Marciano & Sirlin'06

- Dispersion Relations:

$$\Delta_R^V = 0.02467(22)$$

Seng, Gorchtein, Patel & Ramsey-Musolf'18

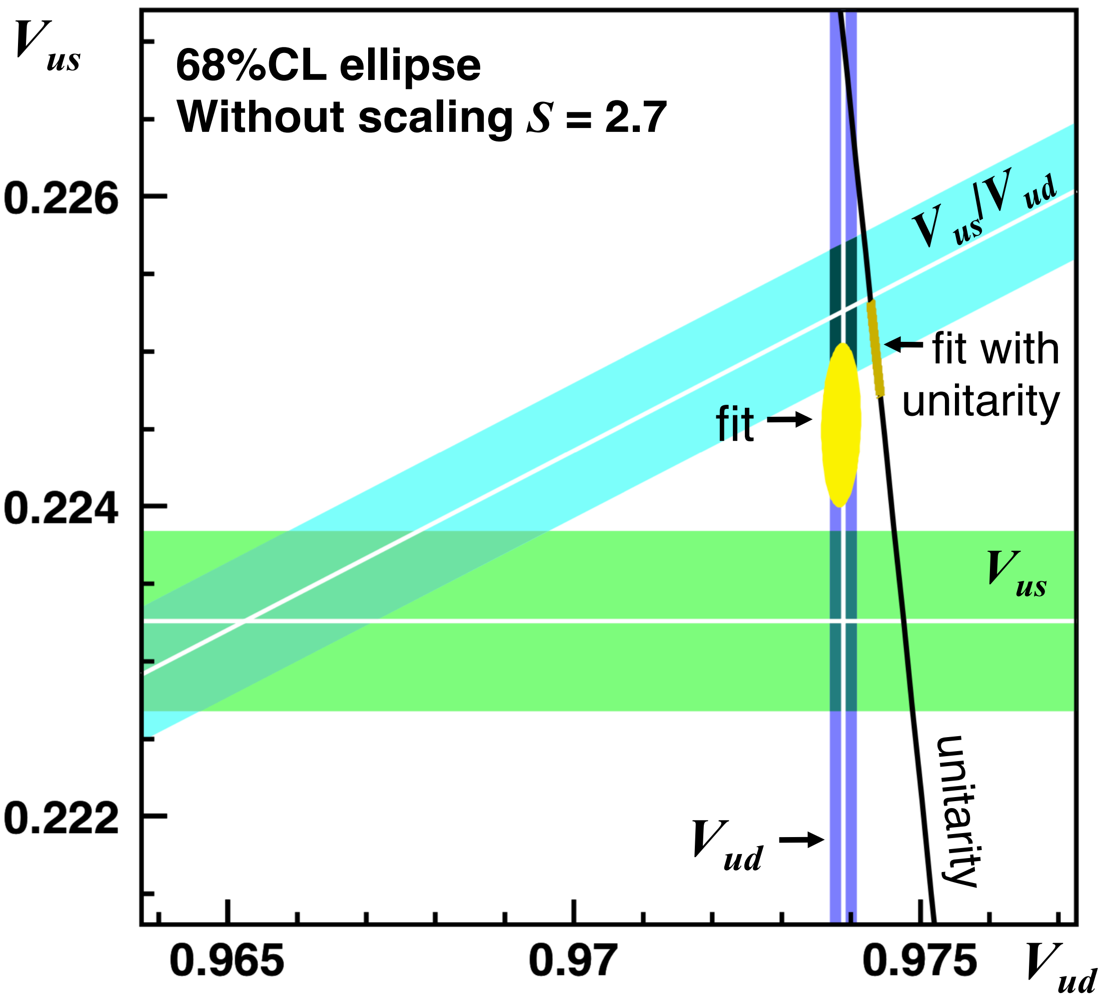
$$\boxed{\left|V_{ud}\right| = \mathbf{0.97418(10)_{Ft}(18)_{\Delta_R^V}}} \Rightarrow \boxed{\left|V_{ud}\right| = \mathbf{0.97370(10)_{Ft}(11)_{\Delta_R^V}}}$$

~1.8σ smaller

⇒ New Analysis $\boxed{\left|V_{ud}\right| = \mathbf{0.97389(19)}}$ *Czarnecki, Marciano, Sirlin'19*

4.5 V_{us} and CKM unitarity: All data, New Vud

N_f **= 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ **= 0.9698(17),** f_K/f_π **= 1.1967(18)**



$|V_{ud}| = 0.97389(19)$
$|V_{us}| = 0.2233(6)$
$|V_{us}|/|V_{ud}| = 0.2313(5)$

Fit results, no constraint

$V_{ud} = \mathbf{0.97386(19)}$
$V_{us} = \mathbf{0.22452(35)}$
$\chi^2/\text{ndf} = 7.5/1\ (0.6\%)$
$\Delta_{CKM} = \mathbf{-0.00119(41)}$
-2.9σ

With scale factor S **= 2.7**

$V_{ud} = \mathbf{0.97368(53)}$
$V_{us} = \mathbf{0.2245(10)}$

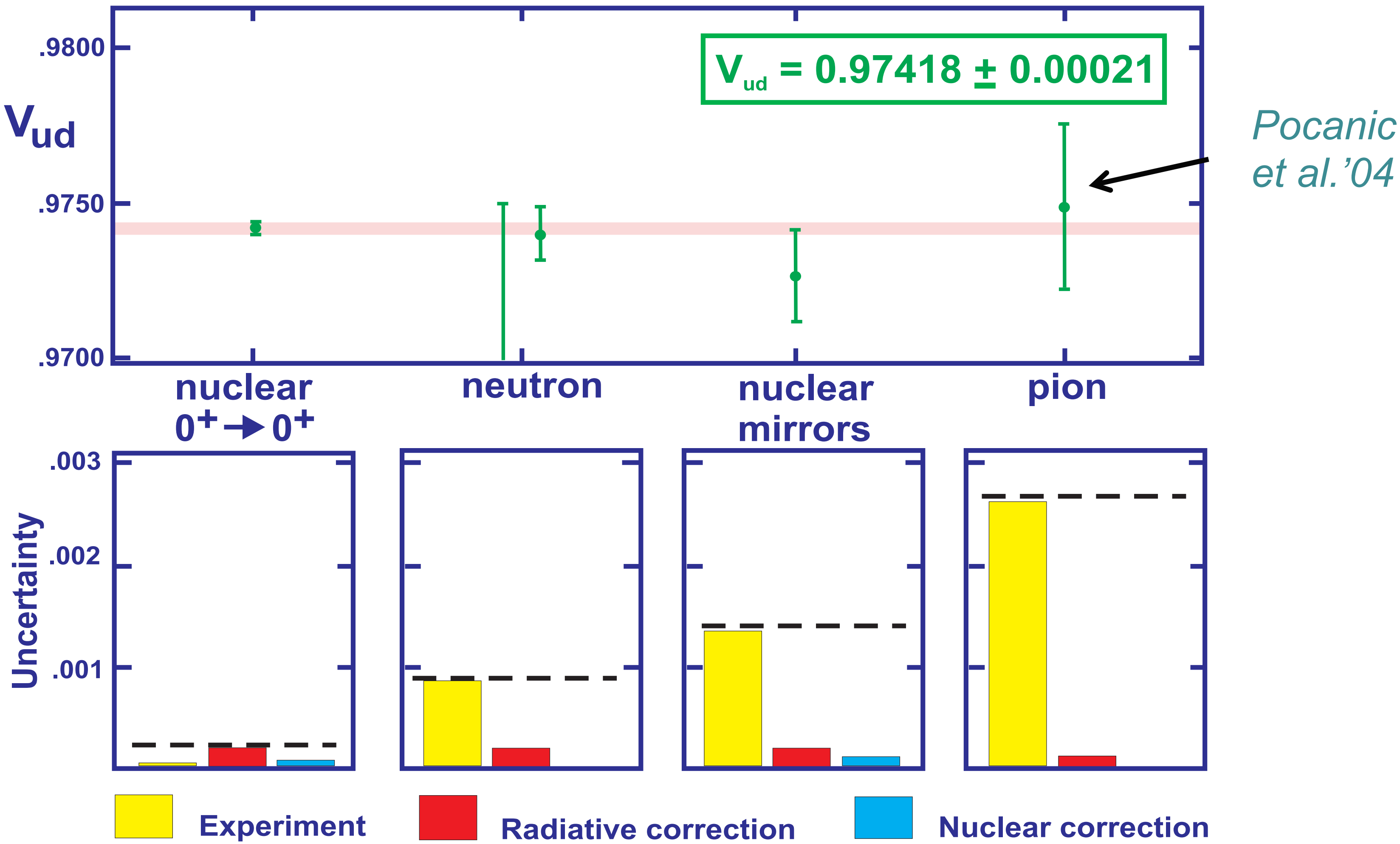
4.6 V_{us} and CKM unitarity: Hint of New Physics?

- With new calculation of radiative corrections: 2.9σ - 4.8σ discrepancy with unitarity ⇒ calculations need to be checked and model dependence understood

- Can we extract V_{ud} differently?

Extraction of V_{ud} : summary

Hardy@Amherst'19



4.6 V_{us} and CKM unitarity: Hint of New Physics?

- With new calculation of radiative corrections: 2.9σ - 4.8σ discrepancy with unitarity ⇒ calculations need to be checked and model dependence understood

- Can we extract V_{ud} differently?
  Yes but for the neutron decay same *radiative correction* to evaluate!
  And also life time experiments (bottle vs. beam) do not agree!

4.6 V_{us} and CKM unitarity: Hint of New Physics?

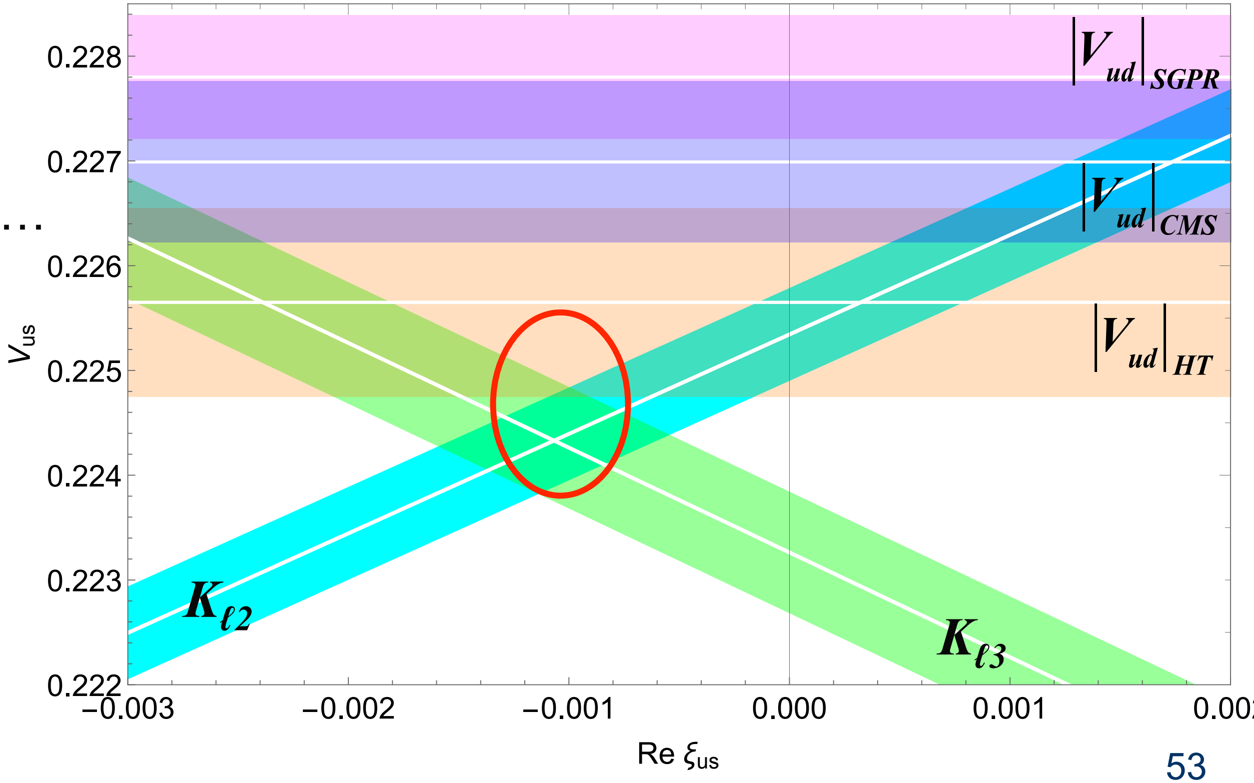
- With new calculation of radiative corrections: 2.9σ - 4.8σ discrepancy with unitarity ⇨ calculations need to be checked and model dependence understood

- If this disagreement correct, what does it tell us? Several studies:

  - 4[th] quark b'
  - gauge horizontal family symmetry
  - Right handed currents…

  Belfatto, Beradze, Berezhiani'19

Crivellin, Hoferichter, Kitahara, E.P. in progress



5. Conclusion and Outlook

5.1 Conclusion

- We have reviewed the different extractions of V_{us} and V_{ud}
  ⇨ We have entered a precision era

- On experimental side many new measurements on kaon decays from **KLOE**, **NA48**, **KTeV**, **ISTRA+** and more to come **NA62**, **OKA**, **KLOE II**, **LHCb**, **TREK E36**

- On theoretical side: small effects start to matters: radiative corrections, e.m. effects, isospin breaking etc
  Many of these effects can now be computed on the lattice in addition to matrix elements

- With new lattice data: tension towards a discrepancy in unitarity of the first row of CKM matrix

- On V_{ud} side: an incredible precision has been achieved on extracting V_{ud} from nuclear beta decays but new radiative corrections

- Experimentalists working hard to extract V_{ud} from neutron side

5.2 Outlook

- 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 but mainly in tau decays, hyperons
    For V_{ud}, understand the situation of the proton lifetime, beta decay of pion?

  - 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?

- Interesting time ahead of us!

6. Back up

V_{ud} from neutron decay

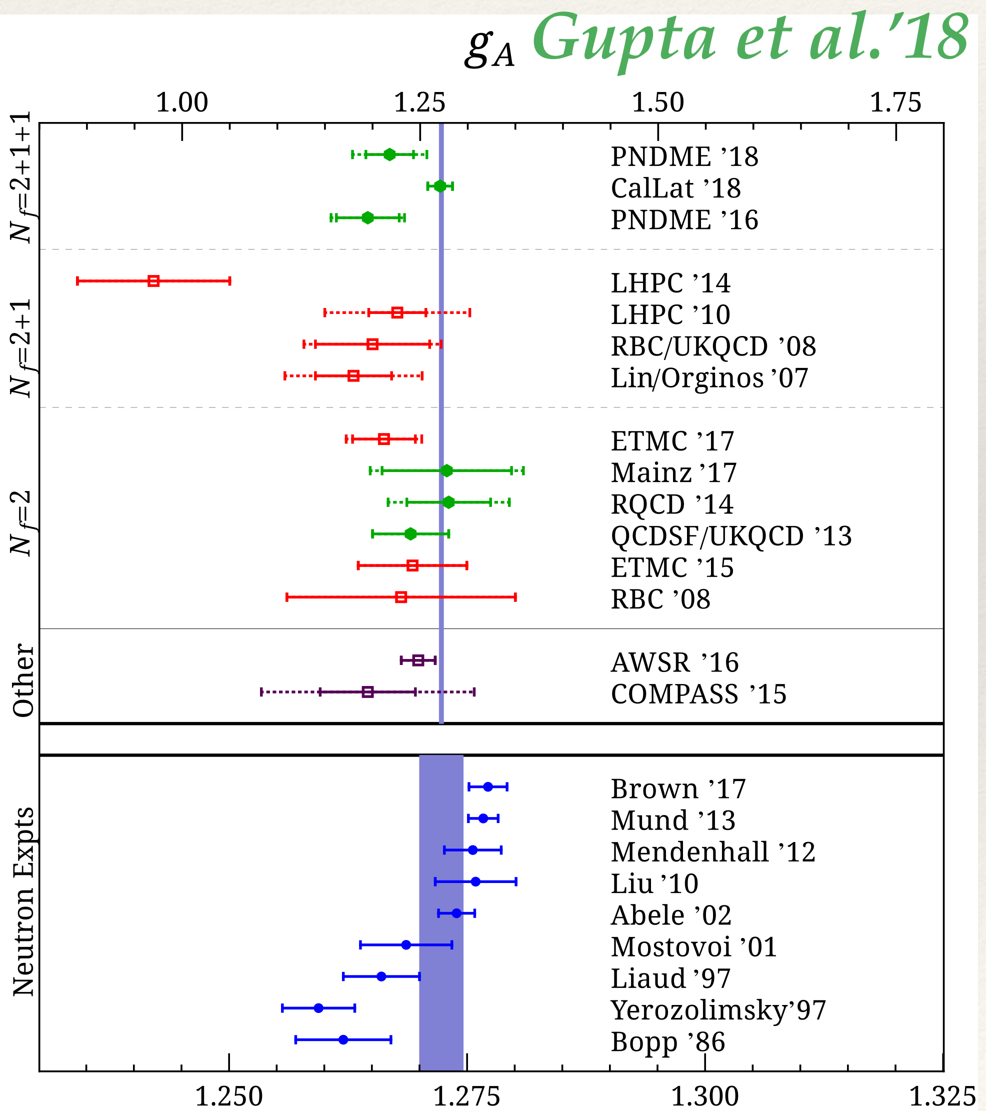
$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ (1 + 3\bar{g}_A^2)} \right]^{1/2}$$

Marciano, Sirlin'06

- Need to measure neutron lifetime τ_n and
- $\lambda = g_A/g_V$: determined through measurement of the neutron β-decay asymmetry parameter A which defines the correlation between the spin of the neutron and the momentum of the emitted electron

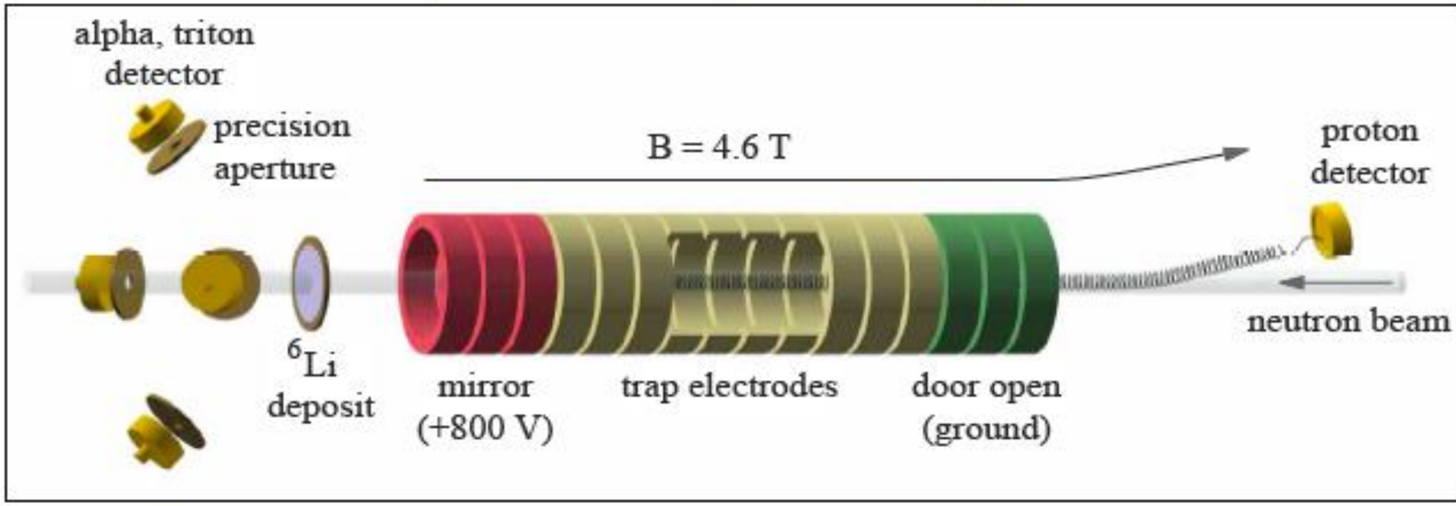
V_{ud} from neutron decay

- Or take g_A from lattice QCD determination:

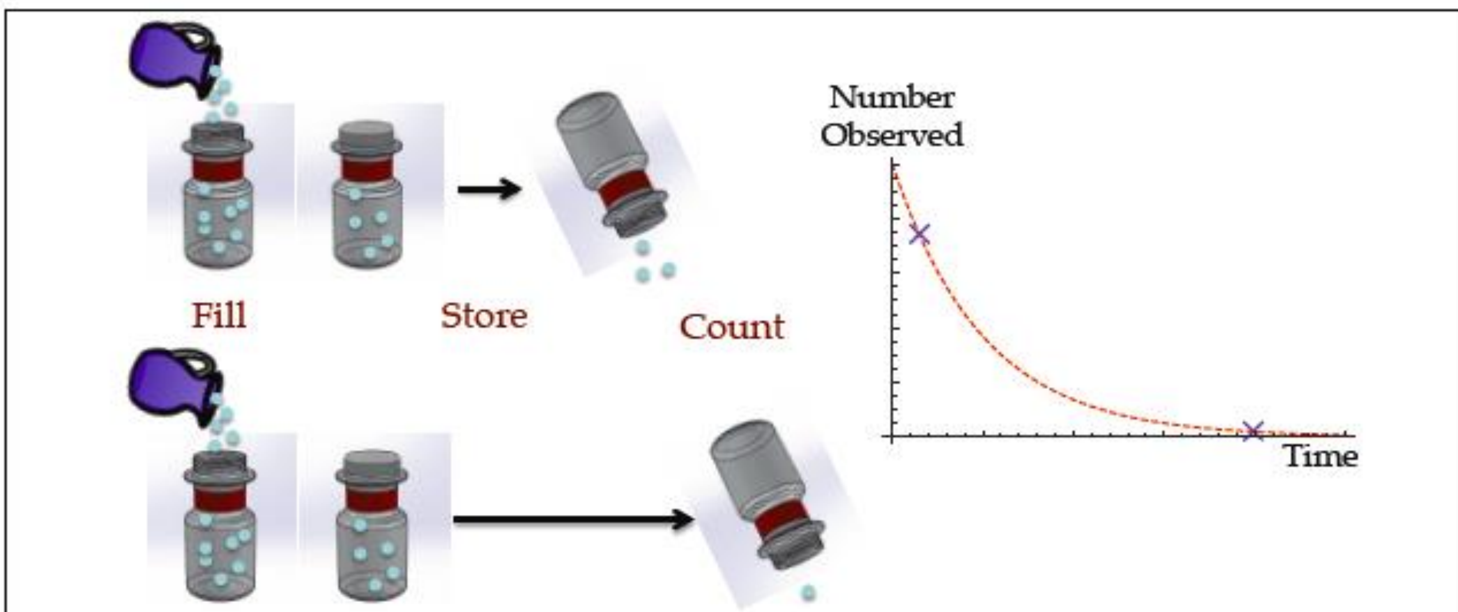


Neutron lifetime measurements : two techniques

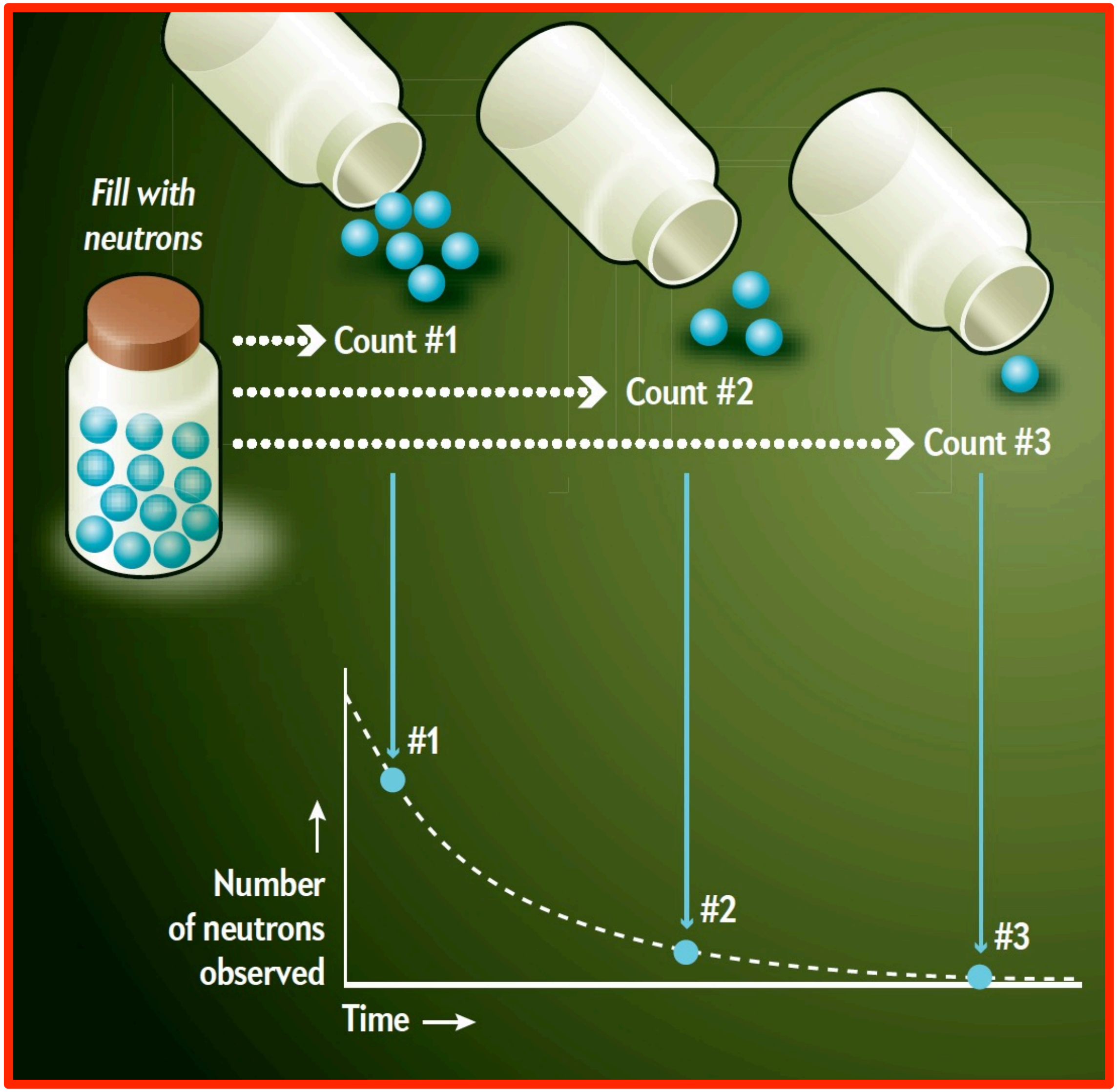
Cold Neutron Beam



Ultracold Neutron (UCN) Bottle



Bottle Experiment



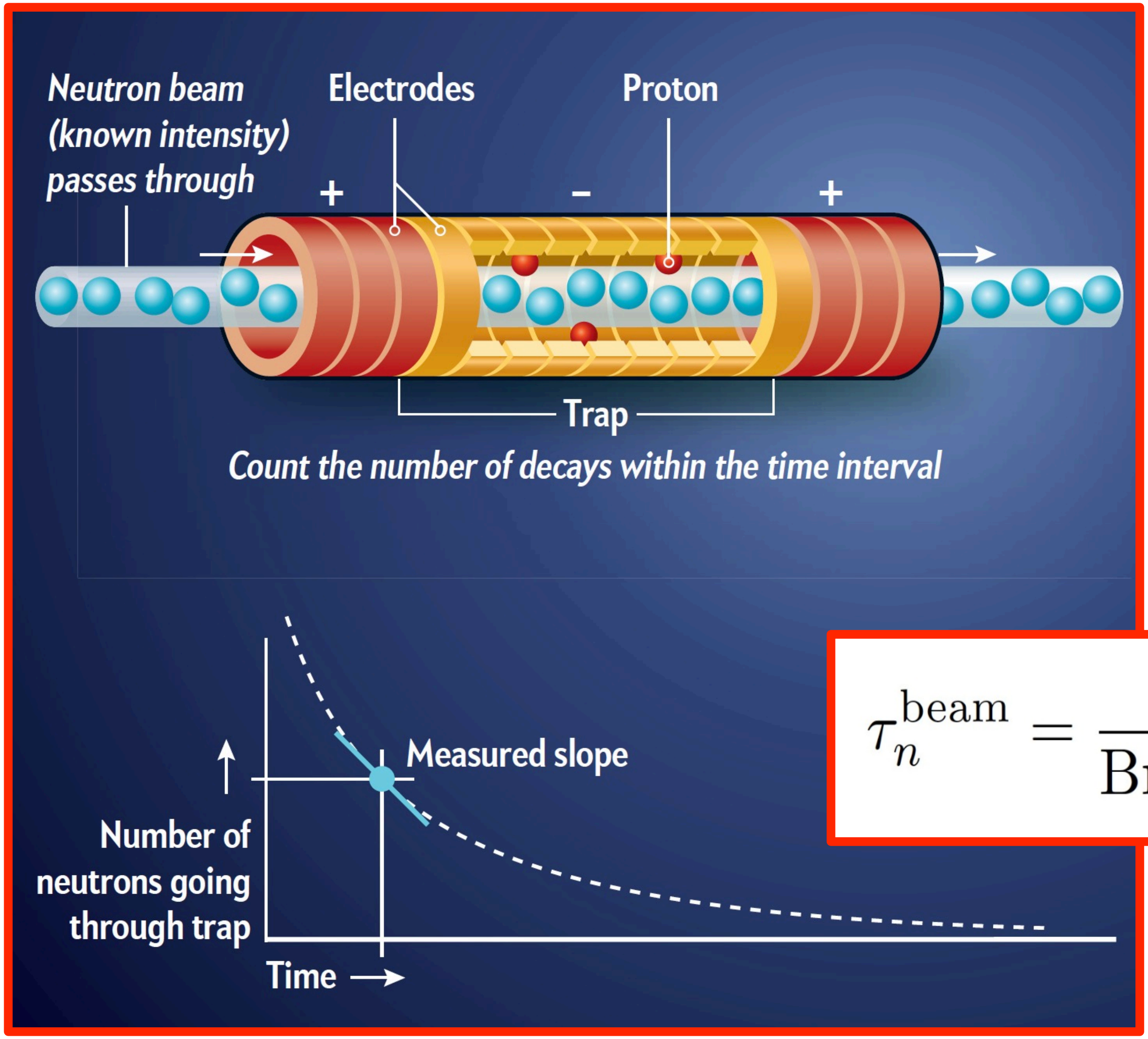
- Data points fit to an exponential decay

$$N = N_0 \, e^{-\lambda t}$$

- Lifetime

$$\tau = \frac{1}{\lambda}$$

Beam experiment

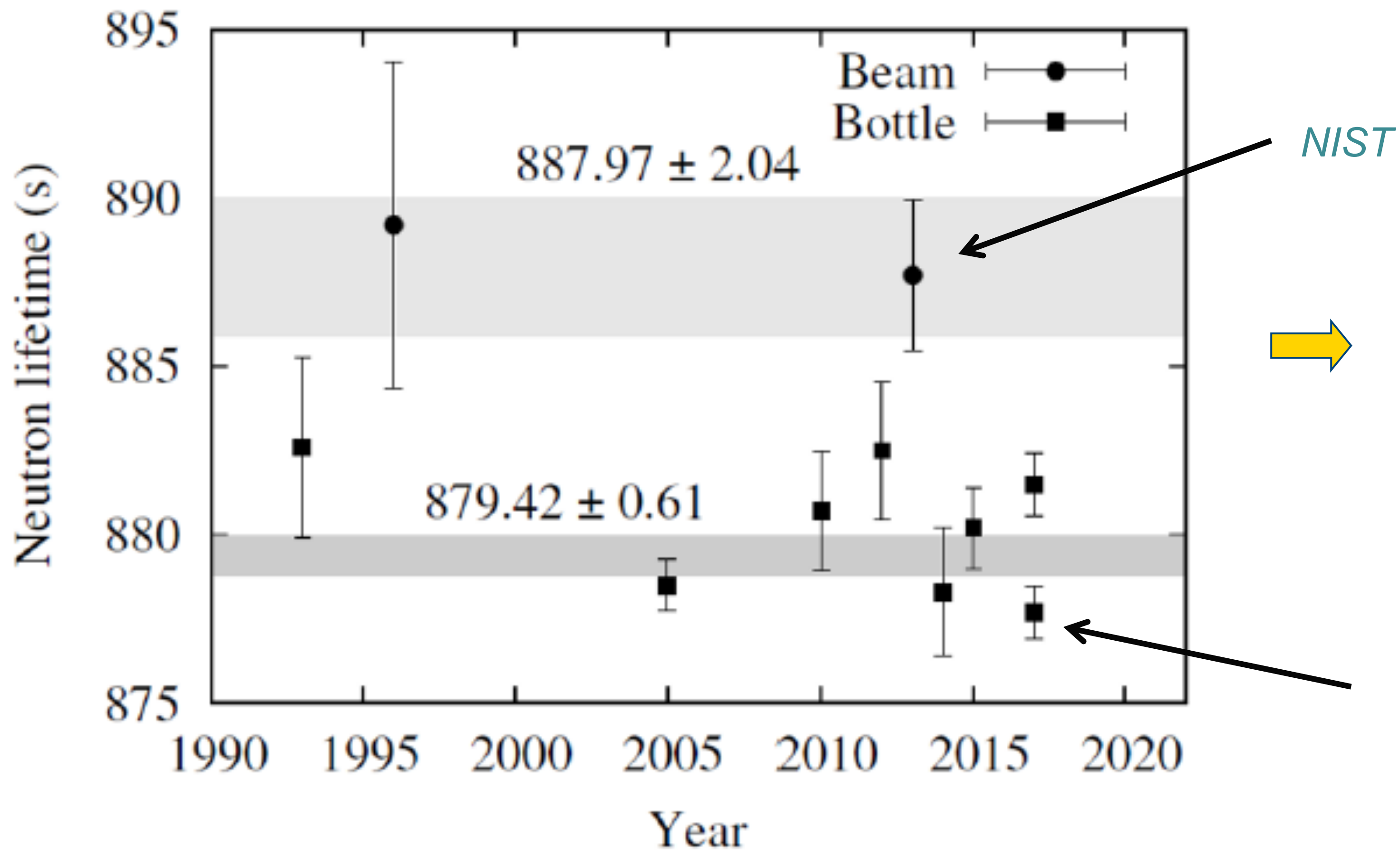


Only the decay rate to protons is measured

$$\boxed{\frac{dN}{dt} = -\lambda N}$$

$$\boxed{\tau_n^{\text{beam}} = \frac{\tau_n}{\text{Br}(n \to p + \text{anything})}}$$

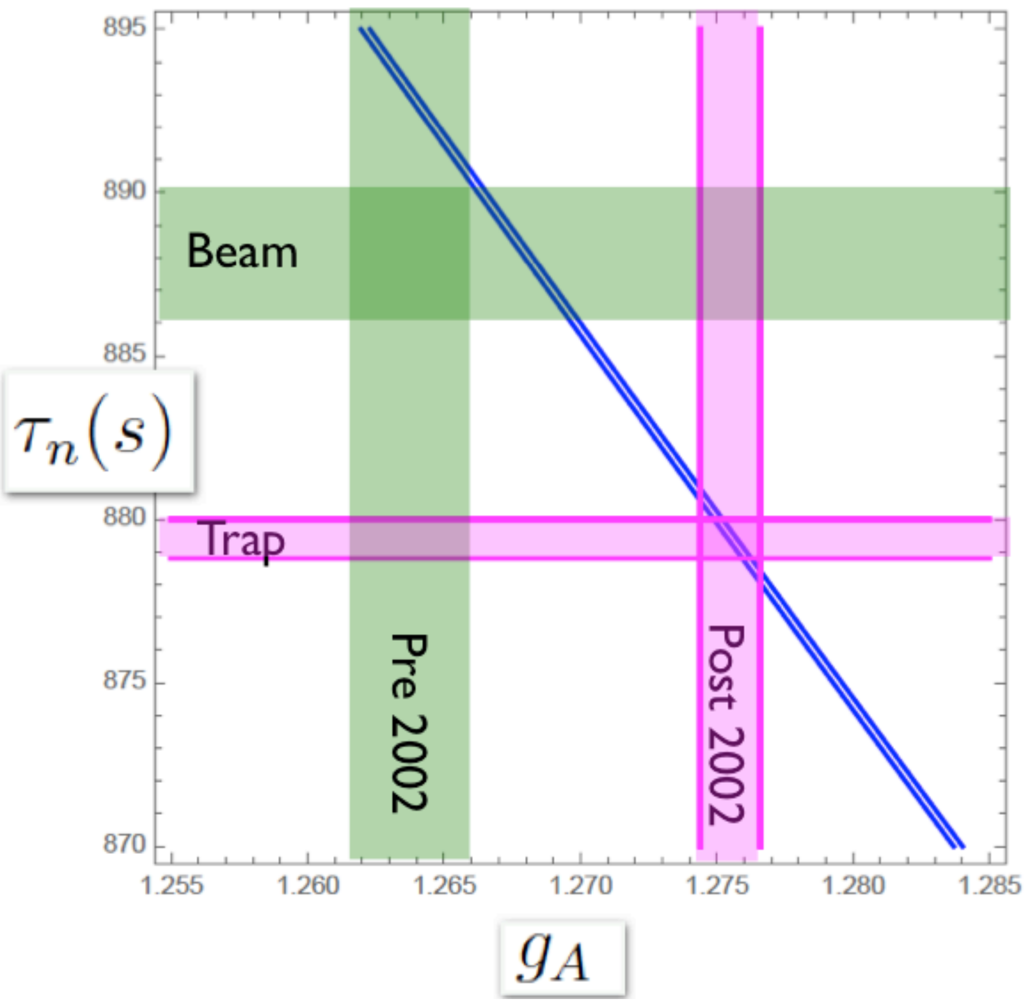
Neutron lifetime measurements : results



Historical Discrepancy!

Neutron lifetime measurements : Interpretation

Czarnecki, Marciano, Sirlin'18



$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ (1 + 3\bar{g}_A^2)} \right]^{1/2}$$

- Input V_{ud} from $0^+ \rightarrow 0^+$: Blue line
- UCN lifetime and post-2002 g_A consistent with SM

Neutron lifetime measurements : Interpretation

$$\boxed{\mathrm{Br}(n \to p + \text{anything}) \approx 99\%}$$

Fornal & Grinstein'18

- Remaining 1% :

$$\boxed{n \to \text{ SM particles (other than } p)}$$ ✗

$$\boxed{n \to \text{ dark particle(s) } + \text{ SM particle(s)}}$$ ✓

$$\boxed{n \to \text{ dark particles}}$$ ✓

Neutron lifetime measurements : Interpretation

$$\boxed{\mathrm{Br}(n \to p + \text{anything}) \approx 99\%}$$

Fornal & Grinstein'18

- Remaining 1% :

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$$\boxed{n \to \text{ dark particles}}$$ ✓

⇨ Problem with neutron stars

Baym, Beck, Shelton, Geltenbort'18

McKeen, Nelson, Reddy, Zhou'18

Motta, Guichon, & A.W. Thomas'18

V_{ud} from neutron decay : prospects to reach 0.02%

Czarnecki, Marciano, Sirlin'18
Cirigliano@Amherst'18

$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ (1 + 3\bar{g}_A^2)} \right]^{1/2}$$

$\delta\tau_n \sim 0.35$ s

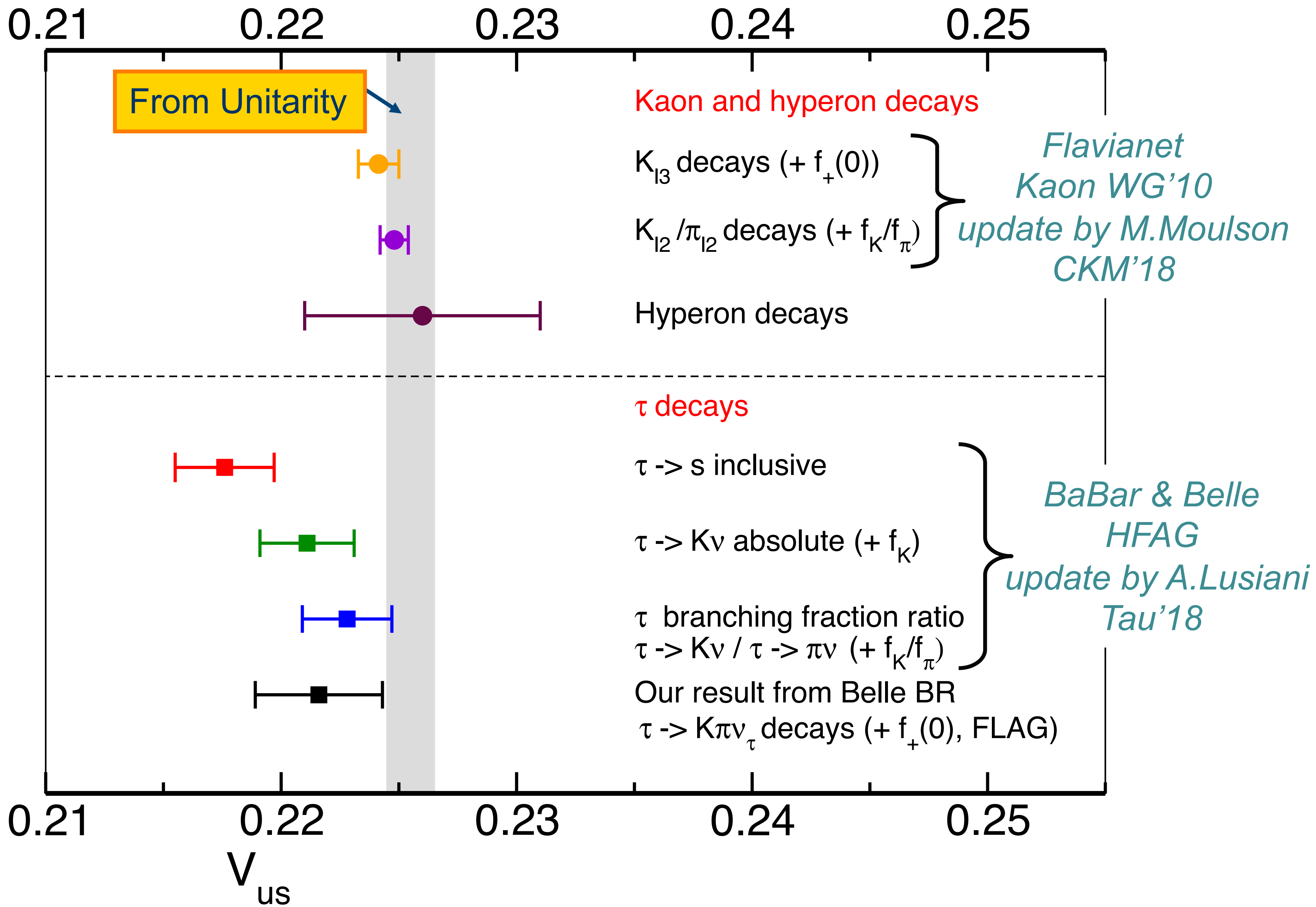
$\delta\tau_n/\tau_n \sim 0.04$ %

UCNτ @ LANL [$\tau_n \sim 877.7(7)(3)$s] is almost there, will reach $\delta\tau_n \sim 0.2$ s
1707.01817

$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$

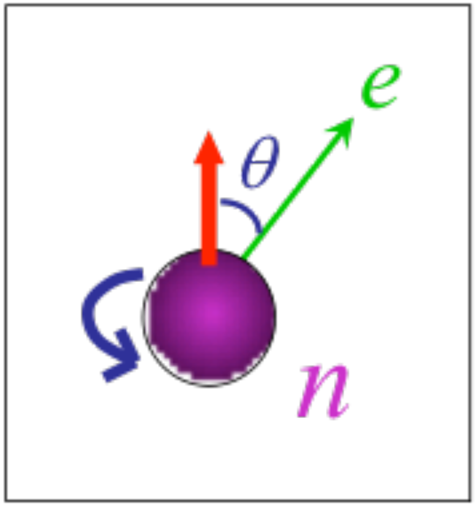
($\delta a/a$, $\delta A/A \sim 0.14\%$)

$\delta A/A < 0.2\%$ can be reached by PERC, UCNA+
$\delta a/a \sim 0.1\%$ at Nab

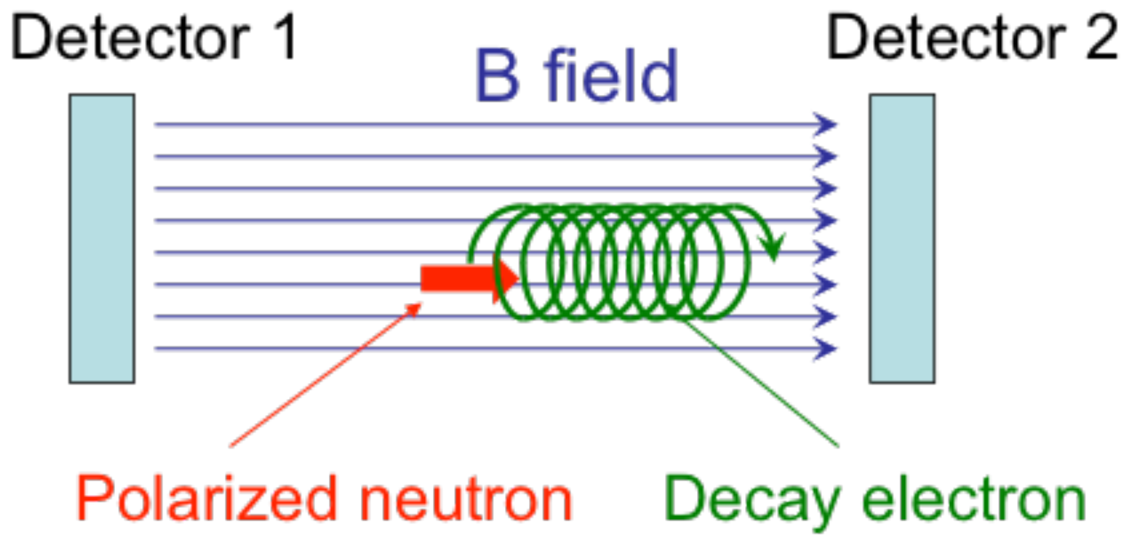


0.21
0.22
0.23
0.24
0.25
From Unitarity
Kaon and hyperon decays
K_{l3} decays (+ $f_+(0)$)
K_{l2}/π_{l2} decays (+ f_K/f_π)
Flavianet
Kaon WG'10
update by M.Moulson
CKM'18
Hyperon decays
τ decays
τ -> s inclusive
τ -> $K\nu$ absolute (+ f_K)
τ branching fraction ratio
τ -> $K\nu$ / τ -> $\pi\nu$ (+ f_K/f_π)
BaBar & Belle
HFAG
update by A.Lusiani
Tau'18
Our result from Belle BR
τ -> $K\pi\nu_\tau$ decays (+ $f_+(0)$, FLAG)
V_{us}

Principle of the *A*-coefficient Measurement (and *B* and *C* as well)



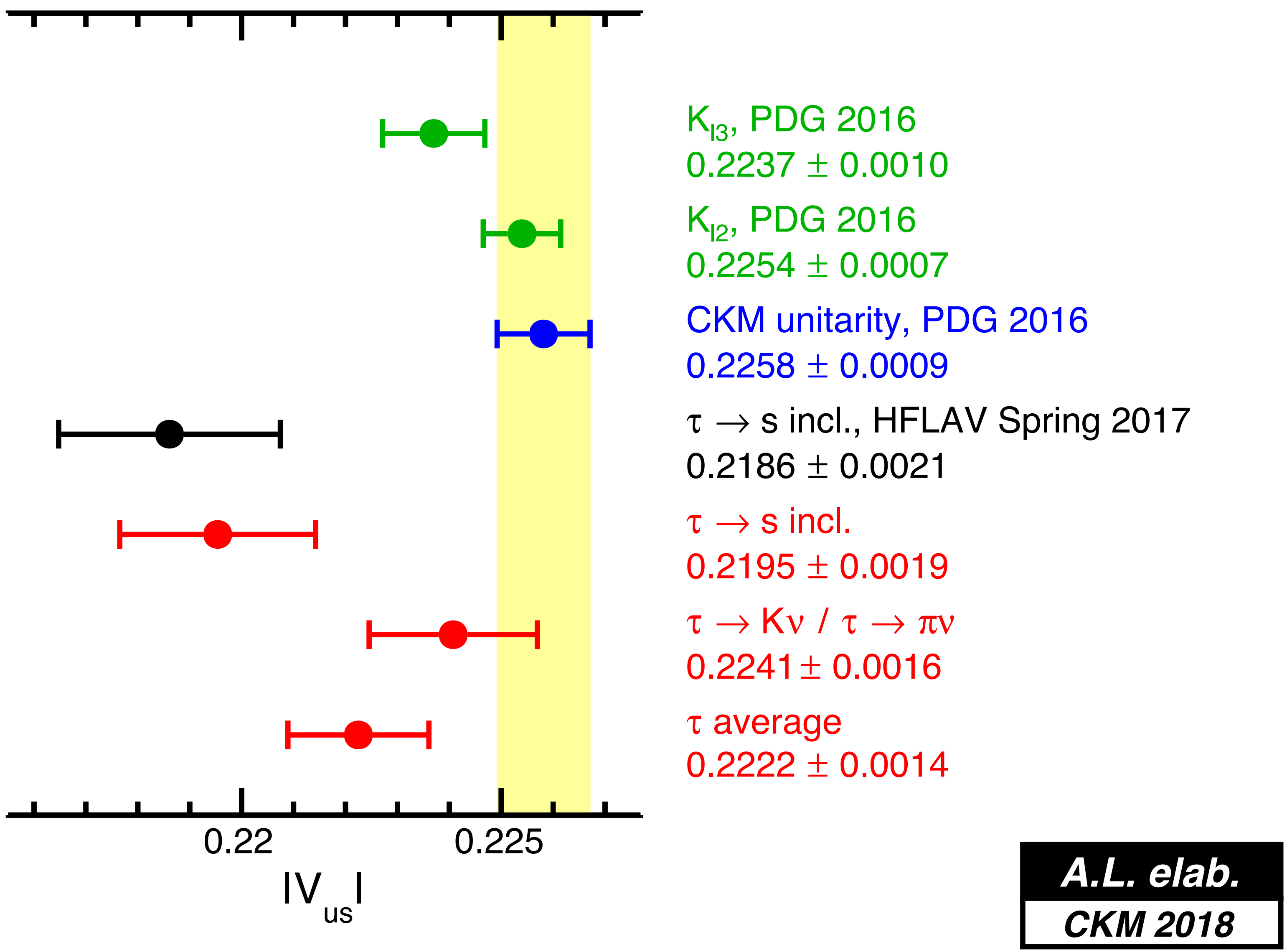
$dW = [1 + \beta P A \cos\theta] d\Gamma(E)$



$$A_{\exp}(E) = \frac{N_1(E) - N_2(E)}{N_1(E) + N_2(E)} \approx \langle P \rangle A \beta \langle \cos\theta \rangle$$

(End point energy = 782 keV)

Determination of V_{us}



Callan-Treiman Low Energy Theorem

Bernard, Oertel, E.P., Stern'06, '08

- Callan-Treiman theorem:

$$C = \bar{f}_0(\Delta_{K\pi}) = \frac{F_K}{F_\pi f_+(0)} + \Delta_{CT} = \underbrace{\frac{F_K |V^{us}|}{F_\pi |V^{ud}|} \frac{1}{f_+(0)|V^{us}|} |V^{ud}|}_{\text{Very precisely known from Br(Kl2/}\pi\text{l2), }\Gamma\text{(Ke3) and }|V_{ud}|} r + \Delta_{CT}$$

$\Delta_{K\pi} = m_K^2 - m_\pi^2$

$\Rightarrow$ $\boxed{B_{\exp} = 1.2446(41)}$

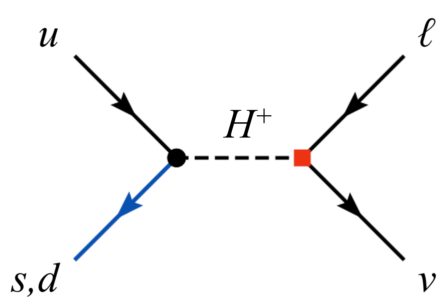
- In the Standard Model : $\boxed{r = 1}$ $\left(\ln C_{SM} = 0.2141(73)\right)$

$\Delta_{CT} = (-3.5 \pm 8).10^{-3}$

NLO value + large error bars in agreement with *Bijnens&Ghorbani'07* *Kastner & Neufeld'08*

- In presence of new physics, new couplings : $\boxed{r \neq 1}$

- Ex:



4.2 Looking for New Physics with K_{l2} and K_{l3}

Bernard, Oertel, E.P., Stern'06, '08

- Callan-Treiman theorem:

$$C = \bar{f}_0(\Delta_{K\pi}) = \frac{F_K}{F_\pi f_+(0)} + \Delta_{CT} = \underbrace{\frac{F_K |\mathbf{V}^{us}|}{F_\pi |\mathbf{V}^{ud}|} \frac{1}{f_+(0)|\mathbf{V}^{us}|} |\mathbf{V}^{ud}|}_{\text{Very precisely known}} \, r + \Delta_{CT}$$

$$\Delta_{K\pi} = m_K^2 - m_\pi^2$$

Very precisely known
from Br(Kl2/πl2), Γ(Ke3) and $|V_{ud}|$

$\Rightarrow$ $\boxed{B_{\exp} = 1.2446(41)}$

- In the Standard Model : $\boxed{r = 1}$ $\left(\ln C_{SM} = 0.2141(73)\right)$ $\Delta_{CT} = (-3.5 \pm 8).10^{-3}$

- In presence of new physics, new couplings : $\boxed{r \neq 1}$

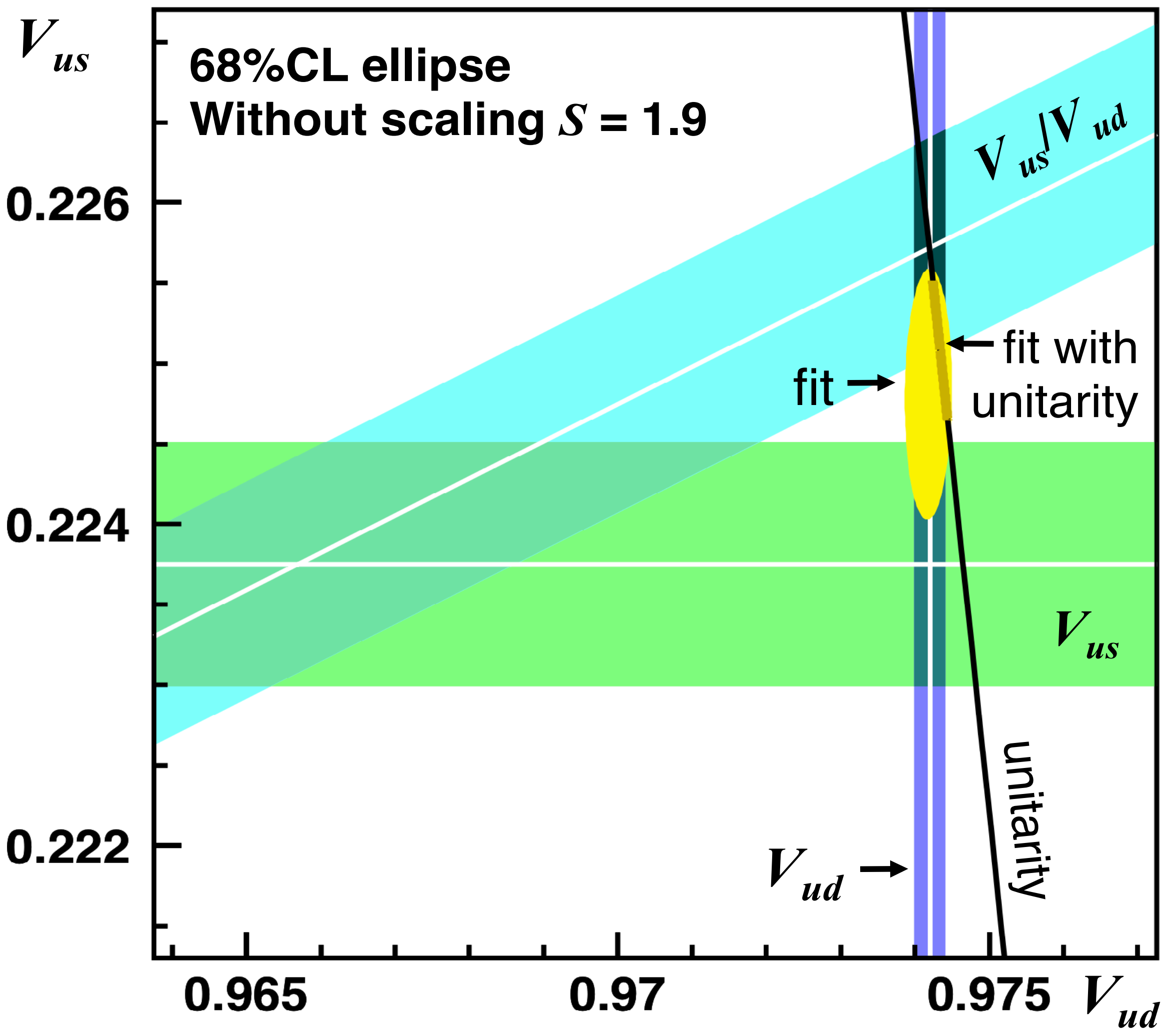
NLO value + large error bars in agreement with
Bijnens&Ghorbani'07
Kastner & Neufeld'08

Experiment K_{e3}+$K_{\mu3}$	ln C
NA48'07 ($K_{\mu3}$ alone)	0.144(14)
KLOE'08	0.204(25)
KTeV'10	0.192(12)
NA48 (preliminary)	?

V_{us} and CKM unitarity: All data, N_f=2+1

N_f **= 2+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ **= 0.9677(27),** f_K/f_π **= 1.1946(34)**

$|V_{ud}|$ = **0.97420(21)**
$|V_{us}|$ = **0.2238(8)**
$|V_{us}|/|V_{ud}|$ = **0.2317(7)**



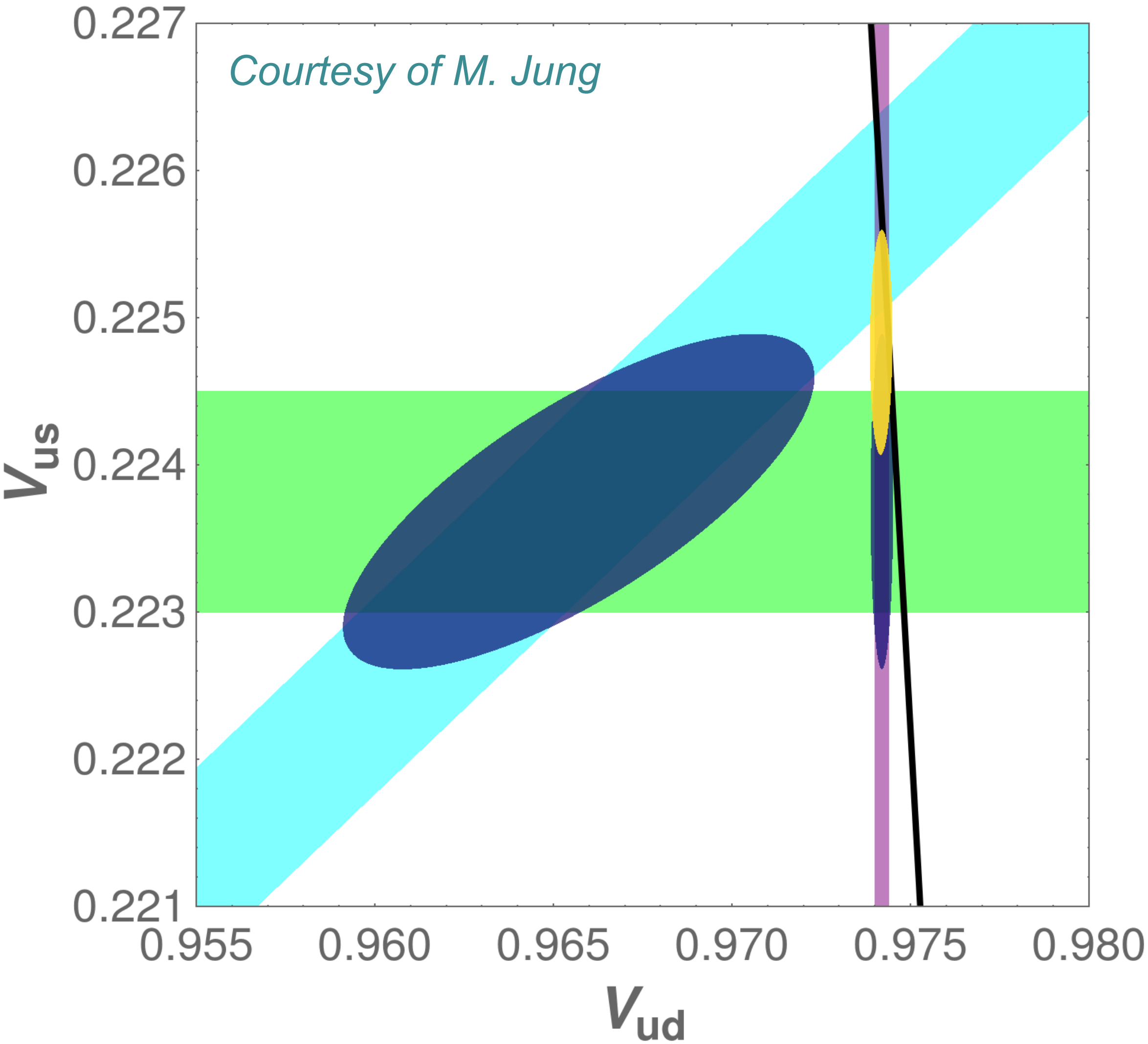
Fit results, no constraint

V_{ud} = **0.97418(21)**
V_{us} = **0.2248(5)**
χ^2/ndf = 3.7/1 (6%)
Δ_{CKM} = **–0.0004(5)**
–0.9σ

5.5 V_{us} and CKM unitarity: All data, N_f=2+1

N_f = 2+1: Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$

$f_+(0)$ = 0.9677(27), f_K/f_π = 1.1946(34)



$|V_{ud}|$ = 0.97420(21)
$|V_{us}|$ = 0.2238(8)
$|V_{us}|/|V_{ud}|$ = 0.2317(7)

Fit results, no constraint

V_{ud} = **0.97418(21)**

V_{us} = **0.2248(5)**

χ^2/ndf = 3.7/1 (6%)

Δ_{CKM} = **–0.0004(5)**

-0.9σ

Only kaons:

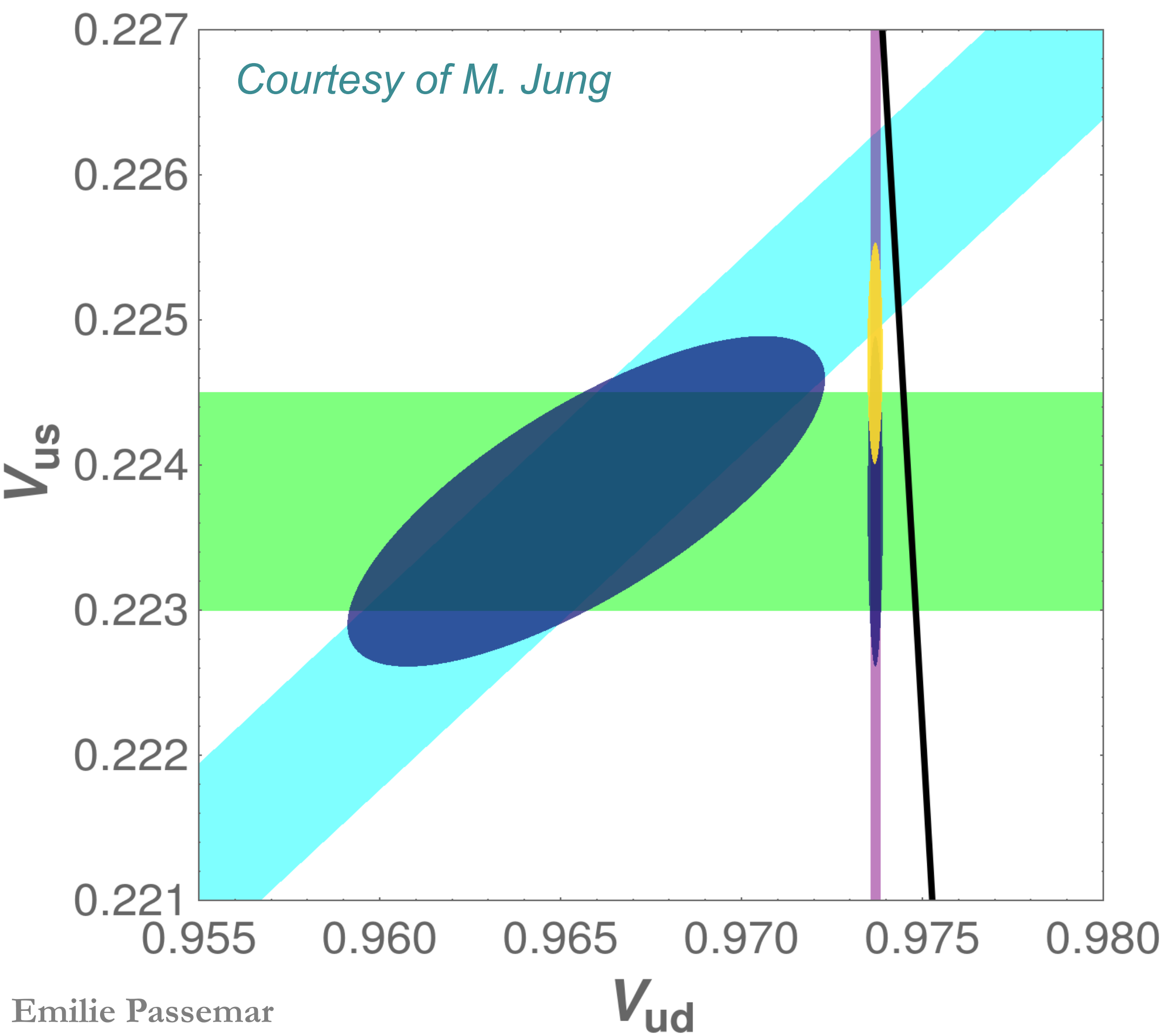
V_{ud} = 0.9657(44)

V_{us} = 0.2238(8)

V_{us} and CKM unitarity: All data, N_f=2+1, New V_{ud}

N_f = 2+1: Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$

$f_+(0)$ = 0.9677(27), f_K/f_π = 1.1946(34)



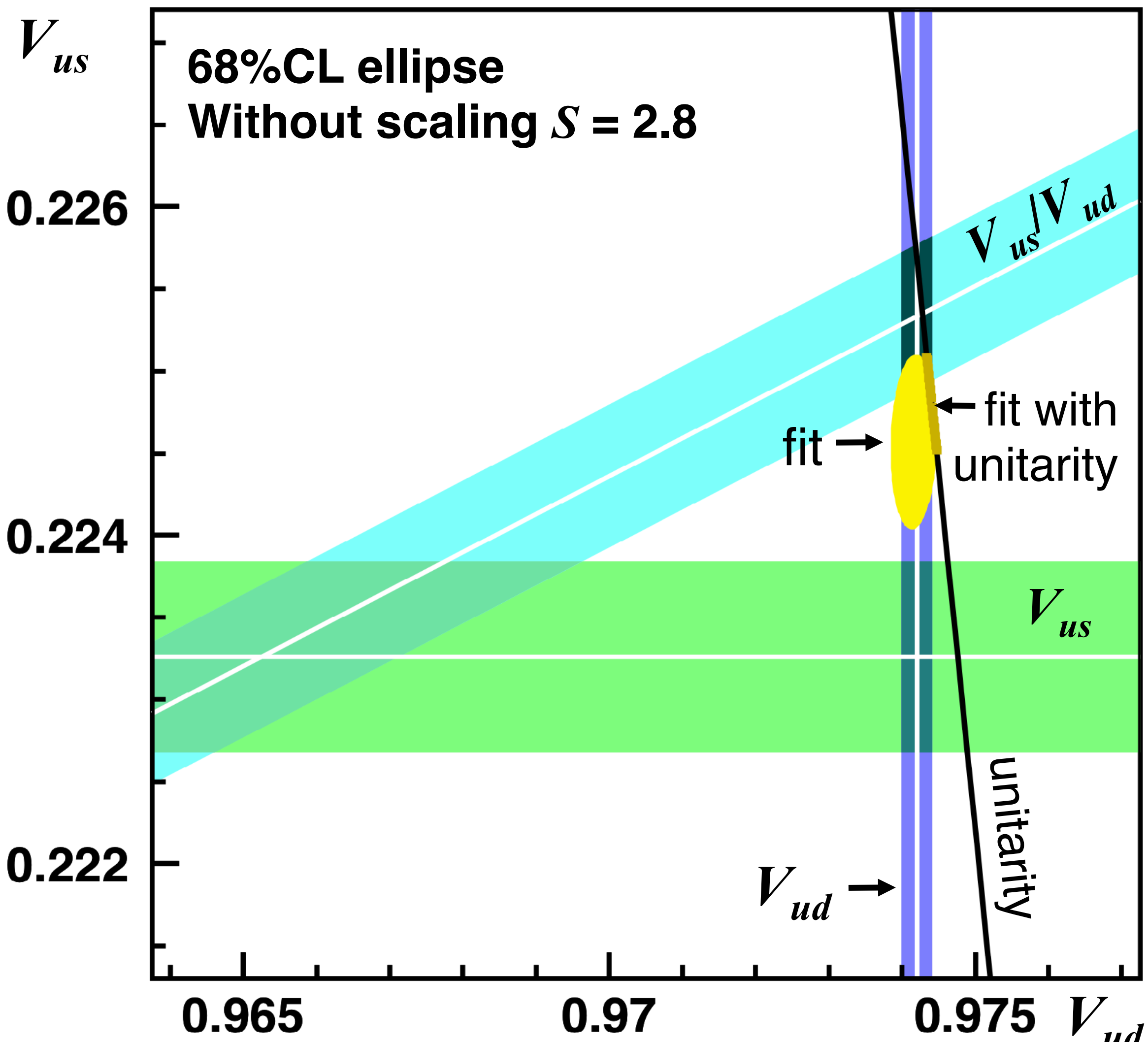
$$\boxed{\Delta_{CKM} = -0.0014(4)}$$

-3.9σ

V_{us} and CKM unitarity: All data, N_f=2+1+1

N_f = 2+1+1: Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ = 0.9698(17), f_K/f_π = 1.1967(18)

$|V_{ud}|$ = 0.97420(21)
$|V_{us}|$ = 0.2233(6)
$|V_{us}|/|V_{ud}|$ = 0.2313(5)



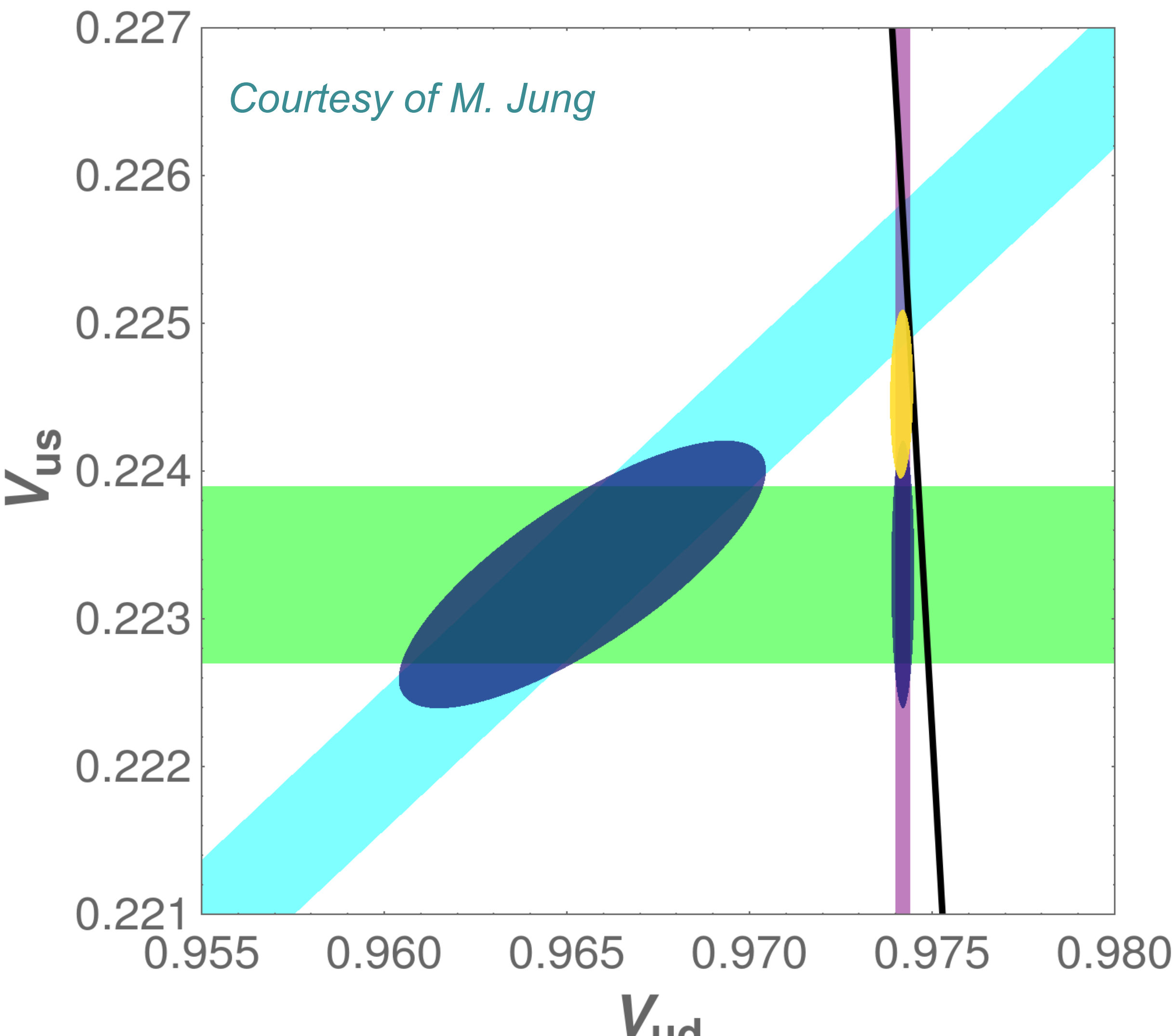
Fit results, no constraint

V_{ud} = **0.97416(21)**
V_{us} = **0.22457(35)**
χ^2/ndf = 8.0/1 (0.5%)
Δ_{CKM} = **−0.0005(4)**
−1.3σ

V_{us} and CKM unitarity: All data, N_f=2+1+1

N_f **= 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$
$f_+(0)$ **= 0.9698(17),** f_K/f_π **= 1.1967(18)**

$|V_{ud}|$ **= 0.97420(21)**
$|V_{us}|$ **= 0.2233(6)**
$|V_{us}|/|V_{ud}|$ **= 0.2313(5)**



Fit results, no constraint

V_{ud} **= 0.97416(21)**
V_{us} **= 0.22457(35)**
χ^2/ndf = 8.0/1 (0.5%)
Δ_{CKM} **= –0.0005(4)**
-1.3σ

Only kaons:

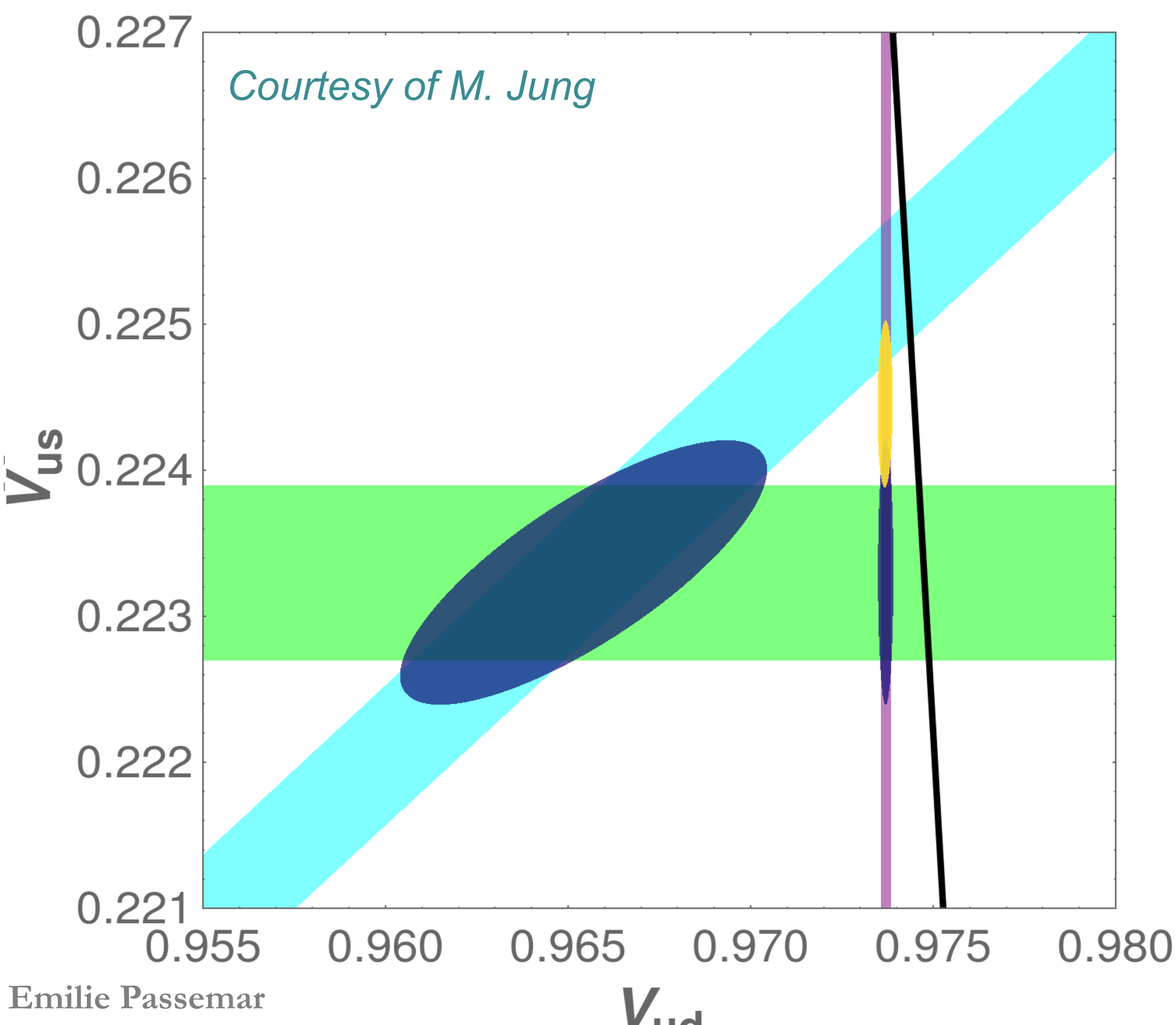
V_{ud}=0.9657(36)

V_{us} = 0.2233(6)

V_{us} and CKM unitarity: All data, N_f=2+1+1, New V_{ud}

N_f **= 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$

$f_+(0)$ **= 0.9698(17),** f_K/f_π **= 1.1967(18)**



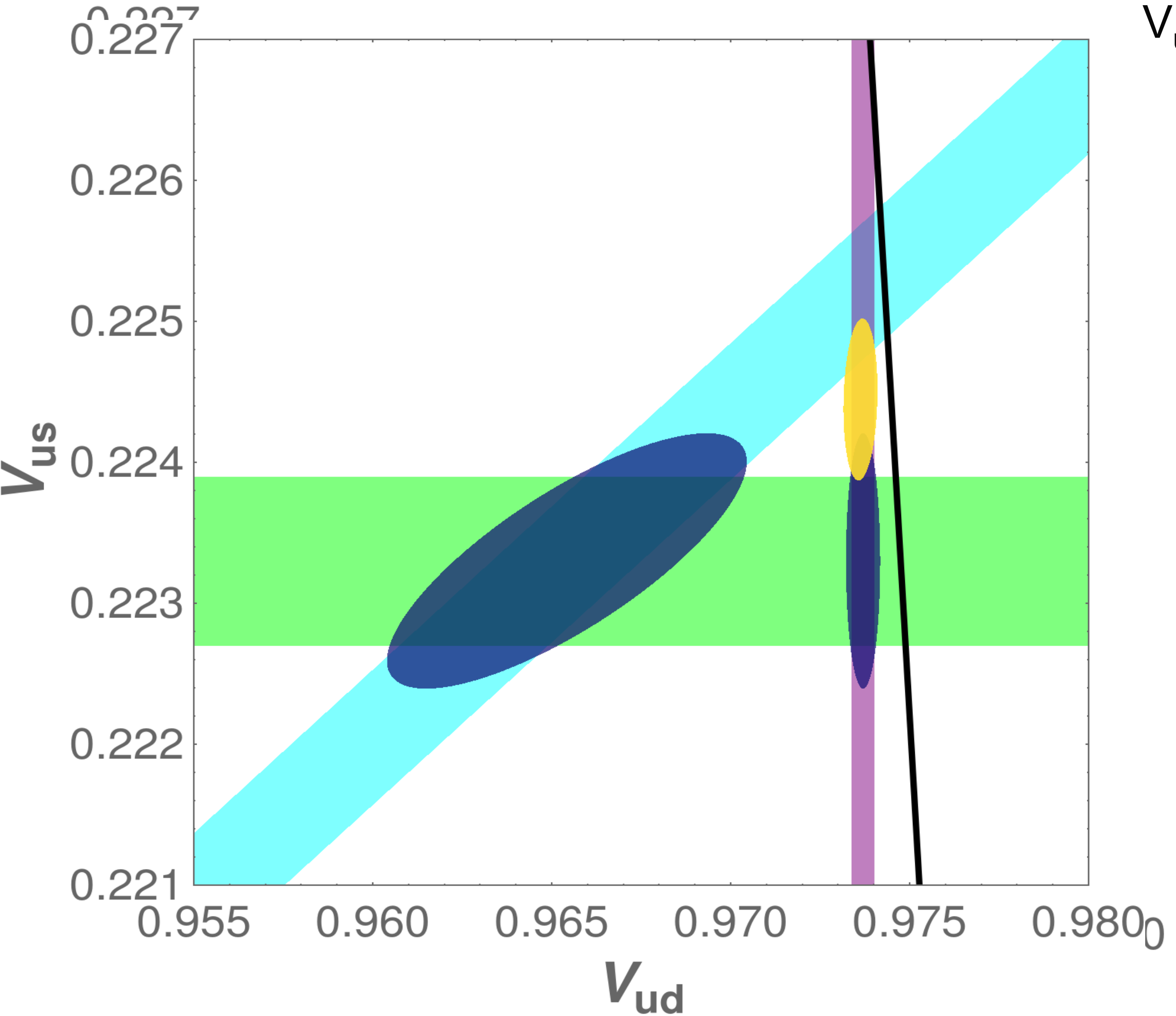
$\boxed{\Delta_{CKM} = -0.0016(3)}$

-4.3σ

V_{us} and CKM unitarity: All data, N_f=2+1+1

***N_f = 2+1+1:** Fit to results for $|V_{ud}|$, $|V_{us}|$, $|V_{us}|/|V_{ud}|$*

$f_+(0)$ = 0.9698(17), f_K/f_π = 1.1967(18)



V_{ud} from Marciano & Sirlin'19

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

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

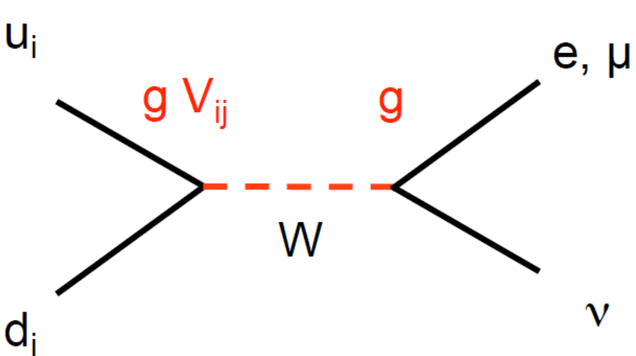
    Description of the weak interactions:

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

Gauge coupling

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

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



Updates: $K^{\pm}$ BRs and lifetimes