Summary of WG1

$|V_{cd}|$, $|V_{cs}|$, $|V_{ud}|$, $|V_{us}|$

CKM 2018, Heidelberg, Sep 21st, 2018

Tanmoy Bhattacharya, Hailong Ma, Rainer Wanke

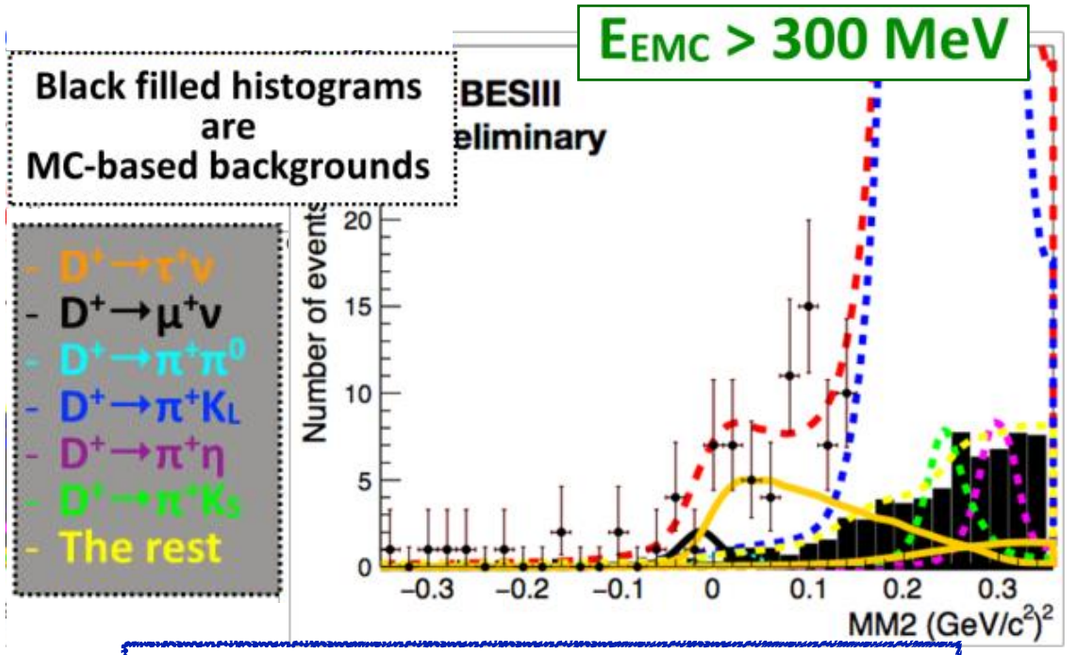
$|V_{cs}|$ & $|V_{cd}|$

Youhua Yang

$|V_{cs}|$ & $|V_{cd}|$ from (semi)leptonic D decays

Currently: <u>BES III only player</u>

- $D^+ \to \tau^+ \nu$: **First observation!**



137 ± 27 $D^+ \to \tau^+ \nu \to \pi^+ \bar{\nu} \nu$

$\mathcal{B}(D^+ \to \tau^+ \nu) = (1.20 \pm 0.24_{stat}) \times 10^{-3}$

in agreement with SM expectation.

- $D_{(s)}^+ \to \mu^+ \nu$: Improved BR & $f_{D(s)} \times |V_{cd(cs)}|$.

  ➜ Most precise single measurements.

- $D^+ \to K^0/\pi^0\, e^+ \nu$, $D^0 \to K^-/\pi^-\, \mu^+ \nu$:

  Improved BRs, form factors, $f_+(0) \times |V_{cs}|$, and LFV.

  $D^+ \to K_L\, e^+ \nu$: $f_+(0) \times |V_{cs}| = 0.728(6)(11)$

  $D^0 \to K^-\, \mu^+ \nu$: $f_+(0) \times |V_{cs}| = 0.718(4)(3)$

Alan Schwartz, Adam Davis

$|V_{cs}|$ & $|V_{cd}|$ from (semi)leptonic D decays

Prospects: Belle (0.9 ab^{-1}) → **Belle II** (50 ab^{-1})

- $D_s^+ \to \mu^+ \nu$: ~ 500 → 27000 events ➜ $\delta\,|V_{cs}| = 0.003_{stat}$
- $D_s^+ \to \tau^+ \nu$: ~ 2200 → 120000 events ➜ $\delta\,|V_{cs}| = 0.003_{stat}$
- $D^+ \to \mu^+ \nu$: → 1250 events ➜ $\delta\,(f_D \times |V_{cs}|) = 0.65_{stat}$ MeV

(Cleo-c: 1.2 MeV)

- $D \to K/\pi\, l\, \nu$: Huge samples of $\mathcal{O}(10^5 - 10^6)$ events.

  ➜ **Precision measurements** of $|V_{cs}|$ & $|V_{cd}|$.

Physics run with full Belle II detector to begin in 2019

Alan Schwartz, Adam Davis

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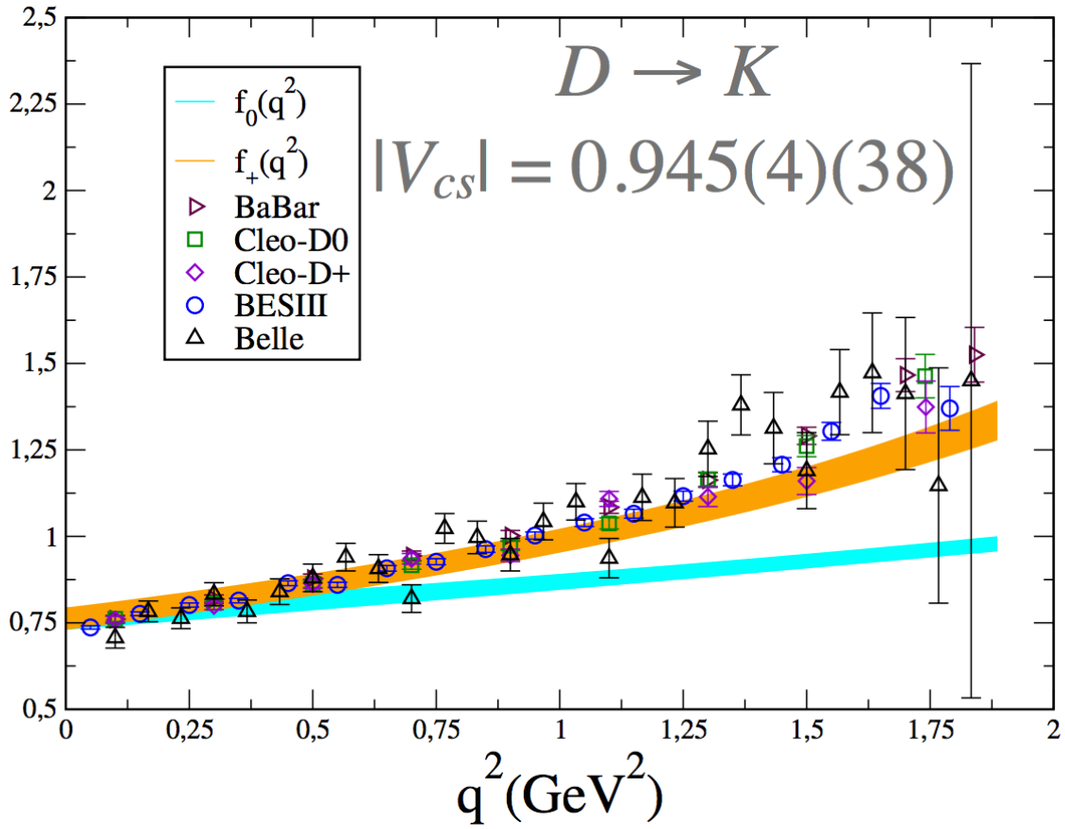
And also LHCb may contribute a lot!

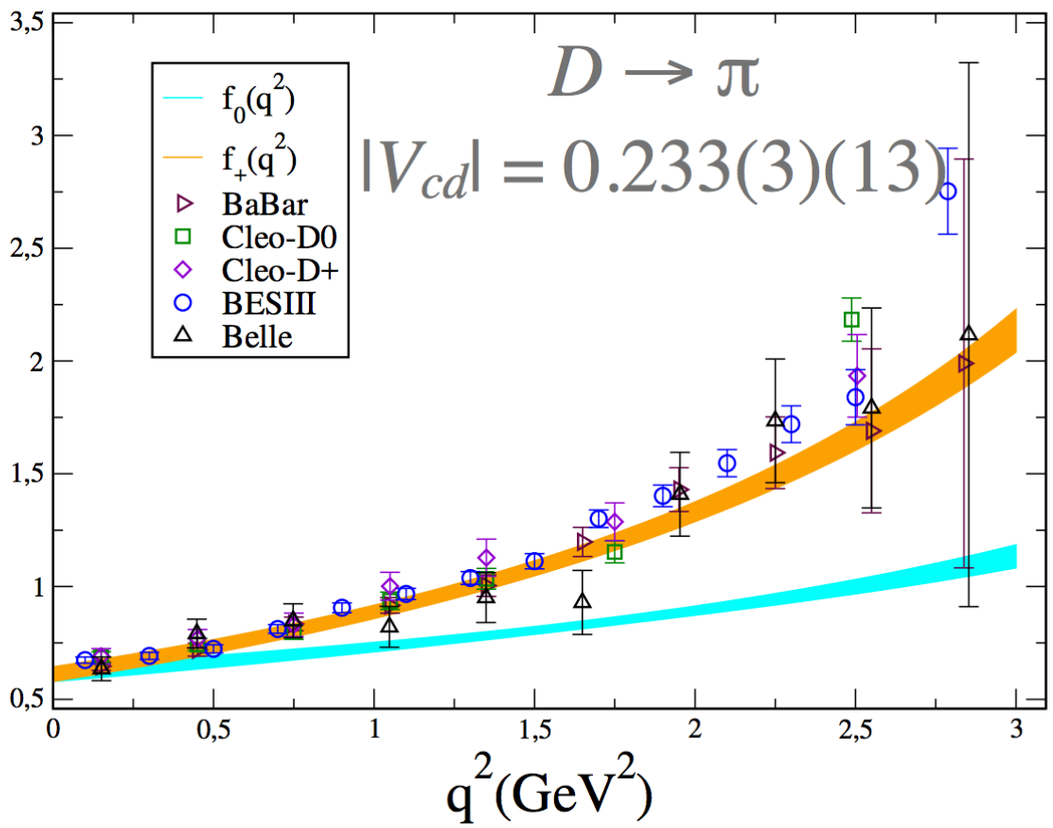
Andreas Kronfeld

$|V_{cs}|$ & $|V_{cd}|$ from (semi)leptonic D decays

Progress on lattice form factors

- New results from ETM removes hypercubic artifacts [arXiv:1706.03017] and determines CKM [arXiv:1706.03657].





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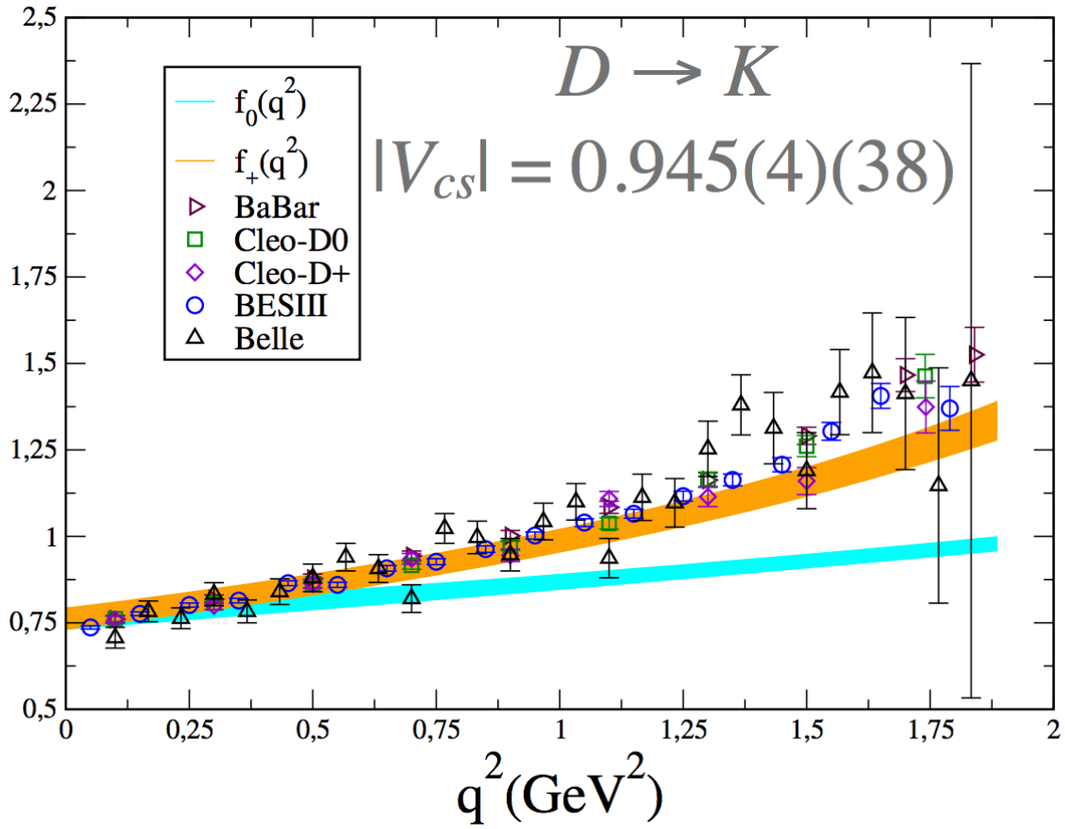
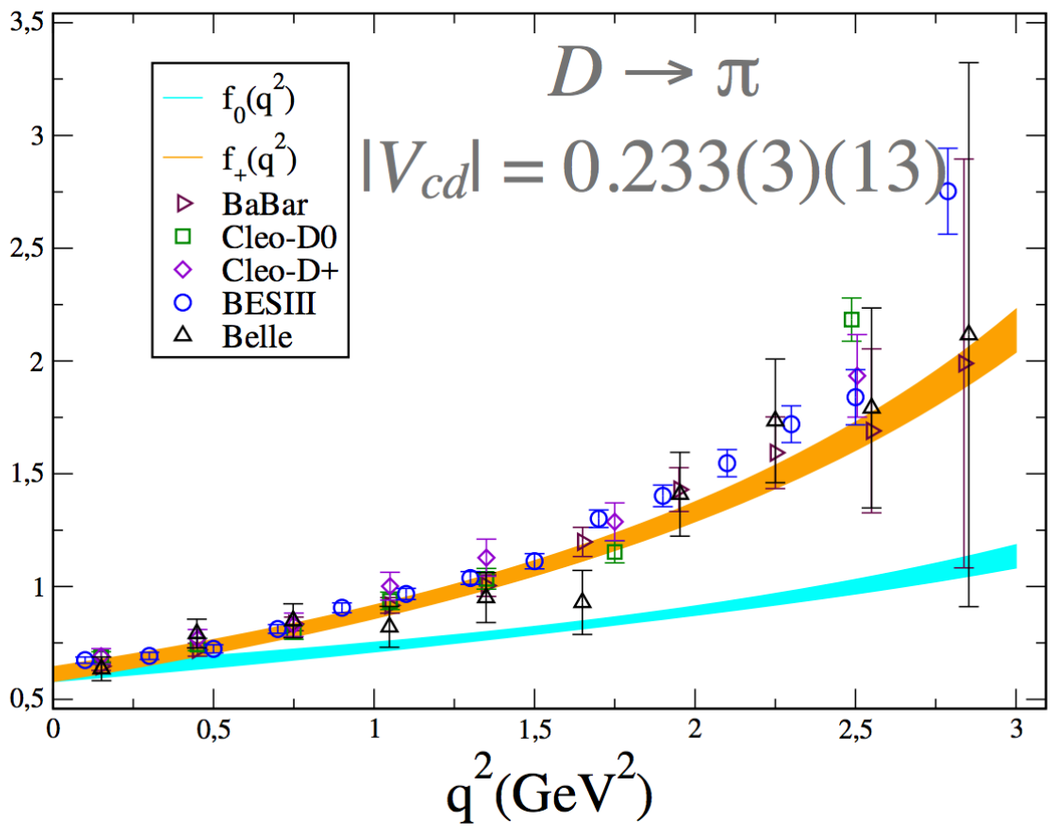
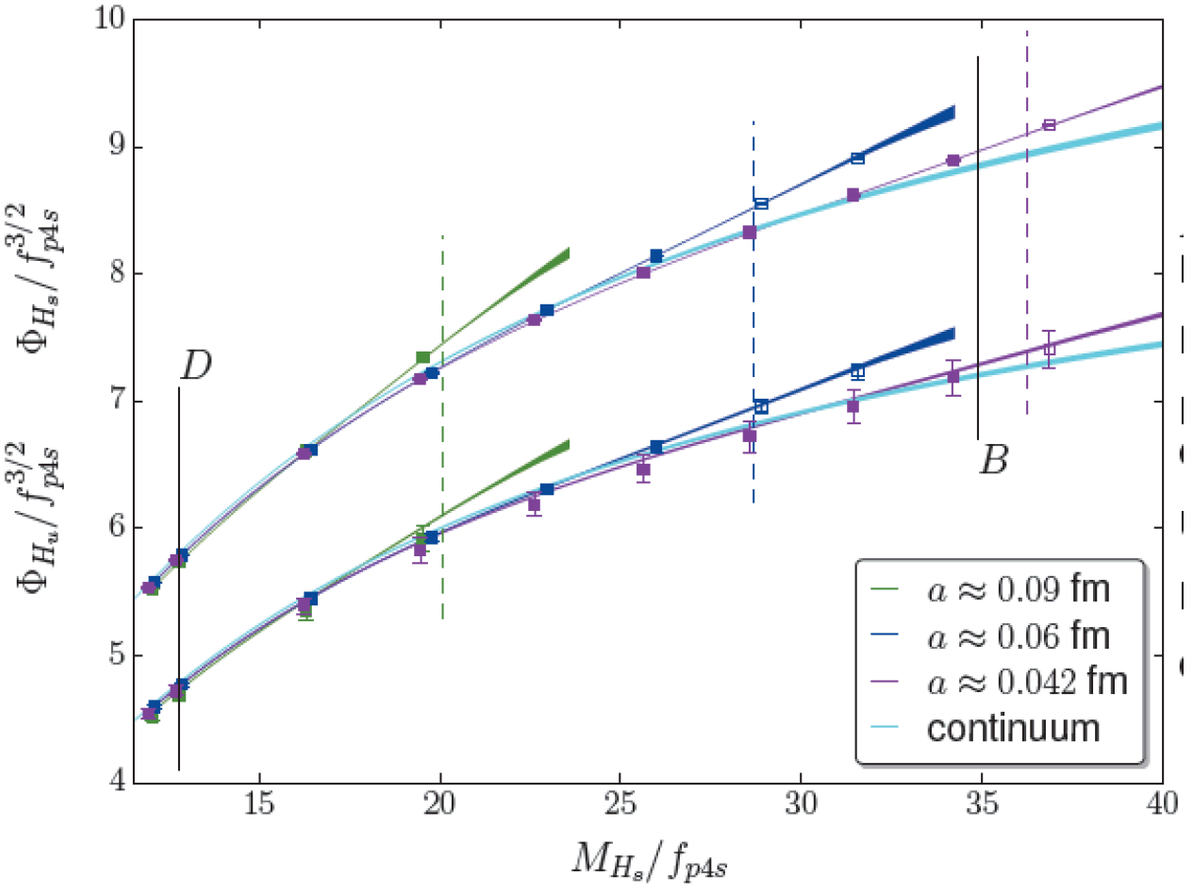
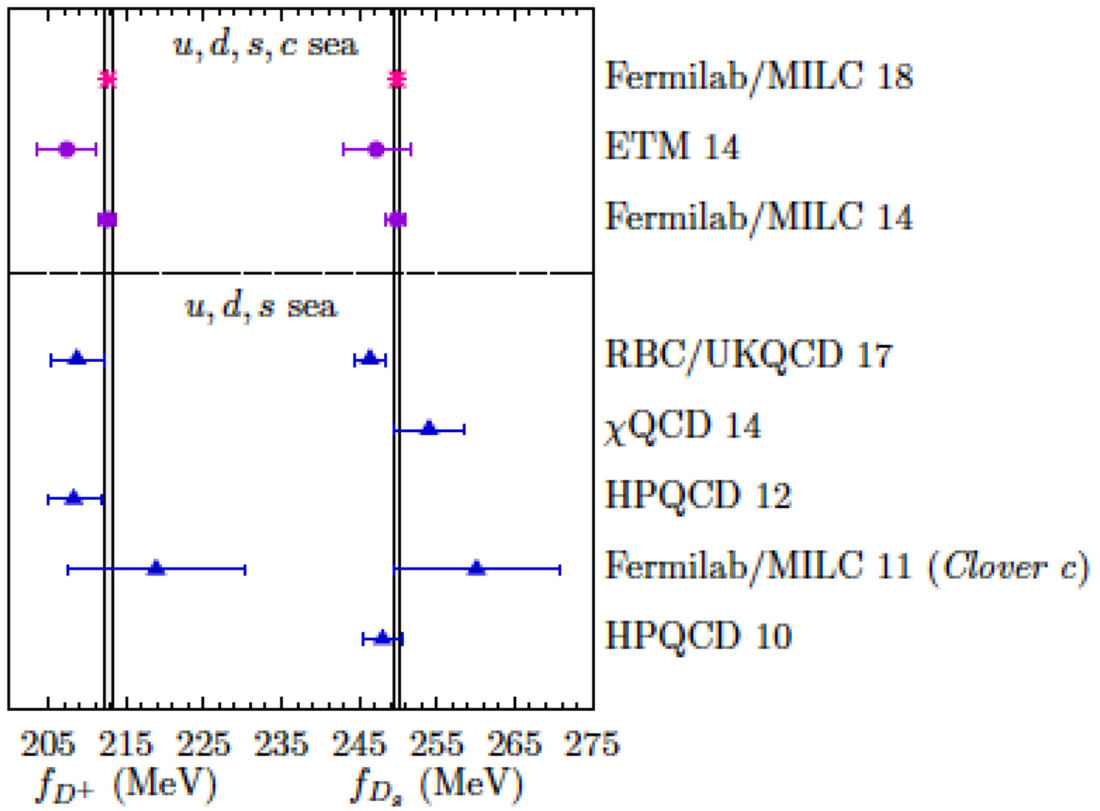




Leptonic decays: decay constants from the lattice





Lattices fine enough to reach the charm mass

$|V_{ud}|$

Alexander Saunders, Emilie Passemar

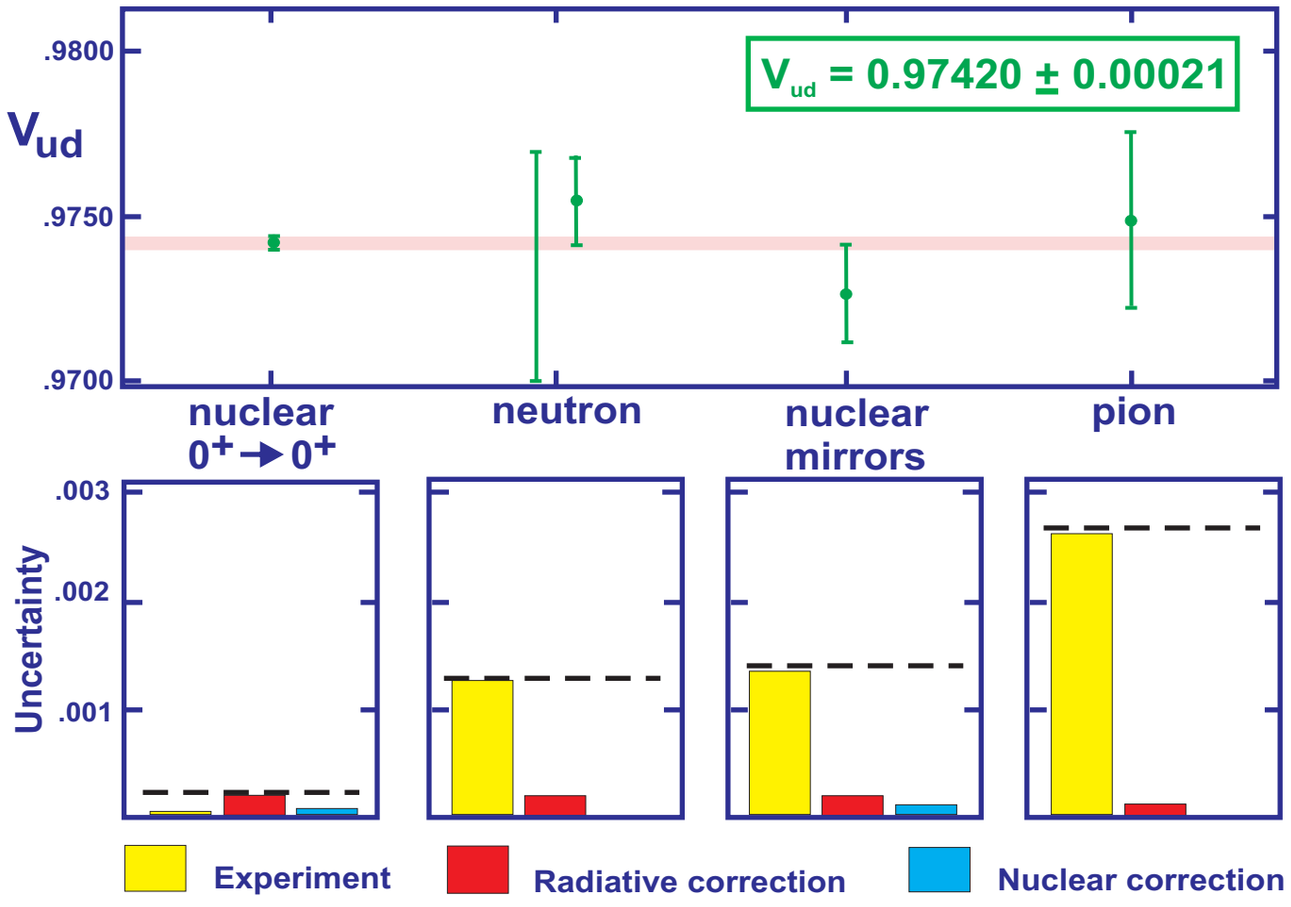
Measurement of $|V_{ud}|$

Towner@CIPANP'18

Traditional method:

- $|V_{ud}|$ from $0^+ \rightarrow 0^+$ transitions.
- Practically not changed since 2016, today (CIPANP'18):

$$|V_{ud}| = 0.97420(21)$$



- Currently discussion about **radiative corrections** (Seng, Gorchtein, Patel, Ramsey-Musolf, arXiv:1807.10197):

New calculation of γW-box contribution to universal radiative correction using dispersion relations and DIS structure functions, but contribution possibly already in part included in structure-dependent radiative corrections.

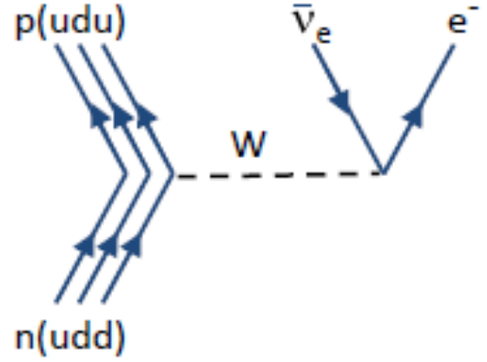
- Would shift $|V_{ud}|$ by –1.5 σ to $|V_{ud}| = 0.97366(15)$.
- **Needs verification!**

Alexander Saunders

$|V_{ud}|$ from Neutrons

Only two free parameters in the standard model:

- Decay asymmetry $\lambda = g_A/g_V$
- Lifetime τ_n
- Needs $\delta\lambda/\lambda \approx 3 \times 10^{-4}$ and $\delta\tau_n \approx 0.3$ s to compete with $0^+ \rightarrow 0^+$ transitions.



$$n \rightarrow p + e^- + \bar{\nu}_e$$

Recent developments:

- **UCNA final result** confirms newer g_A/g_V.
- **Perkeo III preliminary result** confirms newer g_A/g_V.
- Progress in **LQCD** on g_A/g_V.
- **UCNτ lifetime** confirms bottle value.

$$\tau_n = \frac{4908.7 \pm 1.9\ s}{|V_{ud}|^2\left(1 + 3\lambda^2\right)}$$

experiment

$$\lambda = g_A/g_V$$

experiment or LQCD

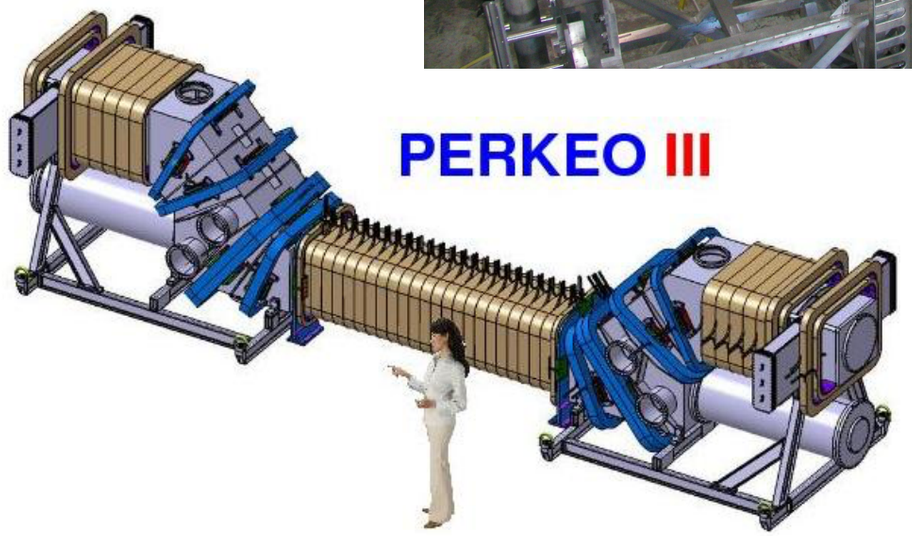
$|V_{ud}|$ from Neutrons – g_A/g_V

New & final UCNA measurement 2018:

- 2007-13 UCN data at Los Alamos.
- $\lambda = g_A/g_V = -1.2772(20)$.
- $\delta\lambda/\lambda \approx 15 \times 10^{-4}$.

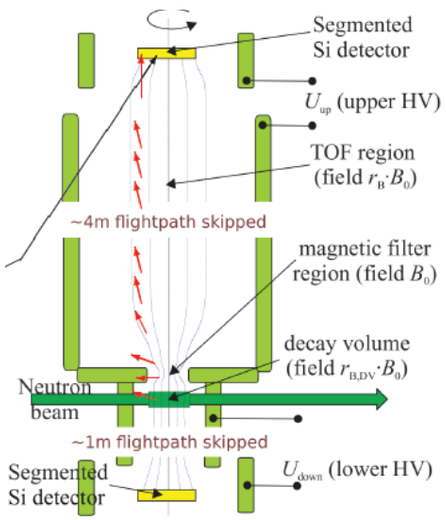
Perkeo III (Heidelberg):

- 60 days of data-taking.
- Expected uncertainty: $\delta\lambda/\lambda \approx 5 \times 10^{-4}$.
- Results very soon.



Nab experiment (Oak Ridge):

- In final construction.
- Goal: $\delta\lambda/\lambda \approx 5 \times 10^{-4}$.



Chia Cheng Chang, Rajan Gupta

$|V_{ud}|$ from Neutrons – g_A/g_V

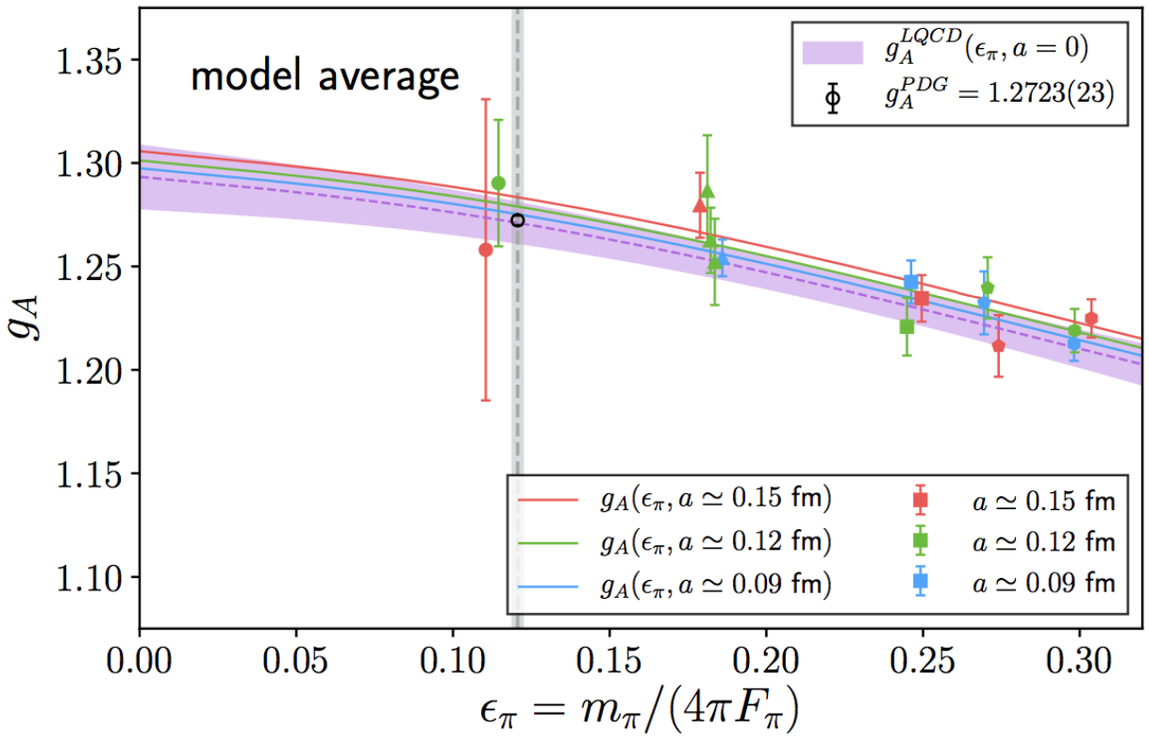
Lattice QCD for g_A/g_V

Best claimed uncertainty still 6x experimental.

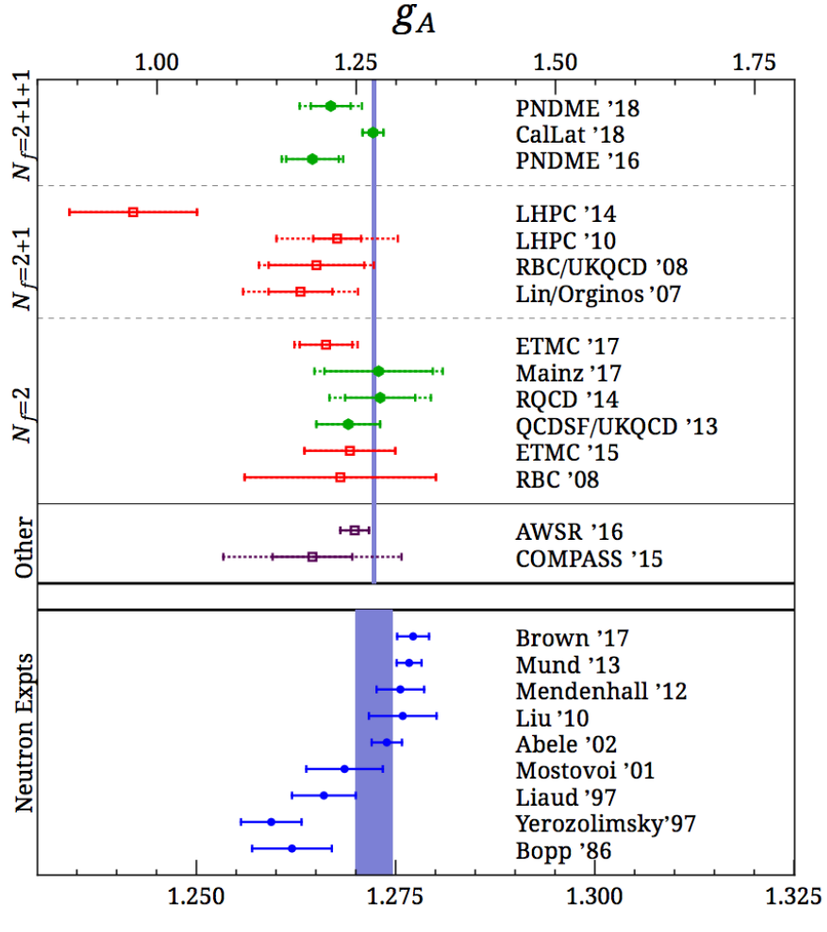
$g_A^{\rm QCD} = 1.2711(126)$ Nature 558, 91-94 (2018)

$g_A^{\rm UNCA} = 1.2772(020)$ Phys. Rev. C 97, 035505

Lattice error budget still contested: two groups get different results.



Extrapolation of results to the physical quark mass

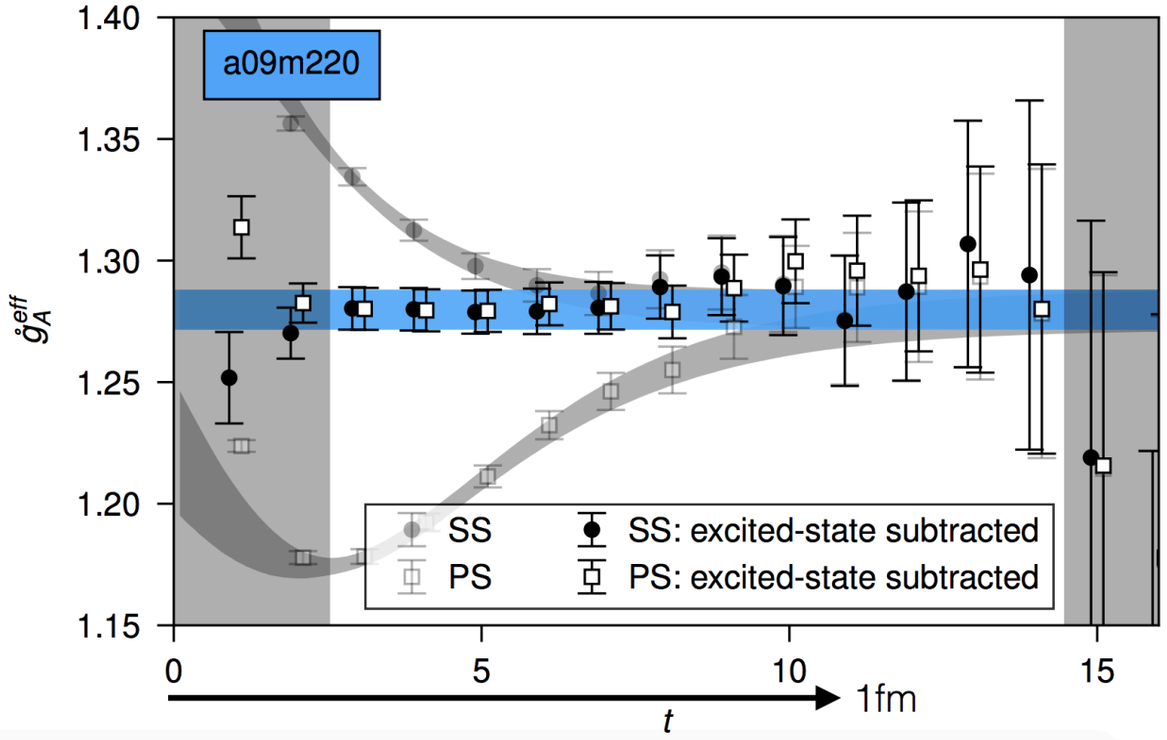


Comparison of lattice with experiment

$|V_{ud}|$ from Neutrons – g_A/g_V

	PNDME	CalLat
a15m310	1.228(25)	1.215(12)
a12m310	1.251(19)	1.214(13)
a12m220S	1.224(44)	1.272(28)
a12m220	1.234(25)	1.259(15)
a12m220L	1.262(17)	1.252(21)
a09m310	1.235(15)	1.236(11)
a09m220	1.260(19)	1.253(09)

The two collaborations agree on the raw data but not on the errors



CalLat has smaller errors because they extract from data contaminated by multiple excited states by effectively a single subtraction. PNDME plays safe. Are excited state effects smaller than expected in g_A?

Extrapolation from heavier quark masses (physical point has low statistics) and coarser lattices (finest lattice not analyzed). PNDME has 0.06 fm and see a decrease. Assign larger errors?

Have all systematics been properly estimated? Cross-checks are being performed…

Alexander Saunders

$|V_{ud}|$ from Neutrons — Lifetime

UCNτ at Los Alamos:

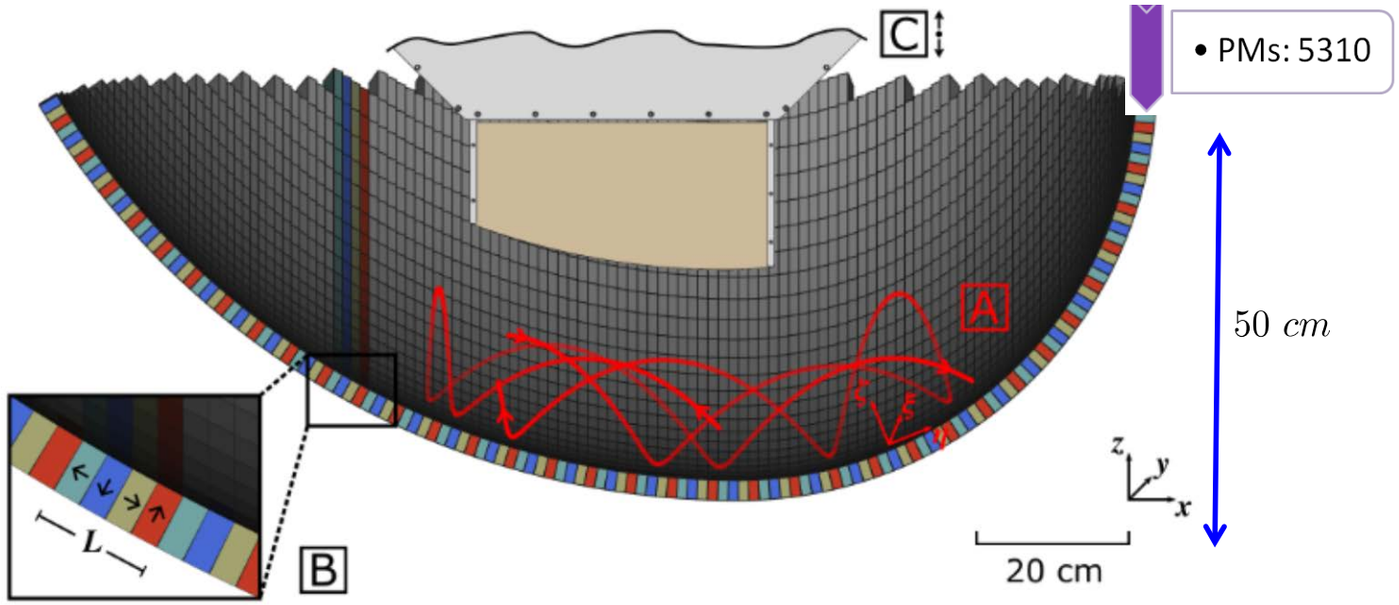
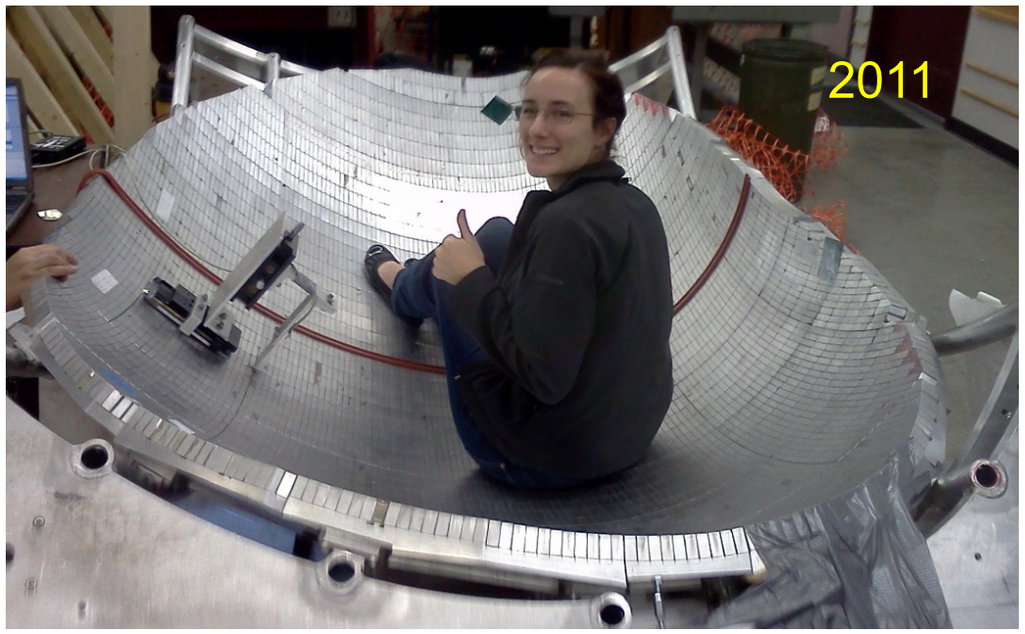
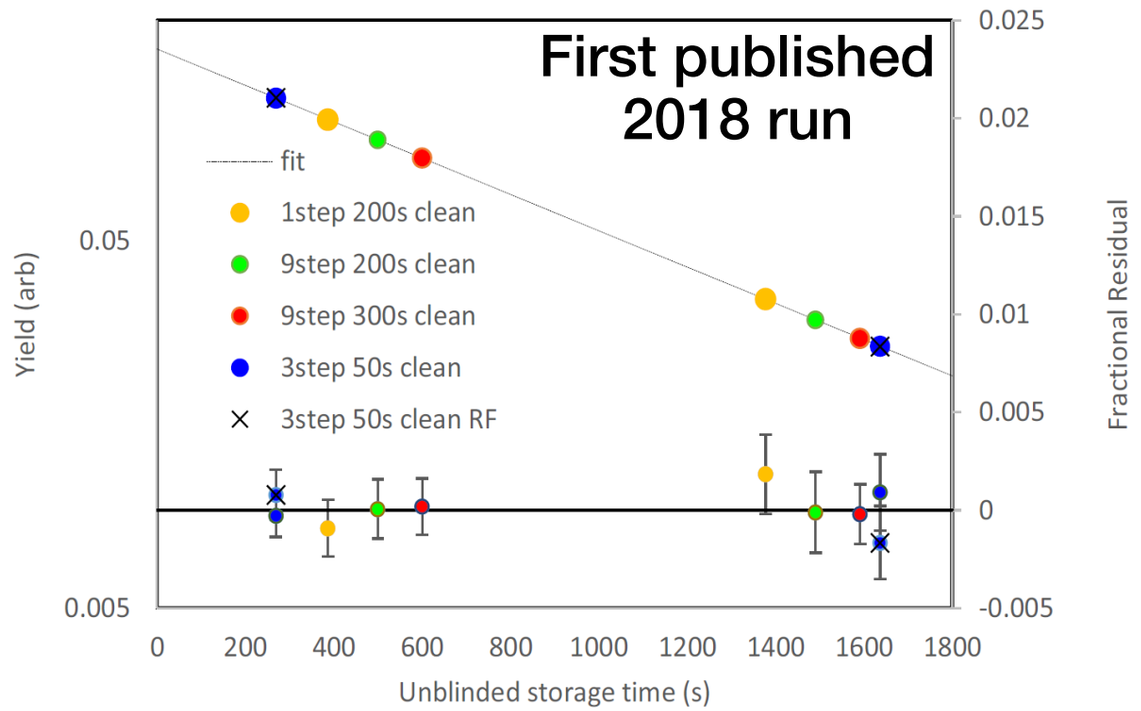


Figure 1: The UCNτ apparatus. **A** UCN trajectory inside the trap which enters and leaves the page as indicated. **B** Arrows indicating the magnetization direction for the Halbach Array. Colored strips show rows of identical magnetization. **C** The *in-situ* detector which can be raised out of the trap and lowered to the bottom. The khaki color is the active area of ^{10}B.

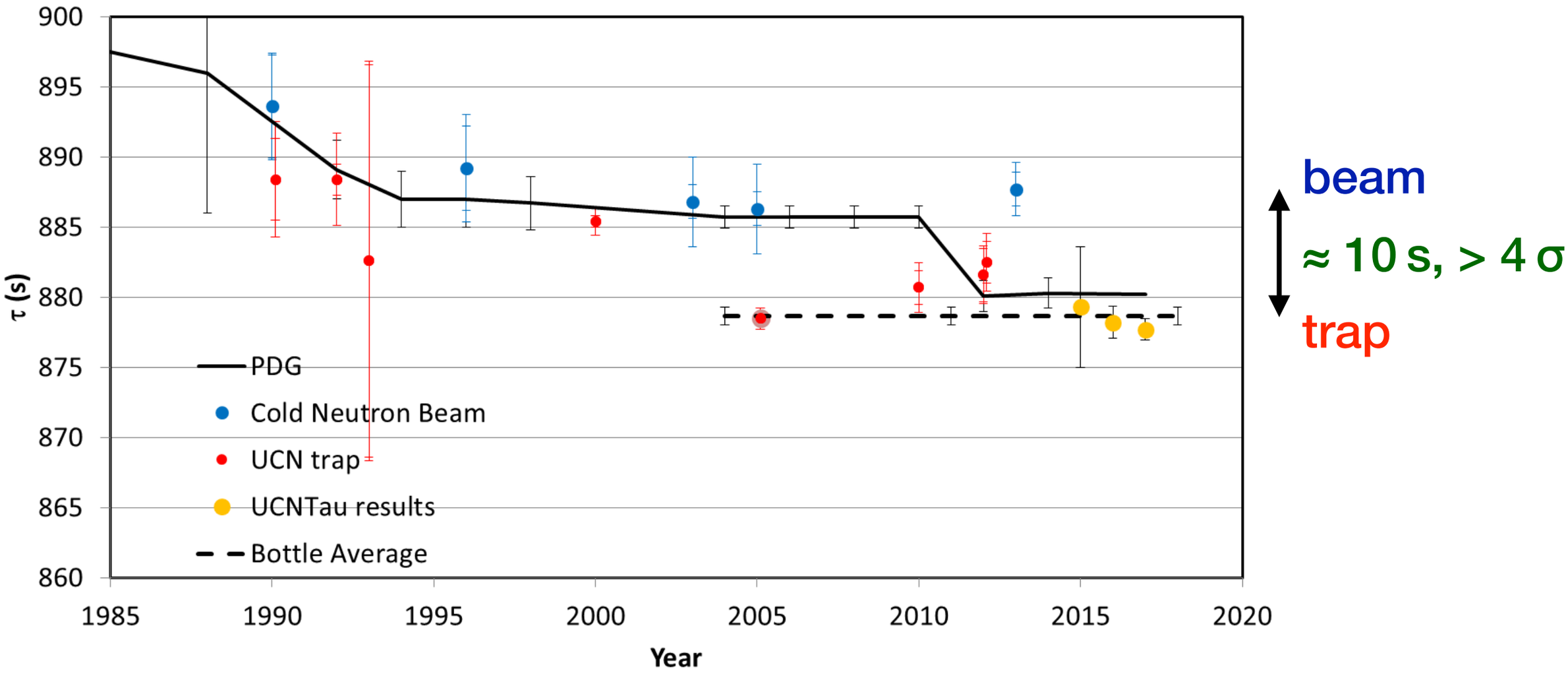




Pattie et al., Science 360, p. 627 (2018).

$|V_{ud}|$ from Neutrons — Lifetime

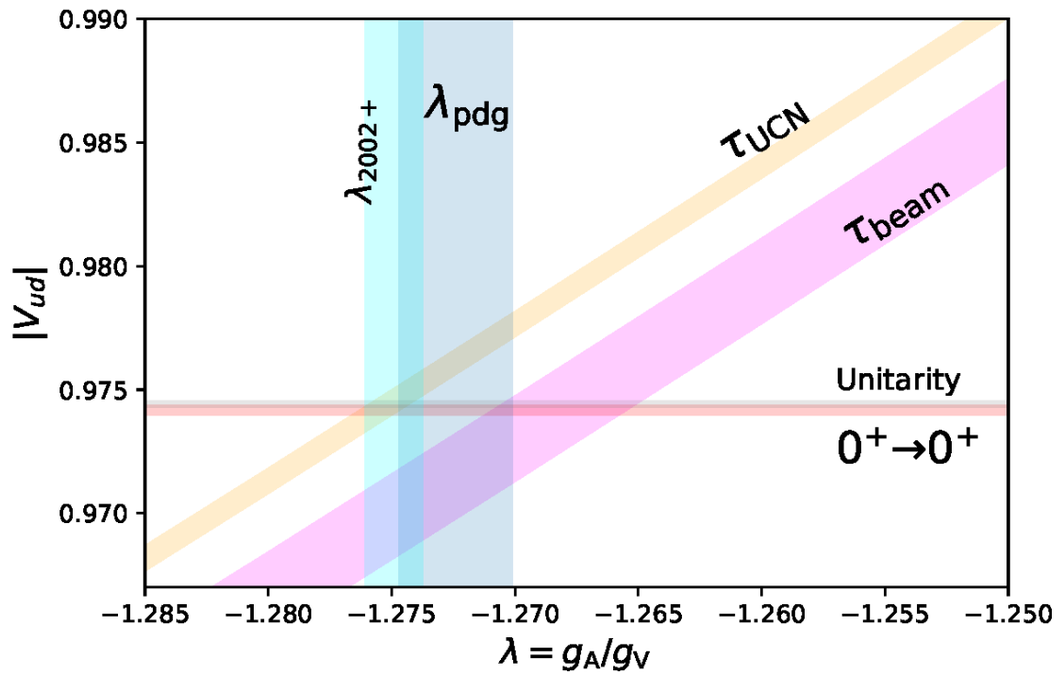
UCNτ results confirm trap results with independent systematics:



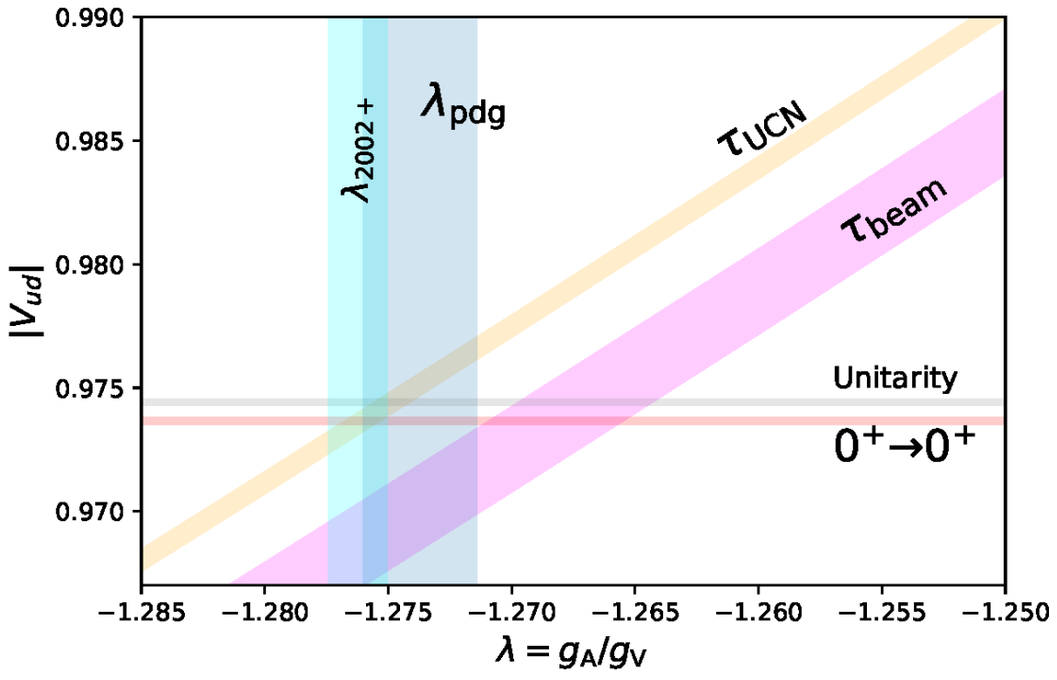
$|V_{ud}|$ from Neutrons

Improvements in the last half year:

6 months ago



Today



$|V_{us}|$

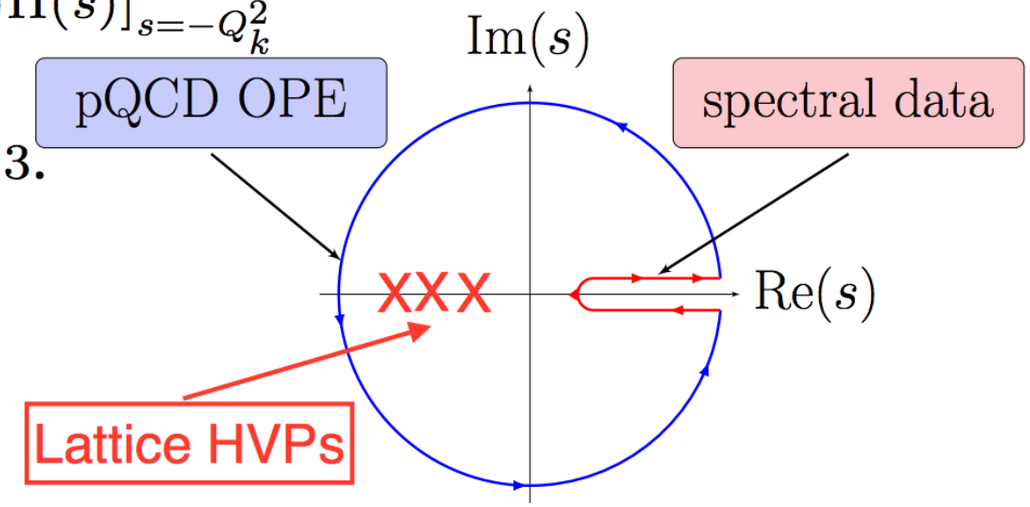
$|V_{us}|$ from τ Decays — LQCD

Progress in Lattice QCD

- If we have a reliable estimate for $\Pi(s)$ in Euclidean (space-like) points, $s = -Q_k^2 < 0$, we could extend the FESR with weight function $w(s)$ to have poles there,

$$\int_{s_{th}}^{\infty} w_N(s) \mathrm{Im}\Pi(s) = \pi \sum_{k=1}^{N} \mathrm{Res}[w_N(s)\Pi(s)]_{s=-Q_k^2}$$

- $|s| \to \infty$ circle integral vanishes for $N_p \geq 3$.

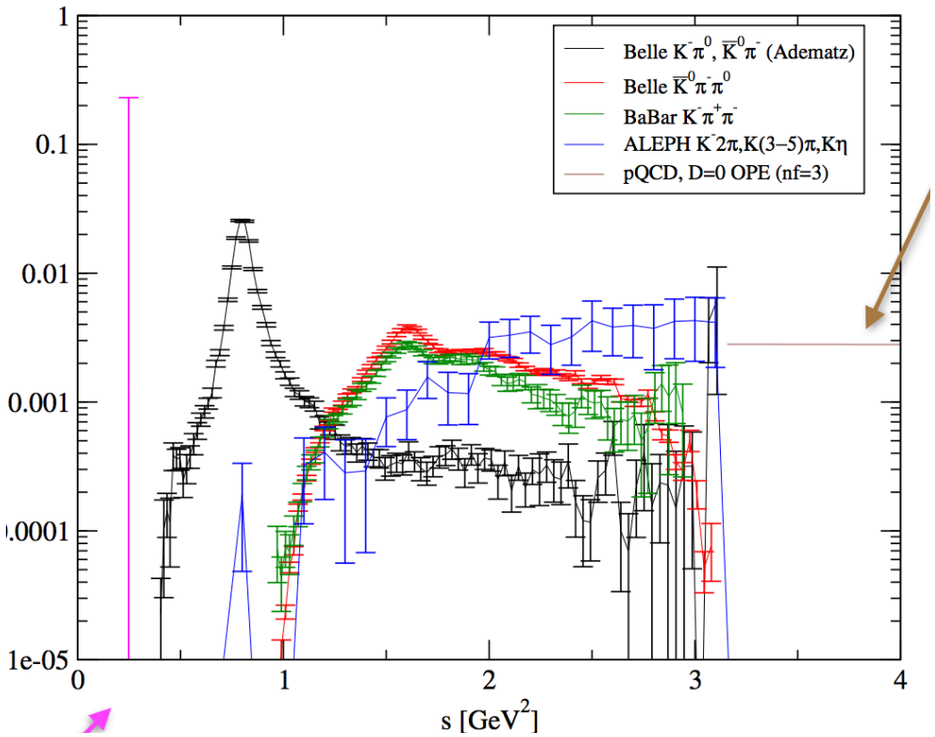


Lattice data allow weights that suppress the uncertain inputs in sum rules.

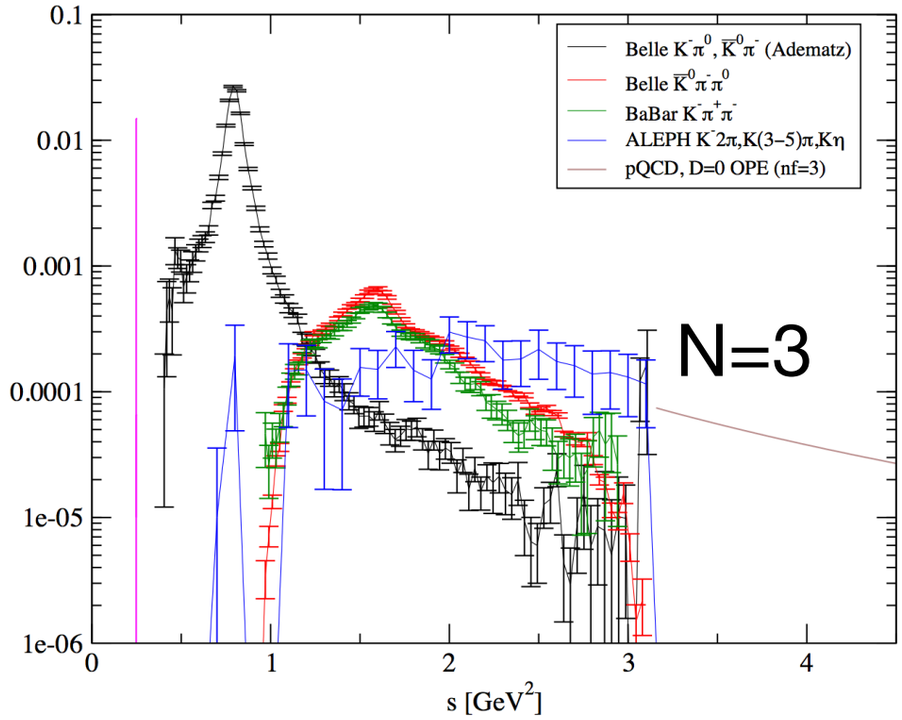
$$|V_{us}| = \begin{cases} 0.2233(15)_{exp}(12)_{th} & \text{for } \gamma_K[\tau_K] = 0.0012061(167)_{exp}(13)_{IB} \\ 0.2260(3)_{exp}(12)_{th} & \text{for } \gamma_K[K_{\mu 2}] = 0.0012347(29)_{exp}(22)_{IB} \end{cases}$$

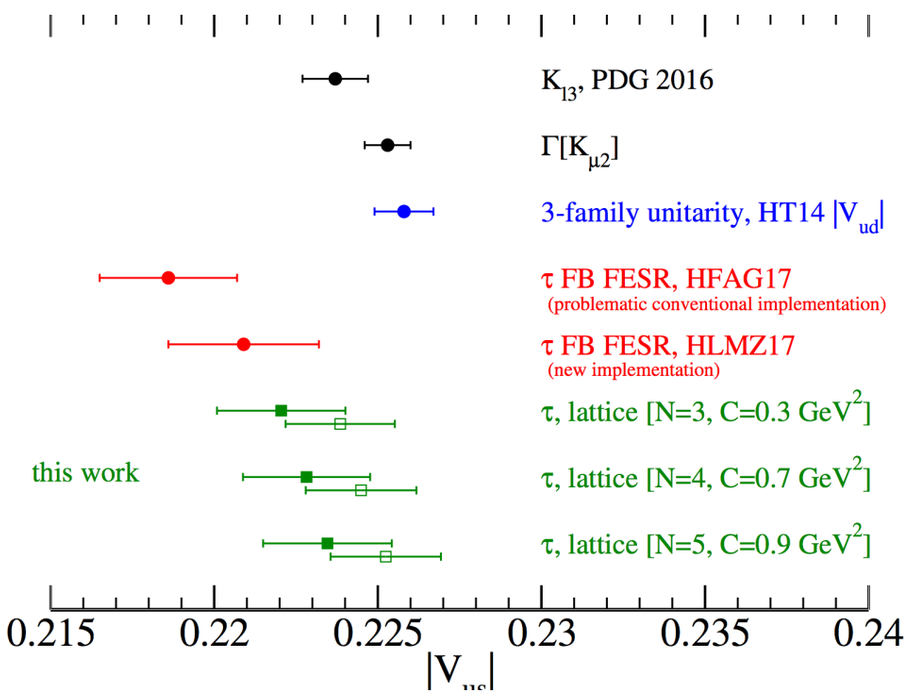
The final determination of the CKM matrix element for two ways of estimating the kaon pole.

$|V_{us}|$ from τ Decays – LQCD



$\omega(s)\rho(s)$





Our results including all sys error from τ inclusive decay

$$|V_{us}| = \begin{cases} 0.2228(15)_{exp}(13)_{th}[0.9\%], & for\ \gamma_K[\tau_K] \\ 0.2245(11)_{exp}(13)_{th}[0.8\%], & for\ \gamma_K[K_{\mu 2}] \end{cases}$$

for $N = 4, C = 0.7$ [GeV^2], vs $V_{us} = 0.2258(9)[0.4\%]$ from PDG17
($c.f.\ V_{us} = 22333(60)[0.3\%]$ FNAL/MILC 18 [A. Kronfeld's plenary talk]

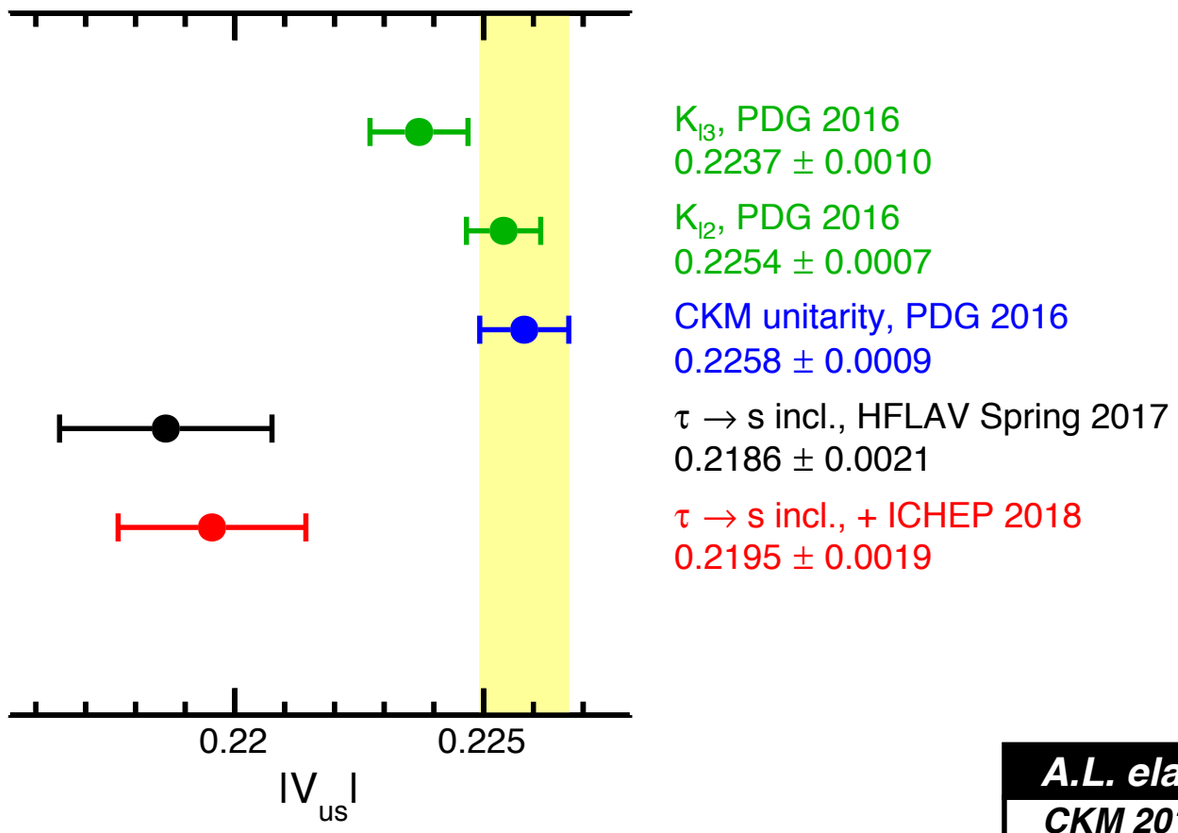
By using updated BF for $K, K\pi$ [A. Lusiani CHARM 2018] ,

$$|V_{us}| = \begin{cases} 0.2242(13)_{exp}(13)_{th}[0.8\%], & for\ \gamma_K[K_{\mu 2}] \\ 0.2256(10)_{exp}(13)_{th}[0.7\%] & for\ \gamma_K[K_{\mu 2}] \end{cases}$$

$|V_{us}|$ from τ Decays

New since CKM 2016:

- New preliminary BaBar results (ICHEP 2018) on 6 channels $\tau \to K\, n\pi^0\, \nu_\tau$ (n=0,1,2,3) and $\tau \to \pi\, n\pi^0\, \nu_\tau$ (n=3,4).



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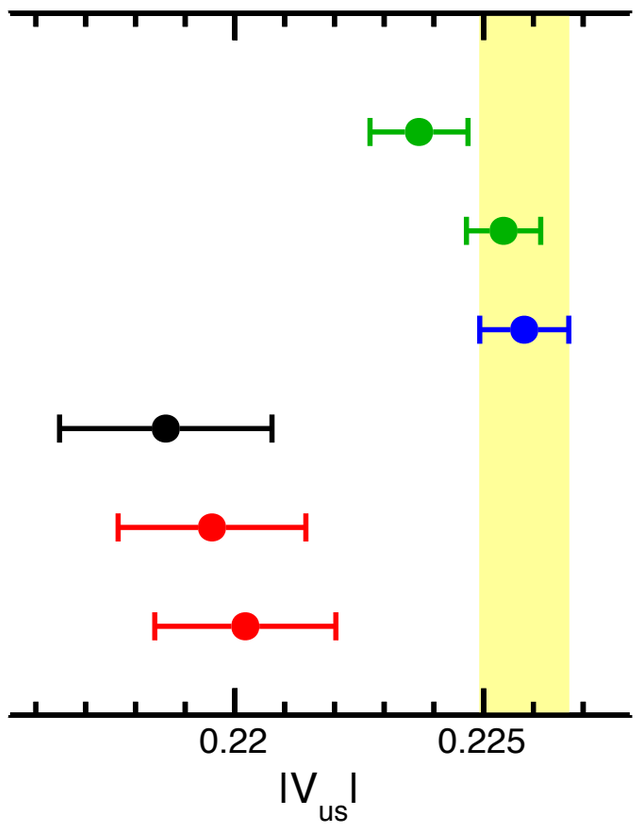
- Use of kaon BRs to predict τ BRs (M. Antonelli *et al.*, JHEP 10 (2013) 70), e.g.:

$$\mathrm{BR}(\tau \to \bar{K}\pi\nu_\tau) = \frac{2m_\tau^5}{m_K^5}\,\frac{\tau_\tau}{\tau_K}\,\mathrm{BR}(K \to \pi e\bar{\nu}_e) \times \text{corrections}$$



K_{l3}, PDG 2016
0.2237 ± 0.0010

K_{l2}, PDG 2016
0.2254 ± 0.0007

CKM unitarity, PDG 2016
0.2258 ± 0.0009

$\tau \to$ s incl., HFLAV Spring 2017
0.2186 ± 0.0021

$\tau \to$ s incl., + ICHEP 2018
0.2195 ± 0.0019

$\tau \to$ s incl., + ICHEP + kaons
0.2202 ± 0.0018

A.L. elab.
CKM 2018

$|V_{us}|$ from τ Decays

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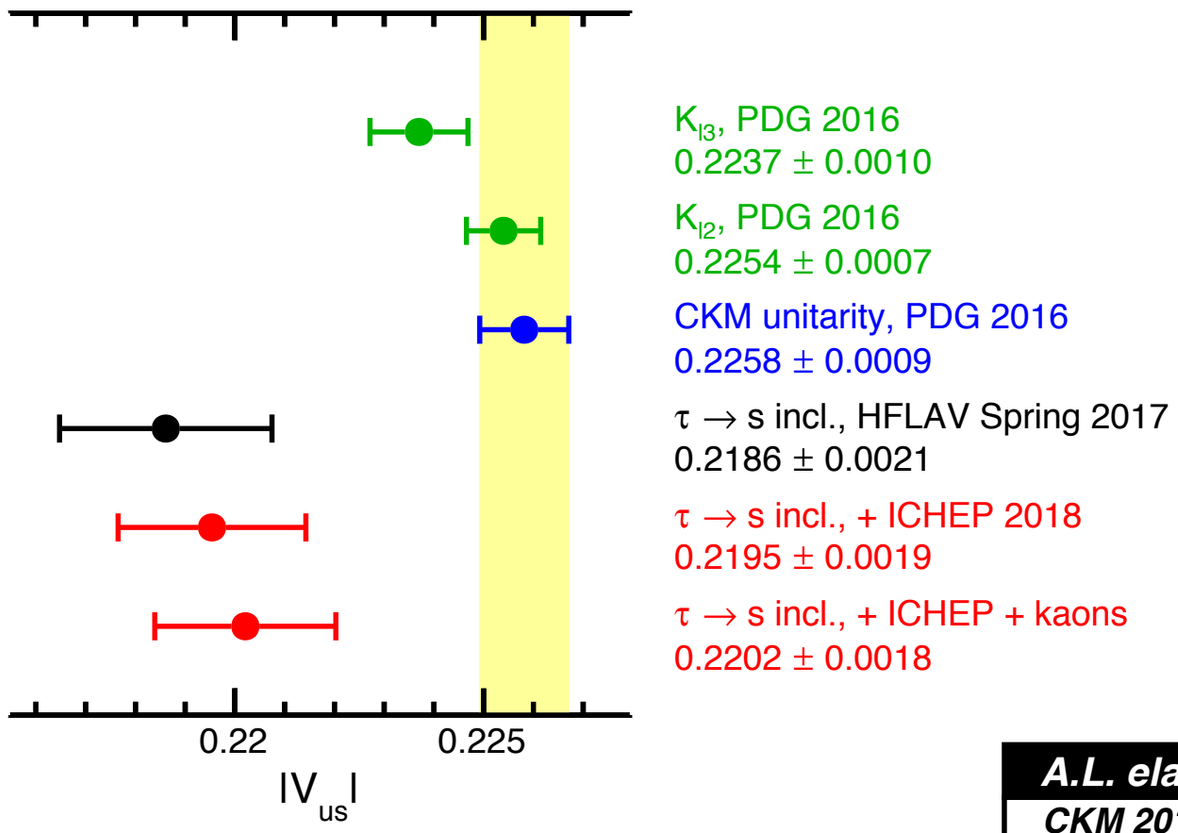

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0.2186 ± 0.0021

$\tau \to$ s incl., + ICHEP 2018
0.2195 ± 0.0019

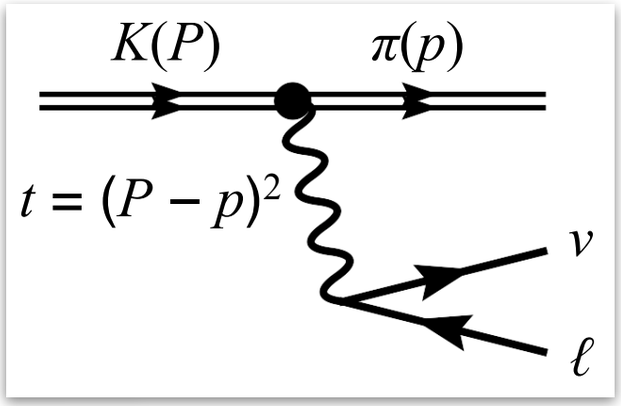
$\tau \to$ s incl., + ICHEP + kaons
0.2202 ± 0.0018

A.L. elab.
CKM 2018

Experts believe the disagreement comes from the theory.

Emilie Passemar

$|V_{us}|$ from Kaon Decays



Master formula for $K \to \pi\, l\, \nu$ (K_{l3}) decays:

($l = e, \mu$)

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

Experimental inputs:

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

$I_{Kl}(\lambda_{Kl})$ 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

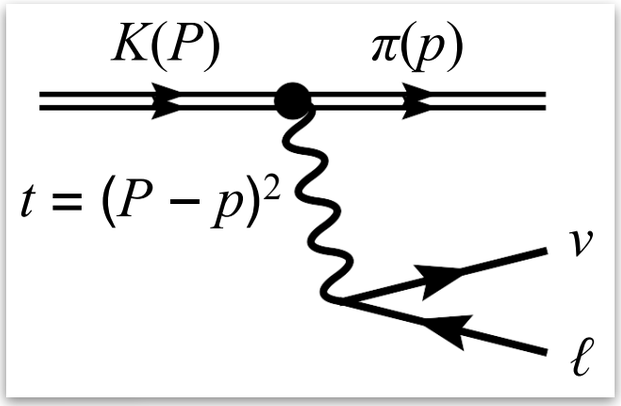
$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer (t=0)

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

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

Emilie Passemar

$|V_{us}|$ from Kaon Decays



Master formula for $K \to \pi\, l\, \nu$ (K_{l3}) decays:

($l = e, \mu$)

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

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

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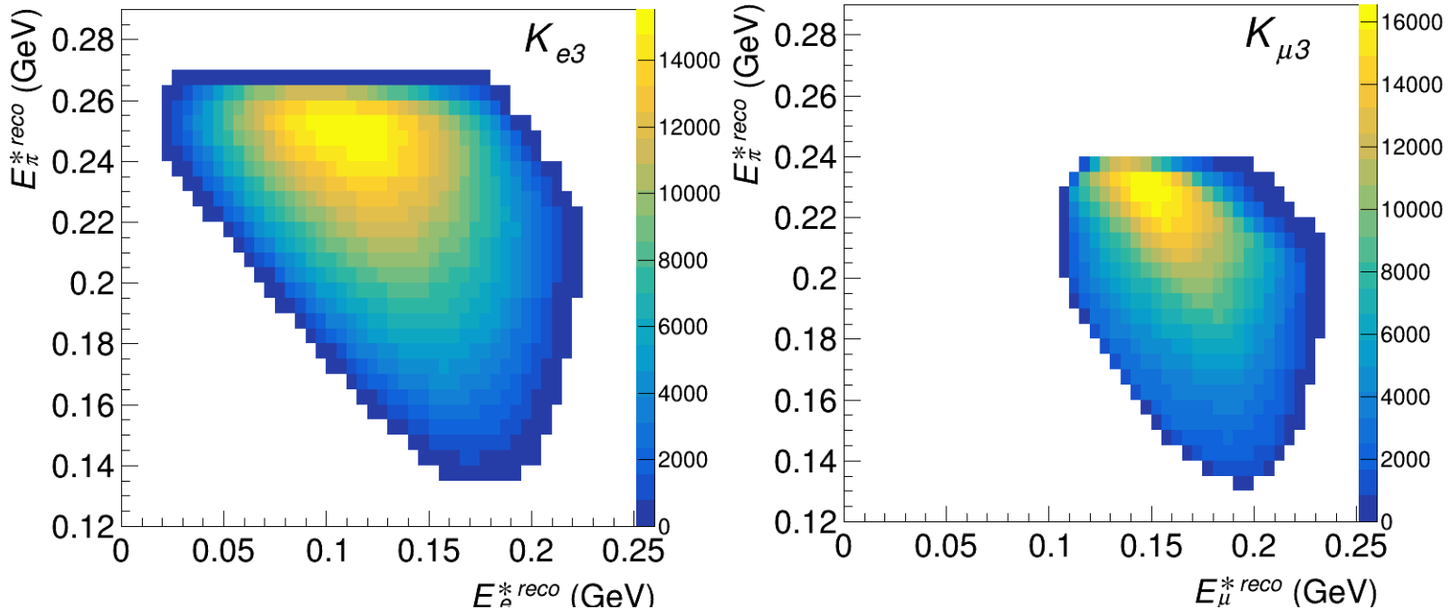
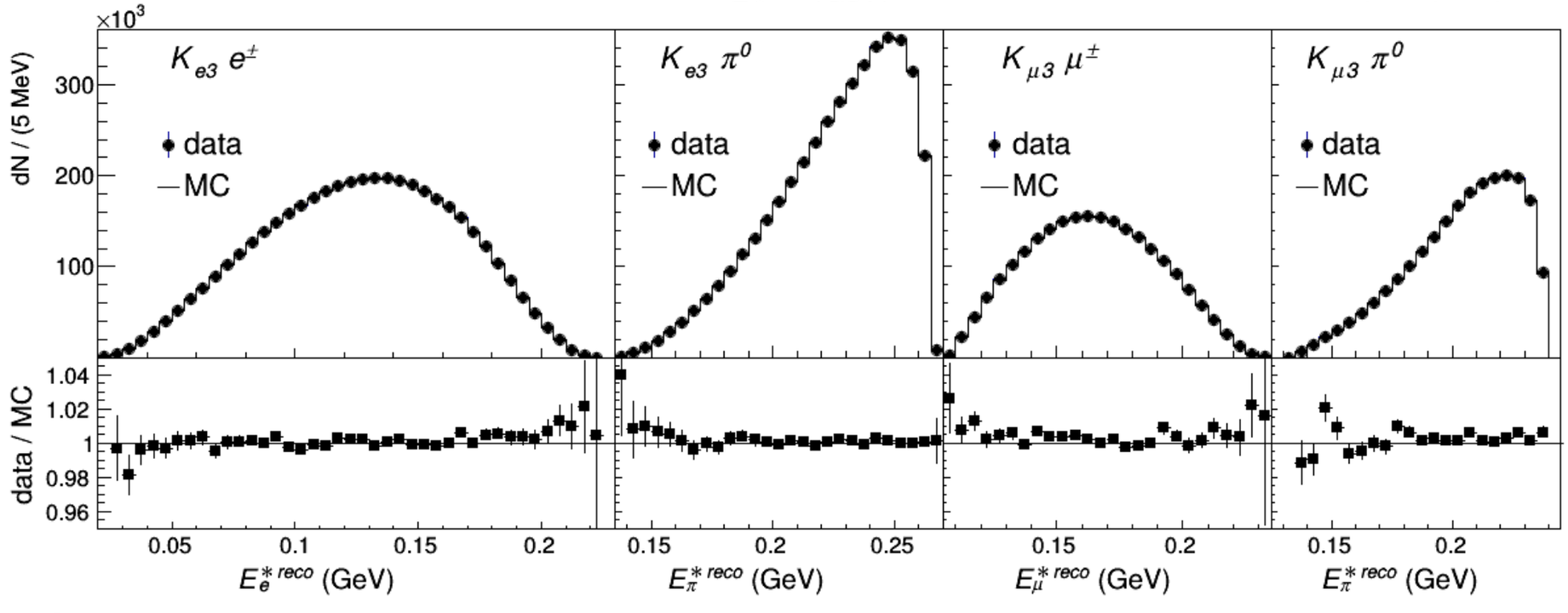
Experimental progress: New NA48/2 measurement of K_{l3} form factors

Dalitz plots:

- 4.4×10^6 $K^{\pm} \to \pi^0 e^{\pm} \nu$
- 2.3×10^6 $K^{\pm} \to \pi^0 \mu^{\pm} \nu$



Dalitz plot projections:



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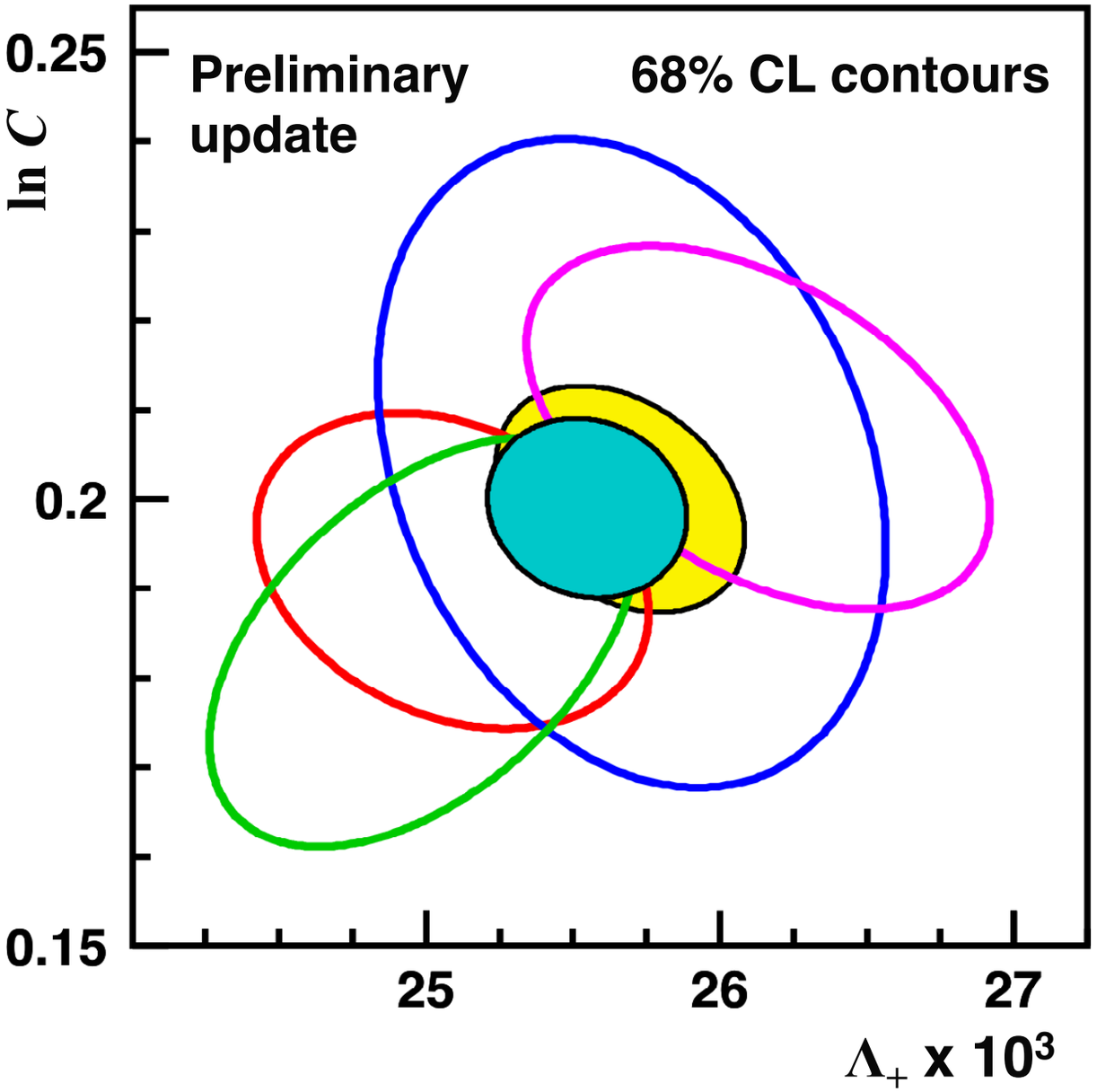
$K_{\ell 3}$ avgs from **KTeV** **KLOE** **ISTRA+** **NA48/2**

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

$|V_{us}|$ from Kaon Decays

Theoretical progress on isospin corrections:

$$\Delta^{SU(2)} \equiv \frac{f_+(0)^{K^+\pi^0}}{f_+(0)^{K^0\pi^-}} - 1$$

Strong isospin breaking

Quark mass differences, η-π^0 mixing in $K^+\pi^0$ channel

$$= \frac{3}{4}\frac{1}{Q^2}\left[\frac{\overline{M}_K^2}{\overline{M}_\pi^2} + \frac{\chi_{p^4}}{2}\left(1 + \frac{m_s}{\hat{m}}\right)\right] \qquad Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

$\chi_p{}^4 = 0.252$
NLO in strong interaction
O(e^2p^2) term $\varepsilon_{\mathrm{EM}}{}^{(4)} \sim 10^{-6}$

$= \mathbf{+2.61(17)\%}$ **Calculated using**

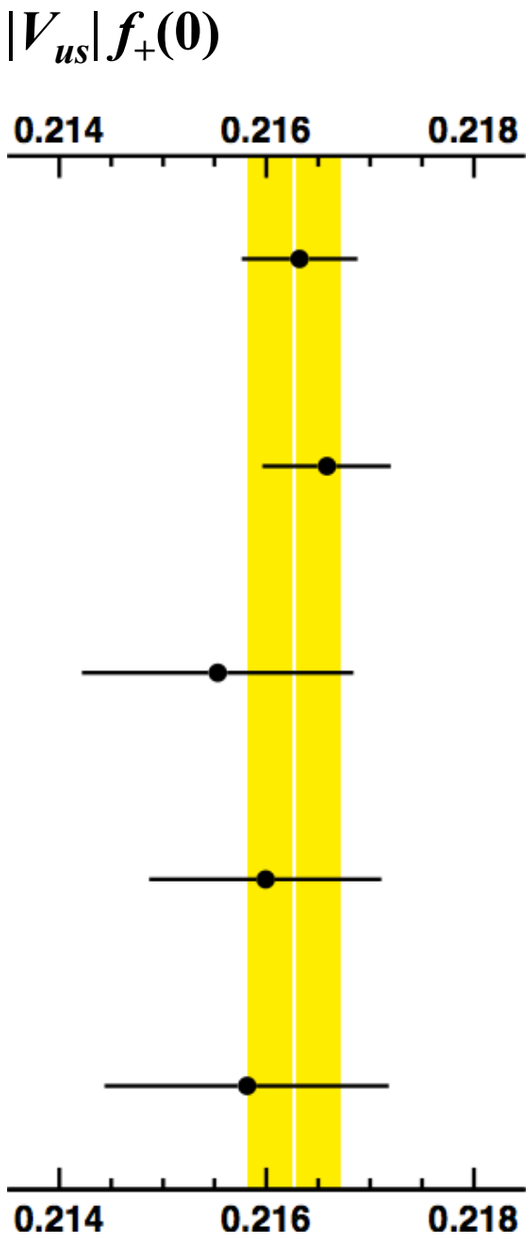
$Q = 22.1(7)$ $\quad M_K = 494.2(3)$ Isopsin-limit meson masses

$m_s/\hat{m} = 27.43(13)(27)$ $\quad M_\pi = 134.8(3)$

- Calculation scheme of Kastner & Neufeld ’08, Cirigliano et al. ’02
- LECs from Bijnens & Ecker ’14

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)%**

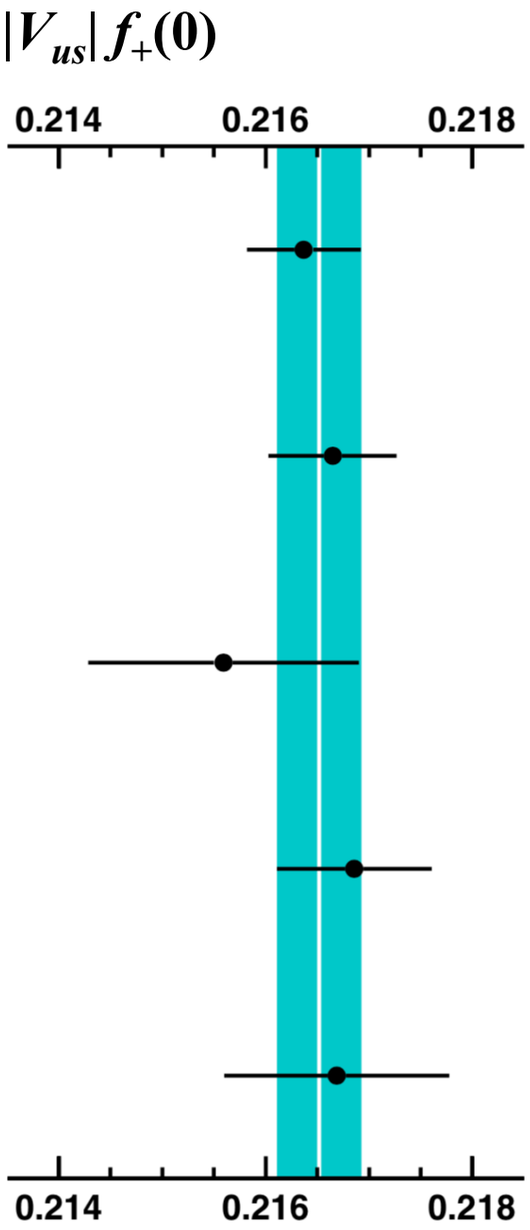
$|V_{us}|$ from Kaon Decays — 2016



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

$|V_{us}|$ from Kaon Decays — Now

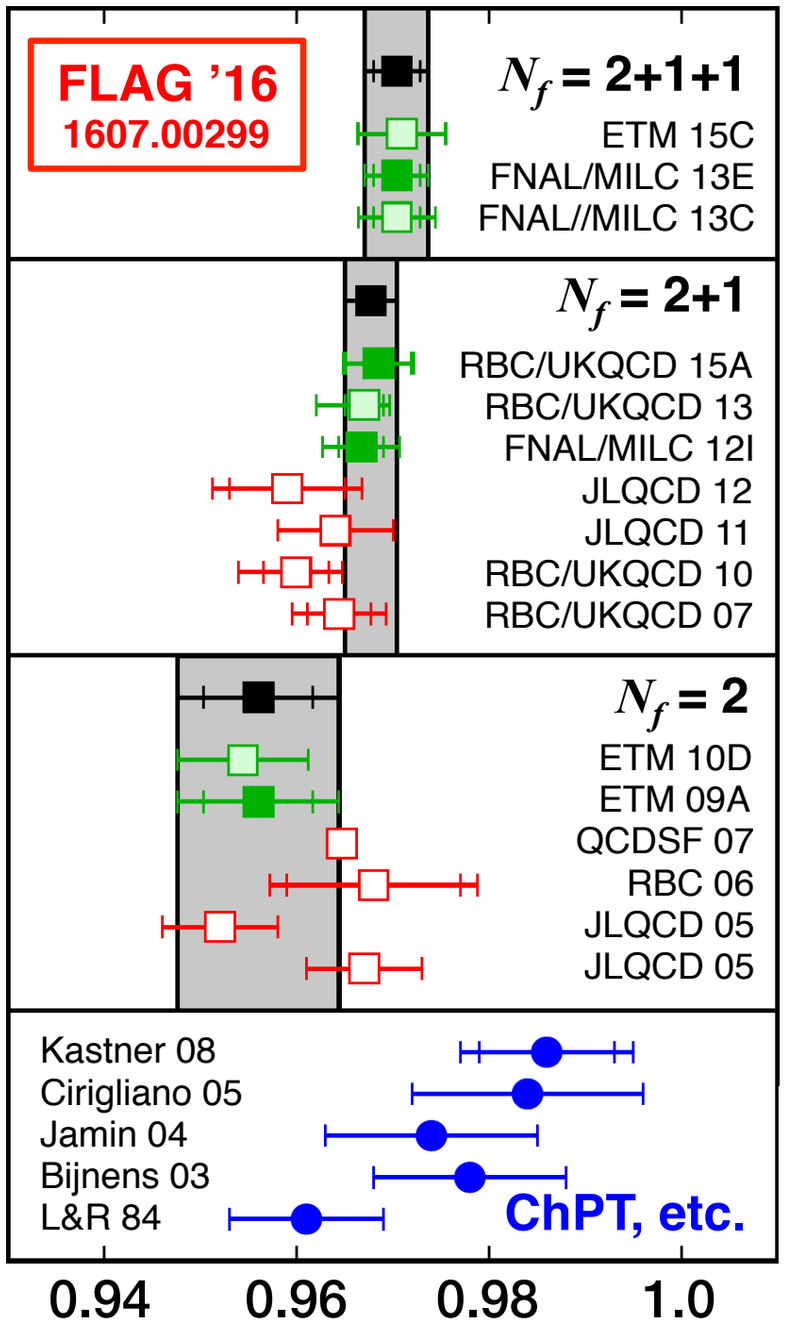


		% err	Approx. contrib. to % err from: BR	τ	Δ	Int
$K_L e3$	0.2164(6)	0.26	0.09	0.20	0.11	0.05
$K_L \mu 3$	0.2167(6)	0.29	0.15	0.18	0.11	0.07
$K_S e3$	0.2156(13)	0.61	0.60	0.02	0.11	0.05
$K^{\pm} e3$	0.2169(8)	0.35	0.27	0.06	0.21	0.05
$K^{\pm} \mu 3$	0.2167(11)	0.50	0.45	0.06	0.21	0.07

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

$|V_{us}|$ from Kaon Decays

Significant progress on $f_+(0)$



FLAG'16 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 $f_+(0) = 0.9636(^{+62}_{-65})$ 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

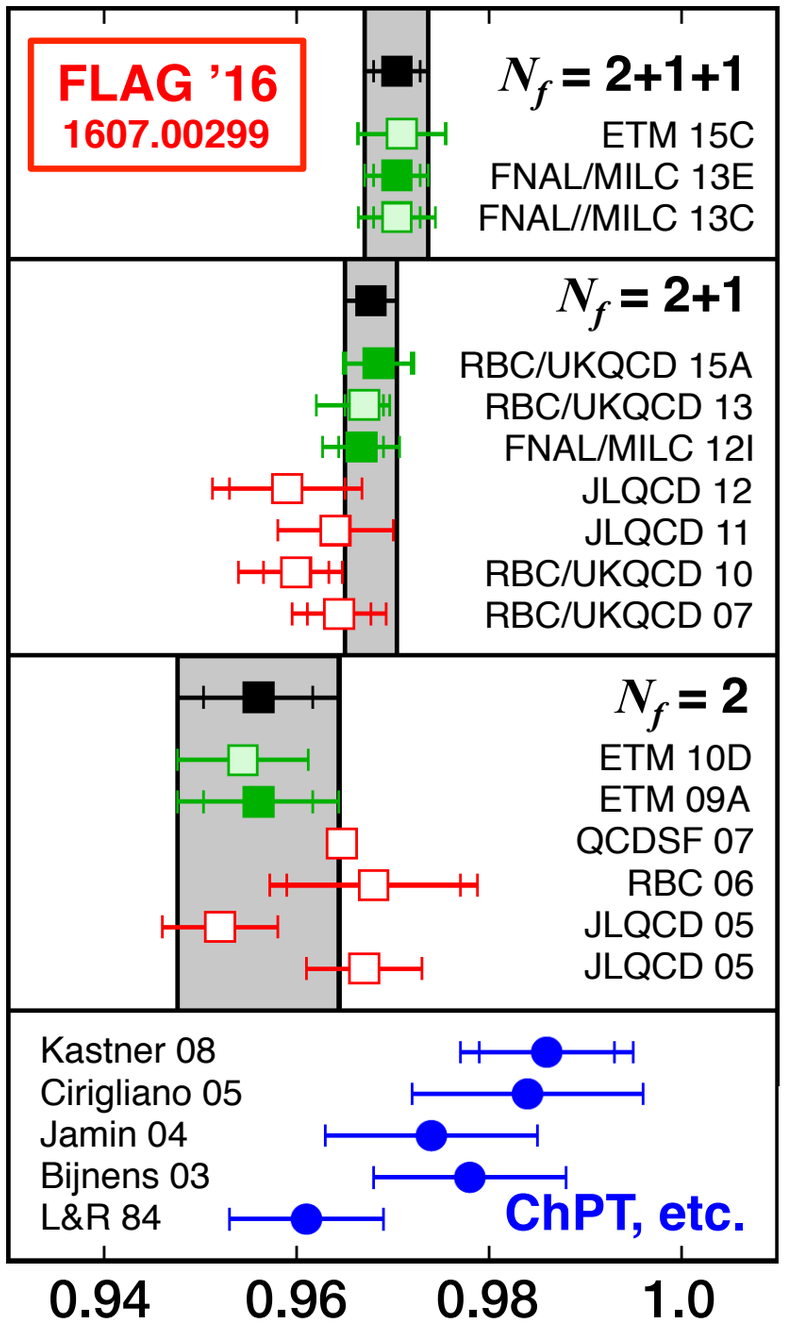
$f_+(0) = 0.9696(15)(11)$ 1809.02827
FNAL/MILC update 13E

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 42

$|V_{us}|$ from Kaon Decays

Significant progress on $f_+(0)$



CKM 2018

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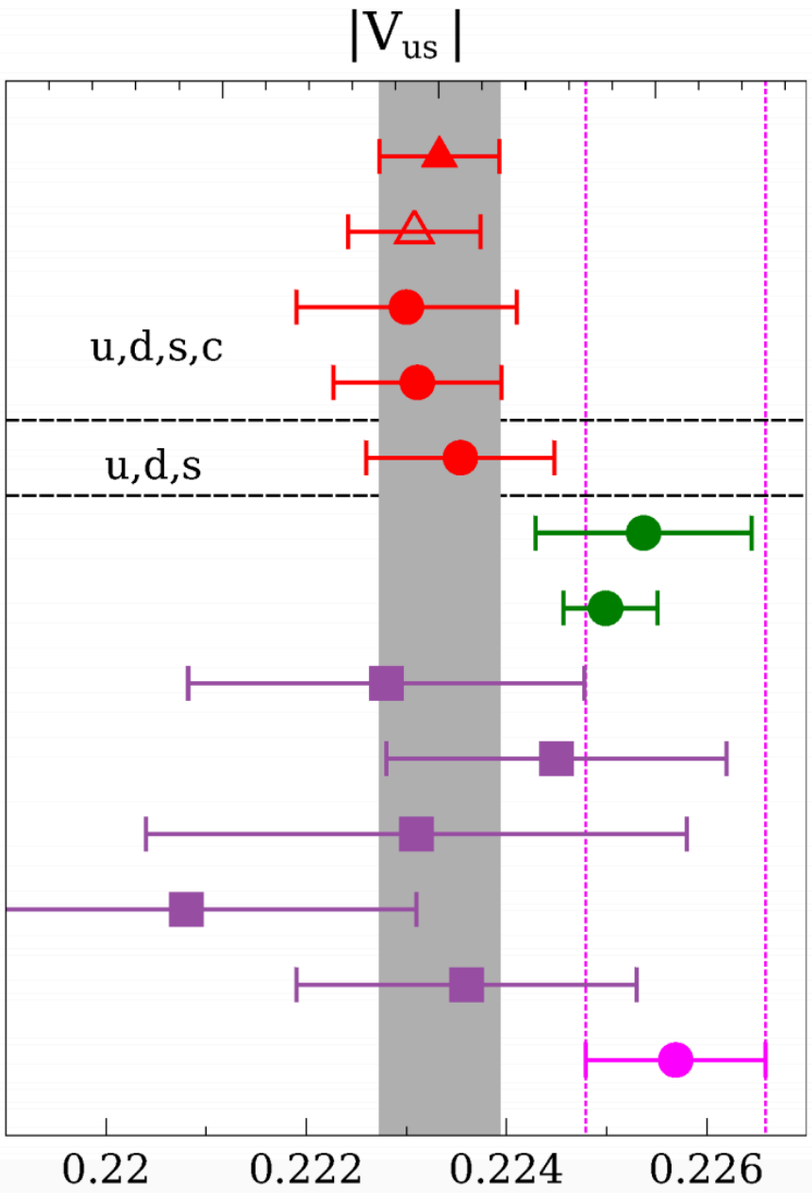
Significant progress in lattice form factors



This work $|V_{us}| = 0.22333(42)_{\text{expt}}(43)_{f_+(0)}$

This work (only neutral kaon exp. data)

K_{l3} ETMC 2016

K_{l3} Fermilab Lattice/MILC 2014

K_{l3} RBC/UKQCD 2014

K_{l2} FLAG 2016 + f_K FLAG N_f=2+1

K_{l2} + f_K/f_π Fermilab Lattice/MILC 2017

τ→ s inclusive, Boyle et al. 2018

τ→ s inclusive + K_{l2} input, Boyle et al. 2018

τ→ s inclusive, Hudspith et al. 2017

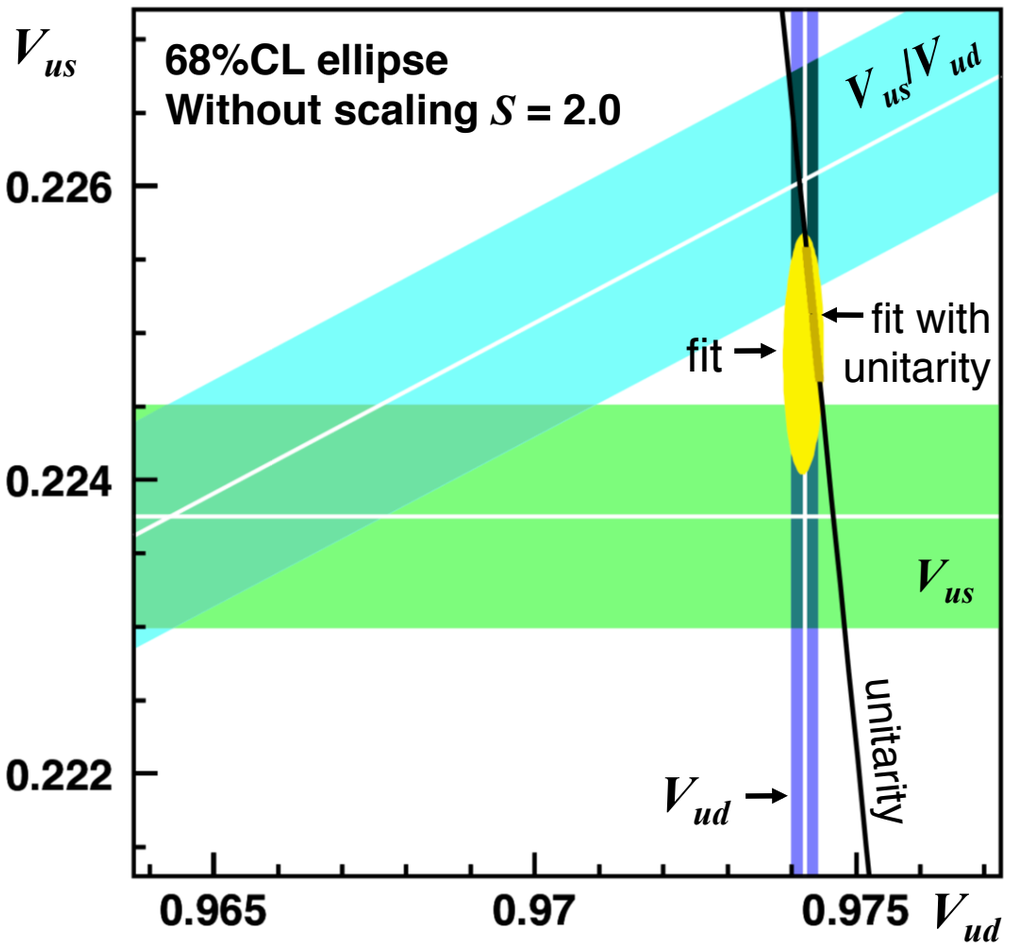
τ→ s inclusive, Hudspith et al. 2017 + HFLAV 2016 exp. input

$\tau \to K \ell \nu / \tau \to \pi \ell \nu$ HFLAV2017+ f_K/f_π Fermilab Lattice/MILC 2017

Unitarity with $|V_{ud}|$=0.97420(21), RC from Marciano & Sirlin 2005

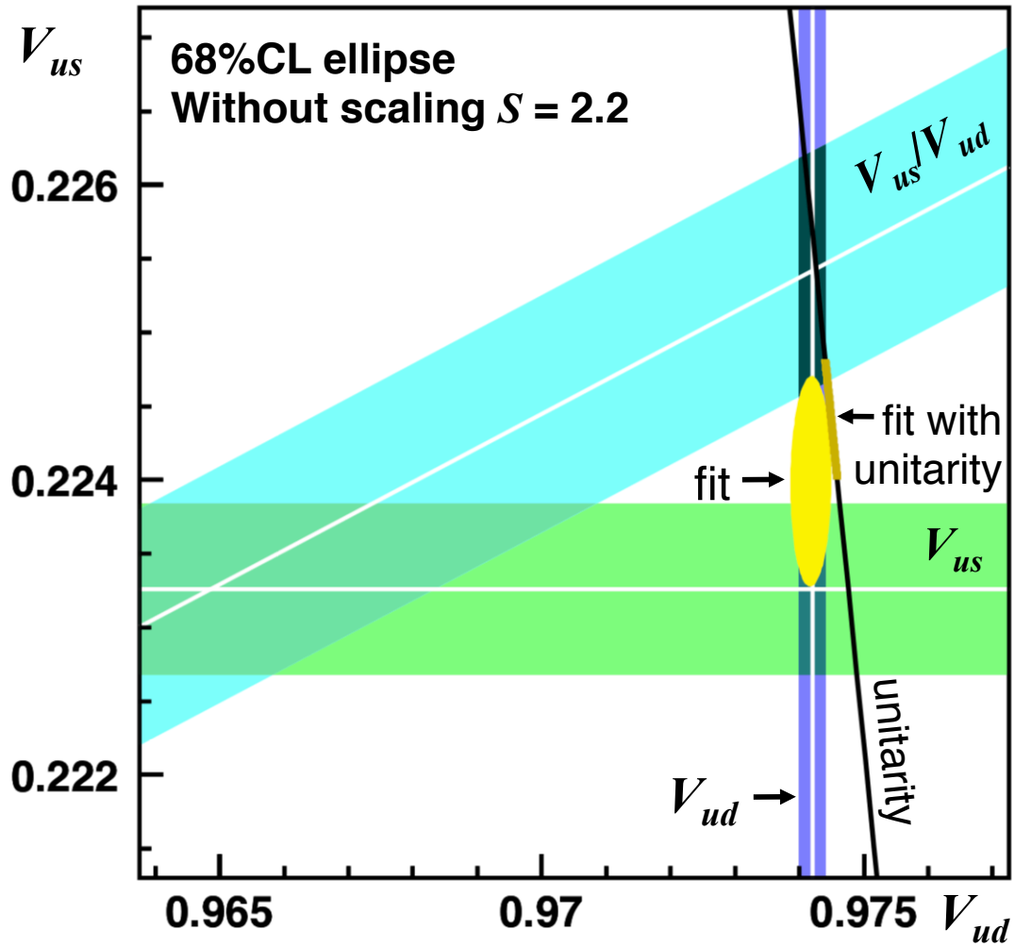
$|V_{us}|$ from Kaon Decays

N_f = 2+1: $f_+(0) = 0.9677(27)$
$f_K/f_\pi = 1.1927(38)$



Fit result: (no scaling $S = 2.0$)
$|V_{ud}| = 0.97418(21)$
$|V_{us}| = 0.2249(5)$

N_f = 2+1+1: $f_+(0) = 0.9698(17)$
$f_K/f_\pi = 1.1960(40)$



Fit result: (no scaling $S = 2.2$)
$|V_{ud}| = 0.97418(21)$
$|V_{us}| = 0.2240(5)$

Status of $|V_{ud}|$ & $|V_{us}|$

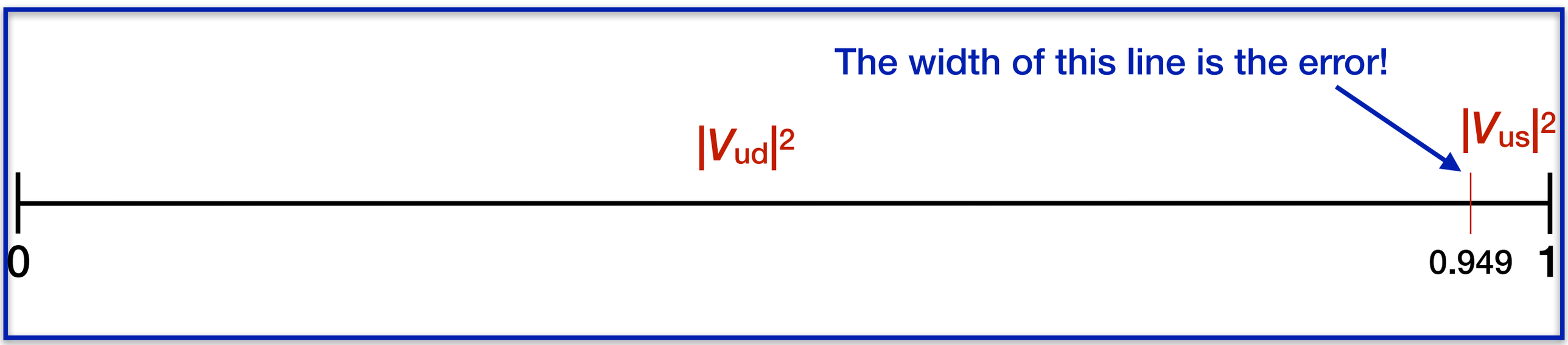
„<u>Unitarity line</u>“ of the first CKM row:

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

- $|V_{ub}|^2 \approx 10^{-6}$ ➜ $\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 - 1 \neq 0$ *is new physics!*
- Current status: $\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 - 1$

$= 0.94903(41) + 0.05018(22) - 1$

$= -0.0008(5)$ *…now 1.7 σ…*



Conclusions

Guide to measure $|V_{ud}|$, $|V_{us}|$, $|V_{cd}|$, $|V_{cs}|$:

- Need of high-precision & high-statistics experiments:
  BaBar, Belle II, BES III, KLOE, KTeV, LHCb, NA48, Perkeo III,
  UCNA, UCNτ, …

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  (radiative corrections, isospin breaking, higher order corrections, …)

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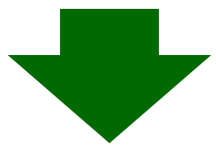

- Many improvements in $|V_{ud}|$ & $|V_{us}|$, now again some tension?
- Some improvements in $|V_{cd}|$ & $|V_{cs}|$, many more to come!