5. CKM first row unitarity

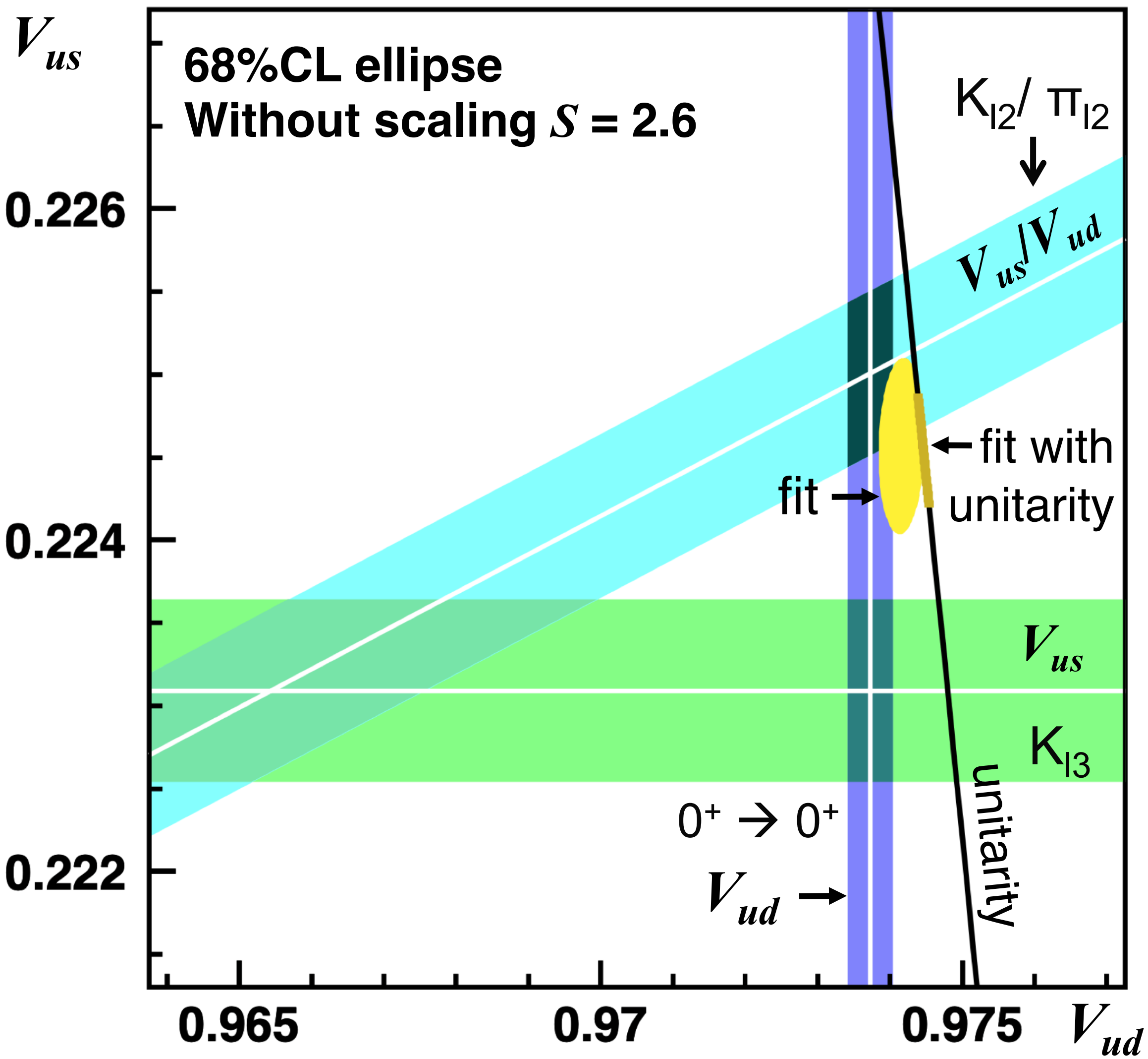
➡ See Talks on Tuesday afternoon RF2 session

Cabibbo Anomaly

M.Moulson, E.P.@CKM2021

- Recent discrepancy with CKM unitarity:

$|V_{ud}| = 0.97373(31)$
$|V_{us}| = 0.2231(6)$
$|V_{us}|/|V_{ud}| = 0.2311(5)$



Fit results, no constraint

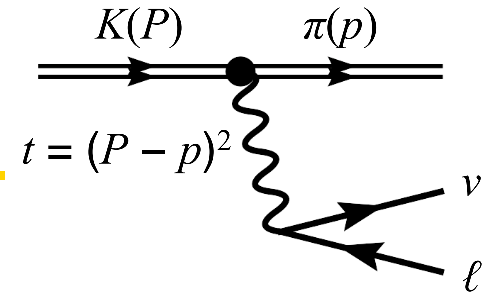
$V_{ud} = 0.97365(30)$
$V_{us} = 0.22414(37)$
$\chi^2/\text{ndf} = 6.6/1$ (1.0%)
$\Delta_{CKM} = -0.0018(6)$
-2.7σ

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

Negligible ~2×10^{-5}
(B decays)

Broad sensitivity to BSM scenarios

V_{us} from K_{l3} ($K \to \pi l \nu_l$)



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

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

Average and work by Flavianet Kaon WG *Antonelli et al'11* and then by *M. Moulson*, see e.g. *Moulson.@CKM2021*

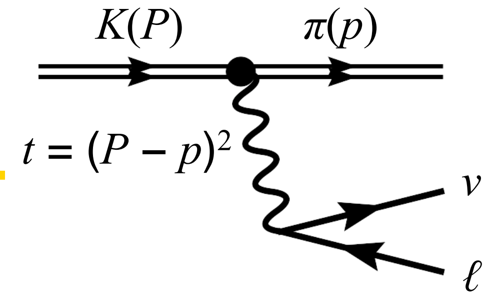
Experimental results on BRs, lifetime and FFs from:
KLOE, *KTeV*, *NA48*, *ISTRA*

- New results on K^+ BRs from *KLOE-2* and *ISTRA+*
- New results on K^+ FFs by *NA48/2* and *OKA*
- Since 2018: First experimental measurement of BR of $K_S \to \pi\mu\nu$

BR($K_S \to \pi\mu\nu$) = (4.56 ± 0.20) ×10^{-4}

KLOE-2
PLB 804 (2020)

V_{us} from K_{l3} ($K \to \pi l \nu_l$)



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Average and work by Flavianet Kaon WG *Antonelli et al'11* and then by *M. Moulson*, see e.g. *Moulson.@CKM2021*

Theoretically

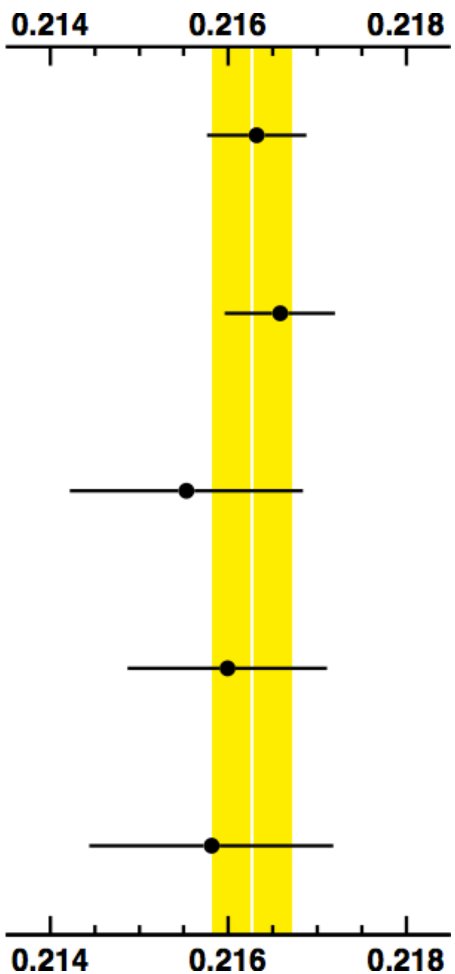
- Update on long-distance EM corrections for K_{e3} *Seng et al.'21*
- Improvement on Isospin breaking evaluation due to more precise dominant input: quark mass ratio from $\eta \to 3\pi$ *Colangelo et al.'18*
- Progress from lattice QCD on the $K \to \pi$ FF

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

$f_+(0)V_{us}$ from K_{l3} - 2011

M.Moulson, E.P.@CKM2021

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



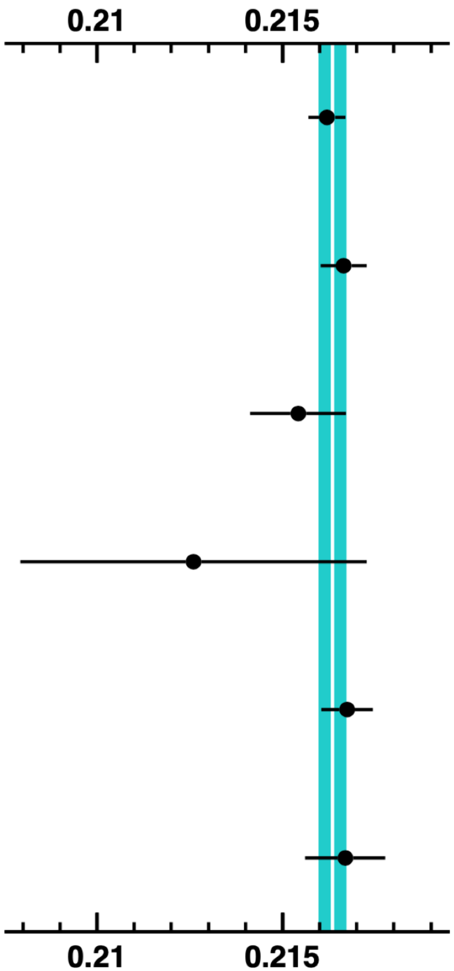
Approx. contrib. to % err from:

		% 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%)**

$f_+(0)V_{us}$ from K_{l3} - now

M.Moulson, E.P.@CKM2021



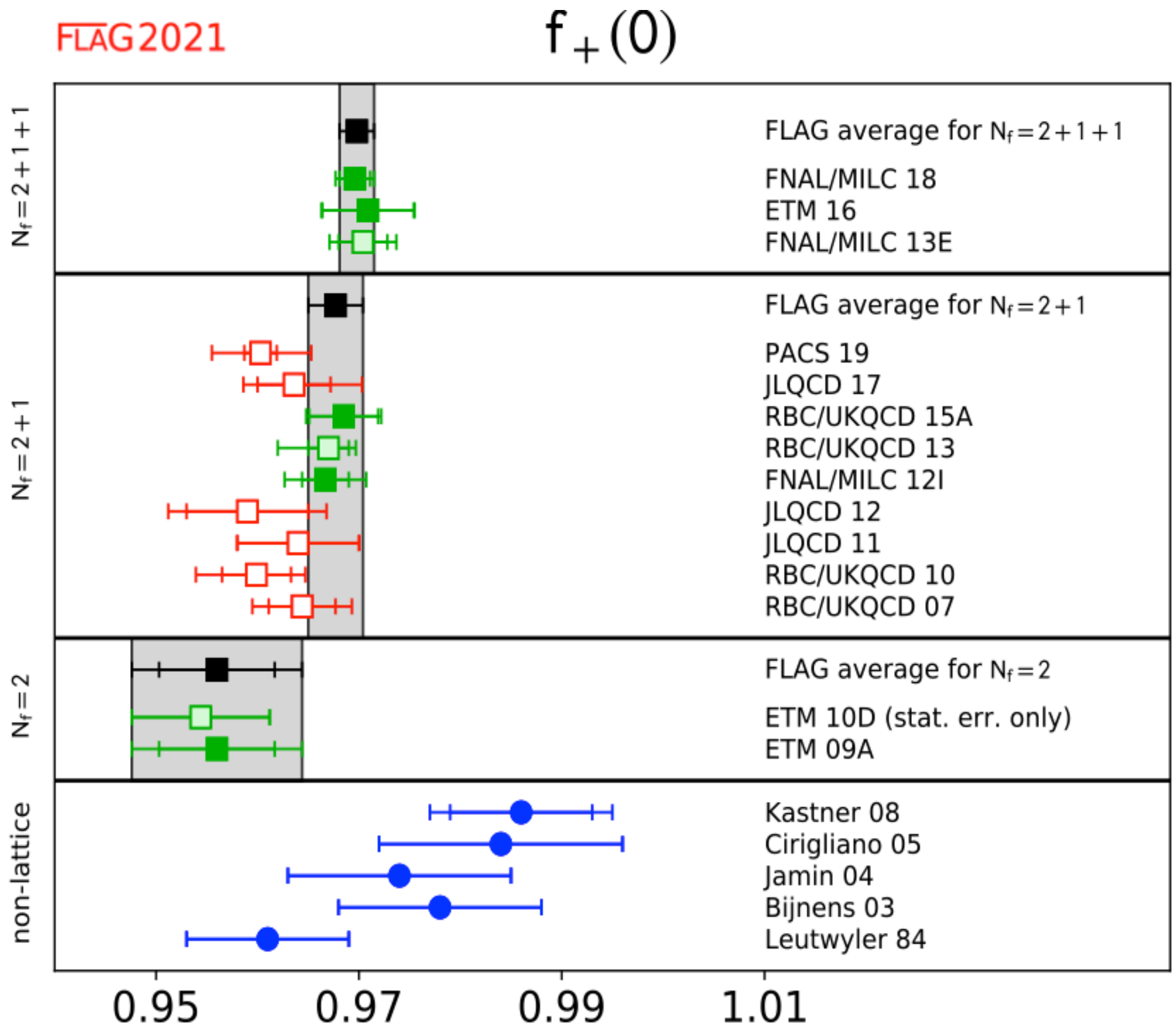
Approx. contrib. to % err from:

		% err	BR	τ	Δ	Int
K_Le3	**0.2162(5)**	**0.23**	0.09	0.20	0.02	0.05
$K_L\mu3$	**0.2167(6)**	**0.29**	0.15	0.18	0.11	0.07
K_Se3	**0.2154(13)**	**0.60**	0.60	0.02	0.02	0.05
$K_S\mu3$	**0.2126(47)**	**2.2**	2.2	0.02	0.11	0.07
$K^\pm e3$	**0.2167(7)**	**0.32**	0.27	0.06	0.17	0.05
$K^\pm\mu3$	**0.2167(11)**	**0.50**	0.45	0.06	0.21	0.07

Average: $|V_{us}|\,f_+(0)$ = 0.21635(38) χ^2/ndf = 2.14/5 (83%)

$f_+(0)$ from lattice QCD

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



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

0.18% uncertainty

to be compared to

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

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

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

➡ Lattice uncertainties at the same level as exp.

-3.2σ away from unitarity!

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

V_{us}/V_{ud} from K_{12}/π_{12}

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

- Recent progress on radiative corrections computed on lattice:

  Di Carlo et al.'19

- Main input hadronic input: f_K/f_π

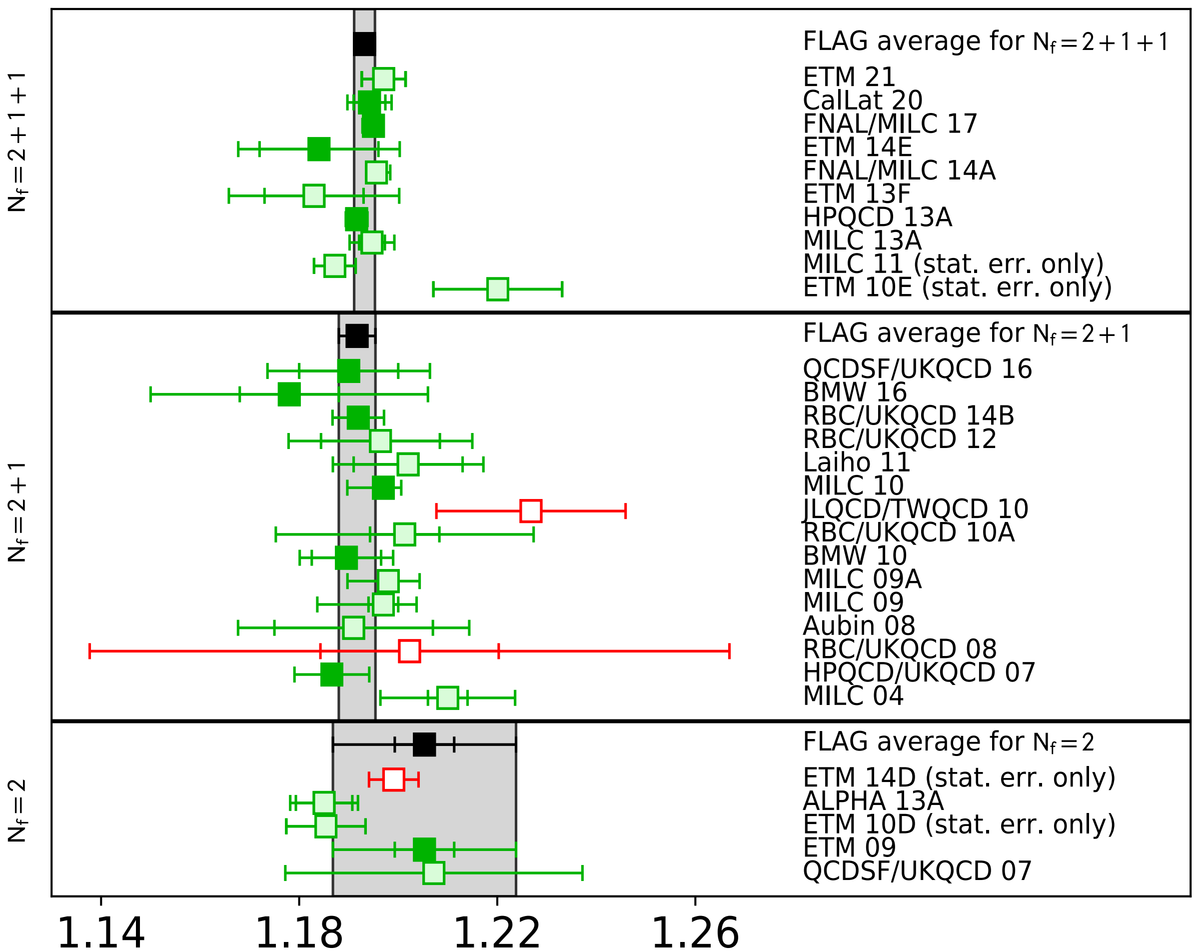
- In 2011: V_{us}/V_{ud} = 0.2312(4) $_{exp}$(12)$_{lat}$

- In 2021: V_{us}/V_{ud} = 0. 2311(3)$_{exp}$(4)$_{lat}$ the lattice error is reducing by a factor of 3 compared to 2011! It is now of the same order as the experimental uncertainty.

  -1.8σ away from unitarity

V_{us}/V_{ud} from K_{l2}/π_{l2}

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



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

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

0.18% uncertainty

Results have been stable over the years

For average substract IB corr.

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

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

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

Experimental Prospects for V_{us}

On Kaon side

- *NA62* could measure several BRs: $K_{\mu 3}/K_{\mu 2}$, $K \rightarrow 3\pi$, $K_{\mu 2}/K \rightarrow \pi\pi$
- Note that the high precision measurement of BR($K_{\mu 2}$) (0.3%) comes only from a single experiment: KLOE. It would be good to have another measurement at the same level of accuracy

- *LHCb* : could measure BR($K_S \rightarrow \pi\mu\nu$) at the < 1% level?
  $K_S \rightarrow \pi\mu\nu$ measured by KLOE-II but not competitive
  τ_S known to 0.04% (vs 0.41% for τ_L, 0.12% for $\tau_\pm$)

- V_{us} from Tau decays at *Belle II*: WP soon on ArXiv
  https://www.slac.stanford.edu/~mpeskin/Snowmass2021/BelleIIPhysicsforSnowmass.pdf

  Belle II with 50 ab^{-1} and ~4.6 x 10^{10} τ pairs will improve V_{us} extraction from τ decays
  Inclusive measurement is an opportunity to have a complete independent extraction of V_{us} ⇨ not easy as you have to measure many channels

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

HFLAV'21

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

V_{us} from Hyperon decays

V_{us} can be measured from Hyperon decays:

- **$\Lambda \to p e \nu_e$** Possible measurement at *BESIII, Super τ-Charm factory?*

- Possibilities at *LHCb*? *Talk by Dettori@FPCP20*

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu_\mu}$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu_\mu}$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu_\mu}$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

R = ratio of production

ϵ = ratio of efficiencies

- To be able to extract V_{us} one needs to compute form factors precisely

  ⇨ Lattice effort from *RBC/UKQCD*

Theoretical Prospects for V_{us}

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

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

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

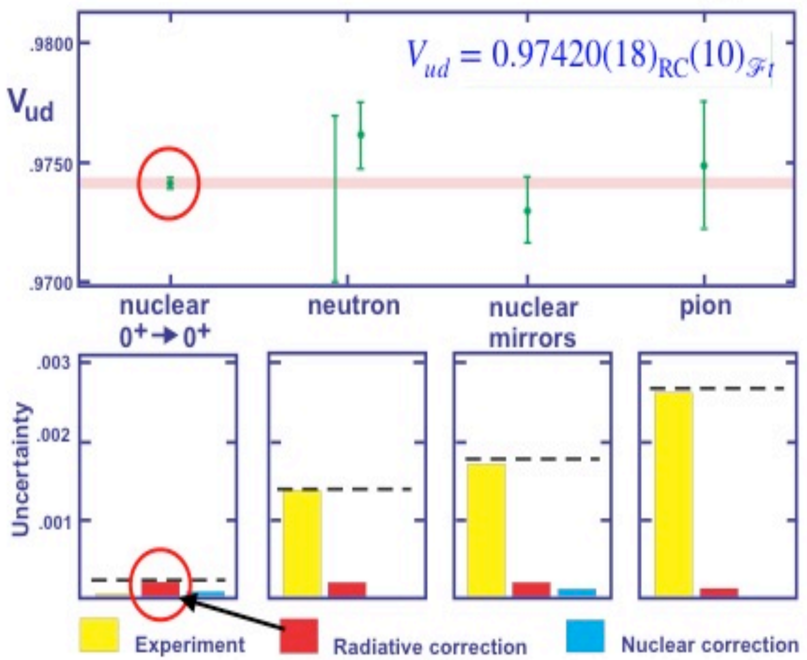
⇨ **Aim: Per mille level within 10 years**

$|V_{ud}|$ from $0^+ \rightarrow 0^+$ superallowed β decays

See Talk by Misha Gorshteyn @CKM2021

PDG 2018:

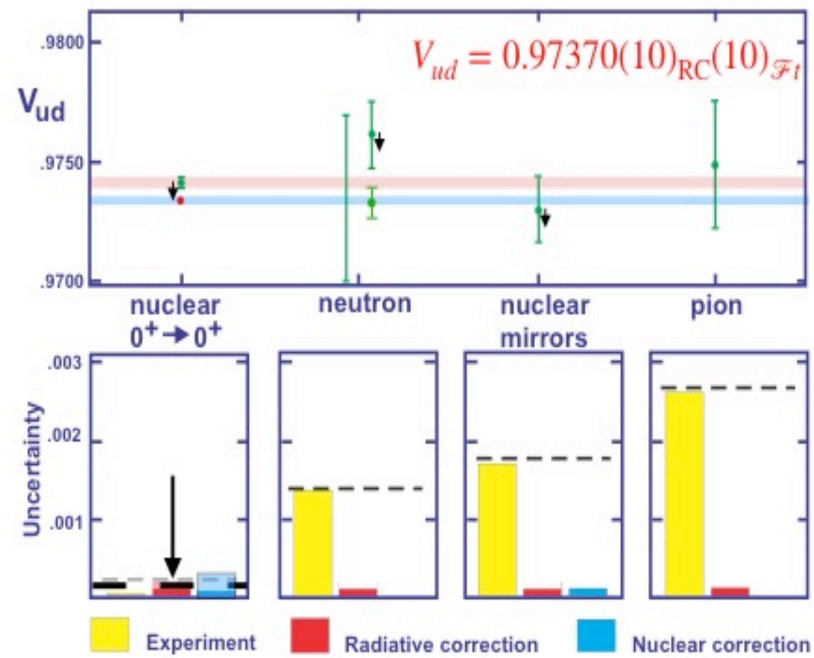
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{V_{ud}}(2)_{V_{us}}$$



PDG 2020:

Figure adapted from J. Hardy

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



Recent improvement on the theoretical RCs +Nuclear Structure Corrections

➡ Use of a data driven dispersive approach

Seng et al.'18'18, Gorshteyn'18

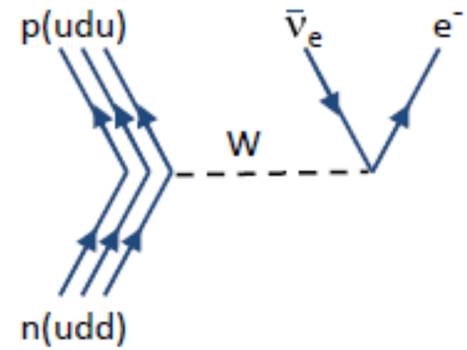
$|V_{ud}|$ from Neutrons

- Master Formula:

$$|V_{ud}|^2 = \frac{5024.7s}{\tau_n (1+3\lambda^2)(1+\Delta_R)}$$

Lifetime $\qquad \lambda = g_A / g_V$

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



- Needs $\delta\lambda/\lambda \approx 3 \times 10^{-4}$ and $\delta\tau_n \approx 0.3$ s to compete with $0^+ \rightarrow 0^+$ transitions.
- Theoretically, the radiative corrections are under control (same as for $0^+ \rightarrow 0^+$)
- Recent progress :
  - New Perkeo III result: *PERKEO III* result improves world-average of beta asymmetry by factor 5! Half of it is due to the reduction of the scale factor

    $$A = -0.11958(21),\ S = 1.2 \quad \lambda_A = -1.2757(5)$$

  - Tension with *aSPECT* result: $\lambda_{avg} = -1.2754(13),\ S = 2.7$

$|V_{ud}|$ from Neutrons

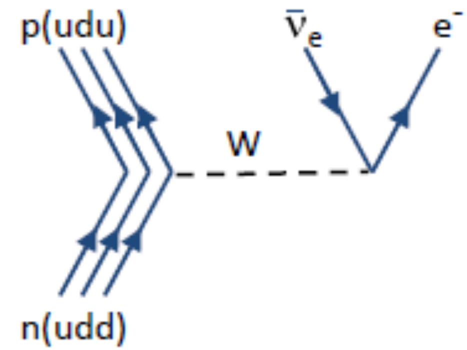
- Master Formula:

$$|V_{ud}|^2 = \frac{5024.7s}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

Lifetime (τ_n)

$\lambda = g_A / g_V$

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



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    ⇨ $A = -0.11958(21),\ S = 1.2 \quad \lambda_A = -1.2757(5)$

  - New result for Lifetime from *UCNτ* $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

    ⇨ improvement by a factor of 2.25 compared to previous result

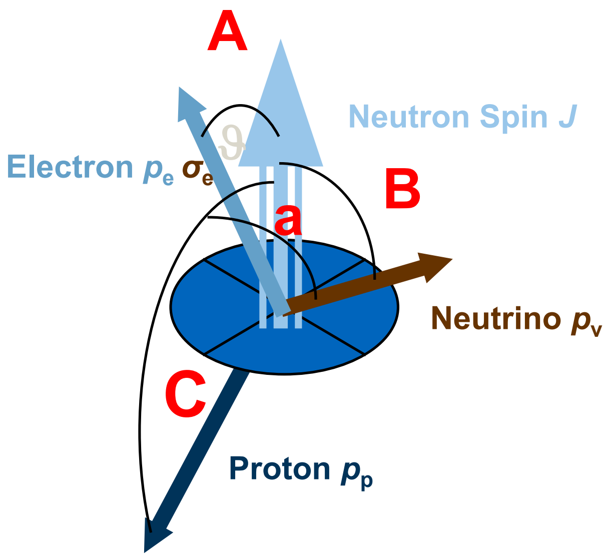
Measurement of g_A

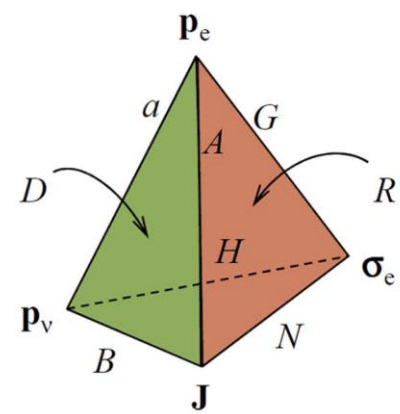
Correlations in Neutron Decay

Bastian Märkisch@CKM2021

Determination of $\lambda = g_A/g_V$ from neutron decay via angular **correlations**; (typically) **beta asymmetry *A***, or **electron-neutrino correlation *a*:**

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \qquad a = \frac{1 - \lambda^2}{1 + 3\lambda^2}$$





O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

Typically, **specialised** instruments / setups required for different observables.

More on neutron beta decay: Falkowski, *et al.*, J. High Energ. Phys. 2021, 126 (2021)
Dubbers & BM, Ann. Rev. Nucl. Part. Sci. 71, 139-163 (2021)

See also results from aCORN at NIST and aSPECT at Grenoble

$|V_{ud}|$ from Neutrons

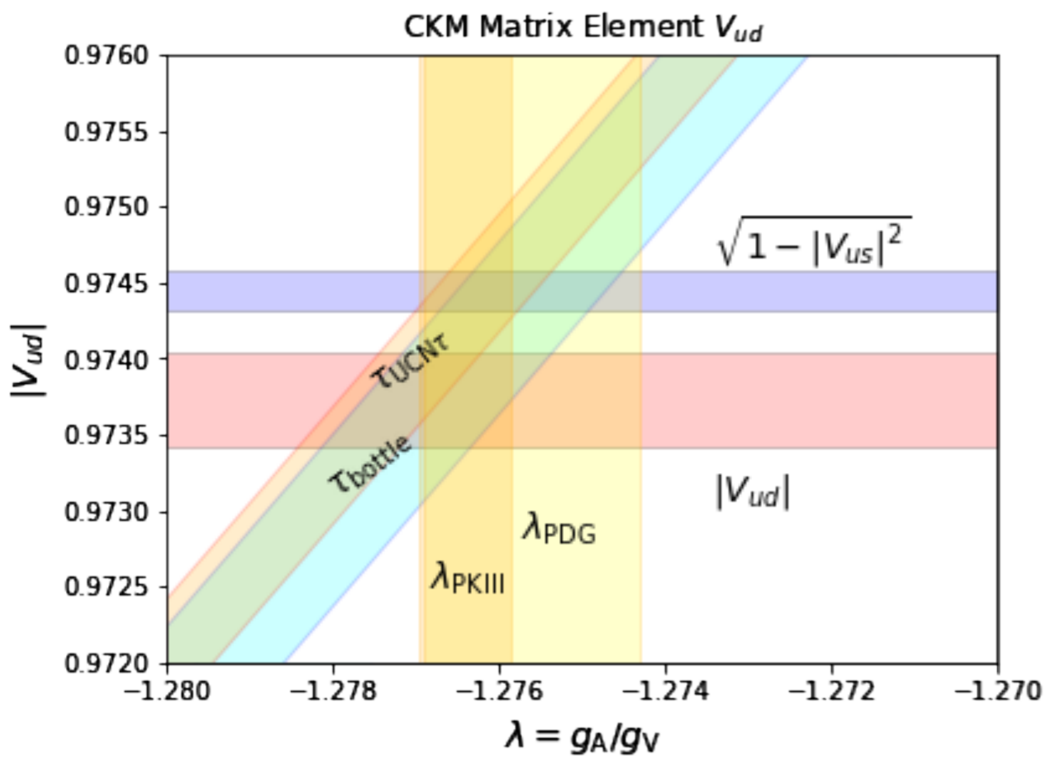
See Talk by Chen Yu Liu @CKM2021

- Using *UCNτ* result for τ_n and *PERKEOIII* result for g_A

  ⇨ Agreement with unitarity

- But Beam and Bottle experiment for τ_n give different results

- There are tension on g_A results before and after 2002



Prospects:

- *UCNτ* + (immediate future): elevator loading, reaching $\delta t = 0.1$ s

  UCNτ 2 (future): superconducting coils (conceptual design), reaching δt=0.01 s

- *Nab* at the SNS is currently commissioning

  ⇨ goal $\delta\lambda/\lambda \sim 0.03\%$

$|V_{ud}|$ from pion β decay: $\pi^+ \to \pi^0 e^+ \nu$

- Theoretically cleanest method to extract V_{ud} : corrections computed in SU(2) ChPT

Sirlin'78, Cirigliano et al.'03, Passera et al'11

- Present result: *PIBETA* Experiment (2004) → **Uncertainty: 0.64%**

$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.036 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.003_{\pi e2}) \times 10^{-8} \left(\pm 0.6\%\right)$$

⇒ $\left|V_{ud}\right| = \mathbf{0.9739(28)_{exp}(1)_{th}}$ to be compared to $\left|V_{ud}\right| = \mathbf{0.97373(31)}$

- Reduction of the theory error thanks to a new lattice calculation for RC *Feng et al'20*

- Next generation experiment PIONEER Phase II and III measurement at 0.02% level ⇒ will be competitive with current $0^+ \to 0^+$ extraction

- Would be completely independent check! No nuclear correction and different RCs compared to neutron decay

Czarnecki, Marciano, Sirlin'20

- **Opportunity to extract V_{us}/V_{ud}** from $\dfrac{B(K \to \pi l \nu)}{B(\pi^+ \to \pi^0 e^+ \nu)}$ EW Rad. Corr. cancel

Improve precision on $B(\pi^+ \to \pi^0 e^+ \nu)$ by x3 ⇒ $V_{us}/V_{ud} < \pm 0.2\%$

6. Physics Opportunities in studying rare η and η' decays

→ See Talks in Wednesday morning RF2 session
And WP ArXiv: 2203.07651 [hep-ex]

Experimental program in η and η' decays

From S. Tulin

Upcoming experiments:

Jefferson Eta Factory (JEF) at Jefferson Lab – Hall D (approved)

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

per 100 days

Rare Eta Decays TO Probe new physics (REDTOP)

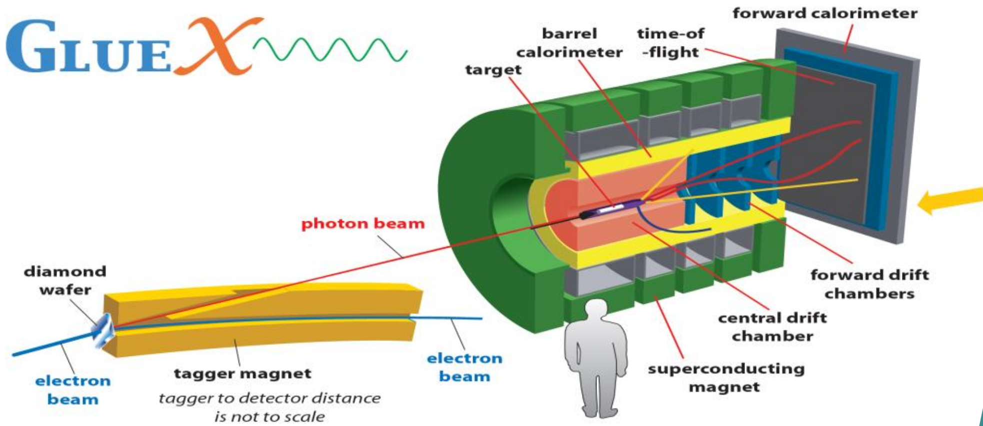
Phase I (untagged mode)	2×10^{14}	10^{13}	3 years
Phase II+ (tagged mode)	1×10^{14}	10^{13}	

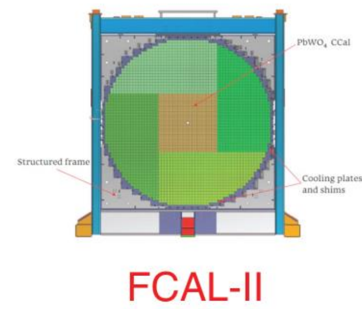
Previous experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim 3 \times 10^7$ (p+d), $\sim 5 \times 10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim 10^7$	$\sim 5 \times 10^7$

Jefferson Eta Factory (JEF) experiment γ beam (10 GeV) on H target

GlueX + upgraded forward calorimeter at Jefferson Lab (Hall D)

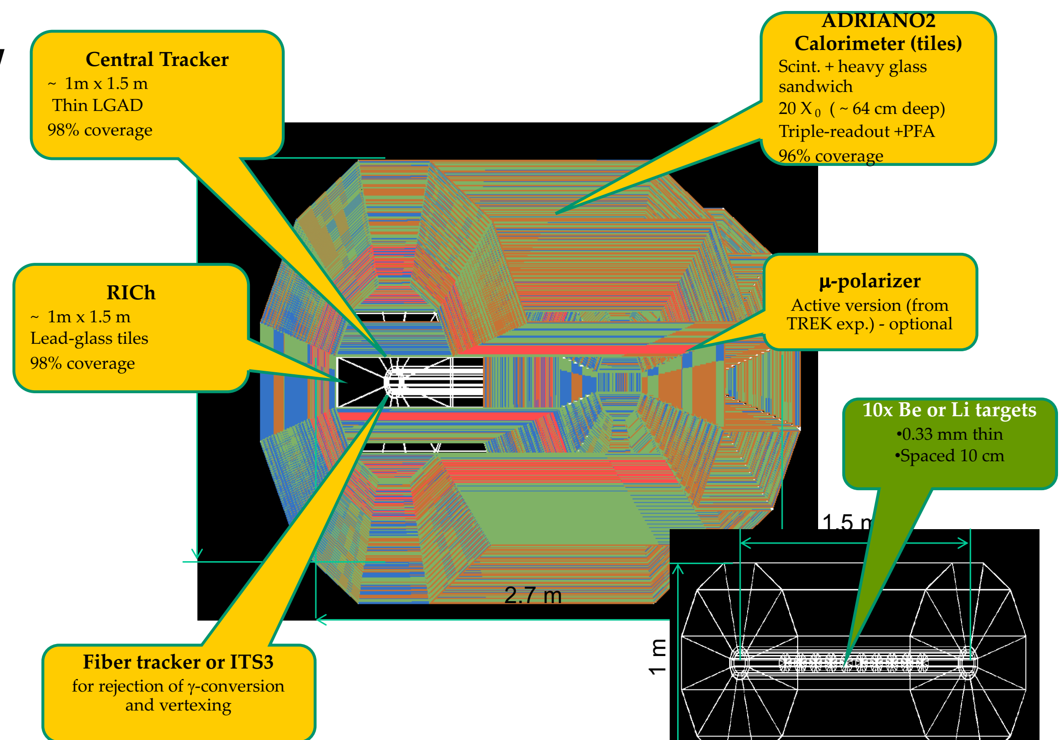




Data taking expected in 2024

Rare Eta Decays TO Probe new physics (REDTOP)

Proton beam (1-3 GeV) on nuclear target (Be/D)



From S. Tulin

Physics Motivation

Standard Model highlights
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests
- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)
- Vector bosons
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp\nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, E.P., Tulin'21

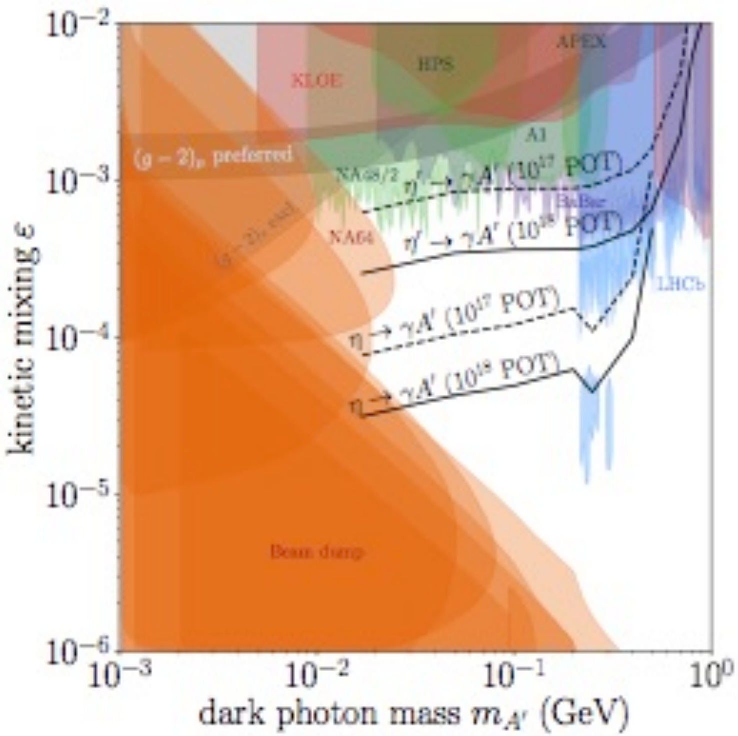
New Light Particles beyond the SM

See e.g. Fayet'07, Reece & Wan'09, Bjorken et al.'09, Batell et al.'09

Dark photons and other hidden vector bosons

$$\mathcal{B}(\eta \to A'\gamma) = 2\varepsilon^2 \mathcal{B}(\eta \to \gamma\gamma) \left|\bar{F}_{\eta\gamma^*\gamma^*}(m_{A'}^2, 0)\right|^2 \left(1 - m_{A'}^2/M_\eta^2\right)^3 .$$

- Resonances in the dilepton invariant mass spectrum for $\eta^{(\prime)} \to \ell^+\ell^-\gamma$



Projected sensitivies for visibly-decaying A′ from η, η′ decays at REDTOP for:

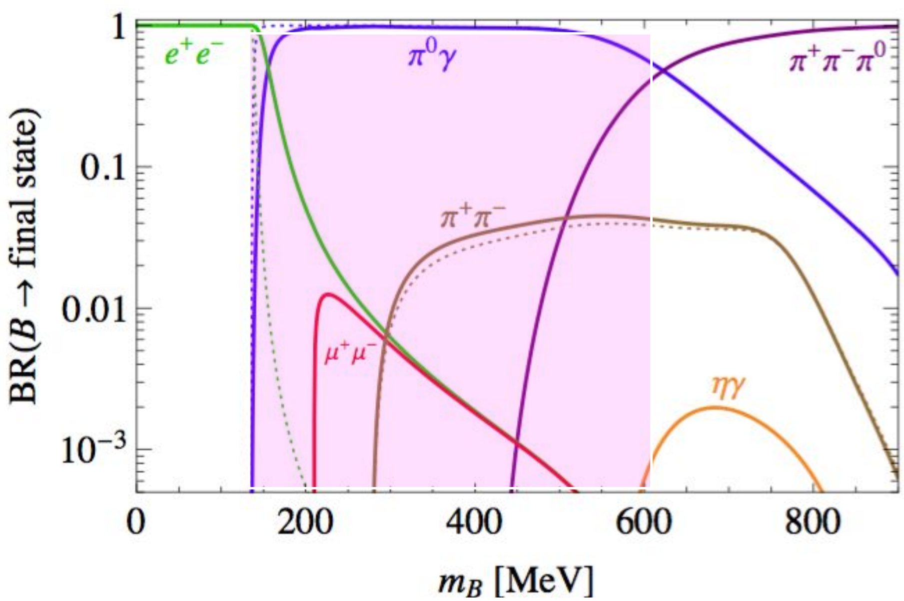
- Dashed: expected flux 10^{17} POT
- Solid: : expected flux 10^{18} POT

Dark shaded band is preferred to explain $(g-2)_\mu$ anomaly, while other shaded regions are exclusions.

Dark photons and other hidden vector bosons

- Leptophobic vector bosons: B boson from gauged $U(1)_B$ symmetry

  ⇨ non-leptonic signatures, e.g., *$\pi^0\gamma$ resonance* in $\eta \to B\gamma \to \pi^0\gamma\gamma$



Leptophobic B′
(dark ω, γ_B , or Z′): $\frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu$

Gauged baryon symmetry $U(1)_B$

Lee and Yang'55

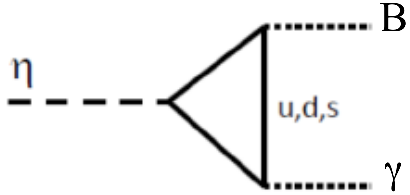
- $m_B < m_\pi$ is strongly constrained by long-range forces searches
- $m_B > 50$ GeV investigated by collider experiments.
- GeV-scale domain is nearly untouched:

  ⇨ a *discovery opportunity*!

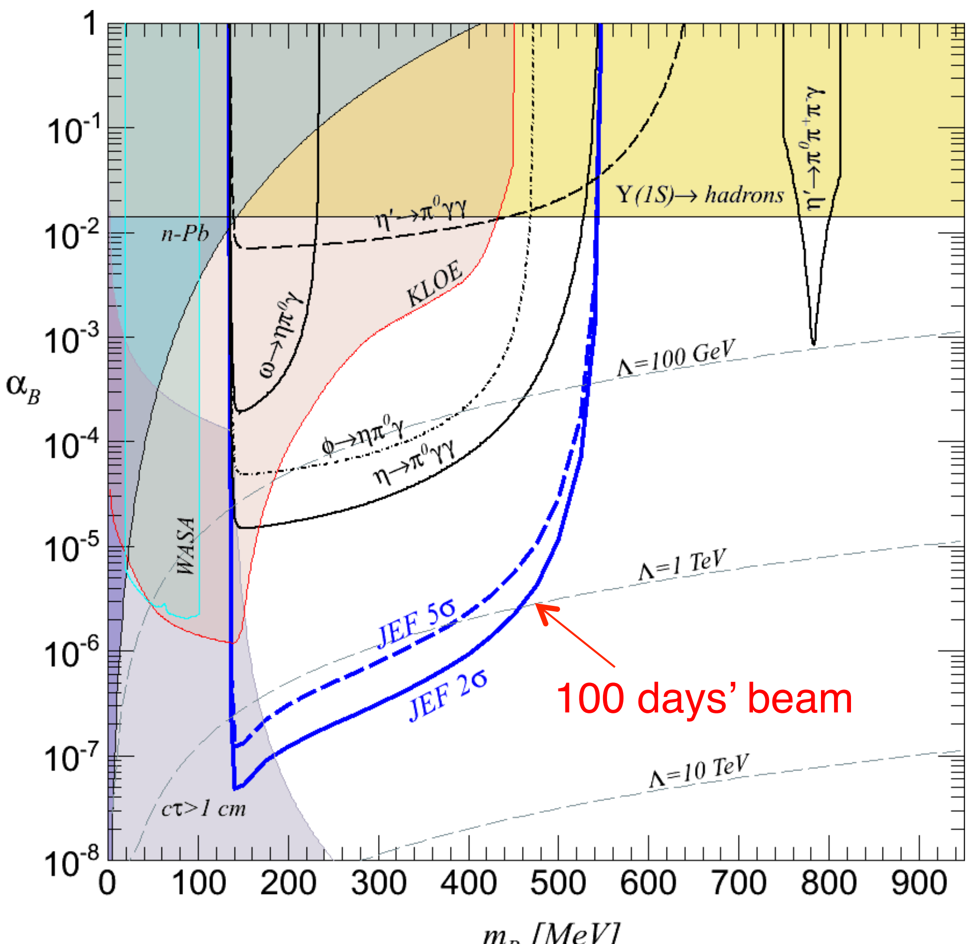
JEF Experimental Reach for B

From L. Gan

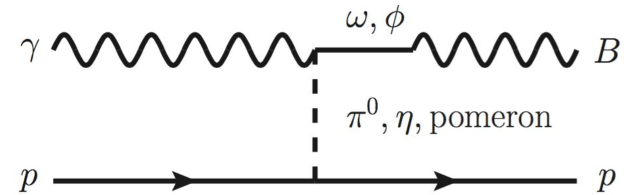
1. Meson decay $\eta \to B\gamma \to \pi^0\gamma\gamma$

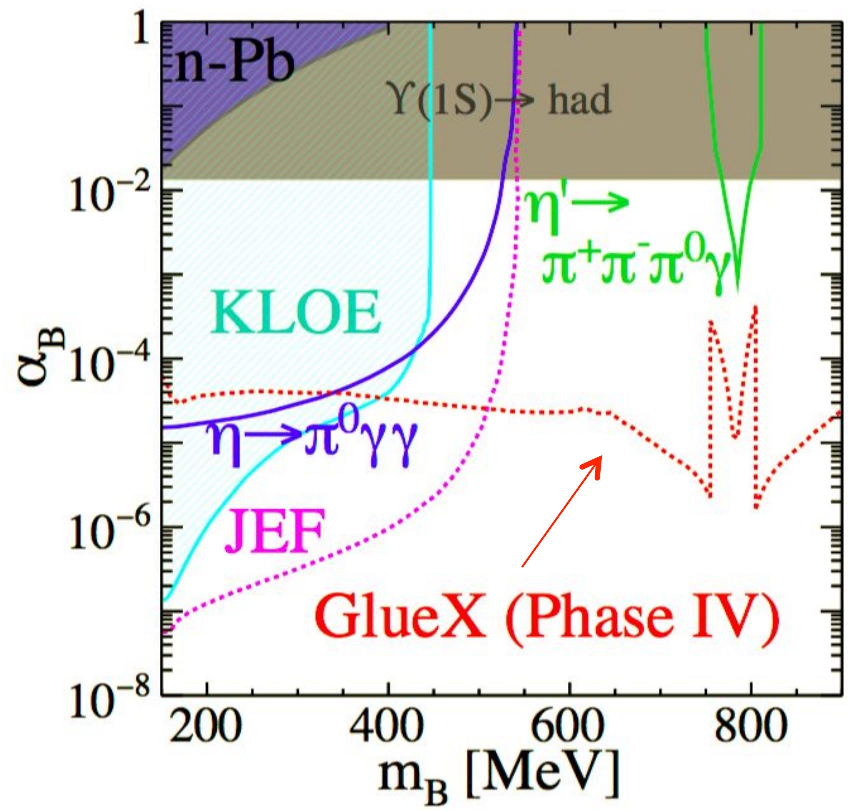


PL, B221, 80 (1989)
PR,D89,114008



2. Photoproduction $\gamma p \to Bp$





arXiv:1605.07161

New Light Particles beyond the SM

Scalar particles

- η(′) decays ⇨ the strongest limits on a scalar *S* coupling to *light quarks* instead of heavy quarks
  - For leptophobic scalar, signal channels are: η(′) → π0γγ or η(′) → 3π with S a *γγ* or *2π resonance*.
  - For more general models, S can be discovered as a *dilepton resonance* in $\eta^{(')} \to \pi^0 \ell^+ \ell^-$ channel motivated mainly for C and CP searches

⇨ Work remains to be done:

- Map out the more general parameter space for these decays
- Compute the transition form factors for η′ decays needed to access a wider range of m_S

Here only 2 examples of search for New light particles but much more can be done ⇨ 4 portals can be studied with REDTOP

P and CP violation

- A large number of P,CP-violating η(′) decays indirectly excluded from extremely stringent neutron EDM bounds

- The only exception: investigation of the *muon polarization asymmetries* in $\eta \to \mu^+\mu^-$: EDM constraints at 2 loop order

Sanchez-Puertas'19

$$\mathcal{L}_{\rm eff} = -\frac{1}{2v^2}\Big\{ \mathrm{Im}\, c^{(1)2211}_{\ell equ}\big[(\bar\mu\mu)(\bar u i\gamma^5 u) + (\bar\mu i\gamma^5\mu)(\bar u u)\big] - \mathrm{Im}\, c^{2211}_{\ell edq}\big[(\bar\mu\mu)(\bar d i\gamma^5 d) - (\bar\mu i\gamma^5\mu)(\bar d d)\big] - \mathrm{Im}\, c^{2222}_{\ell edq}\big[(\bar\mu\mu)(\bar s i\gamma^5 s) - (\bar\mu i\gamma^5\mu)(\bar s s)\big]\Big\}$$

⇒ probe flavour-conserving CP-violation in the second generation possible with REDTOP statistics

Discrete symmetry tests and lepton flavor violation

REDTOP sensitivity studies:

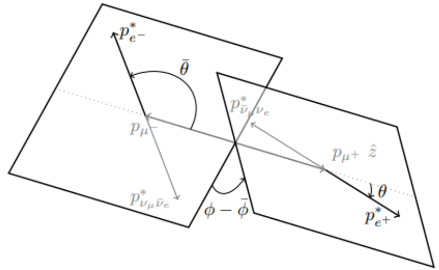


FIG. 11. Kinematics of the process. The decaying muons' momenta in the η rest frame are noted as $p_{\mu^\pm}$, while the $e^\pm$ momenta, $p^*_{e^\pm}$, is shown in the corresponding $\mu^\pm$ reference frame along with the momenta of the $\nu\bar{\nu}$ system. The $\hat{z}$ axis is chosen along p_{μ^+}.

introduced two different muon's polarization asymmetries,

$$A_L = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N} = \mathrm{Im}[4.1 c^{2222}_{\ell edq} - 2.7(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-2}, \quad (47)$$

$$A_\times = \frac{N(\sin\Phi > 0) - N(\sin\Phi < 0)}{N} = \mathrm{Im}[2.5 c^{2222}_{\ell edq} - 1.6(c^{(1)2211}_{\ell equ} + c^{2211}_{\ell edq})] \times 10^{-3}, \quad (48)$$

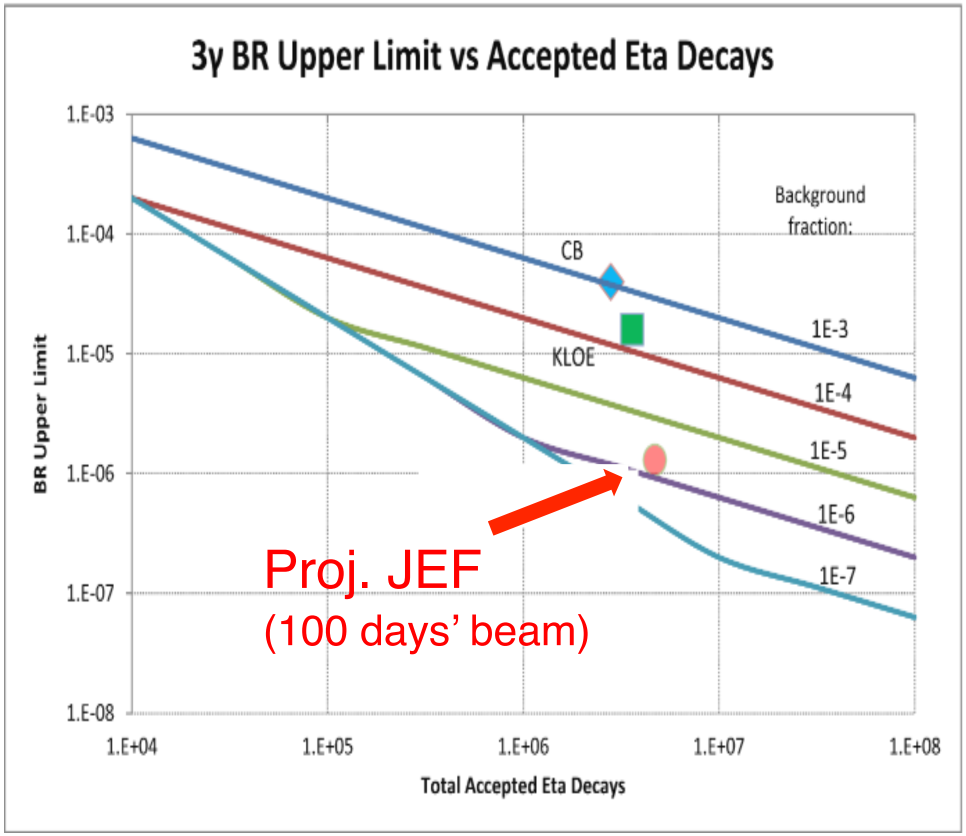
Process	*Trigger* L0	*Trigger* L1	*Trigger* L2	*Reconstruction + analysis*	**Total**	Branching ratio sensitivity
$\eta \to \mu^+\mu^-$	66.3%	16.3%	51.9%	69.6%	3.9%	$2.7 \times 10^{-8} \pm 3.0 \times 10^{-10}$
Urqmd	21.7%	1.7%	22.2%	8.6×10^{-3}%	7.0×10^{-6}%	-

$$\Delta(c^{1122}_{\ell equ}) = 0.1 \times 10^{-1}, \quad \Delta(c^{1122}_{\ell edq}) = 0.1, \quad \Delta(c^{2222}_{\ell edq}) = 6.6 \times 10^{-2},$$

Discrete symmetry tests and lepton flavor violation

C and CP violation

- $\eta(')\to 3\gamma$: *C*, *P*-violating but *CP*-conserving.



JEF could Improve the
BR upper limit
by one order of magnitude

Discrete symmetry tests and lepton flavor violation

C and CP violation

More processes can be studied

- C- and CP-violating asymmetries in the $\eta \to \pi^+\pi^-\pi^0$ Dalitz-plot

Gardner & Shi'20
Kubis et al. 21

- C- and CP-violating channels used to search for new light particles:
  $\eta(') \to \pi^0 l^+ l^-$ and $\eta(') \to 2\pi^0 l^+ l^-$

Discrete symmetry tests and lepton flavor violation

Lepton Flavour Violation

- In light of strong constraints on $\mu \to e$ conversion on nuclei, further theoretical study is needed to motivate searching for $\eta(') \to e^{\pm}\mu^{\mp}$

- But decays that violate charged lepton flavour by two units, $\eta(') \to e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$ are worth investigated since they are not similarly constrained

Lepton Flavour Universality Violation

- $\eta \to \gamma e^{+}e^{-}$ vs $\eta \to \gamma \mu^{+}\mu^{-}$

JEF program

Time line

- The data collection for non rare decays has been in progress since fall 2016. A significant improvement on the light quark mass ratio will be achieved in the next 3-4 years by a combination of a new Primakoff measurement of the η radiative decay width and the improvements in the Dalitz distributions of $\eta \rightarrow 3\pi$ for both charged and neutral channels.

- The second phase of JEF will run with an upgraded forward calorimeter:
  - 2018 - 2023, development of an upgraded forward calorimeter (FCAL-II) with a PWO crystal insert
  - 2024: first run with an upgraded FCAL-II for rare decays expected

- Within 100 days of beam time for the phase II, JEF will have sufficient precision to explore the role of scalar meson dynamics in chiral perturbation theory, to search for sub-GeV dark gauge bosons (vector, scalar, and axion-like particles) by improving the existing bounds by two orders of magnitude

REDTOP program

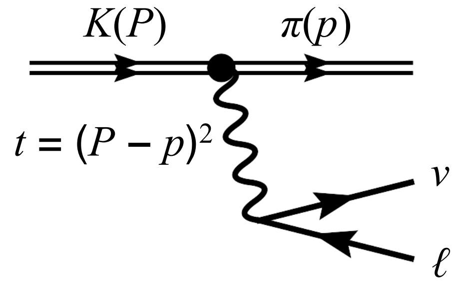
- Proposed REDTOP experiment at several laboratories:
  - Fermilab
  - HIAF
  - GSI
  - CERN
  - BNL
- Projected η production rate at the level of 1.1×10^{14} (a factor of ten more forphase II) per year.
- Expected backgrounds in REDTOP about several orders of magnitude higher than in the JEF experiment compensated for by an enormous η yield.
- The recoil detection technique considered for phase II will help further reducing the backgrounds.
- The proposed muon polarimeter (and an optional photon polarimeter) for the REDTOP apparatus will offer additional capability to measure the longitudinal polarization of final-state muons (and possibly photons), which are not available in most other experiments, including JEF.

REDTOP program

- In the foreseeable future, REDTOP will offer the most sensitive probes for the rare charged decay channels, while the JEF experiment will remain leading in the rare neutral decays because of lower backgrounds and higher experimental resolutions
- The JEF and REDTOP experiments are complementary to each other, promising a new exciting era for $\eta(')$ physics.

4. Back-up

V_{us} from K_{l3} ($K \to \pi l \nu_l$)



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

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

Recent progress on theory side:

- Theoretically update on long-distance EM corrections for K_{e3}

$\Delta^{EM}(K^0_{e3})$ = (0.50 ± 0.11) % ⇒ **(0.580 ± 0.016) %**

$\Delta^{EM}(K^+_{e3})$ = (0.50 ± 0.11) % ⇒ **(0.105 ± 0.024) %**

Seng et al.'21

- Improvement on Isospin breaking evaluation $\Delta^{SU(2)} \equiv \frac{f_+(0)^{K^+\pi^0}}{f_+(0)^{K^0\pi^-}} - 1$

⇒ better Q value determination from Lattice QCD or eta decays

Colangelo et al.'18

- Progress from lattice QCD on the $K \to \pi$ FF

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

2.1 V_{us} from K_{l3}

Matthew Moulson, Chien Yeah Seng

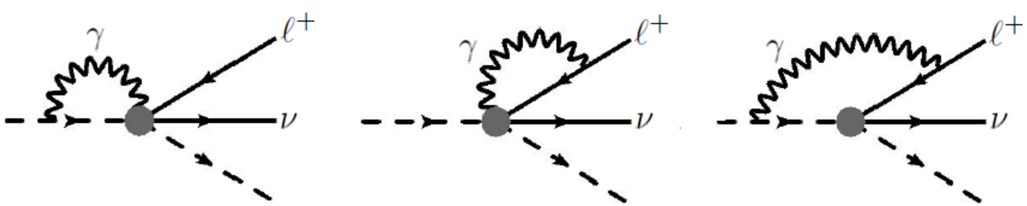
Progress since 2018:

- First experimental measurement of BR of $K_S \to \pi\mu\nu$

  BR($K_S \to \pi\mu\nu$) = (4.56 ± 0.20) ×10^{-4}

KLOE-2
PLB 804 (2020)

- Theoretically update on long-distance EM corrections:



Up to now computation at fixed order e^2p^2 + model estimate for the LECs

Cirigliano et al. '08

New calculation of complete EW RC using hybrid current algebra and ChPT (Sirlin's representation) with resummation of largest terms to all chiral orders

– Reduced uncertainties at O(e^2p^4)

– Lattice evaluation of QCD contributions to γW box diagrams

Seng et al.'21

2.1 V_{us} from K_{l3}

Matthew Moulson,
Chien Yeah Seng

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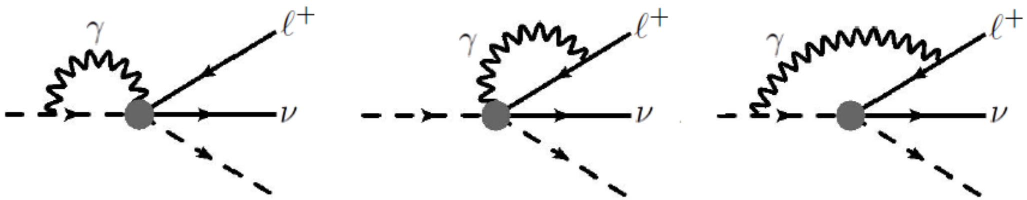


Only K_{e3} at present
For $K_{\mu3}$ modes continue to use
Cirigliano et al. '08

	Cirigliano et al. '08	Seng et al. '21
$\Delta^{EM}(K^0{}_{e3})$ [%]	0.50 ± 0.11	**0.580 ± 0.016**
$\Delta^{EM}(K^+{}_{e3})$ [%]	0.05 ± 0.13	**0.105 ± 0.024**
ρ	+0.081	**–0.039**

Progress since 2018:

- Theoretical progress on isospin breaking correction

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

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 $\varepsilon_{\mathrm{EM}}{}^{(4)} \sim 10^{-6}$

Cirigliano et al., ’02; Gasser & Leutwyler, ’85

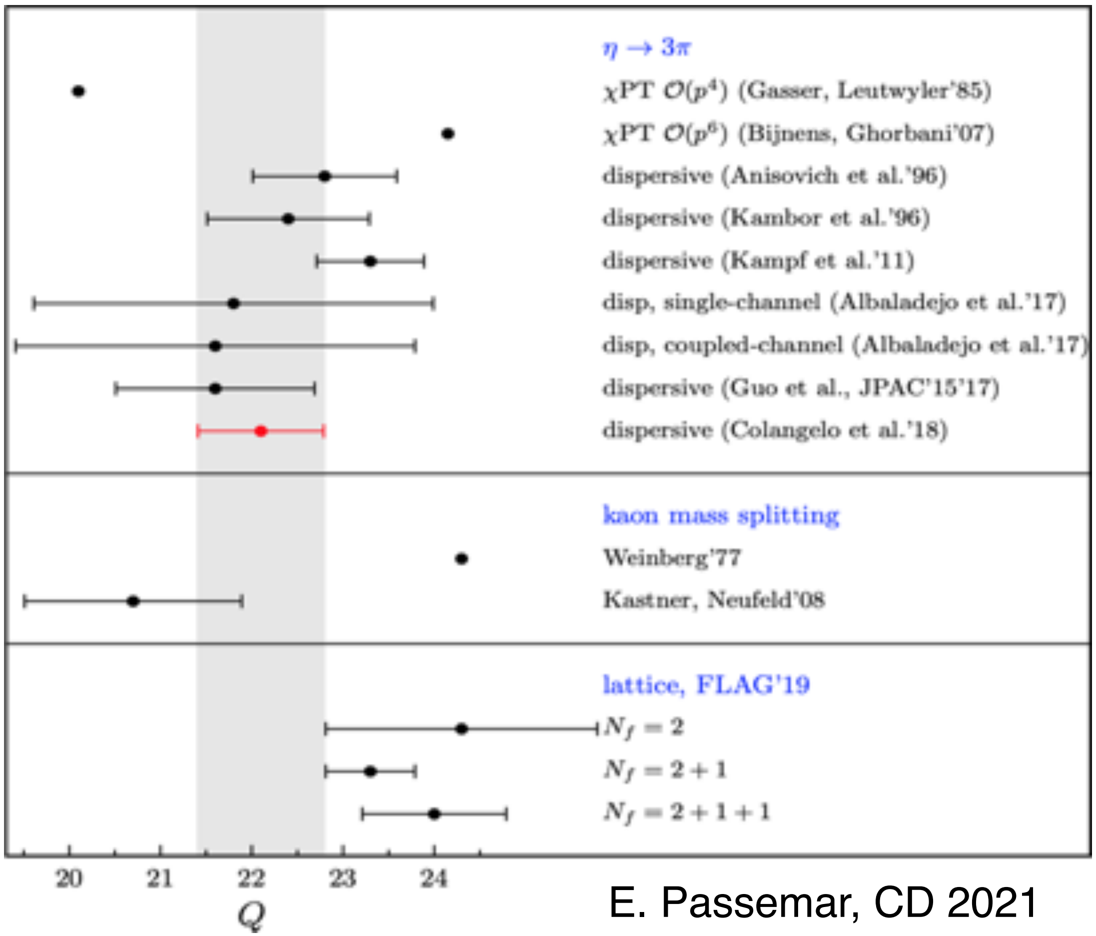
$= +2.61(17)\%$ **Calculated using:**

$Q = 22.1(7)$	Colangelo et al. ’18, avg. from $\eta \to 3\pi$
$m_s/\hat{m} = 27.23(10)$	FLAG ’20, $N_f = 2+1+1$ avg.
$M_K = 494.2(3)$, $M_\pi = 134.8(3)$	Isospin-limit meson masses from FLAG ’17

Test by evaluating V_{us} from $K^\pm$ and K^0 data with **no** corrections:
Equality of V_{us} values would require $\Delta^{SU(2)}$ **= 2.86(34)%**

2.1 V_{us} from K_{l3}

Previous to recent results for Q, uncertainty on $\Delta^{SU(2)}$ was leading contributor to uncertainty on V_{us} from $K^{\pm}$ decays



E. Passemar, CD 2021

Reference value of Q from dispersion relation analyses of $\eta \to 3\pi$ Dalitz plots

Colangelo et al., '18

Q = 22.1 ± 0.7

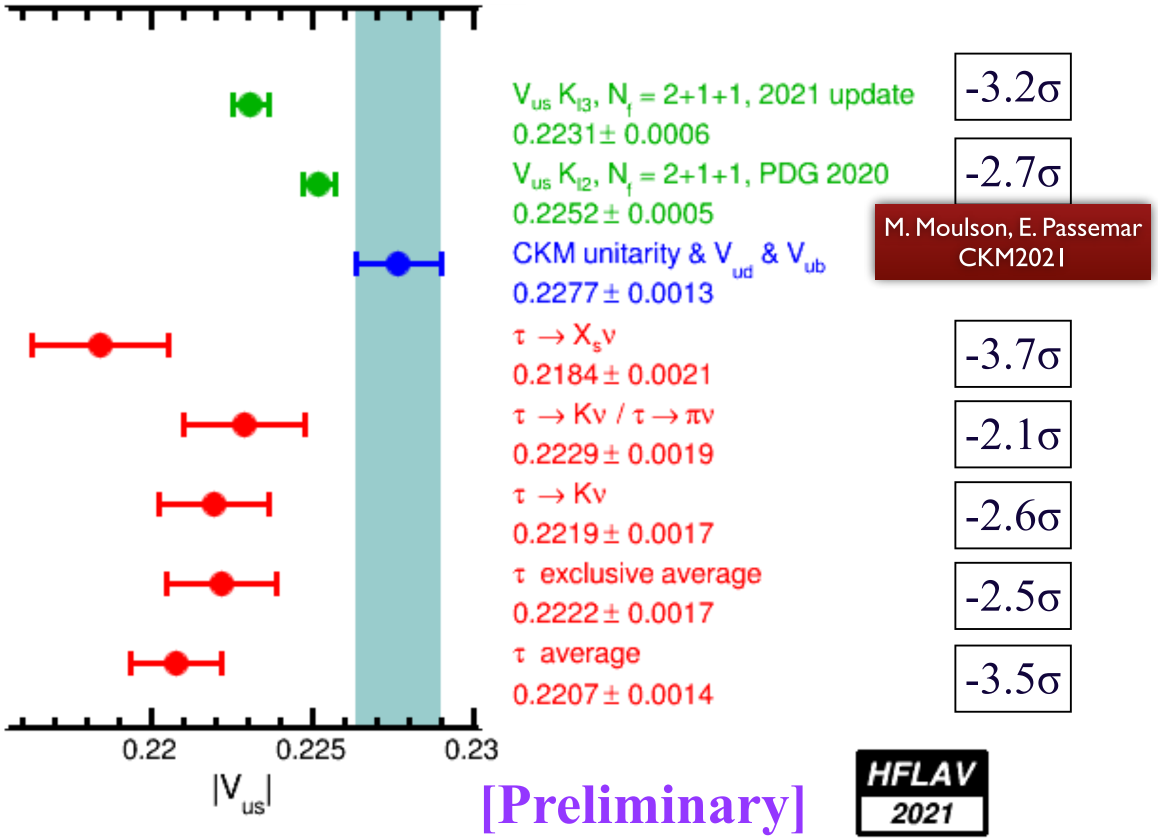
Lattice results for Q somewhat higher than analytical results

But, lattice results have finite correction to LO expectation:

$$Q_M^2 \equiv \frac{\hat{M}_K^2}{\hat{M}_\pi^2} \frac{\hat{M}_K^2 - \hat{M}_\pi^2}{\hat{M}_{K^0}^2 - \hat{M}_{K^+}^2}$$

Low-energy theorem: Q has no correction at NLO

V_{us} from Tau decays



- Belle II with 50 ab^{-1} and ~4.6 x 10^{10} τ pairs will improve V_{us} extraction
- Inclusive measurement is an opportunity to have a complete independent measurement of V_{us} ⇨ not easy as you have to measure many channels

V_{us} from Tau decays

e 13: HFLAV 2021 τ branching fractions to strange final states.

Branching fraction	HFLAV 2021 fit (%)
$K^-\nu_\tau$	0.6957 ± 0.0096
$K^-\pi^0\nu_\tau$	0.4322 ± 0.0148
$K^-2\pi^0\nu_\tau$ (ex.K^0)	0.0634 ± 0.0219
$K^-3\pi^0\nu_\tau$ (ex.K^0,η)	0.0465 ± 0.0213
$\pi^-\overline{K}^0\nu_\tau$	0.8375 ± 0.0139
$\pi^-\overline{K}^0\pi^0\nu_\tau$	0.3810 ± 0.0129
$\pi^-\overline{K}^0 2\pi^0\nu_\tau$ (ex.K^0)	0.0234 ± 0.0231
$\overline{K}^0 h^- h^- h^+\nu_\tau$	0.0222 ± 0.0202
$K^-\eta\nu_\tau$	0.0155 ± 0.0008
$K^-\pi^0\eta\nu_\tau$	0.0048 ± 0.0012
$\pi^-\overline{K}^0\eta\nu_\tau$	0.0094 ± 0.0015
$K^-\omega\nu_\tau$	0.0410 ± 0.0092
$K^-\phi(K^+K^-)\nu_\tau$	0.0022 ± 0.0008
$K^-\phi(K_S^0K_L^0)\nu_\tau$	0.0015 ± 0.0006
$K^-\pi^-\pi^+\nu_\tau$ (ex.K^0,ω)	0.2924 ± 0.0068
$K^-\pi^-\pi^+\pi^0\nu_\tau$ (ex.K^0,ω,η)	0.0387 ± 0.0142
$K^-2\pi^-2\pi^+\nu_\tau$ (ex.K^0)	0.0001 ± 0.0001
$K^-2\pi^-2\pi^+\pi^0\nu_\tau$ (ex.K^0)	0.0001 ± 0.0001
$X_s^-\nu_\tau$	2.9076 ± 0.0478

HFLAV'21

$$R_\tau \equiv \frac{\Gamma\left(\tau^- \to \nu_\tau + \text{hadrons}\right)}{\Gamma\left(\tau^- \to \nu_\tau e^- \overline{\nu}_e\right)} \approx N_C$$

parton model prediction

$$\delta R_\tau \equiv \frac{R_{\tau,NS}}{|V_{ud}|^2} - \frac{R_{\tau,S}}{|V_{us}|^2}$$

SU(3) breaking quantity, strong dependence in m_s computed from OPE (L+T) + phenomenology

$$\delta R_{\tau,th} = 0.0242(32)$$

Gamiz et al'07, Maltman'11

$$|V_{us}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,NS}}{|V_{ud}|^2} - \delta R_{\tau,th}}$$

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

2.9σ away from unitarity!

$|V_{ud}|$ from $0^+ \to 0^+$ superallowed β decays

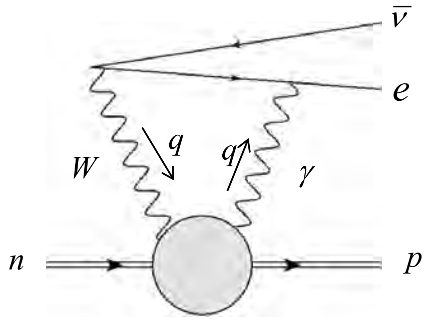
See Talk by Misha Gorshteyn @CKM2021

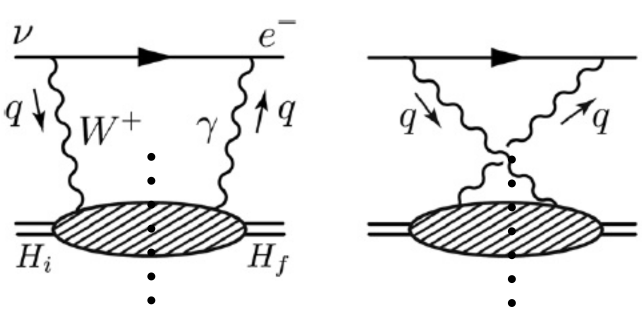
Recent improvement on the theoretical RCs:

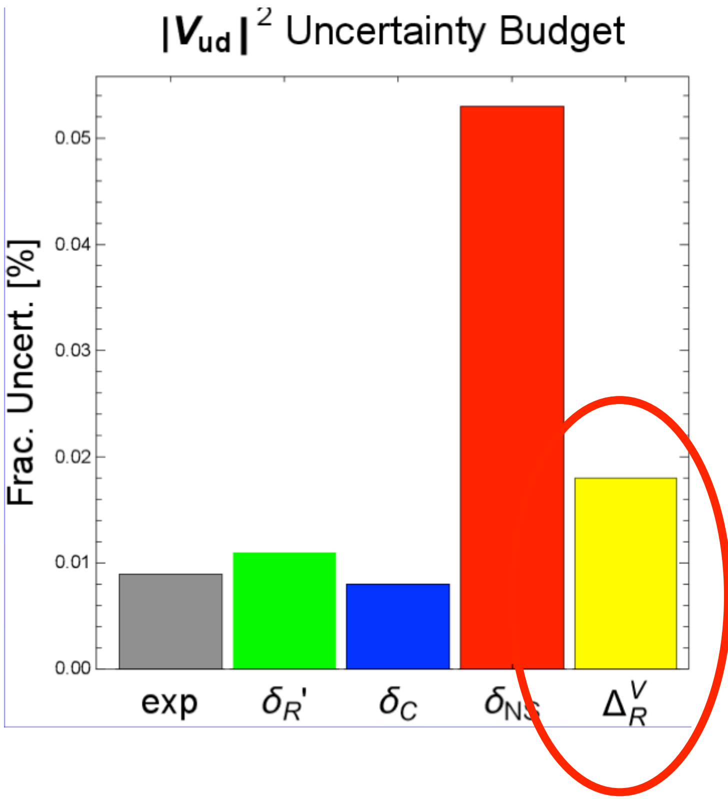
- Universal Radiative corrections have been reevaluated using Dispersion Relations:

  ➡ allow to combine independent inputs

  Experimental neutrino data +
  lattice QCD + ChPT + Regge phenomenology







Seng, Gorshteyn, Patel, Ramsey-Musolf'18,
Seng, Gorshteyn, Ramsey-Musolf'18,
Gorshteyn'18

1.2 $|V_{ud}|$ from $0^+ \rightarrow 0^+$ superallowed β decays

See Talk by Misha Gorshteyn @CKM2021

Recent improvement on the theoretical RCs:

- Universal Radiative corrections have been reevaluated using Dispersion Relations:

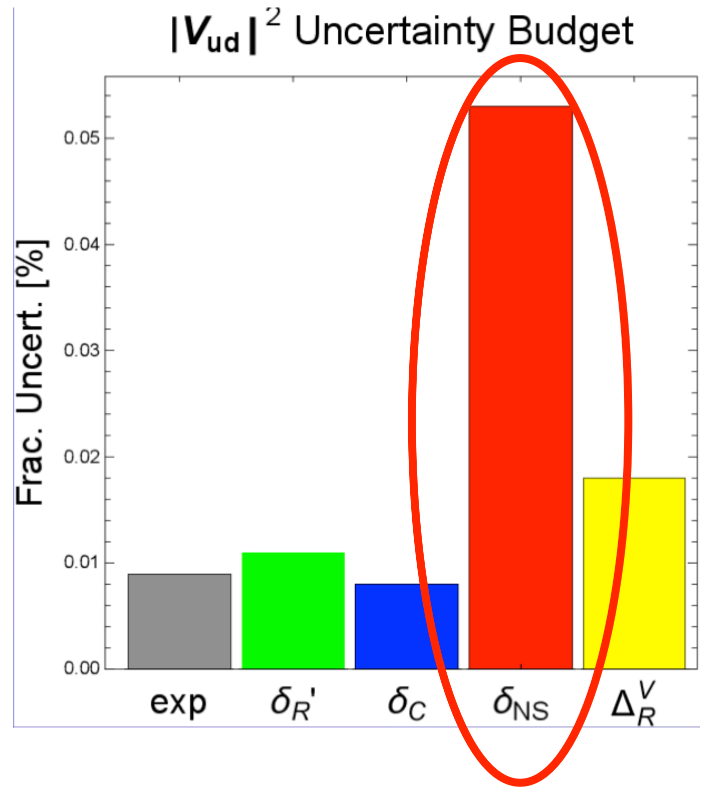
  ⇨ allow to combine independent inputs

  Experimental neutrino data +
  lattice QCD + ChPT + Regge phenomenology

- Nuclear Structure Corrections: largest source of uncertainties in V_{ud} extraction
  Corresponds to the fact of introducing nuclear corrections

Old estimate: $\delta\mathcal{F}t = -(1.8 \pm 0.4)s \quad + \quad (0 \pm 0)s$

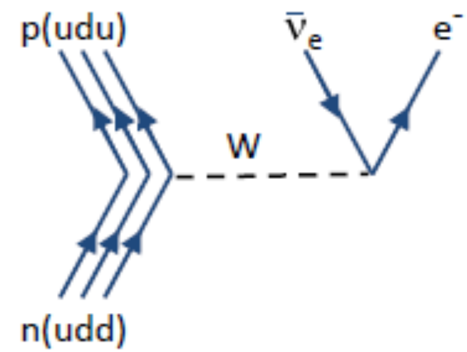
New estimate: $\delta\mathcal{F}t = -(3.5 \pm 1.0)s \quad + \quad (1.6 \pm 0.5)s$



$|V_{ud}|$ from Neutrons

- Only two free parameters in the standard model:
  - Decay asymmetry: $\lambda = g_A / g_V$
  - Lifetime: τ_n

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



- Master Formula:

$$\left|V_{ud}\right|^2 = \frac{5024.7s}{\tau_n\left(1+3\lambda^2\right)\left(1+\Delta_R\right)}$$

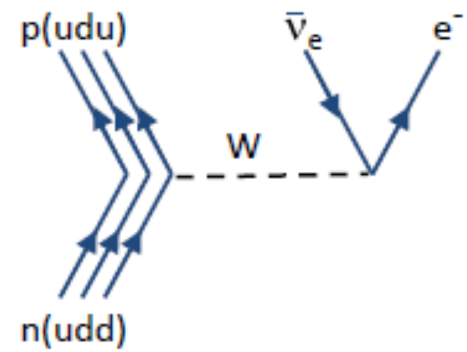
- Recent progress :
  - New Perkeo III result: *PERKEO III* result improves world-average of beta asymmetry by factor 5! Half of it is due to the reduction of the scale factor

⇨ $A = -0.11958(21),\ S = 1.2 \quad \lambda_A = -1.2757(5)$

$|V_{ud}|$ from Neutrons

- Only two free parameters in the standard model:
  - Decay asymmetry: $\lambda = g_A / g_V$
  - Lifetime: τ_n

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



- Master Formula:

$$|V_{ud}|^2 = \frac{5024.7s}{\tau_n \left(1 + 3\lambda^2\right)\left(1 + \Delta_R\right)}$$

- Recent progress presented here:
  - New result for Lifetime from *UCNτ*

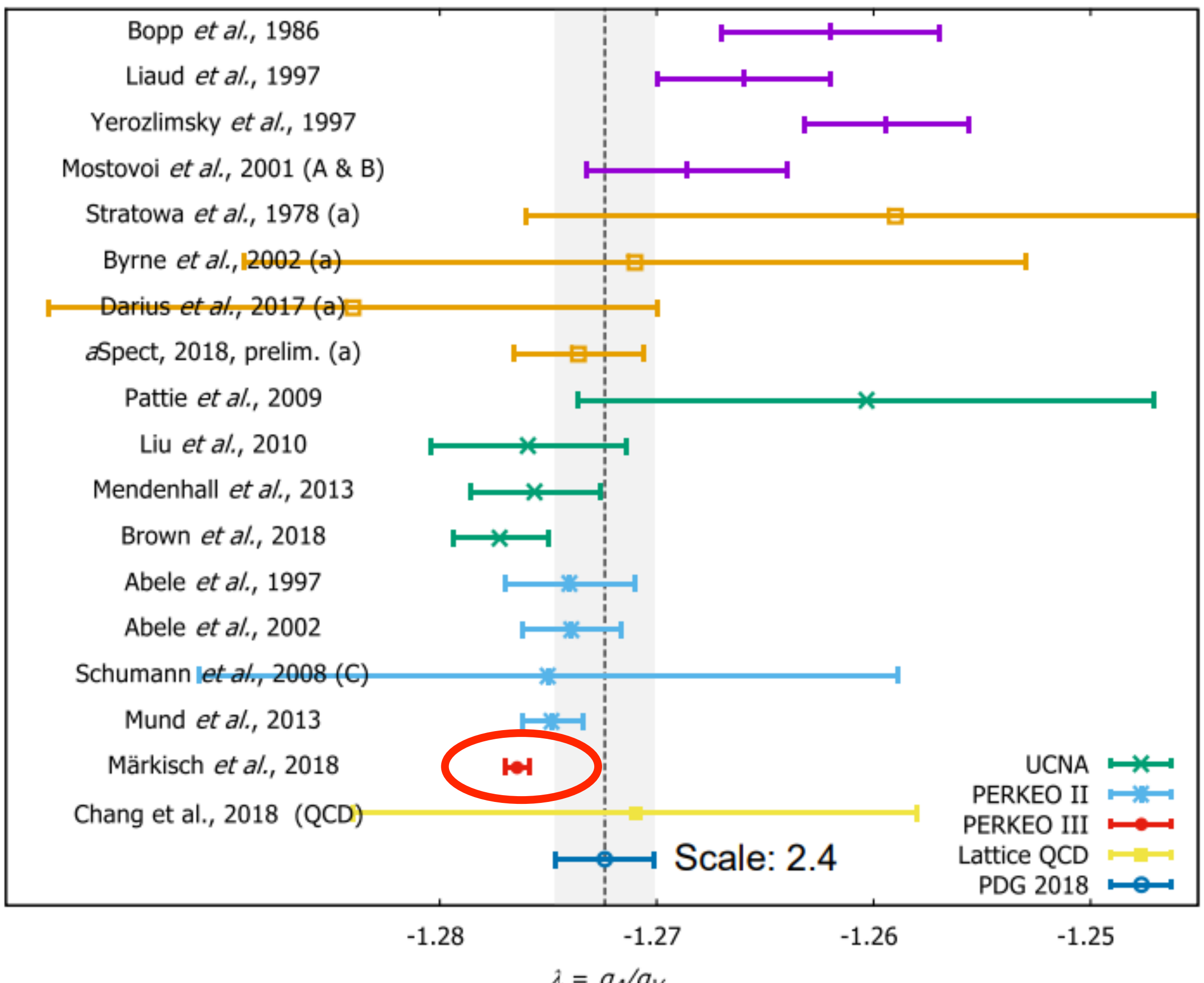
  ➡ improvement by a factor of 2.25 compared to previous result

Measurement of g_A

Bastian Märkisch

Axial Coupling: Status

Results from beta asymmetry A, unless where noted otherwise



PERKEO I

electron-neutrino correlation *a*

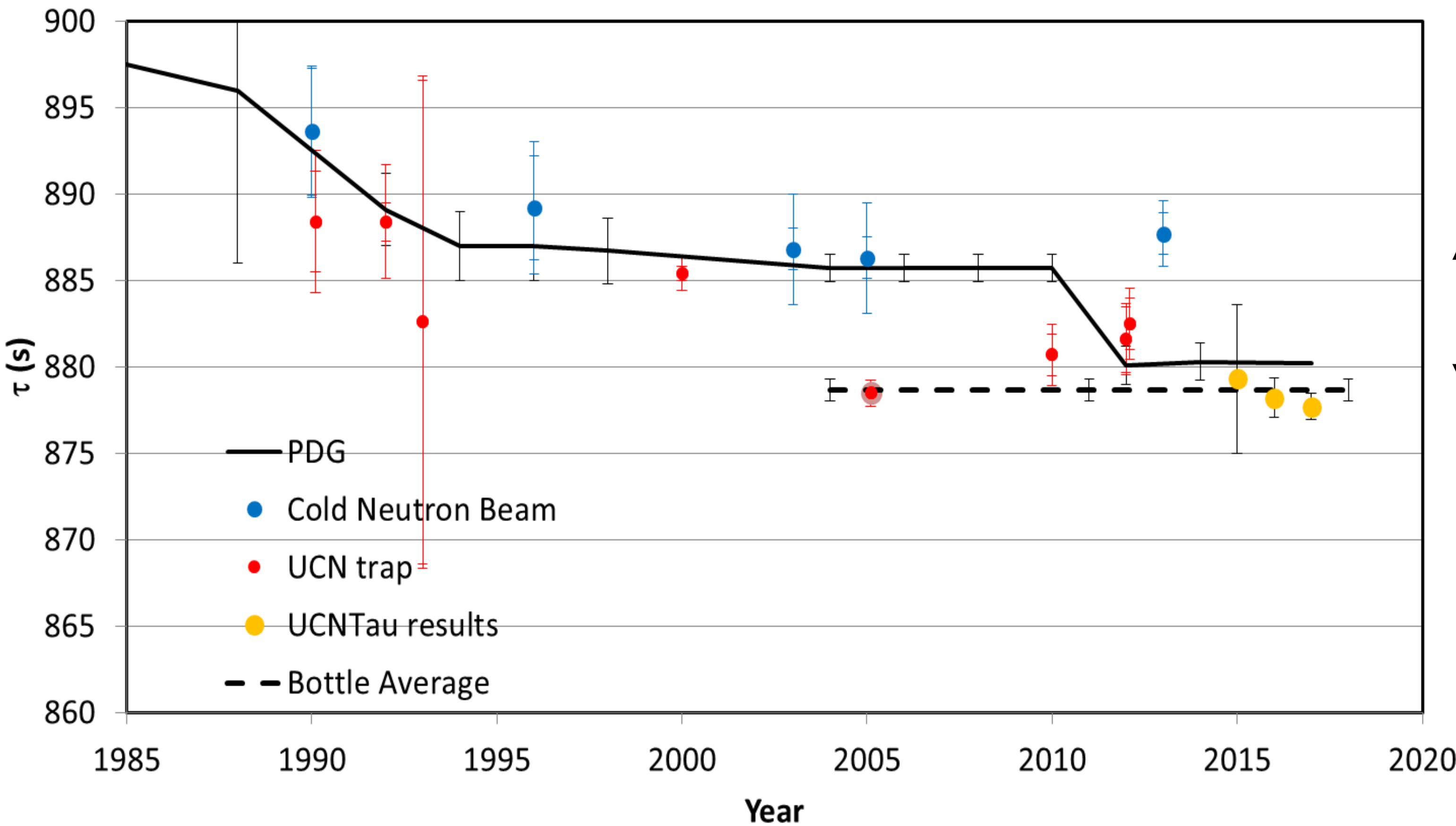
UCNA
(newer results mostly include older data)

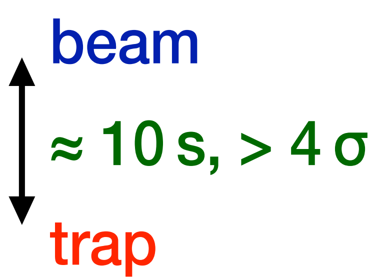
PERKEO II
(newer A results include older data)

PERKEO III

Chen-Yu Liu

UCNtau results (2018)





UCNτ results confirm trap results with independent systematics

Measurement of neutron lifetime

Chen-Yu Liu

New Result: $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

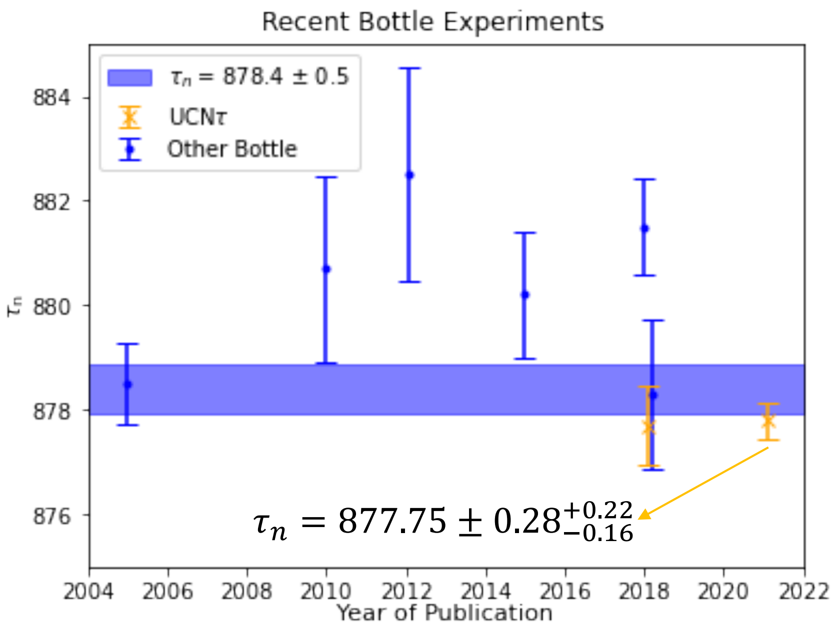
Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap…
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$	

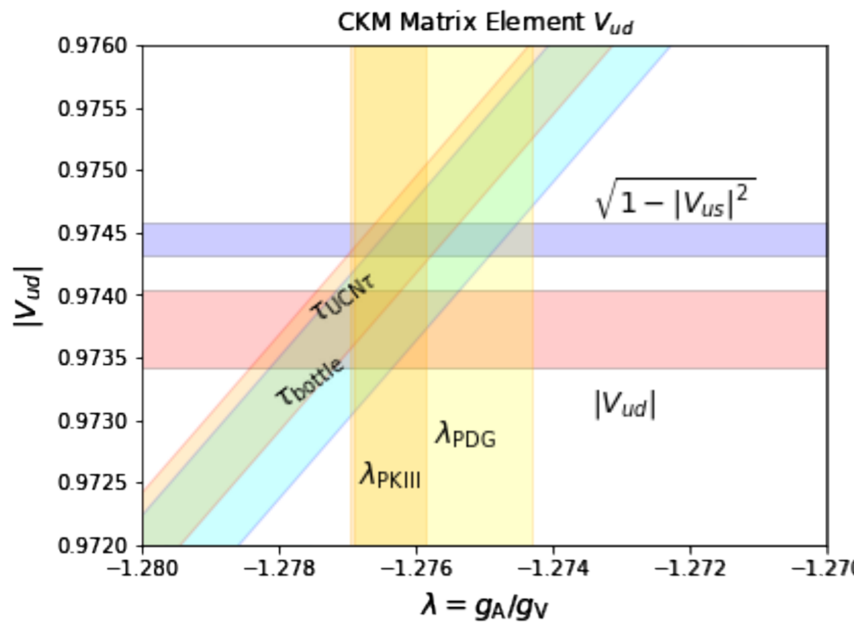
F. M. Gonzalez et al. Phys. Rev. Lett. 127 162501 (October 13, 2021)

UCNτ

Chen-Yu Liu

With new UCNtau lifetime result (+ Perkeo III), the extracted V_{ud} agrees with the CKM unitarity.





We report a measurement of τ_n with 0.34 s (0.039%) uncertainty, improving upon our past results by a factor of 2.25 using two blinded datasets from 2017 and 2018. The new result incorporates improved experimental and analysis techniques over our previous result [Science **360**, 627 (2018)].

This is the first neutron lifetime measurement precise enough to confront SM theoretical uncertainties.

28

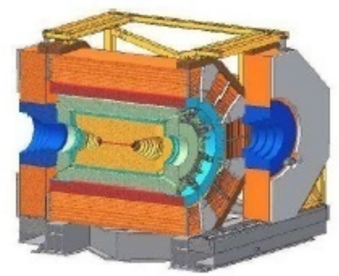
World competition in η decays

From Liping Gan

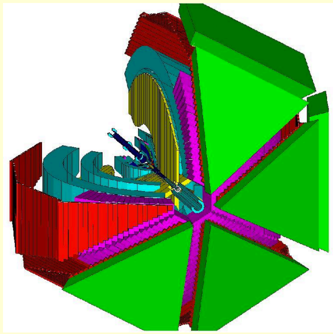
e^+e^- Collider

KLOE-2 at DAφNE

BESIII at BEPCII

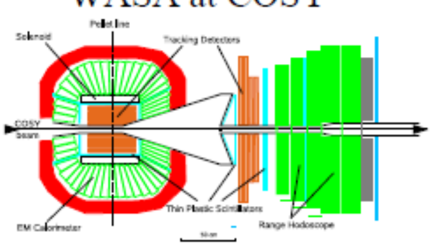


CLAS



Fixed-target

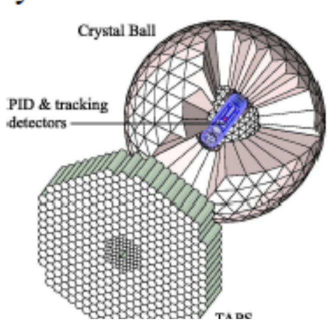
WASA at COSY



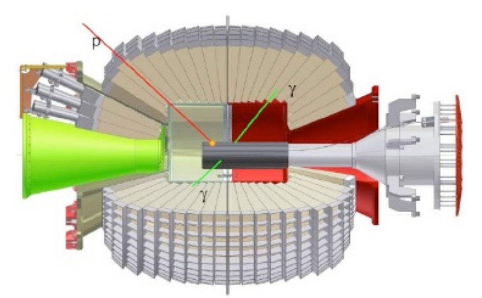
hadroproduction

photoproduction

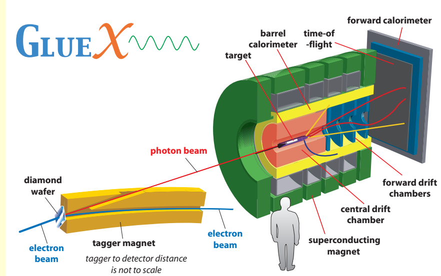
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab

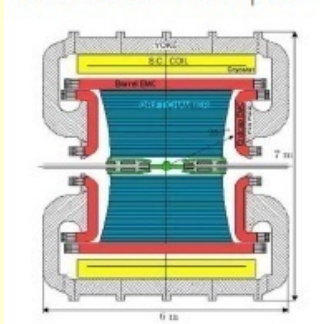


World competition in η decays

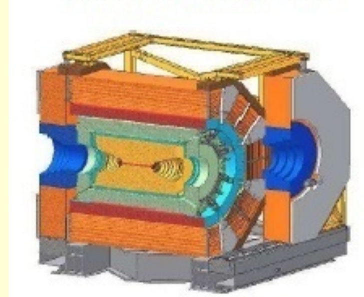
From Liping Gan

e⁺e⁻ Collider

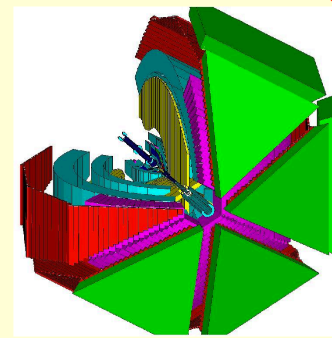
KLOE-2 at DAφNE



BESIII at BEPCII

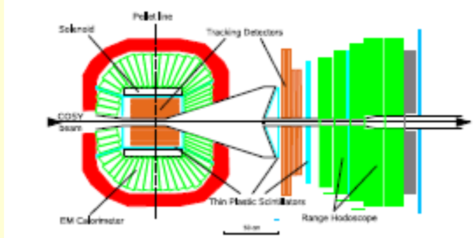


CLAS



Fixed-target

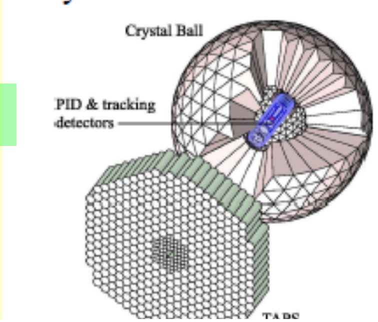
WASA at COSY



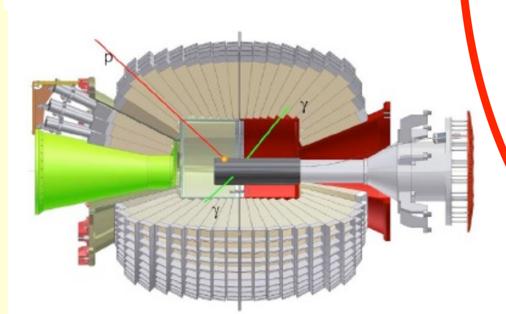
hadroproduction

photoproduction

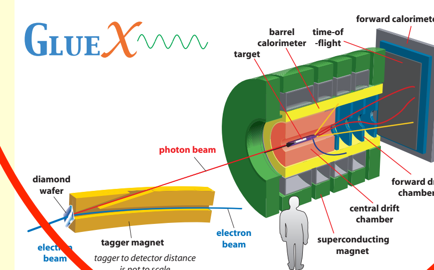
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab

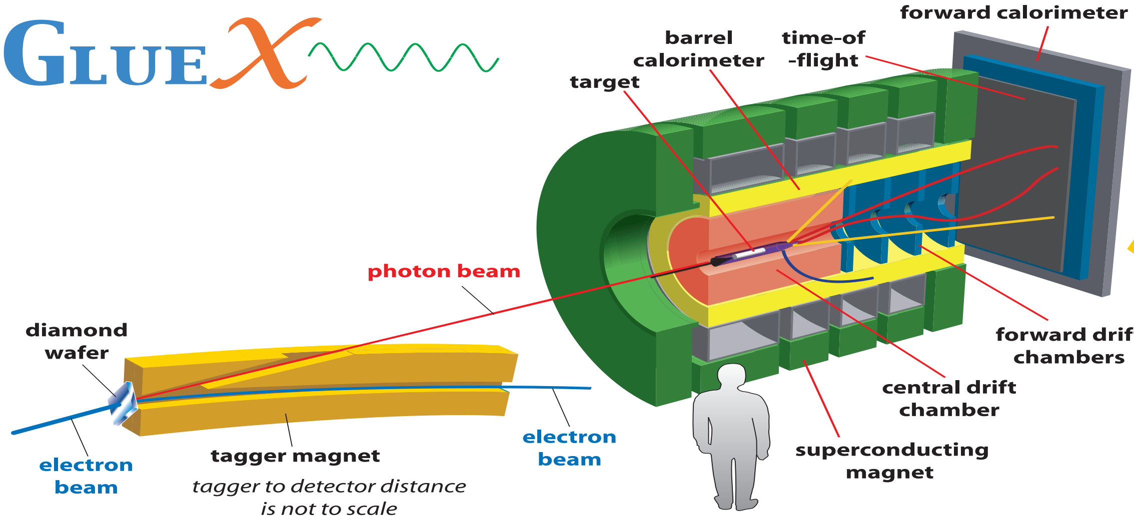


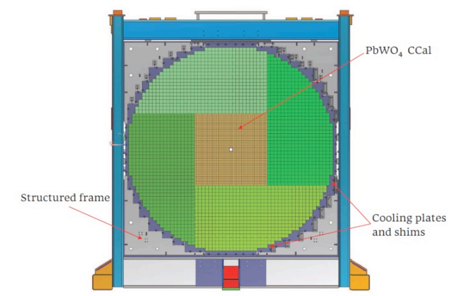
JEF program

- The ongoing JLab Eta Factory experiment will open a new avenue for precision measurements of various decays of η and η' in one setting, with unprecedented low backgrounds in rare decays, particularly in neutral modes.

JEF program

GlueX





FCAL-II

Simultaneously measure η/η' decays: $\eta \rightarrow \pi^0\gamma\gamma$, $\eta \rightarrow 3\gamma$, and …

- η/η' produced on LH_2 target with 8.4-11.7 GeV tagged photon beam:
  $\gamma + p \rightarrow \eta/\eta' + p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η decays

JEF program

- The ongoing JLab Eta Factory experiment will open a new avenue for precision measurements of various decays of η and η′ in one setting, with unprecedented low backgrounds in rare decays, particularly in neutral modes.

- Highly boosted η and η′ by a~12 GeV photon beam will help reducing the experimental systematics, offering complementary cross checks on the results from A2, BESIII, KLOE-II, WASA-at-COSY, and future REDTOP experiments, where the produced mesons have relatively small kinetic energies in the lab frame.

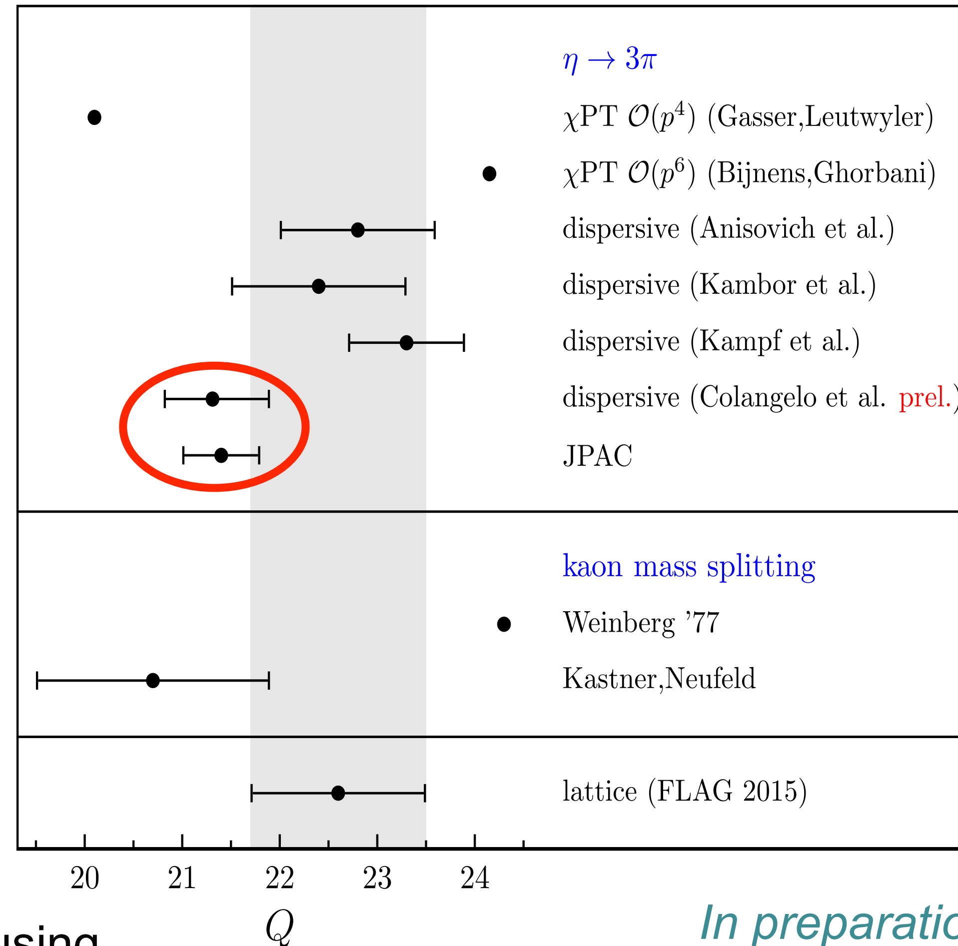
2.6 $\eta \to 3\pi$

- Isospin violating process ⇨ possibility to extract the quark mass ratio Q:

$$\Gamma_{\eta\to 3\pi} \propto \int |A(s,t,u)|^2 \propto Q^{-4}$$

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \left[\hat{m} \equiv \frac{m_d + m_u}{2}\right]$$

$$A(s,t,u) = \frac{N}{Q^2} M(s,t,u)$$



- M(s,t,u) determined through the dispersive analysis of the data but for N one has to rely on ChPT

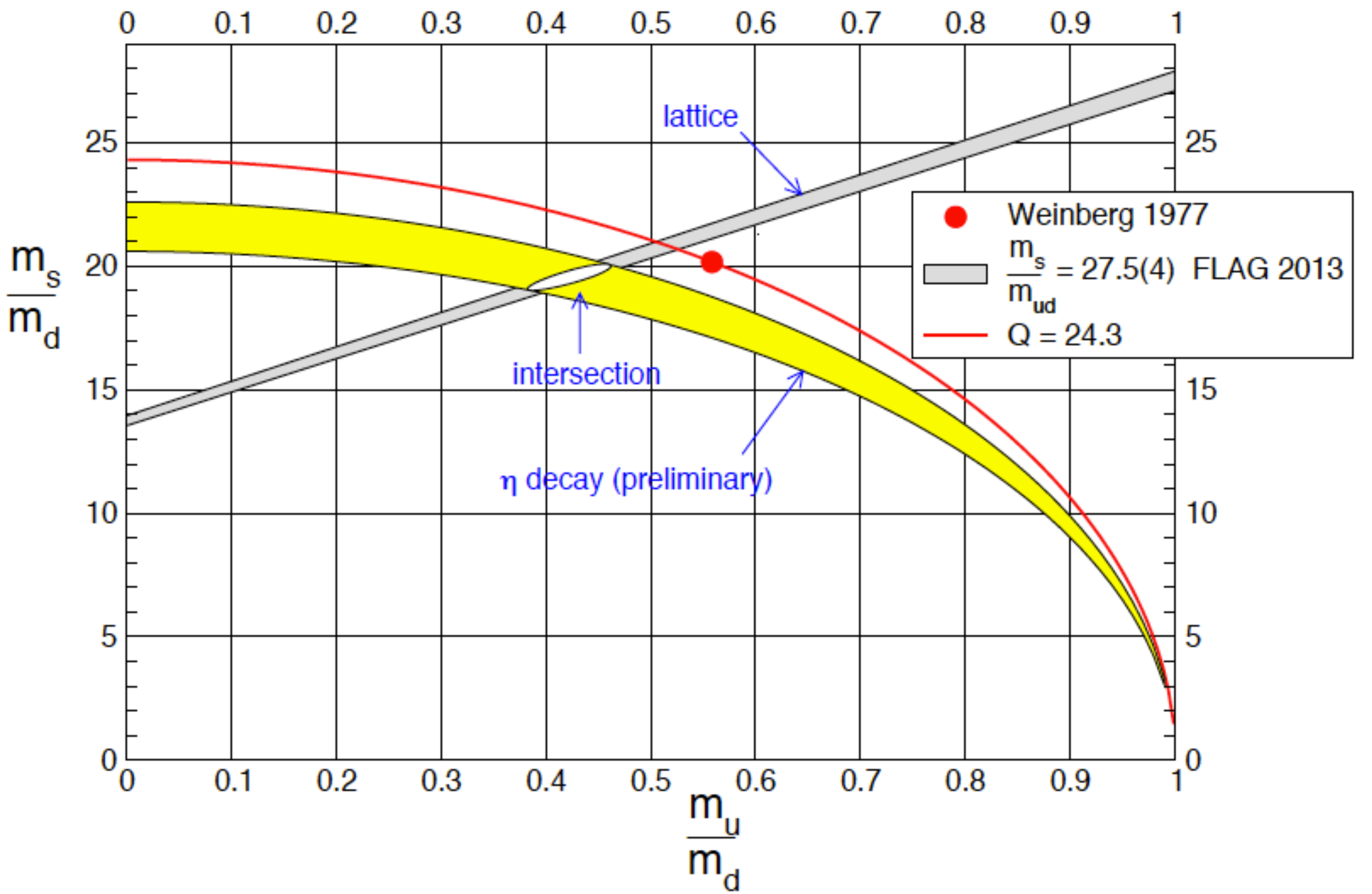
In preparation

- Analysis by JPAC *Guo et al'15* using

WASA@COSY $Q = 21.4 \pm 0.4$ and *KLOE-2@DAϕNE* $Q = 21.7 \pm 0.4$

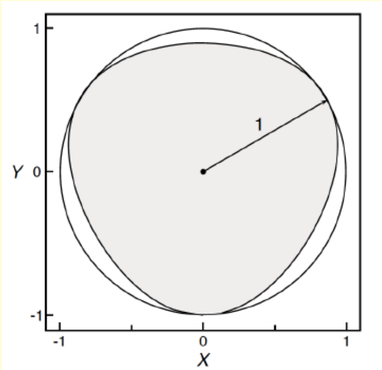
2.6 $\eta \to 3\pi$ and light quark masses

H. Leutwyler



Experimental Measurements of $\eta\rightarrow3\pi$

From Liping Gan



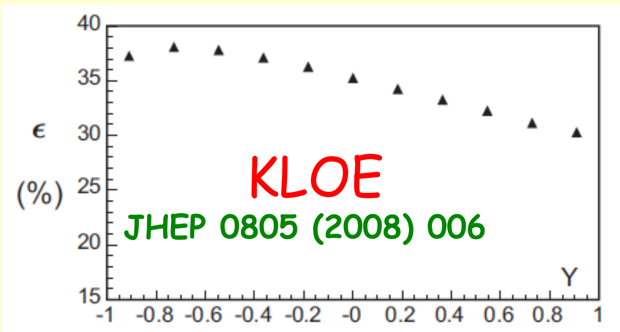
$$X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)$$

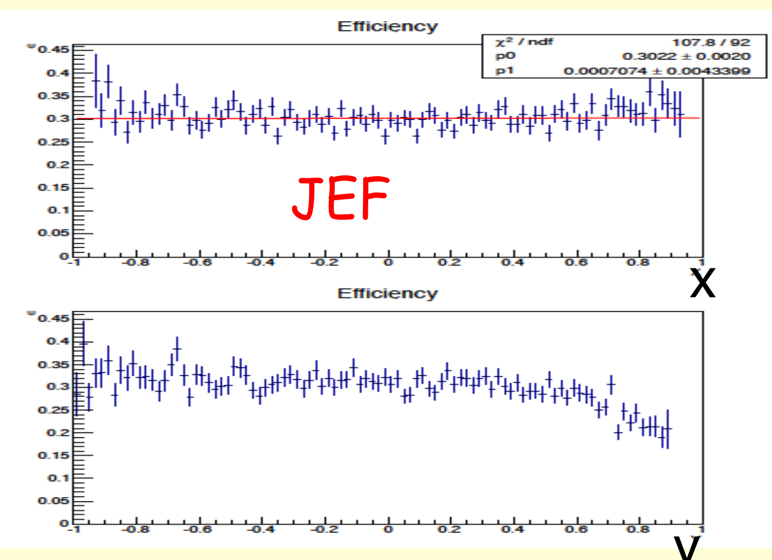
$$Q_c \equiv M_\eta - 2M_{\pi^+} - M_{\pi^0}$$

$$Y = \frac{3}{2M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1$$

$$Z = X^2 + Y^2$$

Exp.	$3\pi^0$ Events (10^6)	$\pi^+\pi^-\pi^0$ Events (10^6)
Total world data (include prel. WASA and prel. KLOE)	6.5	6.0
GlueX+PrimEx-η +JEF	20	19.6





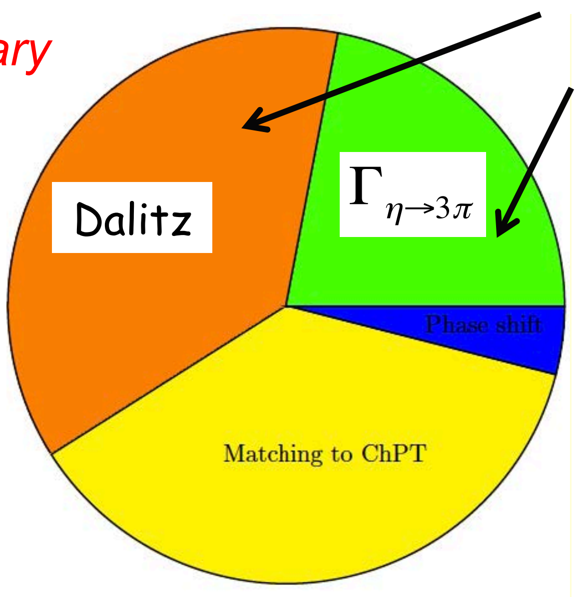
- Existing data from the low energy facilities are sensitive to the detection threshold effects
- JEF at high energy has uniform detection efficiency over Dalitz phase space
- JEF will offer large statistics and improved systematics

2.6 $\eta \to 3\pi$ and light quark masses

Colangelo, Lanz, Leutwyler, E.P., in preparation

- Uncertainties in the quark mass ratio (rough attempt)

Preliminary



Can be investigated and reduced at *JEF*