RF2: Strange and light quarks

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Snowmass Day

September 23, 2021

Outline

3 main topics:

1. Rare η and η' decays
2. Rare Kaon Physics
3. First-row CKM unitarity and lepton universality tests

1. Rare 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 with a TPC for Optical Photons (REDTOP) possibly at Fermilab (proposed)

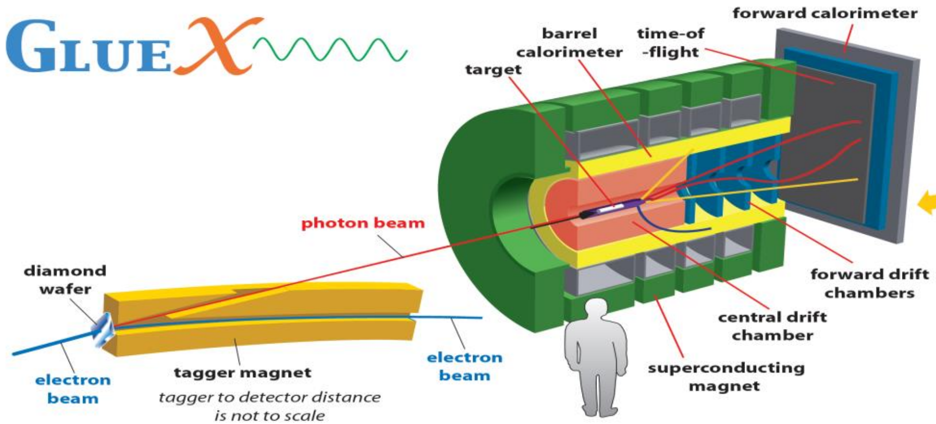
Phase I (untagged mode)	2×10^{13}	10^{11}	per year
Phase II+ (tagged mode)	1×10^{13}	10^{11}	

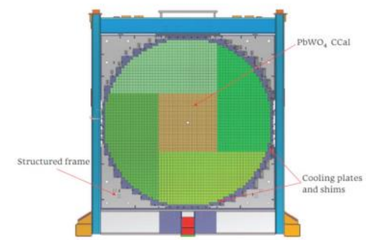
Previous experiments:

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)

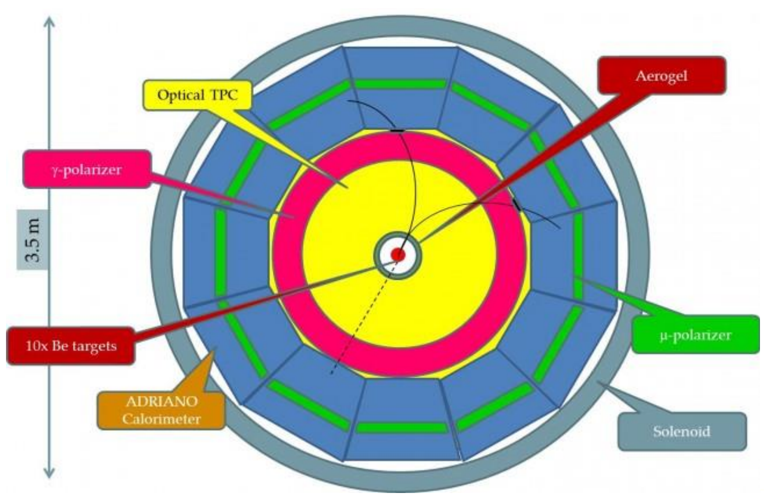


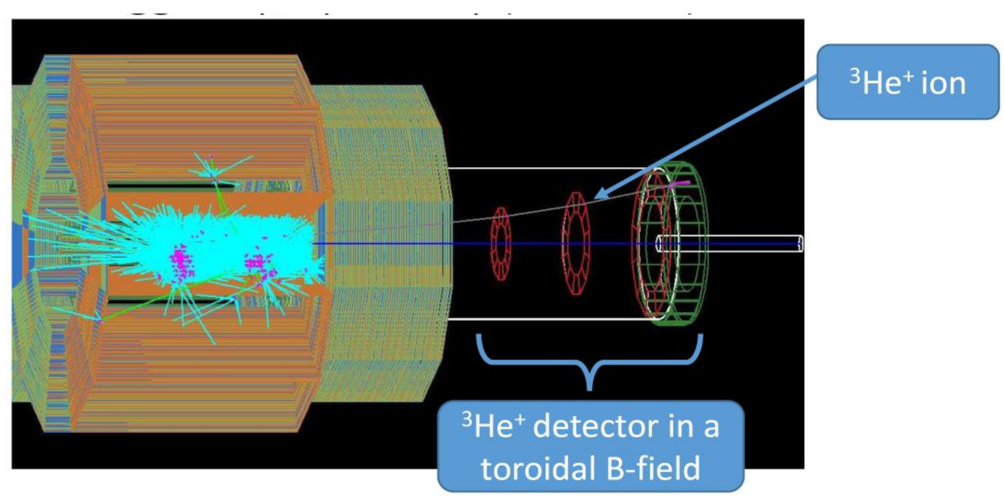


FCAL-II

Data taking expected in 2024

Rare Eta Decays with a TPC for Optical Photons (REDTOP)
Proton beam (1-3 GeV) on nuclear target (Be/D)





Very rich physics program at η and η' factories

From S. Tulin

RF/SNOWMASS21-RF6_RF2_Sean_Tulin-117.pdf
RF/SNOWMASS21-RF2_RF0_Sergi-085.pdf

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, Passemar, ST [arxiv:2007.00664]

2. Rare kaon decays

Situation before ICHEP 2020

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	**<17.8**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300

*Approx. error on LD-subtracted rate excluding parametric contributions

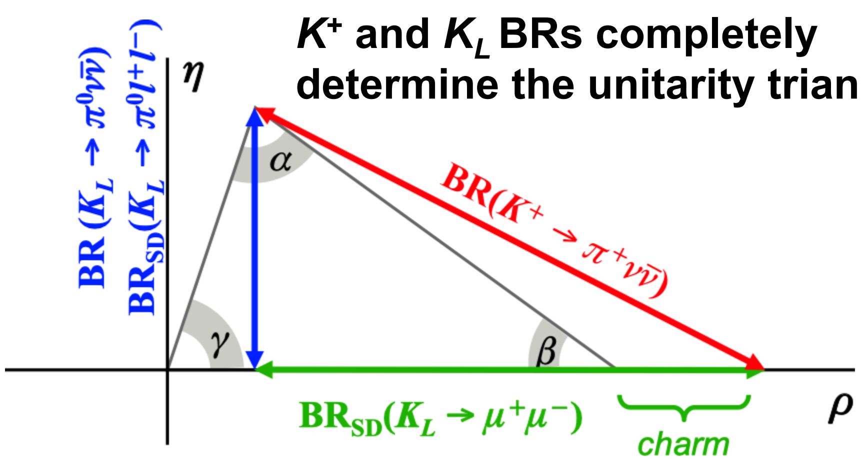
Theory err. under control

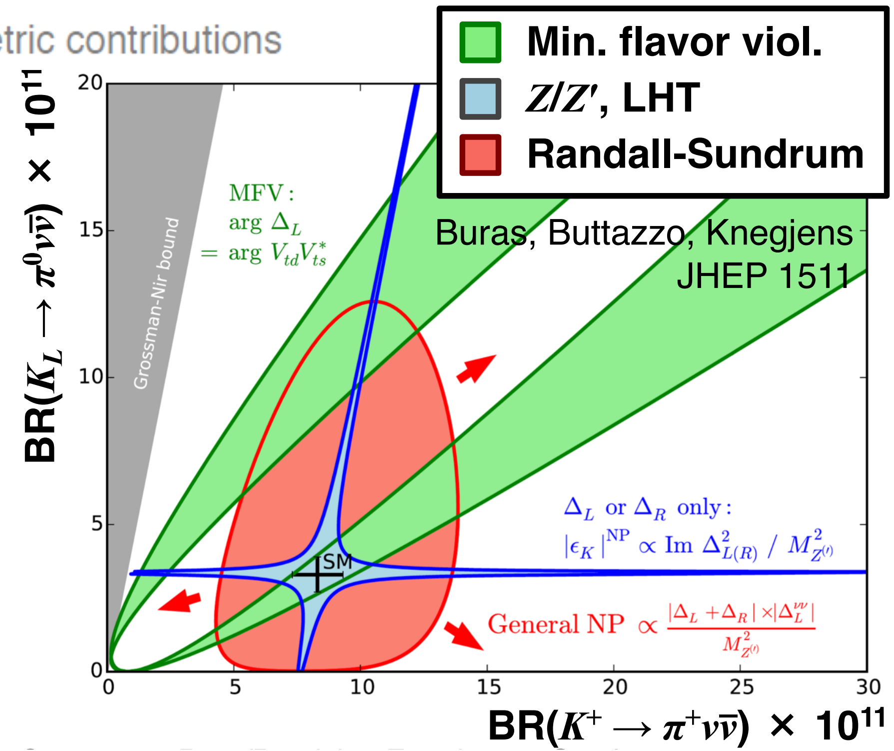
→ Plan from lattice QCD

Golden channel: $K \to \pi\nu\bar{\nu}$

Very suppressed in the SM, through FCNC

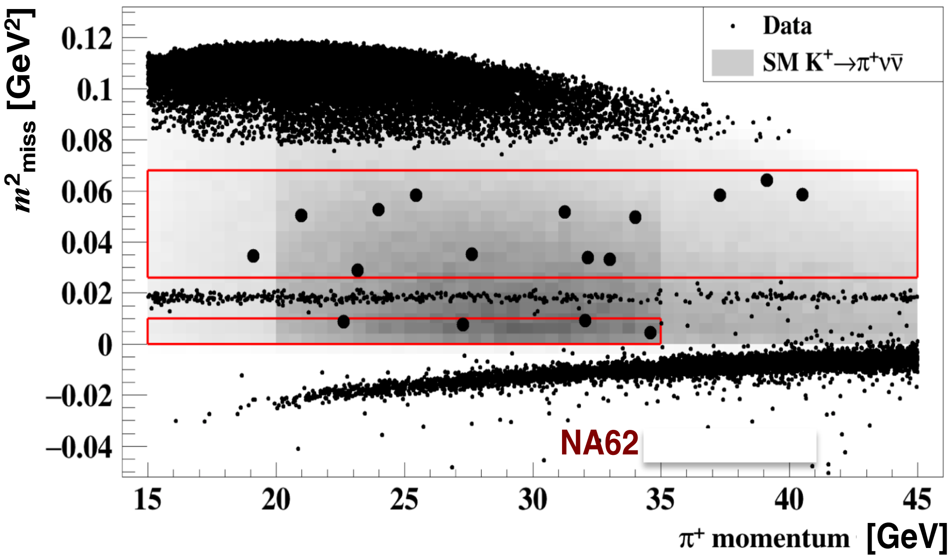
High sensitivity to BSM : corr. K_L and K^+

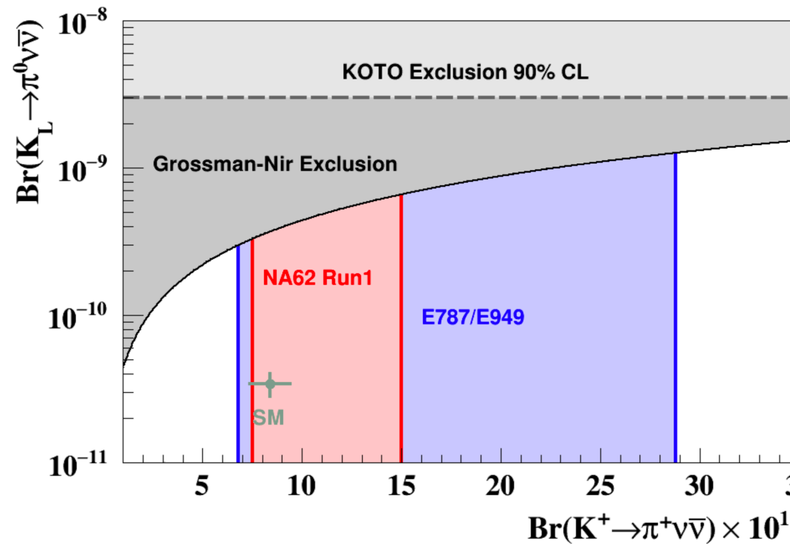




Run1 NA62 results *JHEP 06 (2021) 093*

With 2018 data





NA62 experiment: $BR\left(K^+\to\pi^+\nu\bar{\nu}\right)=\left(10.6^{+4}_{-3.4}\,|_{stat}\ \pm 0.9_{syst}\right)x10^{-11}$

- Run 1 (2016-2018) :
  Expected signal (SM): 10 events, Expected background: 7 events
  Total observed: 20 events, 3.4σ significance

- Plans for NA62 Run 2 (from LS2 to LS3): Data taking resume in July 2021 with
  - Key modifications to reduce background
  - Higher beam intensity: 70% → 100%

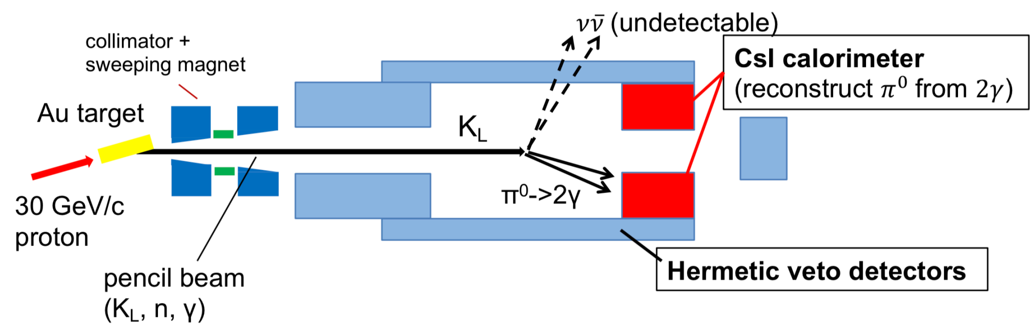
➡ **Expect to measure BR($K^+\to\pi^+\nu\nu$) to better than 20%**

KOTO experiment: *PRL 126, 121801'21*

- Limit based on 2016-2018 data: $K_L \to \pi^0 \nu\bar{\nu}$: $(\pi^0 \to)$ 2γ + nothing

$$BR\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 4.9 \times 10^{-9}\left(90\%\ \text{C.L.}\right)$$

3 events observed in signal region



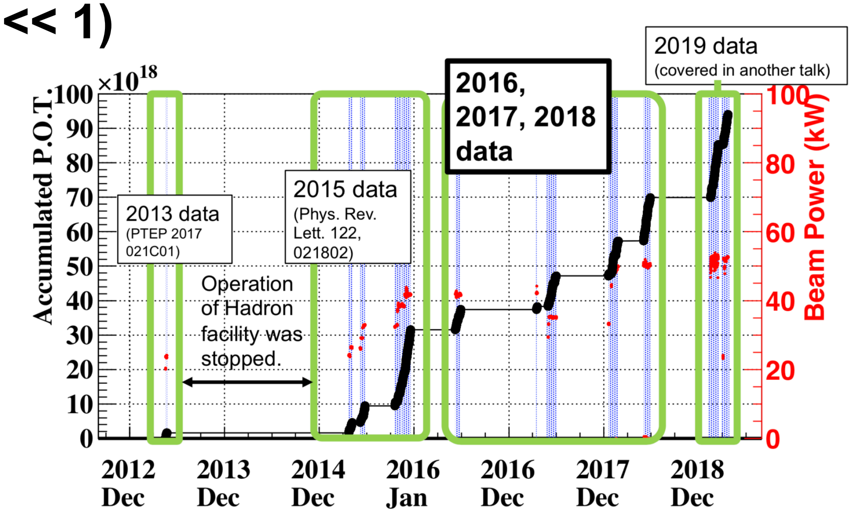
- Blind analysis of 2016-2018 data:

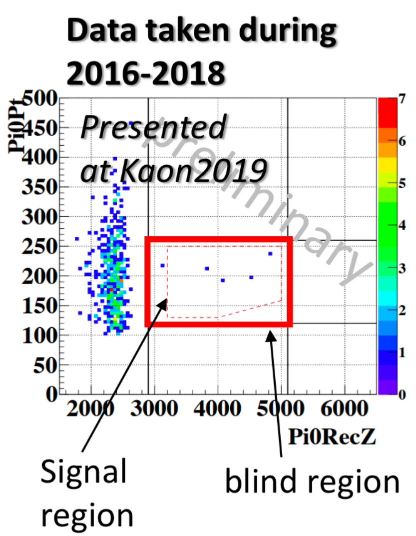
4 events in the signal region (expected << 1)

*1 event from mistake in cut application

*Additional background from charged kaon decay identified

*Upstream detector needed to veto K+: Prototype installed for 2020 run and Design in progress for higher efficiency UCV





KOTO Step-1 expects to reach SM single event sensitivity by 2025

Plots from Shinohara, KAON 2019 and Shimizu, ICHEP 2020

LHCb experiment:

- LHCb expanding its physics reach towards strange physics complementary to the core program
- Encouraging Run 1-2 results on $K_S^0 \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$
- Large samples available on tape
- Run 2 giving new results with improved trigger
- Upgrade trigger ⇨ unprecedented sensitivities on many channels
- Complementary to ***K_L*** and ***K^+*** dedicated experiments

LHCb major player for K_S and hyperons rare decays

Sensitivity Studies ArXiv:1808.03477

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K_S^0 \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K_L^0 \to \mu^+\mu^-$	~ 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
$\Lambda \to K_S^0 \to \mu^+\mu^-$	~ 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

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K_S^0 \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^-e^+$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K_L^0 \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5)$\times 10^{-3}$	~ 2.0	~ 8.0

R = ratio of production

ϵ = ratio of efficiencies

Next Generation experiments:

- Required to make a precision measurement $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and to make a significant observation of $K_L \rightarrow \pi^0 \nu\bar{\nu}$
  - Would become a very high priority if hints of new physics from NA62 or KOTO
  - In absence of hints, more precise measurements $\Rightarrow$ potential discovery

- **High intensity K^+ and K_L beams at SPS, CERN :** **RF/SNOWMASS21-RF2_RF0-010.pdf**
  3 phases with same primary beamline and interchangeable detectors
  1. "NA62x4": $K^+ \rightarrow \pi^+ \nu\nu$
  2. KLEVER: $K_L \rightarrow \pi^0 \nu\nu$
  3. Intermediate stage: K_L beam + charged-particle tracking/PID:
     $K_L \rightarrow \pi^0 l^+ l^-$; LFV and radiative K_L decays

  $K \rightarrow \pi\nu\nu$ **and** $K \rightarrow (\pi)\mu e$ **offer complementary tests for discrepancies observed in B decays**

- **KOTO Step-2**
  - construction around 2025 and ~100 events at SM level with S/N~1 (3y data).
  - Two major upgrades :
    - Higher kaon flux: reduce targeting angle from 16 degrees to 5 degrees, increase target length from 60 mm to 102 mm
    - Increase detector acceptance: increase calorimeter radius from 2 m to 3 m, increase fiducial region from 2 m to ~15 m

Next Generation experiments:

- **Fermilab based experiment?**
  - Well-developed proposals exist
  - Could be enabled by planned upgrades to Fermilab accelerator complex

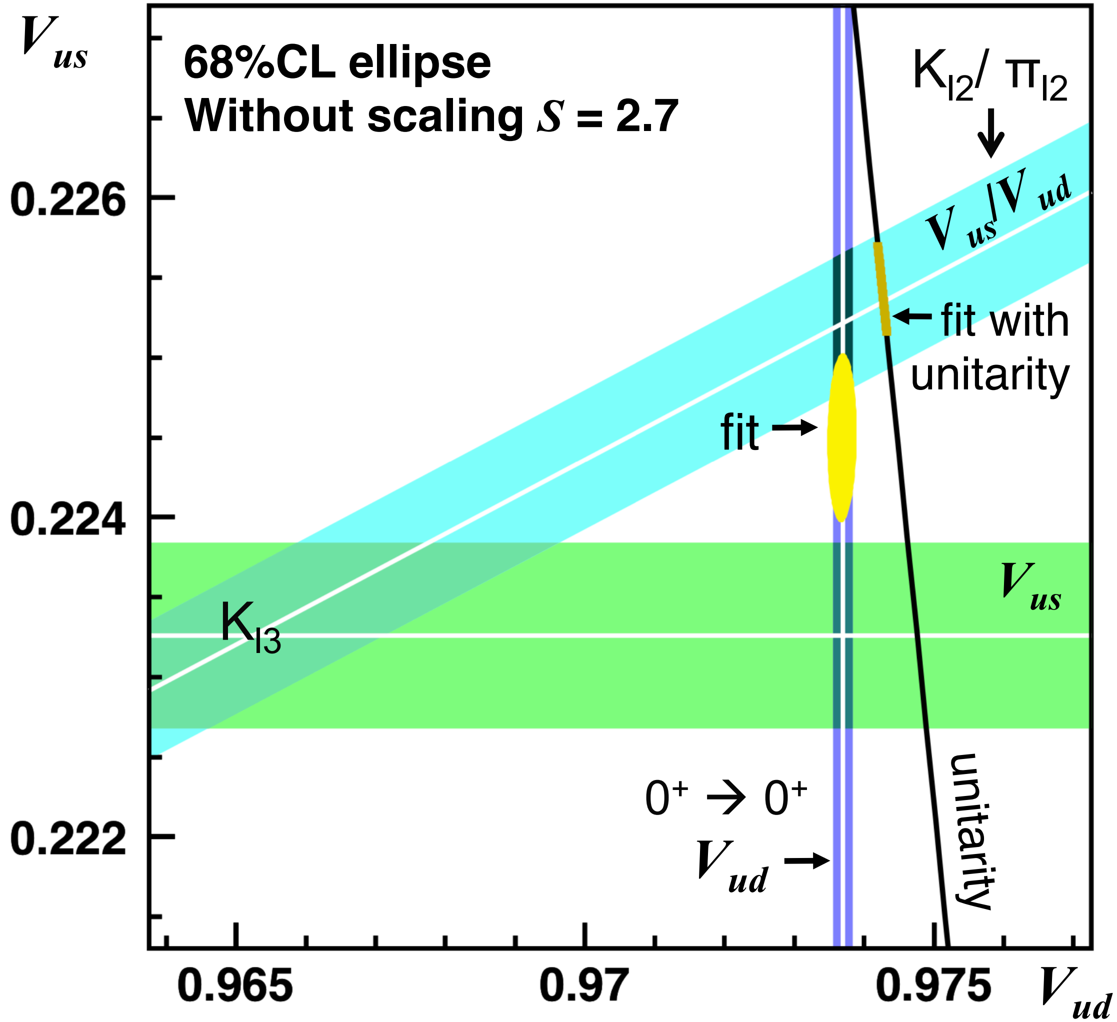
  Potential Snowmass message from Rare & Precision Frontier: *design FNAL upgrades to facilitate a broad physics program*

- **Examples of opportunities for discussion and high-level cooperation:**
  - Detector ideas and R&D: Calorimeters with photon vectoring; in-beam vetoes; signal processing and readout
  - Simulation: Benchmarking for MC and event generators; techniques for generation of large samples

- **Message from US Kaon LOI**: Both out of intellectual interest and a desire to maintain breadth in the US physics program, the US kaon physics community would like to explore possibilities for expanded US participation in the current and next-generation rare kaon decay experiments at JPARC and CERN.
  We would also like to hold open the possibility for more major contributions to these experiments or for a complementary US-based experiment if the science points in that direction.

3. First-row CKM unitarity and lepton universality tests

- Recent discrepancy with CKM unitarity:



$|V_{ud}|$ = 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

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

Broad sensitivity to BSM scenarios :

Discrepancy with CKM unitarity: -4.8σ due to change in theory inputs:

$f_+(0)$ from lattice QCD:
2σ inconsistency between K_{l3} and K_{l2} results for V_{us}
V_{us} from K_{l2} consistent with unitarity up to new V_{ud} evaluation

Leptonic decays of kaons and pions: V_{us}/V_{ud} from K_{l2} ($K\rightarrow\mu\nu$) / π_{l2}($\pi\rightarrow\mu\nu$)
Full QCD**+**QED decay rate on the lattice
⇨ Inclusion of EM and IB corrections :
- Perturbative treatment of QED on lattice established
- Formalism for K_{l2} worked out

Prospects for RBC/UKQCD: Calculation at the physical point in 2-3 years with
- continuum extrapolation
- non-perturbative renormalisation of the weak Hamiltonian in QCD**+**QED
- isospin breaking effects for sea quarks
- lattice calculation of real photon emission

Exploring to calculate QED corrections in infinite volume analytically to eliminate power-law finite volume errors

⇨ **Aim: Per mile level within 10 years**
Application of the method for **semileptonic Kaon** (K_{l3}) **and Baryon decays**

V_{ud} side: new radiative corrections to $0^+ \rightarrow 0^+$ superallowed beta decays:

2.9σ - 4.8σ discrepancy with unitarity

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

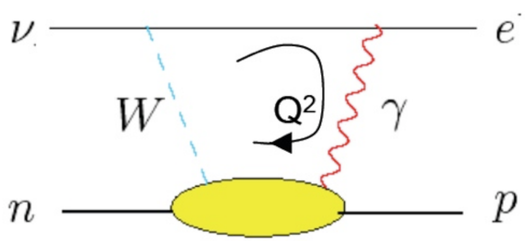
$$(1+RC) = (1-\delta_C)\,(1+\delta_R)\,(1+\Delta_R)$$

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

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

Nucleus-independent
short distance rad. corr.

- New calculation based on Dispersion Relations



Inputs needed: DIS of neutrino on nucleon but also quasi elastic neutrino nucleon data

$$|V_{ud}| = 0.97418(10)_{Ft}(18)_{\Delta_R^V}$$ ⟹ $$|V_{ud}| = 0.97370(10)_{Ft}(10)_{\Delta_R^V}$$

~1.8σ smaller

Marciano & Sirlin'06

Seng, Gorchtein, Patel & Ramsey-Musolf'18

The quest for explaining the top-row CKM unitarity deficit:

- Revisit evaluation of RC to extract V_{us} from $0^+ \rightarrow 0^+$ superallowed beta decays:
  - Improved γW box inputs
  - Evaluation of γW box on the lattice
  - Modern ab-initio calculations of nuclear corrections δ_C, δ_{NS}
- Radiative corrections (EM+IB) in K_{l2} decays

Hardy@Amherst'19

Can we extract V_{ud} differently?

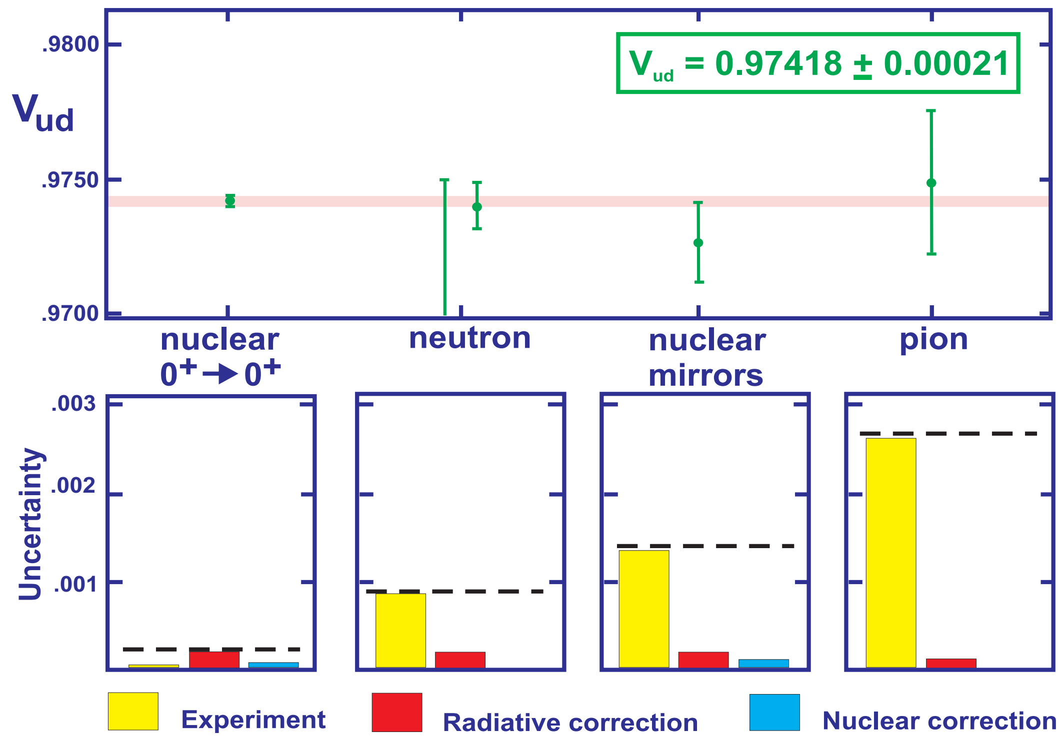
- **From neutron decays**

  *UCNτ → UCNτ+ → Next Gen
  *UCNA → UCNA+ → Next Gen
  *Radiative Corrections:
  lattice QCD and
  effective field theory.

  Effort undertaken at LANL

- **From** $\pi^+ \rightarrow \pi^0 e^+ \nu$

  PIENUXE proposal



Conclusion

3 main topics with interesting proposals for the future

1. Rare η and η' decays

2. Rare Kaon Physics

3. First-row CKM unitarity and lepton universality tests

Please contact us if you are interested to contribute !

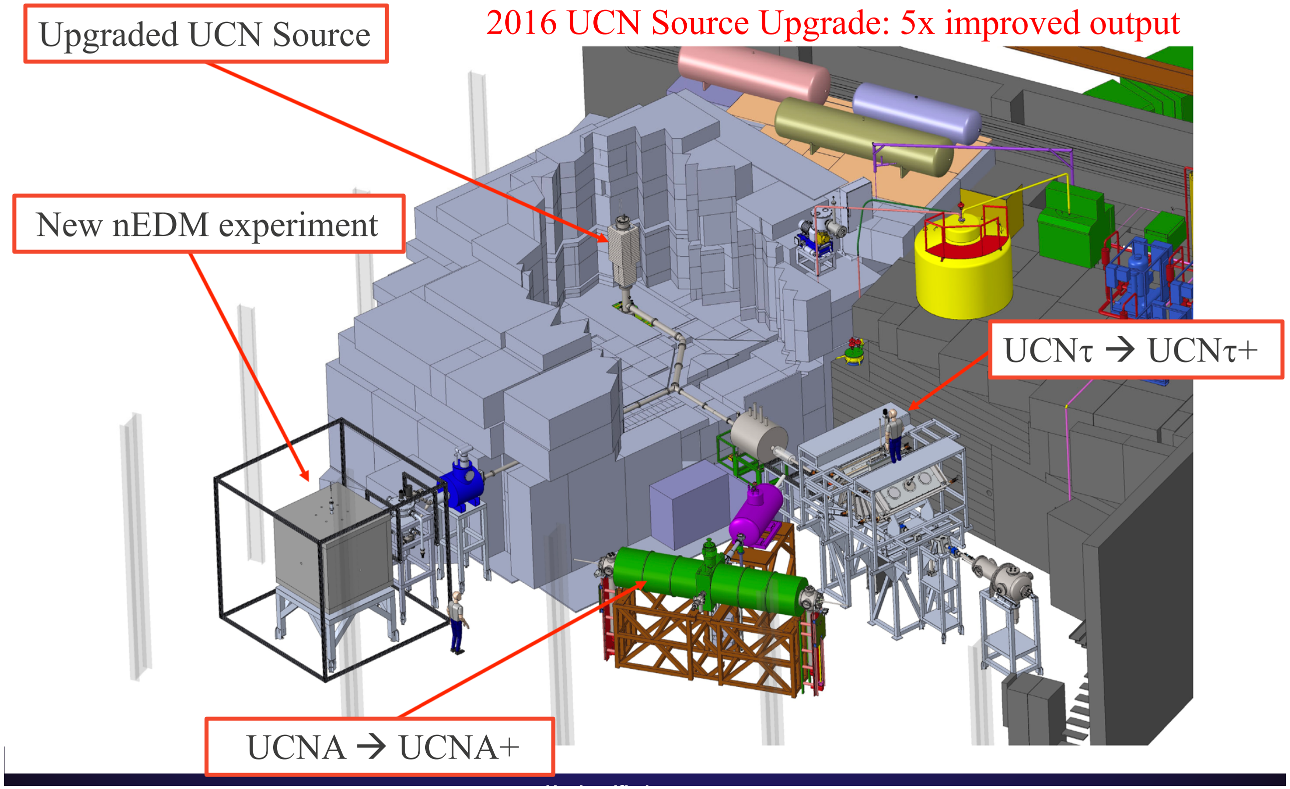
Web: https://snowmass21.org/rare/weaksud

Mailing list: SNOWMASS-RPF-02-LIGHT-QUARKS@FNAL.GOV

Slack channel: rpf-02-light-quarks

Back-up

V_{ud} from neutron decay



- Requires

  *UCNτ → UCNτ+ → Next Gen
  *UCNA → UCNA+ → Next Gen
  *Radiative Corrections: lattice QCD and effective field theory.

All three efforts are underway at LANL to resolve the V_{ud} – SM discrepancy.

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

$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.036 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.003_{\pi e2})\ x10^{-8}\ (\pm 0.6\%)$$

$$\left|V_{ud}\right| = 0.9739(28)_{exp}(1)_{th}$$

Next Generation experiment: Goal 0.06%

Opportunity to extract V_{us}/V_{ud} from $\dfrac{B(K \to \pi l \nu)}{B(\pi^+ \to \pi^0 e^+ \nu)}$ *Czarnecki, Marciano, Sirlin'20*

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

Marciano & Sirlin, Cirigliano

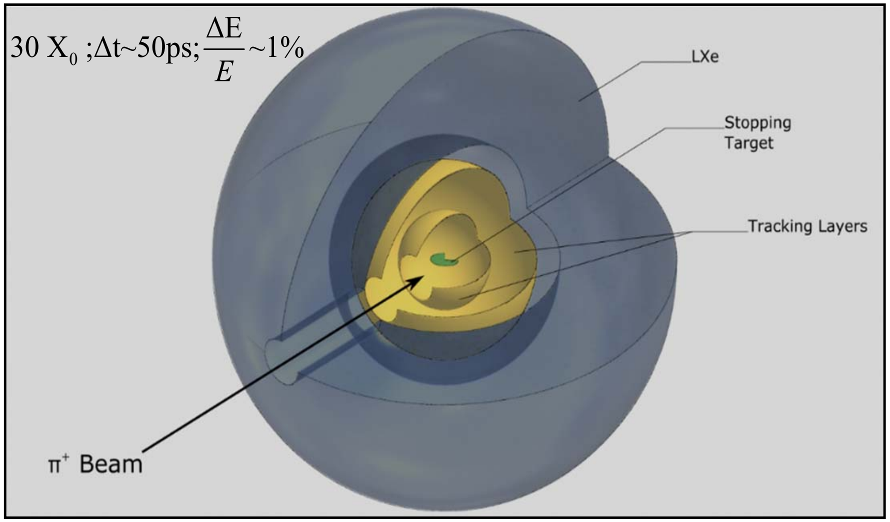
Test of LFU from $R^{theory}_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = (1.2353 \pm 0.0002)\, x10^{-4}$ (0.016%)

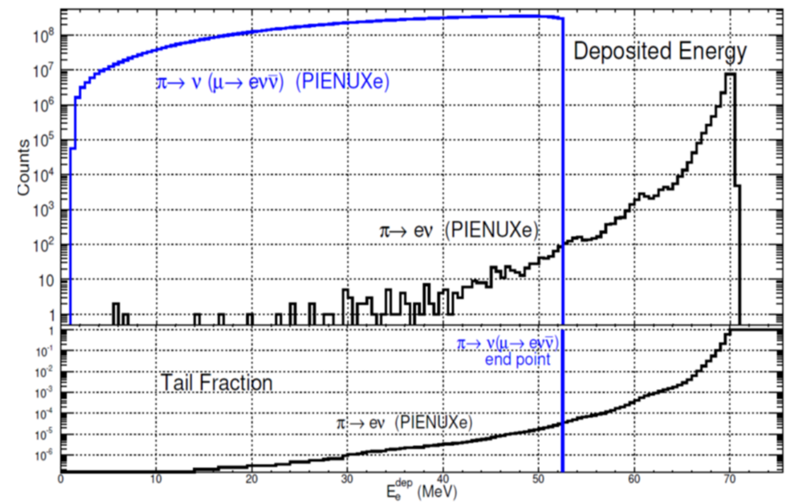
Present Experimental result: $R^{\exp\pi}_{e/\mu} = 1.2327 \pm 0.0023 x10^{-4}$ (0.19%) *PDG'20*

→ **Goal next generation PIENUXE: 0.015%** → $\dfrac{g_e}{g_\mu} \sim (\pm 0.0075\%)$

V_{ud} from pion β decay: $\pi^+ \rightarrow \pi^0 e^+ \nu$ *and Lepton Flavour Universality*

PIENUXE: New Rare π Decay Experiment with LXe





Faster calorimeter response time x10-100.

Low energy tail reduced x 10

$$\pi^+ \rightarrow e^+ \nu$$

- π^+Beam: 75 MeV/c ; $2\text{x}10^5$ Hz
- Tracking –SciFi-SiPM, Si pixels
- LXe calorimeter
- Sensitivity, Precision: 10^8 events ±0.015% in 1 yr

$$\frac{g_e}{g_\mu} \sim (\pm 0.0075\%)$$

$$\pi^+ \rightarrow \pi^0 e^+ \nu$$

- π^+Beam: 75 MeV/c ; $3\text{x}10^7$ Hz
- Sensitivity, Precision: 10^6 events ±0.1% in 1 yr

$$V_{ud} \sim (\pm 0.03\%) \qquad \frac{V_{us}}{V_{ud}} \sim (\pm 0.1\%)$$