Rare K decays off and on the lattice

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Lattice 2023-Fermi Lab

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Key Points

1. **K+ =>pi+ nu nu off and on the lattice**

   Pheno: WIP with E. Lunghi: Impr determination of Vub using Gounaris+Sakurai;

PRL'60

2207.52860

2212.01424

See also ATS et al

1910.10644

1806.11520

1701.02858

Lee + Zumino.

PRD'67

+ Improvements in eps' and in K-UT
Expt progress and status
Lattice: RBC-UKQCD several papers

Key points (contd)

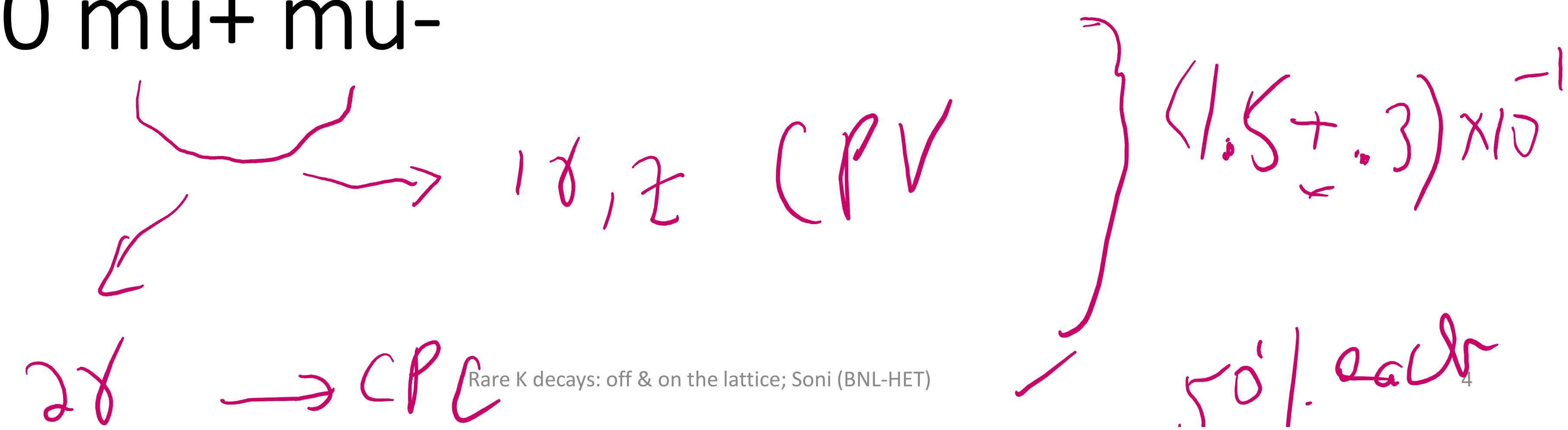
- **2. KL => pi0 nu nu ; Gold-plated but experimentally exceedingly challenging. Status & Outlook**

  3.KL=>pi ee ; Early work; interesting pioneering paper & PhD thesis by German Valencia.
  Atwood + AS unpublished
  Important paper on background issues by Greenlee
  Because of the extremely important point due Greenlee, it does not seem that KL=> pi ee is useable

  4. K0=> pi0 mumu i.e. KL AND KS extremely useful to study for experiments, pheno AND for the lattice.
  WIP with Stefan Schacht

  Summary

Main purpose: strongly advocate that lattice community should pay high priority to get precise results for K0 to pi0 mu+ mu-



K-UT: A dream for some

Blucher, Winstein and Yamanaka '09; see also Buras

Construction of a Kaon UT

- Click to add t

GOLD

LITTENBERG PRD'89

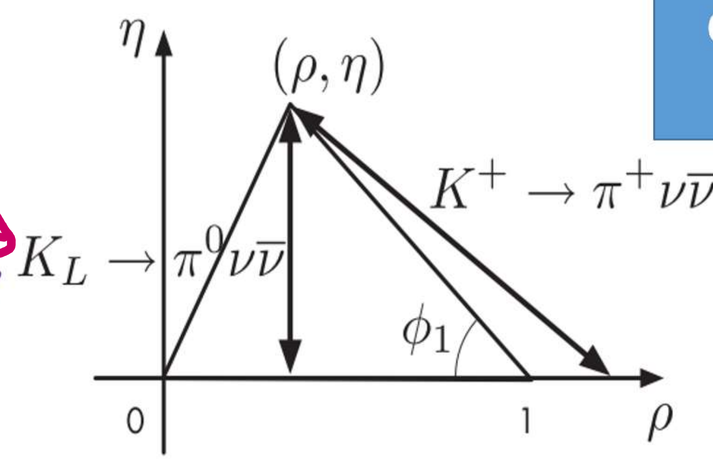
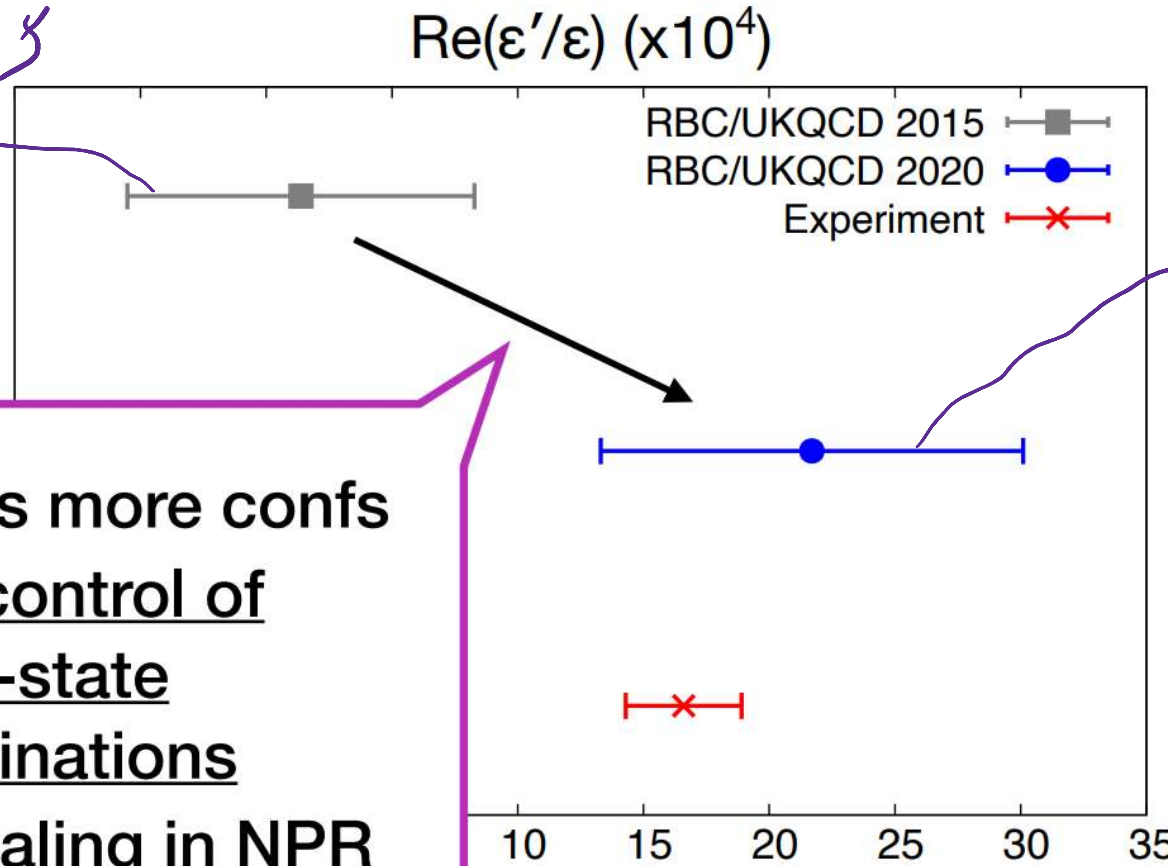


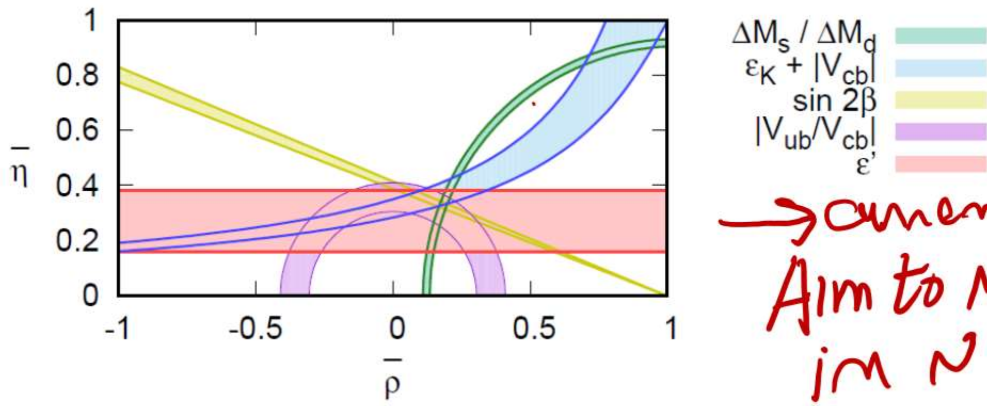
Fig. 14. Unitarity triangle.

Lehner+Lunghi+AS PLB'2016

Instead of [or in addition to] $K_L \to \pi^0 \nu\bar{\nu}$ can now plan on using ϵ'/ϵ



- 3+ times more confs
- <u>Better control of excited-state contaminations</u>
- Step scaling in NPR



→ current systom ~35%.
Aim to reduce This
in ~3 M to ≈15%.

FIG. 12: The horizontal-band constraint on the CKM matrix unitarity triangle in the $\bar{\rho} - \bar{\eta}$ plane obtained from our calculation of ε', along with constraints obtained from other inputs [6, 70, 71]. The error bands represent the statistical and systematic errors combined in quadrature. Note that the band labeled ε' is historically (e.g. in Ref. [72]) labeled as ε'/ε, where ε is taken from experiment.

Precision performance

		32^3 G-parity BC (previous work)	24^3 Periodic BC	32^3 Periodic BC (w/o AMA correction)
	# of configurations	741	258	107
Error % (statistical)	$\Delta I = 1/2$ ME via Q_2^{lat}	10%	14%	14%
	$\Delta I = 1/2$ ME via Q_6^{lat}	6.5%	8.9%	11%
	Re A_0	11%	13%	14%

Preliminary (24^3 Periodic BC and 32^3 Periodic BC columns)

- Good precision performance of PBC (ME with excited-state ππ) compared to G-parity BC calculation (ME with ground-state ππ)

PBC
effort
MasaakiT
etc

Quantity	This work	Experiment
$\mathrm{Re}(A_2)$	$1.74(15)(48) \times 10^{-8}$ GeV	$1.479(4) \times 10^{-8}$ GeV
$\mathrm{Im}(A_2)$	$-5.91(13)(1.75) \times 10^{-13}$ GeV	...
$\mathrm{Re}(A_0)$	$3.13(69)(95) \times 10^{-7}$ GeV	$3.3201(18) \times 10^{-7}$ GeV
$\mathrm{Im}(A_0)$	$-9.3(1.5)(2.8) \times 10^{-11}$ GeV	...
$\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$	18.0(4.4)(7.4)	22.45(6)
$\omega = \mathrm{Re}(A_2)/\mathrm{Re}(A_0)$	0.056(14)(23)	0.04454(12)
$\mathrm{Re}(\varepsilon'/\varepsilon)$	$31.8(6.3)(11.8)(5.0) \times 10^{-4}$	$16.6(2.3) \times 10^{-4}$

Masaaki T
et al
2306.06781

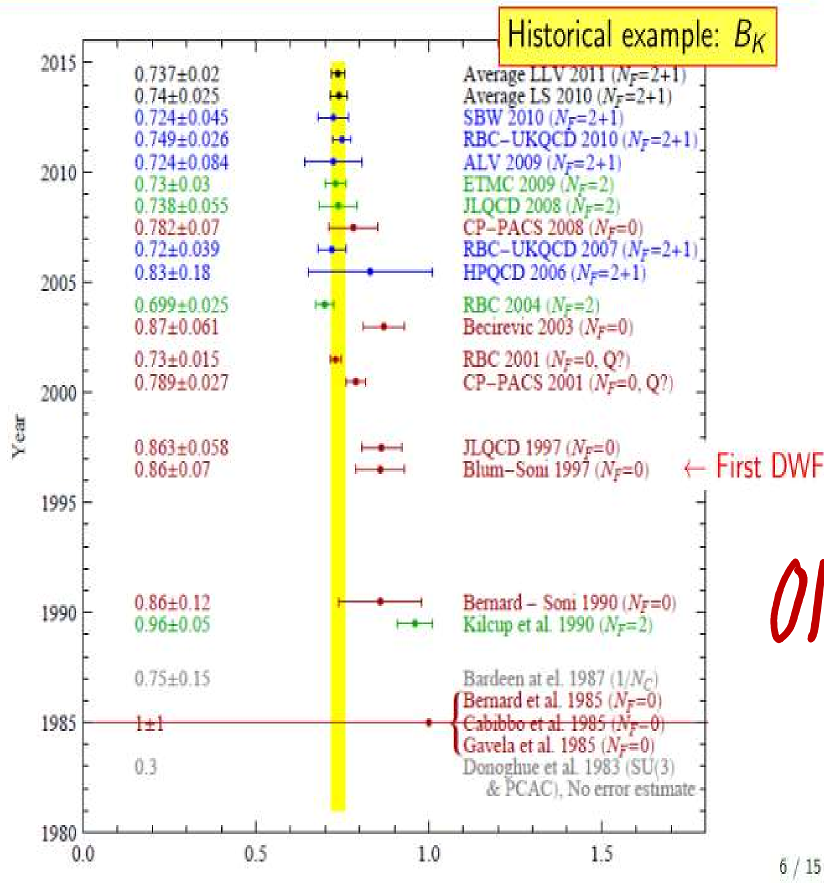
TABLE I. A summary of the primary results of this work shown in the middle column. The values in parentheses give the statistical and systematic errors, respectively. For the last entry the systematic error associated with electromagnetic and isospin breaking effects is listed separately as the third error, which we inherit from the estimation in Ref. [2] based on the large-N_c expansion of QCD and ChPT [49]. The corresponding experimental values are shown in the right column if applicable.

Key points (so far) on our PBC effort

- **Demonstrated that with GEVP matrix elements of ground and 1st two excited states can be extracted quite well**
- **Good quality of signals with PBC obtained rather efficiently**
- **On our way to get results from 2 lattice spacings**
- **Optimistic that we can get epsilon' in the continuum limit (for the iso-symmetric) case in**

about a year…That should appreciably reduce one of the major source of systematic errors.

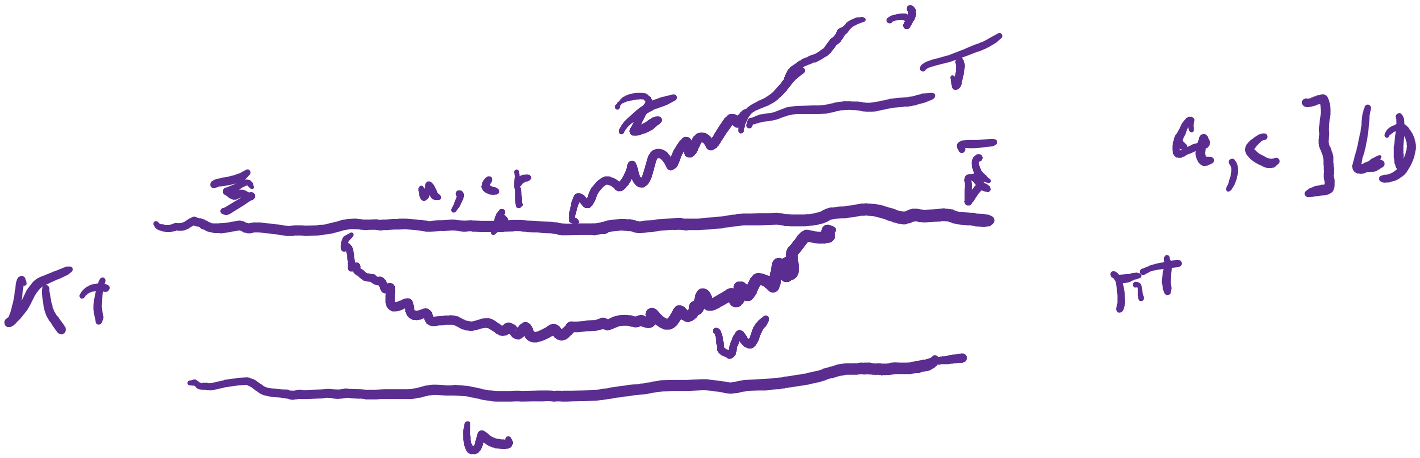
Power of the lattice: Only method to systematically reduce the NP error!



AB-Initio Calculations

$$B_K = \frac{\langle K|(\bar{s}d)^2|\bar{K}\rangle}{8/3\, f_K^2\, m_K^2}$$

ONE ILLUSTRATION



WITH ENRICO LUNGI

TRY Reduce LD uncertainty

WIP

=

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}.$$

NLO

In the above formula, the explicit numerical uncertainty is the theoretical one originating from QCD and electroweak uncertainties, which amounts to 3.6%. Taking the latest values (28) for $|V_{cb}|_{\mathrm{avg}} = (41.0 \pm 1.4) \times 10^{-3}$ and $\gamma = (72.1^{+4.1}_{-4.5})^\circ$, one finds the following:

$$B(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.5 \pm 1.0) \times 10^{-11}.$$

The predictions are currently dominated by the parametric uncertainty that will plausibly be reduced by new measurements of $|V_{cb}|$ and γ by LHCb and Belle II.

cannot be detected. A long series of decay-at-rest searches for $K^+ \to \pi^+ \nu\bar{\nu}$ have culminated with the final results of the BNL E787/E949 experiments, which found the following (50):

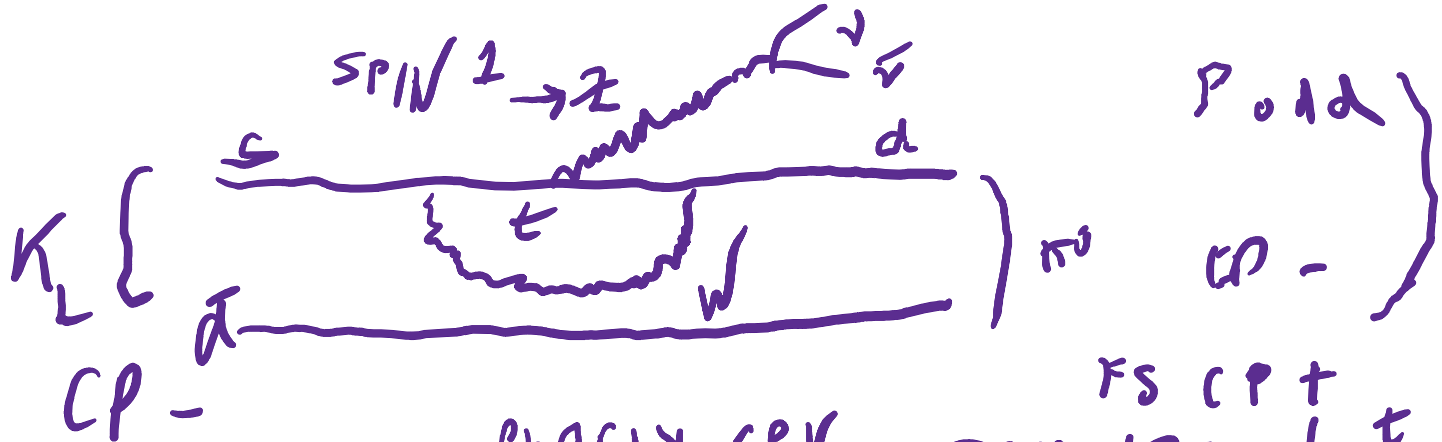
$$B(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{E787/E949}} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}.$$

From these analyses, the best upper limit, at 90% confidence level (CL), has been obtained:

$$B(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62(2016\text{–}2017)}} \leq 17.8 \times 10^{-11}.$$

The 2016–2017 data also allow one to set a 68% CL mean value for the branching ratio:

$$B(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62(2016\text{–}2017)}} = (4.8^{+7.2}_{-4.8}) \times 10^{-11}.$$



PURELY CPV

DOMINATED by t

LITTENBERG PRD 1989

GOLD PLATED

KOTO@JPARC

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^2 \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^2,$$

which, taking the latest values (28) for $|V_{cb}|_{\text{avg}} = (41.0 \pm 1.4) \times 10^{-3}$, $|V_{ub}|_{\text{avg}} = (3.82 \pm 0.24) \times 10^{-3}$, and $\gamma = (72.1^{+4.1}_{-4.5})^\circ$, leads to the following numerical prediction:

SM $$B(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.2 \pm 0.6) \times 10^{-11}.$$ ←

While the experimental situation for $K^+ \to \pi^+ \nu\bar{\nu}$ shows that we have two independent experimental techniques that can reach SM sensitivities, with the NA62 experiment on the way to making a precise measurement, the situation for the neutral mode is more complex. Progress has been hampered by the lack of a clean experimental signature because no redundancy is available once the π^0 mass is used as a constraint to reconstruct the decay vertex. The KOTO experiment at J-PARC builds on the experience of the predecessor experiment E391a (67), which was performed at KEK. It is based on the technique of letting a well-collimated "pencil" beam enter the decay region surrounded by high-performance photon vetoes. By vetoing extra photons and applying a transverse momentum cut (150 MeV/c) to eliminate residual $\Lambda \to n\pi^0$ decays, KOTO is expected to reach SM sensitivities by the mid-2020s. The KOTO experiment has published the best upper limit (68):

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_{\text{KOTO}} < 3.0 \times 10^{-9} \text{ (90\% CL)}.$$ ←

~ about 2 orders of magnitude to go

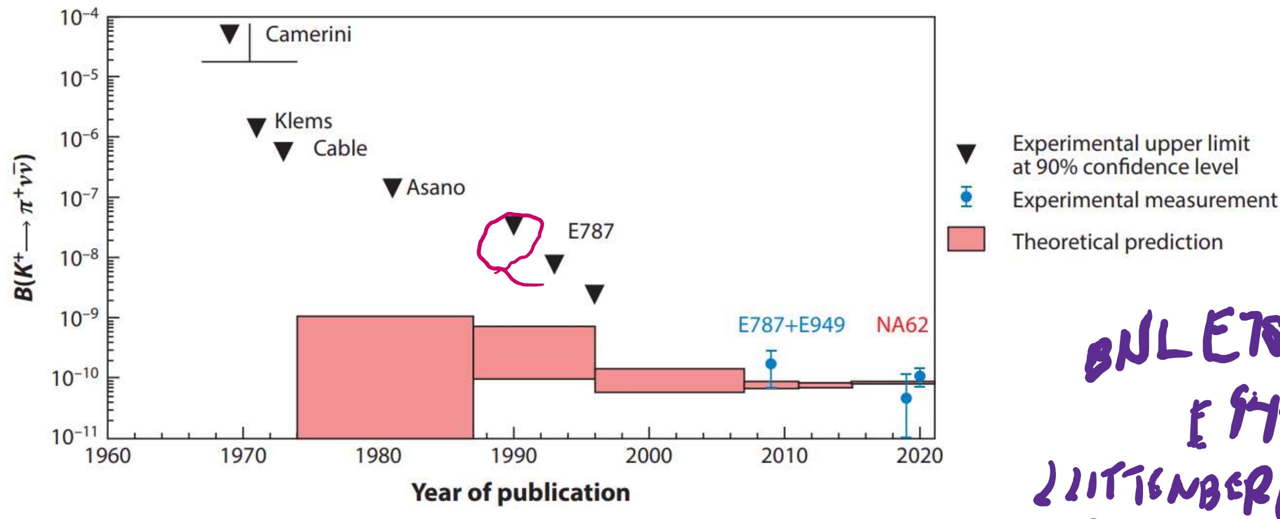


Figure 4

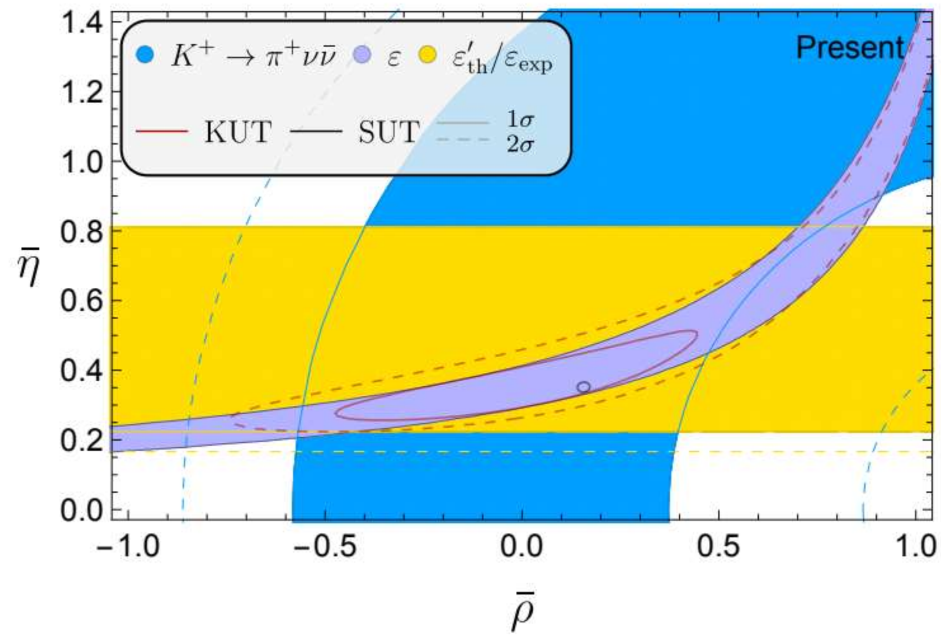
Timeline of theoretical predictions and experimental results for $K^+ \to \pi^+ \nu \bar{\nu}$ (10, 51, 57–64). Figure adapted with permission from Reference 58; copyright 2020 CERN for the benefit of the NA62 Collaboration.

the NA62 Collaboration reported the following:

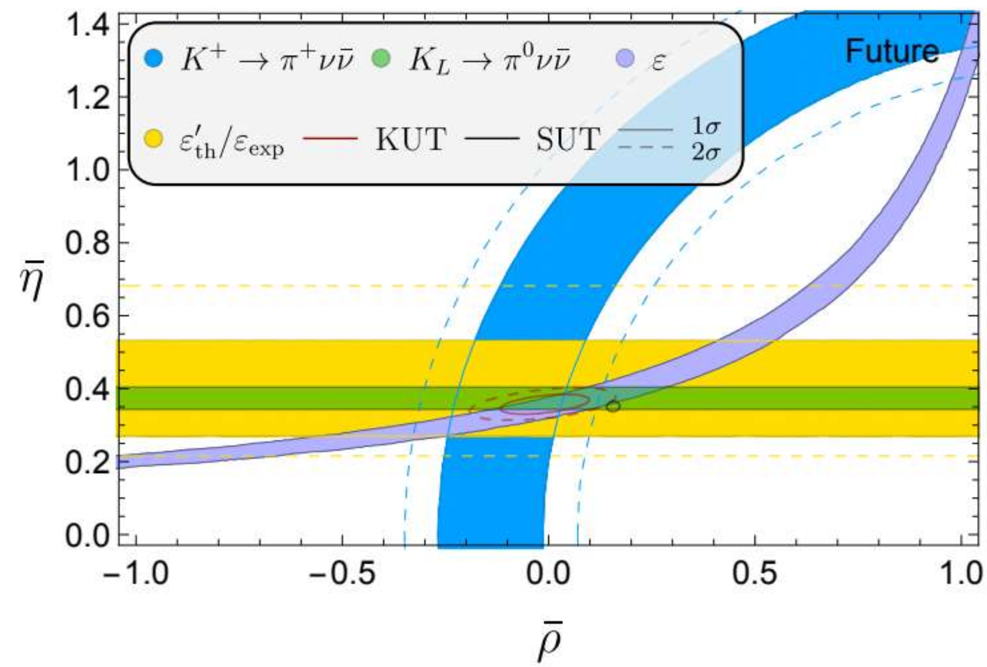
$$B(K^+ \to \pi^+ \nu \bar{\nu})_{\mathrm{NA62(2016\text{–}2018)}} = (11.0^{+4.0}_{-3.5}{}_{\mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11},$$

BNL E787 + E949
LITTENBERG
PANOFSKY
PRIZE

$10^{-8} \to 10^{-10}$
$\approx$ 20 years

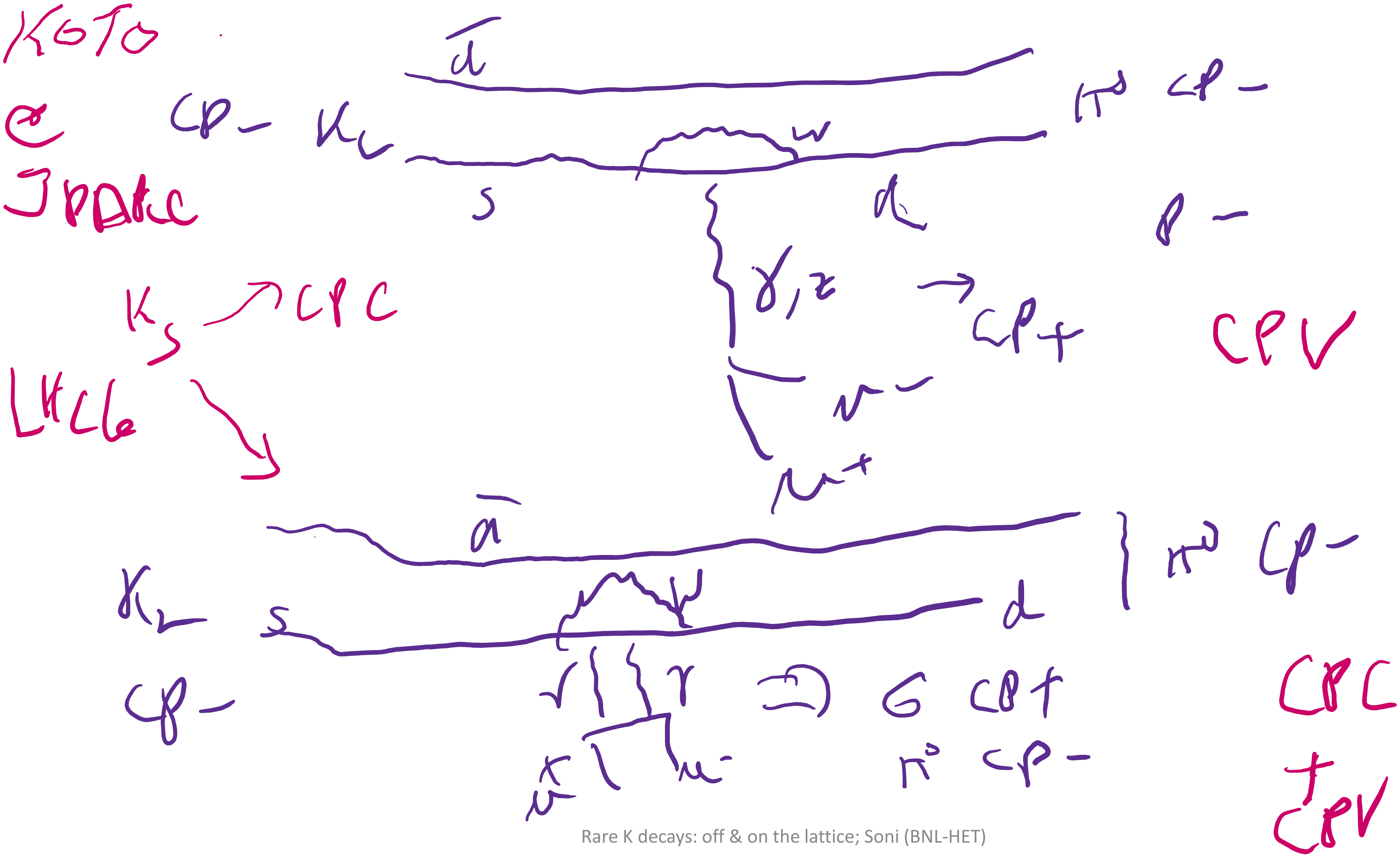


Lehner + Lunghi + AS PLB'16


$K^+ \to \pi^+ \nu\bar{\nu}$
$K_L \to \pi^0 \nu\bar{\nu}$
ε
$\varepsilon'_{\rm th}/\varepsilon_{\rm exp}$
KUT
SUT
1σ
2σ
Future
$\bar{\eta}$
$\bar{\rho}$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.5
0.0
0.5
1.0

Remaining points

- **Given that KL=> pi0 nu nu is exptally so challenging why don't (can't) we try replace with KL=>pi0 e+ e-?**
- **1st very nice attempt in this direction was made in a beautiful PhD thesis work of German Valencia; see also PRD'87 paper by DHV**
- **Also Atwood + AS (unpublished)**
- **(insurmountable) difficulty is the "Greenlee" background**
- **(see PRD Greenlee '90)**
- **Why not consider KL=> pi0 mu+ mu-?**
- **Existing work on KL=> pi0 mu+ mu- by Isidori et al; WIP by Schacht+AS**


KOTO
@
JPARC
CP-
K_L
s
d
W
π⁰ CP-
γ, Z
CP+
CPV
K_S → CPC
LHCb
CPC
+
CPV

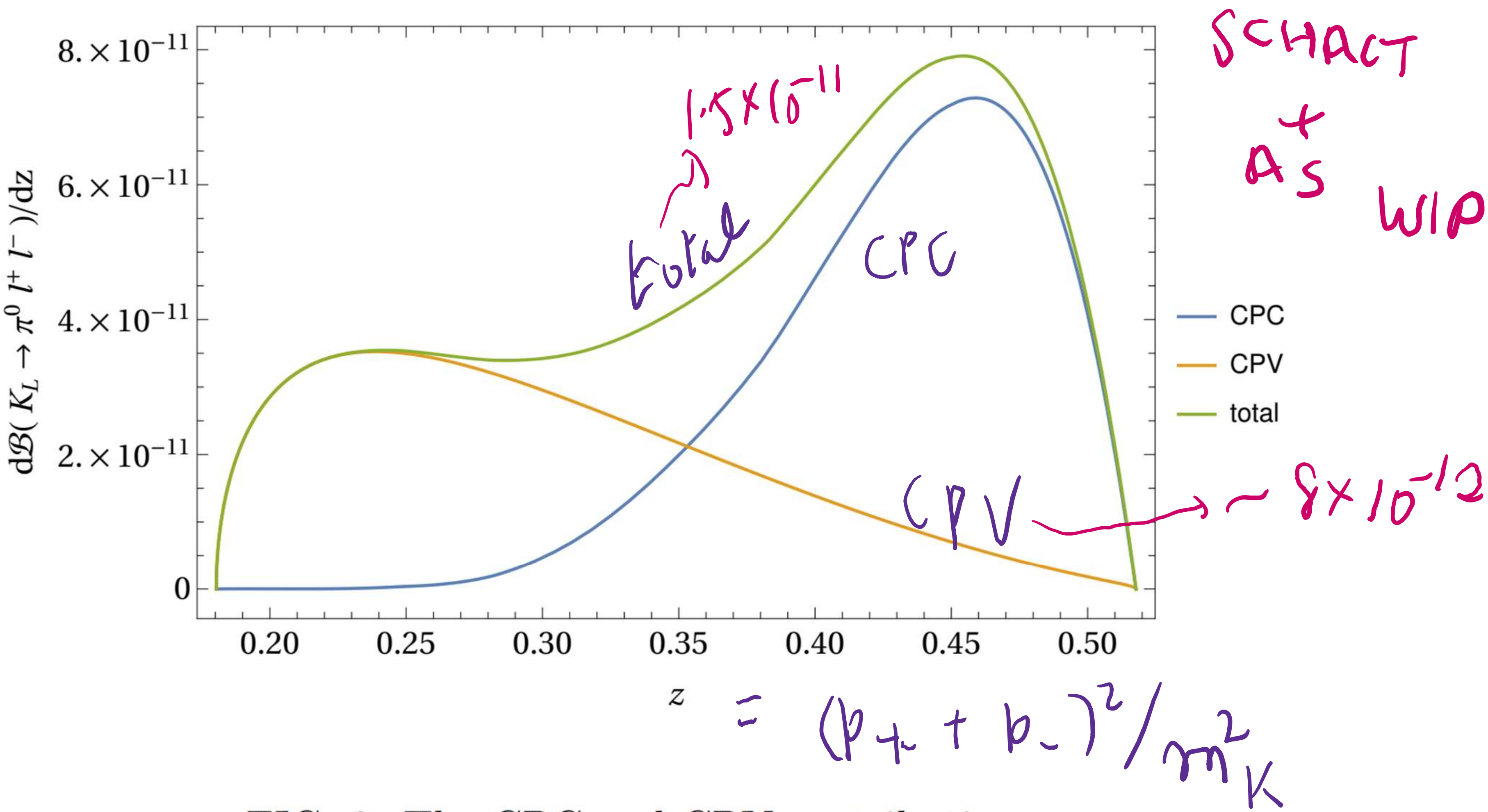


FIG. 2. The CPC and CPV contributions.

Summary

- Considerable progress on the experimental and the theory front on K+ => pi+ nu nu……This is one important pillar in Kaon UT
- KL => pi0 nu nu while gold plated, experimental progress near the SM prediction is highly unlikely to come for many years perhaps for 10 years
- Meantime theoretical progress on eps' will continually improve and provide a very useful constraint on the KUT.
- Experimental progress on K0 [both KL and KS] to pi0 mu+ mu- by KOTO at JPARC as well as LHCb is strongly advocated
- In particular precision study by the lattice of K0 => pi0 mu+ mu- is strongly

suggested….In this regard existing and ongoing work of RBC-UKQCD on K+ => pi+ nu nu is noted. Noted is also En-Hung Chao and Norman Christ et al's work on a related mode KL=> mu+ mu-

In fact if you can do precisely Kl3….you should seriously consider K^0 to pi0 mu+ mu-